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# Estimation of azimuthal anisotropy from VSP data using multicomponent S-wave velocity analysis

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## ABSTRACT

Observation of azimuthal shear wave anisotropy can be useful for characterization of fractures or stress fields. Shear wave anisotropy is often estimated by measuring splitting of individual shear wave events in vertical seismic profile (VSP) data. However, this method may become unreliable for zero-offset (marine) VSP where the seismogram often contains no strong individual shear events, such as direct downgoing shear wave, but often contains many low-amplitude PS mode converted waves. We have developed a new approach for estimation of the fast and slow shear wave velocities and orientation of polarization planes based on the multicomponent linear traveltime moveout velocity analysis. This technique is applicable to zero-offset VSP data, and should take advantage of the presence of a large number of shear wave events with the same apparent velocity (which, for a horizontally layered medium, should be close to the interval velocity). The approach assumes that the VSP data are acquired in a vertical well drilled in an orthorhombic medium with a horizontal symmetry plane (including horizontal transverse isotropy). The main idea is to estimate the dominant apparent velocity for a given polarization direction by measuring the coherency of the seismic signal of a large number of events as a function of the apparent velocity. The algorithm was tested on marine three-component (3C) VSP acquired in the North West Shelf of Australia, and on land 3C VSP acquired with different sources in the same borehole located in Otway Basin, Victoria. These tests show good agreement between anisotropy parameters (magnitude and orientation) derived from the VSP and cross-dipole sonic log data.

## INTRODUCTION

Observation of shear wave anisotropy is widely used for such purposes as characterization of fractures, orientation of fracture sets (Crampin, 1985, Horne et al., 1997, Horne, 2003), and estimation of stress field parameters (Turner and Hearn, 1995, Johnson and Rasolofosaon, 1996).

Shear wave (S-wave) azimuthal anisotropy can be evaluated from multicomponent seismic measurements using the shear wave splitting (Crampin, 1985). In an orthorhombic medium with a horizontal symmetry plane that is not tetragonal, two shear waves with different velocities can propagate along the vertical direction, and the polarizations of these two waves are aligned with the two horizontal symmetry axes of the medium. The difference between the velocities of these waves can be estimated by measuring the increase of the time delay between them with the depth. This method is particularly effective if the data are acquired with a controlled shear wave source. If two orthogonally polarized shear wave sources $(Sx, Sy)$ and two-component (2C) recording $(Rx, Ry)$ are available (so called $2C \times 2C$ acquisition geometry), one can obtain seismograms containing either only fast or only slow wave using the Alford (1986) rotation, i.e., reorienting both sources and receivers to match the symmetry axes of the medium.

Originally, the Alford rotation was developed for land seismic surveys acquired with S-wave sources. The same method is also applicable for vertical seismic profile (VSP) geometry. However, possible changes of orientation of the symmetry axes of the layers with depth can cause complications: at each interface where such change occurs, each fast or slow shear wave propagating across the interface will split again, and thus the number of the waves will be doubled. To overcome this problem, Winterstein and Meadows

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(1991) proposed a layer-stripping approach, which was further developed by Thomsen et al., (1999).

In practice, 9C (3C receivers plus three polarized sources (Sx, Sy, Sz)) and 2C × 2C acquisition geometries are seldom used in VSP acquisition due to the much higher cost of such surveys. Most zero-offset VSP surveys are acquired with P-wave sources, which can also generate S-waves (Lash, 1985; Yang et al., 2007). Intensity of these S-waves and their polarization depend on both the type of the source and near-surface heterogeneities. In offshore zero-offset VSP, all shear waves are converted PS events. Several shear wave polarization analysis techniques have been developed for such cases (Turner and Hearn, 1995, Lavely and Bates, 1996). These techniques mainly originate in global seismology, where observation of shear wave splitting without having a controlled shear wave source is typical. For instance, Bowman and Ando (1987) proposed a so called rotation-correlation method based on maximization of the crosscorrelation function between orthogonal components containing the fast and slow shear waves. Silver and Chang (1991) proposed to model shear wave splitting by projecting the initial shear wave onto the fast and slow directions and introducing time shifts. In this case, orientation of the fast and slow waves and time delay between them could be derived from parameters of the operator which can correct 2C records for presence of anisotropy. Such approaches usually involve independent analysis of a single 2C or 3C geophone record and will not benefit directly from multilevel VSP acquisition.

In general, most of the existing approaches suffer from interference between multiple shear wave events. Low signal-to-noise ratio (S/N) for shear waves makes the analysis of time delays of individual events difficult and unreliable. Bakulin and Mateeva (2008) propose an approach based on a virtual source method to simulate the response of controlled shear wave sources from horizontal components of 3C receivers. This approach takes advantage of the presence of numerous differently polarized events. However, it still requires a 2C × 2C VSP acquisition setup. Gaiser et al., (2009) demonstrated applicability of a similar approach for creating shear wave pseudosources from horizontal receivers for 3D VSP data acquired with a P-wave seismic vibrator.

In this paper, we introduce an alternative approach to estimation of the fast and slow shear wave velocities, and the orientation of the polarization planes, based on multicomponent velocity analysis. This technique is applicable to zero-offset VSP data acquired with a single source, and should benefit from presence of a large number of interfering shear waves.

## MULTICOMPONENT VELOCITY ANALYSIS

Our approach is to apply a technique similar to standard velocity analysis, well known from common midpoint (CMP) data processing (Taner and Koehler, 1969), but applied to traces in a given depth interval on horizontal components of a 3C VSP seismogram.

We assume that zero-offset VSP data are acquired in a vertical borehole drilled in a horizontally stratified medium. We also assume that layers are orthorhombic with a horizontal symmetry plane, including horizontal transverse isotropy (HTI). Parameters of azimuthal anisotropy (including orientation of symmetry axes in the horizontal plane) can vary from layer to layer. We also assume that the horizontal components of the multicomponent VSP data are oriented prior to the analysis, and each component keeps its orientation constant for all depth levels.

The main idea is to estimate the velocity of a large number of events as a function of the polarization azimuth of these events. This is done by computing the overall coherency of all the events on a seismogram as a function of the polarization azimuth and velocity (slope in time-depth domain). General data analysis workflow is schematically shown in Figure 1 and 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), as illustrated in Figure 1a.
2) For the whole range (0–180°) of azimuths, we compute the horizontal component $H(\alpha,t,z)$ rotated to the azimuth $\alpha$ (Figure 1b):

$$H(\alpha,t,z) = H_1(t,z)\cos(\alpha) + H_2(t,z)\sin(\alpha). \quad (1)$$

3) To determine the apparent velocity as a function of the azimuth, we need to compute the velocity spectrum in the chosen depth interval (Figure 1c). This can be done by computing the coherency of the seismic signal along a linear time-distance curve $t(z) = t_0 + \Delta z/V$ where $t_0$ is a reference time, $\Delta z$ is the vertical distance from the top of the depth interval, and $V$ is the apparent velocity. This is similar to the approach used for estimation of the velocity of refracted waves proposed by Landa et al., (1995). Note that this is different from the stacking NMO velocity

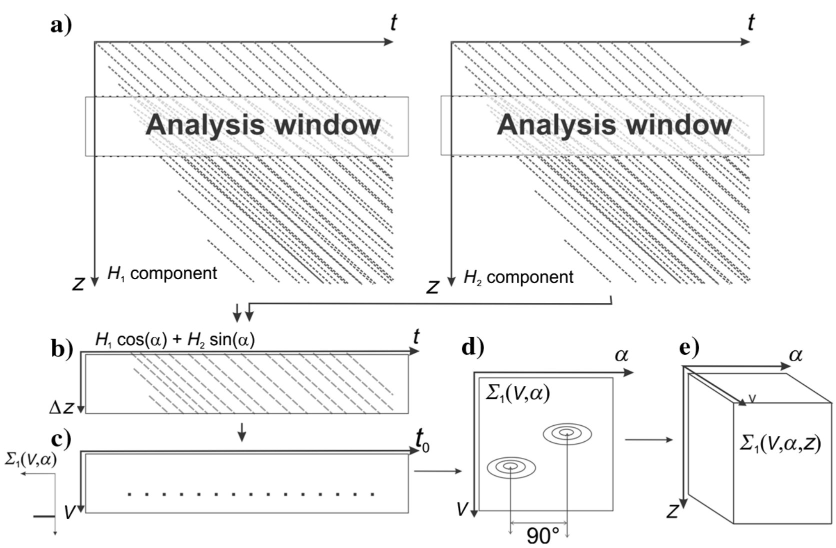


Figure 1. Principal workflow of the multicomponent velocity analysis. (a) Oriented horizontal components of 3C VSP seismogram; (b) analysis window containing horizontal component oriented at azimuth $\alpha$ (this cartoon represents the horizontal component corresponding to the fast direction); (c) apparent velocity spectrum for one azimuth $\alpha$; (d) azimuthal velocity spectrum derived from a set of single azimuth velocity spectra by stacking along time axis; (e) azimuthal velocity spectrum computed for all depth analysis windows combined into 3D volume.

analysis for reflection seismic data, where the time-distance curves are hyperbolas.

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

$$C(t_0, V, \alpha) = \frac{\sum_{j=1}^{N} \left( \sum_{i=1}^{M} D_{ij} \right)^4}{M \sum_{j=1}^{N} \sum_{i=1}^{M} D_{ij}^2}, \qquad (2)$$

where $D_{ij} = H(\alpha, t_0 + \Delta z_i / V + (j - N/2)\Delta t, \Delta z_i)$ is a $j$th sample in the window with samples on trace $i$ along the traveltime curve (after rotation), $M$ is the number of traces in the depth interval analyzed, $V$ is current scanning velocity, $\Delta z_i$ is the distance from the top of the depth window used for the semblance computations, $t_0$ is reference time and $\Delta t$ is sampling interval. This formula differs from the semblance function by the fourth 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 the fast and slow shear waves in a given depth interval, this stacked "azimuthal velocity spectrum" — as a function of apparent velocity and azimuth of polarization — 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 will obtain a 3D volume $\Sigma_1(V, \alpha, z)$ (Figure 1e). Interactive picking of the corresponding extrema on depth slices gives the fast and slow shear wave velocities and azimuths as a function of depth.

## SYNTHETIC EXAMPLE

To test the method described above, we generated a simple synthetic seismogram simulating a 2C VSP record obtained in a single constant velocity azimuthally anisotropic layer with a fixed orientation of the principal axes (Figure 2). We assume that a large number of downgoing S-waves can propagate in this layer along the borehole (with raypaths parallel to the receiver line). In real data these can be downgoing PS waves, multiples, etc.; however, their nature is not important for the analysis approach. Each S-wave event can be either a fast or slow wave, characterized by corresponding polarization and velocity; no other S-waves can exist in such media. Under these assumptions, we do not need to use computationally expensive 3D anisotropic finite-difference methods or trace rays to generate the synthetic example.

To simulate the presence of two sets of interfering shear waves, we populated each of the two orthogonally oriented horizontal components with a number of linear downgoing events with either "fast" or "slow" S-wave velocity. One of the horizontal components contains only "fast," another — only "slow" events. The events have random time delay uniformly distributed between 0 and overall record length, and random amplitudes uniformly distributed between −1 and 1. In this synthetic example, we ignore all factors affecting amplitude decay with depth, so every event preserves its amplitude within the layer. Impulse seismograms of these horizontal components were convolved with the zero-phase Ormsby wavelet and rotated in the horizontal plane. This was done to obtain two horizontal components; each of them contains both fast and slow waves. In this synthetic example, receiver depth is referenced to the top of the anisotropic layer and time is referenced to the time of arrival of the P-wave to the first receiver.

The following list summarizes the source and receiver acquisition parameters of the VSP, and the medium properties:

- receiver depth range: 700 m
- receiver depth spacing: 10 m
- impulse: Ormsby, 5-10–30-70 Hz
- record length: 2.8 s (only first 1 s of the record is shown in Figure 2)
- sampling rate: 2 ms
- number of events: 500
- compressional wave velocity: 3000 m/s
- fast shear wave velocity: 1500 m/s; azimuth of polarization: 30°
- slow shear wave velocity: 1350 m/s; azimuth of polarization: 120°
- P-wave and S-wave velocities and S-wave orientations constant over the entire depth range

The synthetic data were processed with the 2C velocity analysis algorithm. The principal tuning parameters of the algorithms are similar to those of the standard NMO velocity analysis, and include the size of the time window for computing the semblance function and the velocity scanning range (the azimuth scanning range is always from 0° to 180°). The size of the sliding depth window for computing velocity spectra will influence azimuth/velocity/depth resolution. Figure 3 shows the azimuthal velocity spectrum obtained with a 200-m depth window (Figure 3a) and with a 400-m

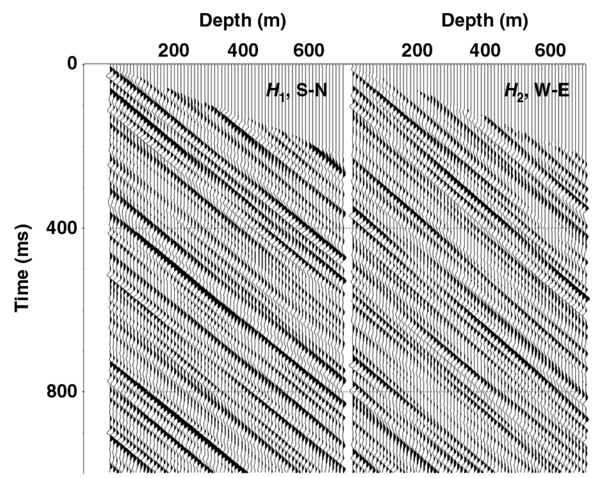


Figure 2. Synthetic zero-offset VSP data example, horizontal-components oriented in south-north ($H1$) and west-east ($H2$) directions.

depth window (Figure 3b); the time window length for semblance computation is 60 ms. Extrema representing the fast and slow shear waves are clearly pronounced in both panels and correspond to the correct velocity and azimuth values. For this constant velocity case, we observe that increase of the depth window improves the velocity and azimuth accuracy. In practice, velocity varies with depth, so increase of the depth window should result in decrease in the resolution in vertical (depth) direction.

## FIELD DATA EXAMPLE 1: MARINE ZERO-OFFSET VSP (RIG SOURCE)

We applied the multicomponent velocity analysis to a marine rig VSP data set acquired in the Exmouth subbasin, in the North West Shelf of Australia. Strong azimuthal P-wave anisotropy was previously reported as possible explanation of azimuthal variation of NMO velocities in this area (Hung et al., 2006). Shear wave anisotropy was also observed in a cross-dipole shear sonic log recorded in the same well (Figure 6d). The aim of our analysis is to estimate the shear wave splitting from VSP data and compare the results to both sonic log data and surface seismic data. The geological medium around the borehole is represented by horizontally layered, mainly siliciclastic deposits, with dips not exceeding 1°–2° (Sidi and Duncan, 2007).

### Acquisition parameters and data conditioning

VSP data were acquired within a 891–2388-m depth interval with receiver depth spacing of 15 m. A nonoriented 3C VSP tool was used for the survey. The borehole is almost vertical, with maximum lateral deviation from the wellhead of ~31 m toward the source point position located 65 m away from the wellhead. An airgun array was used as a seismic source. Record length is 5 s, and sampling rate is 1 ms.

In order to prepare the data for the multicomponent velocity analysis, several preprocessing steps were implemented. Horizontal components of the data were oriented using hodogram-based polarization analysis of the direct P-wave. Results of the orientation are presented in Figure 4a. Due to the small source offset, this procedure is not very robust and may affect the quality of the shear wave polarization azimuth estimation. Amplitude decay compensation was performed using single-function divergence correction (time raised to the first power) applied to all of the traces. This method is chosen in order to preserve the relative amplitude on all components. Ideally, the velocity analysis should be performed on a record containing downgoing shear waves only. To subtract downgoing P-waves, we applied 2D spatial filter in *z*-*t* domain with a very sharp directivity pattern (240 m or 17 traces sliding depth window, mean alpha-trimmed with 30% rejection). Finally, an Ormsby bandpass filter (5-10–50-90 Hz) was applied to suppress high-frequency noise. The result of the preprocessing is shown in Figure 4b. The residual wavefield on the horizontal components shows a large number of interfering downgoing shear waves, partially covered with other events. S/N for these waves is insufficient for analysis of individual events.

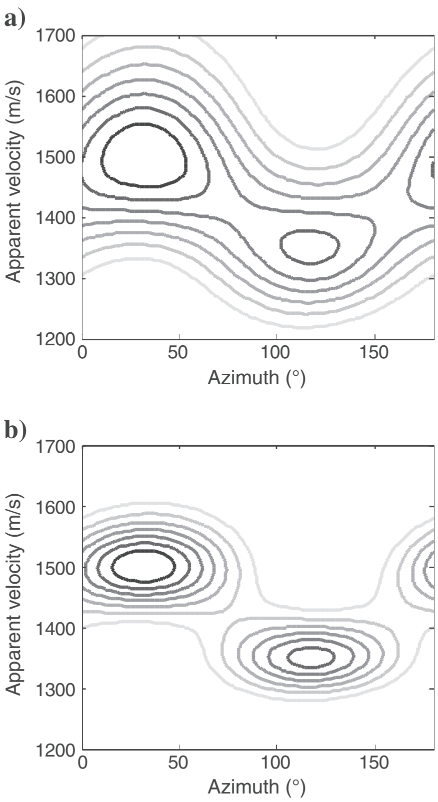


Figure 3. Azimuthal velocity spectrum obtained for the synthetic data example with depth window size of 200 m (a) and 400 m (b).

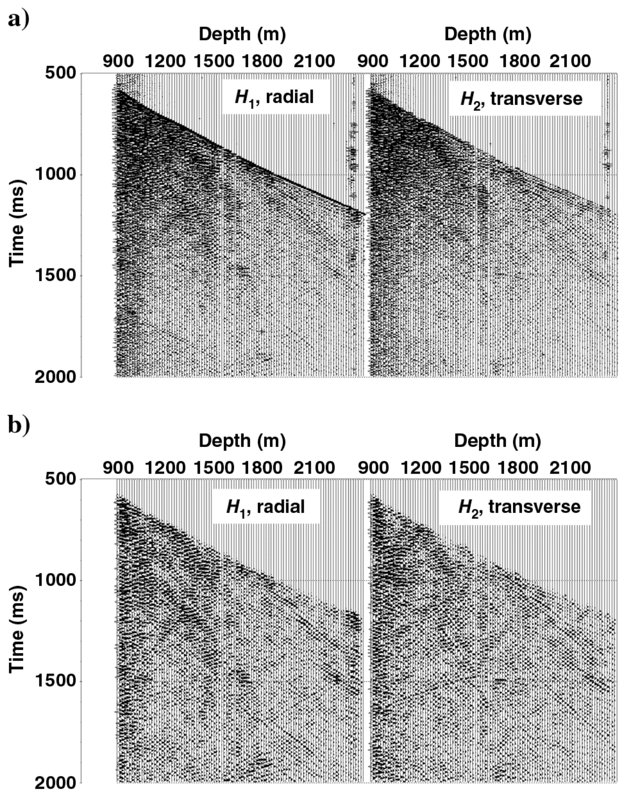


Figure 4. Oriented raw (a) and preprocessed (b) horizontal-components of 3C rig VSP data acquired in the North-West Shelf of Australia. *H*1 is oriented in the radial direction (towards the source), *H*2 in the transverse direction.

## Shear wave anisotropy estimation

A multicomponent velocity analysis was applied to the preprocessed data set. The time window for computing the semblance function was selected to be 60 ms, and velocity spectra were computed for the whole receiver range with the step of 20 m. We used 0–2500 ms record time range for computations.

An example of the azimuthal velocity spectra showing presence of one shear wave only is presented in Figure 5a. Only one extremum is visible; it corresponds to $PS_V$-waves polarized approximately in the vertical source/receiver plane.

For receiver depths below 1600 m, the peaks representing fast and slow shear waves are clearly pronounced. This is illustrated in Figure 5b-d by examples of azimuthal velocity spectra obtained for depths of 1700 and 1900 m. We found that the optimum depth window is about 200 m because it provides acceptable resolution in both velocity/azimuth and depth (Figure 5b). However, for depth intervals below ~1.9 km we increased the depth window to 280–300 m to simplify interpretation of the spectrum (Figure 5c and 5d.

Results of the multicomponent velocity analysis and comparison with cross-dipole sonic log data obtained in the same borehole are presented in Figure 6. In addition to fast and slow shear velocities, and azimuth of their polarizations, we show the depth dependency of the Thomsen's anisotropy parameter computed with respect to the horizontal symmetry axis (assuming HTI symmetry, Thomsen, 2002). A reasonably good match between shear wave velocities and anisotropy parameter obtained from VSP and log data is observed. Velocities obtained from the VSP data analysis represent values averaged in a depth window of at least 200 m, so they cannot follow all the detail observed in log data. Absolute values of the velocities are systematically higher for the results of VSP data analysis. This may have been caused by possible problems with log data processing. The match between Thomsen's shear wave anisotropy parameters obtained with the two methods is very good. Azimuths of polarization of fast and slow waves also show good agreement between seismic and log data, but we expect lower accuracy for VSP due to the poor quality of the horizontal components orientation due to the fact that the lateral source offset from the wellhead is very small.

P-wave anisotropy estimations (Hung et al., 2006) in the same area show 2%–4% variation between surface seismic stacking velocities in the slow and fast directions with the "fast" azimuth of about 130°. The cumulative nature of the stacking velocities suggests that the magnitude of the anisotropy is consistent with the borehole data. Indeed, if we convert interval S-wave velocities into rms velocities (extending the top isotropic layer from the uppermost receiver to the sea surface using a constant S-wave velocity), cumulative $\gamma$ will range from 0% to 4%, reaching 4% at about 2.2 km depth. This is consistent with the values reported by Hung et al., (2006) for P-waves for the same depth.

Given that there are no noticeable fractures observed in the image logs, the most probable cause of the observed azimuthal seismic anisotropy is anisotropy of the stress field and related opening and closure of microcracks or compliant grain contacts (Nur, 1971, Sayers, 2002, Scott and Abousleiman, 2005, Gurevich et al., 2011). Indeed, this area is known for large differences between maximum and minimum horizontal stresses (Hillis and Reynolds, 2003).

## FIELD DATA EXAMPLE 2: LAND ZERO-OFFSET VSP

Unlike marine VSP, where no shear waves can be generated by the source, land VSP records often contain strong shear waves whether the data are acquired with conventional P-wave sources such as explosives, weight drops, or vertical vibrators. However, without dedicated shear wave sources (such as horizontal SH vibrators), polarization of these shear waves is controlled by the S-waves produced by P-wave sources and P-waves that convert to S-waves. This feature should be beneficial for the multicomponent velocity analysis.

The algorithm was applied to CRC-1 borehole drilled in Victoria, southeast Australia within the scientific program of the CO2CRC Otway Project conducted by the Cooperative Research Center for Greenhouse Gas Technologies (CO2CRC) (Urosevic et al., 2010). This is the first Australian demonstration project of $CO_2$ geosequestration and 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. To monitor any possible leakages of the gas into other

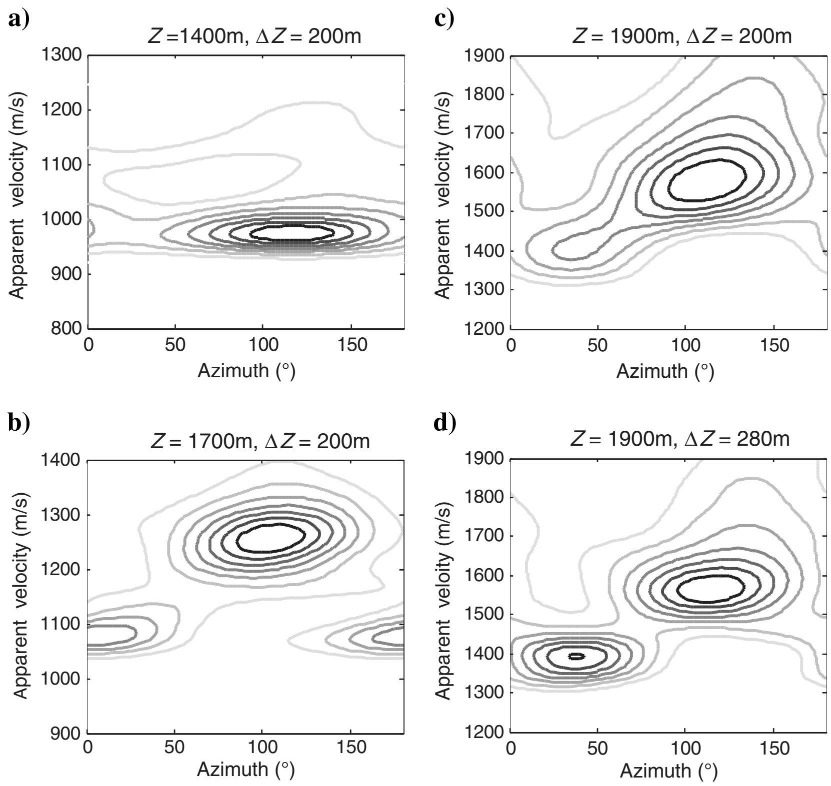


Figure 5. Azimuthal velocity spectra obtained for the marine rig VSP data. (a) Measured depth 1400 m, depth window size 200 m; (b) measured depth 1700 m, depth window size 200 m; (c) measured depth 1900 m, depth window size 200 m; (d) measured depth 1900 m, depth window size 280 m.

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 the years 2000, 2008, 2009, and 2010). Simultaneously with two of the surveys (2008 and 2010), 3D VSP surveys were also acquired. Several zero offset and offset VSP surveys were also acquired in two boreholes (Naylor-1 and CRC-1) in 2007–2010. Investigation of seismic anisotropy is important for the project, because it could affect seismic imaging and could also be potentially used for monitoring purposes. Presence of azimuthal shear wave anisotropy for the Otway basin was previously reported by Turner and Hearn (1995).

## Acquisition parameters and data conditioning

During January 2010, two zero offset VSP surveys were acquired in CRC-1 borehole with a three-week long interval using two different sources: weight drop and IVI minibuggy. Parameters of the surveys were

- VSP down hole tool: 3C Schlumberger VSI, 8 downhole shuttles
- Source: Vibroseis, IVI minibuggy, at 9000 lbs, 12.5 s sweep 10–150 Hz (ZVSP, OVSP) or weight drop, concrete breaker Hurricane Force 9, operational weight 720 kg (ZVSP)
- Record length: 3 s
- Acquisition depth interval: 517–1900 m
- Receiver depth spacing along borehole: 15 m (for 517–1455 m depth range) and 7.5 m (for 1455–1900 m depth range)
- Zero-offset VSP shot point location: Azimuth 105.5°, offset 89.7 m

The objective for the repeat zero-offset VSP was to evaluate performance of these two sources; no changes in the subsurface were expected. However, because these were two separate VSP surveys, the downhole tool was independently pulled down and up for each survey. Thus, repeated shear wave anisotropy analysis can provide estimates of errors related to two independent estimates and the differences in orientation of the horizontal components using polarizations of the direct P-wave.

For the VSP surveys in the CRC-1 well, the tool orientation data were not available. Thus, as in the marine VSP example, we had to orient VSP data via analysis of the polarization of the direct P-wave. Figure 7 shows both horizontal components rotated into radial and transverse coordinates based on this orientation analysis. Downgoing waves are represented by the direct P-wave, converted PS-waves, low-frequency source-generated S-waves, and tube waves.

In general, the presence of a direct shear wave should provide us with a significant amount of shear wave energy to conduct the multicomponent velocity analysis. In order to precondition the data, we applied only a band-pass filter (15-25–40-90 Hz), spherical divergence correction and top muting (40 ms below the direct P-wave arrival).

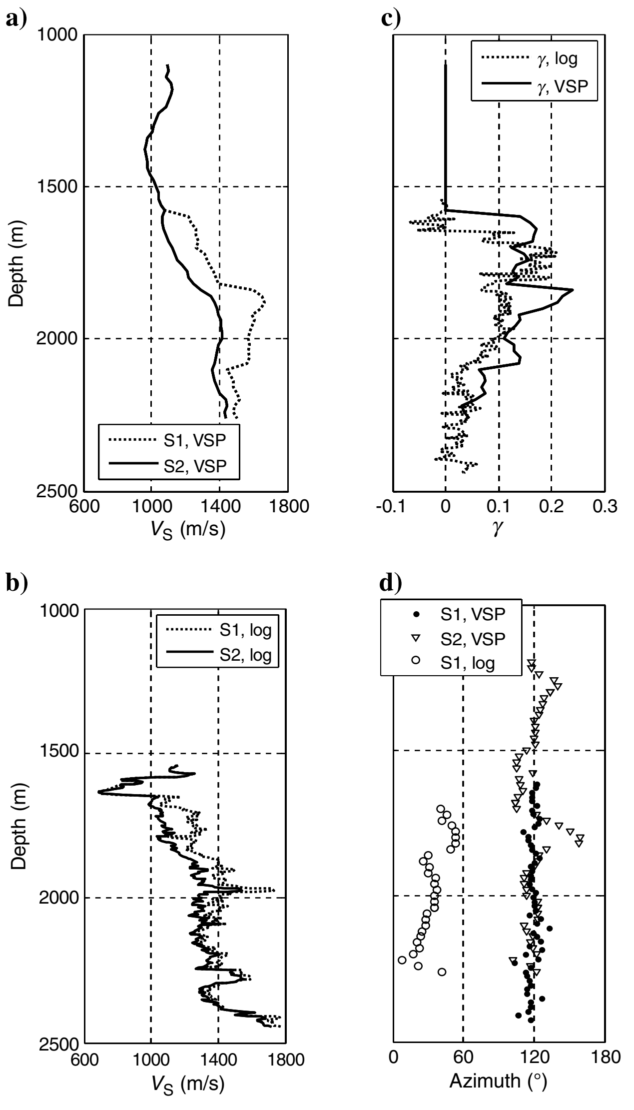


Figure 6. Comparison between fast and slow shear wave velocities obtained from (a) VSP data analysis and (b) cross-dipole sonic log, (c) Thomsen's parameters, and (d) azimuths of polarization planes determined from marine zero-offset VSP and cross-dipole sonic log data.

## Shear wave anisotropy estimation

Azimuthal velocity spectra were computed for both the weight drop and vibroseis data sets using a 200 m running depth window, the first 2 s of the record and a 60 ms time window to compute the semblance function. An example of such spectra for one of the depth levels (720 m) is presented in Figure 8. One can see that, despite some minor differences, these plots demonstrate very similar azimuthal velocity spectra. Extrema corresponding to the fast and slow shear waves have azimuths of ~140° and ~50°, respectively. Minor mismatch between the azimuths obtained in the two surveys can possibly be explained by imperfect orientation of the data. Interestingly, while the separation between the extrema on azimuthal spectra computed for the weight drop data is almost exactly 90° (~47.5° for the slow and ~137.5° for the fast wave), the separation between the extrema computed for vibroseis is ~100° (~50° and ~150° respectively). We speculate that this could be attributed to the distorting effect of tube waves. Indeed, analysis of the seismograms shows that the level of tube wave noise is significantly higher on the vibroseis data. Tube waves (symmetrical radial mode) should have radial polarization (with respect to the borehole axis); however, observed polarization on VSP data can be affected by the construction of the tool and its coupling (Mjelde, 1992). Multilevel Schlumberger VSI tool would most likely have all of the shuttles oriented in similar directions in the horizontal plane for each borehole position of the tool, and also would produce continuous changes in their orientation along the borehole. This means that tube waves are expected to have similar polarization for all receiver points in the vicinity of the receiver level used for the azimuthal velocity analysis. Keep in mind that, for this particular depth level (720 m), the velocity of the fast shear wave (~1.3 km/s) is quite close to the tube wave velocity (~1.4 km/s), so we could expect the extremum corresponding to the fast wave in Figure 8a (vibroseis) to be contaminated by presence of the tube wave.

The results of the velocity analysis for all levels as well as S-wave parameters measured using cross-dipole log data are presented in Figure 9. In cases where it was impossible to identify presence of both fast and slow shear waves on the velocity spectra, only one extremum was picked. Having repeated VSP measurements for this borehole, it is possible to roughly estimate the accuracy of the estimates. The standard deviation for the velocity values is ~30 m/s, which is about 2% of the absolute velocity value. Estimates of the fast and slow S-wave polarization azimuths (for the depth interval 600–1300 m) are much less robust; the standard deviation for the values obtained for the two experiments is about 12°.

As in the marine example, a good match between the shear wave velocities and corresponding anisotropy parameters obtained from log and VSP data is achieved. The best match is achieved for anisotropy parameter $\gamma$ (again, computed assuming HTI symmetry), the poorest — for azimuths of polarization.

In the depth interval of 600–1300 m, significant azimuthal shear wave anisotropy was observed, reaching values of 0.05–0.1. Fast and slow shear wave azimuths are ~140° and ~50°, respectively. This corresponds to the maximum and minimum horizontal stress orientation directions obtained from the analysis of breakout and drilling-induced tensile fractures (Nelson et al., 2006), and from dominant faulting orientation (Williamson et al., 1990). This suggests that the anisotropy of the stress field is the main cause of the seismic anisotropy. A reasonable agreement between the results obtained from the analysis of the weight drop and vibroseis data is observed.

Below the 1300 m level, it is hard to identify the two shear waves. There are several possible reasons for this. Approximately at this level, the CRC-1 borehole intersects a major fault oriented in a northwest-southeast direction which could affect stress field parameters in the vicinity of the borehole. Other possible reason is the lower quality of orientation of the data for the lower part of the borehole (due to smaller P-wave incidence angles).

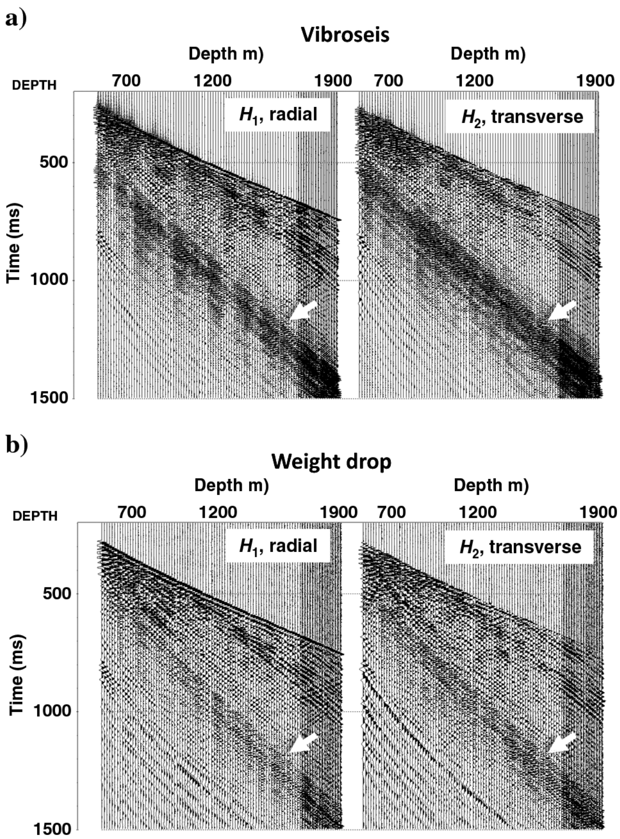


Figure 7. Oriented horizontal components of 3C zero-offset VSP data acquired in CRC-1 borehole, Otway basin, Victoria. (a) Data set acquired with IVI minibuggy vibroseis; (b) data set acquired with weight drop data. $H1$ oriented in radial direction (towards the source); $H2$ oriented in transverse direction. Note difference in the level of tube noise (marked with the white arrow).

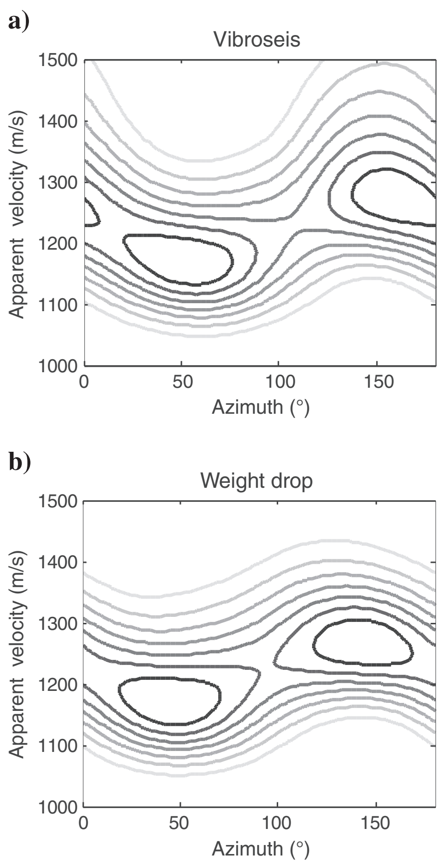


Figure 8. Azimuthal velocity spectra obtained for the zero-offset VSP data acquired in CRC-1 borehole, measured depth of 720 m, (a) vibroseis data, (b) weight drop data.

## DISCUSSION

Most VSPs acquired by contractors for the oil and gas industry are zero-offset single source surveys. The proposed multicomponent velocity analysis can be used to detect the presence and estimate parameters of azimuthal shear wave anisotropy in such cases.

The proposed technique is based on the analysis of the apparent velocity of a number of different events as a function of the azimuth of their polarization. As such, this technique is not affected by the complexity of the overburden unless it significantly changes the direction of propagation of shear waves in the analyzed interval.

The proposed multicomponent velocity analysis is an interactive technique, and is similar to the standard interactive stacking velocity analysis used in CMP data processing. If waves other than S-waves are present in the data, then they will create additional extrema in the azimuthal velocity spectra. If velocities of these waves for a given depth interval are close to the velocities of the shear waves, then they can distort the results like the tube waves discussed above. However, for simple cases, the processing can be automated. Additionally, it should be possible to use not only downgoing, but also upgoing shear waves if they are propagating along the borehole.

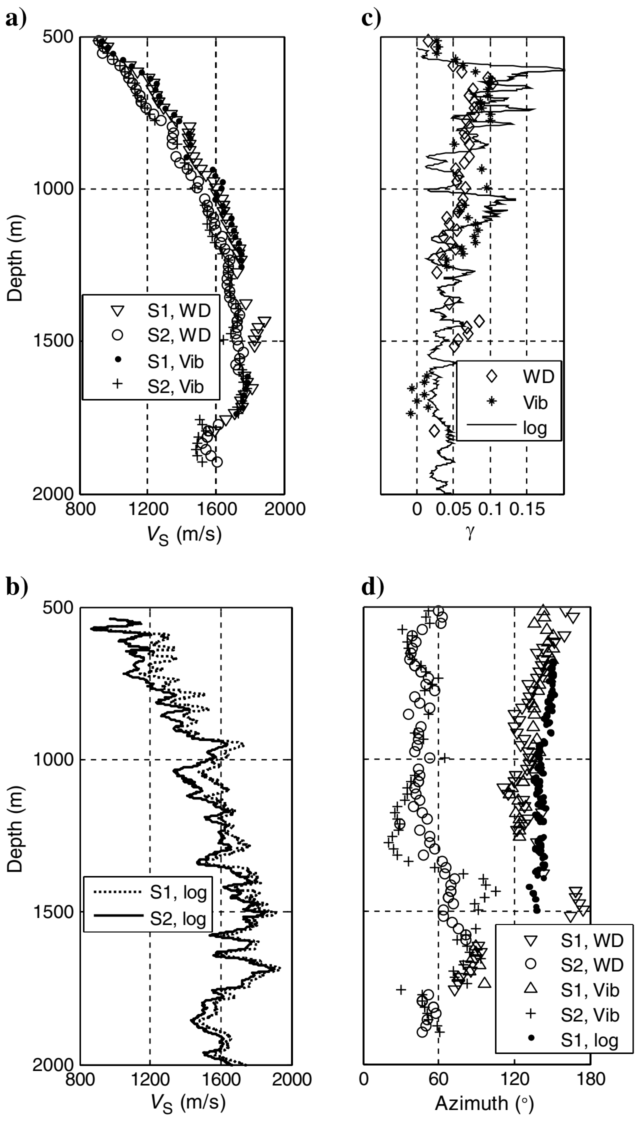


Figure 9. Comparison between fast and slow shear wave velocities obtained from (a) VSP data analysis and (b) cross-dipole sonic log, (c) Thomsen's parameters, and (d) azimuths of polarization planes determined from CRC-1 zero-offset VSP acquired with weight drop and vibroseis data and cross-dipole sonic log data. Abbreviations 'WD' and 'Vib' are used to denote VSP data acquired with weight drop and vibroseis sources, respectively.

Possible changes in the orientation of the principal directions of the medium with depth can also be handled by the method. Vertical resolution is determined by the length of the depth window used for the analysis. The presence of several depth intervals with different orientations of principal directions within one vertical analysis window could create additional extrema and result in blurring of the image. Length of the depth window is a tradeoff parameter between accuracy in determination of velocities and azimuths of the waves on one hand, and vertical resolution on the other.

In our description of the method, we have assumed that the VSP data were acquired in a vertical well in media with horizontal symmetry planes. The current version of the multicomponent velocity analysis is equally applicable when the direction of propagation of all shear waves is coincident with the trajectory of the borehole and the symmetry planes are orthogonal to the direction of propagation. This limitation can be relaxed, as the difference between apparent and layer velocity remains below 1% for angles between the borehole and the direction of wave propagation of up to 8°. However, the approach is not applicable to offset VSP data acquired in areas with steep dips. To observe the shear wave splitting along the borehole, the method requires media to be monoclinic, HTI, or orthorhombic with the symmetry axes to be coincident with the borehole trajectory (there is no shear wave splitting for tetragonal media along the symmetry axis of 90° rotations). When this condition is violated (i.e., for a tilted TI medium), we should still be able to observe the presence of all shear waves. However, it would not be possible to compute the anisotropy parameter $\gamma$ without additional constraints.

Another limitation of the approach is that it requires the presence of both polarized shear waves. For instance, if all shear waves (including the one generated by the source and PS conversions) are polarized along only one principal direction, it would not be possible to detect the shear wave anisotropy. This problem can be overcome by an appropriate positioning of the source point with respect to the expected orientation of the symmetry axes.

Accuracy of the method should be dependent both on properties (degree of azimuthal anisotropy) of the medium, and the parameters of the survey (such as S/N achieved). Our Otway example shows that the approach should provide small errors in absolute velocity values; in our example the error is about 2%. Azimuths of polarization of the fast and slow shear waves can be derived with significantly poorer accuracy; standard deviation for azimuths computed between the two successive surveys is over 10°.

We believe that the quality of the orientation of the horizontal components for 3C receivers is the key factor affecting the accuracy of the multicomponent velocity analysis. In those cases when orientation of horizontal components is performed using polarization of the direct P-wave, factors affecting quality of the orientation change gradually with depth. This can result in incorrect estimations of S-wave polarization; however, estimates of the fast and slow velocity will be less affected. Problems with precise orientation are a common issue for all methods of anisotropy estimation from zero-offset VSP data.

## CONCLUSIONS

We have presented a new approach for estimation of shear wave azimuthal anisotropy from 3C VSP data analysis. This approach is based on the analysis of apparent velocities of differently polarized shear events recorded over given depth intervals. The proposed technique:

- provides a possibility to analyze zero-offset VSP data obtained with standard acquisition technique, even in a marine environment
- benefits from the presence of large number of low-amplitude shear wave events
- allows us to evaluate changes in azimuth of polarization plane with depth
- is simple in both implementation and application to data.

Field data tests show good agreement between anisotropy parameters derived from VSP and from cross-dipole sonic log data for a marine VSP data example and a good repeatability of the results when applied to a repeated land VSP survey acquired with different seismic sources.

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## REFERENCES

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

Bakulin, A., and A. Mateeva, 2008, Estimating interval shear wave splitting from multicomponent virtual shear check shots: Geophysics, **73**, A39–A43, doi: 10.1190/1.2952356.

Bowman, J. R., and M. Ando, 1987, Shear wave splitting in the upper-mantle wedge above the Tonga subduction zone: Geophysical Journal of the Royal Astronomical Society, **88**, 25–41.

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

Gaiser, J. E., R. Ramkhelawan, I. Vasconcelos, and J. Faragher, 2009, Elastic-wavefield interferometry using P-wave source VSPs, Wamsutter field, Wyoming: 79th Annual International Meeting, SEG, Expanded Abstracts, **28**, 4095–4099.

Gurevich, B., M. Pervukhina, and D. Makarynska, 2011, An analytical model for stress-induced anisotropy of dry rocks: Geophysics, **76**, WA125-WA133.

Hillis, R. R., and S. D. Reynolds, 2003, In situ stress field of Australia, *in* R. R. Hillis, and R. D. Müller, eds., Evolution and dynamics of the Australian Plate, Geological Society of Australia, pp. 49–60.

Horne, S., 2003, Fracture characterization from walkaround VSPs: Geophysical Prospecting, **51**, 493–499, doi: 10.1046/j.1365-2478.2003.00391.x.

Horne, S., C. MacBeth, J. Queen, W. Rizer, and V. Cox, 1997, Fracture characterization from near-offset VSP inversion: Geophysical Prospecting, **45**, 141–164, doi: 10.1046/j.1365-2478.1997.3170237.x.

Hung, B., F. M. Zhang, J. Sun, M. Stanley, and A. Osadchuk, 2006, An automated 3D method for azimuthal anisotropy analysis in marine seismic data: 68th EAGE Conference & Exhibition, Extended Abstract, H035.

Johnson, P. A., and P. N. J. Rasolofosaon, 1996, Nonlinear elasticity and stress-induced anisotropy in rock: Journal of Geophysical Research Solid Earth, **101**, 3113–3124, doi: 10.1029/95JB02880.

Landa, E., S. Keydar, and A. Kravtsov, 1995, Determination of a shallow velocity depth model from seismic-refraction data by coherence inversion: Geophysical Prospecting, **43**, 177–190, doi: 10.1111/gpr.1995.43.issue-2.

Lash, C. C., 1985, Shear waves produced by explosive sources: Geophysics, **50**, 1399–1409, doi: 10.1190/1.1442009.

Lavely, E. M., and C. R. Bates, 1996, Problems in the analysis of multi-component VSP data: The Leading Edge, **15**, 937–941, doi: 10.1190/1.1437396.

Mjelde, R., 1992, Reflection and polarization of tube waves as seen in VSP data: Geophysical Prospecting, **40**, 605–617, doi: 10.1111/gpr.1992.40.issue-6.

Nelson, E., R. Hillis, M. Sandiford, S. Reynolds, P. Lyon, J. Meyer, S. Mildren, and C. Rogers, 2006, Present-day state-of-stress of southeast Australia: Journal of the Australian Petroleum Production and Exploration Association, 283–305.

Nur, A., 1971, Effects of stress on velocity anisotropy in rocks with cracks: Journal of Geophysical Research, **76**, 2022–2034, doi: 10.1029/JB076i008p02022.

Sayers, C. M., 2002, Stress-dependent elastic anisotropy of sandstones: Geophysical Prospecting, **50**, 85–95, doi: 10.1046/j.1365-2478.2002.00289.x.

Scott, T. E., and Y. Abousleiman, 2005, Acoustic measurements of the anisotropy of dynamic elastic and poromechanics moduli under three stress/strain pathways: Journal of Engineering Mechanics, **131**, 937–946, doi: 10.1061/(ASCE)0733-9399(2005)131:9(937).

Sidi, F. H., and G. Duncan, 2007, Seismically constrained petrophysics in the Scarborough area: Exploration Geophysics, **38**, 120–124.

Silver, P. G., and W. W. Chan, 1991, Shear wave splitting and subcontinental mantle deformation: Journal of Geophysical Research Solid Earth, **96**, 16429–16454, doi: 10.1029/91JB00899.

Taner, M. T., and F. Koehler, 1969, Velocity spectra—digital computer derivation applications of velocity functions: Geophysics, **34**, 859–881, doi: 10.1190/1.1440058.

Thomsen, L., 2002, Understanding seismic anisotropy in exploration and exploitation: SEG Distinguished Instructor Short Course, Society of Exploration Geophysicists and European Association of Geoscientists and Engineers.

Thomsen, L., I. Tsvankin, and M. C. Mueller, 1999, Coarse-layer stripping of vertically variable azimuthal anisotropy from shear wave data: Geophysics, **64**, 1126–1138, doi: 10.1190/1.1444619.

Turner, B., and S. Hearn, 1995, Shear wave splitting analysis using a single-source, dynamite VSP in the Otway Basin: Exploration Geophysics, **26**, 519–526.

Urosevic, M., R. Pevzner, A. Kepic, P. Wisman, V. Shulakova, and S. Sharma, 2010, Time-lapse seismic monitoring of $CO_2$ injection into a depleted gas reservoir—Naylor Field, Australia: The Leading Edge, **29**, 164–169, doi: 10.1190/1.3304819.

Williamson, P. E., M. G. Swift, G. W. Obrien, and D. A. Falvey, 1990, 2-Stage early cretaceous rifting of the Otway basin margin of southeastern Australia—Implications for rifting of the Australian southern margin: Geology, **18**, 75–78, doi: 10.1130/0091-7613(1990)018<0075:TSECRO>2.3.CO;2.

Winterstein, D. F., and M. A. Meadows, 1991, Changes in shear wave polarization azimuth with depth in Cymric and Railroad Gap oil-fields: Geophysics, **56**, 1349–1364, doi: 10.1190/1.1443155.

Yang, L., Z. Qinghong, B. Leiying, and W. Xiucheng, 2007, Pure S-waves in land P-wave source VSP data: Applied Geophysics, **4**, 173–182, doi: 10.1007/s11770-007-0035-6.