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Estimating interval shear-wave splitting from multicomponent virtual shear check shots

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ABSTRACT

Measuring shear-wave splitting from vertical seismic profiling (VSP) data can benefit fracture and stress characterization as well as seismic processing and interpretation. The classic approach to measuring azimuthal anisotropy at depth involves layer stripping. Its inherent weakness is the need to measure and undo overburden effects before arriving at an anisotropy estimate at depth. That task is challenging when the overburden is complex and varies quickly with depth. Moreover, VSP receivers are rarely present all the way from the surface to the target. That necessitates the use of simplistic assumptions about the uninstrumented part of the overburden that limit the quality of the result. We propose a new technique for measuring shear-wave splitting at depth that does not require any knowledge of the overburden. It is based on a multicomponent version of the virtual source method in which each two-component (2-C) VSP receiver is turned into a 2-C shear source and recorded at deeper geophones. The resulting virtual data set is affected only by the properties of the medium between the receivers. A simple Alford rotation transforms the data set into fast and slow shear virtual check shots from which shear-wave splitting can be measured easily and accurately under arbitrarily complex overburden.

INTRODUCTION

Vertical seismic profiling (VSP) with shear waves is a well-established method to characterize azimuthal anisotropy in the subsurface (Alford, 1986; Winterstein and Meadows, 1991; Thomsen et al., 1999). Anisotropic materials support two shear modes with different speeds along the same direction. The polarizations of the two modes are aligned with the symmetry axes (principal directions) of the medium. Estimating these principal directions can help characterize fracture-set orientations and directions of principal stresses. The relative difference in the velocities between the fast and slow shear waves, known as shear-wave splitting, can be related to fracture density and to the difference between principal stress magnitudes.

Estimating shear-wave splitting from 2-C $\times$ 2-C vertical seismic profiling (VSP) data (i.e., from two orthogonal shear vibrators and two horizontal receiver components) is relatively straightforward when symmetry axes do not vary with depth. If VSP sources are polarized along the principal axes, each source generates only a fast or a slow shear mode, and no shear signal is recorded on the receiver component orthogonal to the source. If source polarization does not coincide with either symmetry axis, then two shear wave modes are excited — in essence, the projection of the source on each principal direction acts as a separate source giving rise to both modes. Then, to estimate principal directions, one needs to perform Alford rotation (Alford, 1986) on the 2-C $\times$ 2-C data set with various trial angles to find an angle that minimizes cross-diagonal components. After such a rotation, each diagonal component of the data set contains only one of the two shear-wave modes (fast or slow), allowing the velocities of the fast and slow waves to be measured separately.

In practice, however, formations of interest are located at depth, and it is common for overlying layers to possess azimuthal anisotropy with variable orientation. Because each individual shear wave incident on an azimuthally anisotropic layer with arbitrary orientation would split into two modes, fast and slow, the number of waves doubles with each additional layer. That makes the analysis challenging, especially for deeper layers.

To estimate vertically variable azimuthal anisotropy from shear-wave VSP data, a layer-stripping technique has been proposed (Winterstein and Meadows, 1991; Thomsen et al., 1999). It starts with the top layer and establishes the principal directions by performing Alford rotations with trial angles. Then, the maximized diagonal components are analyzed for velocities (shear-wave splitting) in the top layer. To proceed with the next layer, the anisotropy in the top layer is stripped off by undoing the time lag between the fast and slow shear waves accumulated there.

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This technique is subject to the following limitations:

- It is applicable only to vertical propagation in horizontally layered media,
- If the principal directions in the overburden vary from layer to layer and are unknown, then layer stripping requires instrumenting the well with receivers from top to bottom.
- If there are uninstrumented anisotropic intervals, the principal directions in them would have to be inferred from other geologic and geophysical information.
- As a result of the interpretative nature of the stripping process, errors accumulate with depth.
- The presence of azimuthal anisotropy in the overlying layers does not allow reliable estimation of polarization directions at the beginning of each new layer or inside thin layers (the so-called inertia effect identified by Winterstein and Meadows, 1991).

This letter introduces an alternative technique free of these limitations. It utilizes a multicomponent version of the virtual source method (Bakulin and Calvert, 2004, 2005).

MULTICOMPONENT VIRTUAL CHECK SHOT WITH SHEAR WAVES

The virtual source method (VSM) was introduced by Bakulin and Calvert (2004, 2006) as a method for imaging below complex overburden. Placing downhole receivers below the most complex part of the overburden and crosscorrelating the responses at two receivers allows reconstructing new data as if the first receiver acted as a virtual source (VS). In essence, we perform specialized redatuming that requires no information about the velocity between surface sources and downhole receivers.

In its simplest application, virtual check shot (Bakulin and Calvert, 2005; Bakulin et al., 2007), this technique is used to reconstruct direct arrivals between receivers along the well and to estimate velocity profiles for P- or S-waves. In isotropic media, a shear virtual check shot can be created by crosscorrelating the inline horizontal components of two receivers (Bakulin et al., 2007). In azimuthally anisotropic media, crosscorrelating two horizontal components from a single source is not enough. Here, we explain how to obtain a multicomponent virtual check shot with appropriate amplitudes using 2-C $\times$ 2-C VSP data acquired in a vertical well in arbitrary azimuthally anisotropic media.

For simplicity, let us consider a horizontally layered medium. Each layer is azimuthally anisotropic (orthorhombic) and has vertical symmetry planes with arbitrary orientation. A 2-C $\times$ 2-C VSP is acquired in a vertical well. The goal is to estimate the principal directions and shear-wave splitting between two depth stations. With two types of surface sources (orthogonal shear vibrators along the x- and y-directions) and two horizontal components per VSP receiver (x and y), eight possible crosscorrelations could be made between traces from a common surface source to two depth stations: $xx_1 * xx_2$, $yx_1 * yx_2$, $xy_1 * xy_2$, $yy_1 * yy_2$, $xx_1 * xy_2$, $yx_1 * yy_2$, $xy_1 * xx_2$, and $yy_1 * yx_2$, where the first letter denotes source polarization, the second letter denotes the receiver component, and the subscript identifies the receiver location (1 or 2).

Naive assumptions may suggest $xx_1 * xx_2$ should correspond to an x-component recording from a VS at receiver 1 polarized in the x-direction. However, Wapenaar (2004) and physical intuition suggest that when principal directions in the overburden are unknown, all crosscorrelations should be used on equal footing to obtain a 2-C $\times$ 2-C VS data set. This is achievable with the following expressions:

$$
\begin{aligned}
xx_{VS} &= xx_1 * xx_2 + yx_1 * yx_2,\\
yy_{VS} &= xy_1 * xy_2 + yy_1 * yy_2,\\
xy_{VS} &= xx_1 * xy_2 + yx_1 * yy_2,\\
yx_{VS} &= xy_1 * xx_2 + yy_1 * yx_2. \qquad (1)
\end{aligned}
$$

Here, xx_{VS}, yy_{VS}, xy_{VS}, and yx_{VS} are the virtual 2-C $\times$ 2-C data set obtained after redatuming so that the first receiver is turned into a shear VS. For brevity, we omit summation over source locations along the surface in the expressions in equation 1.

It is straightforward to validate these expressions for a homogeneous anisotropic medium. Consider plane harmonic waves in the vertical direction with phase functions proportional to $e^{i\omega t^F}$ and $e^{i\omega t^S}$, where $t^{F,S}$ is the traveltime of the fast or slow mode. When principal directions are aligned with the coordinate axes, then $xy_{1,2} = yx_{1,2} = 0$ and the expressions in equation 1 reduce to

$$
\begin{aligned}
xx_{VS} &= xx_1 * xx_2,\\
yy_{VS} &= yy_1 * yy_2,\\
xy_{VS} &= yx_{VS} = 0, \qquad (2)
\end{aligned}
$$

which are analogous to those in isotropic media, but xx_{VS}, yy_{VS}, each now carries only fast or slow modes that have different speeds. When principal directions are not aligned with the coordinate axes, each source (x or y) splits into two secondary sources along the principal directions, thus exciting both fast and slow modes. The magnitudes of these secondary sources can be established by simple geometric projections. As a consequence, a single-component recording (x or y) would contain both fast and slow arrivals.

Taking as an example the crosscorrelation $xx_1 * xx_2$ from an x-component source, we find that it contains four different arrivals: two physical ones with phase $e^{i\omega(t_2^F - t_1^F)}$ and $e^{i\omega(t_2^S - t_1^S)}$ and two unphysical ones with phase $e^{i\omega(t_2^S - t_1^F)}$ and $e^{i\omega(t_2^F - t_1^S)}$, where $t_{1,2}^{F,S}$ is the traveltime of the fast or slow arrival to receiver 1 or 2. However, when crosscorrelations $xx_1 * xx_2$ and $yx_1 * yx_2$ from both x- and y-sources are combined, the unphysical cross-terms cancel out, leaving only the physical response xx_{VS}, as if a VS polarized in the x-direction were detected by the x-component of the second receiver station. This response contains only two physical arrivals: the fast wave ($e^{i\omega(t_2^F - t_1^F)}$) and the slow wave ($e^{i\omega(t_2^S - t_1^S)}$) between receivers 1 and 2. Similar cancellation occurs for all the other components of the multicomponent VS.

The VS data set obtained in this way has correct ratios between amplitudes. This can be verified by Alford rotation to the principal axes, which should diagonalize the data set so the fast and slow modes are isolated on the diagonal components and cross-diagonal components are zero. An example is shown in the next section.

It is important to note that surface source magnitudes should be equal to cancel the cross-terms and have proper amplitudes in the VS data. This condition is analogous to the requirement of identical source wavelets in the scalar version of VSM (Bakulin and Calvert, 2006). Finally, note that the simple expressions in equation 1 are also supported by the more elaborate analysis of Wapenaar and Fokkema (2006) for a completely general case.

SYNTHETIC EXAMPLE

Let us apply the multicomponent virtual shear check shot to the layered model shown in Figure 1. Consider a zero-offset VSP with two orthogonal shear sources acting at depth zero in a homogeneous isotropic half-space. The isotropic half-space is underlain by three orthorhombic layers with horizontal symmetry planes. Their vertical symmetry planes, however, have different azimuths. We use 3D dynamic ray tracing to generate synthetic data that contain only transmitted shear waves. Because the azimuth of the symmetry axes varies with depth, the number of the shear arrivals doubles with every additional layer. Thus, the wavefield becomes progressively more complicated with depth (Figure 2). In the isotropic top layer, each source (x, y) excites a single component of displacement in the same direction; but by the time waves reach the deepest layer, interfering arrivals show up on all receiver components with a similar strength.

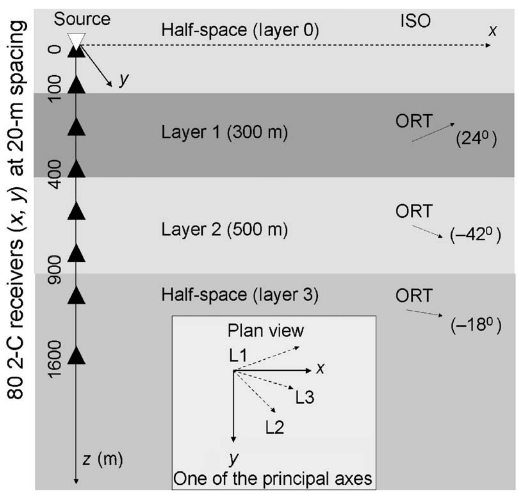

Figure 1. Horizontally layered model used for testing the VS approach. The orientation of the natural x-axis of each orthorhombic layer is marked by an arrow. Density and P-wave velocity are fixed throughout the model (2500 kg/m^3, 2000 m/s). Shear-wave velocities are $V_1 = V_2 = 1000$ m/s in layer 0 (isotropic half-space); $V_1 = 1000$ m/s, $V_2 = 846$ m/s in layer 1 $[(V_2 - V_1)/V_1 = -15\%$ splitting$]$; $V_1 = 900$ m/s, $V_2 = 1000$ m/s in layer 2 $[11\%$ splitting$]$; $V_1 = 970$ m/s, $V_2 = 1000$ m/s in layer 3 $[3\%$ splitting$]$. A 2-C source (x and y) acts in the upper half-space. A vertical well is instrumented with 80 2-C receivers (x and y) spaced at 20 m over the 20–1600 m depth interval.

We apply equation 1 to construct a 2-C $\times$ 2-C VS data set from the synthetic VSP. For simplicity, we do not perform any summation over surface shot locations, which typically is required — we consider only the stationary phase contribution coming from the pair of x, y sources at the wellhead. Redatumed data sets with a VS at the top of each layer are shown in Figure 3. Note that turning a receiver in the isotropic layer into a VS leads to a data set with zero cross-components. This is easily explained by the expressions in equation 2, which are applicable in the isotropic case. Also, the number of arrivals inside each anisotropic layer is reduced to two (as opposed to $2^{(n+1)}$ where n is the number of overburden layers). However, these two interfering arrivals show up on all four components of the 2-C $\times$ 2-C data sets because the symmetry axes of the layers do not coincide with the x and y receiver orientations.

Performing Alford rotation with known principal axis angles produces the nearly diagonal data sets in Figure 4. Now, fast and slow shear modes show up separately on the xx- or yy-component and exhibit remarkably clean and consistent waveforms starting from the first receiver located at the VS location. This repeatable character of the waveforms allows accurate estimation of shear-wave splitting using simple crosscorrelation between xx- and yy-components at each receiver depth. The resulting time lags and shear-wave splitting are shown in Figure 5a and c. Note the lack of an inertia effect near the top of each layer; the redatuming has removed the effect of the overburden. For comparison, we estimated the same values from the original VSP using traditional layer stripping (Figure 5b). Despite the fact that we used exact angles for the Alford rotation of the VSP (principal directions known from the model), the results were substantially less accurate, clearly suffering from the inertia effect as well as struggling to pick up the small splitting in the bottom layer.

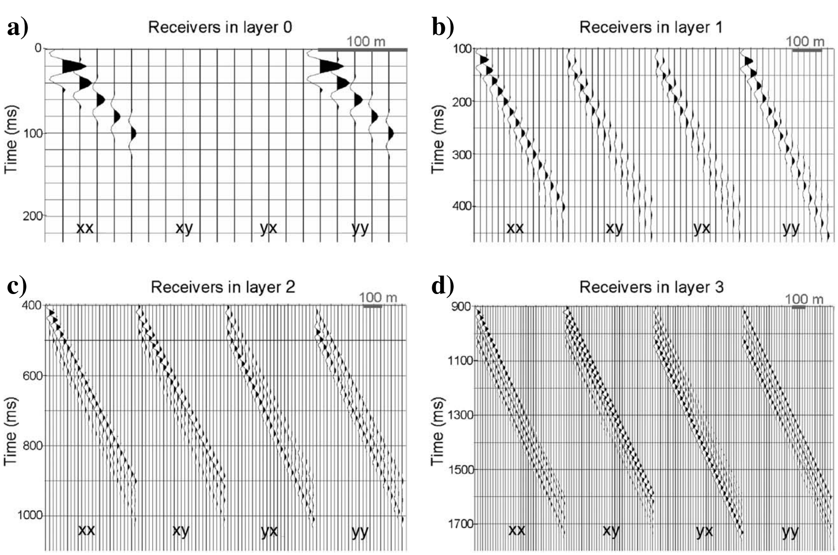

Figure 2. A 2-C $\times$ 2-C synthetic VSP containing only transmitted shear waves generated by dynamic ray tracing in the model shown in Figure 1. Note the escalating complexity of the wavefield with depth.

DISCUSSION

Although our discussion and synthetic example were confined to a 1D model, VSM is applicable to any type of heterogeneous and anisotropic media. Therefore, the new technique gives us an opportunity to estimate interval shear-wave splitting of deep layers located beneath 3D, complex, and anisotropic overburden. Summation over a number of surface sources (i.e., walk-away or 3D VSP) would be required to achieve proper illumination along the well under complex overburden. For a vertical well, two identical shear vibrators operating in orthogonal directions are all we need on the source side. For strongly deviated wells, a vertical surface source may also be needed.

Because VSM does not require any knowledge of the overburden, we no longer need to instrument the entire well with receivers or possess a priori information about principal directions in

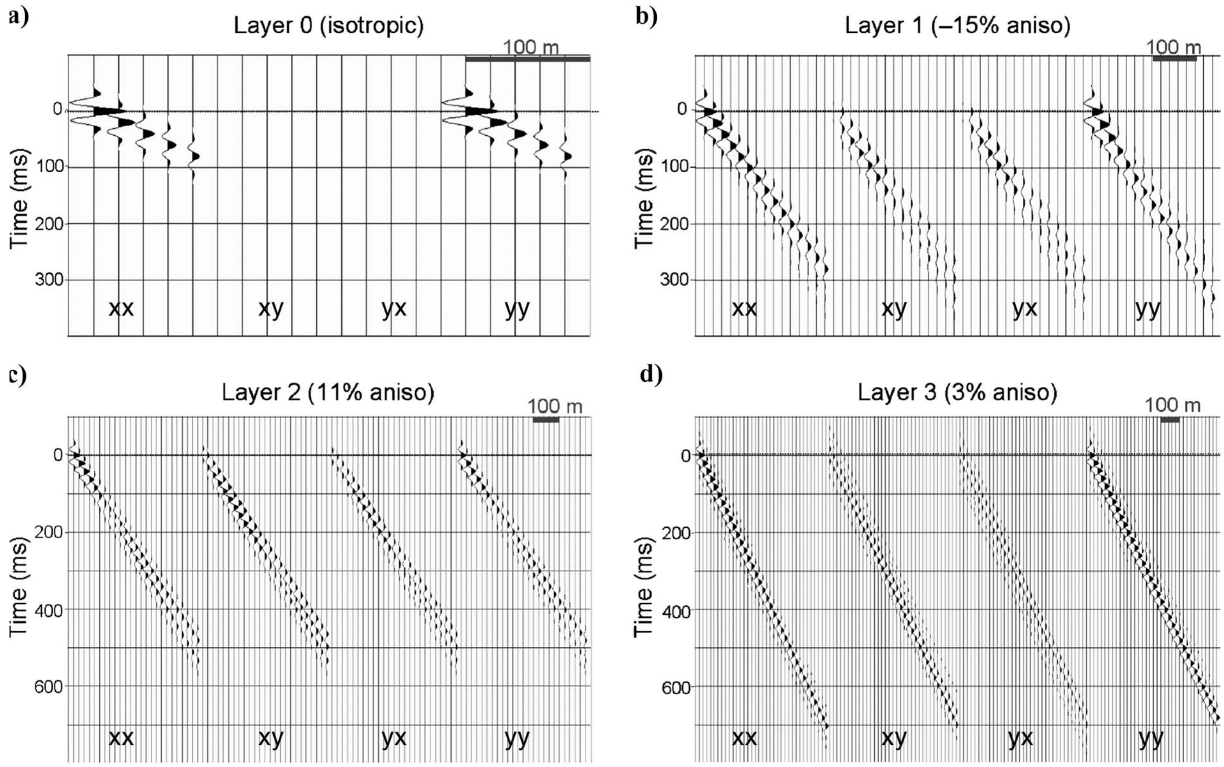

Figure 3. VS data sets obtained with expressions in equation 1 for receivers in (a) layer 0, (b) layer 1, (c) layer 2, and (d) layer 3. In each layer, the topmost receiver was turned into a VS. Note the simple wavefield in the deep layers as compared to Figure 2.

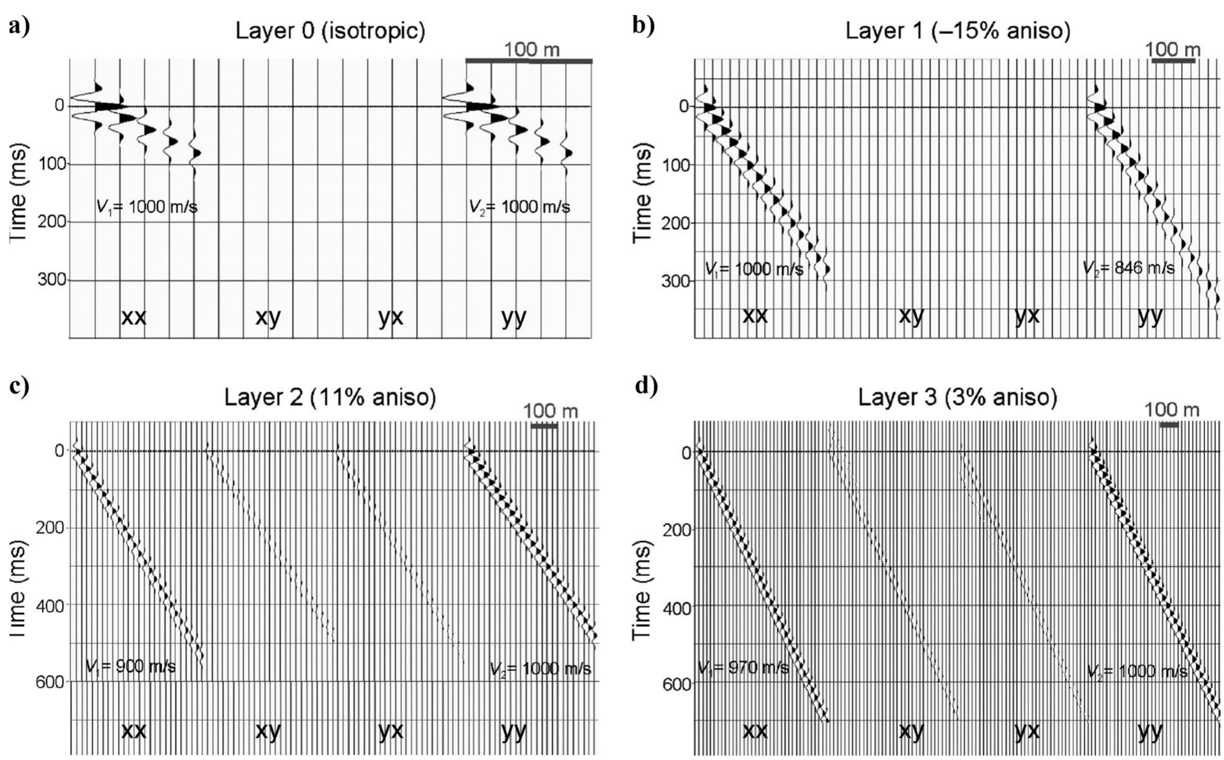

Figure 4. Same as Figure 3 but after Alford rotation performed inside each layer with the angles from Figure 1 (for layers 2 and 3, those angles contain ~0.5° rounding error compared to the true angles used when generating the synthetic VSP). Fast and slow shear-wave velocities measured from *xx* and *yy* overall moveout are shown in the plots and are in excellent agreement with the model.

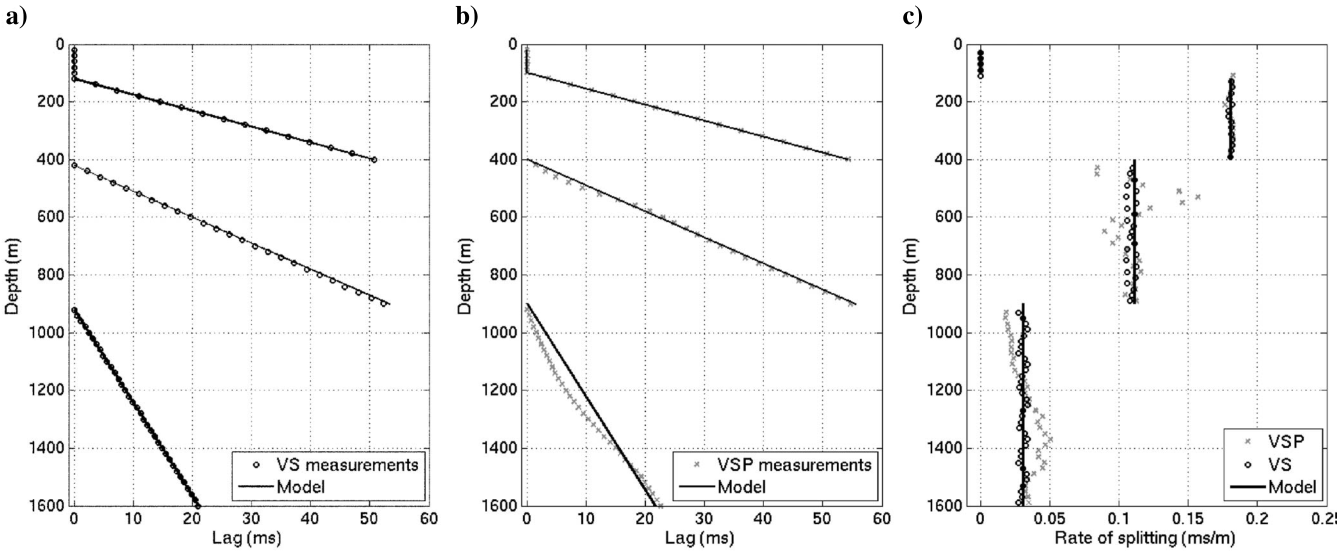

Figure 5. Estimated traveltime delays between fast and slow shear waves using (a) VS data and (b) conventional layer-stripping technique applied to VSP data. Note the inertia effect in (b). The estimated shear-wave splitting (c), corresponding to the slope in (a) and (b), demonstrates the higher accuracy achieved by VSM.

the overburden to estimate shear-wave splitting at depth.

A VS can be created at any receiver location. Therefore, the new technique will not suffer from error accumulation with depth, unlike the VSP layer-stripping technique. Similarly, the new technique is free of inertia effects because the overburden influence is completely removed from the VS data.

All of these reasons suggest that the new technique may deliver substantial improvements over the currently used layer-stripping approach. Moreover, the use of the 2-C × 2-C virtual data set obtained in this way can be extended beyond virtual check shots; it can be used for look-ahead VSP imaging with fast and slow shear waves, unaffected by overburden complexities. That opens a whole new field of possibilities for fracture and stress detection at depth and may greatly facilitate the interpretation of multicomponent surface seismic data.

CONCLUSIONS

We have described a new technique for estimating interval shear-wave splitting under arbitrary overburden. It is based on a multicomponent version of the VSM and requires as input a 2-C × 2-C VSP. Such a data set can be redatumed and converted into a virtual 2-C × 2-C data set as if one of the receivers were turned into a 2-C VS. A synthetic example confirms the ability of the new technique to accurately estimate interval shear-wave splitting under overburden with variable orientation of the principal axes. The successful diagonalization of the VS data by Alford rotation implies that the amplitudes of the 2-C × 2-C virtual data set are in appropriate ratios. A prerequisite for success is that the *x* and *y* shear vibrators have equal magnitudes or be scaled in processing.

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REFERENCES

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

Bakulin, A., and R. Calvert, 2004, Virtual source: New method for imaging and 4D below complex overburden: 74th Annual International Meeting, SEG, Expanded Abstracts, 2477–2480.

———, 2005, Virtual shear source: A new method for shear-wave seismic surveys: 75th Annual International Meeting, SEG, Expanded Abstracts, 2633–2636.

———, 2006, The virtual source method: Theory and case study: Geophysics, **71**, no. 4, SI139–SI150.

Bakulin, A., A. Mateeva, R. Calvert, P. Jorgensen, and J. Lopez, 2007, Virtual shear source makes shear waves with airguns: Geophysics, **72**, no. 2, A7–A11.

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.

Wapenaar, K., 2004, Retrieving the elastodynamic Green's function of an arbitrary inhomogeneous medium by cross correlation: Physical Review Letters, **93**, 254301.

Wapenaar, K., and J. Fokkema, 2006, Green's function representations for seismic interferometry: Geophysics, **71**, no. 4, SI33–SI46.

Winterstein, D. F., and M. A. Meadows, 1991, Shear-wave polarizations and subsurface stress directions at Lost Hills field: Geophysics, **56**, 1331–1348.