Processing of seismic data in the presence of anisotropy

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ABSTRACT

Processing techniques for extracting the polarization directions of the fast, and slower split shear waves, together with their travelt ime splitting from vector wavefield data, form the basis of prospective procedures for imaging details of the internal structure of subsurface rocks. A recently developed technique involving the independent rotation of the source polarization direction, and geophone axes, provides an effective processing tool for extracting the effects of anisotropy from shear-wave data. It is theoretically capable of handling nonorthogonal polarization directions of split shear waves. It is further developed, and its performance examined using vertical seismic profiling (VSP) shear-wave datasets for different anisotropic earth models, and computed using full-wave modeling. The procedure works well for shear waves propagating through an earth model with a uniform crack strike with depth, but produces inaccurate estimates of polarization and time-delay when the crack strike varies abruptly with depth. It is unlikely that other techniques could do better under these circumstances, as the problems arise due to the complexities introduced by multiple shear-wave splitting.

INTRODUCTION

The vector analysis of shear waves provides an opportunity to improve upon existing seismic methods for imaging the subsurface. A phenomenon that must necessarily be incorporated into this framework is anisotropy (Sriram et al., 1990). The most diagnostic effect of anisotropy on the shear wavefield is to cause shear-wave splitting (Crampin, 1985). This characteristic has been observed in shear waves propagating through the upper crust in a wide variety of seismic scenarios (Crampin and Bush, 1986; Crampin, 1987) and is thought to be a property of most rocks including sedimentary basins in at least the uppermost 10 to 20 km of the crust (Crampin and Atkinson, 1985). In this phenomenon, a single shear-wave incident upon a region of effective anisotropy splits into two waves, polarized in different directions (which are fixed by the direction of propagation through the medium) and traveling at slightly different velocities. The shear-wave splitting depends upon the symmetry and orientation of the anisotropy systems representing the crustal material, the degree of anisotropy, the length of the propagation path, and the direction of propagation.

Shear-wave processing may be approached with two objectives: first, it is useful to compensate for the effects of anisotropy in order to obtain a sharp image of the subsurface, which may subsequently be correlated with the results of the P-wave analyses. From such correlations, depth distributions of lithology indicators such as $V_p/V_S$ may also be constructed. Due to the nature of shear-wave splitting outlined above, problems arise in this work if an attempt is made to construct accurate processing procedures utilizing conventional P-wave philosophies. The second objective is to extract the more subtle information about the nature and orientation of the internal structure of the subsurface by examining the finer details contained within the shear wave train. Information on the anisotropic system(s) which represent the effect of the medium through which the shear waves propagate may be derived by estimating parameters of the split shear waves such as the polarization directions of the fast and slow shear waves, the time-delay between corresponding split shear waves, and their relative amplitudes. This in turn may be converted into information on the physical properties of the rocks, such as fracture density and orientation. The present work concentrates on extracting estimates of the polarizations of both the leading and slower split shear waves, and their corresponding time-delay from shear-wave data. In recent years, many techniques for estimating these parameters have been developed and applied by workers in exploration seismology. For example: Alford (1986); Naville (1986); Nicoletis et al. (1988); Lefevre et al. (1989); Igel and Crampin (1990); and Esmer soy (1989). MacBeth and Crampin (1991) classify and compare all of these and other published techniques. Here, we
examine the recently developed technique of Igel and Crampin (1990), and place its relevance to the investigation of subsurface anisotropy.

**PROCESSING PROCEDURE**

Rotational analyses

The processing technique is based upon the axiom, given two datasets recorded with the same acquisition geometry and source position, but with different (nonparallel) horizontal source polarizations, another dataset corresponding to an arbitrary source polarization \( \theta \), in the horizontal plane, can be constructed. It is consequently possible to rotate the source polarization in the horizontal plane, monitoring the corresponding dataset, until it becomes aligned along the fast and slow polarization directions of the medium. The coincidence of these directions can be detected as most of the recorded energy in the horizontal plane will then lie in one particular direction, and the polarization diagrams will be strongly linear. This approach has, in one form or another, constituted the basis of recent procedures for measuring the anisotropy in upper crustal rocks. For example, the method of Alford (1986) monitors the energy on in-line and cross-line geophone components, for in-line and cross-line source polarizations, while rotating the medium. This procedure effectively rotates the source polarizations and geophone components synchronously about the vertical axis. A condition of minimum energy or event coherence for the off-diagonal elements of the resultant data matrix signifies the best rotation angle. This technique is now in common use on reflection data (which was the original application) and also on VSP data (Winterstein and Meadows 1990). It has been used to obtain a gross average of the anisotropic properties over several seismograms, or to extract fine details using independent values for each seismogram. The technique is developed using a different approach, again for reflection data, by Thomsen (1988), and a quantitative criterion is offered to monitor the condition of alignment with the polarization directions of the medium. A further development has been an analytic expression for the optimum rotation angle based upon the minimization of the off-diagonal energy (Murtha, 1988). Queen and Rizer (1990) discuss the assumptions behind the matrix rotation concept and the minimization criteria. The technique of Igel and Crampin (1990) extends this idea of rotation by effectively rotating both source polarization and geophone components separately, forming a spectrum of energy values as a function of the two rotation angles. The source polarization is rotated in the horizontal plane, and for each direction a dataset is computed. From the horizontal components of this dataset, a polarization energy spectrum is calculated, which measures the amount of energy in each direction in the horizontal plane. The end product of this processing step is a matrix of directional energy of the geophone versus source polarization angle. This technique has been applied to VSP and reflection data by Igel and Crampin (1990), who also ascertained its performance in the presence of noise, together with the uniqueness and stability of the resultant solutions. Here, we present the technique in the context of seismic processing for anisotropy, apply it to synthetic seismograms derived from several VSP geometries and models, and examine its performance. The present work forms a prelude to an investigation to compare crustal conditions under which the results of a synchronous source-geophone rotation or the matrix equivalent of the separate source-geophone rotation are valid.

**Algorithm details**

The technique can be visualized by first considering the position vector associated with the displacement, \( \mathbf{u}(\theta, t) \), at a particular geophone level due to a source polarization \( \theta \). For each source orientation and each trace in the dataset \( \mathbf{u}(\theta, t) = (x(t), y(t))^T \) is transformed into a function of direction \( \phi(\theta, t) \), where:

\[
\phi(\theta, t) = \tan^{-1} \left( \frac{y(t)}{x(t)} \right); \tag{1}
\]

and the energy in that particular direction:

\[
e(\theta, t) = x(t)^2 + y(t)^2. \tag{2}
\]

A further rearrangement of the seismogram is made by collecting together all of the energies which lie within a particular range of directions \( (\phi_i - \delta \phi \leq \phi \leq \phi_i + \delta \phi) \), to form an energy histogram as a function of direction. Each seismogram trace is now expressed in terms of the distribution of directional energy within the time window of interest, thus eliminating the time variable. If this procedure is repeated for all source polarizations, then a matrix of energy as a function of source polarization \( \theta \) and horizontal direction \( \phi \) is established. This energy function is termed the "polar energy spectrum," \( F(\theta, \phi) \), by Igel and Crampin (1990). Physically, the procedure is equivalent to rotating the source polarization and geophone axes separately and monitoring the recorded energy along a particular direction in the horizontal plane.

For an isotropic material, the distribution \( F(\theta, \phi) \) will be unity when the displacement direction \( \phi \) equals the source polarization \( \theta \), and will otherwise be zero, i.e., the displacement vector will follow the source polarization. This behavior is illustrated in Figure 1(a). The distribution of the energy along the diagonal band in Figure 1(a) is constant. For a uniform anisotropic medium, there are distinct maxima in the function, corresponding to the polarization directions of the leading, and correspondingly slower split shear wave [Figure 1(b)]. Generally, depending upon the degree of splitting, or quality of the records, energy may be present at most other values of \( \theta \) and \( \phi \). In general, the maxima need not be separated by 90 degrees, and nonorthogonal \( qS1 \) and \( qS2 \) polarizations can be accommodated. If the polarization directions of the split shear waves vary with depth (for example, gradual variation of crack strike), it may be possible to observe two main energy peaks for the function [Figure 1(c)]. In this case, the two maxima are positioned at values of \( \theta \) and \( \phi \) which correspond to the \( qS1 \) and \( qS2 \) polarization directions for the material in the immediate vicinity of the source, and the immediate vicinity of the geophone. The exact nature of the variations under which the method can be applied is currently under investigation. Polarization directions of the medium are estimated by searching the energy matrix computed for each geophone, and locating the positions of the energy peaks. For this work, \( \theta \) and \( \phi \) are varied between 0 degrees and 180 degrees.
in increments of 10 degrees. The values of $\phi$ corresponding to the energy peaks in $F(\theta, \phi)$, are chosen as the polarization directions of $qS1$ and $qS2$.

The time-delay between the corresponding split shear waves is evaluated by rotating the horizontal geophone axes of the original data (in-line or cross-line) so that the axes are aligned along the fast and slow polarization directions determined by the procedure above. Again, to generalize the procedure, these axes are not constrained to be orthogonal. The horizontal displacements on each geophone axis are cross-correlated—a robust procedure which is in common use in the analysis of shear-wave splitting in exploration seismics (for example: Becker et al., 1990; Murtha, 1989). The position of maximum correlation yields the time-delay.

**APPLICATION TO VSP DATA**

**Treatment of data from a seismic survey**

Before processing the shear-wave data, it is useful to establish the expected behavior of the polarizations and time-delays. Figures 2 and 3 schematically illustrate the typical behavior of the shear waves for a simple seismic VSP survey. Data are recorded from a fixed offset VSP, with geophones positioned down a vertical well (Figure 2). The earth model is a simple homogeneous anisotropic medium bounded by a plane horizontal reflector at depth. The effect of reflection coefficients on the observed polarization are not included in this illustration. This medium is assumed to consist of a homogeneous isotropic material permeated by parallel, vertically aligned, liquid-filled microcracks striking east-west. The anisotropy arising from such aligned microcracks is known as extensive-dilatancy anisotropy or EDA (Crampin, 1987).

The rays to the geophones pass through this anisotropic medium at a wide range of different angles of incidence (from 20 degrees to 70 degrees). Figures 3 and 4 illustrate the expected variation in the polarizations and time-delay for the angular range. At the particular azimuth of the shot line in Figure 2, and for angles of incidence smaller than around 35 degrees, the polarizations of the fast and slow split shear waves assume an alignment along and perpendicular to the crack strike. The arrivals which fall within this category are delineated by the dotted box in Figure 3(a). This includes the reflected waves as the propagation angles are steeper due to

**Fig. 1.** Expected matrix of energy function versus $\theta$ and $\phi$ resulting from the application of the independent rotation of source and geophone to waves propagating through: (a) Isotropic medium—recorded polarization follows source polarization, leading to a diagonal ridge of maxima. (b) Homogeneous and anisotropic medium—one set of crack directions: function forms two peaks corresponding to fast and slow shear waves, where both source and geophone orientations are equal. (c) General anisotropic medium with vertical variation of EDA-crack strike—it is anticipated that two energy peaks are obtained corresponding to $qS1$ and $qS2$. Geophone orientations correspond to the crack orientations of the material surrounding the recording instrument, the source orientation may take other values.

**Fig. 2.** Raypaths for the arrivals through a homogeneous anisotropic material with a single reflector. Acquisition geometry lies in a constant plane of azimuth (between the east-west and north-south directions) and angles of incidence for the rays range from 20–70 degrees. The source polarization vector is inclined to the horizontal (x-y) plane.
the geometry of the raypaths. For more horizontally traveling arrivals, this alignment is not followed, and the depth profile exhibits a rapid change in polarization angles [Figures 3(a) and (b)]. Invariant polarization angle for the leading shear wave as a function of geophone position, cannot therefore be justified (even for a homogeneous anisotropic medium). The angle between the two split shear waves also cannot be considered as invariant, as it is orthogonal only within certain limits [compare the difference between the two corresponding curves in Figure 3(b)]. These characteristics of the shear waves are more fully demonstrated in equal-area plots of the horizontal polarizations and time-delays (Figure 4), which shows variations with azimuth and angle of incidence. Note that this behavior is a combination of two factors: the polarizations in Figure 4 represent vectors projected onto a horizontal plane from rays traveling at a range of acute angles of incidence from 0 to 90 degrees; and the raypaths are orthogonal to the planes of constant phase (Crampin, 1985). The behavior of the time-delay between split shear waves varies in a less erratic way than the polarizations, which may make abrupt changes and swings over a small range of propagation directions. These

![Fig. 3. Schematic illustration of the character of recorded split shear-waves corresponding to Figure 2. (a) Each pair of split shear-wave arrivals is drawn with corresponding polarization vectors projected onto the horizontal plane (relative to north and east directions) with associated time-delays. (b) Qualitative expression of the variation in polarization angle (measured relative to east direction in an anticlockwise direction) and time-delay which would be obtained from measurements of the shear-wave arrivals in Figure 2. Solid circles represent qS1 value and open circles represent qS2. Solid line is the direct arrival and dotted line the reflected arrival.](image)

![Fig. 4. Equal-area plots are a way of portraying three-dimensional variations over a hemisphere of directions on a plane, circular surface. The labeled dots refer to directions in Figures 2 and 3. (a) Shear-wave polarizations are plotted with solid bars corresponding to the faster shear wave and the broken bars corresponding to the slower shear wave. The horizontal projections model the expected polarizations as seen by the horizontal instruments for vertical EDA-cracks striking in the east-west direction, with a crack density of 0.04. (b) The three-dimensional distribution of time-delay is a contour plot displayed in units of millisecond per kilometer of the propagation path. The raypaths a–f in Figure 2 map onto a line of points in the projection plane as shown.](image)
conditions may be summarized as: (1) polarization of shear waves may be different for each geophone level (depth) and each arrival on a particular seismogram; (2) polarizations of the split shear-wave pair may not be orthogonal; (3) time-delays are less erratic functions than polarization angles. In order to extract reliable estimates of shear-wave splitting, processing techniques must take (1) and (2) into account. It must also be emphasized that in the earth’s crust the polarization and time-delay variations are expected to be more complex as many different symmetry (anisotropy) systems may be present. An example of such complexities is highlighted by the properties of a mixture of two systems representing EDA-cracks and anisotropy due to alternating thin layers, yielding a sequence of point singularities (Wild and Crampin, 1991), and other anomalies. Such complexities may be exacerbated by variations in the properties with depth. In the case of a zero or near-offset VSP where the angles of incidence may all be close to the vertical, the polarization of the leading shear wave at each geophone may be assumed to be constant with depth and the condition of treating each geophone level independently may be relaxed.

### Table 1. Details of seismic acquisition geometry and model, used to compute synthetic seismograms to test the processing algorithm.

<table>
<thead>
<tr>
<th>Material</th>
<th>Type</th>
<th>Isotropic Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-space</td>
<td>Anisotropic</td>
<td>$V_p$ (km/s) 5.00, $V_s$ (km/s) 2.89, crack density 0.04, crack strike N15°W</td>
</tr>
</tbody>
</table>

Source: in/cross-line polarization, 100 m offset in east-west direction. Geophones: 50 placed from 25 m to 1250 m depth.

### Table 2. Details of seismic acquisition geometry, and model used to compute the AMC synthetic seismograms.

<table>
<thead>
<tr>
<th>Material</th>
<th>Type</th>
<th>$V_p$ (km/s)</th>
<th>$V_s$ (km/s)</th>
<th>crack density</th>
<th>crack strike</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMC1 500 m</td>
<td>isotropic</td>
<td>4.10</td>
<td>2.30</td>
<td>0.02</td>
<td>E-W</td>
</tr>
<tr>
<td>AMC2 500 m</td>
<td>anisotropic (cracked)</td>
<td>4.23</td>
<td>2.35/2.31</td>
<td>0.02</td>
<td>E-W</td>
</tr>
<tr>
<td>AMC3 500 m</td>
<td>isotropic</td>
<td>4.24</td>
<td>2.36</td>
<td>0.10</td>
<td>E-W</td>
</tr>
<tr>
<td>AMC4 500 m</td>
<td>anisotropic (cracked)</td>
<td>4.17</td>
<td>2.63/2.24</td>
<td>0.02</td>
<td>E-W</td>
</tr>
<tr>
<td>AMC5 500 m</td>
<td>anisotropic (cracked)</td>
<td>4.36</td>
<td>from 2.43/2.38 to 2.49/2.44</td>
<td>0.02</td>
<td>E-W</td>
</tr>
<tr>
<td>AMC6 500 m</td>
<td>anisotropic (cracked)</td>
<td>4.47</td>
<td>2.49/2.44</td>
<td>0.02</td>
<td>E-W</td>
</tr>
<tr>
<td>half-space</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: in/cross-line polarization, 500 m offset in N45°E. Geophones: 60 placed from 50 m to 3000 m depth.

### Table 3. Details of seismic acquisition geometry, and model used to compute synthetic seismograms to test the processing algorithm.

<table>
<thead>
<tr>
<th>Material</th>
<th>Type</th>
<th>Isotropic Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1 200 m</td>
<td>anisotropic</td>
<td>$V_p$ (km/s) 2.50, $V_s$ (km/s) 1.44, crack density 0.04, crack strike N15°W</td>
</tr>
<tr>
<td>Layer 2 500 m</td>
<td>anisotropic</td>
<td>$V_p$ (km/s) 4.00, $V_s$ (km/s) 2.31, crack density 0.04, crack strike N30°E</td>
</tr>
<tr>
<td>Half-space</td>
<td>anisotropic</td>
<td>$V_p$ (km/s) 5.00, $V_s$ (km/s) 2.89, crack density 0.04, crack strike N-S</td>
</tr>
</tbody>
</table>

Source: in/cross-line polarization, 100 m offset in E-W direction. Geophones: 50 placed from 25 m to 1250 m depth.
cracks have an aspect ratio of 0.001. Each model is excited by horizontal, near-offset, in-line and cross-line source polarizations. The resultant wavefield is recorded on a number of three-component geophones arranged vertically into the medium. Tables 1, 2 and 3 give details of the acquisition geometries and models used in the analysis.

Model A—Homogeneous anisotropic half-space.—Synthetic seismogram data generated by the basic acquisition geometry in Table 1 are shown in Figures 5(a) and 5(b). Some polarization diagrams in the horizontal plane are shown as a visual check of the crack-strike direction, which coincides with the initial shear-wave onsets for most of the deeper geophones, as expected. The shear waves are simply windowed and processed. The displacement directions \( \phi \) (polarization direction of medium at geophone level) and the corresponding time-delays output from the processing technique are displayed in Figure 6 as a function of depth. Both estimates of the \( qS1 \) and \( qS2 \) polarizations do, to some degree, follow the irregular behavior of the polarizations for the near-surface geophones (this behavior relates to the phenomenon described above). The records for the top few geophones are also complicated by P-wave interference. At depths beyond geophone 12 at 300 m for \( qS1 \), and geophone 7 at 175 m for \( qS2 \) the polarizations of the shear-waves are correctly estimated. For each seismogram, the maxima in the energy matrix were located at positions with equal values of \( \theta \) and \( \phi \), as expected for a medium with uniform anisotropic orientation. The time-delay profile displays jumps which are related to the sample interval of the seismograms. For this function there also appears to be a close correspondence to the expected model values, except at the top few geophones.

Model B—Multilayered model of alternating isotropic and anisotropic layers with an embedded layer of strong anisotropy.—A number of research groups have been organized into an anisotropy modeling collaboration (AMC) to calculate full-wave synthetic seismograms in specified VSPs and reflection surveys for a given anisotropic multilayered

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**Figure 5.** In-line source (a) and cross-line source (b) synthetic seismogram sections corresponding to a half-space model. Polarization diagrams are drawn to provide a visual check with the crack strike. Arrows drawn on particle motions give direction of motion and larger arrowheads show direction of initial onset. Solid circles on lower right-hand section indicate those transverse component seismograms used for polarization diagrams.
Fig. 6. Results from applying processing algorithm to the synthetic data of Figures 5(a) and 5(b). Solid lines are expected polarization profiles, and dashed lines are estimated profiles. (a) Horizontal polarizations of qS1 and qS2. Note the nonorthogonality of expected profiles for the top few geophones. (b) Corresponding time-delays between pair of split shear waves.

Fig. 7. In-line source (a), and cross-line source (b) synthetic seismogram sections corresponding to AMC VSP model with some selected polarization diagrams. Diamonds mark the position of an interface between two layers. Arrows drawn on particle motions give direction of motion and larger arrowheads show direction of initial onset. Solid circles on lower right-hand section indicate those transverse component seismograms used for polarization diagrams.
model, so that the data may be compared (Thomsen, 1989). Preliminary results were presented at the SEG Summer Workshop in Snowbird, Utah, 1989. The offset VSP data for a 45-degree azimuth is chosen for analysis in this present work. The VSP data derived from the AMC model (Table 2) are displayed in Figures 7(a) and 7(b). The crack orientations are the same (45 degrees with respect to radial direction) for each anisotropic layer. There is no irregular polarization behavior in the top geophones in this case, as the first layer with a thickness of 500 m is isotropic. This particular model features a strongly anisotropic layer which begins at 1500 m and extends to 2000 m depth, simulating a highly fractured reservoir rock. The particle motions in Figure 7(a) show a clear indication of splitting in all layers (apart from the first isotropic layer) with the direction of initial shear-wave onset along the crack strike. A pronounced cruciform shape is observed below and within the reservoir material. In this layer, the difference in shear-wave velocities gives rise to a predicted time-delay of 60 ms/km compared to 8 ms/km for each of the other anisotropic layers. The estimated polarizations and time-delay profiles are displayed in Figure 8. The polarization directions of the medium, given by the φ coordinate of the peaks on the energy matrix, are well determined (with fluctuations of around ±5 percent and the sharp increase in the time-delay in layer 4 is closely followed. The θ and φ coordinates of the peaks in the energy matrix are equal for most of the geophones.

Model C—Two anisotropic layers overlying an anisotropic half-space with different directions of natural axes.—The procedure is now applied to two layers above a half-space, the material in each layer containing cracks with a different direction of strike. The seismogram data for this model (Table 3) are shown in Figures 9(a) and 9(b). The maximum time-delay associated with layer 1 is 4 ms, 10 ms in layer 2, and 9 ms to the deepest geophone in the half-space. The seismogram sections show P-waves, shear-waves, P-S conversions, S-P conversions, and reflected shear-waves. For this study, only the directly transmitted shear waves are processed. The estimated profiles of polarization direction, and time-delay are shown in Figure 10. Here it can be seen that the trends in the polarization and time-delay are only approximately followed, with many departures from the actual values. The irregular polarization behavior of the top six geophones is present again in this model, and is only very approximately followed by the processing routine. There are many local maxima in the energy matrix $F(θ, φ)$ making selection a difficult and unreliable procedure. For most of the solutions, θ and φ are not equal, emphasizing the problem of treating source and geophone together in this case.

The main reason that the processing procedure does not perform well in this situation is the layers of differently oriented anisotropic material, which produces multiple shear-wave splitting. The resultant particle motion is consequently much more complex than the previous two cases. This phenomenon may be understood by considering the two-layered medium in Figure 11. In the first medium, two split shear-waves are formed with a time delay $δ1$ between them. Each of these shear waves gives rise to two further split shear waves on entering the second medium. Hence, there are now four split shear waves, the time delay between each component in a pair separated by the second medium being $δ2$, and between corresponding pulses separated by the first medium $δ1$. In the general case, this process may occur many times in both reflection and transmission, leading to a complex recorded wavetrain. Although the polarizations of the different arrivals align according to the preferred polarizations of the medium in the immediate vicinity of the geophone, the rotation of source and geophone may not now relate directly to the desired medium properties. In addition to this problem the likely differential attenuation between the individual split shear-wave components in the field data ensures that the source polarization and geophone displacement cannot be reliably related to the crack strike direction. The estimated time-delay profile also reflects the additional complexity in this model. The appropriate time-delay to be measured is for the path length associated with the medium in which the geophone is placed. Thus, each time a new medium is encountered the time-delay should be reset to zero (Figure 10). The estimated values do not appear to follow this trend even though care has been taken to pick the first peak of the correlation function.

**DISCUSSION AND CONCLUSIONS**

A method, which may be visualized as separately rotating source polarization and geophone axes, has been presented as a shear-wave processing tool for seismic data. It is applied to three different VSP, synthetic seismogram, data sets of increasing complexity. The technique works well on the shear-wave data for an anisotropic half-space (model A) and multilayered model (model B), both of which have a uniform crack strike orientation with depth. The procedure follows the changes in time-delay gradient for model B. In model C, which has two layers of anisotropic material over an anisotropic half-space, each material possessing a distinctly different crack strike, the method does not adequately resolve the crack strike. It is unlikely that synchronous source-geophone rotation would do better under these circumstances. This disparity is mainly attributed to multiple shear-wave splitting. There is a suggestion in the results of models B and C that the technique may resolve irregular variations in the polarizations, and that these polarizations may be nonorthogonal. The technique is theoretically capable of handling this situation. If reliable and accurate parameters for shear-wave splitting are to be extracted from shear-wave data, processing techniques must cope with the effects of variations in the crack strike with depth, nonorthogonal $q51$ and $q52$ polarizations, and the phenomenon of multiple shear-wave splitting. These difficulties are compounded by the more fundamental issues in processing field data. For example, the processing procedure above requires two-component (in the horizontal plane) data for at least two different source polarizations (again in the horizontal plane), recorded with the same acquisition geometry. Consequently, the relative excitation of the two source components and relative coupling effects between geophone components must be equalized for both in-line and cross-line data sets. This situation may be difficult to achieve in practice.
Fig. 8. Results from applying processing algorithm to the synthetic data of Figures 7(a) and 7(b). Diamonds again mark interface positions. Solid lines are expected polarization profiles, and dashed lines are estimated profiles. (a) Horizontal polarizations of qS1 and qS2. Note the nonorthogonality of expected profiles for the top few geophones. (b) Corresponding time-delays between pairs of split shear waves.

Fig. 9. In-line source (a) and cross-line source (b) synthetic seismogram sections corresponding to model in Table 3, with some selected polarization diagrams. Arrows drawn on particle motions give direction of motion and larger arrowheads show direction of initial onset. Solid circles on lower right-hand section indicate those transverse component seismograms used for polarization diagrams.
Fig. 10. Results from applying processing algorithm to the synthetic data of Figures 9(a) and 9(b). Diamond symbols again mark interface positions. Solid lines are the expected profiles, and dashed lines are the estimated profiles. (a) Horizontal polarizations of qS1 and qS2. Note the nonorthogonality of expected profiles for the top few geophones. (b) Corresponding time-delays between pair of split shear waves. The expected saw-tooth behavior of the profile is a consequence of multiple shear-wave splitting.

Estimating polarizations and time-delay from shear-wave data form the first stage in the prospective imaging of the internal structure of the subsurface. In theory, it is possible to relate the geophone position and chosen arrival to directions of propagation within the various constituents in the medium. The next stage thus involves working from the polarization and time-delay data as a function of direction of propagation, to construct an inverse problem to predict the range of possible constituent anisotropic materials which may give rise to these estimates. From this, it may be possible to interpret the results in terms of range of physical attributes of the material. The inversion for anisotropic layers has been achieved for VSPs recorded at several azimuths, and polarizations of the leading split shear wave by MacBeth (1990, 1991). This work suggests that future expectations of imaging subsurface anisotropy with, at least, VSP data may prove hopeful.

This present study is a preliminary test of the separate source-geophone rotation technique. A further investigation is currently underway to compare rotation techniques for different anisotropic crustal conditions and to determine the most suitable procedure for shear-wave processing.

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