EXTENSIVE-DILATANCY ANISOTROPY: RELATIVE INFORMATION IN VSPs AND REFLECTION SURVEYS'

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ABSTRACT


Shear-waves have complicated interactions with the free surface, particularly in the presence of low-velocity surface layers, topographic irregularities, and the expected near-surface crack and stress anomalies. Consequently, it has been suggested that shear-waves should be recorded subsurface in vertical seismic profiles (VSPs), in order to extract accurate information about the in situ crack and stress geometry contained in shear-wave splitting. This paper compares the information in synthetic shear-waves in reflection gathers and VSPs, in order to assess the relative merits of the two techniques for investigating shear-wave splitting. Synthetic seismograms demonstrate that in the presence of even very simple surface layers, shear-waves recorded in reflection surveys at the surface have polarizations which may not indicate crack and stress geometry at depth. In contrast, shear-waves recorded in VSPs are relatively unaffected by surface layers and near-surface stress and crack anomalies, and the behaviour of shear-wave splitting is dominated by the structure of the rock mass in the vicinity of subsurface geophones. Matrix rotations of multicomponent-multisource shear-wave reflection data to extract the information contained in the split shear-waves, are found to be directly meaningful only in situations where crack orientations do not change with depth.

INTRODUCTION

Shear-wave splitting has now been observed in a wide variety of geological situations including reflection surveys (Alford 1986; Lynn and Thomsen 1986; Willis, Rethford and Bielanski 1986) and vertical seismic profiles (VSPs) (Becker and Perelberg 1986; Bush 1990), in sedimentary basins. Shear-wave splitting is characteristic of almost all shear-wave propagation in the uppermost 10-20 km of the crust (Crampin 1987a). The splitting is caused principally by propagation through the distributions of stress aligned, parallel, vertical, fluid-filled microcracks, cracks and preferentially aligned pore-space, which pervade most rocks in the crust and are

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known as extensive-dilatancy anisotropy or EDA (Crampin, Evans and Atkinson 1984; Crampin 1985, 1987a).

Since analysis of the detailed waveforms of the shear-waves is important for estimating the internal structure of the rock mass, it is desirable to minimize any disturbance to the behaviour of the split shear-waves as they travel through the reservoir to the recording instrument. Shear-waves have complicated interactions with the free surface (Booth and Crampin 1985), particularly in the presence of low-velocity surface layers, topographic irregularities and the expected near-surface crack- and stress-anomalies (Crampin 1990). Consequently, it has been suggested that shear-waves should be recorded subsurface in VSPs, rather than in surface reflection lines, in order to preserve the valuable information about crack and stress geometries contained in the shear wavetrain (Crampin 1987a; Crampin, Lynn and Booth 1989). VSPs, however, are expensive, especially in the high-cost production environments where information about crack and stress geometries would be particularly valuable.

We compare the relative information in synthetic shear-wave seismograms from reflection surveys and VSPs in the presence of near-surface layering. We also examine the viability of matrix rotations of multicomponent-multisource data to extract the anisotropic parameters from recorded shear-wave data.

Note that the terminology used for seismic anisotropy is given by Crampin (1989). In general, the faster and slower split shear-waves are referred to by $qS1$ and $qS2$, respectively. However, for propagation in symmetry planes through the crack normals, it is convenient to refer to the shear-waves as $qSP$, polarized (P)arallel, and $qSR$, polarized at (R)ight angles to the plane through the crack normals.

**Degradation Effects of Surface Layers**

The presence of EDA-cracks in a rock mass causes the incident shear-waves to split into (usually) two approximately orthogonal components (Fig. 1). In the absence of any other forms of anisotropy, the faster split shear-wave is aligned parallel to the strike of the cracks, for near-vertical raypaths. These cracks are, in turn, typically aligned parallel to the maximum horizontal stress. Thus, the polarization of the leading split shear-wave is likely to be related to the orientations of the hydraulic fractures and the preferential directions of flow within the reservoir, which are commonly subparallel to the stress direction. The distribution of the normalized delay between the two shear-waves can be interpreted in terms of crack density and aspect ratio. Hence, recording shear-waves with three-component geophones can provide valuable information about the internal structure of the reservoir.

There are several phenomena, however, which may cause the information contained in the split shear-waves to be lost or distorted, especially if recorded at a free surface. The particle motion of a shear-wave will be distorted if recorded at the surface outside the shear-wave window (Evans 1984). [The shear-wave window is the solid angle at the surface bounded by angles of incidence of $\sin^{-1}(V_p/V_s)$, within which shear-waves can be recorded without distortion (Booth and Crampin 1985). This critical angle is about 35° for a Poisson’s ratio of 0.25.] Irregular surface topog-
Fig. 1. Schematic illustration of shear-wave splitting. A shear-wave entering a region of aligned cracks necessarily splits into (usually) two phases with different polarizations and different velocities. The phase polarized parallel to the face of the cracks meets less impedance and travels faster and is less attenuated than the phase polarized perpendicular to the crack face. $\sigma_v$, $\sigma_h$ and $\sigma_h$ are the vertical, maximum horizontal and minimum horizontal stresses, respectively.

raphy may mean that, locally, the angle of incidence of the incoming shear-wave is outside the shear-wave window, leading to distortion of the shear-wave polarizations, even for arrivals which are apparently within the window for a horizontal surface. Similar distortions are seen in synthetic seismograms calculated for shear-waves interacting with internal interfaces and internal shear-wave windows have been defined (Liu and Crampin 1990) within which the shear-waves remain undistorted.

Booth and Crampin (1985) describe the distorting effects of $S$- to P-mode conversions at a low-velocity layer on the interpretation of shear-wave polarizations recorded above small earthquakes. Similar effects may be expected to occur for wide-offset reflection surveys where an $S$- to P-converted phase can arrive earlier than the direct shear-wave. This could make picking the polarization of the leading (faster) split shear-wave difficult in reflection surveys.

The shear-wave wavetrain will be further distorted if the waves pass through surface layers with different crack orientations. [Changes in crack orientation with depth have been inferred from seismic data in both the Silo field, Wyoming (Martin and Davis 1987), and the Lost Hills field, California (Squires, Kim and Kim 1989)]. Initially, the shear-wave will split into two components polarized by the orientations
in the first layer it encounters. On entering a second layer with different crack orientations (Fig. 2), the polarized components of the first layer will each undergo further splitting into new polarizations, generally giving four shear-wave arrivals. The polarization of the leading split shear-wave, in each pair of arrivals, is now fixed by the crack distribution in the second anisotropic medium and direct information about the crack parameters of the first medium is hidden. If the path length is short or the degree of anisotropy small, the split shear-waves will overlap making the determination of delay times difficult. Several automatic methods exist for measuring polarization directions and delays (Naville 1986; Nicoletis, Client and LeFeuvre 1988). For these to yield the accurate results that appear to be possible, the signals must not be too seriously degraded by interactions with near-surface anomalies.

**EDA-cracks**, like hydraulic fractures, tend to be aligned perpendicular to the direction of minimum compressive stress, and are expected to be vertical, striking parallel to the maximum horizontal compression at depths where the direction of minimum stress is horizontal. Nearer the surface, however, the minimum stress is likely to be vertical and may cause anomalies in the orientations of fluid-filled inclusions (Crampin 1990). This may result in the orientations of **EDA-cracks** within the reservoir rock being different from the orientation of cracks in such near-surface conditions.

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**Fig. 2.** A schematic illustration of double splitting. A shear-wave entering an anisotropic medium will split into two components. If the split shear-waves then enter a second anisotropic layer with a different crack orientation each of the waves will split into two. This gives a total of four shear-waves. The first shear-wave arrival will be polarized parallel to the cracks in the second layer.
layers. There is some observational evidence for such near-surface anomalies. Douma, Den Rooijen and Schokking presented (51st EAEG meeting, West Berlin, 1989) results from an 80 m deep VSP in clay, where both core samples and shear-wave polarizations indicate the presence of cracks in the near-surface which dip at 40°. Kerner, Dyer and Worthington (1989), in an even shallower VSP (45 m), identified only transverse anisotropy (azimuthal isotropy) consistent with the horizontally orientated inclusions expected very near to the surface by Crampin (1990). With reduced lithostatic compression, the crack densities in shallow rocks may also be higher than those at depth (Crampin, McGonigle and Bamford 1980). Localized stress and crack anomalies due to the presence of faults, intrusions or topographic features may also cause EDA-crack orientation to change with depth.

**Modelling Near-surface Layers**

Synthetic seismograms were calculated with the ANISEIS software package for a series of simple anisotropic models to show the effects of near-surface layering on the shear-wave signals recorded both at the surface and subsurface. The models, listed in Table 1 and illustrated in Fig. 3, are consistent with simplified velocity structures from the North Sea. In each layer, the crack-induced anisotropy is modelled as a transversely isotropic medium with a horizontal axis of symmetry (Hudson 1980, 1981).

The models consist of a layer (CMAIN) whose crack and stress geometry are the target zone of interest, and a series of different surface layers, whose thickness, crack geometry, and velocity vary between models, and present possible realistic surface

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anomalies. The crack orientation in the CMAIN layer remains constant with the cracks striking R $120^\circ$T (where R and T represent the radial and transverse directions, respectively). Crack densities of 0.04 were used throughout. This gives a shear-wave velocity anisotropy of about 4%, similar to that often observed in a wide range of geological structures (Alford 1986; Martin and Davis 1987). A horizontal shear-wave source with a mean frequency of 25 Hz was used to generate synthetic seismograms for two azimuths of the acquisition plane relative to the crack strike, and three source orientations for each of the models. A representative selection of these seismograms is presented to show the effects of near-surface layers. Synthetic seismograms were calculated for a reflection gather, a zero-offset VSP, and a 200 m offset VSP for each of the models. The offsets were chosen so as to minimize the number of raypaths intersecting interfaces and the free surface at angles greater than the shear-wave window, the disturbing effects of which have been discussed by Booth and Crampin (1985).

The behaviour of the body waves in the CMAIN layer are displayed in Fig. 4 and similar variations occur in the other anisotropic materials used in these models.
Passage through an anisotropic medium causes shear-waves to split into two components, each with a different polarization and different velocity (Fig. 4a). For ray-paths subtending angles less than about 30" at the crack faces (for thin cracks), the shear-wave $qSR$ polarized parallel to the cracks is faster; for larger angles the shear-
wave polarized in the plane through the normals to the cracks, \( q_{SP} \), is the first arrival. The two shear-waves intersect at a line singularity (Crampin 1989). For this angle of incidence to the cracks, the two shear-wave polarizations have the same velocity. When the polarization of the leading shear-wave is calculated for all azimuths and angles of incidence (Fig. 4b), the faster split shear-wave is polarized parallel to the cracks over a broad band of angles of incidence and azimuths. However, abrupt changes in polarization of the leading split shear-wave are seen at the edge of this region where the two shear-wave sheets may be considered to intersect. The normalized delay between the two shear-waves is maximum for propagation parallel to the cracks (Fig. 4c) and falls to zero at a line singularity, beyond which the delay peaks again before falling to zero for propagation perpendicular to the cracks, where there is no preferential polarization.

**Results**

Model 1 (Table 1) represents a control model with no surface layer, where the shear-waves are only affected by the \( C_{MAIN} \) layer. Figure 5 shows shear-wave seismograms and polarization diagrams (PDs) for a reflection gather and two VSP offsets in Model 1. The first motions of the leading split shear-waves in the PDs of the reflection line, the zero-offset VSP, and all except three geophones of the 200 m offset VSP are in the direction of the strike of the cracks within the \( C_{MAIN} \) layer. The exceptions, the three uppermost geophones in the 200 m offset VSP, are where the polarizations show the anomalous behaviour expected in directions close to the line singularity (Figs 4b and c), where the time delays are small, and the (radial) polarization of the source is only slightly modified, leading to abrupt changes in the direction of the initial take-off direction of the leading split shear-wave between raypaths either side of the line singularity. The first and second geophones in the 200 m offset VSP show a change from anticlockwise to clockwise motion in the PDs. Such changes in direction of rotation are characteristic of raypaths either side of a line singularity in the shear-wave velocity surface of a medium with hexagonal (transversely isotropic) symmetry (Douma and Crampin 1990).

The polarity of first motion in the PDs for the reflection line is reversed with respect to that seen in the PDs for the VSPs, although still parallel to the strike of the cracks. This phase change is caused by the reflection at the base of the \( C_{MAIN} \) layer and is a result of the shear-wave reflection coefficients at that interface (Achenbach 1973; Crampin 1987b). [Note that similar anomalous behaviour occurs for shear-wave reflections even at isotropic/isotropic interfaces (Liu, Crampin and Yardley 1990).] The patterns displayed in the PDs for the reflection line and the VSPs are different due to the different path lengths in the anisotropic medium and the polarity reversal at the reflecting interface. However, the important diagnostic properties of the shear-wave signal are the polarizations of the leading split shear-wave (not necessarily the polarities) and the delays between the fast and slow split shear-waves, and not the patterns in the PDs. The PD patterns are dependent on many features including the frequency, amplitude, phase, polarization and pulse
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Normalized synthetic seismograms and PDs for the horizontal plane in Model 1 (control). Source is a radial horizontal force. The PDs are windowed around the main shear-wave arrival and the horizontal geophones are aligned in the R and T directions. From the left, the seismograms and PDs are: a reflection gather; a zero-offset VSP; and a 200 m offset VSP. The EDA-cracks strike at R 120°T. The crack orientation is clearly seen in the initial polarization of the (faster) split shear-wave arrival in the PDs of the reflection survey, zero-offset VSP, and the deeper geophones of the 200 m offset VSP. The direction of first shear-wave motion in the PDs is marked by an arrow. The numbers in the top left corners of some of the PDs indicate the gains applied to the original signals relative to the unnumbered PDs.

The PDs for the wider-offset geophones in the reflection line have become distorted as a result of the difference in the reflection coefficients of the two split shear-waves at a plane reflector. In general, these different reflection coefficients cause each of the incident split shear-waves to split again on reflection, causing the distortion. This is a very common phenomenon. The different reflection coefficients between SV- and M-waves even at an isotropic/isotropic interface (Achenbach 1973; Crampin 1987b) can cause phase changes between the reflected SV- and SH-components producing effects very similar to shear-wave splitting, with a resulting change in polarization of the reflected waves. In an anisotropic medium, this means...
that each of the incident shear-waves excites both shear-wave polarizations upon reflection giving a total of four shear-wave arrivals at the surface. The delay observed between the first and second shear arrivals for the wider-offset geophones in the reflection line is only developed during the path from the reflector to the surface. The difference between the reflection coefficients increases with angle of incidence and such anomalies are seen for reflection of shear-waves with angles of incidence greater than about 10° when the incident shear-waves are not strictly \( SH \) or \( SV \). The exact angle is dependent on the velocity contrast at the reflecting interface. In a reflection line in an isotropic earth, where the source polarizations are usually \( SH \) and \( SV \), such distortions will not occur. However, this type of distortion of the shear-wave signal is likely to be observed in the general anisotropic case, whenever the acquisition plane is not parallel to the crack strike.

Inclusion of such anomalous signals in common midpoint stacking (CMP) techniques for reflection data will give rise to inaccurate determinations of time-delay and polarization. Thus, CMP techniques may lead to degradation of shear-wave signals at non-vertical incidence reflections at horizontal reflectors and, perhaps more seriously, at reflections from small-offset signals at dipping reflectors.
Model 2 has a single low-velocity anisotropic surface layer of 50 m thickness in which the cracks strike at R $75^\circ$T, in contrast to the $\text{CMAIN}$ layer where the cracks strike at R $120^\circ$T. The PDs and seismograms for the reflection line in this model (Fig. 6) are distorted, whereas the PDs for the VSPs remain essentially unchanged, except that the time-delay in the $\text{CMAIN}$ layer at the shallowest geophones is smaller because of the shorter raypath in the $\text{CMAIN}$ layer. The PDs for the reflection line are further complicated by the fact that the signal must travel twice through the surface layer, both before and after it travels through the $\text{CMAIN}$ layer. The first motion in the PDs for the reflection line in this model (Fig. 6) lies between the crack orientations in the surface layer and those in the $\text{CMAIN}$ layer. The surface layer is thin, and only causes small delays between the fast and slow shear-waves within the layer, so that the visible first motion is a superposition of the fast and slow shear-waves, which have a small time-delay (phase difference), and thus the resulting interference lobe does not lie along the crack direction. Nevertheless despite these anomalies in the reflection data, estimates of the anisotropy of the $\text{CMAIN}$ layer could be made by
identifying the patterns in the PDs from the VSPs (if the source pulse shape is known), which are characteristic of the orientation and relative time-delay of the split shear-waves.

The anisotropic surface layer has been increased in thickness to 200 m in Model 3 (Fig. 7). The first motions in the PDs for the reflection data align with the crack orientation in the surface layer and not the crack orientation in the MAIN layer. This is because the delay between the fast and slow shear-waves in the surface layer is large enough to give a clear initial direction. This means that the polarizations and delays in the MAIN layer are effectively obscured. The VSP arrivals are more complex than in previous cases as passage through a 200 m surface layer means that two separated shear-waves form the incident wave for the MAIN layer. The top geophone in the zero-offset VSP is at the base of the surface layer and shows this split incident wave. This causes a small precursor to the main arrival (marked by a dot in Fig. 7) at geophones 4, 5 and 6. These precursors are still polarized parallel to the MAIN cracks but in the opposite direction. The first motion of the main arrival is marked by an arrow in the diagrams. Such a low amplitude precursor might be expected to be hidden by noise in field data. The shallow geophones in the 200 m
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offset VSP are complicated by the effects of reflections and refractions at the interface and only the deepest geophone clearly displays the properties of the \textit{CMAIN} layer. Thus the crack orientation in the \textit{CMAIN} layer can still be picked out by visual inspection of the PDs at the deeper geophones of the VSPs even in the presence of a 200 m layer, while the PDs for the reflection line are dominated by the surface layer.

Model 4 (Fig. 8) shows the effects of decreasing the velocity of the surface layer for the same crack density. The time-delay between the split shear-waves in any direction in this layer is larger than in Model 2 (Fig. 6), because of the larger number of cycles for the given path length. This increases the distortion in the PDs of the reflection line compared to Fig. 6, but again has only marginal effects on the VSPs. This shows that the sensitivity of shear-waves to the disturbances caused by surface layers is greater for a lower layer-velocity, due to the greater number of wavelengths in the layer. Similar distortions of reflection survey data were seen for all calculated source orientations and offset azimuths.

Data from the Paris Basin (Bush 1990) suggest that near-surface layers may be the source of a large amount of the observed anisotropy. In such cases changes in crack orientation between the reservoir and the surface layers could have a marked effect on reflection data even for thin surface layers.

\textbf{Rotation of Seismograms}

Alford (1986) proposed a method for extracting shear-wave polarizations and delays by matrix rotation of multicomponent-multisource data. This method assumes that the shear-wave polarizations are constant (only one crack orientation) and rotates the source and geophones together so that only one shear-wave component is emphasized by maximizing the coherence on the main-diagonal stacks and minimizing coherence on the off-diagonal stacks. More general rotations are also used, where the source is rotated independently with each geophone, rather than the whole stack. As the crack parameters in the preceding models are known, it is possible to simulate this method in the presence of changing crack orientations with depth and examine its usefulness.

Model 1 was repeated (Fig. 9) with the source polarization and geophones aligned parallel to the cracks. This gives minimum coherence on most of the cross components for both the VSPs and the reflection line. However, the offset geophones for the reflection line and the shallow geophones for the 200 m offset VSP show non-linear motion which is visible on both the horizontal geophone components. In the case of the reflection line this is caused by the different reflection coefficients of the incident shear-waves, described above. The reflection from the base of the \textit{CMAIN} layer causes both shear-wave polarizations to be excited. Post-stack rotation of this data yields a maximum energy direction which is a few degrees anticlockwise from the X-direction if a uniform rotation is sought for all geophones and the wider-offset geophones are included in the gather. However, most rotations are now performed prestack which leads to incorrect rotations of the farthest-offset geophones. When the rotated traces are stacked together the signal is degraded by
Fig. 9. Model 1 repeated with the source and geophones aligned parallel to the cracks (R 120°T). PDs show linear motions as only the fast shear-wave has been excited (except for wide-offsets where the fast shear-wave is not polarized parallel to the cracks). The X-direction is parallel to the source.

The inclusion of the far-offset traces. Even in the simplest case of a single anisotropic layer, matrix rotations will not yield the correct crack orientation if traces with angles of incidence greater than about 10° (for this velocity structure) are included. If rotations were optimized geophone by geophone, the derivation of the polarization of the first arrival is one or two degrees away from the strike of the cracks for the zero-offset reflection, but increases to about 40° for the 500 m offset. The shear-waves received at the uppermost geophone in the 200 m offset VSP propagate at 45° to the crack faces, and for such large angles of incidence the polarization of the fast shear-wave is not expected to be parallel to the crack orientation (Fig. 4b). In the case of Model 1, where there is only one crack orientation, this method will yield estimates of the polarization of the faster shear-wave only if ray-paths with steep angles of incidence are used. An orthogonal rotation would align the source perpendicular to the cracks and yield estimates of the polarization of the slower shear-wave, and hence allow the delay to be estimated. It must also be noted that standard processing techniques such as moveout corrections may further distort the signal, because conventional P-wave techniques do not allow for
simultaneous processing of two shear-wave signals with different wave speeds and polarizations.

Model 3 was recalculated with the source and the geophones aligned parallel to the cracks in the surface layer (R 75°T). The cross component has only been minimized for the top geophones in the VSPs which lie in the surface layer. The X-direction is parallel to the source.

**FIG. 10.** Model 3 repeated with source and geophones aligned parallel to the cracks in the surface layer (R 75°T). The cross component has only been minimized for the top geophones in the VSPs which lie in the surface layer. The X-direction is parallel to the source.
Fig. 11. Model 3 repeated with source and geophones aligned parallel to the cracks in the CMAIN layer (R 120°T). The cross component has not been minimized at any of the geophone positions. The X-direction is parallel to the source.

**DISCUSSION**

Whilst it is not possible to examine all effects of surface layers, it is clear from these simple examples, and from existing field data, that there is a wide range of circumstances in which surface recorded shear-wave data may be contaminated by crack (and stress) anomalies in near-surface layers. More complicated examples would only further confirm this conclusion.

Experimental data from shallow VSPs (Douma, Den Rooijen and Shhokking, 51st EAEG meeting, West Berlin, 1989; Kerner et al. 1989) and field data (Martin and Davis 1987; Squires et al. 1989) show near-surface crack anomalies and changing crack orientation with depth. Together with the theoretical considerations mentioned above, it is likely that such near-surface crack and stress anomalies are commonly present. The extent of such anomalies will be visible in VSP data sets allowing the modelling of the crack and stress geometries (and probable direction of fluid flow within a reservoir) at the site. However, shear-wave data from reflection surveys, although it may show shear-wave splitting, may be difficult to interpret in detail.
In these models with only two anisotropic layers and one change in crack orientation, it would be possible to reconstruct the polarization directions of the fast and slow shear-waves in the \textit{CMAIN} layer, if the arrivals were well separated, by vector addition of the surface recorded shear-waves. However, in real sedimentary sequences any change in crack orientation in near-surface layers might well be a gradual change with depth, which would make simple vector addition difficult. Even if there were an abrupt change of orientation, the slower shear-wave is expected to have a larger attenuation than the faster wave, due to its interaction with the fluid-filled microcracks, and direct vector additions would be invalid.

It is also clear that while rotation of seismograms using multicomponent-multisource data is effective for near vertical propagation in a structure with only one crack orientation, it is not a viable method for more general cases, where the presence of different crack orientations or anomalous signals caused by reflections will lead to complicated behaviour.

Further complications will occur in sedimentary basins where periodic thin layer (PTL) anisotropy is present together with \textit{EDA}. In such cases the polarization of the leading split shear-wave may not be parallel to the crack orientation and may change direction with offset even for offsets within the shear-wave window (Crampin 1988; Bush 1990). Any CMP stacking of such data along a given azimuth would yield an average polarization, and hide information about the variation of polarization direction with offset which would allow detailed modelling of the data. The nature of the shear-wave signal is a function of both azimuth and angle of incidence and currently it appears better to study single source-receiver raypaths than to stack data over a range of angles of incidence.

The distorting effects of surface layers and anomalous signals from reflections together with the degrading effects of stacking mean that \textit{VSPs} provide the most useful tool for examining shear-wave anisotropy in reservoirs. \textit{VSPs} allow the investigation of shear-wave signals along single raypaths from a range of offsets to a range of depths in the structure, and gives the opportunity of complete modelling of the rock structure, even in the case of mixed \textit{EDA} and PTL-anisotropy (Bush 1990).

\textbf{Conclusions}

The problems of surface recording of shear-wave data have been discussed before with regard to surface topography (Evans 1984) and the effects of the shear-wave window (Nuttli 1961, 1964; Booth and Crampin 1985). This study has identified further problems associated with surface recording in the presence of near-surface layers, particularly those which have a different crack orientation from the reservoir rock (caused by near-surface crack and stress anomalies).

It is possible to draw the following conclusions:

1. The polarization of the leading split shear-wave is determined by the anisotropic alignment of the last medium through which the shear-wave has travelled, provided the time-delay in that medium is sufficient, relative to the period of the signal, to produce identifiable shear-wave splitting.
2. Subsurface geophones within the reservoir rock will give a shear-wave first arrival with a polarization determined by the crack geometry of the reservoir rock, if an adequate time-delay has built up between the first and second shear-wave arrivals. However, surface geophones will be principally affected by anisotropic, and possibly isotropic, near-surface anomalies, so that shear-wave data recorded at the surface may show clear shear-wave splitting, but it may be difficult to recognize whether this splitting is the result of near-surface structures or deeper anisotropic layers.

3. Reflection from an interface will create further shear-wave arrivals (if the signal does not propagate vertically or if it is not polarized strictly $SH$ or $SV$). These may give anomalous delays between shear arrivals and will contaminate any CMP stacking of reflection line data even for relatively steep angles of incidence.

4. Rotation of seismograms from multicomponent-multisource data sets may not yield direct information about crack parameters in the presence of changing crack orientations with depth. Such rotations can also be affected by differences in reflection coefficients between $SV$- and $SH$-waves if wide offsets are included in the stack or where dipping interfaces give rise to wide angle reflections.

**Acknowledgements**

We thank Applied Geophysical Software Inc. and Macro Ltd for permission to use the ANISEIS package for calculating the synthetic seismograms. This work was supported by the Edinburgh Anisotropy Project and the Natural Environment Research Council and is published with the approval of the Director of the British Geological Survey (NERC).

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