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PROCESSING AND INTERPRETING VECTOR WAVE-FIELD DATA

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ABSTRACT

A processing and interpretation philosophy is proposed for vector wave-field data recorded from multicomponent VSP, reflection and cross-hole seismic experiments. This philosophy differs from conventional scalar and multicomponent procedures, as the aim is to enhance the anisotropic information content. Some reorganization and modification of more standard approaches is required, but the majority of techniques within the philosophy are necessarily new, being specific to the vector-based phenomenon of anisotropy. These new techniques incorporate different displays of the recorded shear-wave motion (initial vector image), provide enhancement, or conditioning, of this image through various transformation steps and give estimates of anisotropy parameters that are appropriate for a subsequent inversion step. Interpretation of different aspects of the multicomponent data are then made in terms of the internal structure of the subsurface rocks. This philosophy is followed in several referenced examples.

INTRODUCTION

At present there is still a divide between observational and theoretical anisotropy (Crampin and Lovell, 1991) with insufficient emphasis on the complete processing of multicomponent data for anisotropy. The need for a distinctly different approach from standard processing practices has been recognized for some time, perhaps as far back as Jolly (1956). However, interest did not begin to expand until the SEG meeting in 1986 where seismic anisotropy was highlighted as a possible tool for examining the internal structure of hydrocarbon reservoirs (Alford, 1986; Lynn and Thomsen, 1986; Willis et al., 1986). There is now a large body of evidence to support the phenomenon of anisotropy as providing a convenient framework with which to process and ultimately interpret the vector wave field (see for example Martin and Davis, 1987; Kaneshima, 1990; Crampin and Lovell, 199 1). Although there are many different isolated techniques for analyzing shear-wave splitting, there is no reported method for combining these together with other processing techniques to produce a consistent stream specifically for interpreting multicomponent data. Here we present work which is aimed at addressing this problem.

Multicomponent data carry information associated with both the overall seismic structure (background model) and the internal structure of the subsurface rocks. The background model is usually evaluated by analyzing traveltimes and amplitudes to provide the gross structural relief of the subsurface, whereas the internal structure, consisting primarily of stress-aligned pores and cracks in the rock fabric, is determined predominantly by the differential information in split shear waves. This information, contained in shear-wave arrivals with different polarizations and time separations, typically between 5 and 40 ms, must be estimated using an entirely different approach from conventional processing for the background medium. Here, we propose a strategy which permits an accurate and consistent treatment of anisotropic wave propagation. The major objective of our philosophy is to image the pore-crack structure of the hydrocarbon reservoir using an efficient and self-consistent flow of conditioning, processing and interpretation. Procedures have been developed for manipulating the vector shear-wave image through a variety of steps to a final form where interpretation of anisotropy parameters as a pore-crack model can be verified by full-wave modelling.

PROCESSING SEQUENCE

The flow chart in Figure 1 outlines the various stages in the processing sequence, from the raw unprocessed data to the final interpretation as pore-crack constituents of the rock. Although the acquisition geometry often strictly limits the actual information about anisotropy contained by the data set, and ideal data should be gathered from an appropriately optimized acquisition geometry (MacBeth et al., 1993a), we

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believe this scheme will ensure a consistent and reliable interpretation of most multicomponent data. The sequence is iterative, as it is sometimes necessary to repeat a previous stage using parameters refined by the current stage.

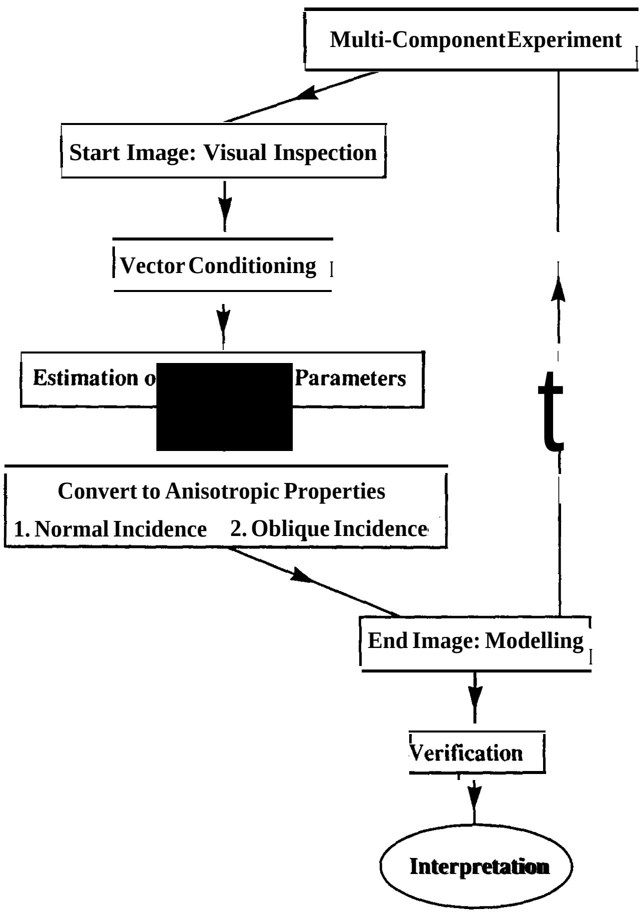

Fig. 1. Flow chart illustrating the processing and interpretation sequence which constitutes the multicomponent philosophy of the Edinburgh Anisotropy Project.

Initial image

The first step is to display the data for quality control and to identify various arrivals of interest. Three visual representations are currently possible for this purpose. The most commonly used representation for multicomponent data trace matrix (Tatham and McCormack, 1991), where the recorded traces are arranged with each row corresponding to a particular geophone component for the various source motions. This representation is chosen as it is a convenient way of examining the qualitative aspects of the entire data set, such as amplitude variations, frequency content and wavelet shape. To provide a more quantitative inspection of the initial onsets of the waves, and in particular the relative time delays between traces, the polarization diagram is used. The diagram provides a plot of a planar slice through the recorded three-component particle motion (Crampin, 1985). Figure 2 shows polarization diagrams in the horizontal plane for a near-offset VSP in the Lost Hills, California. The particle motion displayed in the polarization diagrams are sensitive to fine time shifts in the component traces, and the consistency of these diagrams over the depth range shown indicates a weakly anisotropic interval with little change in the splitting initially caused by the overburden.

The third method of display combines three-component traces as a one-component display by utilizing coloured attribute plots (Li and Crampin, 1991a, b). Shear-wave attributes of instantaneous amplitude and polarization are useful for examining the consistency of shear-wave splitting in seismic sections and identifying a particularly prominent split shear wave for further analysis. These displays are most useful for large data sets, for which the polarization diagrams do not give a sufficiently global view of the entire data set, and the data matrix representations are not sufficiently sensitive to indicate details of the splitting. Figure 3a illustrates this representation for a synthetic VSP in which there are planar structural boundaries with alternating layers of isotropic and anisotropic materials. Consistency of splitting throughout the direct and reflected arrivals is identified. The colour attribute displays are most effective for surface data for which there are a large number of traces. Figures 3b and c demonstrate this for data from a reflection profile shot in south Texas.

Vector conditioning

The next stage, vector conditioning, clears and focuses the signal for further processing. Vector conditioning is defined here as corrections applied to the recorded image to prepare it for further processing and subsequent interpretation. An example of a situation where we might apply this conditioning stage is to compensate VSP for the twisting of the receiver tool in the borehole and the deviation of the borehole in VSP data, by rotating the data so that the source motions and geophone axes are aligned along a common coordinate frame (DiSiena et al., 198 1). In reflection data, vector conditioning is used so that the best subsurface image is obtained while preserving the character of the vector wave field. Conditioning prior to stacking includes vector gain recovery and amplitude balancing, while both before and after stacking vector deconvolution can be applied as an overburden correction. Vector deconvolution is particularly important when examining depth variations in the anisotropy parameters (MacBeth et al., 1993b). Deconvolution procedures may also be used to collapse the shear-wave splitting information contained in multiples into an enhanced common wavelet or to give an estimate of the source signature for the modelling stages that follow. Other vector conditioning steps involve polarization filters for the coloured attribute image to exclude anomalous polarizations which may prevent a clear image of the subsurface (Li and Crampin, 1991a, b). We also include in the final stages of this conditioning separation of the upgoing and downgoing wave fields if appropriate and the windowing of distinct shear-wave arrivals.

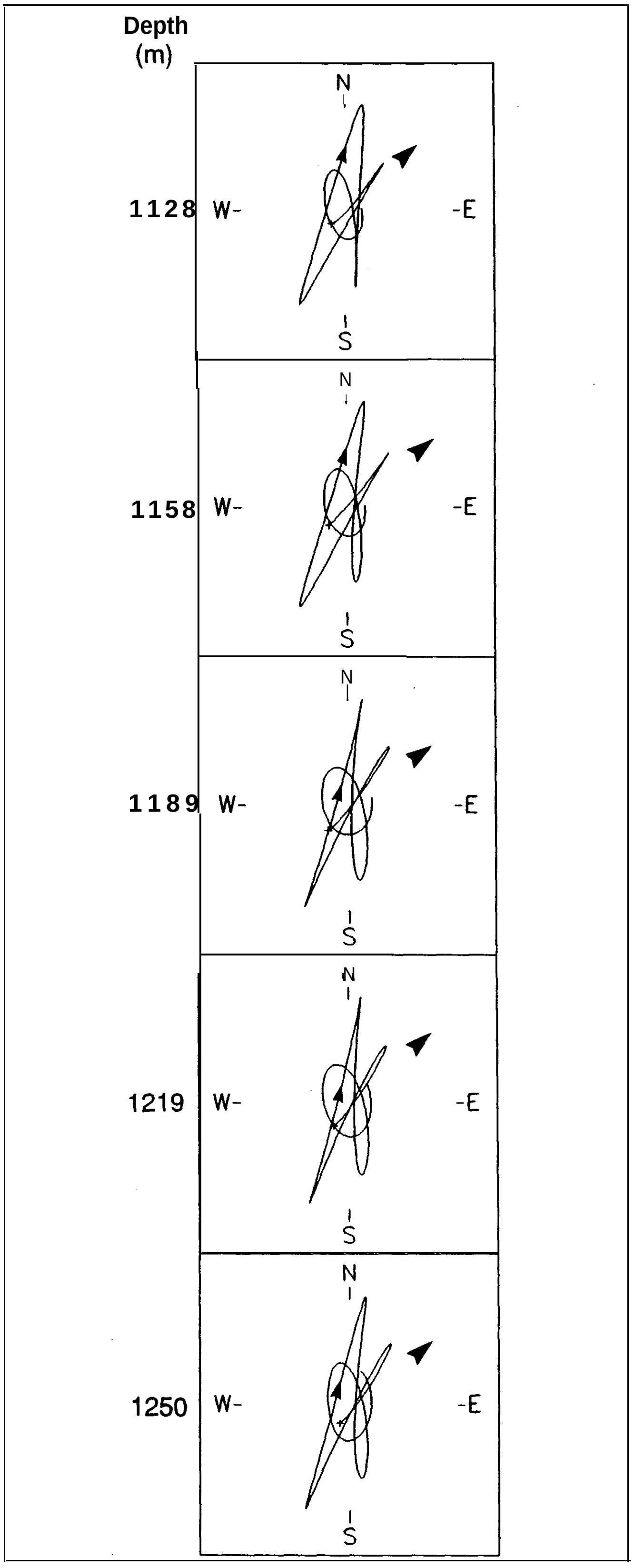

Fig. 2. Polarization diagrams showing the motion of the direct shear-wave arrival recorded on five horizontal geophones from the in-line source of a VSP in the Lost Hills Field. The splitting shown here is typical of the whole section, which shows little anisotropy relative to the overburden. The direction of the motion and the direction of the initial onset are indicated by arrows.

Estimation of shear-wave parameters

Central to our philosophy is the automation of shear-wave analysis for large seismic data sets, combined with flexibility achieved through the development of techniques to resolve shear-wave splitting based upon different acquisition requirements and mathematical assumptions. This stage is reached through a variety of different estimation techniques. The techniques are divided into three groups: those suited to a single source, dual orthogonal sources for which certain symmetries in the shear-wave motion may be exploited and combinations of two or more sources. Table 1 gives mnemonics for the techniques, together with details of the underlying assumptions, data for which they are judged to be applicable and references to their origin. The techniques may be applied to data from single or multiple sources and geophones and may provide local (over a small depth interval) or cumulative measurements of the wave field. The variety offers flexibility when analyzing different types of multicomponent data, together with the necessary degree of redundancy so that the shear-wave splitting can be determined accurately. Some of the single-source techniques rely upon knowledge of the source direction; others do not, and so prove useful for analyzing converted waves. The dual-source techniques are used when data are recorded either from two shear sources with orthogonal motions or from two or more shear motions which are not colinear, in which case the data are transformed to equivalent orthogonal source motions. Multisource techniques are also available for obtaining a stable least-squares estimate with no prior knowledge of the source motion.

Figure 4a shows a single-source example of local estimates for differential time delays between adjacent geophone levels in a synthetic data. For these data local estimates were appropriate as the model consisted of alternating layers of isotropic and anisotropic material. The dual-source cumulative estimates of Figure 4b do not delineate the anisotropic layers of the model in this case. Another example (Figure 5) is provided by near-offset VSP field data from the Lost Hills, California. Since source imbalance is suspected for these data, a single-source technique is separately applied to each source component of the data. Agreement between the estimates from single and dual-source techniques suggests that source imbalance is not a significant factor with these data. Some of the techniques have been specifically adapted to reduce processing time and storage difficulties associated with manipulated large data sets. An example of a technique designed for surface data is given by Li et al. (1993).

Conversion to anisotropic properties

Before the estimates can be converted into the anisotropic model that constitutes the end-image, a further consistency check is required for a vertically inhomogeneous anisotropic structure. For near-offset VSP or surface data, this is done by decomposing the wave field into the contributions derived from different parts of the propagation path and then reassembling it. This process is accomplished by overburden correction procedures for an anisotropic nonlinear overburden. The correction is partly based upon a vector convolution

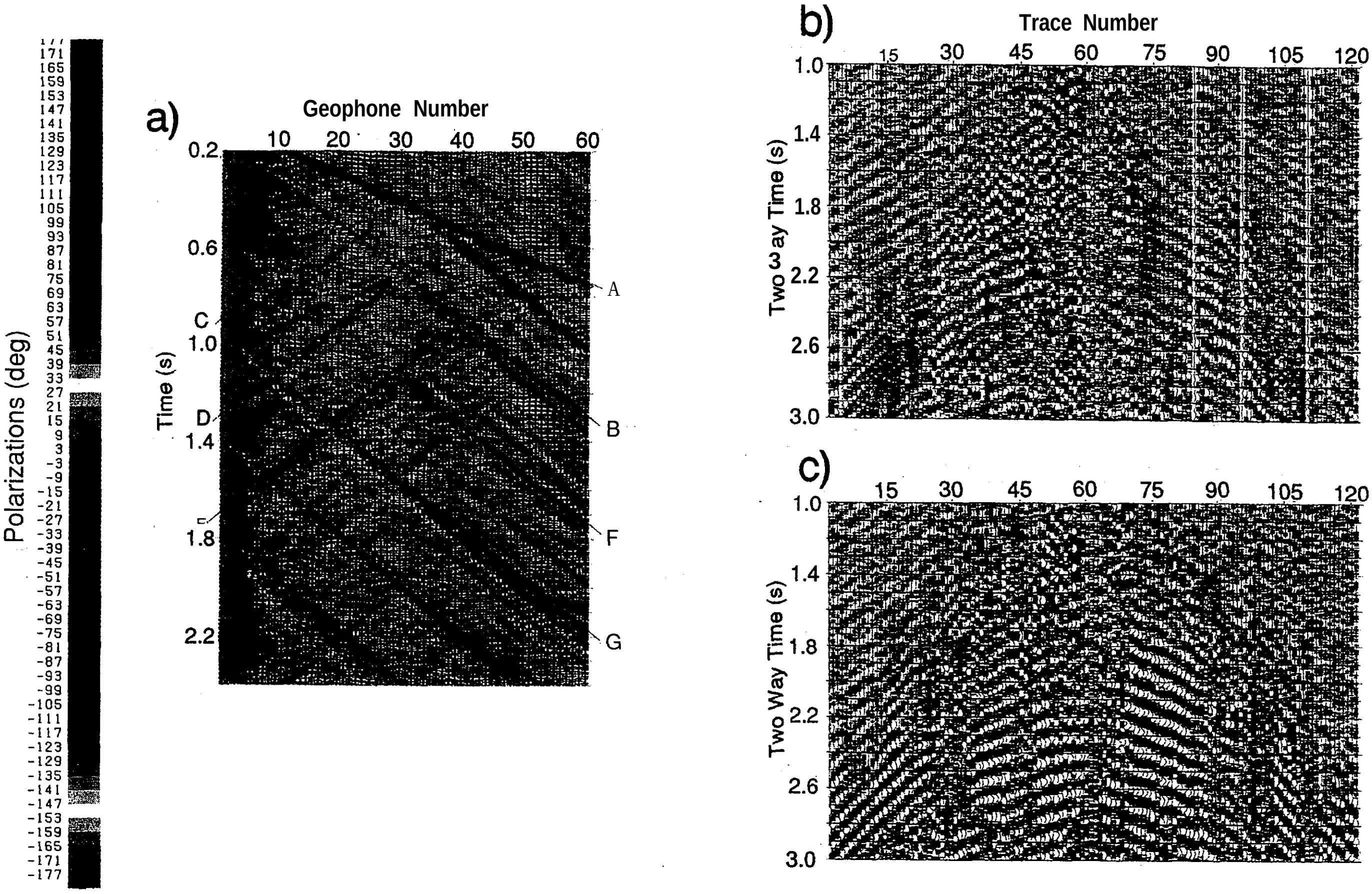

Fig. 3. (a) Display of shear-wave attributes of instantaneous amplitude and polarizations (overlaid in colour) from the horizontal geophone components of the in-line source component of synthetic VSP data (Thomsen, 1989). No conditioning was necessary. There is evidence of shear-wave splitting on the direct (Event B), reflected (Events C, D and E) and multiple (Events F and G) shear-wave arrivals (Event A is the P-wave arrival). The splitting of the direct shear arrival is indicated by the colour change from blue to red/orange, suggesting a 90° polarization change from –45° to 45°, as the *qS*2 replaces the *qS*1. (b and c) Shear-wave attributes for a four-component reflection line shot in south Texas, where the line was placed at 39° to the regional fracture strike direction. The in-line (b) and cross-line polarization attributes (c) show coherent blue events, indicating polarization of approximately –50°, and weak red/orange events, indicating polarizations of approximately 40°. This suggests that the shear waves have split and that the source components have excited both their own and the respective orthogonal receivers.

model of shear-wave splitting (Zeng and MacBeth, 1993) and can be applied to VSP and reflection data (MacBeth et al., 1992). An automatic indication of the required correction parameters for. a VSP may be obtained from algebraic computation.

A data base of anisotropic wave behaviour, combined with anisotropic ray tracing, is used to invert for anisotropic parameters of shear-wave splitting when oblique raypath data are analyzed. The data base stores P- and shear-wave polarizations and velocities for a range of anisotropic models with orthorhombic symmetry, formed by combining matrix anisotropy due to fine-layering with crack-induced anisotropy. Examples of the patterns of behaviour for these models are given by Wild and Crampin (199 1). Matching the behaviour patterns to the offset recordings for *P*- and shear waves gives details of the anisotropic model which cannot be resolved at normal incidence (MacBeth, 1991). As field data sets are always limited by azimuth, incidence angle, frequency, area1 coverage and other (often financial) constraints, the inversion will not produce a unique solution but a range of solutions satisfying the observations. The inversion procedure has been applied to VSP data and is currently being adapted to cross-hole data. Figure 6 shows an example of the type of solution which this stage can yield, in this case for a combined analysis based on the polarization of the leading shear wave and the time delay between split shear waves. The inversion chart displays the solutions together with the nonuniqueness.

End-image and verification

The final stage in the processing sequence is to combine the information acquired in previous steps in order to construct a consistent anisotropic model of the subsurface. VSP estimates at near- and far-offsets can be adjusted to their proper position in the subsurface and an end-image formed. If surface data are available, this provides information on lateral variations from the borehole. The end-image consists of a composite anisotropic plane-layered model for the data set or, as is more likely, a range of possible models. Plane-layered models appear to provide an adequate representation for the subsurface layering for cases in regions of uniform geology that have currently been analysed (Crampin, 1993). The verification stage reassembles the data using synthetic seismograms and examines the match with real data. The

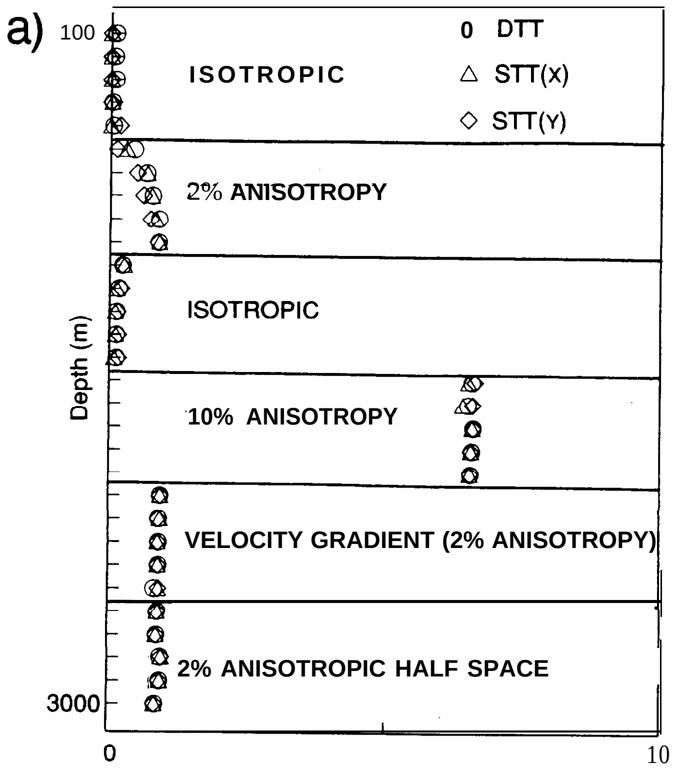

Fig. 4. **(a)** Local estimates of the time delay between split shear waves from synthetic VSP data (Thomsen, 1989) for adjacent geophone levels, plotted against depth. The model features a strongly anisotropic layer from 1500-m to 2000-m depth, simulating highly fractured reservoir rocks with a crack strike of 45° to the in-line direction. The model structure is overlaid (solid line) for comparison. The estimates show the boundaries between the isotropic zones and the zone containing 2% differential shear-wave anisotropy. They also estimate the expected time delays of approximately 1.2 ms and 6.5 ms for the 2% and 10% anisotropic zones, respectively. The zone simulating a gradient in the velocity of the background matrix has a constant 2% anisotropy.

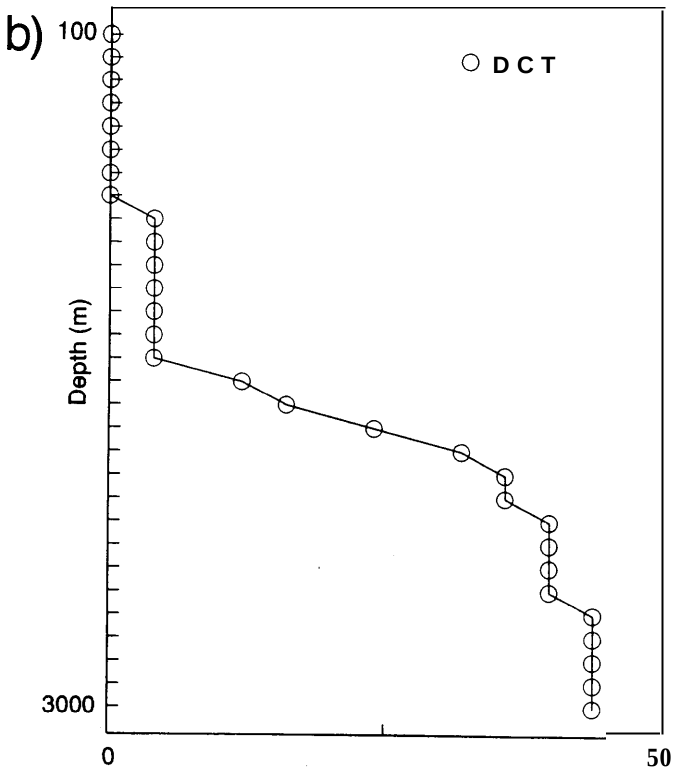

Fig. 4. **(b)** Cumulative estimates of time delay for the same VSP data, which are more difficult to interpret in this case than the local values.

seismograms are created using a full-wave modelling package based upon a reflectivity technique (Taylor, 1992). The final test in this verification procedure is the exact comparison of the time shift sensitive polarization diagrams for each three-component recording. If the data set is large, colour-attribute plots or multicomponent plots may be compared with a selection of polarization diagrams. Further refinements, which may reduce the range of acceptable models, can then be performed before an interpretation of the internal geometry of the rock mass is made.

INTERPRETATION

Interpretation of the final anisotropic model is the most important stage in the analysis of the vector wave field. Presentations of high-quality matches between synthetic and observed data showing anisotropy cannot be made without addressing the physical meaning or implication. As might be expected with a multiparameter phenomenon such as anisotropy, there is a nonuniqueness in the physical models that can give rise to the particular range of anisotropic models estimated from a specific data set. Controversy arises as to what the anisotropy means and how to interpret it (Crampin and Lovell, 1991). Consequently, almost every set of seismic observations showing a restricted range of anisotropic effects can be simulated by three-dimensional configurations of a variety of isotropic discontinuities (Schoenberg and Muir, 1989; Hudson, 1991). Our particular interpretation is based upon a consistent model which fits past and current analyses of the vector wave field in a wide range of circumstances.

One of the difficulties in physically examining the internal structure of the rock mass so that it may be directly related to anisotropy results is that there are over 20 phenomena controlling the anisotropic behaviour which are themselves either directly or indirectly controlled by stress. Once the local stress field has been disturbed by drilling, mining or excavation, the in-situ fabric geometry will be modified. It is then impossible to restore the fabric to its original condition because of the wide variety of time constants of some of the reactions concerned. This means that it is impossible to examine the in-situ pore and crack distributions directly and difficult to confirm any detailed interpretation [see Crampin (1993) for a fuller discussion]. Consequently, it is almost always difficult to confirm that any interpretation is correct by direct physical examination of the in-situ crack distributions.

Interpretation is also hindered because, although seismic anisotropy contains information about the symmetry, orientation, and sometimes the relative geometry of the internal structure of the rock mass, direct information about the scale

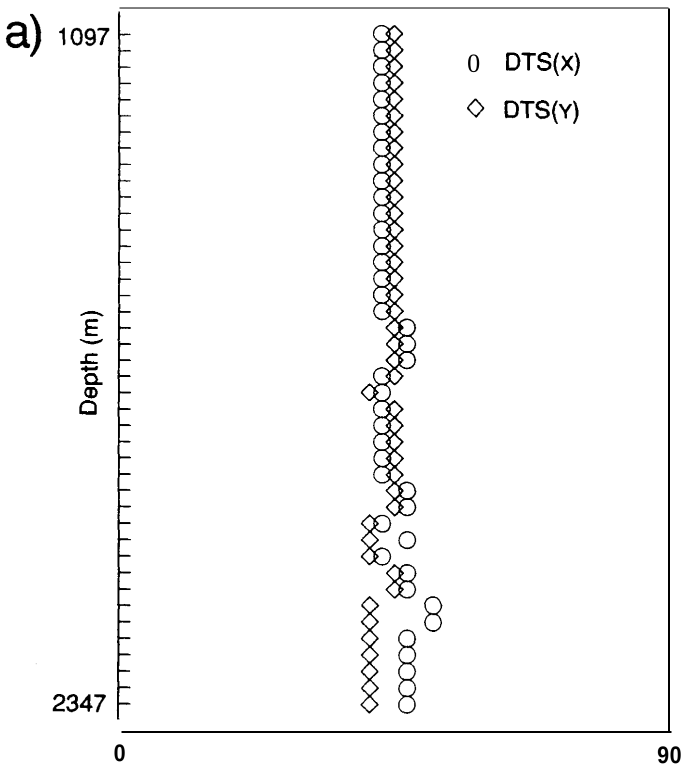

Fig. 5. Results of single-source and dual-source estimation techniques applied to data taken from a VSP in the Lost Hills, California. Preestimation vector conditioning consisted of rotating the recorded data into in-line and cross-line coordinates using information from gyrodata, applying a 3 to 40 Hz band-pass filter to reduce noise, f-k filtering to remove upgoing waves, and picking of the direct shear-wave arrivals. **(a)** Estimates of the polarization of the leading split shear wave made by applying a single-source technique to the in-line [DTS(x)] and cross-line [DTS(y)] source components.

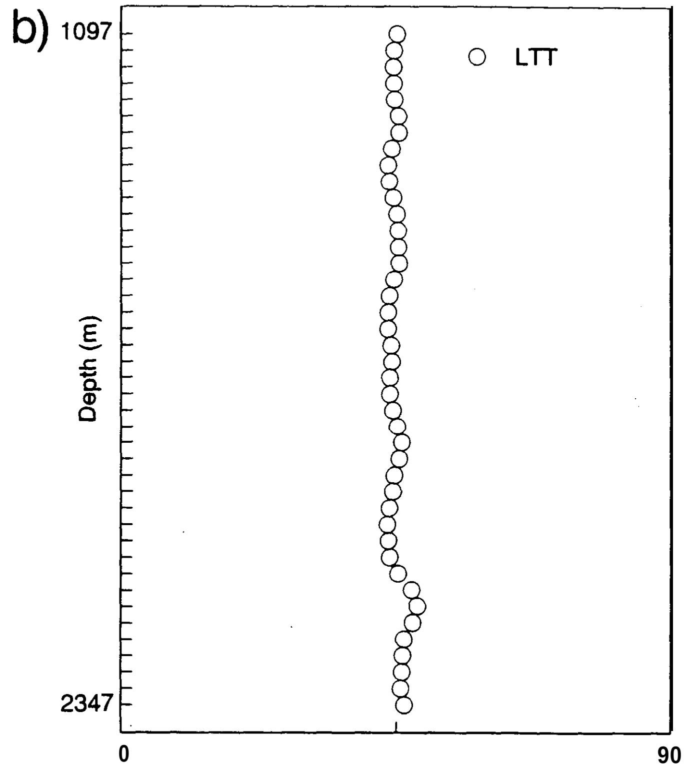

Fig. 5. **(b)** Estimates of the polarization of the leading split shear wave made by applying a dual-source technique (LTT) to data from both horizontal source components. The polarizations estimated by the single- and dual-source techniques are consistent with each other and show a polarization angle of approximately 45°.

of the internal structures sampled has not yet been obtained, and scale (particularly fracture size) is one of the most important parameters in the interpretation. This is because the effective anisotropy defined for the seismic response necessitates wavelengths that are always much longer than the dimensions of the inclusions, so that our current interpretation is scale invariant. Crampin (1993) lists references where similar effects are seen in shear-wave splitting for signals of over three orders of magnitude in both frequency and path length, with similar effective anisotropy seen in all cases.

Extensive-dilatancy anisotropy (EDA) is defined by the effective anisotropy caused by distributions of fluid-filled cracks, microcracks and preferentially oriented pore space of the rock fabric (Crampin, 1993). The EDA model is used because these effective seismic inclusions are the only source of the shear-wave splitting component of the anisotropic wave field that can produce similar effects for the wide range of frequencies and path lengths cited in Crampin (1993). Using the hypothesis to simulate anisotropic behaviour, an increase in anisotropy has been directly correlated with fracturing in the Austin Chalk (Mueller, 1991, 1992) and there are a growing number of studies (e.g., Li et al., 1993; Yardley and Crampin, 1993) where hydrocarbon production correlates positively with the degree of observed shear-wave anisotropy. These successes imply that anisotropy estimates derived from shear-wave splitting can be correlated with fractures within the reservoir.

Discussion and Conclusions

It is necessary to process and interpret the vector wave field for anisotropy differently from standard approaches. A sequence of procedures has been developed involving data conditioning, processing and inversion which provide a shorter route to obtaining a reliable anisotropic model for full-wave modelling than trial-and-error modelling. This is achieved using techniques which effectively display, manipulate and invert multicomponent data. These techniques have been brought together in a workstation-based Shear-Wave Analysis Package.

Case studies to illustrate this processing and interpretation flow have been presented at the fourth and fifth International Workshops on Seismic Anisotropy. Marine data were analyzed by Campden and Crampin (1991) that illustrate the utility of single-source techniques for estimating shear waves. Yardley and Crampin (1993) present various VSP data analyzed using the techniques. As no offset P-wave or gyrodata was available for their data, a technique based on

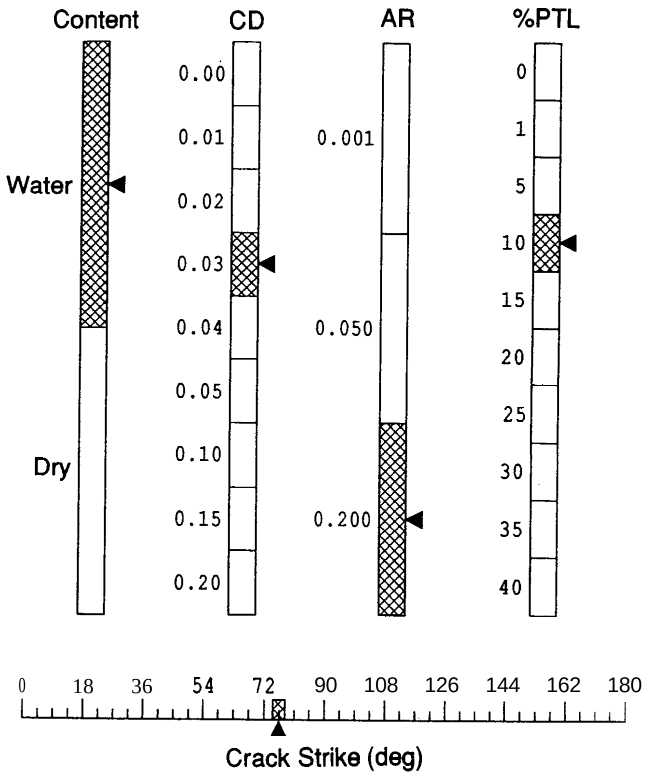

Fig. 6. Data base inversion of leading shear-wave polarizations and time delays from an azimuthal VSP at the Conoco Borehole Test Facility (Queen and Rizer, 1990). The solutions are represented as an inversion chart, with the anisotropic parameters in the data base represented as boxes. CT refers to the content which may either be wet (W) or dry (D), CD is the crack density, AR is the aspect ratio, %PTL is the differential shear-wave anisotropy for the matrix anisotropy, and the crack-strike (or horizontal rotation angle of the orthorhombic system about a vertical axis) is given by the horizontal bar. The solution that gives the best fit to the inversion is indicated by solid triangles, whereas parameters given by solutions that have a probability threshold of 0.9 of the best fit are shaded. The results suggest that there are large, water-filled cracks, with a crack density of 0.03 and an alignment of N76°E. Fine-layering is also present, with a 10% differential shear-wave anisotropy. The crack strike derived from these inversions is consistent with results from Queen and Rizer (1990) who expected the dominant N76°E direction but were unsure about their interpretation of orthogonal fracture sets.

asymmetry was implemented to determine the geophone misorientations. In their study, a single-source technique was also employed to analyze converted shear-wave arrivals. Slater et al. (1993) present analysis of an anisotropic cusp from a seismic experiment specifically designed to optimize acquisition geometries for the estimation of anisotropy (MacBeth et al., 1993a). Li et al. (1993) further demonstrate the benefit of using the fast algebraic transforms for reflec tion data and the interpretational benefits of attribute plots. Liu et al. (199 1, 1993) analyze reverse-VSP data using the dual-source procedures.

The advancement of processing and interpretation stages into more complicated geology requires a solid foundation of knowledge from simpler data sets in regions of relatively plane-layered geology. Evolution to more complicated cases

Table 1. Applicability of shear-wave polarization and time-delay estimation techniques.

	Near Offset		Offset	
	Single Source	2 or more Noncolinear Sources	Single Source	2 or more Noncolinear Sources
Land VSP	DTS OST STT OTT	DCT DIT LTT OTT DTT	STT OST	LTT DTT
Marine VSP	DTS OST STT OTT		STT OST	
Cross Well	OST	LTT	STT	LTT DTT
Reflection	*	DCT LTT	N/A	N/A

SINGLE-SOURCE TECHNIQUES

DTS Direct Time Series fit (Campden and Crampin, 1991): fits horizontal traces by iterative rotational procedure. No source direction is required so suitable for marine data.

OST Original Single source Transform technique: evolution of original deterministic procedure to evaluate an average transfer function between three or more geophone levels and one or more sources. Best resolution at normal incidence but also suitable for offset-VSP data. This technique is similar to Esmersoy (1990), Leaney (1990) and Cho and Spencer (1992).

STT Single source Transform Technique (Zeng and MacBeth, 1993): algebraic development of OST, giving a rapid interval measurement between three depth levels.

DUAL-SOURCE TECHNIQUES

DCT Dual source Cumulative Technique (Zeng and MacBeth,1993): algebraic version of Alford rotation (Alford, 1986). Minimizes energy contributed to off-diagonal components of data trace matrix.

DIT Dual source Independent Technique (Zeng and MacBeth, 1993): algebraic singular value decomposition of the vector wave field, derived from the independent source-geophone technique (MacBeth and Crampin, 1991). May be used to separate medium effects from source and geophone inaccuracies and, hence, as a guide in the conditioning stage.

LTT Linear Transform Technique (Li and Crampin, 1993): applies linear transformation to horizontal traces to provide a convenient separation of split shear waves and parameter estimates. Gives similar results to DIT when applied to VSP data. Particularly useful for surface data, providing a reduction in the number of processing steps. Also works for nonorthogonal source polarizations and, thus, can be applied to offset VSPs.

DTT Dual source Transfer matrix Technique (Zeng and MacBeth, 1993): least-squares estimate of transfer matrix between two depth levels and then interpretation using symmetries of dual orthogonal sources.

MULTISOURCE TECHNIQUES

OTT Original Transform Technique (Lefeuvre et al. 1992): obtains a stochastic estimate of the transfer matrix between two depth levels.

* No technique has yet been developed to process reflection single-source multicomponent data for shear-wave splitting attributes.

can only be made when the phenomena in the simpler case are better understood. For this reason, the present processing flow has concentrated on plane-layered structures and modelling. When a better understanding of the application of anisotropy for reservoir characterization has been gained in these areas, it will then be appropriate to move to more complex geology.

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