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OPTIMAL ACQUISITION GEOMETRY FOR DETERMINING SEISMIC ANISOTROPY

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ABSTRACT

Resolution of subsurface anisotropy using multicomponent shear-wave experiments depends critically upon the geometric distribution of raypaths sampled. Raypaths at inappropriate azimuths and incidence angles may not contain enough information about the anisotropy. The preliminary version of a scheme for determining the optimal acquisition geometry required to estimate subsurface anisotropy is introduced. The scheme is based upon a data base of shear-wave behaviour for a variety of anisotropic models. The procedure is used to confirm a preacquisition strategy for determining walkaway VSP geometries in the Caucasus Basin in Russia. Initial analyses of the data acquired from this experiment indicate anisotropic cuspoidal arrivals, which are rarely seen in seismic data. This feature may not have been observed had the recording geometry not been optimal.

INTRODUCTION

Multicomponent data offers a new challenge to acquisition technology as well as to processing and interpretation. Acquiring the vector wave field for the purpose of imaging the internal structure of the rock mass using the phenomenon of seismic anisotropy places extra demands upon the field crew and recording equipment to ensure that the volume of data is accurately represented, adequately labelled, and consistently follows established orientation and polarity conventions. However, even with the appropriate technology and field practice, data may not be suitable for extracting the full information content provided by the compressional and shear waves. Acquisition geometries adapted from conventional practice also prove to be costly as they may not provide adequate resolution of the anisotropic parameters of interest. Instead, a new acquisition geometry is required which uses anisotropy as the working framework for interpreting the vector wave field. This has been recognized in recent years, and the layouts of several notable VSP seismic studies have been designed for shear-wave splitting (Queen and Rizer, 1990; Winterstein and Meadows, 199 1 a, b). As anisotropy is a multiparameter phenomenon, inversion is inherently nonunique even for high-order symmetry systems (MacBeth, 1991a, b). The finite number of directional recordings in real data, together with experimental error in the observed wave-field and raypath determinations, further limits the resolving ability of the inversion process. The nonuniqueness for a particular parameter cannot always be reduced by using a wider coverage of three-dimensional raypaths. What is required is an acquisition geometry with *particular* raypaths designed to limit the nonuniqueness, so that the data can be interpreted data with a minimal ambiguity. As is well recognized in 3-D seismic surveys, the chances of making discoveries using investigative techniques are increased if a geometry is designed for a particular play (Salvador, 1989). Similarly, the source and geophone configuration for acquiring multi-component shear-wave data requires special attention, so that maximum use is made of all available resources. An optimum geometry attempts to provide adequate energy on all compressional and shear waves with raypaths which ensure a good resolution of the anisotropic parameters which are to be investigated. This approach is well recognized in experimental practice in Russia (Brodov et al., 1984; Cliet et al., 1991).

We are currently at the juncture of major advances in processing and interpreting anisotropy data. This, combined with an extensive body of anisotropy observations from over two decades, provides an ideal opportunity to pursue the design of an optimal acquisition geometry. Sufficient information on shear-wave splitting has now accumulated to make definitive statements about what one may expect in a shear-wave survey in a homogeneous and uniform geological structure. It appears, from observations of most earthquake and controlled source experiments made over the past decade, that the polarizations of the leading shear wave propagating subvertically through the upper crust consistently align with the stress field, orienting along the maximum compressive stress (Crampin and Lovell, 1991). This conclusion appears universally applicable to igneous and

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metamorphic rocks. The polarizations also display some consistency with core fractures, borehole televiewer images and outcrop fracture patterns (Queen and Rizer, 1990). In sedimentary basins it appears that fine-layering anisotropy (the acronym, PTL, strictly used for periodic sequences of thin layers, is also used to refer to this type of anisotropy) of the rock matrix combines with fracture-induced (EDA) anisotropy (Crampin, 1993) to give an orthorhombic symmetry (Bush and Crampin, 1991) with the shear-wave polarizations recorded from raypaths at normal incidence also aligning along the maximum compressive stress direction. Given the regularity of these observations it may therefore be assumed in most areas with plane-layered geology that an anisotropic model with EDA (vertical cracks) or PTL (horizontal layers) anisotropy, or both, will simulate the directional behaviour of the seismic waves. It should also be possible to use known local stress, predetermined fracture patterns and multiazimuth field tests (see below) to align experiments with this anisotropy, with wireline and core logs providing information on the matrix anisotropy. These can be used to form a suitable guess of the anisotropic model, which may then be used to predict the seismic wave behaviour for the different design geometries. These predictions, used in combination with an inversion procedure, determine the likely nonuniqueness of the anisotropic parameters for each design configuration, given prespecified experimental inaccuracies. The key to the successsful design depends upon the ability to invert a wide range of wave-field estimates. This can be achieved though the use of data base technology (MacBeth, 199 la, c) allied with experience of past experimental designs for the area.

OPTIMIZATION USING DATA BASE INVERSION

Anisotropic data base

The use of data base schemes in earth sciences has become increasingly popular in recent years as increased availability of hardware facilitates the mass storage of data. These data bases offer distinct advantages over active, analytically based schemes for solving complicated nonlinear problems, such as wave propagation in anisotropic structures, whilst compromising only in finer resolution. The type of data base used for this work consists of precalculated wave-field estimates of the behaviour of compressional and shear waves through a variety of predetermined anisotropic materials. For each discretely sampled three-dimensional direction, specified by the local incidence at the geophone and the ray azimuth, the data base stores polarizations and group and phase velocities for each wave type. The data base is constructed so that it covers all effective anisotropies likely to be encountered in the field, whilst remaining compact by taking into account any overlap of information due to symmetries in the anisotropic behaviour. Any problems in the computation of the eigenvalues and eigenvectors of the anisotropic materials are encountered and solved during initialization of the data base using ANISEIS (Taylor, 1991) so that the inversion can be quick and stable. In principle, the scheme is flexible so that the user may combine relative or absolute traveltimes and polarizations derived from different arrivals in the seismogram. Perhaps the most important advantage of this approach is the relative ease with which we can incorporate quite complicated a priori constraints relating to the known geological structure, well logs, dipmeter surveys, outcrop fracture directions or other relevant geophysical knowledge.

Quantitative evaluation of the optimum geometry

This work presents a preliminary version of an algorithm for data base acquisition design in which *polarizations of the leading shear wave were used.* For this reason, the discussion below and the ensuing case study relate to the polarizations of VSP data only.

The design procedure begins with a suitable guess at an anisotropic model, based upon past and present geophysical information for the borehole and its immediate area, and the likely position of the reservoir zone. Different design apertures (raypath windows) are selected to image this zone. The number and size of these apertures will depend upon the number of VSPs that can be logistically and financially afforded in addition to the physical limitations in deployment of the equipment due to natural or artifical obstacles and lease boundaries. For the final source-geophone configuration and best guess at the anisotropic model local ray directions at each geophone are computed using anisotropic ray tracing. These directions are then used to extract the polarizations from the data base. It is then assumed that these polarizations are those which would be observed, and an estimation error of 5° is assigned. This error is chosen so that the inferred crack strike may be accurate enough to combine with geological and geophysical data for reservoir modelling. The error may be reasonable if factors of experimental control relating to the source and geophone are confined to within a specified (not unreasonable) tolerance (Zeng and MacBeth, 1993). This set of polarizations is then compared with those in the data base for the same or neighbouring ray directions within ±10° in incidence angle and ±5° in the azimuth determination. Data base (theoretical) and predicted (observed) values are compared for each anisotropic model using an L_2-norm for the objective function (MacBeth, 199 lc). This is related to an χ^2-value for final representation and a probability statistic defined. Although this statistic may not be physically meaningful, it is used as a threshold for acceptance of the solutions. The relative quality of the various designs is judged by using the percentage of acceptable solutions, given a particular threshold probability value.

PRELIMINARY CASE STUDY

Proposed VSP experiment

In 1991, an opportunity was presented to test these ideas when the Edinburgh Anisotropy Project was invited to collaborate with Neftegeofizika Geolkom, Moscow, and Stavropol-Neftegeofizika, Stavropol, in the acquisition of a multiazimuth VSP in the Juravskoe Oilfield in the Caucasus Basin (Slater et al., 1993). The aim of the VSP experiment was to determine the anisotropic structure of a productive *clay reservoir* and to compare it with the structure in a similar nonproductive layer in a similar terrain obtained with another VSP 5 km away. The experiment was to be in an area of flat-lying geology with 870 m of sandstones, limestones and clays, overlying a uniform 1200-m layer of clay with the reservoir layer situated at the bottom of this clay layer. The relatively flat surface topography of the area offered a free choice of design geometry.

The schedule, based upon past experience of this area (Brodov et al., 1984), consisted of a zero-offset P-wave VSP, an offset shear-wave VSP and several walkaway shear-wave VSPs at both wells. In the first stage of the experiment, it was planned to perform multiazimuth tests to obtain the crack-strike directly in the field. This consists of physically rotating the shear-wave source at near-offset in a full circle by 15” intervals. The records were then to be inspected in the field and the crack strike determined by the direction of maximum rectilinearity. These tests provided the reference orientation for the design parameters. A near-offset shear-wave VSP with two orthogonal source orientations was also planned with 5- or 10-m spacing down to the reservoir layer. This could be used to further confirm the multiazimuth crack-strike determinations and evaluate the crack density. The next stage consisted of two P-wave sources at approximately 500-m offset to orient the geophones; these were planned to have azimuths differing by 60” or 120”. Detailed analysis of the anisotropic structure of the reservoir layer was to be obtained using offset and walkaway VSPs. For the offset VSPs, three-component geophone levels were to be located at 10-m intervals, from 2500 m to 700 m, and 100-m intervals, from 600 m to 100 m, in the well bore, with the source position to be decided. Three walkaway lines were proposed, two shear-wave and one P-wave, each with seven source locations positioned between 500 m out to 2500 m with exact details to be decided. In-line and cross-line source polarizations were to be shot for the shear-wave data. There were to be two geophone levels 100 m apart above and below the reservoir layer at approximately 2000-m depth. The design input to be confirmed by quantitative evaluation based on the data base acquisition design algorithm were the azimuths of the offset and walkaway lines (Figure 1).

Design using anisotropic data base

The data base used in this present work consists of polarizations of the leading split shear wave for a range of three-dimensional directions sampled at 4.5” intervals in azimuth and incidence angle through different anisotropic models simulated by permeating matrix (PTL) anisotropy by aligned, vertical microcracks using the method of Hudson (1986). This gives an orthorhombic symmetry characterized by three mutually orthogonal planes of symmetry and a number of point singularities (Crampin, 1991). A range of materials are created, with microcracks varying in strike from 0” to 180°, with wet or dry content, and aspect ratio 0.001, 0.05 or 0.20. The crack density ranges from zero (pure PTL) to 0.20 and the matrix anisotropy from zero (pure EDA) to 40% birefringence. Although it is possible to also constrain the dip of the fine-layering and the cracks, these parameters are fixed at 0” and 90” in this present study as it was reasonable to assume horizontal geology. This gives four descriptive parameters for the cracks and layering, with one further orientation parameter giving the crack strike. This parameter set is found to be more convenient than nine independent elastic constants, as the variation in shear-wave behaviour with each parameter is intuitive and more easily followed. However, to aid conversion between the two representations, some of the solutions below are displayed as both crack-matrix parameters and elastic constants.

An anisotropic model, corresponding to one that may be expected at the Juravskoe site, was initially chosen from the data base using a velocity model taken from previous near-offset studies in a similar area and an expected birefringence of 15% for the PTL anisotropy (Brodov et al., 1984). Table 1 gives the parameters of this model. Using this model, the expected polarizations for the leading split shear wave were extracted from the data base for five different azimuthal lines and two groups of angles of incidence (Figures 1 and 2) to give a total of ten data apertures. The first set of incidences (Group 1) ranged from 6” (near normal incidence) to 42” in steps of 6” and corresponded to the offset VSPs. The second (Group 2) ranged from 5” to 65” in steps of 10” and corresponded to the walkaway VSP. These angles of incidence were determined from the minimum and maximum limits set by ray tracing through the expected anisotropic model. Separate inversions were carried out for each angular aperture in Figure 2 corresponding to trial azimuths in Figure 1 and analyses made to determine the number of total possible anisotropic models that satisfied the inversion criteria. Solutions for probability thresholds of 0.75, 0.90, 0.95 and 0.99 were obtained. The relation of these threshold points and the reliability of the inversion solution is discussed by MacBeth (1991c).

Table 1. (a) Parameters of anisotropic model used in azimuth optimization.

Isotropic matrix material	Crack properties	Matrix anisotropy
P-wave velocity: 2.40 km/s	density: 0.05	%PTL: 15
S-wave velocity: 1.33 km/s	aspect ratio: 0.001	dip: 0°
V_P/V_S: 1.8	content: water	
Density: 2160 g/cm^3	dip: 90°	

(b) Elastic constants c_{ijkl} (GPa), corresponding to the anisotropic model used to design the azimuths of the Caucasus' VSPs.

ij \ *kl*	11	22	33	13	23	12
11	11.93					
22	4.28	11.93				
33	3.47	3.47	8.99			
13	0	0	0	2.76		
23	0	0	0	0	2.48	
12	0	0	0	0	0	3.43

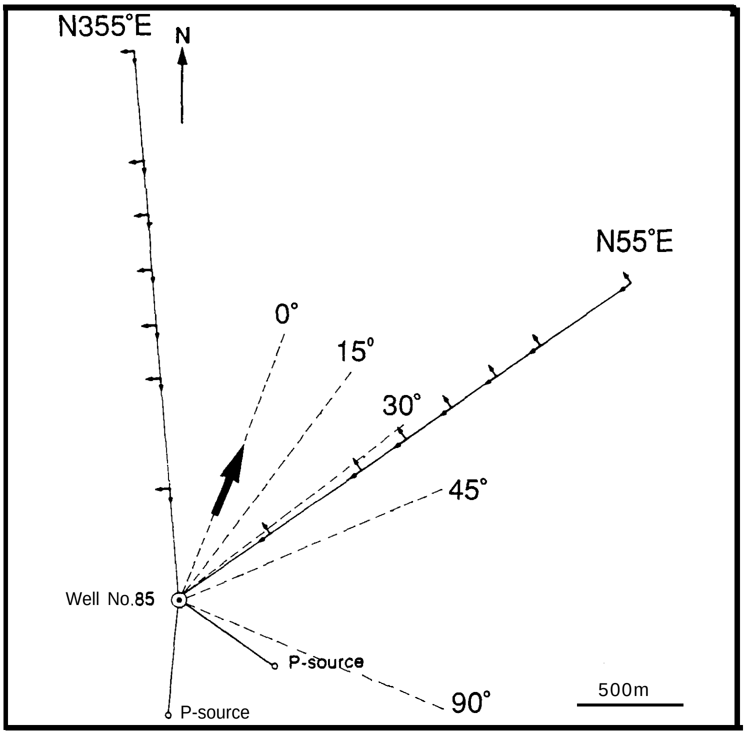
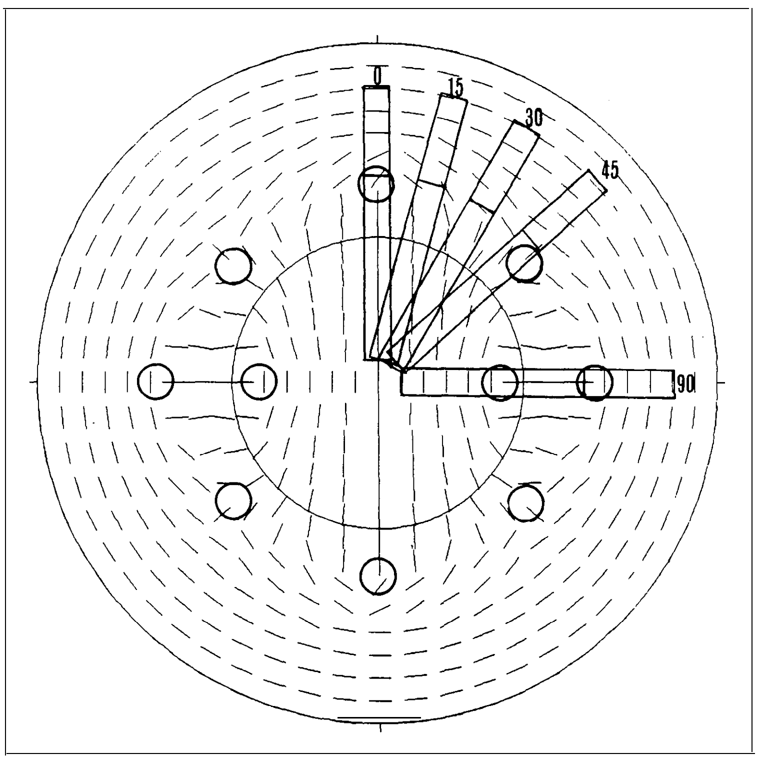


Fig. 1. Proposed field layout for the Caucasus VSP experiment with tria azimuths (dotted lines) for the walkaway and offset VSPs which are analysec using the data base inversion. Solid lines correspond to the lines used in the final field acquistion and the large arrow to the crack strike determined from nultiazimuth tests.



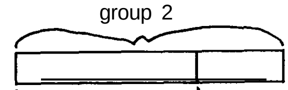


Fig. 2. Equal-area plot of polarizations for leading shear wave, corresponding to the anisotropic model of Table 1. This pattern has been recovered from the data base entry for this model. Limits of the apertures used in the design are drawn as rectangles at five different azimuths: 0°, 15°, 30°, 45" and 90° to the crack strike. At each azimuth there are two data apertures, representing the angles of incidence for the offset VSP (Group 1) and a wider range for the walkaway VSP (Group 2). Open circles indicate directions of disruptive behaviour near and at point singularities.

Table 2a gives details of the solutions for each angular aperture, and for the different probability thresholds, with Figures 3a through 3e showing charts of the inversion solutions for each azimuth and a probability threshold of 0.95. The left-hand charts show solutions for the offset VSPs and the right-hand charts show solutions for the walkaway VSPs. The open triangles correspond to the actual model used to compute the observed (expected) polarizations (Table 1), the solid triangles correspond to the best inversion solutions, and the shaded areas indicate the solutions which are above the probability threshold of 0.95. This representation shows overlapping parameter values of each solution, so that not all of the parameter combinations will be good solutions, but it is convenient for studying the degree of nonuniqueness. The inversion charts for the 0” azimuth (parallel to the crack strike) (Figure 3a) show that it appears impossible to determine a unique solution for the inversion within these prescribed limits, with many models satisfying both VSPs. There is a lower limit on the percentage of PTL anisotropy. It is interesting to note that in this case the crack strike is totally unresolved as many PTL models may fit the observed (expected) polarizations. In contrast, the 15” azimuth (Figure 3b) allows all crack-matrix parameters to be resolved for both offset and walkaway experiments. Changing the line azimuth to 30” (Figure 3c) increases the nonuniqueness for the offset VSP again, with the aspect ratio and content now becoming unresolved, although the walkaway data still resolve the model parameters. The trend continues for the offset VSPs at 45” azimuth (Figure 3d), with a further degradation in the offset inversion results, with only the crack strike and the percentage of PTL remaining resolved. The final set of solutions for a line perpendicular to the crack strike (Figure 3e) is completely unresolved for these threshold values, with only crack strike remaining adequately resolved. Angles between 45” and 90” were not chosen as they gave identical results to the conjugate angles, above.

Table 2. (a) Details of inversion solutions for different offset (Group 1) and walkaway (Group 2) VSP designs. Last four columns give percentage of anisotropic models in data base which have objective functions greater than the threshold probability values of 0.99, 0.95, 0.90 and 0.75, respectively.

Azimuth (°)	VSP Group	CPU (min)	Percentage of total >0.99	>0.95	>0.90	>0.75
0	1	24	1.9522	2.0210	2.2928	3.6608
0	2	24	0.7583	0.7623	0.8483	1.5895
15	1	24	0.0026	0.0026	0.0064	0.0818
15	2	24	0.0013	0.0026	0.0038	0.0506
30	1	24	0.0013	0.0141	0.0510	0.3000
30	2	24	0.0013	0.0017	0.0514	0.0596
45	1	24	0.0013	0.0206	0.0574	0.5399
45	2	24	0.0013	0.0026	0.0643	0.0526
90	1	24	0.0051	0.0164	0.0229	0.1475
90	2	24	0.0049	0.0183	0.0281	0.1715

(b) Range of elastic constants c_{ijkl} (GPa) corresponding to the anisotropic models accepted by the inversion at a 0.95 probability threshold value for the walkaway at an azimuth of 15°.

ij \ *kl*	11	22	33	13	23	12
11	11.93					
22	4.28	11.93				
33	3.47	3.47	8.99			
13	0	0	0	2.76		
23	0	0	0	0	2.49 -2.43	
12	0	0	0	0	0	3.55 -3.49

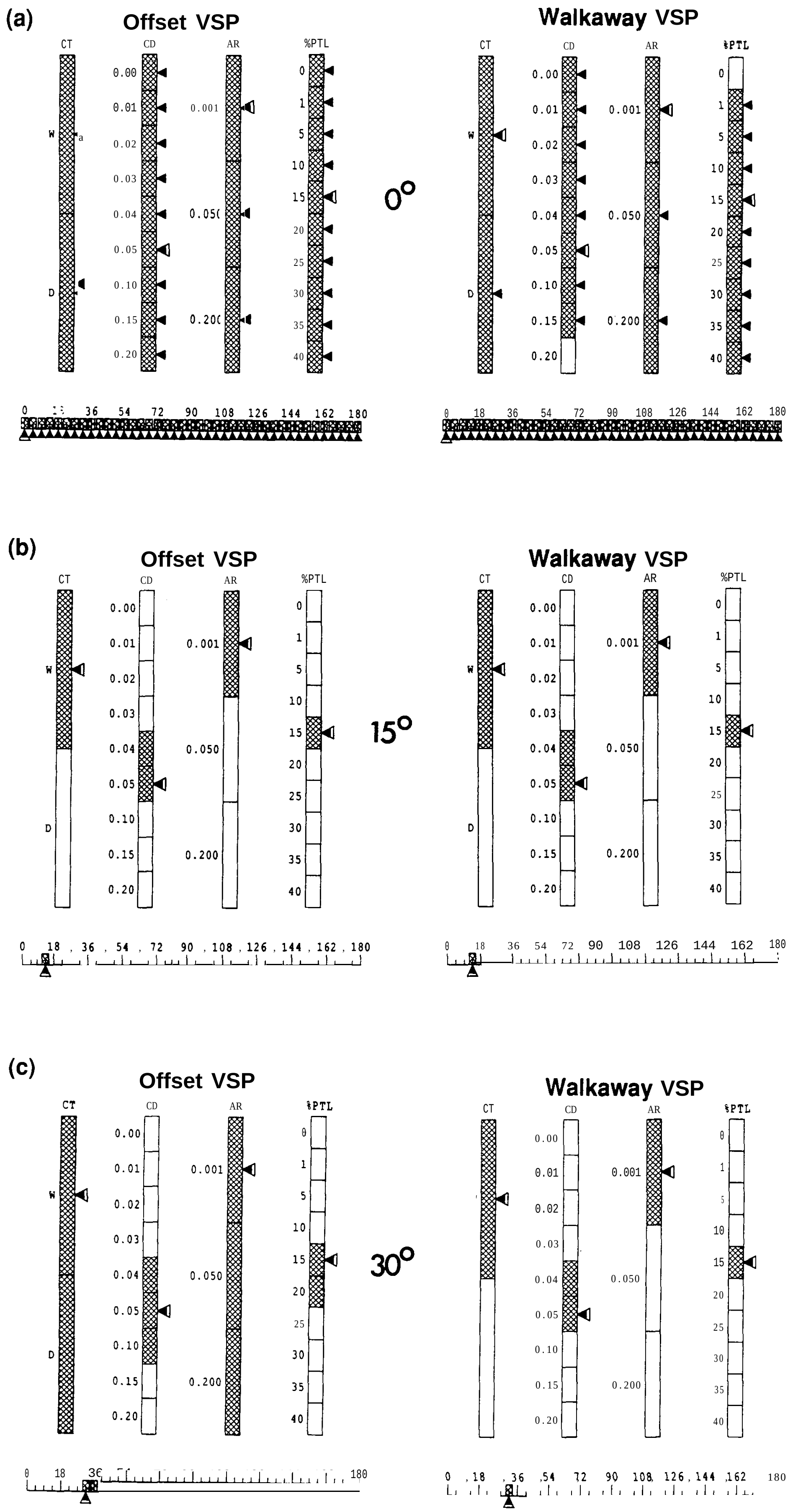
(c) Range of elastic constants c_{ijkl} (GPa) corresponding to anisotropic models accepted by the inversion at a 0.95 probability threshold value for the walkaway at an azimuth of 45°.

ij \ *kl*	11	22	33	13	23	12
11	11.93 -10.89					
22	4.29 -3.91	11.93 -11.79				
33	3.47 -3.09	3.47 -3.33	8.99 -8.85			
13	0	0	0	2.76		
23	0	0	0	0	2.69 -2.43	
12	0	0	0	0	0	3.75 -3.43

From this theoretical study several quantitative recommendations can be made, which should be adopted when planning the shear-wave VSP if a prospective inversion is to have the best chance of producing a narrow range of anisotropic models and the least ambiguous interpretation of the anisotropy. Clearly the source azimuth should not be parallel or perpendicular to the crack strike, and for this specific set of polarizations the offset VSP appears unsuitable to resolve the anisotropy except at an azimuth of 15”. Azimuths of either 15” and 30” (or 60” and 75”) appear to be the most suitable for the walkaway VSP. The azimuth of 45” may also be used, as it shows only a slight loss in the resolution for aspect ratio.

Practical implementation of the proposed experiment

In August and September 199 1, EAP associates travelled to the Caucasus to participate with the data acquisition. VSPs were carried out at both wells. The VSP acquisition proceeded in approximate accordance with the original proposals, with the exception of the shear-wave offset VSPs which were not fully recorded. Normal incidence multiazimuth tests were performed as planned, revealing the presence of crack-induced anisotropy and azimuthal isotropy due to the clay matrix. The orthorhombic combination was close to that


(a)
Offset VSP
Walkaway VSP
0°
(b)
Offset VSP
Walkaway VSP
15°
(c)
Offset VSP
Walkaway VSP
30°
CT
CD
AR
%PTL
W
D
0.00
0.01
0.02
0.03
0.04
0.05
0.10
0.15
0.20
0.001
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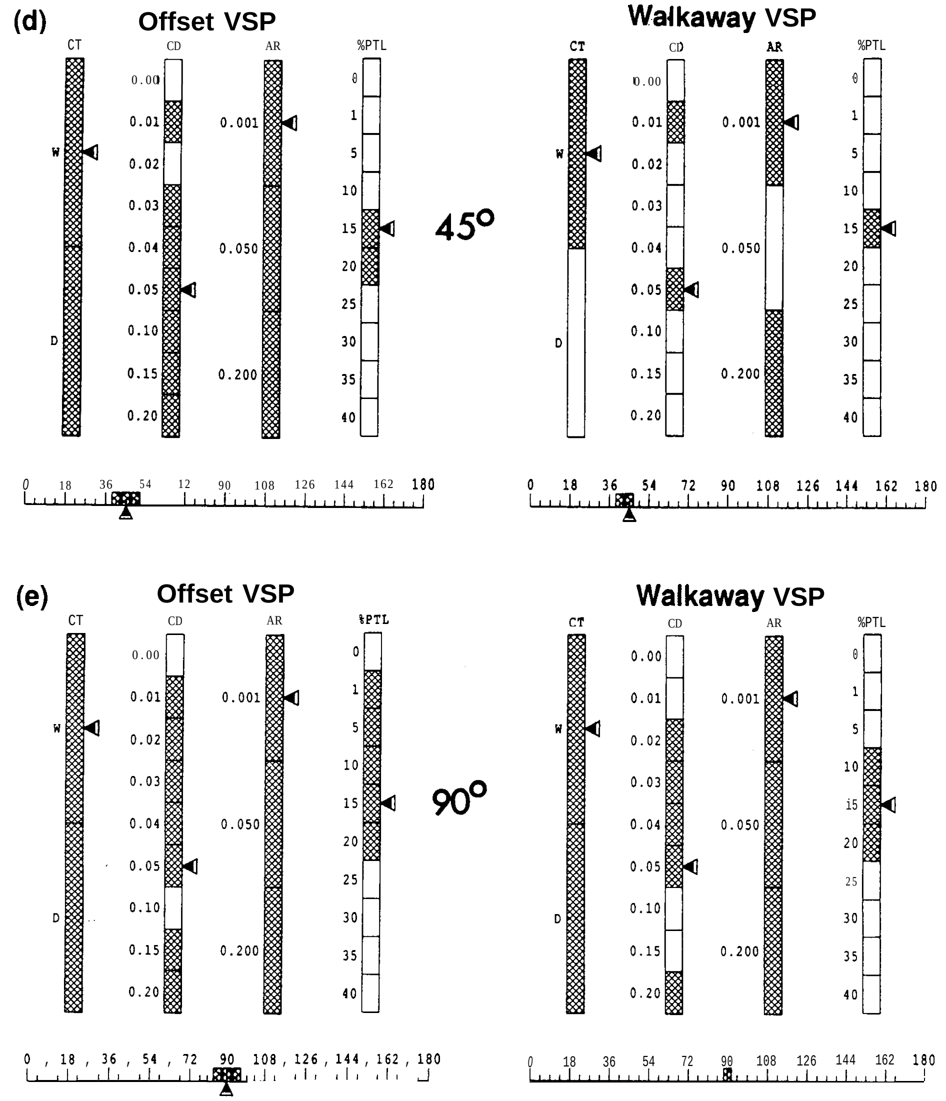

Fig. 3. A series of ten inversion charts showing the anisotropic parameters resolved by inverting polarizations contained within each different data aperture of Figure 2. CT refers to crack content which may be either wet (W) or dry (D), CD is the crack density, AR the aspect ratio, %PTL the differential shear-wave anisotropy for the matrix anisotropy, and the rack strike (or horizontal rotation angle of the orthorhombic system about a vertical axis) is given by the horizontal bar. The solutions are for a probability threshold of 0.95. The left-hand chart corresponds to offset VSP solutions and the right-hand chart to the walkaway VSP for azimuths of: (a) 0° (parallel to the crack strike); (b) 15°; (c) 30"; (d) 45°; and (e) 90° (perpendicular to the crack strike). The aperture for the offset VSP contains seven angles of incidence from 6° to 42° in increments of 6°. The aperture of the walkaway VSP has seven angles of incidence from 5° to 65° in increments of 5°. The open triangles correspond to the actual parameter values for the model solution. The solid triangles correspond to the best solution found by the inversion, given by a maximum in the objective function (there may be more than one best solution). The shaded areas on vertical bars and along azimuth scale indicate solutions which are acceptable within experimental error, with values for the objective function greater than the threshold probability.

used in the design model. Two 520-m offset P-wave shots, 60° apart, were then used to orient the geophones. To allow for an uncertainty of 15" in estimating crack strike an azimuth of 30" was chosen, as this would maximize the chance of being near the optimum design. Two shear-wave walkaway VSPs at azimuths +30° and -30" from the crack strike, and the sources, were placed as suggested by our combined experimental and theoretical results for optimization of the acquisition geometry.

The data are currently being analysed. Preliminary analysis demonstrated the presence of an anisotropic cusp (Slater et al., 1993) present on walkaways from strong anisotropy in the 1200-m thick uniform clay layer, consisting of azimuthal isotropy and a smaller component of crack-induced anisotropy. This feature of the shear-wave behaviour might not have been observed without the use of optimum acquisition geometry to adequately sample the shear-wave behaviour. This shear-wave behaviour was subsequently matched using full-wave modelling and 34% birefringence for the PTL component. Further analyses of the cusp may well resolve the anisotropic model.

Discussion and Conclusions

The results of this study underline the importance of planning optimal acquisition geometry for shear-wave VSPs to interpret important features of anisotropic behaviour so that the ambiguity in data interpretation for the anisotropic model may be reduced. This is critical for a phenomenon such as anisotropy which has a large number of independent variables and large inherent nonuniquenesses. The design algorithm provided quantitative confirmation that the experimental geometry was suitable for determining shear-wave anisotropy. Although the present analysis concentrates on polarizations, the design algorithm has now been adapted to include P-wave and shear-wave velocities, time delays and polarizations for anisotropic models based on a variety of background V_P/V_S values. The full design algorithm will be implemented on an interactive workstation environment. It is suggested that this type of optimum design is necessary when observing and interpreting all multicomponent data, whether it is VSP, reflection or cross-hole. It could be particularly useful in marine VSPs, where converted shear waves must be analysed to extract the anisotropy. In this case it is more critical to obtain optimal acquisition geometry, so that there is maximum energy in the converted waves and well-resolved anisotropic parameters. As the design algorithm progresses it may be possible to restrict experimental studies to image one specific anisotropic parameter.

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