Fracture characterization at the Conoco Borehole Test Facility using shear-wave anisotropy

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SUMMARY
Two multi-component near-offset VSP experiments are used, in conjunction with borehole data, to characterize the subsurface fracture system at the Conoco Borehole Test Facility, Oklahoma. Time delays between the fast and slow split shear-waves are observed to correlate with the heavily fractured sandstone formations. Inversion of the shear-wave splitting estimates is achieved using a Genetic Algorithm which incorporates an anisotropic ray tracing scheme. The inversion results suggest that the fracture orientation is sub-vertical. A method of determining fracture dip using an opposite azimuth VSP method is suggested.

INTRODUCTION
Observations of seismic anisotropy are thought to be related to sub-surface fracture distributions. Such information can be critically important to the successful development of a hydrocarbon reservoir. In this paper we present a study of shear-wave birefringence which is interpreted in terms of a fracture system. The results from this are compared with independent borehole and surface data relevant to the fracture system.

The near-offset VSP experiments were shot about two different wells within 1 km of each other at the CBTF. The acquisition geometries are essentially the same with the exception that the source azimuths were approximately diametrically opposite. These VSP’s are identified as the 33-l VSP and the Peel VSP (Figure 1).

33-1 VSP
A vibroseis source truck was located 36 m (120 ft) along the azimuth N279°E relative to the well 33-l. The vibroseis source was operated in in-line and cross-line shear-wave modes and a vertical P-wave mode. Seismograms were recorded at 50 levels between the depths of 152 m (500 ft) and 887 m (2910 ft) using a constant geophone spacing of 15 m (50 ft).

Peel VSP
In this experiment the vibroseis source trucks were sited 64 m (210 ft) from the well Peel along the azimuth N122°E. In-line and cross-line shear-wave sources and a vertical P-wave source were used to excite seismic energy which was recorded at 44 equi-spaced depth levels between 306 m (1003 ft) and 951 m (3120 ft).

DATA PROCESSING
Seismograms from both VSPs were of good quality with a high signal to noise ratio. Initial processing consisted of demultiplexing, stacking and rotation of the horizontal geophone components to compensate for downhole tool rotation. Application of shear-wave estimation techniques to determine the time delay between the fast and slow split shear-wave waves and the polarization direction of the fast shear-wave yielded good results. Further improvements could be achieved after the application of f-k filtering and near-surface correction (Zeng 1994). This latter step is a deconvolution operation which is intended to remove the highly variable effects of the near-surface.

STRATIGRAPHIC CORRELATION
The results obtained for the shear-wave birefringence observed for the two VSP experiments show a good correlation with the reported stratigraphy at the CBTF (Figure 2). The large time delay gradients for the two depth ranges 422 - 617 m and 677-767 m correspond to sandstone formations. Sandstones are more likely to support open fractures than rocks such as shales or carbonates. This is due to the large grain size of sandstones which leads to rough fracture surfaces. These are more resistant to closure than the smooth fracture surfaces observed in shales or carbonates (Ehlig-Economodes, Ebbs and Meehan 1990). This correlation suggests that the shear-wave birefringence is sensitive to the presence of open fractures in the sandstones. This conclusion is supported by borehole televiewer (Figure 3) and core data which indicate that the highly anisotropic zone at 700 m corresponds to intense natural fracturing (Queen et al. 1992). This depth interval has also been observed to correspond to known fluid loss in all of the deep wells at the test-site which is attributed to large open fractures within this zone.

GENETIC ALGORITHMS
Genetic Algorithms (GA) are claimed to be global non-linear optimization techniques which are receiving increasing attention within the geophysics community, (for example Sen and Stoffa 1992). The underlying process which GA’s attempt to emulate is evolution. This is achieved through the use of a population of models which are represented in terms of character strings, analogous to chromosomes. These are manipulated by genetic operators in such a way that, on average, better models are generated in subsequent populations which are nearer to the global optimum. In this paper we employ a GA to minimise an RMS misfit objective function defined in terms of the observed and predicted shear-wave estimates derived from a ray tracing algorithm.

INVERSION METHOD
The misfit function to be minimized by the GA is defined to be

\[
f(m, \tau^p, \tau) = \frac{1}{2} \sum \Delta \tau(m, \tau^p, \tau) + \sum \Delta p(p^p, p)\]

(1)
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where

$$\Delta \tau (\tau^0, \tau^m, \delta \tau) = \frac{1}{N} \sum_{j=1}^{N} \frac{(\tau^0_j - \tau^m_j)^2}{\delta \tau_j}; \tag{1b}$$

and

$$\Delta p(p^0, p^m, \delta p) = \frac{1}{N} \sum_{j=1}^{N} \frac{(p^0_j - p^m_j)^2}{\delta p_j}. \tag{1c}$$

$\tau$ and $p$ are vectors of the time delays and the horizontal projections of the fast shear-wave polarizations. $m$ is the model parameter vector for which shear-wave splitting observations are calculated by the ray tracing algorithm. The subscript $j$ identifies the observation number. The superscripts identify quantities relating to the model, superscript $m$, and the observed, superscript $0$, vectors. $\delta \tau$ and $\delta p$ are error estimates associated with the observed time delays, $\tau^0$, and fast shear-wave polarizations, $p^0$, respectively. The shear-wave splitting estimates are assigned estimated errors of $10^\circ$ for the fast shear-wave polarizations and 2 ms for the time delays. Fast shear-wave polarization estimates associated with time delays less than 1 ms are assigned an estimated error of $20^\circ$. This reflects the uncertainty of the estimation technique for which the fast shear-wave polarization is unlikely to be well resolved.

The predicted shear-wave splitting observations, $\hat{\tau}^0$ and $\hat{p}^0$, are calculated using a ray tracing algorithm for a layered anisotropic model based about a perturbation defined by the model vector, $m$. In this paper we present results based upon the Hudson crack model (Hudson 1980) although other more flexible parametrization schemes have also been employed. The layered model for the CBTF uses fourteen layers which are calculated from logging information and, for shallow depths, reverse VSP surveys (Queen personal communication). The imposition of a common symmetry axis for each of these regions is applied to avoid any problems associated with multiply split shear waves.

INVERSION RESULTS

The best model to be found by the GA possesses a misfit of $f(m, \tau^0, p^0) = 0.338$, indicating that on average all the model observations fall within the estimated error bounds. This model corresponds to a sub-vertical crack system orientated N50°E and dipping 25° towards the south east. This result is in good agreement with previous studies at the CBTF (Home and MacBeth, 1994; Liu, Crampin and Queen 1991) and surface observations (Queen personal communication). However it should be noted that this result is non-unique. This is illustrated in Figure 4. The crack orientation for models sampled by the GA within the fitness range $0 < f(m, \tau^0, p^0) < 1$ are plotted. Each point on this plot represents a model sampled by the GA and is coloured according to the corresponding fitness. Although most models are clustered around

the orientation corresponding to the optimal model there are several other significant solutions.

DISCUSSION AND CONCLUSIONS

A GA has successfully been applied to the problem of inverting shear-wave splitting estimates from two near-offset VSP experiments from the CBTF. This method indicates that the observed shear-wave anisotropy at the test site is likely to be due to the presence of a sub-vertical fracture system. The fracture dip is resolved due to the use of the inclusion of a second VSP survey shot along an opposite azimuth. For non-vertical fracturing observations of shear-wave birefringence along opposite azimuths will be different, providing the chosen azimuth does not coincide with the fracture strike. This acquisition geometry may be particularly important if horizontal drilling is to be employed. In these cases directional drilling is chosen to intersect the fractures perpendicularly to maximise productivity.

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REFERENCES


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Figure 1 - Plan views showing the acquisition geometries used to obtain the multi-component near-offset VSP datasets.

Figure 2 - A comparison of the reported stratigraphy at the Conoco Borehole Test Facility, Oklahoma and the shear-wave splitting estimates obtained from the two near-offset VSP experiments. The regions of large time delay gradients correlate with the sandstone formations, as indicated. This suggests that these zones are heavily fractured.
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Figure 3 - Borehole televiewer images from the 33-1 well showing a) an induced fracture striking between N55°E and N65°E and b) stress induced borehole breakout.

Figure 4 A scatter plot showing of crack strike and crack dip for the models sampled by the Genetic Algorithm. The dots represent crack orientations for the different models and are shaded according to the fitness of the solution. The direction of the crack dip is indicated in the corner of each quadrant. The best solution found by the Genetic Algorithm is outlined in white.