The potential of measuring fracture sizes with frequency-dependent shear-wave splitting

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Introduction

The success of seismic anisotropy is its ability to provide subsurface fracture orientations as derived from the polarization of the faster shear wave, and spatial distributions of fracture intensity inferred from time-delays between the faster and slower shear waves (Crampin 1985, Li 1997). However, the reservoir engineers' reluctance to accept seismic anisotropy as a routine technique for fracture characterization is partly because of its failure to provide information about sizes of fractures. Although both grain scale micro-cracks and macro-scale fractures are considered to cause seismic anisotropy, reservoir engineers are more interested in the latter as permeability in many hydrocarbon reservoirs is believed to be dominated by formation-scale fluid units (in the order of meters).

The interpretation of anisotropic measurements made from seismic data requires theoretical models that relate measurable seismic parameters to macroscopically determined rock properties. Based on the assumption that the scale length associated with fractures is considerably smaller than the seismic wavelength, a description of the average properties of the medium will be sufficient.

The two most popular models for the average properties are the Thomsen equant porosity model (Thomsen, 1995) and Hudson's model (Hudson, 1981). Thomsen's model assumes perfect fluid pressure equalization between the cracks and the surrounding rock while Hudson's model assumes that the cracks are isolated with respect to fluid flow. Both models predict frequency independent behaviour.

In both models the magnitude of the anisotropy is related to the crack density, although the precise dependence is different in each case. This crack density is defined as $\varepsilon = Na^3$ where N is the number of cracks per unit volume and a is the crack radius. Unfortunately, radically different fracture distributions can have the same crack density. This is because a few large cracks can give the same crack density as many smaller cracks. Figure 1 demonstrates this concept. Both cases have identical crack densities, but the fluid flow response would be expected to be markedly different in each case.

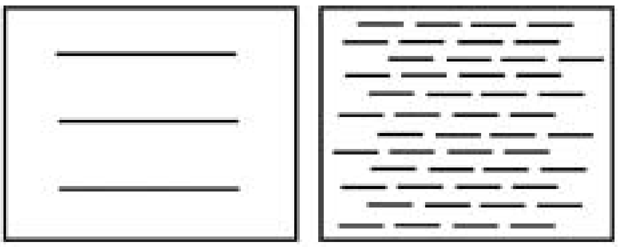

Figure 1 *The same crack density can be caused by a few large fractures as shown on the left or many small cracks as shown on the right.*

If we are constrained to work within the conventional equivalent medium approach, then we can only obtain crack density and orientation from the seismic data. To obtain information on fracture size which can be useful for permeability prediction we require a different approach. In this study we investigate the possibility of using the frequency dependence of anisotropy to derive such information. We begin by reviewing a new theory which models frequency dependent anisotropy. The theory is then calibrated and tested against laboratory data, before we conclude with an application to field data.

Theoretical model

The microstructural model of Chapman et al. (2002) considers an unfractured, isotropic rock in which all relevant length scales are identified with the grain scale. Recently this model has been extended (Chapman, 2003) with the introduction of an aligned fracture set, where the size of the fractures is allowed to be greater than the grain scale, giving a two scale model. Frequency dependent velocity and attenuation can be calculated as a function of angle of propagation.

In contrast to previous, single scale models the scale length of the fractures can play an important role at seismic frequencies. This is found to be particularly critical for the case of 'meso-scale' fractures; fractures which are larger than the grain scale but still much smaller than the seismic wavelength. An important example is the frequency dependence of shear-wave splitting which is sensitive to the fracture scale. This suggests the use of this attribute to invert for fracture size.

Laboratory calibration

Mathematical models for wave propagation in fractured media can only be tested by comparison with laboratory measurements. To this end, Rathore et al. (1995) developed a method to manufacture synthetic sandstone samples containing cracks of known geometry and orientation. Velocity and attenuation were then measured as a function of angle at ultrasonic frequencies. It has been established in a number of papers that Thomsen's equant porosity model gives a satisfactory match to the data while Hudson's model performs poorly.

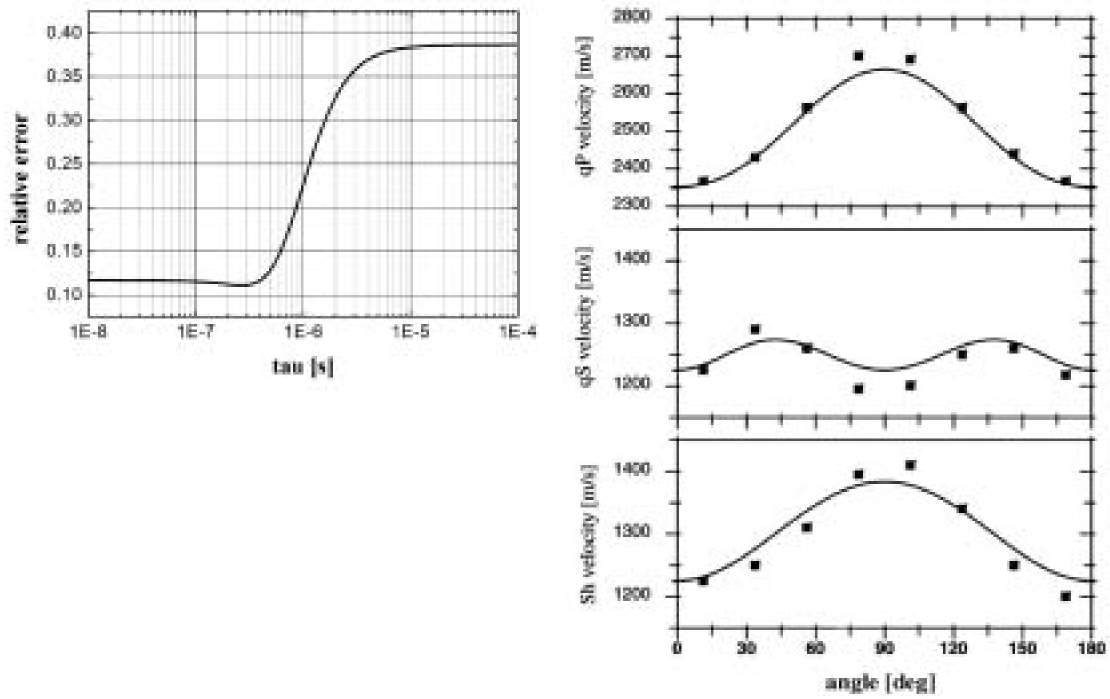

Figure 2 *Relative error between measured and modelled velocities as a function of τ. There is a fairly indistinct minimum at τ=0.27μs. This value was used to model the velocities shown on the right.*

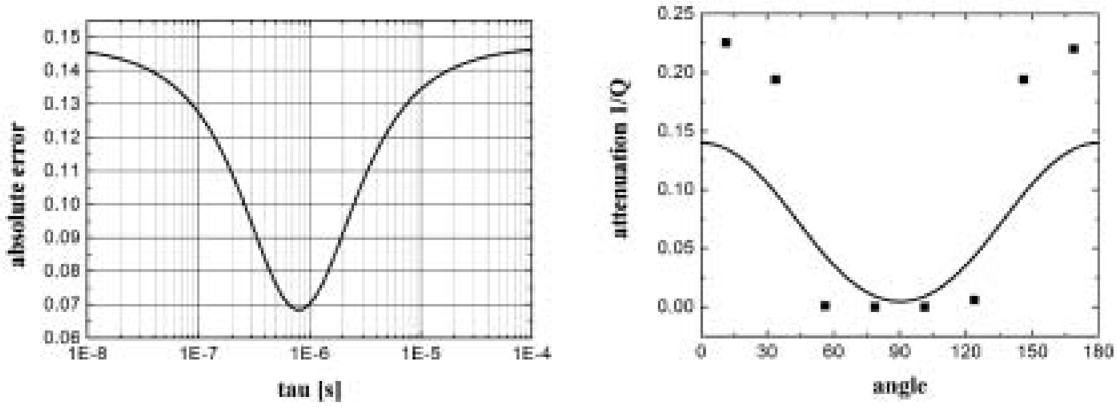

Figure 3 *Misfit between measured and modelled qP-wave attenuation as a function of τ and modelling results for the best fit. There is a distinct minimum in nearly the same place as in Figure 2.*

We now proceed to test Chapman's model against the Rathore data. The values of the relevant rock properties are given by Rathore et al. (1995). For the application of the Chapman model in this case we have only one unknown parameter, the time scale constant τ. We therefore seek the value of τ which will minimize the misfit between data and model.

Figure 2 shows the misfit of the velocities as a function of the chosen τ. A rather indistinct minimum exists for a τ value of 0.27 μs. We also show the velocity modelling corresponding to this τ value. A very satisfactory match is achieved.

The modelling for the optimal τ value is not significantly better than would be achieved in the low frequency limit. If we are to use the obtained τ value to guide the application of the model to other datasets then it is desirable to obtain tighter bounds on τ. To this end we attempted to model the attenuation data reported by Rathore et al. (1995). Figure 3 shows that there is now a much more distinct minimum in the same place as the earlier minimum occurred. The attenuation modeling is also given.

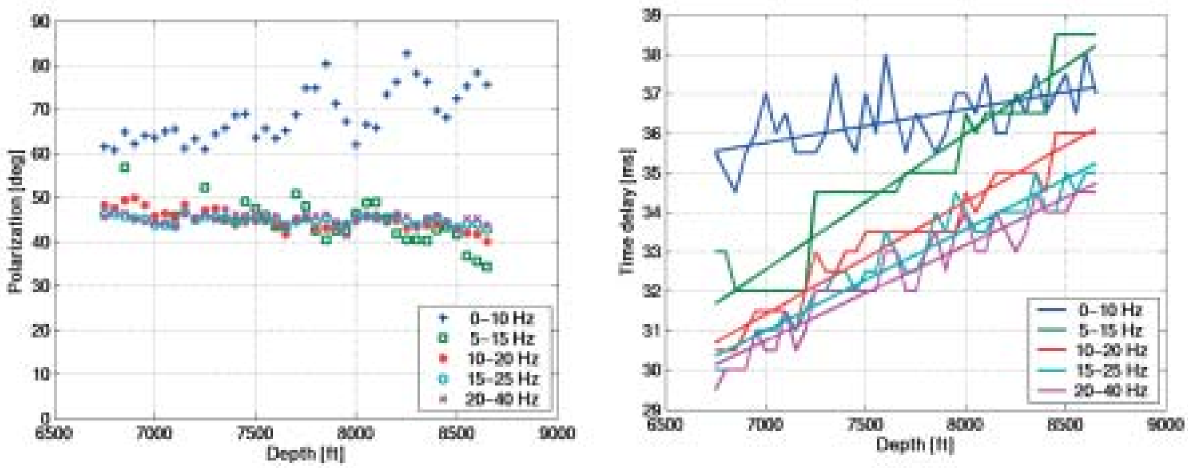

Figure 4 *Polarization angles of the fast shear wave and time delay between the split shear waves for different frequency bands. The results for 0-10 Hz are unreliable, since there is no coherent energy in the data below 10 Hz. The polarization angles are consistent around 43°, while the time delay shows a systematic decrease with frequency.*

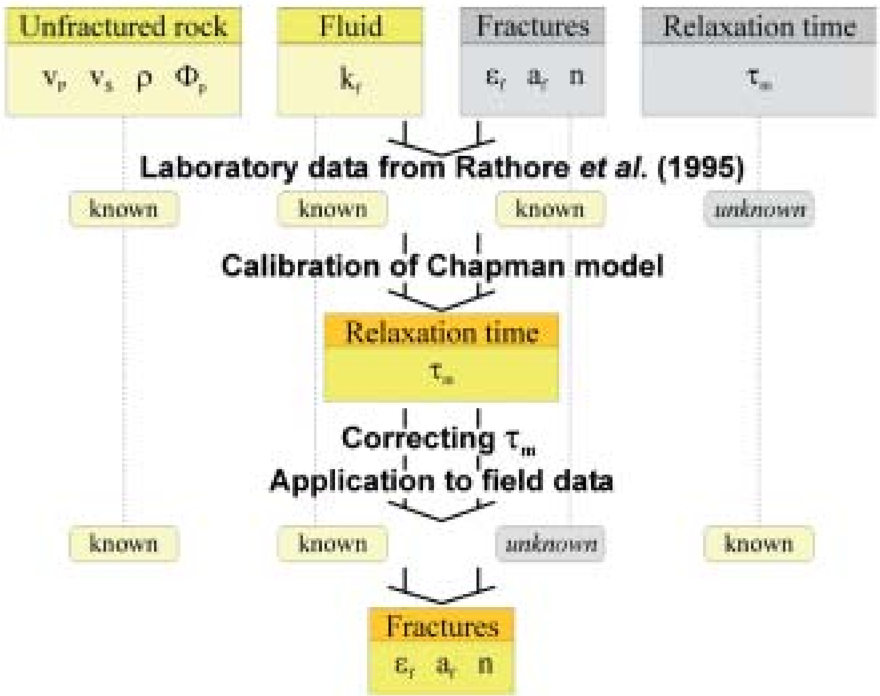

Figure 5 *Outline of the approach for application of the model to field data and estimation of fracture parameters (fracture density ε_f, fracture radius a_f and fracture orientation n).*

Application to field data

We now apply the model to 2X2 VSP data from the Bluebell-Altamont field in the Uinta basin, Utah. Our aim is to estimate fracture density, orientation and size from the data. The field contains a fractured gas reservoir, the Green River formation, which is a sandstone with generally low porosity and permeability. Production from the reservoir is believed to be primarily controlled by size, orientation and concentration of natural fractures (Lynn et al., 1999). Characterization of these fractures by seismic means would clearly be welcomed by the reservoir engineers.

The dataset is a near-offset VSP with the source located

550 ft west of the well. Three-component receivers were placed at depths from 2800 ft to 8650 ft with 50 ft spacing. The reservoir is located between the depths of 6687 ft and 8591 ft.

Shear-wave splitting was observed in the VSP data and analyzed from direct arrivals. The polarization angle of the fast shear-wave was found to be consistent at N43W throughout all receiver depths. This direction is identified with the fracture strike.

Lynn et al. (1999) found that there is anisotropy in the overburden, specifically that the shear-waves had a time delay of 28 ms at a depth of 2800 ft. Between 2800 ft and the top of the Green River formation at 6700 ft the time delay increases by only about 2 ms, so the anisotropy of the rock is small. A sharp increase in time delay occurs in the Green River formation, indicating the presence of fractures.

We now analyze the data from the Green River formation for frequency dependent shear-wave splitting. The data were filtered into various frequency bands and then analyzed for polarization angles and time delays between the split shear-waves. The results are shown in Figure 4. The polarization angles are consistent around 43° for all frequency bands except the lowest one (0-10 Hz). Inspection of this frequency band reveals no coherent energy. Therefore the results for this frequency band are unreliable and should not be used for further analysis. The corresponding time-delays show important behaviour. Disregarding, once again, the lowest frequency band, we see a systematic decrease in time-delay with increasing frequency. Our concept is to use this information to invert for the fracture radius.

Figure 5 outlines our approach. The key problem to be overcome is the estimation of parameters. When we modelled the Rathore data we knew the fracture parameters. The only unknown was the time scale τ which we were able to use as a fitting parameter. For the VSP data we know neither τ nor the fracture parameters. We therefore propose to correct the τ value obtained from the Rathore experiment to match the different petrophysical properties of the Green River formation, and so reduce the unknowns to simply the fracture parameters.

Theory predicts that τ is proportional to fluid viscosity and inversely proportional to permeability. Since the fluid is known in each case, water in the Rathore experiment and natural gas for the Green River formation, the viscosity correction is straightforward. The permeability correction is more difficult, since we have permeability values for neither case. However, we do know the porosities in each case, and we only require the ratios of the permeabilities rather than the absolute values. We therefore propose to use the extended form of the Kozeny-Carman relationship (Mavko and Nur, 1997) to infer the permeability ratio from the known porosity ratio. Performing these corrections we arrive at a corrected τ value of 6 μs.

We then scanned in various values for the crack density and fracture radius and computed the time delay as a function of depth for each frequency band. The resulting relative errors compared to the data are given in Figure 6. We can see a clear minimum of the relative error. Zooming in allowed this minimum to be picked as a fracture density of 0.0375 and a fracture radius of 3 m.

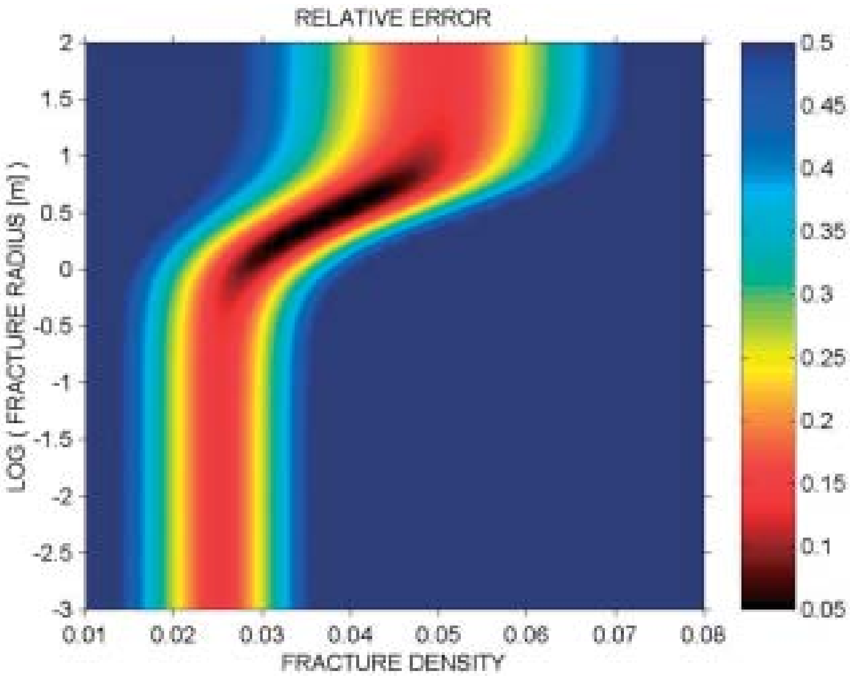

Figure 6 *Relative error between measured and computed time delay as a function of frequency for a wide range of fracture densities and fracture sizes. There is a clear minimum at a fracture density of 0.0375 and a fracture radius of 3 m.*

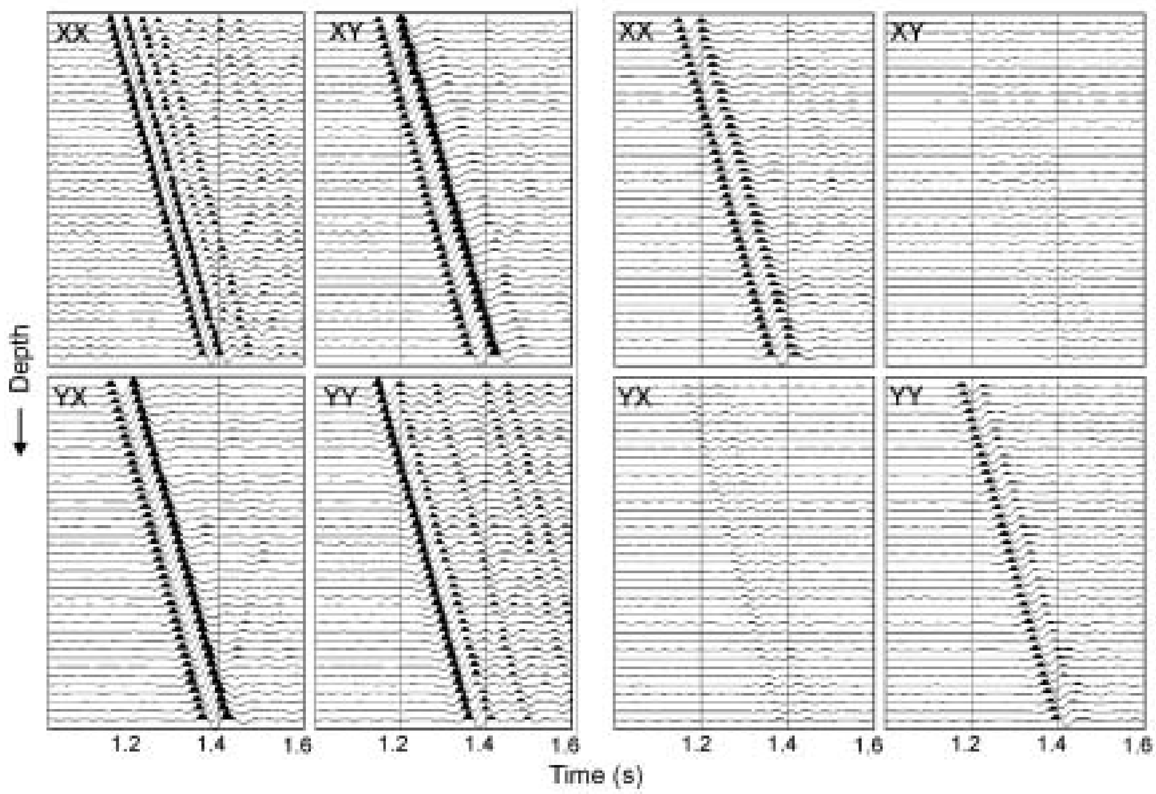

Figure 7 *4C shear wave data before (left) and after (right) Alford rotation.*

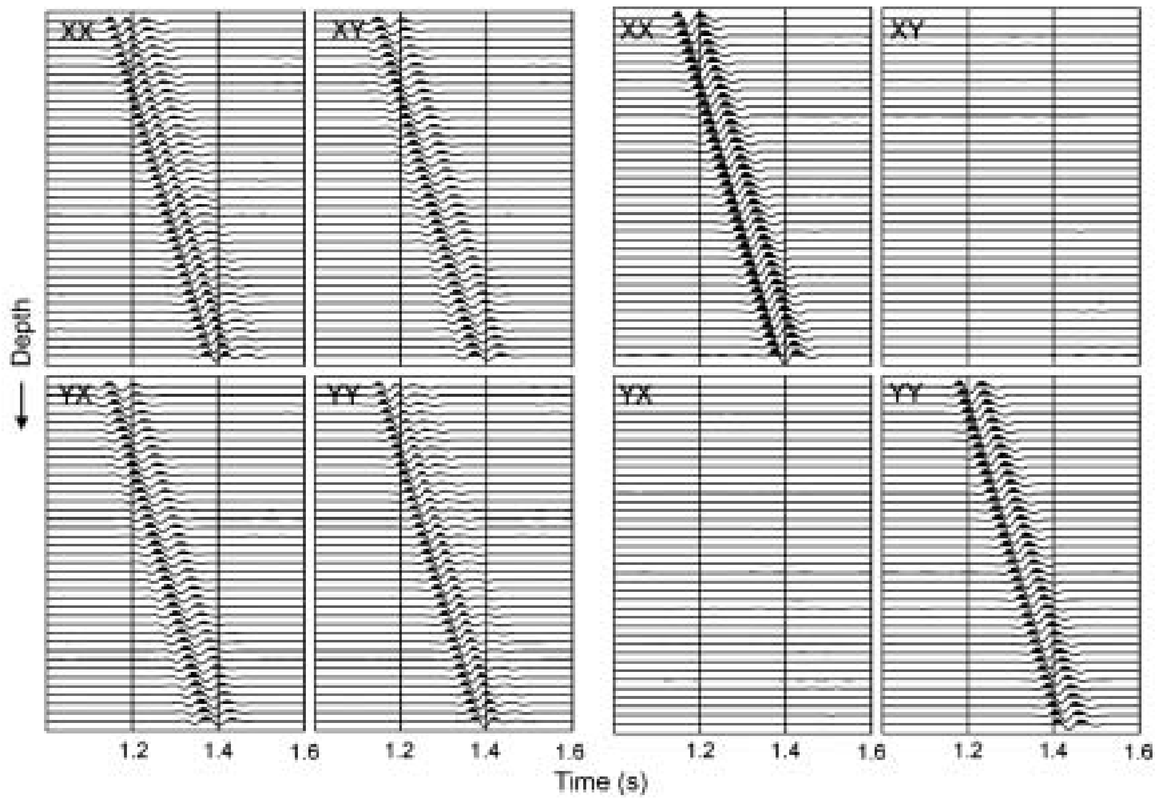

Figure 8 *4C synthetics before and after Alford rotation.*

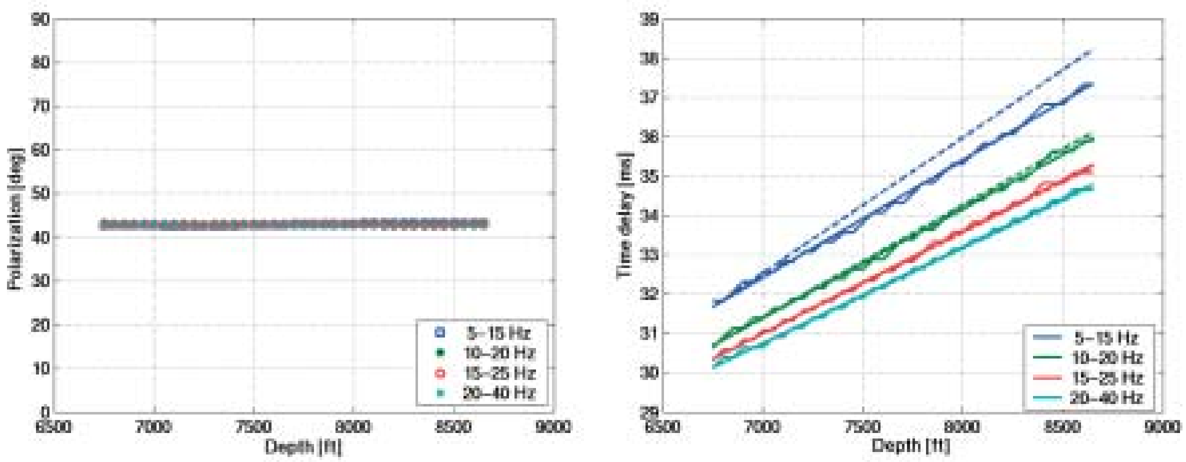

Figure 9 *Polarization angles and time delays measured from the synthetic data for different frequency bands. The polarization angles are constant at 43 degrees. The time delays decrease with increasing frequency. The dashed lines show the results from the real data for comparison. There is a satisfactory match.*

Figure 6 has an interesting physical interpretation. The lower limit of the diagram is what one would compute using the Thomsen (1995) model. The estimated fracture density would lie somewhere between 0.02 and 0.03. The upper limit of the diagram is what would be derived with the use of Hudson's (1981) model. Here fracture density would be estimated at around 0.05. Neither model would give any information on the fracture size. Our approach uses the data itself to infer where the fracture density lies between the two extremes predicted by the rival theories and provides an estimate of the length scale.

We now proceed to carry out forward modelling to ensure that the effects we are interpreting can be observed on synthetic seismograms. We use a simple four layer earth model where the reservoir behaviour is considered to be anisotropic and frequency dependent. The modeling uses a new form of the full waveform modeling package ANISEIS (Taylor, 2002) which can handle frequency dependent anisotropic elastic constants. The 4C VSP data is shown in Figure 7 compared with the synthetics in Figure 8.

We now process the synthetics in the same way as the real data. Figure 9 shows the results. The polarisations are seen not to vary with frequency. The time delays as a function of depth do vary with frequency. We compare the values derived from the synthetics with those derived from the data. It can be seen that there is a satisfactory match.

It is interesting to compare our estimate of the fracture size, which was derived from seismic data alone, with independent borehole data. Following an analysis of cores and FMS images, Lynn et al. (1999) deduced the existence of metre scale fractures. We conclude that our deduced value for the fracture size matches direct observations satisfactorily.

Conclusions

Standard equivalent medium theories may be used to invert observations of seismic anisotropy for the mean fracture density and orientation. However, it is not possible to discriminate between the effects of a few large fractures or many small cracks. Recent theoretical developments suggest that the observation of frequency-dependent shear-wave splitting could in principle allow us to determine an average scale length for the fractures.

We calibrate our model against the laboratory measurements of Rathore (1995). This provides a test of our model, and provides a basis for the application to field data. We invert the field data for fracture size and density, and find that the resulting fracture size matches geological evidence. Synthetic modelling confirms our interpretation.

If additional validation for this approach can be provided with further field data, it may be possible to create fracture length 'maps' in addition to the standard fracture intensity and orientation maps, effectively imaging sub-seismic fractures. This is a necessary step towards the establishment of a robust link between seismic anisotropy and permeability anisotropy.

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