The effect of anticlines on seismic fracture characterization and inversion based on a 3D numerical study

Yungui Xu1,2, Gabril Chao3 Xiang-Yang Li24
1 Geoscience School, University of Edinburgh, UK
2 British Geological Survey, Edinburgh, UK
3 TOTAL E&P, Aberdeen, UK
4 China University of Petroleum, Beijing, China

Summary

This work presents a 3D numerical study of the effect of anticline on seismic fracture density inversion with singular value decomposition (SVD) technique in an area where a pilot application study with the same technique has previously been carried out. The effect of the anticline structure was studied by inverting synthetic datasets which were generated using 3D Finite Difference modeling in fractured media. Two anisotropic 2.5D models with different thickness for the fractured reservoir as well as one isotropic 2.5D model were designed and full-wave synthetic datasets were calculated. The SVD inversion technique was then applied to the three datasets in order to assess the influence of the anticline in the fracture density inversion results. From the outcome of this study, we find that fracture density is well resolved in the apex of the anticline whilst it is over-estimated at the two flanks of the anticline. Moreover, the results indicate the leading term in the SVD decomposition is the most robust and reliable attribute for fracture density inversion.
Introduction

Considerable efforts have been made to reveal the characteristics of natural fracture network in fractured reservoirs. Many such efforts involve analysis of amplitude variation with azimuth and offset (AVAz) in P-wave seismic data in order to estimate fracture orientation and fracture density distribution. Accurate estimation of these fracture parameters can aid in reducing uncertainties and optimizing production of fractured hydrocarbon reservoirs. However, the estimation process poses a big challenge in terms of inversion schemes, integration of different types of data and the possible geological complexity of fractured reservoirs.

In this work we study the effect of anticlines on fracture density inversion by means of 3D numerical modeling in fractured media and an inversion technique based on the singular value decomposition (SVD) of AVAz data (Varela et al., 2007). Our numerical models are based on a geological structure which contains a relatively thin fractured gas reservoir within an anticline (Figure 1). General AVAz analysis assumes that the earth model is horizontally layered; the presence of an anticline structure violates that assumption. From this point, the motivation of this study is to explore the effect of the presence of the anticline on the fracture estimates if we perform the AVAz SVD inversion analysis using 3D synthetic datasets. We focus our analysis on the variation of the azimuthal AVO response at the top of the fractured reservoir. In previous work in the area (Chao et al., 2010), an inversion study for fracture orientation and fracture density using a combined Ruger-SVD method revealed an area of high fracture density at the fractured reservoir marker around an existing well (shown in Figure 1). Fracture density values of up to 0.26 were obtained. The seismic inversion results were consistent with existing FMI log data. However, the presence of the anticline may potentially affect the inversion estimates. With the purpose of investigating the influence of the anticline in the fracture density inversion, we designed 2.5D synthetic fractured reservoir models based on the geological model and subsequently applied the SVD inversion method to obtain the fracture density from the numerical synthetic data. In this way, inverted values as function of position above the anticline can be compared with the true value imposed during the modeling.

Modeling in 3D fractured media and data processing

To assess the effect of the anticline on the fracture density inversion, three 2.5D models with the same geometry parameters (Figure 2) were built: two of them are HTI models in which the second HTI layers represent the fractured reservoir with different thickness (in Figures 4a and 4b, Model 1 has a thin fractured layer, and Model 2 has a thick fractured layer); the third is an isotropic model (Model 3, Figure 4c) that is produced by removing the fractures in Model 1. The comparison of the inverted results among the three models reveals the effect of the anticline whilst the comparison of the results between Model 1 and Model 2 indicates possible thin layer effects. A 3D model that shows no variation of medium parameters in the Y direction is referred to as a 2.5D model, although it is a real 3D model when input for 3D Finite Difference modeling (Xu et al., 2010). The parameters for the models are carefully selected using information from seismic data (horizons, velocity model and previous fracture density inversion) and elastic logs (Vp and Vs). The isotropic layers are characterized by Vp, Vs and density parameters. The elastic matrix for the anisotropic medium is required in order to model the fractured reservoir. The anisotropic elastic constants of the elastic matrix are obtained by applying Hudson’s equivalent medium theory (Hudson, 1980). A homogeneous fracture density of 0.26 is used according to a previous study in the area (Chao et al., 2010). Then we design the optimal seismic geometry (Figure 2) for full azimuth coverage whilst trying to minimize the computation time. 117 shots are recorded along one shot line for each of the models, and it took 3 weeks to acquire all 117*3 shotgathers on a 22 node Linux PC-cluster.

Conventional seismic data processing of P-wave data follows after the acquisition of the shotgathers: that is, trace header setting, CMP binning, velocity analysis, NMO, stack and horizon picking. Note that the CMPs along the Y direction are merged to form a single CMP which contains full azimuth amplitudes for AVAz analysis. The picking time at the top of the reservoir in the stack section is projected back to the NMO-corrected CMP gathers to extract the full azimuth amplitudes for each
CMP gather. The amplitudes of each CMP are then converted to reflection coefficients using the original velocity model for the purpose of the SVD fracture density inversion.

**Method: SVD Fracture density inversion**

According to the modified SVD method for fracture density inversion from AVAz data (Varela et al., 2007), the first step is to construct a reflectivity matrix based on anisotropic Zoeppritz equations at the interface between the upper isotropic medium and the lower fractured/HTI medium. The medium rock properties are obtained from well logs. Realizations of the elastic values are taken to account for lateral variations away from the well. Chapman’s anisotropic rock physics model (Chapman, 2003) is used to calculate the equivalent elastic constants for the fractured medium for the different realizations and full range of fracture density considered (from 0 to 0.4 in this study). The reflectivity matrix calculated at different incident angles and different azimuths contains the full AVAz response of the reservoir. Singular value decomposition of the matrix yields basis functions and seismic attributes which are used to represent the reflectivity coefficient as below:

\[
R(f_d, \theta, \phi) = C_1(f_d, \theta) f_1(\phi) + C_2(f_d, \theta) f_2(\phi) + C_3(f_d, \theta) f_3(\phi) + \ldots
\]  

In equation 1 the basis functions \((f_1, f_2, f_3, \ldots)\) change with azimuths \((\phi)\) and the seismic attributes \((C_1, C_2, C_3, \ldots)\) are associated with fracture density \((f_d)\) and offset or incident angle. Figure 3 shows the basis functions and seismic attributes for this study.

The next step is to invert the fracture density from the synthetic data. The inversion of the reflection coefficients from each CMP over the base function yields measured seismic attribute \(C_1, C_2\) and \(C_3\). The fracture density is then inverted at each CMP by correlating the measured and the modelled seismic attributes.

**Result analysis**

As the inversion procedure produces a fracture density value for each incident angle considered, the mean value is subsequently taken. Results through inversion of the different seismic attributes \(C_1, C_2\) and \(C_3\) are considered. The most robust results are obtained using \(C_1\) and \(C_2\). The results obtained using \(C_3\) are significantly noisy (Figure 4k, l and m).

Model 1 is the closest to the real structure in the vicinity of the well location (Figure 1). The results for this model indicate that the fracture density values obtained using the attribute \(C_1\) at the top of the anticline structure are close to the real fracture density value of 0.26 (Figure 4e). At the flanks of the anticline, the inverted fracture density values are higher than 0.26 (Figure 4e) due to dip-related effects. The results from the attribute \(C_2\) revealed a lower fracture density than expected (Figure 4h). Overall we can conclude that the presence of the anticline enhance the inverted values for fracture at its flanks but shows almost no effect in the middle location.

From Figure 4f, i and l, we can see that the results from Model 2 are almost exactly the same as the results from Model 1, which reveals that there is no effect from the thickness of the fractured layer and consequently tuning effects are negligible. The thin layer in this study is sufficiently thick to separate the reflections from the top and the bottom of the fractured reservoir.

The results from Model 3 are shown in Figure 4g, j and m. In this model there is no fracturing and only the response of the anticline is considered. The obtained fracture densities are very close to zero at the apex of the anticline but relatively large values of fracture density are obtained at the flanks of the anticline and can be attributed to the pseudo anisotropy generated by the dipping structure.

**Conclusions**
This work presents a 3D numerical study on the effect of an anticline on fracture density inversion using a method based on SVD decomposition of AVAz data. 3D Finite Difference in structured anisotropic media is applied to generate the synthetic data used in this study. The results indicate that the SVD method is a reliable approach to directly estimate the fracture density. The effect of the anticline on the inversion results has been assessed. The fracture density can be resolved accurately at the apex of the anticline, whilst that at the flanks tends to be over-estimated. The sensitivity analysis of the inversion results also indicate that the seismic attribute C1, related to the leading term in the SVD decomposition is the most robust and reliable attribute for fracture density inversion.

Acknowledgements

We thank Geoscience Research Center TOTAL E&P UK for support this project and permission to present this work. We also thank EAP sponsors for support Y. Xu’s PhD project. Special thanks to the GRC staff for valuable discussions and advice.

References


Figure 1 The 2.5D model is extracted and simplified from the stack velocity model cross the anticline on the top of which a well was previously drilled. The red layer represents the fractured reservoir which is about 110 meters in thickness. The other layers are considered to be isotropic layers. The vertical solid black line represents the well where FMI logging was carried out. The FMI logs show that high density fractures develop in the reservoir.

Figure 2 2.5D fractured model used for anisotropic modeling and its survey geometry. Red stars and blue dots represent source and geophone respectively. 117 shots are recorded along one shot line. No medium parameter variations are considered along the Y direction (perpendicular to the paper).

Figure 3 SVD decomposition of the reflectivity matrix yields the base functions f1, f2 and f3 which show azimuth dependence and seismic attributes C1, C2, and C3 which present a direct mapping with fracture density over the complete range of incident angles considered in this study. Three attributes show different sensitivity to fracture density at different offsets/incident angles.
Figure 4: Three models (a, b and c) are only shown in XoZ plane. The same color indicates the same medium parameters. The red represents the fractured reservoir, and others are isotropic layers. The subplots from e to m, where the X axis represents CMP number and the Y axis represents the mean fracture density inverted with C1, C2 and C3.