Fracture characterization by seismic anisotropy analysis at Awali anticline structure, Bahrain: Case Study

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Summary

The Amplitude Versus Azimuthal AVAZ analysis has proved to be an important tool for characterizing fracture distributions and orientations of hydrocarbon reservoirs. This paper is aiming at the application of this tool for characterizing the fractures in Bahrain field reservoirs. Better understanding of faults and fractures distribution is essential to optimize EOR strategy and reservoir management. Regional analysis is possible by looking at faults distribution characterized by structural attributes analysis validated by regional stress and geological information. The investigation at local scale is more cumbersome but an Amplitude Variation with Azimuth (AVAz) method based on azimuthal Fourier Coefficients (FCs) proves to be a simple and powerful tool to characterize fractures distribution validated by FMI data. The anisotropy information was then used to update and improve the reservoir model long production history matching.

Introduction

Bahrain field was controlled by two major tectonic events; first is the north-south trend folding which was believed to be caused by an inverted basement fault and as a result produced the Bahrain low relief asymmetrical anticline. The outward thickening of Khuff and Sudair is evidence that the uplift started pre Khuff and continued episodically till Turonian/Mishrif time. This has inflicted considerable tensile stress at the crest of the anticline which led to development of the flora structure and central graben. The second major event is when the Zagros Suture units thrusted over the Arabian Plate during two distinct phases of obduction and collision, during the Late Cretaceous and Mio-Pliocene which exposed the field to NW-SE shearing stresses. These younger NW-SE faults caused segmentation and tilting of the north-south graben fault. As anticipated, both tensile and shear fractures have developed in different areas within both the crestal parts of Bahrain Structure and within its limbs. However, the asymmetrical geometry of the anticline is reflected in the fracture distribution, trend and frequency. The steeper limb of the anticline bears more developed fractures than the gently dipping limb. The asymmetry of the anticline is not equally well displayed by the post-erosional units above the unconformity “Base Blue Shale”, where a gentler anticline is displayed. Hence within this gentle part of the anticline the fracture pattern is less developed, less frequent and evenly distributed. .A detailed characterization of faults and fractures distribution is crucial to reservoir production. Such features may increase the flow but they may as well decrease, divert or block the flow depending on their properties. Large scale analysis of faults can be done by looking at structural attributes from seismic data for example. However smaller local scale features such as fractures require the use of method like AVAz. Anisotropy description through seismic FCs has the advantage to look at the subtle local variations and departures from the global anisotropy trend (Delbecq et al., 2013).

First we characterize the global trend of fracture distribution by analysing large scale fault systems. Then we compute anisotropy parameters from azimuthal FCs analysis and compare them to independent log measurements (FMI) at well location to estimate the level of accuracy of the method. The estimated anisotropy information is then used to update the reservoir model for a better understanding of the production history.

Anisotropy analysis using Fourier coefficients

The azimuthal PP reflectivity can be expressed as a sum of FCs (e.g. Downton et al., 2011) for given incidence angle θ and azimuth ϕ as follows:

$$R_{PP}(\theta,\phi) = r_0(\theta) + r_2(\theta)\cos 2(\phi - \phi_{sym}) + r_4(\theta)\cos 4(\phi - \phi_{sym})$$

where r_i is the magnitude of the i^{th} FC and ϕ_{sym} the symmetry axis perpendicular to the fracture strike. The magnitude of the FCs contains useful information to describe the anisotropy and fracture properties (Downton and Roure, 2015). The 2^{nd} FC is proportional to the anisotropic gradient for a small incidence angle and the 4^{th} FC is related to the anellipticity variation. A well-known limitation of the AVAz method is the 90 degree ambiguity in the anisotropy orientation. Downton (2016) discusses different ways to solve this issue.

Due to a limited range of angles both in the azimuth and incidence domains, we applied the azimuthal Fourier coefficients method directly on P-impedance volumes obtained from post-stack inversion of azimuthal sectors. The interpretation of the FCs remains similar to the original method where the magnitude of the 2^{nd} FC is related to the fracture density.

Real data example

The study was performed at Awali, a regional anticline which shows high fractured structure, the result of its geological evolution where different sequence layers were deposited and subsequently different types of folds caused oil traps (reservoirs) to form. The formation of individual structures appears to have resulted from vertical uplift rather than compressive stresses (Willis, 1963). Each oil trap has different characteristics, further complicating the anisotropy description at a global scale.

At a regional scale, structural features such as faults are interpreted and validated by matching them to available data including fault cuts. The observed faulting structures are similarly observed in paleo-structural maps used to trace the growth of the field. This preliminary step in the analysis was useful to get a detailed description of the fractures distribution regional background.

The results obtained from the Fourier Coefficients method provide additional anisotropic information at a much smaller scale compared to the information coming from the faults. Figure 1 shows the fractures orientation and density along different stratigraphic horizons. The black lines indicate the fracture orientation while the line length is proportional to the fracture density. The map colour also corresponds to the fracture density. The orientation is only displayed in zones with significant anisotropy magnitude. The FMI data are plotted in terms of red lines at well locations. The estimation of the local fracture orientation from FCs correlates well with independent data coming from FMI.

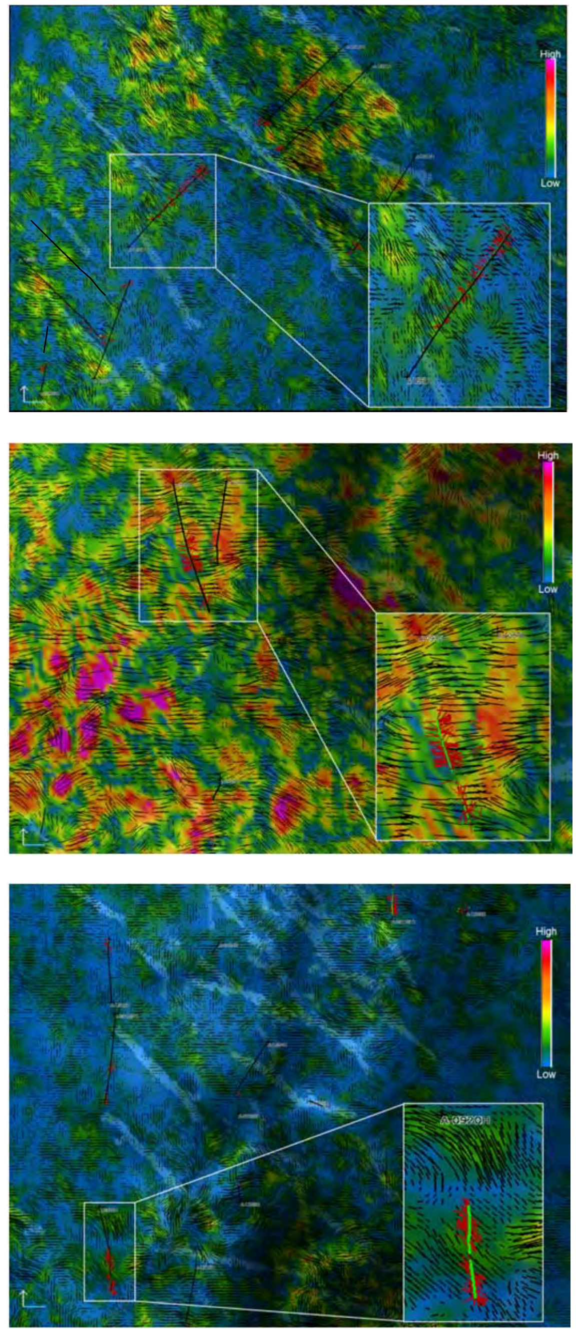

Figure 1: Anisotropy characterization at three horizons (top, middle and bottom) integrating fault location (in white in the

background), fracture orientation (black lines), fracture density (colour) and FMI logs (red lines at wells location).

The above estimated gradient and the symmetry axis of the anisotropy in conjunction the seismic Ant-track attribute were extensively used during the simulation of Ahmadi reservoir. Ahmadi reservoir is known to be tight but fractured reservoir with very low matrix permeability. Ignoring the role played by the fractures makes the history matching impossible without compute total effective permeability by multiplying the permeability by a factor. Hence, seismic anisotropy was used in conjunction with Ant-track seismic attribute to distribute the permeability multiplier. Doing that involved normalizing the attribute values to range between zero and one and then applying a function to enhance the permeability. This leaded to better history matching results shown in Figure-2.

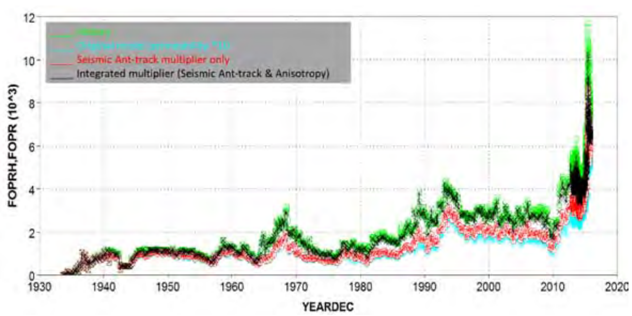

Figure 2: Production history matching using single porosity model.

Dual porosity dual permeability model was also used to simulate the same Ahmadi reservoir. Seismic anisotropy and seismic ant-track were again used but this time to generate a stochastic fracture network. The anisotropy intensity Bani was used to distribute fractures density and the Anisotropy azimuth to define orientation. The initial results from this model were very encouraging as shown in Figure-3.

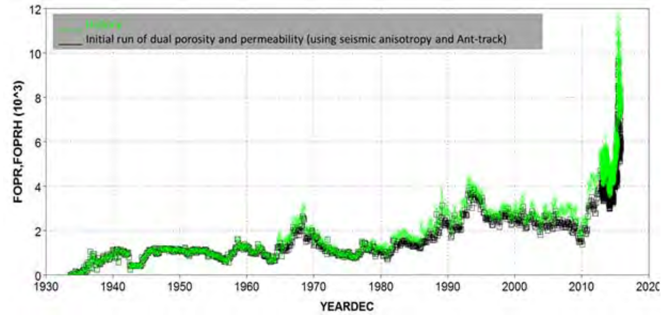

Figure 3: Production history matching using dual porosity model dual permeability.

Conclusions

The integration of independent data at different scales allows for a better characterization of the anisotropy. Faults analysis allows defining a regional trend which is validated with fault cuts and regional geological information. The variations at local scale such as fractures are usually more difficult to capture but are easily identified using azimuthal Fourier coefficients. The fracture orientation estimated from seismic is consistent with the FMI data from deviated and horizontal wells at different reservoir levels. Including the anisotropy information in the reservoir model results in a better matching of the production history.

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