Analysis of travel-time and attenuation anisotropy in walkaround and walkaway VSPs from Tiguentourine field, Algeria.


Abstract

Theoretical models predict that both travel-time and attenuation anisotropy can be used to derive information about the fracture network. In this paper we analyse a range of azimuthally varying attributes from walkaround and multi-azimuth walkaway VSP data from a fractured gas reservoir in Algeria. Anisotropy is detected in both dynamic and kinematical attributes, and reasonably consistent estimates of the fracture strike direction are derived. The magnitudes of the effects are different however, and it is noticeable that the attenuation anisotropy is strongly localised in the fractured reservoir. This suggests that the attenuation anisotropy is particularly sensitive to the fracture and fluid properties. The results of the study are validated through modelling exercise.
Introduction

It is now widely accepted that seismic anisotropy can be a useful tool to provide information about subsurface fractures, and the theoretical basis has been various equivalent medium representations of fractured media. The interpretation of the measured seismic velocity anisotropy in terms of fracture parameters is limited mostly to fracture orientations and densities. Fracture scales and fluid properties may potentially be measured from frequency-dependent seismic anisotropy and dynamic attributes, such as attenuation anisotropy.

In this study we analyse both kinematical and dynamic attributes of transmitted P-wave arrivals as a function of azimuth and depth from two walkaround (WAR) and four walkaway (WAW) VSP data. While the principal anisotropy directions which are inferred from the various attributes are similar, the magnitudes of the anisotropic attributes and their correlation with the rock properties are very different. This underscores the argument that kinematical and dynamic anisotropic attributes have different frequency contents.

Background Theory

Many theories have been developed to describe the anisotropic variation of velocity and attenuation in fractured media. The fractures have a much stronger influence on P-waves travelling normal to the fracture planes, which leads to a maximum in the attenuation. This effect is sensitive to the saturating fluid, the scale length and the connectivity of the fracture system. Theoretically, the attenuation anisotropy may be very different from the travelt ime anisotropy, and the two attributes potentially contain different information about the fracture system.

Analysis of VSP data

The Tiguentourine field is located in Algeria and is operated by the In Amenas Association, a joint venture between BP, Sonatrach and Statoil, it’s known as a fractured thin sand reservoir. In Number 2004, four multi-azimuth walkaway (WAW) and two semi-circle (walkaround) VSP data were acquired in a deviated well. The objective was to measure seismic anisotropy for fracture characterisation. In particular, the two walkaround (WAR) VSPs were specifically designed to search for azimuthal variation in the reservoir as WAR geometry is best suit to detect azimuthal anisotropy (Horne, 2003). The acquisitions were designed to give optimal geometries for detecting fracture-related seismic anisotropy.

Our approach is to perform a series of multi-azimuthal attribute analysis and to search for their systematic variations with source-receiver azimuth. Specifically, for analysing down-going wavefields in a VSP geometry, the attributes that we prefer to use and then to compare are:
• First-break travel-time or velocity – derived from a straight ray-path assumption
• Amplitudes – RMS amplitudes from three components
• Frequency – azimuthal spectral characteristics, centre frequency, instantaneous frequency (derived from complex trace analysis)
• Attenuation or inverse of quality factor – two methods can be used: standard spectral ratio methods and more advanced instantaneous frequency (IF) methods. The later is used in this study.
• 3-C attribute analysis: including 2(3)-C instantaneous polarization analysis, transverse-radial amplitude ratio method, shear-wave splitting analysis.

For each attribute, we performed cosine fitting to determine the principal directions and magnitude of the anisotropic variation. The data was fit to both a cosine 2-theta and cosine 4-theta azimuthal variation. Significant cosine 4-theta variation was evident in the data, suggesting perhaps the presence of multiple fracture sets. Figure 1 shows the rose diagrams for inferred fracture strike directions derived from both traveltime and amplitude anisotropy for the WAR and WAW surveys.

In the case of the WAR example, we considered the average frequency of the arrivals both parallel and perpendicular to the fracture strike as a function of depth. As shown in Figure 2, significant separation in the frequencies occurs at the depth level corresponding to the top of the reservoir. This is interpreted as being due to azimuthally varying attenuation in the fractured gas reservoir.

Modelling

We have performed a modelling study to validate the interpretation of the data in terms of rock physics theory. The modelling was carried out using the ANISEIS commercial software package. This code implements the reflectivity method, but allows the use of materials with frequency-dependent elastic properties.

The first step was to create a velocity model. We blocked the velocity model into 7 layers, with the reservoir layer being at the bottom. Within each layer, we performed Backus averaging to provide a representative transversely isotropic material with a vertical axis of symmetry (VTI). Fractures were introduced into the reservoir layer, following the model of Chapman (2003), so our model was that of an HTI reservoir with a VTI overburden. We were able to consider propagation at various azimuths with respect to the fracture strike and various offsets.

When we compute the frequency with depth profiles for propagation parallel and perpendicular to the fractures, in Figure 3, we see that the frequencies separate at the reservoir level, as was observed in the field data. This effect is the result of the azimuthal variations in attenuation in our model, and does not follow if we model the anisotropy with frequency independent, elastic, theories.

By increasing the offset, we see that the separation in frequency increases in conformance with what we found in the VSP data. The modelling also indicates that the separation in frequency is very sensitive to the saturating fluid, with gas saturation
tending to lead to a much greater azimuthal change in frequency. This suggests that the detection of such azimuthal frequency variations may well be able to provide information about lateral changes in fluid saturation.

Conclusions

The fundamental conclusions of this study are that we have detected seismic anisotropy in the travel-time, amplitude and frequency in the VSP data from the Tigentourine field. Overall, a consistent pattern emerges with the symmetry of anisotropy appearing to be to a first approximation transversely anisotropic with a horizontal axis of symmetry somewhere around 130 degrees, corresponding to a fracture strike of around 40 degrees. The P-wave anisotropy from the walkaround is about 3 to 4%, while from the walkaway is around 2% or less.

While the fracture strikes inferred from the different attributes are similar, we note that the behaviour of the attributes is not the same. Azimuthal travel-time anisotropy is shown to exist in the overburden, but is stronger in the fractured reservoir. Our analysis suggests, however, that azimuthal attenuation anisotropy does not exist in the overburden, but is strong in the reservoir. This change of behaviour underscores the basic theoretical argument that the information content of attenuation anisotropy is different from that of standard travel-time anisotropy, with the attenuation anisotropy responding strongly to fluid saturation and fracture scale information.

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References


Figure 1: Rose diagrams of inferred fracture strike directions from WAW survey (left) and WAR survey (right), using traveltime (top) and amplitude (bottom) attributes.

Figure 2: Average frequency with depth profiles from the WAW survey parallel (blue) and perpendicular (right) to the fracture direction. Note the separation in the frequency profiles at the top of the reservoir (Receiver 6).

Figure 3: As Figure 2, but for the synthetic modelling including the effect of azimuthally varying attenuation in the fractured reservoir.