

Examples of the Determination of Fracture Parameters From P-Wave Seismic Data

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Abstract

Several examples of the use of **Amplitude Versus Angle** and **Azimuth** (AVAZ) analysis to determine azimuthal seismic anisotropy from pre-stack seismic data are compared to other methods of detecting fracture orientation and intensity in the same reservoirs. The AVAZ method consistently shows fractures that are similar to those indicated by these other methods, indicating that it can be used to detect open natural fractures between wells. The implication is that these seismic anisotropy measurements can be used in fractured reservoir characterization.

Introduction

The use of AVAZ analysis of pre-stack seismic data to estimate azimuthal anisotropy has been shown to be useful in the identification of open, fluid-filled fractures in a number of different reservoirs throughout the world; e.g. Roberts et al (2001), Smith and McGarrity (2001), Gray and Head (2000), Hall et al (2000), Gray et al (1999) and Lynn et al (1996). The authors' confidence in the AVAZ method's ability to capture information about the fractures in a reservoir has steadily increased through using this technology over the last four years. Only by using AVAZ on many different reservoirs and having the results consistently tie other information about fractures have we been able to gain this confidence. This paper attempts to show that the AVAZ technique does generally appear to capture information about the open, fluid-filled fractures that influence reservoir fluid production. This is done by showing several reservoirs from various basins around the world in which the AVAZ technique has proven successful. Success is judged by the ability to produce results comparable to other methods of estimating the presence of fractures, such as mud-loss, borehole information, fluid flow and estimations of regional and local stresses. A method for checking the AVAZ effect in the pre-stack seismic data by visualizing it at a single sub-surface location using standard interpretation software is also shown.

Method

The technique for analyzing Horizontally Transverse Isotropic (HTI) media using amplitude variations with angle and azimuth proposed by Rüger (1996), is used to estimate azimuthal seismic anisotropy in rocks from pre-stack seismic data. It is assumed that these rocks, when fractured and subject to the vertical and horizontal stress fields they encounter at depth, are often approximately horizontally transverse isotropic. This is because the vertical and local horizontal stress fields likely only leave one set of fractures open. Evidence for the validity of this assumption can be ascertained from the reservoirs studied in the experiments described below (e.g. Figure 1).

Examples

Seismic anisotropy measurements can be made of the parameters of Rüger's (1996) AVAZ equation using only pre-stack, P-wave seismic data. The effect of fractures on the azimuthal and offset response of the seismic data can be seen in Figure 1. This effect is composed of two components: an amplitude component that appears as a systematic change in the azimuthal amplitudes at long shot-receiver offsets and a velocity component that appears as a systematic variation in the time of the reservoir event. The amplitude component is clearly much stronger than the velocity component in this example. The amplitude varies by 100% of the background amplitude at 1400m offset, while the velocity varies by 4% of the background velocity. This result is typical of all of the reservoirs that the authors have studied to date and is consistent with other published values (e.g. Smith and McGarrity, 2001).

In this presentation, several examples of estimating seismic azimuthal anisotropy using Rüger's (1996) AVAZ technique using pre-stack, P-wave seismic data are compared to other independent methods of identifying fractures that have been used in these reservoirs.

One example is a steam-injection pilot study in a fractured carbonate reservoir. Based on temperature measurements in the reservoir from observation wells around the steam injector, the temperature change due to steam in the reservoir does not have radial symmetry. This suggests that there is an asymmetry in the distribution of the steam in the reservoir. In this case, the azimuthal seismic anisotropy measured using AVAZ on the pre-stack, P-wave seismic data appears to provide an explanation for the observed temperature distribution – if it is assumed that the observed anisotropy is caused by open, fluid-filled, vertical fractures. In this case, it is likely that these open fractures are causing the seismic anisotropy and are steering the steam away from some of the observation wells and toward other wells via a complex fracture system. It appears that this complex fracture system is observed between the wells with the seismic azimuthal anisotropy measurements because they provide an explanation for the steam distribution in the reservoir.

The second example is associated with a well in Wyoming, USA, that has produced 1.7 BCF of gas over the last three years. After the drilling of this well, potential reservoir sand zones were identified using traditional borehole methods like gamma ray logs. These reservoir sands are very tight and only produce economically if their permeability is enhanced by the presence of natural fractures. So, hydraulic fracture treatments were applied to these sands to connect the wellbore to the hoped for natural fracture system. The locations of these fracture treatments correlate very well with zones of significant seismic anisotropy identified by the AVAZ technique. This observation of anisotropy is not due to the fracturing created by the fracture treatments since these fractures occur in a range much closer to the borehole than the anisotropy occurs. Rather, the fracture treatments are being done in areas of high anisotropy. Since the fracture treatments are only done where sand is observed in the borehole, then it appears that the sands are preferentially fractured in this reservoir. This observation makes sense after some thought, for tight sands are likely to be significantly more brittle and therefore fracture more easily than the shales in which they are encased. Thus, it appears that the seismic anisotropy measurements are acting as a sensitive lithology indicator in this reservoir, identifying reservoir quality sand bodies. The authors have observed this phenomenon in other sand-shale reservoirs as well, where zones of high or low seismic anisotropy take on distinctively channel-like features. The high anisotropy presumably associated with sand-filled channels and the low (HTI) anisotropy presumably associated with shale-filled channels. The measurements around this borehole also

suggest that the reservoir is not being drained in a radial pattern around the well but in an asymmetric manner associated with the fracturing, which is consistent with the observations in the first example.

The third case involves extensive work done by Bunge (2001) on core and EMI logs from horizontal wells in the Weyburn field in Saskatchewan, Canada. Core analyses, interpretations of EMI logs (similar to FMI logs) in horizontal boreholes both indicate the presence of three significant fracture sets in this reservoir. Seismic AVAZ analysis was done on the P-wave part of the 3D shot by Colorado School of Mines in 1999 over part of this field. Bunge's results for fracture azimuth derived from these EMI logs are compared to the azimuth of anisotropy derived from the seismic data using the AVAZ technique. Both methods pick up the three major fracture sets at similar orientations, which are the orientations expected for fractures in the Weyburn field.

The fourth case shows the results of a test of AVAZ analysis using an ocean bottom cable (OBC) seismic survey acquired over a field Offshore Abu Dhabi (Roberts et al, 2001). This OBC acquisition provides significantly better azimuthal coverage than traditional marine streamer acquisition. Therefore, these data are suitable for AVAZ analysis. In this example, the anisotropy derived from the seismic data using AVAZ shows consistent azimuths similar to the known major stress direction in the area and, in this case, the anisotropy direction remains consistent throughout the study area. The anisotropic effect in these data increase with the depth of the rock, which makes sense as the deeper rocks are older and harder and therefore more brittle because they have been and are subject to greater vertical stress and have had more time to lithify.

Discussion

Numerous examples, four of which are discussed above, show that anisotropy derived from seismic data using Rüger's (1996) technique shows the same azimuth and intensity as is indicated by various other methods of identifying open fractures, such as fluid flow in the reservoir, mud-loss, borehole measurements and stress fields.

The implication of these results is that this AVAZ technique appears to correctly identify the orientation and relative intensity of open, fluid-filled fractures in many cases. This, in turn, implies that many fractured rocks, when subject to the stresses that they encounter at the reservoir depth, behave as though they are HTI media, even if multiple fracture sets are present. This observation can be explained if the rocks are undergoing sufficiently strong vertical and horizontal stresses. Should this turn out to be true in general, it simplifies the analysis of fractures in these rocks. Seismic fracture analysis can then be done on the pre-stack data from many existing 3D seismic surveys using this AVAZ technique, provided that these surveys have sufficient azimuthal coverage. Spatial variations in fracture azimuth observed in some of these reservoirs can be explained by spatial variations in local horizontal stresses that occur due to cracks in the rocks – the fractures. In scenarios where multiple fracture sets are observed, these variations in local stress fields are likely to be the norm. The corollary of this is that injection and production should open and close fracture sets where pressure changes occur. Therefore, changes in anisotropy over time could be a sensitive indicator of injection and production effects. This effect has already been observed, e.g. Davis and Benson, (2001).

As indicated in two of the above examples, fractures likely cause complex drainage patterns around wells. Assuming the seismic azimuthal anisotropy measurements can capture fracture information between the wells, it is within the realm of current technology to account for connectivity of the fracture system around these wells and thereby allow for better development of fractured reservoirs (e.g. Ouenes and Hartley, 2000). Existing technologies can be used in conjunction with AVAZ measurements of seismic anisotropy between the wells to capture flow due to fractures around the wells. This information could potentially be turned into reservoir parameters describing features of the fractured reservoir, such as fracture permeability. Once this information is imported to the reservoir simulator, complex drainage patterns associated with the fractures can be assessed and a reservoir development plan generated, which includes these effects, thereby allowing for increased efficiency in producing naturally fractured reservoirs.

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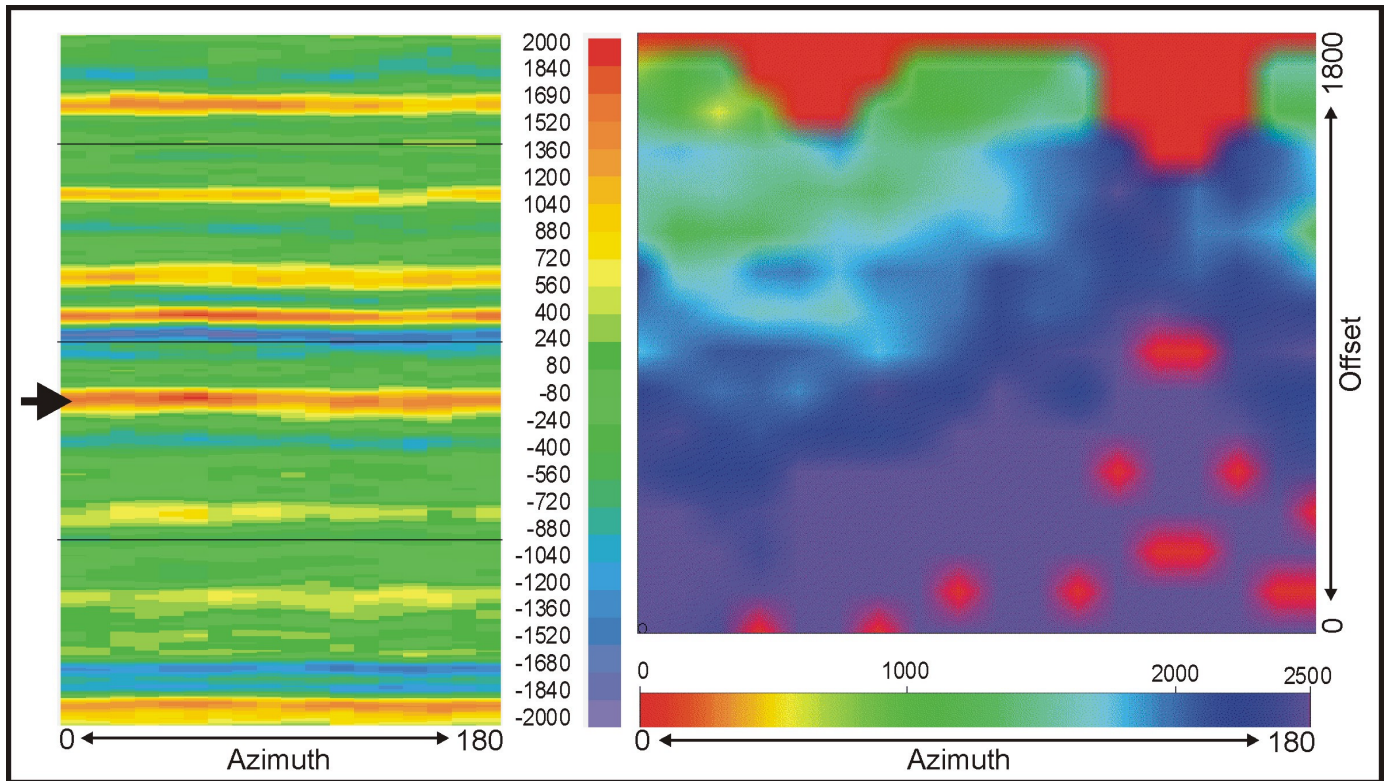


Figure 1: Offset-Azimuth cube created to show the AVAZ effect at a single subsurface location of pre-stack seismic data. This cube is created by sorting pre-stack seismic data from a single subsurface point and outputting this information into a 3D volume with the in-lines associated with azimuth and the cross-lines associated with offset. This allows for easy visualization of anisotropic effects using standard interpretation software. Shown on the left is a 1400 m offset time-section through the cube, with the reservoir level indicated by the arrow. Notice that both a systematic variation in amplitude on the order of two times the background amplitudes (the AVAZ effect) and a systematic variation of the residual moveout on the order of 2ms (the azimuthal velocity effect) can be seen at the reservoir level. On the right is an offset-azimuth time slice, which shows the AVAZ effect discussed above as increasing changes in amplitude with azimuth with increasing offset. (After Cheadle et al, 2001).