vienna2006

P146

Anisotropic Azimuthal Attenuation as an Indicator of Fracture Properties, a Case Study on Time-Lapse Walkaround VSP Data

I. Varela* (University of Edinburgh), M. Nasser (Shell), M. Chapman (British Geological Survey) & E. Liu (British Geological Survey)

SUMMARY

We present an analysis of a time lapse walkaround, multilevel vertical seismic profile (VSP) data set from a carbonate field in Oman which has a long history of steam injection and production. The aim of this study is to compare changes in traveltime and attenuation variations in response to fracture orientation. The method used for calculating the attenuation factor Q, is based on the instantaneous frequency technique. Velocities and attenuation are sensitive to the fractures, presenting shorter travel times and lower attenuation in the direction of the fracture plane. We show through the case study the effectiveness of the method and the potential of azimuthal attenuation and travel-time studies of P-waves for fracture characterization.

Introduction

The use of amplitude and attenuation studies for fracture characterization has become a topic of increased interest. Lynn *et al.* (1998) argue that azimuthally dependent P-wave AVO response can be related to the orientation of open fractures and relative fracture intensity, Maultzsch *et al.* (2005) interpret P-wave attenuation anisotropy in terms of open fracture orientations. Attenuation studies have potential information on fluid saturations and fracture characterization.

The focus of this analysis will be on studying the azimuthal anisotropic response of attenuation and traveltime to gain information about the fracture network around the borehole.

In an otherwise isotropic media containing vertically aligned fractures, simple models suggest that the variations of travel time and attenuation with azimuth can be written with a good approximation to first order with one term of their Fourier series, i.e. following a cos2φ behaviour. The hypothesis is that the data presents azimuthal anisotropy due to fractures in the Natih interval. We compare the Bayesian information criterion (BIC) values of the travel time to first breaks and attenuation per receiver level fitted to a cos2φ and to a straight line. The latter would account for the null hypothesis of no azimuthal anisotropy, or where its effect cannot be detected within the experimental error given.

Method: Calculating relative Q

The method used for calculating relative attenuation makes use of complex trace analysis (Taner *et al.,* 1979, Barnes, 1998) with the following methodology: (1) For each receiver level window the seismic traces around the first arrivals; here a Blackman window of 101 miliseconds was used. (2) Calculate the Hilbert transform and the damped instantaneous frequency (derivative against time of the instantaneous phase) of each trace with the following equation:

$$f(t) = \frac{1}{2\pi} \frac{x(t)\frac{dy(t)}{dt} - y(t)\frac{dx(t)}{dt}}{x^2(t) + y^2(t) + \varepsilon^2}$$

where $x(t)$ is the seismic trace, $y(t)$ is its Hilbert transform, and ε is a damping factor that minimizes the noisy low amplitude areas without affecting the instantaneous frequency when the amplitude envelope is large. (3) Weight the instantaneous frequency by the seismic trace amplitude envelope:

$$f_w(t) = \left| \frac{\sum_{tm-T}^{tm+T} f(t)W(t)}{\sum_{tm-T}^{tm+T} W(t)} \right|$$

where $W(t)$ is the seismic trace amplitude envelope, with $W(t) = |y(t)|^2$, $2T$ is the weighting window length and tm is the time at which the amplitude envelope reaches its maximum. (4) Choose a reference azimuth, (5) Iteratively, attenuate the trace from the reference azimuth, with an attenuation operator, until the weighted instantaneous frequency value at the amplitude envelope maximum (of the synthetically attenuated trace) matches that of the analysis trace (trace at different azimuth). The Q value corresponding to this match will be the relative Q between the reference trace and the analysis one.

The attenuation operator used is $A(w) = e^{-\frac{iwa}{\pi}\ln\left(\frac{w}{w_r}\right)} e^{-\frac{w}{2}a}$, where w is angular frequency, w_r is a reference angular frequency, and a is the cumulative attenuation as a function of distance traveled. a is equal to the average time difference between the travel time to a shallow receiver (t_{as}) and a deeper receiver (t_{ad}) divided by Q, or in equation form $a = \frac{t_{ad} - t_{as}}{Q}$.

This instantaneous frequency (IF) method for attenuation is presented by Dasios *et. al.*, (2001) for calculating relative Q between near- and far-offset surface seismic traces. Dasios *et. al.*, (2001) compare the IF method with the traditional logarithm spectral ratio (LSR) and conclude that the IF method is more stable for sonic data compared to the LSR, especially in data with high background noise levels. In the current study IF will be used to calculate relative azimuthal attenuation on VSP data.

Oman Walk-around time-lapse VSP data

We analyze the P-wave response of a time lapse walk-around (WAR) VSP data set from a carbonate field in Oman. The data consists of three surveys acquired in 2002, 2004 and 2005, each containing one walkaround VSP around well 1, with an offset of 300m. It has 32 receivers cemented in the well separated by 6.75m each, ranging from depths of 110.75 to 320m.

Geological setting

The field studied is located in the Omani Ghaba Salt Basin, SW of the Maradi Fault zone. Regional plate movements molded the complex structure of the area (Loosveld *et al.,* 1996). The acquired VSP data is located in the crestal area of the carbonate field, cutting through three geological units, the Fiqa shales, the Natih fractured carbonate formation which extends approximately from 190m to 260m, and the Nahr Umar shale unit, from shallow to deep respectively. The producing hydrocarbon reservoir, Shuaiba which has a low matrix permeability and a strong fracture network, is located bellow the deepest receiver of the VSP data, thus from the top of the reservoir only the reflected waves will be recorded. Although the reservoir under production in these wells is the Shuaiba; in other fields the Natih fractured carbonate is the main reservoir.

The Natih fractures have been previously studied (van der Kolk *et al.*, 2001) at reservoir depths and surface outcrops. At reservoir depths only one set of open fractures with a NE-SW orientation is normally present. However closer to the surface another set of fractures develops in response to the stress release. Van der Kolk *et al.* (2001) argue that these fractures might also extend to the Fiqa shales that are on top of the Natih field.

Analysis: Azimuthal Travel time and attenuation anisotropy

The general NE orientation for the three surveys in Figure 1 of minimum attenuation matches that of minimum travel time (Figure 1), which is expected to be parallel to the fracture planes; furthermore, it coincides with the fracture plane orientation presented by van der Kolk *et al.* (2001) in Figure 2. This agreement shows the potential that attenuation studies, through the instantaneous frequency method, bring to fracture characterization.

Travel time to the first breaks for the 2002, 2004 and 2005 surveys present a clear sinusoidal variation with azimuth (Figure 3a). The attenuation data presents a less clear sinusoidal behavior, however the azimuthal dependence is still persistent (Figure 3b). When inverting for the parameters C1, C2, φ from the function C1+C2cos2(φ-φo), which would correspond to a first order to a Fourier decomposition of the variation of the data with azimuth, it is clear that the Natih carbonates present an anomalous behavior.

A Bayesian Information Criterion (BIC) was calculated to analyze how well this approximation fits the data, obtaining larger BIC values for the azimuthal anisotropy - indicating a better fit- than those from the straight line azimuthally independent model.

In search for further break down by depths of the possible orientations the data is separated by stratigraphic units as shown in Figure 1. The small deviations between the orientations from the Natih interval (green) and those from the Nahr Umar shale (black) are negligible given the scattering of the data and the errors between the data and the model (Figure 1).

The direction of minimum attenuation from the receivers in the Nahr Umar shale is highly consistent through the three surveys, presenting a N45E orientation in 2002 and 2005, and N40E in 2004. The Natih carbonates show a similar orientation as that from the Nahr Umar shale, with a shift of a few degrees towards the east in the three surveys. This orientation and that presented by the azimuth of minimum travel time agrees with the direction of the fracture plane studied in the area by van der Kolk *et al,* (2001). However, the Fiqa shales present an almost 90° shift from the main orientation of the Nahr Umar shales in year 2002, and a 30° shift to the east in year 2005. For an interpretation of the orientation changes in the Fiqa shales a comparison with the other two remaining wells becomes necessary.

Conclusions

We have calculated relative azimuthal attenuation per receiver level for a walkaround time-lapse multilevel VSP data set with a novel technique based on the instantaneous frequency method presented by Dasios *et al.* (2001). The general NE fracture orientation obtained from azimuthal attenuation and traveltime analysis for the overburden of the Shuaiba reservoir in the carbonate field studied coincides with that of the Natih formation as described by van der Kolk *et al.* (2001). This agreement shows the potential of azimuthal attenuation studies of P-waves for fracture characterization, where P-waves present a direction of minimum attenuation in a direction parallel to the fracture plane.

Acknowledgments

We would like to thank PDO and Shell for providing the VSP data. We are also grateful to the Oman Ministry of Oil and Gas for permission to present this data. This work is supported by the Edinburgh Anisotropy Project (EAP) of the British Geological Survey, and is published with the approval of the Executive Director of BGS and the EAP sponsors.

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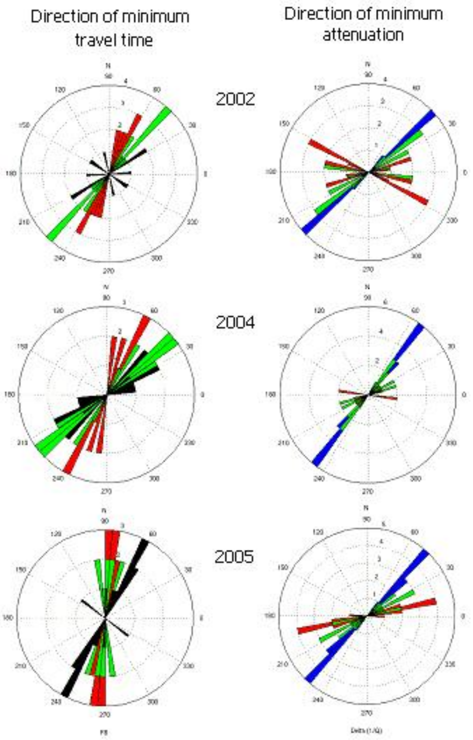


Figure 1 (left). Direction of minimum travel time to first breaks (left) and direction of minimum attenuation (right) for surveys 2002, 2004 and 2005 from top to bottom respectively. The orientations are separated by receiver levels. Directions corresponding to receivers above the Natih interval are colored in red, from the top of the Natih to the base of the Natih in green, and from the base of the Natih to the top of the reservoir in black (travel time) and blue (attenuation).

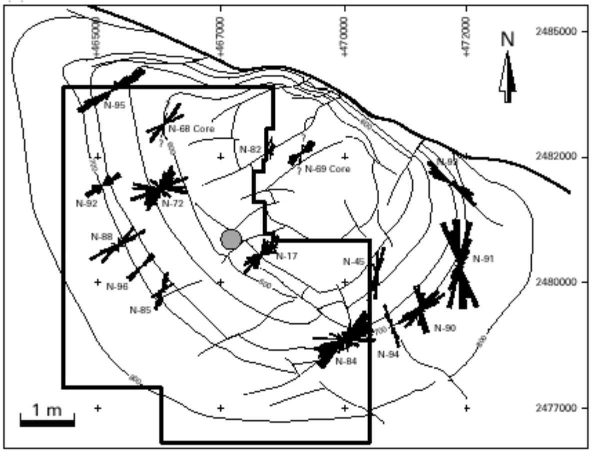
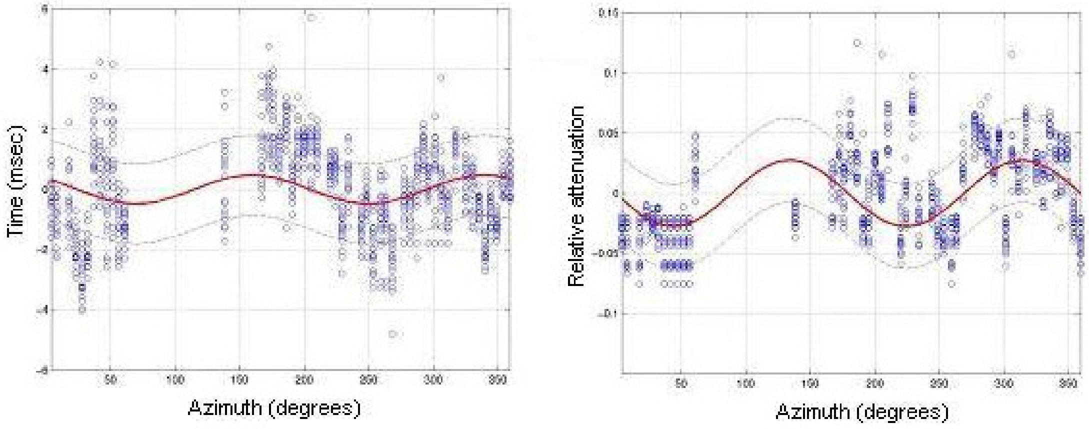


Figure 2 (above). Natih fracture orientations, modified from van der Kolk *et al.* (2001).



(a) (b)

Figure 3 Cosine fit to normalized travel time for first breaks (a) and attenuation (b) from the top of the Natih to the top of the reservoir, i.e. depths greater than 180m. Surveys 2005.