Analysis of azimuthal variation in P-wave signature from orthogonal streamer lines

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Summary

Drilling into fractured reservoirs demands an understanding of the fracture distribution and the associated stress field to reduce the risk of failure. The seismic method provides the key to this risk reduction. Here, assuming fracture-related azimuthal anisotropy, we present a generalization of existing formulae for fracture detection. This uses the three P-wave attributes, amplitude, NMO velocity and traveltime, derived from marine seismic data shot along orthogonal directions. The attribute field formed between two orthogonal survey lines displays a \( \cos 2\phi \) variation with the line azimuth measured relative to the fracture strike. Thus, two pairs of orthogonal lines may be used to quantify the fracture strike by cross-plotting these attributes. The technique is applied to data from the North Sea and verified using full-wave modelling.

Introduction

In a medium containing fracture-related horizontal transverse isotropy (HTI), both the AVO gradient (Ruiger, 1996) and the NMO velocity (Tsvankin, 1997) show elliptical variation with azimuth. This feature forms the basis of many P-wave techniques for fracture detection (MacBeth et al., 1997; Mallick et al., 1998; Grechka and Tsvankin, 1998). However, when applied to marine towed-streamer data with limited azimuthal coverage, these techniques may sometimes introduce severe error propagation and magnification during processing, which limits their application.

Here we present a different approach to determine fracture orientation using orthogonal streamer lines. In the offshore environment, orthogonal 2D lines are often found as surveys are shot and repeated during the evolution of the field. Thus it is indeed worthwhile to consider an approach that capitalises this orthogonal line characteristic. We extend the azimuthal moveout analysis of Li (1997) for such line configurations to AVO and NMO velocity analysis, and present a generalized approach to fracture detection using P-wave attributes.

Directional P-wave signature

To guide our analysis, we firstly consider a numerical calculation to examine the effects of anisotropy on the three P-wave attributes: amplitude, velocity and travel time. For this, a three-layered model is constructed (Figure 1). Through solving the Kelvin-Christoffel equations (Helbig, 1994), the amplitude, slowness (inverse of the velocity) and travel time of all three body waves in every direction can be calculated. Our numerical results confirm that for fracture-related azimuthal anisotropy, the three P-wave attributes show near-elliptical variations with azimuth. Moreover, the major axis of the ellipse points along the fracture strike, and the ellipticity indicates the fracture intensity (Figure 2).

Analytic expressions

Accurate numerical solutions are useful for understanding wave propagation and verifying processing results. However, they do not reveal insight into the various parameter dependencies. This gap is often filled using approximate analytic expressions based on Thomsen (1986) for weak anisotropy. Such formulae are offered by Li and Mavko (1996), Ruiger (1996), Tsvankin (1997), and Li (1997, 1999), amongst others.

A generalization of the resultant formulae is possible to encapsulate all of the azimuthal variations for the
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Figure 2. Azimuthal variations of (a) vertical slowness in layer 2, (b) amplitude at the interface between layers 1 and 2, and (c) interval travel time for layer 2 (bottom minus top). The X- and Y-axes represent horizontal slowness along those axes.

three $P$-wave attributes:

$$ F(\theta, \phi) = A(\theta) + B(\theta) \cos 2\phi + C(\theta) \cos^2 2\phi, \quad (1) $$

where $F(\theta, \phi)$ represents either the $P$-wave amplitude, the inverse of the squared NMO velocity ($1/v_{NMO}^2$), or the travel time. $\theta$ is the incidence angle, $\phi$ is the azimuthal angle measured from the fracture strike, and $A(\theta)$, $B(\theta)$, and $C(\theta)$ are azimuthally invariant coefficients.

Figure 3. The proposed four-line configuration: line 1 is perpendicular to line 3, and line 2 is perpendicular to line 4.

Processing method for orthogonal lines

Assume a four-line configuration forming two orthogonal sets (Figure 3). Introduce $\varphi_0$ as the angle between lines 1 and 2, $\Delta F_{31}$ as the difference of the attribute between lines 3 and 1, and $\Delta F_{42}$ as the difference between lines 4 and 2. We have,

$$ \Delta F_{31} = -2B(\theta) \cos 2\phi, \quad (2) $$

and

$$ \Delta F_{42} = -2B(\theta) \cos (\phi + \varphi_0). \quad (3) $$

Thus, the fracture strike is determined by

$$ \tan 2\phi = \frac{\Delta F'_{42}}{\Delta F'_{31}}, \quad (4) $$

where

$$ \Delta F'_{42} = \frac{\Delta F_{31} \cos 2\varphi_0 - \Delta F_{42}}{\sin 2\varphi_0}. \quad (5) $$

Equation (4) indicates the differential attributes between the two orthogonal lines are linearly-dependent. For the amplitude and traveltime attributes, this implies that the cross-plot of the two differential attributes will reveal a linear trend at the direction of $2\phi$.

Full-wave modelling results

To test the above approach, full-wave modelling is carried out for the model in Figure 1 and the four-line acquisition configuration in Figure 3. The calculated synthetic CMP gathers are shown in Figure 4. Equation (4) is applied to picked amplitudes, velocity and travel time, respectively. The cross-plot of the differential amplitudes and the travel times confirms the predicted linear trend (Figure 5). The average angle estimated from all three attributes closely agrees with the model parameter of 15° to two decimal places.
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Figure 4. The NMO-corrected full-wave synthetic CMP gathers of the four lines in Figure 3. The bottom-target event for Line 3 is aligned, but over-correction occurs on the other three lines.

Figure 5. (a) The cross-plot of the differential travel times picked from Figure 4. (b) The same as (a) but for the differential amplitudes.

Figure 6. (a) The contour map of the target top, and (b) the line geometry and the resultant NMO ellipse.

Field data analysis

We apply the method to a field dataset provided by Fina Exploration. All three attributes will be assessed for their merits in determining the fracture strike. The data are from a salt-induced structure in the Central North Sea with intensive faulting in the area (Figure 6a). Four streamer lines are selected, intersecting each other at well A (Figure 6b). The target is the Ekofisk and Tor formations in the Chalk sequence. The chalk sequence is approximately 200m thick and is known to be fractured. High hydrocarbon saturations are believed to be related to the fractured/fault zones.

To examine the azimuthal variation of moveout (traveltime), it is convenient to apply NMO-correction to the data, as shown in Figure 7. The top-target event for all four lines is relatively flat, whilst the bottom target event for lines 1, 2 and 4 is over-corrected, and the degree of over-correction varies between the lines. This reveals a clear azimuthal variation of traveltime. The pattern of the variation suggests that the line 3 is close to the fracture normal, as the NMO velocity along the fracture normal is slow. If the slow velocity
is used for NMO correction, the events will be over-corrected. This is consistent with the full modelling (Figure 4).

The final cross-plotting results of the traveltime and amplitude are shown in Figure 8. The traveltime cross-plot reveal a clear trend, and the calculated angle is 26 degrees clockwise from line 1 (N73°E). However, the amplitude results are scattered, giving no preferred direction. The result of NMO velocity analysis is N75°E, as shown in Figure 6, which is in good agreement with the travel time analysis.

Discussion and conclusions

Azimuthal AVO relies on the detection of subtle amplitude variations, and is difficult to implement in repeated surveys of various vintages. Extensive effort must be placed on wavelet shaping and matching to make this analysis possible. For azimuthal NMO velocity analysis, magnification of propagated errors is of some concern both in the Dix equation for interval measurements and in the least square fitting of the NMO ellipse (Al-Dajani and Alkhalifah, 1998).

The use of attribute fields between two orthogonal lines has the potential in overcoming some of the above difficulties. The method has good flexibility in handling variations in acquisition conditions because of the differential procedures used, as demonstrated in the real data example. The final cross-plot analysis makes the method relatively robust, and accommodates for error magnification that may arise during processing. Moreover, due to the generalized form of these attributes, they can be normalized to produce a single robust cross-plot and a common solution.

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