Fracture Detection by Azimuthal Differential Residual Moveout

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In this paper, we implement a method for extracting fracture attributes in weak HTI (Horizontal Transverse Isotropic) media based on P-wave azimuthal variation of differential residual moveout. Specifically, we calculate the time-variant trim statics at the top and the bottom of the target, and then compute the difference. These differential time-variant trim statics are used to extract fracture orientation and Thomsen's delta parameter. We explore the efficacy of the method on a land dataset. Our result shows that the algorithm provides a stable and consistent solution.

Introduction

Fracture information is very important to oil and gas exploration and exploitation. Open fractures can hold fluid or provide a pathway for hydrocarbon migration. Therefore detailed information about fracture distribution and intensity can help optimize drilling locations. In recent years, geophysicists have proposed various fracture-detection methods using P-wave reflection data, most of which exploit either Amplitude Variation with incident angle and AZimuth (AVAZ) (Lynn et al., 1996; Rüger, 1998; Gray et al., 2000) or Velocity Variation with AZimuth (VVAZ) (Tsvankin, 1997; Li, 1997; Grechka and Tsvankin, 1998; Zheng, 2006). Typically, the amplitude method provides superior spatial information compared to the velocity method, but it is less stable (Todorovic-Marinic et al., 2005). Zheng (2006) developed a fracture-detection method that keys on the difference between time-variant trim statics (defined below) measured at the top and the bottom of the target to directly extract Thomsen's delta parameter and fracture orientation. This technique retains the stability associated with the velocity method, but at the same time it provides good vertical resolution by effectively removing the confounding influence of the overburden. In this paper we implement this method for wide-azimuth land data for the first time in the industry.

Method

In our implementation, we assume the target has weak HTI anisotropy and is embedded in an isotropic background. Typically, after NMO we observe systematic residual moveout with respect to offset and azimuth due to the presence of the anisotropy. For each CMP location, the residual moveout can be extracted by matching each individual prestack trace with an external pilot trace (which may be generated, say, by stacking the NMOed data). We define *time-variant trim static* (TVTS) as the time shift applied to a time window (typically much smaller than the trace length) of

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the prestack trace such that after the time shift, the time window has maximum cross-correlation with the corresponding time window (typically centered on a horizon pick) of the pilot trace. For each target at each CMP, we can calculate two TVTS values, t_1 and t_2, associated with horizon picks at the top and base of the target, respectively. In the context of weak HTI anisotropy, the difference between these two static values is a measure of the differential residual moveout. Zheng (2006) proved that

$$\Delta t = t_2 - t_1 = -\frac{2D \cdot v_{\text{int}}}{v_{rms}^{\ 2}} \delta^{(v)} \frac{\sin^2 \theta}{\cos \theta} \cos^2(\phi - \phi_{sym}), \tag{1}$$

where Δt is the differential residual moveout, D is the thickness of the target, v_{int} is the interval velocity, v_{rms} is the RMS velocity at the target base, $\delta^{(v)}$ is Thomsen's delta parameter in HTI coordinates (which can be used as an indicator of fracture intensity), θ is the incident angle, ϕ is the azimuth of the prestack seismic trace, and ϕ_{sym} is the symmetry axis of the HTI anisotropy (which is perpendicular to the fracture orientation). The goal of this method is to calculate $\delta^{(v)}$ and ϕ_{sym} given redundant seismic data. Equation 1 is non-linear, but it can be linearized as

$$\Delta t = C_1 f(\theta) + C_2 f(\theta) \cos(2\phi) + C_3 f(\theta) \sin(2\phi), \tag{2}$$

where $C_1 = 0.5k\delta^{(v)}$, $C_2 = 0.5k\delta^{(v)} \cos(2\phi_{sym})$, $C_3 = 0.5k\delta^{(v)} \sin(2\phi_{sym})$, $f(\theta) = \sin^2 \theta / \cos\theta,$ and

$$k = -\frac{2D \cdot v_{\text{int}}}{v_{rms}^{\ 2}}.$$

After we calculate parameters C_1, C_2 and C_3 by inversion, we can convert them to fracture attributes by

$$\delta^{(v)} = 2\sqrt{C_2^2 + C_3^2} / k, \tag{3}$$

$$\phi_{sym} = 0.5 \tan^{-1} \frac{C_3}{C_2}. \tag{4}$$

Unfortunately, there is an ambiguity in the inversion result (Zheng et al., 2004). Specifically, for each pair of parameters, we can always derive another solution by changing the sign of $\delta^{(v)}$ and rotating the symmetry axis ϕ_{sym} by 90 degrees. Therefore, we need other information about the sign of $\delta^{(v)}$ or the approximate direction of ϕ_{sym} to constrain the solution. Fortunately, for most geological settings it is reasonable to assume that the sign of $\delta^{(v)}$ does not change across the survey. Therefore the ambiguity is typically manifest as a single "bulk" rotation of the symmetry axis by 90 degrees and global polarity reversal of $\delta^{(v)}$, rather than the more unsettling situation in which the orientation flip-flops by 90 degrees from CMP to CMP. Thus, even when we have no a priori information about the fracture attributes, we can still use the solution in "reconnaissance mode", keeping in mind the aforementioned ambiguity.

Processing for Fracture Detection

From equation 2, we know that the accuracy of the differential trim statics computation profoundly affects the quality of the inversion result. Consequently, we need to pay careful attention to noise suppression at the pre-processing stage. Typically, there are two kinds of noise we try to remove: random noise and multiples. We choose to attack random noise by 4D prestack FX filtering (Wang 1996). Since we are not interested in amplitude, we can design harsh filters for our purpose. After cleaning up the data in this way, we typically run high-resolution Radon multiple attenuation.

Prior to performing the inversion (equation 2), we form a supergather consisting of prestack traces whose CMP's are proximal to the analysis CMP. Differential TVTS values for all these traces are then fed to the inversion. This supergathering process stabilizes the inversion by improving offset and azimuth coverage, and also by increasing data redundancy. Of course a trade-off exists such that the bigger the superbin size, the more stable the inversion but at the expense of decreased lateral resolution. Therefore tests must be done to determine optimal superbin size. Figure 1 displays the processing flow we designed for fracture detection:

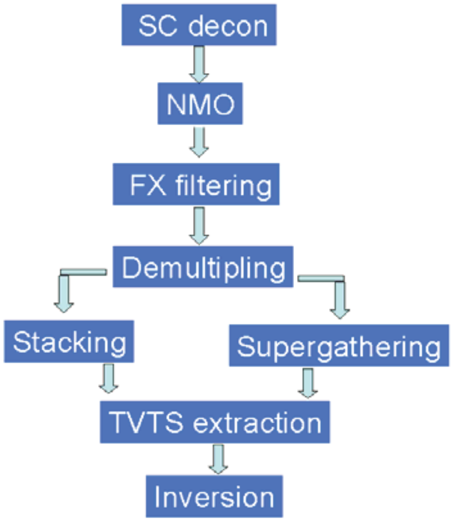

Figure 1. Processing flow for fracture detection by inversion of azimuthal differential time-variant trim statics. SC decon denotes surface consistent decon. TVTS denotes time-variant trim statics.

Field Data Example

Figure 2 shows the extracted delta parameter and the data residual norm. The residual norm, which quantifies the CMP-by-CMP data misfit associated with the inversion, is an important diagnostic tool for interpreters. As we see in Figure 2, the edge part of the survey has larger errors than the center part, which explains why we get suspicious parameters (large $\delta^{(v)}$ and incoherent fracture orientation) around the periphery.

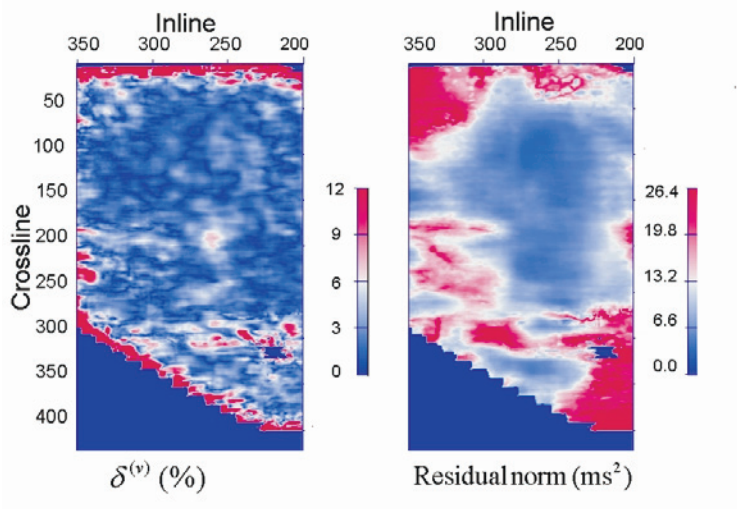

Figure 2. Inverted delta parameter and the data residual norm.

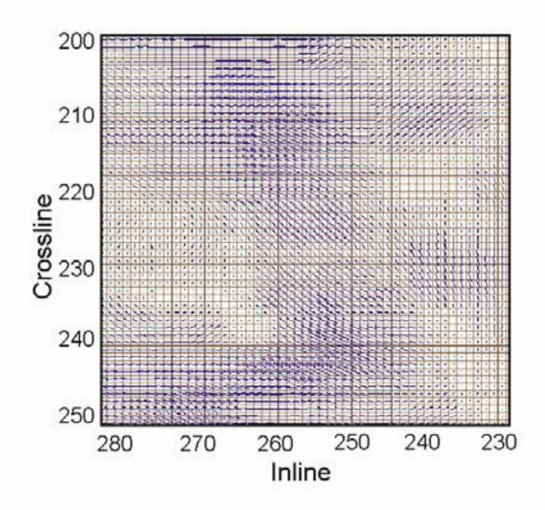

Figure 3. Fracture orientation and $\delta^{(v)}$ plotted in vectors. Each cell represents one CMP bin. The vector length is proportional to the detla parameter, and the direction represents the fracture orientation.

Figure 3 displays the vector plot of the fracture attributes for a portion of the survey interior (i.e. away from the edge). We can see the dominant fracture orientation is NW-SE in reference to the inline direction. Further information from geological observations and well log data is required to confirm the inversion result, which is the subject of current investigation.

Figure 4 compares the observed differential TVTS values to the predicted values computed by forward modeling the inverted attributes at a center location (inline 260 and crossline 200). It is clear that our algorithm honors the seismic data. At the same time, as we observe in Figure 3, the algorithm gives a consistent solution for the survey.

Conclusions

We have implemented and tested a fracture-detection method using horizon-based residual moveout. The method can yield a reasonable solution for fracture intensity and orientation. Further interpretation is required to calibrate the solution with other input data in order to make the solution unique and meaningful in a geological sense.

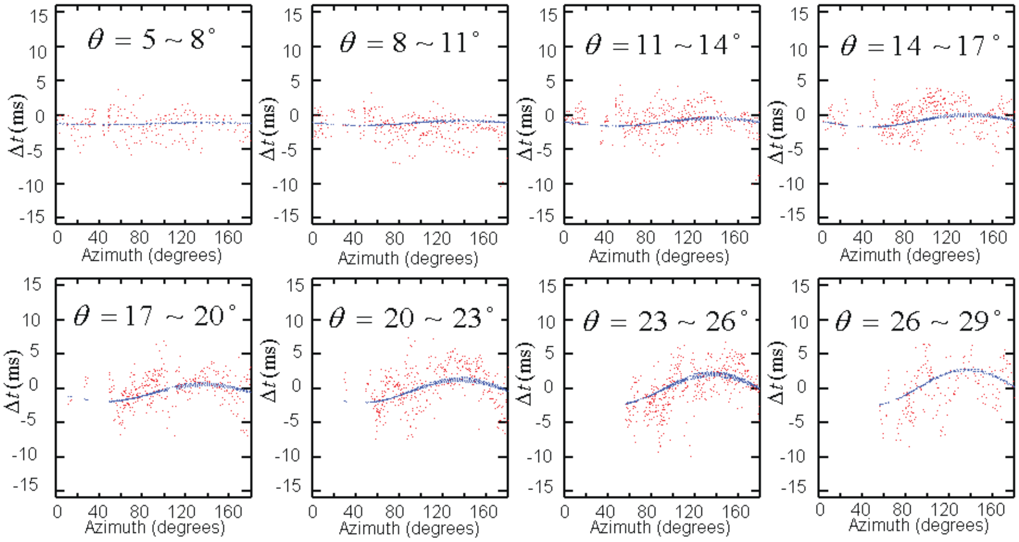

Figure 4. Observed differential residual moveouts (red) vs. predicted values (blue). X-axis: azimuth. Y-axis: differential residual moveout in milliseconds. The eight panels show the comparison for eight incident angle ranges.

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