VVAZ vs. AVAZ: practical implementation and comparison of two fracture detection methods

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SUMMARY

We present robust implementations of two vertical fracture detection methods. Assuming that the fracturing can be described by a horizontally transverse isotropic (HTI) medium, we implement two independent algorithms that examine the azimuthal dependence of P-wave reflection amplitudes and stacking velocities, respectively. In the amplitude approach, we use multi-azimuth and multi-offset data to extract the standard Rüger parameters. In the velocity approach, we employ a new technique using the difference between time-variant trim statics measured at the top and base of the target to invert for fracture orientation and Thomsen's delta parameter. Field data results obtained using the two methods are similar except for some spatial offset.

INTRODUCTION

Accurate fracture characterization is becoming increasingly important in hydrocarbon exploration and exploitation. Because open fractures may hold fluid and may provide a pathway for hydrocarbon flow, 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 resolution 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 base 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. For comparison, we also implement the amplitude method based on Rüger's equation (1998).

THEORY

Velocity method

In our implementation, we assume the target has weak HTI anisotropy. 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 NMO corrected 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 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 presence of weak HTI anisotropy, the difference between these two static values is a measure of the differential residual moveout. Zheng (2006) proved that

$$\Delta t = t_1 - t_2 = -\frac{2D\cdot v_{\text{int}}}{v_{rms}^2}\delta^{(v)}\frac{\sin^2\theta}{\cos\theta}\cos^2(\phi-\phi_0), \tag{1}$$

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 acquisition azimuth of the prestack seismic trace, and ϕ_0 is the strike direction of the fracture. The goal of this method is to calculate $\delta^{(v)}$ and ϕ_0 given redundant seismic data. For inversion, we linearize the equation as below:

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

where

$$C_1 = 0.5k\delta^{(v)},$$

$$C_2 = 0.5k\delta^{(v)}\cos(2\phi_0),$$

$$C_3 = 0.5k\delta^{(v)}\sin(2\phi_0),$$

$$f(\theta) = \sin^2\theta/\cos(\theta),$$

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

Given redundant differential residual moveout data, we can invert for the three coefficients C_1, C_2 and C_3. 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 fracture orientation ϕ_0 by 90 degrees. Therefore, we need other information about the sign of $\delta^{(v)}$ or the approximate direction of ϕ_0 to constrain the solution. Fortunately, for many 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 fracture orientation by 90 degrees and global polarity reversal of fracture intensity, 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. In the present approach, we make the assumption that $\delta^{(v)}$ is positive with the consequence that the inverted fracture orientation may have a global error of 90 degrees if the true sign of $\delta^{(v)}$ is negative. Under this assumption, we can unambiguously calculate two “apparent” fracture parameters by

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

$$\phi_0 = 0.5\tan^{-1}(C_3/C_2).$$

Amplitude method

We have also implemented the popular AVAZ technique based on Rüger’s equation which describes the P wave amplitude dependence on azimuth and incident angle in an HTI medium (Rüger, 1998) as below:

$$R_{pp}(\phi,\theta) = A + [B^{iso} + B^{ani}\cos^2(\phi - \phi_{sym})]\sin^2\theta, \qquad (3)$$

where A is the intercept, B^{iso} is the isotropic gradient, B^{ani} is the anisotropic gradient (which is a measure of fracture intensity), ϕ is the acquisition azimuth and ϕ_{sym} is the symmetry axis which is perpendicular to the fracture orientation ϕ_0. The goal of AVAZ inversion is to extract these four parameters (A, B^{iso}, B^{ani} and ϕ_{sym}) from amplitudes extracted from the wide-azimuth 3D prestack data volume.

Similar to the velocity method, the AVAZ solution is not unique (Rüger, 1998; Zheng et al., 2004): one can rotate the symmetry axis by 90 degrees and change the sign of the anisotropic gradient B^{ani} and still fit the observations. In practice we force B^{ani} to be positive to make the solution unique, with the consequence that the inverted symmetry axis may have a global error of 90 degrees if the true sign of B^{ani} is negative. Note that B^{ani} and $\delta^{(v)}$ don't necessarily have the same sign according to the following formula (Rüger, 1998):

$$B^{ani} = 0.5(\Delta\delta^{(v)} + 2(\frac{2\bar{\beta}}{\bar{\alpha}})^2\Delta\gamma), \qquad (4)$$

where $\bar{\alpha}$ is the average P-wave velocity, $\bar{\beta}$ is the average S-wave velocity, and $\Delta\delta^{(v)}$ and $\Delta\gamma$ are the changes in Thomsen's delta and gamma parameters across the interface, respectively.

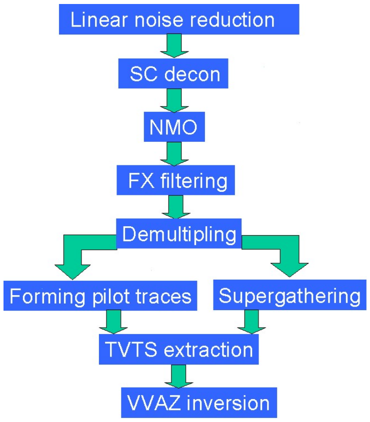

Figure 1. Processing flow for VVAZ inversion. SC decon: surface consistent deconvolution. NMO: normal moveout. TVTS: time-variant trim statics.

Processing flow for AVAZ/VVAZ inversion

The accuracy of the differential trim statics computation profoundly affects the quality of the VVAZ inversion result. Consequently, we need to pay careful attention to noise suppression at the VVAZ pre-processing stage. We typically use a local linear Radon transform approach to remove linear noise (e.g. ground roll) and a 4D prestack FX filtering approach (Wang 1996) for random noise suppression. Since we are not concerned with relative amplitude preservation in the VVAZ approach, we can use harsh filters. After cleaning up the data in this way, we may 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 the lower the lateral resolution. Therefore tests must be done to determine an optimal superbin size. Figure 1 displays the processing flow we use for VVAZ inversion:

The processing flow for AVAZ inversion (Figure 2) is similar to that for VVAZ inversion; however, care must be taken to preserve relative amplitude information. Therefore, we follow an "AVO-friendly" processing approach that avoids trace-by-trace scaling in favour of surface-consistent amplitude corrections. For computational efficiency, we construct a supergather at each CMP location by partially stacking traces into regular azimuth and offset bins. This strategy increases the S/N ratio and reduces the cost of inversion; however, as a side effect, it may introduce smearing of input data across azimuths, CMPs and offsets.

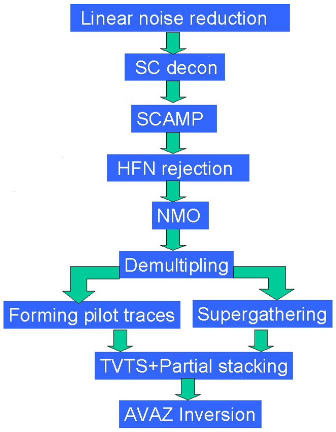

Figure 2. Processing flow for AVAZ inversion. SC decon: surface consistent deconvolution. SCAMP: surface consistent amplitude scaling. HFN: high-frequency noise. NMO: normal moveout. TVTS: time-variant trim statics.

VVAZ vs. AVAZ

In this section, we compare and contrast the VVAZ and AVAZ methods. First, although both methods can provide a qualitative measure of fracture intensity, neither can give a unique estimate of fracture orientation. VVAZ is more economical than AVAZ since the input data of the former consist of the relatively sparsely sampled differential residual moveout information, while those of the latter consist of the more finely sampled amplitudes. VVAZ inversion is more stable because it inverts traveltime rather than amplitude, and in practice, it is not easy to preserve relative amplitude information in the presence of noise. On the other hand, AVAZ may provide superior spatial resolution since it inverts local amplitude on a time-slice basis (by contrast, VVAZ captures the cumulative traveltime information between two horizons and therefore it provides an average estimate of the anisotropy between two horizons). Considering the pros and cons of these two methods, we recommend using both methods whenever possible.

FIELD DATA TESTS

We applied both algorithms to a real dataset. Figure 3 compares the results of the two methods. Figure 3a is the inverted delta parameter from the VVAZ run, and Figure 3b is the inverted Rüger parameter B^{ani} from the AVAZ run. The fracture intensity patterns obtained using the two methods are similar. In particular, there are three zones (marked A, B and C on the figures) which reveal large values for the estimated fracture intensity. Our results for zone A are consistent with field observations from the area which suggest strong fracturing (at the time of writing no field information was available from zones B and C). Moreover, a certain local maximum in inverted fracture intensity closely matches a drilling location for which the well encountered strong fracturing at the target level. Interestingly, Figures 3a and 3b reveal some spatial offset between the two results. One possible explanation is that the input data of the velocity method embody cumulative traveltime information between top and base of target, while the input data of the amplitude method carry information about the interface between target base and the underlying medium.

Figure 4 zooms in an area of interest and displays the fracture attributes in vector format. In many places the fracture attributes determined by VVAZ and AVAZ methods are similar; however, at other locations they don't agree (the inconsistency between the two orientation estimates is especially striking in places). Several factors may account for these discrepancies. First, although the parameters $\delta^{(v)}$ and B^{ani} (computed by then VVAZ and AVAZ algorithms, respectively) are assumed to be indicators of fracture intensity, it is important to note that from the viewpoint of rock physics they are not necessarily well correlated. In particular, B^{ani} depends on both $\Delta\delta^{(v)}$ and $\Delta\gamma^{(v)}$ (equation 4). This lack of spatial correlation can cause discrepancies in the estimates of both fracture intensity and orientation (in particular, the precise nature of the orientation discrepancy may be quite complicated because of the aforementioned inversion ambiguities). Second, the inversions may be compromised by noise in the input data. Third, the input information may be smeared due to the influence of geological structure, a problem which could in theory be alleviated by running azimuth-limited prestack migration.

CONCLUSIONS

We have implemented and tested two fracture detection methods which exploit azimuthal variations in time-variant trim statics and reflection amplitude, respectively. These two independent methods yield similar solutions for

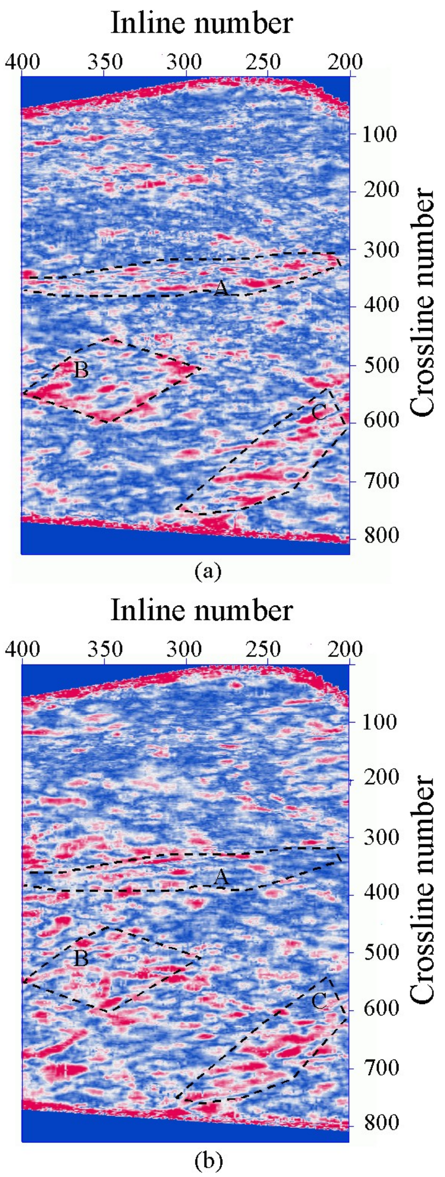

Figure 3: Comparison between the two fracture detection methods. (a) Thomsen's parameter $\delta^{(v)}$ obtained via VVAZ inversion. (b) Anisotropic gradient (B^{ani}) obtained via AVAZ inversion.

fracture intensity and (to a somewhat lesser degree) for fracture orientation. In spite of this overall similarity, there is some spatial offset between the solutions, and this discrepancy warrants further study. In general, the results agree well with field observations, and we recommend using both techniques whenever possible to minimize the risk of misinterpretation.

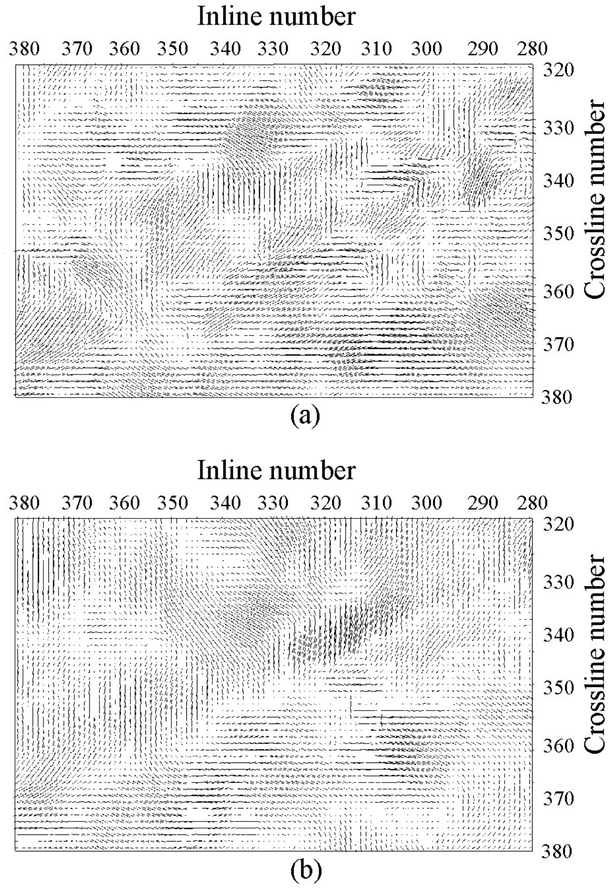

Figure 4: Fracture attributes displayed in vectors. The length of the vector is proportional to fracture intensity and the orientation of the vector is the inverted fracture orientation. (a) Result of VVAZ inversion (fracture intensity given by $\delta^{(v)}$). (b) Result of AVAZ inversion (fracture intensity given by B^{ani}).

EDITED REFERENCES

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REFERENCES

Gray, F. D., and K. Head, 2000, Fracture detection in the Manderson Field: A-3D AVAZ case history: 70th Annual International Meeting, SEG, Expanded Abstracts, 1413–1416.

Grechka, V., and I. Tsvankin, 1998, 3-D description of normal moveout in anisotropic inhomogeneous media: Geophysics, 63, 614–629.

Li, X., 1997, Viability of azimuthal variation in P-wave moveout for fracture detection: 57th Annual International Meeting, SEG, Expanded Abstracts, 1555–1558.

Lynn, H. B., K. M. Simon, C. Bates, and R. Van Dok, 1996, Azimuthal anisotropy in P-wave 3-D (multiazimuth) data: The Leading Edge, 15, 923–928.

Rüger, A., 1998, Variation of P-wave reflectivity with offset and azimuth in anisotropic media: Geophysics, 63, 935–947.

Todorovic-Marinic, D., B. Mattocks, R. Bale, D. Gray, and S. Roche, 2005, More powerful fracture detection: Integrating P-wave, converted wave, FMI and everything: Presented at the National Convention, CSEG.

Tsvankin, I., 1997, Reflection moveout and parameter estimation for horizontal transverse isotropy: Geophysics, 62, 614–629.

Wang, X., 1996, Random noise attenuation of pre-stack seismic data by surface consistent prediction in frequency domain: Presented at the National Convention, CSEG.

Zheng, Y., 2006, Seismic azimuthal anisotropy and fracture analysis from PP reflection data: Ph.D. dissertation, University of Calgary.

Zheng, Y., D. Todorovic-Marinic, and G. Larson, 2004, Fracture detection: Ambiguity and practical solution: 74th Annual International Meeting, SEG, Expanded Abstracts, 1575–1578.