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Minimizing Fracture Characterization Uncertainties Using Full Azimuth Imaging in Local Angle Domain

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Summary

Shale plays are naturally heterogeneous and frequently anisotropic due to tectonic stresses and fracturing. Determining stress or fracture intensity and its orientation from the seismic method is a desirable outcome for the drilling engineer, but a challenging one for geophysicists, particularly at significant depths in the subsurface. Wide Azimuth (WAZ) data is routinely used to study the amplitude variation with angle and azimuth (AVAZ) and velocity variation with angle-azimuth (HTI velocity). Vertical fractures in the presence of VTI are the simplest real life geological scenario. An orthorhombic anisotropic model is required (Leon Thomson, 1986) to describe the kinematics of wave propagation in this media. Orthorhombic models require 9 interval parameters to describe them fully. Inversion procedures to derive them are very unstable for field data and difficult to implement. Time imaging, which uses straight-ray approximations and relies upon surface azimuth measurements for imaging and analysis, only yields effective anisotropic parameters. This approach is not very suitable as the anisotropy could be as small as 1%, and may be unrecoverable because of averaging in the time migration process.

In this paper, using field data from the Eagle Ford, North America shale play, we present a most efficient and stable method based on local angle domain imaging in VTI/TTI media with full azimuth tomography in the depth domain using interval parameters, which can measure anisotropy as low as 1%. This efficient and technically sound approach brings the turnaround time to 6 weeks as opposed to 6 months for projects based on sector processing commonly employed in the industry.

Keywords*: AVAZ, Anisotropy, Tomography, HTI, Fracture*

Introduction

Fracture characterization is one of the most challenging problems for geophysicists today. Unconventional shale resource play development worldwide has necessitated acquisition of wide azimuth/full azimuth seismic data. An appropriate imaging technology is required to get the full return on these investments. Wide azimuth data acquisition was pushed by the need to improve sub-salt imaging in the Gulf of Mexico. But there have not been many changes in imaging technology to handle the rich azimuthal information in the data effectively. The current imaging approaches make use of azimuth sectors based on source-receiver azimuths measured on the acquisition surface. This approach is not only cumbersome but fundamentally flawed as in complex media, such as sub-salt, the surface and sub-surface azimuth may differ drastically. Also sectored sampling is sub-optimal for identifying and inverting the azimuthal velocity and amplitude variation in fractured shale reservoirs. Proper sampled azimuthal data (full azimuth data) input to full azimuth tomography, can help to reduce velocity ambiguity and imaged full azimuth angle gathers are most suited for HTI RMO(Z) (residual moveout) and AVA(Z) (amplitude versus angle) inversion in the presence of vertical fractures in the sub-surface in shale plays.

In this paper, we demonstrate the application of an innovative full azimuth Imaging and reservoir characterization system based on the decomposition of seismic data in a local angle domain system (Koren et al., 2007, 2008, 2011) to a rich azimuth data set from the North America Eagle Ford shale play. Eagle Ford shale thickness in the study area reaches around 200 feet and is present at

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about 12000 feet in the subsurface. The workflow consists of Full azimuth tomography, HTI RMO and AVAZ inversion using full azimuth gathers.

Field data description

Table 1 table shows the detail of WAZ data acquisition parameters. Figure 1 shows the fold map of coverage area and azimuth offset distribution

22 receiver lines, 170 channels each
Recoding Patch 27720 X 27885 feet
Source Line Interval: 1980 feet
Source Point Interval: 165 Ft
Source Line Orientation: SW-NE
Receiver Interval: 165 Ft
Receiver Line Interval: 1320 Ft
Average 90 fold

Table 1: showing Field parameters

Initial Velocity Modeling and Full Azimuth Tomography

We start with a smooth velocity model obtained by constrained velocity inversion (CVI, Koren et al., 2006) and update the velocity model using full azimuth tomography. The detail workflow is shown in figure 2. Figure 3 shows the full azimuth directional and reflection gathers. Directional gathers are used to get the dip and azimuth of the subsurface reflection points and used to constrain the tomography matrix and full azimuth reflection gathers are used to pick the residual surfaces (continuous in reflection angle and azimuth) which are input to tomography.

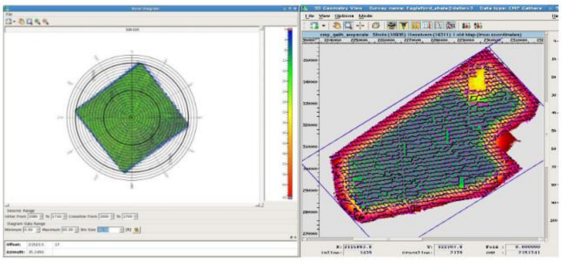

Figure 1: showing fold map and Azimuth distribution

Full Azimuth Residual move-out (RMO) Inversion

The presence of vertical fractures in the rock can be modeled as HTI anisotropy. Vertical fractures in the presence of layering give rise to orthorhombic anisotropy which is difficult to deal with as it requires 9 independent layer parameters. In practice, under the assumption of small anisotropy we first model the velocity overburden above the Eagle Ford Shale as isotropic or TI depending on the geology of the area. An isotropic/TI tomography is run to get the background velocity model. Using the background model full azimuth gathers are generated and used for HTI analysis. We employ a horizon based HTI parameter inversion (Koren et al., 2009) at the base of fractured reservoir. Figure 4 show a full azimuth reflection gather (0-360 degree) for a constant reflection angle of 35 degree. Sinusoidal moveout with azimuth as seen at the base of Eagle ford shale in the gather is an indicator of the stressed/fractured Eagle Ford shale. The azimuthal variation of the RMO can be described by the equation given below.

$$\frac{\Delta\tau(\theta,\varphi)}{\tau_0} = -t_g^2\theta\left[\alpha_1 Sin^2(\varphi-\varphi_{axis}) + \alpha_2 Cos^2(\varphi-\varphi_{axis})\right]$$

Where $tg2\theta = \tan 2(\theta)$, $\alpha 1 = \Delta v_{rms}/v_{rms}$ (along the fast velocity axis), $\alpha 2 = \Delta v_{rms}/v_{rms}$ (along the slow velocity axis), θ is the reflection angle, and φ is azimuth of the reflection, φ_{axis} the azimuth of the axis of symmetry. We define the elliptic parameter as $\delta 2 = \alpha 1 - \alpha 2$ which is proportional to the fracture intensity. Figure 5 shows the result of RMO inversion at the base of Eagle Ford Shale.

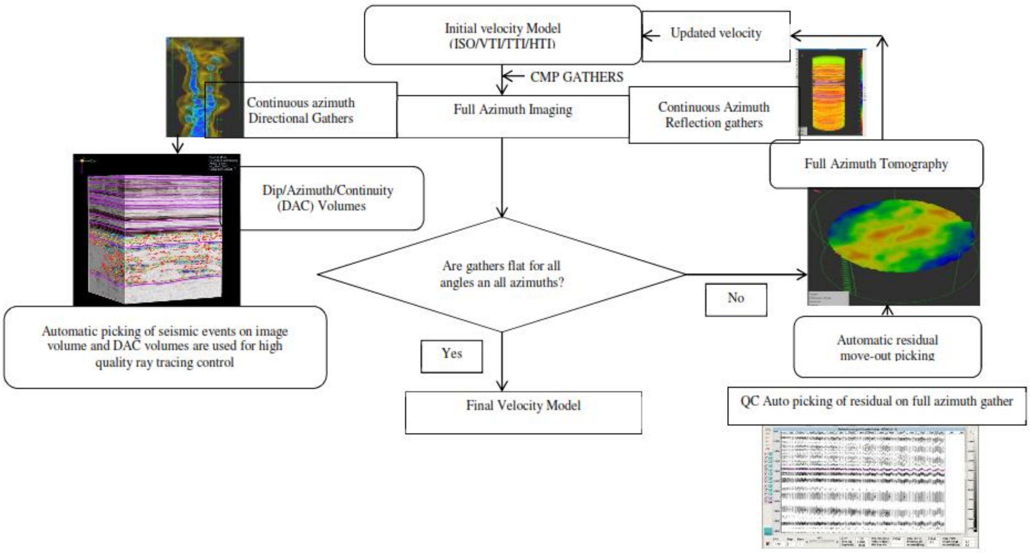

Figure 2: Full azimuth tomography workflow

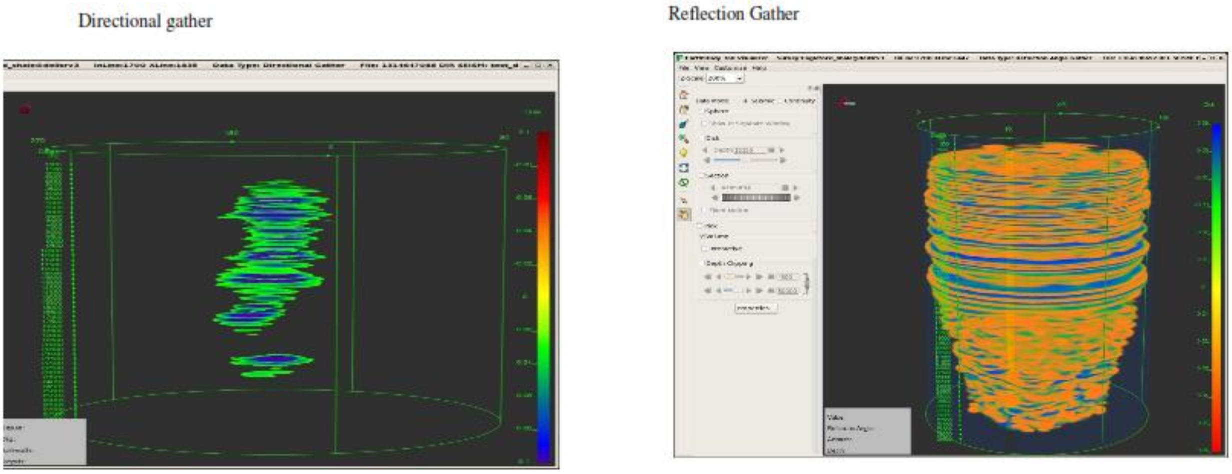

Figure 3: Full azimuth directional and reflection gathers

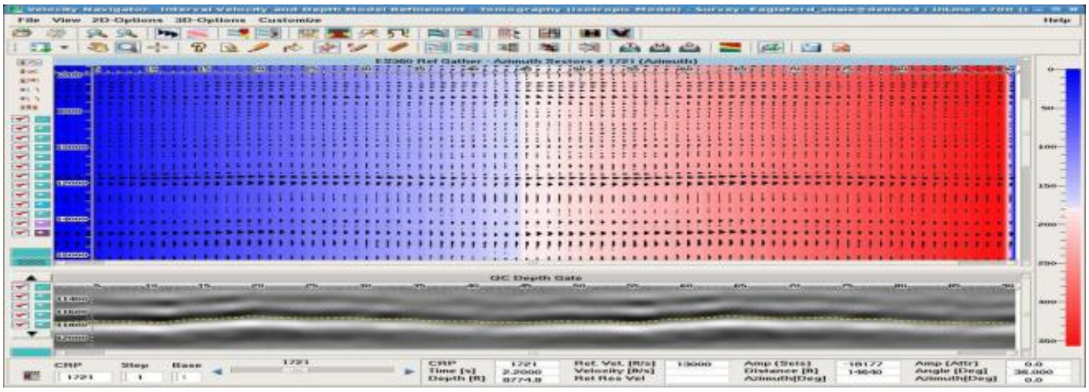

Figure: 4 Velocity variations with azimuth on a full azimuth gather

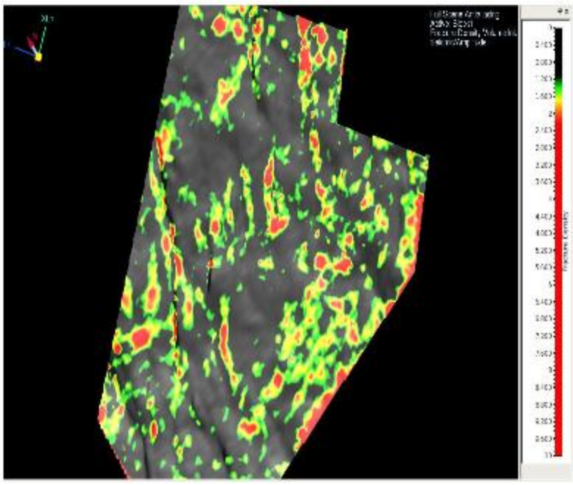

Figure 5: The Delta2 (fracture/stress intensity) map from HTI RMO inversion

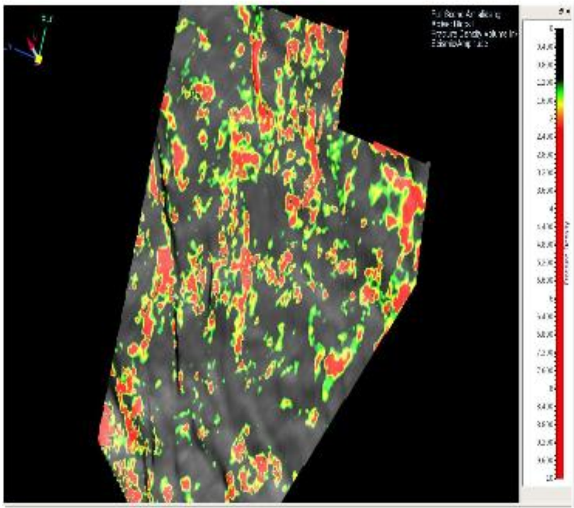

Figure 6: Fracture intensity map from AVAZ inversion

AVAZ Inversion

AVO behavior of fractured rock can be given (Ruger , 1998) as

$$R(\theta,\varphi) = I + [\ G + G_{aniso} \cos2(\ \varphi - \varphi axis)\ ] \sin2(\theta)$$

Where $R(\theta,\varphi)$ is reflection coeffiecient at the reflection angle θ and reflection azimuth φ, G is the isotropic gradient, G_{aniso} is the anisotropic gradient due to stress/fractures and φ is the azimuth of fracture strike. We perform AVO inversion by fitting the above equation to each data point on the full azimuth gather (Canning et al. 2009) after flattenting the gather based on HTI residual. Figure 6 shows the result after AVAZ inversion on Eagle Ford data set.

Discussion

HTI anisotropy as seen from the inversion map is very small (< 1%) but the patterns are very systematic. We also see that the inversion from RMO and AVAZ are highly correlatable giving the confidence in inversion results. Figure 7 shows the delta2 map overlaid by vectors and also vectors overlaid on acquisition geometry. The orientation of theses vectors are in the direction of minimum stress and the magnitude is proportional to the delta2 values (fracture intensity). The stability of the inversion can be seen as these vectors are perpendicular to the trend of delta2 values which represents the fracture strike. Overlay on acquisition geometry helps to see any bias due to acquisition geometry

Conclusions

Full azimuth decomposition and imaging can be used to detect HTI anisotropy on the order of less than 1% and allows geoscientists to work with material (layer) parameters in depth rather than effective parameters in time. It dramatically reduces project time when compared to the sectored approach for any fractured reservoir characterization including shale plays.

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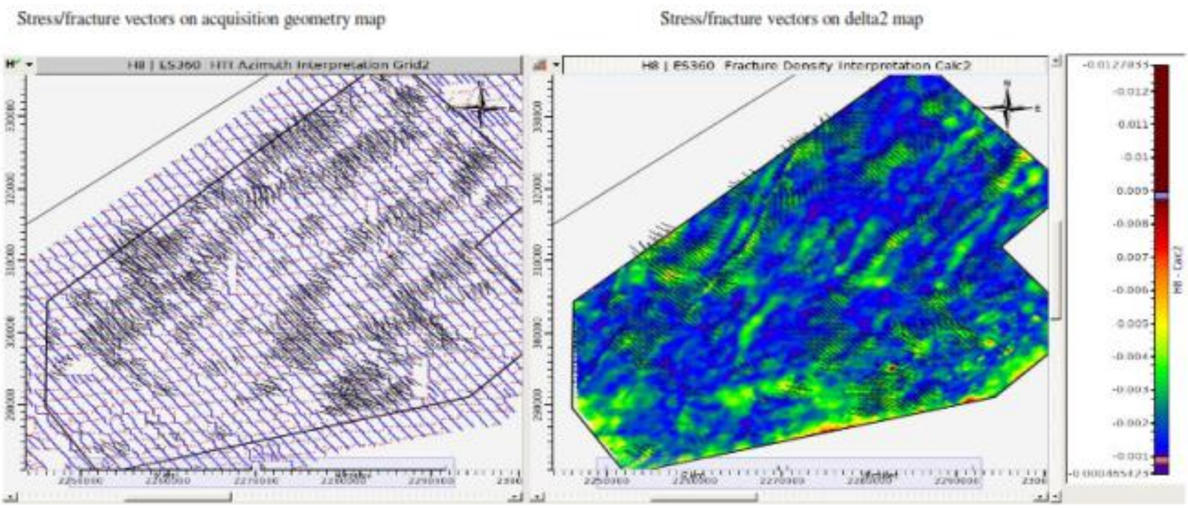

Figure 7: Anisotropic vector overlay on the seismic acquisition and the Delta2 Map

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