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Unconventional Play Fracture Characterization Through Orthorhombic Depth Model Building

Guy Hilburn*[1], Amit Pendharkar[1], William Keller[2], René Mott[2], Jorge Peinado[2], Austin Jumper[2], Victor Kriechbaum[2]; 1. TGS, 2. EnerVest.

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Abstract

Orthorhombic model building and depth imaging can provide information uplift in several ways over more simplistic kinematic models. For unconventional onshore seismic projects time processed results are typically used to suggest a smooth velocity function to attempt to correctly position events vertically, and an azimuthal correction may be applied to the final image gathers to determine directionality of stresses, and therefore fractures, in the subsurface. By adding a depth orthorhombic model building flow to the end of time processing, both models and imaging results are improved. This leads to more accurate lateral and vertical placement of events, improved image interpretation due to focusing and positioning, and an interpretable suite of models to suggest reservoir characteristics such as fracture density and orientation. Taken together, these improvements make drilling and production decisions less risky and more reliable.

Introduction

Onshore hydrocarbon production increasingly depends on resource generation from unconventional reservoirs, which are characterized by strong fracturing of the source rock. When these fractures are open, due to some specific alignment of subsurface stresses, they allow for the flow of gas and oil. However, when they are closed, as when the dominant stress is perpendicular to the fracture orientation, this flow is impeded. Optimal production is therefore obtained when well bores are drilled perpendicular to the path of the open fractures, and across the dominant stress direction, in order to intersect as many open fractures as possible. This method effectively increases the volume of the producing region. This effective volume can be further enhanced during hydraulic fracturing, a process also dependent on the borehole being oriented perpendicular to existing fractures.

The orderly system of subsurface stress and fracture orientation allows for the probing of reservoir properties through models of the earth's kinematic anisotropy. Sound propagation is faster in directions of higher stress, which are also aligned with preferential fracture orientations in unconventional reservoir rock. The imprint of this azimuthal velocity anisotropy can be seen in full azimuth seismic datasets as differential azimuthal moveout in image gathers.

The typical seismic industry standard approach to modeling unconventional play anisotropy is by applying a postprocessing correction to prestack time migration (PSTM, or time processed) imaging results. This often takes the form of a horizontal transverse isotropy (HTI) correction, which defines horizontal fast and slow propagation directions, without need for a true vertical velocity. This is a useful final step for a PSTM flow, to quickly generate an estimate of the magnitude and direction of azimuthal anisotropy. However, expanding this process to a full orthorhombic prestack depth migration (PSDM) and model building project can provide meaningful uplift in a variety of ways.

As with most geophysical applications, the use of seismic data to guide production decisions is an exercise in uncertainty limitation. The industry has learned to utilize PSTM results in ways which mitigate their inherent inaccuracy and reduce uncertainty through leveraging of a priori information, such as depth information from previously drilled wells. However, as acquisition, processing, and validation techniques improve, and as computational efficiency increases, the use of orthorhombic PSDM results for azimuthal analysis in unconventional exploration is quickly becoming more feasible and realistic.

PSDM processing can yield many benefits over PSTM. By defining a true velocity, the vertical and lateral positioning of events in the subsurface can be improved. This leads to an overall improvement in imaging quality and focusing of features. Importantly for unconventional situations, this can also lead to a large uplift in fault and fracture imaging and coherence. Having correctly positioned features, both in the image and model, also allows for better consideration of the overburden in determining azimuthal behavior. In regions with strong contrast and variation in model parameters, a postprocessing flattening of PSTM gathers may not correctly take into account the full propagation environment for the wavefield.

While there are many ways in which PSDM results may improve on PSTM, it is also an inherently more complex situation which necessarily requires additional constraints on results. Without adequate validation and verification, the increase in uncertainty cannot be justified. This is even more true for the orthorhombic situation, where similar datasets are being used to derive a great deal more kinematic information. The expansion of the industry standard model of anisotropy, tilted transverse isotropy (TTI), to the tilted orthorhombic model requires expanding the model space from five to nine parameters, and greatly increases uncertainty in model building (Hilburn et al., 2017).

Fortunately, there are a myriad of methods which may be used to motivate and constrain the accurate generation of orthorhombic results, and then to validate these qualitatively. Fracture systems which influence azimuthal sound propagation are typically on very short scales, much smaller than seismically-resolvable features (Tsvankin et al., 2010). However, these systems are also expected to mimic the directionality of large scale faults, which often are visible in seismic images. The improvement in fault imaging obtained by applying a PSDM flow can greatly enhance the chance to verify the directionality of an azimuthal velocity field through comparison with local faults. Similarly, in areas with important salt features, estimates of stress magnitude and directionality can be obtained through geomechanical modeling, and these can then be correlated with tomographic results.

This work will describe the suggested orthorhombic workflow for unconventional reservoir fracture characterization, and the novel tools used for validation and verification will be introduced. This process has been applied to a well understood central Texas Austin Chalk dataset, with promising results in determination of fracture orientation and density. Imaging uplift, model interpretability, and both added value and uncertainty are analyzed and discussed.

Theory and Method

The expected correlation of stress, which influences propagation velocity, and aligned fracture systems in unconventional reservoirs suggests that orthorhombic model building is appropriate for a PSDM flow to characterize these geological situations. Azimuthally varying stresses lead directly to azimuthal velocity variations which are not taken into account by simpler anisotropic schemes.

The TTI model is defined by two angles which describe the dipping and azimuthal directionality of the sedimentary bedding, by the velocity normal to the bedding V_0, and by two parameters, ε and δ, which describe how the velocity changes away from the normal to the bedding. Near-to-mid angle wavefield propagation is most strongly influenced by δ, while high angle propagation is controlled by ε, with sound speeds along the bedding higher than across the bedding. This situation is straightforwardly expanded to attain the tilted orthorhombic model, which allows for variation in propagation velocity by azimuth. The additional angle α describes the rotation of the fast direction in the subsurface, thereby defining fast and slow axes. The ε and δ parameters are expanded to ε_1, ε_2, δ_1, and δ_2, with the subscript 1 denoting the parameters with influence along the fast axis, and subscript 2 denoting the parameters along the slow axis. These orthorhombic ε and δ parameters behave exactly as their TTI counterparts, along their respective axes. The final new parameter δ_3 describes the deviation from a true ellipse of the velocity distribution between the fast and slow axes, and is typically small and unrelated to the TTI δ value (Tsvankin, 1997).

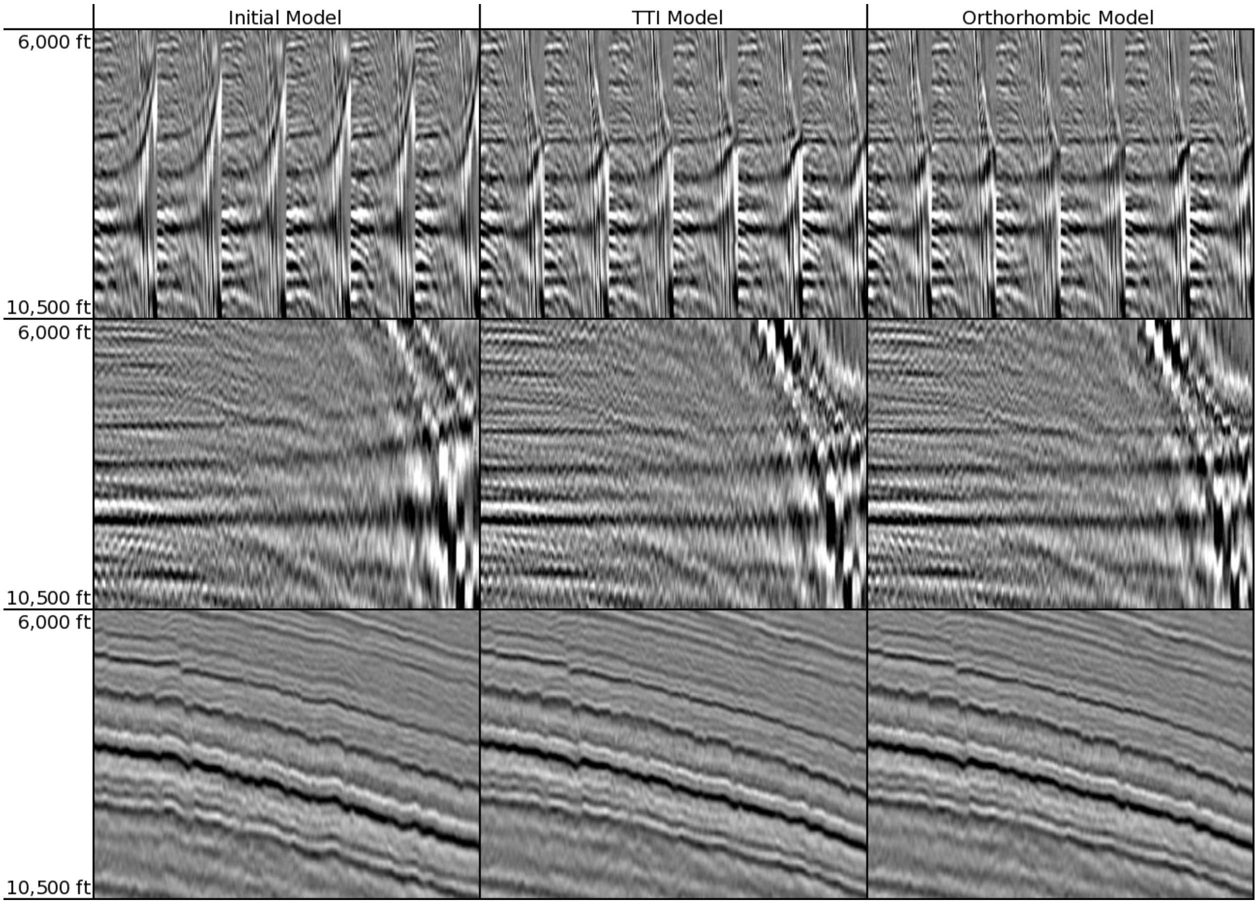

Figure 1: PSDM common azimuth sorted gathers (top row), common offset sorted gathers (center row), and stacked image (bottom row), for the initial model (left column), final TTI model (center column), and final orthorhombic model (right column).

The orthorhombic model building process begins at the conclusion of TTI model building and tomography. Once image gathers are macroscopically flattened across all offsets by updating the TTI model, orthorhombic tomography can be used to resolve the remaining azimuthal moveout differences. This involves a tomographic iteration to build the initial orthorhombic model, and then one or more iterations of orthorhombic tomography, to update the azimuthal parameters (Tiwari et al., 2015).

The initial orthorhombic model building process requires migrating azimuthally-sectored data using the final TTI model. Each azimuthal migration is then used as the basis for an iteration of TTI tomography, updating only each azimuth's ε and δ models. This provides an azimuthal distribution of ε and δ at each point in the model grid, which may be fit to provide the azimuthal fast direction angle α. This also yields initial estimates of the orthorhombic parameters ε_1, ε_2, δ_1, δ_2, and δ_3. At this point α is fixed and will not be changed with subsequent model building steps, but further iterations of orthorhombic tomography may be used to update the other azimuthal properties until the desired gather flatness is obtained (Hilburn et al., 2017).

Results

The presented workflow was applied to a 3D PSDM dataset obtained in south central Texas, largely in Lee county, through the well-known Eagle Ford shale play. Along with the Eagle Ford itself, producing reservoirs in this region can be found in the Austin Chalk and Buda formations, with typical depths from 7,000 to 10,000 feet. This region has been extensively studied, and its dominant fracture direction is known to be in the SW-NE direction (Haymond, 1991; Li and Mueller, 1997).

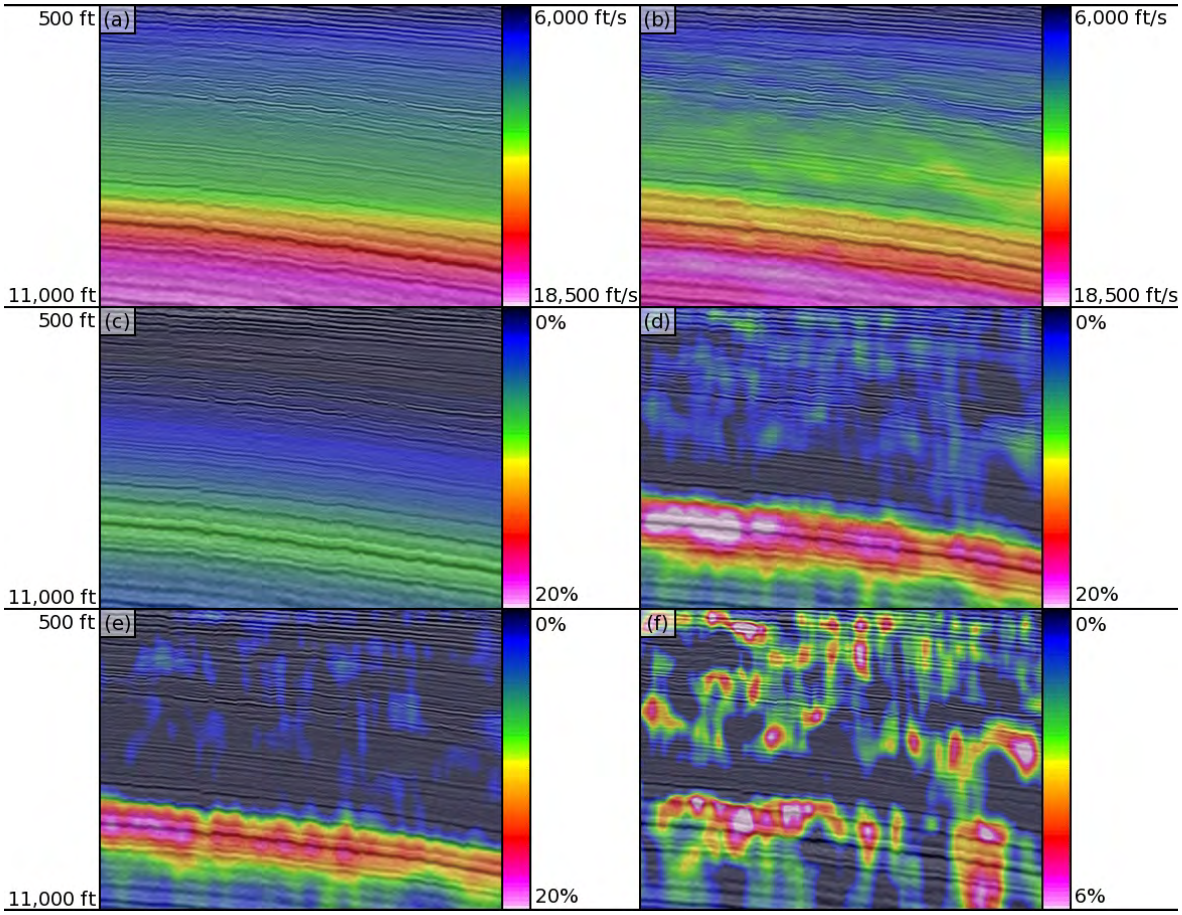

Figure 2: PSDM models: initial velocity model (a), final velocity model (b), initial TTI δ model (c), final orthorhombic δ_1 model (d), final orthorhombic δ_2 model (e), and final orthorhombic δ_1-δ_2 (f).

Imaging improvements through the model building process are shown in Figure 1. The velocity model building steps improve overall gather flatness and simplify the stacked image structure, but there is an obvious azimuthal moveout imprint in the gathers which remains unsolved. Following orthorhombic model building, the gathers are even flatter overall, due to some small bulk TTI corrections, and the azimuthal undulations are largely resolved, suggesting accurate directionality and magnitude for the orthorhombic anisotropy. As the gathers are better aligned, the focusing of the stacked image also improves, primarily helping highlight the fault planes through the area of interest. Deeper horizons, particularly below the strong fault blocks, are geologically simpler following tomography, suggesting that the detailed model is an improvement on the very smooth initial model.

The model changes through the process are shown in Figure 2, for V_0, δ_1, and δ_2. The results for ε are not shown for brevity, as they follow a very similar pattern to δ, but lack some sensitivity in the deeper portions of the model. Of particular interest in the models is the amount of lateral detail required to obtain the best imaging results. All of the parameters show good adherence to the fault planes visible through the region of interest, and this level of detail was necessary to adequately resolve the azimuthal moveout differences.

Discussion

Through the model building process, a variety of quality checks were applied to ensure results made good geological and geophysical sense. The most basic of these is migration gather flatness. As with a typical imaging project, each iteration of tomography is expected to systematically reduce residual moveout. The overall velocity error should decrease consistently during the velocity and TTI model building steps, while the azimuthal moveout disparity should shrink during the orthorhombic iterations, along with any bulk moveout which may be attributed to TTI correction during the orthorhombic updates.

As expected, the imaging improvements during orthorhombic model building are noticeable, but modest, particularly in comparison to the large changes seen during velocity model building. However, it is useful to take a closer look at the image features we are most interested in for unconventional plays – the fault planes. In order to view the faults best, it is necessary to use some method to extract them from the imaging. Figure 3 shows horizon slices along the Austin Chalk formation from coherence volumes generated from the final PSTM and PSDM images. The coherence calculation highlights features which interrupt the dominant directionality of the image, so in many cases they can strengthen the signal from fault planes while diminishing that of coherent sedimentary layers. This makes for an ideal qualitative check of the imaging improvements. PSDM-generated coherence shows much better continuity and consistency in the fault planes, allowing for improved interpretation opportunities.

To best utilize the coherence volumes to check the validity of orthorhombic results, they are overlaid with vectors representing the azimuthal anisotropy, as shown in Figure 4 for two horizons of interest. While these do not show a perfect correlation between major fault directionality and the kinematically derived fast direction, there is a consistent SW-NE trend, matching the known dominant fracture orientation. Through the more orderly center region of the volume, there are locations which correlate very well with the orthorhombic fast direction, particularly in areas of strong anisotropy, where the fast and slow velocities are significantly different.

The interpretability of the model volumes is vital for the usefulness of these types of results, and it can be seen that both directionality, suggesting fracture orientation, and magnitude, indicative of the fracture density, of the azimuthal anisotropy match well with expectations and do not appear to violate any of the several validation methods applied.

Conclusions

Applying an orthorhombic PSDM model building flow to an unconventional play seismic dataset can produce interpretable models which enhance the value of the seismic imaging and provide imaging uplift. This process begins with the final TTI PSDM model and requires one or more extra iterations of tomography. A variety of techniques are used to validate and verify the results, to help alleviate the added uncertainty of the orthorhombic model space.

This process has been used on an unconventional survey from Texas, with the orthorhombic PSDM project improving on the HTI-corrected PSTM results in a number of ways. Imaging improvements are seen in the geological simplification of deep horizons and fault plane clarity of the final PSDM image. This can be enhanced for interpretation by calculating coherence volumes, which are useful for viewing regional fault behavior. In this well explored area, the major fault directionality matches the known dominant fracture direction, providing additional checks on the model results. The kinematically derived azimuthal anisotropy matches these physical features, particularly in areas of high anisotropy, when orthorhombic vectors are overlaid on horizons extracted from the coherence volume.

Leveraging seismic data for better imaging and more realistic models can help guide drilling decisions and reduce production risks. In the case of unconventional plays, orthorhombic model building is ideally suited to help examine the aligned fracture systems which play a vital role in production, by providing imaging uplift and geological model interpretability.

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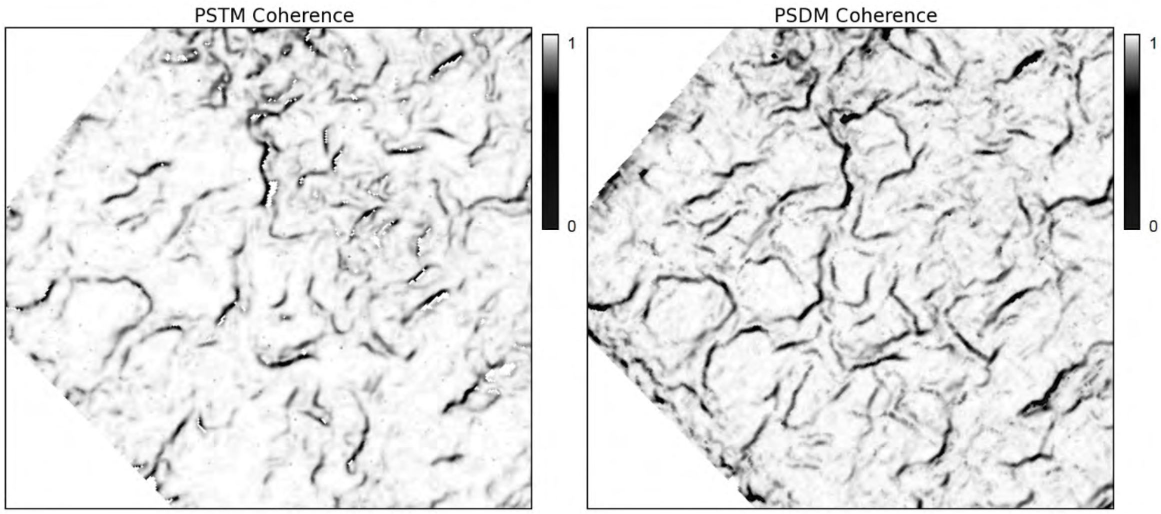

Figure 3: Coherence extracted along the Austin Chalk horizon, for the final PSTM image (left) and final PSDM image (right).

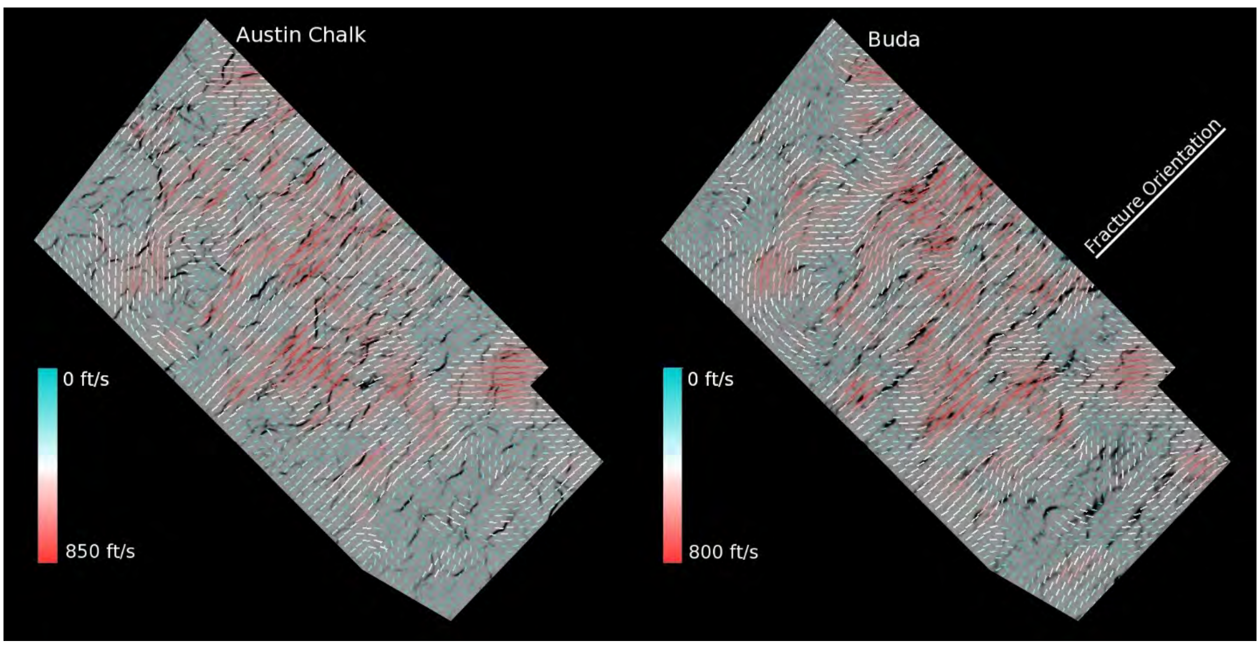

Figure 4: Coherence along two geological horizons, from the final PSDM image, with vectors overlaid to describe the orthorhombic anisotropy. The vectors are oriented along the orthorhombic fast velocity direction, and their color and length scale with the magnitude of the anisotropy, calculated as $V_0(\delta_1-\delta_2)$.

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