# Azimuthal Processing For Unconventional Resource Plays Using An Orthorhombic Velocity Model

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## Summary

Oil and gas production from tight, fractured reservoirs (sandstone, carbonates and shale) has increased significantly over the last decade. These hard rock targets are often characterized by vertically aligned fractures (i.e. HTI) embedded in a layered sequence (i.e. VTI). In this geologic setting, seismic velocities and η can vary with azimuth and depth. This is orthorhombic anisotropy and can be described by an orthorhombic velocity model with VTI and HTI velocity models being special cases. In this paper, we present a method and workflows to take orthorhombic anisotropy into account in seismic time imaging. Synthetic data and real data from unconventional resource plays demonstrate that the proposed method and workflows can produce sharper images, better preserve AVO/AVAZ integrity and increase incident angle available for AVO/AVAZ analysis.

## Introduction

Orthorhombic media is the natural extension of VTI (Vertical Transverse Isotropy) and HTI (Horizontal Transverse Isotropy) media. The moveout of P-waves in orthorhombic media is nonhyperbolic (Xu and Tsvankin, 2004). It is governed by the azimuth of one of the vertical symmetry planes ($\beta$ , the azimuth of $V_{fast}$), the NMO velocities ($V_{fast}$ and $V_{slow}$) in the symmetry-plane directions, and three anisotropic "anellipticity" coefficients ($\eta_1$,$\eta_2$ and $\eta_3$). As shown by Grechka and Tsvankin (1999b), the parameters $\beta$, $V_{fast}$, $V_{slow}$, $\eta_1$, $\eta_2$ and $\eta_3$ are responsible for all time processing steps for orthorhombic anisotropy, including NMO correction, dip-moveout (DMO) removal and time migration.

The estimation of velocity parameters for orthorhombic media is the key for azimuthal processing using an orthorhombic velocity model. The proposed methods by Wojslaw and Stein (2010), and Jenner (2011) estimate the VTI and HTI anisotropic parameters separately with a cascaded approach and consider $\eta$ to be independent of azimuth.

We will first describe our method to simultaneously estimate the velocity parameters for an orthorhombic media. Workflows are then proposed for seismic time imaging. Finally synthetic and real data examples from unconventional resource plays are used to demonstrate the benefits of including orthorhombic anisotropy in seismic time imaging.

## Theory and Method

For a single orthorhombic layer model (Figure 1), the moveout equation for conventional P-waves can be approximated by equation (Xu and Tsvankin, 2004):

$$T^2_{(x,\alpha)} = T_0^2 + \frac{x^2}{V^2_{nmo(\alpha)}} - \frac{2\eta_{(\alpha)}x^4}{V^2_{nmo(\alpha)}[T_0^2 V^2_{nmo(\alpha)} + (1+2\eta_{(\alpha)})x^2]} \qquad (1)$$

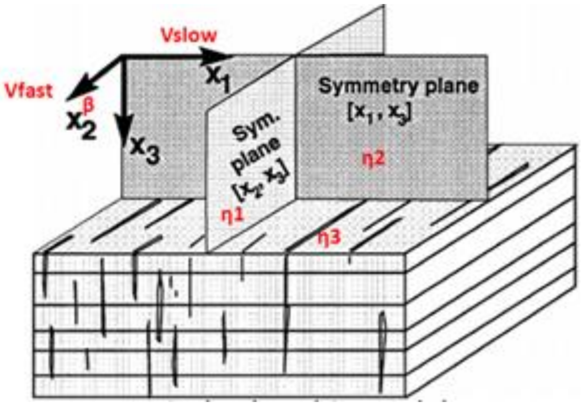

Figure 1: Orthorhombic model (Pech and Tsvankin 2004).

where $T_{(x,\alpha)}$ is the total travel time, $T_0$ is the zero-offset travel time, x is the source-receiver offset, $V_{nmo(\alpha)}$ is the azimuth-dependent NMO velocity, which is

$$V_{nmo(\alpha)}^{-2} = \frac{sin^2(\alpha-\beta)}{V_{slow}^2} + \frac{cos^2(\alpha-\beta)}{V_{fast}^2} \tag{2}$$

and $\eta_{(\alpha)}$ is azimuth-dependent $\eta$, which is

$$\eta_{(\alpha)} = \eta_1 sin^2(\alpha-\beta) + \eta_2 cos^2(\alpha-\beta) + \eta_3 sin^2(\alpha-\beta)cos^2(\alpha-\beta) \tag{3}$$

where $\alpha$ is the source-receiver azimuth.

The orthorhombic velocity parameters are estimated simultaneously. The input is either Common Offset Vector (COV) or azimuth-sectored isotropic pre-stack migrated gathers. In the estimation of the orthorhombic parameters, the initial model is the “best” picked isotropic PSTM velocity field. For strong HTI anisotropy, “best” isotropic velocity is usually between $V_{fast}$ and $V_{slow}$. For strong VTI anisotropy, “best” isotropic velocity is often slightly faster than the vertical velocity. The estimation of orthorhombic parameters is stabilized by proper data preparation, constrains and the characteristics of parameters associated with seismic data.

## Synthetic Example

Figure 2 shows synthetic data containing four events and random noise. The events are from isotropic, VTI, HTI and orthorhombic models. The exact parameters are shown on the right side of the panel. The isotropic NMO corrected gathers (Figure 2, Left) are used to estimate the orthorhombic parameters simultaneously with azimuth-independent $\eta$ (Figure 2, Middle) and azimuth-dependent $\eta_{(\alpha)}$ (Figure 2, Right). The results show that the simultaneous estimation of orthorhombic velocity parameters is accurate and stable, even with a significant level of noise. The comparison of the orthorhombic event between the Middle and Right panels demonstrates that taking azimuth-dependent $\eta_{(\alpha)}$ into account yields a more accurate image.

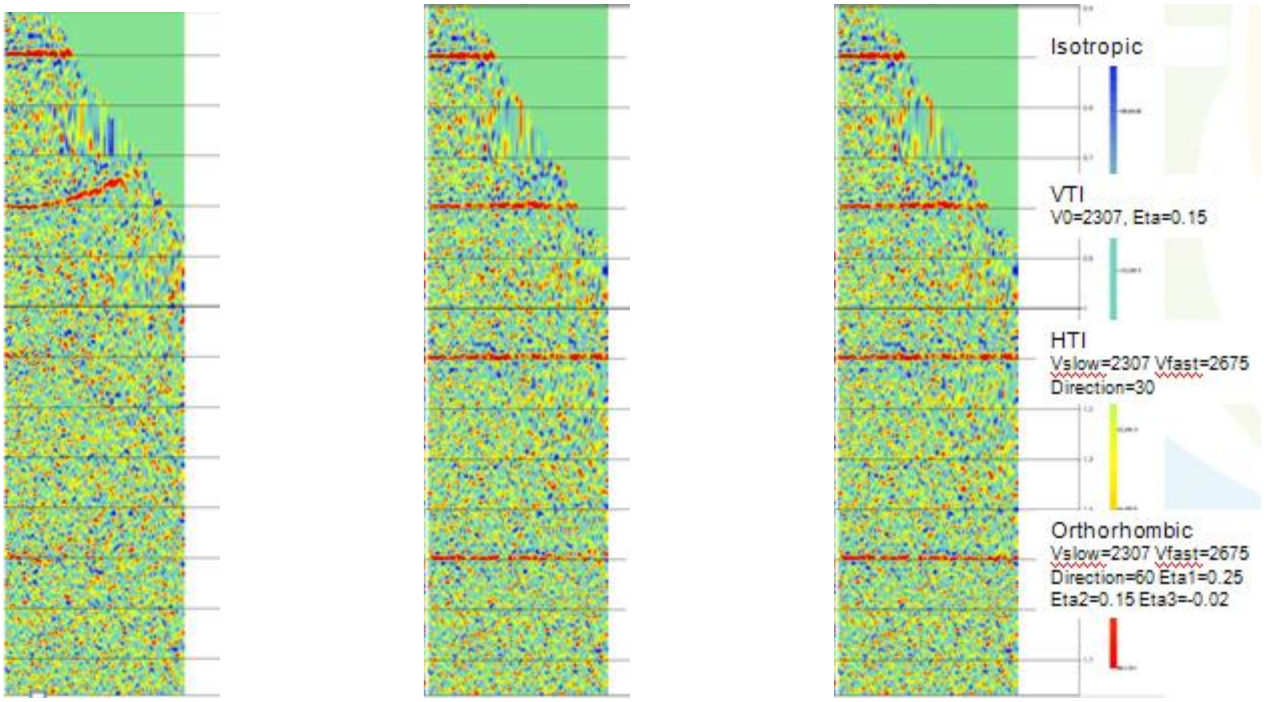

Figure 2: NMO corrected CDP gather with different velocities models. Left: “Best” isotropic velocity; Middle: Orthorhombic velocity model with azimuth-independent $\eta$; Right: Orthorhombic velocity model with azimuth-dependent $\eta_{(\alpha)}$.

## Real Data Examples

Orthorhombic velocity estimation and PSTM were applied to datasets from two shale gas plays and one shale oil play.

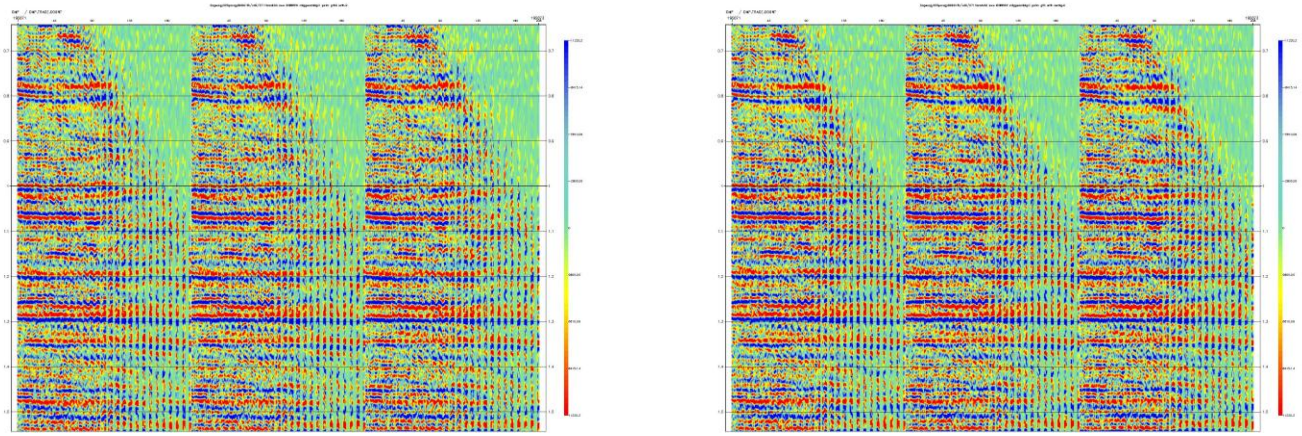

Figure 3: Example image gathers after isotropic (Left) and orthorhombic (Right) PSTM

The first example is from a shale gas play (Figure 3). From the isotropic gathers (Figure 3, Left), significant orthorhombic anisotropy is observed. Orthorhombic velocities estimated from the isotropic migrated gathers are used in orthorhombic PSTM. The comparison of gathers in Figure 3 shows that not only the events are flattened, but the events for medium to larger offsets are also better focused, therefore amplitude variations with azimuth and offset are better preserved.

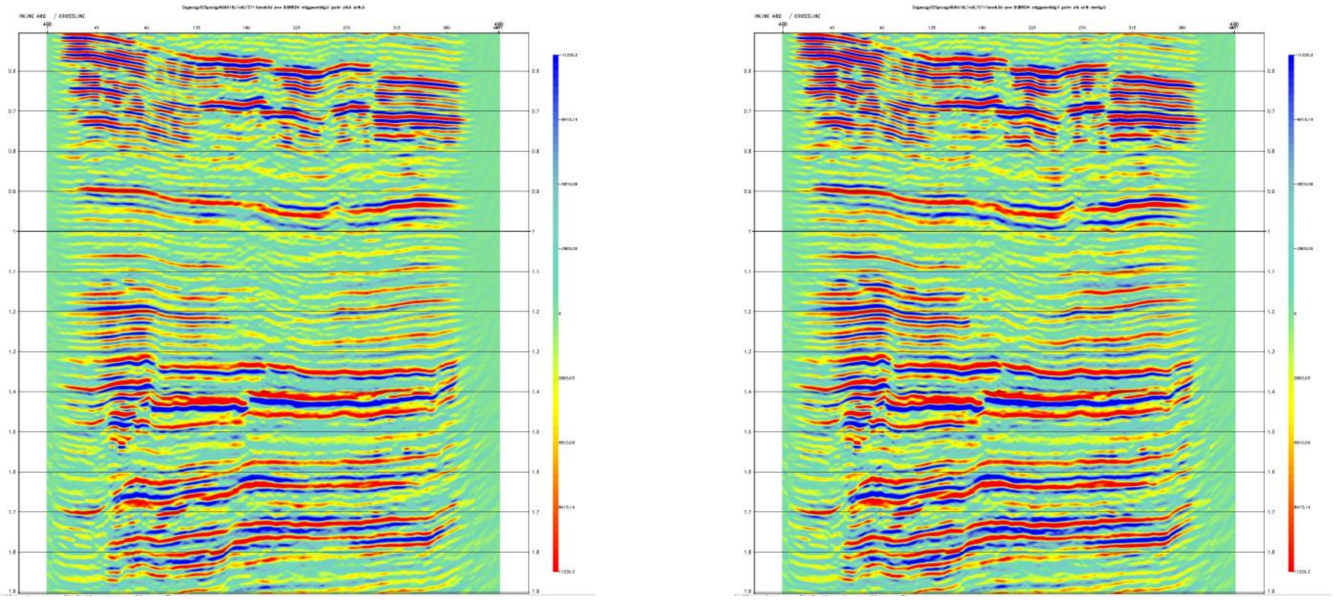

Figure 4: Example stack section after isotropic (Left) and orthorhombic (Right) migration

Improvements, although subtle, are observed in the stacks of the PSTM gathers in Figure 4. The orthorhombic PSTM stack shows improved sharpness and consistency on some events.

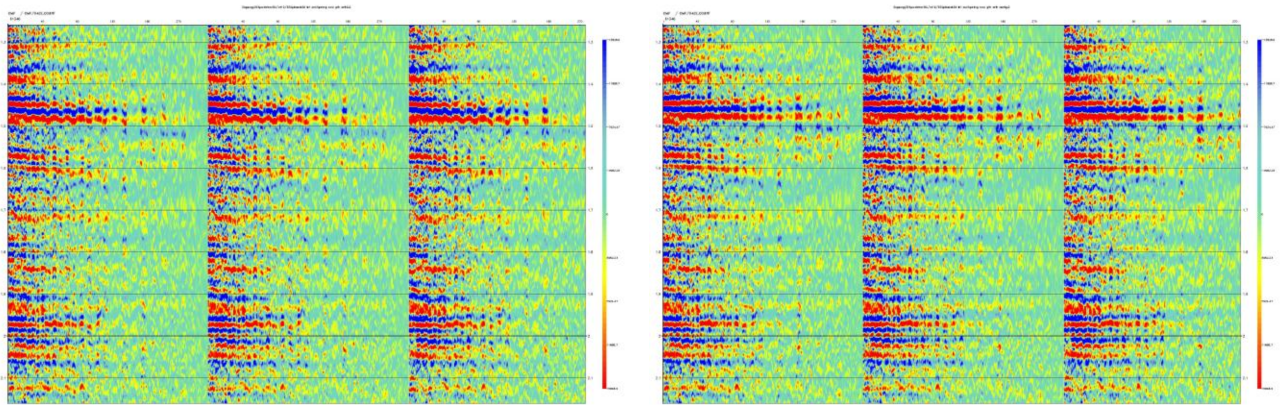

Figure 5: Example gathers after isotropic (Left) and orthorhombic (Right) migration

A second shale play example exhibits significant HTI anisotropy (Figure 5). The processing flow for this dataset is the same as in the first example.  The observations from these PSTM gathers are consistent with those from the first example.

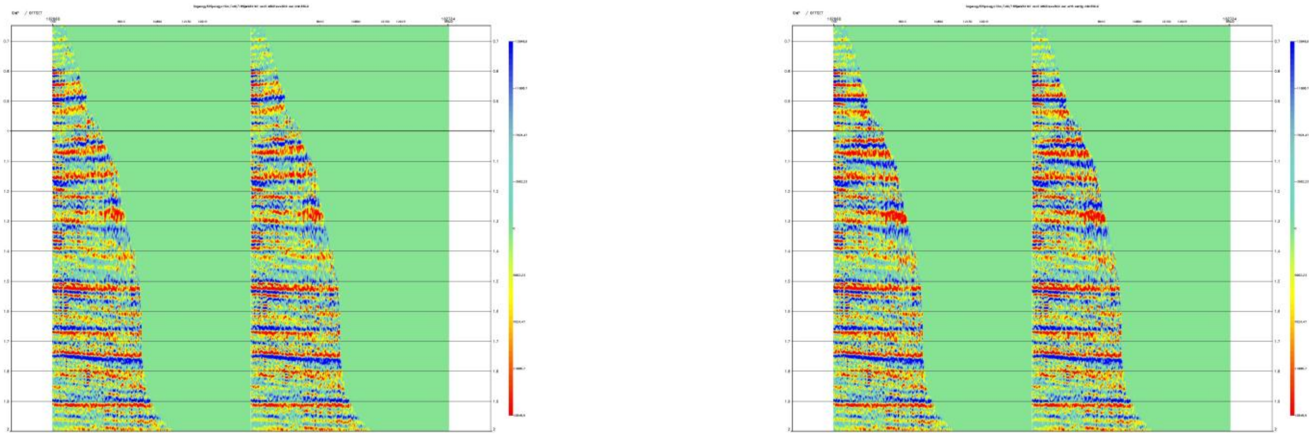

Figure 6: Example gathers after isotropic (Left) and orthorhombic (Right) curve-ray migration

The third example is from a shale oil play. This data has significant VTI anisotropy and therefore curve-ray PSTM is used. After isotropic curve-ray PSTM (Figure 6, Left), the shallow events are still showing strong intrinsic VTI anisotropy. Weak azimuthal anisotropy is observed in this survey, although it is not very significant after checking orthorhombic velocity model [($V_{fast}$ - $V_{slow}$)/$V_{slow}$]. This example demonstrates that with the correction of orthorhombic anisotropy, we can use the data with larger incident angle (i.e. more open mute) for AVO/AVAZ analysis.

## Conclusions

We have developed and demonstrated a stable, practical and effective method and workflows for azimuth processing and imaging using orthorhombic velocity model. Data examples show the robustness of the method to simultaneous estimate the orthorhombic velocity parameters. Real datasets from unconventional resource plays demonstrate that taking orthorhombic anisotropy into account in pre-stack time migration can improve the flatness of gathers, provide larger reliable incident angles and better preserve amplitudes. These enhancements improve imaging and should be beneficial for subsequent AVO/AVAZ analysis.

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### References

Goodway W., J. Varsek, and C. Abaco, 2007, Isotropic AVO methods to detect fracture prone zones in tight gas resource plays, CSPG CSEG Convention, Expanded abstract.

Grechka, V., and Tsvankin, I., 1999a, 3-D moveout velocity analysis and parameter estimation for orthorhombic media, Geophysics, 64, 820 – 837.

Grechka, V., and Tsvankin, I., 1999b, 3-D moveout inversion in azimuthally anisotropic media with laterally velocity variation: Theory and a case study, Geophysics, 64, 1202 – 1218.

Jenner, E., 2011, Combining VTI and HTI anisotropy in prestack time migration: Workflow and data examples, The Leading edge, 30. No. 7, 732-739.

Pech, A., and Tsvankin, I., 2004, Quartic moveout coefficient for a dipping azimuthally anisotropic layer, Geophysics, 69, 699-707.

Treadgold, G., Sicking, C., Sublette, V., and Hoover G., 2008, Azimuthal processing for fracture prediction and imaging improvement, SEG Expanded Abstracts, 988 – 992.

Wojslaw, R., Sten, J., 2010, Orthorhombic HTI + VTI wide azimuth prestack time migrations, SEG Expanded Abstracts, 292 – 296.

Xu, X. and Tsvankin, I., 2004, Geometrical-spreading correction for P-waves in layered azimuthally anisotropic media, SEG Expanded Abstracts.