Tilted Orthorhombic Imaging for Full Azimuth Towed Streamer Data in Deep Water Gulf of Mexico

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Summary

Recently, tilted transverse isotropic (TTI) imaging has become a standard practice in deep water Gulf of Mexico (GOM) to resolve the anisotropic effects of wave propagation in salt-withdrawal mini-basins. When compared to isotropic and vertical transverse isotropic (VTI) imaging, TTI prestack depth imaging generally provides flatter common image gathers (CIGs) for wide azimuth (WAZ) data, improves image focusing, and significantly reduces well/seismic mis-ties. This anisotropy is thought to arise from the geometry of sedimentation processes, with the “tilt” applied by subsequent tectonic activity. However, the presence of significant tectonic stress or uneven stress can cause fractures in thin-bed layers, which results in additional directional velocity variation for seismic wave propagation, or azimuthal anisotropy around the bed normals. In these cases, the transverse isotropic assumption is insufficient to explain conflicting residual moveouts among CIGs of different azimuths from TTI imaging. A more general anisotropic model, tilted orthorhombic (TOR), is needed to cope with azimuthal velocity variation in these complex geological settings. In this paper, we use a full azimuth (FAZ) data set from Keathley Canyon, Gulf of Mexico, to derive both TTI and TOR models. With the TOR model, we observe improved gather flatness among azimuths and improved structural imaging. We also demonstrate the advantage of FAZ data in detecting azimuthal anisotropy over WAZ data.
Introduction

Over the last five years, tilted transverse isotropic (TTI) imaging has become a standard practice in deep water Gulf of Mexico (GOM) to resolve the anisotropic effects of wave propagation in salt-withdrawal mini-basins. However, the presence of significant tectonic stress or uneven stress can cause fractures in thin-bed layers, which results in a directional velocity variation for seismic wave propagation, or azimuthal anisotropy (Lynn and Michelenai, 2011). In these cases, the transverse isotropic assumption is insufficient to explain conflicting residual moveouts among common image gathers (CIGs) of different azimuths. A more general anisotropic model, tilted orthorhombic (TOR), is needed to cope with azimuthal velocity variation in these complex geological settings.

While a TTI model requires five parameters, a TOR model is represented by nine parameters (Tsvankin, 1997). Deriving a set of reliable TOR parameters is a challenging - yet still feasible - task, due to the advances in acquisition and anisotropic imaging technology. First, wide azimuth (WAZ) data have been acquired in most of the deep water blocks in the GOM, and full azimuth (FAZ) data are surging quickly to improve subsurface illumination (Bowling et al., 2010; Mandroux, F., 2012, p.c.). FAZ data provide abundant azimuthal information for deriving these nine parameters. Additionally, during the last couple of years, ray tracing and tomography (Hung et al., 2006; Han and Xu, 2012; Li et al., 2012), Kirchhoff and beam migration (Xie et al., 2011), and reverse time migration (Zhang and Zhang, 2011) have been developed to handle TOR anisotropy.

In this paper, we show limitations of a TTI model representation with full azimuth data and perform TOR model building to remove the inconsistent residual moveouts among azimuths. By correcting for the velocity variations due to uneven stress and/or fractures in the overburden, TOR provides better focusing of subsurface structures in the area. We also demonstrate that FAZ enables us to study TOR anisotropy more effectively than WAZ data.

Figure 1: a) Location of the FAZ survey in Keathley Canyon, GOM. b) A seismic section across the complex overburden area reveals a thrust fold belt in the supra-salt region. c) The rose diagram shows the offset and azimuthal coverage. We use the portion of FAZ data with effective full azimuth coverage up to 10km.

Full Azimuth Towed Streamer Data in the Central GOM

The study area is located in Keathley Canyon, in the central Gulf of Mexico (Figure 1a), which is to the interior of the Sigsbee Escarpment and features complex salt structures. A seismic section through the area reveals faults, carapaces and faulted fold structures in supra-salt region (Figure 1b). Fractures are expected to generally parallel fault strikes in the area (Hilley et al., 2001). The FAZ towed streamer data are acquired using multiple vessels and configurations designed to maximize azimuth
variation while maintaining good offset distribution (Mandroux, F., 2012, personal communication). Although we have offsets greater than 10km in this survey, we only use offsets up to 10km for this study. As we see the rose diagram shows full azimuth coverage up to 10km with reciprocity (Figure 1c).

![Image](image1.png)

**Figure 2:** a) Definition of seven azimuth-offset sectors of the FAZ survey; b) Definition of snail CIGs (Lecerf et al., 2009): increasing offset with azimuth cycles; c) TTI seven-azimuths CIG panels; d) TTI snail CIGs;

The FAZ data are divided into seven azimuth sectors (15°, 45°, 70°, 90°, 110°, 135°, 165°) by azimuth-offset binning (Figure 2a). These seven sectors are migrated to produce the CIGs for multi-azimuth TTI tomographic joint inversion. After three iterations of TTI tomography, we still observe conflicting residual moveouts among azimuths near the folded areas. As azimuth changes from 15° to 165°, we observe the residual curvature gradually evolving from over-corrected to under-corrected, and then to flat, which indicates the need for different apparent velocities in each azimuth to flatten the gathers (Figure 2c). We also sort the data into ‘snail’ CIGs (Lecerf et al., 2009) as defined by Figure 2b, which show a distinct and significant wobbling effect in the snail CIGs (Figure 2d). Clearly, both types of CIGs reveal the limitation of a TTI model in the presence of tilted orthorhombic anisotropy.

**Effect of Azimuth for Detecting Tilted Orthorhombic Anisotropy**

![Image](image2.png)

**Figure 3:** TTI Residual curvature with simulating WAZ geometry. a) azimuth-offset CIGs b) snail gathers. The wiggle display shows zoom in section of Snail gathers.
Here we discuss the effectiveness of FAZ versus WAZ for detecting the tilted orthorhombic effect in the overburden. We limit the crossline offset to 4km to simulate WAZ geometry. Figure 3a shows that the WAZ lacks the resolution to detect inconsistent curvatures among azimuths for several azimuth sectors. Although we still observe the wobbling effect in snail gathers with the simulated WAZ data (Figure 3b), it is not as clear as the FAZ data (Figure 2d) due the lack of far offset in some azimuth sectors. Clearly FAZ has advantage over WAZ in detecting tilted orthorhombic anisotropy. This also may explain how TTI might generate a reasonable model with WAZ data and unwittingly ignore the possible existence of orthorhombic anisotropy.

**Tilted Orthorhombic Tomography of FAZ Data**

For tilted orthorhombic model building, an initial velocity model is extracted from a smoothed velocity model with TTI tomography. Each of the seven azimuths is updated independently using TTI tomography to yield flat CIGs. The parameters of the individual TTI models are then converted to the set of orthorhombic parameters ($v_0$, $\varepsilon_1$, $\varepsilon_2$, $\delta_1$, $\delta_2$, $\delta_3$, $\alpha$) (Han and Xu, 2012; Li et al., 2012). Dip and azimuth models, $\theta$ and $\phi$, are inherited from the TTI model building. At a location near the faulted fold area (marked with a red star, Figure 4a), the direction of fast velocity ($\alpha$) is conformal with the inconsistent curvatures from CIG shown in Figure 2c: TTI CIGs from the 15° azimuth are overcorrected more than those from other azimuths, indicating the azimuth is approximately the expected direction of fast velocity. The difference between $\varepsilon_1$ and $\varepsilon_2$, ranging from 0.03 to 0.06 (Figure 4b), shows the strength of azimuthal anisotropy: the larger the difference, the stronger the orthorhombic anisotropic effect. Overall, we observe that the fastest velocity direction and the strength of azimuthal anisotropy ($\varepsilon_1 - \varepsilon_2$) are consistent with geologic settings. Indeed, we see the direction of the fast velocity is consistent with the strikes of fractures in our study area (Figure 4a).

![Figure 4: a) Estimated fast velocity direction on the surface; b) Azimuthal anisotropy ($\varepsilon_1 - \varepsilon_2$).](image)

After three iterations of TOR tomographic updates, we observe how the gathers are both more consistent across azimuths and flatter overall with TOR imaging. Additionally, the wobbling effects in the snail gathers are greatly reduced (Figure 5a and 5b). The events in the stack are both sharper and more continuous in the supra-salt folded belt (Figure 6).

![Figure 5: FAZ Tor tomography output: TOR seven-azimuth panels (a) and TOR snail CIG (b)](image)
Conclusions

The recently available FAZ data in the Gulf of Mexico provide abundant azimuthal information needed to derive a realistic anisotropy model from the supra-salt overburden. By combining the effective TOR model building approach with FAZ towed streamer acquisition, we observe that 1) FAZ data are more effective in detecting azimuthal anisotropy than WAZ data, and 2) TOR model building with FAZ can better resolve anisotropy in the overburden in the presence of fractures and uneven stress. TOR PSDM with FAZ data improves the imaging of overburden structures. Furthermore, the geologic meaningfulness of the derived azimuthal anisotropy is justified by the observation that the fast velocity direction in the TOR model is consistent with the strikes of fractures in our study area.

Figure 6: a) FAZ RTM sedimentary flood image with model updated by TTI tomography; b) FAZ RTM sedimentary flood image with model updated by TTI tomography and TOR tomography;

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Reference

Li, Y., Han, W., Chen, C., Huang, T. [2012] Velocity model building for tilted orthorhombic depth imaging, SEG Technical Program Expanded Abstracts