High resolution tilted-orthorhombic tomographic inversion to improve velocity modeling and imaging: a case study of its impact on subsalt

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Summary

Several wide-azimuth (WAZ) surveys in the Gulf of Mexico have been acquired to resolve the structure in a complex subsalt region. Long-offset wide-azimuth data can be very beneficial over conventional wide-azimuth acquisition in terms of imaging deeper targets and steeply dipping complex overhangs.

Whenever seismic waves encounter layered media, the velocity they experience parallel to the layering is often greater than the velocity perpendicular to the layering. A transversely isotropic (TI) job flow results in improved imaging for these geological regimes. When sediment layering demonstrates considerable dip, tilted-transverse isotropy (TTI) can improve the imaging over vertical-transverse isotropy (VTI), which best describes purely horizontal layers. In the presence of fractures within thin layered media, it has been observed on multiazimuth data that VTI and TTI approaches are not sufficient in resolving conflicting azimuthally varying residual moveout (RMO) on the common-image gathers (CIG's). However, extending the velocity model from TTI to orthorhombic anisotropy can resolve the discrepancy in the moveout observed for a CIG across different azimuths.

In this paper we will present a case study demonstrating a method of improving subsalt imaging using image-guided tilted orthorhombic (IG-TORT) tomography and imaging on newly-acquired long-offset wide-azimuth Declaration data. In addition, the data is combined with the existing Justice WAZ data in the Gulf of Mexico.

Introduction

Wide-azimuth data acquisition in the Gulf of Mexico has gained a great deal of interest as it provides better subsurface illumination and fold coverage needed to improve imaging, especially beneath complex salt bodies and overhangs.

In recent years, the industry has made continual advances in 3D data acquisition, including narrow azimuth (NAZ), WAZ, rich azimuth (Howard, 2007) and coil shooting (Moldoveanu and Kapoor,2009). WAZ data provides better azimuthal coverage than NAZ, but still suffers from a limited offset range. Hence, these datasets are lacking when imaging poorly illuminated structures such as steeply dipping complex salt overhangs or subsalt. In the Gulf of Mexico, long-offset data has been proven to enhance the imaging of subsalt (Li et al., 2010). Multiazimuth long offset data can further assist anisotropic parameter estimation. When coupled with advanced orthorhombic model building and imaging these methods improve final imaging.

Rock heterogeneity and horizontal stratification imply TI elastic behavior (Schoenberg 1997). The axis of symmetry in the TI cases is defined normal to the rock bedding, assuming that seismic velocity across the transverse plane is independent of azimuth (Thomsen, 1986). In TI models, the velocity of seismic waves is slow parallel to the axis of symmetry and fast perpendicular to the axis of symmetry. Depending on the dip of the sediment layers, vertical transverse isotropy (VTI) and tilted transverse isotropy (TTI) approaches are commonly used to account for anisotropy in layered media.

Uneven horizontal and vertical stresses caused by overburden in layered media may result in fractures within the rock. Aligned vertical fractures within thin layered media lead to azimuthal anisotropy. This azimuthal anisotropy causes inconsistent moveout on CIG's among the various azimuths of the seismic data. To improve imaging in a geological regime dominated by horizontal layering and vertical fracturing, an algorithm is needed which handles both the polar and azimuthal anisotropy simultaneously. In this geologic scenario, extending the model building and imaging from TTI to tilted orthorhombic (TORT) is a logical step to compensate for both polar and azimuthal anisotropy.

In this paper, we will present results of TTI migration over different azimuths to show the limitations of this method, followed by enhanced results from image-guided tilted orthorhombic tomography (IG-TORT). Additionally, the benefits of multiazimuth long offset data are incorporated in the final imaging results.

Survey Area

The Declaration wide azimuth survey is newly acquired 3D seismic data using the StagSeis acquisition technique, with 16 km inline offset and 4800 m of crossline offset.

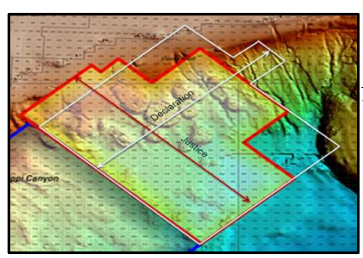

Figure 1: Survey Location map

This survey is located in the Gulf of Mexico and covers 406 OCS blocks in the Mississippi Canyon, coinciding with preexisting Justice WAZ 3D data, which covers 335 OCS blocks (Figure 1). Survey acquisition is directionally orthogonal to the Justice survey, with longer offsets and greater azimuthal coverage; aimed to enhance subsalt illumination. This survey combination is ideally suited to orthorhombic seismic imaging.

Figure 2 (a) and 2 (b) show the offset and azimuth distribution for Declaration and Justice 3D WAZ surveys. Declaration rose diagram plotting assumes source and receiver reciprocity.

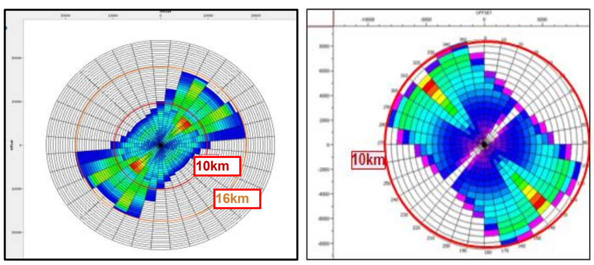

Figure 2: (a) Declaration WAZ-3D offset-azimuth map (b) Justice WAZ 3D offset-azimuth map.

IG-TORT model building

Orthorhombic model building can be divided into three main steps.

1. First, we derive a good TTI velocity model which accounts for polar anisotropy and yields approximately flat gathers for all azimuth sectors.
2. Second, we derive the initial orthorhombic model using the final TTI velocity and six anisotropic parameter models.
3. Third, we refine the initial orthorhombic model using high-resolution image-guided grid tomography.

Step 1 - TTI velocity model building

In the first step, the initial velocity model is calibrated using the available check shots to ensure a good tie with well data. One pass of Kirchhoff prestack depth migration is done using the calibrated model. The CIG's are then used in Focusing Analysis (Cai et al., 2009 and He et al., 2009) to derive the best possible anisotropic parameters at the CIG locations.

Justice WAZ data are divided into three azimuths. Each of these azimuths is migrated using the TTI model. For each azimuth, RMO on CIG's is analysed and used to perform independent ray tracing. These ray files are then combined and inverted to derive the change in the velocity that best serves to reduce the RMO on CIG's for all azimuths simultaneously.

Three iterations of azimuth sector grid tomography were performed to optimize the velocity model in the suprasalt region.

Step 2 - Initial orthorhombic model building

Declaration WAZ data was acquired orthogonal to the Justice WAZ, making a perfect combination for orthorhombic migration. Each survey's data were first divided into six azimuths starting from 0^0 to 150^0 with an increment of 30^0.

TTI migration is done for each azimuth sector data. TTI tomography is performed for all six azimuths independently to derive the epsilon and delta fields for each.

The final TTI models provide six azimuthal epsilon and delta fields. In the next step these models are fit to an approximate ellipse to derive the initial orthorhombic parameters (V_0, ε_1, ε_2, δ_1, δ_2, δ_3, α) (Li, 2012). The remaining orthorhombic parameters ax and ay are retained from the TTI models.

Step 3 – Refining the orthorhombic model

After deriving the initial TORT models, all six azimuth sectors are migrated. Offset-dependent RMO picking and ray tracing are performed on CIG's for each azimuth. The individual ray coverage maps are depicted in Figure 3.

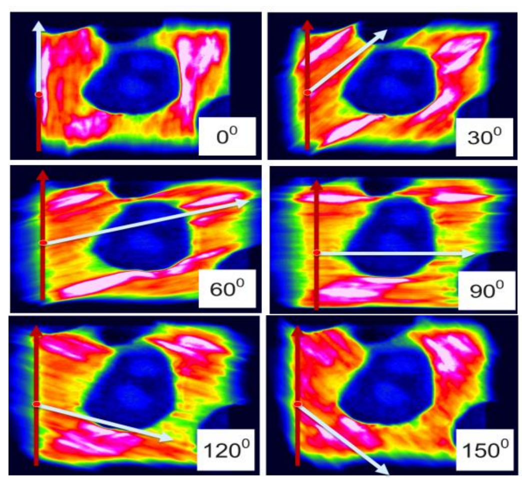

Figure 3: Azimuthal ray tracing QC file

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For image-guided tomography (IGT), we derive several attributes to precondition the inversion, ensuring the solution respects the underlying geology (Hale, 2009a).

The first step in the IGT process uses the TORT-migrated stack to calculate a set of tensors describing the directionality and continuity of reflectors (Hilburn et al., 2014). Using these tensors, we then define an array of update zones whose boundaries are specified by minimizing the structure-oriented propagation time within the underlying image. The zonal distribution, tensors, and propagation time are used to describe the direction and strength of smoothing during the IGT inversion. All six ray tracing results are used in conjunction with the IGT parameters to perform an IG-TORT inversion, which yields a geologically-conformed solution.

Orthorhombic tomography results

Data from all six azimuth sectors were migrated separately using both TTI and orthorhombic approaches. Figure 5 (a) shows TTI CIG's from all azimuths. The events from 0^0 to 30^0 inside the yellow rectangular show over correction, azimuth 60^0 and 150^0 gathers are under corrected, while from 90^0 to 120^0 events appear flat. Figure 5 (b) shows orthorhombic migration results after one iteration of IG-TORT tomography models. The moveout inconsistencies are reduced following the model updates.

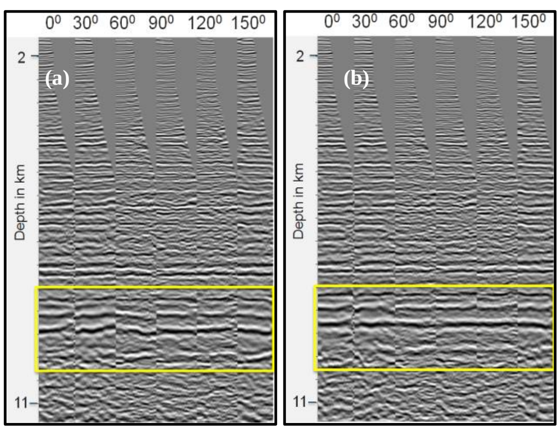

Figure 5: (a) TTI CIG gather for six azimuth (b) CIG gather from the image-guided tilted-orthorhombic migration.

Additional verification of focused multiazimuth CIG data is visualized by combining all azimuths into single "snail" CIG's (Hung et al., 2006; Lecerf et al., 2009).

Figure 6 (a) displays snail CIG's from the final multiazimuth TTI migration and Figure 6 (b) shows a snail CIG after the orthorhombic migration using the model following the first iteration of IG-TORT. The wobbling effect on the snail gather shown in Figure 6(a) has been reduced in Figure 6 (b).

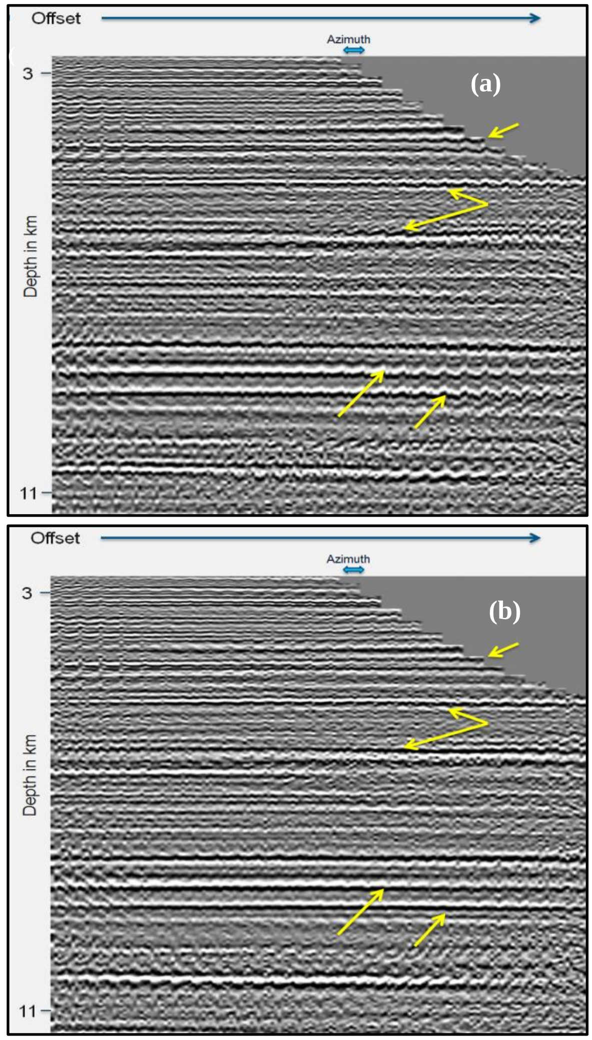

Figure 6: (a) TTI snail gather (b) orthorhombic snail gather after one tomography update

In order to improve efficient quality control, we have generated a 3D azimuth deviation cube which measures an rms percentage of RMO inconsistency for a given CIG gather. In the ideal case, the 3D azimuth deviation cube will be zero.

Figure 7 (a) is a depth slice from the 3D azimuth deviation cube, measured on gathers from a final TTI migration. Next, Figure 7 (b) is a similar depth slice from the orthorhombic prestack depth-migrated gathers, with an

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applied first iteration model update using image guided orthorhombic tomography. Clearly the reduced azimuthal RMO inconsistency is evident after the first IG-TORT model update.

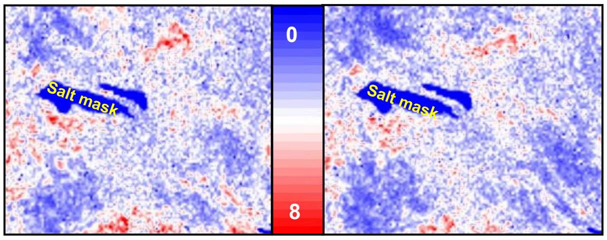

Figure 7: (a) RMS 3D azimuth deviation cube depth slice on the final TTI gather (b) RMS 3D azimuth deviation cube depth slice on orthorhombic migrated gather using the first iteration of IG-TORT model update.

Figure 8 (a) highlights the Kirchhoff prestack depth migration (KPSDM) stack from the final azimuth sector TTI migration. Event continuity near the two yellow arrows is broken, possibly introducing a false structural fault interpretation. Figure 8 (b) shows the orthorhombic KPSDM stack, using the updated model after the first iteration of IG-TORT. Similar indicated event continuity is much improved, which provides a more confident interpretation. Salt closure and the near salt overhang imaging is unresolved on the orthorhombic KPSDM stack. Therefore, the data was then migrated using the orthorhombic reverse time migration (Suh, 2014) approach. Salt closure and the signal to noise ratio near the salt overhang are much improved in the orthorhombic RTM stack as shown in Figure 8 (c).

Conclusions

Declaration long offset data was acquired orthogonal to the preexisting Justice WAZ 3D, providing a rich azimuth distribution. This enables the model building approach to be extended from conventional to orthorhombic, incorporating all azimuths. Image-guided tilted-orthorhombic tomography derives a model that honors geology in terms of layering and faults. This structurally preconditioned orthorhombic inversion provides a high-resolution velocity model update. We have shown that after one iteration of IG-TORT the wobbling effect in snail gathers from orthorhombic PSDM is reduced considerably when compared to conventional TTI PSDM. Also, we have demonstrated a qualitative representation of the wobbling in terms of a 3D azimuth deviation cube that helps analyze the IG-TORT tomography per iteration. Additionally, with orthorhombic KPSDM, it is evident that using a high-resolution model can improve event continuity. While as expected, Kirchhoff can underperform in complex salt imaging, this can be resolved using orthorhombic RTM.

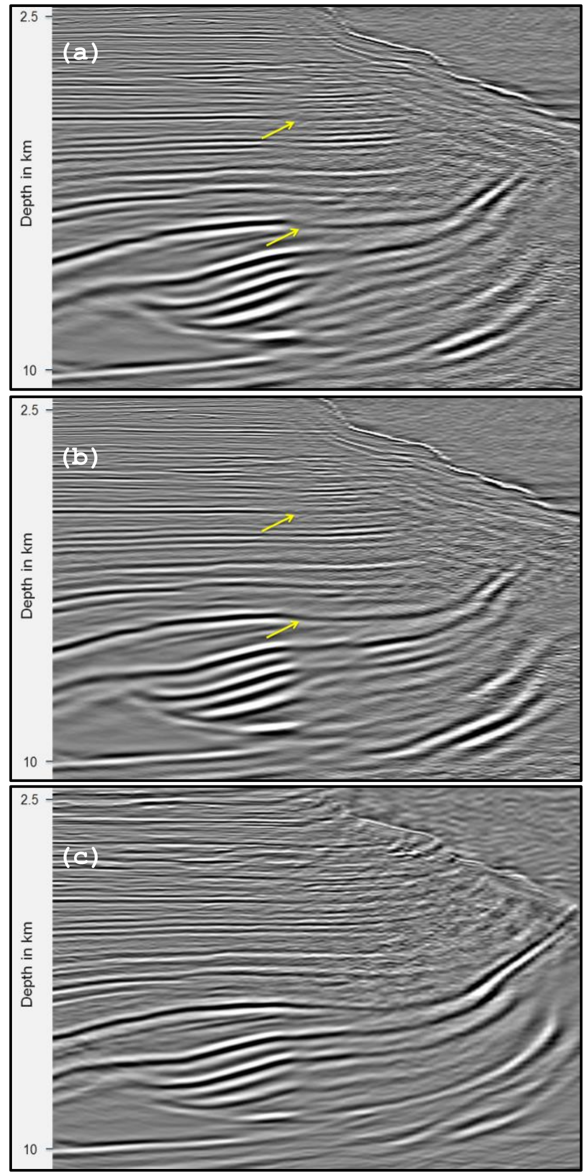

Figure 8: (a) TTI KPSDM stack (b) orthorhombic KPSDM stack (c) orthorhombic RTM stack.

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EDITED REFERENCES

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