Summary

Recent advances in marine seismic acquisition, e.g., wide, and full azimuth, are providing data sets in the deep-water Gulf of Mexico that were uneconomical a decade ago. Seismic processing techniques and technologies are rapidly developing to keep pace with the advances in acquisition. A recent trend in the Gulf of Mexico is to build and image complex salt areas with tilted transverse isotropy (TTI) velocity models and imaging algorithms capable of handling extreme velocity complexity. This paper summarizes the results from a TTI model building and complex imaging project in the central Green Canyon area. Imaging improvements and velocity field convergence (as demonstrated by well ties) were achieved with the TTI workflow. This case study also shows the benefits from using multiple, fit-for-purpose imaging algorithms through the model building process.

Introduction

Initial velocity models are important to the success of a depth imaging project. Tomographic-driven velocity updates are susceptible to errors in the initial model, and convergence to the correct velocity field will occur in fewer iterations when the initial model is closer to the true model. Model building in areas where anisotropy is significant places additional emphasis on getting the initial velocity model parameters correct. TTI velocity models require five parameters (Vp, ε, δ, dip, and azimuth) compared to vertical transverse isotropy (VTI) models requiring three parameters (Vp, ε, and δ), or single parameter isotropic (Vp) models. Uncertainty in each additional parameter, i.e., ε, δ, dip, and azimuth, has a compounding effect on the accuracy of the initial model and in turn on the probability of converging on the correct model with tomography. The added effort to build TTI models is typically rewarded with more accurate images, improved event focusing, correct placement of dipping reflectors, and improved well ties. Previous authors have noted the improvement from TTI imaging in the Gulf of Mexico and in the hydrocarbon basins of Brazil and West Africa (Bakulin et al., 2010; Zdraveva and Cogan, 2011; Huang et al., 2010).

TTI Model Building

In this study we start with a smooth velocity model, free of obvious artifacts from incorrect anisotropy assumptions. Thomsen’s epsilon and delta are derived from 1D ray tracing at well locations and Vnmo calibration for delta. Four wells within or near the survey area were used. Figure 1 summarizes the well-based analysis at one well location. Vp from checkshots (solid dark blue line) and the smooth initial velocity model (dashed dark blue line) were in good agreement. The olive green dashed line is a smoothed delta derived using the picked Vnmo function and the checkshot velocity in the well-known relationship that equates delta to the ratio of these two velocities. The solid cyan and red lines are delta and epsilon, respectively, derived from windowed scanning at the well location. During the scanning process, delta was constrained to the Vnmo-derived delta curve. The dashed versions of the cyan and red curves are the smoothed averages that reasonably fit all of the well data in the survey. The smoothed Vp and averaged epsilon and delta were used to build the initial model. Dip and azimuth were derived from VTI-imaged legacy data. Dip and azimuth were recomputed after each iteration of tomography.

Comparisons of the initial Vp model with a legacy image using a VTI assumption are shown in Figure 2. The legacy VTI model appears more detailed but velocity errors associated with the VTI assumption in a TTI medium are beginning to appear.
TTI imaging and model building

The initial TTI model was updated with three iterations of TTI anisotropic common-image-point reflection tomography as described by Woodward (2008).

Imaging Algorithms

Imaging for velocity model building and salt interpretation employed multiple migration algorithms, depending on the imaging objective. Suprasalt sediment velocities, updated by tomographic iterations, used Kirchhoff depth migration to generate gathers and images. A TTI Kirchhoff algorithm is capable of producing high-frequency images and naturally produces gathers without additional computational overhead. The cost for high-bandwidth TTI images and gathers is low compared to Gaussian beam and reverse time migration (RTM) algorithms. Kirchhoff migration fails to produce an accurate image for prismatic waves or other types of multi-pathing (Bevc and Biondi, 2002). These conditions rarely occur in the suprasalt section.

Salt overhang areas present a problem for conventional tomographic velocity updates. For suprasalt updates, rays travelling through salt are not used until the correct salt body geometry can be interpreted. The salt body cannot be defined until all of the suprasalt sediment updates are complete. This creates a circular problem for sediments beneath salt overhangs. One solution is to execute additional passes of tomography for the sediments beneath the salt overhangs once the salt top and first base salt are interpreted. This tomo update requires an accurate set of gathers for data beneath the salt. Gaussian beam migration is a useful tool because it naturally produces gathers and better handles the multi-pathing and complex ray paths below the salt body. An imaging comparison of a Kirchhoff and Gaussian beam migration from this project is shown in Figure 4. The beam image is everywhere less noisy, and images the salt flanks and sediments near the salt.

For the wide-azimuth data in this project, it was appropriate to continue with multiazimuth tomography. The Gaussian beam migrations were run for three azimuth sectors. Residual moveout was picked on the output gathers and fed...
TTI imaging and model building

into the tomography. The velocity update beneath the salt overhangs tends to be small and localized near the flanks of salt. Figure 5 shows another RMO attribute, root mean square (RMS) of gamma for a window measured from just below the top salt to the base of the overhang. The RMS gamma on the bottom row of Figure 5 shows a 2-3% reduction in the RMO around the flanks of the salt between the initial model and the final through-salt tomography.

Figure 5. RMO attribute (RMS gamma) for through-salt tomography. Dark colors show high RMO, light colors show low RMO. Before tomography (top) shows more moveout around salt flanks compared to after tomography (bottom).

Salt Model Building

To properly image the complex wavefield at the base and below salt bodies, RTM is generally accepted as the preferred algorithm. This project used RTM for all of the salt model interpretation work, starting from the salt flood stage. Successive iterations of RTM floods and salt interpretation were used to construct the final salt body model. An iteration of salt inclusion modeling was also used. The amplitude characteristics within the salt were used to identify the shape of the inclusion in the velocity model (Schoemann et al., 2010). Although attributes can be used to model the inclusions directly, in this case, only large inclusions with a discernable top and base were interpreted. This workflow resulted in improvements in the base salt and subsalt image.

TTI Imaging Examples

For the final salt body imaging, both Kirchhoff migration and RTM were used. The RTM would provide the structural interpretation volume and the Kirchhoff migration would be used to generate AVO products in the suprasalt areas. Final images and velocity models in the study area can be compared to two vintages of legacy data; a 2005 isotropic model and migration, and a 2008 VTI anisotropic model and migration.

The TTI imaging produced a velocity model that is accurate in terms of tying limited well information, geologically plausible, and consistent with the seismic data as demonstrated in gather flatness indicators. Figures 6 and 7 illustrate some of the improvements in the TTI imaging over the legacy VTI image. In Figure 6, the circled area demonstrates one of the biggest changes between the velocity models. The VTI model on the left side shows inconsistent velocities as a function of dip. 9500-ft/s velocities (yellow) at the bottom of the basin slow down (green-blue) and then abruptly speed up (yellow-green) as the dips steepen on the left side of the basin. Velocities as a function of dip are much more consistent in the TTI model on the right image in Figure 6. The arrow indicates improvements to the salt flank imaging; although this is probably due to the use of RTM instead of wavefield extrapolation migration (WEM) as well as a more accurate salt interpretation.

Figure 7 is another example of a geologically consistent TTI velocity model. The image on the left is the legacy VTI model overlaid on the WEM. The image on the right is the new TTI model overlaid on the RTM. The rapid velocity changes in the circled area on the VTI model are in poor agreement with the geology and indicate instability in the model from the VTI assumption. The TTI model on the left has a more continuous velocity behavior and is geologically plausible. The arrow in the TTI image shows better focusing of the salt weld in the TTI RTM.

Conclusions

Many parts of the Gulf of Mexico require TTI anisotropy. Model building and imaging projects like the one in this case study demonstrate the benefits from converting legacy VTI models to TTI, and imaging with high-end migration algorithms. Those benefits can be summarized as: improved well ties with geologically plausible velocity models, velocity models that are consistent with the wide-azimuth seismic data, and improved images around and below complex salt bodies.

Wide-azimuth data were an enabling technology for building TTI models. Improved illumination and better sampling in three azimuths gave tomography sufficient resolution to separate velocity heterogeneity from anisotropy errors. As marine acquisition efforts continue to advance in the Gulf of Mexico, e.g., more full-azimuth data are acquired, the data available for velocity modeling will also improve. Full-azimuth data sets may be the enabling technology for future orthorhombic anisotropy model building and imaging projects.
TTI imaging and model building

Figure 6. Comparisons of VTI anisotropic velocity model and WEM image (left) to the TTI velocity model and RTM image (right). Areas of improved salt flank imaging (arrow) and simplified velocity model (circle) are indicated.

Figure 7. Comparisons of VTI anisotropic velocity model and WEM image (left) to the TTI velocity model and RTM image (right). Improved imaging of the weld between the two salt bodies is indicated with a black arrow and evidence for a geologically simpler velocity model is circled.

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EDITED REFERENCES
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