Leveraging anisotropic workflows in changing times: Two case studies from the eastern Gulf of Mexico
Michael O’Briain*, WesternGeco; Todd Jones ,Wai-Ching Ho, Tom Kastner, Noble Energy; Donal Griffin,
Consultant; Olga Zdraveva, Marta Woodward, and Chris Ennen, WesternGeco

Summary
In the pursuit of ever improved imaging in the Gulf of Mexico a number of trends in velocity model-building workflows appear to be emerging. A first trend has been the shift towards increasingly more complex anisotropic as part of prestack depth migration (PSDM) workflows. A good example is the move from vertical transverse isotropy (VTI) imaging to tilted transverse isotropy (TTI) imaging in complex areas. Another trend, particularly in production settings, is the growing requirement for delivery of seismic images that tie all available well data together with an understanding of the uncertainty associated with that image. A final trend is the realization that additional drilling regulations are likely to require a much more thorough understanding of the shallow section.

A flexible model-building workflow is therefore needed that can be tailored depending on project objectives and the availability of additional data. Such a workflow would allow for a proactive approach in anticipation of additional regulations, while maximizing the value that can be derived from the velocity model.

In this paper we present two case studies from the eastern Gulf of Mexico with different degrees of geological complexity and project objectives. We illustrate the use of a flexible and adaptable workflow for anisotropic model building and suggest the trends that such a workflow may capture in the future.

Introduction
In recent years we have seen great advances in imaging technology, which, together with new wide-azimuth acquisition, have resulted in greatly enhanced images in even the most complex structural settings as shown by Kapoor et al. (2007). With more advanced algorithms such as reverse-time migration, there comes the requirement for earth models with even greater resolution and accuracy. To achieve this accuracy, accounting for anisotropy and incorporating all available non-seismic data and knowledge into the model building process is becoming increasingly important.

Depth imaging with VTI models requires estimating of three model parameters, vertical velocity $V_{p0}$ and Thomsen parameters $\delta$ and $\varepsilon$. Extension to TTI requires an additional two parameters describing the tilt of the symmetry axis. It is not possible to uniquely determine $\delta$ and $\varepsilon$ from the tomographic inversion of seismic data alone. Incorporation of well information and ensuring that the inversion process produces a model that is both geologically and geomechanically plausible are required.

The two case studies included in this paper (Figure 1) use variations of a generic anisotropic model building workflow as described by Zdraveva and Cogan (2011). In the first, less geologically complex setting, we demonstrate how VTI tomographic model building with well marker constraints and simultaneous update of multiple anisotropic parameters was successfully used to produce a fully calibrated earth model suitable for production objectives. In the second case we illustrate how structural complexity requires a TTI tomographic model building approach with both well constraints and the geological constraints of steering filters to produce a final model suitable for exploration objectives.

Figure 1: Location of two case studies in the Eastern Gulf of Mexico, Case Study 2 (left), Case Study 1 (right)

Anisotropic model building workflow
Figure 2 illustrates a generic TTI workflow that was described by Zdraveva and Cogan (2011). This generic workflow allows for great flexibility and was easily adapted to the available information and geological objectives of the two projects.

One of the underlying premises of the workflow is the recognition that anisotropy can have a significant effect on the positioning of events and it is, therefore beneficial to introduce anisotropy as early in the flow as possible. Such an initial estimation, provided that it is in the ballpark, can be refined during subsequent iterations provided that we do...
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a recalibration of the velocity model followed by a minimum of at least one additional iteration of tomography.

Multiscale CIP tomography as described by Woodward et al. (2008) is used to update the velocity model. It is an iterative process involving remigrating the data after each update. During the early iterations emphasis is on solving velocity heterogeneity so typically $V_{p0}$ alone is updated. Larger scale-length variations in the model are solved for first, and with each successive iteration, shorter scale-length variations in $V_{p0}$ are introduced.

For the two case studies presented in this paper, we began with step 2 because there were enough wells available to characterize the spatial variation in anisotropy. In the iterative loop between steps 4 and 5, we introduced various constraints to the tomography.

The workflow is easily adapted, depending on the project objectives. For example, Sayers et al. (2002) showed the benefits of using a tomographically derived velocity model for pore pressure estimates. In Case Study 2 the workflow was therefore adapted to allow for an additional high-resolution iteration focused on shallow-hazard objectives in parallel with the main velocity model building effort.

Another natural extension of the workflow could be the quantified study of the uncertainties associated with the final model as explained by Osypov et al. (2010). The output from uncertainty workflows is a set of equally probable models that explain all observed data. The statistical analysis of these models can provide valuable information to help reduce exploration risk (e.g., trap failure), drilling risk (e.g., dry wells), and volumetric uncertainties.

Tomography with additional constraints

The multiscale tomography as implemented allows for great flexibility in terms of the addition of constraints to guide the solver to converge to the desirable solution. Geological constraints can be added by the judicious weighting of picks along interpreted horizons or within specific geologic intervals; thus, helping emphasize layering in an implicit way without introducing explicit horizons. Alternatively, more implicit geological constraints can be added with the use of preconditioning steering filters or a combination of both.

As discussed by Bakulin et al. (2010a,b), when the data measurements constrain the problem well, it is reasonable to implement the preconditioner as a 3D, nondirectional, isotropic smoother. With this method, a 3D scale-length smoother is used that varies in X and Y as a function of depth and produces the smoothest possible model that will flatten the gathers. However, when the data are insufficient to constrain the problem, we can use steering filters as described by Clap et al. (1998) to shape the update to follow geological constraints. The steering filters are calculated from a dipfield that, in turn, is estimated from the seismic data itself. Tomographic preconditioning then takes the form of smoothing the property updates directionally along structural dip rather than horizontally as in the isotropic case.

In later iterations of tomography, with long-wavelength heterogeneity accounted for, additional well constraints can be added to help the solver converge to a solution that also minimizes mis-ties at wells. These well-constraints may take the form of marker mis-ties, VSP, or check-shot constraints. To both reduce mis-ties and maintain gather flatness it is necessary to allow the tomography solver to also update anisotropic parameters in addition to $V_{p0}$.

Case Study 1: A production environment

This first case study from the Mississippi Canyon area in the eastern Gulf of Mexico covers an area of 70+ Outer Continental Shelf (OCS) blocks and is located in water depths of approximately 6500 ft. The target reservoirs in this complex area are of mid Miocene age, located in
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relatively flat lying geology at depths of 18000 ft and away from complex salt structures as seen in the right panel of Figure 1. This reprocessing project incorporated three phases of underlying nonexclusive narrow azimuth data. The objective of the project was a similar high-resolution anisotropic prestack image over the area with emphasis on amplitude preservation and detailed well calibration to enable accurate depth positioning.

An initial estimate of Thomsen’s $\delta$ and $\varepsilon$ trends was derived by averaging spatially variable functions from previously processed data. Depth errors at this initial stage were under 2%. These profiles were then hung from the water bottom and, together with a $V_{p0}$ created by scaling and smoothing a legacy isotropic velocity field, were extrapolated to create 3D property volumes. These volumes formed the initial VTI model going into tomography.

Following the first iteration of tomography, 1D forward modeling and inversion at each well was used to make a further refinement to the initial anisotropy trends. This is illustrated in Figure 3 where we see the analysis at one such well location.

After the 2nd iteration of tomography, depth errors were just under 1% so for this and the final 3rd iteration well-marker constraints were added to further reduce mis-ties. The tomography was allowed to simultaneously update $V_{p0}$ and $\varepsilon$ to maintain gather flatness. The final mis-ties were thus reduced to $< 0.2\%$ (33 ft). The mis-tie reduction from iteration to iteration is shown in Figure 4. An example section showing the $\Delta V_{p0}$ and $\Delta \varepsilon$ for the well-constrained iteration is illustrated in Figure 5. We see clearly that the update with constraints has not introduced any anomalous ‘bulls-eyes’ around the well and the smoothly varying $\varepsilon$ trend has been maintained.

Case Study 2: An exploration environment

The second case study is from the Ewing Bank area of the eastern Gulf of Mexico, extending over 100+ OCS blocks in water depths ranging from 80 to 1200 m. In contrast with the previous case study, the geological setting is considerably more challenging as shown in the left panel on Figure 1. The area is characterized by a dramatic salt canopy with complex salt wings, overhangs, and welds, together with associated steeply dipping minibasins. Suprasalt carapaces, dirty salt, and sediment rafts further complicate the picture. The targets are the poorly illuminated Miocene structures in the subsalt mini basins.

The overall objective is an improved image for structural interpretation by means of accurate velocity model building, high-end imaging algorithms, and high quality wide-azimuth (WAZ) input data. Additional objectives are; 1) to minimize depth prediction errors (+/- 100ft at target), 2) a well-defined salt and velocity model for a drilling program, and 3) velocities suitable for pressure prediction work.

The structural complexity mandated the use of TTI imaging to stabilize some of the non-geologic variability seen on the VTI model in the deep minibasins. This was confirmed in the comparison shown in Figure 6 where we see a section from the final tomographic TTI sediment velocity model compared with the original VTI model. The initial TTI model was a smoothed version of the legacy VTI model with the dip and azimuth for the symmetry axis taken from the seismic image volume, assuming complete structural conformance.
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The velocity model building took a similar approach to the previous case study. 1D modeling and inversion at well locations was used to come up with initial Thomsen’s parameters $\delta$ and $\varepsilon$. Tomography with well marker constraints and simultaneous updating of $V_p$ and $\varepsilon$ on the final two tomographic iterations enabled reducing average mis-ties to $< 0.75\%$, in line with project objectives.

The velocity model building differed in that additional geological constraints were added to the tomography because of the structural complexity. These led to more stable and geologically conformable velocity updates. The benefits of this approach are illustrated in Figure 7, in an area of overturned exotic raft sequences comprised of anomalous high velocities. Additional iterations of localized tomography with selective weighting of picks, together with steering-filter preconditioning, were successful in stabilizing the update where the conventional isotropic tomography preconditioner failed to produce a reasonable update. These geologic constraints helped recover velocities in the raft center of around 3660 ft/s. The final updated model in the area of the raft is shown in Figure 7b, compared with the model before the localized tomography with steering filters.

At the time of writing, the sediment tomography has been completed and the project has commenced two parallel phases. In one phase, the project is beginning salt definition with the objective of imaging the deeper section. In a parallel phase, additional, higher-resolution tomography is being run focusing on the shallow to mid section with an emphasis on producing a high-quality velocity model that will be suitable for pressure prediction work and hazard identification.

Summary and conclusions

Two case studies, showed the application of a flexible anisotropic model building approach that makes use of all available information and can be tailored to meet project objectives. We illustrate VTI imaging with well constraints, realizing an objective of improved resolution and minimal mis-ties. We also showed TTI imaging with geological constraints in an exploration environment achieving success, for both improved deep structural imaging and shallow hazard identification.

As a new era in deep-water drilling unfolds, workflows such as the ones described are, likewise, evolving to meet future challenges. Such workflows will better leverage the potential of the velocity model towards producing an improved image, not only in the more traditional subsalt section but also in the shallow section, minimizing drilling uncertainty and risk.

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