



Building Anisotropic Models for Depth Imaging: comparing different approaches

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Abstract

Seismic images are only as good as the velocity models used to produce them. As we move from “easy oil” to “difficult oil”, targets in subsalt, sub-basalt, and deep complex areas, we can no longer build the simple isotropic models of the past. To fully leverage the potential of new data types (e.g., wide azimuth and long offsets), we have to move to anisotropic imaging (VTI or TTI) in all geological provinces. Incorporating anisotropy increases our ability both to focus the seismic data and to accurately position our seismic images for drilling decisions. While these goals are achievable with anisotropic models, they are only met when geology and data from boreholes are intimately incorporated into velocity model building from the very start. We discuss several different approaches for anisotropic model parameter estimation and we illustrate some of the possible strategies for model building with case studies from the Gulf of Mexico and West Africa.

Introduction

Anisotropic depth imaging with vertical or tilted transversely isotropic (VTI or TTI) models has become the dominant industry practice in recent years. However deriving all the parameters needed to describe a transversely isotropic medium throughout a 3D model suitable for depth imaging is far from trivial. A TTI model requires five parameters: symmetry-axis velocity (V_{p0}), Thomsen parameters ϵ and δ , and two angles describing the tilt of the symmetry axis. Over the last decade, we have developed many methods and techniques for deriving anisotropic parameters and building and updating VTI and TTI models for depth imaging. We have organized them in multiple workflows that enable us to pursue flexible approaches, optimally using all the information available in any situation. The three case studies included in this paper illustrate the importance of having a broad portfolio of tools and techniques that allow the design of fit-for-purpose model building strategies.

For all of the studies, we build anisotropic models using variations of the generalized workflow described by Zdraveva and Cogan (2011) and evaluate the final model correctness by the impact on image and model quality and ties to well data. We start with models from previous imaging efforts, either isotropic or anisotropic, using a single compaction trend hung from the water bottom. We

then compare against wellbore-calibrated TTI models or models fine-tuned by using tomography with well marker constraints. Because many anisotropic models will fit a single surface-seismic data set, we evaluate the final model correctness not only on image focusing, reduction of residual curvature, and ties to well data, but also on the geological and geomechanical plausibility of the model and image.

Anisotropic parameters derivation and different approaches for 3D model building

Because surface-seismic data alone do not constrain all anisotropic parameters, an important step of any anisotropic model building workflow is to evaluate Thomsen's parameters and build local anisotropic models around wells where additional information is available. Examples of such techniques include:

- 1D layer-stripping modeling and inversion with well data.
- Localized tomography with well data (Bakulin et al., 2010a and 2010b).
- Tomography with uncertainty analysis (Bakulin et al., 2009).
- Trial-and-error scenarios in combination with 3D tomographic inversion with quick feedback loop.

The first technique is applicable only to 1D VTI media and vertical wells: whereas, all the other methods can be applied to general 3D TTI media and allow incorporation of borehole data from deviated wells.

Once we have local anisotropic models around each well, we need to be able to construct a global 3D anisotropic model and propagate ϵ and δ away from and between wells. The latter can be achieved using a variety of techniques:

- Assume compaction, average and smooth local results and hang them from the Water bottom
- Interpolate local results using a structural framework composed from interpreted horizons
- Interpolate local results using volumes of NMO velocity and anellipticity (η) derived from layered 1D VTI inversion (Fowler et al 2008)
- Interpolate local results using a calibrated rock physics model (Bacharach 2010) or rock physics correlations and basin modeling.

Figure 1 shows a schematic of the generalized anisotropic model building workflow described by Zdraveva and Cogan (2011) that uses all methods and techniques described above. It has five main steps: (1) Evaluation of anellipticity over the full project area; (2) Derivation of Thomsen's δ and ϵ at well locations; (3) Construction of a model with all three or five 3D property fields required to describe a VTI or TTI medium; (4)

Validation of the model; (5) Several iterations of multiscale common image point (CIP) tomography for V_{P0} fine tuning.

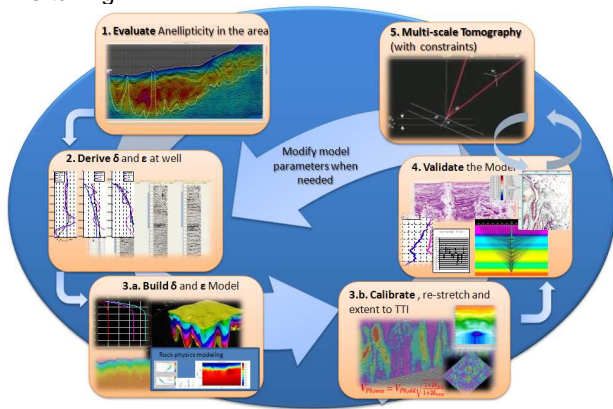


Fig. 1 - Generalized workflow for anisotropic model building, easily adaptable to availability of any additional information.

This workflow allows the anisotropic parameters ϵ and δ to be adjusted as required during the iterative loop between the last two steps. As long as we recalibrate the V_{P0} and do at minimum one additional tomography iteration after the adjustment, the normal convergence logic of the multiscale tomography loop will not be destroyed.

Case study from Walker Ridge area of Gulf of Mexico

The Walker Ridge area of the Gulf of Mexico is characterized by shallow allochthonous salt sheets of variable thickness and water depths ranging from 1,500 m to more than 3,000 m. In this case study we use wide-azimuth (WAZ) data over 180 outer continental shelf (OCS) blocks and nine wells, and we compare the imaging and well mis-ties arising from migration with three models: a legacy isotropic model; a VTI model calibrated with three wells; same VTI model refined by running tomography with explicit Wilcox marker constraints. The workflow used follows closely steps 2 to 5 of Figure 1. Local models were built around three public-domain wells using 1D modeling and inversion. An averaged, smooth trend fitting all of them was extracted. Figure 2 shows the results from the 1D analysis at one of the wells.

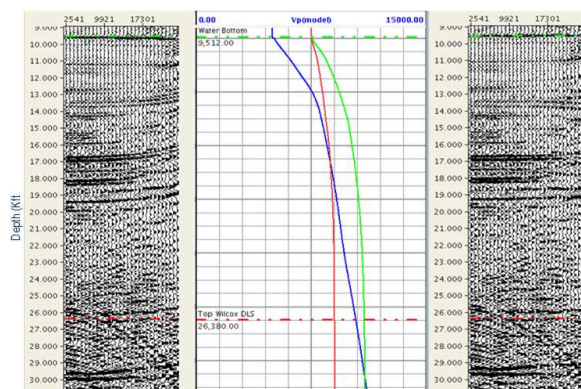


Fig. 2 - 1D modeling and inversion at well location: modeled moveout on seismic gather in isotropic medium,

with check-shot velocity clearly showing the need to incorporate anisotropy (left), calibrated velocities and derived ϵ and δ (middle), and a gather with corresponding modeled moveout (right).

The average ϵ and δ profiles were hung from the water bottom, V_{P0} from a 2005 isotropic model was calibrated and three iterations of extra-salt multiazimuth (MAZ) multiscale tomography (Woodward et al 2008) were run to finetune V_{P0} , with all salt bodies masked out. What most makes this case study interesting is that after final definition of the salt bodies, an additional iteration of tomography was run to update V_{P0} subsalt and away from salt using explicit well marker constraints for the target Wilcox horizon. Figure 3 compares the results from a legacy isotropic model and from the new VTI model, both before and after the tomography update with marker constraints in the area of three of the wells.

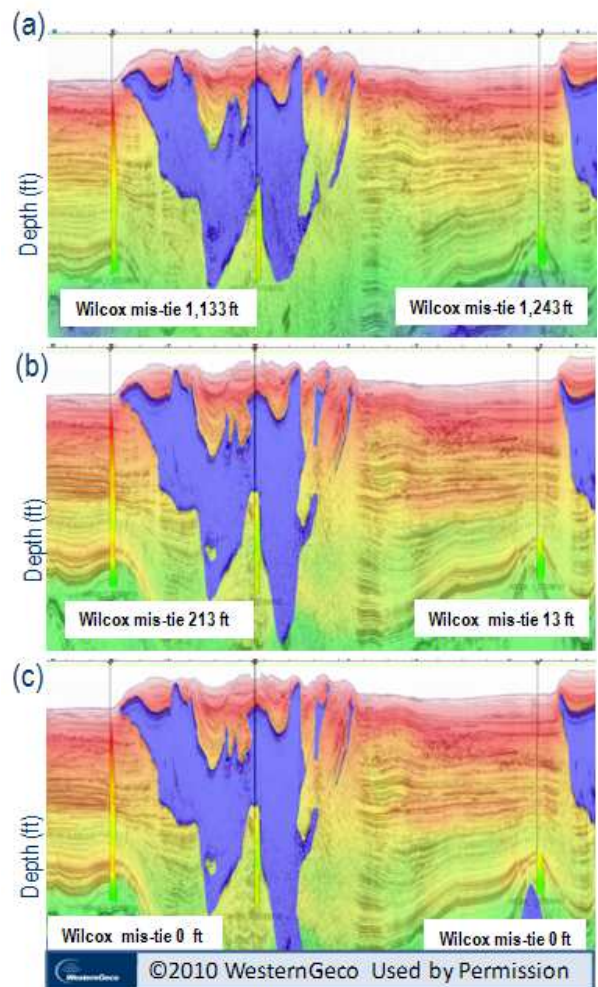


Fig. 3 - Seismic image produced by WEM with velocity model and wells overlaid on it: (a) Isotropic model; (b) VTI model before constrained tomography and (c) VTI after constrained tomography, note the 0ft mis-tie in the two wells in deep basin areas.

We obtained very high-quality images with the two VTI models and, for all wells in the area, mis-ties were dramatically reduced compared to the legacy isotropic

model where they were well above 1000 ft. We demonstrated that, by running tomography with explicit well-marker constraints, we were able to reduce mis-ties in all wells in the area to less than 100 ft at a target depth of close to 30 k ft, including wells that were used neither in the initial analysis nor as constraints in the tomography.

Case study from Green Canyon area of Gulf of Mexico

In this case study, we built a 3D TTI model over more than 400 OCS blocks using WAZ seismic data and check-shot and wireline log data for 11 wells. As a starting point we used an existing simple VTI model built using uncalibrated ϵ and δ trends hung from the water bottom and V_{PO} updated with three iterations of MAZ multiscale Tomography. In 2010 the Thomsen parameters ϵ and δ were estimated at 11 public domain wells by jointly using well and surface-seismic data in a 1D layer-stripping modeling and inversion (Zdraveva et al. 2010) scheme. The new calibrated ϵ and δ profiles were obtained by averaging and smoothing five of these profiles in an attempt to remove high-frequency features that could not be accurately propagated in the subsurface over such a large area.

The profiles were then used together with a V_{PO} field from the second iteration of the old VTI model and a structural framework consisting of two major horizons and water bottom to construct a TTI model using a method described by Zdraveva et al. (2010). Figure 4 shows delta fields overlaid on seismic data for the old VTI model and the new TTI model.

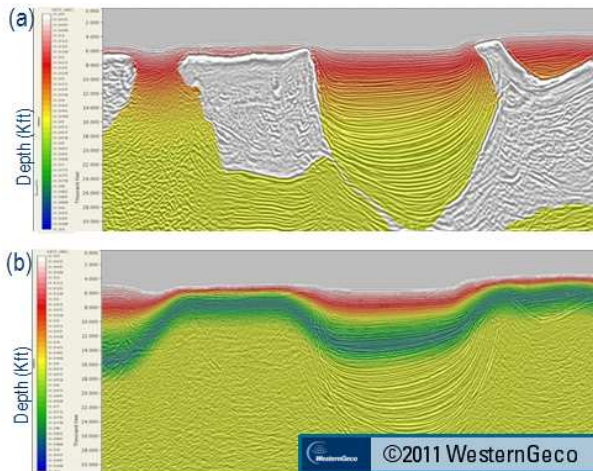


Fig. 4 - Delta overlaid on seismic data: (a) old simple increasing with depth trend and (b) new derived at wells trend propagated along horizons.

Symmetry axis tilt was extracted from seismic images and modified by reducing the dip; hence, making the tilt to be non-conformant to the structure. Thomsen parameters ϵ and δ were kept static: whereas, sediment velocity was updated with two more iterations of MAZ multiscale tomography. Results were evaluated by studying well mis-ties in more than 20 wells in the area and in all of them they were reduced by the TTI model. Figure 5 compares images for the two models after the corresponding final iteration of tomography. All seismic events are shallower in Figure 4b because of the slower velocities induced by larger values of the Thomsen

parameters. The focusing looks similar: however, 2b ties the deviated well much better. In addition, the velocities are more geologically plausible and free of artifacts and the gathers are better flattened with minimal differences between the three azimuths used in the tomography.

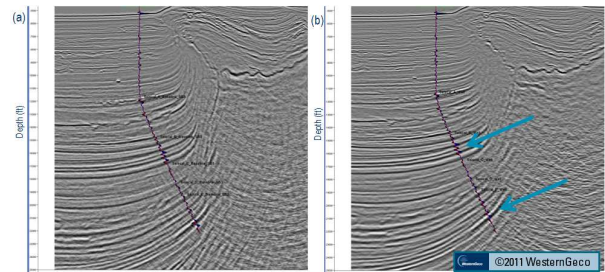


Fig. 5 - Kirchhoff Migration image with synthetic generated at deviated well overlaid: a) old VTI model and b) new TTI model. The blue arrows indicate the improved match of the TTI results with the synthetic.

Case study from Kwanza basin, offshore Angola

The third example will illustrate the usefulness of scenario testing with a fast feed-back loop for model building in complex areas. It is from a deeper-water area of Kwanza basin with very limited well control where only old relatively short-offset narrow azimuth (NAZ) data are available for large-scale exploration imaging. In 2009, we built a regional TTI model over more than 12000 km² in the area, using only one well (Zdraveva and Cogan, 2011). In 2010, we decided to revisit the ϵ and δ parameterization and to upgrade them from regional profiles hung from the water bottom, to a spatially variable δ honoring the topography of the top Albian horizon (which marks the transition to carbonate in the lithological section), and a compatible ϵ calculated from a 3D η field derived using 1D direct non-linear travelttime inversion (Fowler et al 2008).

To prove the concept, we limited the area of investigation to 3000 km² and used rapid beam imaging to provide fast feedback of the effects of model changes on the seismic images, the velocities and the residual moveout. After rebuilding and recalibrating the existing TTI model, we ran two additional iterations of tomography to refine the V_{PO} . Figure 6 shows the improvement in the seismic image as quantified by a single-parameter measurement of residual curvature in the seismic gathers. The new TTI model flattens the gathers much better than the simpler regional one.

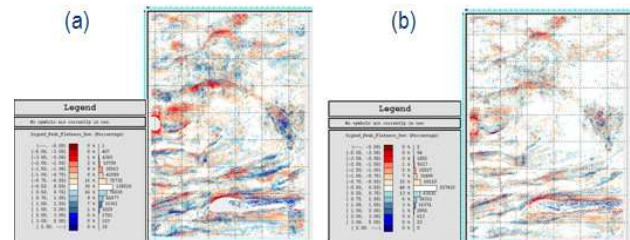


Fig. 6 - Attribute maps of residual curvature of gathers and corresponding histograms for window from water bottom to top salt: (a) regional TTI, (b) spatially variable ϵ and δ . Note the overall reduction of the residual curvature resulting in the significant centering of the histogram.

Because many anisotropic models can flatten the data, especially in the absence of wells, Figure 7 compares the plausibility of the geometry of the base salt for the two TTI sedimentary models. The image in 7b was produced with rapid beam migration (Nichols and Tran 2008) by demigrating the wave-field extrapolation migration (WEM) image with old TTI salt flood model and remigrating with new TTI salt flood model built with map-migrated top salt horizon.

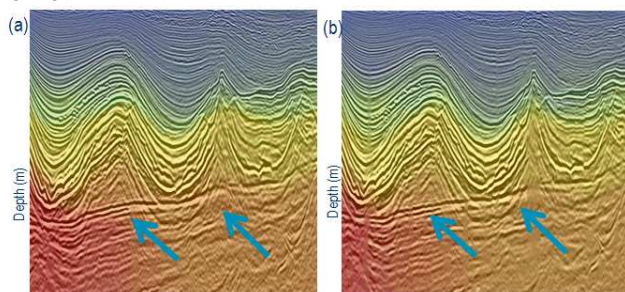


Fig. 7 - Migrated images with velocities overlaid on seismic data: (a) WEM with regional TTI salt flood model (b) Zero-offset rapid beam migration with new TTI salt flood model. Blue arrows indicate the area of improved base salt flattening.

We observe that new TTI model improves the flatness of the base of salt and better focuses some of the subsalt events. This, together with the improved residual curvature statistics, indicates that usage of spatially variable ε and δ fields have the potential to further improve the imaging of pre-salt targets in the Kwanza basin area.

Summary and conclusions

We have discussed and compared several approaches to building anisotropic VTI and TTI models in three case studies from the Gulf of Mexico and West Africa. These approaches, based on a single generalized workflow, range from using ε and δ profiles simply hung from the water bottom, through averaged borehole-calibrated profiles interpolated with approximate horizons, to fully spatially variable ε and δ fields controlled by explicit and detailed horizon interpretation and 3D η fields. We observed that even single-function smooth calibrated ε and δ fields dramatically improve well ties compared to isotropic models. Adding interpreted horizons during propagation of Thomsen parameters throughout the volume and introducing TTI results in convergence to geologically plausible velocities and images with improved well ties. In addition, we demonstrated that, with a good anisotropic model well mis-ties can be reduced further, running the final iteration of tomography with explicit well constraints.

In general, we can solve not only for V_{P0} , but for some combination of the five anisotropic properties using borehole and surface-seismic data together in a 3D steering-filter tomography (Bakulin et al., 2010b). Alternatively, tomography with uncertainty analysis (Bakulin et al., 2009) can be used to find nearby models in the surface-seismic data null-space that provide a better fit to the well data, while keeping the seismic gathers flat.

In summary, we have shown that integration of non-seismic data, together with a balanced combination of different methods and techniques for anisotropic parameter estimation and algorithms allowing fast feedback loop, could provide a fit-for-purpose solution to the most challenging cases of anisotropic model building.

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