Improved pre-salt imaging in Kwanza basin by TTI Model building with geological constraints
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Summary
We present a case study from the Kwanza basin offshore Angola where we built a detailed tilted transversely isotropic (TTI) model over an area of more than 8000 km² with very limited well control using different types of geological constraints. We incorporate general knowledge of the area and analysis of data anellipticity in the process, derive Thomsen’s δ in wells from a neighboring area, and use spatially variable ε and δ fields, honoring the variation of the anellipticity and the geometry of the provided horizon interpretation. During velocity update iterations, we use tomography with implicit and explicit geological constraints to speed-up the convergence and optimize the image. The results are compared against images produced with both a much simpler regional TTI model and a legacy isotropic model. We demonstrate that accounting for TTI in complex media is a prerequisite for producing geologically plausible and interpretable images, and that adding data- and interpretation-driven complexity in the TTI models improves further the imaging of pre-salt targets.

Introduction
Following a series of significant pre-salt discoveries in Brazil, deep-water Angola has become a focus of intensive exploration. To answer the increased demand for interpretable images of pre-salt targets in the deep-water Kwanza basin, large amounts of narrow-azimuth (NAZ) moderate-offset seismic data acquired in the late 1990s were considered for reprocessing and imaging. In spite of the limited well control, in 2009, we built a regional TTI model in the area of interest as described by Zdraveva and Cogan (2011). Due to a change in the scope of the project, in 2010, we modified the imaging strategy and moved to a more detailed TTI model, incorporating interpretation of the top Albian horizon into the process and adding implicit and explicit geological constraints during Tomographic updates.

It is well known that surface seismic data alone cannot uniquely resolve all the parameters of an anisotropic subsurface, and scarceness of the well information in the deep-water Kwanza basin poses a big challenge, especially when accurate and detailed models are required. The objective of this case study is to compare the results of using two different strategies for building large-scale TTI models in areas with very limited well control, and demonstrate that: (1) by introducing anisotropy, we can image successfully pre-salt targets in complex media, even with NAZ towed-streamer data with relatively short cable length, and (2) addition of geologically plausible detail into anisotropic parameters and implicit and explicit geological constraints in tomography can further improve the quality and interpretability of the images.

TTI model building with Geological constraints
We use a variation of the anisotropic model building workflow described by Zdraveva and Cogan (2011). This workflow consists of five main steps: (1) Evaluation of anellipticity (η) over the full project area; (2) Derivation of Thomsen’s δ and ε at well locations; (3) Construction of a model with all five 3D property fields required to describe a TTI medium; (4) Validation of the model; (5) Several iterations of multiscale common image point (CIP) tomography for $V_{p0}$ fine tuning.

The main differences between the two TTI model-building strategies compared in this paper are in how ε and δ are propagated through the model space in step (3) above, and in the use of implicit and explicit geological constraints in step (5). For the regional TTI model, δ and ε compaction driven trends were simply hung from the water bottom, while for the new TTI model we create a spatially variable δ and ε with the help of interpretation of the top Albian horizon corresponding to a change in the lithological column to carbonates that are much less anisotropic. In addition, we also use the full spatial variability of the anellipticity from step (1) above. Three iterations of multiscale CIP tomography (Woodward et al. 2008), were run to update $V_{p0}$ in both cases but with different preconditioning. Steering filters (Bakulin et al., 2010) were used with the new TTI model in an attempt to better resolve the carbonate section of the model. This implicit geological constraint in tomography helps to speed-up the convergence in the areas that are poorly constrained by data alone, like the carbonate layer. In addition, explicit geological constraints enabled by the top Albian interpretation were used in the last iteration of tomography by introducing a set of dense multiparameter picks in the zone of the model where carbonates are present. These extra picks were weighted appropriately and used in the global tomography iteration simultaneously with all other post-salt multiparameter picks. Imposed in this way, explicit geological constraint helps to delineate the carbonate zone nicely, eliminating the need to introduce a separate geobody into the model.

The criteria for judging the correctness of the results while comparing the different models are the same as for the validation step in the model building workflow. In cases with no well control we analyze the effects of the model change on resulting seismic images and by how the $V_{p0}$
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responds after a tomographic update. The two main criteria used in this study are: (1) the models’ ability to ‘explain’ the seismic data by producing geologically plausible and well-focused images with minimum residual curvature on gathers as measured by $\gamma$ (Al-Yahya, 1986) and (2) the convergence to $V_{p0}$ free of artifacts when viewed in 3D, consistent with rock physics and geomechanics.

TTI model building proof of concept

The 8000-km$^2$ area of interest is situated on the continental shelf slope and in the deep-water portion of the Kwanza basin. In 2009, we built a regional TTI model with the help of a single well penetrating the shallow portion of the section (Zdraveva and Cogan 2011) to prove that successful TTI imaging is possible in spite of the limited well control in the area. We evaluated anellipticity by layered 1D VTI inversion at selected locations and averaged the results to produce a single regional $\eta$ trend. We derived a depth-varying $\delta$ function at the well, and calculated a compatible $\epsilon$ trend. A regional 3D TTI model was built by extrapolating $\delta$ and $\epsilon$ trends along the water-bottom horizon and computing structurally conformant tilt of symmetry axis from existing images.

Figure 1 compares salt flood images produced with legacy isotropic model and the regional TTI model, both updated with CIP tomography. On the results produced with the isotropic model, we observe geologically implausible velocities and structures in the deeper portions of the sedimentary basins, especially in areas with high dips and in the pre-salt area (Figure 1a, white and black arrows, respectively). After introducing regional TTI (Figure 1b), flanks of the structure indicated by the white arrow are much better imaged, the structure itself is broader, and its crest is simplified. The base of salt is much flatter and more plausible and pre-salt events are better focused. Velocities are well-behaved and free of artifacts. Examination of residual curvature of the gathers showed significant reduction for the TTI model.

Based on all these improvements, we concluded that even an approximate regional anisotropic parameterization for TTI medium explained the seismic data much better than the isotropic medium assumption. Figure 2 shows a final image produced with a regional TTI model from another 3900-km$^2$ survey in the deeper-water area. One can observe a very well-focused image with reasonably well-behaved and geologically plausible base of salt reflection, as well as many interpretable pre-salt events down to a depth of 9 km.

In 2010, we performed a test to prove the benefits of incorporating the geologic information in the process and built a detailed TTI model over a 2000-km$^2$ portion of the survey. First, we studied stratigraphic sections from all available wells in the shallow part of the Kwanza basin and this, together with joint analysis of two more check shots and 2D seismic data from the neighbouring area, allowed us to modify the regional $\delta$ trend and make it more representative. Finally, we built a fully spatially variable 3D $\delta$ field by hanging a trend from the water bottom and merging it with the top Albian horizon to reduce its magnitude and make it reflect the change in lithology to carbonates that are much less anisotropic. The use of fast
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beam migration (Nichols and Tran 2008) enabled us to test several models to see if the use of the additional stratigraphic information, well data, and top Albian interpretation in model building could improve further our ability to achieve geologically plausible results.

Figure 3 Migrated images with velocities overlaid on seismic data: (a) Regional TTI salt flood model, (b) Detailed TTI salt flood model and (c) Detailed TTI salt model based on modified δ trend. Black arrows indicate the area of improved base salt flattening.

Figure 3 compares the plausibility of the geometry of the base salt for three TTI salt-flood models: regional simple TTI model and two detailed TTI models using spatially variable anisotropic parameters based on top Albian interpretation and two different δ trends: regional one from 2009 model and the new, modified one. We observe that the detailed TTI model on Figure 3c best improves the flatness of the base of salt making it consistent with the regional interpretation. This, in conjunction with the improved residual curvature statistics after two tomography iterations, indicates that usage of modified δ trend and spatially variable ε and δ fields have the potential to further improve the imaging of pre-salt targets in the Kwanza basin area.

Improved TTI model with geological constraints

We started by conducting a full-volume layered 1D VTI inversion, executed after the legacy isotropic depth migration, that provided us with spatially variable 3D η field. Then, using a well-known formula, we calculated a compatible ε field from the 3D η field and the spatially variable 3D δ field built from the modified δ trend and the top Albian interpretation. The angles describing the tilt of the anisotropy axis were initially derived from the regional TTI seismic image and then modified at any additional tomography iteration. Figure 4 illustrates the differences between regional and detailed δ fields and the spatial variability of the 3D η field.

Figure 4 (a) Regional 3D δ field; (b) Detailed 3D δ field and (c) 3D η field.
The three additional iterations of TTI multiscale CIP tomography were run by using steering filters for preconditioning instead of the conventional isotropic smoothing operator used to update the regional TTI model. Figure 5 shows a comparison between a tomography update with and without steering filters. We can observe that, when using preconditioning with directional smoothing (figure 5b), the update closely follows the geology as expected. Where there is good signal in the data, this signal drives the velocity update and is not overridden by the implicit structural constraint.

At the last iteration of tomography, we added as well explicit geological constraint, enabled by interpreted top Albian and top salt horizons, to further influence the update of $V_{p0}$ in the carbonate zone above salt. Figure 6 shows the improvement in the seismic image produced after the final tomography iteration as quantified by $\gamma$.

Lighter colors on the attribute maps indicate less residual curvature. While it is obvious that the overall background $\gamma$ has been reduced, the most significant changes occur along the steeply dipping salt flanks (black circles in Figures 6a and 6b) where the influence of the implicit and explicit geological constraints is bigger. Clearly, the new TTI model, built with the help of geological constraints, flattens seismic gathers more; hence, it explains the seismic data much better than the simpler regional anisotropic model.

This project is currently in final stages of salt geometry refinements and preliminary salt flood images demonstrate improved focusing and interpretability of the pre-salt targets.

Conclusions

We presented a successful strategy for building detailed TTI models by using geological constraints. We illustrated that accounting for TTI in complex media is a prerequisite for successful imaging of pre-salt targets and a must even when well information is scarce or not existing within the boundaries of a given seismic survey. We demonstrated that usage of geologic interpretation in the construction of the 3D $\epsilon$ and $\delta$ fields combined with explicit and implicit geological constraints during tomographic updates, yields more accurate images of the subsurface. In addition, by using the information contained in the seismic data to its full potential through honouring the spatial variability of anellipticity, we achieved improvements in imaging across a large area of complex geology.

As exploration and development matures in Angola, the existing narrow-azimuth, limited-offset seismic data may be augmented with wide- or full-azimuth, long-offset data. Accurate models from TTI imaging workflows as one described in this paper will be important for designing the next generation of seismic surveys.

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EDITED REFERENCES
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