Large-scale TTI Imaging in Areas of Limited to No Well Control

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Abstract

Depth imaging with anisotropic models has been shown to deliver more geologically plausible and accurate images. Derivation of accurate parameters describing anisotropic properties of the medium requires incorporating well information. However, there are vast exploration areas around the world with very limited to no well control that do require high-quality anisotropic imaging to allow adequate interpretation of deeper targets. We use a simple workflow that allows building of tilted transversely isotropic (TTI) models in areas of very limited well control. We present a case study from the Kwanza basin offshore Angola where we built a detailed TTI model over an area of more than 8000 km^2. We incorporate general knowledge of the area and analysis of data anellepticity 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. The results are compared against images produced with both an isotropic model and a much simpler regional TTI model. The results illustrate that accounting for TTI in complex media is a prerequisite for producing geologically plausible and interpretable images, and that adding interpretation driven complexity in the TTI models could further improve the interpretability of pre-salt targets.

Introduction

Following a series of significant pre-salt discoveries in Brazil, deepwater Angola has become a focus of intensive exploration. The primary objectives of large-scale imaging in the area are to create accurate images that are appropriate for regional interpretation, identify prospective areas, and plan exploration wells. The need to account for anisotropy when imaging post-salt targets in the sedimentary basins of West Africa was demonstrated early by Ball (1993). The importance of introducing TTI offshore Angola was discussed and nicely illustrated by Boudou et al. (2008).

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. It is well known that surface seismic data alone cannot uniquely resolve all the parameters of an anisotropic subsurface. To limit the non-uniqueness in parameter estimation, the majority of traditional anisotropic model building workflows rely heavily on well control and explicit interpretation of many horizons. The biggest challenge we face in many exploration areas around the world, including parts of the Kwanza basin in this study, is the lack of well control. In addition, there is an apparent perception in the industry that successful anisotropic depth imaging cannot be done in the absence of local well information. However, the lack of well control does not change the characteristics of the subsurface, and trying to ignore the fact that the Earth is inherently anisotropic may render seismic images useless for mapping deeper targets in complex media.

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 to no well control and demonstrate that, by introducing anisotropy we can image successfully pre-salt targets in complex media even with narrow-azimuth towed-streamer data with relatively short cable length.

Method

The two strategies we want to compare are variations 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 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.

The main differences between the chosen strategies are in how ε and δ are propagated through the model space in step (3) above and in the use of geological constraints in step (5). For the regional TTI model, δ and ε 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 use the full spatial variability of the anellipticity. Three iterations of multiscale CIP Tomography (Woodward et al. 2008), were run to update V_{P0} in both cases: however, steering filters (Bakulin et al., 2010) were used with the new TTI model in an attempt to resolve better the carbonate section of the model. Explicit geological constraints defined by the top Albian interpretation were used in the last iteration of tomography.

The criteria for judging the correctness of the results while comparing the different strategies, 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} 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 γ (Al-Yahya, 1986), and (2) the convergence to V_{P0} free of artifacts when viewed in 3D and consistent with rock physics and geomechanics.

Regional TTI model building strategy

In 2009 we built a regional TTI model over an area of more than 8000 sq km^2 on the slope and in the deepwater portion of the Kwanza basin, using narrow-azimuth (NAZ) data and one well (Zdraveva and Cogan, 2011). We evaluated anellipticity by layered 1D VTI inversion (Fowler et al., 2008) at sparse locations away from salt and areas with high dips. We averaged the results to produce a single regional η trend, derived a depth-varying δ function in the only well available in the area, and calculated a compatible ε trend. A regional 3D TTI model was built by: (1) extrapolating regional δ and ε trends along the water-bottom horizon, (2) calibrating the velocities of a legacy isotropic model that had undergone two iterations of tomography, and (3) computing 3D dip and azimuth from existing images.

Figure 1 compares salt flood images produced with the final isotropic model after four iterations of tomography and the final regional TTI model where V_{P0} was updated with three additional tomography iterations. We observe geologically implausible velocities and structure in the subsalt area and in the deeper portions of the sedimentary basins, especially in areas with high dips (Figure 1a. blue and white arrows, respectively). After introducing regional TTI (Figure 1b), flanks of the structure indicated by white arrow are much better imaged, the structure itself is broader, and its crest simplified. The base of salt is also much flatter and more plausible. Velocities are better behaved and free of artifacts. Examination of residual curvature of the gathers showed that it was reduced significantly for the TTI model. Based on all these improvements we concluded that even an approximate regional anisotropic parameterization for TTI medium explains the seismic data much better than the isotropic medium assumption.

The same regional δ and ε trends have been used since mid 2009 for building TTI models in the deepwater area of the Kwanza basin to image more than 10000 sq km^2 of NAZ seismic data. Figure 2 shows a final Adaptive Beam migration image from a 4000 sq km^2 survey completed in late 2009. There are no wells in the deep waterarea of the Kwanza basin, so we cannot prove that the regional anisotropic models would position reflectors at the correct depth. However, 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 10 km.

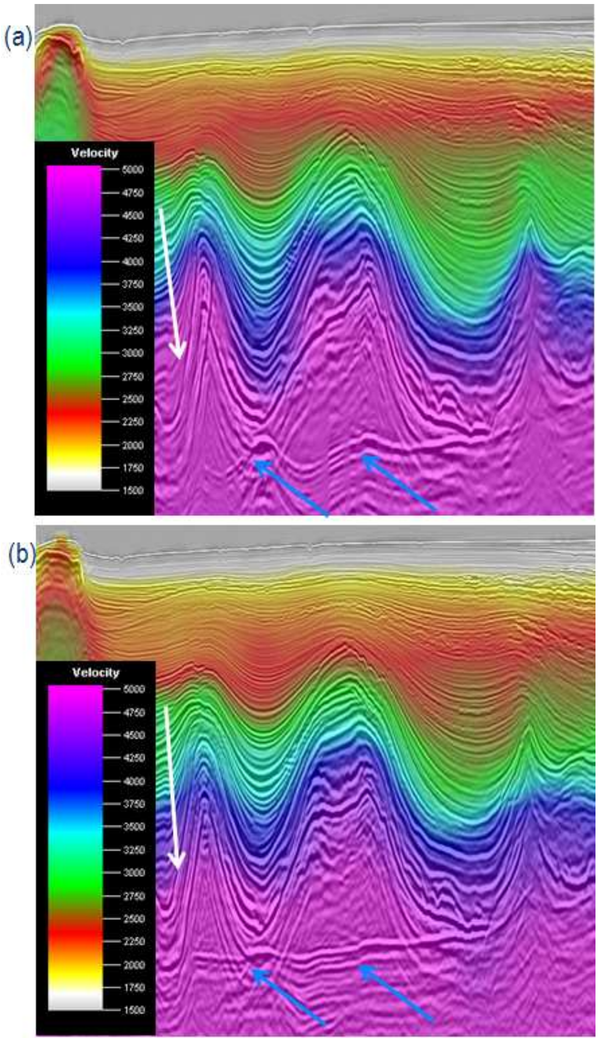

Fig. 1 - Migrated images with corresponding V_{P0} overlaid on seismic data: (a) Isotropic – note the unrealistic curvature of base of salt (blue arrows) and very high velocities on the flank of the structure (white arrow), (b) regional TTI - note the improvements at base of salt and flanks of structure.

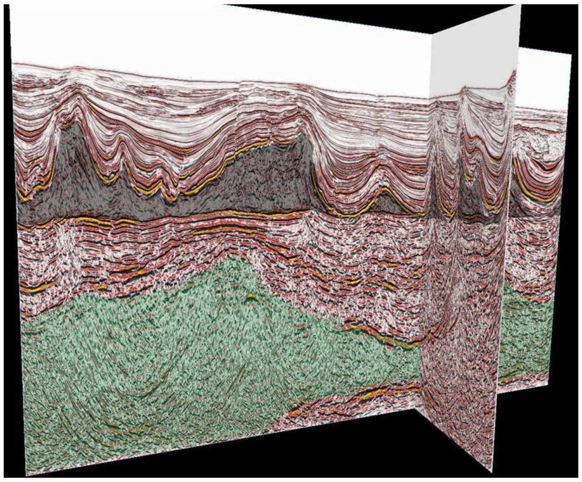

Fig. 2 - Regional TTI adaptive beam migration in deepwater area of the Kwanza basin

New strategy for more detailed TTI model building

In 2010, we built a new TTI model, starting by a full-volume layered 1D VTI inversion, executed after the legacy isotropic depth migration, and an interpretation of the top Albian horizon. The top Albian interpretation allowed us to isolate the areas of the model where carbonates are present and treat anisotropic parameters differently there. Figure 3a shows a map view of the top Albian horizon interpreted from an image produced with the regional TTI model, while Figure 3b shows an average η extracted in the window between the water bottom and top of salt. It is clear that η varies spatially and that its variation is closely related to the thickness of the sedimentary column. Excluding the salt structures, the spatial changes in η correlate well with changes in the top Albian topography.

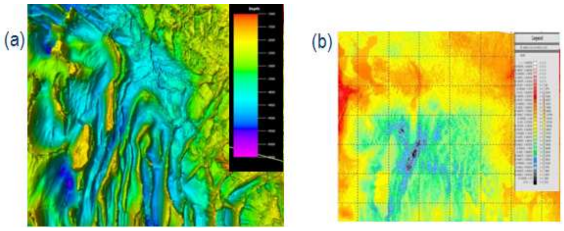

Fig. 3 - (a) Depth of top Albian horizon; (b) Map of the average η from dense, direct 1D VTI inversion.

We modified the regional δ derived in 2009 by analyzing two additional wells in neighboring areas where some 2D seismic data became available. The new δ trend we obtained reaches the same maximum value at a shallower depth and then stays constant in the full sediment column. From this new analysis, we created a spatially variable δ field by hanging the new trend from the water bottom. Where the new trend, intersects with the top Albian horizon, we lower its magnitude to reflect the change in lithology to carbonates that are much less anisotropic. Next, we calculated a compatible ε field from the 3D η using a well-known formula. With the 3D anisotropic fields constructed, we calibrated the velocities from the regional TTI model to reflect the changes in δ, but maintain the same gather flatness. The angles describing the tilt of the axis are initially taken from the regional TTI model and then modified after each tomography iteration.

Figure 4 compares a depth slice through the regional and new spatially variable ε field at 3500 m. We can observe the increased magnitude and much larger spatial variability following closely the features observed on the η map shown on Figure 1b.

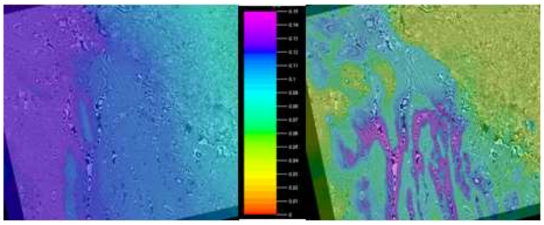

Fig. 4 - Depth slice through ε at 3500m: (a) Regional TTI model; (b) New TTI model.

TTI tomography

The three additional iterations of TTI multiscale CIP tomography used steering filters instead of the conventional isotropic smoothing operator (Bakulin et al., 2010). Steering filter tomography will help to speed-up the convergence in the areas that are poorly constrained by data alone, e.g., carbonate zones. Figure 5 shows a comparison between a tomography update with and without steering filters for iteration one. We can observe that, when using steering filters, the update follows the geology closely as expected. Where there is good signal in the data, this signal drives the velocity update and is not overridden by the structural constraint.

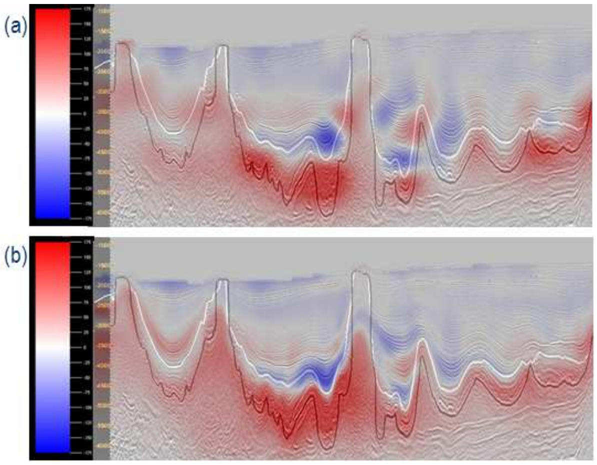

Fig. 5 - Velocity update from the first tomography iteration overlaid on seismic data with top Albian (white) and top salt (black) interpretation shown: (a) without steering filters, (b) with steering filters.

In addition to steering filters, at the last iteration of tomography, we added explicit geological constraints with the help of the top Albian interpretation. The constrains were 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 γ. Lighter colors in Figure 6 indicate less residual moveout. While the overall background γ has been reduced, the most significant changes ocurr along the salt flanks (black circles in Figure 6). Clearly, the new TTI model flattens seismic gathers: hence, it explains the seismic data much better than the simpler regional anisotropic model.

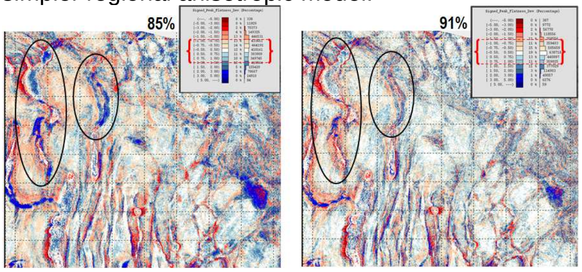

Fig. 6 - Attribute maps of statistical analysis of γ for window from water bottom to top Albian: (left) regional TTI, (right) new TTI model. Note the overall reduction of

the residual curvature expressed in increased percentage of data with residual error of less than 1.5%, marked by red brackets.

Because many anisotropic models can flatten the data, especially in the absence of constraints from wells, Figure 7 compares the plausibility of the geometry of the base salt for the two TTI salt-flood models. The new TTI model with spatially variable ε and δ and explicit use of the top Albian horizon better aligns the base of salt to be consistent with regional interpretation.

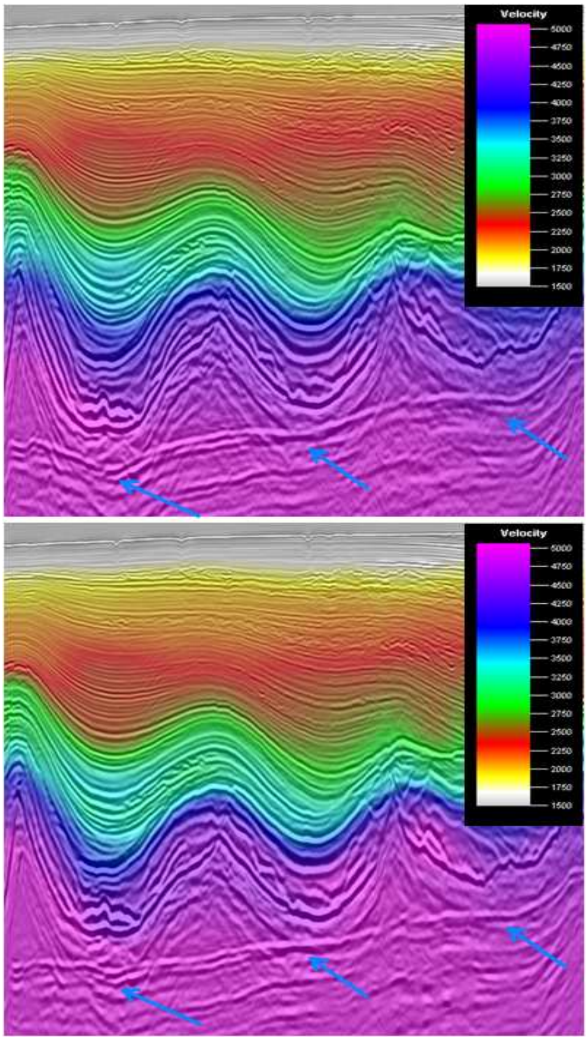

Fig. 7 - Migrated images with velocities overlaid on seismic data: (a) regional TTI and (b) new TTI. Note how it affects the flatness of the base salt (blue arrows).

Imaging with the new TTI shows improvement in the sediment velocities and structure above salt, as well as the base salt structure. We expect this will translate into an improved image of the pre-salt targets. This project is currently in a salt body definition stage and we will report the final results when they are available.

Summary and conclusions

We presented two different strategies for building TTI models in areas of limited well control that were used successfully for imaging more than 18000 sq km^2 of NAZ data in the Kwanza basin, offshore Angola. Using a simple regional TTI model, we produced interpretable and geologically plausible images with conventional narrow-azimuth data acquired with 4.8-km long cables. We illustrated that accounting for TTI in complex media is a prerequisite for successful imaging of pre-salt targets, even when well information is scarce or not existing within the boundaries of given seismic survey.

We demonstrated that, by using the information contained in seismic data to its full potential (spatial variability of anellipticity), we could achieve improvements in imaging across a large area of complex geology. Adding geologically plausible constraints to the derivation of 3D ε and δ fields and using geologic information explicitly (carbonate interpretation) and implicitly (steering filter tomography) for model building yields more accurate images of the subsurface.

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 described in this paper will be important for designing the next generation of seismic surveys.

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