Building anisotropic models for depth imaging: from imaging parameters to Earth model

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Velocity model is the bridge that links our data with our images of the subsurface. Therefore our images can only be as good as our velocity models. Moving to "difficult oil" in sub-salt, sub-basalt and generally deeper targets, we can no longer afford the compromises of simplistic models we did in the past. Doing that leads to poor or no image areas. To fully leverage potential of new data types (wide azimuth, long offsets), we have to put a realistic complexity into our models. To address these challenges industry moved into using anisotropic earth models as a new standard (vertical and tilted transverse isotropy or VTI and TTI). Incorporating anisotropy increases our ability to fit the data and image every single piece of it. However growing expectations requires not only focusing the image but also accurately positioning seismic images for drilling. While this is achievable with anisotropic models, it only occurs when geology and data from boreholes are intimately incorporated into velocity model building from the very start.

Since seismic data does not constrain all anisotropic parameters, first step is to build local anisotropic models around wells where additional information is available. We are developing portfolio of tools that addresses these issues:

- Manual 1D layer-stripping inversion with well data
- Localized tomography with well data
- Tomography with uncertainty analysis
- Manual trial-and-error 3D inversion with quick feedback loop

The first technique is only applicable to VTI and 1D media, whereas other methods can be applied to general 3D TTI media and allow incorporation of borehole data from deviated wells. Figure 1 shows results of case study of localized tomography jointly inverting seismic and checkshot data for

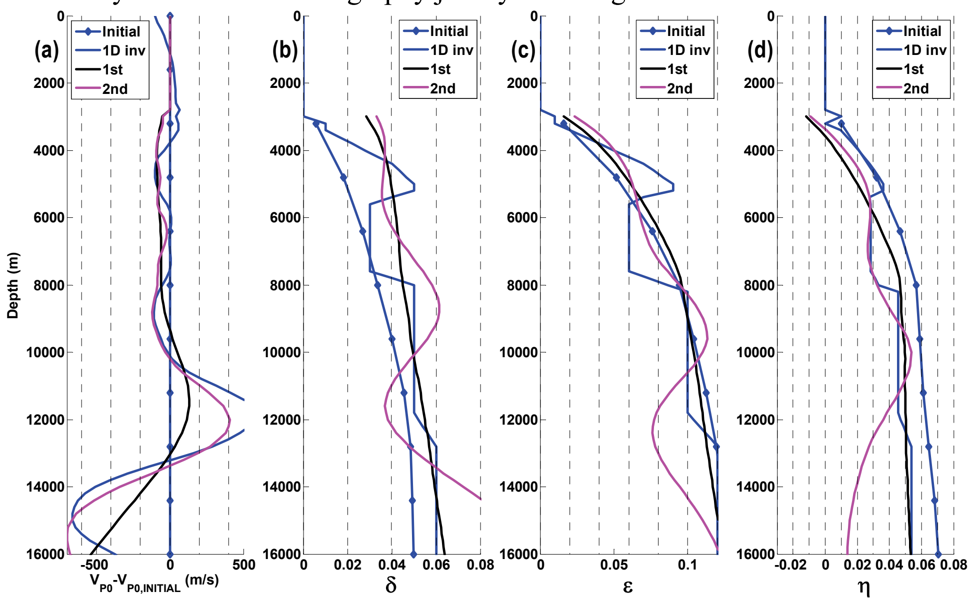

Figure 1 *Profiles of model parameters along the vertical well after each iteration of a three-parameter (V_{P0}, ε, and δ) VTI tomographic inversion of joint seismic and checkshot data for the first scenario: (a) velocity; (b) δ; (c) ε; (d) η. Velocity is shown as a difference between the current velocity in each iteration and the initial velocity. Curves labelled "1D inv" refer to smoothed velocity estimated from checkshot traveltimes and an anisotropic parameters derived by manual 1D layer-stripping inversion of a single depth gather.*

vertical velocity and Thomsen parameters.

Figure 2 shows case study of tomography with uncertainty where 500 realizations of depth model have been built with different velocity and Thomsen parameters. Using well markers from borehole one can select the model that ties the wells. Alternatively even in the absence of well data, tomography with uncertainty provides convenient means to come up with one can select only models that satisfy any additional geological or rock physics constraint available for the area of interest.

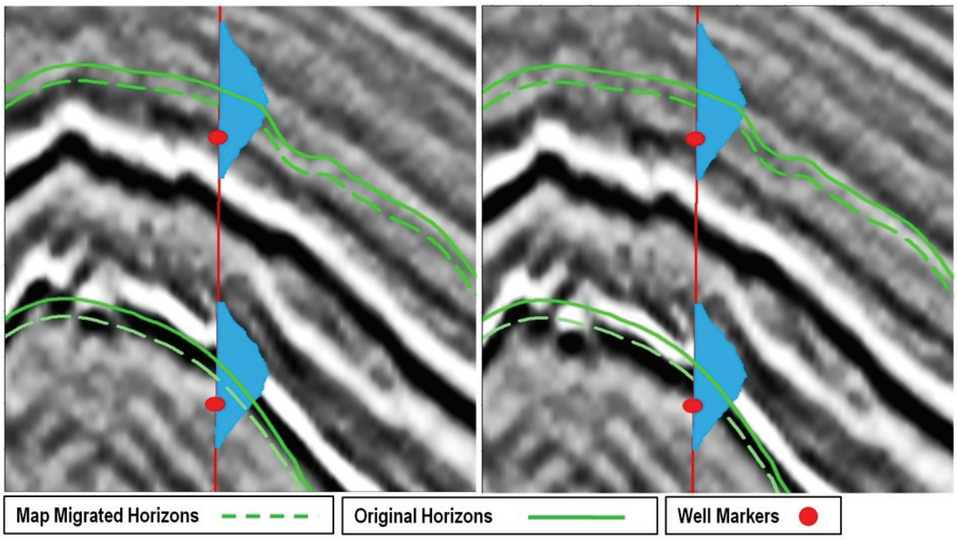

Figure 2 *Migrated imaging with horizons and well markers. The blue histograms show the distributions of 500 map-migrated horizons around the original horizons. Left panel: with original velocity model; Right panel: with perturbed velocity model.*

Once we were able to build local anisotropic models around each well, at a second step we need to construct a global anisotropic model. This can be achieved using variety of techniques:

- interpolating local results using structural framework derived from seismic
- interpolating local results using volumes of NMO velocity and parameter η derived from time-domain inversion
- interpolating local results using rock physics correlations and basin modeling.

Figure 3 shows case study where VTI model was built for 100 blocks of Gulf of Mexico using wide-azimuth seismic and borehole data from 18 wells. One can clearly see that borehole calibration leads to more realistic values of anisotropy. In addition anisotropy has meaningful lateral variation and follows subsurface geology.

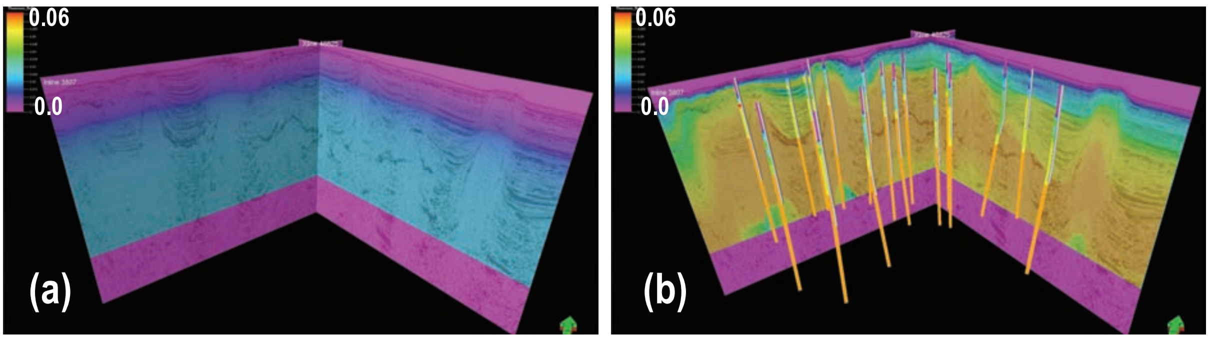

Figure 3 *Thomsen's δ volume for (a) initial model and (b) final borehole-calibrated mode interpolated between wells using horizons. Tracks of 18 wells are shown together with the corresponding Thomsen's δ profiles shown as logs along the wells.*

Another possible approach is to use automatic direct nonlinear 1D VTI inversion in time-domain that delivers a volumes of NMO velocity and parameter η. Figure 4 shows case study example where these volumes are derived from wide-azimuth data. With additional calibration of Thomsen δ parameter at wells, this provides an opportunity to build a 3D initial anisotropic model for depth imaging.

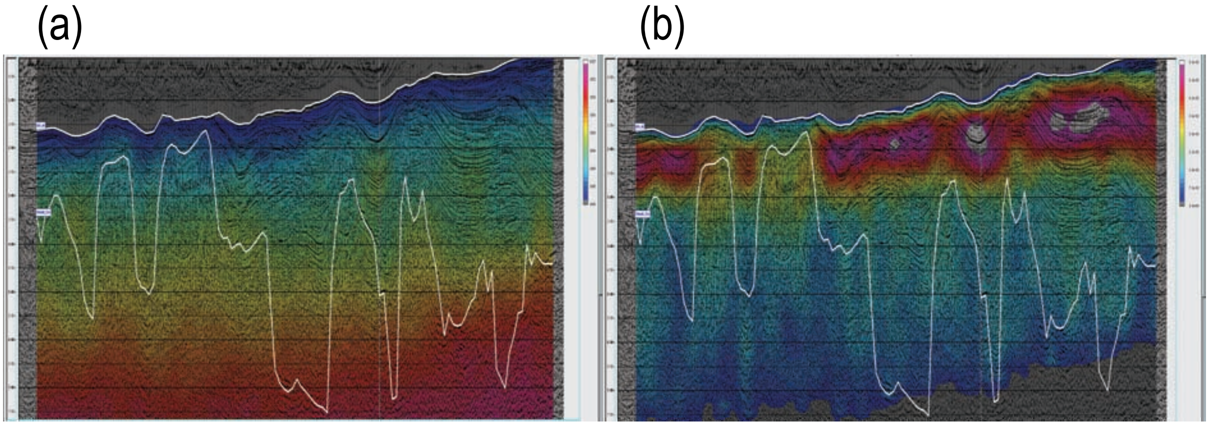

***Figure4** Anisotropic parameters obtained by automatic direct nonlinear 1D VTI inversion in time-domain: (a) NMO velocity; (b) anisotropic parameter η. White lines show first crude versions of time horizons for water bottom and top salt.*

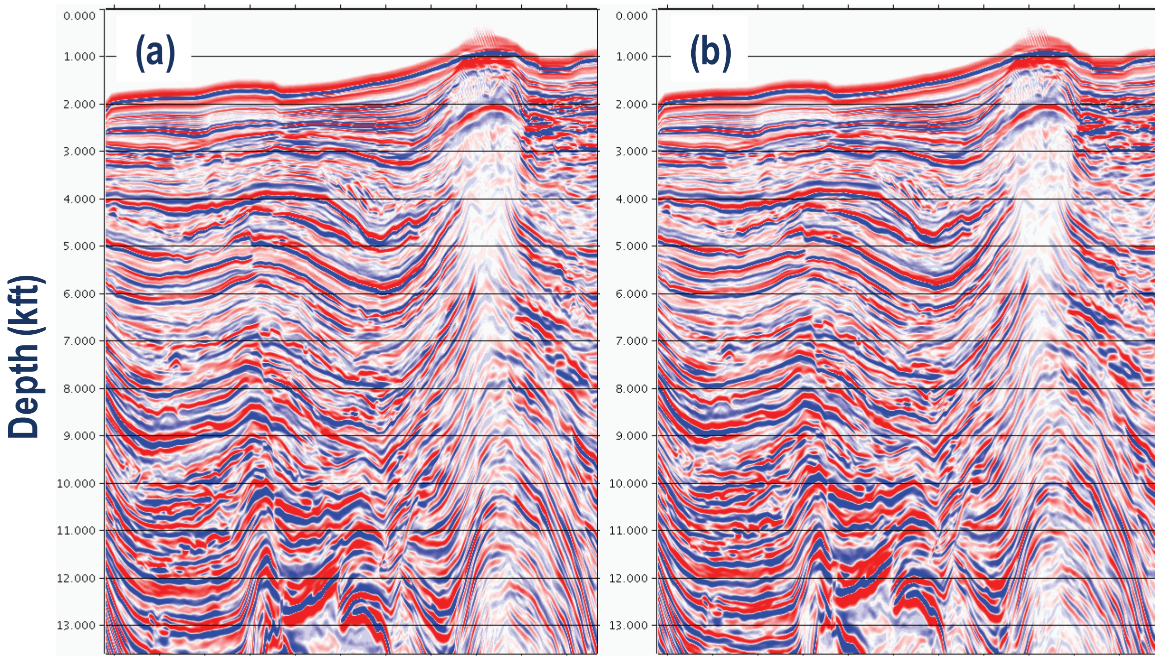

***Figure 5** Images obtained by Rapid Beam Migration using (a) initial model and (b) borehole-calibrated model shown on Figure 3. Note general shift upwards increasing with depth in the new image. Such a shift greatly improves well ties.*

Rapid Beam Migration allows fast remigration of calibrated models (Figure 5) that facilitates quick re-interpretation and validation of final fit to the well data. Figure 6 quantifies movement of the top salt horizon with surface remigration and allows quick look in understanding how this movement is controlled by depth and dip of the top salt.

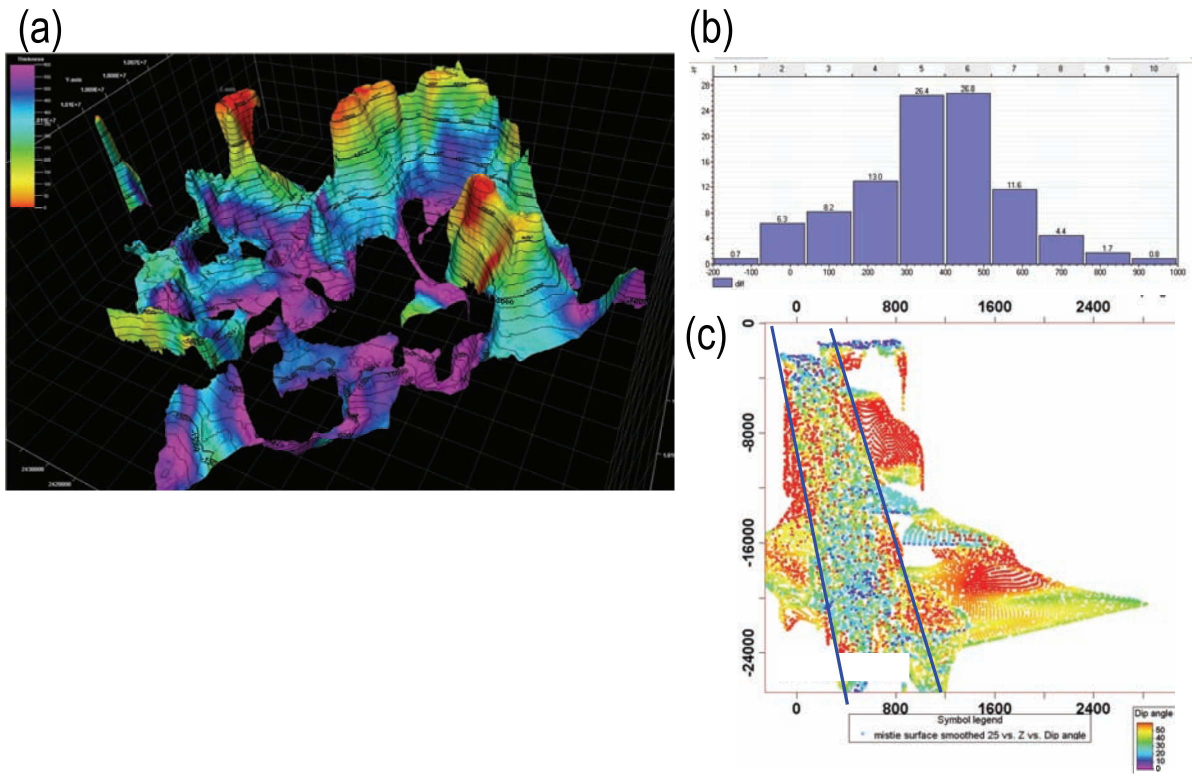

Figure 6 *Quantifying movement in top salt horizon using re-migration: (a) difference in top salt between initial model (Figure 3a) and final calibrated model after additional tomography run; (b) histogram showing that average movement was ~ 400 ft upward; (c) cross-plot of the movement versus depth colour-coded by geological dip of the top salt horizon highlighting that extreme movement is mostly associated with large dips.*

Conclusions

We are creating a comprehensive portfolio of methods and tools that allow building geologically plausible VTI and TTI models for depth imaging. Incorporating borehole and other data is an essential part of every step. We will highlight several new methods that are applicable to calibrating anisotropic VTI and TTI models in the presence of complex structure and borehole data from deviated wells. None of the methods is a silver bullet, but their balanced combination can provide fit-for-purpose solution to the most challenging cases of anisotropic model building. Quick feedback loop is of essence in all these applications and it seems to be satisfied with Rapid Beam Migration. Building large models requires ability to interpolate anisotropic properties from wells in a geologically meaningful way. We show case study demonstrating one example and quantify movement in imaged events and improvements in well ties. We speculate on a future directions that need to be pursued to make a velocity models a true part of the earth model consistent with geology and all other measurements.

Acknowledgements

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