True depth anisotropy in complex geological settings

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Abstract

Over the years, our increase understanding of anisotropy has allowed us to improve the way we treat velocity at a single location in the subsurface. In complex geological settings where positioning is important, accurately correcting for anisotropy becomes critical for resolution and accurate well placement. Simple constant anisotropic parameters, in most cases, are not an accurate representation of the earth given the variation of the heterogeneity of the subsurface. It is therefore essential for anisotropy to vary spatially and vertically. In this paper we demonstrate a method and workflow for addressing the variability of the delta and epsilon parameters across many wells and show how using our true depth technique and picking for epsilon we can greatly improve our, anisotropic models and hence the resolution of the stack.

Introduction

Wave propagation in the elastic earth is known to be generally anisotropic. In many cases of exploration interest, the observed anisotropy manifests itself as Vertical Transverse Isotropy (VTI). For P-wave propagation, the relevant parameters are the vertical compressional P-wave velocity V_{P0}, δ (delta) -- describing the near-vertical P-wave propagation and ε (epsilon) – the fractional difference between the vertical and horizontal P-wave velocities (Thomsen, 1986). Prestack Depth Migration (PSDM) of compressional data in the anisotropic case therefore requires three scalar fields: V_{NMO}, epsilon, and delta. The short-spread moveout velocity V_{NMO} will create flat gathers in both the isotropic and anisotropic cases, but incorrect depths for non-zero delta. V_{NMO} is proportional to V_{P0} through the delta parameter according to $V_{NMO} = V_{P0}\sqrt{1+2\delta}$. The "moveout" part of the PSDM is controlled by V_{NMO} and epsilon while the final depths of reflectors in the section are controlled by delta. The anisotropic parameter delta cannot be determined from moveout analysis of seismic data alone; it can only be obtained using the additional information provided by well measurements. One can use complicated and expensive simultaneous inversion methods for V_{P0}, ε, and δ (Bakulin, et.al, 2009). More practical methods to determine delta are based on the mistie between interpreted seismic horizons and the associated well tops (Sareen, et.al, 2012). Epsilon may be determined by migration scans over a range of values (Gedaly and Liao, 2007). These approaches are generally used in a layer-stripping workflow, which requires a new PSDM for each anisotropic layer -- an expensive and time-consuming approach.

Method

Single pass construction of delta volumes

Our approach is based on the observation that the isotropic velocity model and the scaled (anisotropic) velocity model must both give the same vertical traveltimes for the initial and final migrated horizons. For every layer that we have well depths and interpreted seismic horizon depths at the top and bottom, the vertical traveltimes must match. If we consider delta to be a constant interval value within each layer, then we have

$$\int_{z_{seistop}}^{z_{seisbot}} \frac{dz}{V_{NMO}(z)} = \int_{z_{welltop}}^{z_{wellbot}} \frac{dz}{V_{P0}(z)} = \sqrt{1+2\delta}\int_{z_{welltop}}^{z_{wellbot}} \frac{dz}{V_{NMO}(z)}. \quad (1)$$

For each layer in the model, then, we can determine an "interval" delta quantity

$$\delta = \frac{1}{2}\left[\left(\frac{\Delta t_{seis}}{\Delta t_{well}}\right)^2 - 1\right]. \quad (2)$$

Careful attention must be paid to the depths of the delta model layering: from equation (1), note that the layer boundaries for the delta are defined by the well depths, and have no connection to the seismic depths. Our solution method is depicted in Figure 1. For the top of the first anisotropic layer (it does not necessarily have to be the surface), well tops are assumed to be the same as the horizon (Figure 1a). For each well that has a marker at the next horizon, equation (2) is used to compute a layer delta (Figure 1b). These deltas are then interpolated to the entire grid using a scattered data interpolation (Figure 1c). Finally, since we now have a full grid of vertical traveltimes Δt_{seis}, well depths $z_{welltop}$, and deltas, we can rearrange equation (2) as

$$\int_{z_{welltop}}^{z_{wellbot}} \frac{dz}{V_{NMO}(z)} = \frac{\Delta t_{seis}}{\sqrt{1+2\delta}} \quad (3)$$

and solve numerically for $z_{wellbot}$ at every point of the areal grid to determine a new marker horizon which matches the depths at the known wells (Figure 1d). This horizon now becomes $z_{welltop}$ for the next layer, and the process is repeated until the volume is filled. In this way, we can generate consistent well depths for those wells that are missing some tops.

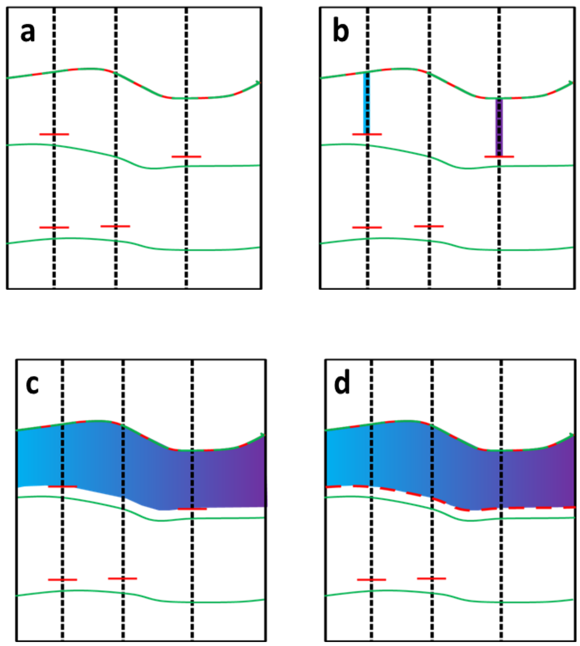


Figure 1 *Step by step development of the delta model. There are 3 layers and 3 wells, with seismic horizons in green and well tops in red (a). Layer deltas are determined at the well locations (b), then interpolated within a 2D plane and used to fill the layer thickness(c). A new well horizon may then be determined (d).*

Epsilon picking with anisotropic raytracing

Once the delta model is determined and the data are remigrated, gathers may still not be flat due to the influence of epsilon. In order to pick the proper epsilon, residual moveout curves are computed using interactive anisotropic raytracing similar to that used for eta picking in the time domain (Hellman, et. al., 2013). In the anisotropic case, raytracing is accomplished by modifications to Snell's law according to group angle θ, ray angle ϕ and directional velocity. Since we have already migrated with the correct delta model, we set $\delta=0$. Assuming "weak anisotropy" (Thomsen, 1986), the velocities and angles are determined by:

$$V_p(\emptyset) = V_p(\theta) = V_{P0}\,(1 + \varepsilon\ \sin^4\theta) \quad \text{(4a)}$$

$$\tan\emptyset = \tan\theta\,(1 + 4\varepsilon\ \sin^4\theta) \quad \text{(4b)}$$

The anisotropic ray tracing is accomplished by incorporating equations (4) into the Snell algorithm. As seen in Figure 2, the raytraced moveout curves are plotted over the migrated gathers as events are selected in depth. These curves are updated interactively as epsilon is changed until the curve overlays the event. Picks are made in a top-down fashion, as shallow epsilon layers affect the deeper curves due to anisotropic raytracing. Blue curves in the figure are those with no epsilon, but have curvature due to the overburden. Once the epsilons are determined for all of the desired depths and CDP locations, an epsilon volume is created and a final anisotropic migration is run.

Example

The methodology has been applied to many Brazil datasets in the Campos and Santos Basins. The one discussed here involved a 3D Bi Azimuthal survey. Geological settings include carbonates and salt. Signal processing was applied to the data. The targets in this field are the Tertiary turbidites, carbonates of the Eo/Neo Cretaceous and the pre-salt carbonates within the Eo Cretaceous. This was followed by several iterations of tomography. There were a total of 20 wells and 4 interpreted horizons of interest. The 3D delta model was constructed from these wells and the initial velocity model. The interpolated delta maps that were produced for the top 4 layers are shown in Figure 3, and are an important quality control component of the method. The data were migrated, and an epsilon model was subsequently constructed from the new gathers with interactive raytraced picking. Inline slices of the final V_{NMO}, delta, and epsilon volumes are shown in Figure 4, while corresponding PSDM inline sections are shown in Figure 5, passing through one of the wells. Interpreted horizons are shown on both sections, and it can be seen that the horizons on the anisotropic migrations are now aligned with the well depths. Gathers from around the well are shown in Figure 6. The initial gathers are flat, but do not tie the wells. After migration with delta only, the depths are correct, but residual moveout has been introduced. Migration with both delta and epsilon has produced gathers that are both flat and tied to the wells.

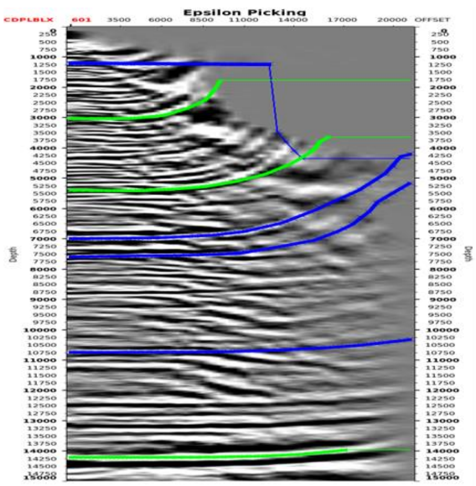
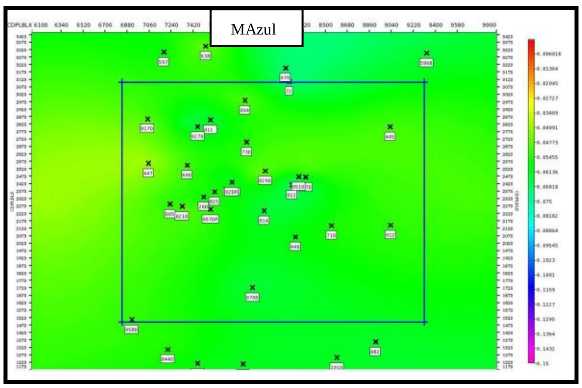
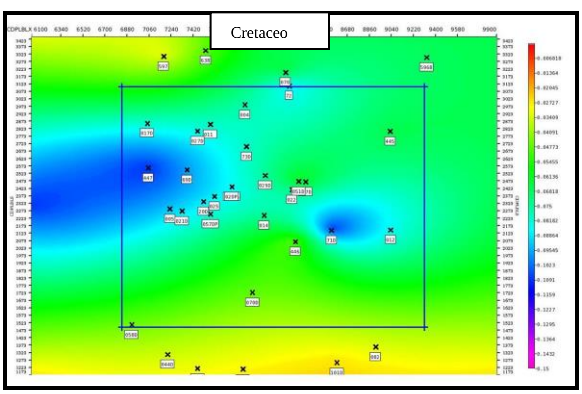
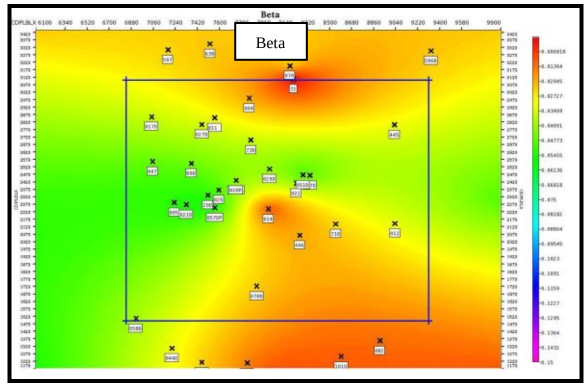


Figure 2 *Epsilon picking. Green represents positive epsilon, while blue are curves with zero epsilon.*







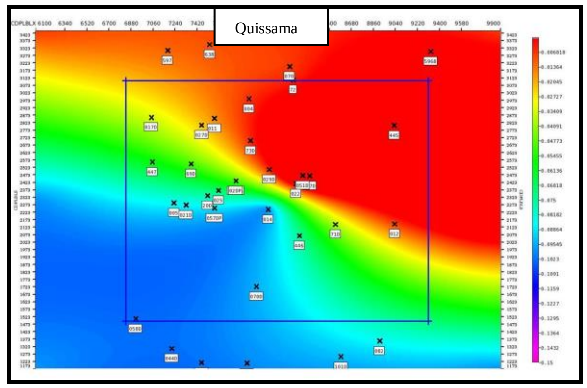


Figure 3 *Interpolated delta maps. Delta values range from 0.02 to 0.06 in the MAzul, .02 to 0.09 in the Cretaceo, .01 to 0.06 in the Beta, and.006 to 0.09 in the Quissama.*

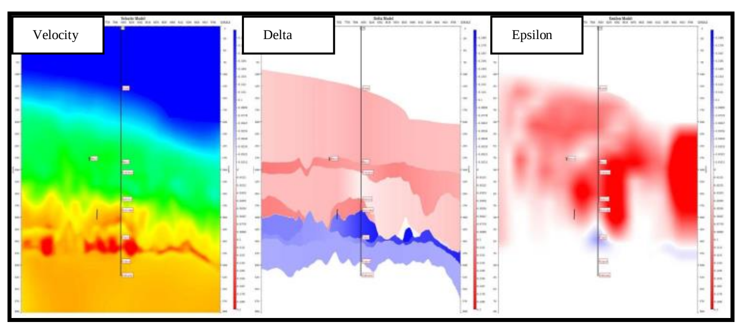


Figure 4 *Depth velocity model, anisotropic delta model, and anisotropic epsilon model. Well tops show for the major intervals.*

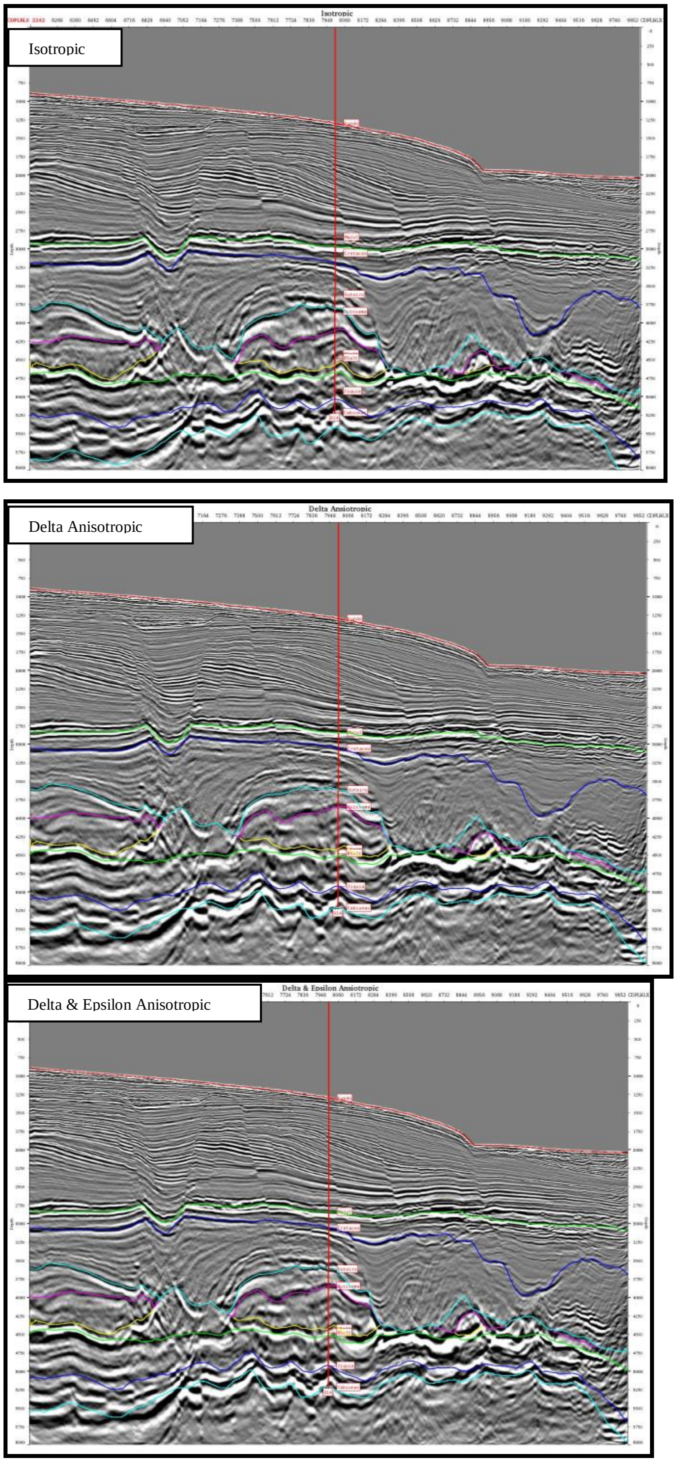


Figure 5 *Migrated stacks. (a) Isotropic migration, (b) Migration with the delta model, and (c) Migration with both the epsilon and delta models.*

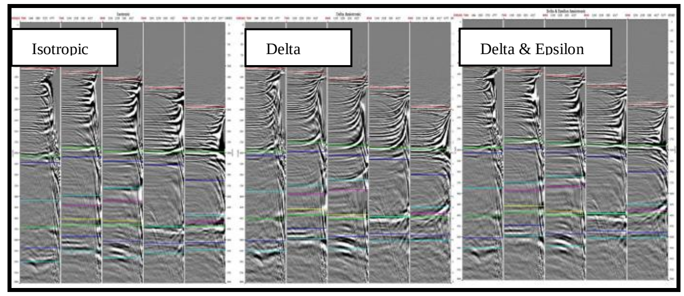


Figure 6 *Migrated gathers near the well. On the left is the isotropic migration, in the middle is the migration with the delta model, and on the right is the migration with both the epsilon and delta models.*

Conclusions

We have presented a method for constructing the delta and epsilon models for anisotropic PSDM in a single pass for each. A key point is that the delta layers are bounded by the well depths, and not the seismic horizon depths. These delta values are interpolated areally between wells on a layer by layer basis. Some field examples may contain dozens of wells with many horizons, so this method allows for both missing tops and editing of questionable tops. Epsilon models are obtained at selected locations by interactive raytraced fitting of residual moveout curves to migrated data gathers. The full epsilon volume is then filled by interpolation. The entire workflow consists of an isotropic migration, a single pass delta volume creation, anisotropic migration to tie the wells at near offsets, a single pass determination of the epsilon model, and a final migration that produces flat gathers which tie the wells.

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