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Simultaneous Anisotropic Tomography with Rock Physics Constraints - Gulf of Mexico Example

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SUMMARY

Simultaneously solving for velocity, epsilon, and delta in anisotropic tomography is very challenging. Surface seismic data only is not sufficient for this joint problem. In this work, a model covariance function was built using rock physics to constrain the joint anisotropic tomography. An example from Gulf of Mexico was presented to demonstrate the effectiveness of the method.
Introduction

Vertical transverse isotropy (VTI) and tilted transverse isotropy (TTI) anisotropic model building has become an industry routine for oil and gas exploration in complex geology setting (Zdraveva et al. 2011). Tomography in the imaging domain has been an industry standard velocity model building tool for a decade (Woodward et al. 2008). However, tomography remains as an ill-posed and underdetermined problem due to the large size of the model space and the limitation of the surface seismic geometry. The tomographic solution, especially during anisotropic model building, is not unique, and model parameter ambiguity is significant due to the null space of the tomography operator (Osypov et al. 2008).

Borehole measurements, for example, checkshot transit times, can be used jointly with surface seismic data in tomography to constrain anisotropic parameters at well locations (Bakulin et al. 2009). Beyond hard measurement, we can incorporate geological knowledge such as rock physics. Li et al. (2011) demonstrated a constrained traveltine tomography in which the solution is constrained with the results of stochastic rock-physics modelling of compacting shale (Bachrach 2011a). We follow this approach to demonstrate a post-migration grid tomography with a VTI case study in the Gulf of Mexico. The theory and workflow are also discussed in the method section.

Method

To incorporate geological information into anisotropic tomography as constraints, we employ a spatial variant covariance function at each point in the earth model. We start with the linearized tomography problem that can be written as

$$\mathbf{L} \Delta \mathbf{m} = \Delta \mathbf{z},$$

where $\Delta \mathbf{z}$ is the moveouts picked from common-image gathers, $\mathbf{L}$ is the tomography operator including differentials of earth properties to the depth, and $\Delta \mathbf{m}$ is the model update ($\Delta v$, $\Delta \varepsilon$, and $\Delta \delta$). The objective function is formulated as

$$\Phi(\Delta \mathbf{m}) = \| \mathbf{L} \Delta \mathbf{m} - \Delta \mathbf{z} \|^2_0 + \| \Delta \mathbf{m} + (\mathbf{m}_{prior} - \mathbf{m}_0) \|^2_{\mathbf{C}_0},$$

(1)

where $\mathbf{D}$ refers to the data covariance matrix, which is a measure of error in the data, and $\mathbf{m}_{prior}$ is the mean of prior model distribution. In this study, our initial model, $\mathbf{m}_0$, is the stochastic rock physics mean, and then, $\mathbf{m}_{prior} - \mathbf{m}_0$ vanishes. The spatial variant covariance function is implemented as a covariance matrix, which can be written as

$$\mathbf{C}_0 = \mathbf{SC}_{rock} \mathbf{S}^T,$$

(2)

where $\mathbf{S}$ is the steering filter and $\mathbf{C}_{rock}$ contain the rock-physics covariance,

$$\mathbf{C}_{rock} = \begin{bmatrix} C_{vv} & C_{v\varepsilon} & C_{v\delta} \\ C_{\varepsilon v} & C_{\varepsilon\varepsilon} & C_{\varepsilon\delta} \\ C_{\delta v} & C_{\delta\varepsilon} & C_{\delta\delta} \end{bmatrix}.$$ 

(3)

The steering filter (Clapp et al. 2004) in equation (3) defines the spatial correlation of properties. It is implemented to perform directional smoothing along the structural dip in the image. The spatial variant rock-physics covariance matrix $\mathbf{C}_{rock}$ defines both the variances of the properties and the correlation between them. On the diagonal of the matrix, $C_{vv}$, $C_{\varepsilon\varepsilon}$, $C_{\delta\delta}$ is the variances of P-wave velocity, epsilon, and delta. The off-diagonal terms are the correlation between them, for example, $C_{vc}$ is the correlation between velocity and epsilon. This prior knowledge is very hard to get with seismic data only; we employ a stochastic process (Bachrach 2010) of the calibrated compacting shale model (Bachrach 2011a) to define these covariances. Figure 1 shows the results of 2000 realizations of stochastic rock-physics modeling for the case study area. The results show that velocity and anisotropic parameters are correlated; Delta is positively correlated with slow velocity and negatively correlated with fast velocity. Also, both anisotropic parameters’ variances are smaller for slow velocities than for fast velocities. The stochastic results are fitted to a multi-Gaussian distribution for different velocity ranges. The resulting covariance functions are assigned point-wise to subsurface locations as a function of initial velocity.
The detailed workflow for the rock-physics-constrained tomography is described below:

1. Build an initial model with a compacting shale model, calibrated with available well logs.
2. Perform stochastic rock-physics modelling around initial model. Estimate the prior covariance for anisotropic parameters from the result.
3. Migrate seismic data with the current model, estimate structural dip from poststack imaging, and pick residual moveouts on prestack common image gatherers.
4. Perform simultaneous P-wave velocity, epsilon, and delta inversion to optimize the objective function as written in equation (1).
5. Check the residual moveouts with the updated model for convergence and repeat the iteration if necessary.

**Figure 1** The black dots are realizations of stochastic simulation. Green ellipses represent one standard deviation of multi-Gaussian distribution fitted to the cloud. Directions of ellipses illustrate how velocity is correlated with anisotropic parameters and the axis lengths of ellipses represent the magnitude of the covariance.

**Example**

We applied the method to the northern part of the Green Canyon area in the Gulf of Mexico, extending the work of Bachrach et al. (2011b). We mainly focused on the sediment column in the minibasins, where the compacting shale model is expected to be valid. We performed one iteration of rock-physics-constrained tomography and migrated the seismic data with Kirchhoff depth migration. Offset gathers before and after tomography were compared in Figure 2.

**Figure 2** Common image gather before and after constrained tomography.

Figure 3 shows the model update of this iteration of constrained tomography. We can see that updates in all properties are following the structure, which is the effect of applying steering filters. As a
control experiment, a relaxed unconstrained tomography was performed as well; the anisotropic parameters are not strongly correlated with velocity in the unconstrained case. For the constrained solution, as shown in Figure 3, the updates between velocity and delta are positive correlated for the shallow section and negatively correlated for the deep section, while the velocity and epsilon are positively correlated everywhere. The velocity and anisotropic update are correlated in accordance with the constraints we defined in Figure 1.

![Figure 3](image)

**Figure 3** Green ellipse is prior model distributions from rock physics (one standard deviation); Red ellipse is a relaxed general prior model distribution (one standard deviation); red dots are solution without rock-physics constraints; green dots are the solution with rock-physics constraints.

Gamma QC (Al-Yahya 1986) was also performed over the whole migrated volume. We display, layer by layer, the gamma map before and after this iteration of constrained tomography. In the shallow sections, the gathers are slightly over corrected in the initial model; after one constrained tomography, this bias was corrected. The gamma QC shows that most of gamma values in all layers are improved. These QC results prove that our method effectively converges to a solution that reduces the data misfit and improves residual moveouts in gathers.

![Figure 4](image)

**Figure 4** Residual moveouts analysis. a) Layers configured for Gamma analysis. b) Gamma map before and after rock-physics-constrained tomography; the positive gamma value is displayed as blue and stands for under-corrected gather; the negative gamma value is displayed as red and stands for over-corrected gather.
Conclusions

Stochastic rock-physics modelling provided a systematic process to convert rock physics knowledge into effective constraints for anisotropic tomography. Simultaneous inversion of velocity, epsilon and delta are demonstrated using Gulf of Mexico field data. The rock-physics-constrained tomography converges to a solution that reduces the moveouts in post migrated common image gathers. The formulation of the model space constraints in this work provides a flexible way to integrate soft knowledge into model building process for depth imaging projects.

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References


