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Geological and Rock Physics Constraints in Anisotropic Tomography

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SUMMARY

Because anisotropic models are unconstrained by surface-seismic data alone, we must learn to incorporate other non-seismic measurements and knowledge into the model building process. For this purpose, we demonstrate the regularization of anisotropic tomography with a preconditioning method which smooths updates along geological dip and constrains cross-property correlations to follow the predictions of rock-physics for compacting shales. The method is applied to the Green Canyon area in the Gulf of Mexico.

Introduction

By moving from analysis of simple moveout to analysis of complex moveout, from narrow azimuth data acquisition to wide azimuth data acquisition, and from layered models to hybrid gridded models, we have learned as an industry to fully exploit almost all of the kinematic information available in surface seismic data. As a result, modern ray-trace tomography builds isotropic P-wave velocity models with great success. Anisotropic models remain a challenge, because they are not constrained by surface-seismic data alone. We are able to build useful anisotropic models locally, where we can combine borehole seismic data and surface seismic data, provided we have good illumination around the VTI or TTI axis of symmetry (Bakulin et al, 2010a, 2010b). Away from wells, we must find other constraints to build models that will correctly depth our seismic images.

In this paper, we discuss how we can introduce geological and rock-physics based constraints into tomography, by regularizing the problem with the method of preconditioning. We review the method and we present a VTI case study in the Green Canyon area of the Gulf of Mexico. We constrain simultaneous updates of Thomsen parameters vp0, epsilon and delta to both follow geological layering and to preserve cross-property correlations in shale, as predicted by rock physics.

Method

Regularization “refers to a process of introducing additional information in order to solve an ill-posed problem or to prevent overfitting. This information is usually of the form of a penalty for complexity, such as restrictions for smoothness or bounds on the vector space norm” (Wikipedia, 2013). In the mid to late 1990’s, the Stanford Exploration Project studied regularization via reparameterization, through the method of preconditioning (Harlan, 1995; Fomel and Claerbout, 2003). Figure 1 (left) shows tomography equations set up to solve simultaneously for updates to all 3 Thomsen parameters (vp0, epsilon and delta) in this fashion, fitting a combination of surface-seismic data depth errors Δz and borehole-seismic data traveltime errors Δt. L contains the ray-traced Frechet derivatives relating changes in the model properties to changes in the data errors. In the objective function Φ, the magnitude of the internal model-update parameter $\Delta v'$ for velocity (or more generally $\Delta\alpha'$) is penalized by a damping parameter λ, then scaled and spatially smoothed or shaped by a preconditioner (or reparameterization) operator P. P is the square root of a prior covariance estimate of the property update; it converts the internal uncorrelated “primed” parameter (e.g. $\Delta v'$) to the actual earth property (e.g. Δv) delivered as an update---hence the “reparameterization”. The prior covariance estimate is imposed on the model update as a soft constraint, where it does not contradict the data.

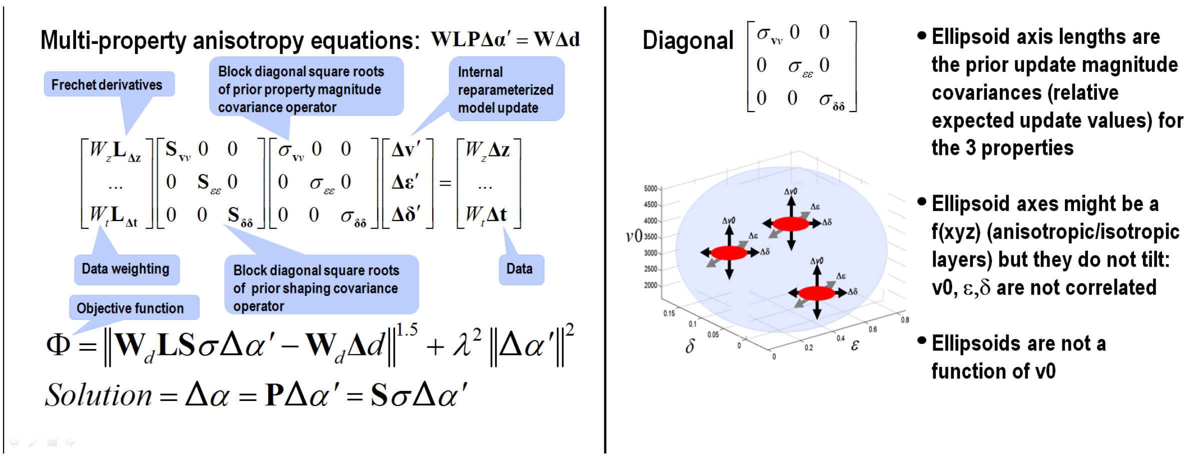

Figure 1 *Left: Tomography equations for updating vp0, epsilon and delta, regularized with preconditioning. Right: σ is the square root of the prior property update magnitude covariances.*

P constrains the shape of the update with the smoother S, and the magnitude of the update with the scaling parameter σ. S introduces a geological, stratigraphic constraint into the solution when it is a directional smoother, steering updates along interpreted geological dip (Clapp et al, 2004; Bakulin et al, 2010c); σ introduces other geological information by controlling the relative magnitudes of the updates for the different properties. Figure 1 (right) diagrammatically shows how the block-diagonal σ values may be interpreted as the axes of ellipsoids representing the square root of the prior magnitude covariance for uncorrelated properties. σ may also be interpreted as creating a property-variable (and possibly spatially variable) damping parameter λ.

Because anisotropic properties do not always follow geological reflectivity or stratigraphy, we need other constraints besides directional smoothing along dip and relative property-magnitude scaling to simultaneously update anisotropic properties away from wells. Bachrach (2010, 2011a) showed how rock physics can be used to stochastically model correlations between Thomsen parameters vp0, epsilon and delta. Through careful perturbation of mechanical compacting factors, mineral components, and diagenetic conditions, calibrated with a well, he produced a cloud of likely combinations of P-wave velocity, epsilon and delta values in sandy shale, as shown in Figure 2 (right). The uncorrelated (unrotated) prior-covariance ellipsoids of Figure 1 (right) are now correlated (rotated) and a function of velocity. Li et al (2011) first published a preconditioning scheme in which a tomography solution was constrained with such rock-physics cross-property correlations through introduction of off-diagonal terms (hence coordinate transformations) in the preconditioning σ operator of Figure 2 (left). For multi-parameter estimations, such cross-correlations between P-wave velocity, epsilon and delta at each subsurface location are powerful constraints.

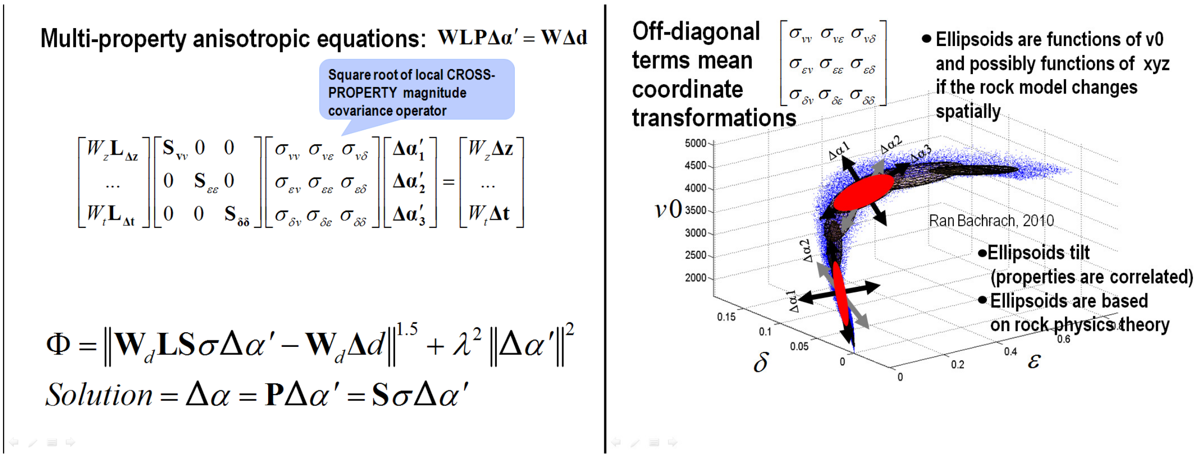

Figure 2 *Left: Tomography equations for updating vp0, epsilon and delta with rock physics constraints, regularized with preconditioning. Right: σ is the square root of the prior cross-property update magnitude covariances, derived with rock physics stochastic modeling.*

Example

Yang et al first published an example of rock physics constraints applied via preconditioning to a VTI Gulf of Mexico example in 2012 (Yang et al, 2012; Yang et al, 2013), extending work begun in Bachrach et al, 2011. Figure 3 shows orthogonal slices through a 3D Thomsen parameter cloud like that of Figure 2, calibrated for sandy shales in the Green Canyon prospect of that study. The black points in the cloud are realizations of stochastic simulation, generated by perturbing terms in the rock-physics functions; the green curves are slices through ellipsoids, marking 1 standard deviation in multi-Gaussian distributions fitted to the cloud. Note how delta is positively correlated with vp0 at low velocities (up shallow), but negatively correlated at high velocities (down deep). Note how epsilon is always positively correlated with velocity, at least beyond the mud zone. Note also how the ellipsoid widths and hence the standard deviations increase with velocity.

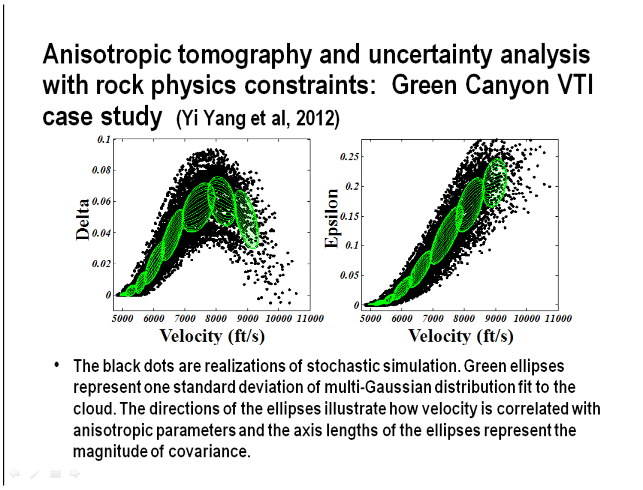

Figure 3 *The results of 2000 realizations of stochastic rock-physics modeling for the Green Canyon area compacting shale.*

Figure 4 shows vp0, epsilon and delta updates from an anisotropic tomography run with the rock-physics constraint pictured in Figure 3. The 3 properties were solved for simultaneously. Because S was a directional smoother for all 3 properties, the updates tend to follow the seismic dip. An anisotropic tomography was also run without the rock-physics constraint. The cross-plots compare the rock-physics constrained and unconstrained results. Because, for the rock physics constraint, delta is positively correlated with velocity up shallow and negatively correlated down deep, cross plots were constructed separately for the shallow (top plots) and deep (bottom plots) parts of the model. The cross plots on the left and right show velocity/epsilon update pairs and velocity/delta update pairs, respectively, for all points in the model. The red and blue dots correspond to the unconstrained and constrained solutions, respectively. The rock-physics constrained solution clearly conforms to rock physics theory; much of the unconstrained solution does not.

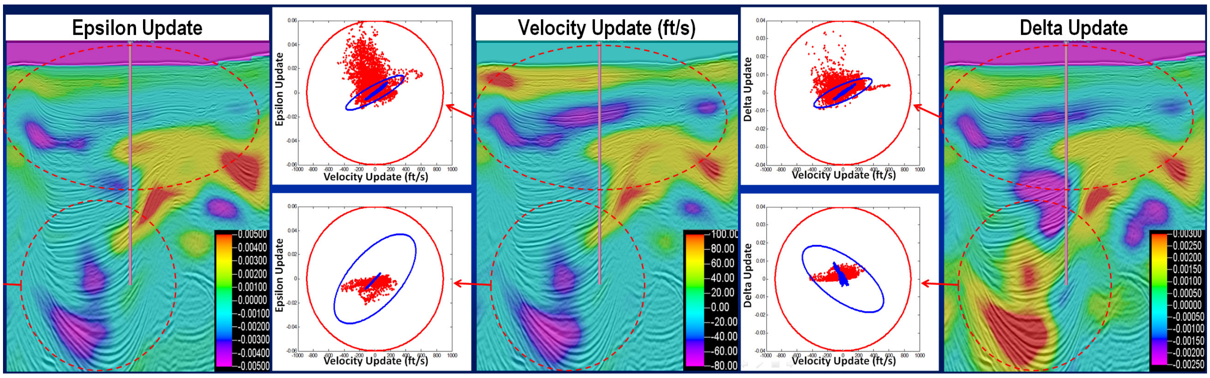

Figure 4 *Thomsen parameter updates for a rock-physics constrained tomography run. Cross plots compare the constrained updates (blue) to updates from a tomography run without rock-physics constraints (red).*

Both solutions flattened the gathers and improved focusing, but they produced different models that imaged structure at different depths. This null space or data insensitivity is the problem we face when building anisotropic models with surface-seismic data alone. Many models will explain the data and flatten the gathers. A model that flattens the data and is also consistent with rock-physics predictions of property correlations is more likely to be correct.

Conclusions

As the industry chases after increasingly risky prospects, we must build anisotropic models to correctly position seismic images in depth. Because anisotropic models are unconstrained by surface-seismic data alone, we must learn to incorporate other non-seismic measurements and knowledge into the model building process. For this purpose, we demonstrate the regularization of anisotropic tomography with a preconditioning method which smooths updates along geological dip and constrains cross-property correlations to follow the predictions of rock-physics for compacting shales.

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