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Tilted Orthorhombic Model Building with Geomechanics: Theory and Observations

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SUMMARY

We layout the workflow to build a stress induced orthorhombic model using the excess fracture compliance rock model. In comparison to the third-order elasticity method previously used, this workflow has the advantage to possess no constraints on the background material symmetry and principal stress directions. We also demonstrate how this workflow will be of key use on a Gulf of Mexico (GOM) case study by showing the strong correlation between the observed azimuthal anisotropy from data and the principal stress direction.
Introduction

Orthorhombic model building is the natural incremental step for improving a TTI velocity model that is not able to resolve residual azimuthal moveout. Because the numbers of free parameters in an orthorhombic model for P-wave imaging is large (five to six Tsvankin’s parameters per grid point), estimating all of these parameters is a challenging task, and any method that may help constraining the directionality and distribution of the orthorhombic parameters in space, will greatly facilitate model building.

Stressed and fractured medium can have complex symmetry, and in particularly under triaxial state of stress sediments can become orthorhombic Prioul et al. 2004. Bachrach et al. 2008 showed that azimuthal velocity variations around salt bodies correlates with the state of stress in the subsurface. Bachrach et al. 2008 and Rodriguez et al. 2014 have also demonstrated how orthorhombic model can be built using third-order elasticity (TOE) which is a linearized approach for computing the stress induced anisotropy.

As an alternative to TOE, a rock model formulated in terms of fracture compliances can be used to describe stress sensitivity of the rock elastic stiffness tensor. Sayers 2006 and Collet et al. 2014 have shown different method to derive stress dependent rock model which can be used for calculating the elastic stiffness of a stressed medium.

In this paper we describe how to compute the stress induced anisotropy for the general case where the stress and the subsurface structure (dip) are not aligned. We highlight an example of a GOM case study where this method will be of great benefit by showing how a geomechanic model clearly reproduce the orthorhombic pattern derived from orthorhombic moveout analysis.

Theory: Stress-induced anisotropy

Following Sayers et al. 1995 and Sayers 2006 we characterize a cracked/fractured medium using the excess compliance model where the effective elastic compliance of the stress sensitive sediment is given by the excess compliance model to be:

$$ S_{ijkl} = S_{ijkl}^0 + \Delta S_{ijkl} (Z_n, Z_t) $$(1)

We define the response of the fractured system to stress assuming the fracture compliance is stress sensitive and is given by (Schoenberg et al. 2002):

$$ Z_n = Z_{n0} \exp(-\sigma_n / \sigma_{Cn}) $$

$$ Z_t = Z_{t0} \exp(-\sigma_n / \sigma_{Ct}) $$

Where $Z_{n0}$ is the normal fracture compliance at zero stress, $\sigma_n$ is the stress normal to the fracture plane and $\sigma_{Cn}$ and $\sigma_{Ct}$ are coefficients governing the normal and tangential compliance stress sensitivity of the given fracture. This notation is consistent with the linearized analysis given by Sayers 2006.

Given any point location the TTI model in terms of compliance $S_{ijkl}$ , and the stress tensor state $\sigma_{ij}$ express both in the global coordinate, we can express these respectively by $S_{ijkl}^F$ and $\sigma_{ij}^F$ in a given orthonormal basis $X^F = (x_1^F, x_2^F, x_3^F)$ with $x_3^F$ being the normal to the fracture plan. Using the latest coordinate system we can express the stress normal to fracture by $\sigma_n = (\sigma_{ij} x_i^F) x_3^F = \sigma_{33}^F$ and the excess compliance terms $\Delta S_{ijkl}^F$ possess only 3 non-zero components: $\Delta S_{33}^F = \alpha_{33}^F + \beta_{333}^F$ and $\Delta S_{55}^F = \Delta S_{44}^F = \alpha_{13}^F$. In the most general case, this model generates a fully complex anisotropic system (21 nonzeros components—triclinic system). In order to use this model for orthorhombic imaging we express this triclinic system in a higher order of symmetry by using an efficient algorithm to compute the closest orthorhombic material symmetry in terms of Federov norm, den Boer 2014. Following this workflow we are able to treat any stress state, with any given fracture orientation, without being bounded by the hypothesis that these two have to be aligned. In this exercise, we can expect fracture plane to be defined by the $[\sigma_{33} \quad \sigma_{13 \text{max}}]$ plane only, or both in the bedding plane and the
$[\sigma_y \quad \sigma_{H_{\text{max}}}]$ plane as illustrated in Figure 1 – we define our three principal stress direction with the compressive convention by $\sigma_y \geq \sigma_{H_{\text{max}}} \geq \sigma_{h_{\text{min}}} \geq 0$. In the following example we show a case in Gulf of Mexico where the principal stress direction correlates strongly with the orthorhombicity observed from data, suggesting that the application of such a workflow will be successful as an alternative or as a support from data observation.

![Figure 1 Description of possible scenario for fractured system: (top) fracture are aligned with the $[\sigma_y \quad \sigma_{H_{\text{max}}}]$ plane, (bottom) Fracture and grain contact are expected to be on the structural tilted isotropic plane as well as in the $[\sigma_y \quad \sigma_{H_{\text{max}}}]$ plane.](image)

Correlation between stress modeling and seismic TOR parameter estimation: GOM example

We use in this example the combination of wide azimuth and coil survey of the southern part of Green Canyon area in the GOM, this survey revealed azimuthal anisotropic behavior as described by Rodriguez et al. 2014. We built an orthorhombic velocity model using only the seismic data as follows: We first derive tomographically the best fit TTI model which explain the moveout for all azimuths. Then four TTI velocity models are derived using sectored TTI tomography, updating epsilon and delta only for the different azimuth sectors [15°, 45°, 75°, and 135°]. Using the result of these four TTI model, we compute the fast direction of the orthorhombic model by fitting an ellipse on the delta observed. The expected azimuthal anisotropy is represented by the difference between $\delta_1$ and $\delta_2$ being respectively the large and small axis of the ellipse. We define this model as “data-driven.” In Figure 3 we present the data driven results in terms of the direction associated with the larger $\delta_1$ parameter.

Independently, we build a geomechanic model by deriving the material properties (density, Young modulus and Poisson’s ratio) from the velocity $V_p$, and consider hydrostatic pore pressure. Salt geometry is introduced using the seismic image. This model was built using the simplest assumptions possible, reproducing the little information we possess during any exploration study. The model was built using the finite element software. The stress tensor computed was decomposed in the three principal direction with $\sigma_y \geq \sigma_{H_{\text{max}}} \geq \sigma_{h_{\text{min}}} \geq 0$. In Figure 2 we present the results of the stress modelling. We follow Bachrach et al. 2008 and assigned very low Poisson’s ratio to the salt. This ensure the salt will not sustain shear stresses as in general it is visco-elastic. The outcome of this technique is that the maximum horizontal stress is perpendicular to the salt body. Therefore, due to the salt complexity the directionality of $\sigma_{H_{\text{max}}}$ varies in space.

When we compare the observation of these two independent models by plotting the fast direction versus the $\sigma_{H_{\text{max}}}$ vector (expected azimuthal fast direction). We observe in Figure 3, that for a moderate depth, the fast direction suggested by the data is strongly correlated with the $\sigma_{H_{\text{max}}}$ direction. This results is observed systematically at different depth of our model. For example, in Figure 5 we observe a case very shallow where the $\sigma_y$ is strongly tilted and is correlated with the fast direction and in second order aligned/close to $\sigma_{H_{\text{max}}}$.
We also note that this correlation deteriorates with depth, for instance in Figure 4, we compare the suggested fast direction from data observation, versus the $\sigma_{H\text{ max}}$ direction with color representing the azimuthal anisotropy expected for a deep layer around the salt dome. This breaking down of correlation could be explain in our opinion by two factor: 1) when going deeper we have poor velocity resolution going deeper into the basin; 2) the material stress sensitivity is reduced with depth.

![Figure 2 Results of the stress model (principal directions) juxtaposed with the salt body.](image)

**Conclusions**

In this study we show good agreement between travel times derived TOR model and stresses. The variation in the observed anisotropic parameters and their principal directions derived by elliptical fit to tomographically derived sectored TTI observations is in good agreement with the direction of the maximum horizontal stress. The spatial pattern associated with the seismic observation is controlled by the stresses which are varying fast due to the presence of salt. We thus conclude that stress modelling in areas of complex salt geometry provide a valuable constraint on the directionality of the seismic velocity and its orthorhombic nature. We also note that the mapping of stress to seismic velocity should be done using a general theory that takes into account the tilt of the layer which is significant near the salt.

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**References**

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Figure 3 Left: (top) Fast direction suggested by data processing; (bottom) $\sigma_{H\text{max}}$ direction; right: Observed orientation projected on a TTI plane at a point location.

Figure 4 Comparison of the fast direction suggest by data (left) and stress model (right).

Figure 5 Shallow point where $\sigma_Y$ is tilted and is aligned with the fast direction from data observation.