Building TTI depth models using anisotropic tomography with well information

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Summary

Tilted transverse isotropy (TTI) is becoming recognized as a more realistic description of anisotropy in sedimentary formations than vertical transverse isotropy (VTI). This is especially true in complex geological settings. While model building approaches for VTI are well understood, similar approaches for TTI media are in their infancy, even when symmetry-axis direction is known. We present an approach that allows building localized anisotropic models utilizing joint inversion of seismic and well data. We present a synthetic data example of anisotropic tomography applied to a layered TTI model with a symmetry-axis tilt of 45 degrees. We demonstrate three cases of introducing additional information. In the first case velocity along the symmetry axis is known and tomography inverts for Thomsen's ε and δ. In the second case, tomography inverts two Thomsen parameters and velocity from a joint dataset that consists of seismic data and vertical checkshot traveltimes. In contrast to the VTI case, such inversion is non-unique. To combat non-uniqueness in the third case we supplement checkshot and seismic data with the Thomsen's δ profile from an offset well. This allows recovery of correct profiles for velocity along the symmetry axis and Thomsen's ε. We conclude that TTI model building may remain non-unique even in the presence of well information. Therefore additional assumptions need to be added or uncertainty analysis has to be conducted to pick a geologically plausible model from a range of equivalent models.

Introduction

Vertical transverse isotropy is a useful approximation that describes seismic anisotropy of subsurface formations. However widespread application of VTI depth imaging reveals that often the direction of the symmetry axis may not be vertical. Indeed, if sedimentary formations have been deposited in a layer-cake geometry and were later folded by tectonical forces, then tilted transverse isotropy with the axis perpendicular to bedding may be me a more appropriate description. Such media are sometimes referred to as structurally conformant transverse isotropy (Audebert et al, 2006). However, in an alternative geological scenario, tectonic action and deposition may occur together and the symmetry axis may not be perpendicular to bedding. In yet another scenario, sediments may be subjected to anomalous stresses around salt bodies which can result in a stress-induced anisotropy (Bachrach and Sengupta, 2008). Since in this case symmetry is controlled by principal stress directions that are neither vertical nor horizontal, nor perpendicular to the bedding axis, then general TTI or even an orthorhombic medium is expected. For any of these scenarios we should be able to build an anisotropic model for depth imaging that is governed by geologically plausible anisotropic velocity field. In practical circumstances it usually requires supplementing seismic data with some kind of well information. For a VTI depth models checkshot survey or depth markers usually resolve the existing ambiguity and provide a unique depth model that fits all the data. We extend a similar methodology to the TTI case and demonstrate that more challenges are expected for TTI media and additional data may be required to constrain a unique model.

Synthetic example

Let us apply anisotropic tomography with well constraints to a simple deepwater model (Figure 1). The subsurface is represented by layered TTI sediment with a uniform symmetry-axis tilt of 45 degrees (Figure 1a). The model has smooth vertical variation of velocity and anisotropy (Figures 1,2,5). Two pronounced velocity inversions are present in the model. They are also accompanied by anisotropy reductions (Figures 1,2,5). A cable length of 12 km is assumed. A prestack gather computed with anisotropic ray tracing is shown in Figure 1b. Reflected events from 49 density-contrast interfaces are located every 200 m.

We assume that the tilt angle of the symmetry axis is known and apply anisotropic reflection tomography (Woodward et al., 2008) to solve for a local TTI model

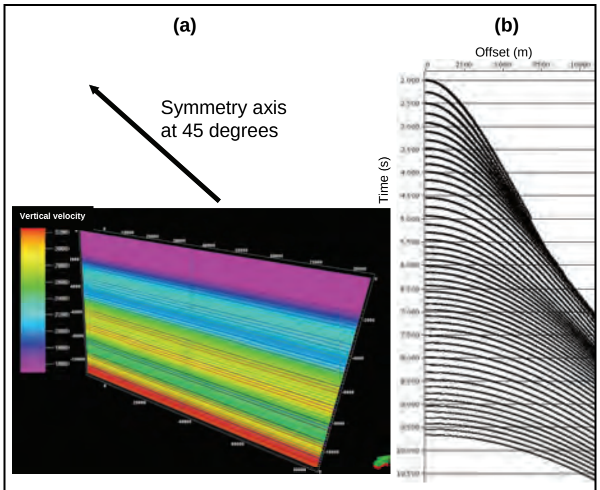

Figure 1: Deepwater horizontaly layered TTI model used for tomography: a) velocity V_{P0} (along symmetrey axis) slice with 49 density reflectors; symmetry axis is tilted by 45 degrres away from vertical for all layers; b) prestack gather. Water depth is at 1500 m.

using joint inversion of seismic and well data. We apply a mute of 50 degrees to the data before inversion. This limits the useable offsets to less than 8 km for events above 6 km; it limits half-opening angles to less than 40 degrees for events deeper than 8 km.

We consider three different scenarios for the well data:

- knowledge of V_{P0} from either an acoustic log in deviated well, a Virtual Checkshot or an offset well;
- checkshot survey in a vertical well;
- checkshot survey in vertical well and correct profile of Thomsen's δ from an offset well.

First, we present tomographic results for all three scenarios. Then we attempt to explain them using theoretical analysis and discuss differences between these scenarios.

Two-parameter inversion after fixing V_{P0}

Let us assume that well data are available from a deviated well drilled along the TTI symmetry axis (45 degrees to the vertical in our case). Velocity along the well can then be estimated either from acoustic logging or by performing Virtual Checkshot (Mateeva et al., 2006). Alternatively one may utilize a V_{P0} profile from an offset well. After fixing V_{P0} to its correct values, we attempt tomographic reconstruction of δ and ε from long-offset reflection seismic data. While for the VTI case such an inversion would be unique and stable, we find that for this TTI case only an approximate model is recovered (Figure 2). Individual values of Thomsen parameters and δ in particular show errors of 0.05 and more. Nevertheless the final model provides image gathers that are as flat as in the true model.

Three-parameter inversion of seismic and vertical checkshot data

In the second scenario we assume the availability of a vertical well with a checkshot survey acquired every 50 m from 1.5 km to 11 km. We invert joint seismic and checkshot data for three parameters (V_{P0},ε and δ) around the well. Since we have long-spread data such an inversion would result in a unique recovery of the true model in a VTI case. To our surprise, TTI inversion leads to a different model (Figure 3) that provides a reasonable fit to the checkshot (Figure 4) and that flattens the image gathers, but that has a geologically implausible ε and δ.

Two-parameter inversion of seismic and vertical checkshot data after fixing the correct profile of Thomsen's δ from an offset well

In the third scenario we supplement the vertical checkshot with the additional knowledge of the correct profile of Thomsen's δ from an offset well. Tomography performs a two-parameter inversion (V_{P0} and ε) of the seismic and checkshot data and recovers excellent estimates of the unknown parameters at all depths (Figure 5).

Weak-anisotropy analysis of the results

Why did such a different models provide similar fit to this seemingly complete dataset? In order to obtain analytical insight into the problem it is instructive to obtain weak-anisotropy expressions for all *P*-wave TTI signatures at hand. For a single horizontal TTI layer with a 45 degree tilt of the symmetry axis these signatures are expressed as follows (Tsvankin, 2001; Pech et al, 2003):

$$V_{nmo} = V_{P0}\left(1+1.25\varepsilon-0.75\delta\right), \tag{1}$$

$$V_V = V_{P0}\left[1+0.25(\varepsilon+\delta)\right], \tag{2}$$

$$A_4 = \frac{2\eta}{t_{P0}^2 V_{P0}^4}. \tag{3}$$

Here V_{P0},ε, and δ are three independent Thomsen parameters that describe the TTI velocity field; $\eta \approx \varepsilon - \delta$; V_V denotes velocity in the true vertical direction; V_{nmo} describes the moveout velocity from a horizontal reflector; A_4 is a quartic moveout coefficient describing *P*-wave traveltime behavior at long offsets. Various numerical coefficients arise after substituting values of zero reflector dip and tilt of the symmetry axis (45 degrees).

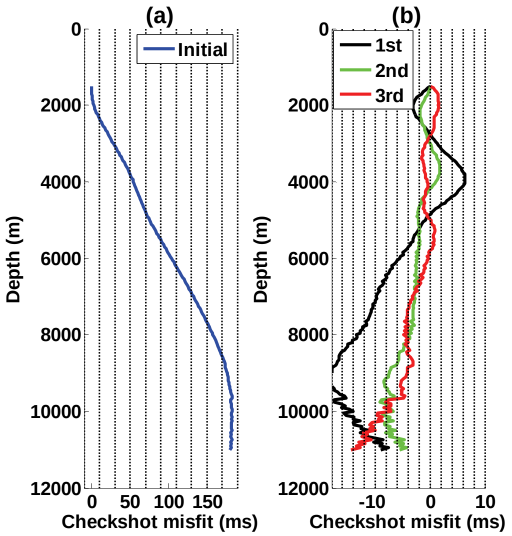

Figure 4: Misfit in checkshot traveltimes for initial model (a) and all subsequent tomography iterations (b) for the second scenario of joint three-parameter inversion of seimsic and checkshot data. Misfit is computed as a difference between experimental and predicted traveltimes.

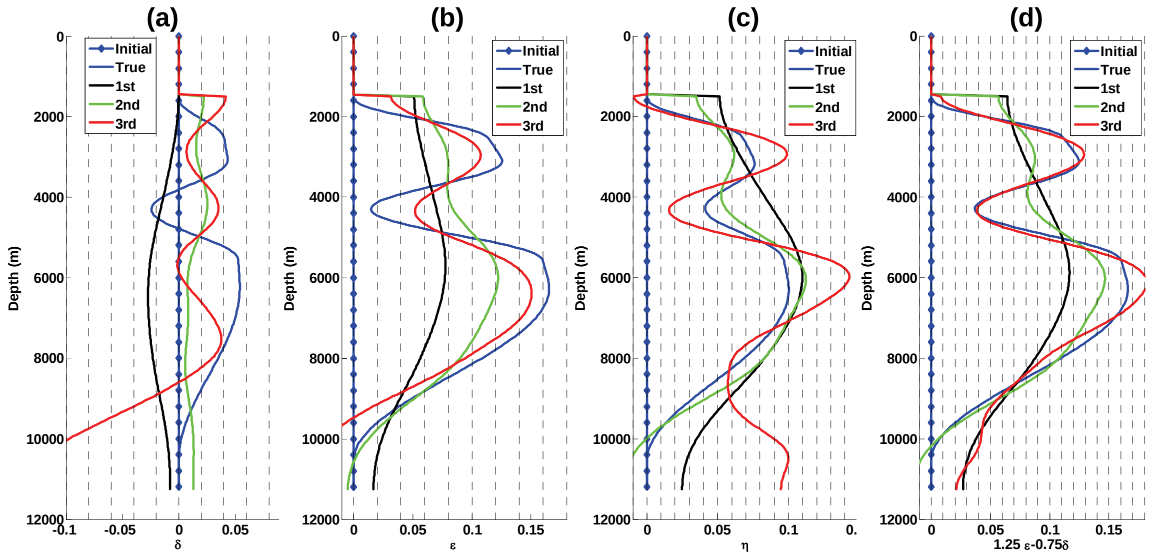

Figure 2: Results of a two-parameter inversion (ε and δ) of seismic data after fixing velocity along the symmetry axis (V_{P0}). Anisotropy profiles after each iteration are shown together with initial (zero) and true models: (a) δ; (b) ε; (c) η; (d) parameter combination *(1.25ε-0.75δ)*, that controls NMO velocity (equation 1). While this parameter combination is tightly constrained (d), δ and ε themselves are determined with errors. In particular δ is not well resolved.

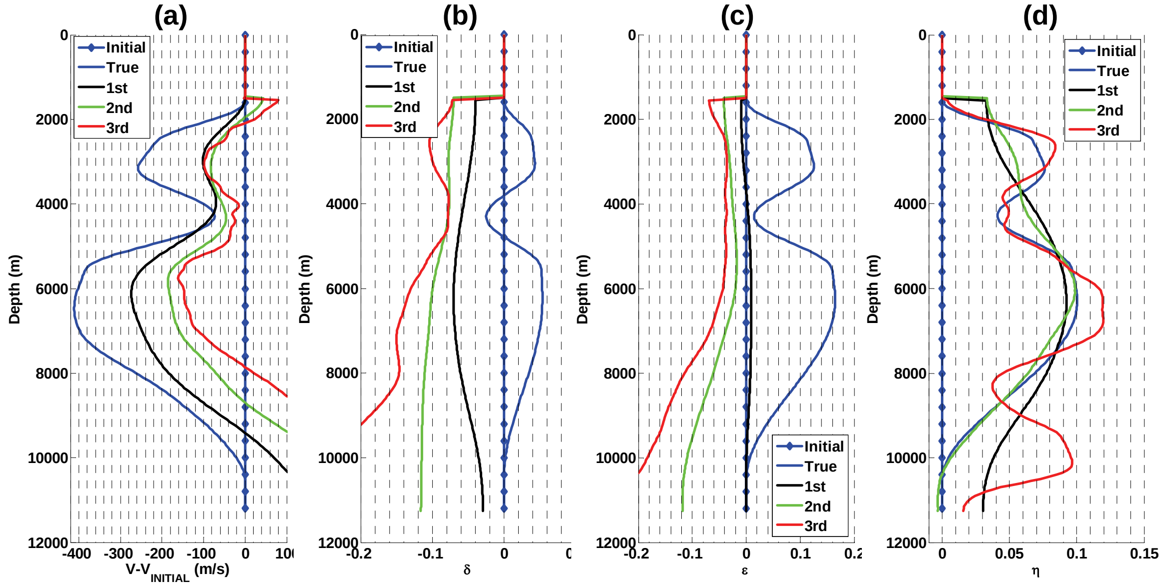

Figure 3: Results of a three-parameter inversion (V_{P0}, ε and δ) of seismic and vertical checkshot data. Velocity and anisotropy profiles after each iteration are shown together with initial and true models: (a) update in velocity shown as a difference between current velocity at each iteration and initial velocity profile; (b) δ; (c) ε; (d) η. Note that whereas parameter combination $\eta \cong \varepsilon - \delta$ is relatively well constrained, tomography recovers one of the equivalent models with incorrect V_{P0}, δ and ε. Note that parameter η in our case plays the same role as δ in VTI case relating vertical velocity and V_{nmo}.according to equation (4). Even though vertical velocity (V_V) is constrained by the checkshot, we are unable to resolve ε and δ individually, because in our case both short and long-spread moveouts are controlled by η (see equations 3 and 4).

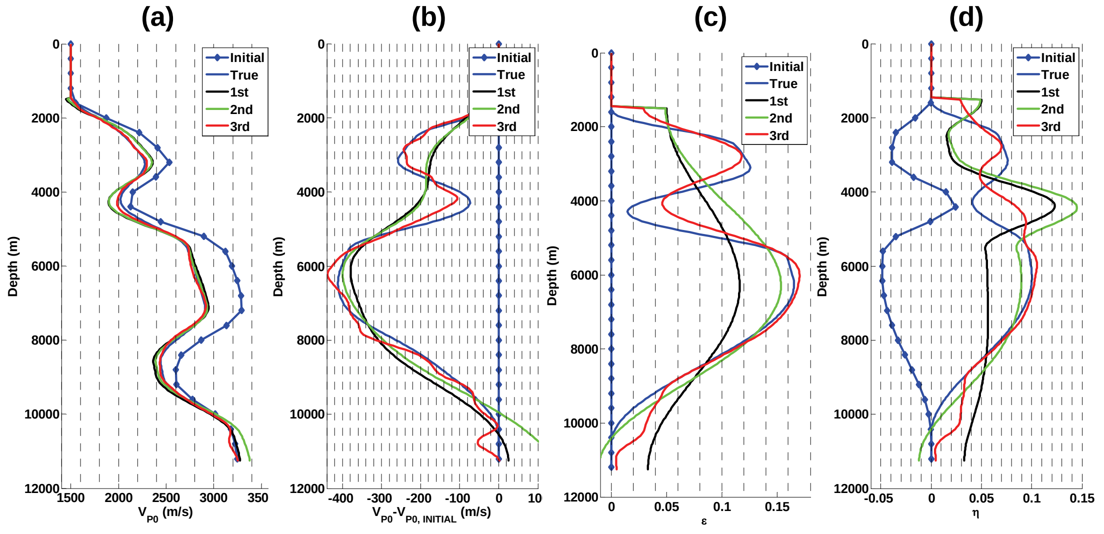

Figure 5: Results of a two-parameter inversion (V_{P0}, ε) of seismic and vertical checkshot data after fixing δ profile to a true values. Velocity and anisotropy profiles after each iteration are shown together with initial and true models: (a) velocity along symmetry axis; (b) update in velocity shown as a difference between current velocity at each iteration and initial velocity profile; (c) ε; (d) η.

In the first example the information constrained by the seismic data is equivalent to equations (1) and (3). Indeed, we observe that combination *(1.25ε-0.75δ)* that controls V_{nmo} is best determined (Figure 2d). Parameter η is less well-determined. This observation is analogous to a VTI case where the trade-off between V_{nmo} and A_4 leads to substantial uncertainty in the quartic coefficient and thus in η (Tsvankin, 2001). Individual parameters are less well determined likely because combinations *(1.25ε-0.75δ)* and *(ε-δ)* from equations (1) and (3) are too similar to constrain them separately, thus creating additional ambiguity.

For the second case when checkshot data is available we add information equivalent to equation (2). It is instructive to combine equations (1) and (2) and thus rewrite (1) in the following weak-anisotropy form

$$V_{nmo} = V_V\left(1+\eta\right). \qquad (4)$$

It becomes obvious that three measurements (V_{nmo} , V_V and A_4) do not constrain all three parameters (V_{P0}, ε, δ) because equations (4) and (3) constrain only η, whereas equation (2) constrains a combination of all three desired quantities. In the absence of any additional information, tomography retrieves an equivalent model with correct η and V_V but incorrect individual parameters V_{P0}, ε and δ.

When δ is additionally constrained as in the third example, then tomography correctly recovers V_{P0} and ε, as expected from the weak-anisotropy equations above.

Conclusions

We presented an approach to build local TTI depth models for three practical scenarios when well data is introduced via fixing velocity along symmetry axis, providing vertical checkshot traveltimes or combining vertical checkshot and true δ profile from an offset well. Guided by VTI predictions, we expected that each of them will allow building a correct TTI model. However we observed increased ambiguity in the parameter estimation and only the third scenario resulted in recovery of the true model. We were able to explain the observed ambiguity by developing weak-anisotropy equations for all measured seismic signatures. It appears that combination of horizontal reflectors and symmetry axis tilt of 45 degrees may be the culprit for severe non-uniqueness in case of typical data (seismic and vertical checkshot). This study highlights challenges associated with TTI velocity model building from narrow-azimuth surveys. We expect wide-azimuth data to provide additional constraints and reduce such ambiguity. We anticipate that this approach of well-constrained tomography can be applied to inversion for anisotropy in 2D and 3D TTI models and would allow anisotropic calibration with deviated wells.

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EDITED REFERENCES

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