Migration velocity analysis and imaging for tilted TI media

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Summary

Tilted transversely isotropic (TTI) formations cause serious imaging distortions in active tectonic areas (e.g., fold-and-thrust belts) and in subsalt exploration. Here, we introduce a methodology for P-wave prestack depth imaging in TTI media that properly accounts for the tilt of the symmetry axis as well as for spatial velocity variations. For purposes of migration velocity analysis (MVA), the model is divided into blocks with constant values of the anisotropy parameters ϵ and δ and linearly varying symmetry-direction velocity V_{P0} controlled by the vertical (k_z) and lateral (k_x) gradients. Since tilt is not well constrained by P-wave data, the symmetry axis is kept orthogonal to the reflectors in all trial velocity models. The MVA algorithm estimates the velocity gradients k_z and k_x and the anisotropy parameters ϵ and δ in the layer-stripping mode using a generalized version of the method introduced by Sarkar and Tsvankin for factorized VTI (TI with a vertical symmetry axis) media.

Synthetic tests confirm the robustness of our MVA methodology and show that ignoring the influence of tilt may lead to significant image distortions and errors in parameter estimation. The ability of our MVA algorithm to separate the anisotropy parameters from the velocity gradients can also be used in lithology discrimination and geologic interpretation of seismic data in complex areas.

Introduction

Transverse isotropy with a tilted symmetry axis (TTI) describes dipping shale layers in fold-and-thrust belts and near salt bodies (e.g., Tsvankin, 2005). TTI symmetry can also be caused by a system of parallel dipping fractures embedded in otherwise isotropic rock (Dewangan and Tsvankin, 2006a). Serious distortions caused by TTI layers in conventional (isotropic) seismic imaging are well documented in the literature (e.g., Vestrum et al., 1999; Kumar et al., 2004). Since the influence of tilt creates ambiguity in parameter estimation, a major problem in seismic processing for TTI media is accurate velocity analysis and model building.

P-wave kinematic signatures for tilted transverse isotropy can be described by the symmetry-direction velocity V_{P0}, Thomsen parameters ϵ and δ, and the orientation of the symmetry axis. In 2D models treated here, the symmetry direction is described by the angle ν (tilt) with the vertical. Estimation of this parameter set even for a single TTI layer generally requires combining P-wave data with mode-converted PS-waves (Dewangan and Tsvankin, 2006a, 2006b). For shale layers, however, the symmetry axis is usually orthogonal to the layer boundaries, which helps to make velocity analysis more stable.

Here, we present an extension of the MVA algorithm developed for VTI media by Sarkar and Tsvankin (2004, 2006) to tilted transverse isotropy. The symmetry axis is assumed to be orthogonal to the reflectors and confined to the vertical incidence plane. The model is composed of "quasi-factorized" TTI blocks, in which the Thomsen parameters ϵ and δ are constant, while the symmetry-direction velocity V_{P0} is a linear function of the spatial coordinates. These blocks are not strictly factorized because reflectors may have arbitrary shape, and the symmetry-axis orientation may vary within each block. The velocity-analysis and imaging results are compared with those obtained by VTI algorithms to illustrate the need to account for tilt in anisotropic imaging.

Methodology

For TI layers with the symmetry axis orthogonal to the reflector, the dip-line P-wave normal-moveout (NMO) velocity is described by the isotropic cosine-of-dip dependence (Tsvankin, 2005):

$$V_{\text{nmo}}(\nu) = \frac{V_{\text{nmo}}(0)}{\cos\nu} = \frac{V_{\text{nmo}}(0)}{\sqrt{1 - p^2\, V_{P0}^2}}\,, \qquad (1)$$

where $p = \sin\nu / V_{P0}$ is the ray parameter of the zero-offset ray; note that p can be determined from time slopes on the zero-offset or stacked section. In some cases (e.g., for a bending layer), it may be possible to directly estimate the zero-dip NMO velocity given by

$$V_{\text{nmo}}(0) = V_{P0}\,\sqrt{1 + 2\delta}\,. \qquad (2)$$

Then equation 1 can be used to find the vertical velocity V_{P0}, which can be substituted into equation 2 to obtain δ. In our algorithm, the velocity V_{P0} is assumed to be known at the top of each block, so δ can be determined directly from the NMO velocity in equation 1. The parameter ϵ is not constrained by NMO velocity and has to be estimated from nonhyperbolic moveout controlled by the anellipticity parameter $\eta \equiv (\epsilon - \delta)/(1 + 2\delta)$ (Pech et al., 2003).

To make the modeling and migration algorithms of Sarkar and Tsvankin (2004) suitable for TTI media, we employ ray-tracing software that can handle an arbitrary tilt of the symmetry axis (Seismic Unix codes "unif2aniso" and "sukdsyn2d"; see Alkhalifah, 1995). At the parameter-estimation step, we keep the symmetry axis orthogonal to the reflectors and update the parameters k_z, k_x, ϵ, and δ. To constrain the vertical gradient k_z, we use two reflectors located at different depths in each TTI block. The residual moveout in image gathers, which is minimized during the iterative parameter updating, is described by the

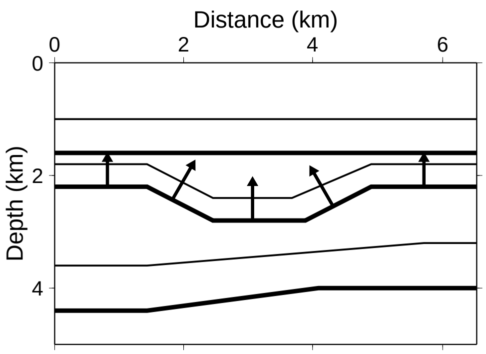

Fig. 1: Model with a TTI syncline sandwiched between two isotropic layers. The bold lines mark the layer boundaries; the additional reflectors used in MVA are shown by the thinner lines. The parameters of the TTI layer are V_{P0} = 2.3 km/s, $k_z = 0.6\ s^{-1}$, $k_x = 0.1\ s^{-1}$, $\epsilon = 0.1$, and $\delta = -0.1$ ($\eta = 0.25$). The symmetry axis (marked by the arrows) is orthogonal to the layer's bottom; the dips are 30°. The top layer has V_{P0} = 1.5 km/s, $k_z = 1.0\ s^{-1}$, $k_x = \epsilon = \delta = 0$; for the bottom layer, V_{P0} = 2.7 km/s, $k_z = 0.3\ s^{-1}$, and $k_x = \epsilon = \delta = 0$. The velocity V_{P0} is specified on top of each layer at the 1 km coordinate.

nonhyperbolic equation discussed in Sarkar and Tsvankin (2004). The MVA and Kirchhoff prestack depth migration are applied in the layer-stripping mode starting at the top of the model.

For TTI media with a positive vertical gradient in V_{P0}, reflections from steeply dipping interfaces often arrive at the surface as *turning* rays (Tsvankin, 2005). Hence, our algorithm properly accounts for turning-ray reflections in the computation of the traveltime field used by the migration operator.

Tests on synthetic data

We computed synthetic seismograms and tested our MVA/imaging algorithm on several common geological models that often include TTI layers. Two examples, for a TTI syncline and a salt dome flanked by uptilted shale layers, are discussed below.

Syncline model

The first model includes a TTI syncline with dips of 30° sandwiched between two isotropic layers (Figure 1). The isotropic layers are vertically heterogeneous but have no lateral velocity gradient, while the TTI layer is both vertically and laterally heterogeneous. As required by the MVA algorithm, each layer contains two reflecting interfaces, with every second reflector representing the boundary between layers. Synthetic data are generated by anisotropic ray tracing and consist of 260 shot gathers with shot and receiver intervals of 25 m and 40 traces per gather.

We applied our MVA algorithm to 10 image gathers lo-

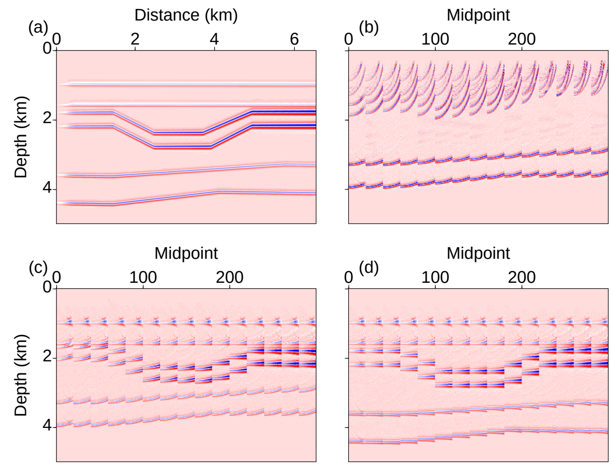

Fig. 2: (a) Image of the model from Figure 1 obtained after MVA and prestack depth migration. The estimated parameters of the first (subsurface) layer are $k_z = 0.99\ s^{-1}$ and $k_x = \epsilon = \delta = 0$. For the second (TTI) layer, $k_z = 0.59\ s^{-1}$, $k_x = 0.09\ s^{-1}$, $\epsilon = 0.09$, and $\delta = -0.11$. For the third layer, $k_z = 0.29\ s^{-1}$ and $k_x = \epsilon = \delta = 0$. The error for each parameter varies from ±0.01 to ±0.02, if the depth picking error is assumed to be ±5 m. Image gathers obtained (b) with the initial isotropic model before MVA; (c) after six iterations of MVA for the first two layers; (d) after MVA for all three layers.

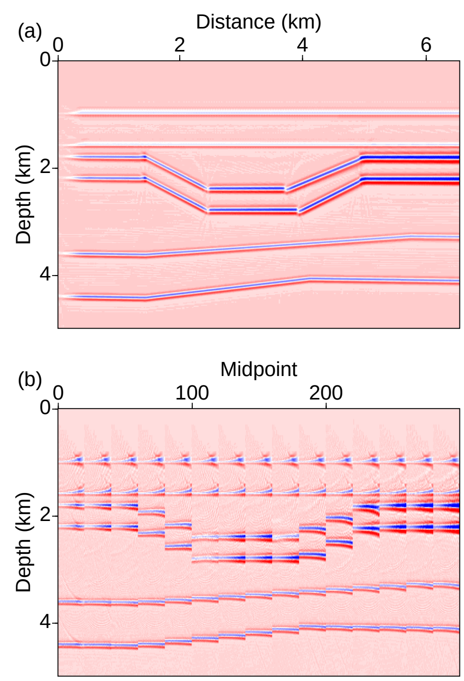

Fig. 3: (a) Image of the model from Figure 1 obtained after applying MVA under the assumption that the second layer is VTI. The estimated parameters of the second layer used in the migration are $k_z = 0.53\ s^{-1}$, $k_x = 0.12\ s^{-1}$, $\epsilon = 0.15$, and $\delta = -0.06$ ($\eta = 0.24$). (b) The corresponding image gathers.

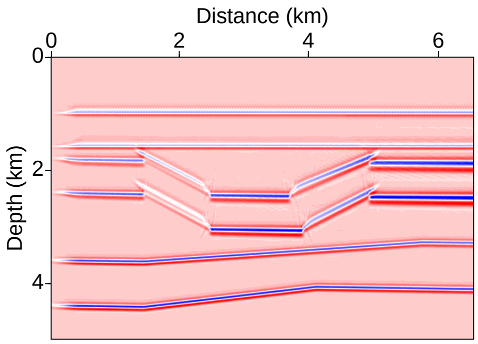

Fig. 4: Same as Figure 3a (i.e., the image for the best-fit VTI model), but the thickness of the TTI layer from Figure 1 is increased by 200 m. The estimated parameters are $k_z = 0.52$ s^{-1}, $k_x = 0.12$ s^{-1}, $\epsilon = 0.13$, and $\delta = -0.08$ ($\eta = 0.26$).

cated at horizontal coordinates ranging from 1.5 km to 5 km (Figure 2). The initial velocity model used in the first iteration of MVA is homogeneous and isotropic. The velocity V_{P0} was specified at one location at the top of each layer. The inverted parameters are close to the true values, and all reflectors in the migrated image are well focused and positioned (Figure 2a).

If the symmetry-direction velocity V_{P0} is known, the NMO velocities in the TTI layer can be inverted for the parameter δ (see equations 1 and 2). Although in the introduction this result is discussed for a homogeneous TTI medium, it remains valid for our heterogeneous model because we estimate the velocity gradients by using image gathers at different depths and lateral positions. In contrast to VTI media, where the parameter ϵ (with a known V_{P0}) can be found from dip-dependent NMO velocity, estimation of ϵ in TTI media generally requires using nonhyperbolic moveout. The relatively large offset-to-depth ratios (reaching two) used in the velocity analysis for the syncline model are sufficient to provide a constraint on ϵ.

The improvements achieved by the MVA algorithm in reducing the residual moveout in image gathers are illustrated in Figures 2b-2d. Upon completion of the parameter estimation for all three layers, image gathers are flat throughout the model (Figure 2d).

Since most anisotropic imaging algorithms used in industry are designed for VTI media, it is important to evaluate the influence of the tilted symmetry axis on the results of MVA and migration. To emulate a VTI processing sequence, we repeated the MVA without allowance for a tilted symmetry axis (i.e., the second layer was treated as VTI). After several iterations of parameter updating, the image gathers were largely flattened, and the image quality was only marginally inferior to that achieved for the true model (Figure 3). The parameters k_z, ϵ, and δ of the second layer, however, are distorted by the MVA algorithm, which has to flatten image gathers in the TTI layer with the incorrect tilt of the symmetry axis. It is interesting to note that the best-fit VTI model has an accurate value of the anellipticity parameter η.

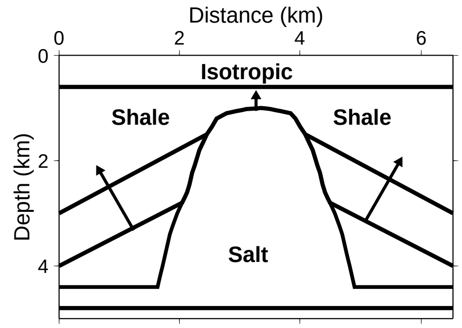

Fig. 5: Simplified salt model that includes a salt dome overlaid by a TI shale formation. The symmetry axis in the shale (marked by the arrows) is vertical on top of the salt and orthogonal to the bedding in the uptilted layers, which are dipping at 30°. The parameters of the shale are $V_{P0} = 2.6$ km/s, $k_z = 0.6$ s^{-1}, $k_x = 0.2$ s^{-1}, $\epsilon = 0.3$, and $\delta = 0.15$. The subsurface horizontal layer is isotropic with $V_{P0} = 1.5$ km/s, $k_z = 1.0$ s^{-1}, and $k_x = \epsilon = \delta = 0$; for the salt body, $V_{P0} = 4.5$ km/s, $k_z = k_x = 0.1$ s^{-1}, $\epsilon = \delta = 0$.

The ability of the VTI algorithm to compensate for the influence of tilt decreases for a larger relative thickness of the TTI syncline (Figure 4). Because of the more significant contribution of the interval traveltime in the TTI layer, the dipping reflectors in Figure 4 are misfocused and shifted in the vertical direction. Such artifacts can serve as an indication that the medium above the distorted reflectors may have a tilted symmetry axis.

Salt-dome model

The next test is performed for a simplified salt model, which can be considered typical for subsalt exploration plays. The model includes an isotropic salt dome with steep flanks overlaid by a TI shale formation. The symmetry axis in the shale is vertical directly above the dome and tilted (orthogonal to the bedding) in the dipping layers on both sides of the salt body (Figure 5).

When tilt is incorporated in the MVA algorithm, both the dipping reflectors and the salt dome are well focused and positioned (Figure 6). For purposes of MVA, the shale formation was divided into two blocks along the vertical axis of the salt dome. Errors in the anisotropy parameters and velocity gradients are relatively small, although ϵ is not as well constrained as δ. The larger error in ϵ is expected because, as discussed above, this parameter does not influence NMO velocity and is constrained only by nonhyperbolic moveout on long spreads.

If MVA does not take into account the tilt of the symmetry axis in the shale, the flanks of the salt body are somewhat shifted laterally and look blurry (Figure 7a). Also, the image gathers, especially those near the salt, are not completely flattened (Figure 7b). Note that the VTI algorithm distorted the parameter δ and, to a lesser extent, the velocity gradients in the shale. Clearly, ignoring the tilt of the symmetry axis in dipping TI layers

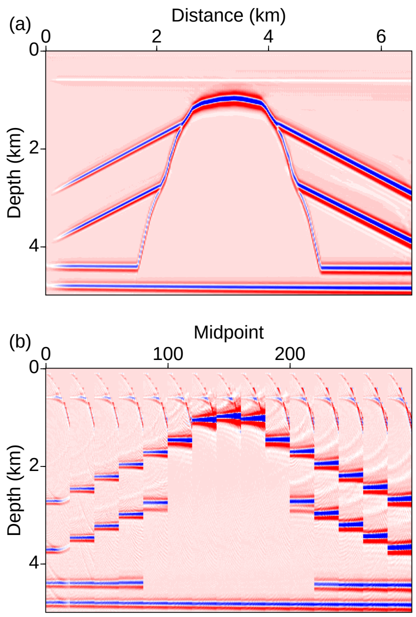

Fig. 6: (a) Image of the salt model from Figure 5 obtained after MVA and prestack depth migration. The estimated parameters of the first subsurface layer are $k_z = 0.97\ s^{-1}$ and $k_x = \epsilon = \delta = 0$. For the shale layer to the left of the salt, $k_z = 0.58\ s^{-1}$, $k_x = 0.19\ s^{-1}$, $\epsilon = 0.34$, and $\delta = 0.14$. To the right of the salt, $k_z = 0.59\ s^{-1}$, $k_x = 0.18\ s^{-1}$, $\epsilon = 0.32$, and $\delta = 0.15$. For the salt, $k_z = 0.09\ s^{-1}$, $k_x = 0.1\ s^{-1}$, and $\epsilon = \delta = 0$. (b) The corresponding image gathers.

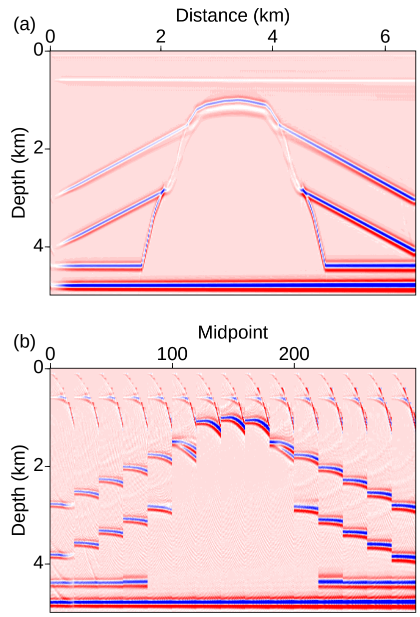

Fig. 7: (a) Image of the model from Figure 5 obtained after applying MVA under the assumption that the shale formation is VTI. The estimated parameters for the shale layer to the left of the salt are $k_z = 0.62\ s^{-1}$, $k_x = 0.17\ s^{-1}$, $\epsilon = 0.32$, and $\delta = 0.12$. To the right of the salt, $k_z = 0.62\ s^{-1}$, $k_x = 0.18\ s^{-1}$, $\epsilon = 0.30$, and $\delta = 0.11$. (b) The corresponding image gathers.

in the overburden may cause serious problems in imaging salt bodies and, therefore, subsalt reservoirs.

Conclusions

The combination of tilted transverse isotropy and structural complexity in many important exploration plays makes it imperative to apply advanced migration velocity analysis methods and prestack depth imaging. Here, we presented an MVA methodology for P-waves in heterogeneous TTI media based on dividing the model into "quasi-factorized" blocks. Parameter updating and Kirchhoff depth migration are performed in the layer-stripping mode starting at the surface, with the symmetry-direction velocity V_{P0} specified at a single point in each block and the symmetry axis kept orthogonal to the reflectors. Synthetic tests demonstrate that our MVA algorithm accurately reconstructs the velocity gradients k_z and k_x and the anisotropy parameters ϵ and δ, which ensures high image quality. Since the parameter ϵ in TTI media with a fixed symmetry-axis orientation is estimated from nonhyperbolic moveout, the offset-to-depth ratio in MVA should reach at least two. Also, the residual moveout in image gathers has to be described by a nonhyperbolic equation.

To emulate a VTI processing sequence applied to TTI media, we also performed MVA without allowance for a tilted symmetry axis (i.e., the anisotropic layers were treated as VTI). The MVA algorithm can achieve partial flattening of image gathers with the incorrect tilt, but at the expense of distorting the medium parameters, especially ϵ and δ. Although such artificial adjustments in ϵ and δ improve image quality, the migrated sections are inferior to those generated with the TTI model. Also, the ability of the VTI algorithm to compensate for the influence of tilt decreases for more complicated models and TTI layers with relatively large thickness or strong anisotropy.

The MVA methodology introduced here provides a practical tool for building TTI velocity models with minimal *a priori* information about the symmetry-direction velocity. Combined with prestack depth migration, this MVA algorithm can be efficiently used to image targets beneath TTI formations in structurally complex environments.

Acknowledgments

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