Anisotropic migration velocity analysis: Application to a dataset from West Africa

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Summary

Although it is widely recognized that anisotropy can have a significant influence on the focusing and positioning of migrated reflection events, conventional imaging methods still operate with isotropic velocity fields. Here, we present an application of a migration velocity analysis (MVA) algorithm designed for factorized \( v(x, z) \) VTI (transversely isotropic with a vertical symmetry axis) media to an offshore data set from West Africa. By approximating the subsurface with factorized VTI blocks, it is possible to decouple the spatial variations in the vertical velocity from the anisotropic parameters with minimal a priori information.

Since our method accounts for lateral velocity variation, it produces more accurate estimates of the anisotropic parameters than those previously obtained with time-domain techniques. The values of the anellipticity parameter \( \eta \) found for the massive shales exceed 0.2, which confirms that ignoring anisotropy in the study area can lead to substantial imaging distortions, such as misstacking and mispositioning of dipping events. While some of these distortions can be removed by using anisotropic time processing, further marked improvement in image quality is achieved by prestack depth migration with the estimated factorized VTI model.

Introduction

Migration algorithms suitable for imaging data from heterogeneous media of relatively simple symmetry (e.g., transversely isotropic) are readily available today. Therefore, the main difficulty is not in the imaging step, but in reconstituting a sufficiently accurate spatially varying, anisotropic velocity field. It is critically important to represent the subsurface with the simplest possible model that (1) allows for anisotropy and adequately describes spatial velocity variations; (2) permits full understanding of the inherent ambiguities; and (3) requires minimal a priori information to resolve the relevant parameters.

Such a model for P-wave imaging in the presence of transverse isotropy was suggested by Sarkar and Tsvankin (2003a; hereafter referred to as Paper I) who approximated the subsurface by a factorized \( v(x, z) \) VTI medium with constant gradients in the vertical velocity. The Thomsen anisotropic parameters \( c \) and \( \delta \) in factorized media are constant, while the P-wave vertical velocity is described by \( V_{\rho 0}(x, z) = V_{\rho 0} + k_x x + k_z z \), where \( V_{\rho 0} \) is the velocity at the origin of the coordinate system \( (x = 0, z = 0) \), and \( k_z \) and \( k_x \) are the vertical and horizontal velocity gradients, respectively. In Paper I, we show that P-wave reflection moveout constrains only four combinations of the five medium parameters \( V_{\rho 0}, k_x, k_z, c, \) and \( \delta \):

1. the normal-moveout (NMO) velocity at the surface
   \[ V_{\text{nom}} = V_{\rho 0} \sqrt{1 + \frac{2 \delta}{c}}; \]
2. the vertical gradient \( k_x \); and
3. the combination \( k_z = k_x \sqrt{1 + \frac{2 \delta}{c}} \) of the lateral gradient \( k_x \) and \( \delta \); and
4. the Alkhalifi-Tsvankin (1995) anellipticity parameter
   \[ \eta \equiv \left( 1 - \frac{\delta}{c} \right) \] estimation of the parameters \( V_{\rho 0}, k_x, c, \) and \( \delta \) requires minimal a priori information, such as knowledge of the vertical velocity at a single point in the medium.

Sarkar and Tsvankin (2003b), hereafter referred to as Paper II, proposed a migration velocity analysis (MVA) algorithm to invert for the parameters of factorized VTI media. To separate the influence of anisotropy from that of vertical heterogeneity, it is necessary to use image gathers along two reflectors sufficiently separated in depth. The residual moveout of events in image gathers is evaluated by a semblance operator that accounts for the nonhyperbolic (long-spread) moveout needed to constrain the parameter \( \eta \). The velocity analysis is performed through an iterative two-step procedure that includes Kirchhoff prestack depth migration followed by an update of the medium parameters. In Paper II, the MVA algorithm is implemented in the layer-stripping mode, wherein the model is divided into factorized VTI blocks or layers, and the medium parameters are estimated one factorized block at a time. The algorithm assumes \( V_{\rho 0} \) to be known at one point in each factorized block and searches for \( k_x, k_z, c, \) and \( \delta \).

Application of the factorized \( v(x, z) \) model to two lines from a dataset acquired by Chevron Overseas Petroleum Co. in West Africa yields more accurate, laterally varying anisotropic velocity fields and greatly improved imaging of many structural features.

Brief overview of the geological history

The geology of the area (offshore Angola) is largely governed by tectonic rifting that occurred around the early Cretaceous. The most recent tectono-stratigraphic units in the order they were formed are (1) prerift with gentle tectonism; and (2) regional subsidence with major tilting. The regional subsidence phase, which dates back to the Oligocene and Miocene times, is characterized by a rapidly deposited regressive sequence, turbidites, shaly clastics, and high-pressure shale. The ubiquitous presence of shales makes the subsidence unit strongly anisotropic,
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Fig. 1: Stacked section after prestack depth migration with the estimated parameters in five blocks. Block I is water with \( V_{p0} = 1500 \text{ m/s} \); block II is isotropic with the parameters \( V_{p0} = 2000 \text{ m/s} \) and \( k_x = 0.8 \text{ s}^{-1} \); for block III, \( V_{p0} = 3000 \text{ m/s}, \) \( z = 452 \text{ m} \) = 1740 m/s, \( k_x = 0.6 \pm 0.03 \text{ s}^{-1} \), \( k_x = 0.3 \pm 0.01 \text{ s}^{-1} \), \( \epsilon = 0.3 \pm 0.03 \), and \( \delta = 0.06 \pm 0.02 \); for block IV, \( V_{p0} = 5000 \text{ m/s}, \) \( z = 310 \text{ m} \) = 1625 m/s, \( k_x = 0.65 \pm 0.03 \text{ s}^{-1} \), \( k_x = 0.0 \pm 0.01 \text{ s}^{-1} \), \( \epsilon = 0.35 \pm 0.03 \), and \( \delta = 0.1 \pm 0.02 \); and for block V, \( V_{p0} = 7000 \text{ m/s}, \) \( z = 1235 \text{ m} \) = 2230 m/s, \( k_x = 0.83 \pm 0.01 \text{ s}^{-1} \), \( k_x = 0.04 \pm 0.01 \text{ s}^{-1} \), \( \epsilon = 0.19 \pm 0.03 \), and \( \delta = 0.06 \pm 0.03 \). The dashed lines show block boundaries and the arrows mark the two prominent geological markers used in the velocity analysis for block V. The first [shallow] marked reflector is the bottom of the subsidence unit, and the second reflector is the bottom of the postrift unit. Note that the block boundaries of the velocity field do not follow the geological markers.

which is well documented in the literature (e.g., Alkhalfi et al., 1996). The early Tertiary postrift deposition unit is less anisotropic and includes marine clastics and carbonates, nonmarine red beds, and transgressive sequences.

First line

Accurate imaging for the first line required dividing the subsurface into five factorized blocks (Figure 1). As in Paper II, \( V_{p0} \) was constrained by assuming that the vertical velocity varies continuously between blocks II and III, blocks II and IV, and blocks IV and V while parameters \( k_x, k_z, \epsilon, \) and \( \delta \) in each block were estimated using our MVA algorithm. Since blocks I-IV are laterally homogeneous, the choice of the point of continuity was not important. For the fifth block, which has a significant lateral variation in \( V_{p0} \), the point of continuity was identified by first migrating the data with a purely isotropic velocity field and then selecting a location on the boundary of blocks IV and V that is close to the gathers with the smallest residual moveout (Paper II). Image gathers after migration with the estimated parameters are shown in Figure 2; note that most events are flat.

The results of the velocity analysis are summarized in the depth sections of the vertical velocity and parameter \( \eta \) in Figures 3 and 4. As expected, the ubiquitous presence of shales in the subsidence unit at depths less than 2 km make blocks III and IV strongly anisotropic, with values of \( \eta \) exceeding 0.2. The deeper postrift unit also exhibits

Fig. 2: Common-image gathers after prestack depth migration with the estimated parameters. Most undercorrected events stack at extremely low velocities, and likely are interbed multiples.

Fig. 3: Depth section of the estimated vertical-velocity field. The dashed lines mark the block boundaries. The values in the legend are in m/s.

Fig. 4: Depth section of the parameter \( \eta \).

Fig. 5: Comparison of the time-depth curves estimated from the MVA at midpoint 5 km (dashed) and derived from sonic logs and check-shot data in a borehole close to the seismic line (solid).
non-negligible anisotropy and is characterized by moderate lateral velocity variation. In the subsidence unit, the maximum offset-to-depth ratio for the two reflectors used in the velocity analysis is close to two, which is large enough to provide sufficiently tight constraints on the parameter \( \eta \). In the postrift unit, however, the maximum offset-to-depth ratio is suitable for evaluating \( \eta \) only for the shallow reflector.

For this line, our maximum value of \( \eta \) exceed 0.2, which is larger than \( \eta_{\text{max}} \approx 0.1 \) obtained by Alkhalfih (1996). Although this discrepancy seems to be quite significant, nonhyperbolic moveout inversion of horizontal events is known to be hampered by the tradeoff between \( \eta \) and the NMO velocity. As shown by Grechka and Tsvankin (1998), the uncertainty in \( \eta \) estimates for offset-to-depth ratios of about two can reach \( \pm 0.1 \). This instability in the inversion for \( \eta \) may have influenced our MVA technique and Alkhalfih’s time-domain algorithm in different ways, in particular because the model assumptions in the two methods are not the same. On the whole, we believe that our estimates of \( \eta \) are more accurate, both because of the careful treatment of the spatial velocity variations and the higher stability of MVA (compared with time-domain techniques) in the presence of noise. The accuracy of our results is confirmed by the close match of the time-depth curve computed from our estimated vertical velocity with borehole data (Figure 5).

**Second line**

In this section, we apply our algorithm to another line from the same data set, where the subsurface structure is more complicated, and the anisotropy parameters and vertical velocity vary significantly in both vertical and horizontal directions.

The final depth-migrated section and the factorized VTI blocks that comprise the model are shown in Figure 6. The medium parameters in each block (Figures 7 and 8) were estimated using the same procedure as that applied to the first line. For blocks II, III, IV, and V, the MVA was performed with a fixed value of the vertical velocity at the top of each block. We assumed that \( V_{p0} \) was continuous between blocks I and II, I and V, II and III, and II and IV. Since the vertical velocity in blocks I, II, III, and V is almost laterally invariant, the choice of this point of continuity was not important. For the fourth block, however, the lateral gradient \( k_z \) is substantial, and the continuity point was identified by applying homogeneous isotropic migration, as discussed above for the first line.

The maximum offset-to-depth ratio for most reflectors in block IV is less than two, which is insufficient for estimating the parameter \( \eta \) from nonhyperbolic moveout of subhorizontal events. To constrain \( \eta \), we used reflections from the prominent fault plane with a dip of about 35° at the bottom of this block. Reflections from the shallow segment of the same dipping fault plane also provided important information for the inversion in block III. We had to ignore anisotropy in block VI because \( \eta \) could not be obtained from either nonhyperbolic moveout (the maximum offset-to-depth ratios were close to one) or dipping events. The velocity \( V_{p0} \) at the top of the block and the gradients \( k_x \) and \( k_y \) were estimated from the hyperbolic portion of the moveout curve for two reflectors sufficiently separated in depth.

Comparison of our depth-migrated image in Figure 9a and the anisotropic time-migrated image in Figure 9b illustrates further improvements achieved by the MVA and prestack depth migration. Better focusing and continuity are observed for the major fault plane between midpoints 2 and 8 km and several reflectors just above and below it, for the subhorizontal reflectors at midpoint 4.5 km and depth 1.4 km, and for the fault plane at midpoint 7.5 km and depth 3 km. Since time migration ignores the lateral velocity variation in block IV, the antithetic faults, which are clearly visible at midpoint 4 km and depth 2 km on the depth-migrated section, appear fuzzy in Figure 9a. Perhaps the most dramatic difference between the two
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![Graphs showing depth section of estimated vertical-velocity field and parameter η.](image)

Fig. 7: Depth section of the estimated vertical-velocity field. The values in the legend are in m/s.

Fig. 8: Depth section of the parameter η. Images is in the shape and position of the two prominent reflectors that define the top and bottom of the postrift unit (between depths 2.5 and 5 km).

Discussion and conclusions

We applied to offshore data from West Africa a migration velocity-analysis method designed for VTI models composed of factorized layers or blocks. In agreement with the results of previous studies (Alkhaliifah et al., 1996), we found massive shales in that area to be strongly anisotropic, with the parameter η on one of the lines exceeding 0.2. The reconstructed velocity field also indicates the presence of substantial lateral heterogeneity in some of the layers, which cannot be handled by time-domain techniques. Anisotropic prestack depth migration with the reconstructed velocity field resulted in a number of significant improvements in image quality compared to the time sections of Alkhaliifah et al. (1996).

Flat image gathers after the iterative migration velocity analysis suggest that the factorized v(x, z) VTI medium provides an adequate approximation for realistic, spatially varying anisotropic velocity fields. Although the vertical velocity can seldom be constrained by P-wave reflection data alone, the field-data example discussed here indicates that the assumption of a continuous vertical velocity field offers a practical way to build anisotropic models for prestack depth migration with minimal a priori information. Furthermore, in the absence of pronounced velocity jumps across medium interfaces, the time-depth curve obtained from the MVA algorithm closely matches the curve computed from borehole data.

References


