Anisotropic migration and model building for 4C seismic data: A case study from Alba
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Summary

Assuming a scatter point located beneath a stack of layers with vertical transverse isotropy (VTI), we derive an accurate double-square-root (DSR) converted-wave (C-wave) diffraction equation, and incorporate the equation into the Kirchhoff prestack time migration. The DSR is controlled by five parameters: P- and S-wave stacking velocities \( V_{P2} \) and \( V_{S2} \), vertical velocity ratio \( \gamma_0 \), and anisotropic parameters \( \eta_{eff} \) and \( \xi_{eff} \), which define the anisotropic velocity model for migration. We demonstrate using real data how to build the anisotropic model from reflection moveout analysis, and evaluate the merit of prestack time migration. The DSR equation has a similar form to its isotropic counterpart, which allows an efficient implementation of prestack time migration. Applications to real data show that the C-wave imaging obtained by the new approach is more focused and coherent than the imaging by isotropic methods.

Introduction

For C-wave prestack migration in the presence of anisotropy, the key issue is how to generate a reliable anisotropic velocity model (Nolte et al., 1999). For transverse isotropy with a vertical axis of symmetry (VTI), it requires the estimation of all four Thomsen’s parameters to build an anisotropic velocity model, and so far there is no practical solution to this problem. Additional concern also arises with the cost-effectiveness of anisotropic time migration, since the exact migration requires calculation of the group velocity vector for each propagation direction. To address these issues, we derive an anisotropic double-square-root (DSR) equation for a scatter point located beneath a stack of VTI layers, and incorporate it into prestack migration. This is an extension of Li and Druzhinin (2000) in which a single-layer DSR equation is used and is thus restricted to homogeneous media. The new DSR equation is valid for vertically inhomogeneous anisotropic media, and is fully determined by five parameters which can be estimated from non-hyperbolic moveout analysis.

We apply this method to the Alba 4C dataset from the North Sea (MacLeod et al., 1999) to illustrate the concept of anisotropic model building and evaluate the merit of anisotropic migration. The Alba data was acquired in block 16/26 in the UK sector of the North Sea. The Alba Field is a high porosity Eocene sand reservoir approximately 15km long (NW-SE) by 1.5 to 3.0km wide, at a depth of 1800-2000m (MacLeod, et al., 1999). It is sealed by low permeability shales. The purpose of the survey is to image the top of the sand using converted-waves, since the P-wave impedance contrasts between the sand and the overlying shales and the intra-sand shales are small, while the corresponding S-wave impedance between the sand and the shales is large. The data used were recorded for a sail line extracted from the 5th swath of the survey, and the receiver cable is below the sail line.

Processing of the P-wave data

The P-wave data include the hydrophone data and the vertical component data. The objective is to obtain the P-wave velocity fields and the final stacked and migrated sections for correlation analysis. Thus we focus on the vertical component. Non-hyperbolic analysis is carried out, following Alkhalifah (1997), to examine possible anisotropic effects. We find that the anisotropic parameter \( \eta \) is small: around 0.02-0.06. The anisotropic effects may then be neglected. As a result, the remaining processing is relatively straightforward. Figure 1 shows the final stacked section, in comparison with the final pre-stack migrated section. The migrated result shows substantial improvement. A very reliable P-wave velocity model is thus obtained.

![Figure 1. P-wave processing results from the vertical component: (a) final stacked section, and (b) pre-stack migrated section.](image)

Converted-wave imaging

The main challenge in the converted-wave analysis is to account for the anisotropic effects in the overlying shales, and the non-hyperbolic moveout. The vertical velocity ratio
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Consider a scatter point at \((x,z)\) located immediately below a stack of VTI layers (Figure 1). The C-wave diffraction curve can be derived as,

\[
I_c = \left\{ \frac{t_{c0}}{1 + \gamma_0} \right\}^2 \left[ \frac{(1 + \eta_0)(1 + \eta_i)(1 + \eta_j)}{V_{PP}^2} \right] + \frac{(x + h)^2}{V_{PP}^2} - 2\eta_0 \Delta t_i^2 + \frac{(x + h)^2}{V_{PP}^2} - 2\eta_0 \Delta t_i^2 ,
\]

where

\[
\eta_0 = \frac{1}{8t_{c0}V_{PP}^2} \left[ \sum_{i=1}^{n} \frac{V_{PP}^2}{t_{c0}^2} \Delta t_{p0}(1 + \gamma_0) - t_{p0}V_{PP}^2 \right],
\]

and

\[
\zeta_0 = \frac{1}{8t_{c0}V_{PP}^2} \left[ \sum_{i=1}^{n} \frac{V_{PP}^2}{t_{c0}^2} \Delta t_{s0}(1 - \gamma_0) - t_{s0}V_{PP}^2 \right].
\]

Subscript \(i\) denotes interval quantities. \(t_{c0}\) is the vertical two-way time, \(h\) is the half source-receiver offset, \(\eta_0\) is the anisotropic parameter defined by Alkalifah (1997) and \(\zeta_0\) is defined as \(\zeta = \gamma_0^2 \eta_0\), where \(\gamma_0\) is the effective velocity ratio (Thomsen, 1999). Although equation (1) is an approximation, it is accurate up to, at least, offset-depth ratio of 2.0 (Yuan, 2000).

### Kirchhoff prestack time migration

Given \(V_{P2}, V_{S2}, \gamma_0, \eta_{eff}\) and \(\zeta_{eff}\), equation (1) can be utilized to perform anisotropic Kirchhoff prestack time migration. Similarly to isotropic migration (Solid et al., 1997), the anisotropic migration may also be implemented as a weighted summation of amplitudes along diffraction curves, that is,

\[
I(\tau, y, b, h) = \int W(\tau, y, b, h) \frac{\partial}{\partial t} u(\tau = t_c, y, b, h) db ,
\]

where \(I\) is the imaging, \(\tau = t_{c0}\) is the time depth, \(W\) is a weighting function, \(b = (x-y)\) is the imaging point offset from the midpoint, \(u\) is the input data, and \(t_c\) is the anisotropic diffraction curve defined by equation (1).

### Construction of the anisotropic velocity model

Equation (1) contains five parameters: \(V_{P2}, V_{S2}, \gamma_0, \eta_{eff}\) and \(\zeta_{eff}\) and needs to be constructed from the four C-wave moveout attributes: \(V_{C2}, \gamma_0, \eta_{eff}\) and \(\zeta_{eff}\), as described in the accompanied abstract Li et al. (2001). This requires a Dix-type layer-stripping procedure. Note that \(\chi_{eff}\) is defined as,

\[
\chi_{eff} = \eta_{eff} \gamma_0^2 - \zeta_{eff} .
\]

and equation (2) can be re-written as,

\[
\eta_{eff} = \frac{1 + \gamma_0}{8t_{c0}V_{PP}^2} \left[ \sum_{i=1}^{n} \frac{V_{PP}^2}{t_{c0}^2} \Delta t_{c0}(1 + \gamma_0) - t_{c0}V_{PP}^2 \right],
\]

\[
\zeta_{eff} = \frac{1 + \gamma_0}{8t_{c0}V_{PP}^2} \left[ \sum_{i=1}^{n} \frac{V_{PP}^2}{t_{c0}^2} \Delta t_{s0}(1 - \gamma_0) - t_{s0}V_{PP}^2 \right].
\]

Thus, for each input parameter set \((V_{C2}, \gamma_0, \eta_{eff}\) and \(\chi_{eff}\)) at time \(t_{c0}\), the following steps can be used to construct the anisotropic velocity model (Figure 3):

1. Invert \(V_{P2}\) and \(V_{S2}\) from \(V_{C2}, \gamma_0\) and \(\eta_{eff}\).
2. Convert \(V_{P2}\) and \(V_{S2}\) and the average ratio \(\gamma_0\) to interval parameters \(V_{P2}, V_{S2}\) and \(\gamma_0\).
3. Use equations (5) to build a Dix-type layer-stripping procedure to determine $c_i$.
4. Calculate the effective parameters $\eta_{\text{eff}}$ and $\xi_{\text{eff}}$ using equation (6).

**Updating the anistropic velocity model**

It is a common practice to update the model during migration. Updating is achieved by analyzing the residual moveout in the common imaging point (CIP) gathers. Model updating should be restricted to $V_{C2}$ and $\chi_{\text{eff}}$. Updating the model can be very time consuming, since each update requires re-construction of the velocity model by the layer-stripping procedure in Figure 3. In practice, a two-step procedure may be used. We first update $V_{C2}$ by analyzing the residual moveout in near offset traces without considering anisotropy, and thus make no changes to $\chi_{\text{eff}}$. Once $V_{C2}$ is satisfactorily determined, we use the far-offset traces to update $\chi_{\text{eff}}$. Fortunately, we find that one or two iterations are usually sufficient.

![Figure 4](image1.png)

Figure 4. Results of reflection moveout analysis over CCP gather 550: (a) $V_{C2}$, and (b) $\gamma_0$, $\gamma_{\text{eff}}$ and $\xi_{\text{eff}}$.

**Converted-wave processing results**

Moveout analysis, as described in the accompanying paper (Li et al., 2001), is applied to the data to determine $V_{C2}$, $\gamma_0$, $\gamma_{\text{eff}}$ and $\chi_{\text{eff}}$. Figure 4 shows the result for CCP gather 550. These parameters are then used to construct the velocity model ($V_{P2}$, $V_{S2}$, $\gamma_0$, $\eta_{\text{eff}}$ and $\xi_{\text{eff}}$, as shown in Figure 5) following the procedures in Figure 3. Note that $\eta_{\text{eff}}$ is very small as shown in Figure 5b, compared with $\xi_{\text{eff}}$ and $\chi_{\text{eff}}$. This confirms that the effects of anisotropy on the $P$-wave is negligible. Residual moveout in CIP gathers are used to update the velocity model. Figure 6 shows an example of this process. The final imaging achieved by anisotropic migration shows considerable improvement in focusing the faults and small structures, compared with the isotropic migrated imaging (Figure 7).

![Figure 5](image2.png)

Figure 5. The migration velocity model at CIP gather 550: (a) $V_{P2}$ and $V_{S2}$ and (b) $\eta_{\text{eff}}$ and $\xi_{\text{eff}}$ as well as $\chi_{\text{eff}}$ for comparison.

![Figure 6](image3.png)

Figure 6: Updating the migration velocity model using CIP gathers. (a) An original CCP gather. (b) A CIP gather with initial migration parameters. (c) and (d) are the gathers after updating $V_{C2}$ and $\chi_{\text{eff}}$, respectively.
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Conclusions

We have extended the single-layer DSR equation to vertically inhomogeneous, anisotropic media and presented an accurate and efficient approach for anisotropic prestack time migration. The initial velocity model is constructed from reflection moveout analysis with parameters \( V_{C2} \), \( \gamma_0 \), \( \gamma_{eff} \) and \( \chi_{eff} \). These parameters are then converted to \( V_p \), \( V_S \), \( \eta_{eff} \) and \( \zeta_{eff} \) for the DSR equation using a Dix-type scheme. Migration velocity updating is possible, but it should be restricted to \( V_{C2} \) and \( \chi_{eff} \) only. Updating of \( V_{C2} \) is achieved by aligning the near-offset events, and updating of \( \chi_{eff} \) by aligning the far-offset events in the CIP gather. Application to real data verifies the approach and shows significant improvement in imaging quality. The model obtained from this migration scheme may then be used for pre-stack depth migration.

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