Anisotropic velocity analysis using marine 4C seismic data

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Summary

Failure to account for anisotropy may lead to errors in seismic processing. For transversely isotropic media with a vertical axis of symmetry, Alkhalifah and Tsvankin (1995) have shown that a single anisotropy parameter \( \eta \), together with the small-offset normal moveout (NMO) velocity for PP-reflections, is sufficient to perform all time-related processing of P-waves data. Recent developments allow multi-component seismic data to be acquired at the seafloor (Berg et al., 1994a; Berg et al., 1994b). By using measurements of the small-offset traveltimes of PP- and PSV-reflections, reliable estimates of \( \eta \) can be made in the absence of any depth or vertical velocity information. The method is used to determine the variation in \( \eta \) with time for a seafloor 4C dataset.

In tro duction

The principal cause of anisotropy in sedimentary basins is the presence of shales that are anisotropic as a result of layering and a partial alignment of plate-like clay minerals. This anisotropy may often be described, as being transversely isotropic with a vertical axis of symmetry (VTI). Azimuthal anisotropy due to vertical fractures and unequal horizontal stresses may also occur, but will not be considered here.

For VTI media, Alkhalifah and Tsvankin (1995) have shown that a single anisotropy parameter \( \eta \), defined by

\[
\eta = \frac{1}{2} \left( \frac{v_{P,P}^2}{v_{NMO,P}^2} - 1 \right),
\]

together with the NMO velocity \( v_{NMO,P} \) for PP-reflections from a horizontal reflector is sufficient for performing all time-related processing of P-waves data including NMO, DMO, prestack and poststack time migration. \( v_{H,P} \) is the horizontal velocity for P-waves.

In this presentation, a practical scheme for anisotropic velocity analysis, in the absence of any information on depth or vertical velocities, using a small-offset traveltime of PP- and PSV-reflections is used to determine the variation in \( \eta \) with time for a seafloor 4C dataset. It is shown that this information is sufficient to describe the non-hyperbolic moveout of PP- and PSV-reflections from a horizontal reflector observed at wide offsets, even though only small-offset data is used in the analysis.

Theory

The elastic stiffness tensor of a TI medium may be described by five independent elastic stiffnesses. If the axis of rotational symmetry is chosen to lie along \( x_3 \), the non-zero density-normalized elastic stiffnesses \( a_{ij} \) are \( a_{11} = a_{22}, a_{33}, a_{12} = a_{33}, a_{13} = a_{23}, a_{44} = a_{55} \) and \( a_{66} = (a_{11} - a_{12})/2 \). It is not possible to obtain all these from conventional surface seismic data as a result of the tradeoff between vertical velocity and depth and the limited range of offsets normally used (Tsvankin and Thomsen, 1994). Schoenberger et al. (1996) suggested a simple three-parameter transversely isotropic model (ANNIE) as a reasonable first approximation for the elastic behavior of a wide variety of shales. The non-zero density-normalized elastic stiffnesses \( a_{ij} \) for ANNIE are \( a_{11} = a_{33} = \lambda + 2\mu, a_{55} = \lambda - 2\mu, a_{12} = a_{33} = a_{23} = \lambda, a_{14} = a_{35} = \mu \) and \( a_{66} = (a_{11} - a_{12})/2 = \mu_\theta \), where \( \lambda, \mu \) and \( \mu_\theta \) are the three parameters of the model.

For a horizontal reflector in a homogeneous TI medium, the three parameters \( \lambda, \mu \) and \( \mu_\theta \) for ANNIE may be estimated from the small-offset NMO velocities \( v_{NMO,P} \) and \( v_{NMO,SV} \) for P- and SV-waves and the vertical S- and P-wave traveltime \( t_P \) and \( t_{PS} \) as follows:

\[
\lambda = (1 - 2/\gamma_0) v_{NMO,P}^2, \quad (2)
\]
\[
\mu = v_{NMO,P}^2/\gamma_0^2, \quad (3)
\]
\[
\mu_\theta = (1 + \gamma_0^2/\gamma_2^2) v_{NMO,P}^2/2\gamma_0^2, \quad (4)
\]

where \( \gamma_0 = t_P/t_P^0 \) and \( \gamma_2 = v_{NMO,P}/v_{NMO,SV} \) in the notation of Thomsen (1998). \( t_P^0 \) and \( v_{NMO,SV} \) may be obtained from the NMO velocity and vertical traveltime for PP-reflections and the NMO velocity and small-offset traveltime for P-waves with mode convert to shear at the reflector (PSV-modes) using the following equations (Seri and Sriniv, 1991):

\[
t_{PS}^0 = t_P^0 + t_{PS}^0, \quad (5)
\]
\[
t_{PS}^0 = t_{PS}^0 v_{NMO,PSV}^2 = t_{PS}^0 v_{NMO,P}^2 + t_{PS}^0 v_{NMO,SV}^2, \quad (6)
\]

where \( t_{PS}^0 \) is the vertical two-way traveltime of the mode-converted P-SV-reflection.

Examples

To test this scheme, traveltimes were computed for PP- and PSV-reflections from a horizontal reflector in a homogeneous VTI medium with elastic stiffnesses obtained from wide-aperture, multiple-offset vertical seismic profiles (VSPs) by Leahey (1994) for shales. These elastic stiffnesses are listed in Table 1. Also included in this table are the elastic stiffnesses measured by Jones and Wang (1981) for Greenhorn shale.

Figures 1 and 2 compare traveltime squared \( (t^2) \) versus source-receiver offset squared \( (x^2) \) for PP- and PSV-reflections computed using the reported elastic stiffnesses.
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and those determined for ANNIE with $\lambda$, $\mu$ and $\mu\nu$ obtained
from the NMO and zero offset traveltimes for $PP$- and $PSV$-reflections using equations (2-6). The depth of
the reflector is 3 km. For the computations using ANNIE, the depth was taken as the depth giving the correct verti-
cal traveltimes for $P$-waves using the small-offset NMO ve-
locity (since $v_{P,P} = v_{NMO,P}$ for ANNIE). The agreement
between the exact and approximate scheme is good for
both $PP$- and $PSV$-reflections; the approximate curves in
several cases being indistinguishable from the exact re-
sults to within the width of the curve drawn. The main
disagreement occurs for the $PP$-reflection for the South
China Sea example, for which the non-hyperbolic move-
out is overpredicted. This results from an overprediction
of $\eta$, as may be seen in Table 2, which compares the esti-
mated value of $\eta$ with the value calculated from the mea-
sured elastic stiffnesses for these examples. For ANNIE,
$\eta$ takes the value

$$\eta = \frac{\mu\nu - \mu}{\lambda + 2\mu} = \frac{1}{2\sqrt{\nu}} \left( \frac{\gamma_2^2}{\gamma_2} - 1 \right).$$

Table 1: Measured TI elastic stiffnesses from five walkaways and from ultrasonic data (Leaney, 1994).

<table>
<thead>
<tr>
<th>Shale</th>
<th>$a_{11}$</th>
<th>$a_{13}$</th>
<th>$a_{33}$</th>
<th>$a_{55}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Java Sea−1a</td>
<td>10.95</td>
<td>4.87</td>
<td>7.49</td>
<td>1.34</td>
</tr>
<tr>
<td>Java Sea−1b</td>
<td>8.24</td>
<td>4.19</td>
<td>5.92</td>
<td>0.95</td>
</tr>
<tr>
<td>Java Sea−2</td>
<td>6.84</td>
<td>3.24</td>
<td>6.07</td>
<td>1.20</td>
</tr>
<tr>
<td>South China Sea</td>
<td>6.99</td>
<td>2.64</td>
<td>5.53</td>
<td>0.95</td>
</tr>
<tr>
<td>West Africa</td>
<td>12.48</td>
<td>3.67</td>
<td>8.60</td>
<td>2.25</td>
</tr>
<tr>
<td>Greenhorn</td>
<td>14.17</td>
<td>4.42</td>
<td>9.38</td>
<td>2.23</td>
</tr>
</tbody>
</table>

Table 2: Exact and estimated values of $\eta$ for the shales listed in Table 1.

<table>
<thead>
<tr>
<th>Shale</th>
<th>Exact</th>
<th>Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Java Sea−1a</td>
<td>0.219</td>
<td>0.218</td>
</tr>
<tr>
<td>Java Sea−1b</td>
<td>0.158</td>
<td>0.153</td>
</tr>
<tr>
<td>Java Sea−2</td>
<td>0.152</td>
<td>0.167</td>
</tr>
<tr>
<td>South China Sea</td>
<td>0.429</td>
<td>0.469</td>
</tr>
<tr>
<td>West Africa</td>
<td>0.303</td>
<td>0.317</td>
</tr>
<tr>
<td>Greenhorn</td>
<td>0.341</td>
<td>0.355</td>
</tr>
</tbody>
</table>

The proposed method is seen to give accurate estimates of
$\eta$, despite these shales being strongly anisotropic. Since
a knowledge of $v_{NMO,P}$ and $\eta$ are sufficient for perform-
ing all time-related processing of $P$-wave data (Alkhail-
lah and Tsvankin, 1995), the proposed method provides
a practical scheme for anisotropic velocity analysis given
only small-offset $PP$- and $PSV$-reflection data. In addi-
tion, the long-offset (non-hyperbolic) traveltimes of both $PP$-
and $PSV$-reflection data in a laterally ho-

geneous medium is predicted by the present approach,
despite only small-offset data being used in the analysis.
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Fig. 3: Comparison of the exact and estimated values of $\eta$ for the sedimentary rocks listed by Thomsen (1986) (+) and the shales listed by Vernik and Liu (1997) (●).

Fig. 4: Moveout velocities for PP- and PSV-reflections measured at several CCP locations for a marine 4C data set.

The wide-offset moveout curves for both PP- and PSV-reflections from a horizontal reflector in a laterally homogeneous medium can be adequately described using only the vertical traveltimes $t^v_P$ and $t^v_{PSV}$ and the small-offset NMO velocities $v_{NMO,P}$ and $v_{NMO,PSV}$.

As a further check, the predicted values of $\eta$ were compared with the exact values for the sedimentary rocks listed by Thomsen [1986] and the shales listed by Vernik and Liu [1997]. This comparison is shown in Figure 3. The prediction is good for positive values of $\eta$, the normal case in sedimentary basins (Sayers, 1999).

Application to a marine 4C data set

For velocity analysis of mode-converted shear waves, the data must be sorted into common conversion point (CCP) gathers. Thomsen (1998) gives an accurate approximation to the CCP in terms of the ratio $\gamma_0 = v_{NMO,P}/v_{NMO,SV}$ of the average vertical PP- and SV-wave velocities and an effective velocity ratio $\gamma_{eff} = \gamma_0^2/\gamma_2$, where $\gamma_2 = v_{NMO,P}/v_{NMO,SV}$ is the ratio of the small-offset moveout velocities for PP- and SV-waves. Figure 4 shows the moveout velocities for PP- and PSV-reflections measured at several CCP locations for a marine 4C data set, while Figure 5 shows $\gamma_0$, $\gamma_2$ and $\gamma_{eff}$ calculated from the vertical traveltimes and moveout velocities of correlated PP- and PSV-reflections. The decreasing values of $\gamma_2$ and $\gamma_{eff}$ with decreasing two-way traveltime at small times is probably due to the breakdown in the hyperbolic moveout assumption at shallow depths. Using the vertical traveltimes of correlated PP- and PSV-reflections, the moveout velocities of PP- and PSV-reflections at these times were calculated from the fit shown in Figure 4 and converted to interval moveout velocities. The corresponding variation of interval $\eta$ with P-wave two-way time shown in Figure 6 was then obtained using equations (2-7). $\eta$ is seen to increase with increasing depth as would be expected if the clay platelets in shales become aligned with increasing compaction (Sayers, 1994).

Conclusion

A practical scheme for anisotropic velocity analysis in the absence of any information on depth and vertical velocities has been used to determine the variation of anellipticity $\eta$ with two-way traveltime for a marine 4C data set. This method uses small-offset traveltimes and NMO velocities of PP- and PSV-reflections and was motivated by the recent development of techniques for measuring multi-component seismic data at the seafloor (Berg et al., 1994a; Berg et al., 1994b). Although only small-offset data is used in the analysis, the long-offset (non-hyperbolic) traveltime moveout of both PP- and PSV-reflections in a laterally homogeneous medium is accurately predicted by this approach. The wide-offset moveout curves for both PP- and PSV-reflections from a horizontal reflector in a laterally homogeneous medium can be adequately described using only the small-offset traveltimes and NMO velocities of PP- and PSV-reflections.
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Fig. 5: $\gamma_0$, $\gamma_2$ and $\gamma_{eff}$ calculated from the vertical travel times and move out velocities of correlated PP- and PSV-reflections.

References


