Robust Estimation of Fracture Directions from 3D Converted Waves

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Outline

- Introduction
- The polarity method
- Synthetic example of geometry problem
- The least-squares method
- Synthetic results
- Real data example
- Conclusions
Introduction

- Azimuthal anisotropy, principle causes
  - fractures
  - stress

- Azimuthal anisotropy, seismic signatures
  - VVAZ (Velocity Variation with Azimuth)
  - AVAZ (AVO Variation with Azimuth)
  - Shear-wave splitting
Introduction

- Shear-wave Splitting
  - "If two S-waves travel in the same direction with different polarizations and speeds they are split." (Winterstein, 1989, Geoph. 55, 1070)
**Introduction**

- **Shear-wave splitting requires two analysis/processing steps**
  1. Estimation of the anisotropy directions and magnitude.
  2. Correction for shear-wave splitting within the imaging process.

- **Estimation methods**
  - Radial-transverse ratio (Garotta, 1989)
  - Transverse polarity flip detection (Li, 1998)
  - 3-D Alford rotation (Gaiser, 2000)
  - Least-squares method (this talk)
# Geometry assumptions

<table>
<thead>
<tr>
<th>Method</th>
<th>Azimuth Distribution Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial / transverse energy ratios</td>
<td>Regular</td>
</tr>
<tr>
<td>Polarity flip</td>
<td>Regular</td>
</tr>
<tr>
<td>3-D Alford rotation</td>
<td>Orthogonal pairs</td>
</tr>
<tr>
<td>Least-squares</td>
<td>At least 2 different azimuths</td>
</tr>
</tbody>
</table>
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Azimuthal polarity variation

Polarity reverses across isotropy plane
(fracture strike, or S1 direction)

Polarity reverses across symmetry plane
(fracture normal, or S2 direction)
Transverse polarity flip detection

Transverse

Phase Flip Semblance

azimuth (degrees)

80  170  260  350

azimuth (degrees)

60  90  120

+1

-1
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Model

- Model: 3 layers each 500m thick
  - isotropic top layer
  - HTI layer: S1 azimuth 40°
  - HTI layer: S1 azimuth 80°

- Modeling assumptions
  - near vertical incidence shear-wave propagation
  - vector decomposition occurs
  - neglect other variations with azimuth for the S1 and S2 modes

- Wavelet
  - Zero phase 30Hz Ricker
Synthetic receiver gather

Radial component

Transverse component

Time (sec)

Source-receiver azimuth (degrees)

S1
S2
After stripping layer 2

**Radial component**

- Time (sec) vs. Source-receiver azimuth (degrees)

**Transverse component**

- Time (sec) vs. Source-receiver azimuth (degrees)

Markers S1 and S2 indicate specific events or data points.
Geometry for synthetic

- Derived from an actual OBS survey
- Shot line dropped to the left
- Offsets limited to a maximum of 500m
Synthetic receiver gather

Radial component

Transverse component

Time (sec)

Source-receiver azimuth (degrees)
Transverse component

Reflection from Bottom Layer 2

Reflection from Bottom Layer 3
Transverse component amplitude
Top event
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Under our assumptions, amplitude of an event (either S1 or S2 arrival) on the transverse component is

\[ A_T(\theta_i) = C \sin[2(\phi - \theta_i)] \]

\[ i = 1, \ldots, N \]

\(N\) traces with azimuths \(\theta_i\)

\(\phi\) : S1 direction

\(C\) : constant scale factor for the event at a given time.
Least-squares algorithm

Recall:

\[ A_T(\theta_i) = C \sin[2(\phi - \theta_i)] \quad i = 1, \ldots, N \]

Rewrite:

\[ A_T(\theta_i) = C (\sin(2\theta_i) \cos(2\theta_i)) \begin{pmatrix} -\cos(2\phi) \\ \sin(2\phi) \end{pmatrix} \]

Only depends on Geometry

Only depends on Fracture Direction
Recall:

\[ A_T(\theta_i) = C \sin [2(\phi - \theta_i)] \]

for \( i = 1, \ldots, N \),

Rewrite:

\[
\begin{pmatrix}
A_T(\theta_1) \\
A_T(\theta_2) \\
A_T(\theta_3) \\
\vdots \\
A_T(\theta_N)
\end{pmatrix}
= C
\begin{pmatrix}
sin(2\theta_1) & cos(2\theta_1) \\
sin(2\theta_2) & cos(2\theta_2) \\
sin(2\theta_3) & cos(2\theta_3) \\
\vdots & \vdots \\
sin(2\theta_N) & cos(2\theta_N)
\end{pmatrix}
\begin{pmatrix}
-\cos(2\phi) \\
\sin(2\phi)
\end{pmatrix}
\]
Least-squares algorithm

Recall: \[ A_T(\theta_i) = C \sin[2(\phi - \theta_i)] \quad i = 1, \ldots, N \]

Rewrite: \[ A_T = CL \begin{pmatrix} -\cos(2\phi) \\ \sin(2\phi) \end{pmatrix} \]

Least-square solution:
\[ C \begin{pmatrix} -\cos(2\hat{\phi}) \\ \sin(2\hat{\phi}) \end{pmatrix} = (L^T L)^{-1} L^T A_T \]
Least-squares method

- **Advantages**
  - No scanning required
  - Doesn’t require regular azimuthal sampling

- **Drawback**
  - Neglects effect of AVO, therefore best applied in limited offset ranges

- **Note**
  - In special case of 2 orthogonal azimuths, $\mathbf{L}^T \mathbf{L}$ is the identity matrix, so get a simple rotation
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Results on synthetic data

- Noise added to synthetic data
  - RMS amplitude 3% of peak signal
- Layer stripping procedure
  - Estimate S1 direction for first HTI layer
  - Remove effects of layer
  - Estimate S1 direction for second HTI layer
  - Remove effects of layer

Comparison of Polarity Flip results vs. Least-squares:

<table>
<thead>
<tr>
<th>Model</th>
<th>HTI 1</th>
<th>HTI 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40°</td>
<td>80°</td>
</tr>
<tr>
<td>Polarity Flip</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>33.75°</td>
<td>76°</td>
</tr>
<tr>
<td></td>
<td>6.9%</td>
<td>4.4%</td>
</tr>
<tr>
<td>Least-squares</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>39.81°</td>
<td>79.41°</td>
</tr>
<tr>
<td></td>
<td>0.2%</td>
<td>0.7%</td>
</tr>
</tbody>
</table>
Transverse component, 3% noise

Reflection from Bottom Layer 2

Reflection from Bottom Layer 3
1st layer stripped: polarity flip estimate
1st layer stripped: least-squares estimate
2nd layer stripped: polarity flip estimate
2nd layer stripped: least-squares estimate
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Field data example

- Carbonate play in North America
- Workflow
  - Superbinning with a radius of 2000ft.
  - Azimuthal binning into 72 sectors of 5°.
  - NMO stacking over offsets greater than 2000ft.
  - Analysis with spatial intervals of 330ft.
- Azimuth decimation to assess robustness for poor geometry
  - Remove half of azimuth sectors
  - Remaining azimuths: 90°-175° and 270°-355°.
Anisotropy: S1 direction and $\Delta t$

Polarity Flip    Least-squares

All azimuth sectors
Anisotropy: S1 direction and $\Delta t$

Polarity Flip  Least-squares

Half azimuth sectors
Half azimuth sectors

Polarity Flip

Least-squares
Conclusions

- Transverse component behavior is sensitive to azimuthal anisotropy directions
- Polarity based method works well, for adequate azimuthal sampling
- For poor azimuth sampling, polarity based method is suboptimal
- Least-squares method is robust in presence of irregular azimuth distribution
- No binning of azimuths is required
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