Shear Wave Splitting Parameter Estimation Using a Regular Distribution of Azimuths

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Summary

Analysis of shear wave splitting involves measuring the variability of data as a function of azimuth. Conventional acquisition geometries lead to missing azimuths which can cause non-uniqueness in the inversion of splitting parameters. A popular approach is to borrow missing azimuths from neighbouring subsurface locations (superbinning), but this can have the effect of smearing parameter estimates. In this paper we consider an alternate procedure in which missing azimuths are obtained via 5D interpolation. We find that 5D interpolation provides gathers that allow for easier visual identification of shear wave splitting, and results in reliable estimates of splitting parameters.

Introduction

In the presence of Horizontal Transverse Isotropy (HTI) converted waves are split into fast and slow waves which are then projected onto the radial and transverse components. The radial component displays a sinusoidal-like travel time pattern across azimuth, while the transverse component displays polarity flips corresponding to the isotropy and symmetry planes. Two parameters can be used to describe shear wave splitting: the azimuth of the fast direction of the splitting layer, and the travel-time difference between a shear wave propagating in the slow and fast directions. A typical first step in the inversion of splitting parameters involves organizing data into Asymptotic Conversion Point (ACP), Common Conversion Point (CCP) (Bale et al., 2005), or Common Transmission Point (CTP) gathers (Cary, 1995). Radial and transverse gathers for a limited offset range are then input to one of many inversion algorithms. A common problem for any inversion process is non-uniqueness. Given limited noise-contaminated data and a forward modelling operator, many model parameters may fit the data. This leads to the question– which model parameters should we choose? The inaccuracies of our forward modelling operator should also to be considered. Is it reasonable to assume a vertical angle of incidence after NMO correction? Is our subsurface binning reasonable? Have we maintained the vector relationship between radial and transverse components? Other factors to consider are improper orientation of the data (Cary, 2002; Li and Grossman, 2012), and differential attenuation of fast and slow wavefields (Li and Grossman, 2012). All of these factors can influence the estimation of shear wave splitting parameters.

To stabilize the inversion of shear wave splitting parameters it is common practice to use traces from neighbouring bin locations (superbinning). This inherently assumes that the parameters vary smoothly with subsurface coordinates. There are two reasons why this is a reasonable assumption– anisotropic horizontal stress fields or fracture regimes can be treated with effective medium parameters (Bakulin et al., 2000) and are thus likely to vary smoothly, and the shear wave splitting we observe in converted wave data come from a conversion point that varies with depth and has a time-lag that can depend on the angle of transmission through a splitting layer. A drawback of the superbinning strategy is that to populate missing azimuths the radius of the superbinning might need to extend beyond a radius that is reasonably justified by these assumptions.

5D interpolation has previously been shown to be a practical alternative to superbinning in the characterization of AVO anomalies (Hunt et al., 2010). 5D interpolation can be thought of as a more rigorous form of superbinning. Instead of directly copying traces from nearby bins, 5D interpolation uses traces from a much larger region to predict missing traces. In this paper we consider a 5D vector interpolation strategy that simultaneously interpolates radial and transverse gathers (Stanton and Sacchi, 2011). The output of this process are gathers that are regularly sampled in offset and azimuth with a preserved vector relationship between components. Such data allow for easy visual identification of shear wave splitting, and are well suited for shear wave splitting parameter estimation.

Theory

Assuming vertical incidence the forward modelling of shear wave splitting is given by

$$
\begin{bmatrix} R(\omega,\theta) \\ T(\omega,\theta) \end{bmatrix} = \begin{bmatrix} cos\alpha & sin\alpha \\ -sin\alpha & cos\alpha \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & e^{-i\omega\Delta t} \end{bmatrix} \begin{bmatrix} cos\alpha & -sin\alpha \\ sin\alpha & cos\alpha \end{bmatrix} \begin{bmatrix} R'(\omega,\theta) \\ T'(\omega,\theta) \end{bmatrix} \tag{1}
$$

Where $\alpha = \phi_{fast} - \theta$ (Silver and Chan, 1991; Simmons, 2009). In plain english Equation (1) states that we rotate the data into the fast and slow directions, apply a time lag to the slow direction, then rotate back to the radial and transverse directions. The input data to this formula are the radial (R') and transverse (T') components in the absence of shear wave splitting, θ corresponds to the source to receiver azimuth, ϕ_{fast} is the azimuth of the fast direction (measured counter-clockwise from East), and Δt is the time delay between fast and slow directions. The equation is applied below the travetime of the splitting layer (reflections that occur above an HTI layer are unaffected). In the case of a single splitting layer the input radial component should be flat across azimuth and the transverse component should contain only zeros. To model multiple splitting layers a "layer stacking" approach can be used which involves applying Equation (1) successively from deep to shallow layers.

To remove the effects of shear wave splitting we use

$$
\begin{bmatrix} R'(\omega,\theta) \\ T'(\omega,\theta) \end{bmatrix} = \begin{bmatrix} cos\alpha & sin\alpha \\ -sin\alpha & cos\alpha \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & e^{i\omega\Delta t} \end{bmatrix} \begin{bmatrix} cos\alpha & -sin\alpha \\ sin\alpha & cos\alpha \end{bmatrix} \begin{bmatrix} R(\omega,\theta) \\ T(\omega,\theta) \end{bmatrix} \tag{2}
$$

Removing the effects of multiple splitting layers is done using a "layer stripping" approach which involves applying Equation (2) successively from shallow to deep layers. Note that Equation (2) is identical to Equation (1) except that the time lag is of the opposite sign.

Many methods exist to invert for shear wave splitting parameters. In this paper we consider a scanning method with a cost function that seeks to minimize the energy on the transverse component and maximize the energy on the radial component for the layer stripped data.

Examples

Our example data is from a land survey in Alberta, Canada that displays the effects of shear wave splitting. Source and receiver coordinates are shown for a single ACP gather in Figure (1). Many azimuths and offsets are missing. After 3x3 superbinning some missing azimuths are recovered, but not all of them, and the gather remains irregularly sampled. To populate nearly all offsets and azimuths a larger radius of superbinning (10x10) may be necessary, but at the expense of smearing estimates over the region of the superbinning. After interpolation all offsets and azimuths are regularly sampled. Figure (2) shows radial and transverse components for the same gather before and after shear wave splitting analysis and compensation. Notice that the many missing offsets and azimuths make visual identification of shear wave splitting very difficult. Also notice that after estimation and compensation of shear wave splitting there still remains a large amount of energy on the transverse

component (the splitting analysis was run on 3x3 superbinned data giving layer-stripped splitting parameters of $T_1 = 400ms$, $\phi_{1fast} = 99°$, $\Delta t_1 = 1ms$; $T_2 = 600ms$, $\phi_{2fast} = 110°$, $\Delta t_2 = 1ms$; $T_3 = 800ms$, $\phi_{3fast} = 99°$, $\Delta t_3 = 1ms$). Figure (3) shows the same gather after 5D vector interpolation. Notice the sinusoidal-like appearance of the radial component at ∼800ms, and the polarity flips across azimuth in the transverse component. After shear wave splitting analysis and compensation the radial component appears more flat, and the energy on the transverse component has been largely attenuated (the splitting analysis was run on non-superbinned data giving layer-stripped splitting parameters of $T_1 = 400ms$, $\phi_{1fast} = 106°$, $\Delta t_1 = 1ms$; $T_2 = 600ms$, $\phi_{2fast} = 104°$, $\Delta t_2 = 2ms$; $T_3 = 800ms$, $\phi_{3fast} = 95°$, $\Delta t_3 = 1ms$).
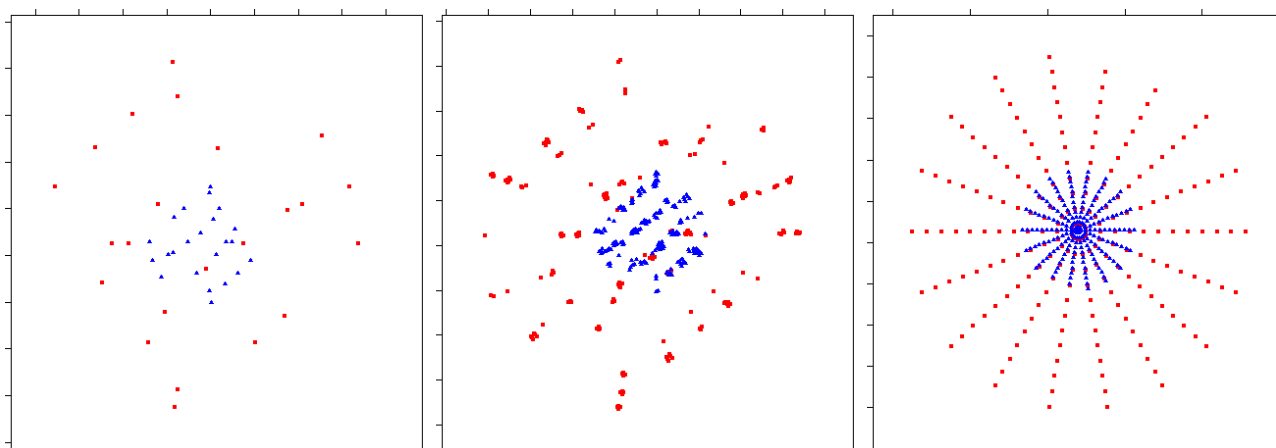

Figure 1 *shot* and *receiver* coordinates corresponding to a single Asymptotic Conversion Point (ACP) location. From left to right: input data, data after 3x3 superbinning, and data after 5D interpolation.
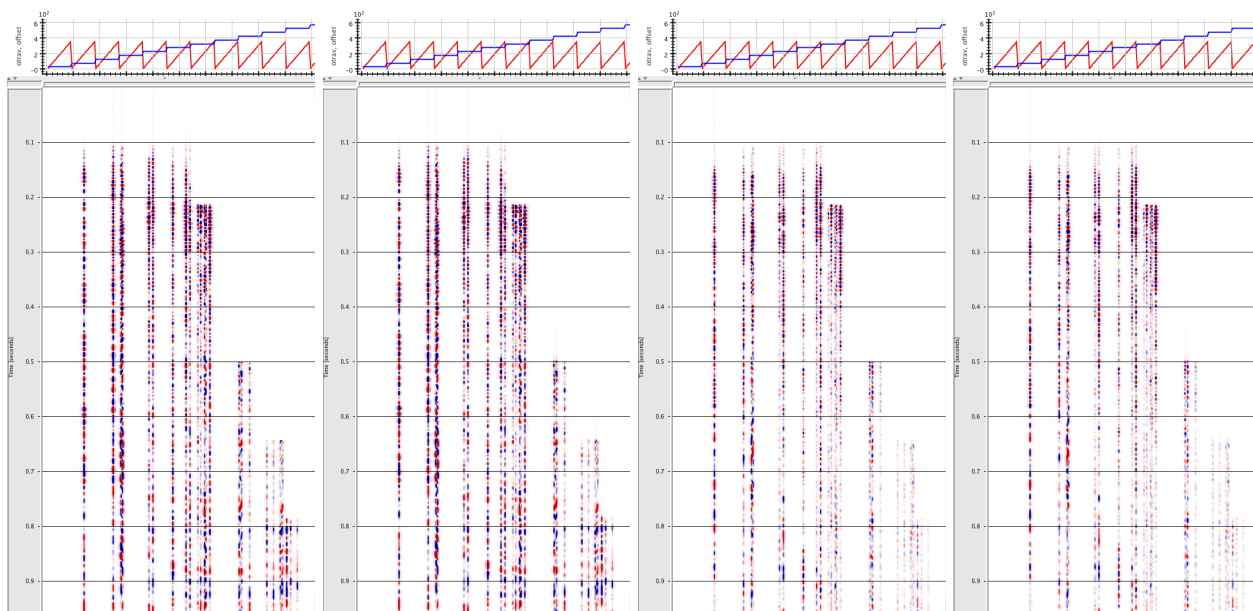

Figure 2 *Input data for a single ACP location. From left to right: Radial component before SWS correction, Radial component after SWS correction, Transverse component before SWS correction, Transverse component after SWS correction. Above the gathers are plots of azimuth and offset.*

Conclusion

We have investigated the use of 5D vector interpolation to populate missing azimuths prior to shear wave splitting analysis and compensation. We find that shear wave splitting is easier to visually iden-
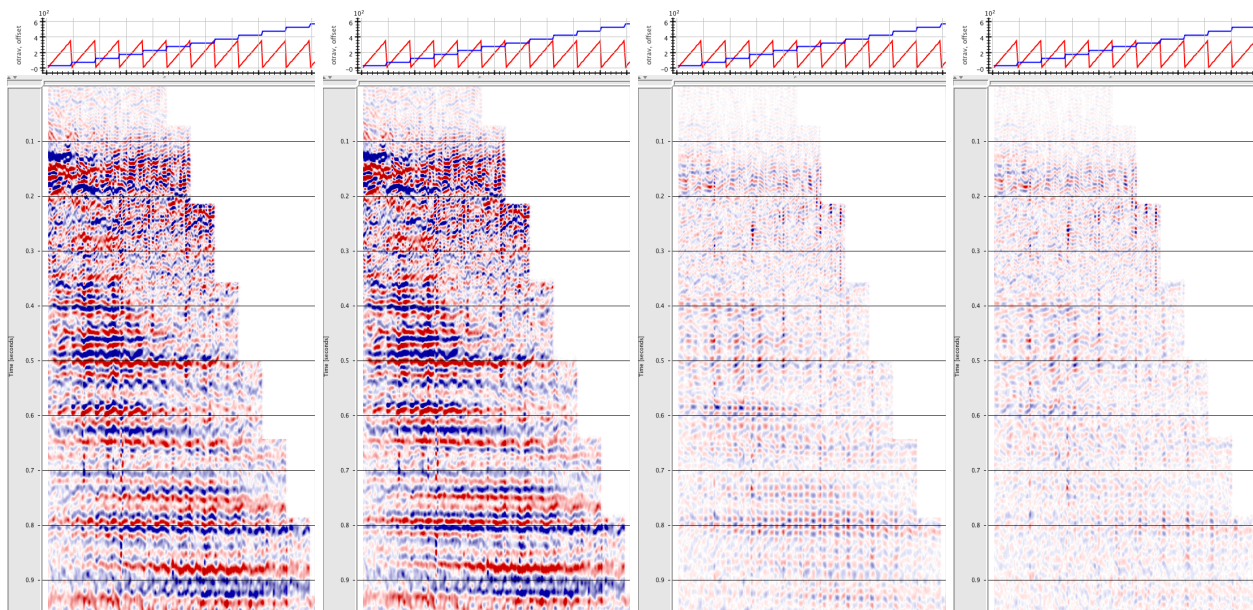
Figure 3 *Interpolated data for a single ACP location. From left to right: Radial component before SWS correction, Radial component after SWS correction, Transverse component before SWS correction, Transverse component after SWS correction. Above the gathers are plots of azimuth and offset.*

tify after 5D interpolation, and our results show that reasonable splitting parameters can be estimated from such data. One drawback of the method is that binned data are input to the interpolation, which could cause error if traces are far from their bin center. Future work could involve developing a vector interpolation method that utilizes exact coordinates (such as the Anti-Leakage Fourier Transform (ALFT)).

Acknowledgements

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