

Processing 3-C Heavy Oil Data for Shallow Shear-wave Splitting Properties

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Summary

We demonstrate several aspects of processing 3-C data to obtain anisotropy information from shear-wave splitting. This includes: analysis for unknown or uncertain field orientations of the receivers; a new method of splitting analysis which uses both radial and transverse component data to estimate the S1 direction, which is compared with a transverse only method; and some analysis of the difference between P-S1 and P-S2 imaging versus anisotropy-corrected “radial-prime” (R’) imaging.

Introduction

Lately there has been increasing interest in using PS data from multicomponent surveys over heavy oil or oil sands reservoirs for characterizing stress – particularly in the overburden and as it relates to caprock integrity analysis. An example of time-lapse stress analysis from PS data for the overburden is described in some detail in Wikel et al. (2012). The basic principle is that the increases in stress associated with production activity (in that case the Toe-to-Heel-Air-Injection or “THAI” method), give rise to anomalies in the amount of shear-wave splitting as measured by the time delay between S1 and S2 (fast and slow shear) modes. Hence, the accurate measurement of shear-wave splitting attributes, such as orientation and time delay, is of paramount importance for monitoring thermal recovery methods. Shear-wave splitting measurement is also important elsewhere, such as fracture analysis for shale gas plays.

In this paper we will look at several aspects of this process, including analysis to verify correct orientation of the receivers, comparison of two shear-wave splitting analysis methods and some observations from imaging of the S1 and S2 modes directly. This is in contrast to the alternative combined result from correction and rotation back to radial, sometimes referred to as “radial-prime” (R’). The processing results are demonstrated using two heavy oil datasets.

Orientation Analysis

It is desirable when acquiring a 3-C survey to consider the information required to properly process the data. From a geometry point of view, this means not only accurate field positioning of source and receivers, but also accurate orientation of the inline direction of the 3-C receivers. Without reliable orientation information, estimation of azimuthally dependent quantities required for splitting analysis is impossible, and even simple radial PS output is adversely affected. A typical practice is to orient the receivers towards magnetic north, and apply the magnetic declination correction in processing. Sometimes practical considerations (e.g. difficult ground conditions) can compromise this ideal. In the survey illustrated in figure 1, the orientations of some of the receivers were measured after the survey was acquired (the receivers with no line segments in the figure had already been picked up). There was enough variance from the nominal orientation (magnetic North) that we decided to estimate orientations of all the receivers from the data, providing an opportunity to compare measured and estimated values where available. The method used for orientation analysis is based on the

assumption that first breaks measured on both vertical and horizontal components are radially oriented P-wave arrivals. This assumption warrants some scrutiny, as it neglects near surface effects such as anisotropy and scattering. However, we found the analysis to be fairly robust when applied over many shots for each receiver. We also estimated a standard deviation of the individual shot-based measurements for each receiver. This gives an error estimate which is overall too conservative (i.e. larger than actual errors), but useful to identify suspect locations. Comparison of the radial and transverse rotated data using the two different orientations showed that in general the orientations estimated from first breaks were at least as plausible as the recorded ones. Ultimately, we processed the entire dataset with the estimated values.

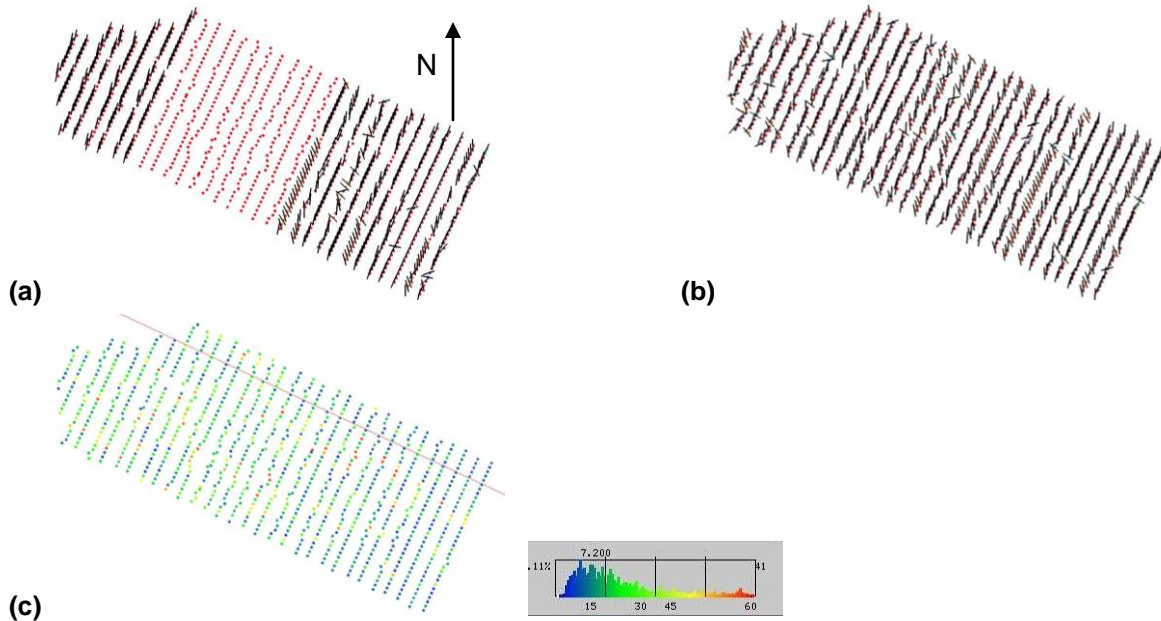


Figure 1: Comparison of field orientations (a) and estimated orientations (b) using first break radial-vertical match. The absent field orientations are locations where receivers had been removed prior to field measurement. In (c) the estimated errors are shown, based on standard deviation of individual shot-based orientation estimates.

Shear-wave Splitting Analysis

Shear-wave splitting analysis can be viewed as a two-step process: first, estimate orientation of the S1 direction, and; second, estimate the time-delay between S1 and S2. Typically the transverse component is used to estimate the orientation, based on the azimuthal position of polarity flips or using an amplitude fitting approach (see for example Li, 1998). We refer to this as the T-only method.

However, amplitude information from the radial can also be incorporated in the process. We describe an algorithm to do this, based upon the theoretical form of the radial and transverse amplitude variations for an S1 direction ϕ , and N traces with radial directions θ_i . Assuming there are two time functions $A_1(t)$ and $A_2(t)$ which correspond to the S1 and S2 reflected amplitudes, then the radial and transverse amplitudes $R(t, \theta_i)$ and $T(t, \theta_i)$ can be written as

$$\begin{pmatrix} R(t, \theta_i) \\ T(t, \theta_i) \end{pmatrix} = \begin{pmatrix} 1 & \cos(2\theta_i) & \sin(2\theta_i) \\ 0 & \sin(2\theta_i) & -\cos(2\theta_i) \end{pmatrix} \begin{pmatrix} \bar{A}(t) \\ \Delta A(t) \cos(2\phi) \\ \Delta A(t) \sin(2\phi) \end{pmatrix}, \quad (1)$$

for $i = 1, \dots, N$, where $\bar{A}(t) = \frac{1}{2}[A_1(t) + A_2(t)]$ and $\Delta A(t) = \frac{1}{2}[A_1(t) - A_2(t)]$.

Equation (1) can be inverted in a least-squares sense, provided $N \geq 2$. The second and third terms of the solution vector can then be combined to determine ϕ . We refer to this as the R+T method.

What is the advantage in using both radial and transverse as opposed to transverse alone? A common assumption is that since the signal-to-noise ratio on the radial is higher than on the transverse, then an estimate using radial data in addition to transverse will be more robust. However, equation (1) makes it clear that the signal of interest is the deviation $\Delta A(t)$ from the background amplitude $\bar{A}(t)$. This deviation signal is no stronger (on average) on radial than it is on transverse. However, it does have a different sensitivity to the azimuth distribution, and so may help in areas where the azimuth distribution is poor.

Figure 2 shows a comparison of orientation estimates measured on a heavy oil dataset at the Devonian level (about 1 second PS time) using 5x5 and 11x11 superbin sizes between T-only and R+T based methods. The receiver line spacing for this survey is 150m, which causes a noticeable acquisition footprint to contaminate the analysis results for shallow targets. As is seen in figure 2, for 5x5 superbin sizes, the footprint is somewhat reduced using the R+T method compared to the T-only method. However, if the superbin size is increased to 11x11, which is necessary to remove the footprint satisfactorily, then both methods perform equally well.

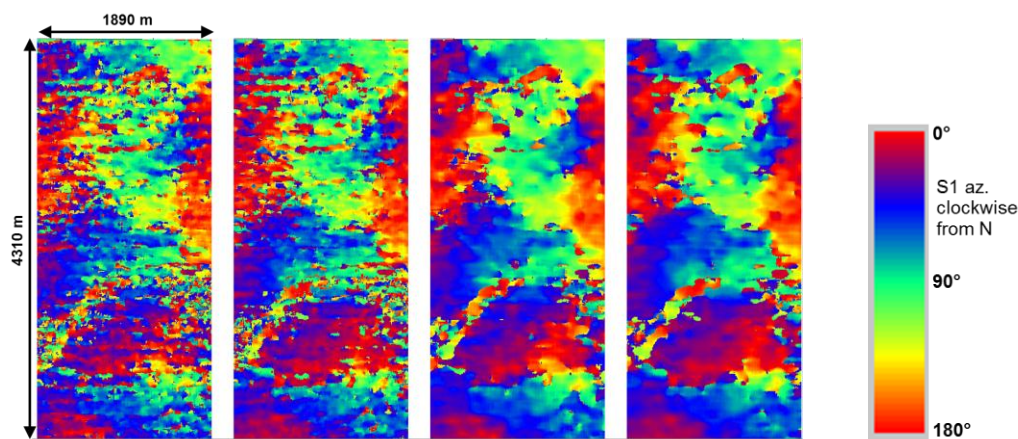


Figure 2: Comparison (from left to right) of S1 azimuth estimates with superbinned input, using 5x5 T-only, 5x5 R+T, 11x11 T-only and 11x11 R+T.

P-S1 and P-S2 versus R'

There are two alternative ways to image the PS data after shear-wave splitting analysis.

Perhaps the most obvious is to rotate data to S1 and S2 directions and image these two datasets (P-S1 and P-S2) separately. This is not as straightforward as it first sounds, as both P-S1 and P-S2 have azimuthal amplitude variations related to the source-receiver azimuth, including polarity changes. These must be dealt with appropriately, for example by the weighted stacking method of Bale et al. (2000). In this approach the P-S2 can be left in delayed time, or shifted to match P-S1.

The alternative approach is to shift the P-S2 data to match P-S1 first and rotate back to the radial-transverse coordinate system. The resulting data may be referred to as radial-prime and transverse-prime (R' and T'). In order to layer strip through multiple layers, it is necessary to compute R' and T' for each layer in succession, in order to perform analysis for the subsequent layer. Often the R' dataset is the most suitable for the final goal of imaging the reservoir.

Nevertheless, there can be advantages in analysis of P-S1 and P-S2 images separately, in particular for amplitude subtleties or spectral response. Figure 3 shows a comparison of data from the same heavy oil survey used in figure 2, processed for P-S1 and P-S2 images, and compared with a R' image. Figure 3(a) shows a portion of the image from one line, while figure 3(b) compares the amplitude spectra for the three images. What is notable is that the P-S1 image is richer in the higher frequencies while the P-S2 is biased towards lower frequencies. This suggests (assuming equivalent reflectivity responses) that there is some degree of differential attenuation being observed between the two

modes, with the P-S2 mode having greater frequency dependent losses than the P-S1 mode. We have observed this to be fairly prevalent within this dataset. However, there are examples elsewhere of the reverse behavior, as shown in figure 3(c). In both cases, the R' spectrum benefits from the combined contributions of P-S1 and P-S2.

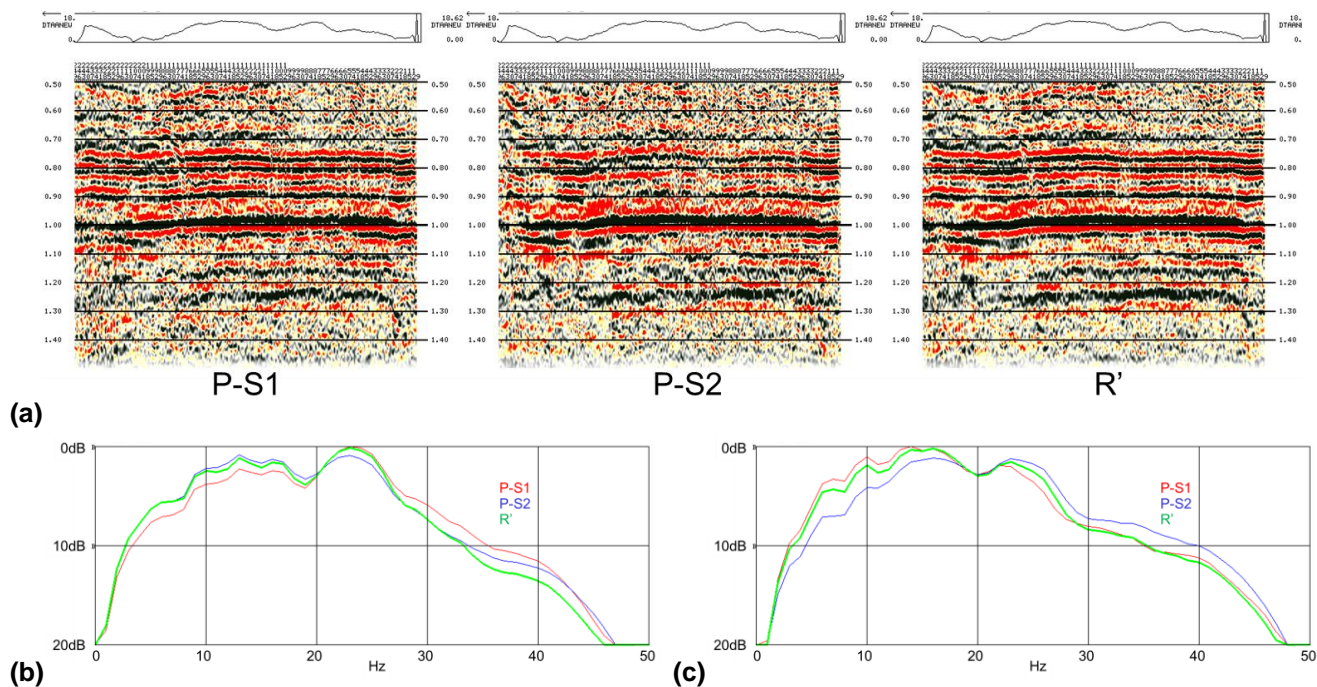


Figure 3: Comparison of amplitudes for different PS imaging methods. The three stacks in (a) show P-S1, P-S2 and R' results, with the S1-S2 time delay profiled above them. The amplitude spectra in (b) are for the window from 700-1350ms. Note that P-S1 is richer in high frequencies and P-S2 is richer in low frequencies. However, a different location (not shown) displays the reverse behaviour, as seen in (c).

Conclusions

PS data is proving useful for identification of stress variation in the near surface over heavy oil reservoirs, in the absence of natural fracturing. To enable this analysis, it is important to accurately measure receiver orientation, or, if necessary, to estimate it as well as possible from the data.

The first step in splitting analysis is to estimate S1 azimuth, which is typically done using the transverse component alone (T-only). We found some marginal benefit to a method using both radial and transverse (R+T), which reduced the footprint on azimuth estimates with large receiver line intervals, but not enough to obviate the need for substantial superbinning.

A comparison of P-S1 and P-S2 data after weighted stacking indicates possible differential attenuation between these modes and that the R' spectrum benefits from the combination of the two modes.

Acknowledgements

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References

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