Modelling True and False Indicators of Shear-Wave Splitting

Peter W. Cary - Sensor Geophysical Ltd.

Summary
Observations of shear-wave splitting from converted-wave seismic surveys are becoming common. When interpreting 3-C data for shear-wave splitting, it is important to be able to distinguish true indicators of shear-wave splitting from false ones. Multicomponent exploration is in its infancy, so it is not unusual for geometry-related problems to exist in acquisition and processing. Land 3-C surveys are often conducted with equipment that is designed for ordinary 1-C data. With three times the normal amount of cable to lay out and plug in, it is possible, and relatively easy, for mistakes to be made regarding which channels are recording which components. In addition, documentation of field operations is often not sufficient for processors to be certain of the orientation of the geophones' horizontal components in the field. There can also be uncertainty about whether the geophones are recording with a left-handed or right-handed coordinate system, or whether the internal wiring in all the geophones is correct. It is important to be aware of the impact of these types of errors since they can lead to false indications of shear-wave splitting where none exists, or inaccurate observations where real shear-wave splitting exists.

Modelling Limited-Azimuth Stacks
Shear-wave splitting of P-S converted waves occurs when an upgoing, reflected shear-wave transmits through an azimuthally anisotropic layer, which can be caused by vertically aligned fractures. The P-S wave splits into a fast P-S1 wave and a slow P-S2 wave, which are polarised in the so-called natural coordinate system associated with the fractures. At the surface, the P-S2 wave arrives a certain time, Δt, after the P-S1 wave, and the two wavefields are measured on the H1, H2 coordinates of the geophones. If more than one azimuthally anisotropic layer exists, the situation becomes more complex, since wavefields split multiple times on the upgoing raypath.

3-D land and OBC surveys generally have the benefit of a wide sampling of azimuths, so a particularly straightforward way to analyse the data for the existence of shear-wave splitting is to generate limited-azimuth stacks after rotating the receivers (in processing) into the radial and transverse directions. The radial direction is measured positive outwards from the source to the receiver, and the transverse direction is 90° clockwise from the radial. In order to get an unbiased sampling of azimuths and good cancellation of noise, a large supergather of common-conversion-point traces from a central portion of the 3-D survey is normally binned and stacked together.

Suppose we generate the radial and transverse limited-azimuth stacks in Figure 1 from a super-CCP gather of a 3-C/3-D survey. There is very little, if any, variation in the radial component with azimuth. However, there appears to be a polarity reversal on the transverse component every 90°. This polarity reversal on the transverse component is what we expect to see if an azimuthally anisotropic layer exists above these reflectors (Li, 1998). Should we therefore automatically assume that this is an indication of shear-wave splitting? The answer is no, since there are a number of factors that can cause polarity reversals to appear on the transverse component other than shear-wave splitting.

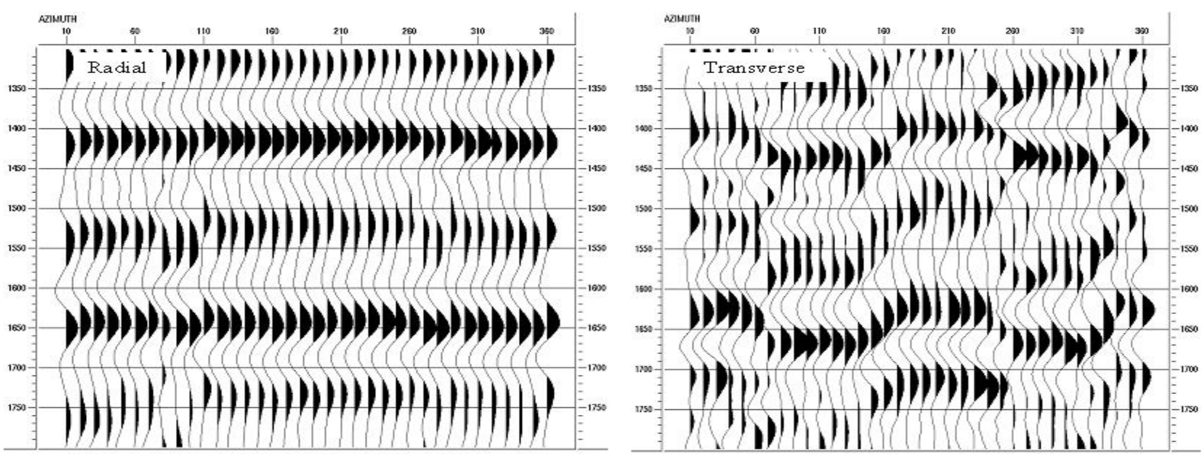

Figure 1: Horizontal-component limited-azimuth stacks from a 3-C/3-D dataset. Traces are stacked within 10° azimuth slices from 10° to 360°.

In a simplified form (ignoring different propagation effects for S1 and S2), the data that should be observed on the radial component, *R(t)*, and on the transverse component, *T(t)*, when there is a single azimuthally anisotropic layer is described by

$$R(t) = S(t)\cos^2\vartheta + S(t-\Delta t)\sin^2\vartheta$$

$$T(t) = S(t)\sin\vartheta\cos\vartheta - S(t-\Delta t)\sin\vartheta\cos\vartheta,$$

where ϑ is the angle between the source-to-receiver (radial) azimuth and the S1 azimuth, and *S(t)* is the seismogram that would be observed without splitting.

If no shear-wave splitting exists, then the limited-azimuth stacks are particularly simple. All of the energy projects onto the radial component and none onto the transverse component, regardless of the azimuth. This situation is depicted with synthetic wavelets in Figure 2. Notice that there is no variation at all in the wavelets on the radial component.

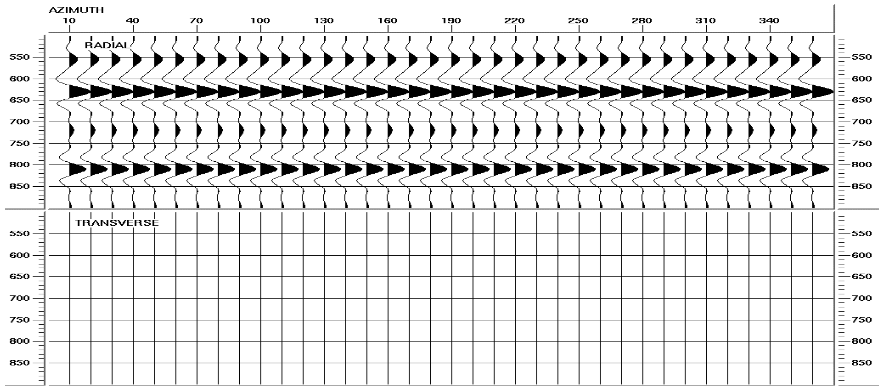

Figure 2: Synthetic limited-azimuth stacks of the radial (top) and transverse (bottom) components when no shear-wave splitting exists.

If there is a single azimuthally-anisotropic layer with a fast (S1) direction that is 70° east of North and a time delay of 14 ms between the S1 and S2 components, then we expect to observe the limited-azimuth stacks in Figure 3. When the source-receiver azimuth aligns with either the S1 or S2 azimuth, then all the energy appears on the radial component and none on the transverse component. Notice that the radial component varies in a sinusoidal fashion with a period of 180 degrees, with the earliest arrivals occurring at the S1 azimuths and the latest arrivals occurring at the S2 azimuths. Therefore, the maximum observed difference in arrival time on the radial component is a measure of the time delay between S1 and S2.

The transverse component, on the other hand, changes abruptly in polarity on either side of the S1 and S2 azimuths, and there is no temporal variation in the wavelets between these azimuths. Land data is often contaminated by significant amounts of non-random noise so trace-by-trace scaling is typically applied. Figure 4 shows what to expect when trace-by-trace scaling is applied before stack. The abrupt change in wavelet polarity every 90 degrees on the transverse component is easy to see, so the observation of this change is often taken as evidence of the existence of shear-wave splitting. The lack of temporal variation between polarity flips, as well as the fact that the wavelet on the transverse component looks like a differentiated version of the wavelet on the radial component, are additional evidence of a single anisotropic layer. In general, an increase in time-delay between S1 and S2 does not cause any visible change in the wavelets on the transverse component other than an overall increase in amplitude that is independent of azimuth. So as the time delay between S1 and S2 increases, the signal-to-noise ratio on the transverse component increases due to increasing signal strength. In general the radial-component stacks will have better S/N than the transverse-component stacks when delay times are small.

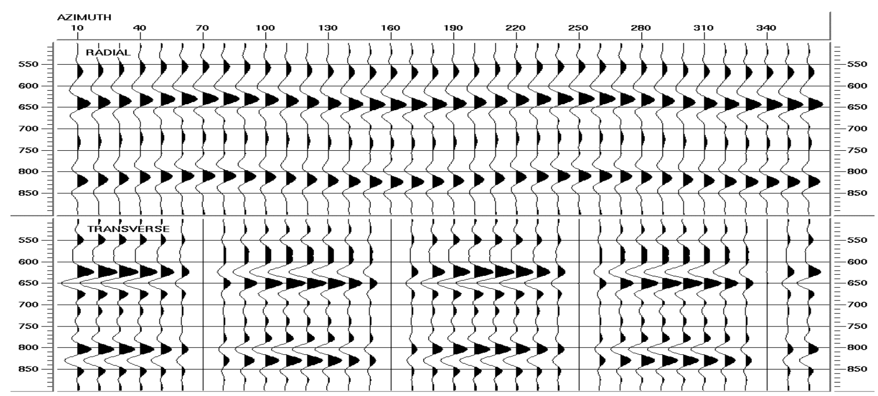

Figure 3: Limited-azimuth stacks for a single anisotropic layer. The S1 azimuth is 70° and S2 arrives 14 ms after S1.

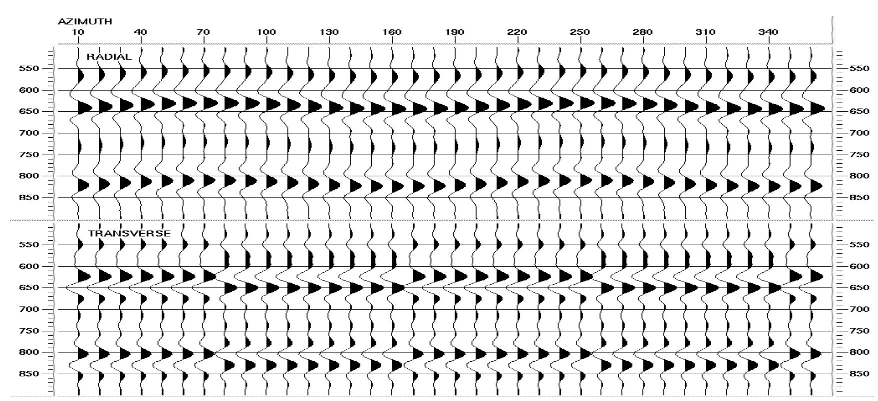

Figure 4: The same as Figure 2 except that each trace is scaled individually. Notice the abrupt polarity change in the transverse wavelet at the S1 and S2 azimuths, and the 90° phase difference between the radial and transverse wavelets.

Pitfalls of Limited-Azimuth Stacks

Based on the modelling in the previous section, we now know that little variation should be expected on the radial-component limited-azimuth stacks (as in Figure 1) when the time delay between S1 and S2 is very small. Figure 5 shows the limited-azimuth stacks for the case where the S1 direction is 45° and the time delay between S1 and S2 is only 2ms. Apart from the fact that the polarity reversals on the transverse stacks appear at about 60°, 150°, 240° and 330° in Figure 1 instead of at 45°, 135°, 225° and 315° as in Figure 5, the over-all similarity of the two figures is good evidence that a small amount of shear-wave splitting really does exist in the real data.

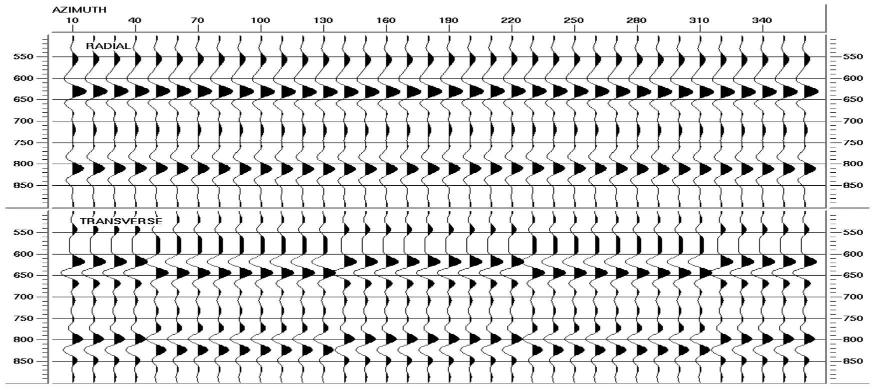

Figure 5: Limited-azimuth stacks for a single anisotropic layer with an S1 azimuth of 45° and time delay of 2 ms.

As an illustration of how limited-azimuth stacks might lead us astray, however, suppose that a set of limited-azimuth stacks from a real 3-C/3-D dataset had the general appearance of Figure 6. Once again there is no discernible variation in the radial component with azimuth, and the polarity reversals that occur on the transverse component every 90° stand out strongly.

But is the polarity flip on the transverse component a reliable indication of the existence of shear-wave splitting in this case? No, it is not. What has actually happened to generate the stacks in Figure 6 is that one out of every twenty receivers has had the H1 and H2 components exchanged. This type of problem does occur in real data, and can be caused by any number of reasons such as incorrect internal wiring of the geophone, or a mistake in plugging phones into cables, which is easily done. If this mistake is not corrected in the processing, then the rotation from H1/H2 coordinates to radial/transverse coordinates is not done correctly for 5% of the traces. There is no real splitting occurring in this case, so the correct limited-azimuth stacks should look like Figure 2. The stacks in Figure 6, however, certainly make it look like splitting does exist, and that the S1 azimuth is at about 45°.

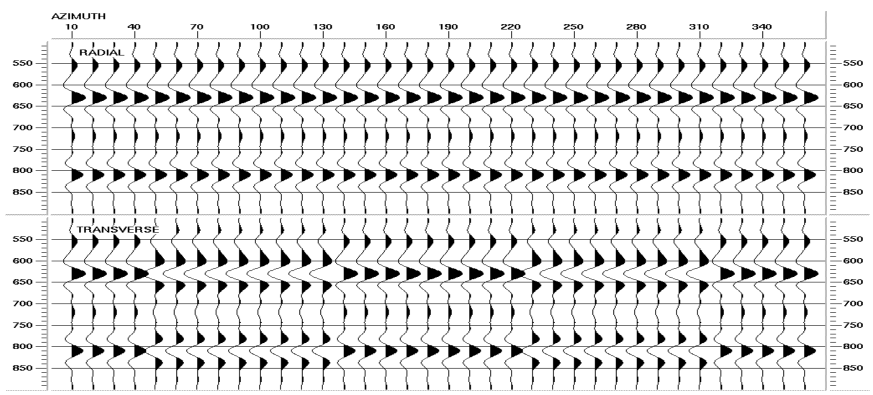

Figure 6: Limited-azimuth stacks that indicate a small amount of shear-wave splitting?

A close examination reveals that the transverse wavelets are out of phase by ±90° with respect to the radial wavelets in Figure 5, but not in Figure 6. This difference in wavelet character can be used to distinguish real from false indications of shear-wave splitting in this case. The problems with individual receivers can be detected early in the processing by examining the polarity of the first-arrival P-wave energy on the horizontal components. This is a tedious and sometimes ambiguous task, however, especially with data that is noisy or acquired with a Vibroseis source, so it is always wise to be on the lookout for features in the limited-azimuth stacks that do not match the modelled response, in case these geometry-related problems are not detected in the processing.

Very often there is no documentation provided to the processor about which way the geophones were oriented or which components were recorded on which channels during a 3-C survey. So it is conceivable that a consistent error could exist in an entire dataset during processing. Figure 7 shows the limited-azimuth stacks that would be calculated for a situation where the H1 and H2 components are mistakenly exchanged for an entire dataset, so none of the rotations from H1/H2 to radial/transverse coordinates are actually done correct in processing. In this situation about the same amount of energy ends up appears on the radial and transverse stacks. Full-azimuth stacks of both components would obviously be very poor because of the polarity changes with azimuth for both components.

Figure 8 shows the correct limited-azimuth stacks that occur for a single layer with an S1 azimuth of 45° and a large time delay of 30 ms. There are enough similarities between Figures 7 and 8 to understand how a false indication of shear-wave splitting could be mistaken for a real one on real, noisy, low-frequency seismic data. Once again, polarity changes on the transverse component are a false indication of shear-wave splitting in Figure 7, as in Figure 6. A close comparison of Figures 7 and 8 reveals several differences in the wavelets that can be used to distinguish real from false effects of splitting on the limited-azimuth stacks. Notice in this case that the phase of the wavelets on the radial component in Figure 7 varies with azimuth, but not in Figures 4 or 5, where the time-delays are smaller.

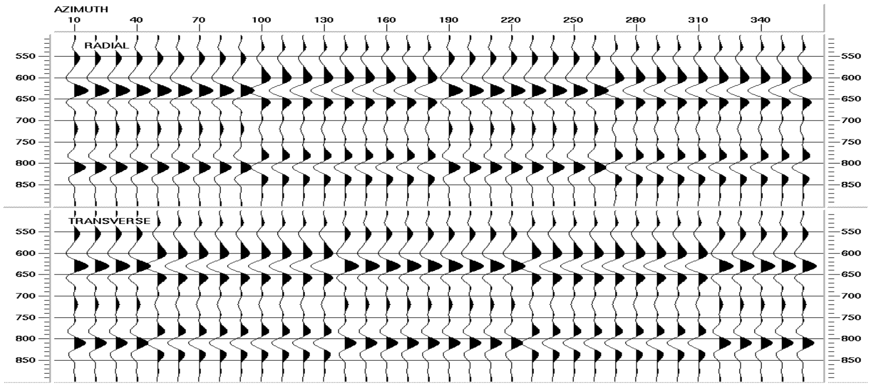

Figure 7: Limited-azimuth stacks that indicate a large amount of shear-wave splitting?

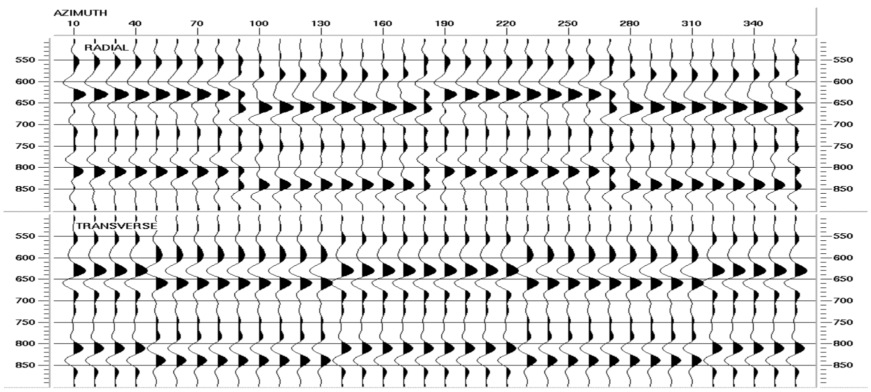

Figure 8: Limited-azimuth stacks for a single anisotropic layer with an S1 azimuth of 45° and a time delay of 30 ms.

Conclusions

Certain geometry-related problems that can exist in present-day 3-C seismic surveys can lead to false indications of shear-wave splitting where none actually exists. Two examples have been shown that indicate that the incorrect limited-azimuth stacks can be distinguished from correct ones if the situation is simple enough. In more complicated situations, it may not be as easy to see the problems in the limited-azimuth stacks. This potential problem can, and should, be prevented by careful examination of the prestack data gathers. A better long-term solution, however, would be to use acquisition systems that are specifically designed for multicomponent seismic exploration. Input/Output's VectorSeis system is presently the only such land multicomponent system.

Acknowledgement

The real data example is provided by kind permission of PanCanadian Energy Corp.

References

Li, X.-Y., 1998, Fracture detection using P-P and P-S waves: 68th Annual Internat. Mtg. Soc. Expl. Geoph., Expanded Abstracts, 2056-2059.