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Azimuthal weighting for layer-stripped gathers

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Summary

A benefit of shear waves in seismic exploration is the ability to provide information beyond that obtained from compressional waves. Shear-wave splitting in fractured media is an example of this, and Mueller (1992) demonstrated the interpretational value of having both fast- and slow-wave volumes obtained from SS data. The stacked sections required for that method can also be conveniently obtained from PS data using a least-squares method proposed by Bale et al. (2000) which appropriately weights the data. However this approach to weighting will no longer be sufficient if the PS1 and PS2 layer-stripped data are to be prestack time migrated, or even CCP-stacked. One possible approach which can be used to prepare the data for migration is 1/cosine scaling (to equalize the signal between traces of differing azimuth). A difficulty in this method is that the scaling of some traces can boost noise excessively and thus a balance must be achieved to enhance signal but keep noise in check.

We demonstrate a method for applying 1/cosine scaling and illustrate its ablility to produce PS1 and PS2 volumes from PS field data.

Introduction

In the presence of azimuthal anisotropy PS reflection data contains composite events, as shear waves polarized in both fast and slow directions make their way to the same receiver at slightly different times. Energy which has passed through a single azimuthally anisotropic layer will appear as two events, that which has passed through two such layers will appear (in principle) as four events, and in general 2^n events may result from passage through *n* layers. It can be imagined that, if one possessed a knowledge of the various anisotropic attributes, such data could be decomposed into 2^n individual datasets, each corresponding to a different combination of fast and slow polarizations in the shear wave's journey.

While tantalizing for interpretation, such an objective is not presently practical. A more compact and achievable goal is to create PS1 and PS2 volumes, and, properly constructed, these are still of rich interpretational value (Mueller, 1992). A PS1 volume can be imagined as the stack that would result if, on each encounter with an azimuthally anisotropic layer, the wavefield's polarization were adjusted to be in line with the fast direction of the medium; in this unphysical scenario no energy would be partitioned away through birefringence. A PS2 volume is imagined similarly, but with adjustment to the slow direction of each layer, and with one other difference as well. We also assume that the time of each PS2 event is adjusted upward so that the only difference between its time and that of the corresponding PS1 event is the traveltime difference of fast and slow waves in the anisotropic layer immediately above the event. Thus no PS2 event is affected by an accumulation of traveltime delays, but rather they only provide information on the characteristics of a single analysis window. In fact in some circumstances even this delay is compensated so that the times of PS2 events are adjusted to equal those of PS1 events, thus allowing constructive summation of the two volumes. Here though our main interest in time shifts is in their interpretational value.

The simplest model that gives rise to an event with shear-wave splitting is one with an isotropic medium overlain by horizontal transverse isotropy (HTI). In this case the time difference caused by vertical passage through a homogeneous HTI layer of thickness Δz is $\Delta t_{SWS} = (\Delta z / V_{S0})\gamma^{(S)}$, where $\gamma^{(S)}$ is a splitting parameter, roughly the fractional difference between fast and slow shear-wave velocities in the medium. A primary difficulty in application of this is identifying the thickness and location of the anisotropic layer. We cannot readily distinguish between a thick layer with weak splitting and a thin layer with strong splitting.

However interpretational value is found not only in the time shifts and polarization directions for each layer, but also in amplitudes of the PS1 and PS2 volumes (Mueller, 1992). Just as the traveltimes of the PS1 and PS2 events correspond to those of the fast and slow directions, reflection coefficients of the two differ as well. Tsvankin & Grechka (2011, eq. 9.56) give B_{PS}^{ani}, the difference in linearized PS reflectivity gradient for the fast and slow directions, for the reverse configuration (isotropic over HTI). Thus we require the negative of their expression, namely,

$$B_{PS}^{\mathrm{ani}} = 2g\gamma^{(V)} - \frac{\delta^{(V)}}{2(1+g)},$$

where g is approximately the average of V_S/V_P across the interface, and $\gamma^{(V)}$ and $\delta^{(V)}$ are HTI analogues of Thomsen's anisotropy parameters for the upper layer, and $\gamma^{(V)} \approx -\gamma^{(S)}$. Thus traveltime differences and amplitude differences are not completely independent of each other.

Any information on anisotropy parameters is useful. It is commonly related to fracture parameters via linear slip theory or Hudson's crack model (see, e.g., Bakulin et al., 2000). In other cases it may be more reasonable to relate it to geomechanical stresses (Cary et al., 2010). It is not our object in this abstract to undertake a detailed interpretation of the present data set. Rather we have tried to explain some of the motivation for creating PS1 and PS2 volumes and to report on some issues in their creation. It is to this methodology that we turn next.

Method

We perform a shear-wave splitting estimate (Li & Grossman, 2012) and use this to combine radial and transverse data sets into PS1 and PS2 data sets. This yields ACP gathers, the traces of which (for a given offset and time window) may be ideally described as having the form

$$u_i^{PS1}(t) = s(t)\cos(\theta_i - \theta_{fast}) + n_{i,1}(t)$$

$$u_i^{PS2}(t) = s(t + \Delta t_{SWS})\cos(\theta_i - \theta_{slow}) + n_{i,2}(t)$$

where the i^{th} trace is shown composed of $s(t)$ (the noise-free signal, unaffected by splitting), a cosine weight imposed by the shear-wave splitting (which depends on the source-receiver azimuth, θ_i), and some random noise, $n(t)$. Bale et al. (2000) showed that a least-squares estimate of $s(t)$ (and the same function shifted by shear-wave splitting Δt_{SWS}) can be obtained as a weighted stack of $u_i(t)$ with cosine weight functions. This is an optimal approach for ACP stacking of PS1 and PS2 data, and for some applications this would serve as the final product.

In this study, however, we wish to apply methods that redistribute energy among different ACP locations, such as common-conversion point stacking or prestack time migration. For these we would like to be able to apply a 1/cosine weight in order to remove the azimuthal variation of the signal strength which comes naturally as a function of the difference between PS1 (and PS2) orientations and the direction in which the wave propagate. This must be approached cautiously, because of the obvious danger of noise amplification. However we have found that if we apply a weight such as 1/(cosine + ε), and judiciously treat those traces having the highest noise amplification, that stacking and other noise reduction techniques enable us to obtain good-quality images.

Example

The method described above was applied to Washout Creek, a 3C-3D data set collected over 66 km^2 near Drayton Valley, Alberta, Canada. Sources are 1 kg dynamite at 9 m depth with 40 m interval and 280 m line interval. Receivers are Sercel DSU3 MEMS accelerometers at 40 m interval and 240 m line interval. The bin size is 20 m x 20 m and the sample rate is 1ms. The nominal fold is 80.

The layer-stripped gathers, obtained as described above, were stacked with a common-conversion point method. Denoising was accomplished by FX deconvolution applied to the inlines, then crosslines, of the stack. Finally we applied Kirchhoff poststack migration.

At this point various products can be extracted for interpretation. The first step generally is picking analogous horizons on the PS1 and PS2 volumes in the zone of interest. Figure 1 illustrates picking events near 900 ms and 1200 ms. There is a visible shift to later times in the PS2 volume.

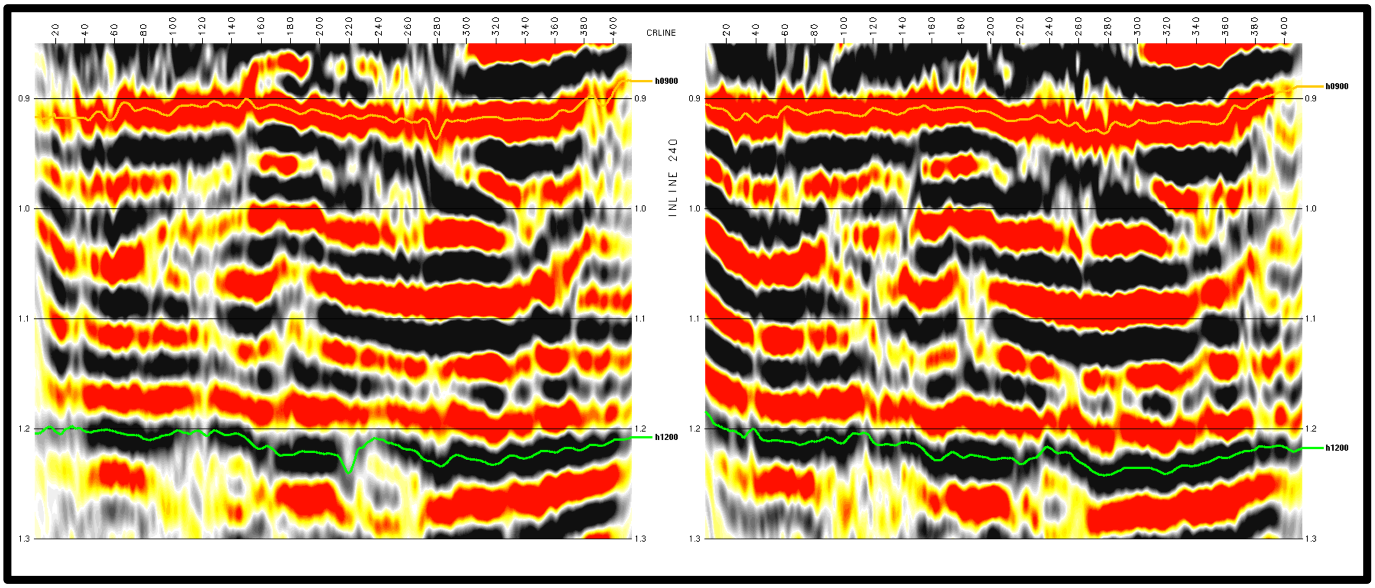

Figure 1. An inline display from horizon picking tool. Two horizons are picked, one near 900 ms and the later near 1200 ms. On the left is the PS1 volume and on the right is PS2.

The horizons picked above can be used to generate the time shifts specific to this event. Time shifts were estimated previously at each CDP as part of the shear-wave splitting for a relevant analysis window, along with fast-direction angles, but only the angles are used in the layer-stripping procedure. The estimated time shifts are used in compensating the PS2 shift in order to stack this event, if desired, but times from horizon differences can have much better vertical resolution in this compensation procedure. They should also be more relevant for fracture analysis. Figure 2 shows the time shifts obtained from the 1200 ms horizon, compared to the time shift obtained for the enclosing window in the shear-wave splitting analysis. They share ranges of values and roughly corresponding areas of greater and lesser intensity.

Finally we can compare amplitudes of the two data volumes along the horizon. We sum the amplitudes in a 30 ms window centred on the selected horizons and plot this in Figure 3. An interesting difference is apparent in that at 900 ms there is only a very mild dominance of PS1 over PS2, but this is more pronounced at 1200 ms. Because of the ambiguity of the expressions above it is not possible to immediately assign physical significance to this difference, but it suggests avenues for further study.

Conclusions

We have demonstrated that it is possible to produce migrated PS1 and PS2 volumes using traces with properly scaled signal. We have also shown that the amplitude differences estimated from different horizons show distinct character which may be of use for interpretation. Although the present results do not invite a quantitative interpretation as yet, they indicate a direction worth pursuing.

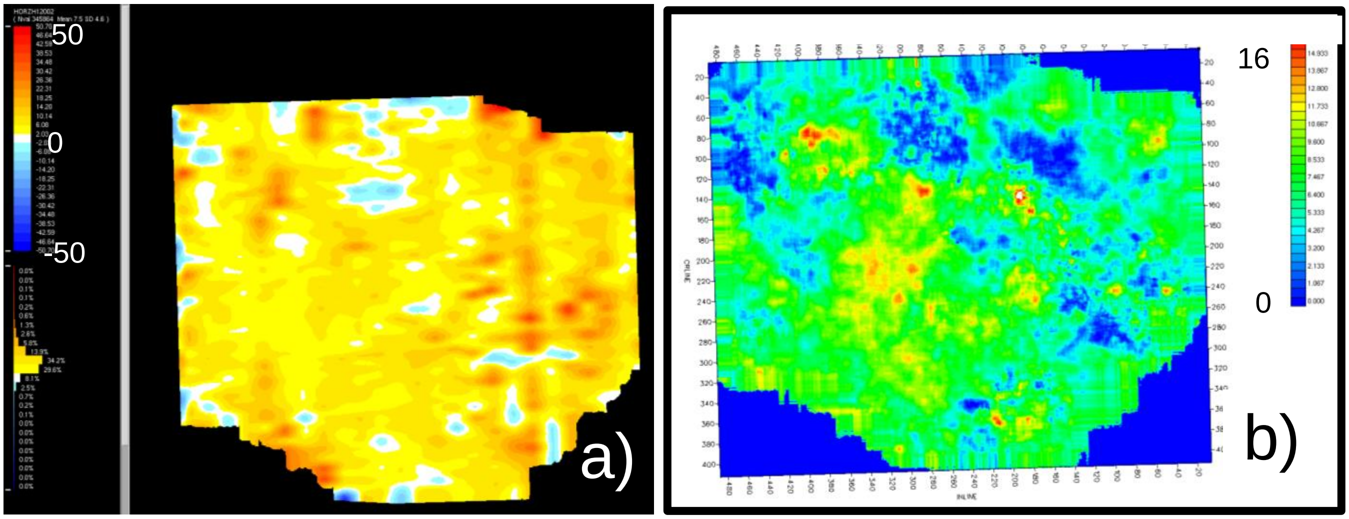

Figure 2. Shear-wave splitting as estimated from a) difference of PS1 and PS2 horizons at ~1200 ms, and b) shear-wave splitting magnitude estimated in window from 850 ms to 1300 ms.

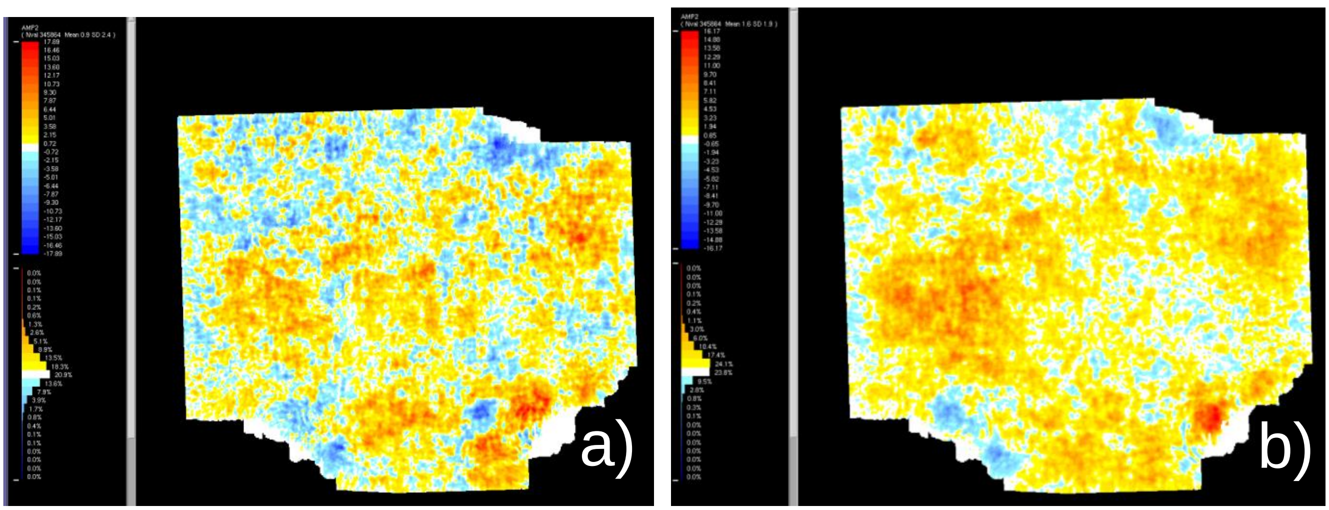

Figure 3. Difference in amplitude between PS1 and PS2 volume in 30 ms window around a horizon picked near a) 900 ms and b) 1200 ms.

Acknowledgements

Data courtesy of Arcis, a TGS company.

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