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Shear-waves processing: Characterization and opportunities of shear-wave splitting

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Summary

Shear-wave datasets are usually affected by the interference of several images due to the birefringence phenomenon. If ignored, this effect can be very detrimental to the quality of the final product. However, by taking properly into account all its aspect, PS images gain high frequencies and the study of the characteristics of the splitting leads to insight on the stress field in the area, as demonstrated by the example of this paper.

Introduction

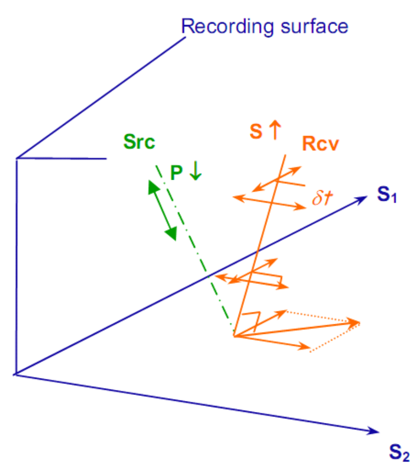

Fig1: Illustration of the travel time difference between polarizations parallel or orthogonal to the anisotropy direction.

Even in the case of conventional compressional sources, a strong horizontal motion can be recorded at the surface due to the conversion mechanism that occurs at any geological interface. More often than not, a single interface will actually produce two orthogonally polarized arrivals at the surface, due to the phenomenon of birefringence, also known as shear wave splitting. The figure 1 above, illustrate this fact: as the horizontal particle motion at the interface travels back to the surface, the propagation velocity is different depending if the polarization is parallel or orthogonal to the fracture direction.

1D PS modeling, mathematical frame-work

In reality there is a continuity between isotropic and anisotropic medium: In the first case, using the notations offig.2, we interpret the seismic wave at surface as simply polarized along the radial direction. However, introducing a transverse reflectivity makes a number of calculations simpler, so we consider as a suitable isotropic model :

$$tr(t) = Rps(t)\cos(\theta - \beta) \qquad (+Rtrsv(t)\sin(\theta - \beta))$$

If instead we suspect some shear-wave splitting is occurring in the dataset we will consider as a better model

$$tr(t) = Rps1(t)\cos(\alpha - \beta)\cos(\alpha - \theta) + Rps2(t)\sin(\alpha - \beta)\sin(\alpha - \theta)$$
$$= Rps(t)\cos(\theta - \beta) + \delta Rps(t)\cos(2\alpha - \theta - \beta)$$

Rps1 is here the fast direction image and Rps2 the slow one. By re-writing the modeling equation using the halfsum Rps=1/2(Rps1+Rps2) and the half difference δRps=1/2(Rps1-Rps2) we can see that the anisotropic model is basically the isotropic model augmented by the anisotropic term in δRps. If for instance, the time difference between fast and slow is small compared to the dominant seismic frequency, the two models are equivalents.

Both modeling show that the recorded traces are actually linear combination of the unknown reflectivities with nonlinear but known coefficients. Therefore we can easily compute estimates by least-square inversion of the observation with the model.

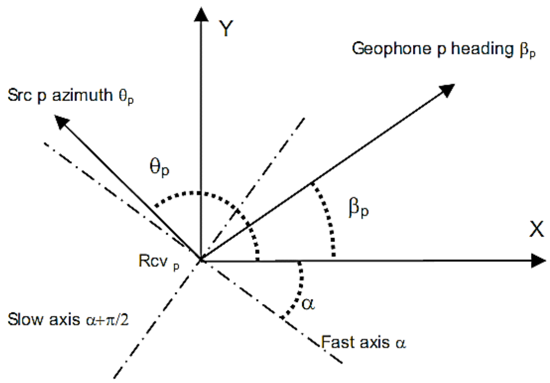

Fig2: Angle schematics for horizontal trace recordings.

Reorientation of the receivers

The very shallow events near the first breaks are usually dominated by the isotropic propagation and the first model applies fully. We know that the transverse reflectivity is not physical, so we can minimize the energy of Rtrsv w.r.t. the geophone direction and hence find the horizontal heading of the sensors. An example of this process is illustrated on fig3 below, taken from a north-sea OBC, the color indicating the geophone instrument code. Despite the absence of any constraints on the directions, the geophones are found mostly orthogonal to each other, and the inline geophone follows the shape of the cable.

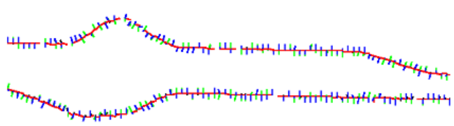

Fig3: Reorientation of the geophones of un-gimballed OBC cables

Anisotropy detection

Most likely α, the anisotropy direction is not known. Taking α as a parameter we can compute $E(\alpha)$, the square error between the observation and the model and then find the value that minimizes $E(\alpha)$. This double minimization (first for the unknown reflectivities Rps and dRps, then α), turns out to be a simple algebraic problem that doesn't require iterative solvers.

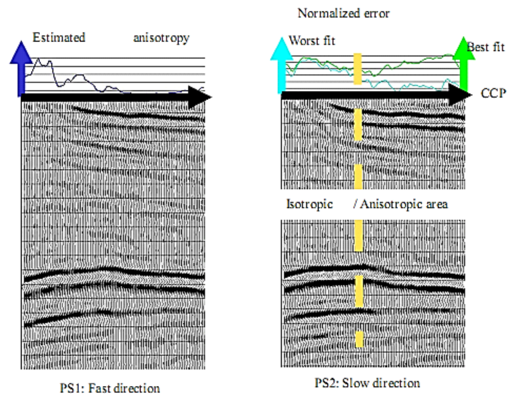

Fig4a: Example for transition between isotropic and anisotropic regime, also reflected in the QC curves.

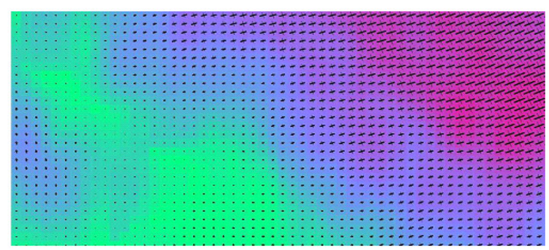

Fig4b: Map of the anisotropy directions, the bars showing the directions are scaled by the observability and the direction and the color reflects the time difference between fast and slow: green small and red large.

Besides, the actual value of minimum error gives a measurement of the fit between the observation and the model, and the range of $E(\alpha)$ is an indication of the observable anisotropy(fig4), that is considering the source-receiver azimuth distribution, the time difference between fast and slow w.r.t. the dominant frequency and also the noise level in the dataset.

Anisotropy compensation

In many cases, spectacular improvements can be achieved by assuming PS1 and PS2 only differ by a time shift. However, in the modeling equations there are no assumptions regarding their differences. Actually, a number of authors expect a differential attenuation between both images. We propose to compute a time and space variant match filter to first correct, and second extract some information such as a differential Q.

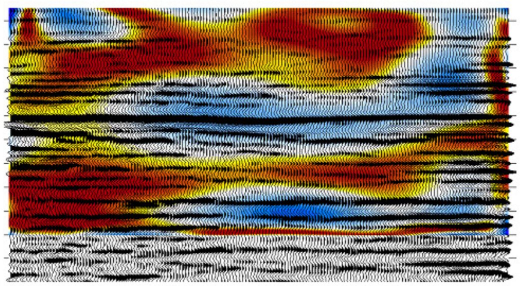

Fig5: matching operators slope:blue+4bB/oct brown-6bD/Oct

In the figure above, based on a land 3C acquisition, we have represented in color the average slope of the operators over the data bandwidth. It's interesting to note that this slope varies much more than expected, and also that there is no apparent correlation with the surface. Even though this picture doesn't translate into a known lithological features of the area, the slope of these operators that have greatly improve the PS2-PS1 match are organized into patterns that seems to be only related to the actual geology.

Conclusions

Shear wave datasets are of very different character than traditional P-Wave seismic. The birefringence in particular is a very predominant effect, usually associated with fracture directions, which cannot be ignored. However, with the proper set of specific tools, this effect can be properly handled and opens new insight on the geophysical properties of the subsurface.

References

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