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Birefringence analysis of 3C PS seismic data: Permian Basin - Case Study, NE Midland

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Summary

Increased exploration activity over the Permian Basin in West Texas has led to using more non-conventional means of acquisition such as incorporating horizontal sensors for multicomponent P-wave and C-wave (PS) imaging. Unique seismic properties from PS, such as Shear Wave Splitting (SWS) induced by azimuthal anisotropy, facilitate fracture characterization, leading to an improved understanding of the reservoir.

This paper applies the method presented by Boiero and Bagaini (2016, 2017) by utilizing their new approach to invert for interval values of SWS intensity (SI), as defined by Chevrot (2000), to obtain a model of anisotropic parameters varying with depth. SI is a robust measurement with respect to structural variations and facilitates estimating key anisotropic properties within a geological formation by analyzing the differences of SI measured at the top and bottom of a geological sequence. The method circumvents iterative layer stripping, which is an advantage for shallow layers where anisotropic parameters are difficult to estimate due to poor coverage, and consequently makes SWS analysis simpler to apply.

Results from two independent SWS birefringence studies of the 3-component (3C) PS data from a NE Midland, Texas, survey will be presented together with a discussion of ongoing work that was prompted in response to the attributes uncovered.

Survey

The 326-square mile NE Midland multiclient 3C-3D survey was acquired in late 2016 over the Permian Basin in NW Texas. Both the PP and PS seismic data were processed simultaneously. The PS processing included noise attenuation, signal processing and anisotropic pre-stack time migration as well as unique converted wave procedures such as vector fidelity, 3C detector orientation and rotation, PS receiver statics, PS to PP event registration and SWS analysis / compensation

Shear Wave Splitting (SWS) analysis

A convenient domain for detecting SWS and for analysis of the fast and slow directions or “principal axes” is after a rotation to radial and transverse directions. Radial refers to the direction aligned with the source-receiver azimuth and transverse is the direction perpendicular to radial. The radial and transverse data can be analyzed pre-stack or after partial stacking into azimuthal sectors. The analysis can also be applied after prestack migration, provided that azimuthal information is retained, for example by using a sectored or offset vector tile (OVT) based migration.

In the absence of any azimuthal anisotropy and assuming a layered medium, there will be no coherent signal present on the transverse component. Therefore, one preliminary indication that shear-wave splitting is present will be observable signal on the transverse component. It should be noted that signal can also arise on the transverse component for other reasons such as structure, so it is important to correlate the presence of events on the transverse to equivalent coincident reflectivity on the radial component. A distinctive feature of SWS is represented by signals on the transverse component that have, when analyzed as a function of azimuth, a period equal to π with polarity reversals every 90°, which is generally not the case with other causes of transverse signal. Past case studies identified unmistakable evidence of SWS and demonstrated almost *text-book* behavior of the azimuthal R/T responses (Johns, *et al*., 2006 and 2007), (Lewallen *et al*., 2011). Observing this kind of periodic signal on the transverse data is considered a first order indication of probable azimuthal anisotropy and the NE Midland PS dataset proved to be no exception Note, the existence of TTI and strong lateral heterogeneity would significantly alter the a π periodicity, so care should be exercised if analyzing complex geology.

SWS analysis can be viewed as a two-step process: first, estimate the orientation of principal or S_1 direction and second, estimate the time-delay between S_1 and S_2. The objective is to estimate the S_1 direction Φ, and time delay Δt for each common conversion point location in the survey at the current analysis interval. Because the earth may contain layers with different stress or fracture regimes leading to different S_1 directions, the recorded shear-waves may have been split multiple times, with both S_1 and S_2 from the deepest layer being split again into new S_1 and S_2 directions from the layer above and so on. These wave phenomena produce considerable complexity of waveform in which the directions for layers are masked by layers above for all but the shallowest layer. Thus, it's important to unravel the effect of the overburden to isolate the SWS characteristics at the target level. To account for the existence of several layers with different S_1 directions, most conventional methods deploy a layer stripping approach (Gaiser 1999, Bale et al. 2009). In each layer stripping step the estimated time delay is computed then applied to the data after rotation to S_1-S_2 coordinates, by first shifting the PS_2 (slow) data to match PS_1 (fast) and then rotating back to radial/transverse (R/T) with this result being referred to as radial prime and transverse prime (R'/T').

To study and analyze the SWS properties from birefringence for this 3C-3D NE Midland survey, both conventional and new independent approaches were examined. The conventional approach consisted of an Alford Rotation method, adapted to PS-waves for course layer stripping (Gaiser, 1997, 1999). Using the 1D theory of Alford (1986), the sub stacked azimuthal 2C data are rotated to 4C (or 2C x 2C) data groups that consist of R and T components from two orthogonal azimuth sectors. The data are corrected in a top-down layer-stripping manner (Winterstein and Meadows, 1991a, 1991b) by computing the principal S-wave directions and time delays in user- defined windows. This means that splitting parameters are estimated layer-by-layer from the top down. Unfortunately, errors in layer stripping occurring in shallow layers often propagate to deeper layers (Haacke, 2013) and can lead to misleading results due to an inadvertent overcompensation of the SWS time delays. Therefore, to mitigate the potential precision discrepancies from layer-stripping, the shear wave SI method was tested and compared to the Alford Rotation results. The SI method is a robust measurement with respect to structural variations and is commutative, which means that it can be summed along a ray and linearly related to interval anisotropic perturbations.

Analysis of the NE Midland PS was conducted on the R/T data after 5D regularization and azimuthal VTI pre-stack time migration. Discrete azimuthal sub-stacks every 30° were then created as input to both SWS analysis methods.

SWS Results (Alford Rotation)

After initiating the 2C x 2C Alford Rotation layer stripping approach it was soon apparent that the time delays in the shallow overburden were of the order of one sample value and not inducing significant anisotropy. It was evident that an overcompensation of the shallow layer(s) was highly probable and without a priori justification it was deemed prudent to limit the analysis to a thick single layer and resolve instead the cumulative effect through the target interval of 1.0-3.0 s PS two-way time. The single layer

SWS attributes averaged over a large time-gate were then applied to the pre-stack R/T data to generate the PS_1/PS_2 modes for subsequent migration and completion of the final PS seismic data volumes.

After identifying an anomalous region of significantly higher anisotropy it was decided to exploit the SI analysis and inversion method to determine the anisotropy interval values within discrete geological layers. There was also interest at this point to undertake a joint PP/PS AVOaz study as it was suggested that the information gleaned from this SI analysis could help to constrain the inversion.

SWS Results (Splitting Intensity)

The inversion revealed relatively isotropic behavior in the first two layers (1000 ms and 1400 ms) comprising the overburden followed by a significant onset of anisotropy at layer3 (1800 ms) corresponding to the Spraberry formation with time shifts of up to 8ms and a W-E principal polarization direction. The anomalous region equates to only 3% anisotropy, which is quite low, but underscores the sensitivity of shear waves, and the SI, to subtle changes in the rock matrix. The measured anisotropy is reduced to 2% at the deepest horizon, layer5 (Strawn), with evidence of an apparent spatial relocation of anisotropic behavior to the NW. The randomness of SWS attributes in the first layer(s) indicates a relatively isotropic overburden (Figure 1)

A benchmark is then made to the single layer Alford Rotation that effectively measured the cumulative effect of the SWS. By integrating the combined SI interval time shifts over layers 3-5 and averaging the dominant fast shear polarization direction, the similarity to the cumulative Alford Rotation result is clearly evident, notwithstanding some notable differences.

Conclusions

In deploying the SWS SI inversion approach, a detailed set of horizon-based interval attributes were derived that described the subtle anisotropic behaviour of the Spraberry formation in the Permian Basin from the NE Midland 3C survey area. The SI method evades accumulative errors from conventional multi-layer stripping techniques. The sum of the individual SI responses correlated closely to the independently derived single-layer Alford Rotation result and provided further confidence in attribute integrity.

The subtlety of the interval anisotropy inferred by the SI inversion raises the question as to whether such intricacies are potentially extractable from the P-wave data alone. It is a question that the ongoing PP / PS AVOaz study will attempt to address, thereby potentially highlighting the advantages of multicomponent data.

Additive Information

The recent results from a PP AVOaz study reveal a very close correlation to the PS SWS attributes (from SI). The corroboration to P-wave anisotropy implies that incorporating the PS into a simultaneous joint inversion, and even AVOaz, would assure the integrity - or at least improve confidence and robustness - of the derived rock properties, including TOC and density.

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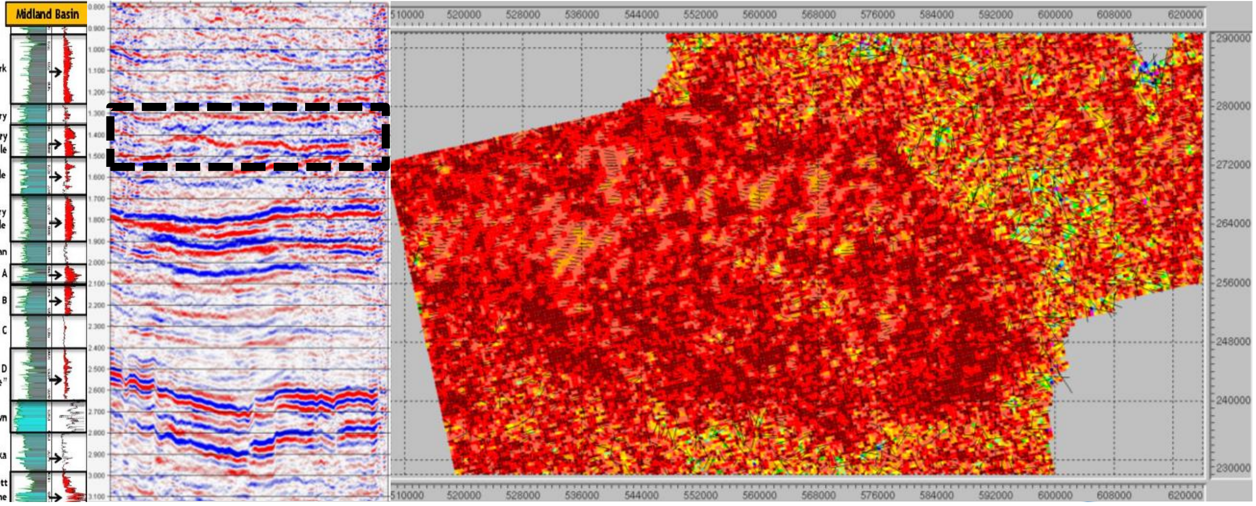
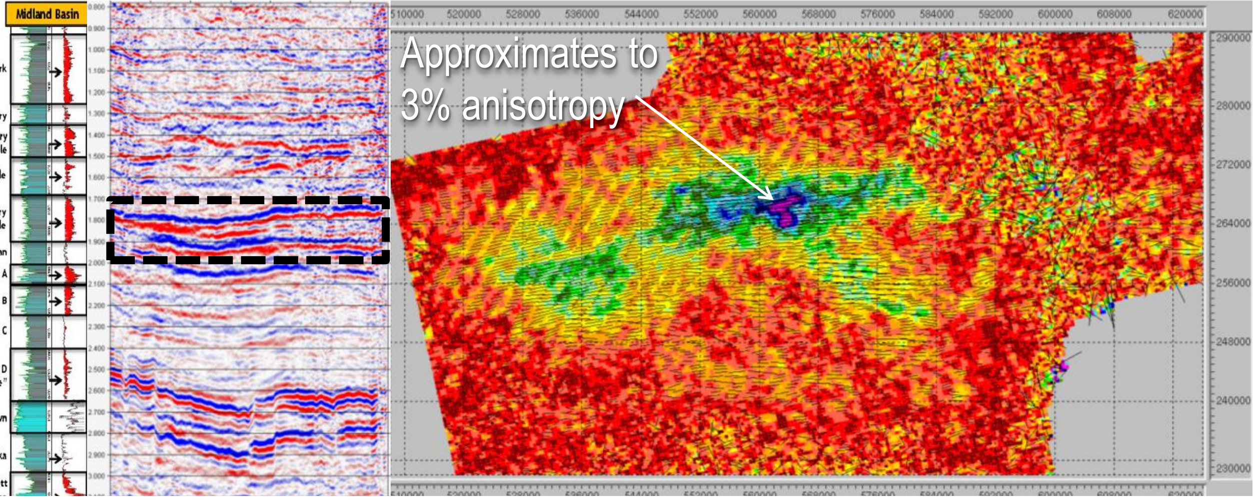
Color: δt_2 splitting time, Vectors: φ_2 S1 (fast) direction

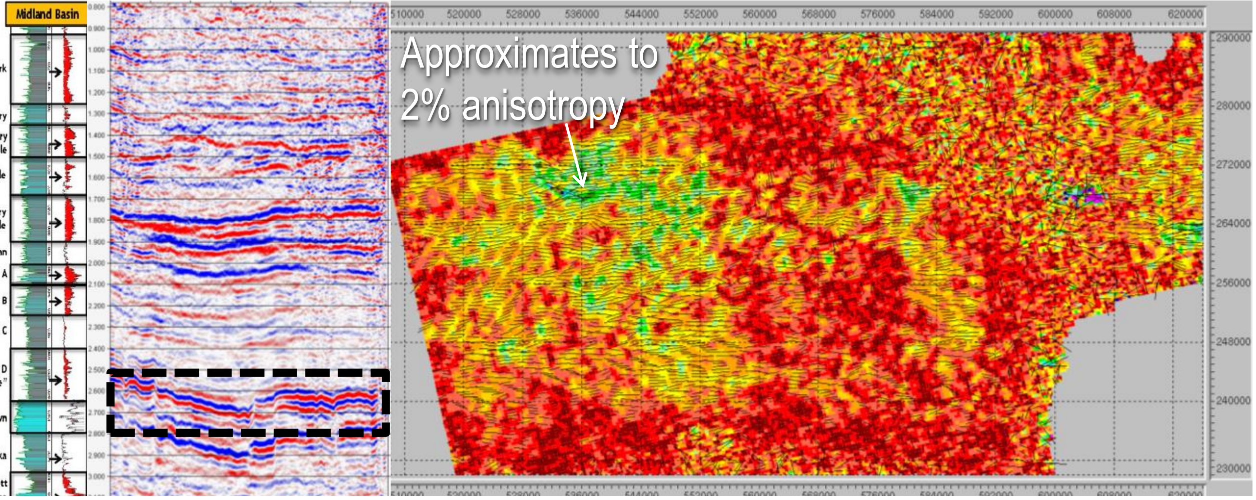


Color: δt_3 splitting time, Vectors: φ_3 S1 (fast) direction



Approximates to 3% anisotropy

Color: δt_5 splitting time, Vectors: φ_5 S1 (fast) direction



Approximates to 2% anisotropy

Figure 1: Spatial color attribute map of SI time shifts δt with overlay of S_1 (fast) direction φ vectors measured at layer2 in the overburden (top), layer3 (middle) at the Spraberry formation, and layer5 at the deeper Strawn formation (bottom), Time shifts range from 0ms (red) to 8ms (violet). The overburden is relatively isotropic down through layer2, and changes at the Spraberry with interval anisotropy approaching up to 3%. Below the Turbidites in the deeper Penn-Strawn formation at layer5 the anisotropy reduces to 2% and shifts to the NW of the survey. The fast shear wave orientation for both intervals is measured to be a 90° W-E direction.

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