Quality Control of Azimuthal Shear Wave Anisotropy Analysis

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SUMMARY

Azimuthal Shear Wave Anisotropy Analysis is based on angular energy contributions from on and off axis dipole tool components. Depending on tool geometry, the number of the receivers that participate in computations varies from 6 to 11. Since the fast shear azimuth is usually only weakly variant with depth, the cross correlation of the angular energy distributions from multiple stations can be computed. This allows one to estimate standard deviation and measure correlation of the angular energy distributions. Other quality measures are also available.

INTRODUCTION

Cross dipole borehole tool data consists of four wave form components. Two of them are recorded in on axis planes (frequently named XX and YY) while other two are recorded in off axis planes (e.g. XY and YX). Cross dipole wave forms are used to derive the fast shear azimuth direction as well as fast and slow flexural wave slownesses. Thus the question arises - how trustful are these results?

In the case of fast and slow flexural wave slownesses, classic quality control techniques like semblance peak value or the goodness and standard deviation (utilizing complex wave form analysis) may be applied. However, the quality control of fast shear azimuth computations remains questionable.

In this paper we present a shear wave anisotropy analysis procedure that delivers various quality control measures related to fast flexural wave azimuthal computations. The principle of this procedure is based on tracking flexural wave arrivals in time domain (in order to get accurate angular energy distributions). Since the introduction of the method we have processed more then 50 wells. The results are repeatable and robust.

METHOD AND RESULTS

The shear wave anisotropy analysis procedure consists of following steps:

Transmitter collocation

This step is required if the X and Y dipole transmitters are not physically collocated.

Flexural wave time domain tracking

Flexural wave arrival time is tracked at each receiver station independently. The travel time searching routine is repeated twice; first utilizing dipole XX wave form (on axis) data and then dipole YY (also on axis) data. At every depth, the faster of the two arrivals is selected thus yielding a vector of depth domain curves that define zero phase arrival time at each receiver level independently. Dipole XX and dipole YY zero phase arrival times will be the same under isotropic conditions since the transmitter data are already collocated. However, when the formation is anisotropic, they will differ by the strength of the anisotropy field (see Figure 1).

Angular energy distributions

Using the time domain tracking profiles (computed in previous step) we calculate angular energy distributions. These are calculated at each receiver level separately for on axis E_{xx} and off axis E_{xy} fields. A unique feature of the algorithm is that computations are guided in time domain and performed within a relatively narrow time band thus reducing the possibility that non-flexural mode waveforms (e.g. Stoneley mode) can contaminate the outcome.

If the formation is anisotropic, on axis angular energy distributions will contain two clearly defined maxima and minima separated by 180 degrees. The waveform rotation angle is tracked through one of the peaks of on axis energy; which one does not matter. The same rotation angle curve should track one of the minimums of the off axis energy. A key quality control indicator will be how well the wave form rotation angle correlates with the magnetically derived logging tool azimuth position curve. If the formation is isotropic, on/off axis energies will either not show peaks or their appearance will be fuzzy and the wave form rotation angle curve will not correlate well with the tool azimuth curve (see Figure 2).

In order to improve the signal to noise ratio, the angular energy distribution data are stacked together across the receiver array. This operation does not significantly degrade vertical resolution because shear wave anisotropy, if present, manifests itself along considerable depth intervals rather then within thin bed boundaries.

The wave form rotation curves (see Figure 2 track #3 and #4 painted in black) and logging tool angular positions (see Figure 2 tracks #3 and #4 printed in blue) are in excellent agreement. Since the wave form rotation curve and the tool angular positions are derived from two different physical measurements, the maximum shear wave stress directions presented on Figure 3 (track #1) must be robust. In other words, their agreement is not a coincidence. Shear wave maximum stress direction variations are small; less then 5 degrees on average (see Figure 3 track #1).

Angular energy coherence and standard deviation

The quality of the fast shear azimuth calculation can be estimated by looking at angular energy cross correlation and its standard deviation. Fast shear azimuth is usually weakly variant with the respect to formation depth in the borehole. Therefore, cross correlation of the angular energy distributions from multiple receiver stations can be computed. These allow us to calculate standard deviation and correlation of the angular energy distributions. Track #5 in Figure 3 shows cross correlation (ACXX - brown curve) and standard deviation (ASXX - blue curve). The standard deviation curve shows that fast shear azimuth computations are accurate – frequently better then 5 degrees. Also, the cross correlation curve (Figure 3 on track #5 - brown curve ACXX) shows that the energy distribution correlation across the receiver array is very high and only marginally lower then theoretical maximum.

CONCLUSION

The proposed shear wave anisotropy analysis quality control procedure consists of following steps:

- Comparison between the wave form azimuthal energy distribution curve and logging tool angular position. Good agreement will yield a robust fast shear wave stress direction.

- Computation of fast shear azimuth standard deviation curve based on the angular energy distribution data. Under anisotropic formation conditions and a good signal to noise ratio, the average standard deviation of the Fast shear Azimuth estimate ought to be less then few degrees.

- An additional quality control measure is correlation across the angular energy distribution wave forms.

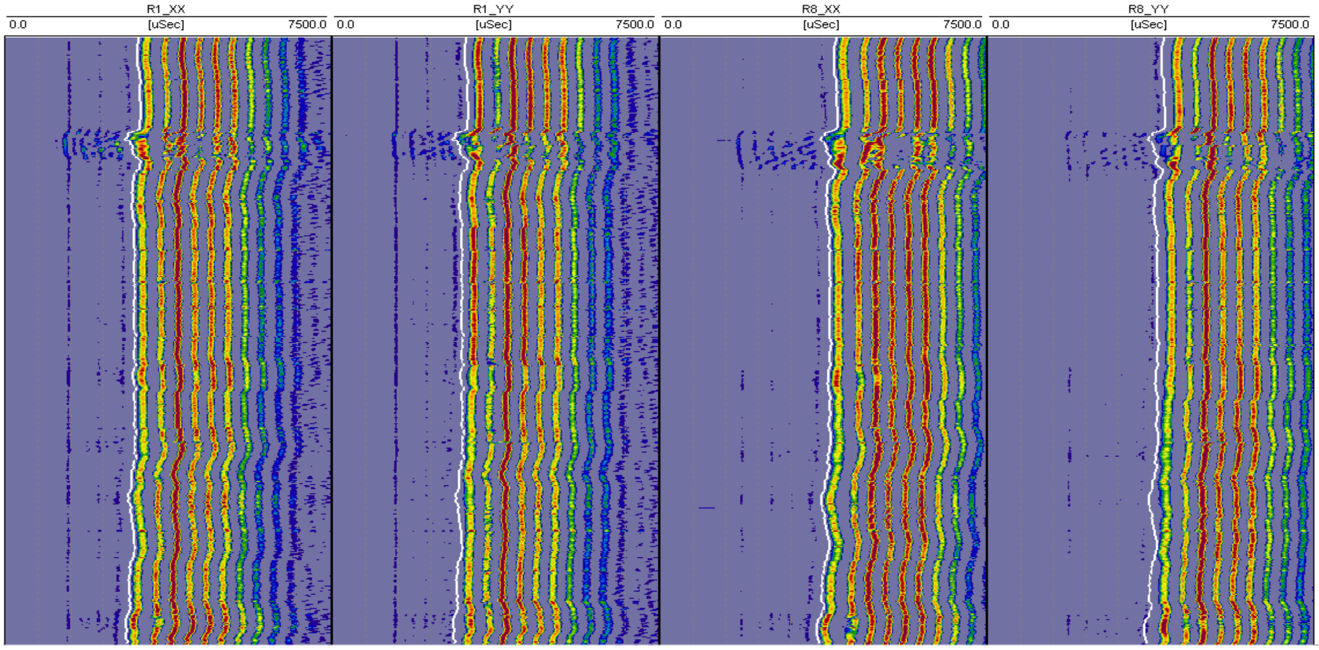

Figure 1. Near and far receiver wave forms recorded over an anisotropic interval shown together with imposed flexural wave arrival time. Track #1 and #3 show dipole XX (on axis) wave forms while tracks #2 and #4 show dipole YY (on axis) wave forms. Note the separation between travel time curves between dipole XX and dipole YY wave forms indicating possible shear wave anisotropy.

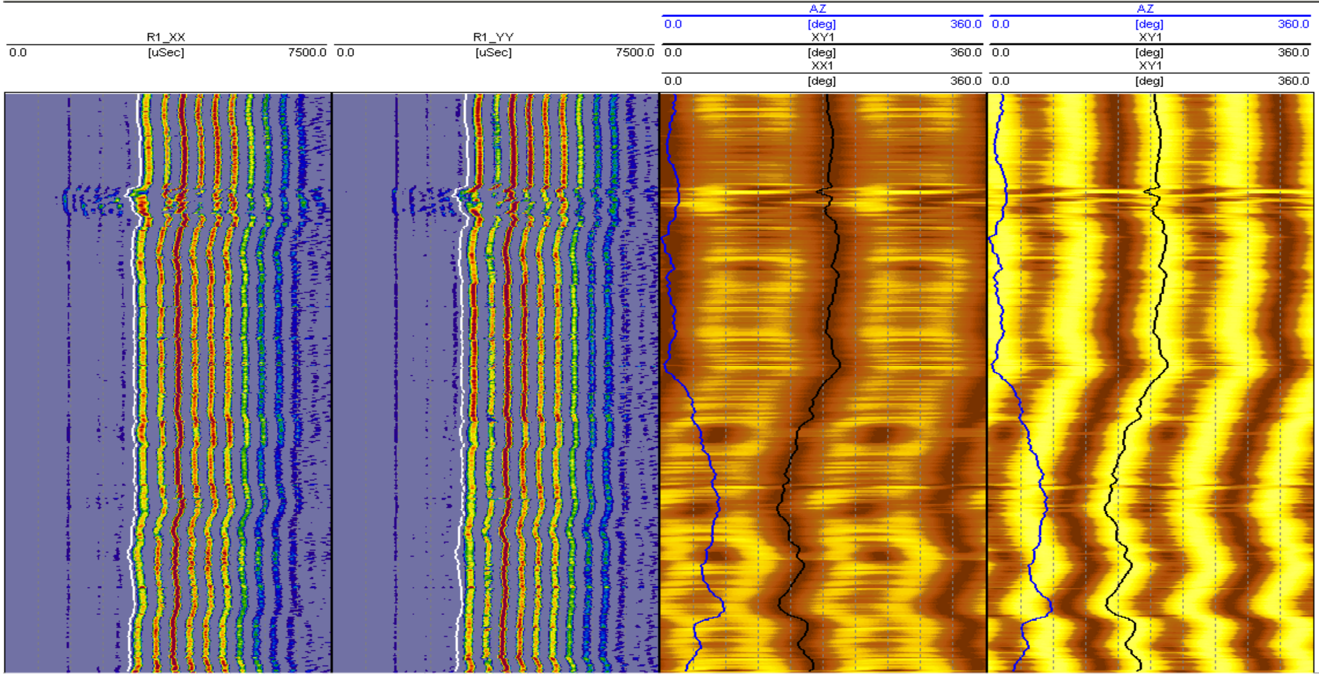

Figure 2. Near and far receiver wave forms recorded over an anisotropic interval shown together with imposed flexural wave arrival time. Track #3 shows dipole XX (on axis) angular energy distribution together with the rotation curve (black) and tool azimuth (blue). Track #4 shows dipole XY (off axis) angular energy distribution. Note excellent agreement (in a mirror image sense) between the rotation curve and tool angular position.

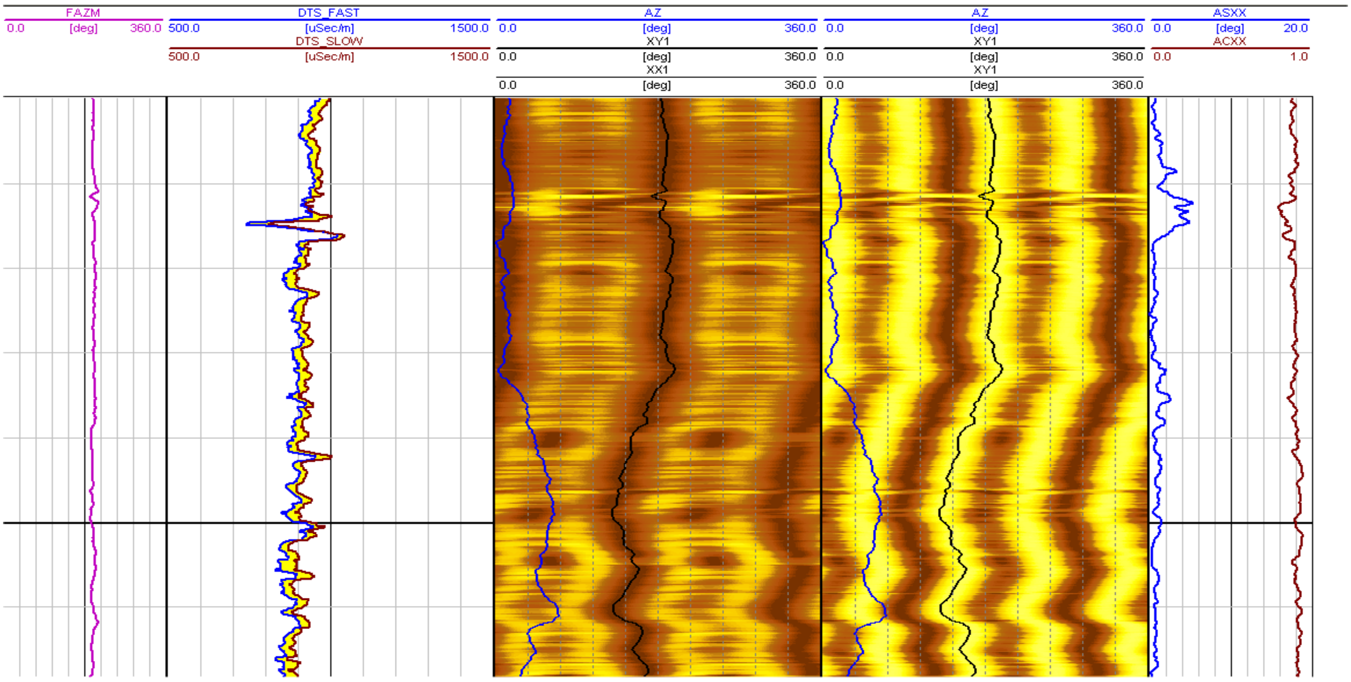

Figure 3. Track #1 shows fast shear azimuth. Track #2 shows flexural fast (blue) and slow (brown) slownesses. Track #5 (ASXX) presents standard deviation across XX energy files (blue), while ACXX shows correlation across angular energy distribution files (brown).