Response of the sonic dipole tool in low compacted rocks in vertical wells.

Carlos Francisco Beneduzi, PETROBRAS S/A Brazil

This paper was prepared for presentation at the 9th International Congress of the Brazilian Geophysical Society held in Salvador, Brazil, 11-14 September 2005.

Abstract

The correct acquisition of shear wave slowness through the flexural mode record with dipole source tool involves several requisites that are , barely, encountered in real conditions. This paper analyses 4 acquisitions in vertical wells drilled in 12 ¼" hole in slow/very slow formations where some of these requisites are violated and the flexural mode is shifted to low frequency borehole modes, where Stoneley mode energy is very high. The obtained shear slowness values are very close to Stoneley values and frequently the slowness Stoneley values are higher than shear values. The Slowness x Frequency plot indicates a coalescence of the modes causing difficulties in the individualization of flexural mode and increasing the uncertainty related to the values attributed to shear wave slowness. In order to minimize the acquisition uncertainty, the following procedures are suggested: acquire the Stoneley mode for QC, run the tool centralized in the hole, with transmitters and receivers properly calibrated and in the data processing, apply bandpass filters to improve the flexural mode response.

Introduction

The introduction of dipole sources in sonic digital tools was announced by service companies as the solution for the shear wave slowness acquisition in slow formations. The dipole source propagation characteristics, however, impose several conditions to obtain a right value for shear slowness, related to borehole shape and diameter, rock characteristics, tool position in the borehole. These characteristics are, barely, fulfilled in a real data acquisition.

The paper emphasizes low/very slow rock acquisitions, associated or not, with large borehole diameters that cause flexural mode to shift to low frequency borehole modes where Stoneley energy is very high.

Four sonic dipole tool records were analyzed in vertical wells, drilled with water base mud, varying from fast/intermediate in the bottom to slow/very slow rocks in the top of the interval,

Acquisition method

Dipole source generates an assimetric compressional wave that induces an oscillation in the horizontal plane of the borehole wall (flexural mode). (Fig. 1) The receivers are pressure sensors 180º apart in a horizontal plane, aligned with the dipole; they record opposite polarity pressure field. The pressure field magnitude of the mode is obtained by the difference between receiver values

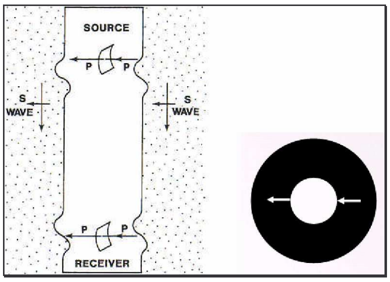

Fig. 1 – Dipole source schematic propagation (Zemanek et al.(1984) modified by Halliburton, (2003))

The mode is dispersive; it starts in the formation shear wave velocity in low frequencies, decreasing, in high frequencies, to the Schölte wave velocity (planar wave that travels in the solid/liquid velocity). (Fig. 2) The maximum energy is reached close to the Airy phase of the mode. In order to minimize the dispersion effects, the source operates in low frequencies (1-2 kHz)

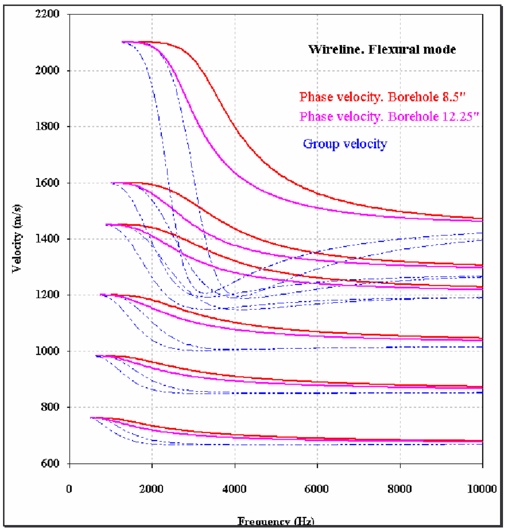

Fig. 2 – Phase and group velocities of flexural mode generated in formations of different shear velocities by 3 5/8" rigid tool centralized in a hole filled with water (Halliburton,2003)

The Stoneley wave, fundamental mode associated with a monopole source, propagates in the borehole as a simetric pressure mode that increases radially until the borehole wall, decreasing exponentially away from that. (Fig. 3)

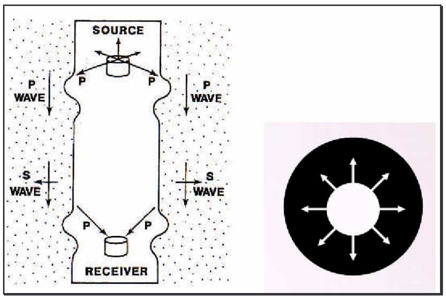

Fig. 3 – Monopole source schematic propagation. The Stoneley wave is the more energetic component generated by these mode. (Zemanek et al. (1984) modified by Halliburton, 2003)

At zero frequency,its group and phase velocities are equal to tube wave velocity and depends on tool physical properties, borehole fluid, formation density and shear wave velocity. The high frequency limit is the Schölte wave velocity. (Halliburton,2003)

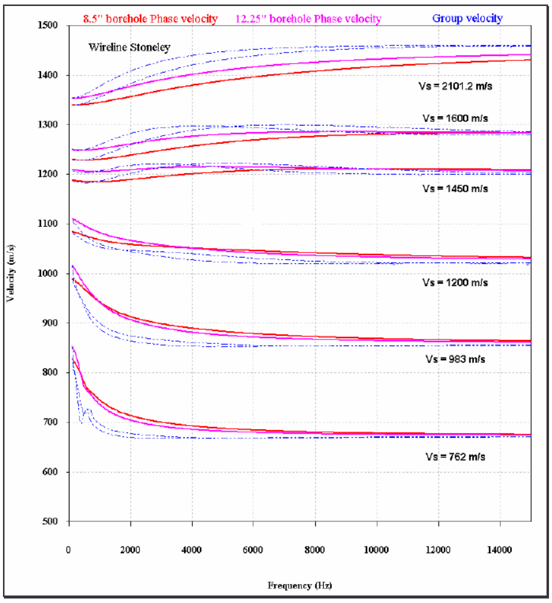

Fig. 4 – Stoneley phase and group velocities in different formation shear velocities generated by 3 5/8" rigid tool, centralized in a hole filled with water (Halliburton, 2003)

In the time domain, the Stoneley increases with low frequency sources, because their energy is concentrated in these frequencies.

In the whole extension of Stoneley frequency spectrum , its slowness is higher than flexural slowness. (Fig. 5) However, in very slow formations and low frequencies, the tube wave slowness can be lower than formation shear wave slowness, causing attenuation in its low frequency part (Halliburton, 2003).(Fig. 4)

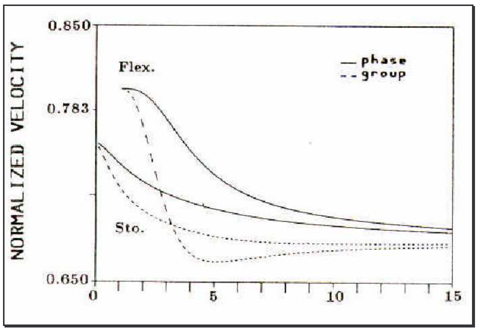

Fig. 5 – Comparison between Stoneley velocity generated by a monopole source and flexural velocity generated by dipole source in slow formation. Velocities are normalized with respect to water velocity (1500 m/s) (Halliburton, 2003).

Acquisition demands

The dipole source propagation characteristics and the technique used in the acquisition of the waveforms by the receivers requires the fulfillment of several conditions:

- Perfect dipole source;
- Calibrated receivers;
- Round hole;
- Centralized tool;
- Isotropic formation;
- Radial shear wave velocity variation absent. (Schlumberger,2005)

Rarely, these conditions are totally fulfilled in a real data acquisition. Many facts contribute to deteriorate the quality of dipole signal:

- Washouts that shifts the flexural mode to the low frequencies. Hole irregularities can generate Stoneley. (Schlumberger, 2005)
- Uncalibrated receivers that allow unwanted modes to be registered, even when the tool is centralized.
- Tool eccentricity that provokes modes excitation related with other sources: monopole, quadrupole,... A centralized tool maximizes the flexural wave detection and removes the unwanted Stoneley components. (Fig. 6) Eccentricity brakes the field pressure symmetry required for a correct flexural acquisition; part of the Stoneley energy is leaked into flexural mode and the tool reading incorporates the Stoneley leakage into flexural (Schlumberger,2005). This leakage becomes important in low frequencies where the Stoneley energy is higher than the flexural (large boreholes drilled in slow formations potenciate these leakage). When eccentricity is an appreciable fraction of borehole radius, slowness values can change, up to 5% (Leslie et al.,1990)

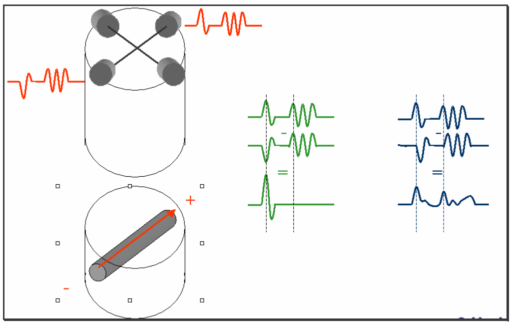

Fig. 6 – Tool eccentricity causes time shift of the waveforms, weakening the flexural signal and not completely removing the monopole signal. (Schlumberger,2005).

- Formation anisotropy splits the shear wave in two perpendicular components with different velocities. The influence over the record is a function of the angle between the tool axis and the TIV and TIH anisotropy.

- Borehole ellipticity produces an effect similar to anisotropy, causing the shear wave to split in two branches aligned according the borehole axis.

Examples

Dipole (1-2 kHz) and Stoneley modes (0.5-2.0 kHz), acquired with wireline sonic tools, were analyzed in 4 vertical 12 ¼" boreholes, drilled with water base mud in siliciclastic rocks, varying from fast/intermediate in the bottom to slow/very slow in the top of the interval. The geologic knowledge of the area let us conclude that TIV and TIH anisotropy effects should be negligible , due to the low dip of the layers and the almost absence of vertical/subvertical fractures.

Two distinct responses can be observed in the analyzed data of dipole and low frequency monopole:

- Intervals where compressional slowness is lower than 110 us/ft (fast/intermediate rocks) present shear slowness distinctively lower than Stoneley slowness

- Intervals where compressional slowness is higher than 110 us/ft (slow/very slow rocks), present shear slowness values very close and even higher than Stoneley values.

In the interval represented by intermediate rocks observe the flexural and Stoneley signals shows high coherence, high amplitude energy in the frequency spectrum (dipole signal appears above 2,0 kHz) ; the Slowness x Frequency plot exhibits both events clearly distincts. (Fig. 8)

The targetof the paper, however, are the slow/very slow rocks where Stoneley and shear slowness values are very close. Slowness x Frequency plots indicate mode signals superimposed, particularly in the frequency range from 1 to 2 kHz, where the major part of non-dispersive flexural signal is located; the frequency spectrum exhibit strong signal attenuation, particularly for the dipole mode. (Fig. 9) This dipole energy attenuation is maintained even when the borehole diameter is regular. (Fig. 10) Frequencies are shifted to values below 2 kHz, and the plot Slowness x Frequency shows the mode events coalescence in the 1-2 kHz frequency range. The similitude of effects in both situations suggests that more than borehole conditions, the measurement is affected by the rock characteristics (sensitivity to the shear modulus?).

These situation greatly difficult the flexural mode individualization, attributing uncertainty to the measurement. Shear slowness values obtained in such conditions are , in a certain degree, affected by Stoneley mode. The question is, in what extension, this influence is exerted and if it is significant to the measurement.

Theory supports that Stoneley slowness lower than shear slowness has the occurence restricted to very slow formations and very low frequencies (below 400 Hz) (Halliburton, 2003). The data analysis of these wells reveals that the cases are more frequent than theory supports. Figure 11 exhibits a 50m interval with this characteristics. Despite high coherencies, the dipole mode appears strongly attenuated with the frequencies concentrated below 2 kHz; mode coalescence is maintained as in the previous examples.

Intervals severely affected by borehole wall irregularities cause the low frequence content of Stoneley mode desappearance and shifts the flexural mode to the low frequencies (Fig. 7). The shear slowness increases significantly producing dubious values of Poisson Ratio. (Fig. 10)

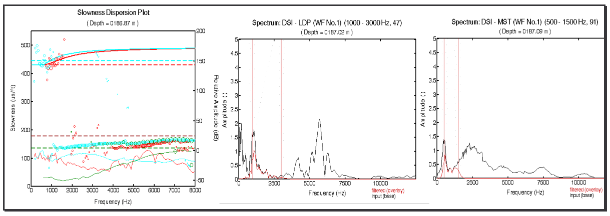

Fig. 7 – Borehole severely affected by diameter irregularities lead to mode convergence the frequencies around 1,0 kHz.

Conclusions

1. Shear wave acquisition in slow/very slow rocks in large diameter boreholes still produces uncertainties in its measurements. Obtained in such conditions, shear wave slowness, is in a certain degree, affected by Stoneley mode. The question is, in what extension this influence is exerted and if it is significant to the measurement.

2. The analysis of four vertical wells indicates that :

- In rocks varying from slow to very slow, Stoneley and shear slowness values are very close.

- In some studied cases, Stoneley and flexural mode coalesce, in others, converge, for the close/equal slowness values in the frequency of the measurement (1-2 kHz).

- Stoneley slowness values lower than shear slowness values, occurs more frequently than foreseen by the theory and in different conditions.

3. We suggest:

- Stoneley mode record for QC, when dipole mode is acquired in slow/very slow rocks in 12 ¼" boreholes or greater,
- Try to minimize the measurement uncertainties with acquisition procedures such us tool centralization and transmitters/receivers properly calibrated.
- When processing the data, adequate the bandpass filters design to the rock characteristics of that particular acquisition, in order to reduce the Stoneley mode effects over the flexural.

References

Halliburton – Down Hole Physics Technical Excellence Group, Houston Technology Center, 2003, Analysis of Wireline and LWD Acoustic Data Well 1-ESS-71, Petrobras, 140 p.

Leslie,H.D., Randall,C.,J., 1990, Eccentric dipole sources in fluid-filled boreholes:Numerical and experimental results, J. Acous. Soc. Am.,Vol.87, nº 6, p. 2405-2421

Schlumberger, 2005, Review of Sonic Measurements in Highly Deviated or Horizontal Wells, (Published internally to Petrobras technicians), 13 p.

Aknowledgments

I'd like to thank PETROBRAS for permission to publish this paper. I'm also in debt to Steven Low (Schlumberger) , André Santos da Silva (Halliburton) for permission to use the text references related with these services companies and Paulo Sérgio Denicol for text revision and discussions.

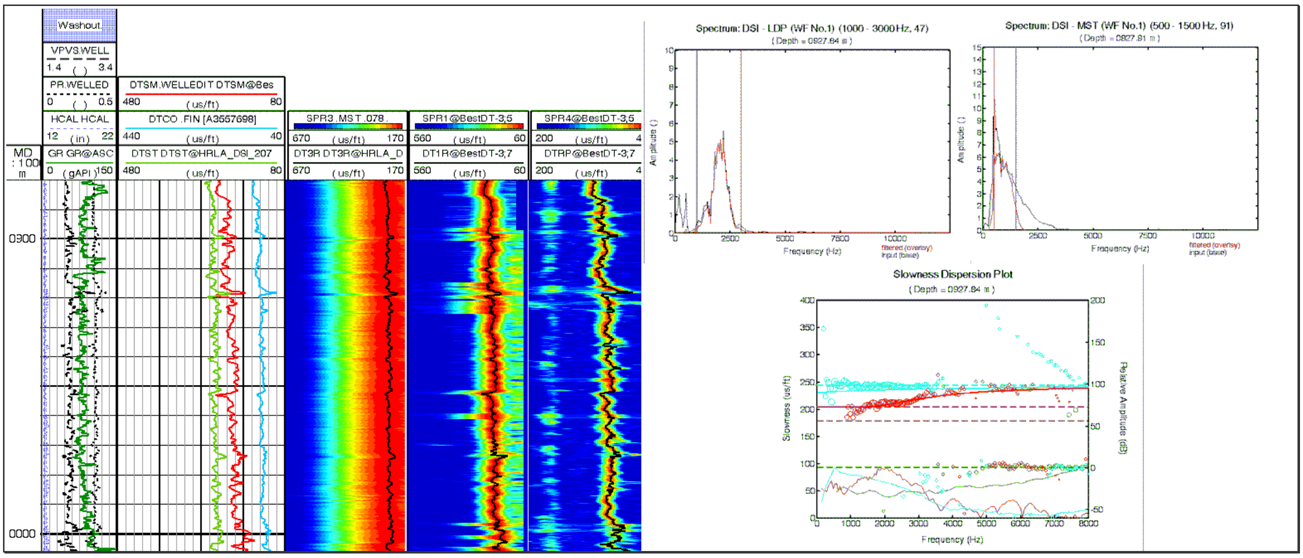

Fig 8 –Well A interval close to the bottom hole in intermediate rocks (compressional slowness (blue), shear (red), Stoneley (green) in track 2)) shows high coherence values for all event. Frequency spectrum for dipole mode and low frequency monopole (upper right) shows high amplitudes for both modes; in the Slowness x Frequency plot (lower right) the events appear distincts and well characterized .

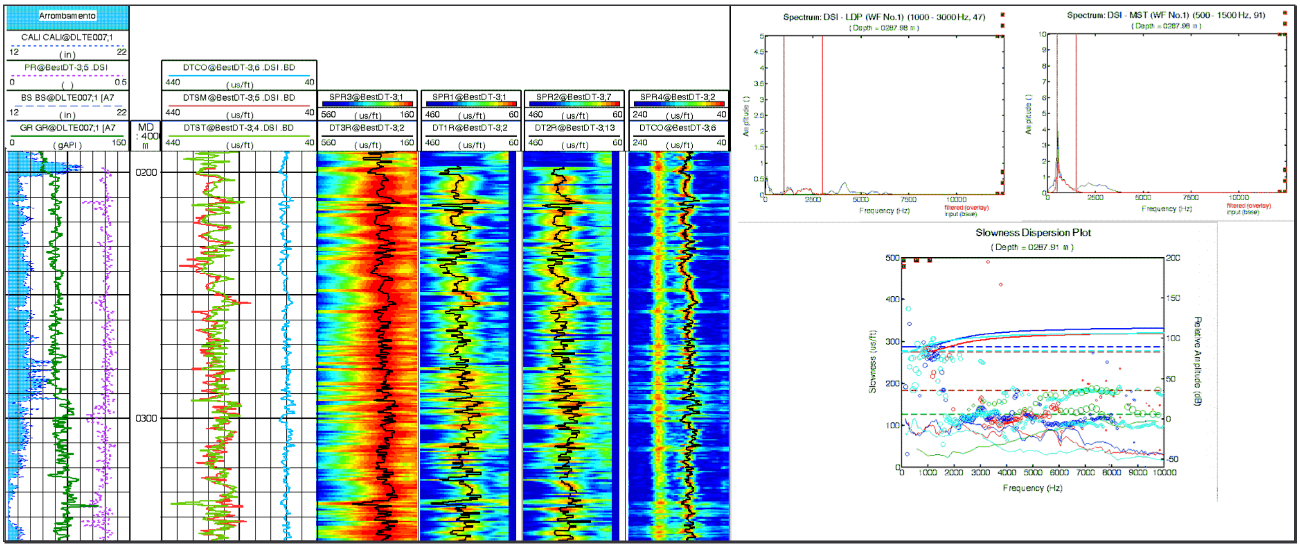

Fig. 9 – Well B slow rocks, affected by irregular borehole diameter showing Stoneley and flexural slowness with close values. Frequency spectrum exhibits signal attenuation, particularly in dipole mode, probably due to borehole conditions. Slowness and frequency converge to an unique point in the Slowness x Frequency plot, creating difficulties to events identification.

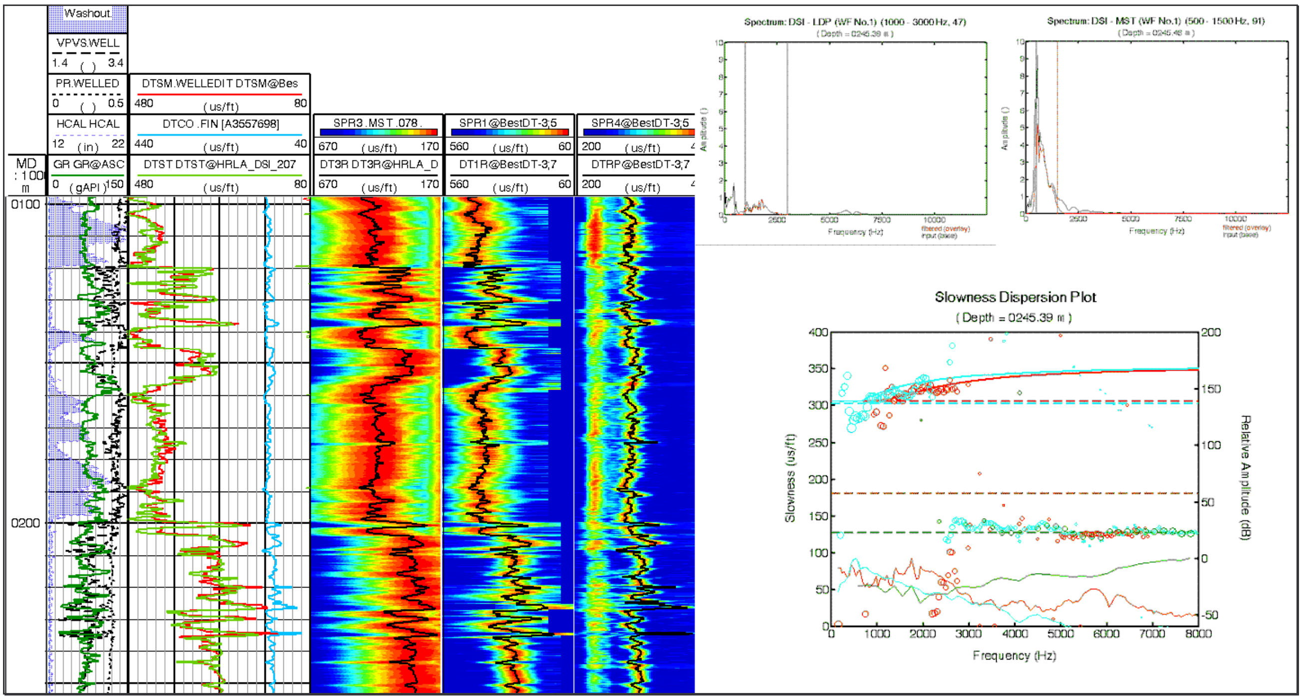

Fig. 10 Well A slow formations alternating washouts with regular borehole diameter (blue shaded área in track 1). At 0245m (regular borehole diameter with Stoneley and flexural slowness values superimposed) the frequency spectrum shows strong flexural mode attenuation and Slowness x Frequency plot exhibits mode coalescence in the frequency range from 1 to 2 kHz what difficults flexural mode event individualization.

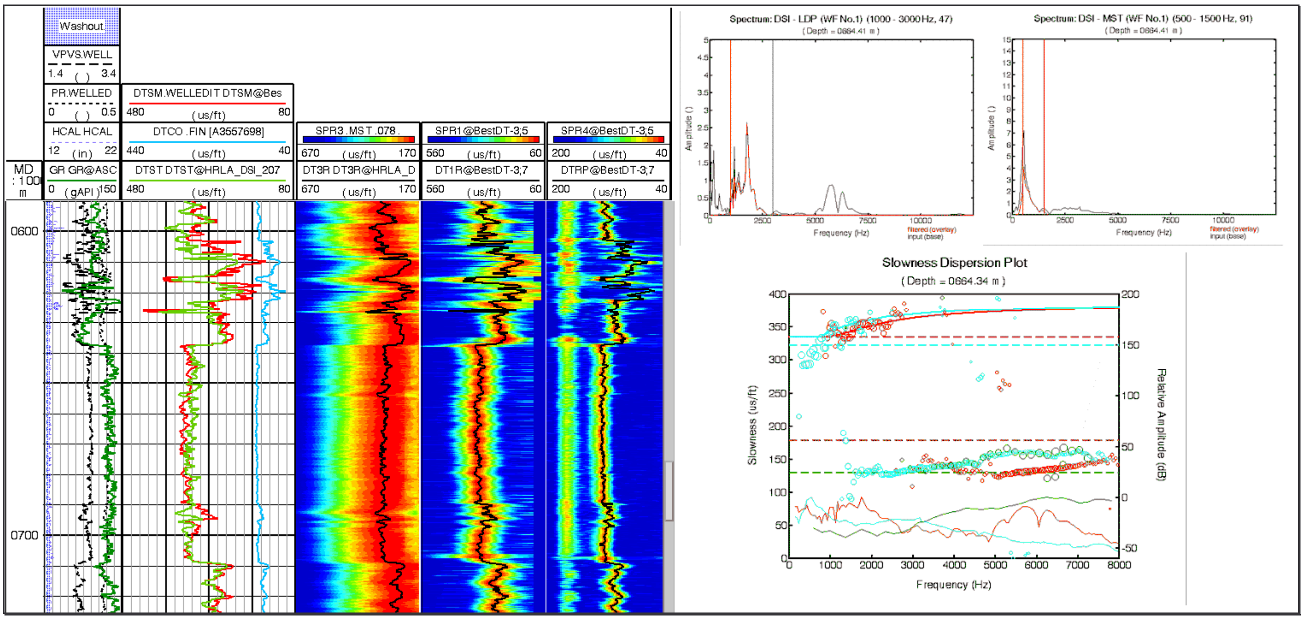

Fig. 11 – Well A slow/very slow rocks in borehole regular diameter showing Stoneley slowness lower than shear slowness in the intv. 0640/0690 m. A point in the interval shows the same characteristics of previous example: frequency spectrum with flexural attenuated, shift to low frequency borehole modes and modes coalescence in the Slowness x Frequency plot.