IDENTIFICATION OF MIXED ACOUSTIC MODES IN THE DIPOLE FULL WAVEFORM DATA USING INSTANTANEOUS FREQUENCY-SLOWNESS METHOD

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ABSTRACT

Dipole full waveform acoustic tools are used to estimate shear wave velocities, especially in soft and poorly consolidated formations. Under ideal conditions dipole source employed by those tools excites only borehole flexural wave that is propagating along fluid-solid interface This frequency dispersed flexural wave is used to estimate the velocity of the formation shear wave. In very soft formations, the dipole source may also excite a phase reversed compressional mode, sometimes referred to as a slow compressional wave (primarily due to its dispersed character).

The above scenario is frequently complicated by the presence of other acoustic modes: e.g. Stoneley waves, tool mode flexural waves, and multiple flexural modes due to shear wave anisotropy. Stoneley waves are generated either due to the tool decentralization, borehole ovality, or due to the dipole source malfunction. Tool mode flexural waves are observed when acoustic isolator underperforms and frequently in highly deviated holes. The Stoneley wave is particularly difficult to identify and suppress during data processing. Like the flexural wave, it propagates along the fluid-solid interface, albeit with the velocity that is affected by formation shear wave slowness and borehole parameters. Very often both waves overlay each other in time and frequency domain (especially at near receiver levels) thus making it difficult to compute flexural wave slowness using conventional processing methods.

Instantaneous Frequency-Slowness Method, derived from complex waveform analysis, is particularly well suited for processing contaminated dipole data sets. The absence of mixed acoustic modes in a dipole excitation creates unique signatures of instantaneous frequency and slowness curves that are characterized by non-linear increases of frequency and slowness as a function of travel time due to dispersive effects. On the other hand, the presence of multiple modes within a processing window modifies the instantaneous frequency and slowness curves in such a way that the presence of competing modes can be detected and under certain conditions identified. Therefore, by analyzing instantaneous frequency and slowness signatures, it is possible to avoid many processing errors resulting from the improper identification of acoustic modes, thus avoiding a mistake frequently made when processing these datasets with other methods.

The Instantaneous Frequency-Slowness Method is presented and discussed. Corresponding examples of field data further validates proposed processing methodology.

INTRODUCTION

Currently, all of the major wireline and logging-while-drilling acoustic tools record full wave forms data. The most commonly utilized processing technique is the semblance method. This method assumes that peak coherence points detected in the time/slowness plane correspond to the true formation arrivals. The core of the algorithm is simple: for a large set of arrival times and slownesses, the semblance value is computed by means of coherence across the receiver array. Calculations are performed within the range of a certain time window, beginning from the assumed arrival time. Thus, the semblance algorithm calculates an amplitude and phase weighted group velocity rather than the transit time based phase velocity. This method behaves well in homogenous strata, delivering formation slowness averaged across the receiver array span. However, the smoothing process that is desirable in noisy environments also degrades vertical resolution, which is problematic when thin-bedded geology is present. Furthermore, there are numerous circumstances when averaging across an array yields false readings. Consider wire line dipole tool data affected by the presence of mixed acoustic modes. It is quite common that either due to an unbalanced dipole source or tool decentralization, the recorded arrivals will consist of (in time domain) the desired flexural wave followed by unwanted Stoneley mode. Under such circumstances the results obtained with semblance method might be biased.

We introduce here the Instantaneous Frequency-Slowness algorithm allowing detection of the mixed acoustic modes when processing any full wave form data recorded either with a wire line or a logging-while-drilling acoustic tool.

INSTANTANEOUS FREQUENCY-SLOWNESS PROCESSING METHOD

The Instantaneous Frequency-Slowness processing is based on the concept of the real time domain waveforms that are converted to the complex form using Hilbert transformation (sometimes referred to as a complex signal analysis; Tanner, 1979). The slowness of the acoustic mode of interest (compressional, shear) is computed by finding constant phase trajectories.

In the initial step, time domain wave forms are converted to the complex form by utilizing modified Hilbert transformation. As the result, the data measured at each receiver level are converted to its time domain real and imaginary components. The real part, in the conjunction with the imaginary part, represents the magnitude and the phase of each time domain sample of the input data.

In the next step, the complex wave form of each receiver level is used to compute its time domain phase arrivals $\Phi_n(t)$, utilizing equation (1).

$$\Phi_n(t) = \tan^{-1} \frac{\mathrm{Im}[H(x_n(t))]}{\mathrm{Re}[H(x_n(t))]} \qquad (1)$$

Where: $x_n(t)$ is the input time domain data recorded at *n-th* receiver level and the *H(...)* function is its modified Hilbert transform. The functions of class (1) vary none linearly within the range of $(-\pi, +\pi)$, and with a periodicity equal to that of the input signal.

Next, the instantaneous frequency curve across each of the receiver pair is calculated by means of an average value of time domain differentiated constant phase trajectory, using the equation (2).

$$F_{i,j}(t) = \frac{\left[\Phi^{-1}{}_j(t)' + \Phi^{-1}{}_i(t)'\right]}{2} \qquad (2)$$

Where the symbol $\Phi^{-1}{}_i(t)'$ denotes time derivative of an inverse solution to equation (1) obtained at the receiver level *i*.

Also, the instantaneous slowness curve across each of the receiver pairs is calculated, utilizing equation (3).

$$S_{i,j}(t) = \left[\frac{\Phi^{-1}{}_j(t) - \Phi^{-1}{}_i(t)}{z}\right] \qquad (3)$$

Where *z* is the spatial interval between receivers *i* and *j* $(j>i)$.

Finally, a single slowness value across each receiver pair is computed by integrating (averaging) equation (3) over the desired travel time interval as follows:

$$\Delta T_{i,j} = \frac{\sum S_{i,j}(t)}{t_{\max} - t_{\min}} \qquad (4)$$

Where the summation is performed over the time interval limited by the t_{min} and t_{max} values.

IFS - DATA QUALITY INDICATORS

The instantaneous frequency and slowness curves are computed (across each receiver pair) for any time sample located within an applied processing time window width. Thus, if, for example, the array consists of eight receiver levels, the IFS method will deliver seven instantaneous frequency logs and, similarly, seven slowness logs. Each log is represented by a vector of time domain samples that are nullified outside of the time interval that was used during the processing session. The time samples that are located inside the applied processing window represent instantaneous frequency and slowness values. Since the borehole flexural wave is dispersed, its IFS curves should reflect this by showing a specific signature (or shape) that depends on travel time and the acoustic mode(s) present within the processing time window. Thus, by analyzing the position, duration, and curvature of the IFS signatures, it is possible to qualify the purity of processed data as follows:

- In the absence of competing modes, while recording the borehole flexural wave from a dipole source, functions of class (2) and (3) should show a simultaneous and non-linear increase of frequency and slowness values across the width of the processing time window. In such a case, equations (2) and (3) can be utilized to estimate the magnitude of the frequency dispersion effects.

- While logging soft formations in the presence of moderate interference with Stoneley mode, the instantaneous frequency curve will show a local maximum or minimum that is located (in time domain) at the interval where the interference between the flexural wave and the Stoneley mode is either constructive (the maximum frequency) or destructive (the minimum frequency). Similarly, the instantaneous slowness curve will also display a maximum or minimum (although weaker) located, approximately, at the same time points as the frequency curve does.

- In the presence of azimuthally distributed shear wave anisotropy, while recording the cross–dipole data, instantaneous frequency and slowness curves will display signatures with multiple local peaks depending on logging tool orientation with the respect to the direction of the fast shear azimuth.

- While logging soft formations if the Stoneley mode is interpreted as the flexural wave (by mistake; for example, due to dipole source failure, logging tool decentralization or severe washouts, improperly applied filters or any combination of the above factors), the instantaneous frequency curve will show a decrease in frequency values across the entire processing time window. This signature unequivocally identifies that the Stoneley mode is being utilized to estimate formation shear slowness rather then the borehole flexural wave.

- In the absence of interfering acoustic modes, while recording the compressional head wave with a monopole source, the instantaneous frequency and slowness curves should remain quasi constant across the entire processing time window width.

EXAMPLES

Figure 1 shows an example with a section of raw cross-dipole waveforms recorded with in line modes only; track #1 – XX and track #3 - YY data respectively. The waves are presented in a variable density log format beginning from 1 mSec up to 6 mSec after the start of the data acquisition. Tracks #2 and #4 show the instantaneous frequency logs computed across the receiver pair #12 with the X and Y sources respectively. Throughout the examples of this document, the instantaneous frequency data will be presented in the form of a black and white variable density log. Low frequency data samples will be mapped into light gray colors while higher frequency data points will be mapped into darker shades of gray color. The mapping legend is printed in the header area of the tracks that are carrying the results obtained with the IFS analysis. In order to enhance image clarity, near receiver wave forms and IFS logs are the only quantities being presented.

Moderate Stoneley mode contamination. A type of a data set that is very commonly encountered while processing dipole waveforms recorded while logging soft formations is shown in **Figure 1**. Track #1 (raw data) and track #2 (instantaneous frequency) present the results obtained with dipole X excitation, while tracks #3 and #4 show the same quantities computed with dipole Y excitation. At the depth labeled “A” the wave forms are of high quality – their time domain signatures presented in the **Figure 2** appear to be very clean without any indication of multiple acoustic modes. However, the results obtained with the IFS method reveal that this apparently high quality data set is affected by a moderate mixed mode phenomenon. **Figure 3** shows the instantaneous frequency signatures. Dipole X calculated curves are printed on left hand side of the image while dipole Y data are on the right side. The horizontal axis represents lapsing time. Instantaneous frequency is plotted in a range from 0.5 kHz to 3.5 kHz (indicated on the vertical axis). Similarly, **Figure 4** presents instantaneous slowness curves plotted from 80 uSec/ft to 380 uSec/ft. The IFS response shows that, as long as the processing window width is relatively narrow (less then 400 uSec in the case being discussed), the computed instantaneous slowness curves will be related mostly to the borehole flexural wave, which is desired. On the other hand, if the processing window width is expanded too much, the Stoneley wave will contribute to the final slowness value. Thus, the processing might either over- or under-estimate formation slowness depending on the selected processing parameters. Therefore the frequency filters (if any) and, even more important, the position and the duration of the processing window need to be properly set up. Other wise any applied processing method will generate erroneous results. Without an instantaneous frequency display, the slowness readings bias would be unnoticed.

Shear wave azimuthal anisotropy. An example in the presence of azimuthally distributed shear wave anisotropy is shown in the **Figure 5**. At the depth labeled “C”, the wave forms are of high quality. Their time domain signatures are presented in the **Figure 6.** The distinctive feature about this interval is that dipole Y plane closely matches that of fast shear azimuth. Consequently, the dipole X plane which is orthogonal to the Y plane points closely toward the slow shear direction. Obviously, due to tool spinning, other depth intervals will display different arrangements. The instantaneous frequency curves computed along the Y plane (see the right hand side of **Figure 7**) show a strong frequency notch down to approximately 1.2

kHz. Since the presented results were obtained before the wave forms were rotated, at a certain time point, the tail of the fast flexural wave will be masked by a lower frequency arriving head of the slow flexural mode, as seen along the Y plane. Lower frequency components are first in the wave train due to its dispersive nature. At the same time, since the X source is almost lined up with the slow direction, the instantaneous frequency signature (see the left hand side of the **Figure 7**) shows a "classic" dispersed character with gradual lift off. Finally, there is strong frequency peak observed at later arrivals that is due to constructive interference between the decaying tail of the slow flexural wave and the front of arriving Stoneley wave. The instantaneous slowness logs (see the **Figure 8**) are showing a modest amount of "waviness", primarily due to residual mixing between the fast and slow flexural waves and a later arriving Stoneley mode.

Severe Stoneley mode contamination. A case with a cross dipole data recorded through a washed out zone is presented in the **Figures 9, 10**, and **11**. The depth of interest is labeled "B" (see **Figure 1**). The instantaneous frequency curves are affected by a strong negative gradient that dominates even early arrivals. This indicates that the entire processing window is contaminated by Stoneley wave. In order to suppress it, higher frequency filters and/or earlier arrivals should be utilized.

CONCLUSION

Instantaneous Frequency-Slowness (IFS) method, a modified complex wave form analysis technique for processing acoustic waveform data, has been introduced and described. The technique works very well with both wire line and logging while drilling full waveform data, including monopole, dipole and quadrupole excitations. The IFS method generates a multitude of instantaneous frequency and slowness wave forms that are computed across adjacent receiver levels. Thus, by analyzing the obtained signatures, it is possible to qualify the purity of processed data. In the case of mixed mode contaminations, different processing parameters such as the frequency filters and/or the position and duration of the processing time window might be suggested.

REFERENCES

Tanner, M. T., Koehler, F., Sheriff, R.E., 1979, "Complex trace analysis", Geophysics, v. 44, p. 1041-1063.

Kurkjian, A.L., Chang, S.K., 1986, "Acoustic multipole sources in fluid-filled boreholes", Geophysics, v. 51, p. 148-163.

Kozak, M., Boonen, P., Seifert D., 2001, "Phase velocity processing for acoustic logging-while-drilling full wave form data", SPWLA proceedings.

ABOUT THE AUTHORS

Marek Kozak is a cofounder of SuperSonic Geophysical LLC located in Newark, California. He holds a Ph.D. in EE/ Measurement Systems from the Warsaw University of Technology in Poland. He has been instrumental in the development of pulsed power wire line induction and acoustic logging tools, and data processing software. Prior to arriving to USA in 1990 he was with the Warsaw University of Technology, conducting research in theoretical and applied magnetics sponsored by Polish Academy of Sciences, teaching classes in measurement of non-electrical quantities, and working as the industry consultant in DSP systems. He is a member of IEEE, SEG and Planetary Society.

Mirka Kozak holds Master's Degree in Computer Science from the Warsaw University of Technology in Poland. Prior to arriving to USA she was working at the Institute of Computer Sc. in Warsaw, Poland, as a researcher in the wide area networking systems. In 1992 she joined Magnetic Pulse Inc. and in 2004 SSG, as a Software Development Engineer instrumental in the development of induction and acoustic data processing software. She is a member of IEEE.

Jefferson Williams is a co-founder of SuperSonic Geophysical LLC. He possesses Bachelor's degrees in Geology and Mechanical Engineering as well as Master's Degrees in Electrical and Civil Engineering. He started his career as a seismologist for Geophysical Services Inc. and later became a Field Engineer for Gearhart Industries. Eventually, he joined MPI where he was a Field and Maintenance Engineer as well as a Log Analyst specializing in acoustic logs. After consulting in acoustic logs for a number of years, he co-founded SuperSonic Geophysical in 2001. He is a member of SPWLA and the Coast Geological Society.

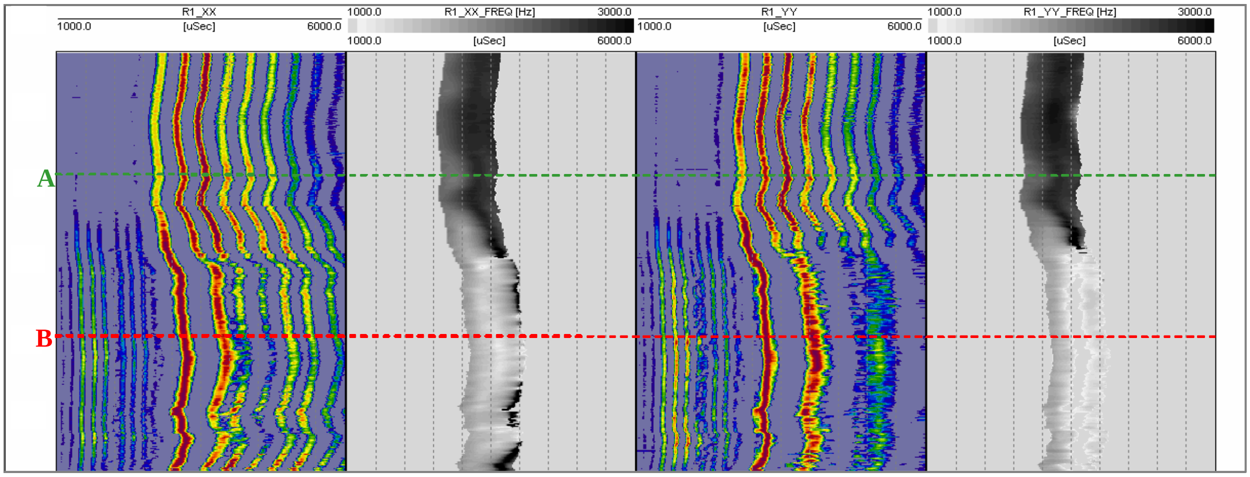

Figure 1. *An example of cross dipole log (in line components only) obtained with the IFS method.*

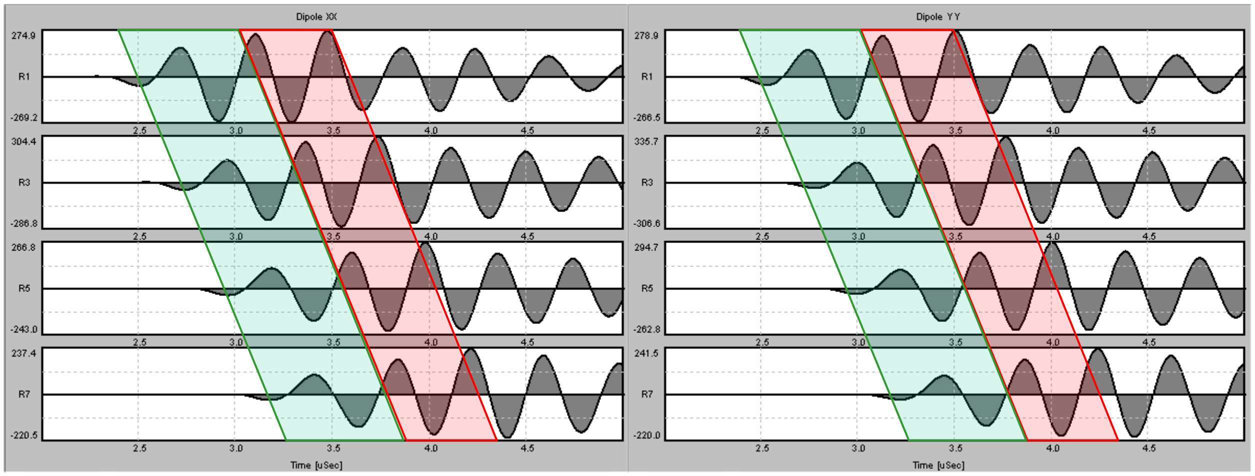

Figure 2. *An example of raw cross dipole wave forms (in line components – odd receiver levels only) recorded at the depth labeled "A".*

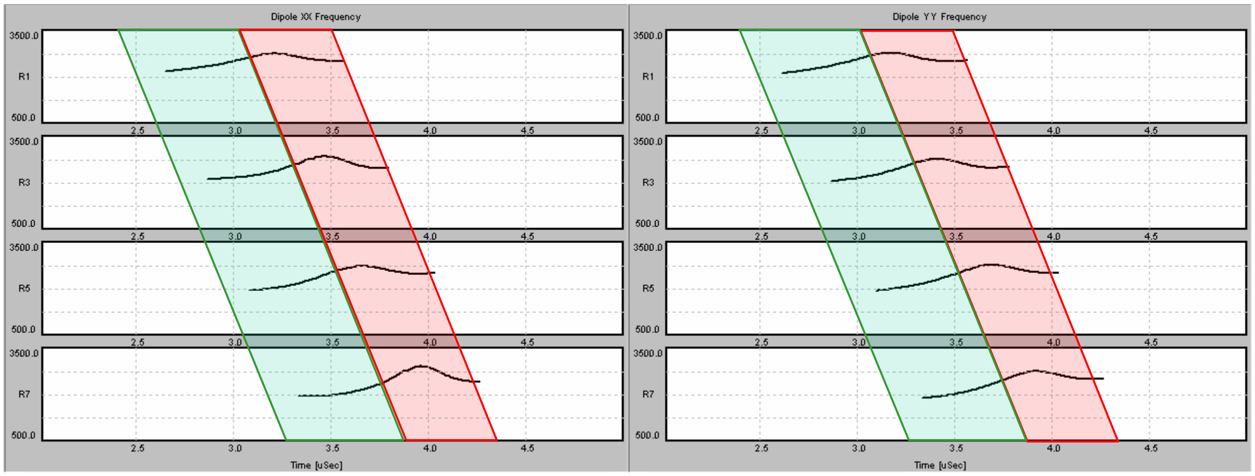

Figure 3. *The instantaneous frequency curves obtained at the depth of "A" across the reciever pair #12, #34, #56, and #78 with the X (the left side of the image) and the Y dipole sources (the rigth side), respectively. The green shading indicates the fragment of the flexural wave where the contaminations are none significant. The red bar shows the time interval that is mixed with Stoneley mode.*

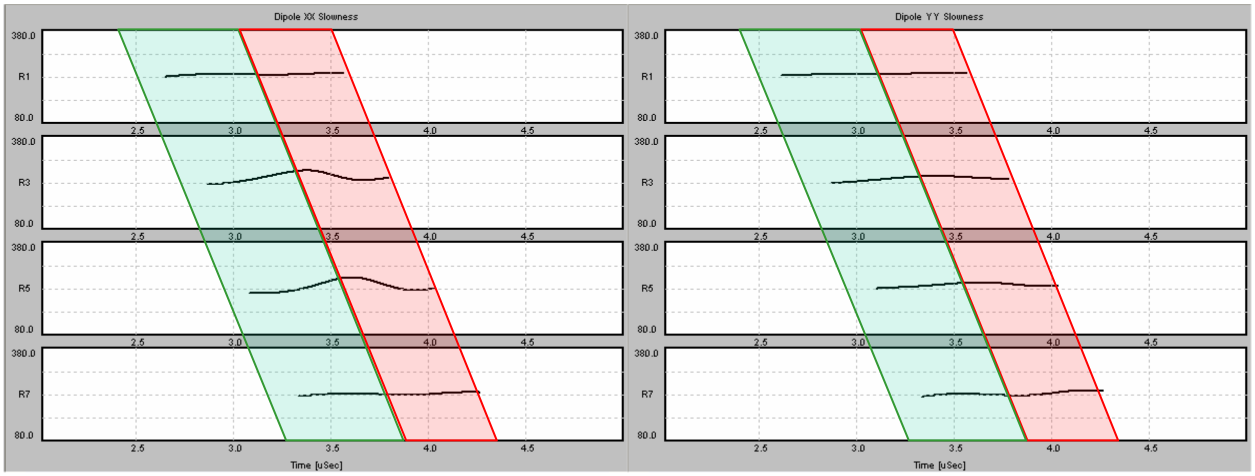

Figure 4. *The instantaneous slowness curvess obtained at the depth of "A" across the reciever pair #12, #34, #56, and #78 with the X (the left side of the image) and the Y dipole sources (the rigth side) respectively. The green shading indicates the fragment of the flexural wave where the contaminations are none significant. The red bar shows the time interval that is mixed with Stoneley mode.*

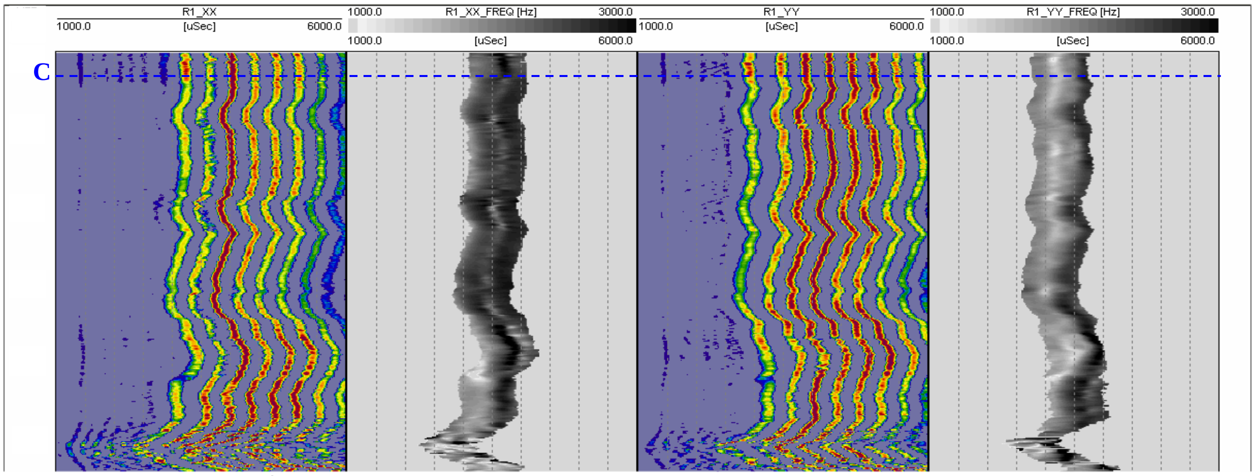

Figure 5. *An example of cross dipole log (in line components only) obtained with the IFS method.*

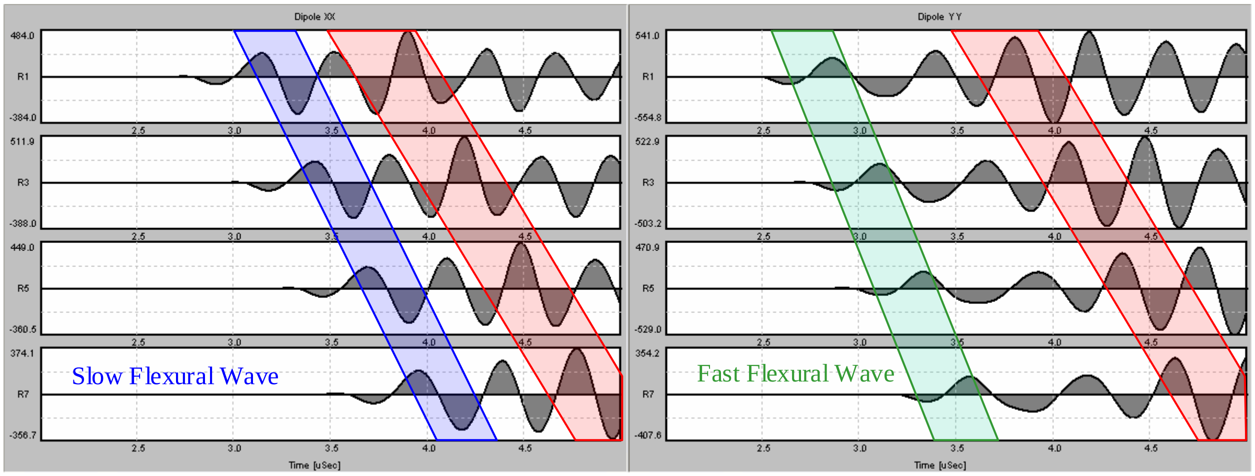

Figure 6. *An example of raw cross dipole wave forms (in line components – odd receiver levels only) recorded at the depth labeled "C".*

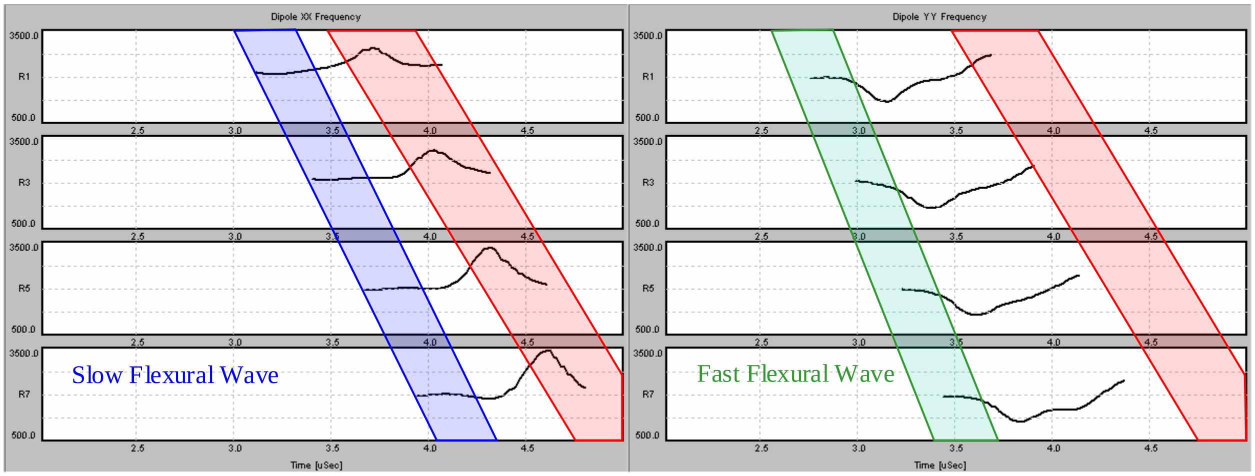

Figure 7. *The instantaneous frequency curves obtained at the depth of "A" across the reciever pair #12, #34, #56, and #78 with the X (the left side of the image) and the Y dipole sources (the rigth side), respectively. The green shading indicates the fragment of fast flexural while the blue one underlines slow flexural wave where the contaminations are insignificant. The red bar shows later arrivals that are mixed with Stoneley mode.*

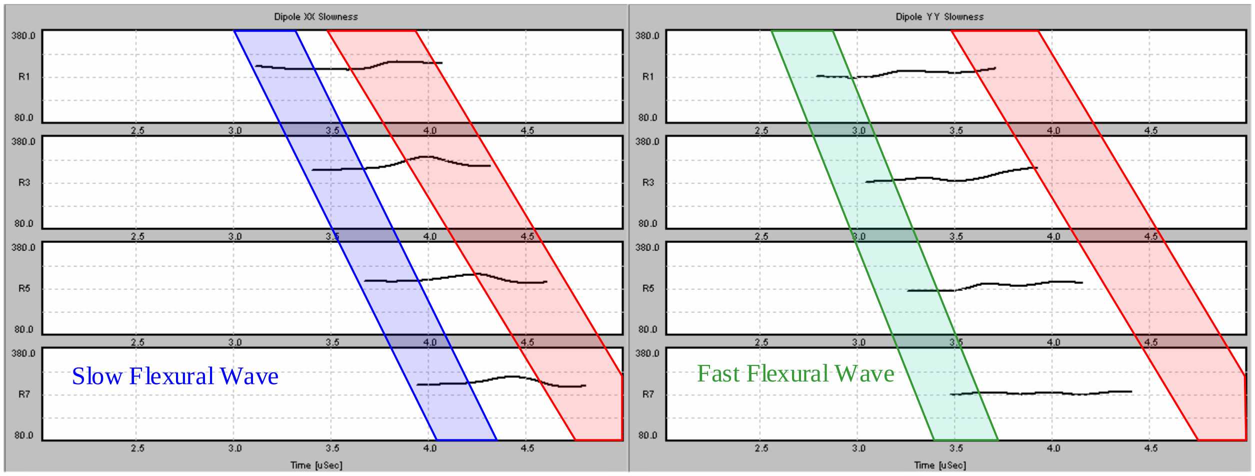

Figure 8. *The instantaneous slowness curves obtained at the depth of "A" across the reciever pair #12, #34, #56, and #78 with the X (the left side of the image) and the Y dipole sources (the rigth side), respectively. The green shading indicates the fragment of fast flexural while the blue one underlines slow flexural wave where the contaminations are insignificant. The red bar shows later arrivals that are mixed with Stoneley mode.*

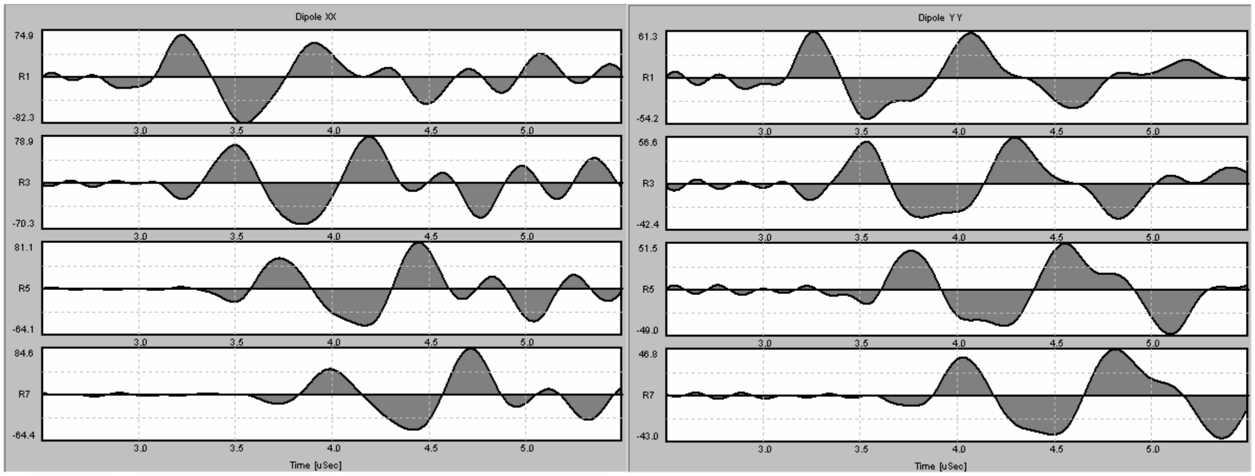

Figure 9. *An example of raw cross dipole wave forms (in line components - odd receiver levels only) recorded at the depth labeled "B".*

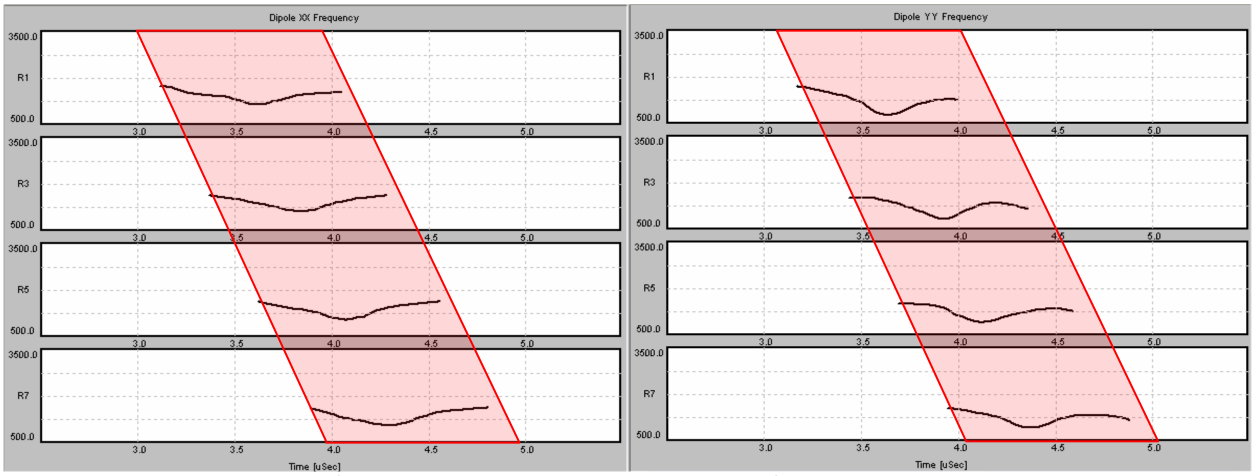

Figure 10. *The instantaneous frequency curves obtained at the depth of "B" across the receiver pair #12, #34, #56, and #78 with the X (the left side of the image) and the Y dipole sources (the right side) respectively. The negative frequency gradient that dominates early arrivals indicates that mixed acoustic modes are present even at the beginning of the processing window width.*

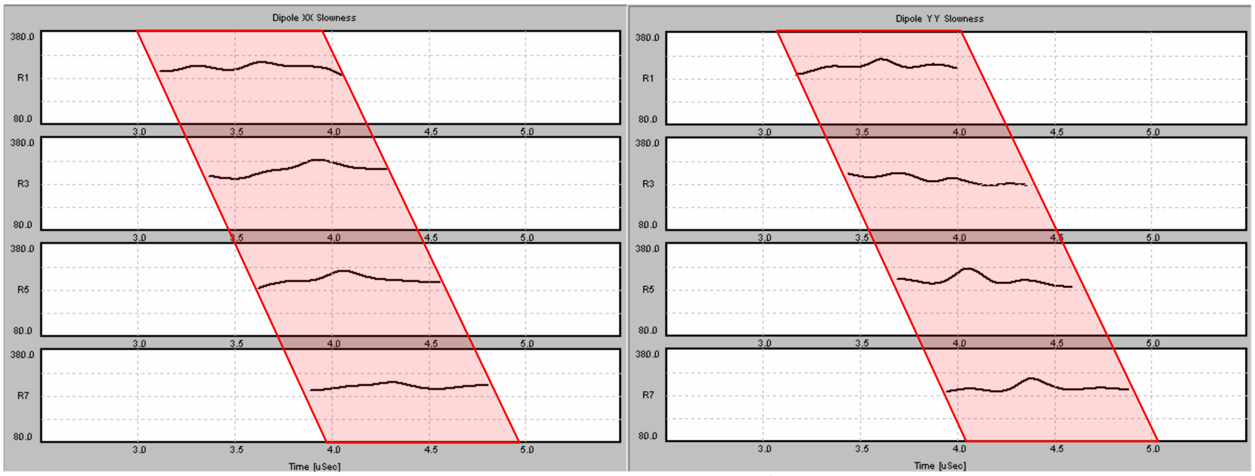

Figure 11. *The instantaneous slowness curves obtained at the depth of "B" across the receiver pair #12, #34, #56, and #78 with the X (the left side of the image) and the Y dipole sources (the right side) respectively. "Wavy" character of instantaneous slowness curves indicates that multiple acoustic modes are present within the entire processing window width.*