A Modular Wireline Sonic Tool for Measurements of 3D (Azimuthal, Radial, and Axial) Formation Acoustic Properties

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ABSTRACT

A comprehensive mechanical characterization of the wellbore rock relies on a three-dimensional (3D) characterization of the acoustic slowness in terms of radial, azimuthal, and axial variations. These acoustic rock property variations arise because of non-uniform stress distributions, mechanical or chemical near-wellbore alteration caused by the drilling process, and formation-intrinsic anisotropy.

A 3D formation acoustic properties characterization is achieved through comprehensive acquisition of broadband waveforms from all borehole modes (monopole, dipole, and Stoneley) coupled with an integrated inversion of all acquired data. Compressional slowness radial variations are enabled through monopole acquisition with a wide range of transmitter-receiver spacings, from very short to very long, unique to this new technology. Shear slowness radial variations are quantified through inversions of the broadband dispersions of the dipole flexural and Stoneley modes over a wide frequency band featured by this new sonic tool. The unique design of the dipole source enables it to be fired in either pulse mode or chirp mode.

Open hole wireline logs from China, Norway, Mexico, Brazil and the United States demonstrate the improved accuracy of both compressional and shear slowness measurements and their radial variations. With the increased number of axial and azimuthal receivers and an acoustically quiet and predictable structure, shear wave anisotropy is estimated more robustly with data showing reliable fast shear azimuth measurements down to 1–2% slowness anisotropy. Shear slownesses from 90 to 900 µs/ft have been measured with this new tool. Improved dispersion curves for both monopole and dipole modes lead to clear identification of formation homogeneity, inhomogeneity, isotropy and mechanisms of anisotropy. Cased hole formation evaluation data demonstrate that shear slowness through casing as high as 450 µs/ft can be measured reliably.

Advanced inversion algorithms accurately estimate 3D rock properties from signals with wideband dispersion curves. Accurate determination of relevant rock properties leads to timely decision making (e.g., regarding perforating, sand control, well placement, and stimulation).

INTRODUCTION

Borehole acoustic measurements have been around for a long time. The reason for their longevity is because the measurements have value for many people in various workgroups - from Petrophysics, Geophysics, Geomechanics, and Reservoir teams. The influence of acoustic measurements spans the lifecycle of the well ranging from seismic to production. Over several decades the measurement has evolved and improved with the purpose of determining accurate formation slowness. Early arrangements consisting of a single transmitter and a single receiver with very short spacing could only measure the compressional slowness in a very limited environment. Borehole compensated devices were then constructed but could not probe deep enough in the formation to read the slowness beyond chemically or mechanically altered zones. The long spacing sonic was developed in the 70s to probe beyond any formation alteration. During the 80s a digital tool made the way to the scene enabling sophisticated processing of digital waveform data similar to that being done in seismic. Later in the decade sonic flexural logging was developed enabling extraction of shear slowness in slow formations, or formation slower than the fluid in the wellbore. These tools featured an arrangement of transmitters and receivers enabling processing of the data to characterize the acoustics in the main shear propagation planes. Analysis of the recorded logs allowed us to further understand the physics and see the potential for improvements. Based on this knowledge, an ambitious vision was conceived for a service to provide a new dimension to sonic data in order to extract radial acoustic properties in addition to the information in the plane orthogonal to the wellbore axis provided by the existing technology. The tool and associated data processing schemes needed to
be designed with the end products in mind. A new vision was conceived based on two components. A tool was needed that would acquire monopole and dipole waveforms over a wide range of spacing and covering a wide frequency band. Simultaneously, associated processing workflows had to be developed to integrate all of the data and derive a set of answers for both traditional and new users who could derive benefit from the new three-dimensional acoustic information. The following provides some insight on the development process and realization of this vision.

TOOL DESIGN AND CHARACTERIZATION

Unlike for other logging technologies it is very difficult to put a sonic tool in a reference environment with well-defined physics. Prior to designing the new sonic tool, a large facility was built featuring a range of reference formations with known characteristics. The acoustics of this environment were measured with a minimum structure tool consisting of sensors positioned on a cable providing a measurement free of tool effects. For logging dipole, but also for Stoneley or even Monopole in conditions inducing a Leaky-P mode the tool effect must be taken into account to ensure the precision of the measurement. Earlier generation tools where designed as flexible as possible in order to reduce the effect generated by the presence of the tool in the borehole. This resulted in complex designs with slotted sleeve and light inner structure to make the tool as acoustically transparent as possible. This approach has two drawbacks: the soft tool structure resulted in mechanically weak devices, limiting the operating range, and the complex tool architecture, although minimizing the tool presence effect in the measurement, could not be characterized for all environments. For the new tool a different approach was taken whereby a simple embodiment was developed featuring acoustics with predictable effects on the measurements that can be included in the processing to obtain accurate products. Figure 1 shows the effect of the tool presence on the flexural dispersion curve that must be taken into account during the computation of the answer products based on the analysis this dispersion curve.

Being simple, the structure of the new sonic tool is easy to predict with finite difference modeling. Through a series of iterations in conjunction with the hardware developments, the computational finite difference model was tuned to perfectly reproduce the tool response in the reference environments of the calibration facility. This approach results in the accurate prediction of the effects of tool presence in all environments. The accuracy of this prediction was verified not only in the reference environment but also in numerous tests conducted in real wells for a wide range of formation slownesses, hole sizes and borehole fluids. Most notably we should mention an extremely fast carbonate logged in a very small 4.9” hole filled with a fast fluid at 176 us/ft slowness where the tool effects were maximized and accurately predicted by the tool model.

Another benefit of the simple tool structure is the ability to predict its effects on the measurement by using a simple equivalent tool model computationally lighter than finite difference modeling and used for real time tool effect corrections to provide accurate real time answer products at the wellsite.

GEOMETRY AND RECEIVER SECTION

The geometry of the new tool was carefully designed to provide acoustic measurements at various radial depth of investigation. In case of radial variation of compressional slowness decreasing away from the borehole face, increasing the transmitter to receiver (TR) spacing enables to measure the acoustic slowness deeper in the formation. This was the base for the development of the long spacing sonic in the 70s.

Fig. 2 - Monopole Radial Profiling concept

In the 80s and 90’s research investigations showed that recording the monopole propagation at multiple TR spacings permits to invert the series of first arrival times to obtain the slowness profile away from the
borehole face at various depth of investigations, as shown in figure 2.

This approach was followed for the design of the new sonic tool that features TR spacings from 1ft to 7ft for the short spacing group and 11ft to 17ft for the far spacing set of measurements. The arrangement of the monopole transmitters has been designed to enable the recording in a borehole compensated (BHC) manner, with the receivers placed in between two transmitters for the short monopole recording, as well as a depth derived borehole compensation (DDBHC) monopole acquisition as featured by long spacing sonic tools.

For other mode of propagation, like flexural or low frequency monopole Stoneley, or Stoneley mode, The TR spacing was chosen to ensure that the borehole modes are well established before reaching the near sensors and the span of the array is long enough to accurately extract the required information for the very long wavelengths featured by these modes. The longest possible array was built for this purpose only limited by the maximum length of the receiver section to allow transportation with logging trucks.

The tool features 13 axial stations separated by 6 inches between them for a total aperture of 6 ft for the receiver array. Eight azimuthal receivers are located every 45 degrees around the tool for each of the 13 stations providing a total of 104 sensors for the whole receiver array. The high-fidelity receivers have been verified to provide a stable response over the whole pressure and temperature operating envelope of the tool. For enhanced accuracy of propagation mode separation and improved signal/noise ratio the receivers are regularly calibrated.

Figure 3 below shows the final geometry of the tool.

**ENHANCED MONOPOLE TRANSMITTERS**

The 3 monopole transmitters have the same design that has been tuned to compensate for the excitation function for the Stoneley mode at low frequency to the cement evaluation mode (CBL) at high frequency through the standard frequency of the monopole P&S modes. They provide much more pressure than previous technology and their tuning to compensate for monopole compressional excitation function ensures a good generation of the typically low monopole P mode in extremely fast formations.

**WIDEBAND FREQUENCY FOR DIPOLE**

For dipole the objective of exciting the flexural mode over a wide frequency band lead to a revolutionary design of the transmitter. In addition to the wide frequency bandwidth the transmitter was designed to provide a linear flat response over the targeted frequency range.

The device that was selected for this purpose was a shaking device consisting of an electromagnetic motor mounted in a cylinder suspended in the tool. This high fidelity device is capable of generating high pressure dipole signal without generating any vibration in the tool because the action-reaction system is contained within the transmitter itself. This 4 inch long transmitter can be assimilated to a point source because it does not generate any pressure field above and below the part of the borehole in front of the shaker.

Another benefit of the linearity of the drive and the flatness of its pressure output is the capability of this device to be activated by a frequency sweep, or Chirp, as described in the picture on figure 4.

In the figure above the monopole measurements are indicated in blue and the dipole measurement in red. The two dipole transmitters are called “0 degree” and “90 degrees” and generate a dipole mode aligned to the tool reference (used also for other measurements) and 90 degrees to it (clockwise looking downhole by convention) respectively.

**Fig. 3 – New Sonic Tool Geometry**

**Fig. 4 - Frequency Sweep (Chirp) drive waveform**

The output pressure spectrum of this drive has been verified in a free field environment in a test facility offshore Japan and the figure below shows the pressure spectrum this firing mode (arbitrary magnitude scale).
The Chirp pulse sustains each frequency during a much longer time than narrow band pulses and therefore provides much more dipole energy than those. The frequency coverage of this dipole drive, between 300Hz and 8kHz, ensures that flexural energy will be provided to the surrounding formation regardless of the conditions. The flexural excitation is maximal at a given frequency, the Airy phase frequency, and is 10dB lower at half and twice the Airy phase frequency. Using the chirp source for dipole logging ensures that the dipole signal to noise ratio is maximized in all cases. Due to the size of the dipole transmitter two different devices are used for firing the flexural signal in line with the tool reference (0 degree dipole) and the orthogonal one (90 degrees dipole). This feature that could be at first thought perceived as a drawback as shown not to be an issue because the quality and repeatability of these transmitters far outweighs the fact that they are not collocated. More on this point is discussed later in this document. As we shall demonstrate in the following paragraphs, the quality of this dipole transmitter yields high quality waveforms resulting in accurate answer products and enabling computations that were not possible with previous technologies.

SUPERIOR QUALITY

Tests after tests the new sonic tool has provided monopole and dipole waveforms with unprecedented quality. Figures 6 on the right shows a set of dipole waveforms recorded in a fast formation and the resulting dispersion curve. The strong dispersion from 125us/ft at 3kHz and below to 200us/ft at 8kHz explains the change in waveform shape across the array in the top plot. The wide frequency coverage of the flexural signal is clearly displayed on the bottom plot. The size of the dots represents the spectral amplitude of the flexural signal and it can be seen that the maximum response lies between 3 and 4 kHz in this case (Airy Phase frequency).
The improvement in quality is even more obvious for cased hole where the absence of degrading noise and vibration with the new dipole transmitter results in waveforms of excellent quality as shown in the example on figure 8 below.

Fig. 8 - Dipole waveforms in cased hole

The improved quality of the waveforms turns into more accurate slownesses determination that can be verified with a new quality control display for dipole, Slowness Frequency Analysis (SFA), consisting of the projection of the dispersion curve on the slowness axis.

Fig. 9 - Dipole data semblance projection (left) and its quality control with SFA (right)

As described in various publications the accuracy of the slowness computation can be verified by controlling that the computed shear slowness lies at the low frequency side of the dispersion, hence the left side of the color pattern as shown on the right side of figure 9 beside the usual semblance processing projection.

Figures 1 and 2 at the end of this document display more example of semblance processing of monopole and dipole data, waveforms of the same and resulting dispersion curves.

ADVANCED ANSWER PRODUCTS

Monopole radial profiling

Compressional radial variations are determined by evaluating both the short and long spacing monopole measurements. Short spacings probe the formation in the near field (shallow) while longer spacings probe the formation in the far field (deep). This concept and the tool geometry that enables this multi-spacing analysis were graphically represented above.

An example of what a final product could look like with the monopole radial profile is presented in figure 10 below.

Fig. 10 - Example of Monopole Radial Profiling results display

From right to left in this figure, we are looking at formation density, hole size and gamma ray in track one, the transit times for the receiver stations from both near and far firings are in track two (for quality control), followed by the alteration flag in track three. This alteration flag is derived by fitting trends of slowness for the very near and the very far spacing, and can be delivered at the wellsite. The radial profiling map in track four is the color mapping of the slowness as a function of depth of measurement from the center of the borehole to one meter, or three feet, into the formation. The last track maps the percentage difference from far field slowness at each depth of investigation, again from zero to one meter.

We can utilize the information from the radial variation of monopole slowness to assist in the decision of
perforating gun selection to ensure that we shoot beyond the damaged zone or possibly to avoid shooting damaged zones altogether (selective perforating to avoid sanding). An alteration quick-look can be provided at the wellsite and further processing could be recommended to better quantify the depth of investigation from the dipole measurements. Combining radial profiling information with data from other evaluation will help to determine the complete picture of the reservoir and as noted previously, provide actionable information on how to complete the well.

Another application of the monopole radial profiling is to use the alteration flag that is available at the wellsite, and shown in the graphic here, for any shallow reading device point selection. As an example, magnetic resonance reads very shallow into the formation and therefore any formation alteration will affect the validity of this measurement. Also, this technique could be utilized to optimize the formation pressure tester point selection for both pressure and samples, as many tight tests are generally thought to be the result of near wellbore alteration. We can therefore minimize the risk of sticking and fishing, by optimizing the program for test location and duration.

**Dipole radial profiling**

The shear velocity responds to the solid framework of the rock and is almost insensitive to fluid effects. From the rock mechanic perspective, it is very informative to evaluate the shear velocity in both the far field as well as the near wellbore to determine changes caused by drilling induced stresses. The Dipole Radial Profiling, described in several papers is a new processing that takes full advantage of the quality of dipole waveforms provided by the new tool.

As shown in figure 11, the flexural slowness variation in frequency can be linked to the variation of shear slowness at different radial depths of investigation. Dipole radial profiling analyzes the difference between the dispersion curve extracted from the dipole data and the dispersion curve corresponding to an isotropic and homogeneous medium. This difference and its variation versus frequency is then inverted into a slowness response versus depth into the formation from the sandface.

**Fig. 11 - Dipole dispersion and depth of investigation**

The figure 12 below shows an example of the Dipole Radial Profiling processing results.

**Fig. 12 - Example of Dipole Radial Profiling results display**

The left track shows the Gamma Ray curve in green and the borehole enlargements in orange. The center track displays the shear slowness between 200 and 1200 us/ft at different radial depth of investigation in the formation. The red curve is the shallowest while the blue curve is the deepest. The right track provides another representation of this radial variation of shear slowness, whereby the radial profile is displayed as a 2D map between the borehole wall on the left edge to 2 ft in the formation on the right side. The shear slowness is indicated by the color of the map, a darker color indicating a shear slowness slower than the far field shear slowness, i.e. characteristic of the rock before the well was drilled. Conversely a light color represents
shear slownesses faster than the deep undisturbed formation. It can be seen in this example that most of this interval displays near wellbore formation with shear slowness slower than the undisturbed one, except below X380 where the formation was competent enough not to see its properties affected by the presence of the borehole or the drilling process.

ENHANCED ANISOTROPY COMPUTATION

Reliable detection of very low stress anisotropy

The extraction of shear anisotropy has been conducted with previous dipole logging tools. The new technology expands the envelope of this processing thanks to the tool characterization, the transmitter response and the resulting dipole data with enhanced signal to noise ratio, the new tool can detect very small amount of anisotropy.

The log below (figure 13) shows such an example.

![Fig. 13 - Detection of very low anisotropy](image)

Although the tool is rotating once every 50ft as indicated by the blue curve on the left track, the tool reliably extract the 10% anisotropy in the zone around X650ft as the very low 1% anisotropy above and below this zone. The detection of the fast shear azimuth angle, shown by the red curve in the third track, is very stable and its accuracy was confirmed by other information.

![Fig. 14 - Dipole anisotropy, regional stress and strike of drilling induced fractures](image)

The figure 14 above shows, in blue, on the left rosette the fast shear azimuth detected by the sonic anisotropy processing and the direction of the regional stress azimuth with the red line. The rosette on the right shows the strike of the drilling induced fractures detected on the oil based mud imaging log. This reliable detection of very low anisotropy values, with a tool rotating in the borehole, demonstrates that the high quality of the dipole measurement is not suffering from the non-collocation of the dipole transmitters.

In addition to the standard anisotropy computation the excellent dipole and Stoneley dispersion curves obtained from the tool data enable to characterize the origin of anisotropy either as stress induced or as intrinsic to the rock. For cases where the plane of anisotropy is not orthogonal to the wellbore the 3D-anisotropy processing is available to extract the shear and compressional slownesses in the 3 main planes of propagation.

The 3D resulting compressional and shear velocities are used as an input for calculating rock properties as input to geophysics and geomechanics.

Cement Evaluation

Cement Bond Logs (CBL) utilizes “E1” detection, which is the first positive half cycle of the casing extensional mode. The E1 peak amplitude, or signal amplitude, is a function of the cement to casing bond. A cement bond log interpretation chart was created using this E1 behavior at the 3ft transmitter to receiver spacing. The bond index (BI) was created to correlate the magnitude of the E1 signal to the bonding of cement to casing. A representation of the bond index can be seen in following figure. The amplitude is maximized when there is no cement behind the casing and minimized when the casing is completely bonded.
This relationship between the amplitude of the first sonic peak and the attenuation occurring in the casing is depicted in the figure 16 below and displayed in the following equation.

$$SA_{21} = C_{21} \cdot P_1 \cdot S_2 \cdot 10^{-ATT D_{21}},$$

where $SA_{21}$ is the signal amplitude of E1 peak; $C_{21}$ represents the coupling between transmitter to casing and casing to receiver; $P_1$ is the transmitter strength; $S_2$ is the receiver sensitivity; $ATT$ is the attenuation of E1 during propagation in a unit length of casing; and $D_{21}$ is the wave path length in casing between P1 and S2. It can be seen that the signal amplitude does not only depend on the bonding of the cement to the casing but is also affected by the tool and the environment in the borehole. All these effects are currently corrected by various normalizations for the tool response, the in-situ temperature and pressure and the fluid in the borehole. CBL logs are also sensitive to eccentricity effects where the signal peak is reduced if the tool is eccentric, providing an inaccurate measurement.

The new sonic tool is addressing all the above issues successfully by applying a different technique to extract the cement bond log that has been evaluated and has long been used in the industry: the attenuation based cement bond log. This approach requires four amplitudes from two transmitters and two receivers disposed in a BHC manner at the appropriate spacing. The equations for the signal amplitudes are provided below the following (figure 17) graphical representation of the concept.

$$SA_{11} = C_{11} \cdot P_1 \cdot S_1 \cdot 10^{-(ATT_{BI=0})}\cdot(c1+d)$$
$$SA_{21} = C_{21} \cdot P_1 \cdot S_2 \cdot 10^{-(ATT_{BI=0})}\cdot(c1)$$
$$SA_{12} = C_{12} \cdot P_2 \cdot S_1 \cdot 10^{-(ATT_{BI=0})}\cdot(c2)$$
$$SA_{22} = C_{22} \cdot P_2 \cdot S_2 \cdot 10^{-(ATT_{BI=0})}\cdot(c2+d)$$

In order to eliminate the effects from variations in transmitters and receivers, fluid effects, and tool normalization the following equation for borehole compensated attenuation (BATT) is utilized:

$$BATT = \log_{10}\left[\frac{SA_{11}\cdot SA_{22}}{SA_{21}\cdot SA_{12}}\right]/2/d,$$

From here a bond index is calculated as follows:

$$BI = \frac{BATT - ATT_{BI=0}}{ATT_{BI=1} - ATT_{BI=0}},$$

where $BI$ is the bond index, $BATT$ is the compensated attenuation, and $ATT_{BI=0}$ and $ATT_{BI=1}$ are expected attenuations in free pipe and completely bonded pipe, respectively. These correct for the pipe and cement characteristics to obtain an accurate log in all cases where those parameters are provided.

For consistency with historical practice a discriminated DCBL output is then calculated with the borehole compensated attenuation as follows:

$$DCBL = CBL_{BI=0} \cdot 10^{-(ATT_{BI=0})\cdot D_{3ft}},$$

where $D_{3ft}$ is the path length at the 3ft transmitter to receiver spacing, $CBL_{BI=0}$ is the cement bond log value in free pipe.
While the standard CBL provided with the amplitude measurement method is sensitive to both coupling and propagation attenuations, DCBL is free of coupling attenuation and provides propagation attenuation over the two feet between selected receiver stations. Thanks to the number of receivers in the array and their position, the new tool also provides an enhanced resolution log with one-foot vertical resolution.

The new tool has an array of eight azimuthal receivers around the tool at thirteen stations axially along the tool and uses all the receivers from the center five stations for the cement evaluation. This arrangement provides information on the tool position inside the casing and compensates for tool eccentricity up to 1/3 of an inch.

An example of Cement Evaluation log is displayed in Figure 21 at the end of this document with comparison to the log obtained by a previous technology making a discriminated CBL measurement. The differences observed are due to the fact that the new tool provides compensation for pipe attenuation (at high values of DCBL) and for cement (at low DCBL amplitudes) while the previous tool does not.

The service can be utilized to simultaneously record cement evaluation and behind casing compressional and shear slowness information. The longer transmitter to receiver spacing, tool geometry and stronger monopole and dipole transmitters result in improved formation evaluation measurements behind casing.

Enhanced permeability estimation and other Stoneley derived products

The estimation of the fluid mobility from the analysis of the Stoneley wave slowness and attenuation has been done for several years with previous sonic tools. Thanks to its enhanced monopole transmitter and its large number of receivers the new sonic tool provides the user with Stoneley waveforms featuring a much wider frequency band and higher signal to noise ratio than its predecessors.

As it does for other propagation modes, the presence of the tool in the borehole has an effect on the Stoneley propagation. The accurate tool effects characterization of the new modular sonic tool has been included in the Stoneley inversion algorithm, which now provides for a more accurate and reliable computation of fluid mobility and formation permeability.

The analysis of the transmitted and reflected energy of the Stoneley wave crossing a fracture plane is used to detect the open fractures crossing the borehole. This processing is more reliable with the new tool that provides increased Stoneley energy at frequencies from 1 to 5 kHz where the fracture effects are more pronounced and the processing more sensitive.

The wide Stoneley frequency band featured by the new tool provides for the extraction of Stoneley dispersion curve enabling the computation of the Stoneley radial profiling. This in turn provides information on the shear propagation in the direction axially aligned with the borehole. This output, in combination with the dipole shear profiling in the two fast and slow shear planes orthogonal to the borehole, enables the characterization the shear propagation in a 3D anisotropic environment.

Imaging

The new modular sonic tool has been designed to record imaging jobs. Its three powerful monopole transmitters transmit monopole compressional and shear energy that reflect at boundary planes several feet away from the borehole and reach back to the tool with high enough a signal to noise ratio to image the reflectors. The processing uses a new technique that does not require the previously necessary ultra-long spacing between transmitters and receivers.

The imaging signal is recorded at the eight azimuths around the tool to enable accurate spatial localization of the reflectors. The distance at which the reflectors can
be imaged depends on the conditions of slowness and attenuation of the surrounding medium. At the time this paper is written, several jobs have been recorded that provided acoustic images of the formation up to 25 ft away from the borehole face.

SUMMARY

A new sonic tool has been presented with unique features enabling reliable recording of wide frequency band acoustic signals for monopole, Stoneley and dipole modes. The waveforms are recorded by 8 receivers located azimuthally every 45 degrees around the tool along a receiver array composed of 13 stations spaced 6 inches apart.

The monopole transmitters used by the tool were designed to output high energy for all frequencies between 300 Hz and 25 kHz. The P&S recording is done with a true BHC configuration at short spacing between 1 and 7 foot spacing and a long spacing mode between 11 and 17 feet for DDBHC processing.

The dipole transmitter is a revolutionary device that provides high power and flat pressure response versus frequency between 300hz and 8kHz. This enables the transmission of a chirp signal generating dipole wave with wide frequency band suitable for all logging environments from small boreholes in fast formations to very large wells in unconsolidated environment.

The tool predictable acoustics are accurately characterized and all the processing schemes that have been designed for this technology include the tool presence in the inversion algorithms.

The wide frequency band and multiple transmitter-to-receiver spacings featured by the tool for all propagation modes enable the computation of new answer products that characterize the 3D propagation of acoustic properties around the borehole in terms of radial, azimuthal, and axial variations. These acoustic rock property variations due to non-uniform stress distributions, mechanical or chemical near-wellbore alteration caused by the drilling process, or formation-intrinsic anisotropy provide invaluable information for timely decisions on perforation, completion, sand control, well placement, and stimulation to name a few.

The service also provides the usual geophysical, petrophysical, cement evaluation and analysis behind casing answer products with the various enhancements described above.

The tool also enables recording for acoustic imaging of reflectors in the formation several feet away from the borehole.

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Fig. 19 - Semblance processing of compressional, fast and slow shear (left) dipole waveforms (right)

Fig. 20 - Dipole, Stoneley and P&S waveforms and dispersion curves
Fig. 21 - Cement Evaluation comparison with new tool in blue compared to another tool providing discriminated bond log in black.