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A New Sonic Array Tool for Full Waveform Logging

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Abstract

For over 20 years, sonic logging has implied compressional velocity logging using first break detection from two-receiver tools. Today, sonic logging techniques can utilize more of the information contained in the acoustic waveform to provide shear- and Stoneley-wave velocity and attenuation measurements. This requires signal-processing techniques for full-waveform analysis. These techniques generally need more spatial samples of the wavefield than are provided by standard two-receiver tools. To fulfill this need, a new multireceiver sonic tool has been designed.

In this paper, we describe a new sonic array tool which has an array of eight receivers spaced 6 in. apart, located 8 ft from the nearer of two transmitters. In addition to array capabilities, standard short- and long-spaced sonic logs are available. A special section has been incorporated to give a mud-velocity measurement. The downhole electronics provide digitized waveform acquisitions with an effective resolution capability of 11 bits.

To extract the additional answers from the full waveform, slowness-time coherence (STC) processing has been developed. Based on semblance techniques, STC identifies coherent arrivals across the array. Examples of waveforms and processed logs from both open and cased wells are presented to illustrate the tool's capabilities.

† Slowness is the reciprocal of velocity and is typically measured in µs/ft. It is synonymous with interval transit time or Δt.

Introduction

After more than 20 years of compressional-wave logging, the field of acoustic well logging is moving toward a more complete analysis of the full sonic waveform. This trend is being driven by the use of other wave components to probe rock properties and mechanical characteristics. Shear-wave logging, for example, can be effectively used in lithology and fluid identification, porosity determination, rock elastic and inelastic properties measurement, and in shear seismics.[1] Stoneley waves can be used to determine shear-wave propagation characteristics in soft, unconsolidated formations where converted shear waves are often absent from the borehole.[2,3] Achieving this requires both digitizing the full acoustic waveform and applying modern signal-processing techniques.

This paper describes a tool and processing technique that addresses both requirements. Digitizing capabilities are placed downhole so that more than one received waveform can be simultaneously digitized free of cable-induced distortion. Instead of the standard two receivers, a linear array of several receivers is used to provide more spatial samples of the propagating wavefield. This allows a much better picture of the composite wave and its propagation characteristics. These additional data make possible the use of more sophisticated array-processing techniques that give unambiguous, more highly resolved estimates of the various wave component slownesses.[4,5†]

In the sections that follow, the tool hardware and logging capabilities are described along with the signal processing. Examples of logs made in open and cased wells illustrate the tool's utility.

Hardware

The hardware for the sonic array tool is shown in Fig. 1. The basic tool is composed of four pieces of equipment: the sonic logging sonde, the sonic logging receiver section, the sonic digitizing cartridge shown in Fig. 2, and the sonic telemetry tool module. A standard, computer-equipped Schlumberger Cyber Service* unit (CSU*) is used for data acquisition and recording. In addition, a high-speed array processor is used to perform waveform analysis at the wellsite.

Sonic Logging Sonde

The sonic logging sonde is one of two pieces containing the sonic transducers. The sonde section contains two fairly broadband (5 to 18 kHz) piezoelectric transmitters spaced 2 ft apart. Their center frequency is about 12 kHz. There are also two piezoelectric receivers spaced 3 ft and 5 ft from the upper transmitter. These receivers have a dual role. In open hole, they are used in conjunction with the two transmitters for making standard short-spaced, 3 ft-5 ft and 5 ft-7 ft depth-derived, borehole-compensated (DDBHC) Δt logs. In cased wells, they are used to make standard 3-ft cement bond logs (CBL) and 5-ft Variable Density* logs (VDL).

Sonic Logging Receiver Section

The sonic receiver section contains an array of eight wideband, piezoelectric receivers. The elements are spaced 6 in. apart with the closest element 8 ft from the upper transmitter when mated with the sonic sonde. Two of these receivers, Receiver 1 and Receiver 5 spaced 2 ft apart, can also be used for making standard long-spaced, 8 ft-10 ft and 10 ft-12 ft DDBHC Δt logs. The receiver section also contains measurement hardware consisting of a closely spaced transmitter-receiver pair to make a continuous mud Δt log. Borehole fluid is drawn through the measurement section as the tool is moved during logging. The eight-array receiver outputs and the two from the sonic sonde are multiplexed with the mud Δt receiver output into the sonic digitizing cartridge.

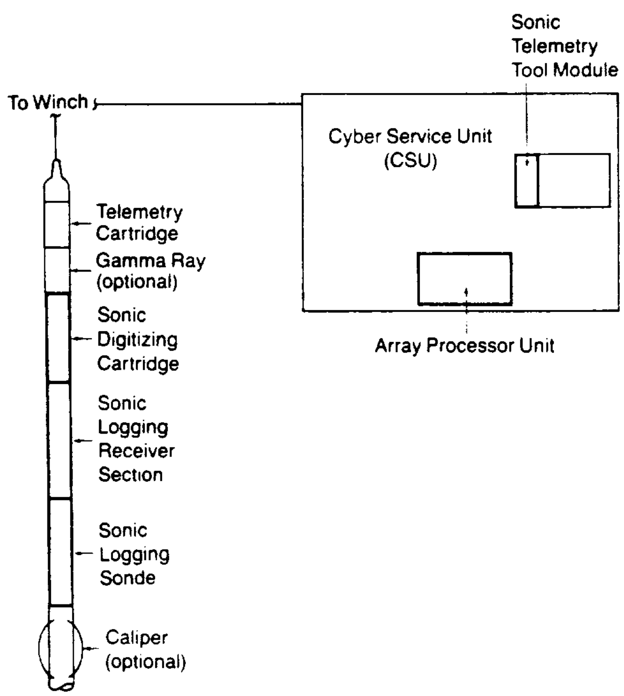

Figure 1—Sonic Array Tool Hardware

* Mark of Schlumberger

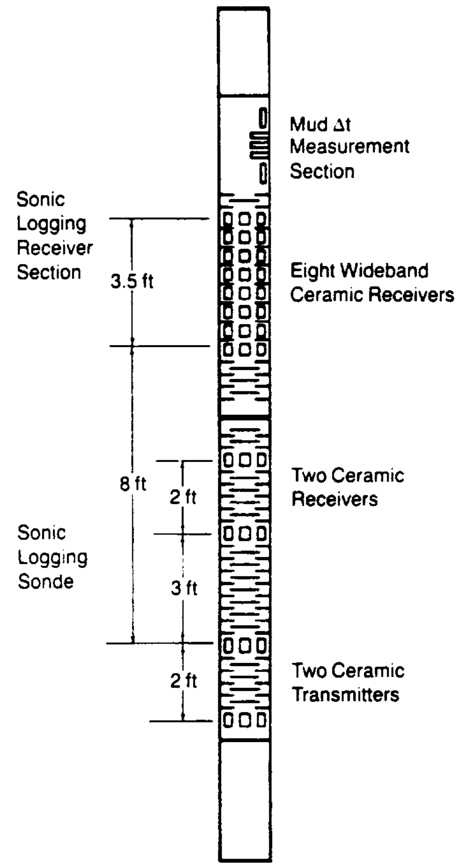

Figure 2—Multipurpose Sonic Sonde Configuration

Sonic Digitizing Cartridge

The sonic digitizing cartridge is a dual-channel system capable of transmitting sonic waveforms in either analog or digital form. The various cartridge functions are controlled from commands telemetered down from the surface. Fig. 3 is a functional block diagram.

Receiver signals entering the cartridge can be directed to either or both of the two channels.

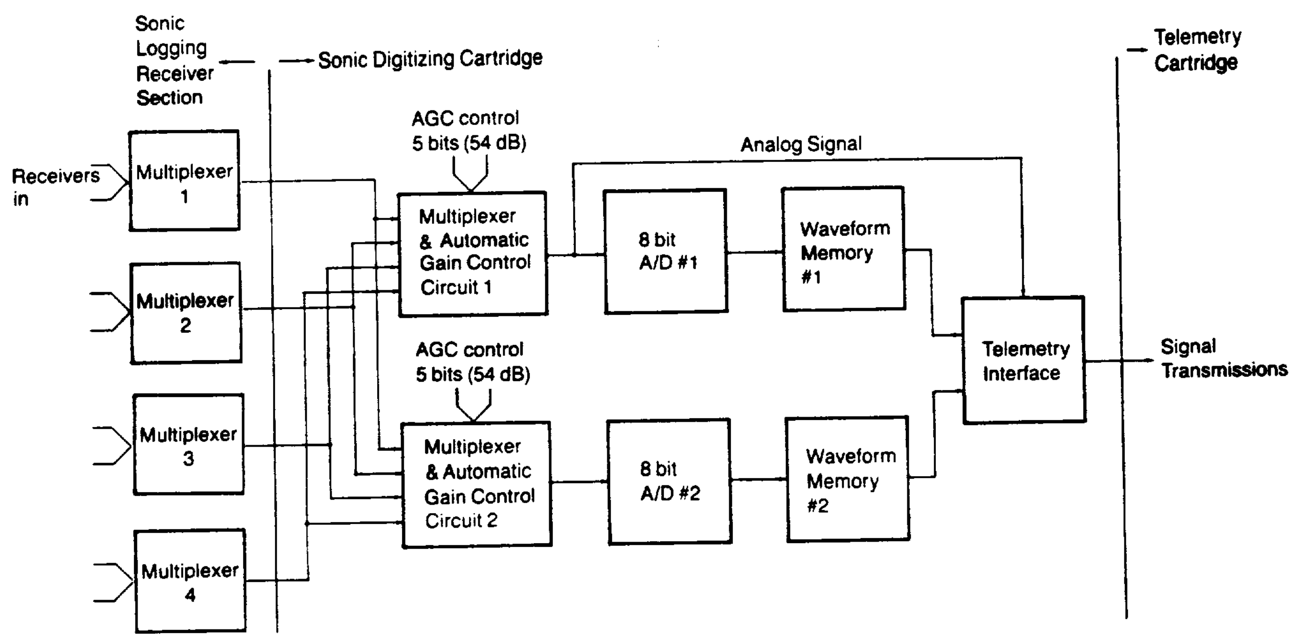

Figure 3—Simplified Block Diagram, Sonic Digitizing Cartridge

Channel gains are independently programmable and can be changed between tool firings on command from the surface. Each channel can be sampled every 5, 10, or 20 μs and digitized to 8 bits. Enough memory is provided for digitizing at least 5 ms of the waveform, 10 ms in some instances. Digitized data stored in memory, then, is telemetered to the surface between tool firings. The analog signal from one of the channels may also be transmitted directly up the logging cable.

Sonic Telemetry Tool Module

The sonic telemetry module is utilized to process the analog signal sent by the sonic cartridge. It employs dual threshold detectors to determine first arrival times and amplitudes. It also generates analog timing signals for uphole display peripherals.

Array Processor Unit

The array processor is a CSU peripheral used to implement the signal processing in real time. It is based on a CSPI miniMAP array processor which is capable of 6.67 million floating-point operations per second. At this speed, for example, it can compute a typical 1024 point fast Fourier transform in 4.2 ms.

Logging Capability

The logging capabilities of the tool reflect its multipurpose nature. CSU software is designed to provide the logging engineer with the flexibility to address particular logging needs with a minimum number of passes in the well. The flexibility is derived from specially tailored combinations of two fundamental modes: analog Δ*t*/CBL, and digital waveform acquisition for processing. Tool specifications and logging capabilities are summarized in Table 1.

For analog Δ*t*/CBL, first arrival detection is made in the sonic telemetry module. The dual threshold scheme reduces cycle skipping. As mentioned earlier, either short-spaced and long-spaced borehole compensated openhole Δ*t* logs or cased hole CBL/VDL logs can be recorded. Simultaneous with this, waveforms taken from the mud measurement section are utilized to determine the mud-wave slowness. This, in turn, may be used in shear-from-Stoneley computations.

Table 1—Tool Specifications

Temperature	175°C
Pressure	20,000 psi
Tool Diameter	3⅝ in.
Tool Length	43.7 ft
Acoustic Bandwidth	5-15 kHz
Waveform Duration	5 ms nominally
Sampling Interval	5, 10, 20 μs
Logging Speed	1400 fph max for 8-rec. array
Wellsite Services (analog WF derived)	3-5 ft, 5-7 ft compressional Δt 8-10 ft, 10-12 ft compressional Δt 3 ft CBL/5 ft VDL Mud Δt
(digital WF derived)	Computed compressional Δt Computed shear Δt (when present) Computed Stoneley Δt (when present)
Processed Interpretation	Mechanical properties—open and cased hole Formation evaluation—open and cased hole Fracture detection Shear synthetic seismogram

For waveforms, short-spaced, long-spaced, array, or combinations thereof can be acquired and recorded. Downhole digitization is used and waveform samples are telemetered to the surface. An example of a set of waveforms digitized from the eight-receiver array is shown in Fig. 4. These array waveforms are appropriate for further processing in the array processor.

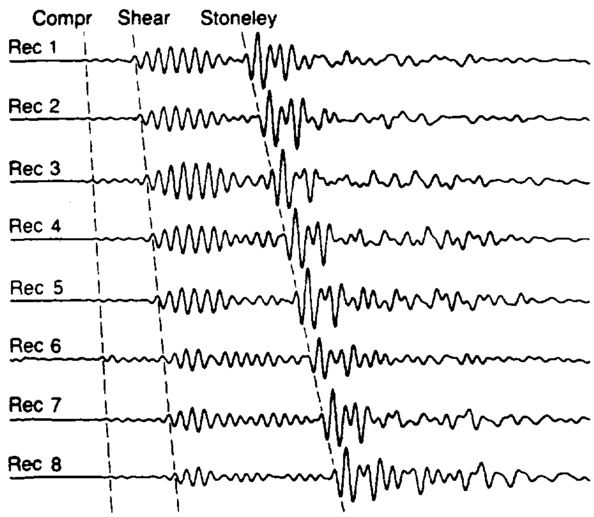

Figure 4—Example Waveforms from the Eight-Receiver Array Sonic Tool

With only two A/D channels, all eight received waveforms cannot be simultaneously digitized from one firing of the tool. Instead, there are two possible modes for waveform digitization:

- Digitize signals from two different receivers simultaneously.
- Digitize one receiver at two different amplification levels.

This latter dual channel mode is used for obtaining greater digitizer resolution on low level portions of the waveform. This is accomplished by operating one channel below saturation for the entire waveform and the other at a higher gain; for example, 10 times low gain. In fact, the two waveforms can be combined to improve digitization resolution after correction for gain and offset differences. By using the higher amplitude channel output when unsaturated and the compensated low channel when the high channel becomes saturated, a higher effective number of bits per sample can be achieved. For a gain ratio of 10, three additional bits are added, bringing the effective resolution to 11 bits.

Control of the amplification gains is automatic. For Δt/CBL logging, gains are maintained for constant, reliable threshold detection. For waveform digitization, gains are adjusted to keep the waveform peak value from saturating the channel (the low gain channel if dual channel mode is used).

Processing

The waveform processing technique used is Slowness-Time Coherence (STC) developed by Kimball and Marzetta.[6] It is a true full-waveform analysis technique. Rather than logging just the compressional- and shear-wave components, it is aimed at finding and analyzing all propagating waves in the composite waveform. STC adopts a semblance algorithm similar to that used in seismic applications for detecting arrivals that are coherent across the array of receivers and estimating their slownesses. Hence, it is ideal for a multireceiver tool such as the one we describe. Furthermore, it does not require first arrival detection and hence is very robust.

The basic STC algorithm is very simple. A fixed-length time window is advanced across the waveforms in small, overlapping steps. For each time position on the first receiver waveform, the window position is moved out linearly in time across the array of receiver waveforms, beginning with a moveout corresponding to the fastest wave expected and stepping to the slowest wave expected. For each of these moveouts, a coherence function is computed that essentially measures the similarity in the waves within the windows. When the time and moveout corresponds to the arrival time and slowness of a particular component, the waveforms within the windows will be almost identical, yielding a high value of coherence. In this way, the set of waveforms from the array is examined over a range of possible arrival times and slownesses for wave components.

More specifically for the eight-receiver array tool with received signals $r_1(t)$, $r_2(t)$, . . . , $r_8(t)$, the STC coherence function is given by

$$\rho^2(s,\tau) = \frac{\displaystyle\int_{\tau}^{\tau+T_w}\left[\sum_{i=1}^{8} r_i\,[t+.5s\,(i-1)]\right]^2 dt}{\displaystyle 8\sum_{i=1}^{8}\int_{\tau}^{\tau+T_w}\left[r_i\,[t+.5s\,(i-1)]\right]^2 dt} \quad \ldots(1)$$

where s is the window moveout (corresponds to slowness); τ is the time position of the window (corresponds to arrival time); and T_w is the window duration. T_w is normally chosen to be equal to the average duration of individual wave-component envelopes. $\rho^2(s, \tau)$ ranges in value from 0 to 1 and equals 1 only when the portions of the waveforms within the windows are identical.

Applying STC to the example waveforms in Fig. 4 produces the contour plot of ρ^2 shown in Fig. 5. Regions of large coherence (values near 1) correspond to the compressional, shear, and Stoneley arrivals.

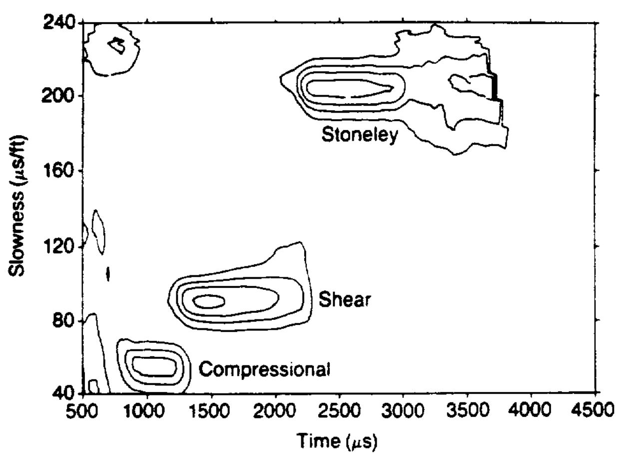

Figure 5—Contour Plot of the STC Coherence Function

To translate this into a slowness log, a search is made for the peak values of $\rho^2(s, \tau)$. For every combination of s and τ, the value of ρ^2 is examined to determine if it is greater than all other values within a specified time and slowness neighborhood. If so, it is a peak. Hence, the information contained in Fig. 5 is reduced to just a few peaks, presumably one for each arrival detected by STC. This process is repeated for each set of array waveforms acquired by the tool while moving up the hole and is used to produce a log. A typical log of the slownesses determined in this fashion is shown in Fig. 6.

An additional step is needed to identify and separate the compressional, shear, and Stoneley arrivals from any others. This is done by examining the slowness, arrival time, and amplitude of each arrival and comparing them with propagation characteristics expected of the compressional, shear, and Stoneley waves for the given physical conditions. Classifying the arrivals in this manner gives a continuous log of wave-component slownesses and amplitudes as shown in Fig. 7.

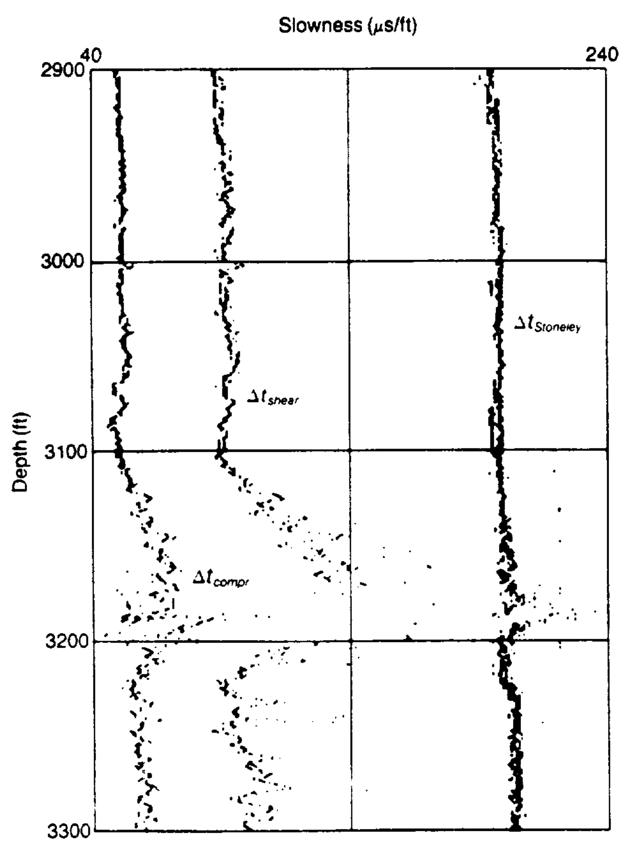

Figure 6—STC Log of Detected Arrivals

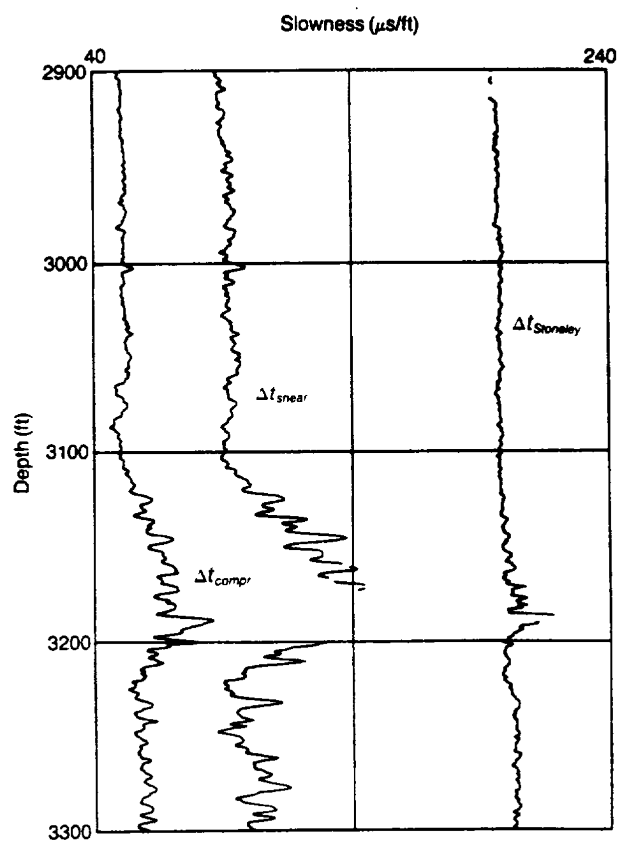

Figure 7a—Log of Classified Component Slownesses

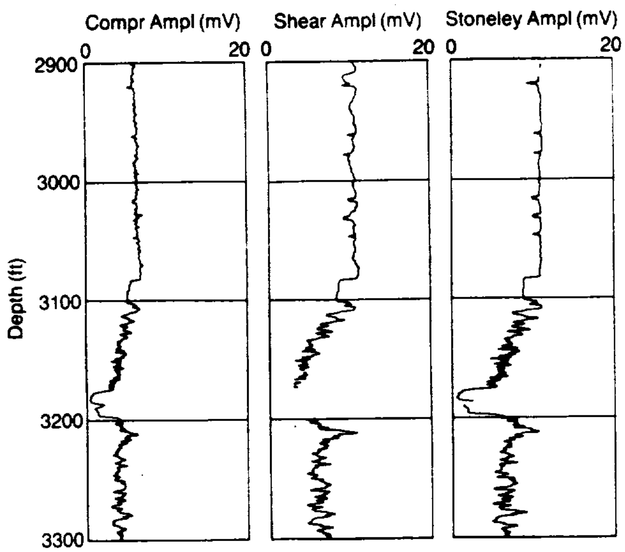

Figure 7b—Log of Classified Component Amplitudes

Log Examples

Results from the Schlumberger test well at Blanco, Texas, give an indication of the tool's performance in open hole. The waveforms of Fig. 4 and the logs of Figs. 6 and 7 are from that well. The formation is mostly low-porosity carbonates and, hence, accounts for both the faster wave-speeds and the strong shear wave. The Stoneley is strong, as well, and exhibits very little variation because the borehole size is consistent.

There is one interesting zone between 3170 and 3200 ft. Here, the shear wave disappears and the Stoneley is reduced in amplitude. Core samples reveal this zone to be highly laminated with possible fractures between laminations. This causes severe shear-wave attenuation. Borehole size also increases in this zone by roughly 0.5 in., causing reductions in Stoneley-wave amplitudes.

An example of tool performance in cased holes comes from a south Texas well. In the zone from 9300 to 9600 ft, the cement bond is generally poor. Cement bond logs indicate the cement coverage to be as low as 30 to 40 percent. Fig. 8 shows the basic STC slowness log. The casing signal is evident in places but drops out when the bond is good. Formation compressional and shear waves are also present. In spite of the poor bond, there is enough formation signal present to give good indications of both formation waves.

Fig. 9 illustrates the continuous logs with the

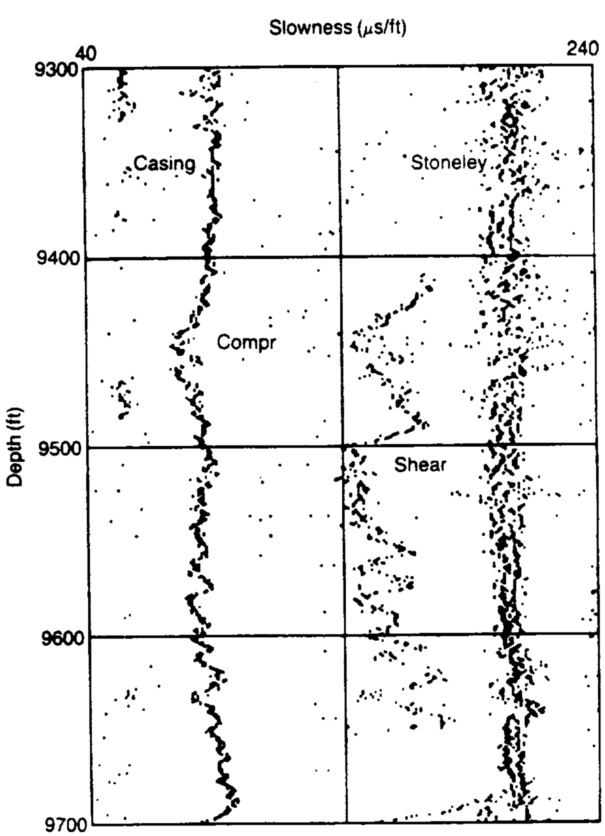

Figure 8—STC Log of Detected Arrivals for Cased Hole Example

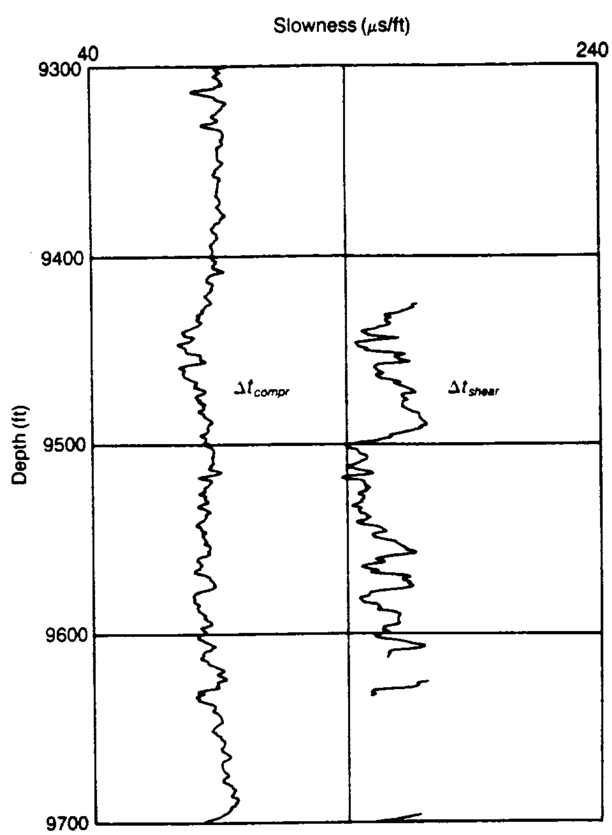

Figure 9—Log of Compressional and Shear Slownesses for Cased Hole Example

casing signals removed. There are gaps in the shear log resulting from zones of poor shear transmission and communication through the casing. In the zone just above this, the bonding drops below 30 percent. Here, the formation waves are very weak and go undetected by the signal processing. This produces gaps in the compressional log as well, as shown in Fig. 10.

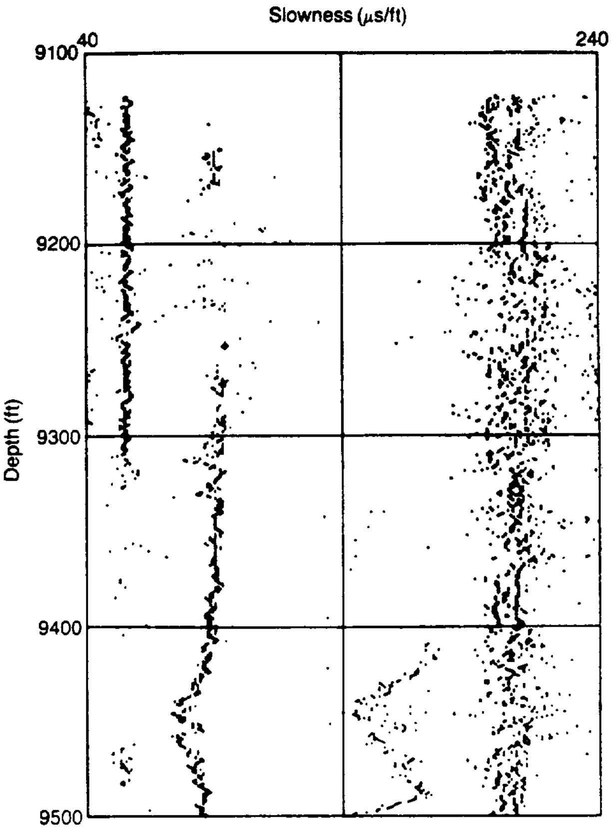

Figure 10—STC Log in Poorly Bonded Zone

Summary

A new sonic tool which features sonic array waveforms as well as conventional first break detection has been introduced. Its capabilities are short- and long-spaced sonic logs, CBL/VDL logs, mud Δt, and, most important, eight-receiver array waveforms. The array waveforms are digitized downhole and transmitted to a wellsite logging system equipped with an array processor for real-time STC processing. Computed measurements include compressional, and shear and Stoneley Δt in open or cased hole. Key applications identified to date are formation mechanical properties, formation porosity behind casing, and seismic correlation.

References

1. Leslie, H. D. and Mons, F.: "Sonic Waveform Analysis: Applications," paper presented at the 1982 SPWLA Annual Logging Symposium, Corpus Christi, July 6-9.
2. Liu, O. Y.: "Stoneley Wave-Derived Δt Shear Log," paper presented at the 1984 SPWLA Annual Logging Symposium, New Orleans, June 10-13.
3. Stevens, J. L. and Day, S. M.: "Shear Velocity Logging in Slow Formations Using the Stoneley Wave," paper presented at the 1983 SEG Annual Meeting, Las Vegas, Sept. 11-15.
4. Kay, S. M. and Marple, S. L.: "Spectral Analysis - A Modern Perspective," *Proc.*, IEEE (Nov. 1981) 1380-1419.
5. McClellan, J. H.: "Multidimensional Spectral Estimation," *Proc.*, IEEE (Sept. 1982) 1029-1039.
6. Kimball, C. V. and Marzetta, T. M.: "Semblance Processing of Borehole Acoustic Array Data," *Geophysics* (March 1984) 274-281.

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