CEMENT AND CASING EVALUATION
USING SONIC AND ULTRASONIC TECHNIQUES

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THE CEMENT BOND LOG

Introduction

The Cement Bond Log/Variable Denisty Log (CBL/VDL) service is used to determine the quality of cement bond to casing and the formation. Some of the recommended uses for the CBL/VDL are:

(1) Determine if vertical isolation exist between zones.
(2) Check effectiveness of a squeeze cement job.
(3) Check possible damage to cement by high pressure testing or injecting.
(4) Locate cement top.
(5) To study various cementing techniques.

Figure 1 displays a standard Log presentation of the CBL/VDL. The CBL/VDL Log displays a CBL amplitude curve, VDL display and a transit time curve. In addition, the Gamma Ray, Casing Collar locator and Bond Index curves will appear.

The CBL curve, which is located in track two is a continuous measurement of sound pulse amplitudes after they have traveled a specified length of casing. These amplitudes are at a minimum in well bonded casing and at a maximum in poorly bonded (free) casing.

The VDL display in track three, complements the CBL amplitude curve by providing additional information about the quality of cement to formation bonding. The VDL displays the varying amplitudes of the arriving sound signals as variations of light intensities.

The sonic transit time is recorded in track one and is used in conjuction with the CBL/VDL to verify their accuracy.

The interpretation methods used with the CBL/VDL compare the response of all three displays to determine the quality of cement bond, since varying parameters may cause one curve to imply false information if analyzed alone.

Theory of Measurement

The transmitter in the sonic tool is caused to fire (vibrate) at a specified repetition rate which in turn produces an elastic compressional wave. An elastic compressional wave is a wave in which the particles of the medium vibrate forward and backward in the direction of wave travel. These compressional waves cause all mediums surrounding the transmitter to vibrate. The mediums allow the compressional waves to travel vertically and horizontally from the transmitter to the receivers. As the elastic wave passes through different mediums i.e. (mud, casing, cement, formation) the different characteristics of each medium affect the velocity, amplitude, and frequency of the elastic wave. (See Figure 2.) For example, in Figure 3 the elastic wave traveling through casing arrives at the receivers first, (except in fast formations) since casing has the fastest travel time characteristics (57 microseconds/foot). The cement and formation waves should arrive next, followed by the wave traveling through the borehold fluid which has a relatively slow travel time characteristic (200 Usec/Ft).

The receivers detect the sum of all waveforms as a composite signal. (See Figure 3). Specifically, upon each transmitter firing, the receivers detect a composite signal that is the summation of the elastic waveforms traveling through the different mediums.

The composite wave signal is common to all the measurements provided by the CBL/VDL system. However, each measurement is based on different portions of the resultant waveform. The VDL display is a study of the entire composite waveform while the CBL and transit time measurements are concerned only with the first waveform arrival. In regard to the composite waveform the first positive peak is referred to as E_1 with subsequent positive peaks denoted as E_3, E_5, E_7 ..., the first negative peak is termed E_2 with subsequent negative peaks denoted as E_4, E_6, E_8 ...

Transit Time Curve

The transit time curve measures the time required for the acoustic wave to travel from the transmitter to the receiver by the fastest route. The transit time usually identifies the arrival of the casing peak, E_1. Identification of this peak is important since its amplitude is measured and indicates the proportion of cement bonding to the casing. Also the transit time curve indicates parameters that may affect the accuracy of the CBL measurement. The transit time measurement is accomplished by the use of an electronic clock which starts counting the moment the transmitter fires and stop counting when the received signal reaches a certain amplitude (detection level). The transit time is the elapsed time recorded by the clock.

In normal operating conditions the transit time curve should remain steady around the predicted arrival of E_1. Transit time variations indicate and verify the following:

(1) Tool centering.
(2) Good bonding.
(3) Casing collars.
(4) Fast formations.

The effect of improper tool centering causes the transit time and the amplitude of E_1 to decrease (see Figure 4). A one quarter inch eccentered tool can reduce E_1 by more than 50%. Detecting eccentering is important due to the fact an eccentered tool causes the amplitude curve to indicate better bonding than actually exists.

In areas of good cement bonding, the amplitude of E_1 decreases causing the transit time to increase in two possible ways. First, transit stretching is caused when the amplitude of E_1 decreases to a point that it barely exceeds the E_1 detection level. As a result, E_1 is not detected at the front of the cycle but near the top, which causes a few microsecond change in the transit time curve. (See Figure 5.) Secondly; cycle skipping is caused when the amplitude of E_1 decreases to a point that is below the detection level. As a result, the entire E_1 peak is skipped and a transit time of E_3 is measured. (See Figure 6.)

Casing collars are indicated by a few microsecond increase in the transit time. This increase is due to the change in pipe thickness and continuity of the wave.

Transit times lower than the predicted arrival of E_1 indicate that there is good cement bonding to a formation which has a faster travel time than that of the casing.

CBL Amplitude Curve

The CBL amplitude measurement records the maximum value of the first waveform arrival (E_1) in millivolts. The higher the amplitude, the poorer the cement bond. The amount of signal attenuation is dependent upon the casing circumference that is well bonded with cement. The basis of interpretation is that a high amplitude represents casing free to vibrate due to poor cement bonding. A low amplitude indicates casing that is well bonded with cement. To measure the amplitude of E_1, an electronic gate is opened for a short time and the maximum value of the signal received within the gate is recorded. (See Figure 7.)

As with the transit time curve, there are several conditions that could cause the amplitude curve to respond incorrectly to the true cement bond condition.

- Tool Centralization

Proper tool centralization is essential in large casing and deviated holes. (See Figure 8.) Proper centering can be confirmed by monitoring the transit time curve as stated previously.

- Eccentered Casing

Eccentered casing is a problem similar to tool eccentering except not as severe. Eccentered casing result in moderate amplitudes.

- Fast Formations

Fast formations such as low porosity dolomites affect the CBL amplitude in that the E_1 peak is not casing arrival but that of the formation.

- Microannulus

A small gap between the casing and cement which is caused by the expansion and then contraction of the casing during the cementing process is referred to as a microannulus. This microannulus will usually not allow communication between zones, however, the microannulus appears as a bad cement job.

Variable Density Display

The variable density log (VDL) provides additional information on cementing conditions. While the CBL relates the amplitude of the acoustic wave arrivals to the cement to casing bond, the VDL gives information pertaining to cement to formation bond.

The dimensions of amplitude, time and depth are incorporated in track three to produce the VDL presentation; one axis is time and the other depth. VDL amplitude is transformed into varying shades of gray across the track. The darkest shades correspond to the largest positive amplitudes while the lightest shades correspond to the largest negative amplitudes. (See Figure 9.) Such a display allows examination of the entire composite wave. The VDL aids in interpretation of the CBL as follows:

(1) Strong casing arrivals confirm the CBL in free casing.
(2) Good bond is confirmed by weak casing and strong formation arrivals.
(3) Fast formations can be distinguished from casing arrivals.

(4) If the mud contains gas, the VDL can indicate the amplitude measurement to be unreliable.
(5) Bed boundaries, casing collars and other discontinuities produce characteristic patterns on the VDL.

Interpretation

By looking at the composite waveform and the amplitude relationships a good understanding of cement bond conditions is provided.

The following log examples help to illustrate how the transit time, CBL amplitude and VDL may be interpreted to determine various cementing conditions.

Uncemented Casing (free pipe) - Example 1 (Figure 10)

In uncemented pipe,most of the acoustic energy travels through the casing to the receiver with little coupling to the formation. The casing, since not dampened by the cement, vibrates causing a large casing signal at the receivers and weak or no formation arrivals. Both the CBL and VDL signals agree in showing large casing signals and no change versus depth in the transit time curve, except at casing collars.

CBL/VDL characteristics in free pipe:

(1) High amplitude.
(2) Strong casing signal arrivals on VDL.
(3) Weak formation signals on VDL.
(4) Clear Chevron pattern on VDL at casing collars.
(5) Steady transit time curve.

Good Bond to Casing and Formation - Example 2 (Figure 11)

Good cement bond to both the casing and formation allows the acoustic energy supplied by the transmitter to be transmitted from the casing to the cement and formation with little energy loss in the casing. The result is a strong fromation signal and weak casing arrivals.

CBL/VDL characterisitics in good cement bond to casing and formation:

(1) Low CBL amplitude.
(2) Weak or no casing arrivals on VDL.
(3) Strong formation arrivals on VDL.
(4) High transit time due to cycle skipping.

Fast Formations - Example 3 (Figure 12)

High velocity formations with low porositites can exhibit transit times less than that of casing. In such conditions formation signals may arrive before the casing signal and the amplitude may not indicate the true bond conditions. However, the formation signal can arrive prior to the casing signal only if the cement present is well bonded to the casing and formation.

CBL/VDL characteristics in fast formations:

(1) Early formation arrivals on VDL.
(2) Transit time curve reads less than the expected casing transit time.

Good Bond to Casing No Bond to Formation - Example 4 (Figure 13)

In this condition most of the acoustic energy is transmitted through the casing to the cement. However, due to the lack of acoustic coupling to the formation little energy is transmitted into the formation. Thus, the formation arrivals are weak or non-existent. This condition occurs quite often and can be contributed to mudcake in the borehole.

CBL/VDL characteristics in good bond to casing poor bond to formation:

(1) Low CBL amplitude.
(2) Weak or no formation arrivals on VDL.
(3) High transit time.

Microannulus - Example 5 (Figure 14)

A microannulus is a small gap between the casing and cement which is normally so minute that vertical isolation is maintained. If a microannulus is present the CBL/VDL will indicate a pessimistic amplitude curve and weak to moderate casing signals.

The solution to the microannulus problem is to relog the interval while applying pressure on the casing which will reduce or eliminate the gap. A reduction in amplitude and weaker casing signals on the pressure pass confirm a microannulus condition.

Channeling - Example 6 (Figure 15)

Channeling is a condition where cement is present but does not completely surround or bond to the casing. If there is continuous channeling, then there may be no hydraulic seal. Attentuation of the acoustic energy is proportional to the percent of casing circumference bonded with cement. Therefore, referring to the CBL/VDL, moderate amplitudes, formation arrivals and casing arrivals would be produced. In the case of channeling, pressuring up on the casing would not change the CBL/VDL.

Quantitative Interpretation

The parameter used to evaluate the success of a cement job is the Bond Index. Bond Index is defined by the expression:

$$\text{Bond Index} = \frac{\text{Attenuation in zone of interest (db/ft.)}}{\text{Attenuation in a well cemented section (db/ft)}}$$

Where the Bond Index can be thought of as the proportion of the circumference of the casing which is bonded. A Bond Index of 1 indicates complete bonding. The minium value of Bond Index which is necessary for zone isolation varies depending on local conditions. Figure 16 shows the length of cemented interval required for zone isolation for varying Bond Indexes and casing sizes. (See Example 7; Figure 17).

Operational Procedure

In the operation of the cement bond log it is advisable to run two logging passes, one with zero PSI well pressure and one with sufficient pressure to eliminate or reduce a microannulus. This procedure can help discriminate a channel from a possible microannulus.

Even when using proper interpretation techniques, many instances will occur when the CBL/VDL Log will not alone define the actual condition of the cement. The main interpretation problems are presented below:

(1) The omnidirectional characteristics of the CBL/VDL imply good centralization to ensure simultaneous first arrivals from all azimuths.

(2) The omnidirectional characterisitics make it difficiult to distinguish high strength cement with a channel from a even distribution of low strength cement, because the amplitudes may be the same in both cases.

(3) The case of a microannulus implies practically free pipe.

(4) In high velocity formations, formation signals arrive before those of the casing and transit times are therefore no longer correct.

THE CEMENT EVALUATION LOG

As stated on the previous page, the Cement Bond Log does have interpretation limits under certain circumstances. Schlumberger's new Cement Evaluation Log (CEL) can be used in conjunction with the Cement Bond Log to obtain a much better interpretation of the total cement condition present in the well. The Cement Evaluation Tool (CET) is an ultrasonic device consisting of 8 transducers spiralled helically around the sonde so that the condition of the cement can be investigated in 8 radial directions around the borehole. This provides a distinct advantage over the sonic logging tool (CBL/VDL), which an omni-directional device. The Cement Evaluation Log can make a distinction between low compressive strength cement and high compressive strength cement containing a channel. This channel detection capability then allows decisions to be made concerning the likelihood and success of cement squeeze cement jobs based on the position and size of the channel. The Cement Evaluation Tool is also somewhat less sensitive to a microannulus condition than the Sonic Logging Tool and therefore, using the two tools, the condition can be detected at much lower wellhead logging pressures. Also, the Cement Evaluation Tool is not affected by the presence of fast formations, which can greatly aid in channel detection through an interval where fast formations are present.

Standard Log Presentation

On a standard logging job, information from the Cement Evaluation Tool is presented using two formats; the cement presentation and the calipers presentation. Both formats will be discussed below.

Cement Presentation

The standard cement presentation is pictured in Figure 18. The most important and informative part of the presentation is the Cement Map in track three. The map is an image presentation based on cement compressive strength as inferred by the

Cement Evaluation Tool. The map can be envisioned as a 360^{0} view of the borehole with the strength of the cement behind the casing presented. The available shadings can range from totally white to totally dark depending upon the inferred compressive strength. The map is normally adjusted so that an inferred compressive strength of 0 psi from any of the transducers would appear as totally white shading on the map, and an inferred strength of 1500 psi would be coded as totally dark. As a result, an area of white shading continuing vertically on the map would be identified as a channel in the cement. The width of the channel could be identified simply by its horizontal extent on the map. Low compressive strength cement would be indicated by shading between white and dark. The Cement Map can be "image rotated" so that the low side of the borehole is in the center of the map.

The remainder of track three (far right) contains 8 small tracks corresponding to transducers 1-8. These tracks contain flags when either of two conditions exist; formation reflections or gas behind the casing. When a formation reflection occurs, a small dark square is visible in the track corresponding to the transducer indicating the reflection. A formation reflection flag indicates that sound energy from the transducer incident upon the casing traveled through the casing and cement to the borehole wall. The sound energy reflected off of the formation wall and traveled back to the transducer. This is an indication that good coupling exists via the cement from the casing to the formation; i.e., good cement is present. A gas flag is a thin line that occurs in the track corresponding to a transducer indicating gas cut cement or free gas behind the casing. If gas flags are present, the compressive strength of the cement existing behind the casing has effectively been reduced to zero by the presence of gas in the cement. Therefore, any hydraulic fracuring or acidizing operation in the area of gas cut cement may introduce communication to undesired zones via the gas cut cement. Gas cut cement is normally not a condition that can be repaired by squeeze cementing. However, once detected by the Cement Evaluation Log, the cement program for a future well could be changed in order to stop the condition from happening again.

Track two consists of a relative bearing curve, mean ratio curve, and maximum and minimum cement compressive strength curves. The relative bearing curve (RB) presents the angle in degrees between transducer #1 and the low side of the hole and is used by the software to image rotate the cement map. It also can indicate the amount of tool twist when moving uphole. The mean ratio curve (WWM) is the average of the normalized response from transducers 1-8. (The normalized response from each transducer is converted to a value of compressive strength and will be discussed later.) WWM can also be used as an indicator of the average cement condition behind the casing. Values lower than "1" usually indicate that cement is present behind the casing, while readings averaging close to "1" indicate that no cement is present. Values greater than 1 indicate the presence of gas cut cement or free gas. The maximum and minimum cement compressive strength curves (CSMX and CSMN) are the maximum and minimum compressive strength indicated by the 8 transducers at each sample interval. The two curves are averaged vertically over 4 feet and horizontally between adjacent transducers. Therefore, in areas where CSMN drops to zero, a potentially squeezable channel exists, i.e., the channel is sufficiently wide and long enough to accept a cement squeeze.

Track one contains information relating to depth and quality control. For depth control, a gamma ray curve and casing collar curve are presented. The casing collar curve (CCLU) is an ultrasonic collar trace generated from time measurements associated with each transducer. Also generated from travel times measured at each transducer is the average caliper curve (CALU). CALU is an ultrasonic caliper measurement which represents the average internal diameter of the casing. CALU can be used to infer the weight of the casing and is also used to pick the normalization parameters for the cement evaluation curves. The eccentricity curve (ECCE) is a measure of the distance between the geometric center of the casing and the geometric center of the tool. The Cement Evaluation Log is less sensitive to tool eccentering than the Cement Bond Log and values of ECCE less than .025 should not affect the log. The final curve, fluid travel time (FTT), represents the time for sound to travel through 1 foot of borehole fluid. FTT is measured from a reference transducer located vertically along the axis of the sonde, and can be used to indicate the type of borehole fluid present in the casing. It is also used by the software to convert the individual transducer travel time measurements into distance measures for caliper calculations.

Calipers Presentation

The calipers presentation, Figure 19, is normally presented along with the cement presentation on a standard cement evaluation logging job. The presentation can provide valuable information concerning the internal condition of the casing in the well. The 8 CET ultrasonic transducer travel time measurements can be converted to 4 independent ultrasonic caliper values using the fluid travel time measurement. These 4 independent caliper readings are presented in track three of the calipers presentation. Additional caliper information is presented in track one in the form of a "Casing Cross Section". The Casing Cross Section is generated from the average of the 4 independent calipers and can be envisioned as an actual cross section of the casing. It can be used in a quicklook manner to detect casing weight changes and major internal defects in the casing. Immediately to the right of the casing cross section is an ovality curve (OVAL) generated from the maximum caliper minus the minimum caliper reading. The ovality curve presents the "out-of-roundness" of the casing. Track one also contains a fluid travel curve identical to that on the cement presentation. As the calipers are computed from the fluid travel time, any invalid fluid travel time measurements will lead to inaccurate caliper measurements.

Relative bearing (the same as on the cement presentation) and tool deviation are presented in track two. Tool deviation (DEVI) is generated from a pendulum assembly located in the downhole cartridge, and since the tool is centralized inside the casing, in most cases represents the deviation of the casing in the wellbore.

CET Normalization

The response of each CET transducer is normalized through the use of two equations, which will be discussed below. Once the CET response has been normalized through the normalization constants present in the equations, the compressive strength values presented on the CET log will be correct.

Each of the 8 CET transducers is addressed separately in sequential order around the sonde. Upon being addressed, the transducer is fired 2 times: once for the W2 measurement and once for W3 measurement (each measurement will be discussed below). At each transducer firing, a pulse of ultrasonic energy is released from the transducer with a frequency bandwidth sufficient to cause the casing to vibrate at its specific resonant frequency. The return waveform from the casing is then received by the same transducer and consists of two components: a reflection of the incident pulse, followed by an exponential section representing the resonance of the casing. The rate of decay of the exponential section of the waveform can be use to infer the strength of the cement behind the casing.

Energy windows are used to determine the decay rate of each return waveform. The first energy window, called W2, is placed on the waveform as shown in Figure 20. The energy within this window is calculated by rectifying and then integrating the section of waveform present within the window. The placement and width of the W2 window is set with respect to the casing size present in the wellbore. This placement will allow a maximum energy difference to be observed between high and low strength cement. The difference between high and low strength cement in terms of the resultant W2 measurement is presented in Figure 21.

Changes in the measured W2 value can also occur as a result of an overall change in the return waveform strength (see Figure 22). In order to insure that these changes will not be inferred as changes due to the condition of the cement behind the casing, each W2 measure is compensated for overall waveform return strength by dividing W2 by the peak amplitude of the associated waveform, called W1, (see Figure 23). W2/W1 then represents a measurement that is independent of overall return waveform strength. As an additional compensating factor, an automatic gain is also applied to each return waveform which maintains the W1 value between prescribed upper and lower limits.

In order to present each transducer response in terms of compressive strength of the cement behind the casing, each W2/W1 value is referenced to a known value, termed the "free pipe value". This free pipe value, called W2FP, is defined as the W2/W1 value observed when logging through free casing with <u>fresh</u> water behind the casing. The W2FP value used for each logging case is different and depends on the casing size and weight, the borehole fluid type and weight, and the depth of the logging interval. Proper values for each logging case are calculated from tabulated charts by the logging engineer at the wellsite.

By dividing W2 by W1, the resultant value obtained will be driven to "1" each time the specific transducer is across from free pipe with fresh water behind the pipe, i.e.,; a known reference point exists. The first normalization equation is then:

$$W2N = \frac{W2}{W1} * \frac{1}{W2FP}$$

Where W2N stands for W2 normalized. W2N is computed for each transducer at each sample interval and then converted to a value of compressive strength through an algorithm dependant upon the nominal thickness of the casing.

When the cement quality is high, some cases will exist where a portion of the sound energy from the transducer incident upon the casing wall will travel through the casing and the cement to the borehole wall. If the surface of the borehole is oriented in a plane parallel to the face of the transducer and is fairly smooth, some sound energy may reflect off the borehole wall and travel back to the transducer. This additional energy incident upon the transducer may add to the W2 measurement resulting in higher than normal W2 values, which would in turn cause pessimistic compressive strength values. If not compensated for, this condition could lead to indications of false channels on the log. The CET software uses a "Formation Reflection Logic" to detect and compensate for reflection of this type.

Non-exponential decay of the return waveform is evident when a formation reflection occurs, see Figure 24. Therefore, if this non-exponential decay can be detected, a formation reflection can be inferred. This is accomplished by the placement of a second energy window on the waveform as in Figure 25. This window is located immediately after the start of exponential decay in a manner so that under no circumstances would a formation reflection enter the window. The energy in the window is calculated in the same manner as in the W2 window and is called W3. W3 is also divided by W1 and the resultant divided by a normalization factor called W3FP. W3FP is the W3/W1 value observed when logging through free pipe with fresh water behind the pipe. The W3 normalization equation is then:

$$W3N = \frac{W3}{W1} * \frac{1}{W3FP}$$

As with W2FP, W3FP is also picked from tabulated charts.

A formation reflection is detected by using the calculated W3N to infer a maximum approximate value for W2N if the decay of the waveform were exponential. If the actual W2N is higher than the value predicted by the formation reflection logic, the decay is termed non-exponential, and a formation reflection is inferred. A formation flag appears on the log, and if the computed compressive strength for the transducer involved is less than 1000 psi, the compressive strength is taken as 1000 psi. This eliminates the possibility of a formation reflection appearing as a channel on the log.

A graphical representation of the CET interpretation model is presented in Figure 26. The model consists of a crossplot of W2N vs. W3N points. Crossplotted points corresponding to exponential decay (points not affected by formation reflections) will fall on the line labeled as the theoretical line, while points corresponding to formation reflections will fall above the "Formation Reflection Boundary" line. If a CET log is properly normalized, the main locus of points corresponding to exponential decay will fall on the theoretical line, and formation reflection points will fall in the formation reflection region and will be properly identified and compensated for on the log.

CET Operational Procedures

Under most circumstances, the Cement Evaluation Log is run in conjuction with the Cement Bond Log. A new modification allows the two to be run in combination in some areas. Pressure equipment should be available at the wellsite in the event a microannulus condition is evident. If pressure is applied when logging with the Cement Bond Log, the same amount of pressure should also be applied with the Cement Evaluation Log. The recommended logging program would be to first log the CBL with no surface pressure applied followed by a pass with 1000 psi surface pressure. This should be followed by a zero and 1000 psi pass with the CET. In certain situations where very good cement is evident on both logs with no surface pressure applied, the 1000 psi passes would not be necessary.

In order to obtain a good CET log, no gas can be present in the wellbore through the logging interval. Gas percoluating from existing perforations may severely hamper the CET response in terms of both cement and caliper information. Heavy muds may also cause poor results due to low transducer return signals. If possible, the mud should be circulated out replaced by a clear fluid, either fresh or brine.

Interpretation

In this section, various log examples will be presented in order to illustrate the typical response of the Cement Evaluation Tool to frequently encountered cement conditions.

Cement Top - Example 1 (Figure 27)

This example presents the CBL and CEL response to a cement top. It can be seen on the CEL that the compressive strength curves both drop to zero and the cement map presents totally white shading. The mean ratio curve (WWM) is reading around "1", which is an indication that the density of the material behind the casing above the cement top is close to that of fresh water.

Channeling - Example 2 (Figure 28)

The first set of logs in Figure 28 are examples of an instance where both the CBL and CEL are indicating channeled cement. However from the CBL alone, it would be very difficult to tell whether a channel, low strength cement, or a microannulus were present. By referring to the CEL a distinct channel can be seen in the cement map, and from the width of the channel and the fact that CSMN drops to zero, it can be concluded that a squeeze cement job should be implemented.

The second set of logs in Figure 28 presents an example where the CBL gave no indication of the presence of a channel. However, by referring to the CEL it can be seen that a very narrow channel indeed does exist. In this case due to the narrow width of the channel, a cement squeeze might not be successful. Even so, if communication with an unwanted zone were evident after the well was on production, the reason would be apparent.

Low Compressive Strength Cement - Example 3 (Figure 29)

In this example, the CBL indicates that possible channeling, microannulus, or low strength cement is present. The CEL indicates that the actual condition is low strength cement. This can be determined by the spotty light shading on the cement map and the relatively low cement compressive strength curves. In this case, a cement squeeze could not improve the condition, and caution must be exercised when hydraulically fracturing in the presence of poor strength cement.

Fast Formation - Example 4 (Figure 30)

The top example is a case where the CBL is severely affected by fast formation arrivals, therefore rendering the bond index curve useless. Form the CEL, a quantative cement analysis can still be achieved from the cement compressive strength curves as the CET is not affected by fast formation arrivals.

In the bottom example, the presence of fast formation arrivals on the CBL completely mask a channel. The channel is clearly identified on the Cement Evaluation Log.

Gas Cut Cement - Example 5 (Figure 31)

When the cement behind casing is cut with gas, its compressive strength is effectively reduced to zero. Therefore, any sort of fracturing or acidizing operation could introduce communication to unwanted zones. In many cases the CBL alone will not indicate the presence of gas cut cement as seen in this example. However, the CEL is a very good indicator of gas cut cement since its response is dependent upon the strength of the material behind the casing. When gas cut cement is present, four indicators become apparent on the CET log; gas flags appear, the compressive strength curves drop to zero, the cement map becomes totally white (since it is dependent upon inferred compressive strength), and WWM is above "1", indicating that the material behind the casing is less dense than fresh water. In order to determine the squeezability of a gas cut cement zone, both the CEL and the CBL should be consulted. If free gas is present behind the casing, the CBL will indicate free pipe and the CEL will present gas flags and WWM values from 1.8 to 2.5. If hydraulic isolation is desired, a squeeze cement job would be necessary. Gas cut cement will appear as a cemented zone on the CBL and on the CEL, WWM values from 1 to 1.5 will be present. Caution should be exercised when attempting to squeeze a gas cut cement zone as cement is present.

Microannulus - Example 6 (Figure 32)

As mentioned earlier, the Cement Evaluation Tool is less sensitive to a microannulus condition than the Cement Bond Log, and therefore can provide correct answers at comparably lower wellhead pressures. In this example, the CEL was not affected at all by the presence of a microannulus. The CBL, however, was affected on both the zero pressure and 1000 psi pass. By using the information provided by the two logs it was concluded that a microannulus did exist and a cement squeeze was definitely not necessary.

CASING INSPECTION WITH THE CEMENT EVALUATION LOG

This section of the paper will focus on the casing evaluation capabilities of the Cement Evaluation Tool. Casing Evaluation is accomplished by three measurements taken from each return waveform at each of the eight CET transducers. Figure 33 presents a typical waveform and the measurements obtained for casing evaluation. The generated logs can present a detailed look at internal casing geometry, internal casing roughness, and casing thickness in 8 radial directions around the casing. All of the necessary measurements can be taken on the same trip into the borehole as when evaluating the cement.

The first measurement is a two way travel time value, termed DTT, which represents the time for sound to travel from the face of the transducer to the casing wall and back to the transducer. This time measurement can be converted to a distance from the face of the transducer to the casing wall by using the fluid travel time calculated from the reference transducer #9. The physical distance from the transducer face to the geometric center of the logging tool is a known value and can be added to the calculated distance from above to obtain a total distance from the geometric center of the tool to the casing wall. This process is carried out for each transducer to yield 8 independent distances from the geometric center of the tool to the casing wall. Using the eccentricity of the tool, these values can be corrected to the geometric center of the casing yielding a final result of 8 internal radii referenced from the geometric center of the casing. These values can be presented on the log in the form of an internal radii map which will be discussed later.

The next measurement (W1) represents the overall return strength of the waveform. Decreases in the W1 value indicate that some of the sound energy from the transducer incident upon the casing wall was scattered by roughness on the inner surface of the casing; i.e. not all of the waveform energy returned to the transducer. A W1 amplitude map can then indicate radial changes in the return waveform strength, which can be used to infer casing internal roughness.

The final measurement is taken from the exponential section of the waveform. A frequency analysis is performed on this section of the waveform in order to identify the resonant frequency of the casing. This resonant frequency can then be converted to a casing thickness value, and used to present 8 values of thickness radially around the casing.

The internal radii and internal amplitude measurements can be obtained with the standard CET tool, while the additional measurement of casing thickness can be obtained using the new digital CET cartridge.

Presentations

The measurements discussed above can be presented in the form of an ULTRASONIC CASING INSPECTION PACKAGE which is comprised of three individual presentations.

Internal Radii Presentation

The standard internal radii presentation is shown in Figure 34. Track one contains 8 ultrasonic internal radii measurements corrected for eccentering, an ovality curve, and a tool deviation curve. As mentioned earlier, the radii measurement are referenced from the center of the casing and represent the radii values one would obtain if viewing from a reference point at the geometric center of the casing. The radii are presented with a sensitivity of 1 inch per track with the readings increasing to the right. The ovality curve is the same as presented on the standard CET calipers presentation, and restating, represents the degree of casing out-of-roundness. Tool deviation is also the same as with the caliper presentation, and represents the deviation of the casing in most circumstances. Track two contains a CASING CROSS SECTION (generated from the average of the internal radii measurements) and a max-min radius overlay. The cross section can be used to obtain a feel for the overall average internal radius of the casing, while the max-min overlay can indicate the degree of variance of radii values radially around the casing. An INTERNAL RADII MAP is presented in track three. The map represents a 360^0 view of the casing inner surface, with decreases in the internal radii values indicated by white shading and increases of internal radii indicated by darker shading. Upper and lower radii limits are set for the map so that if a specific internal radii measurement were less than the lower limit, the shading corresponding to that transducer would be totally white and if above the upper limit, totally black shading would occur. Six incremental shadings between white and black would be present for radii values between the two limits. As with the cement map, the internal radii map can be image rotated.

Internal radii measurements are basically representative of the internal geometric conditions of the casing. Casing defects, whether metallic or non-metallic in nature, can be detected by the measurements. The presentations greatest value is that of general casing internal geometry; highlighting such conditions as overall internal casing I.D. changes (weight changes), localized defects, and continuous defects. (See Figure 35.)

Return Amplitude Presentation

A second presentation in which the internal radii map can be replaced by a return amplitude map is available. As mentioned earlier, return amplitude strength of each CET waveform can be an indicator of internal casing roughness. In SMOOTH casing, each transducer will possess a characteristic W1 value. Decreases from this smooth pipe value indicate that some of the energy incident upon the casing did not return to the transducer because of roughness on the casing inner wall.

The internal amplitude map presents decreases in the return W1 value as areas of darker shading as in Figure 36. The degree of shading indicates the relative amount of return signal loss.

Since any roughness on the casing inner wall, whether from metallic or non-metallic origin, will be detected by the internal return amplitude map, the map can be used in conjuction with Schlumberger's Pipe Analysis Log to differentiate between metallic and non-mettallic roughness on the inside of the casing. Figure 37 is an example of such a case. The Pipe Analysis Log shows no indication of any serious conditions on the casing inner surface from 5470' - 5495'. However, the internal amplitude map shows a sizeable area of return signal loss over the same interval covering approximately 25 percent of the casing. Since the PAL response is basically representative of metallic condition of the casing, and the internal amplitude map to ANY roughness on the inner surface of the casing, it can be concluded that a non-metallic buildup exists. This anomaly can be further confirmed by the internal radii presentation which indicates that a buildup .07" to .1" thick exists at this point in the well. This could be valuable information in the event a close tolerance plug or packer were to be subsequently run in the well.

Ultrasonic Casing Thickness Presentation

A resonant frequency can be obtained from the exponential section of each waveform by frequency analysis, (Figure 38). This frequency can then be used to obtain casing thickness in 8 radial directions around the casing. The results are presented in a casing cross-section display as indicated in Figure 39. Tracks two and three contain 4 independent casing cross-sections generated with internal radii and thickness information from diametrically opposed transducers. The inner surfaces of the cross-sections are generated from internal radii values, while the outer surfaces are generated from the internal radii values plus the calculated thickness values. Track one contains an average caliper curve, ovality, eccentricty, and a max-min thickness overlay. The max-min thickness overlay can be used to obtain an indication of the range of radial thickness variation, while the individual cross-sections can be used to spot detail thickness variations.

Figure 40 indicates the typical response that would be observed upon encountering a casing weight change. As a lighter joint is encountered, the average caliper curve increases, and the max-min thickness both curves decrease. The cross-sections highlight the weight change as increases in the internal radii values and a constant value for the external radii.

Areas of metal loss can be detected as in Figure 41. In this specific case, a cement retainer was set at 5913', and after a cement squeeze, was drilled out. The max-min thickness curves and the cross-sections highlight the fact that approximately .07" of metal was lost around the inner surface of the casing thru the area of the retainer as a result of the drilling operation.

Figure 42 is an example in which a substantial radial thickness variation was observed. This is basically indicated as a bulging on the inner surface of the casing cross-sections.

Casing Inspection Applications

Perhaps the strongest application of the CET casing inspection presentations would be in the area of casing monitoring. If the presentations were generated on a new well, the geometric conditions and casing thickness values could be established for the new casing. Then, throughout the life of the well subsequent runs with the CET would indicate any variations from the base values for internal radii, internal casing roughness, and casing thickness.

Applications also exist in the area of evaluating damage to casing caused by drilling wear on deep wells.

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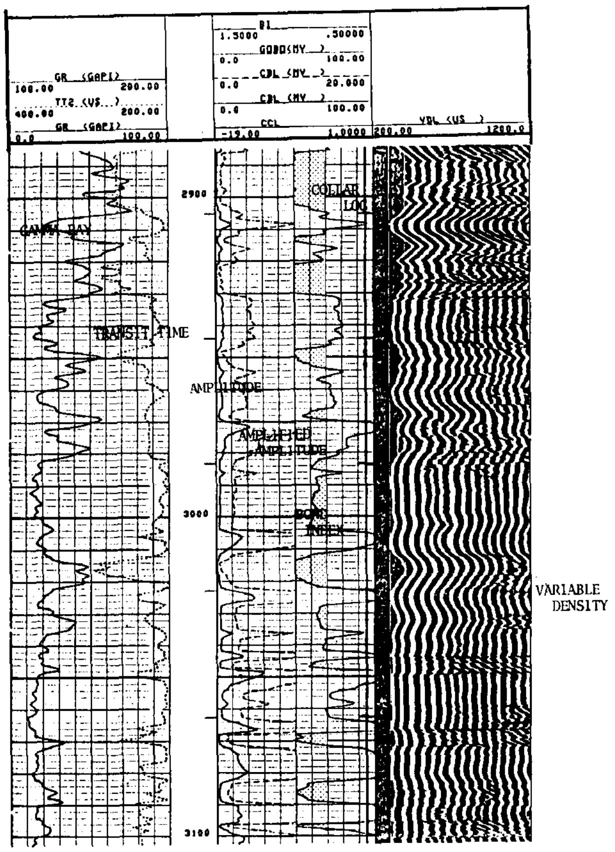


Figure 1

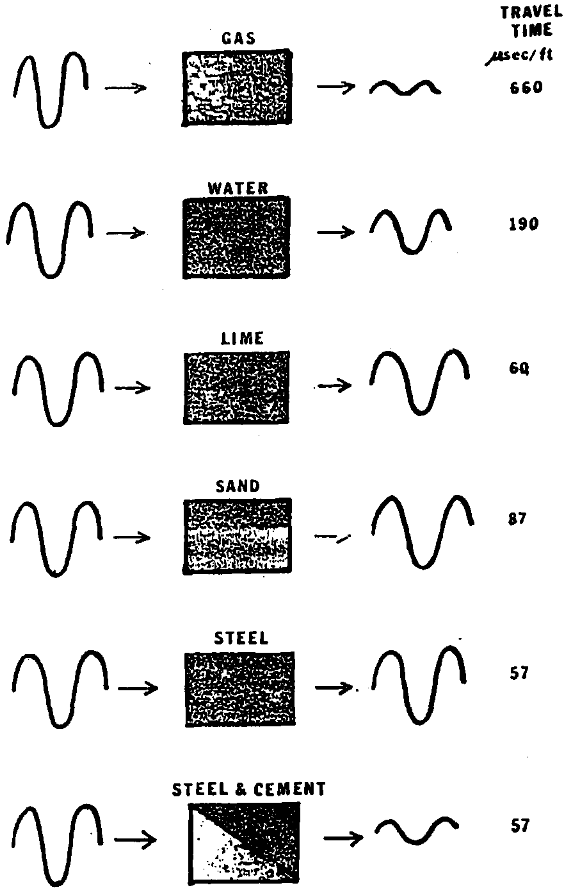


Figure 2

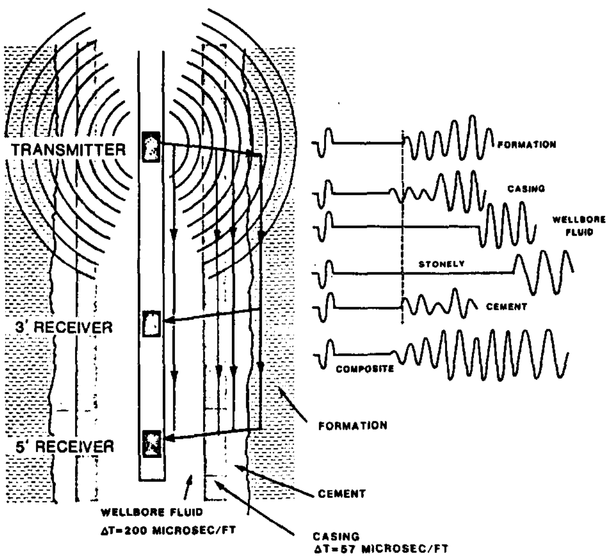


Figure 3

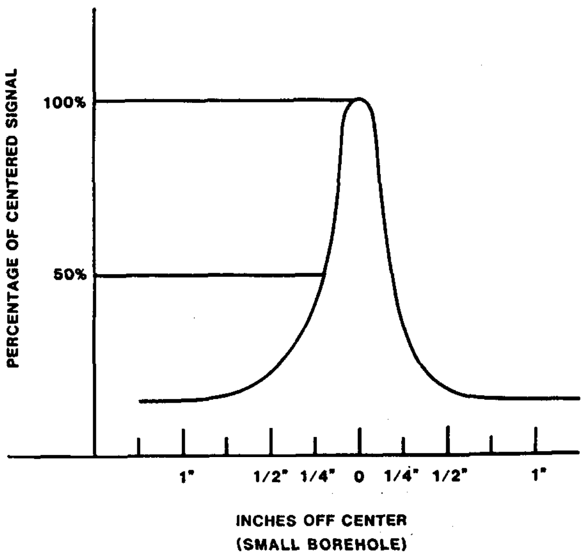


Figure 4

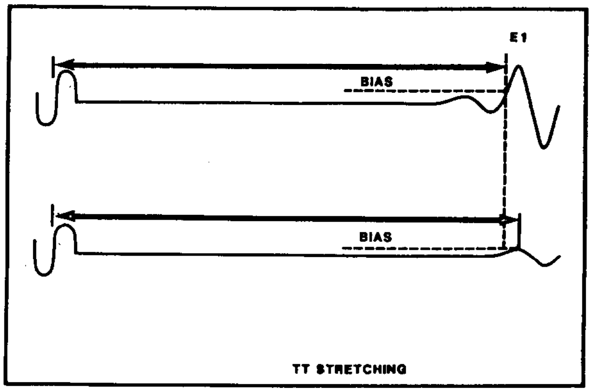


Figure 5

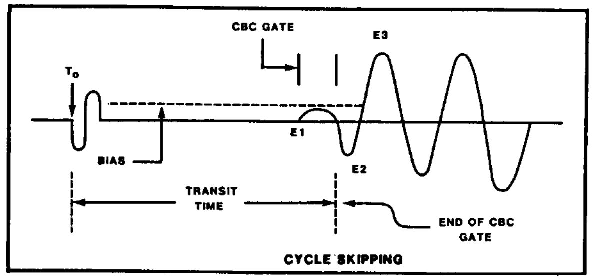


Figure 6

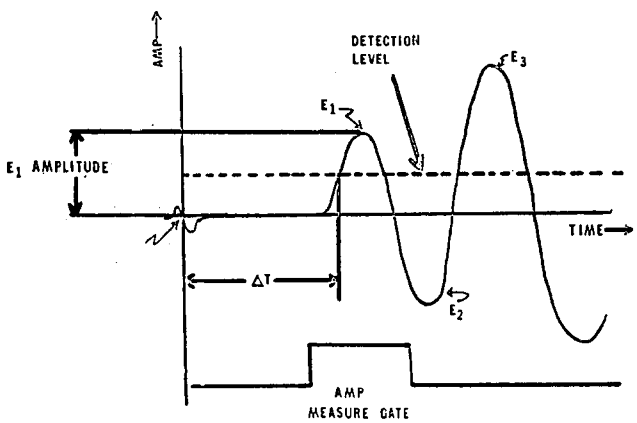
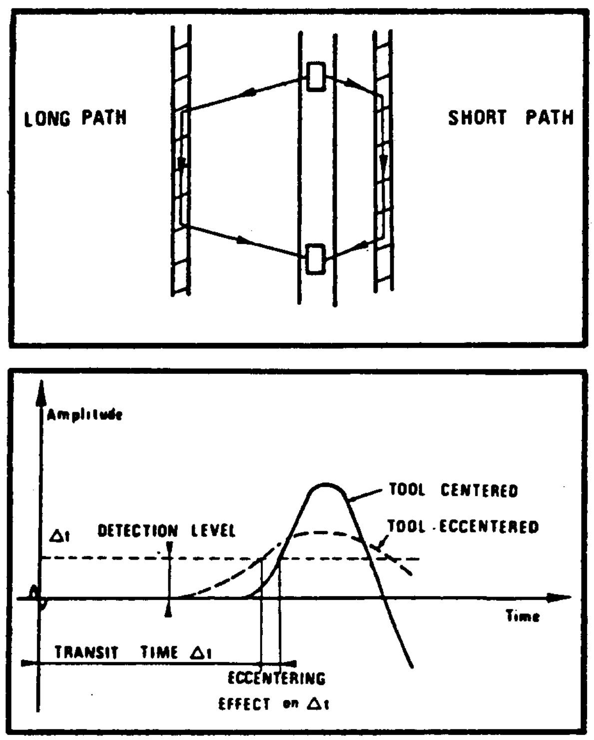


Figure 7



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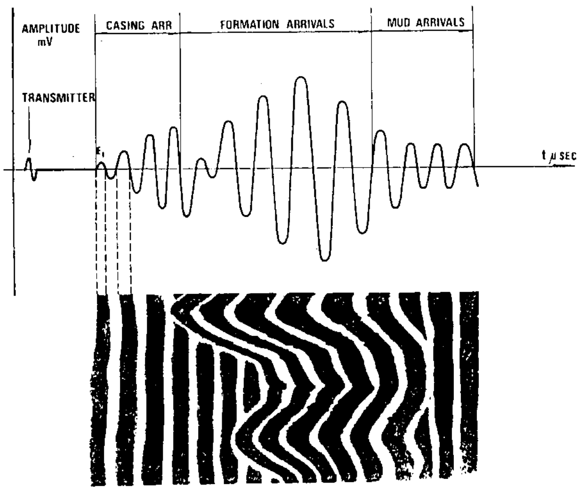

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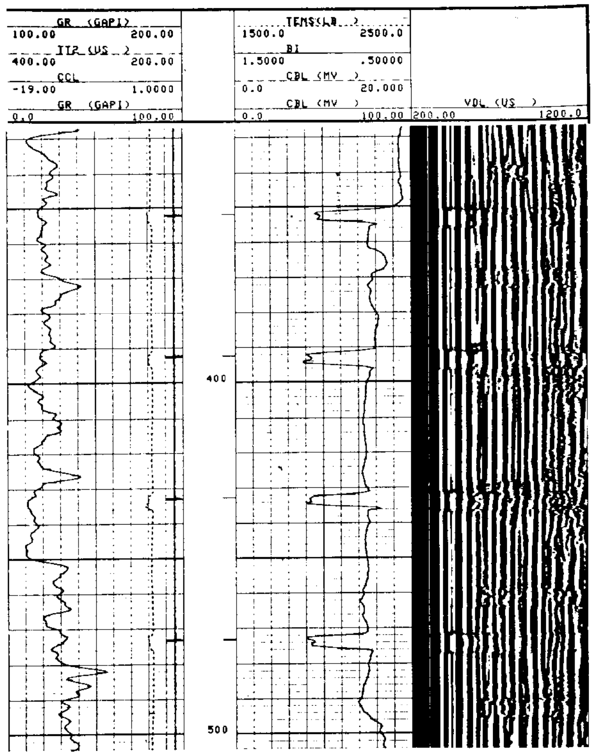


Figure 10 - Example 1

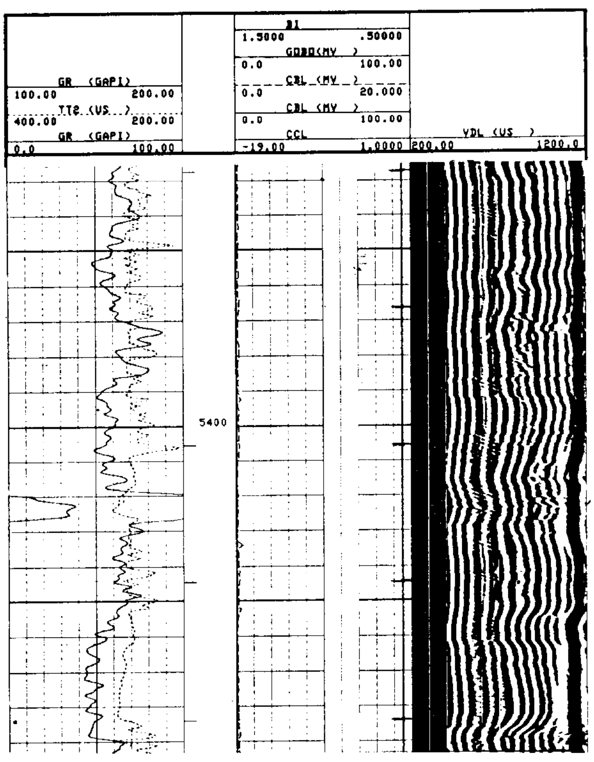


Figure 11 - Example 2

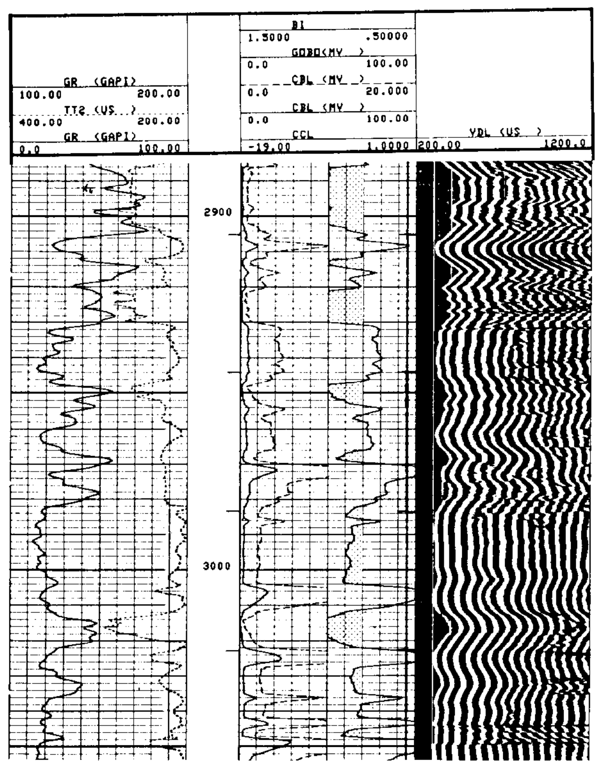


Figure 12 - Example 3

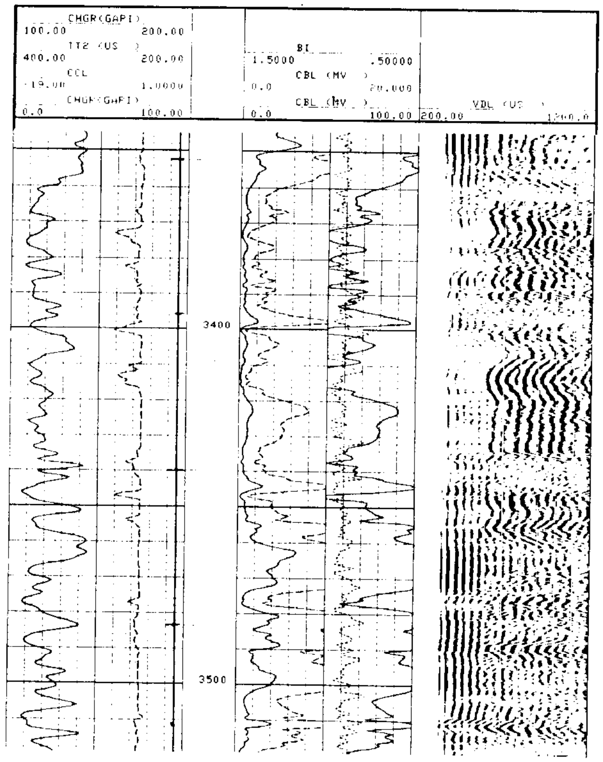


Figure 13 - Example 4

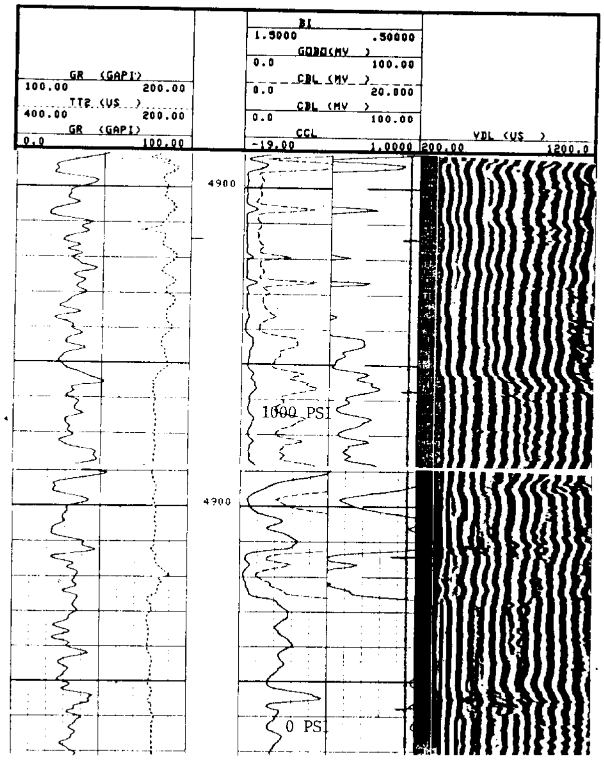


Figure 14 - Example 5

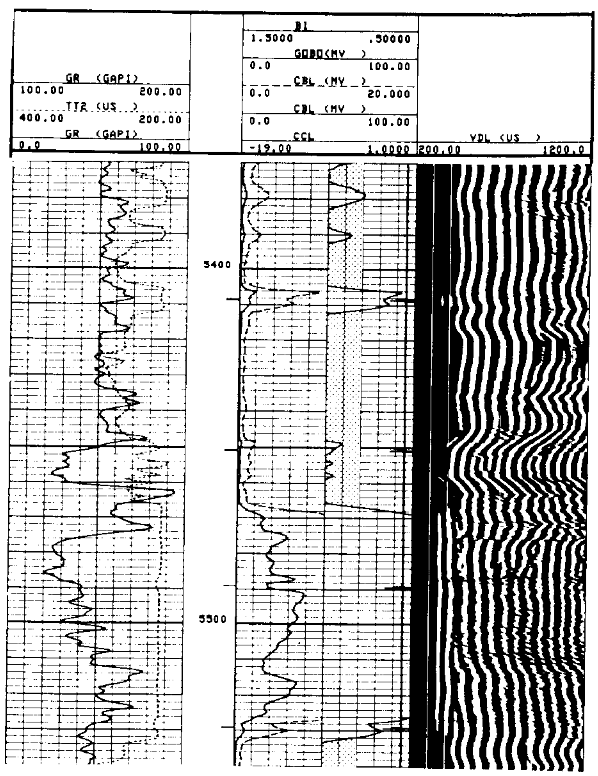


Figure 15 - Example 6

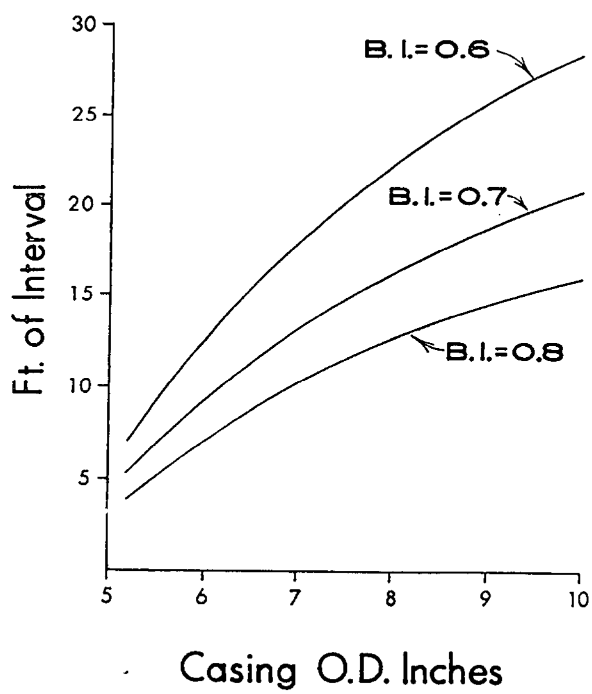


Figure 16

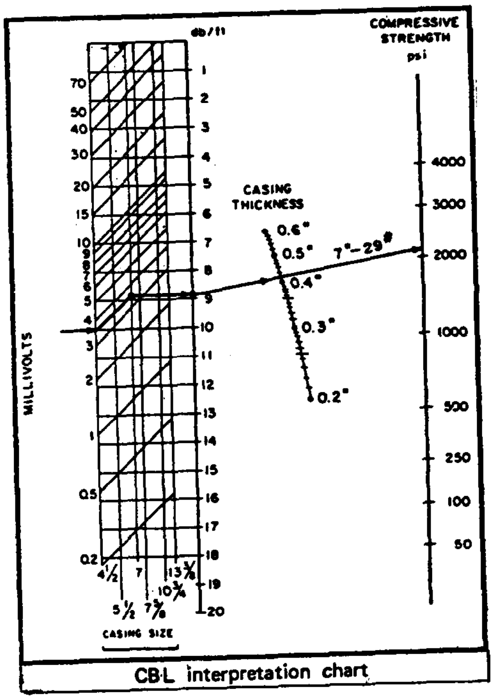


Figure 17

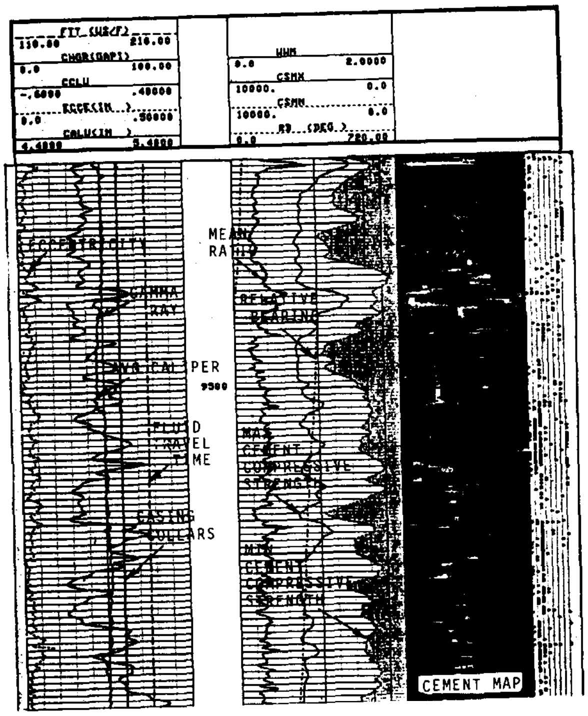


Figure 18 - Standard cement evaluation log presentation

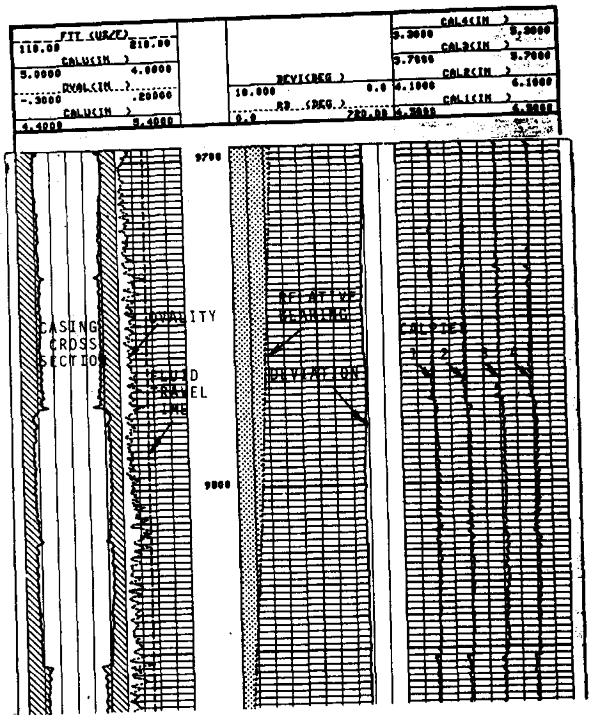


Figure 19 - Standard caliper presentation

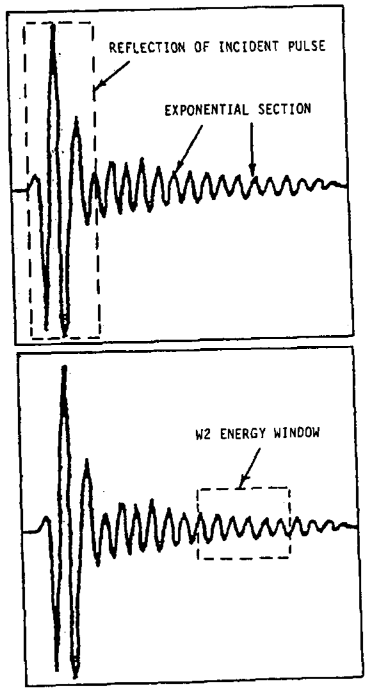


Figure 20 - CET return waveform

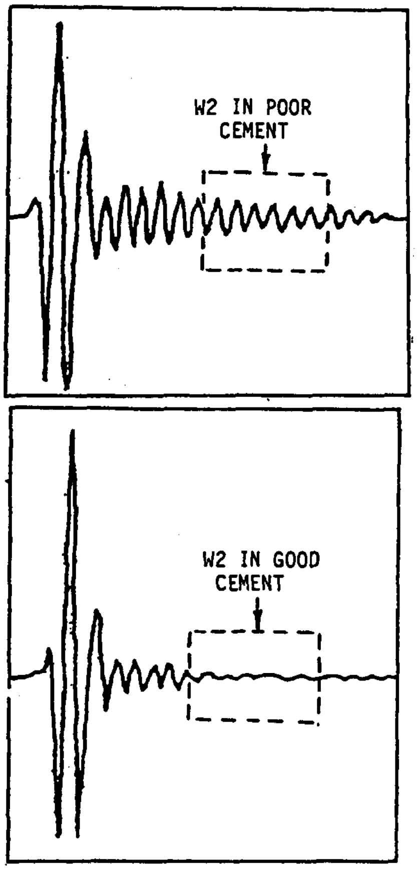


Figure 21

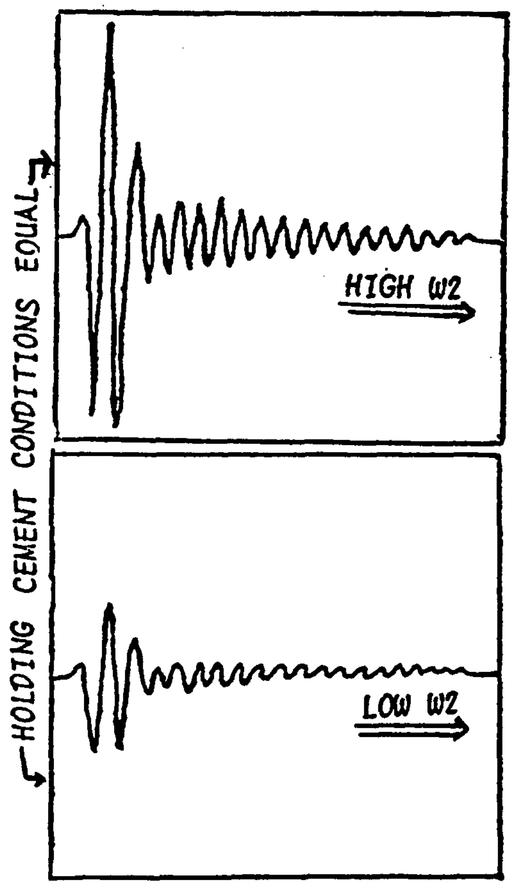


Figure 22 - Overall strength of return waveform affects measured W2 value

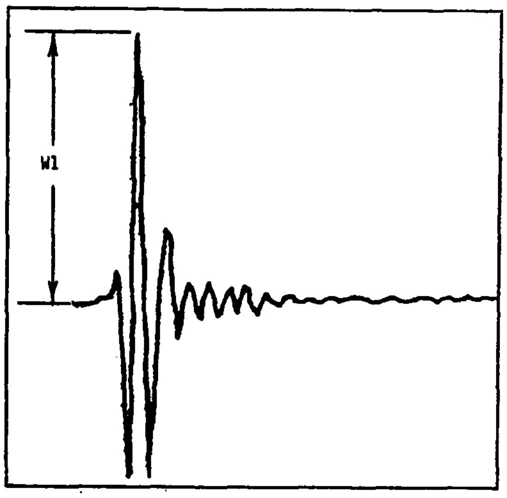


Figure 23

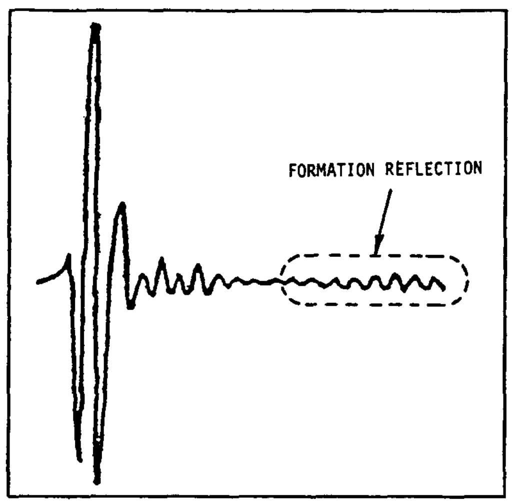


Figure 24

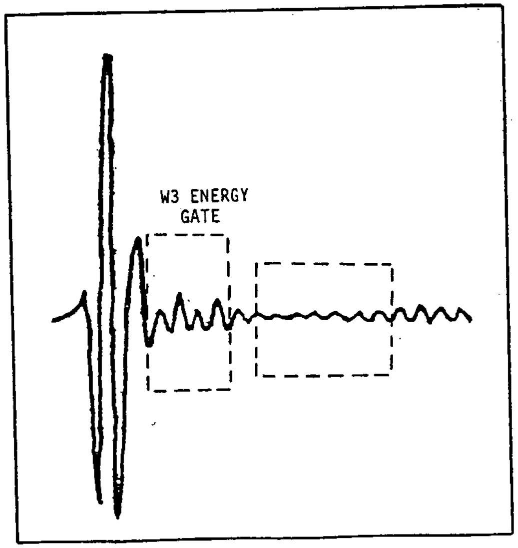


Figure 25

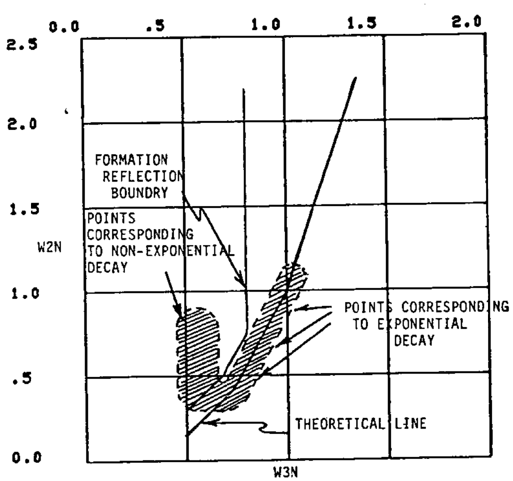


Figure 26 - CET interpretation model

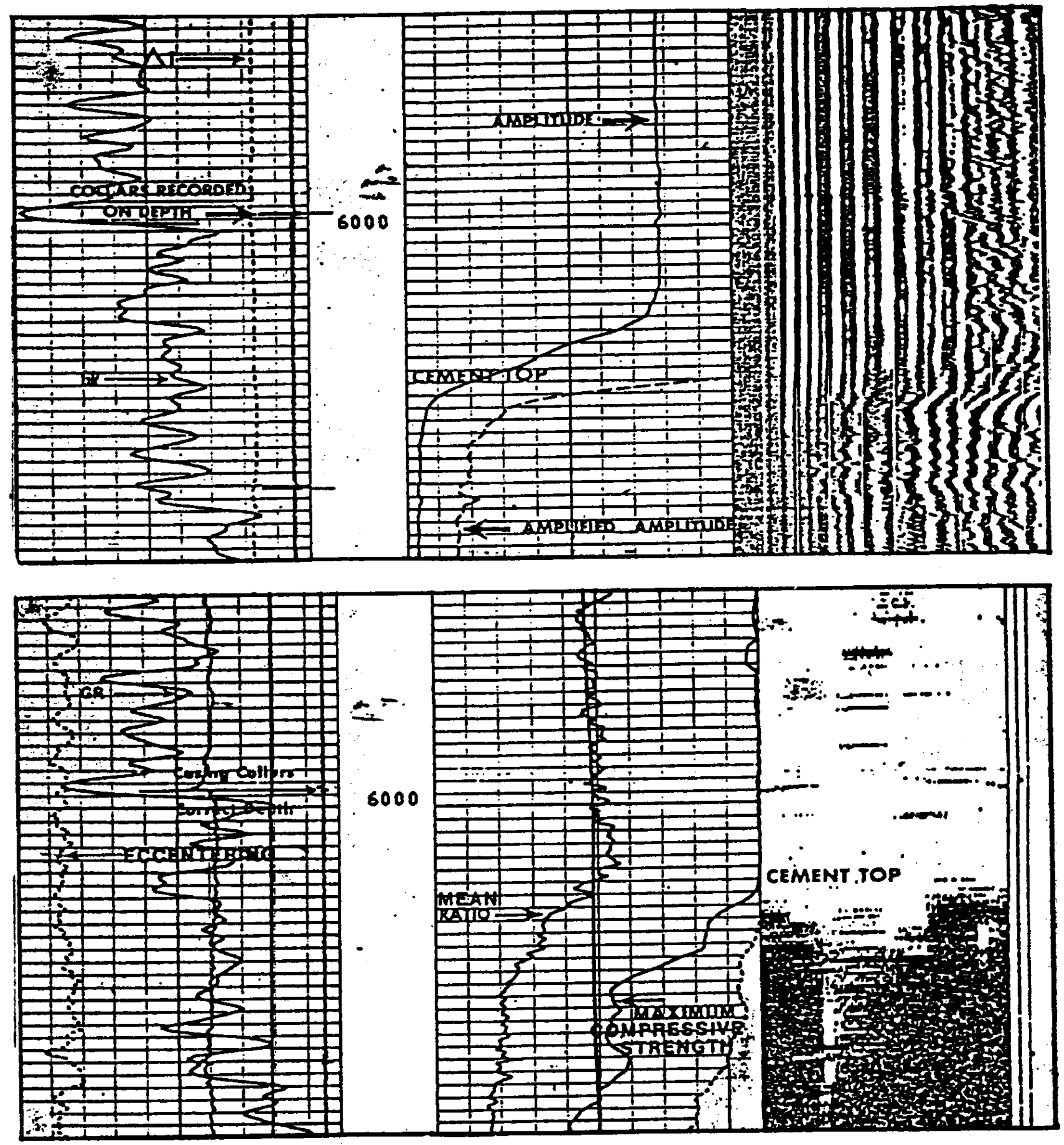


Figure 27 - Example 1 (cement top)

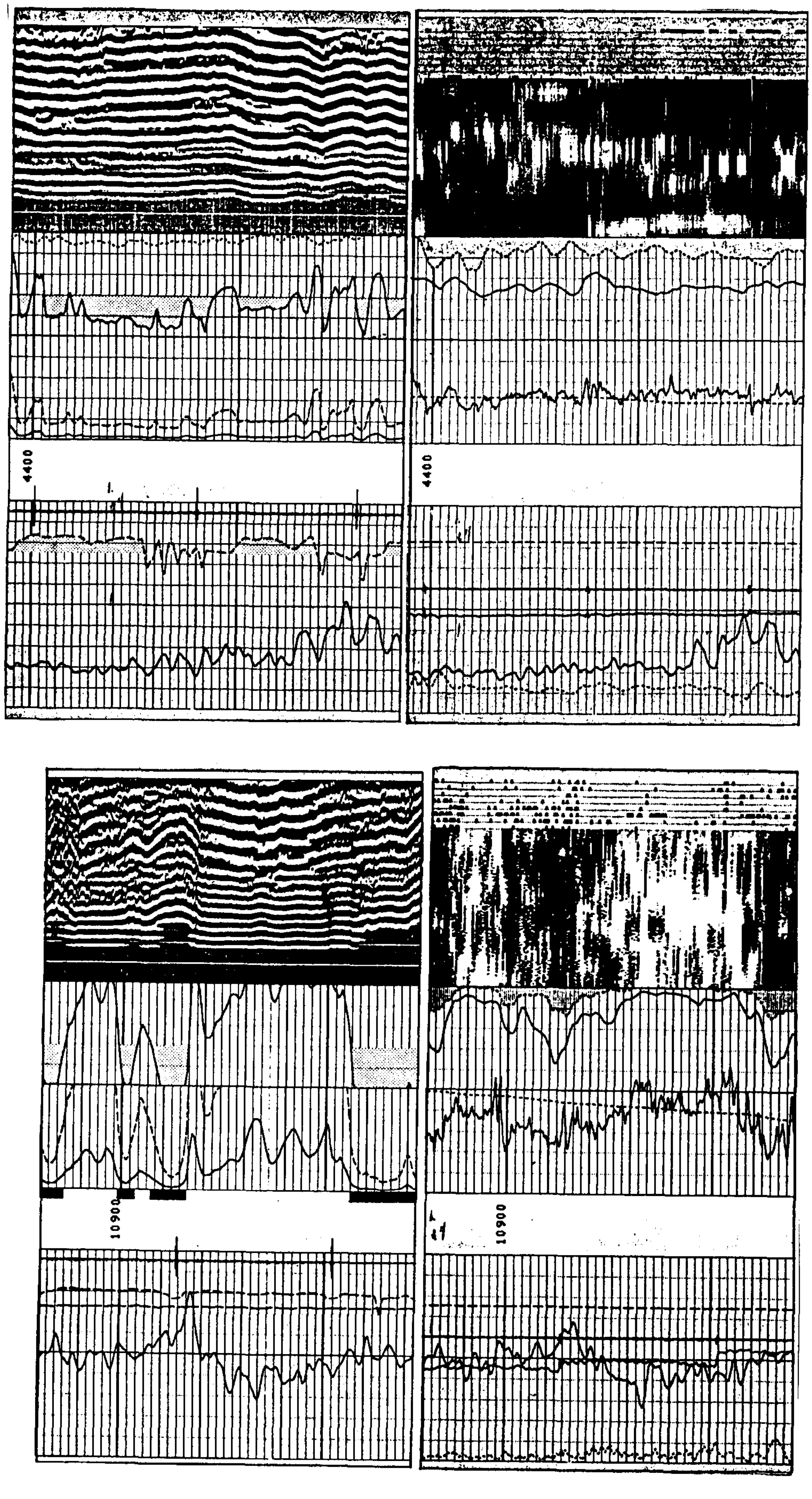


Figure 28 - Example 2 (channeling)

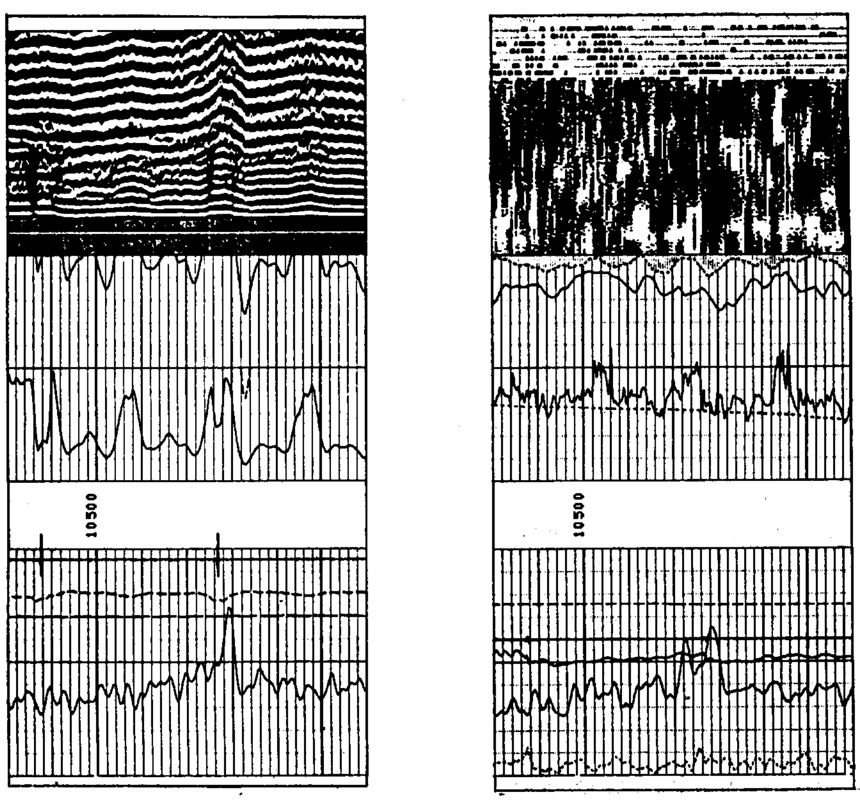


Figure 29 - Example 3 (low compressive strength cement)

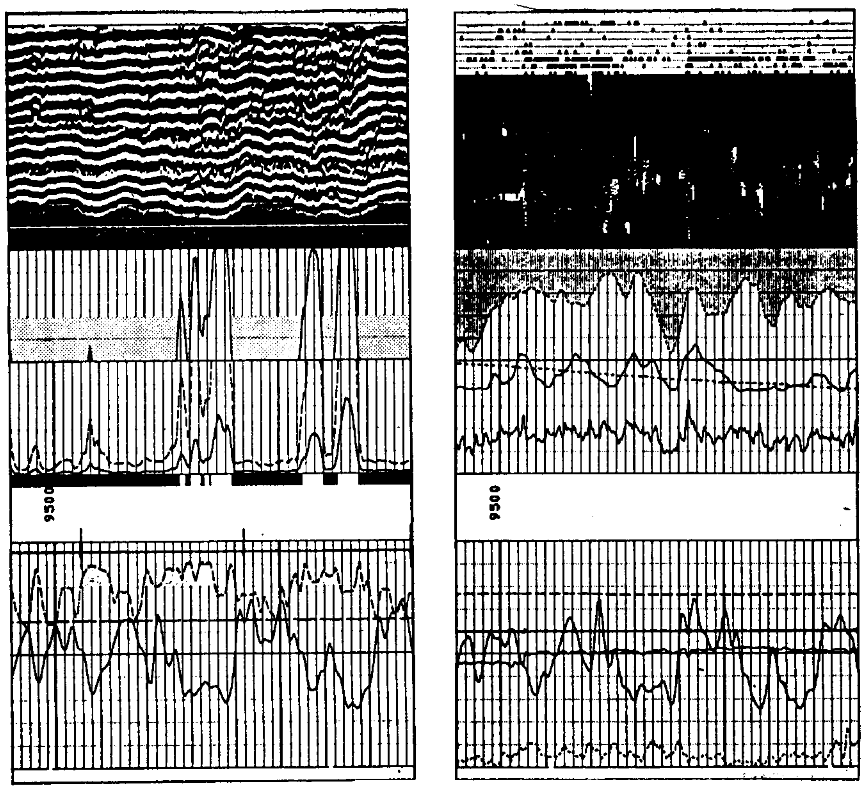


Figure 30 (Part 1) - Example 4 (fast formation)

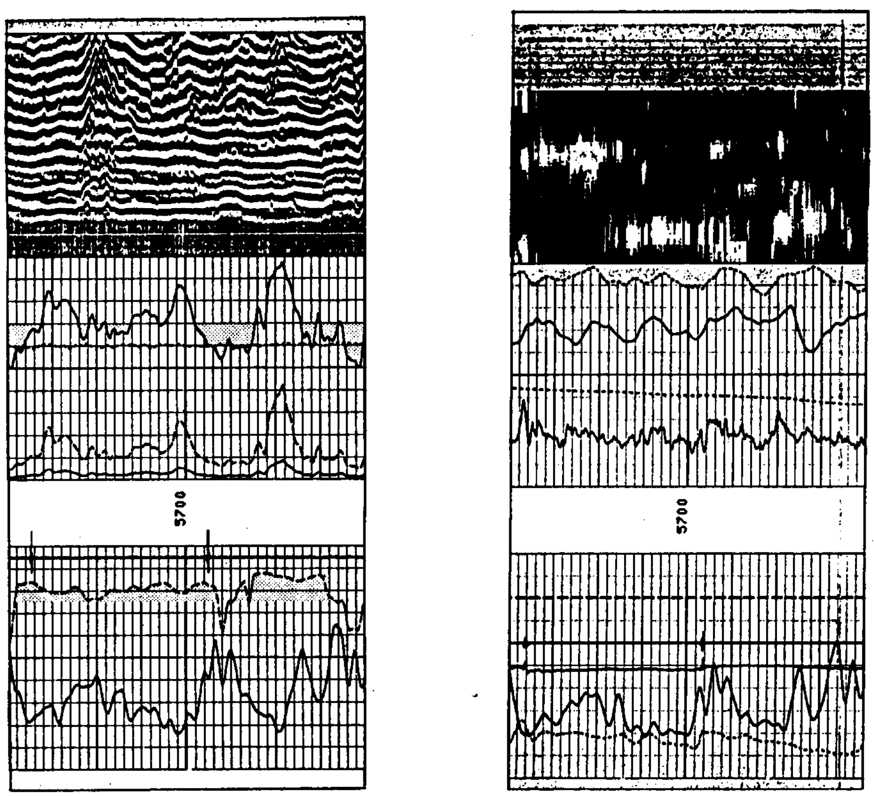


Figure 30 (Part 2) - Example 4 (last formation)

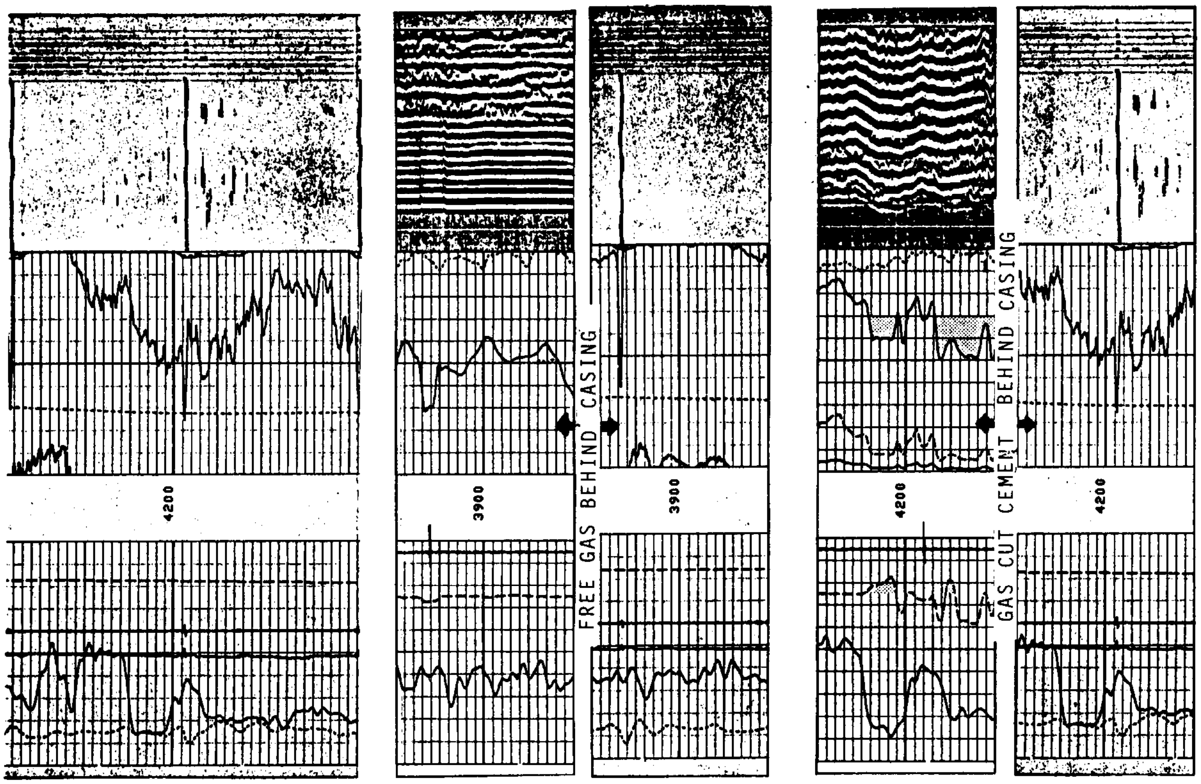


Figure 31 - Example 5 (gas cut cement)

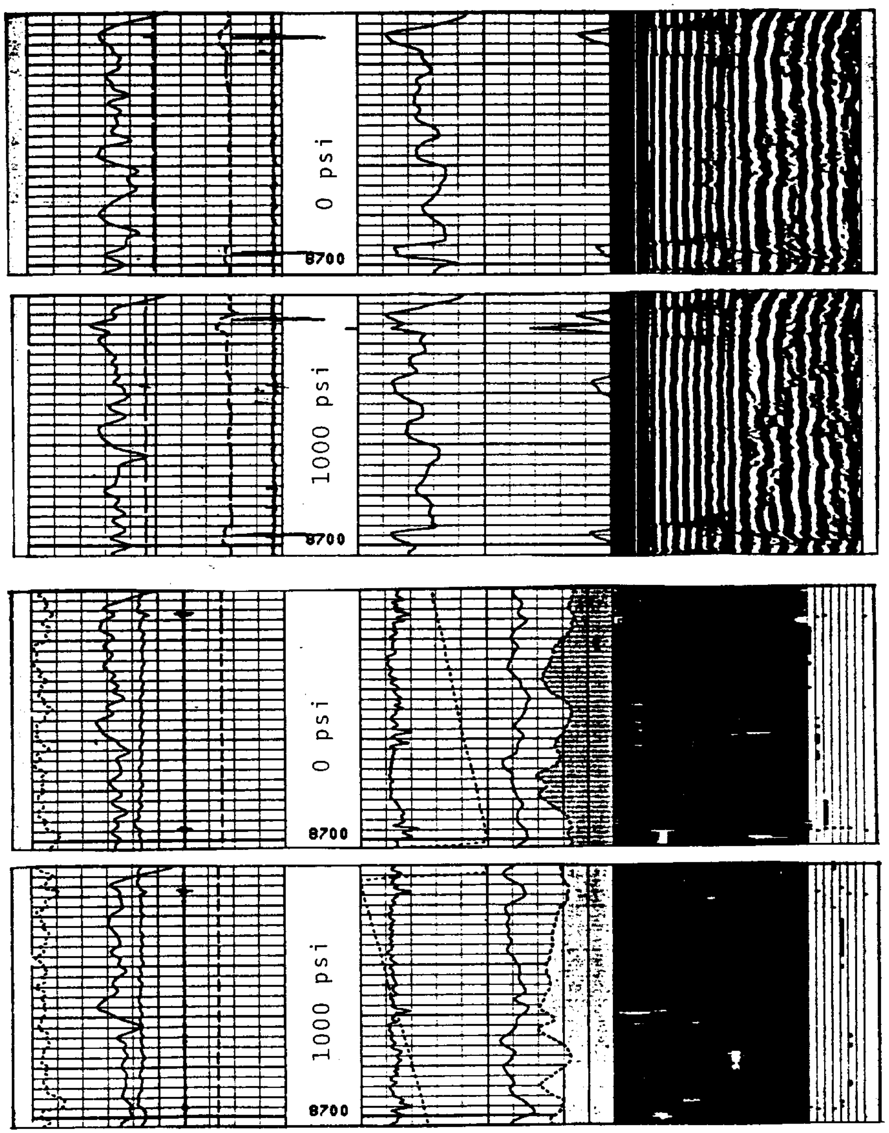


Figure 32 - Example 6 (microannulus)

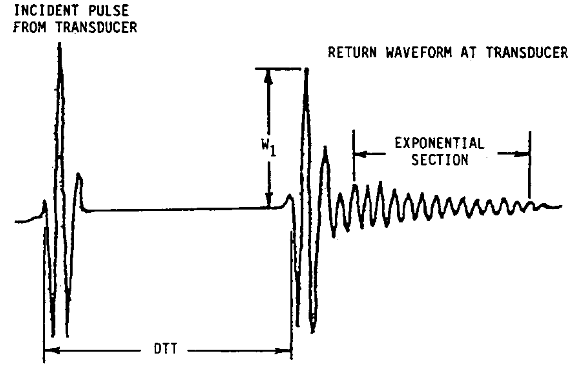


Figure 33 - CET waveform

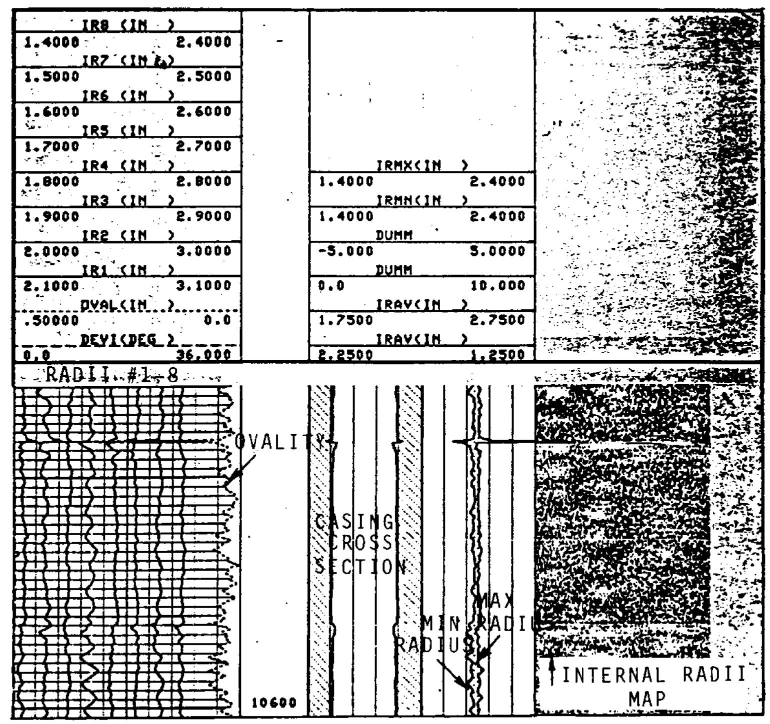
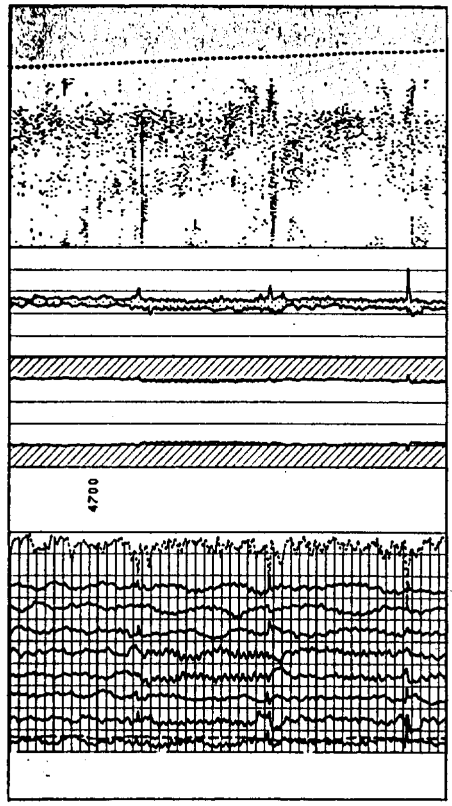
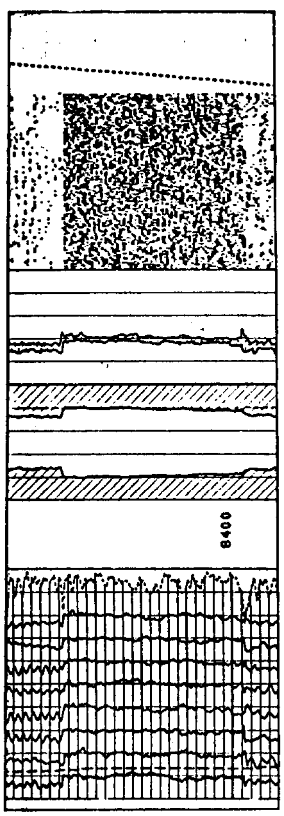


Figure 34 - Internal radii presentation

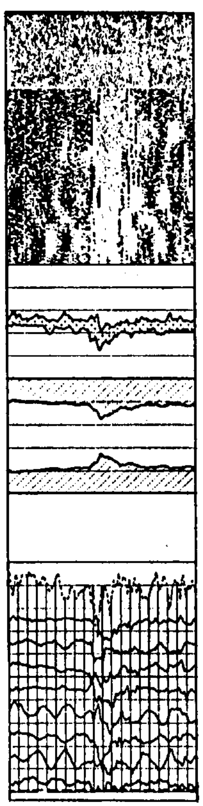


INTERNAL AMPLITUDE MAP

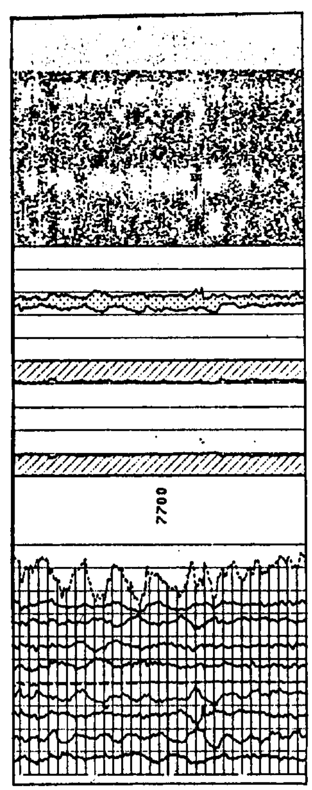
Figure 36



CASING WEIGHT CHANGE



LOCALIZED DEFECT



CONTINUOUS DEFECT

Figure 35

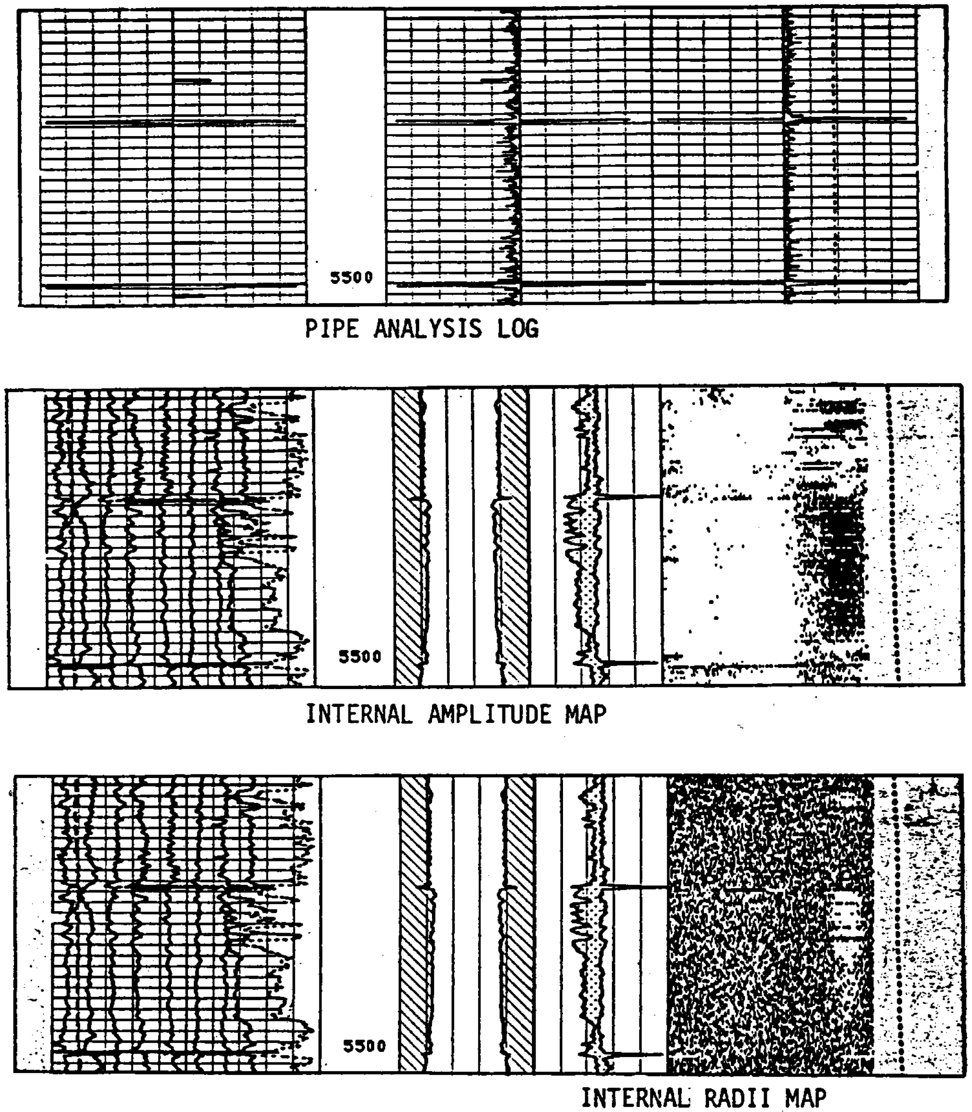


Figure 37

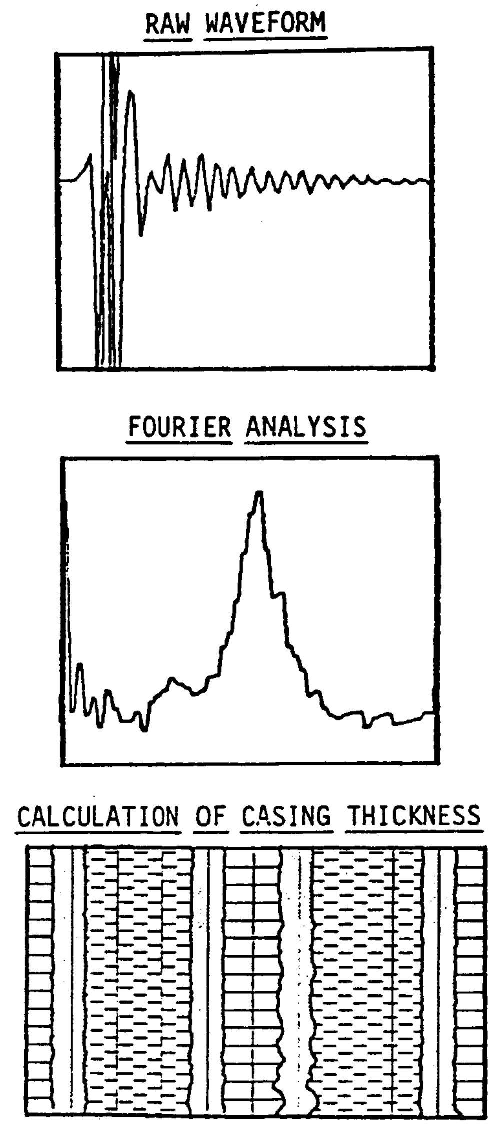


Figure 38 - Thickness from the digital CET

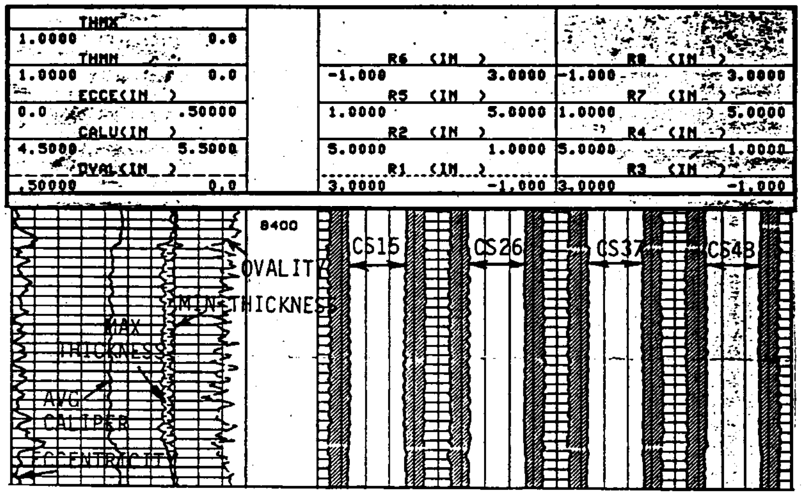


Figure 39 - Ultrasonic casing thickness presentation

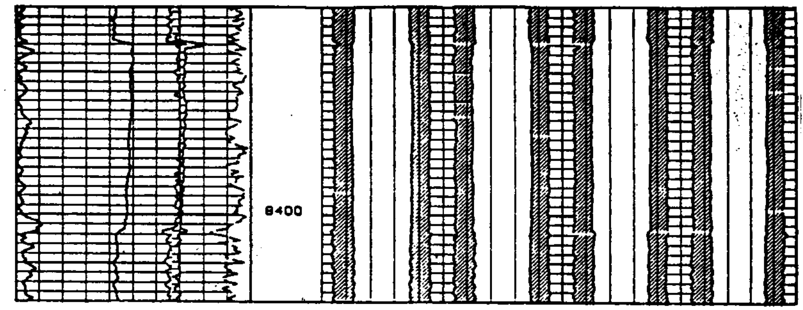


Figure 40 - Casing weight change

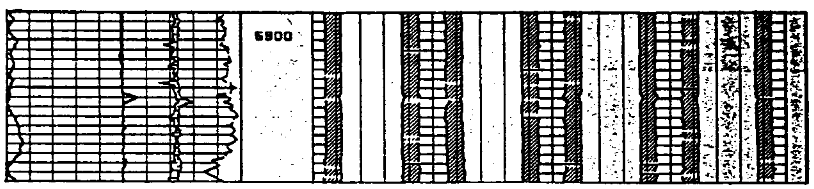


Figure 41 - Area of metal loss

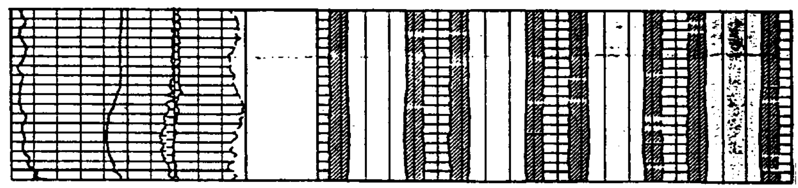


Figure 42 - Radial casing thickness variations