Cement Sheath Evaluation

API TECHNICAL REPORT 10TR1
SECOND EDITION, SEPTEMBER 2008

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Upstream Segment

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1 Introduction

This document is an update of API Technical Report 10TR1, First Edition (June 1996). Great effort has been made to ensure that new technical developments are incorporated, and different views and perspectives are represented by contributions from both operators and service companies. Additionally, the document's relevance to field personnel has been improved by expanding the sections on tool capability, selection, running procedure and log QC. In addition, there is a discussion about how to best incorporate log-interpretation and cementing data into an overall determination of zonal isolation.

2 Framework—Put Cement Sheath Evaluation in Perspective

Cementing is one of the fundamental well-construction technologies for hydrocarbon extraction. The industry spends billions of dollars annually on cementing, and a significant portion is wasted as a result of inappropriate evaluation or incorrect recommendations based on misunderstanding. This document attempts to remedy this situation by gathering into a single treatise the information necessary for meaningful cement-sheath evaluation.

There are a large number of parameters at play throughout the many steps of engineering and effectively evaluating a cement job. Anyone who wants to competently evaluate the quality of a cement job must thoroughly understand all the variables, assemble and comprehend the relevant pieces of information, and reach the proper judgment. Practice, careful observation, and learning from experience will increase the chances for success.

One must understand and never lose sight of the purpose of cement-sheath evaluation. It is ultimately to assess the cement's integrity and ability to achieve its objectives throughout the lifetime of the well. It is not to interpret whether the logs indicate a “good” or “bad” cement bond. Such misguided practice tends to be more prone to error. It can cause financial loss and has, in part, given cement evaluation a bad name. Tools employed in logging operations have various physical limitations that will be described later; for this reason, one must never interpret logs in isolation, without the well and cementing data. Without a clear perspective and strategy for cement-sheath evaluation, one cannot defend against the age-old and often sensible assault.

> *If all we obtain from the logs is comfort when they look good, or discomfort when they look bad, but no confident remedial option, why do we waste time and money running the logs?*

Therefore, performing a cementing job correctly in terms of design and execution is far more important. However, proper evaluation is indispensable, and the evaluation process is a powerful tool if used appropriately to improve future jobs.

This document focuses on logging and evaluation, presenting both the technology and the application from the end user's point of view. Although related key areas of cementing are highlighted wherever possible, the reader is strongly encouraged to gain the necessary knowledge or expertise in those areas elsewhere if needed.

3 A Brief Introduction to Cementing

3.1 Importance of Cement

The two principal functions of a primary cement job are to provide support for the casing and to provide hydraulic isolation between various zones. Cement-sheath evaluation is concerned with the question of whether zonal isolation exists. As emphasized earlier in this document, the evaluation of a cement sheath requires a complete and thorough assessment of the cement job, including job records and cement-evaluation logs. Cement-evaluation logs cannot be interpreted in a vacuum.

The two components of a successful primary cement job are slurry design and mud removal. The slurry must be designed to remain stable under downhole conditions. The pumping of the cement job must be optimized to promote mud removal and allow placement of a competent cement sheath without channels or voids. The following discussion highlights aspects of cement design and placement as they relate to the proper interpretation of cement-evaluation logs.

3.2 Slurry and Set Cement Properties

Density and Acoustic Impedance. Acoustic impedance of the cement sheath (*Z*, commonly expressed in MRayls–10^6 Rayl or Rayleigh) is defined as the product of the cement density and the acoustic velocity in the set cement. Generally speaking, higher density cement provides a greater acoustic contrast with the drilling fluid. This aids log interpretation. Lower-density or contaminated (low acoustic impedance) cement provides less contrast, making interpretation more difficult. Because of their low acoustic impedance, special interpretation techniques are required when assessing high-performance cement systems such as foamed cement or formulations containing glass microspheres or ceramic bubbles.

Density Variations. Varying the cement density changes the acoustic impedance. Therefore, it is important that the cement be mixed as uniformly and as close to the designed density as possible (±0.1 ppg variation from designed density). Deviations from the planned values should be recorded. Ideally, a data-acquisition system should be used to record the slurry density throughout the job. Any density fluctuations should be noted when evaluating the cement log.

Free Fluid/Sedimentation. The slurry must be stable under downhole conditions. Solids settling, pockets of free fluid or lighter-than-designed cement will affect the acoustic impedance and the ability of the cement to provide proper zonal isolation. This is reflected in the log measurement.

***Fluid Loss*.** Excessive fluid loss from the cement slurry during the primary cement job can adversely affect slurry rheology. The altered rheological profile can have a negative impact on mud displacement efficiency. Fluid-loss control is also a very important parameter governing fluid migration through the cemented annulus. Fluid loss can also cause localized microannulus.

Rheology. The rheological profiles and hierarchy of fluids pumped during the cement job determine the mud removal effectiveness. Mud removal effectiveness has a direct impact on cement sheath quality. Computer simulators can be used to optimize the mud-removal process.

***Compressive Strength and Acoustic Impedance*.** Historically, many of the guidelines for cement evaluation log interpretation have been based on cement compressive strength. Acoustic impedance, as outlined earlier, is a better property to use. However, it is important to allow the cement to hydrate sufficiently before running an evaluation log. Generally, at least 48 hours should elapse after cement placement before running a cement evaluation log (see Figure 3.1).

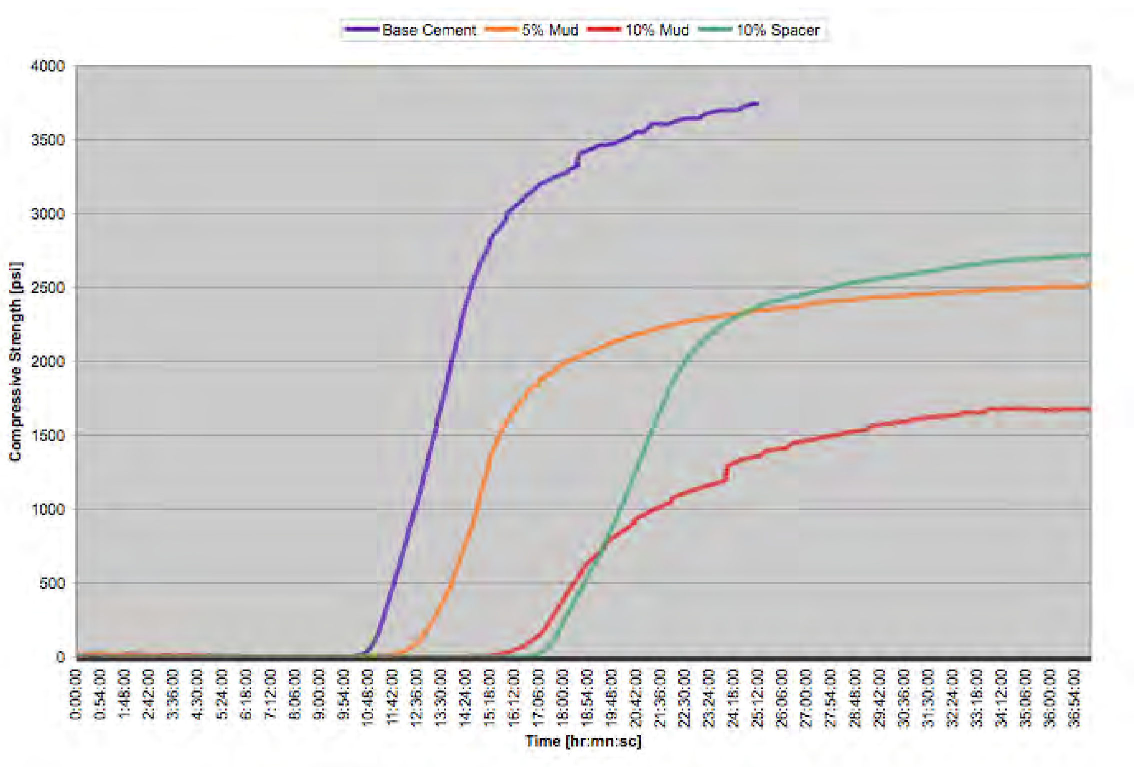


Figure 3.1—Time vs. Compressive Strength Plot (for Base Cement and Base Cement Contaminated Volumetrically with Mud or Spacer)

NOTE: This is used to determine the waiting time on cement hardening before the lower frequency cement evaluation logs should be run.

Cement acoustic impedance (Z) can be determined using lab ultrasonic cement analyzer (UCA) measurement which provides the cement slowness (inverse of acoustic velocity) during cement setting and hardening process (see Figure 3.2).

$$Z = \frac{\text{Density}}{\text{Slowness} \div 25.4} \tag{3-1}$$

where

Z is in MRayl;

Density is in kg/L;

Slowness is in microseconds per inch (µs/in.).

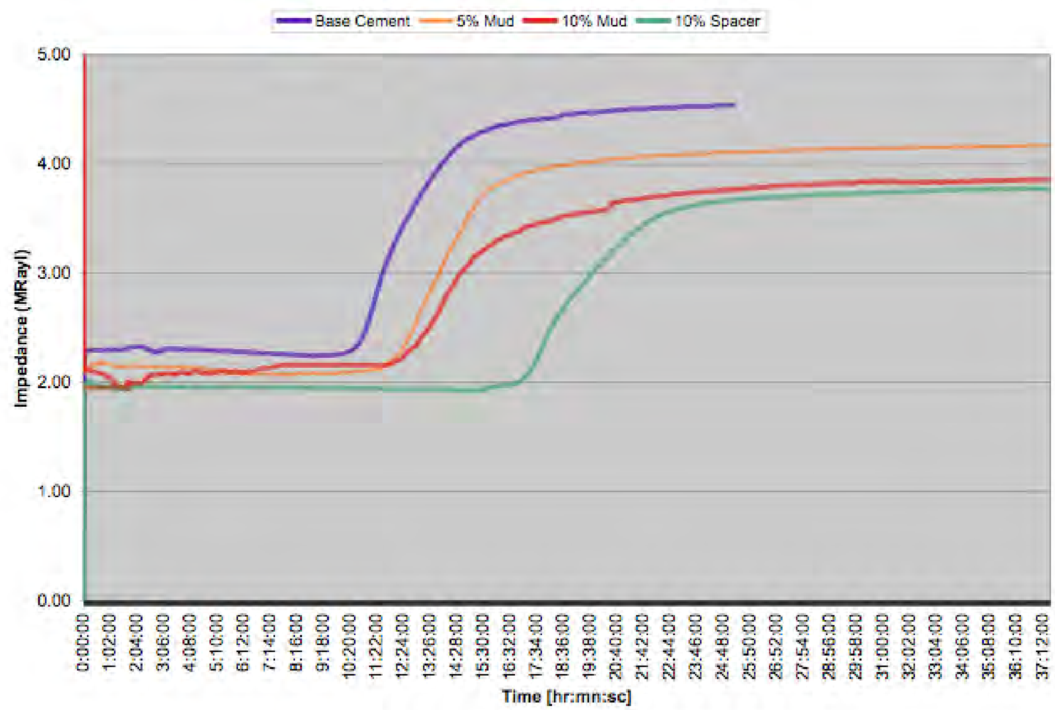


Figure 3.2—Time vs. Acoustic Impedance Plot (for Base Cement and Base Cement Contaminated Volumetrically with Mud or Spacer)

NOTE: This is used to determine the waiting period before a cement evaluation log should be run. This plot helps one to choose the logging parameters for ultrasonic cement evaluation logs.

Static Gel Strength (Transition Time) and "Gas Tight" Cement. Gas invasion into the cement sheath lowers its acoustic impedance and causes log-interpretation problems. For wells with a high gas-invasion potential, special cement designs and testing methods may be employed to minimize gas invasion. One method involves shortening the transition time of the cement slurry. As the cement slurry sets, it changes from a liquid that transmits hydrostatic pressure to a mass with sufficient gel strength to prevent gas influx. The transition time is the period between the beginning of gel-strength development and the attainment of sufficient gel strength to prevent gas influx. Slurries should be tested for gas tightness when the potential for gas invasion or migration exists.

3.3 Mud Removal and the Cement Job

Methods and techniques employed to remove drilling fluid during cement-slurry placement affect the quality of the cement job and may have an impact on the log measurement. Post-cementing practices may also affect log quality.

Pipe Movement. Casing movement, either rotation or reciprocation, has been demonstrated to promote mud removal, reducing or eliminating channels of bypassed mud.

Centralization. Casing centralization promotes mud removal by minimizing the difference between the “wide side” and “narrow side” annular gaps, and reducing the energy required to overcome the mud gel strength. Channels of bypassed mud are reduced or eliminated.

Also, cement evaluation logs require a minimum $^3/4$-in. cement sheath to sufficiently attenuate the sonic signal and attain a good log response. The cement sheath around eccentered casing may not be thick enough to provide sufficient attenuation.

Density and Rheological Hierarchy. Generally, it is easier to displace a fluid with another fluid that is heavier and more viscous. So, in the succession of mud–spacer–lead slurry-tail slurry, each fluid should be more dense and exert more friction pressure than the one preceding it. This promotes good mud removal, a uniform cement sheath and better log response.

Casing Coatings. Thick mill varnish or anti-corrosion coatings can “break” the acoustic coupling between casing and the cement sheath, and cause a log response similar to a microannulus. Weathered or sandblasted casing provides better acoustic coupling.

Lost Circulation. Loss of circulation prior to and during the cementing treatment can negatively affect the attainment of zonal isolation. Loss of fluids to the formation can cause the top of cement (TOC) to be located far below the planned depth. The TOC is very important when determining the quality of the cement log. Monitoring returns during a cement job is critical to accurate log interpretation.

Post-cementing Practices. Pressure testing causes casing to expand. The casing contracts when the test is finished and pressure is released, potentially forming a microannulus that breaks the acoustic coupling between casing and cement sheath and harms log quality. In a similar manner, displacing heavier drilling fluid with lighter completion fluid causes casing to contract and damage the acoustic coupling. A localized loss of shear coupling could also come from radial cracks in the cement induced by the pressure test.

Temperature increases arising from hydrating cement can cause the casing to expand while the cement sets and to contract when the heat dissipates. Any of these scenarios can affect log response. Generally, logs must be run under sufficient pressure to expand the casing and reestablish the acoustic coupling. Both sonic and ultrasonic tools are affected by a microannulus, sonic tools showing the greater effect.

4 Cement Evaluation Tool Types "Categories"

For convenience, cement evaluation tools are often classified according to the frequency of the sound waves they employ: sonic (low frequency) and ultrasonic (high frequency).

4.1 Sonic (and Low-ultrasonic) Evaluation Tools

- CBL—cement bond log; A large-diameter tool with a frequency of 20 kHz; one transmitter and two receivers (3-ft CBL and 5-ft VDL), or a small-diameter tool with a frequency of 23 kHz to 30 kHz; one transmitter and one or two receivers. See Section 5.
- CBT—compensated cement bond log; a large-diameter tool that has two transmitters and three receivers. See Section 6.
- SBT—segmented bond tool; a six-arm tool with a transmitter and receiver on each arm. See Section 7.
- SBL—sector bond log; has one transmitter with three receivers (where one receiver is sliced into 8 to 10 sectors, or the transmitter and one receiver can be sliced into 8 to 10 sectors). See Section 8.

4.2 Ultrasonic Evaluation Tools

- Ultrasonic imaging tool (USIT). See Section 9.
- Circumferential acoustic scanning tool (CAST-V). See Section 9.
- Ultrasonic radial scanner (URS) See Section 9.
- Isolation scanner. See 9.8.

5 Cement Bond Log (CBL)

5.1 Amplitude and Attenuation Physics

The CBL tool emits an acoustic-energy pulse that travels in all directions through the borehole fluid as an expanding spherical wave of sound. When the sound pulse strikes the inner casing surface, some of it is refracted according to Snell's law:

$$\frac{V_1}{\sin\zeta_1} = \frac{V_2}{\sin\zeta_2} \tag{5-1}$$

where

zeta (ζ) is the angle of incidence and refraction;

V is the velocity of sound in the respective media.

Calculations show that the wave front striking the casing at an angle of approximately 17° will refract parallel to the casing wall (see Figure 5.1). The passage of the wave pulse through the casing wall acts as an intermittent pressure pulse, causing the steel of the casing wall to cycle through compression and tension. Cycling the steel through compression and tension causes the casing to "ring, creating sonic waves that travel through the casing fluid and reach the logging-tool receiver. The pressure pulse loses energy as it travels inside the casing wall. This loss of strength, or decay, is commonly referred to as sound attenuation (see Figure 5.2).

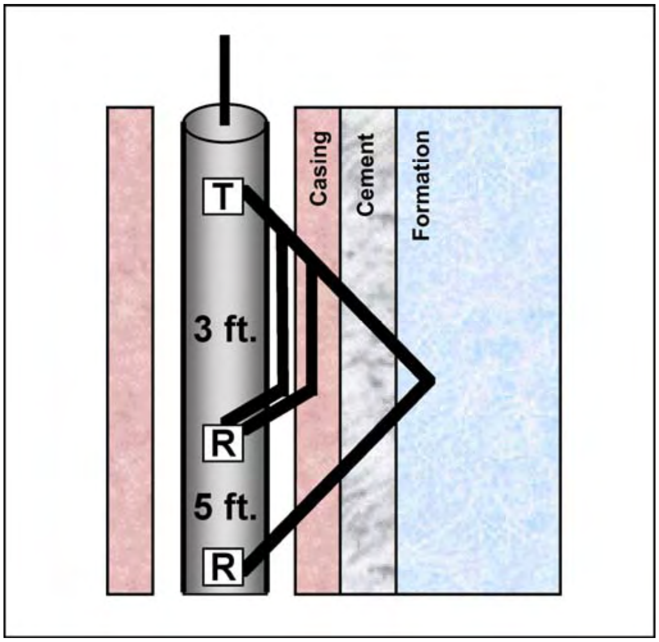


Figure 5.1—Tool Configuration in Which the Angle of the Sound Transmitted Follows Snell's Law

NOTE: The sound travels through the casing and borehole fluid to two receivers that are 3 ft apart (amplitude and travel time measurement) and 5 ft apart (full waveform measurement).

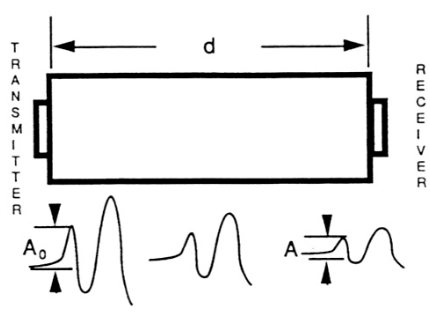


Figure 5.2—Sound Attenuation

NOTE: A_0 is the transmitter amplitude, A is the receiver amplitude and d is the distance between the transmitter and receiver. $\text{Attenuation} = \left(\frac{20}{d}\right)\log\left(\frac{A}{A_0}\right)$.

Some of the acoustic-energy pulse travels through the casing and then through the cement sheath into the formation, and is then reflected back to the tool receiver (see Figure 5.2). The signal paths from the transmitter to the receiver depend on the quality of the acoustic coupling between the cement to the casing (see Figure 5.2). Since the casing wave (see Figure 5.4 and Figure 5.5) typically arrives at the receivers first, its amplitude (energy level in millivolts) and the travel time (in microseconds) from the transmitter to the first receiver can be measured without interference.

At the 3-ft receiver, The first arrival amplitude (known as E_1 or E_2), or the attenuation rate of the received signal, is related to the cement's acoustic properties and the casing-wall thickness (see Figure 5.3), as long as the cement is set (capable of transmitting shear waves) and acoustically coupled to the casing.

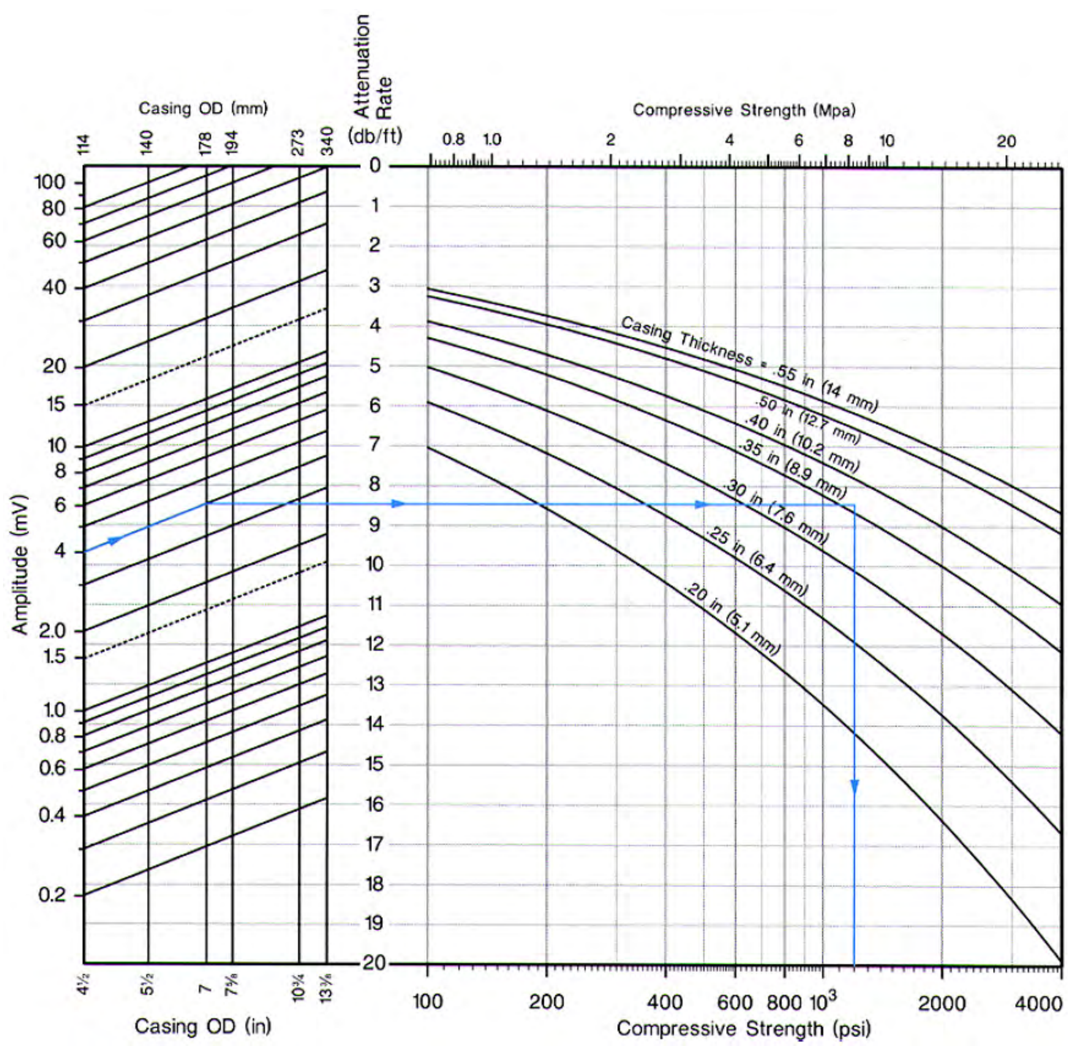


Figure 5.3—Typical CBL Interpretation Chart

NOTE: Cement compressive strength can be derived from casing-size, casing-thickness, amplitude or attenuation data. Inputs of casing size, casing thickness, and cement compressive strength will result in predicting the tool amplitude or downhole attenuation measurement. Each type of tool has similar but unique charts (consult each service company).

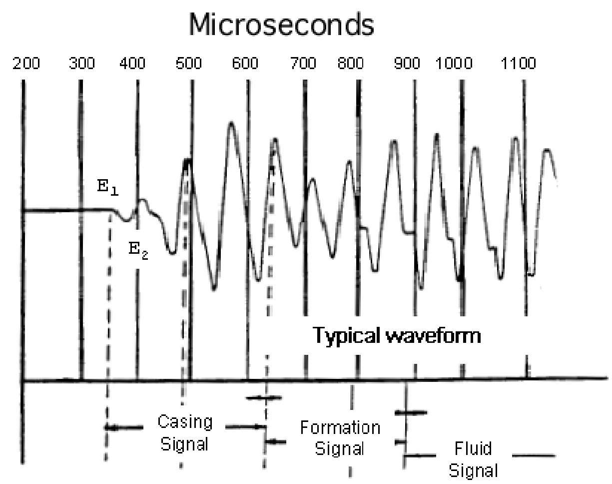


Figure 5.4—Composite Waveform

NOTE: Where E_1 and E_2 are the first arrivals. Above display assumes a formation velocity greater than 90 µs/ft.

5.2 Waveform/Variable Density Physics

The acoustic-waveform signal is recorded at a second receiver that is typically 5 ft from the transmitter. The composite waveform, illustrated in Figure 5.4, is a combination of the casing waveform, the cement-sheath waveform, the formation waveform and the logging-fluid waveform. The waveform reflected from the cement and the formation is indistinguishable. Standard waveform nomenclature lists the first positive peak as the E_1 peak, with subsequent positive peaks denoted as E_3, E_5, E_7, etc. The first negative peak is referred to as E_2, with subsequent negative peaks denoted as E_4, E_6, etc. Figure 5.4 illustrates the typical arrival times for casing, formation, and casing fluid. The composite waveform is affected by the quality of the cement's acoustic coupling to the formation and casing, the shear strength of the cement, the thickness of the cement sheath, and the thickness of the casing wall.

Figure 5.5 illustrates a typical waveform for uncemented casing. The amplitude is highest in free casing because the signal creates a ringing effect that is unattenuated by solid material (cement) coupled to it. When the casing is not acoustically coupled to a high-shear-strength solid in the annulus, the only signal detected by the receiver will be from the casing. This effect can be observed on a bond log when the annulus is filled with unset cement or very weak cement (< 250 psi compressive strength) with thick-wall casing in the hole, a microannulus at the casing-cement interface, gas-cut or foamed cement, mud, water, gas or sloughed formation particles. Good acoustic coupling of the cement to the casing and the formation is required for signal transmission through all of the conductors. The E_1 curve of the free casing waveform should appear on the display between 300 microseconds (µs) to 400 microseconds (µs) when the signal is received at the 5-ft receiver (the travel time of sound through steel is 57 µs/ft).

Figure 5.6 illustrates a waveform when high-shear-strength cement completely occupies the annular space and is acoustically coupled to the casing. The strongest portion of the waveform is the formation signal. The casing signal is very weak. With good casing and formation coupling provided by high-shear-strength, uncontaminated cement, the waveform should reflect formation-bed changes corresponding to, and at the same depth as, the gamma ray (GR) curve. The high shear strength of the cement dampens the pressure-pulse effect during passage of the sonic signal through the length and thickness of the casing wall. This dampening decreases the amplitude of the sound traveling through the pipe and increases the attenuation rate.

The presentation of the composite waveform on the log may be in the form of a "total energy wave" (signature plot, X-Y plot, etc.) or a linear form commonly called a VDL (variable density log) or microseismogram. The presentation is scaled from 200 to 1200 μs. The method of recording the linear presentation from the acoustic waveform is illustrated in Figure 5.7. The linear presentation is shown every 6 in., and the waveforms are presented every 4 ft. A waveform presented every 6 in. would be very messy, and no details could be observed.

Linear presentation makes it much easier to separate casing signals from formation signals. Casing signals will always be straight unless the logging tool is eccentered, and casing collars will be evident. Formation signals usually vary and are rarely straight. The presentation will mimic an openhole sonic DT.†

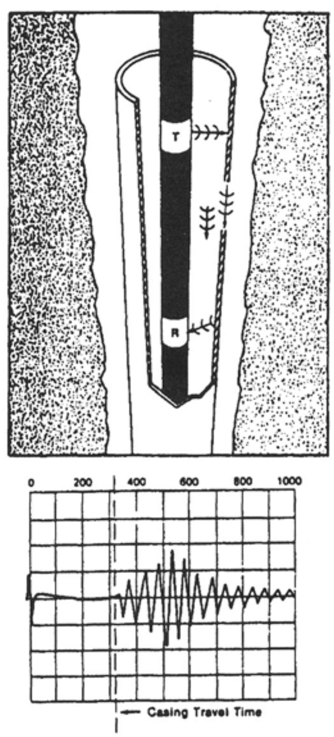


Figure 5.5—Uncemented Casing at Which the Amplitude is at its Maximum Value

† Sonic DT is the duration of time sound travels through a given distance in the formation, typically measured in μs/ft.

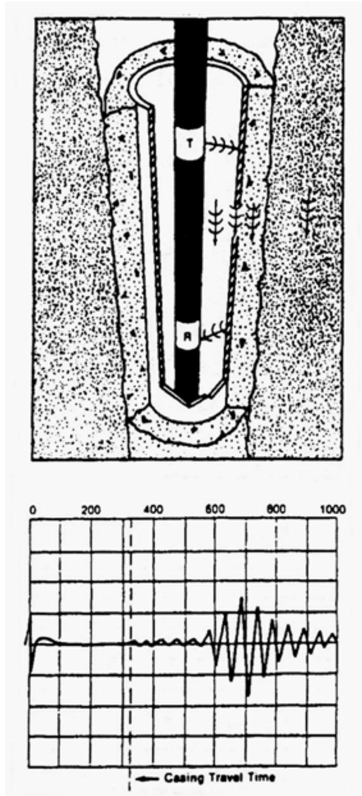


Figure 5.6—High-shear-strength Cement

NOTE: This completely occupies the annular space, and is acoustically coupled to the casing. Casing arrivals are weak and formation arrivals are strong.

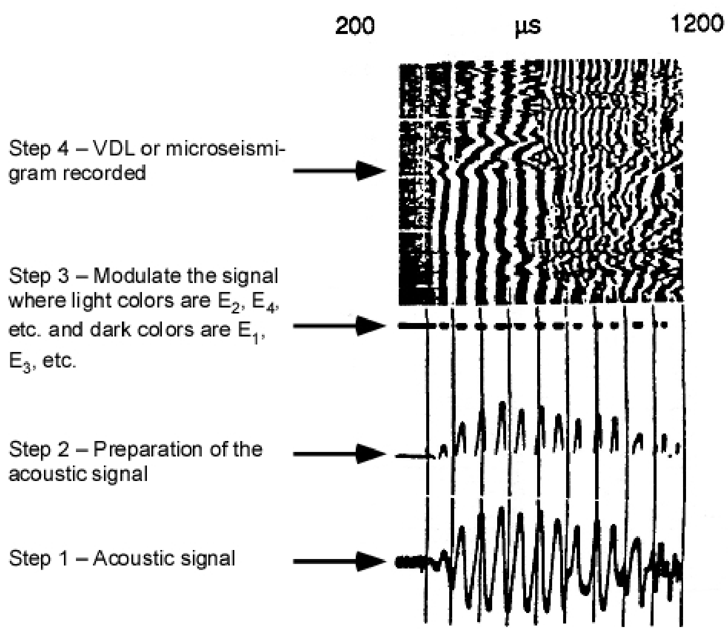


Figure 5.7—Full Waveform Signal Recorded at the 5-ft Receiver

NOTE: This figure shows the process to obtain a VDL or microseismogram.

5.3 Key Requirements

The following are required to produce a valid CBL.

1. A fluid-filled borehole. Gas or air bubbles will induce inaccurate readings.
2. Centralized CBL tool during the run.
3. A bit and scraper run is recommended to remove cement and/or scale from the casing wall.
4. Wellbore schematic.
5. Plot of the cement strength vs. time to determine the time after which logging can produce a valid log (see Figure 3.1).
6. Predicted cement tops for the lead and tail cements.
7. Casing and centralizer report to determine where casing eccentering may occur.
8. Openhole logs with a caliper and lithology.
9. An understanding of fluid type or gas in the formation pore space.

5.4 CBL Presentation

The presentation of CBL logs varies from company to company. An example of a CBL presentation is shown in Figure 5.8. The first track (Track 1) from the left, called the correlation track, shows the GR recording and the travel time (TT) (the TT is the elapsed time from the firing of the transmitter until the first sound is sensed at the receiver). The GR signal is used for correlation between the openhole and cased-hole logs. As shown in the log, the TT (sometimes called the transit time) in the upper portion of the log is consistent and straight at 250 μs, indicating that the tool was well centralized in this portion of the log. This will be discussed later in the quality-control section.

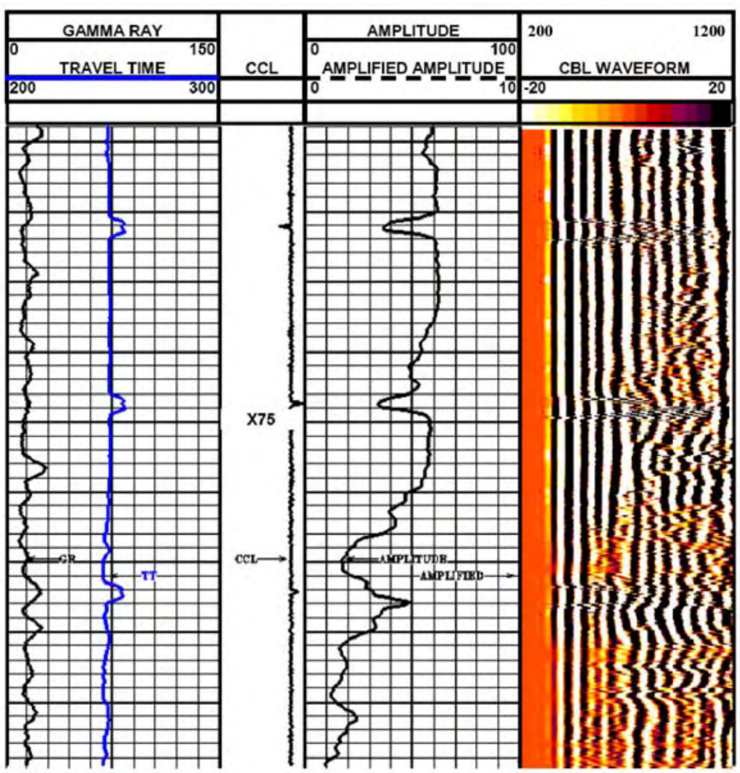


Figure 5.8—Example of a CBL Log

The depth track consists of both the depth and a collar locator or CCL (CCL is sometimes located in Track 1). The CCL is used to find the casing collars and, like the GR, is used for correlation purposes.

Track 2 is to the right of the depth track and typically consists of two curves showing the same E_1 first positive peak-amplitude reading on two different scales. The solid black line is the amplitude presented on a scale of 0 to 100. This curve will normally have a lower scale value of 0 with a variable upper limit. The upper limit should be the free-pipe amplitude, with lower values indicating better quality cement. The amplified or expanded scale curve is the amplitude plotted on a scale from 0 to 10 (or sometimes 0 to 20). This dashed curve only appears when the amplitude curve is lower than the upper scale, and provides more detail about bonded pipe than can be seen on the amplitude curve. In this example the amplitude does not drop below 10 mV, so the amplified presentation is never active.

Track 3 is the CBL waveform or VDL, shaded from white to black. The lighter colors depict the negative peaks of the CBL waveform, and darker colors represent the positive peaks. The color code depends upon the waveform amplitude. In this example, the free-pipe section is indicated by high (black) and very low (white) waveform amplitude. The first three or so black bands on the left represent the sound received from the casing.

5.5 CBL Interpretation

NOTE

This practice is not recommended as a best practice for cement evaluation. It is presented to provide an understanding of the history of CBL interpretation and its flaws.

The CBL-interpretation process is based on the following assumptions:

- cement sheath thickness ≥ 0.75 in. and
- Constant cement compressive strength and density is around the casing circumference and throughout the height of the cement column. (**This is a major flaw in CBL analysis.)**

Warning: A thin, low-density, low-compressive-strength cement sheath placed against thick-walled casing (even in well cemented casings) may each yield a relatively high waveform amplitude (low attenuation), seeming to indicate less than desired casing bonding. If any of the above conditions are present, special care should be used when determining zonal isolation.

***Bond Index (Method #1)**:* The amplitude or the attenuation rate of the received signal is proportional to the casing circumference that is in contact with cement, the casing-wall thickness, and the density, thickness, and shear strength of the cement. The Bond Index is percentage of casing circumference that is bonded to cement (see Figure 5.9).

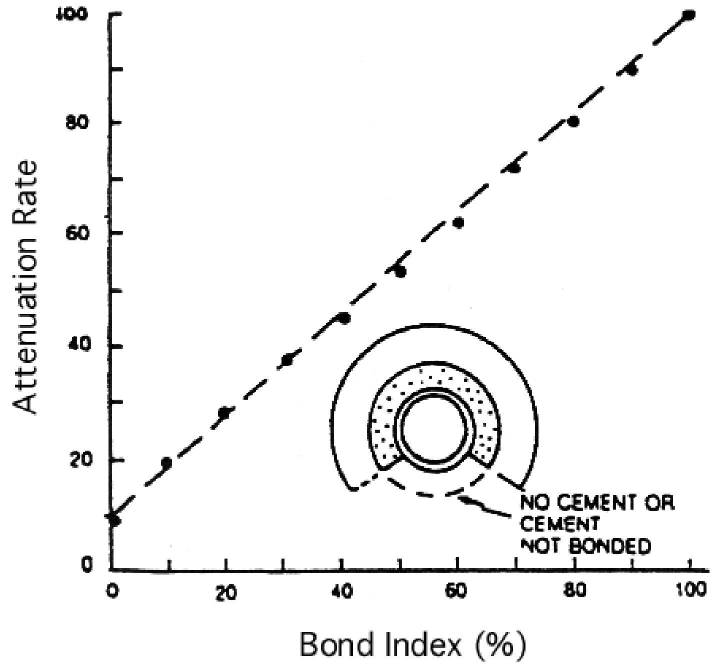


Figure 5.9—Attenuation Rate

NOTE: Attenuation rate is proportional to the casing circumference in contact with the cement (% Bond Index). Bond Index = (Attenuation at zone of interest /Attenuation for 100% cement bond). A major flaw in this analysis the assumption that lack of cement is in the form of a channel.

The amplitude or attenuation is often used as a "bonding indicator" to infer that the cement is "poorly bonded" or "well bonded" to the casing. These "bonding indices", or "bonding percentages", can be totally misleading. There is very little agreement in the industry as to the definition of good bonding vs. poor bonding. The Bond Index is commonly derived from a general ratio:

Attenuation: Amplitude:

$$BI = \frac{A_{fp} - A_{ls}}{A_{fp} - A_{100}} \qquad BI = \frac{\log A_{fp} - \log A_{ls}}{\log A_{fp} - \log A_{100}} \tag{5-2}$$

where

BI is the Bond Index;

A_{fp} is the free-pipe attenuation or amplitude from the log or from service company charts;

A_{ls} is the attenuation or amplitude in any logged section;

A_{100} is the attenuation or amplitude from a 100% cemented section or a service-company chart (e.g. Figure 5.3).

100% Cemented Section

Figure 5.3 is an interpretation chart that may be used to estimate expected amplitude and/or attenuation values for known casing sizes and thicknesses, and cement compressive strength. Each service company publishes an interpretation chart. It is prudent to use charts corresponding to a specific company's tool. Figure 5.3 shows that changes in cement compressive strength, casing size or casing weight will change the amplitude or attenuation value. The change in amplitude or attenuation is interpreted as a changed in Bond Index and not compressive strength. A Bond Index of 40% may be incorrect if the amplitude increase arises from low-strength cement rather than channeling. BI can be misleading when A_{100} is not adjusted for cement compressive-strength changes. Major changes include:

- cement density difference between the lead and tail slurries,
- slower strength-development rates resulting from low curing temperatures in the shallow portion of the wellbore,
- cement contamination by mud, spacer or influx of gas, oil or water into the cement column,
- lithology effects on the signal amplitude and
- change in cement-sheath thickness.

Figure 5.10 illustrates an excellent cement bond (where BI is assumed to be 100%). The amplified amplitude curve shows more detail because of the low amplitude resulting from high cement compressive strength and excellent bonding. The VDL shows good formation signals with no casing arrivals, and has a pattern that correlates to the GR changes.

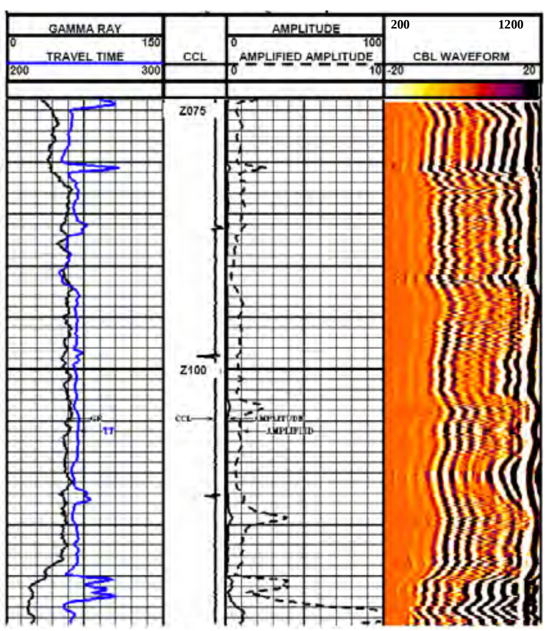


Figure 5.10—CBL Presentation of an Excellent Cement-bond Case

NOTE: Low amplitude is shown, with no casing arrivals and strong formation arrivals on the VDL.

Free-pipe Section

Figure 5.11 is a log section recorded in free pipe (casing with a liquid filled annulus). The amplitudes are very high and constant. The TT is straight. The only anomalies are caused by the collars. The VDL consists solely of straight, parallel bands called “casing arrivals.” These arrivals correlate to the waveform illustrated in Figure 5.5. The casing collars on the VDL exhibit a distinctive diffraction pattern known as chevron patterns.

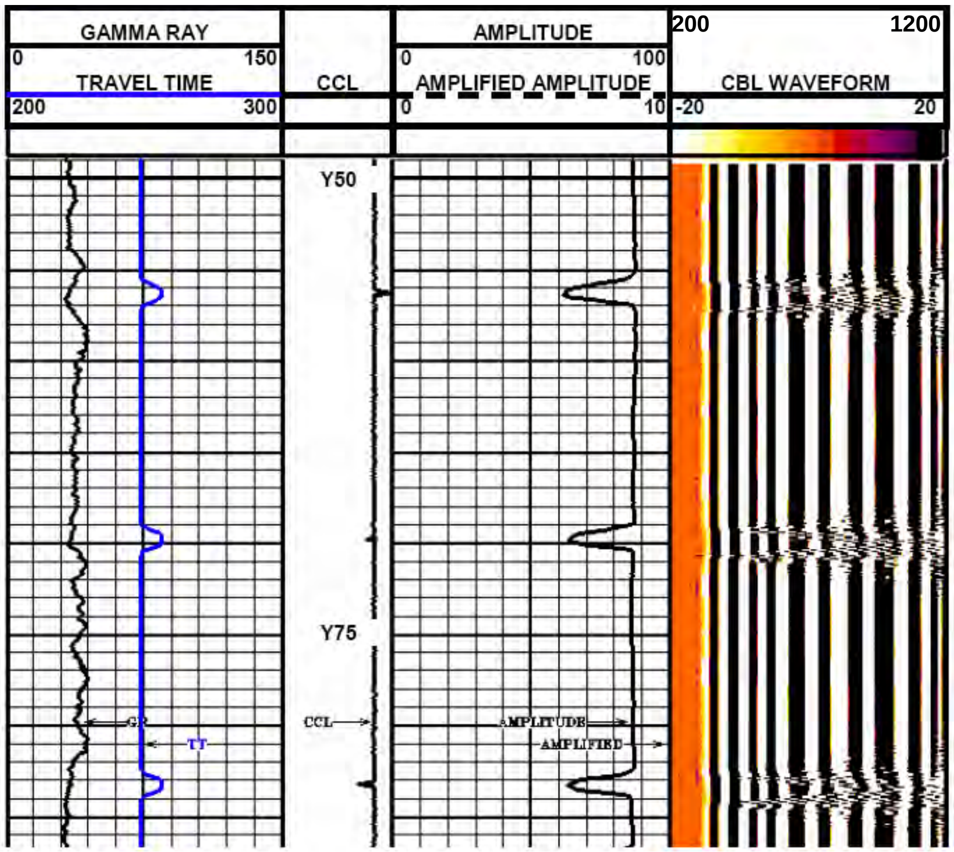


Figure 5.11—CBL Presentation in a Non-cemented Interval (Free Pipe)

NOTE: The observed log character is a high amplitude value, constant VDL signature, and strong collar signals on the amplitude and VDL recordings.

Bond Index (Method #2)

Instead of using equations to calculate Bond Index from the amplitude, the semi-log plot below can be used in its place (see Figure 5.12). The free-pipe amplitude value is entered at 0% Bond Index. The 100% cemented amplitude is entered at 100% Bond Index. In this example, the free-pipe amplitude is 70 mV and the 100% cemented amplitude is 0.2 mV (read from and area of the log with the lowest amplitude). Therefore, an 80% Bond Index would have an amplitude of about 0.6 mV. Percent Bond Index is determined by drawing a line across from an amplitude found on the log to the diagonal line and reading down to the “Bond Index.”

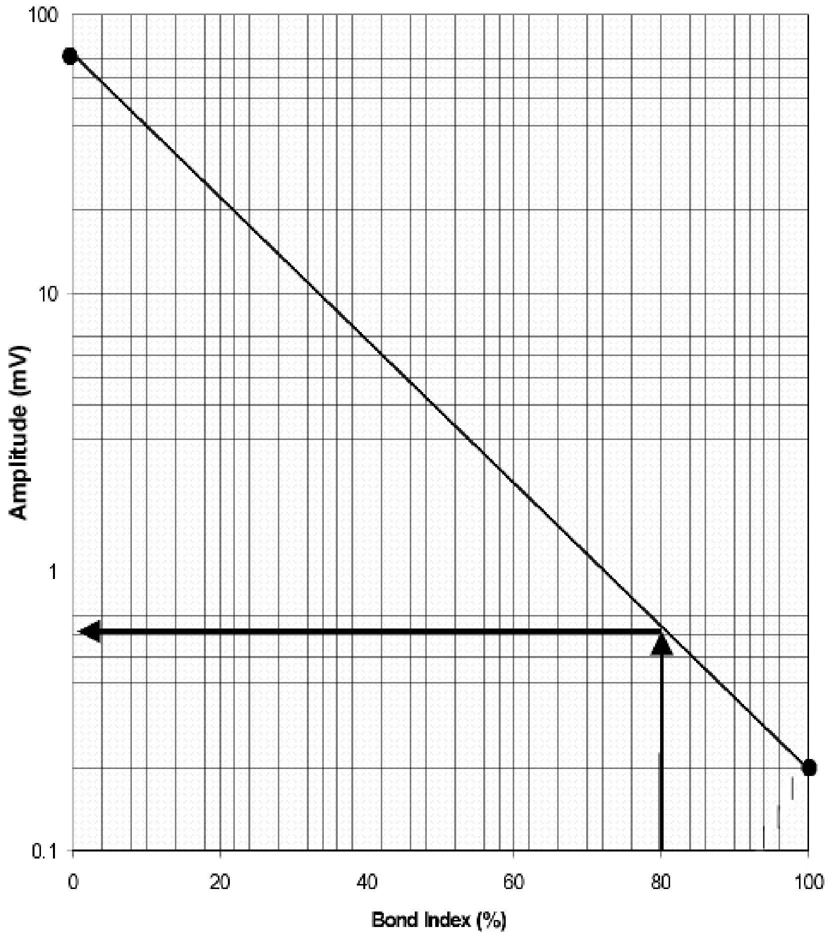


Figure 5.12—Semi-log Plot for Calculating the Bond Index

5.6 CBL Quality Control

Tool Eccentering: The signal TT, normally shown in Track 1 of the log, may be used to detect tool eccentering. When the tool is eccentered in the casing, the bond log quality is highly questionable. "Critical travel time" is defined as the elapsed time (μs) for the signal to travel from the transmitter to the 3-ft receiver via the casing when the tool is centered in the casing. The TT curve should be straight in free pipe, except for consistently spaced, minor increases (shifting to the left) as the tool crosses the casing collars. Tool eccentering in the casing will induce shorter TTs and lower amplitudes (see Figure 5.13). Tool eccentering is easier to see if the TT measurement range is adjusted from the conventional 200 μs to 100 μs. If the tool TT decreases by 4 μs or more, the tool should be pulled from the hole and fitted with additional centralizers or replacement centralizers. TT decreases may also be caused by early signal arrivals from "fast formations," so it is necessary to recognize lithology effects. TT increases do not pose a problem, and are caused by casing collars, very soft formations, and extremely high strength cement in contact with medium-to-thin walled casing.

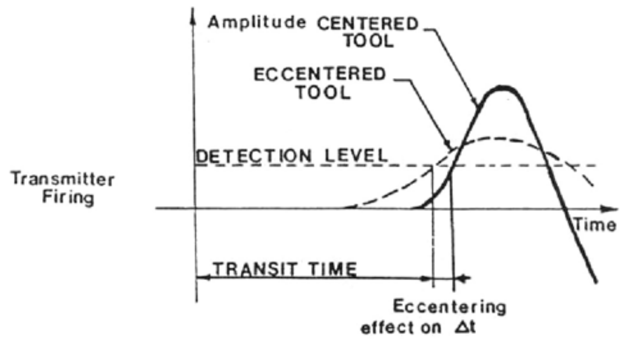


Figure 5.13—Waveform Variations Induced by Tool Eccentering

Cycle Stretch and Cycle Skip: Figure 5.14 illustrates the causes of phenomena known as "cycle stretch" and "cycle skip." Casing signal-detection (threshold) levels are generally set by a "gate" that is fixed at some level below 50% of the free-pipe amplitude, and the arrival time at the leading edge of the E_1 curve. As the E_1 amplitude decreases because of increasing cement strength, the distance to the leading edge of E_1 increases, which also increases the TT. This increase in TT is called "cycle stretch." When the E_1 amplitude falls below the gate detection level, the measurement detects the next available curve—the leading edge of the E_3 curve. This causes the TT curve to "skip" to a much greater value. Cycle stretch and cycle skip infer very high-shear-strength cement in contact with medium- to thin-wall casing. Cycle stretch and cycle skip are generally an indicator of good log quality over that section of the log.

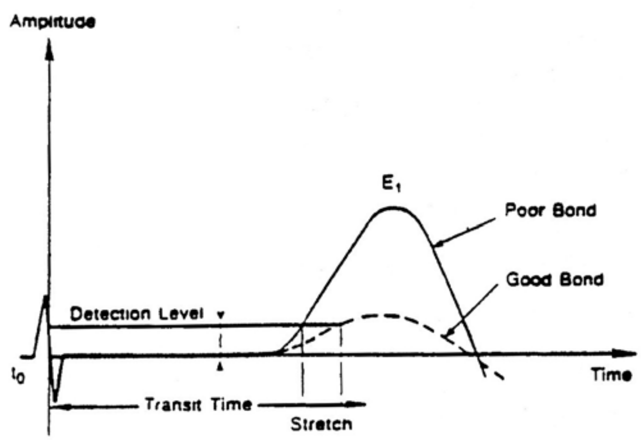


Figure 5.14—Cause of Cycle Skip and Cycle Stretch

Additional Quality Control Indicators

1. Amplitude or attenuation should never read zero.
2. 200 ft of a free pipe section should be run.
3. Free-pipe amplitude should be ±10% of the service-company specifications (may be lower in fluid weights >11 ppg).
4. TT should be within ±10 μs of the service-company specifications (may be different for fast fluid-travel times).
5. 200 ft of repeat log should be run to ensure consistency.

5.7 Limitations (Environmental Effects)

Microannulus/Cement Channels: Figure 5.15 illustrates a typical waveform display when there are cement channels or if a microannulus exists at the casing-cement interface. The casing signal is reflected from a portion of uncemented casing, while the formation reflection is detected through a cemented portion of the casing. Channeling may result from several causes:

- poorly centralized casing,
- poor mud removal,
- inadequate removal of formation cuttings,
- settled barite at the low side of the hole and
- cement slurries exhibiting excessive free water separation and sedimentation after placement.

Microannuli are generally created by pressure changes after the cement has set. Common causes include:

- displacing the casing wiper plug with heavier mud then logging in lighter brine,
- pressure testing casing after the cement is set but before it has a chance to develop sufficient compressive strength,
- casing expansion caused by heat generated during cement setting,
- pressure inside the casing is less at the time of logging than when the cement is cured,
- cool fluids are circulated before running the CBL,
- performing a cement squeeze, and
- drilling ahead while the cement is curing.

One method to discriminate between a channel and a microannulus is to run a pressurized pass and a non-pressurized pass. The recommended amount of pressure in the casing is that required to compensate for previous pressure changes, plus 500 psi for casing expansion caused by the heat generated by cement setting. Typically, 2500 psi is the maximum pressure that can be applied with standard pressure equipment **(check with the service company for the safety limit)**.

A second method to discriminate between a channel and a microannulus involves beginning with a zero-pressure pass, followed by pressuring up to 1000 psi and observing any changes in the amplitude or attenuation and VDL. If no changes occur, increase the pressure in 500-psi increments until amplitude or attenuation and VDL changes are observed. **Typically, 2500 psi is the maximum pressure that can be applied to standard pressure equipment (check with the service company for the safety limit)**. If changes are observed, one may assume a microannulus is present. At this point one option would be to increase the pressure by 500 psi and determine if further improvements occur. A second option is to accept the fact that a microannulus exists and avoid further pressure increases.

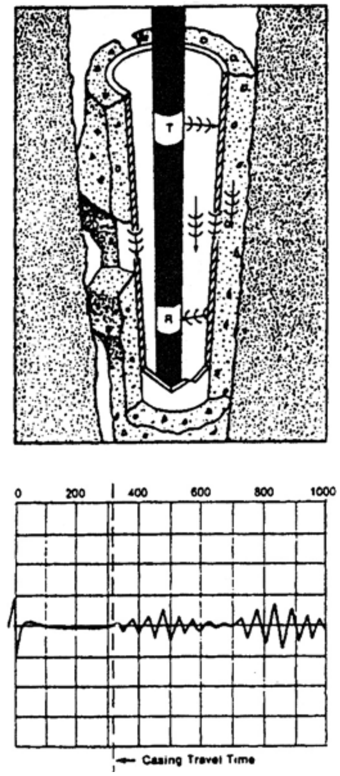


Figure 5.15—Waveform for a Cement Channel or Microannulus

If a microannulus is present, the casing signals will become lighter and may disappear from the waveform when pressure is applied to the casing. If a channel is present, the casing signals will remain. The following equation may be used to calculate the maximum size of the microannulus.

$$\Delta r = \frac{\Delta P \times r^2 \times 2}{t_w \times E} \tag{5-3}$$

where

r is the casing radius, in.;

P is the pressure, psi;

E is Young's Modulus of Elasticity for Steel ($30E_6$ psi);

t_w is the casing wall thickness, in.

Fast Formations:

The sound velocity in casing steel is generally higher than in most other borehole materials; therefore, early arrivals of the composite waveform are usually the casing signal. However, there are exceptions. Table 5.1 illustrates typical sound velocities through various downhole materials.

Table 5.1—Sonic Velocities Through Various Downhole Materials

Material	Transit Time (μs/ft)	Velocity (ft/s)
Anhydrite (Pure)	50	20,000
Dolomite/Calcite	43 – 70	9,740 – 15,856
Quartz (Pure)	52.9	18,900
Water	208	4,800
Air (1 atm)	919	1,088
Steel	57	17,544

Note that the sound velocity through certain rocks is higher than that through steel. This can cause sound traveling through the formation to arrive at the receiver at approximately the same time (or earlier) than the casing signal, and cause confusion when the formation signals are misinterpreted as casing signals. Normally, dolomite or limestone are considered to be fast formations that create this early signal dilemma. Occasionally, anhydrites or near-zero-porosity quartz could have the same effect.

Additional Environmental Effects:

1. Cement curing (see 3.2 on slurry design/compressive strength).
2. Gas contaminated cement (see 3.2 on slurry design/static gel strength).
3. Thin cement sheath (see 5.5 on CBL interpretation).
4. Eccentered casing (see 3.3 on mud removal/casing centralization).
5. Coated casing (see 3.3 on mud removal/coated casing).
6. Identifying cement channels.

6 Compensated Bond Logging Tool (CBT)

6.1 Attenuation Physics

Innovations in bond logging technology led to the development of compensated logging tools for cement evaluation. The basic configuration of the tool is illustrated in Figure 6.1. The primary advantages of the tool include the following:

- measurement of the signal attenuation rate (dB/ft) is independent of casing fluids and transmitted signal strength;
- calibration is improved significantly;
- the TT curve is separated, allowing observation of tool eccentering;
- attenuation rate can be measured within a 1-ft interval instead of signal averaging within a 3-ft to 5-ft interval.

Generally the compensated logging device measures casing signal attenuation between the 2.4-ft to 3.4-ft receivers (see Figure 6.1) and the formation signals at the 5-ft receiver. Signal attenuation from Transmitter No. 1 is measured at a "set" of receivers, then averaged with the signal attenuation from Transmitter No. 2 at the same receivers (signal direction is reversed). Log interpretation is similar to common "bond logs." The microseismogram or VDL signature interpretations remain the same; however, the attenuation rate, dB/ft, is measured instead of calculated and presented on Track 2 of the log (sometimes in tandem with the amplitude curve). Interpretation may be based on a chart similar to that shown in Figure 5.3. Another major advantage of this type of log is that it allows comparison of results from various logging company tools. The attenuation rate is specifically measured, and the effects of transmitter strength, borehole fluids, and tool variances are negated. The results of a cement-evaluation run should yield the same results, regardless of the tool manufacturer.

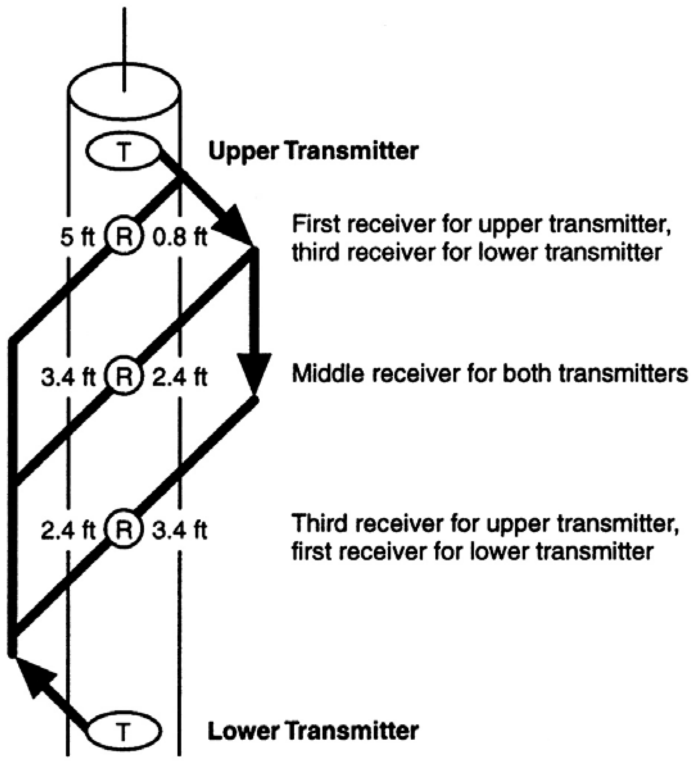


Figure 6.1—Compensated Bond Tool

6.2 Waveform/Variable Density Physics

(See 5.2.)

6.3 Key Requirements

(See 5.3.)

6.4 Compensated Logging Tool Presentation

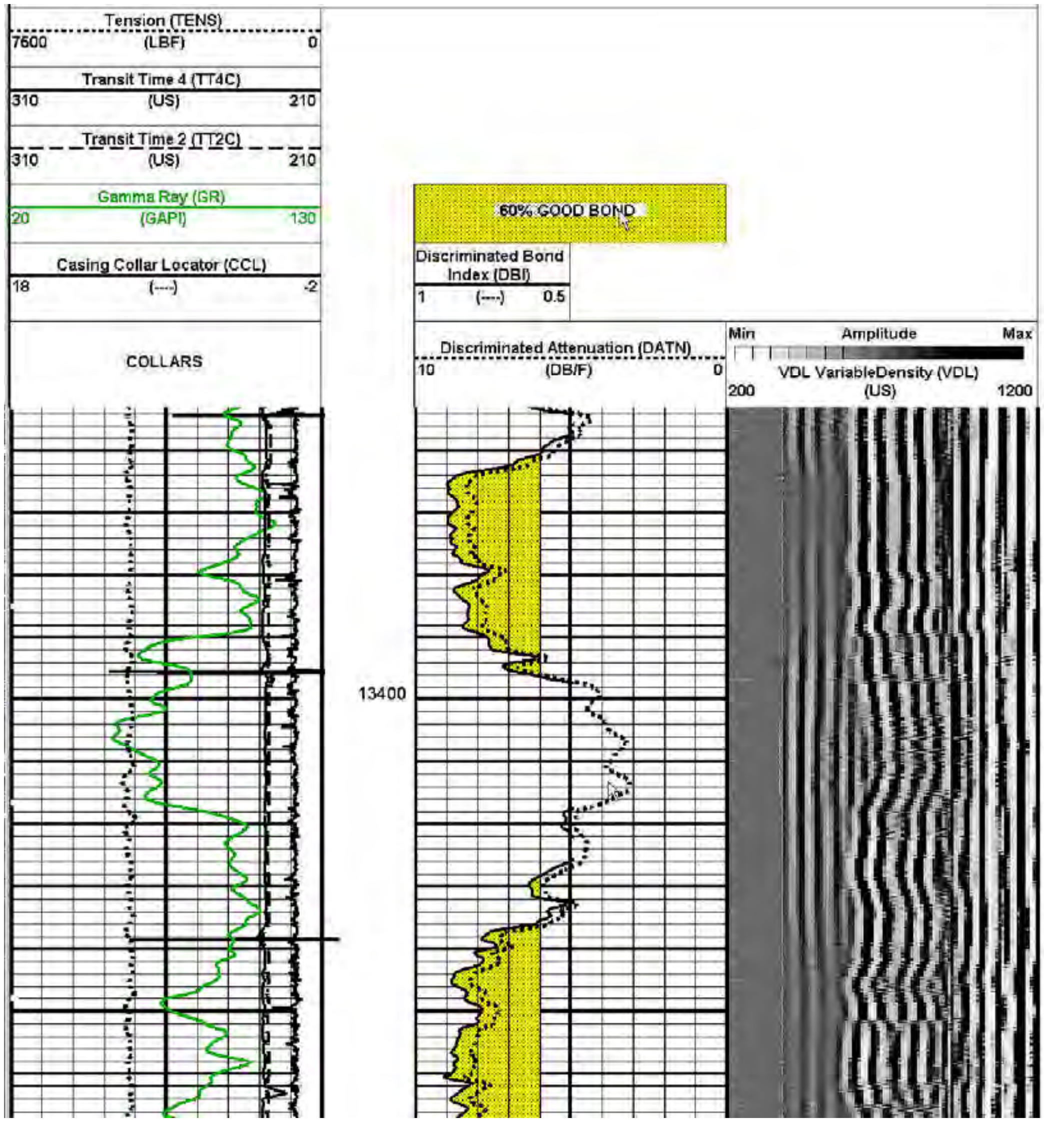


Figure 6.2—Compensated Bond Tool Presentation

6.5 Compensated Logging Tool Interpretation

(See 5.5—Method #1 using Bond Index Attenuation Equation.)

6.6 CBL Quality Control

1. Amplitude or attenuation should never read zero.
2. 200 ft of a free pipe section should be run.
3. Free-pipe amplitude should be ±10% of the service-company specifications (may be lower in fluid weights > 11 ppg).
4. 200 ft of repeat log should be run to ensure consistency.

6.7 Limitations (Environmental Effects)

(See 5.7.)

1. Microannulus.
2. Fast formations (to a lesser extent than traditional CBL due to 1-ft receiver spacing).
3. Cement curing (see 3.2 on slurry design/compressive strength).
4. Gas contaminated cement (see 3.2 on slurry design/static gel strength).
5. Thin cement sheath (see 5.5 on CBL interpretation).
6. Eccentered casing (see 3.3 on mud removal/casing centralization).
7. Coated casing (see 3.3 on mud removal/coated casing).
8. Identifying cement channels.

7 Segmented Bond Log

7.1 Introduction

The SBT is a high-frequency acoustic device that uses compensated logging technology. This unique tool features six pads that are placed against the inner casing surface to measure the casing signal attenuation rate (dB/ft) in each of six, discreet 60° arcs of the casing-cement interface. A standard-frequency VDL tool is part of the service, and it is used to produce full-waveforms for microseismogram presentations. A picture of the complete instrument is displayed in Figure 7.1.

Figure 7.1—Segmented Bond Tool (SBT)

To better appreciate the operation of the instrument's pad section, it is easier to view the pads unfolded in a two-dimensional drawing (see Figure 7.2).

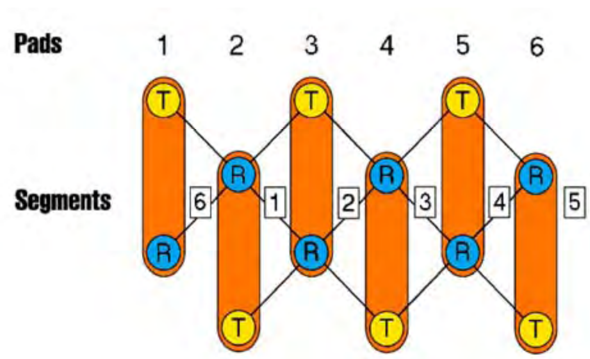


Figure 7.2—Segmented Bond Tool Pad Arrangement

7.2 SBT Physics

The SBT tool employs high-frequency focused transducers mounted on six pads. Motorized arms position each pad with a transmitter and receiver against the casing wall. The tool can be used in casing sizes from 4.5 in. to 16 in., with any type or density of fluid in the casing. A full waveform is produced from the 5-ft, omnidirectional transmitter-receiver module that is run in conjunction with the pad section.

As the transmitters are fired sequentially, amplitude measurements are made on two consecutive and adjacent receivers. A transmitter on the fourth adjacent pad is fired, and amplitudes at the same two receivers (in the opposite direction) are measured (somewhat analogous to the CBT). Energy (amplitude) losses across the receivers are averaged, producing a direct attenuation measurement over a short distance.

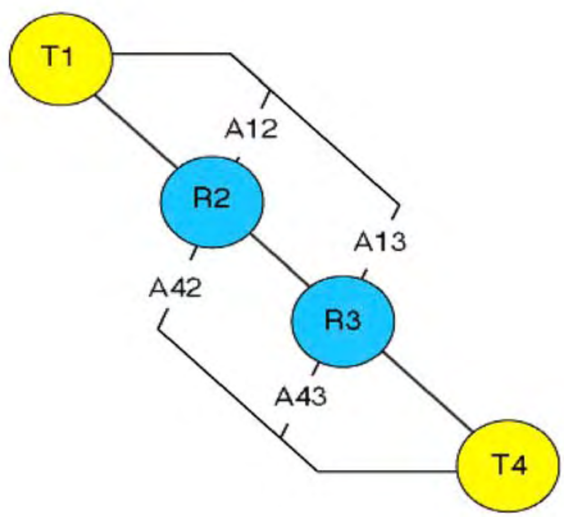


Figure 7.3—Attenuation in Segment 1 from SBT Tool

Attenuation is calculated as follows.

$$\text{Atten} = \frac{10\log_{10}\left(A_{13} \times A_{42}\right)}{\left(R_2 - R_3\right)\left(A_{12} \times A_{43}\right)} \qquad \text{(7-1)}$$

where

A_{xx} is the amplitude at respective receiver;

$R_2 - R_3$ is the physical distance between receivers.

Thus, the measurements are compensated for transducer variations. Calibrations of matching transmitter/receiver pairs are not required. Following acquisition of Segment 1, the remaining Segments 2 to 6 are acquired, and the tool cycle begins again.

7.3 Waveform/Variable Density Physics

(Same as 5.2.)

7.4 Key Requirements

(Same as 5.3.)

7.5 SBT Presentation

(See Figure 7.4.)

Track 1 contains the GR, collar locator, DTMN (DT minimum) and DTMX (DT maximum) curves.

Track 2 is the depth track.

Track 3 displays the six individual attenuation measurements in six "sub-tracks", labeled ATC1, ATC2,…ATC6, with the relative bearing curve (RB) indicating the tool face relative low side of the hole.

Track 4 contains the average and minimum attenuations (ATAV and ATMN).

Track 5 is a cement map that is a graphic form of interpretation of the cement quality.

Track 6 is a VDL display from the 5-ft receiver.

7.6 SBT Interpretation

The GR and collar log are used for correlation and depth control.

The six individual attenuation measurements are labeled ATC1, ATC2,…ATC6. The higher the attenuation, the greater the likelihood of cement presence. The relative bearing (RB) indicates the tool face relative low side of the hole. This feature is used to depict cement anomalies radially around the casing (see cement map discussion below). It is only useful in deviated wells.

The average and minimum attenuations (ATAV and ATMN) are exactly as described. The average is the sum of the six individual attenuations divided by six. The minimum is the lowest of the six individual attenuations. These two curves will normally display some separation. They will nearly stack when certain conditions are satisfied—completely free pipe (no cement) and pipe uniformly cemented around the casing.

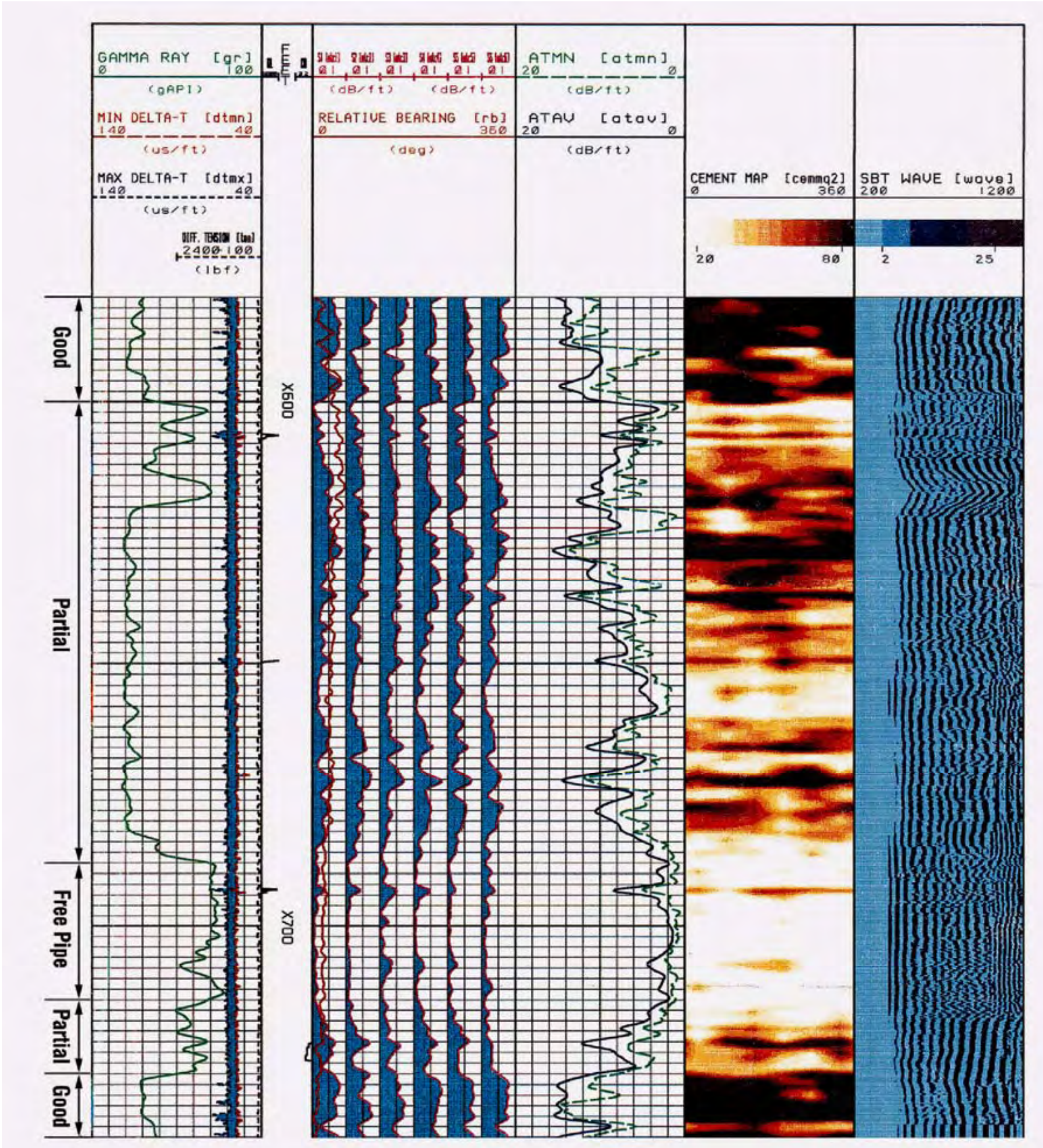


Figure 7.4—SBT Presentation

A cement map is a graphic interpretation that is subject to certain user inputs. The interpreter must understand how the cement map was constructed and know whether reasonable inputs were used in its construction. In the case of the SBT cement map, six regions across the map left to right correspond to the values in each of the six individual attenuation measurements. Higher attenuation rates (better cement) will appear as darker regions on the cement map. Normal user input is automated, and based on inputs of casing size and weight as well as cement compressive strength. The parameters are stated in the log header. For deviated wells, the RB curve mentioned earlier can be used as an input to orient the low or high side of the hole to the middle of the cement map. The purpose of this high-side/low-side option is to detect whether cement anomalies correlate with the high or low side of the casing. The most useful feature of a cement map is the detection of uncemented channels over significant intervals as opposed to isolated voids.

The SBT Interpretation Chart (see Figure 7.5) depicts the relationship between casing-wall thickness and cement compressive strength. The chart should be used as a guideline when evaluating conventional cements (Class H, Class G, etc.) that are not mixed with volume extending additives. When evaluating foamed cements or other cement systems containing low-density additives (e.g. microspheres) or volume extending additives, the relationship between cement compressive strength and cement acoustic impedance tends to be less reliable.

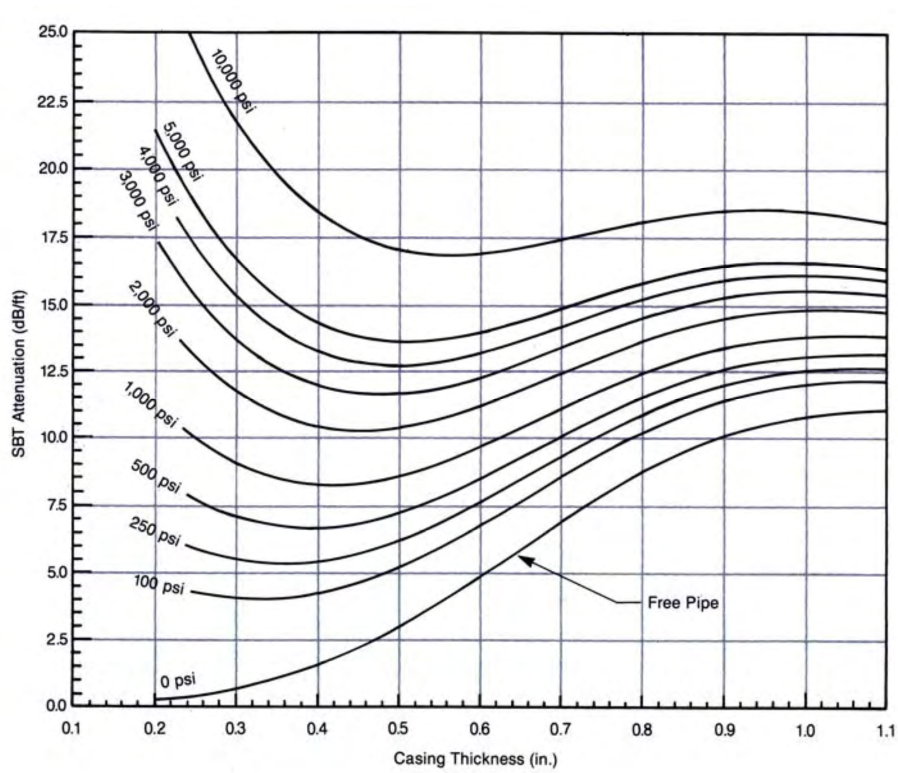


Figure 7.5—SBT Chart to Convert Attenuation to Compressive Strength for Classes G and H Cement

NOTE: Draw a horizontal line from the attenuation measurement on the y-axis, and a vertical line from the casing-thickness on the x-axis. The point at which both lines intersect is the apparent cement compressive strength.

7.7 SBT Quality Control and Recommendations

1. Attenuation should never read zero.
2. Run 200 ft of repeat section.
3. Run 200 ft of a free-pipe section.
4. DTMN and DTMX curves are the primary log-quality indicators. They indicate the degree of casing centralization, and are a direct acoustic couple of the

instrument pads with the casing wall. Excessive internal scale or residual cement may not permit effective acoustic coupling. The two curves should be scaled 140 µs/ft to 40 µs/ft, and should track each other within 4 µs/ft to 5 µs/ft, except across casing collars where greater separation will be present. The two curves should center over the 57-µs/ft value, which is the TT of steel casing. Finally, the DTMN and DTMX curves are excellent indicators of instrument integrity. Should one of the transducers or related circuitry fail, its DTMN and DTMX curves will depart significantly from the standard behavior of the other transducers.

5. Scale the ATC1, ATC2, …ATC6 attenuation rates to 20–0 dB/ft.
6. On the SBT, scale the Attenuation Rate to 0–9 dB/ft and the Cement Map using the SBT interpretation chart. The minimum coloration value should be equal to that of free pipe on the chart (based on casing wall thickness) (see Figure 7.5).
7. The SBT can be run in any casing-fluid density, and in casing sizes up to and including 16 in. Larger sizes have been logged with special arm extenders; however, the log quality is lower.
8. Generate a receiver-calibration and verification summary.

7.8 Limitations (Environmental Effects)

(See 5.7.)

1. Microannulus.
2. Fast formations (to a lesser extent than traditional CBL—reduced transmitter-receiver spacing).
3. Cement curing (see 3.2 on slurry design/compressive strength).
4. Gas contaminated cement (see 3.2 on slurry design/static gel strength).
5. Thin cement sheath (see 5.5 on CBL interpretation).
6. Eccentered casing (see 3.3 on mud removal/casing centralization).
7. Coated casing (see 3.3 on mud removal/coated casing).
8. Identifying small cement channels.

8 Sector Bond Log (SBL)

8.1 Introduction

SBL tools are mandrel-type devices that combine the traditional 3-ft CBL and 5-ft VDL feet measurements (provided by 1 monopole, omnidirectional transmitter and 2 omnidirectional receivers) with an array of eight or six sector transmitters, located next to the monopole transmitter (1.66 ft to 2 ft spacing and circumferentially located at angles from 45° to 60°). The array of directional receivers provides an azimuthal segmented map or image of cement bond quality. This tool has different nomenclatures depending on the service company (e.g. RAL: radial attenuation log; CMT: cement mapping tool; SCMT: slim cement mapping tool; SSBT: slim sector bond tool; SBL: sector bond log).

Slim (1 $^{11}/_{16}$ in.) tools are available for through-tubing operations. High-temperature and high-pressure tools, rated up to 400°F to 420°F and 15,000 psig to 20,000 psig, can be provided.

One type of SBL employs a different tool configuration. This 2 $^{3}/_{4}$-in. tool combines the traditional 3-ft CBL and 5-ft VDL measurements, with an array of eight directional transmitters working in combination with an array of eight directional receivers. The transmitter array is linearly spaced 2 ft from the receiver array, and each sector transmitter-receiver pair is radially spaced 45° apart to scan the cement around the casing circumference. The sector-transmitter resonance frequency is in the low-ultrasonic region between 80 kHz to 120 kHz.

8.2 SBL Physics

There are two types of SBLs; the radial bond tool (RBT) and the sector bond tool (SBT).

The radial bond tool (RBT) uses a method similar to the traditional 3-5 ft CBL-VDL. The six or eight directional receivers analyze the waveforms transmitted along the casing in 45° or 60° sectors of the casing circumference (see Figure 8.1a). The two omnidirectional receivers work in combination to provide the traditional CBL-VDL.

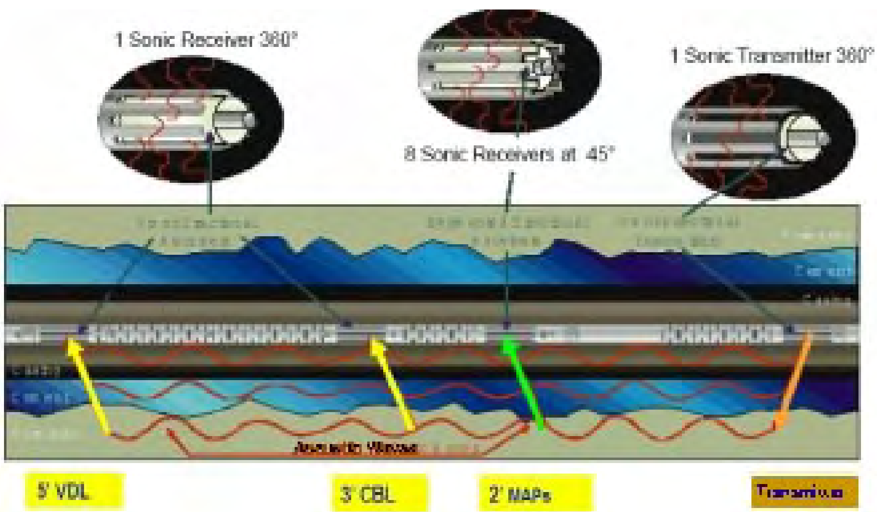


Figure 8.1a—Illustration of the Measurement Principle Used by the Radial Bond Log (Eight Directional Receivers for Cement Mapping)

The sector bond tool (SBT) works in a similar fashion. The eight pairs of directional transmitter-receivers emit an acoutic signal down the casing with each 45° sector transmitter-receiver simultaneously (see Figure 8.1b).

For RBT and SBT, the directional receivers or transmitter-receiver pairs used for radial channel identification.

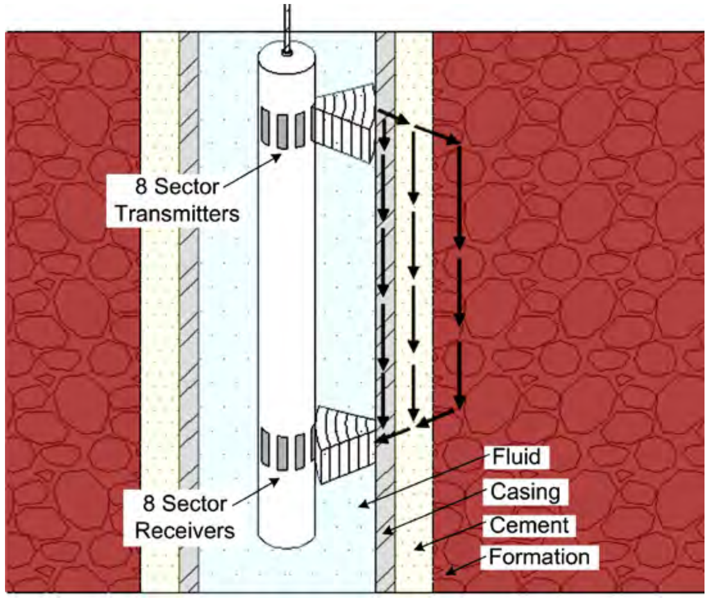


Figure 8.1b—Illustration of the Measurement Principle Used by the SBT

8.3 SBL Waveform/Variable Density Physics

(Same as 5.2.)

8.4 Key Requirements

(Same as 5.3.) A few important key requirements should be emphasized.

1. Tool centralization for slim RBT.
2. Calibration of each directional receiver (RBL) or transmitter-receiver pair (SBT)
3. Tool setup: Casing-size and thickness data, especially for the SCMT (signal processing).

8.5 SBL Presentation

The following are two examples of available SBL presentations. (See Figure 8.2 and Figure 8.3.)

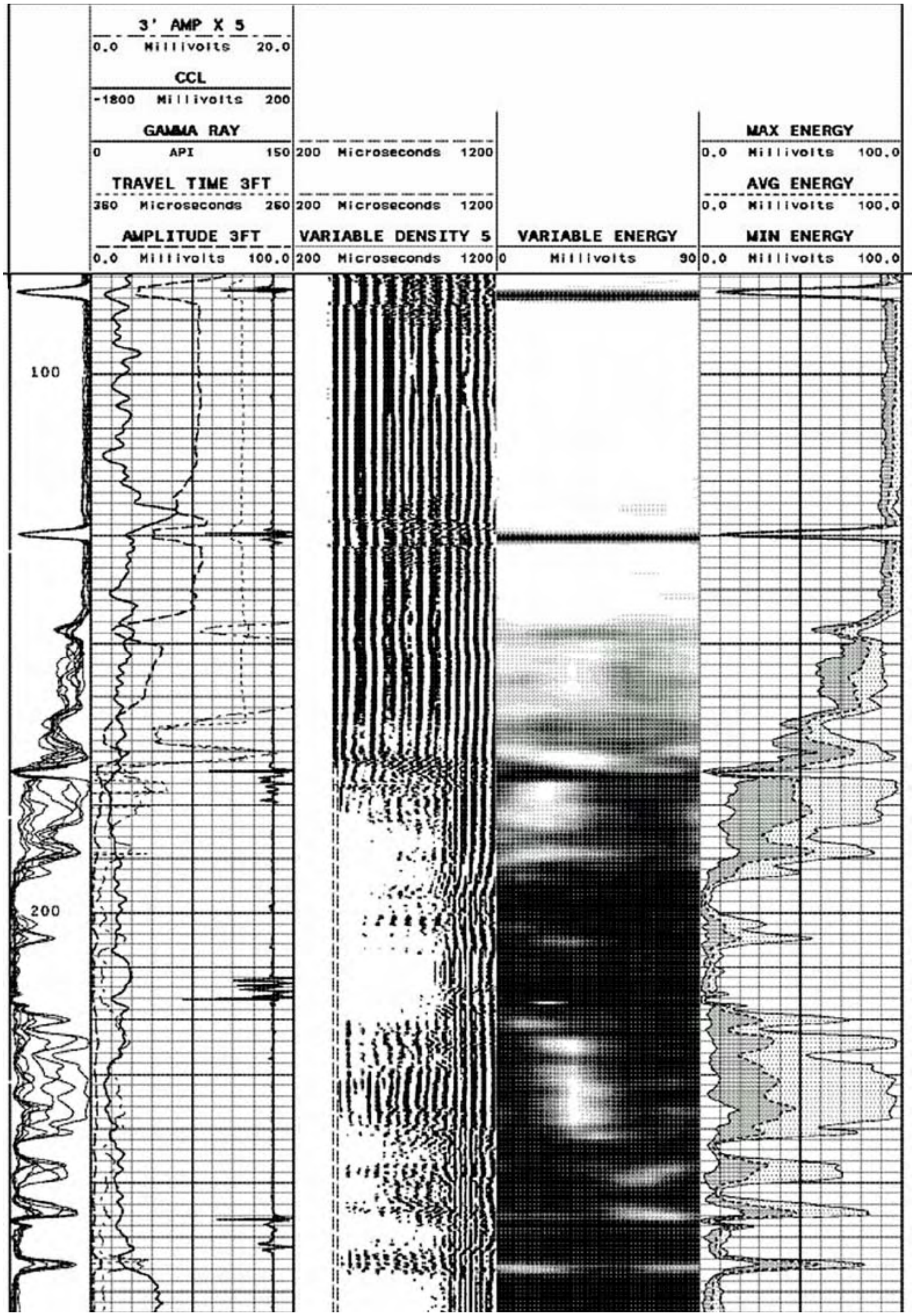


Figure 8.2—Sector Bond Log (SBL) Presentation #1

NOTE: The first track shows the amplitude curves from the 2-ft receiver. The second track contains the 3-ft amplitude, 3-ft TT, GR and collar locator. The third track is variable density log or waveform presentation. Track four is the cement map for cement evaluation, based on the parameter picks for the sectors. The last track has the minimum, maximum and average amplitude from the 2-ft spacing sectors.

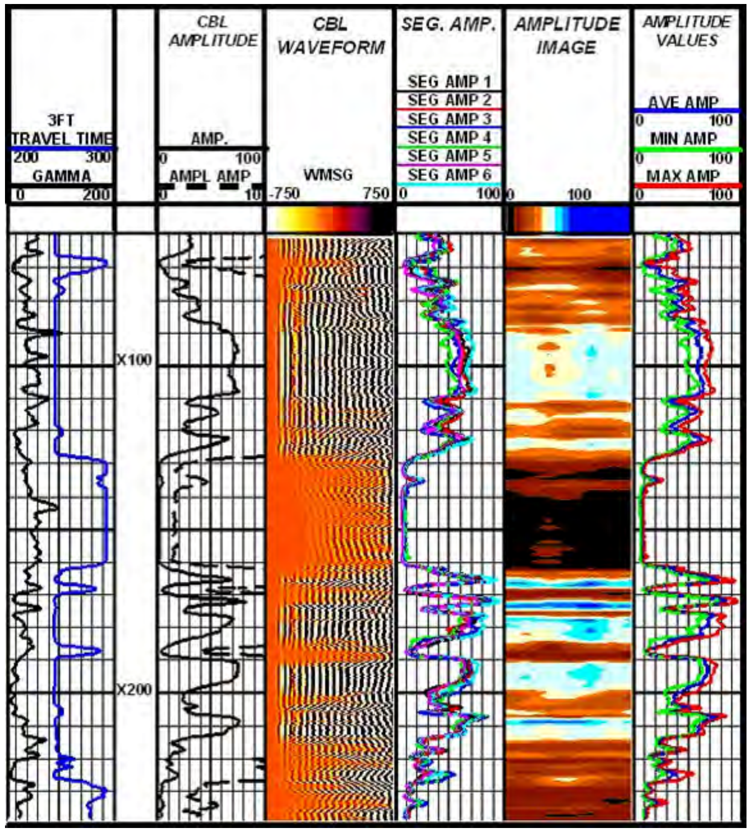


Figure 8.3—Sector Bond Log (SBL) Presentation #2—Radial Bond Log Example (60° Sector Cement Mapping)

NOTE: Track 1 provides the GR and 3-ft TT. The TT is skipping cycles or reading high in areas of cemented pipe-to-pipe coupling, for example at X150. Track 2 provides the standard CBL-amplitude curves. Track 3 is the CBL waveform or VDL. The segmented amplitude readings are in Track 4, with the image created from the segmented amplitude curves in Track 5. In this example, the segmented amplitude image (or cement map) is built from 60° sectors (RBT with an array of 6 directional receivers) used to create the map ranges from black (calculated 100% Bond Index) to dark blue (100% free pipe, no cement), with each color indicating a 10% change in the bond-index calculation. The minimum, maximum, and average amplitude readings are presented in Track 6, which is an indication of the consistency of the cement sheath.

8.6 SBL Interpretation

The basic interpretation of the SBL is divided into three independent measurements: the 2-ft sectors, the CBL and the VDL. The 2-ft sector measurement is intended for channel identification only and not necessarily for compressive-strength or acoustic-impedance calculations. In addition, due to the 2-ft transmitter-receiver spacing and the 45° radial resolution for the 2 $^{3}/_{4}$-in. tool, or the 45° – 60° resolution for the 1 $^{11}/_{16}$-in. tool (depending on the tool provider), the sector receivers only identify channels with high amplitude (near the free-pipe amplitude value). In weak or partially bonded sections the 2-ft sector readings tend to be heavily influenced to the fully bonded amplitude value.

The transmitter-receiver acoustic radiation beam pattern for one 2-ft sector is shown in Figure 8.4. The radiation beam covers 45° with a drop in signal power from the center of the beam or 0° to the edge of the beam or ±22.5° of 1dB. For example, if the amplitude was 100 mV at 0°, then at ±22.5° the amplitude would read 90.5 mV. This result assures full coverage of the casing by eight sectors. The single-beam pattern also reveals that large overlapping areas will exist between adjacent sectors, indicating that a channel may be detected by one or two sectors at the same time. If a channel is smaller than a single beam pattern or detected by two or more sectors, the map will show a channel larger than what is actually present behind the casing. Therefore, the sector map will usually be pessimistic and show more free pipe then actually exists.

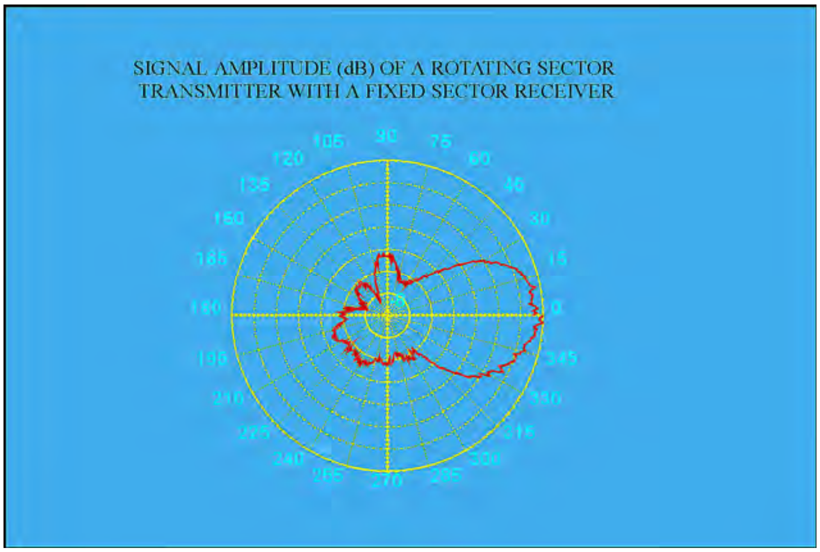


Figure 8.4—Acoustic Radiation Beam Pattern as Seen by a Sector Receiver

NOTE: 0° represents the center of the beam pattern where the signal power is at its maximum. The concentric circles represent the reduction in power in dB. At 15° the signal power as seen by the receiver is approximately 0.5dB and at 22.5° the power has dropped approximately 1 dB. This indicates that the the casing coverage per 2-ft sector is 45°.

Sector bond tool mapping (variable energy display) is used for channel identification only (see Figure 8.5). Once a channel is identified on the sector map, its size may be calculated using the 3-ft amplitude by the simple expression:

$$\text{Channel Size}° = \left(\frac{\alpha_b - \alpha_z}{\alpha_b}\right) * 360° \qquad (8\text{-}1)$$

where

α_b is the attenuation rate of the 3-ft amplitude in a cemented section of the well;

α_z is the attenuation rate of the 3-ft amplitude in the channel section of the well.

This equation assumes that the cemented portion of the circumference is of uniform compressive strength.

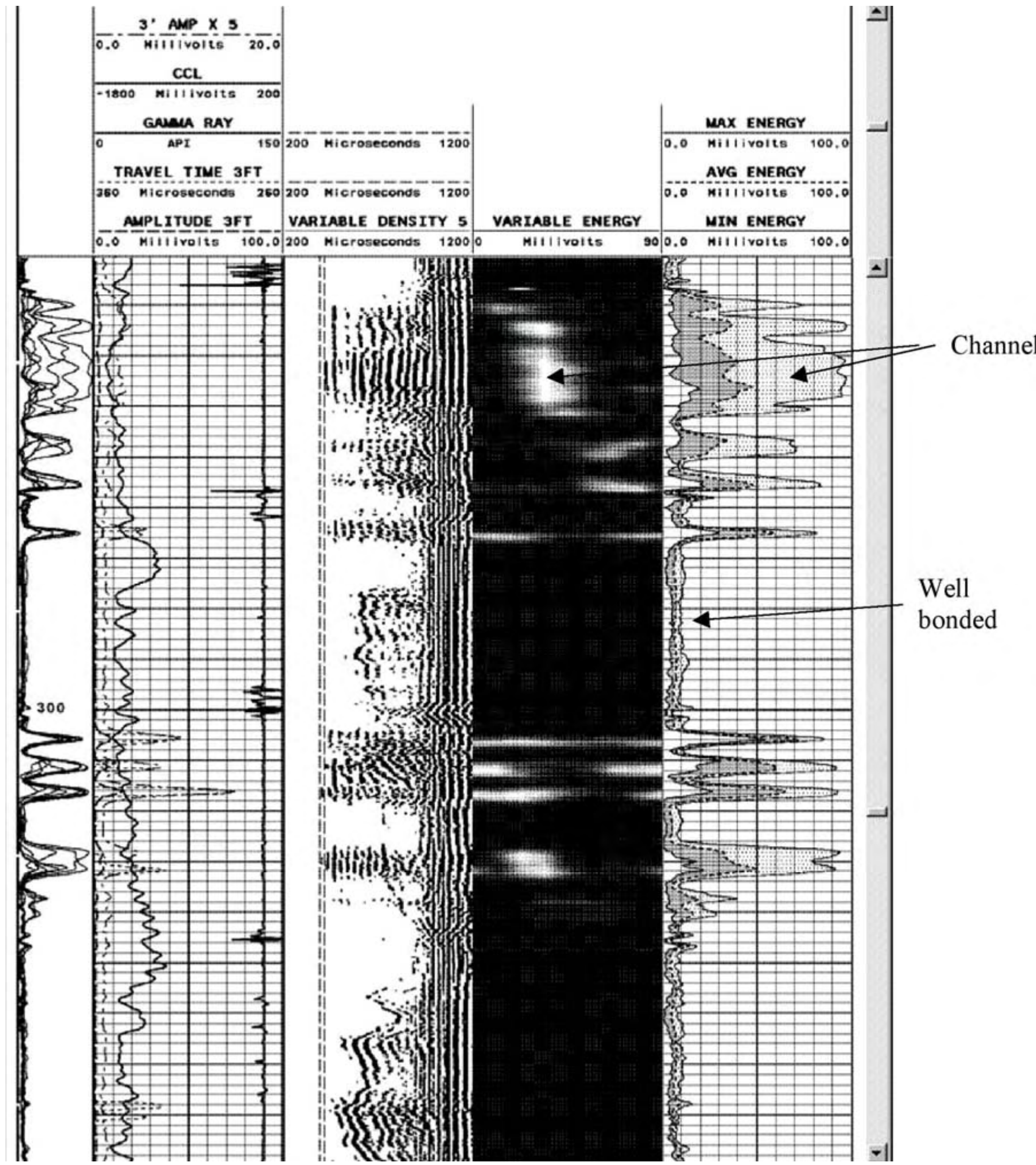


Figure 8.5—Sector Bond Log (SBL) Example Illustrating the Presence of Channels and Well Bonded Sections

NOTE: In a cemented section, all the sector energies collapse near the noise level of the system (typically less than 20 mV).

8.7 SBL Quality Control and Recommendations

SBL interpretation requires the combination of the 3-ft CBL amplitude and the 5-ft VDL logs.

The first QC procedures are a master calibration performed at the service company facility and the free-pipe calibration. Master calibration should be performed in a free-pipe test vessel according to the service company QA/QC program. Correction factors are applied to provide the same response in a radial sector. Free-pipe response measurements are verified in the field across a free-pipe section of casing. It is essential that the field free-pipe measurement be taken in a section of uncemented casing, because formation-casing contact can affect sector responses. The minimum, maximum and average traces should be within 10% of each other. On the map, free pipe appears white with dark stripes on the collars. Sometimes the collars are not clearly detected by the sectors, especially in flush-joint pipe.

The second QC procedure corresponds to a low-amplitude or a cemented section (not always possible to obtain). The minimum amplitude depends upon the tool, wireline and uphole system noise. The expected minimum value for a particular casing size and thickness should be provided by the service company. The map should be black in a cemented section and white in a non-cemented section. The field engineer enters the amplitude parameters that control this shading. Caution should be applied to ensure that the proper parameters have been selected (see 5.3, Key Requirements).

The third QC procedure relates to the calibration balance between sectors. A miscalibrated sector appears as a white or a dark vertical stripe along the entire log. A miscalibrated sector can be recalibrated after logging during playback.

8.8 SBL Limitations (Environmental Effects)

(See 5.7.)

1. Microannulus.
2. Fast formations (to a lesser extent than traditional CBL on the sectors thanks to reduced spacing).
3. Cement curing (see 3.2 on slurry design/compressive strength).
4. Gas contaminated cement (see 3.2 on slurry design/static gel strength).
5. Thin cement sheath (see 5.5 on CBL interpretation).
6. Eccentered casing (see 3.3 on mud removal/casing centralization).
7. Coated casing (see 3.3 on mud removal/coated casing).
8. Identifying small uncemented channels.

9 Ultrasonic Evaluation Tools

9.1 Introduction

Ultrasonic cement-evaluation logs employ a method different from CBL logs to define cement-sheath quality and quantity. These tools identify the material next to the pipe and cannot be used to evaluate cement-to-formation coupling. Therefore, CBL-VDL tools should be run along with ultrasonic tools to observe formation-to-cement coupling. In most cases, ultrasonic tools can evaluate newer complex cement blends including foamed cement, latex-modified cement and ultra-low density or gas contaminated cements. Additional measurements include the pipe internal diameter and pipe thickness, obtained simultaneously with the cement information.

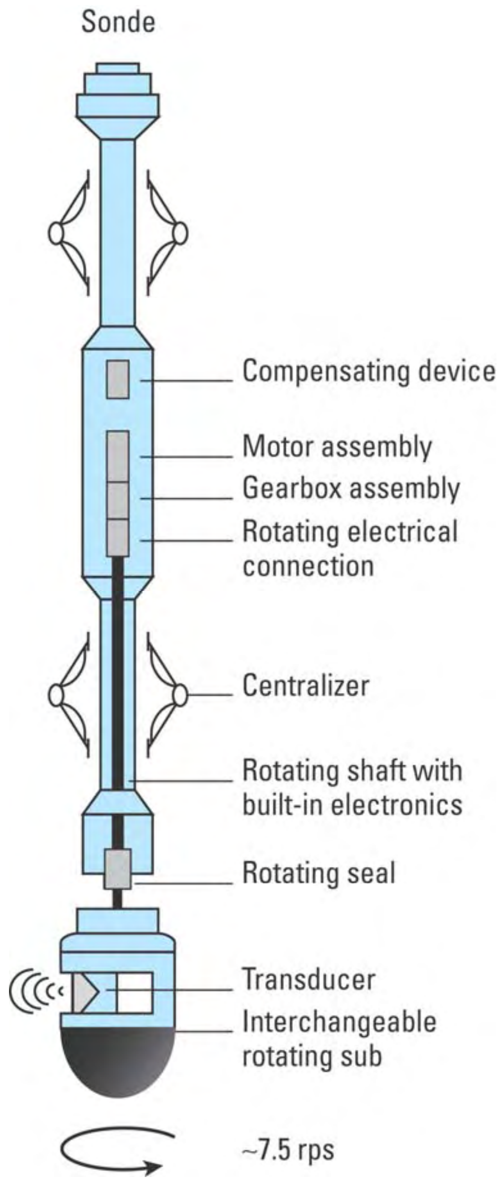
The ultrasonic source and receiver are packaged together as one transducer instead of the source-and-receiver pairing employed in CBL tools. The first-generation ultrasonic tools normally consisted of at least eight different transducers (cement evaluation tool, CET; pulse echo tool, PET) and are not covered in the present report. Second-generation ultrasonic tools employ a single rotating transducer (see Figure 9.1) to produce high-resolution, circumferential data. The rotating transducer provides 36 to 200 measurements per depth sample, at a vertical sampling rate ranging from 2 to 12 samples per ft, depending upon the service company and tool setup. Both the CBL and ultrasonic tools are combinable, allowing data to be recorded in one pass through the wellbore.

9.2 Ultrasonic Tool Physics

Ultrasonic evaluation tools operate at frequencies between 200 kHz and 700 kHz. The basic principle behind the ultrasonic technique is to cause a small area of casing to resonate through its thickness. The transducer transmits a short pulse of ultrasound and senses the echo containing the resonance. If there is fluid behind the casing, the casing will tend to resonate or “ring,” but resonance will be dampened when there is solid cement behind the casing. The resonance is analyzed to determine the cement acoustic impedance.

Ultrasonic echoes yield four measurements (see Figure 9.2):

1. echo amplitude—an indicator of casing condition;
2. internal radius—calculated from the TT of the main echo;
3. casing thickness—calculated from the resonant frequency;
4. acoustic impedance of the material behind the casing—calculated from the form of the resonance.



5.

6.

Figure 9.1—Schematic Illustration of an Ultrasonic Tool

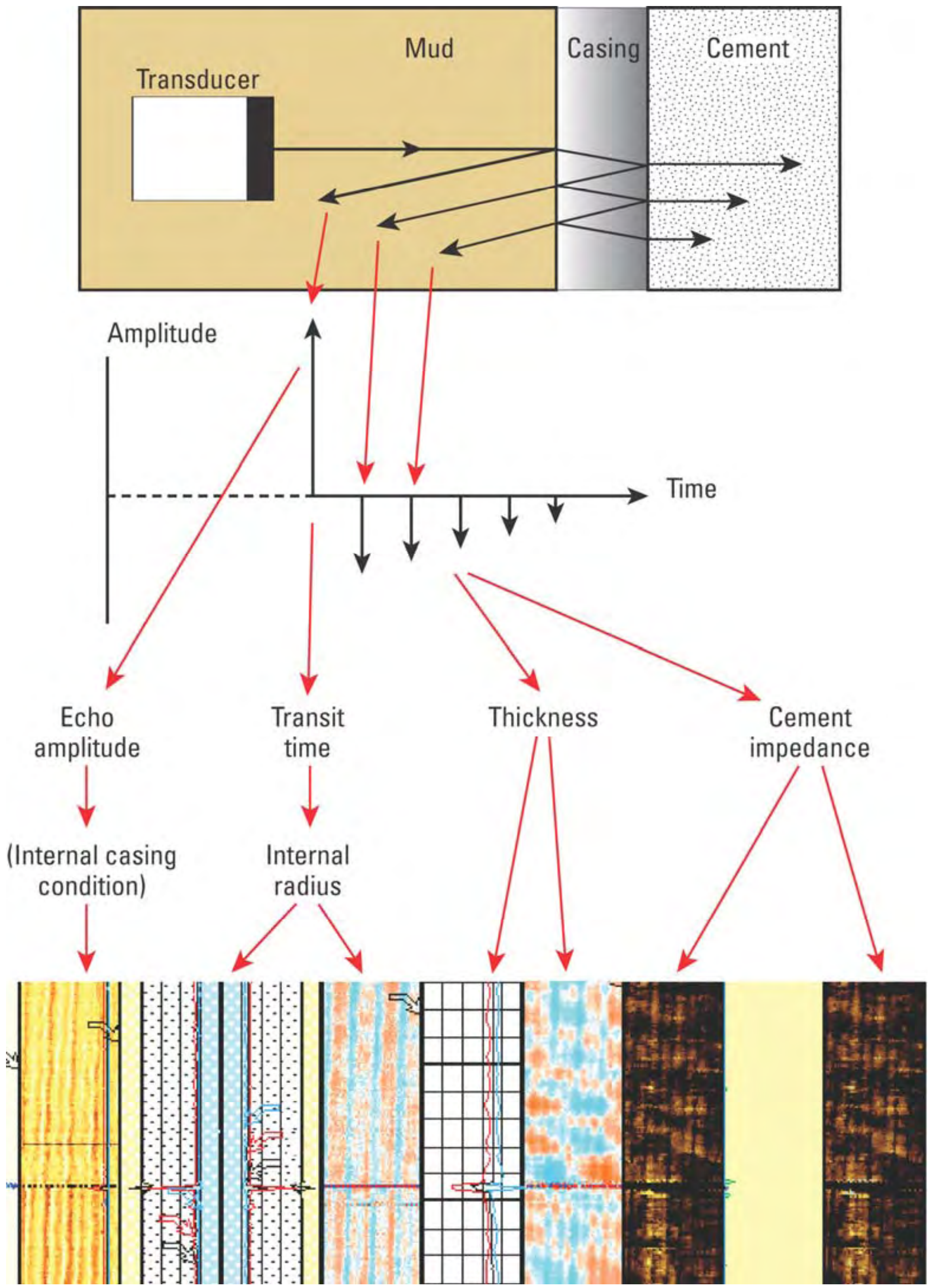


Figure 9.2—Ultrasonic Tools Measure Cement and Casing Information with One Transducer

The physics can be explained by assuming the ultrasonic wave to be planar and incident normally on a flat plate representing the casing. Figure 9.2 shows the wave paths and the echo train obtained from an ideal, infinitely short transmitted impulse. At the boundary between the pipe and the borehole fluid, most of the incident energy is reflected, and the balance is transmitted into the pipe wall. The fractions of incident acoustic pressure that are reflected and transmitted are given by the following formulas.

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (9\text{-}1)$$

and

$$T = 1 + R = \frac{2Z_2}{Z_2 + Z_1} \quad (9\text{-}2)$$

where

R is the reflection coefficient at the boundary between two materials of acoustic impedance Z_1 and Z_2;

T is the transmission coefficient at the same boundary.

Impedance is defined as:

$$Z = \rho \times V \quad (9\text{-}3)$$

where

Z is the impedance;

ρ is the bulk density;

V is the ultrasonic compression-wave velocity.

The pressure-transmission coefficient can be greater than 1, but energy is always conserved because the intensity I is given by:

$$I = \frac{p^2}{Z} \quad (9\text{-}4)$$

where

p is the acoustic pressure.

The first large reflection at the pipe wall returns to the transducer, and is used to calculate the pipe radius. The small fraction of the energy transmitted into the pipe bounces back and forth inside the pipe wall, losing energy into the annulus and into the hole at every bounce. The pressure-reflection coefficient inside the pipe is negative. Thus, the echo train consists of a large reflection from the internal surface of the pipe, followed by an exponentially decaying series of inverted pulses. The time separation (Δt) between negative pulses is equal to the time for the sound wave to pass across the pipe thickness and return to the same surface.

$$\Delta T = \frac{2d}{v_{\text{steel}}} \tag{9-5}$$

where

d is the casing thickness;

v_{steel} is the acoustic velocity in steel (5930 m/s).

The resonant frequency of the pipe is given by:

$$f_0 = \frac{1}{\Delta t} = \frac{v_{\text{steel}}}{2d} \tag{9-6}$$

Figure 9.3 shows typical echoes from free and cemented casings backed by water and cement. The resonance has been magnified to show more detail. This diagram illustrates two points. First, cement behind the pipe dampens the resonance. Second, the resonant frequency (shown by the spacing between the resonance peaks) is the same with water or cement behind the pipe.

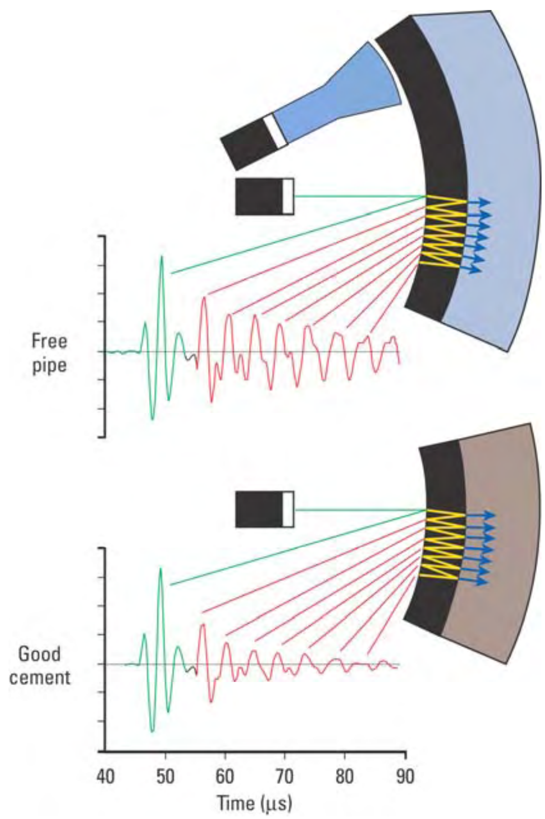


Figure 9.3—Ultrasonic Response to Different Materials in the Annulus

NOTE: The resonance (red) is magnified for clarity. Copyright Schlumberger. Used with permission.

Ultrasonic Imaging Tool (USIT)

The USIT calculates the acoustic impedance of the medium immediately behind the casing. The tool typically makes 36 (or 72 at high resolution) horizontal measurements at each depth segment for simultaneous cement evaluation and casing inspection.

USIT processing is shown in Figure 9.4. The time from transducer firing to main-echo reception is used to calculate a radius. The distance that the tool is eccentered in the pipe is calculated from the radii measurements, and the radii are corrected for eccentering.

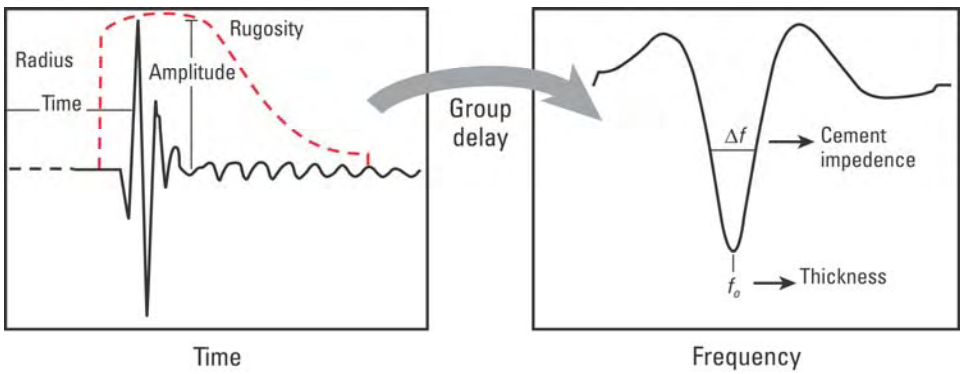


Figure 9.4—Diagram of USIT Signal Processing

NTOE: Copyright Schlumberger. Used with permission.

The early part of the signal, covering the main echo plus roughly the first seven cycles of resonance, is selcted by the dotted red window function shown in Figure 9.4. The group delay spectrum of this signal is calculated as follows:

$$\tau = -\frac{d\phi}{d\omega} \tag{9-7}$$

where

$\phi(\omega)$ is the phase spectrum;

$\omega = 2\pi f$ is the angular frequency.

The group delay spectrum shows the pipe resonance as a dip.

The amplitude of the main echo is measured. It is a qualitative indicator of pipe rugosity and is useful for quality control. In tools other than the USIT, the amplitude is part of the cement processing in that it is used as a first-order correction for mud attenuation, tool eccentering and pipe rugosity.

The USIT is run into the wellbore with a stationary transducer facing a steel plate inside the tool. This provides a measurement of the borehole-fluid velocity (FVEL; Figure 9.9), the borehole fluid impedance (ZMUD, Figure 9.10) and steel plate thickness. This fluid-impedance value is then used as an input to determine the impedance of the material in the casing annulus when logging upward.

Circumferential Acoustic Scanning Tool (CAST-V)

The CAST-V calculates the acoustic impedance of the medium immediately behind the casing. Z is now dynamically calibrated by analyzing the scanning transducer's characteristics during each scan (see Figure 9.5). The tool makes 100 horizontal measurements at each depth segment for simultaneous cement evaluation and casing inspection. The Z calculation uses the following data:

- the transducer's signature (see Figure 9.5),
- the measured casing thickness (THK),
- the acoustic impedance of the borehole fluid (ZMUD),
- the acoustic impedance of the casing, and
- the energy carried by the waveform in the resonance window.

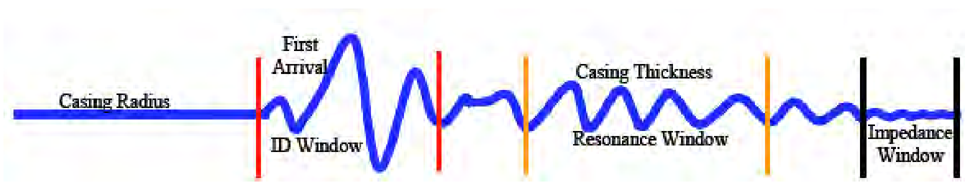


Figure 9.5—Ultrasonic Waveform Breakdown

The THK calculation involves finding the frequency at which the resonance-window signal shows a maximum energy, and the speed of sound in the pipe (in its transverse mode). The pipe is assumed to be made of steel. Logging for cement evaluation inside most oilfield pipes that are made of a single metallic material (e.g. titanium, cast iron, MONEL, etc.) is normally possible, at least in qualitative terms. There is usually considerable contrast between the acoustic impedances of pipe and borehole fluid. The measured thickness values should be corrected by the following formula.

$$THK_{\text{true}} = THK_{\text{measured}} \times \frac{V_{\text{material}}}{V_{\text{steel}}} \tag{9-8}$$

The CAST-V has a separate transducer to record real-time velocity of the fluid in the wellbore. This allows accurate corrections to the casing ID measurement. Knowing the fluid travel time (FVEL) and the fluid density allows real-time calculation of wellbore-fluid impedance (ZMUD), which is then used to determine the impedance of the material in the annulus.

Ultrasonic Radial Scanner (URS)

The URS evaluates cement condition by measuring the acoustic impedance of the material (cement or fluid) behind the casing. This is achieved by recording three casing measurements (1) the internal radius or diameter, (2) the ovality, and (3) the thickness. Another ultrasonic sensor located in the mud column measures the sound velocity and the acoustic impedance of the borehole fluid.

The energy in the resonance window (see Figure 9.5) is inversely proportional to the acoustic impedance of the material behind the casing. The acoustic impedance is computed using the ratio of the first arrival **amplitude** to an integration of the signal in the **resonance window**. This ratio is normalized to the acoustic impedance of the fluid behind the casing.

For proper tool calibration, the impedance of the fluid behind the casing should be known. If the fluid inside the casing is the same as the fluid outside the casing, the tool calculates the acoustic impedance directly.

Figure 9.6 shows the tool response (window area ratio) to acoustic impedance of material behind the casing, with casing thickness as a parameter. Note that, for the same window area ratio, the acoustic-impedance reading is different for a 0.6-in pipe than one with a thickness of 0.1 in.

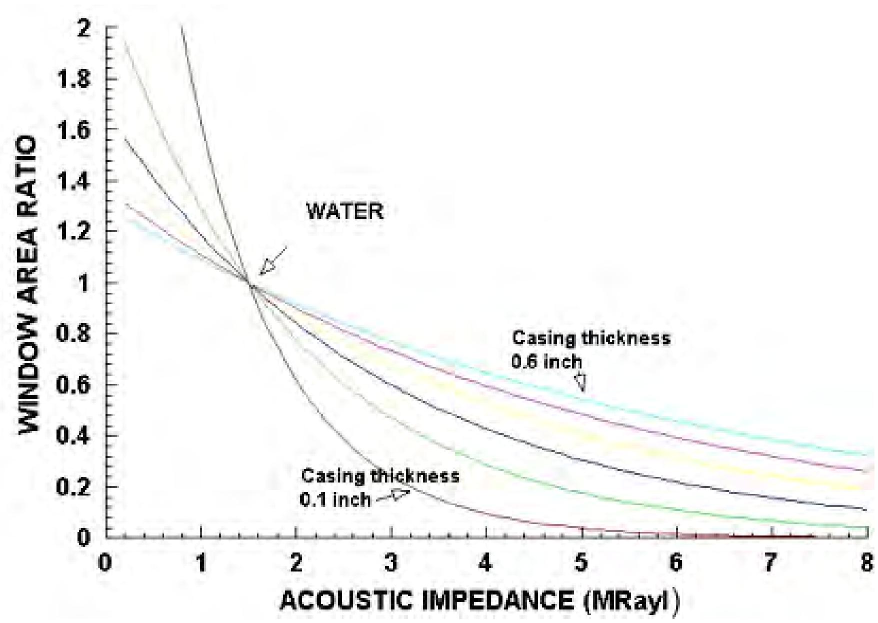


Figure 9.6—URS Tool Response to Acoustic Impedance

9.3 Key Requirements

The following are necessary requirements for ultrasonic cement evaluation logs.

1. A bit and scraper run is recommended to remove cement and scale from the casing wall.
2. The borehole must be filled with liquid. Gas or air bubbles will cause inaccurate readings. If the hydrostatic pressure is insufficient to ensure transducer wettability

with the wellbore fluids, it may be necessary to apply pressure to the wellbore. This will allow the ultrasonic tools to function properly over the entire wellbore.

3. The borehole fluid should be known. This will help the logging engineer select the proper tool, transducer frequency, and placement method before the logging job.
4. Casing size, weight and internal diameter must be known. This is necessary information to assist in pre-job planning and obtain improved results.
5. Ultrasonic tools must be run centralized. Most ultrasonic logs cannot be reprocessed to remove eccentricity errors in the calculation of the impedance values.
6. Density of the fluid in the casing must be known. This will allow proper calculation of mud impedance, which is used in determination of the impedance of the material in the annular space.

The following will improve and simplify the evaluation of the ultrasonic cement evaluation logs.

1. Wellbore schematic.
2. The proper cement curing time prior to logging. This may include plotting the acoustic impedance vs. time to determine the proper logging time. (see Figure 3.2), or consulting a cement report with similar information.
3. Casing and centralizer report to determine where casing eccentering may occur.
4. Wellbore deviation and trajectory to help determine areas of unusual log response.
5. Openhole logs with a caliper and lithology to assist in determining thin cement-sheath locations.
6. Predicted cement tops for the lead and tail slurry.
7. Estimate of the acoustic impedance of the cement in the casing annulus.
8. Estimate of the acoustic impedance of the potential fluid(s) in the casing annulus. This includes mud that was displaced and the fluid used to displace the cement slurry.
9. Any information regarding cement-placement operations that may assist in determining unusual log response. Examples include lost returns, cement to surface and pressures during cement placement.
10. An understanding of fluid type (liquid or gas) in the formation pore space.
11. History of pressures applied to the wellbore may assist in determination of unusual log response. Examples include fluid changes, casing pressure tests, squeeze jobs and stimulation treatments.

9.4 Ultrasonic Presentations

USIT Casing and Cement Map

Log presentations vary from region to region and between service companies. Schemes used for labeling curves also differ. The data can be classified into four types:

1. borehole fluid data;

2. quality control and auxiliary data;
3. casing data (radius and thickness);
4. annular cement data.

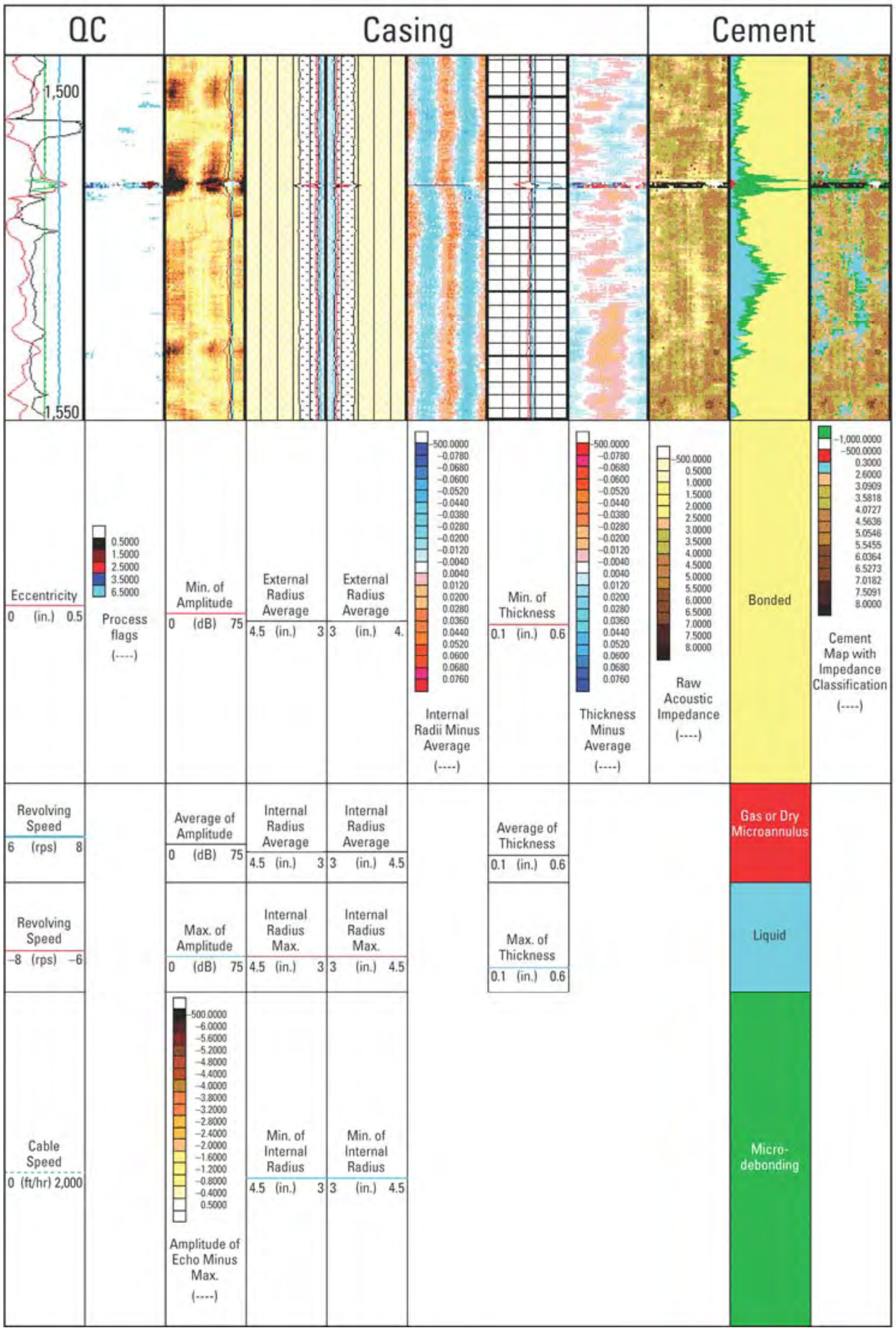


Figure 9.7—USIT Cement and Casing Map

NOTE: See Annex A jargon: USIT micro-debonding. Copyright Schlumberger. Used with permission.

USIT Cement Map

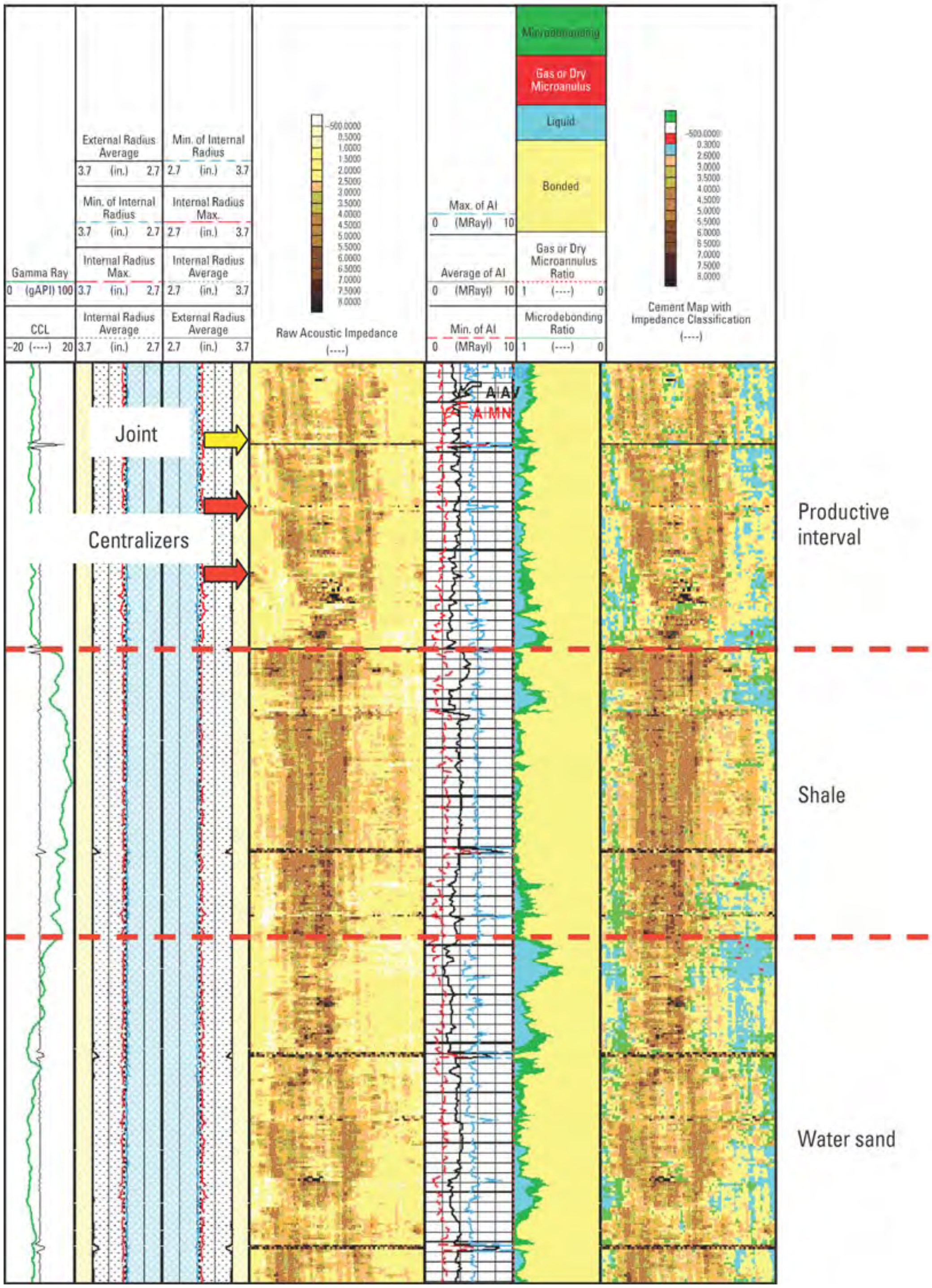


Figure 9.8—USIT Cement Map

NOTE: See Annex A jargon: USIT micro-debonding. Copyright Schlumberger. Used with permission.

USIT Fluid Velocity Data

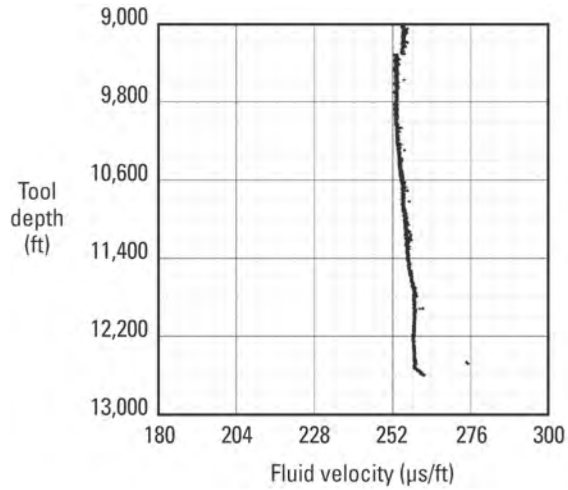


Figure 9.9—USIT Fluid Velocity in the Pipe from the Down Log

NOTE: Copyright Schlumberger. Used with permission.

USIT Acoustic Impedance Data

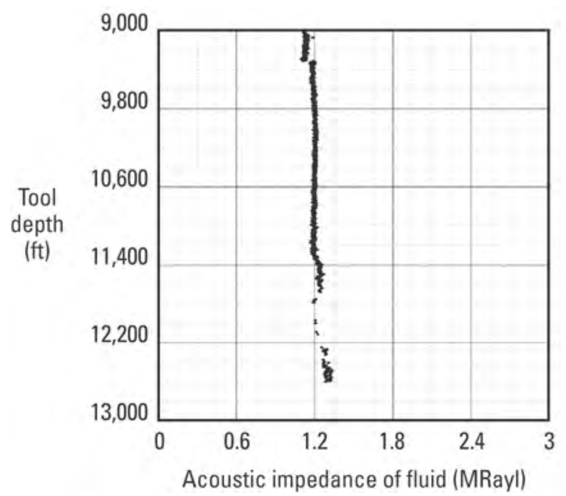


Figure 9.10—USIT Fluid Impedance in the Pipe from the Down Log

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CAST-V/CBL and Impedance Map

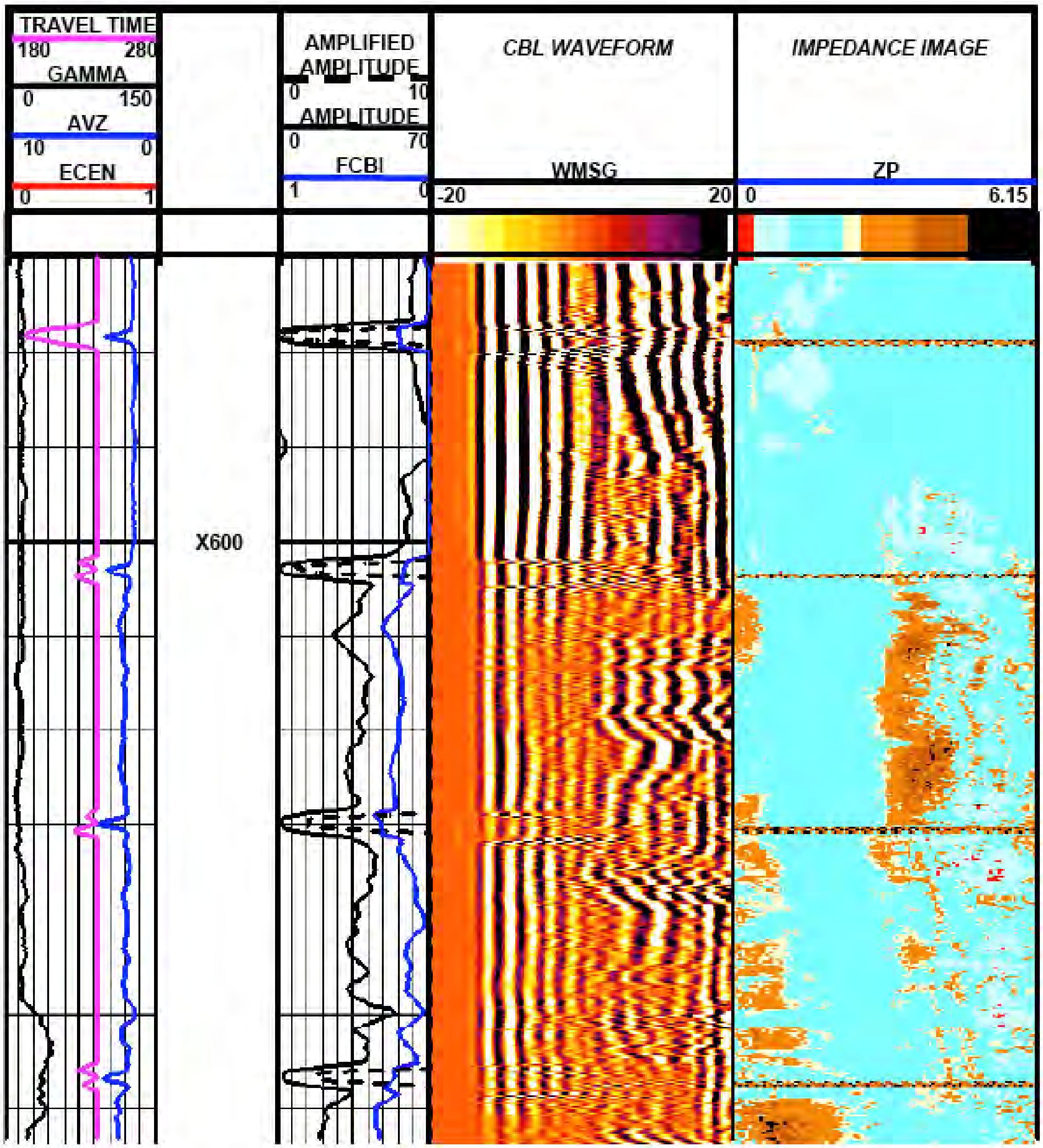

Figure 9.11—CAST-V with CBL/VDL Presentation

<u>CAST-V Quality Control Log</u>

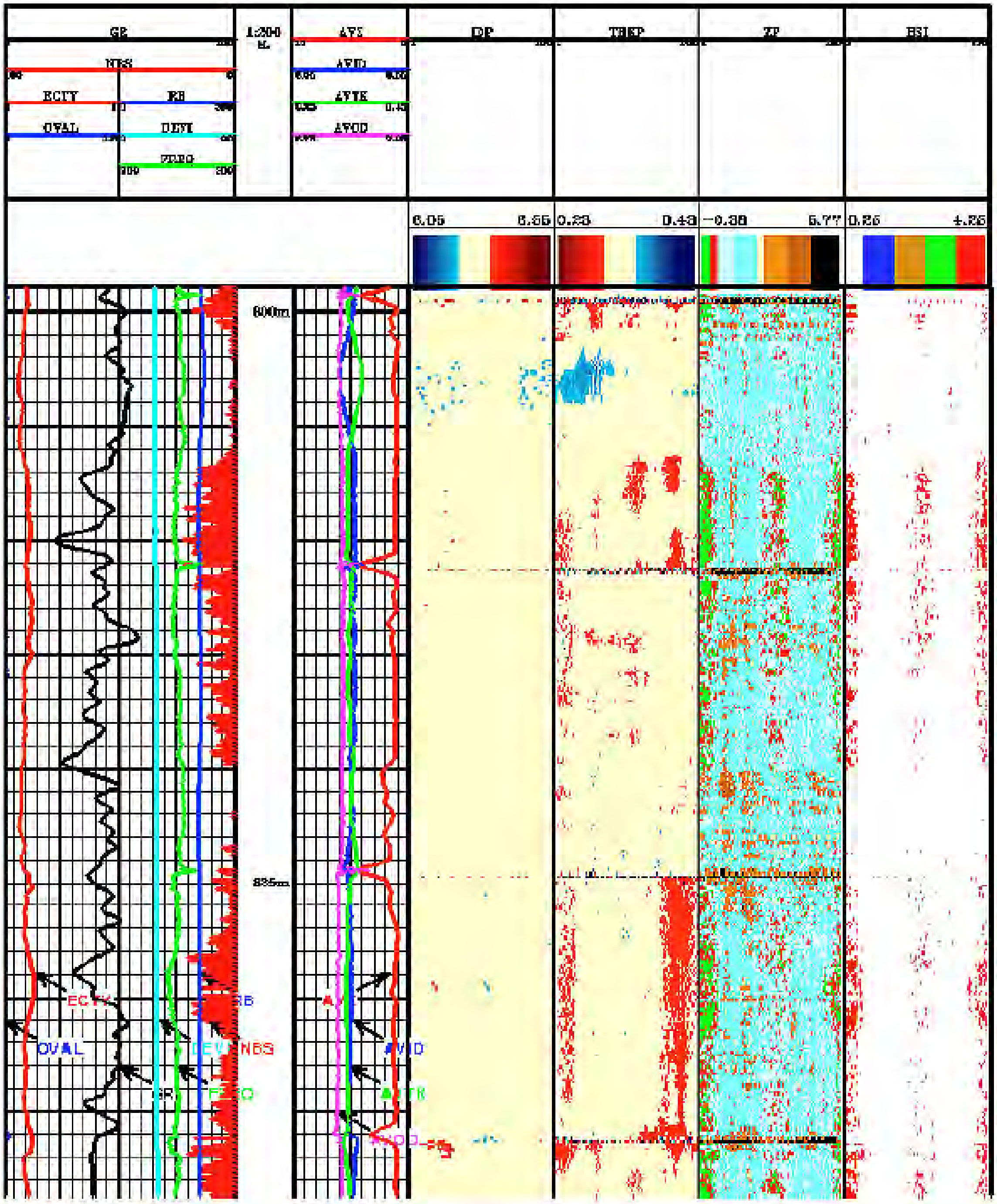

Figure 9.12—CAST-V Quality Control Presentation

NOTE: See Annex A jargon: CAST-V quality control nomenclature.

CAST-V Advanced Cement Evaluation (ACE) Processing

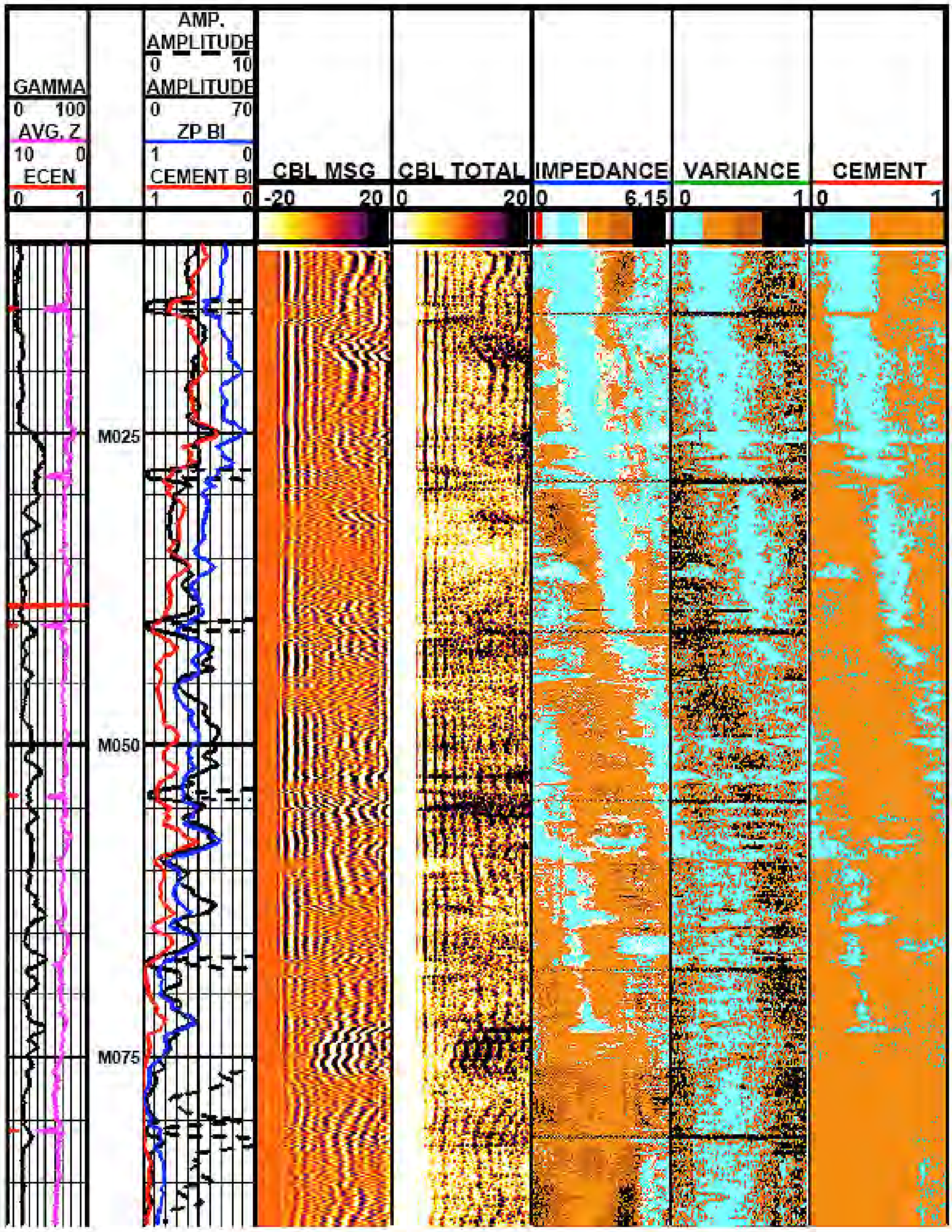

Figure 9.13—CAST-V: ACE Processing

NOTE: See Annex A jargon: CAST-V ACE processing.

URS/CBL Cement Log

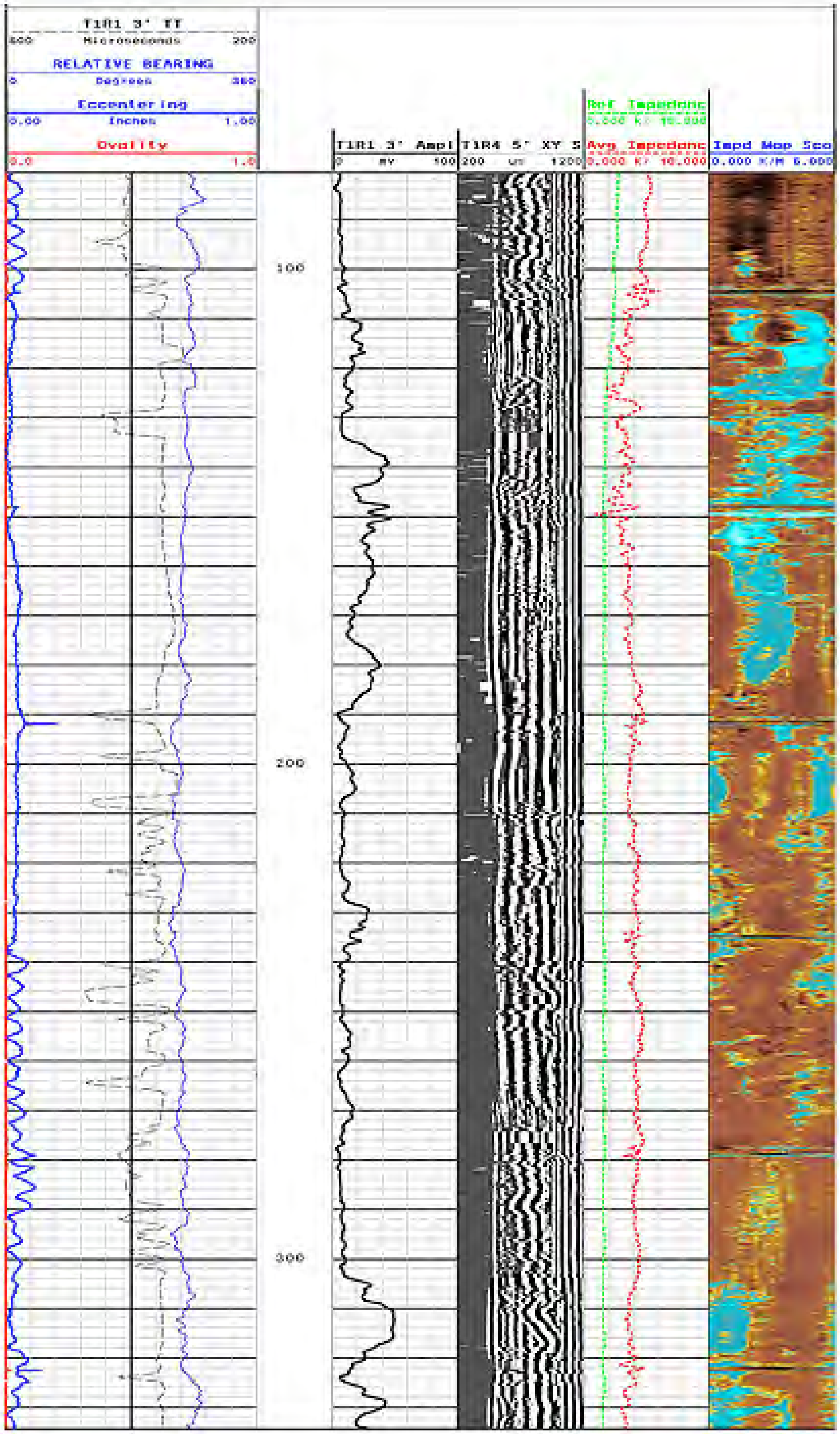

Figure 9.14—URS Tool Mapping

9.5 Ultrasonic Interpretation

<u>Cement Distribution</u>

The ultrasonic image shows the acoustic impedance and the distribution of materials around the casing. Color interpretation is easier than a CBL, but the interpretation must be made with caution (Section 10—The Power and Limitation of the Computer Packages). A combined interpretation with a CBL/VDL provides a more coherent picture of the cement distribution.

Standard color-map interpretation (impedance values are approximate):

Red:	Gas (< 0.3 Mrayl)
Light Blue:	Liquid (0.3 – 2.6 Mrayl)
Green:	Micro-debonded cement (USIT only, see Annex A jargon section: Micro-debonding Processing)
Light Brown:	Low-impedance solid cement (2.0 – 3.5 Mrayl)
Med Brown:	Medium-impedance solid cement (3.5 – 5.0 Mrayl)
Black:	High-impedance solid cement (> 5.0 Mrayl)

As previously discussed, CBL/VDL logging does not readily distinguish cement channels, liquid microannulus and contamination. The ultrasonic log is very sensitive to gas, and is affected by poor casing condition and attenuation in very heavy mud. Table 9.1 contains typical values for ultrasonic measurements of fluids, and Table 9.2 presents those of solids.

Table 9.1—Acoustic Property Estimates for Fluids

Material	Density, lbm/gal	Slowness (Δt), μs/ft	Compression-wave Velocity, $ft.s^{-1}$	Approximate Acoustic Impedance, 10^6 kg/m^2s
Fresh water	8.35	205	4862	1.5
Water + 10% NaCl	9.0	193	5184	1.48
Water + 25% NaCl	10.0	175	5709	2.06
Water + KCl	10.0	189	5282	1.77
Water + 36% $CaCl_2$	11.3	170	5873	2.42
Water + 58% $CaBr_2$	15.3	179	5577	3.10
Sea water	8.6	199	5023	1.57
Diesel oil	7.1	220	4528	1.17
Water-base mud	12.0	214	4659	2.14
Water-base mud	15.0	216	4626	2.7
Oil-base fluid	7.8	230	4331	1.25
Oil-base mud	12.6	245	4068	1.54
Free gas	1.6	780	1280	0.1
Drilling mud	17.0	—	—	3.06
NOTE: Values may vary according to fluid composition.				

Table 9.2—Acoustic Property Estimates of Solids

Slurries	Density lbm/gal	Slowness (Δt) µs/in.	Compression -wave Velocity ft.s^{-1}	Compressive Strength, psi *	Approximate Acoustic Impedance, 10^6 kg/m^{2}s (MRayl)
Foamed Class C cement	9.0	12.0 – 13.1		250	2.1 – 2.3
Foamed Class C cement	9.0	9.8 – 11.0		1000	2.5 – 2.8
Class H or G cement + hollow microspheres	11.2	9.0 – 10.7		> 1000	3.2 – 3.8
Extended Class H or G cement	12.4	11.4 – 11.9		500 – 1000	3.2 – 3.3
Extended Class H or G cement	13.2	10.5 – 11.0		750 – 1000	3.7 – 3.8
Extended Class H or G cement	14.2	9.8 – 10.2		1000 – 1500	4.3 – 4.4
Class H or G cement	15.8 – 16.4	11.2 – 11.7		500	4.2 – 4.4
Class H or G cement	15.8 – 16.4	8.5 – 9.1		1000	5.4 – 5.8
Class H or G cement	15.8 – 16.4	7.8 – 8.3		> 3000	5.9 – 6.2
Class H or G cement + 18% NaCl	16.0	6.3 – 6.6			7.4 – 7.8
Class H or G cement + 300-mesh silica	16.2	7.8 – 8.4		>3000	5.9 – 6.3
Class H or G cement + latex	16.2	8.6 – 8.8		> 2000	5.6 – 5.8
Class H or G cement + 100-mesh silica	17.0	7.6 – 8.2		> 3000	6.3 – 6.8
Class H or G cement + hematite	18.0	8.2 – 8.5		> 3000	6.5 – 6.7
Class H or G cement + hematite	19.0	7.4 – 8.0		> 3000	7.3 – 7.8
Steel casing		4.8	17,500		41.6
Steel casing		4.3	19,450		46.3

NOTES:

Values can vary according to solid composition.
* Laboratory ultrasonic non-destructive strength.

Casing Information

The measured casing radii should be corrected for eccentering. The USIT performs the correction in real time, while CAST-V corrections are completed after logging. This process may affect the image-data results.

The USIT presents the casing image by comparing the radius to the mean value at each depth, with blue indicating smaller radii and red larger radii. Thus, corrosion and wear appear as red areas. The thickness data are usually presented in similar fashion, with red indicating thickness below average and blue thickness above average. The internal radius and thickness are summed to calculate external radius. Internal and external radius curves are shown together with shading to indicate the casing cross-section. Minimum, mean and maximum thickness curves are also plotted separately. Casing information is recorded but not normally shown in the CAST-V cement presentation.

Eccentricity is the maximum difference between two opposing radius measurements. Ovality is the maximum difference between two perpendicular ID measurements divided by 2.

9.6 Ultrasonic Quality Control and Guidelines

The guidelines and tolerances listed below have been supplied by the tool manufacturers.

USIT

- Check the USIT fluid properties measurement and the value of fluid impedanceactually used for processing (ZMUD).
- The repeat section and main log must look the same.
- Acquisition and processing parameters must be written on the log. Check the solid/liquid impedance threshold and the maximum impedance of the color scale. These values should also be indicated on the color scale.
- Check there are no USIT processing flags. Any flag indicates the cement data is invalid at that location. The flag definitions are shown below.

  black: logging speed is too fast
  brown: all data invalid
  red: thickness and cement invalid
  dark blue: thickness and cement invalid
  light blue: cement invalid

- Check that eccentering is inside the recommended tolerance of:

  0.1 × casing outside diameter (in.) × casing thickness (in.)

- Casing radius and thickness must be close to nominal values in uncorroded areas.

- The casing must be in good condition, with accurate radius and thickness measurements. The echo-amplitude image is a good indicator of casing condition. Corrosion and deposits appear as low-amplitude (dark) areas.

USIT Fluid Properties Check (ZMUD)

Figure 9.9 and Figure 9.10 show typical fluid-property measurements with a fluid “velocity” crossplot and a fluid-impedance crossplot. The fluid-velocity curve should be smooth and consistent with the fluid type (see Table 9.1).

The calculated fluid impedance (AIBK) should have low dispersion (below about 0.1 MRayl) and be within 10% of the theoretical value calculated as follows.

1. Clear fluid:

$$Z_{mth} = \rho \times \frac{304.8}{FVEL} \tag{9-9}$$

2. Weighted mud:

$$Z_{mth} = k \times \rho \times \frac{304.8}{FVEL} \tag{9-10}$$

where

Z_{mth} is theoretical mud impedance (MRayl);

ρ is fluid density (g/cm^3);

$FVEL$ is fluid slowness (μs/ft);

k is the correction factor in the range 0.85 to 1.0 (determined by proprietary software).

The value of fluid impedance ZMUD used for log processing must be verified. It should be on the parameter list at the bottom of the log. If the parameters have been zoned vs. depth, then the zoned values of FVEL and ZMUD will be at the top of the log.

If the measured and theoretical fluid-impedance values disagree, the theoretical value should generally be used in brine or oil because the fluid-velocity measurement used to calculate the theoretical value is more accurate than the fluid-impedance measurement. In weighted mud, use of the theoretical value is recommended, but with caution, because firstly the k factor is accurate to only 5% to 10%, and secondly there may be mud solids sedimentation in the well. If possible, the log must be checked in a known free-pipe or uncemented annulus with liquid or gas in the annulus to verify that the value of ZMUD is correct.

ZMUD is the most critical USIT parameter. An error of 0.1 MRayl in ZMUD changes the calculated cement impedance by about 0.5 MRayl.

CAST-V

- Fluid velocity and fluid impedance curves should have a consistent value with no spiking.
- The repeat section and main log must look the same.
- Check the solid/liquid impedance threshold and the maximum impedance of the color scale. These values should also be indicated on the color scale.
- Check for no BAD SHOT INDICATOR—(no shading) all calculations are valid; (blue) invalid travel time; (brown) invalid amplitude signal; (green) invalid casing signal; (red) invalid impedance.
- Check eccentering is inside the recommended tolerance of 0.2 in.
- The casing must be in good condition, and radius and thickness measurements must be accurate to obtain a valid cement log.

9.7 Ultrasonic Limitations (Environmental Effects)

1. *Typical maximum mud density*.
   WBM: 16 lbm/gal (up to 18 lbm/gal depending on conditions)
   NAF: 13 lbm/gal (up to 16 lbm/gal depending on conditions)
2. *Casing eccentering*. It is difficult to distinguish between casing eccentering and a channel. To identify casing eccentering where the casing is leaning close to or against the formation, it is important to review the casing reports to determine poor casing centralization
3. To evaluate fluid displacement, it is important to review cementing reports to determine the following:
   - degree of casing centralization,
   - casing reciprocation while circulating or cementing,
   - solids settling from mud or cement on the low side of the casing,
   - free-fluid separation from the cement slurry, and
   - fluid or gas entry before the cement has set.
4. *Tool eccentering*.
5. *Casing thickness range*.
   0.177 in. to 0.75 in. (4.5 mm to 19.05 mm).
6. Impedance of material behind the casing.
   0 – 10 MRayl
7. *Casing corrosion or scaling*. This affects the cement map. The echo-amplitude image is the best indicator of this problem.
8. *Microannulus*. The ultrasonic measurement is less sensitive than a CBL to a liquid microannulus. The effect of a microannulus on an ultrasonic log is illustrated by Figure 9.15. A pressure pass with an ultrasonic tool is recommended if cement isolation is questionable. Figure 9.16 shows the change in casing dimension arising from pressure changes.

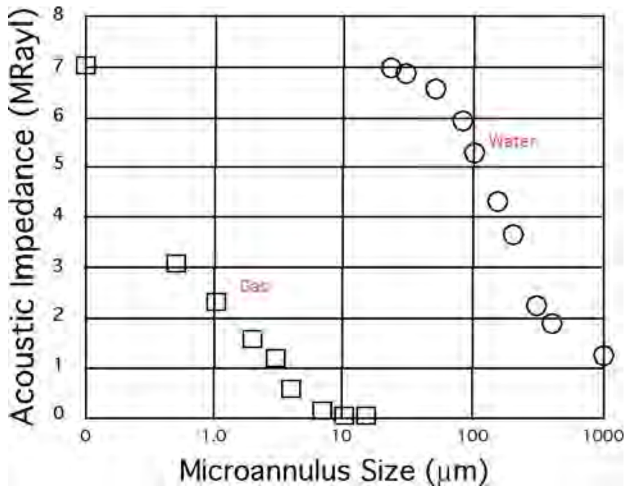

Figure 9.15—Experimental Liquid and Gas Microannulus Effects on the USIT Measurement

NOTE: Acoustic impedance change with microannulus size, using a 4.7-in. diameter, 9-mm thick casing. Copyright of the Society of Petroleum Engineers, reproduced with permission.

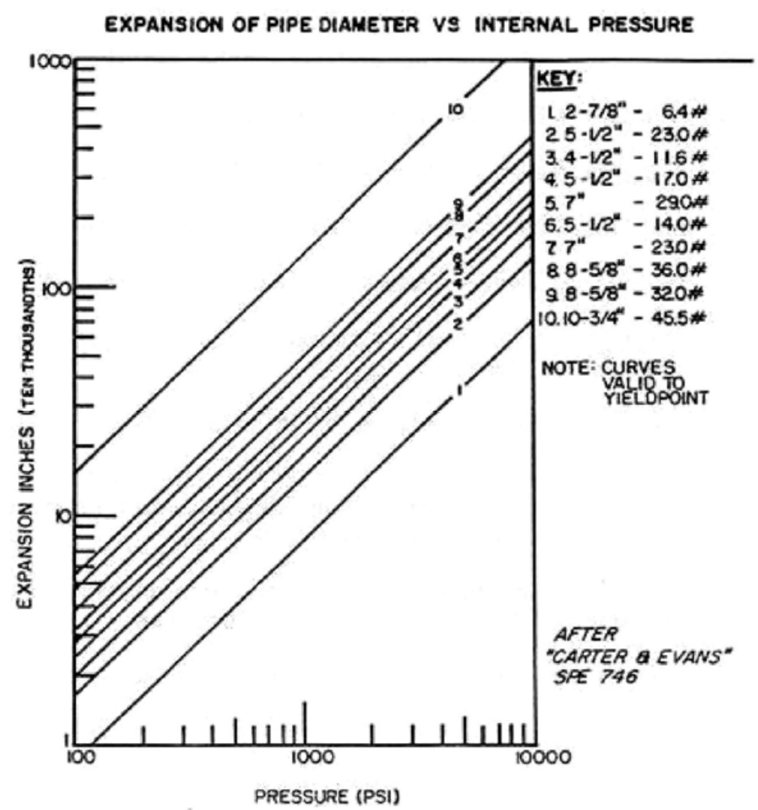

Figure 9.16—Relationship Between Pipe Expansion (Microannulus) and a Change in Pressure

NOTE: Depending upon the microannulus size, there is an effect on both CBL and ultrasonic tools. Copyright of the Society of Petroleum Engineers, reproduced with permission.

9.8 Isolation Scanner Cased-hole Imager

9.8.1 Introduction

Current acoustic ultrasonic techniques for cement evaluation have given ambiguous answers concerning zonal isolation when there is difficulty distinguishing between the acoustic impedances of mud and low-density or contaminated cements in the casing annulus. Furthermore, present ultrasonic tools provide adequate azimuthal coverage, but fail to produce an image beyond the cemented region adjacent to the casing. As a result, diagnosis of the full annulus is limited. To address these limitations, a new imaging tool was developed based on a novel ultrasonic imaging concept.

The new imager combines the classical pulse-echo technique with a new ultrasonic technique that provides echoes arising from propagation along the casing and reflections at the cement-formation interface. Processing of these signals yields an unprecedented characterization of the cased-hole environment in terms of the nature and acoustic velocity of the material filling the casing annulus, the position of the casing within the hole, and the shape of the hole.

This new imager tool is a combination of two casing modes that are at a high enough frequency to maintain the ultrasonic azimuthal and vertical resolutions. The first one is the thickness resonance mode (described in 9.2) with a normal-incidence single transducer. The second one is the flexural mode, never used before in well logging (described in 9.8.2). The combination enables a better evaluation of low-impedance cements, and the flexural mode has the potential to probe the full annulus between the casing and formation.

9.8.2 Flexural Mode

At sufficiently high frequencies ($\geq$ 80 kHz), the ultrasonic transducer pulse interacts with an azimuthally-localized area of the casing. It then becomes appropriate and convenient to approximate this casing area as part of an infinitely-unbounded steel plate. In the frequency range of interest, two modes dominate the wave physics of a fluid-loaded plate. The first mode has a particle displacement that is symmetric with respect to the middle plane and mainly parallel to the plate; it is referred to as the extensional mode (at very low frequencies, it becomes the basis of the classical CBL tools). The second mode has a particle displacement that is asymmetric with respect to the middle plane, and mainly perpendicular to the plate; it is referred to as the flexural mode. Its particle-displacement and spectral characteristics make the flexural mode a prime candidate for probing the cement sheath. The extensional and flexural modes of a plate are also referred to more formally as the two lowest symmetric (S0) and anti-symmetric (A0) Lamb modes, respectively.

9.8.3 Flexural Mode Velocity

The flexural mode is dispersive, meaning that its velocity (phase and group velocities) is frequency dependent. The phase velocity is that of a phase front; i.e. the velocity of the peaks and troughs of a purely sinusoidal wave. The group velocity is the velocity of the wave packet centered on a given frequency.

The calculated phase and group velocities for the flexural mode as a function of frequency are shown in Figure 9.17 for a water-loaded steel plate of 8 mm thickness. The phase velocity is far from constant, meaning that the flexural-wave shape (before taking the envelope) changes rapidly during propagation along the casing. On the other hand, the flexural-group velocity exhibits a peculiar feature—it goes through a maximum around 200 kHz and remains approximately constant over a fairly wide interval of 100 kHz to 400 kHz. This means that all the frequency components of a broadband wave packet within this frequency range will propagate at nearly the same velocity. Hence, the wave packet remains temporally compact. This fact has an important implication. Using the envelope of the flexural wave packet, it is possible to make accurate time-of-arrival and amplitude measurements.

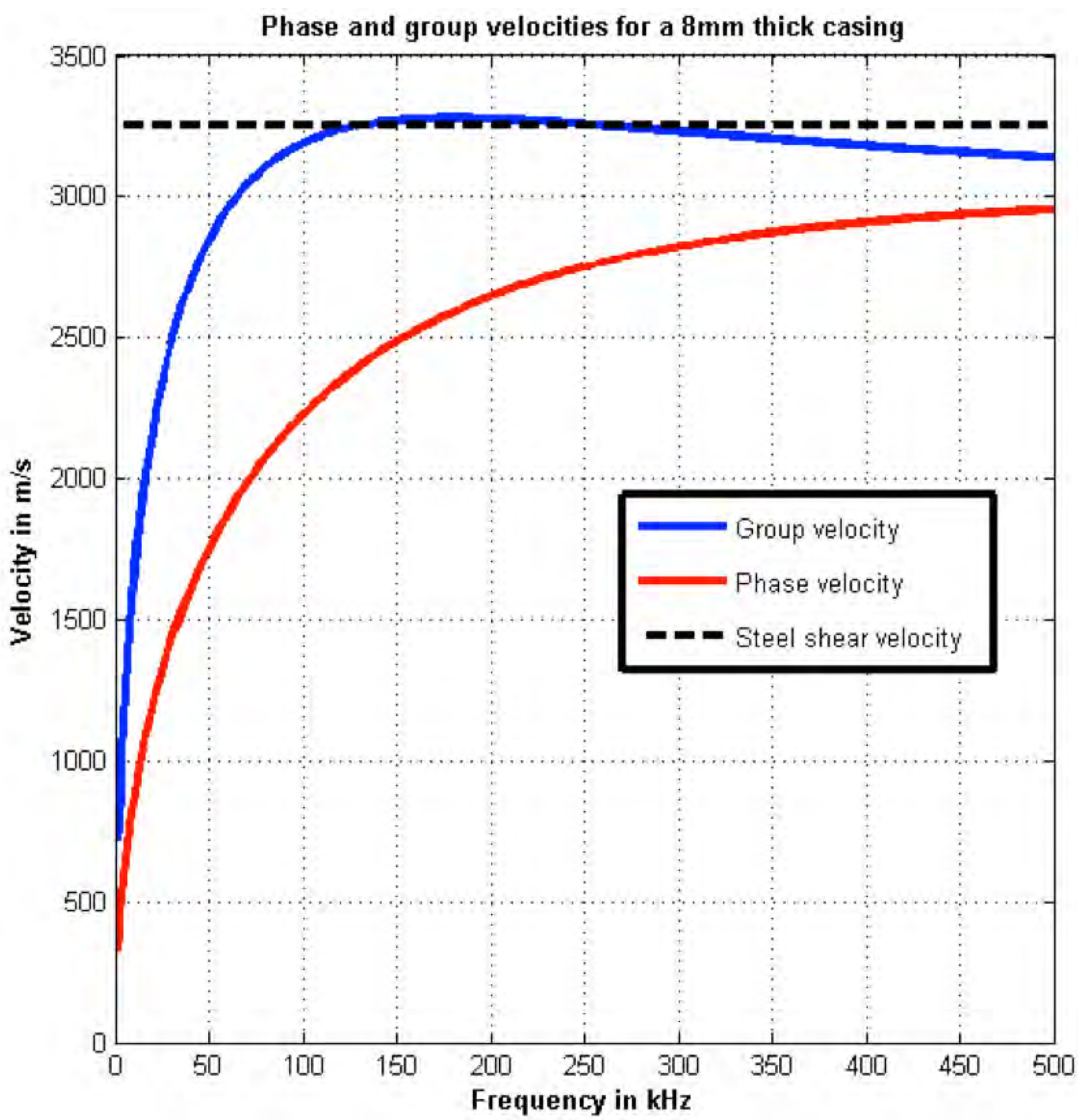

Figure 9.17—Phase and Group Velocity of the Flexural Mode in a 8-mm Thick Steel Plate

The dispersion curves shown in Figure 9.17 also dictate how to excite a flexural wave with a plane wave radiated by the fluid-immersed transducer and impinging on the casing. The phase-matching angle, measured with respect to casing normal, is given by Snell's law.

$$\sin(\theta) = \frac{V_f}{V_{\mathrm{flex}}} \tag{9-11}$$

where V_f and V_{flex} are the fluid velocity and the plate flexural wave phase velocity. This angle is slightly dependent on the fluid velocity and ranges from 28° to 38° when the fluid velocity covers a typical range between 1250 m/s to 1650 m/s. The slower the velocity, the larger the phase-matching angle will be. In a reciprocal way, the flexural wave propagating along the casing reradiates, or leaks, a wave in the materials present on both sides. In particular, this allows the receiving transducer to pick up the signals. The radiated (or leaky) wave in the fluid propagates at an angle again given by Snell's law. Maximizing its reception by the receiving transducer requires the wave to be aligned at the same angle as that which maximizes the wave excitation by the transmitting transducer.

9.8.4 Flexural Mode Attenuation

The radiation into the materials inside and outside of the casing, is accompanied by attenuation of the flexural-wave amplitude along its path. This attenuation is sensitive to the mechanical properties of both materials. The overall attenuation is approximately the sum of the attenuations due to the inner fluid, and the attenuation due to the outer material. The calculated attenuation due to water on one side (with vacuum on the other side to prevent leakage) is plotted in Figure 9.18 as a function of frequency. For an 8 mm thick plate, this curve goes through a broad minimum 0.31 dB/cm over the frequency range of flat group velocity (100 kHz to 400 kHz). The fact that the attenuation is approximately constant with frequency makes it possible to estimate it by measuring the decay rate of the envelope of the received broadband pulse.

This attenuation is inversely proportional to the casing thickness, implying, as anticipated, a lower sensitivity for thicker casings. For a fluid behind the casing, the attenuation is also approximately proportional to the acoustic impedance. For a solid material such as cement bonded to the steel plate, the situation becomes slightly more complex. Apart from the density, acoustic-wave propagation in a solid material is defined by two velocities—the compressional and shear-wave velocities. The effect of a solid material on the flexural attenuation depends on its velocity values (compressional and shear), compared to flexural phase velocity at the central frequency (200 kHz for an 8-mm thick casing). For the flexural wave to radiate into the cement either as a compressional or shear (bulk) wave, the cement's compressional or shear velocity must be smaller than the flexural-phase velocity. At the pulse-center frequency considered, the velocity is about 2650 m/s (this condition can be derived from Snell's law). For cements, the shear velocity is always smaller than 2650 m/s. Consequently, the shear wave is always radiated into the cement annulus. However, the cement compressional velocity can either be larger or smaller than this critical velocity, depending on the cement type and contamination. In the first case, the compressional wave cannot be radiated into the cement annulus (it is said to be supersonic compared to the flexural wave), and this effect decreases the flexural attenuation. The different cases are depicted on Figure 9.19, for fluid, slow cement and fast cement.

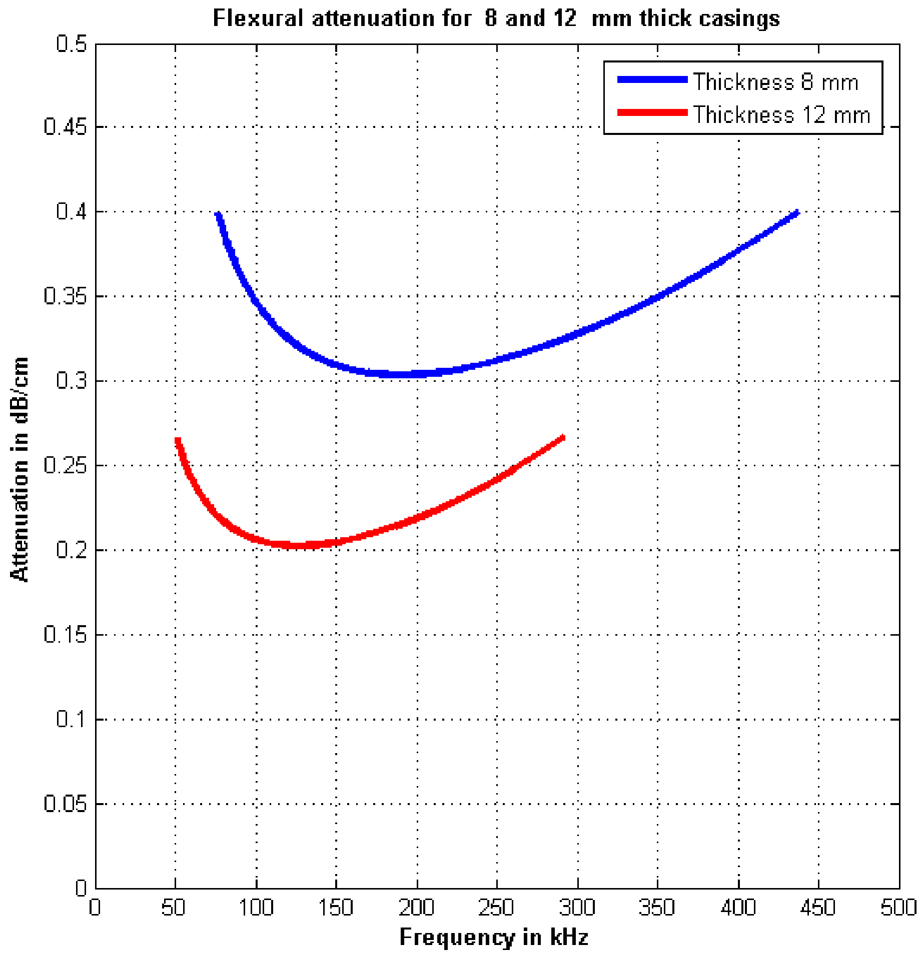

Figure 9.18—Attenuation of the Flexural Mode Due to Radiation in Water on One Side

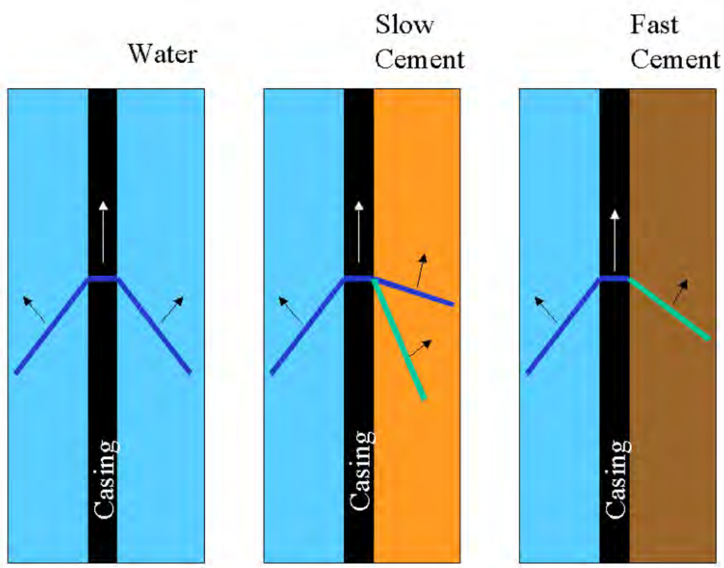

Figure 9.19—Radiation of the Flexural Wave into Water, Slow Cement (V_p < 2650 m/s) and Fast Cement (V_p > 2650 m/s)

NOTE: Compressional wavefronts in blue, shear wavefronts in green.

Figure 9.20 is a plot of the theoretical attenuation vs. acoustic impedance of the material in contact with the casing. The blue curve is relative to a fluid ($V_s = 0$) with a constant velocity of 1500 m/s. The red curve is relative to a solid material, with a fixed density (1500 kg/m^3), and a fixed Poisson ratio (0.30, typical of cements). Below the critical impedance Z_c ($Z_c \approx 3.9$ MRayl), the attenuation increases linearly with the material impedance (liquid or solid). Above Z_c, the attenuation drops rapidly to fairly small values. A given attenuation (for example, 0.31 dB/cm) corresponds to two values of the acoustic impedance, typical either of liquid or good cement. Consequently, the flexural attenuation alone cannot discriminate between liquid and solid, and needs to be combined with another measurement such as the casing resonance technique.

The attenuation effect of casing/cement debonding and a liquid filled microannulus has also been investigated. For cement impedances lower than the critical impedance, the attenuation is reduced by about 15% when the casing and cement are debonded. This effect is similar to what is observed with the pulse-echo technique, by which the reduction in apparent impedance is of the order of 30%. The attenuation reading is not affected by the microannulus width up to ≈250 µm; which is of the same order of magnitude as for the pulse-echo technique. Above the critical impedance, a large attenuation increase is observed as soon as the cement is debonded. This attenuation increases approximately with the cement impedance, again without significant effect from the microannulus thickness up to ≈250 µm. This behavior is notably different from the pulse-echo technique and reduces possible confusion between a good cement with microannulus and mud.

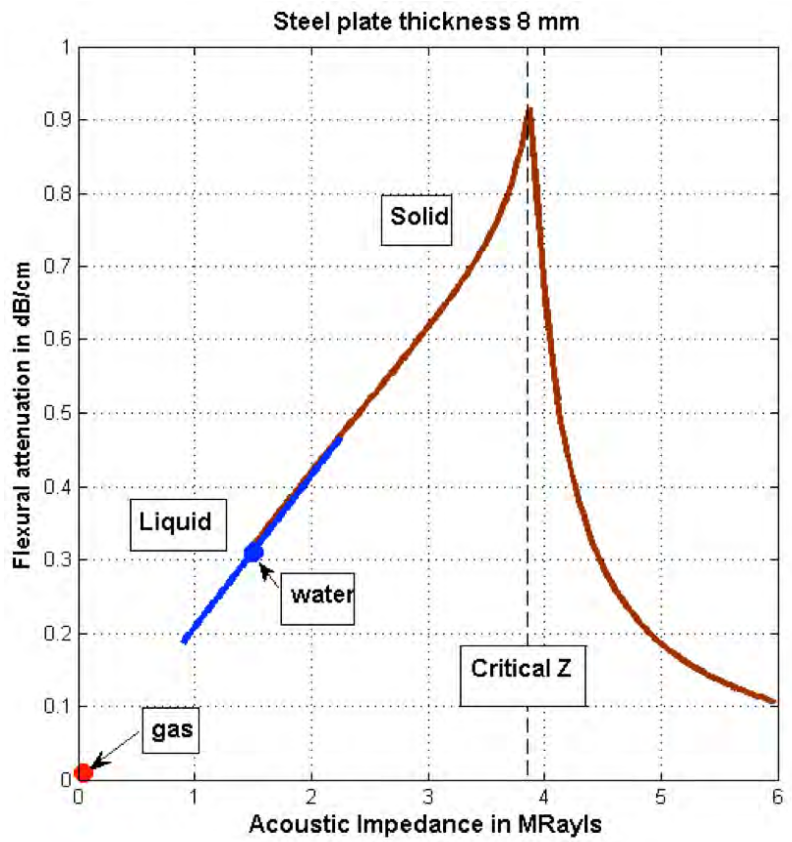

Figure 9.20—Flexural Attenuation at 200 kHz vs. Acoustic Impedance for Gas (Red), Liquid (Blue) and Solid (Brown) Materials

9.8.5 Third-interface Reflections

The information provided by flexural attenuation is related to the state of the material in contact with the casing and does not probe deeper into the cement sheath. However, the pulse radiated by the flexural wave packet into the annulus may be reflected by the third interface, the cement/formation interface (with the casing inner and outer walls being the first and second interfaces seen by the ultrasonic pulse). The casing is actually fairly transparent to this reflected pulse; thus, the pulse can be detected by the receivers at a sufficient signal level. Since the third-interface echo (TIE) propagates through the annulus, it carries information about the annulus geometry and material, as well as formation-wall geometry and acoustic contrast with the annular material.

Depending on the type of material in the annulus, different echoes arise. For liquid annulus, only compressional (P) waves are supported and there is one type of TIE (PP). For fast cement, only the shear (S) wave is excited in the cement and is detected as a shear-shear (SS) echo after conversion into a pressure wave in the logging fluid. For a slow cement, both compressional and shear waves are launched and reflected at the formation wall in addition to partial conversion from P to S (and vice versa) that occurs upon reflection at the same interface. In total, three types of echoes are received, PP, SS or PS/SP (which arrive at the same time). In all cases, multiple reflections between the casing and the formation may also occur.

A simulation of the waveforms computed at a receiver is shown in Figure 9.21, for a water-filled annulus with reflection on a hard formation (the large fluid-formation contrast provides for a large TIE amplitude). The TIE has a large amplitude compared to the casing arrival. For comparison, the pulse-echo technique waveform in the same geometry (also shown in Figure 9.21) barely shows the very small effect of the formation reflection. The strong TIE from the flexural wave makes accurate measurement of the time of arrival and amplitude possible. It should be noted that the TT difference $\delta\tau$ between the casing arrival and the TIE does not depend on the transmitter-to-receiver spacing, transducer standoff with respect to the casing, or properties of the fluid inside the casing. It is a sole function of the annulus thickness and wave velocity. Knowing one quantity allows the computation of the other. For example, if the borehole size is known, the annulus material wave velocity can be computed: the compressional wave velocity for fluids, or both the compressional and shear wave velocities for a slow cement, or the shear wave velocity only for a fast cement. Similarly, if the annulus wave velocity is known, for example from a nearby in-gauge section, then the size of moderate borehole enlargement can be estimated.

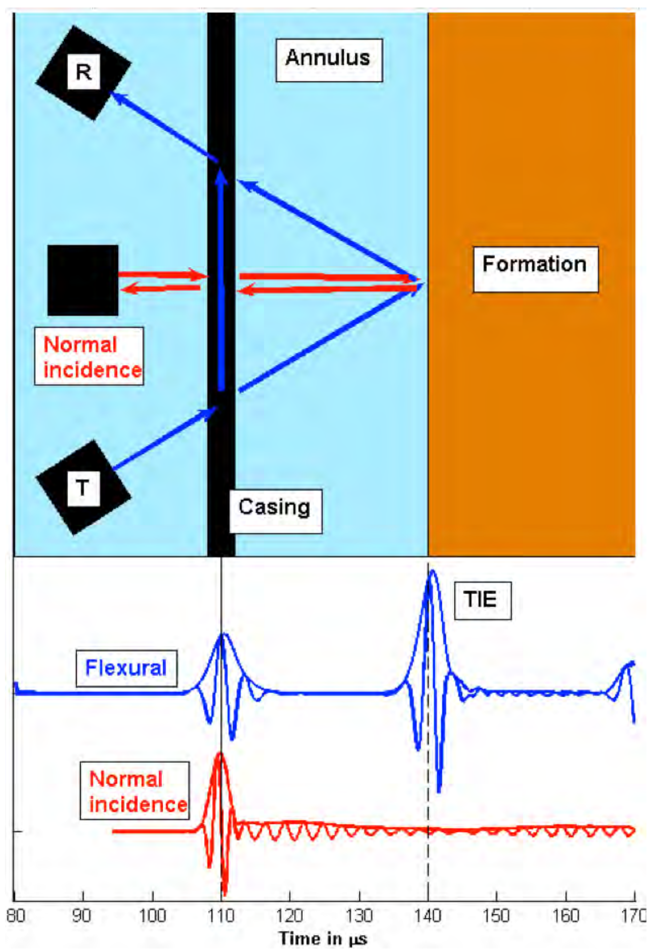

Figure 9.21—Comparison of Pulse-echo and Flexural Synthetic Waveforms and Their Envelope for a 25-mm Water Filled Annulus Between Casing and Formation

However, the TIE may not always be detectable. Several factors that adversely affect the TIE amplitude are given below in decreasing order of occurrence.

- Casing eccentering within the borehole. Along the direction of eccentering, the casing wall and the formation wall are parallel. However, in other directions, they are not parallel, and the TIE is not reflected in the direction of incidence, causing an amplitude drop (see Figure 9.22).
- Attenuation in the annulus material. Although water or uncontaminated set cements have low attenuation, heavy muds or contaminated/unset/foamed cement may have high attenuation.
- Acoustic contrast between annulus material and formation. If the contrast is low, then the TIE amplitude is low. An example would be the contrast between low-density cement and shales. Conversely, in double strings, the contrast is very high, leading to a rather strong TIE.
- Roughness of the borehole, at the scale of the acoustic wavelength or larger, will reduce TIE amplitude.
- Large distance (greater than ≈ 75 mm) between casing and formation, due to large hole or washouts, will move the TIE outside of the recorded window and outside the optimal transmitter receiver spacing.

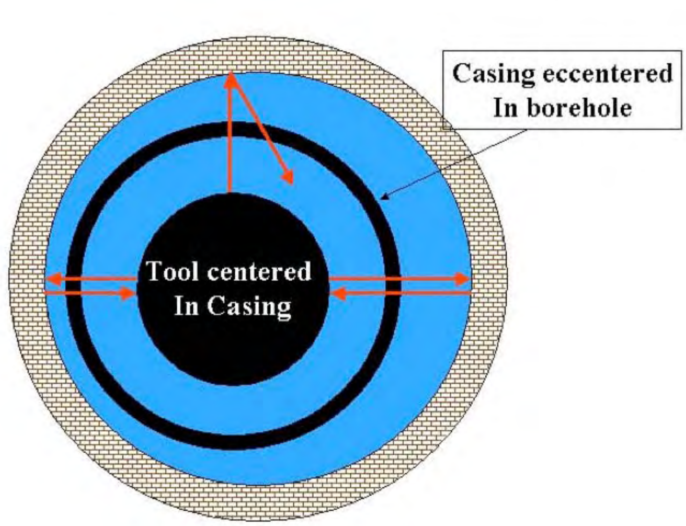

Figure 9.22—Geometry of an Eccentered Casing in the Borehole and Effect on TIE

9.8.6 Tool Description

The architecture of the Isolation Scanner is very similar to the USI tool. The most visible difference is a new rotating sub-assembly supporting four transducers (see Figure 9.23). To optimize the distance from the transducers to the casing and minimize mud attenuation, three sub-assembly sizes are provided to cover the casing range from 4.5 to 9.675 in. The normal-incidence transducer is oriented at 180° from the three flexural transducers. The latter are arranged such that one transmits and two receive the returned signals, providing in particular an amplitude attenuation measurement.

The flexural transducers operate at about 200 kHz, and their azimuthal resolution is similar to the USI transducer (30 mm). The vertical resolution of the attenuation measurement is controlled by the distance between the receivers (4 in.), while the resolution of TIE related measurements is controlled by the transmitter-to-receiver spacing, at about 6 in. The azimuthal sampling is fixed at 10° and the vertical sampling can be adjusted, typically between 3 in. and 6 in.

Because fluid properties can be estimated directly from the two sets of measurements, no dedicated hardware for separate fluid properties measurement is required.

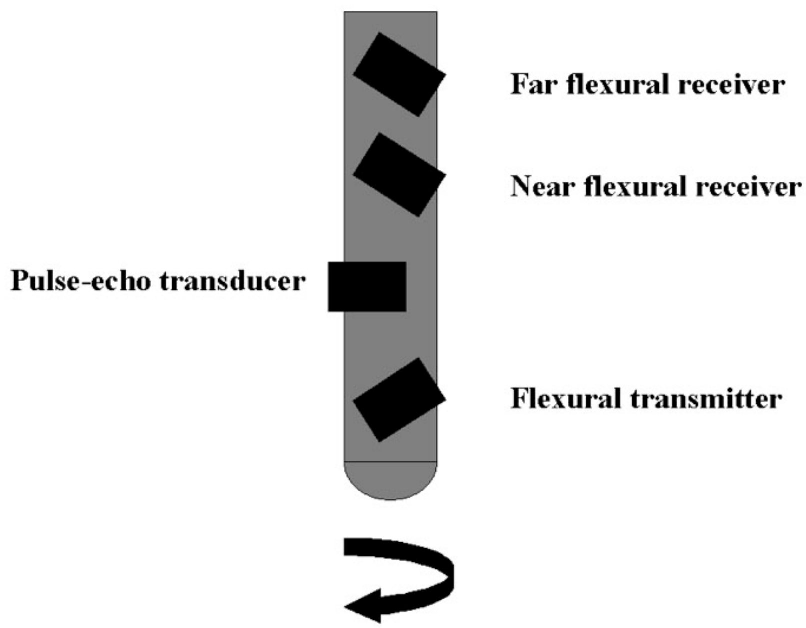

Figure 9.23—Sketch of the Rotating Sub-assembly Supporting the Four Ultrasonic Transducers

9.8.7 Processing

The first aim of the processing is to provide a robust interpreted image of the material immediately behind casing. The inputs to this processing are the pulse-echo cement impedance as delivered by the pulsed-echo transducer, and the flexural attenuation computed from the amplitude of the casing arrivals on the near and far flexural receivers. These two inputs are independent measurements linked to the properties of both the inside fluid and the outside medium. Hence, they are first combined in order to eliminate the effect of the inside fluid, thus eliminating the need for specific hardware for fluid properties measurements. The output is a solid-liquid-gas (SLG) map displaying the most likely material state behind casing. This state is obtained for each azimuth by locating the two measurements (the acoustic impedance and the flexural attenuation) corrected for the effect of the inside fluid on a map giving the area covered by each state. This map is computed in an initialization step before the log, and uses a priori knowledge of the possible materials.

- Gas is defined as a very low impedance material, independently of any input.
- Liquid is defined by the expected acoustic impedance of the mud in the annulus prior to cementing, with some provision for possible deviations from this value.
- Solid is defined by the type of cement used for the cementation. Using a laboratory measured database, this material selection is converted into acoustic properties according to Table 9.8.1, and provisions are made for some contamination or incompletely set cement.

Table 9.3—Acoustic Properties of Uncontaminated Set Cements

Cement	Density [lbm/gal (kg/m^3)]	P-wave Velocity (m/s)	Z (MRayl)
Class G	15.0 (1800)	3000	5.4
Light cement	14.4 (1200)	2800	3.4
Ultra light cement	7.5 (900)	2800	2.5

The next step is to predict the measurements from the expected acoustic material properties, which is trivial for the acoustic impedance, but requires running a model for the flexural attenuation. Then, multiple realizations of the measurement noise are added to generate three clouds of points (solid, liquid, and gas) in on a plot of attenuation vs. acoustic impedance. From these clouds of points, it is possible to define a probability of occurrence for each state (solid/liquid/gas), and the measurement plane can be mapped out into different regions (see Figure 9.24) with three colors corresponding to the different states. The white area corresponds to inconsistencies between the measurements, and may occur, for example, at collar locations.

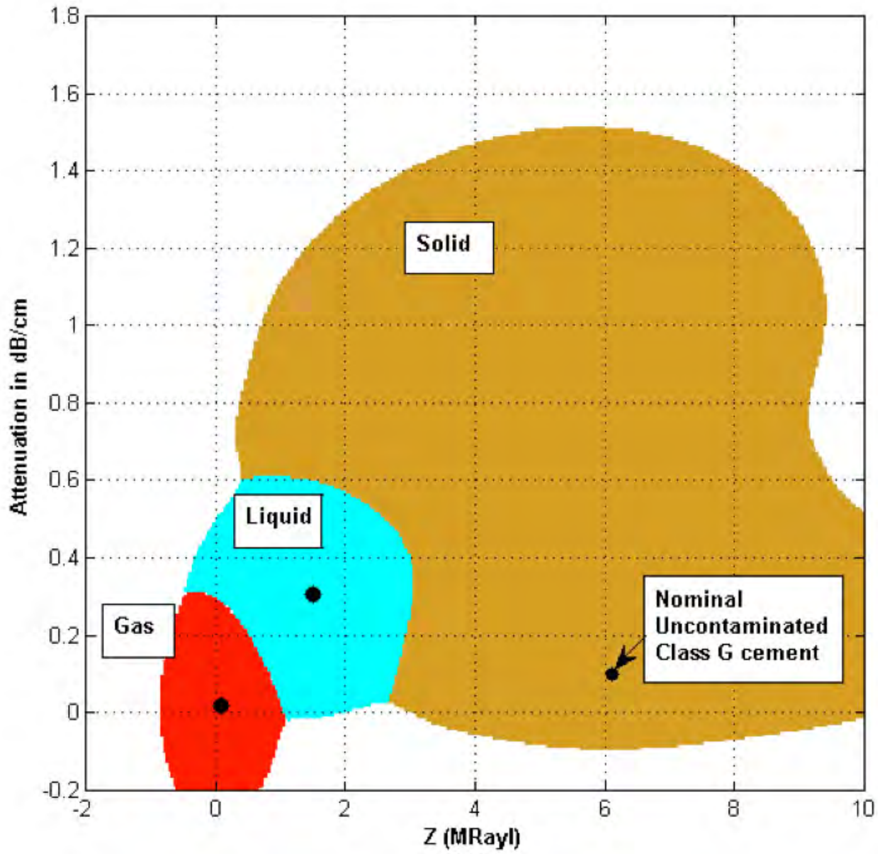

Figure 9.24—SLG Mapping of the Measurement Plane for a Class G Cement

NOTE: *Z* is the impedance estimated from the pulse-echo technique whereas the attenuation pertains to the flexural wave. Copyright Schlumberger. Used with permission.

The channel map is a further simplification of the measured SLG map focusing on the potential significant problems. It only shows the continuous uncemented areas with significant vertical extent. This vertical extent can be adjusted, for example between 2 m and 10 m. The total width of these areas is also evaluated and displayed as a single curve, which indicates the severity of the channeling.

Beyond the SLG map pertaining to material immediately behind casing, the second objective of the processing is to extract relevant information from the TIE and quantify the full annulus between casing and formation. First, the TIE following the casing arrival are detected on the waveform envelope, and their times of arrival and amplitude are measured. From the time difference between TIE and casing arrivals, and provided enough azimuthal coverage is available, it is possible to extract the casing centering in a dimensionless unit, where 100% represents perfect centering, and 0% fully eccentered casing (contacting the formation). Additionally, if the borehole diameter is known, then the casing/TIE time difference can be further converted into a material velocity and displayed as a map.

Isolation Scanner Presentations

The first example (see Figure 9.25) is from a test well with a 7-in., 23-lb/ft casing inside a 9.625-in. casing, with Class G cement. The section shown straddles the cement top. The three left tracks display the SLG map, the two data sets used to compute it, the flexural attenuation and the thresholded pulse-echo cement impedance maps. These last two maps are strikingly different. The flexural attenuation identifies two distinct and very well defined materials, with high and low impedance. The impedance map, somewhat affected by formation reflections from the outer casing, is barely able to distinguish such regions. The interpretation is that higher impedance cement partly displaced lower impedance cement between 330 m and 290 m. The higher impedance material is above the critical impedance and thus has a low attenuation, actually lower than water, as seen from above the cement top. The lower impedance material, either by design or due to contamination, is below critical impedance and its high attenuation leads to the high contrast. Both measurements are combined into the SLG map, and solid is indeed shown where it belongs, for both cement types, thus simplifying the display and the low level interpretation. Collars appear as white streaks because the two measurements are disturbed enough to be inconsistent. It can be noted that the flexural attenuation is much less affected by formation reflection than the impedance map, as long as the two casings are not touching. Contact actually occurs at 255 m, and the attenuation shows some effect.

The four right tracks are related to the TIE information. Track 4 is the map of TIE TT difference with the casing arrival. White zones correspond to difficulty in the automatic TIE picking due to the effects of the annulus material and/or the casing centering. It allows one to spot the sections with high eccentering and the location of the near side, which is indeed consistent with the “galaxy” patterns seen on the impedance map. This TT data is used to compute the casing centering shown on Track 7. This centering varies from ≈100% (perfect centering) to 0% (contact) 10 m above. Track 5 is the TIE amplitude map, and is affected by casing centering (which affects the reflection geometry at the annulus/formation interface and the propagation length inside the annulus) such as in the free-pipe section but also by the material type such as seen in the two cements region. Casing collars from the outer casing string can also be located, for example at 315 and 325 m. Track 6 is the computed annulus velocity map which is obtained from the TIE time map and the knowledge of the outer casing inner diameter. From the top, it shows first a value of 1500 m/s, characteristic of water. Then it gradually increases until 300 m, where it reaches 2000 m/s to 2500 m/s, consistent with the compressional velocity of slow cement. Below 300 m, the TIE are mostly propagated as shear, and the measured velocity drops back to ~1500 m/s, consistent with the shear velocity of a fast cement.

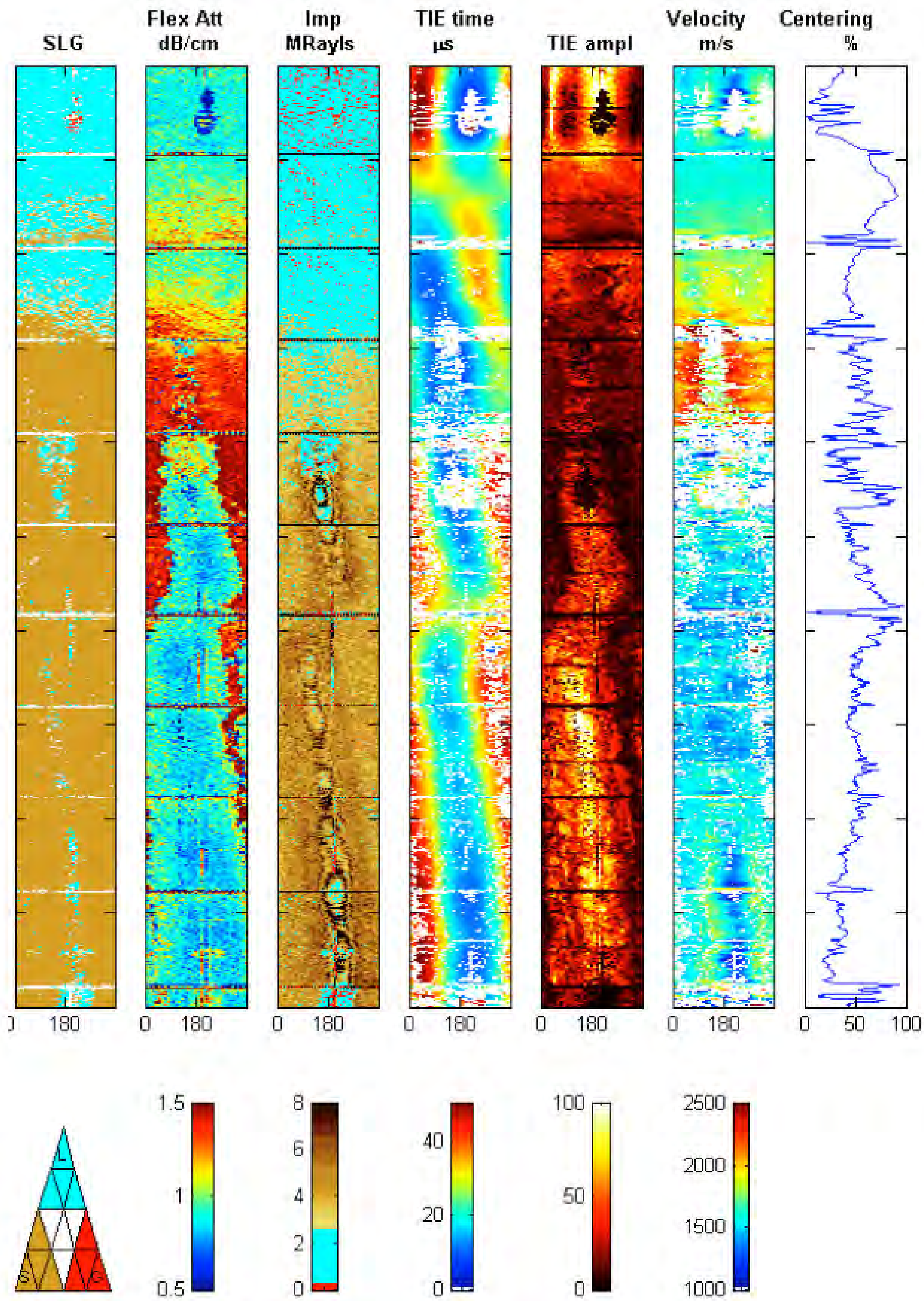

Figure 9.25—Isolation Scanner Example Presentation #1

NOTE: Test well with a 7-in. casing inside a 9.625-in. casing, cement top section. Copyright Schlumberger. Used with permission.

The next figure (see Figure 9.26) is the free-pipe section immediately above in the same well. The white line in the middle of the SLG map track arises from a casing groove due to cable motion, while the red patches along the same azimuths arise from contact between the two casings. This can be verified on the right tracks which display the flexural waveforms along two orthogonal diameters. The first echoes from the centerline of the track are the 7-in. inner casing arrivals, while the next ones are TIE reflections from the outer 9.625-in. casing. Fainter echoes after the first TIE are multiple reflections (up to 5) within the annulus. Such a display provides a geometric sketch of the casing strings, where contact points or potential defects can be located.

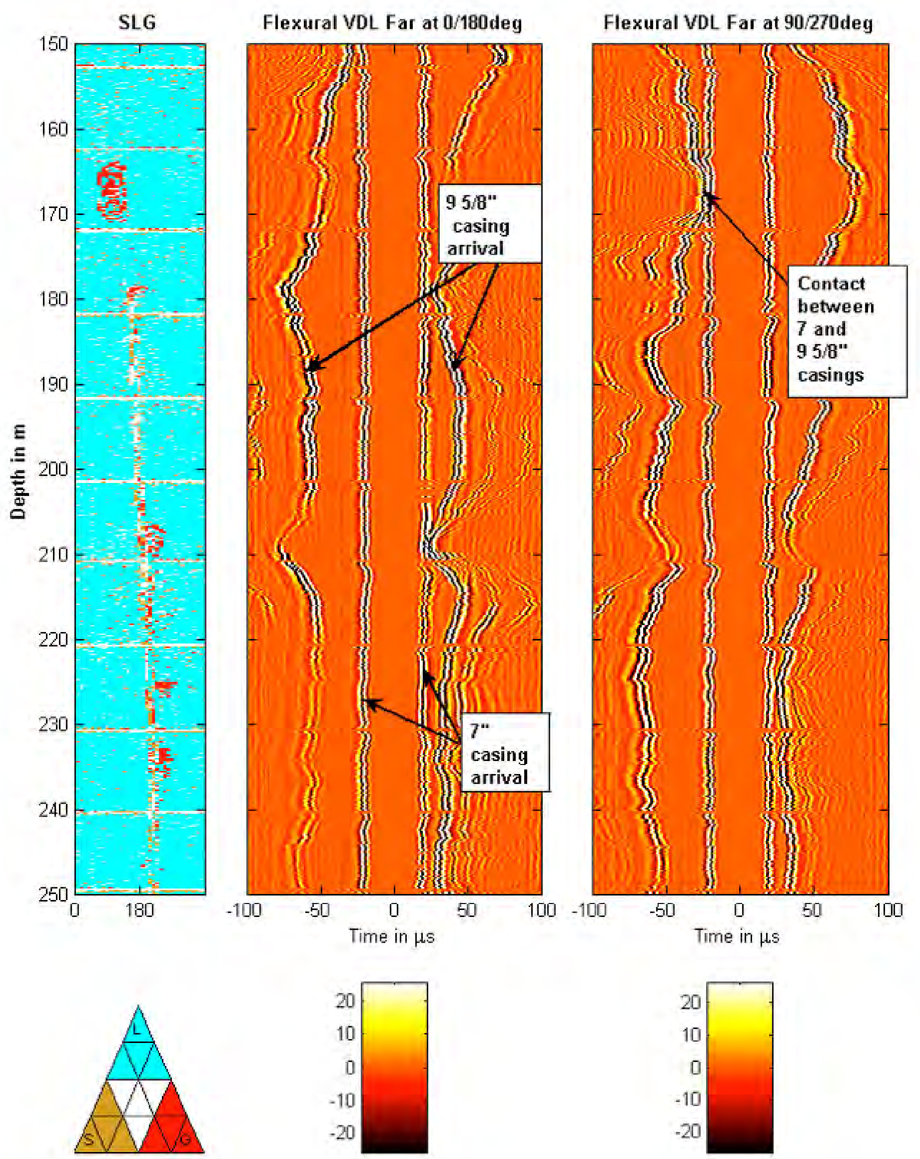

Figure 9.26—Isolation Scanner Example Presentation #2

NOTE: Test well with a 7-in. casing inside a 9.625-in. casing, free pipe section. Copyright Schlumberger. Used with permission.

Figure 9.27 is related to a 9.625-in 47-lb/ft single casing in a vertical well, cemented with a high performance lightweight cement (1.08 g/cm^3). The mud density is 1.3 g/cm^3. The impedance image (Track 5) is affected by the low cement impedance and casing roughness in such a way that locating a channel is virtually impossible. This situation can be contrasted with the flexural attenuation (Track 4) map that indicates a channel between x465 and x480 m with excellent contrast. The processed SLG map (Track 3) maintains the same quality and shows a clear liquid channel embedded within the cement. The SLG map has been further processed by the hydraulic communication algorithm to produce the channel map (Track 6) and the channel-width curve (Track 7). This processing cleans the SLG map by discarding small liquid patches and keeping only the liquid connected channels with a significant vertical extend, 2 m in this case. A polar plot of the flexural waveforms in a VDL fashion allows one to see the geometry of the casing within the borehole. Inspection of the TIE curvature detected within the channel (Figure 9.28) reveals that, despite the presence of a casing centralizer at x474 m, the casing is slightly eccentered in the borehole and the channel is located on the narrow side, contrary to first intuition. The absence of TIE across the cement azimuth may result from a low acoustic contrast between cement and formation. The CBL curve (see Figure 9.27, Track 1) shows a fairly high reading resulting from both the low cement impedance and a water filled microanulus.

Figure 9.29 shows the top part of the same well, in a double string section with a 13.325-in. outer casing. The acoustic impedance map (Track 4) indicates a free pipe section up to xx30 m, with air above. Closer examination suggests a slightly higher reading between xx68 and xx73 m. This can be contrasted with the flexural attenuation map (Track 3) and the subsequent SLG map, which clearly identify this zone as solid. This interpretation is further confirmed by the CBL curve on which an amplitude dip is present in this zone. However, the presence of a non flat interface at xx30 m, between the alleged liquid and air, raises a question. Inspection of the TIE data (Tracks 5 to 8) provides the answer and illustrates their potential benefits in complex situations. The annulus-velocity data show that the section xx68-xx73 m has a velocity ranging from 1800 m/s to 1900 m/s, clearly outside the range of plausible liquid, and corroborating the SLG map. Furthermore, this velocity map and the amplitude map both indicate that this solid material is not homogeneous, but is made of three layers of slightly different materials. Looking at the top (xx30-xx34 m) of the liquid section, one can see that the velocity again reaches 1900 m/s, pinpointing the presence of a solid, although even the flexural attenuation barely shows a slight increase above its fluid values. This solid explains the non flat upper interface and, because it floats on top of water, its density is most probably below 1.0 g/cm^3 and the targeted cement density. A small amount of segregation within the cement slurry is a likely explanation for such a solid. The casing centering (Track 8) is perfect close to the casing centralizer, but 10 m below quickly drops to about 50 %.

Figure 9.30 is a section of another well with a 9.625-in., 47 lb/ft casing inside a 12.25-in. borehole. The mud density is 1.30 g/cm^3, and the cement is Class G with a slurry density of 1.90 g/cm^3. The SLG map (Track 1) indicates uniformly good cement across the zone. The acoustic impedance ranges from 5 to 7 MRayl, with some indication of formation reflections around x810 m. The flexural attenuation (Track 2) exhibits both high (0.9 dB/cm) and low values (0.5 dB/cm), with the low values matching high impedance areas. The cement impedance is thus close to the critical impedance, where the attenuation peaks. The TIE time map (Track 4) confirms that the “galaxy” pattern shown at depth X810 m is indeed due to the closer proximity of the borehole wall. The higher impedance at x725 m and 180° azimuth on Track 3 can also be related to a formation reflection effect. The casing centering curve (Track 8) is 100% close to the centralizers, but eventually drops to below 50% in between for this vertical well. The small oscillations on the time map and the centering curve are an artifact resulting from a corkscrew shape of the borehole, with a period of about 2 m. The annulus velocity map (Track 7) displays a rather uniform value around 1750 m/s, characteristic of the shear velocity of Class G cement. One possible exception is the blue stripe at x775 m. This is more likely due to a slight borehole enlargement than a lower cement velocity. Assuming a constant cement velocity of 1750 m/s would give the possibility to present a cement sheath thickness over the interval. The TIE amplitude map (Track 6) exhibits a striking correlation with the GR (Track 5), with low amplitudes in shaly zones, as can be expected from a lower impedance contrast between the cement and shales. Apart from casing collars and centralizers, this map in Track 5 is also affected by casing centering which creates the two dark vertical stripes seen around x810 m and above x730 m.

10 The Power and Limitation of the Computer Packages

Computer programs are available that take data generated from a cement evaluation tool and convert them into any variety of "cement maps." These maps are intended to aid cement-sheath evaluation and simplify interpretation. Programs are available for both sonic and ultrasonic tools.

The programs manipulate the data for a wide variety of scenarios. From the use of lightweight cement, to the presence of microannuli, the programs attempt to present a different cement map to account for these phenomena.

One common problem with cement maps is the use of varying colors to distinguish "good cement" from "poor cement." These colors are based only on a log response and do not reflect the ability of any cement to provide isolation in the well. This problem has lead many engineers to misinterpret logs and attempt cement squeezes when they are not necessary. Attempting to achieve a cement map that is "all black" is a driving force in many operations.

The user must be aware that the data coming from the well and the cement-job results have not changed. It is only the method of interpretation of the data and the presentation of the cement map that have changed. Data from one well can be manipulated to the point that an excellent cement job can appear to be ineffective, or a very poor job will appear to be excellent. The user must understand what the data manipulation program is doing to change the "look" of the log.

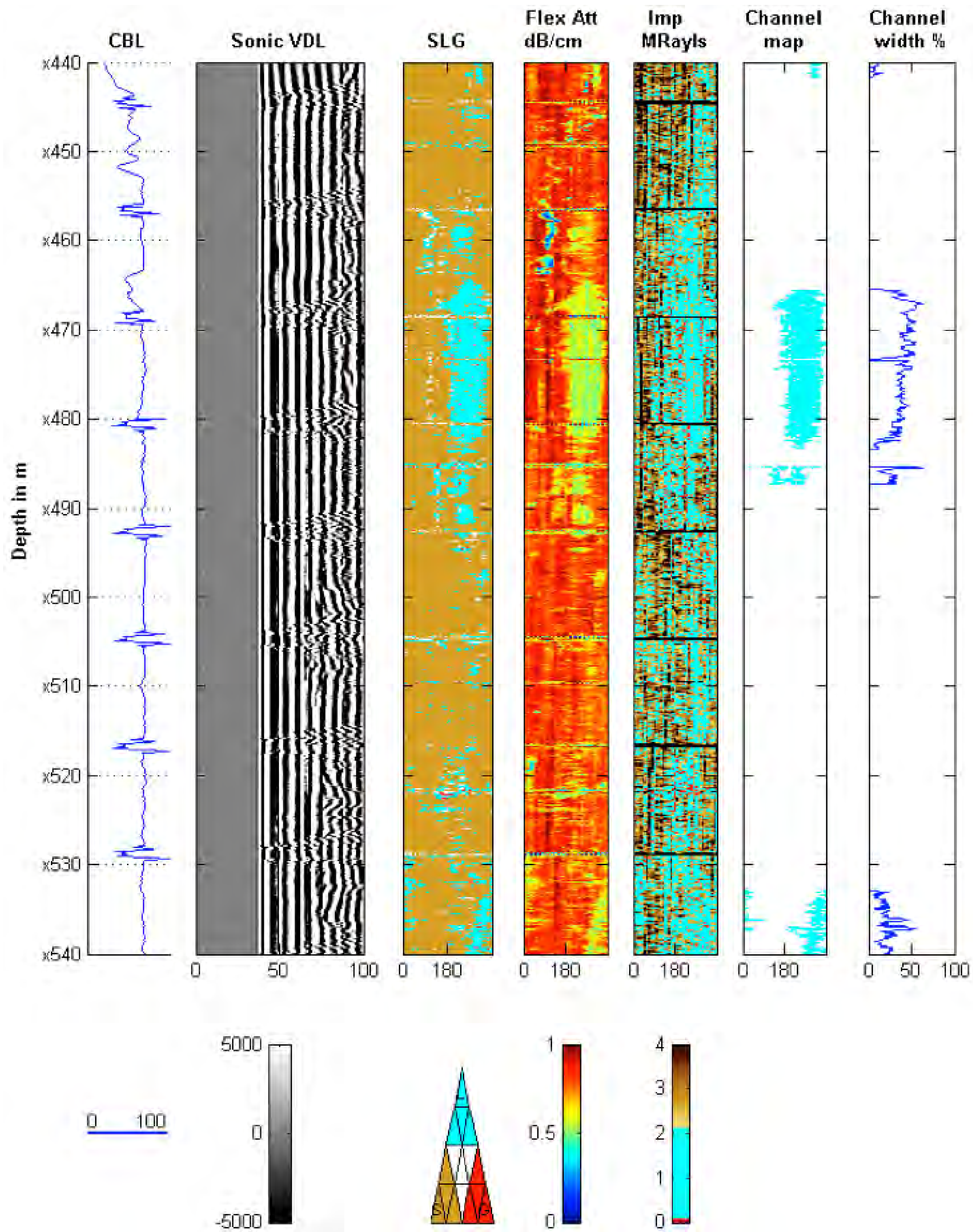

Figure 9.27—Isolation Scanner Example Presentation #3

NOTE: High performance lightweight cement section in a 9.625-in. single string casing. Copyright Schlumberger. Used with permission.

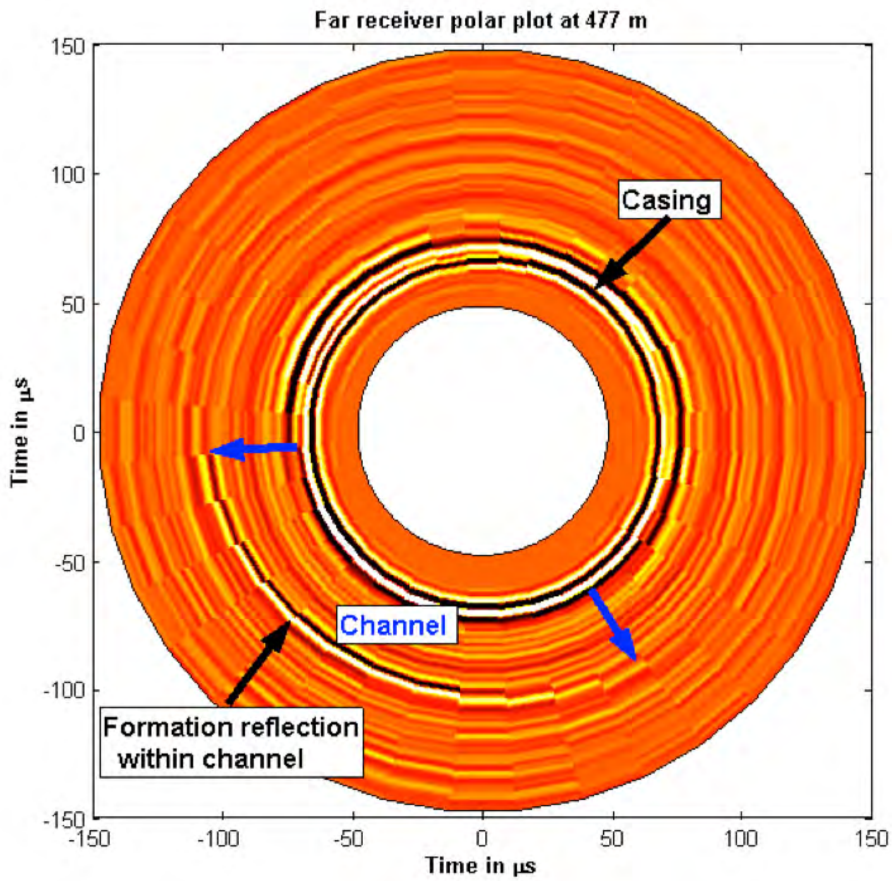

Figure 9.28—Polar Plot Across Channel

NOTE: Polar plot across channel for far receiver at 477 m. Copyright Schlumberger. Used with permission.

Sole dependence on the computer generated cement map to perform cement evaluation is hazardous at best. Proper cement evaluation includes consideration of the well parameters and job performance data. If the cement job was properly performed, the well had full circulation, the cement was mixed to the proper density and all data from location matches the plan, there is little evidence to believe a cement evaluation log that shows no cement behind pipe. The user must search out the reasons for the poor log response to perform a proper evaluation.

11 Pitfalls and Misconceptions in Cement Evaluation Practice

a) Cement evaluation logs are acquired without any objectives or are not acquired at all because they are not deemed to have value.

A lot of money has been wasted running logs and not fully using the acquired data. Opportunities have been missed by not acquiring or using the cement evaluation data for the purpose of improving cementing on future wells or repairing wells with unacceptable cement integrity.

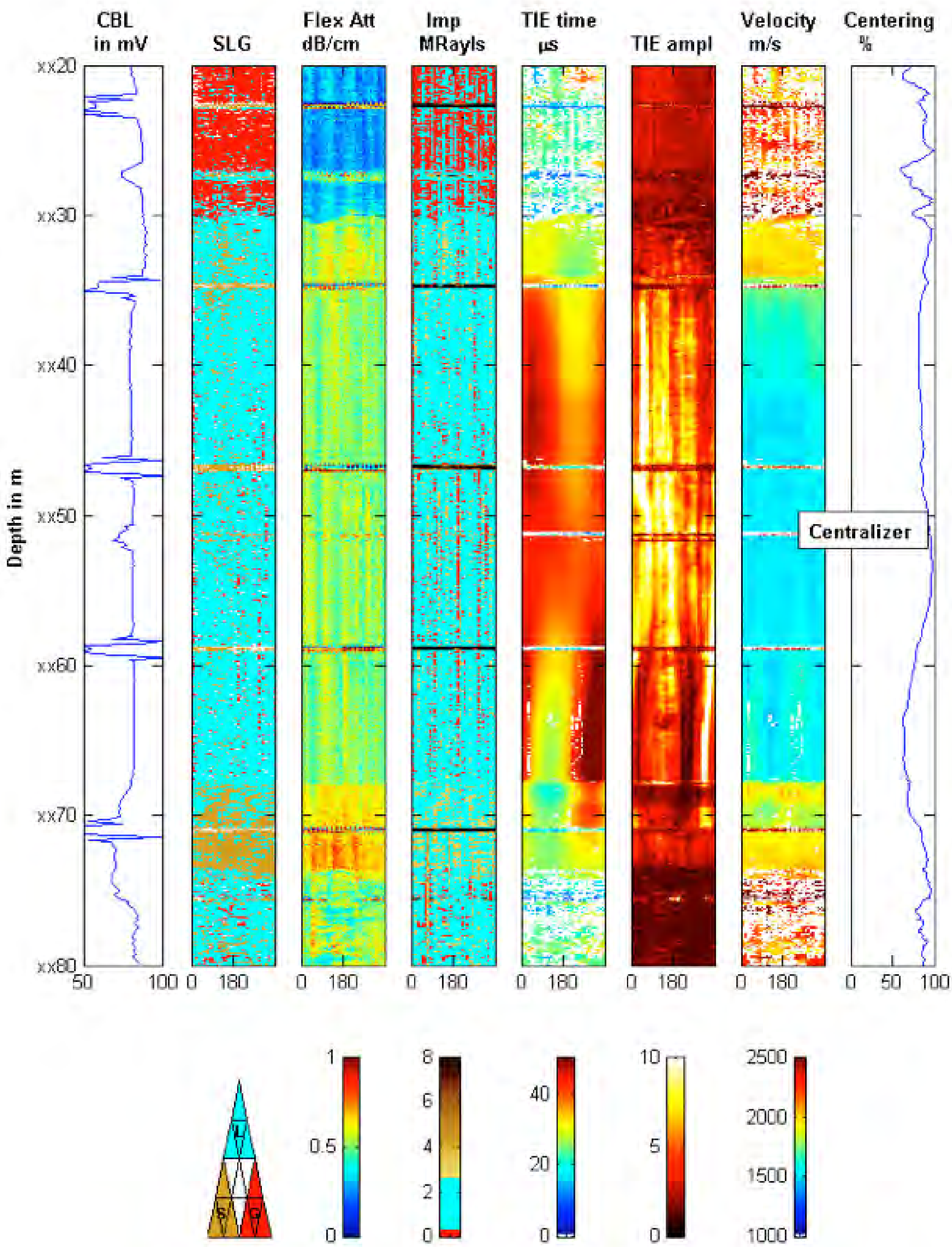

Figure 9.29—Isolation Scanner Example Presentation #4

NOTE: 9.625-in. double casing section above the high performance lightweight cement. Copyright Schlumberger. Used with permission.

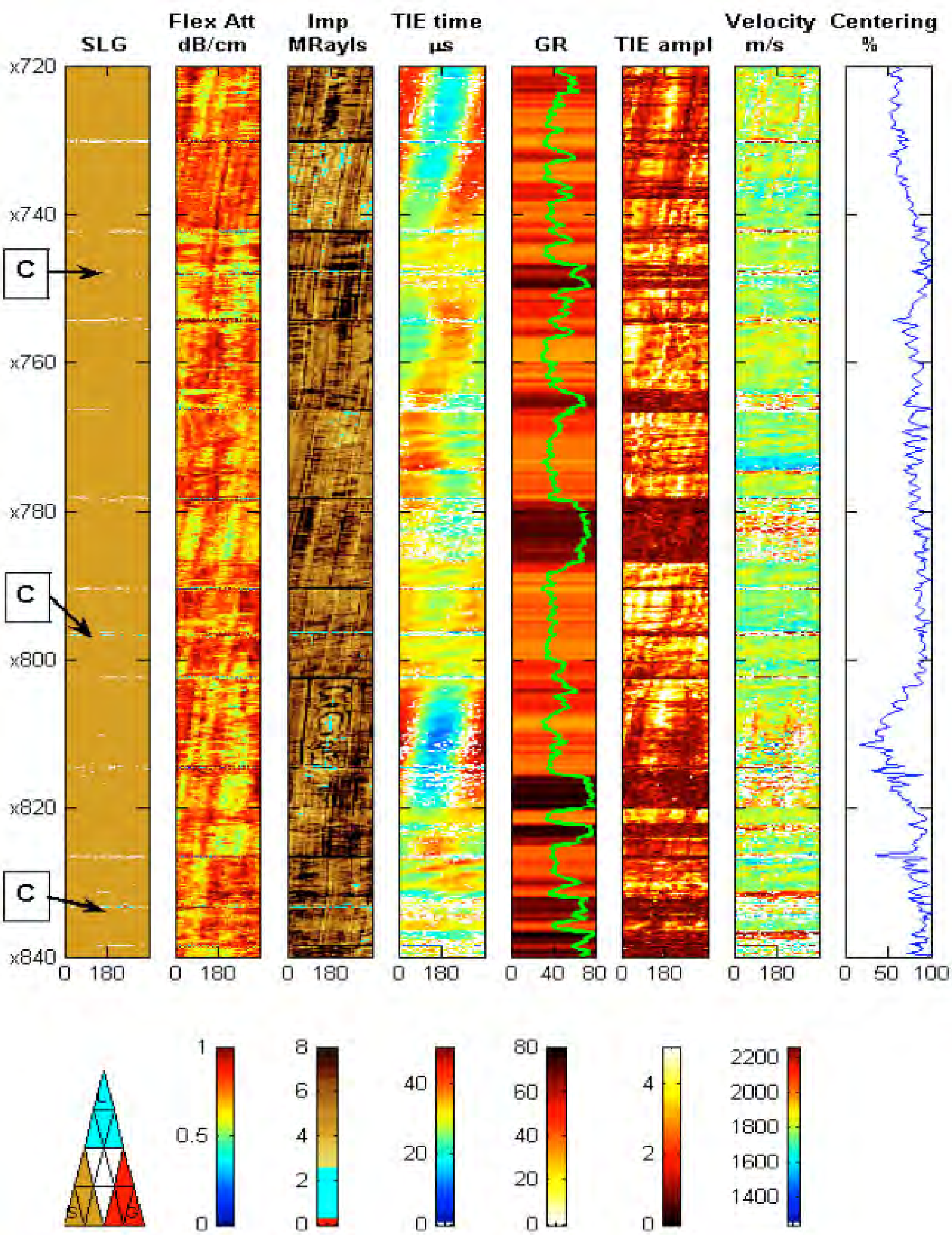

Figure 9.30—Isolation Scanner Example Presentation #5

NOTE: 9.625-in. casing within a 12.25-in. borehole with Class G cement with indications of centralizers' positions. Copyright Schlumberger. Used with permission.

There should be a clear set of objectives for acquiring cement evaluation data. These objectives should be defined by a team composed of representatives from drilling, completion and production. The team should discuss the objectives and attach a monetary value to the decisions made from the log results. These discussions can lead to decisions on running the appropriate cement evaluation logs and possibly obtaining additional information from other sources. Reviewing these objectives with the cementing and logging service companies will drive the importance of obtaining the proper data and getting good quality logs. It is important to have a member of the team with the technical background who has the knowledge and understanding of the logs to ensure they meet the requirements. The information contained in this document should aid in setting attainable objectives.

b) The Bond Index (BI) is used as a quantitative measure of cement sheath quality.

Probably the most common misconception of cement sheath evaluation is the idea of Bond Index. Bond Index has confused generations of engineers and expert practitioners over the years with the belief that it provides a quantitative indication of zonal isolation.

In reality, the Bond Index is simply the percentage of the measured signal (amplitude or attenuation) in relation to the difference between the theoretical value for "perfectly cemented pipe" and the theoretical value for "free pipe." Over the years, the erroneous belief that this translates into the circumferential percentage of the annulus that is filled with cement has been widely accepted by many log interpreters. Furthermore, the unfounded implication that a Bond Index of 80% or greater is indication of a "good bond" has been fostered by the presentation of an 80% BI line on many log presentations.

For example, a Bond Index of 80% could theoretically be interpreted to mean that 80% of the circumference of the pipe is perfectly cemented and 20% of the circumference of the pipe has no cement behind it at all. Were that the case, zonal isolation would certainly not exist because a channel with a width of 20% of the casing circumference would create a significant path for fluids to migrate in the annulus.

Many other factors besides the circumferential cement coverage control the acoustic response from the tool. Changes in cement density, cement compressive strength, and casing thickness are all critical to determining the theoretical amplitude for perfectly cemented casing. An annulus that is completely filled with cement, yet has a lower than expected compressive strength, would give a relatively low Bond Index while still providing perfect zonal isolation. The compressive strength of the cement in the annulus may be lower than what was measured in the lab due to mud contamination, incorrect test temperature or poor density control. For these reasons, Bond Index cannot be relied upon to make quantitative zonal-isolation decisions.

c) A complete indication of the cement/formation interface cannot be inferred from variable density logs (VDL).

A signature of formation arrivals on the VDL is an indication of acoustic coupling between the casing and the formation. A common mistake in log interpretation is to infer that this means cement is filling the annular gap on all sides. Since the acoustic signal from a CBL is not directionally focused, all that is required is a relatively small portion of the annulus to contain set cement in order to see the acoustic signal from the formation. If the casing lays against the wellbore wall, formation arrivals may be evident on the VDL even if no cement is present in the annulus. For these reasons, the VDL should not be the only data relied upon to determine whether cement is in contact with the formation around the entire wellbore circumference.

d) The implications of a microannulus aren't properly understood.

The presence of a microannulus commonly causes misinterpretation of cement evaluation logs. A microannulus affects the acoustic coupling between the pipe and cement, impacting the response of acoustic logs. Rerunning the log under pressure may help regain the acoustic coupling and minimize the impact of the microannulus. By comparing a pressurized and non-pressurized log passes, it may be possible to confirm the difference between a microannulus and an uncemented casing. Alternately, an ultrasonic log that is less sensitive to the presence of a microannulus can be run for such determination.

The presence of a microannulus may or may not be indicative of poor zonal isolation. In some cases a microannulus may allow gas migration behind the casing, manifesting itself as sustained casing pressure or leading to abnormal pressurization of shallower zones. In other cases a microannulus may have no undesirable impact on well performance. Since there are obvious costs associated with properly identifying the presence of a microannulus (e.g. extra logging runs, more expensive tools, etc.) a prediction of the impact of a microannulus on well performance should be made prior to determining the proper logging protocol.

Repairing a microannulus is virtually impossible; therefore, every preventive effort should be made. To avoid a microannulus, observe best practices by minimizing pressure and temperature disturbances after cementing. This can include pressure testing casing after cement plug bump, displacing with lower density fluid or water, etc.

e) Computer generated "cement maps" cannot be relied upon as the sole source of interpretation data.

The presentations for ultrasonic tools include computer generated 2-D color images of calculated acoustic impedance of the material adjacent to the pipe wall. For the lower frequency multiple transmitter and (or) receiver tools, the 2-D image is based on the amplitude or attenuation of the casing arrivals. The scale and step size of the color coding and selection of the colors are all important, and can create powerful visual impressions that do not necessarily reflect reality of the cement integrity. Never be lured into thinking that these are “cement maps.” Always check the scale and step sizes of the color coding, the “cut-off level” and input parameters for non-solid type of materials.

f) Ultrasonic logs do not measure the acoustic impedance of the materials behind the pipe.

One misconception of ultrasonic logs is that acoustic impedance is measured by the tools. The value of acoustic impedance is derived from algorithms that include many inputs. These inputs have been discussed in previous sections, but include information concerning the fluids inside and outside the casing and the casing itself. Some of these values are very critical for correct calculation of acoustic impedance. For example, an input change of 0.1 MRayl in the acoustic impedance of the fluid inside the casing can lead to a 0.5 MRayl change in the calculated acoustic impedance of the cement.

12 Tool Selection Criteria/Guidelines

12.1 Tool Selection Based on the Cement Evaluation Objective

Table 12.1—Tool Selection Based on the Objectives of the Cement Evaluation

Goal	Tool Recommendation	Remarks
Cement top	CBL or LF or US or temperature log	1. Check Tables 2, 3 and 4 below for solid and fluid limitations. 2. It is recommended to run the CBL with the US tool. 3. Treat the CBL as a low frequency tool.
Cement channels	US or LF	1. Check Tables 2, 3 and 4 below for solid and fluid limitations. 2. It is recommended to run the CBL with the US tool.
NOTE: US are the Ultrasonic tools (USI, CAST-V, USIT…) and LF are the low frequency tools for cement channels (SBT, SBL…).		

12.2 Tool Selection Based on the Fluid Inside the Casing

Table 12.2—Tool Recommendation Based on Acoustic Property Estimates of Fluid Inside the Casing

Material	Density (lbm/gal)	Approximate Acoustic Impedance (MRayl)	Tool Recommendation
Fresh water	8.35	1.5	US or LF or CBL
Water + 10% NaCl	9.0	1.48	US or LF or CBL
Water + 25% NaCl	10.0	2.06	US or LF or CBL
Water + KCl	10.0	1.77	US or LF or CBL
Water + 36% $CaCl_2$	11.3	2.42	US or LF or CBL
Water + 58% $CaBr_2$	15.3	3.10	LF or US* or CBL
Sea water	8.6	1.57	US or LF or CBL
Diesel oil	7.1	1.17	US or LF or CBL
Water-base mud	12.0	2.14	US or LF or CBL
Water-base mud	15.0	2.7	LF or US* or CBL
Oil-base fluid	7.8	1.25	US or LF or CBL
Oil-base mud	12.6	1.54	LF or US* or CBL
Free gas	1.6	0.1	None
Drilling mud	17.0	3.06	LF or CBL

NOTES:

US are the Ultrasonic tools (USI, CAST-V, USIT…) and LF are the low frequency tools for cement channel (SBT, SBL…).

* Check with the service company to understand the mud impedance limits of the tool.

12.3 Tool Selection Based on the Fluid in the Casing Annulus

Table 12.3—Tool Recommendation Based on Acoustic Property Estimates of Fluid in the Casing Annulus

Material	**Density** (lbm/gal)	**Approximate Acoustic Impedance, 10^6** (kg/m^2s)	**Tool Recommendation**
Fresh water	8.35	1.5	US or LF or CBL
Water + 10% NaCl	9.0	1.48	US or LF or CBL
Water + 25% NaCl	10.0	2.06	US or LF or CBL
Water + KCl	10.0	1.77	US or LF or CBL
Sea water	8.6	1.57	US or LF or CBL
Diesel oil	7.1	1.17	US or LF or CBL
Water-base mud or spacer	12.0	2.14	US or LF or CBL
Water-base mud or spacer	15.0	2.7	LF or US* or CBL
Oil-base fluid	7.8	1.25	US or LF or CBL
Oil-base mud	12.6	1.54	US or LF or CBL
Free gas	1.6	0.1	US**
Drilling mud	17.0	3.06	LF or US* or CBL

NOTES:

US are the Ultrasonic tools (USI, CAST-V, USIT …) and LF are the low frequency tools for cement channel (SBT, SBL, …).

* Check with the service company to understand the impedance limits to distinguish the fluids from the solids in the casing annulus.

** The US physics may be able to distinguish gas from liquid in the casing annulus (check with the service company).

12.4 Tool Selection Based on the Solid in the Casing Annulus

Table 12.4—Acoustic Property Estimates of Solids in the Casing Annulus

Material	**Density** (lbm/gal)	** **Approximate Compressive Strength** (psi)	** **Approximate Acoustic Impedance** (MRayl)	**Tool Recommendation**
Foamed Class C	9.0	250	2.1 – 2.3	US* or LF*
Foamed Class C	9.0	1000	2.5 – 2.8	US* or LF*
Class H or G + hollow microspheres	11.2	> 1000	3.2 – 3.8	US* or LF*
Extended Class H or G	12.4	500 – 1000	3.2 – 3.3	US* or LF*
Extended Class H or G	13.2	750 – 1000	3.7 – 3.8	US* or LF*
Extended Class H or G	14.2	1000 – 1500	4.3 – 4.4	US or LF*
Class H or G	15.8 – 16.4	500	4.2 – 4.4	US or LF*
Class H or G	15.8 – 16.4	1000	5.4 – 5.8	US or LF*
Class H or G	15.8 – 16.4	> 3000	5.9 – 6.2	US or LF
Class H or G + 18% salt	16.0		7.4 – 7.8	US or LF
Class H or G + 300 mesh silica	16.2	> 3000	5.9 – 6.3	US or LF
Class H or G + latex	16.2	> 2000	5.6 – 5.8	US or LF
Class H or G + 100 mesh silica	17.0	> 3000	6.3 – 6.8	US or LF
Class H or G + hematite	18.0	> 3000	6.5 – 6.7	US or LF
Class H or G + hematite	19.0	> 3000	7.3 – 7.8	US or LF
Steel casing (CBL/VDL)			41.6	US*** or LF***
Steel casing (Ultrasonic)			46.3	US*** or LF***

NOTES:

US are the Ultrasonic tools (USI, CAST-V, USIT…) and LF are the low frequency tools for cement channels (SBT, SBL,…).

* Check with the service company to understand the impedance or compressive strength limits to distinguish the fluids from the solids in the casing annulus.

** Check with cementing service company to be sure a contaminated solid can be distinguished from the fluid in the casing annulus.

*** Casing thickness greater than 0.625 in. and/or casing diameters larger than 13 3/8 in. may be beyond the physics limit of the tool (check with the service company).

13 Zonal Isolation

Interpreting zonal isolation from a cement evaluation log is not a straightforward process and, in many cases, not even possible. Whether fluids will communicate behind pipe cannot be determined from a cement evaluation log alone. A meaningful interpretation of zonal isolation quality from an acoustic log is only possible when, and if, the expected response can be predicted ahead of time. In order to predict the log response and make a sound judgment as to the quality of the zonal isolation, the user must first ask and answer the following questions.

- What is the objective of the cement job?
- What does the other available information suggest about zonal isolation quality?
- What are the limitations of the cement evaluation tool that is being run?
- What remedial action will be taken based upon the evaluation?

13.1 What is the Objective of the Cement Job?

When attempting to determine the quality of cementation, it is important to first define the objectives for the cemented casing string being evaluated. The objectives may be one or a combination of several of those listed below:

- isolate the casing seat for subsequent drilling;
- protect useable water zones;
- prevent gas leakage [inter-zonal or sustained casing pressure (SCP)];
- isolate the production zones (primary and secondary);
- meet regulatory requirements;
- provide structural support for the casing or wellhead;
- protect against casing corrosion.

Clearly defining the objectives helps to define the expected log response that would identify whether or not those objectives have been met. For example, verifying structural support requirements by accurately identifying the top of cement with an acoustic cement evaluation log can be accomplished with a relatively high degree of certainty by looking for an interface between free pipe above and some degree of acoustic coupling below. Comparatively, predicting whether or not sustained casing pressure can be expected is very difficult to do. Even if the cement evaluation log indicates very strong acoustic coupling across the entire length of the cement column, gas migration paths that are not detectable from the log may still exist.

13.2 What Does the Other Available Information Suggest About Zonal Isolation Quality?

One must remember that data from a cement evaluation log is just one piece of information for determining the quality of zonal isolation. Other pieces of information must be evaluated in parallel with the log to better understand the quality of the isolation.

These include:

- Previous experience from offset wells
- Cement job execution parameters
  - Engineered mud removal design, including centralization, density hierarchy, rheology hierarchy, spacer volume, fluid compatibility, annular velocities and use of wiper plugs
  - Job signature, including actual vs. predicted surface pressure and flow rate in vs. flow rate out
  - Losses or flows observed prior to, during and immediately after cementing
  - Volume of fluids pumped prior to observing returns of spacer or cement
  - Operational issues such as equipment malfunction, prolonged shutdowns, poor density control, float equipment failure, etc.
- Production data such as GOR and WOR
- Pressure tests such as leak-off tests (LOT), formation integrity tests (FIT), or pressure integrity tests (PIT)
- Liner top pressure tests (positive and negative differential pressure)
- Acoustic properties of the cement behind the casing vs. time
- Data from other logs such as caliper, GR, temperature, etc.
- Presence of mechanical barriers (e.g. liner top packers)
- Events that have taken place in the well that could have compromised isolation such as reducing fluid density in the casing, high pressure stimulation treatments, etc.

By using the all of the above information that is available, one can obtain an indication of the expected response from the cement evaluation log. Interpretation without incorporating this data may result in erroneous conclusions. For example, if cement returns to surface were observed significantly earlier than expected based on annular caliper volume and surface pressure began to rise earlier than predicted by U-tube simulations, then an indication of mud channels or contaminated cement should be anticipated on the subsequent cement evaluation log.

13.3 What are the Limitations of the Cement Evaluation Tool That is Being Run?

The limitations of the cement evaluation tool and the constraints of the logging operations must be clearly understood prior to running and interpreting the log:

- operating bottomhole temperature and pressure ratings of the tool;
- ability to run the log under applied surface pressure to eliminate microannular effects;
- elapsed time between cementing and logging;
- changes in cement properties along the length of the column due to temperature differentials;
- inability of the tool to operate properly with heavy drilling fluid inside the casing;

- effects of changes in drilling fluid acoustic properties inside the pipe due to fluid compressibility, especially in non-aqueous fluids;
- acoustic interference for pipe-in-pipe situations;
- response of the tool to eccentered casing;
- response of the tool to very thin cement sheaths;
- interference of the acoustic signal when pipe is in contact with the wellbore wall
- fast formation effects;
- differences in acoustic response between "wet" and "dry" microannuli;
- effects of changing casing wall thickness on the acoustic signal;
- effects of casing resonance for certain casing-wall thicknesses;
- unpredictable tool response to the casing-surface roughness;
- degree of azimuthal resolution of the tool;
- degree of vertical resolution of the tool;
- depth of investigation of the tool;
- ability to transport the tool to the depth of interest and maintain proper centralization in high-angle wellbores.

Attempting to interpret an acoustic evaluation log without first understanding the tool limitations in the wellbore environment can lead to an incorrect assessment of zonal isolation. For example, if the goal is to determine whether a mud channel is present across a 5 $^1/_2$ in. × 7-in. liner lap, an acoustic cement evaluation log may not be a suitable tool because it tends to have an erratic response to both a very thin cement sheath and a casing-in-casing geometry.

13.4 What Remedial Action Will be Undertaken Based Upon the Evaluation?

It is also important to consider actions that can be taken based on the results of the evaluation:

- perforate and squeeze;
- modify completion plans;
- take no immediate action but monitor the well for indications of isolation problems;
- take no action on the evaluated well but use the information to redesign future wells for improved isolation.

The user should remember that poor acoustic coupling or the indication of a channel on a cement evaluation log does not guarantee that cement can be successfully squeezed behind the casing. Therefore, if the completion scheme does not limit the ability to perform remedial work at a later date, it may be advisable to delay running an evaluation log until production problems arise. This "wait-and-see" approach may save the cost of unnecessary logging and squeezing operations.

Annex A

Jargon

- **Acoustic Impedance and its Units:** Acoustic Impedance is a characteristic of a material, calculated as the product of the density of the material and the sound velocity in it. The unit of acoustic impedance is kg $m^{-2}s^{-1}$ which is also called Rayleigh, shortened as Rayl. Units are normally expressed in MRayl.

- **Acoustic Impedance in a Liquid:** (see Figure A.1) Solids-free liquids will have a constant or steady acoustic impedance value.

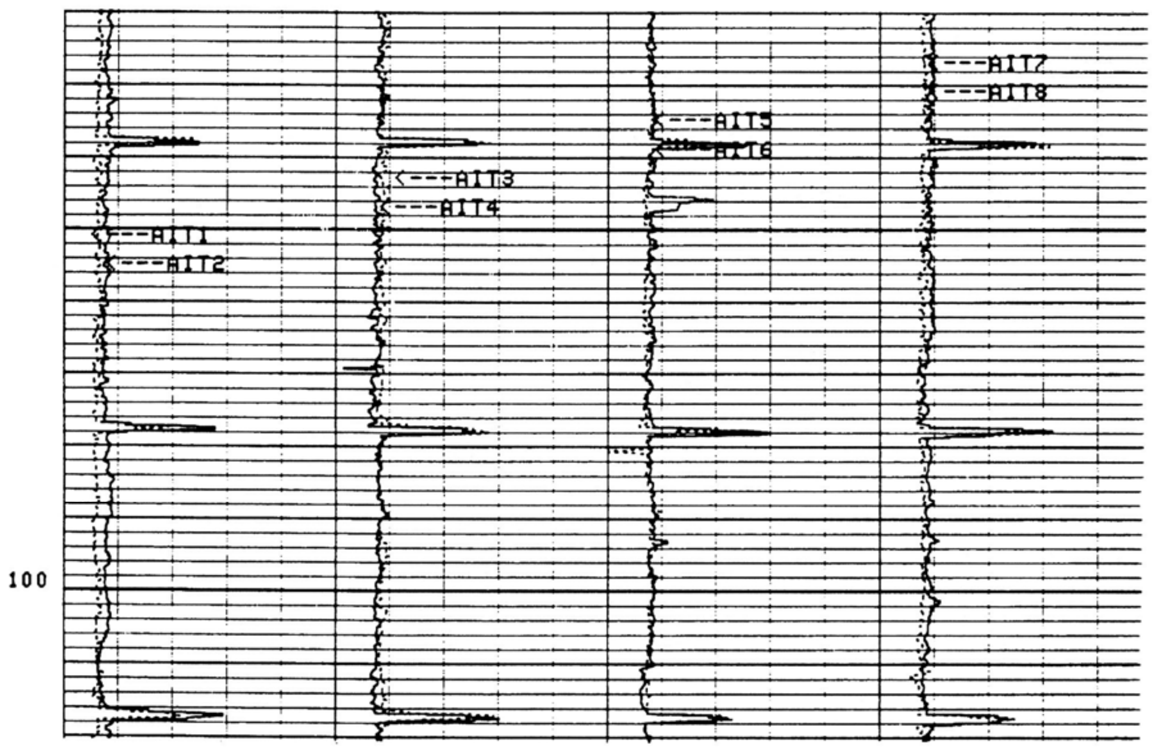

Figure A.1—Impedance Character in Liquid Environment

NOTE: Impedance scale is 0 to 5.0.

- **Acoustic Impedance in Low Impedance Cements (see Figure A.2):** Low impedance solid materials may have impedance values below the color interpretation cutoff values used for mapping. Examples are foamed cements, a dry microannulus and cement contamination by mud or gas. A "low-impedance" solid material usually has more variable measured impedance than a fluid.

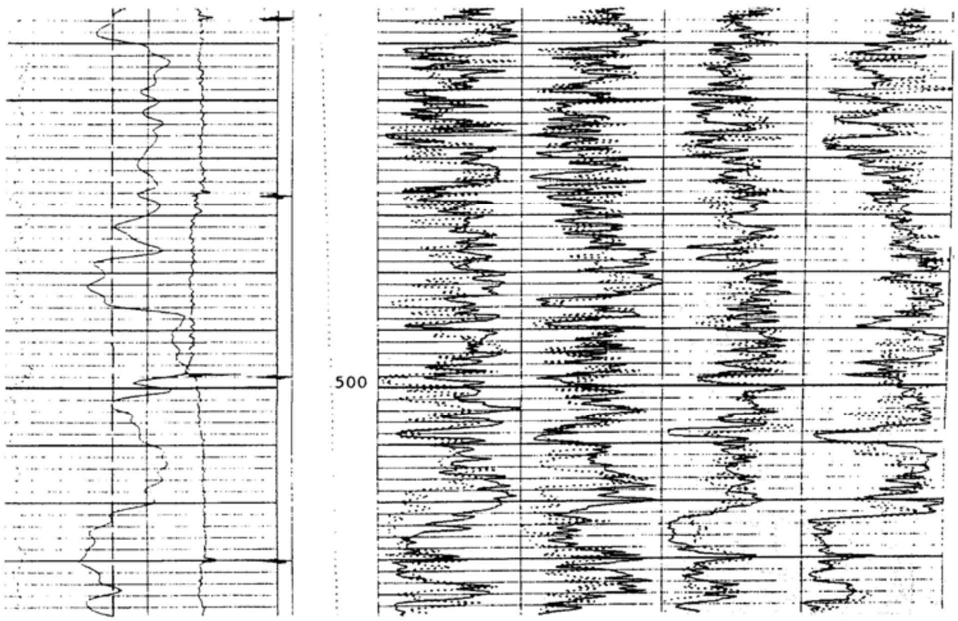

Figure A.2—Impedance Character in Solid Mixed with Fluids

NOTE: Impedance scale is 0 to 10.0.

- **Amplitude:** The strength of the first positive peak in the sound wave traveling along the casing. This value is plotted vs. depth on CBL logs. See E_1, Figure A.5.

- **Attenuation Rate (see Figure A.3):** The rate of energy lost as the sound wave passes through a medium.

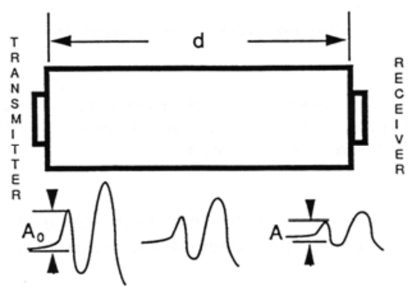

Figure A.3—Attenuation

NOTE: A_0 is the transmitter amplitude, A is the receiver amplitude and d is the distance between the transmitter and receiver. Attenuation in dB/unit distance = $(20/d)^* \log (A/A_0)$.

- **Casing Arrivals, Formation Arrivals, Mud Arrivals (see Figure A.4):**
  The received waveform is extremely complicated. It is a combination of wave trains that have traveled through different media such as casing, formation and mud. Casing arrivals, formation arrivals and mud arrivals are terms that refer to the corresponding portions of the waveform. The tail of one type of arrival will be overtaken by the lead of the next. One cannot clearly see the types of arrivals on a single waveform.

However, when the VDL log is generated, the features of these arrivals usually stand out as shown (see Figure A.4).

The features of casing arrivals and mud arrivals on the VDL are straight stripes starting at known times. This is because the acoustic properties of the steel casing and that of the mud column are usually homogeneous. The sound velocities in the formations, however, can vary substantially along the well, making the formation arrivals wander in time as shown in wiggly stripes.

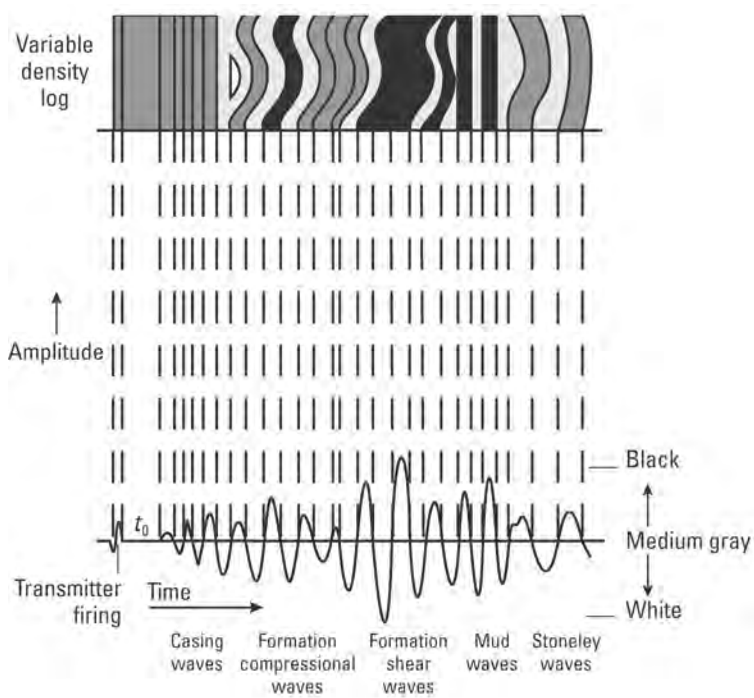

Figure A.4—Waveform Breakdown of Casing, Formation and Mud Arrivals

NOTE: Copyright Schlumberger. Used with permission.

- **CAST-V ACE Processing (see Presentation: Figure 9.13):**

This technique relies on a statistical variation process (SVP) to discern solid crystalline structures, such as cements, from fluids. Solids-free liquids have a consistent or steady impedance measurement (see Figure A.1) while solids, when mixed with either fluid or gas, have a variable measurement (see Figure A.2). A consistent phase, as water, gas, or drilling mud, will exhibit less impedance variation. When tool position is taken into account, an analysis of the vertical and horizontal rate of impedance change permits distinguishing foamed cement from liquid. A resulting variance image is used to distinguish foamed cements from fluids.

SVP assumes that cement in a well annulus is not consistent, and it does not use the impedance values directly to determine whether the material is solid or liquid. Combining the SVP processing with the measured impedance data provides an improved method for cement evaluation.

ZP BI is the normal Bond Index from the impedance map without any processing.

CEMENT BI is the Bond Index from the cement image. This curve should track the amplitude curve from the CBL because the measurements are an indication of cement-to-pipe bond.

IMPEDANCE is the raw impedance measurements from the CAST-V.

VARIANCE is from the SVP computation.

CEMENT is a combination of the IMPEDANCE and VARIANCE information. In the variance track, the lower center section of the image below M075 is shown to be a fluid; however, referring back to Figure 8.12, the impedance is about 3. This is consistent cement due to the low activity level as shown in the previous figure. The inability of variance to distinguish consistent cement and water requires the use of the cement image incorporating the variance results and the original impedance data to correctly interpret the material behind casing. It is still easy to see the channel from M067 to M010 on both the variance and cement image. The section below M075 is determined to be cement by the original impedance data.

- **CAST-V quality control presentation nomenclature (see Presentation: Figure 9.12):**

GR = gamma ray. Provides information on lithology and correlation. Scale should be 0 to 100 API or desired user scale.

NBS = number of bad shots. Total number of bad shots as determined by processing. This will be the number of shots flagged in BSI [bad shot indicator (Track 6)]. Scale should be 100 to 0.

BSI = bad shot indicator. This will provide quality control and allow determination if the data are valid. If there was no problem in the ID, thickness or impedance calculations, the BSI value = 0 (white). If there was a problem in the ID calculation the BSI will have a value of 1 (blue) or 2 (brown). Problems in the pipe thickness calculation will provide a value of 3 (green). Impedance problems will provide a value of 4 (red). Scale should be 0.25 to 4.25.

ECTY = eccentricity. Provides information on tool eccentricity Scale 0 to 1.

OVAL = ovality. Casing ovality as determined by the CAST-V. Scale 0 to 1.

RB = relative bearing. Relative bearing of Shot #1. This is information about the tool rotation. Excessive rotation (360° < 100 ft) can provide less than adequate log readings. Scale 0° to 360°.

DEVI = deviation. Hole deviation measured by the CAST-V.

FREQ = frequency. Calculated frequency of the resonance data, this should be very close to the known transducer frequency. This value should remain steady through out the log. Scale should be ±50 from the known transducer frequency.

AVZ = average acoustic impedance. the average acoustic impedance value is based on the good measurements. It ignores the impedance measurement when the bad shot indicator (BSI) value is greater than zero. The scale of AVZ should be 10 to 0. Referring to Figure 9.12, the red color on the “BSI” map is bad data, which is ignored to calculate the average acoustic impedance (AVZ).

AVID = average casing internal diameter. This is the average pipe ID of the shots with a BSI value of 0, 3 or 4. The AVID ignores shots that have a BSI of 1 or 2. This average value should be close to the known casing ID; however, errors in the mud cell, and transducer calibrations, along with tool eccentricity, can affect this reading. Scale should be ±0.25 from the known casing ID.

AVTK = average pipe thickness. This is the average pipe thickness of the shots with a BSI value of 0 or 4. The AVID ignores shots that have a BSI of 1, 2 or 3. This average value should be close to the known (casing OD–nominal ID)/2. Scale should be ±0.10 from the above thickness. This is a very sensitive scale which can be changed to remove scaling artifacts.

AVOD = average casing outside diameter. This is the known casing size. The value should be ±0.25 from the known casing OD.

IDP = casing internal diameter plot. This is the map of the calculated pipe ID. The average value should be close to the known casing ID; however, errors in the mud cell, and transducer calibrations, along with tool eccentricity, can affect this reading. Red indicates thinning pipe (increase in ID), Blue indicates thickening (ID increase). Scale should be ±0.25 from the known casing ID and be the same as AVID.

THKP = pipe thickness plot. This is the map of the pipe thickness. This average value should be close to the known (casing OD–nominal ID)/2. Red indicates thinning pipe (decrease in thickness), blue indicates increasing pipe thickness. Scale should be ±0.10 from the above thickness and be the same as AVTK. This is a very sensitive scale that can be changed to remove scaling artifacts.

ZP = impedance plot. This is the map of the cement impedance. The only difference between this ZP and the standard ZP scale is that the upper and lower limits are shifted by 0.38. This will allow negative impedance to be shown as green (–0.38 to 0) gas red (0 to 0.38) light fluids (0.38 to 1.15) fluids (1.15 to 2.3), transition materials (2.30 to 2.7), low impedance cement (2.7 to 3.85), medium impedance cement (3.85 to 5) high impedance cement (> 5). Scale should be –0.38 to 5.77.

- **Cement Map.** These maps are intended to show the cement distribution and cement quality around and along the wellbore. Typically, darker shading indicates higher cement-impedance values or attenuation or lower amplitude. Cement maps are part of the SBT, SBL, and ultrasonic presentations.

- **Channel.** An uncemented void in the annulus. It will usually contain mud residuals or a mixture with solids which do not provide fluid isolation. A channel can have an irregular size and shape, and occur anywhere in the annulus.

- **Cycle Skip.** (See Figure A.5.) If the E_1 amplitude is lower than the detection level then the E1 peak will be ignored and the next positive peak having amplitude as great as the detection level will be measured for the CBL amplitude. The TT will be measured off the cycle that is above the detection level. Cycle skip may occur when casing is well cemented or when the logging tool is not centralized. In very strong cements, it is possible that the detection level could be part of E_3, E_5 or even E_7. The TT will be increased by roughly an integer number of the wavelength.

- **Cycle Stretching.** (See Figure A.5.) Stretching means there is an increase in the TT due to the decrease in the El amplitude caused by, for example, an improvement in cement quality. Because the TT is related to the detection level, a decreased peak will reach the detection level later and thus “stretch” the TT.

- **E_1, E_2, E_3 etc.…:** (See Figure A.5.) E_1 means the first waveform peak (positive). Its amplitude is measured in millivolts (mV) and displayed on CBL logs. Similarly, E_2 is the first negative peak following E_1; E_3 is the next positive peak, and so on.

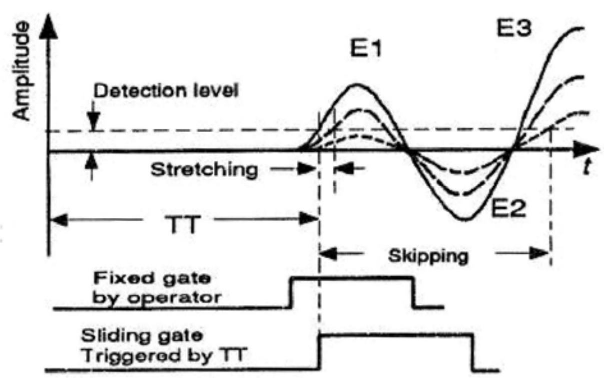

Figure A.5—Amplitude and Travel Time Terminology

- **Fast Formations.** Limestone, dolomite or anhydrite have sound speeds close to or faster than sound speed in steel (17,500 ft/s corresponding to a slowness of 57 μs/ft). On the VDL log, fast formation arrivals may appear before the casing arrivals and override them.

- **Fixed, Sliding or Floating Gates.** (See Figure A.5.) The tool begins measuring only when the E_1 amplitude is about to arrive, and stops measuring when it has passed. This measuring period is called a gate. It is vital that the gate is opened in the correct position on the waveform in order to measure the correct E_1 amplitude. There are two ways of setting the gate: the fixed gate and the sliding gate.

  The fixed gate is set by the tool operator to straddle E_1. Once set, a fixed gate will open and close irrespective of the waveform. The sliding gate is triggered open by the waveform when it has first reached a preset detection level. Most of the time both types of gate will give the same value of E_1. However, when the E_1 position is caused to change by certain conditions (e.g. fast formation), a fixed gate could miss it but a sliding gate would detect it. On the other hand, a sliding gate could be triggered open by E_3 if E_l is lower than the detection level.

- **Formation Arrivals.** See **Casing Arrivals, Formation Arrivals, Mud Arrivals**.

- **Free Pipe:** Free pipe is a section of pipe that is not cemented.

- **Microannulus:** A small separation (or gap) between the casing and cement that is caused by the shrinking casing. This gap reduces the acoustic coupling between the casing and the cement.

  Causes of casing shrinkage include:

    1. The internal casing pressure at time of logging is less than the internal pressure during cement curing;
    2. The borehole temperature at time of logging is less than when the cement cured; or
    3. Drilling ahead while the cement is curing.

- **Mud Arrivals:** see **Casing Arrivals, Formation Arrivals, Mud Arrivals.**

- **USIT Micro-debonding:** (See Figure A.6.) (See Presentation Figure 9.7 and Figure 9.8.) Setting cut-off impedance values to distinguish between gas, liquid and cement may be ambiguous because a number of conditions may cause solid material to have low ultrasonic impedance. These conditions include genuine low-impedance cements (e.g. foamed cement), a dry microannulus and set cement contaminated by mud or gas. Acoustic-impedance variations can distinguish between solids and fluids in the annulus. A liquid or gas phase in the annulus has constant, low impedance (see Figure A.1) while a “low-impedance” solid material usually has more variable measured impedance (see Figure A.2). Gas influx can cause debonding due to dehydration and fractures, but it is just one of several possible mechanisms for variable impedance values.

The USIT micro-debonding algorithm is illustrated in Figure A.6. It calculates the standard deviation of the cement impedance in four directions around each image pixel. If:

1. all four standard deviations are higher than set thresholds, and
2. the cement impedance is low (in the gas or liquid classes),

then the current pixel is considered to be of set cement and locally debonded and is colored green. Usually, two images are presented: the raw acoustic impedance and the interpreted image with micro-debonding.

Statistical processing has certain limitations as follows.

1. The variance thresholds are empirical. Sometimes too much "liquid" (blue) is indicated when the bonding is obviously patchy. On the other hand, casing shape effects, casing rugosity or irregular tool movement sometimes provoke variations in measured impedance that are interpreted as "debonding." Such artifacts must be detected by quality control. The variance thresholds should ideally be tuned in a similar type of casing surrounded by known material, such as free pipe.
2. Solid cement can be associated with a low-variance, low-impedance image. For example, extended dry microannulus has flat near-zero impedance and remains red on the cement map. Homogeneous well-bonded light cement can also have a low variance.

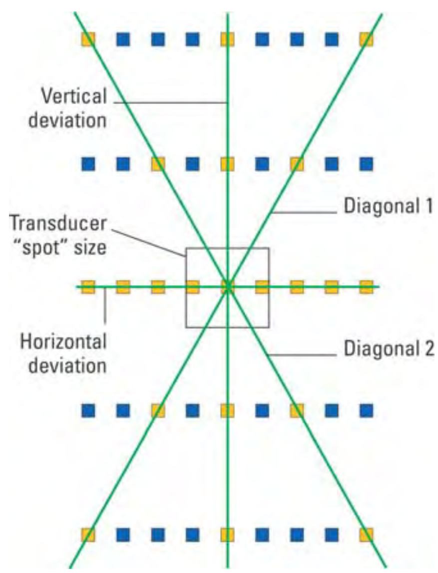

Figure A.6—Illustration of the Micro-debonding Processing for a USIT Measurement Pattern with 36 Radial Samples and 1.5-in. Vertical Sample Rate Inside a 5.5-in. Casing

NOTE: Copyright Schlumberger. Used with permission.

- **TT—Travel Time or Transit Time.** (See Figure A.5.) TT is the time that begins when the transmitter is fired and ends when a determined amplitude peak from the waveform is detected by the receiver.

Annex B

Examples

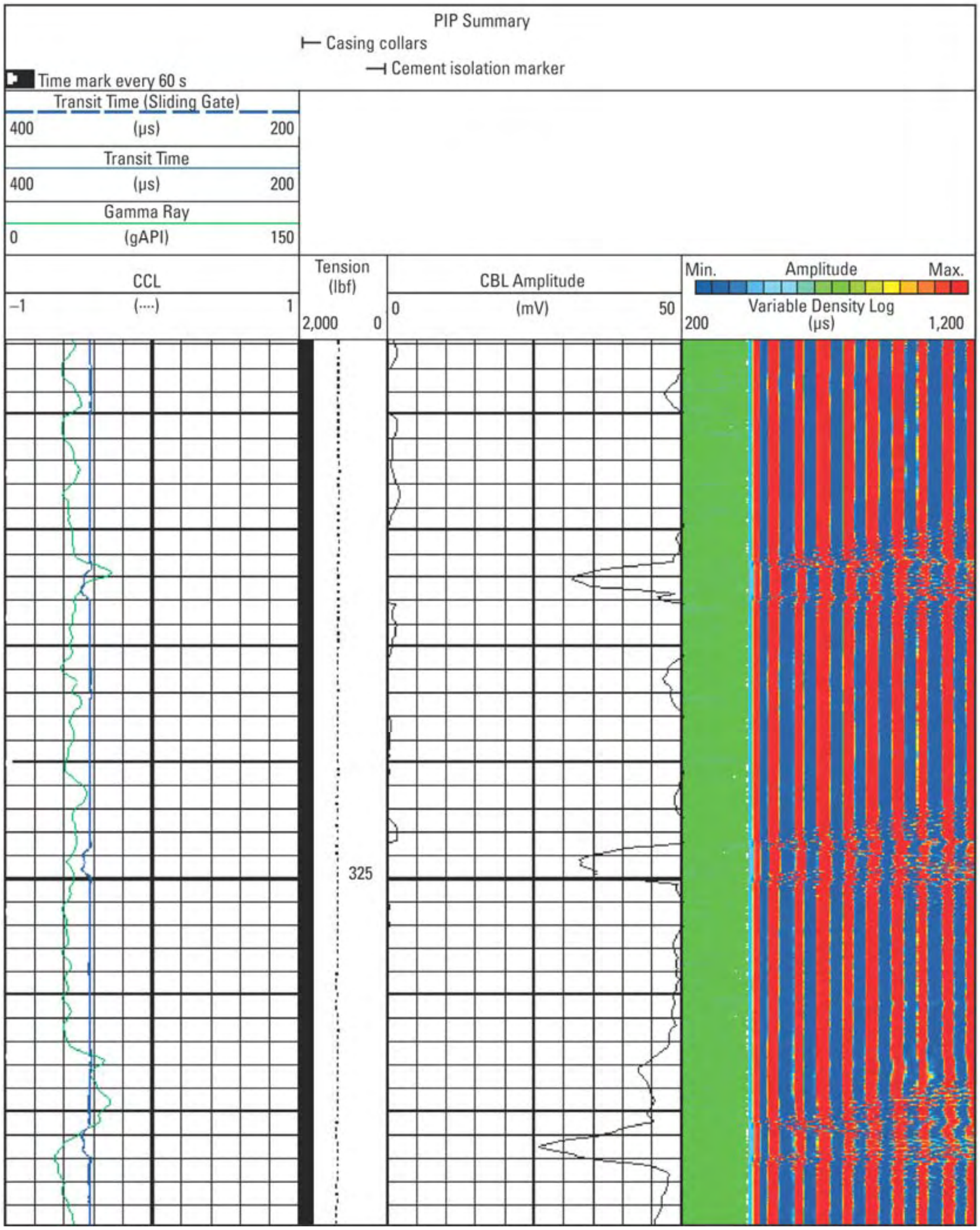

Figure B.1—CBL No Cement

NOTE: Typical example of constant velocity on the VDL with high amplitude (low attenuation). Copyright Schlumberger. Used with permission.

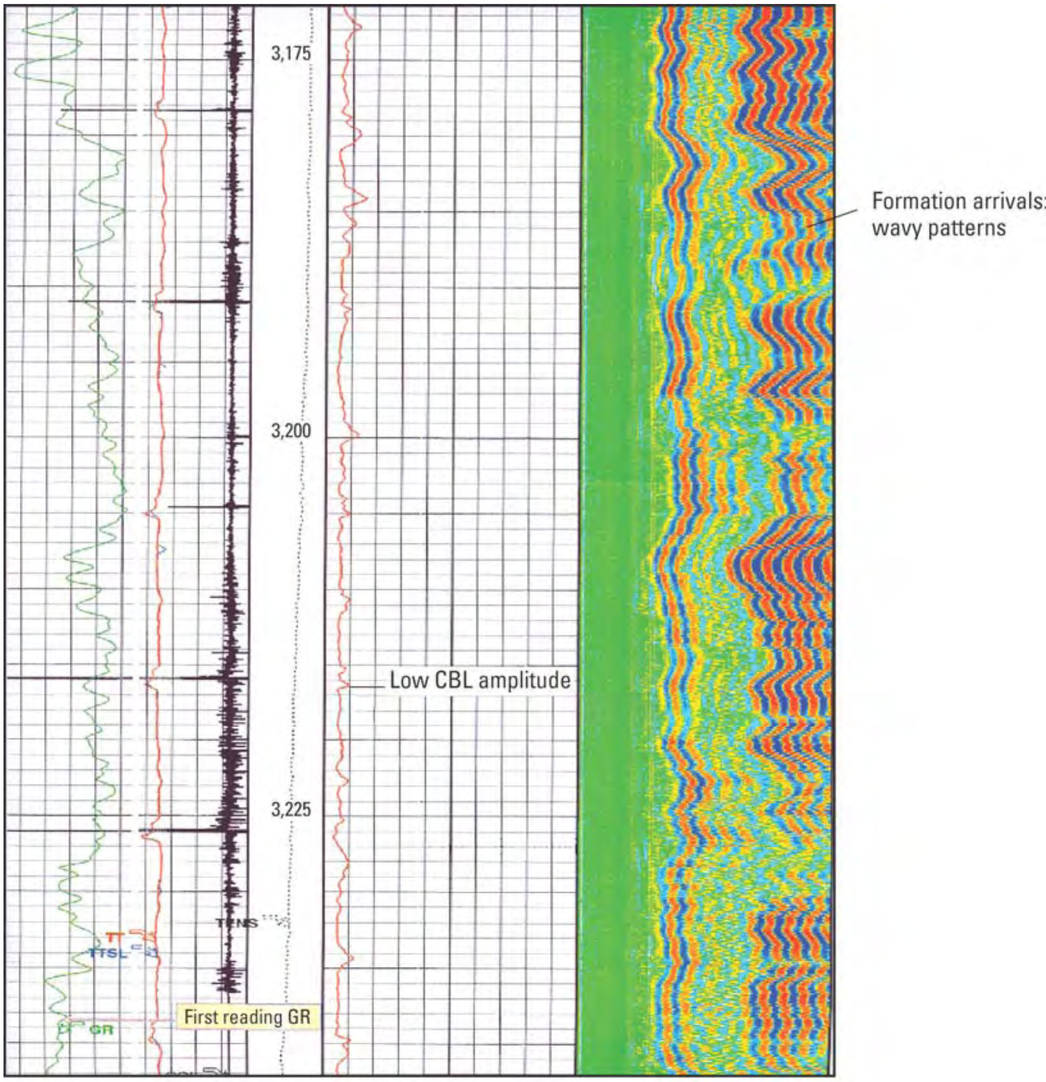

Figure B.2—CBL Cemented Pipe

NOTE: Wavy patterns on the VDL showing good acoustic coupling between the cement and formation. The low CBL amplitude confirms cemented pipe. Copyright Schlumberger. Used with permission.

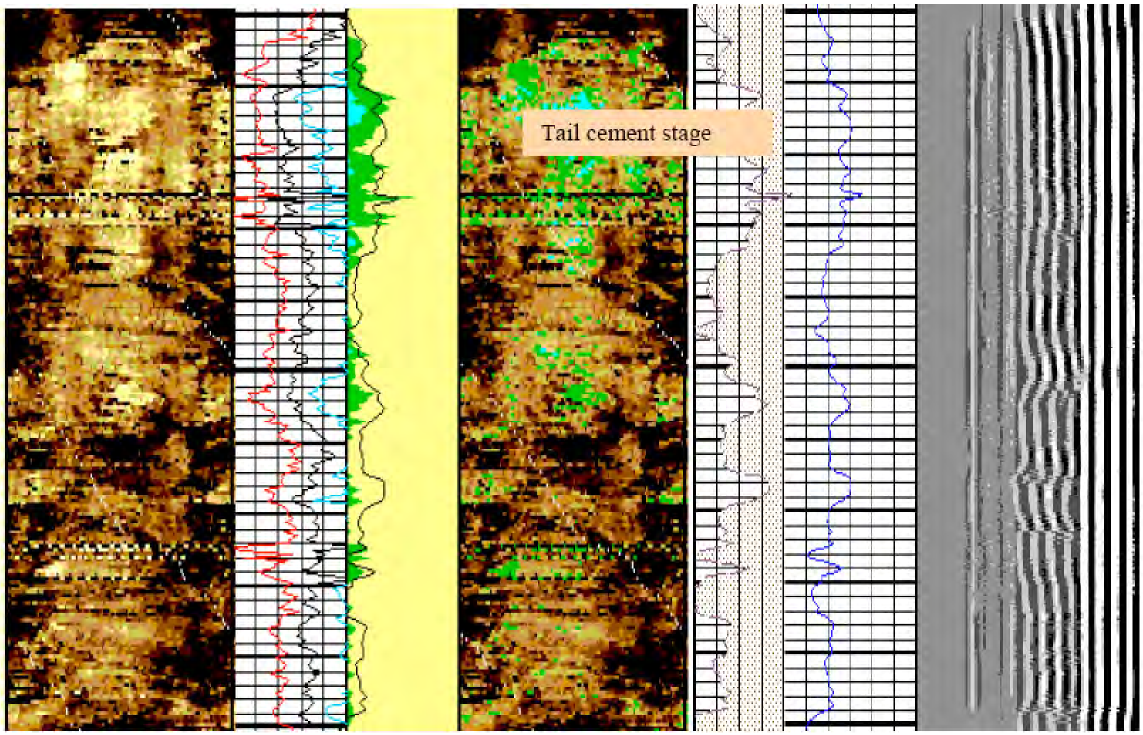

Figure B.3—CBL and Ultrasonic Cemented Pipe

NOTE: Wavy patterns on the VDL showing good acoustic coupling between the cement and formation. The low CBL amplitude confirms cemented pipe. Ultrasonic shows high acoustic impedance. Copyright of the Society of Petroleum Engineers, reproduced with permission.

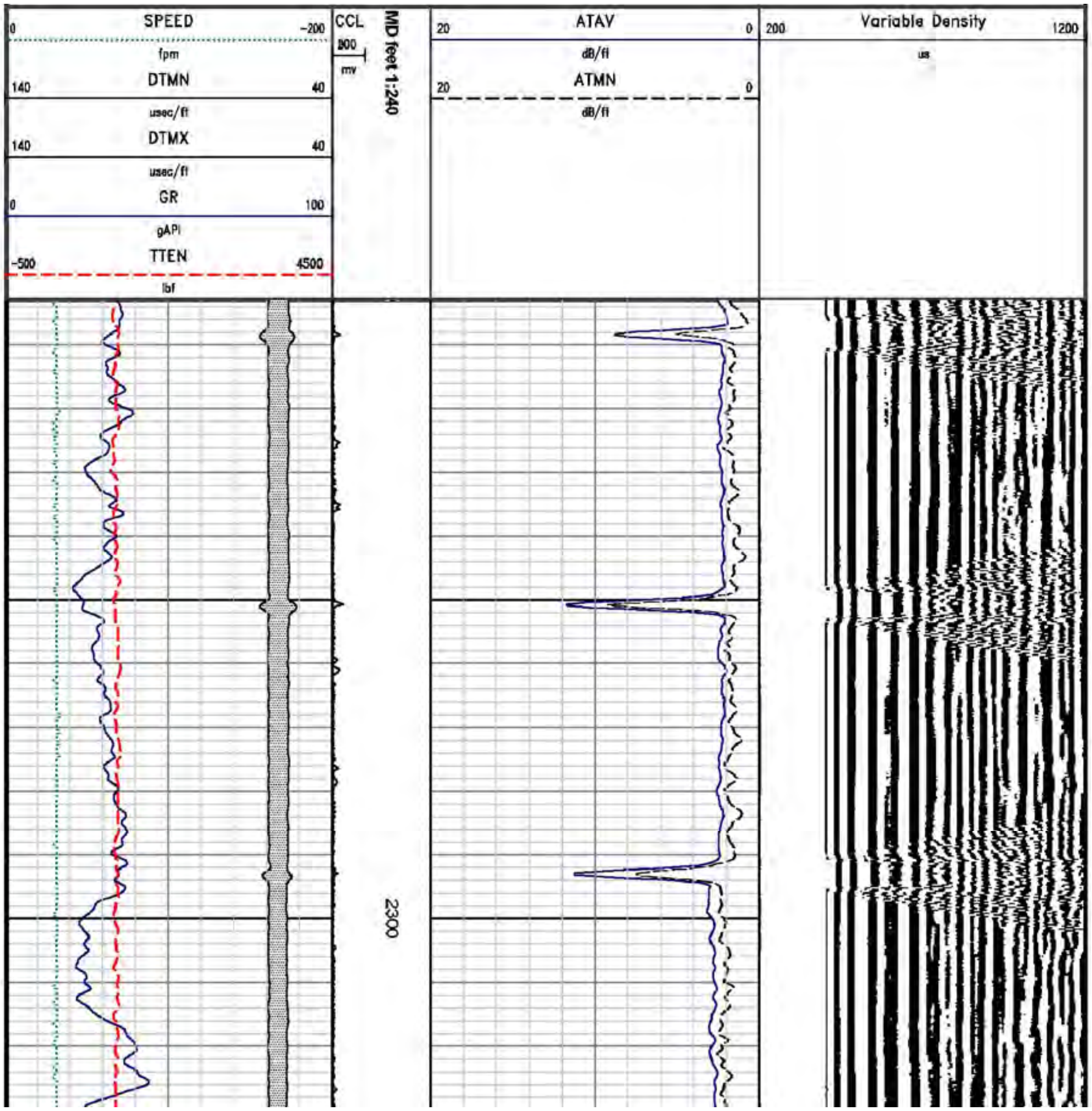

Figure B.4—SBT in Free Pipe

NOTE: Typical example of constant velocity on the VDL with low attenuation.

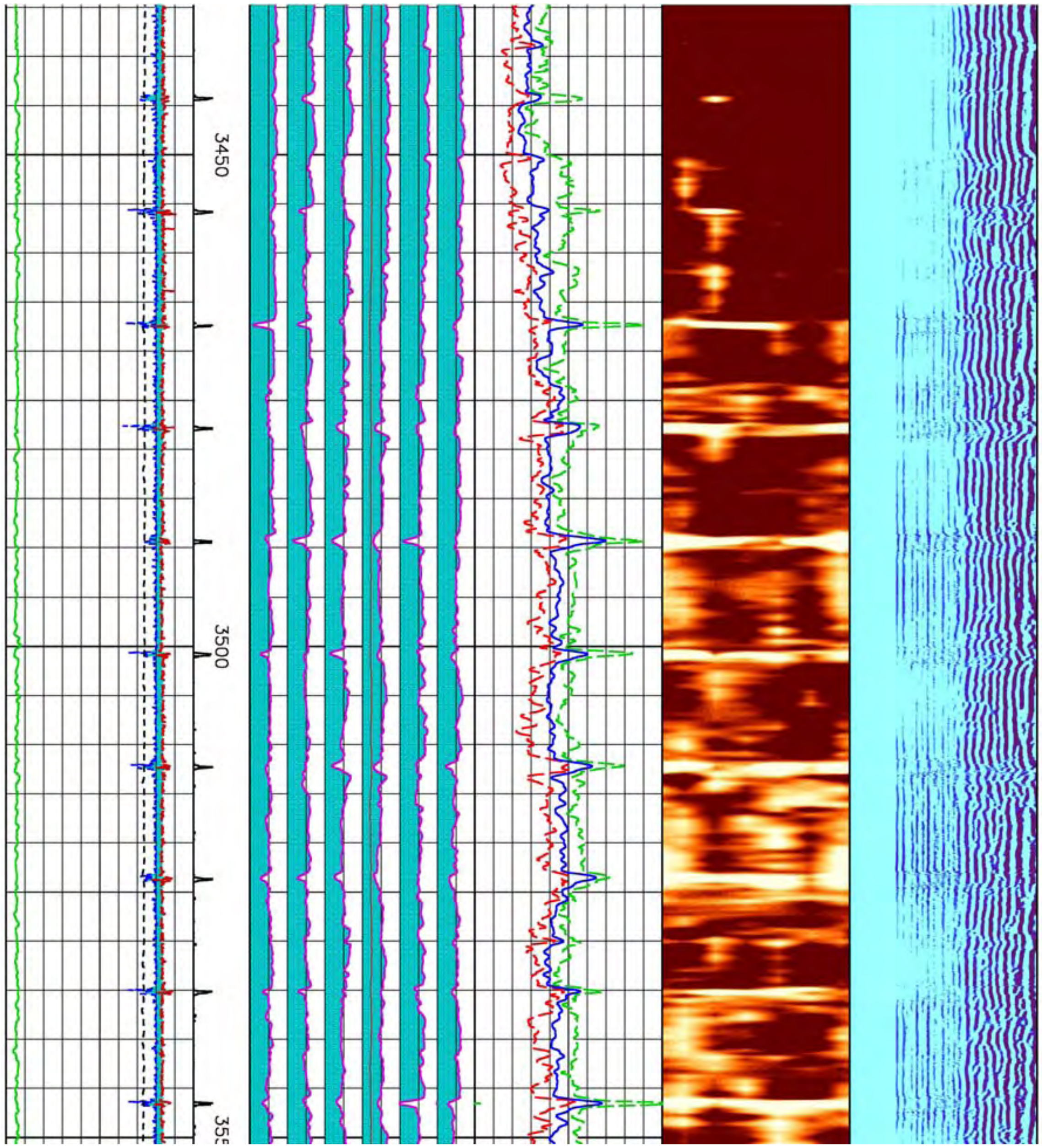

Figure B.5—SBT Cemented Pipe

NOTE: Wavy patterns on the VDL showing good acoustic coupling between the cement and formation. The average and minimum attenuation confirms cemented pipe. The dark shading on the cement map is confirmed by the high attenuation on the six segments. The log was run in 10 $^3/_4$ in. casing that has a thickness of 1 in.

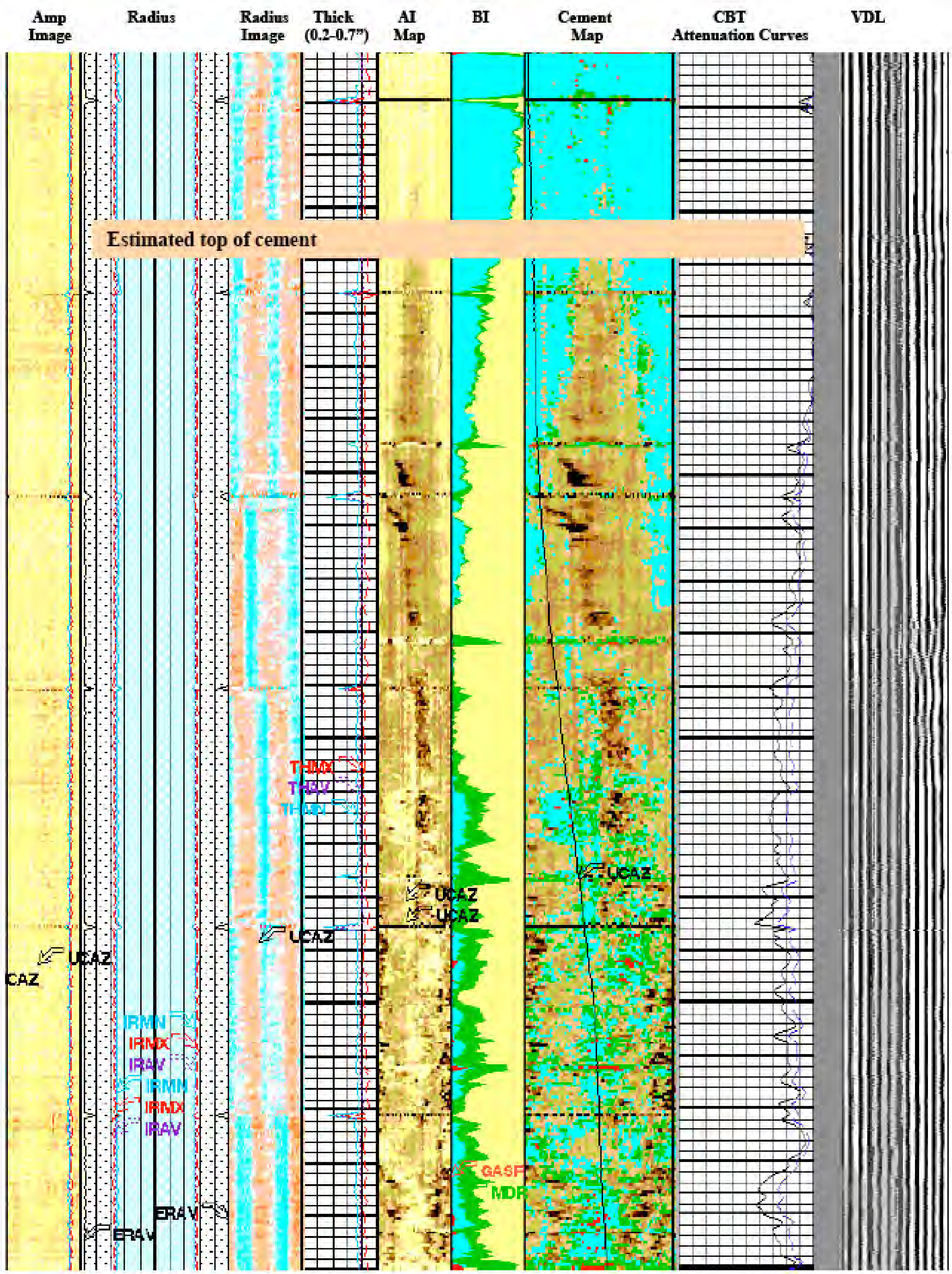

Figure B.6—USIT in Multi-stage Foamed and Lightweight Cement

NOTE: This casing was 9 $^{7}/_{8}$-in., 62.8 lbm/ft completed in a 12.25-in. borehole. The fluid in the borehole during the logging operation was an 11.7 lbm/gal $CaCl_2$. The cement system was a two-stage foamed cement (13.8 lbm/gal and 15.0 lbm/gal) followed by a non-foamed cement (16.3 lbm/gal). There were no cement returns during the job and a small pressure increase at the end of the pumping operation. The intent was to leave a short annular space devoid of cement at the top of the casing section. Copyright of the Society of Petroleum Engineers, reproduced with permission.

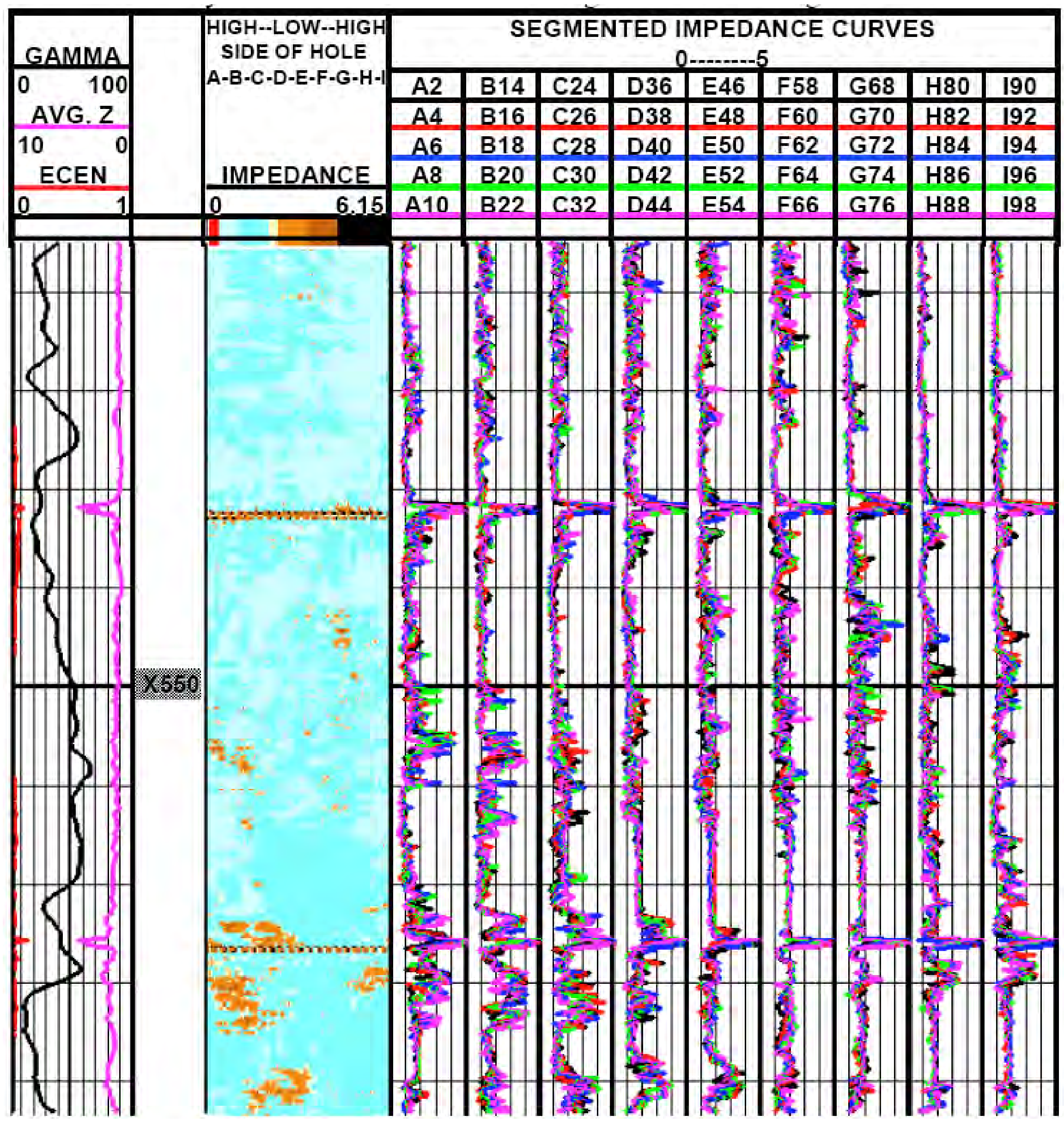

Figure B.7—Lightweight Cement #1a

NOTE: CAST-V standard impedance image with sectional curves providing both the impedance data along with activity levels. Typical evaluation of the original impedance image would indicate free pipe and would be a candidate for a squeeze. The segmented curves indicate that there are solids present due to the activity level and lack of curve stacking over the entire log.

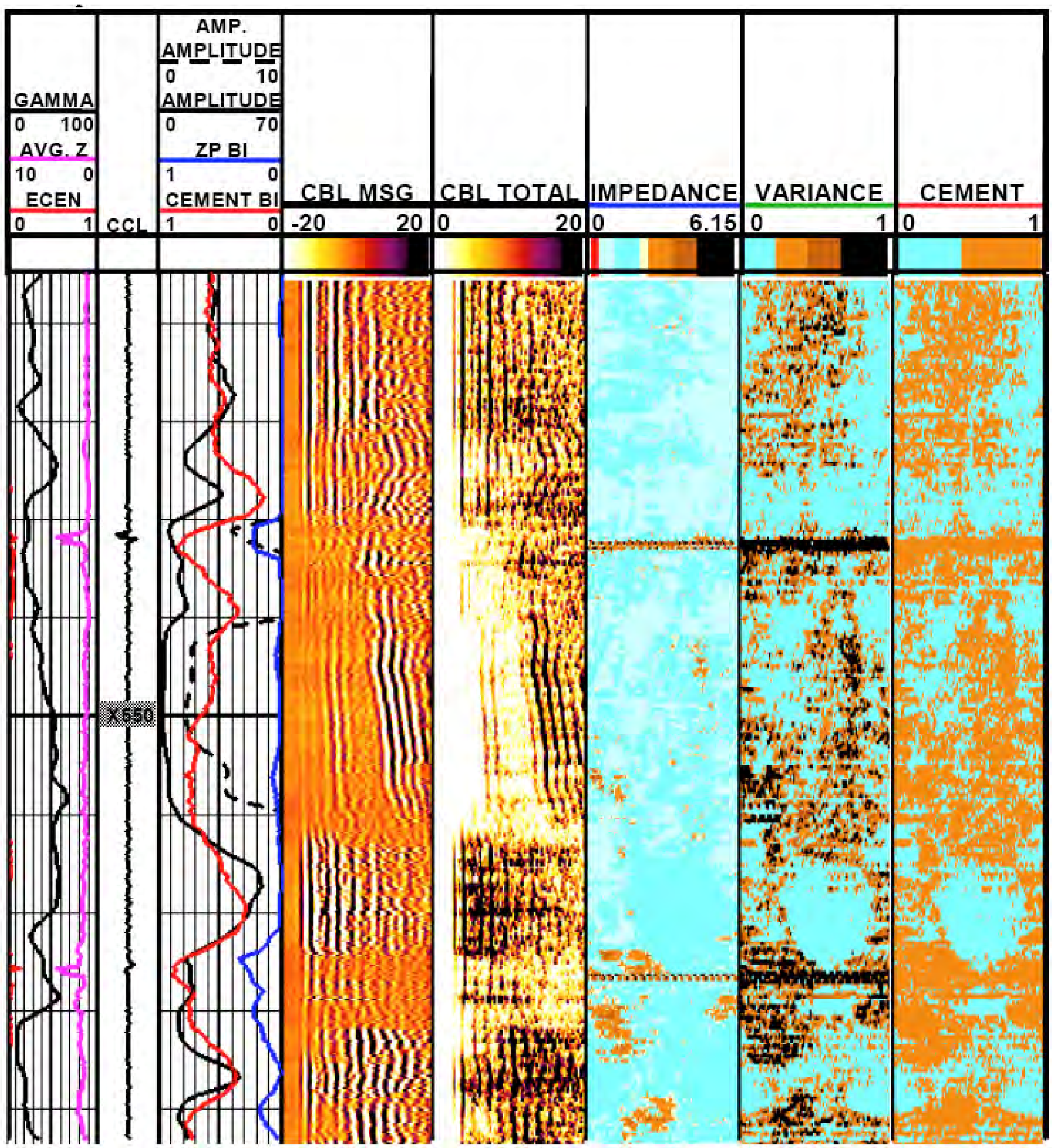

Figure B.8—Lightweight Cement #1b

NOTE: ACE processing of data from Figure #1a shows the cement is very inconsistent and contains cavities, but that vertical zonal isolation is probably achieved. At X570, the void in both cement and variance images corresponds to an indication of less that perfect cement job as indicated by the CBL images. The amplitude curve and the cement BI curves indicate bonding ranging from a high of 90% down to about 25%. Over the entire well, these two curves track each other, indicating essentially equivalent cement quality but measured and calculated from two different devices. Where they separate, the cement is more inconsistent.

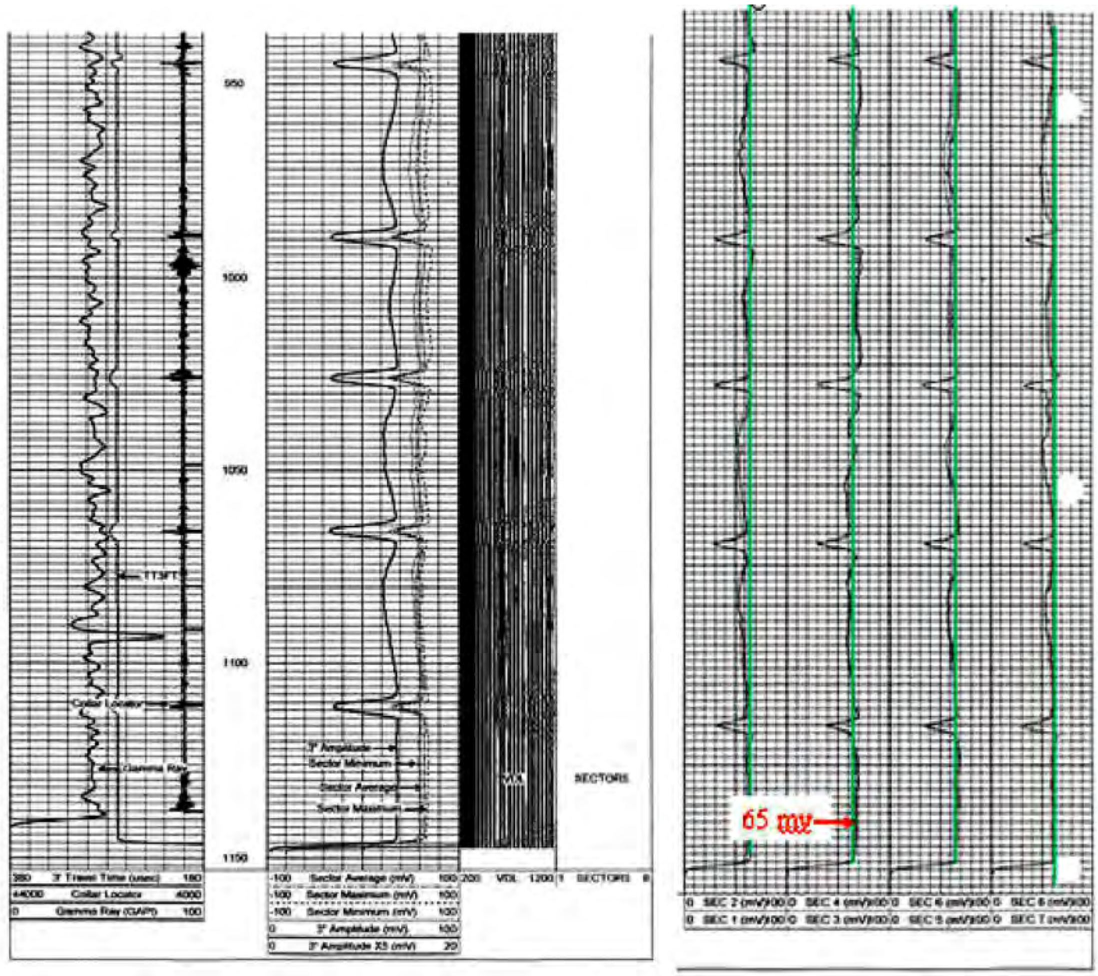

Figure B.9—SBL with No Cement #1a

NOTE: Typical example of constant velocity on the VDL with high amplitude (low attenuation). On the right are the eight sectors. The green lines indicate the values of the eight amplitudes in free pipe.

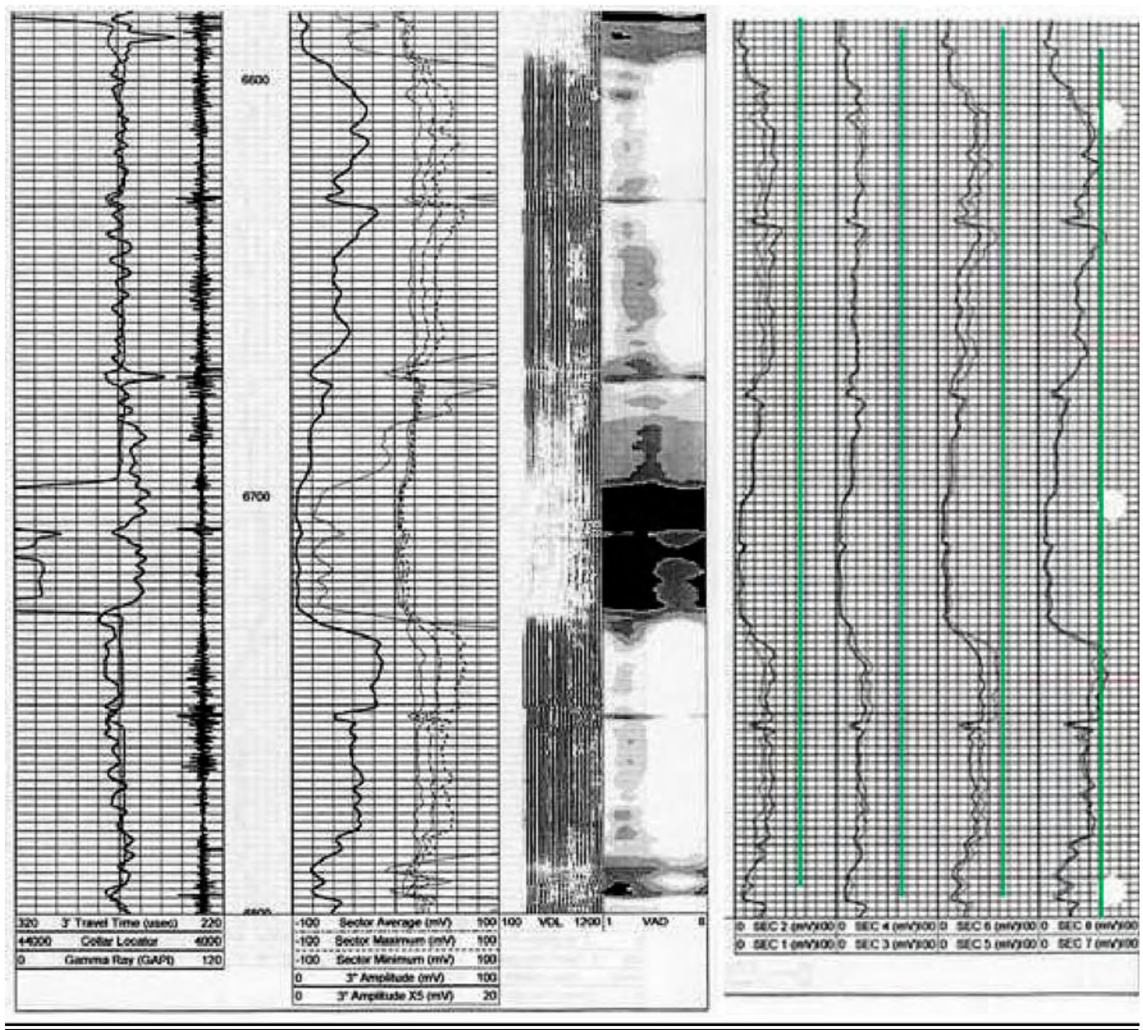

Figure B.10—SBL in Lightweight Cement #1b

NOTE: Improper scaling of the cement map does not identify the lightweight cement. Reviewing the eight amplitude curves with the free pipe values overlay (in green) shows the amplitudes are less than free pipe and cement is present. No cement squeeze was necessary.

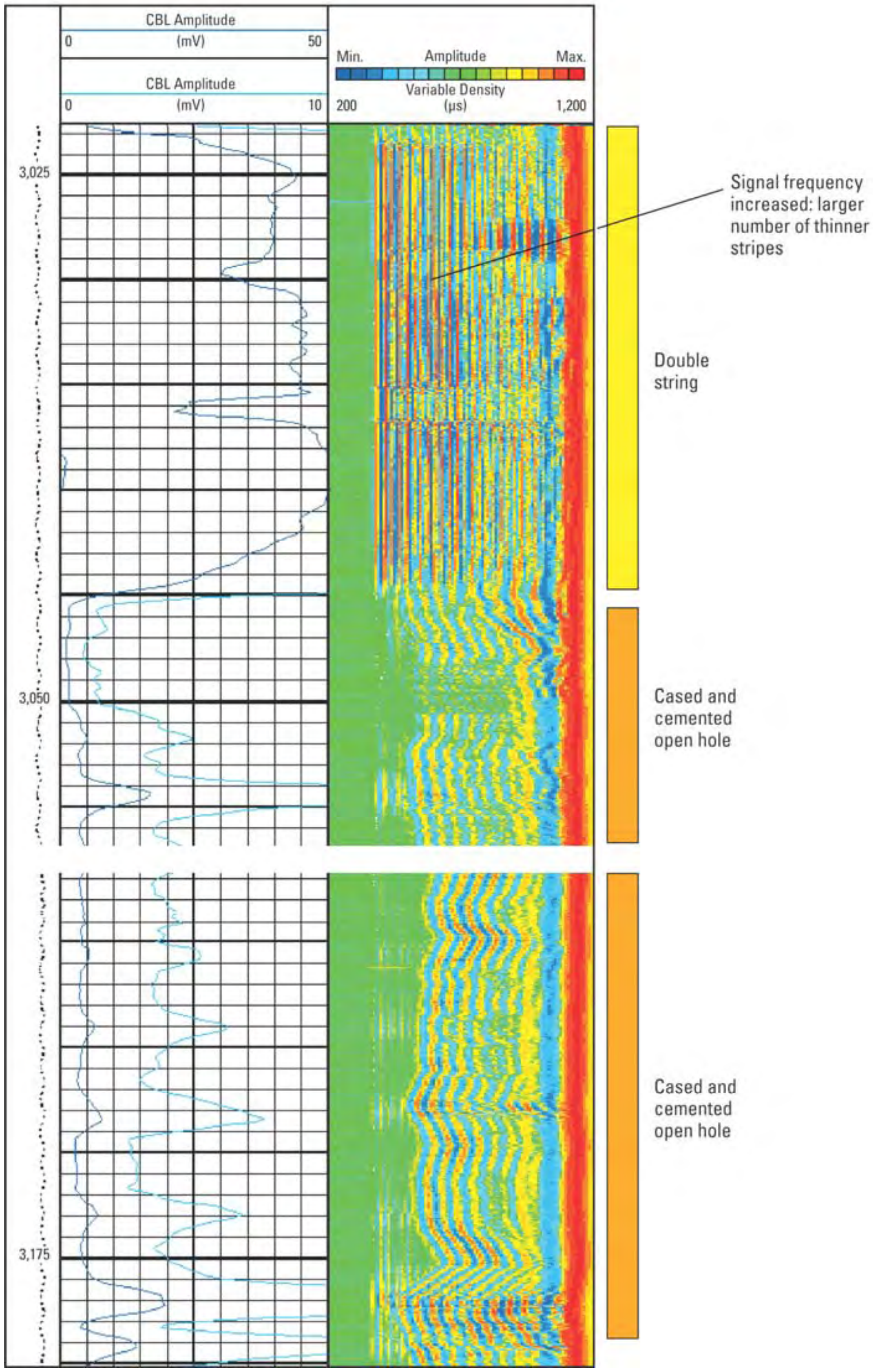

Figure B.11—CBL Two Strings of Pipe

NOTE: In the special case of concentric strings of pipe (e.g. top of the liner), the resonance of the external casing induces strong signal perturbations, leading to an apparent frequency increase of the first few peaks of the waveform. Experiments confirmed with field logs (Jutten, 1988) proved that high CBL amplitudes obtained in concentric casings are often an artifact, because of excellent cementation between the casings, and a measuring gate with excessive amplitude. Copyright Schlumberger. Used with permission.

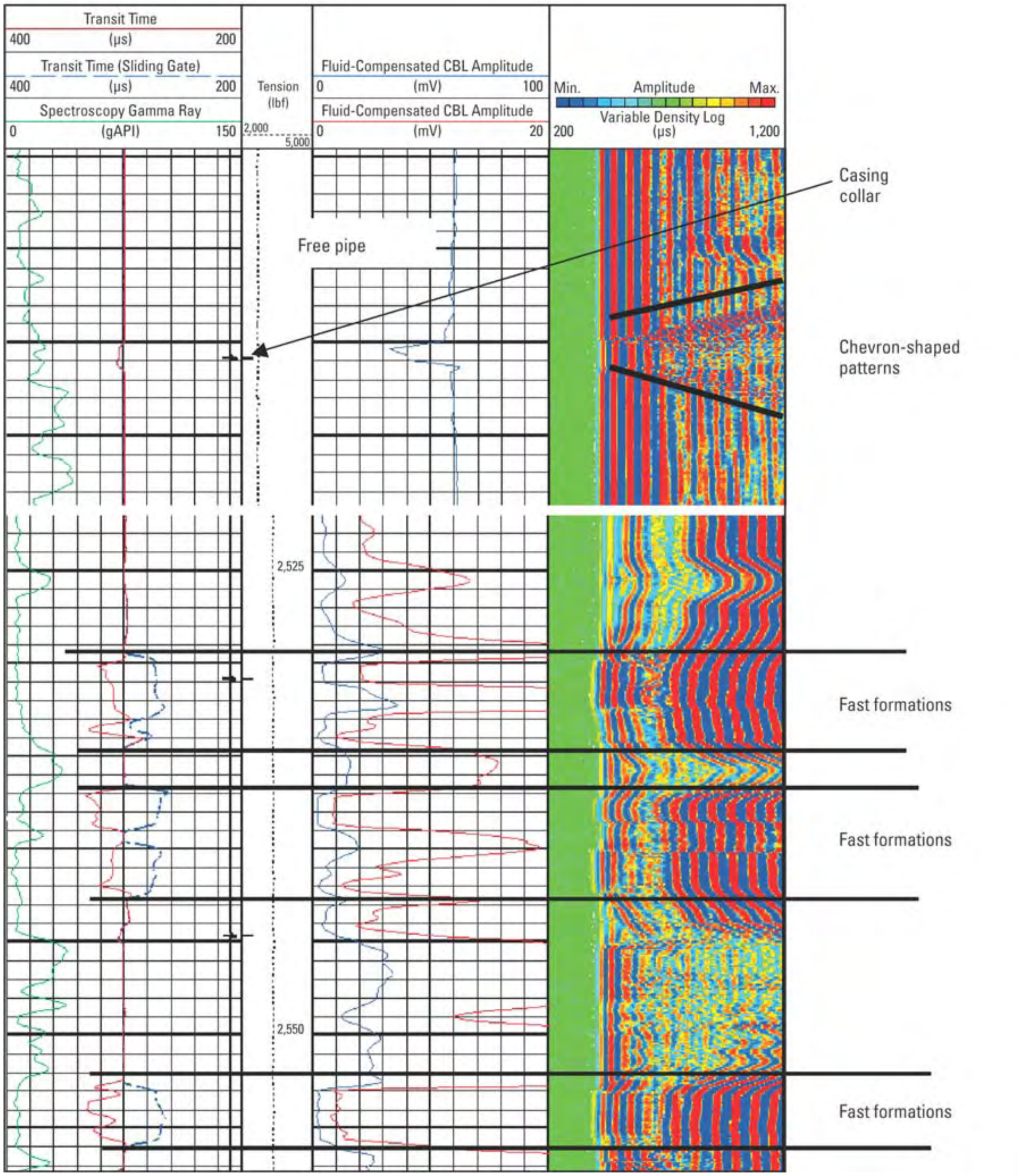

Figure B.12—CBL Fast Formations

NOTE: The free-pipe VDL character is distinct: very straight parallel bands and chevron-shaped diffraction patterns at the collars. In contrast, the cemented portion has wavy bands. The pattern of the bands corresponds to changes in the rock, as indicated by comparing the VDL data in Track 3 to the gamma-ray curve in Track 1. These are formation signals. There is no evidence of a pipe signal. This indicates that the pipe is acoustically coupled to the rock; thus, there is cement in the casing annulus that is bonded to the pipe and formation. Copyright Schlumberger. Used with permission.

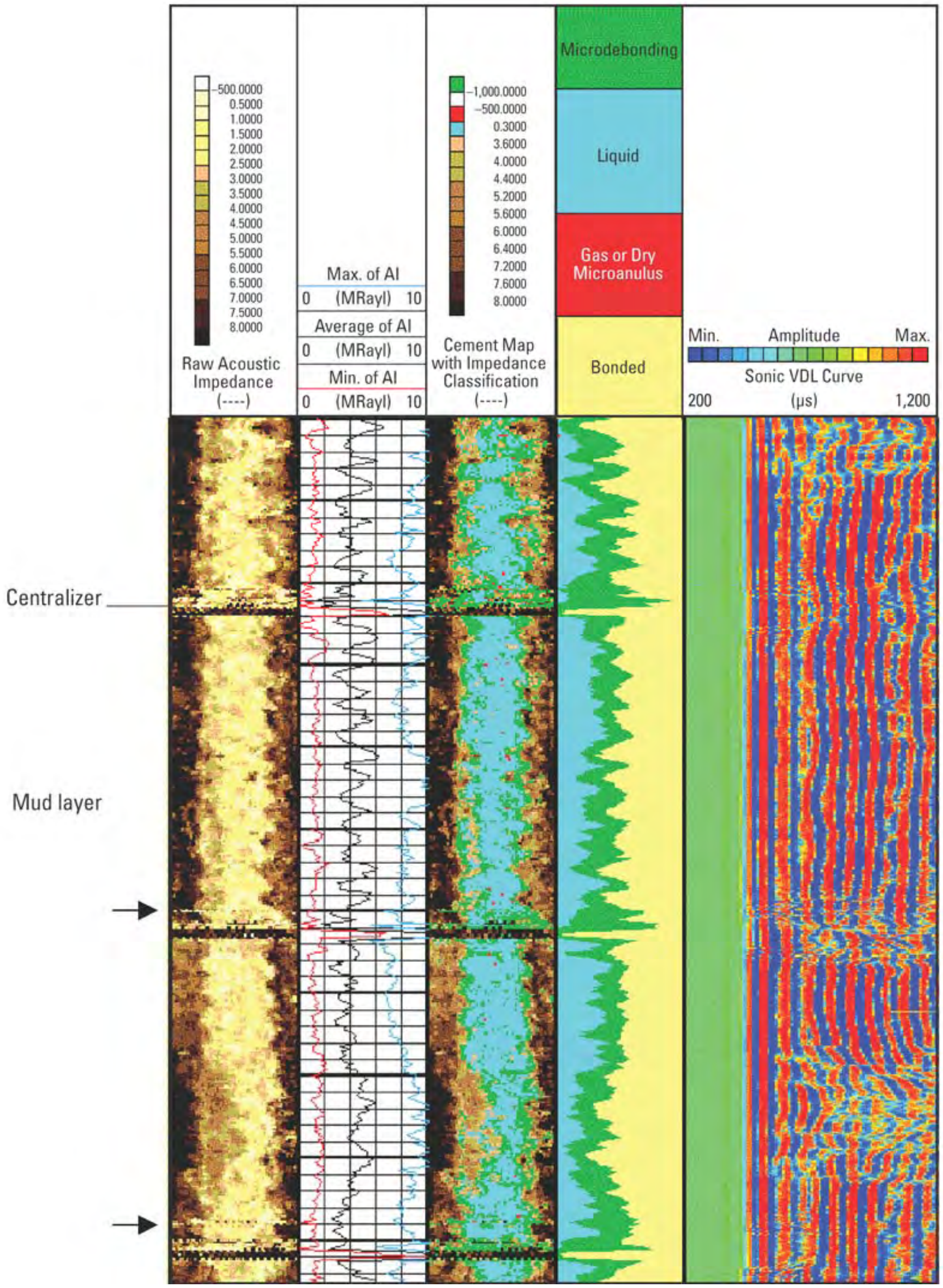

Figure B.13—Ultrasonic in Mud Layer

NOTE: The USI-VDL data in what appears to be a wide channel. However, in this case the cement simulations using cement-placement software gave no reason to suspect a channel. Further simulations suggested that the most likely explanation was cement fingering through the mud, leaving a few millimeters of mud on the casing and formation. Another possibility is that the centralizers are collapsed. Copyright Schlumberger. Used with permission.

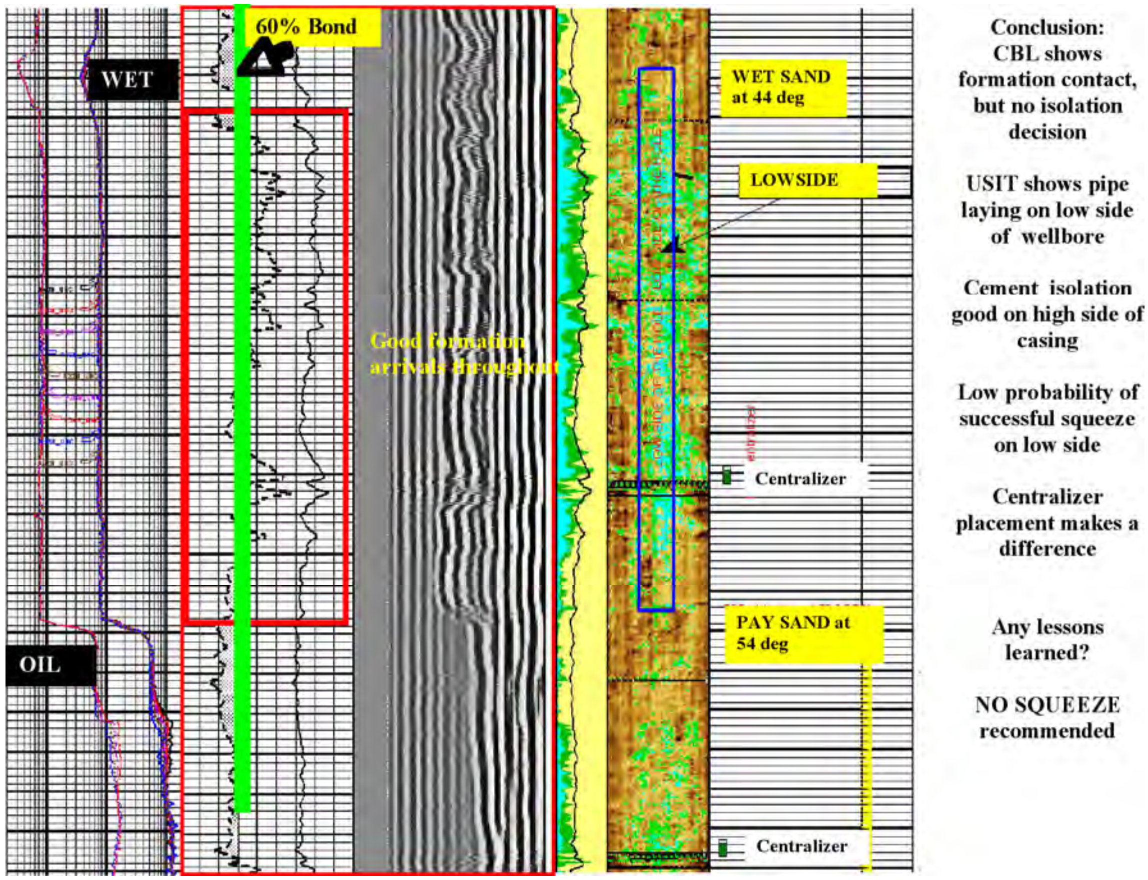

Figure B.14—Lack of Centralizers

NOTE: Poor centralizer placement allows the casing to lean on the low side of the wellbore as indicated by the data from the ultrasonic tool. A CBL by itself would give the impression that a cement squeeze was not necessary. Improved centralizer locations could have resulted in better well clean out and cement quality. The green line in Track 2 indicates the 60% Bond Index cutoff, where higher Bond Index is to the left. The wet sand and pay sand are located at 44° and 54° hole deviation, respectively. (SPE 83483: *Cement Evaluation Under Extreme Conditions*, Presentation Slide Number 9—not included in final paper.)

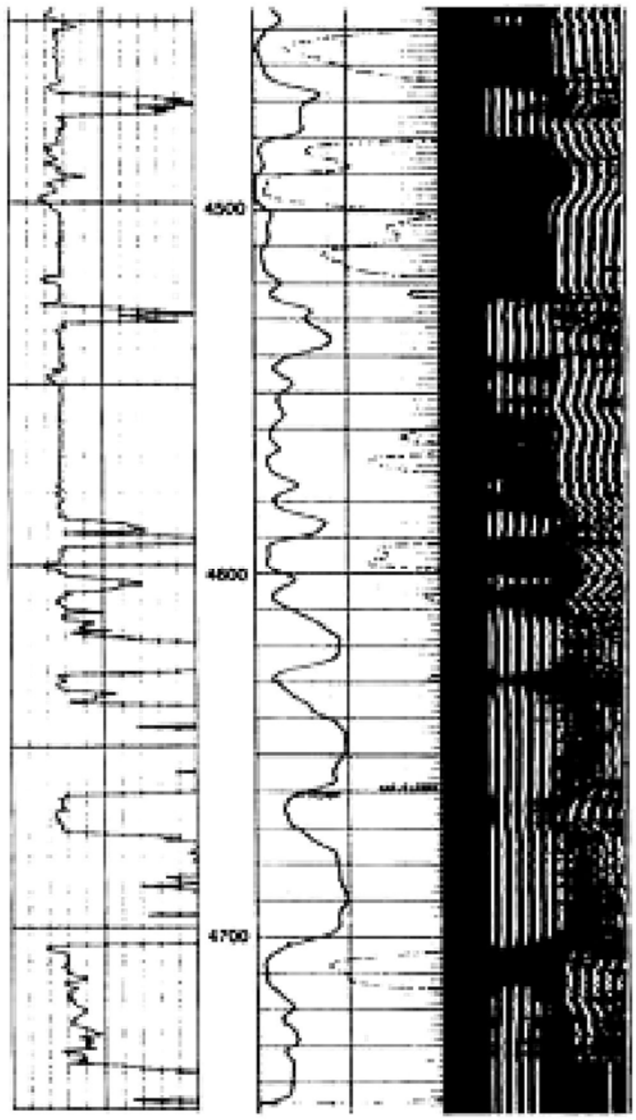

Figure B.15—Caliper Log with CBL

NOTE: The caliper log is in track #1 scaled 6 in. to 16 in. Each washout coincides with a high amplitude and weaker cement on the VDL. The cement is probably mud contaminated through these zones. Copyright of the Society of Petroleum Engineers, reproduced with permission.

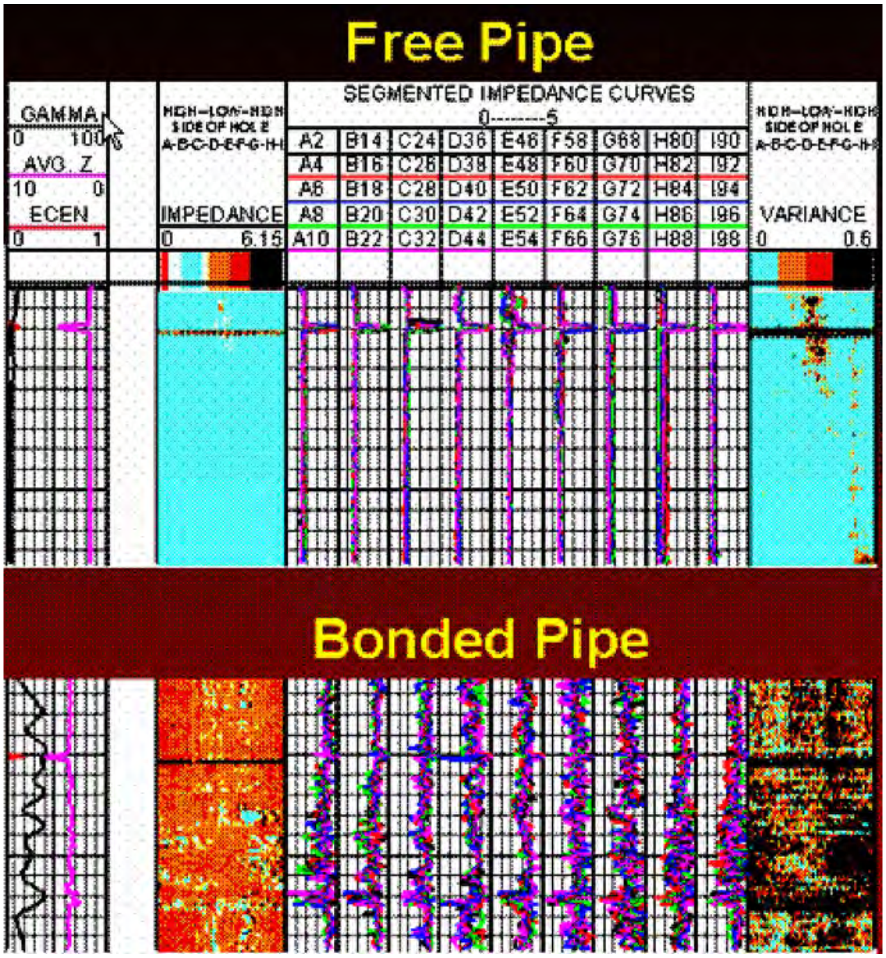

Figure B.16—Impedance Comparison of No Cement vs. Cement Behind the Casing

NOTE: Reviewing the segmented impedance curves shows that in free pipe there is no variance for the impedance curves while the cemented interval has variance.

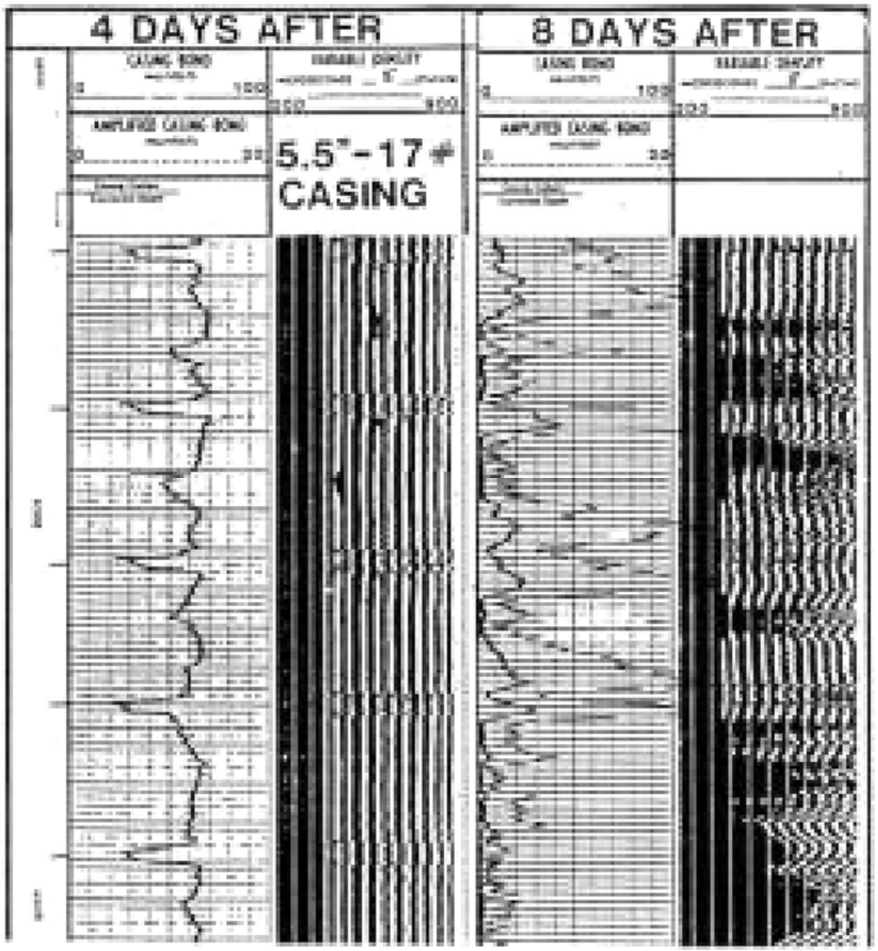

Figure B.17—CBL, Cement Curing

NOTE: Typically, it takes cement 24 to 48 hr to cure but this depends on cement slurry composition and temperature. After four days, a CBL was run to evaluate the cement quality. Based on the log it appeared a cement squeeze was necessary. Four days later, the same log was run showing the cement had cured. It is important to contact the cement company to determine the time necessary to cure the cement based on the cement design and the cement design with 10% mud contamination.

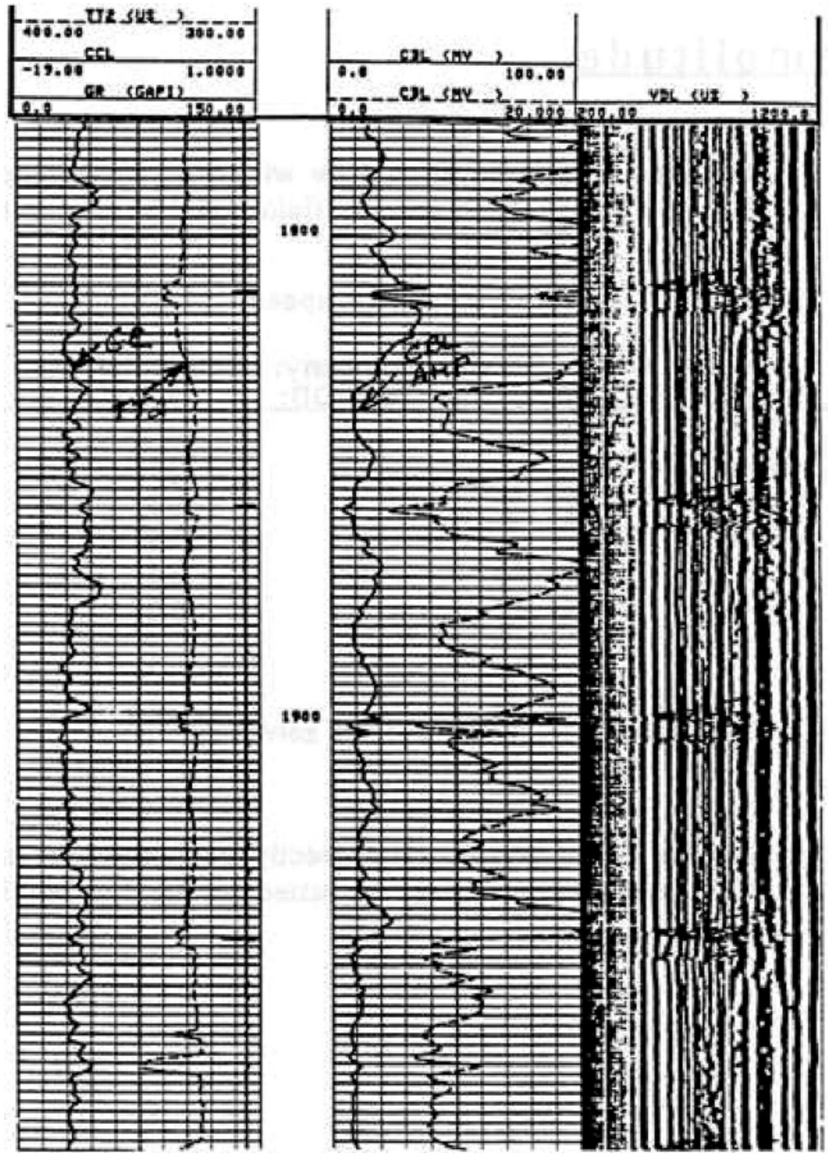

Figure B.18—Eccentered CBL Tool

NOTE: The travel time (TT2) should be a constant value as long as the pipe size and weight do not change (except for collars). A change greater than 4 μs is an indication the CBL tool is not centralized and the amplitude (or attenuation) may be invalid. Note that the lower travel times relates to lower amplitudes.

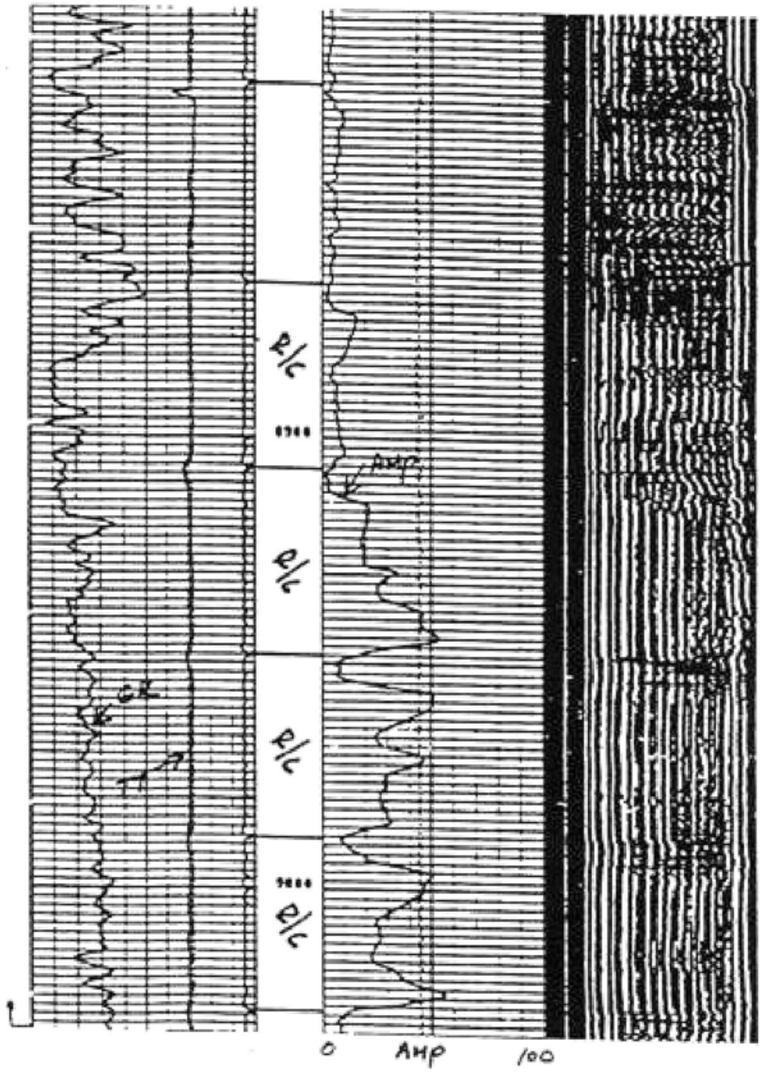

Figure B.19—Polymer Coated Casing

NOTE: If a casing is coated with a polymer, the polymer will react like a microannulus and high amplitudes will be observed on the CBL. Areas on the above log marked R/C are sections with the polymer.

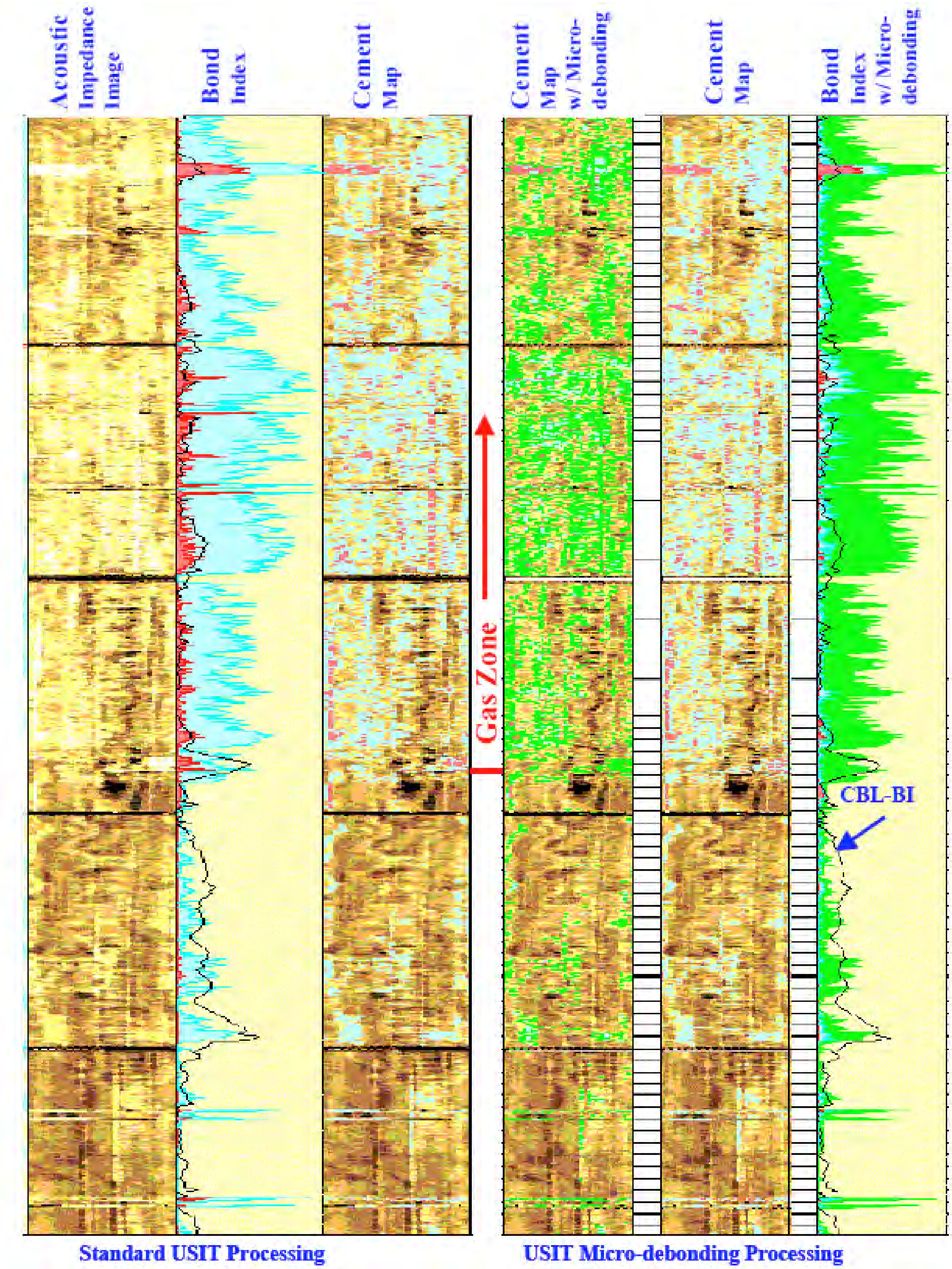

Figure B.20—Gas Contaminated Cement

NOTE: When running ultrasonic logs in areas of gas contaminated cement, it is important to use enhanced processing of the impedance curves. (Example: microdebonding or ACE) to adequately determine the presence of cement.) Copyright of the Society of Petroleum Engineers, reproduced with permission.

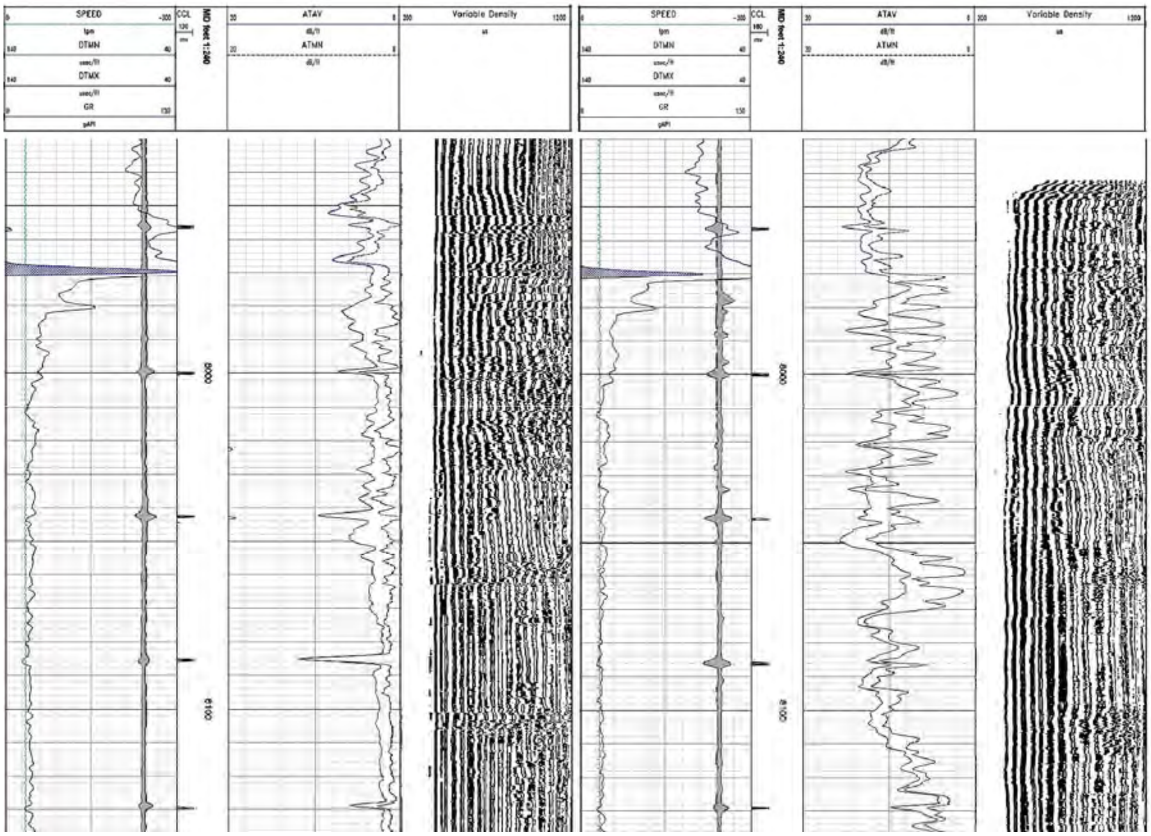

Figure B.21—SBT Microannulus

NOTE: The SBT log on the left was run with no pressure on the well. The attenuations are low and the VDL in the lower portion shows casing collars and very little activity on the entire waveform. The upper section shows more activity on the VDL and the casing collars are not as clear as the lower section. The log on the right was run with pressure on the well. Notice the attenuation is much higher, the VDL has more character and the collars on the VDL are not detected.

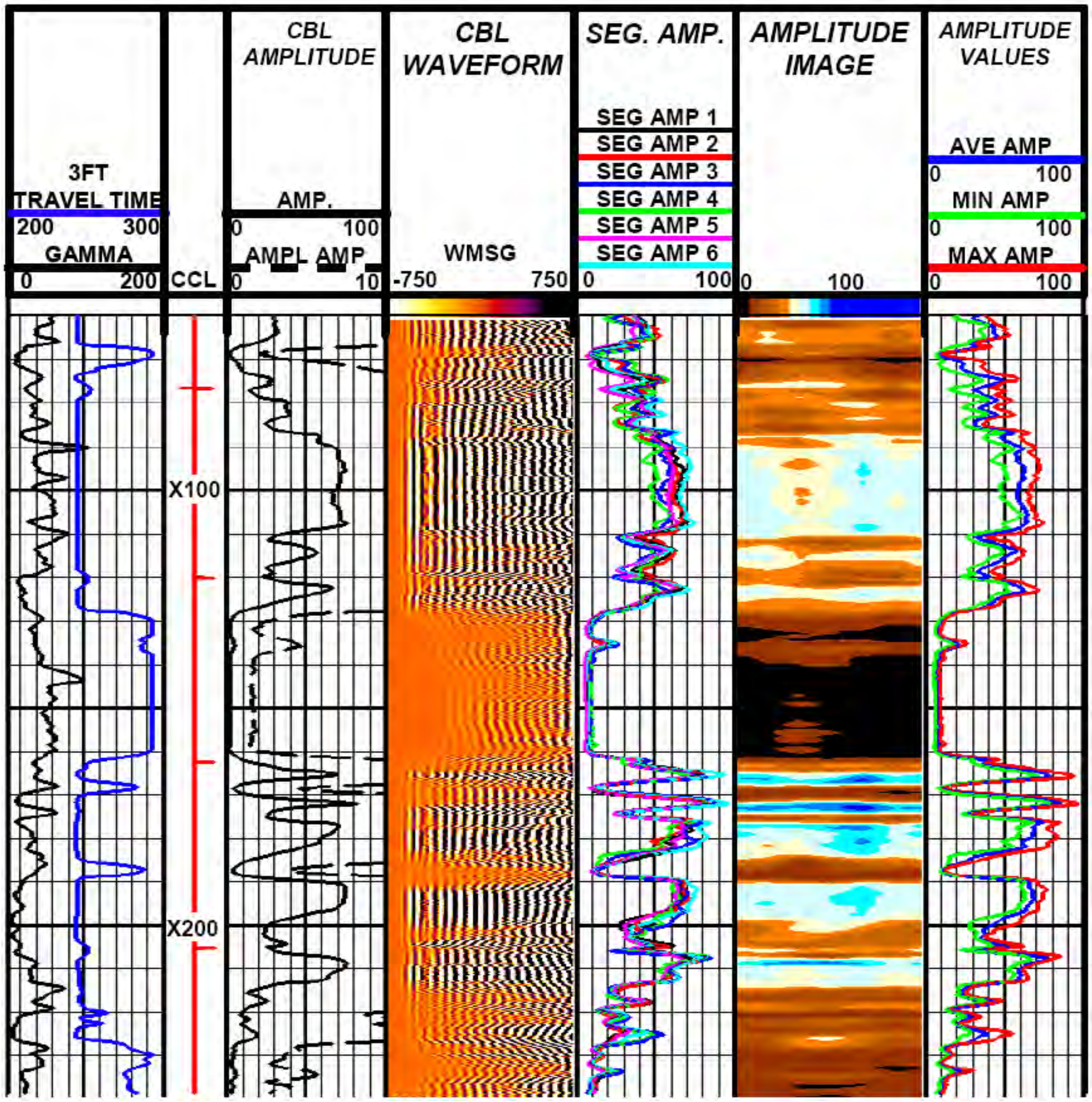

Figure B.22a—Raw Sector Bond Log (SBL)

NOTE: The amplitude image in track 5 is generated from the six radial receivers shown in track 4. The minimum, maximum, and average readings for the same receivers are presented in track 6. Normally, the six or eight individual segmented amplitude readings are not shown. Copyright of the Society of Petroleum Engineers, reproduced with permission.

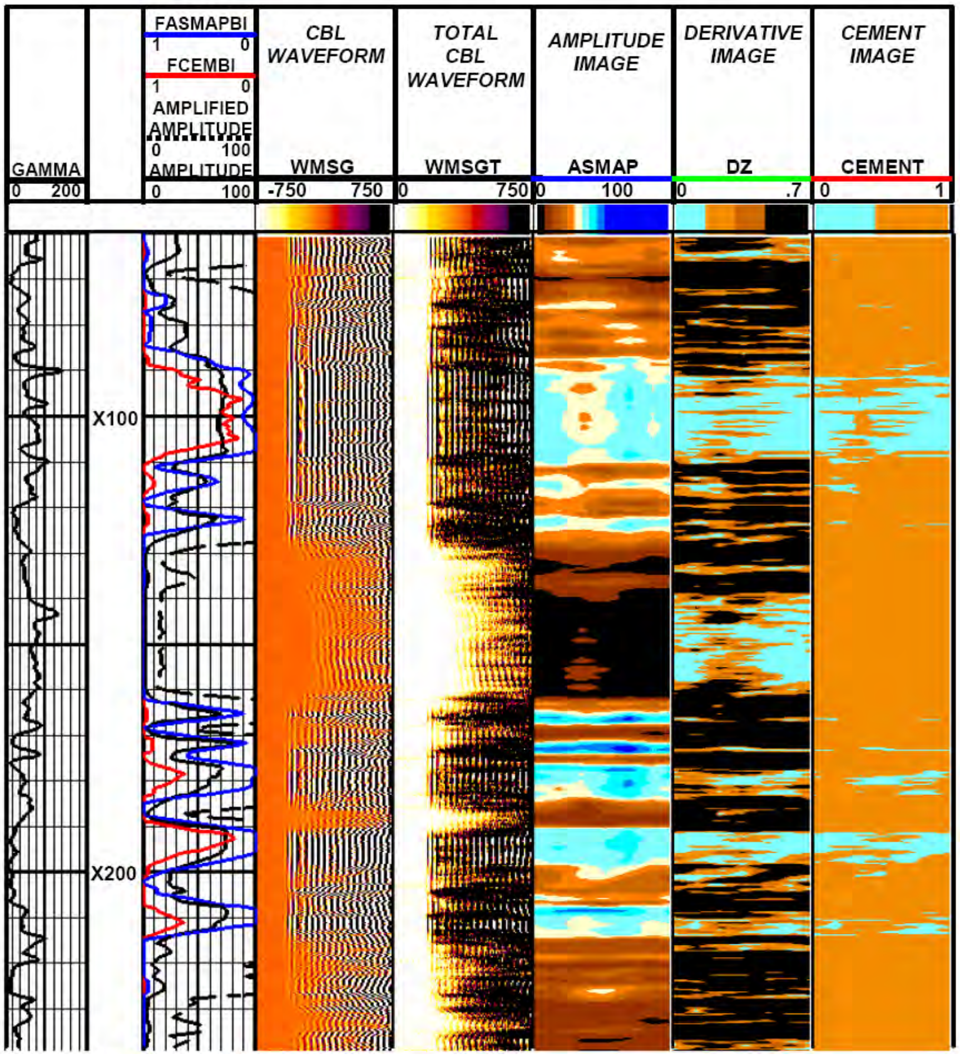

Figure B.22b—ACE Processing from a Radial Bond Tool

NOTE: This is a result of the ACE processing of the radial bond tool data, which uses both the raw data and the variance of the raw data to help determine the cement bond. Track 2 contains two Bond Indexes, one FASMAPBI from the raw data (ASMAP) and the other from the computerized analysis, which is the cement Bond Index (CEMBI) generated from the cement map CEMENT). Track 4 contains the total CBL waveform (WMSGT). Track 6 consists of the DZ image or SVP processing of the raw amplitude data. Track 7 is the cement map, which uses both the SVP and raw data to determine bonding. In the upper free pipe (X090 to X110) zone, the FASMAPBI indicates an average cement-to-casing bond of about 5% while, the FCEMBI indicates about a 25% bond. Where there is an excellent cement bond (X128 to X160), the DZ image indicates fluid; however, upon examination of the six segmented amplitude curves, it is apparent that the cement is very consistent. Therefore, it is necessary to use both the raw data and variance processing to determine the difference between a fluid and solid in the annular space.

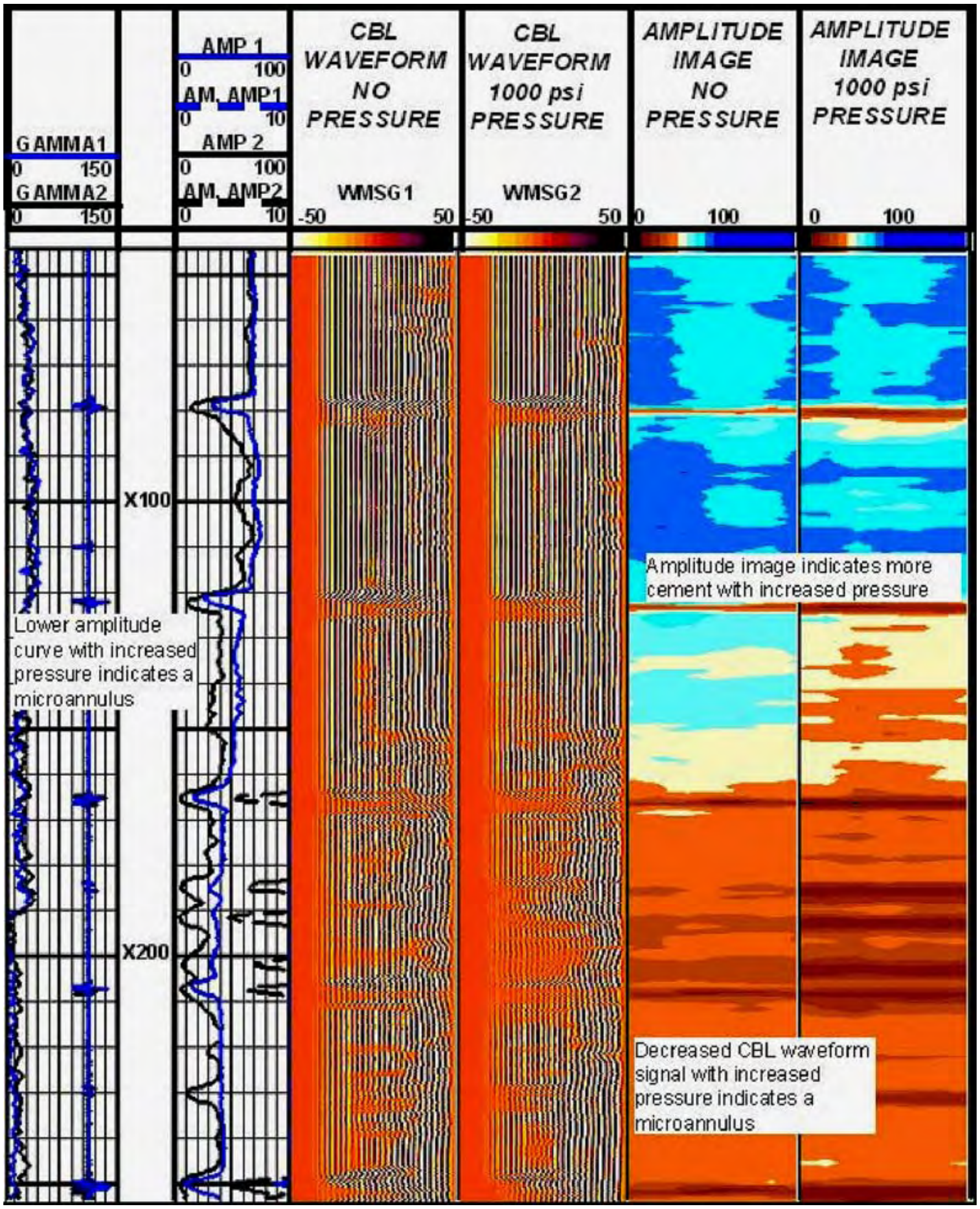

Figure B.23a—Radial Bond Tool Showing Microannulus

NOTE: The radial bond log provides three different measurements all showing a microannulus. With an increase of 1000 psi well head pressure, the VDL/waveform, and CBL Amplitude images show an improvement of the cement sheath. The amplitude curves also show lower readings with the applied pressure.

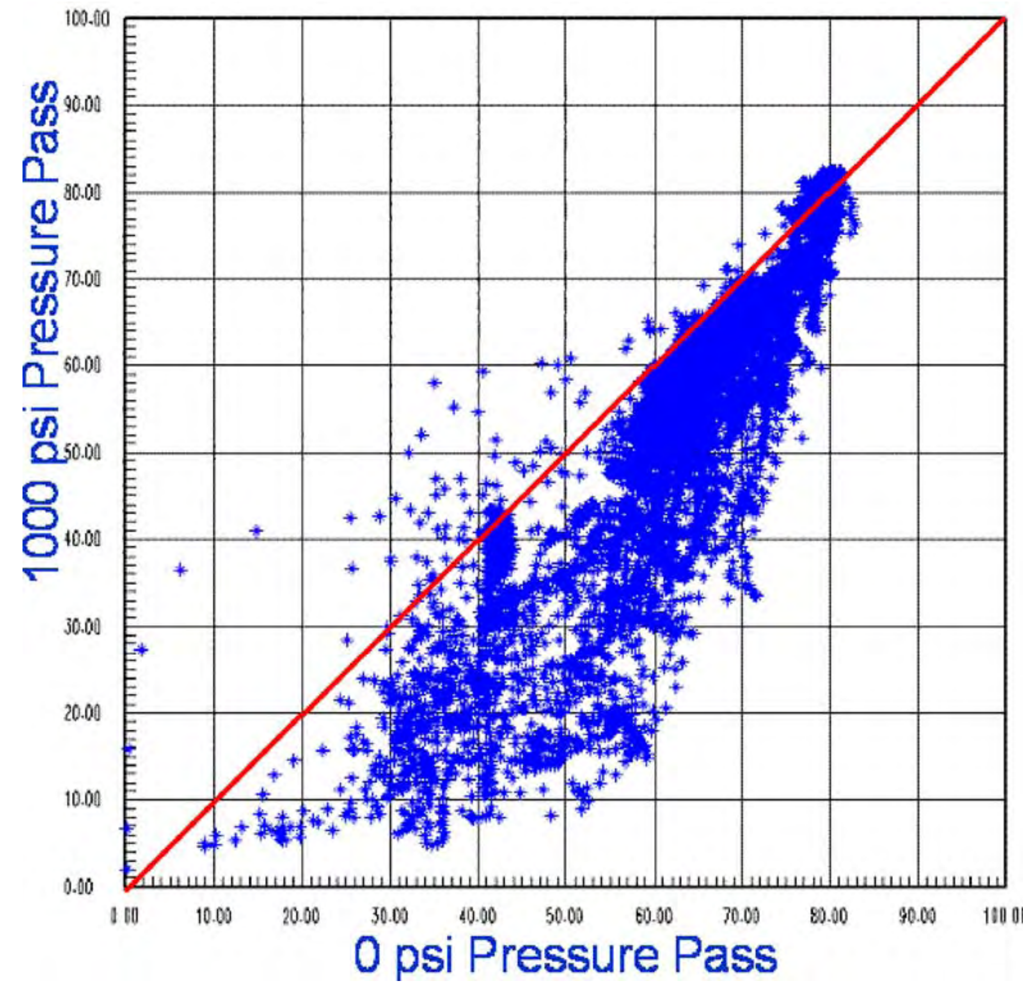

Figure B.23b—Crossplot Comparing CBL Amplitudes with and without Pressure

NOTE: This crossplot compares the amplitude from the radial bond tool shown in Figure B.23a before and after 1000 psi pressure is applied. Notice that high amplitudes (around 80) have very little change indicating free pipe. The red line is at 45°, so anything below the line indicates a higher amplitude without pressure than with pressure. As the wellhead pressure increases the amplitude decreases, indicating a microannulus. For example 50 mV on the 0 pressure pass could be anywhere from 15 mV to 40 mV, indicating an improvement in the cement sheath.

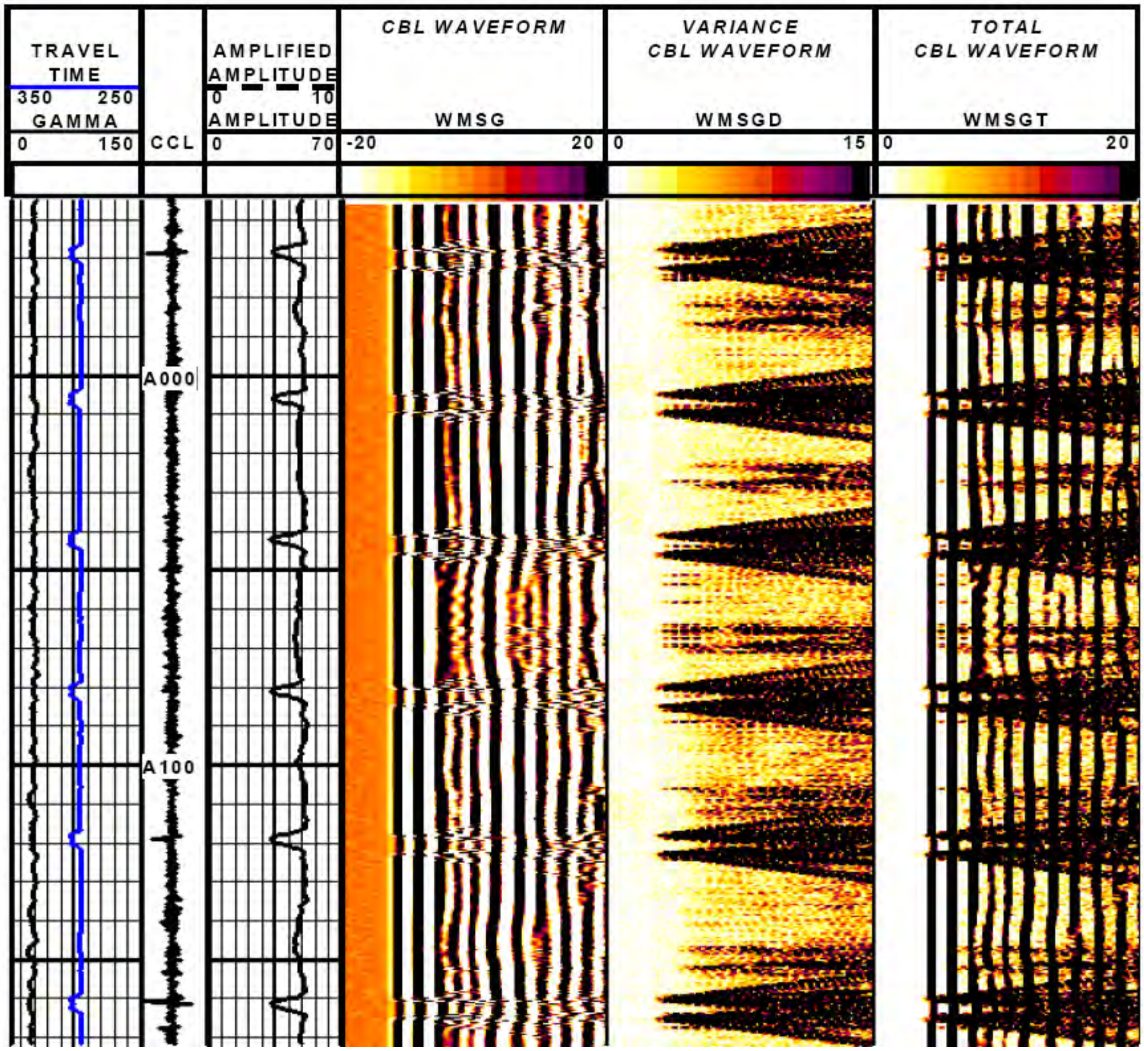

Figure B.24—Computed CBL Response in Two Strings of Pipe

NOTE: The standard CBL acoustic amplitude and MSG are shown in Tracks 2 and 3. Standard interpretation of this 9 5/8-in. casing inside 13-in. casing would indicate that there is very little cement bond due to the classical appearance of the waveform and the high amplitude. With the SVP processing applied to the CBL waveform, the appearance of two sets of collars is noticeable. The second collar response appears as a bonded pipe collar pattern later in time and is spaced about 45 ft apart while the inner string is around 40 ft apart. The outer casing collar response is only possible if there is acoustic coupling between the two strings. This process does not extend to cement evaluation beyond the second string of pipe. SPWLA, Paper EE, 2002.

Annex C

References

[1] Allouche M., Guillot D., Hayman A., Butsch R.J. and Morris C.W.: "Cement Job Evaluation," (Chapter 15*) Well Cementing* (2nd edition.) Nelson, E.B. and Guillot, D. eds., Schlumberger, Sugar Land (2006).

[2] Al-Suwaidi, A., Hun, C., Bustillos, J.L., Guillot, D., Rondeau, J., Vigneaux, P., Helou, H., Ramirez, J.A.M., and Robles, J.L.E.: "Light as a Feather, Hard as a Rock," *Oilfield Review*, 13 (2), Summer 2001, pp. 2 – 15.

[3] Bigelow, E. L., Domangue, E. J., Lester, R. A.: "A New and Innovative Technology for Cement Evaluation," paper SPE 20585, presented at the SPE Annual Technical Conference and Exhibition, New Orleans, September 23 – 26, 1990.

[4] Butsch, R.J.: "Overcoming Interpretation Problems of Gas-Contaminated Cement Using Ultrasonic Cement Logs," paper SPE 30509, presented at the SPE Annual Technical Conference and Exhibition, Dallas, October 22 – 25, 1995.

[5] Carter, L. G. and Evans, G. W.: "A Study of Cement-Pipe Bonding," paper SPE 764, presented at the SPE California Regional Meeting, Santa Barbara, CA, October 1963.

[6] Frisch, G. F., Graham, W. L. and Griffith, J. E.: "Assessment of Foamed-Cement Slurries Using Conventional Cement Evaluation Logs and Improved Interpretation Methods," paper SPE 55649, presented at the SPE Rocky Mountain Regional Meeting, Gillette, WY, May 1999.

[7] Froelich, B., Pittman, D., and Seeman, B.: "Cement Evaluation Tool—A New Approach to Cement Evaluation," paper SPE 10207, presented at the SPE Annual Fall Meeting, Dallas, October 1981.

[8] Gai, H. and Lockyear, C.: "Cement Bond Logs—A New Analysis to Improve Reliability," paper SPE 23729, presented at the Second Latin American Petroleum Engineering Conference, Caracas, Venezuela, March 1992.

[9] Gollwitzer, L. H., and Masson, J. P.: "The Cement Bond Tool," paper Y, *Transactions of the SPWLA 23rd Annual Logging Symposium*, Corpus Christi, TX, July 1982.

[10] Gong, M. and Morriss, S. L.: "Ultrasonic Cement Evaluation in Inhomogeneous Cements," paper SPE 24572 presented at the 67th Annual SPE Technical Conference, Washington, D. C., Oct, 1992.

[11] Goodwin, K. J. and Carpenter, W. W.: "Cement Sheath Evaluation," *API World Wide Cementing Practices*, January 1991; *"Cement Evaluation,"* Western Atlas International, Inc. Internal Publication, 1990.

[12] Goodwin, K. J.: "Guidelines for Cement-Sheath Evaluation," *SPE Production Engineering* (August 1992) 7, No. 3, 280 – 284.

[13] Goodwin, K. J.: "Oilwell/Gaswell Cement-Sheath Evaluation," *JPT*, December 1997.

[14] Griffith, J. E., Sabins, F. L. and Harness, P. E.: "Investigation of Ultrasonic and Sonic Bond Tools for Detection of Gas Channels in Cements," paper SPE 24573, presented at the 67th Annual SPE Technical Conference, Washington, DC, October 1992.

[15] Harness, P. E., Sabins, F. L. and Griffith, J. E.: “New Technique Provides Better Low-Density-Cement Evaluation,” paper SPE 24050 presented at the SPE Western Regional Meeting, Bakersfield, CA, March 1992.

[16] Hayman, A. J., Hutin, R., and Wright, P. V.: “High- Resolution Cementation and Corrosion Imaging by Ultrasound,” paper KK, *Transactions of the SPWLA 32nd Annual Logging Symposium*, Midland, TX, June 1991.

[17] Jordan, M. E. and Shepherd, R. A.: “Cement Bond Log: Determining Waiting-On-Cement Time,” paper SPE 14200, presented at the SPE Fall Meeting, Las Vegas, Nevada, September, 1985.

[18] Jutten, J., Guillot, D., and Parcevaux, P.: “Relationships between Cement Slurry Composition, Mechanical Properties, and Cement Bond Log Output,” paper SPE 16652, presented at the SPE Annual Technical Conference and Exhibition, Dallas, September 1987.

[19] Lester, R. A., “The Segmented Bond Tool, a pad-type cement bond device,” paper A, Transactions of the 12th Annual Canadian Well Logging Society Formation Evaluation Symposium, Calgary, September 1989.

[20] Morris, C., Garcia, C., Wydrinski, R., Tinker, S., Mullen, M., Collins, A.: “Cement Evaluation under Extreme Conditions,” paper SPE 83483, presented at the SPE Western Regional/Pacific Section Joint Meeting, Long Beach, CA, May 2003.

[21] Moulin, E., Revil, P., and Jain, B.: “Using Concrete Technology to Improve the Performance of Lightweight Cements,” paper SPE/IADC 39276, presented at the SPE/IADC Middle East Drilling Technology Conference, Bahrain, November 1997.

[22] Pilkington, P. E.: “Cement Evaluation - Past, Present and Future,” *JPT*, Feb 1992.

[23] Pilkington, P. E.: “Pressure Needed to Reduce Microannulus Effect on CBL,” *Oil and Gas Journal*, 68 – 74, May 30, 1988.

[24] Revil, P. and Jain, B.: “A New Approach to Designing High-performance Lightweight Cement Slurries for Improved Zonal Isolation in Challenging Situations”, paper SPE/IADC 47830, presented at the IADC/SPE Asia Pacific Drilling Technology Conference, Jakarta, September 1998.

[25] Stewart, R. B., and Schouten, F. C.: “Gas Invasion and Migration in Cemented Annuli: Causes and Cures,” paper SPE 14779, presented at the IADC/SPE Drilling Conference, Dallas, February 1986.

[26] Uswak, G. and McLafferty, N.: “Cement Imaging Through Ultrasonics,” paper 93-30, *Transactions of the Petroleum Society of CIM Annual Conference*, Calgary, May 1993.

[27] Zeroug, S. and Froelich, B.: “Ultrasonic Leaky-Lamb Wave Imaging through a Highly Contrasting Layer,” *Proceedings of the IEEE Ultrasonic Symposium* (Nov. 2003) 794 – 798.

[28] Zeroug, S., van Kuijk, R., Froelich, B., Allouche, M., Bose, S., Le Calvez, J. Schoepf, V. Pagnin, A. and Miller, D.: “A Novel Ultrasonic Cased-Hole Imager for Enhanced Cement Evaluation and Cement Sheath Calipering,” paper IPTC 10546, presented at the International Petroleum Technology Conference**,** Doha, Qatar, November 2005.

[29] Zeroug, S.: “Forward Modeling for Ultrasonic Leaky-Lamb Wave based Imaging through a Highly Contrasting Steel Cylindrical Layer,” *Proceedings of the IEEE Ultrasonic Symposium*, August 2004.

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