SPE/IADC-184604-MS

Logging-While-Drilling in Cased Hole to Validate Top of Cement Saving Days of Rig Time: Deepwater Gulf of Mexico Case Studies

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This paper was prepared for presentation at the SPE/IADC Drilling Conference and Exhibition held in The Hague, The Netherlands, 14–16 March 2017.

Abstract

Evaluation of cement placement is an important part of the majority of deepwater wells. Cement placement confirmation is an important step following a cementing operation. More than one technique can be used to provide information about the top of cement (TOC) and about the depth interval of a good bond between the formation and the casing. Determining the length of annular cement coverage, which is an indication of correct cement placement, is useful knowledge before drilling and/or completion operations can proceed. The requirement for additional and improved cement evaluation techniques is greater now than ever before.

A variety of methods can be used to evaluate cement placement. The routine approach after a casing or liner cement job uses a job chart to calculate lift pressure and actual vs. predicted system pressure. These data enable an estimate of cement height in the annulus to be made, but they do not confirm the TOC. These methods vary in accuracy and difficulty, depending on well conditions. Common TOC evaluation methods in specific wellbore casing/liner sections typically require running a temperature survey or cement bond log (CBL) sensors/systems on a wireline. These operations use the rig's critical path time for each wireline run, which can add risk or difficulties, depending on the well trajectory. In addition, cement bond evaluation for large diameter casing can be technically challenging because it can reach the upper threshold measurement limitations for conventional wireline-conveyed CBL tools.

Many operators now use logging-while-drilling (LWD) sonic sensors for compressional and shear data acquisition in openhole environments. Using the same sonic systems, with minimal additional rig time, logging data acquired through the casing/liner strings while running a drilling or clean out assembly can be evaluated to confirm the TOC.

This paper demonstrates how LWD sonic technology can provide confirmation of the TOC, saving a considerable amount of rig time, as compared to performing a dedicated wireline evaluation run or potentially unnecessary cement squeeze operations. The paper presents and discusses Gulf of Mexico (GOM) case studies. Based on various specific challenges, through correct data analysis, TOC evaluation best practices are implemented to optimize the LWD acoustic data acquisition inside the casing/liner. New data examination techniques are reviewed that can be applied to different scenarios, such as TOC evaluation behind dual pipes and real-time assessment for quick data analysis turn-around. In conjunction with the

case studies, the paper also provides information about the LWD cased-hole logging techniques, analysis, and results of the data application.

Introduction

Not all cement jobs progress as planned, and it is not uncommon in GOM deepwater wells to experience partial or no returns. Tight clearances, depleted zones, weak streaks, or mechanical failures pose further challenges to successful cementing operations. Reliable evidence and information for validating a cement job is helpful as part of the operational decision-making process before drilling and/or completion can resume planned operations. As a common rule, operators require confirmation that all cement jobs have met the objectives of each hole section. For cases where surface indicators are inconclusive, evaluation with logging tools might be necessary.

For well construction to be performed as per design requirements and/or the cementing operations to be as intended to meet objectives of the section, several practices and methods are adopted to validate the amount of annular cement lift and bonding. The industry standard approach for predicting the TOC is using the cement job chart and lift pressure trend obtained while pumping cement. The expected pressure increase indicates the cement rises in the annulus. The actual pressure data can then be compared with the simulated and calculated pressures to infer the actual cement height in the annulus. Such methodology is important to follow for prediction purposes, but more information and validation are required for confirming the TOC.

Dedicated wireline cased-hole logging for cement bond evaluation is the standard method used to validate the TOC and the quality of the cement bond. Operators are open to use any other solutions obtained from memory data or in real time that can provide comparable information that they require, especially if such information offers incentives for helping with cost management.

LWD solutions for providing information on cement job validation have potential because of their flexibility and limited impact on rig time. LWD acoustic sensors are well suited for TOC determination for the same reason that wireline measurements are widely accepted in the industry. Following a review of LWD acoustic logs on specific projects with multiple datasets, the credibility of the approach was confirmed, which is encouraging for operators to include the technology in their TOC evaluation process. The benefits such solutions bring can be assessed by reviewing multiple case studies.

Logging Service and Data Acquisition Optimization

An acoustic logging tool consists of at least one transmitter and several series of receivers, referred to as receiver arrays. A sound wave is fired from the transmitter, which propagates and is detected by the receivers. Based on the known distance between the source (transmitter) and the receivers aligned with the source, the time the waves arrive at each receiver facilitates the calculation of the wave's velocity.

In an openhole environment, the acoustic wave propagation occurs through the mud and along the wellbore wall. In a cased-hole environment, the wave propagation only passes the casing if the latter is bonded to the cement. In cases where the bond extends to the formation, wave propagation travels down the formation.

Commonly used LWD sonic tools are primarily designed and setup for openhole logging to measure openhole formation slowness at logging speeds associated with drilling. Such tools were not introduced for cased-hole logging, which implies that some adjustments need to be made to standard logging procedures for secondary objectives, such as TOC evaluation while logging inside casing. As for any logging strategy, it is important to perform a review of the objectives during the prejob stage and ensure all are optimized based on the tool capabilities and operational constraints for the measurement-while-drilling (MWD)/LWD bit run.

The sonic tool starts data acquisition as a field programmed time delay expires, regardless of the rig operation (trip in, drilling, trip out, etc.). This is facilitated by most LWD acoustic tools being battery powered. A sonic acquisition firing is followed by the storage, in the dedicated tool memory, of the full waveforms used for (1) post-processing, (2) downhole computation of acoustic semblance(s), and (3) real-time data transmission to surface of high-coherence arrivals from the downhole computed semblance(s).

The acquisition flexibility of such tools, off the critical path of rig operations (**Fig. 1**), enables data logging inside casing for cement evaluation purposes. Care is taken to configure the tool appropriately to acquire data while inside the cased hole. The tripping speed (i.e., logging speed), if it needs to be restricted, should be agreed upon while in the planning phase, specifically when logging close to the target zone(s). The aim is to log depth intervals of the theoretical and expected TOC with 100 ft or greater overlap while tripping in the hole and possibly another pass while tripping out of the hole. It might be necessary to perform a data analysis of both trip-in and trip-out data acquisitions if environments have changed between the two passes, such as if wellbore fluid density changed during the trip.

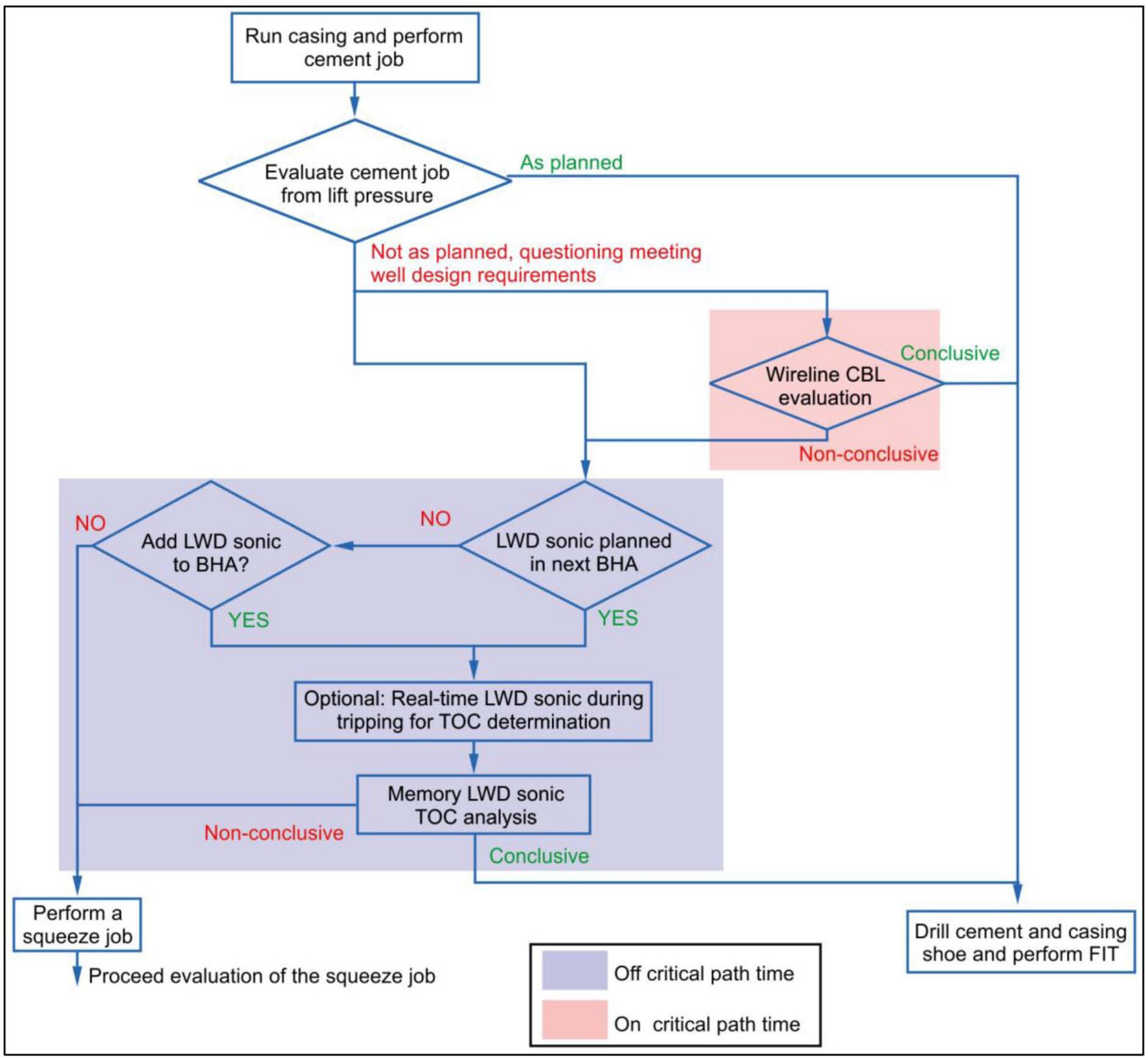

Figure 1—Flowchart illustrating a simplified workflow process for LWD sonic TOC analysis.

Other operational considerations include acoustic firing mode(s) selection at specific frequencies and data sampling rates for both real-time and memory. Most recent LWD acoustic tools are capable of firing multiple acoustic modes (i.e., monopole, dipole, quadrupole) during the same sampling period, which allows for independent datasets from each firing during the same pass; for instance, two monopole firings at different frequencies. The prejob stage also needs to emphasize the importance of good depth tracking for such acquisition during the tripping of the bottomhole assembly (BHA).

Table 1 summarizes the average logging speed for different passes for which data acquisition can be used. Those averages are from Case Study No. 2 discussed later in this paper, considered as a typical clean-out run. It shows the stages for which different data acquisition passes are performed by default during tripping for cased-hole LWD acoustic logging datasets. LWD passes consist essentially of a trip-in pass at a logging speed, allowing for satisfactory data density across the zone of interest, and a trip-out pass. These passes allow for two independent logging datasets once the time-based memory LWD acoustic data (raw waveforms) are processed against the time/depth curve.

Table 1—Average tripping speeds during the clean out run for Case Study No. 2 presented in the case studies section of this paper.

Operation	Average speed (ft/hr)
Trip-in up to ~500 ft before expected TOC inside the casing	~1,500
Trip-in up to TOC inside the casing	~400
Drill cement inside the casing	Slow rate of penetration (ROP)
Trip-out	~1,800

Data Analysis Methodologies

The waveforms acquired by the receiver closest to the transmitter for each receivers array are used for the TOC data analysis. Acoustic waveforms acquired inside casing respond as follows (Market et al. 2004).

- If a good cement bond exists, the casing signal will be weak and the formation signal strong.
- If a poor cement bond exists, the ringing of the casing will be strong and the formation signal weaker.

The plot in **Fig. 2** presents an LWD acoustic data acquisition behind a single string of casing. When reviewing the waveforms acquired by the closest receiver to the transmitter for one of the receivers array, a clear contrast can be identified at approximately X1,400 ft. The two intervals above and below that depth illustrate the two conditions mentioned previously.

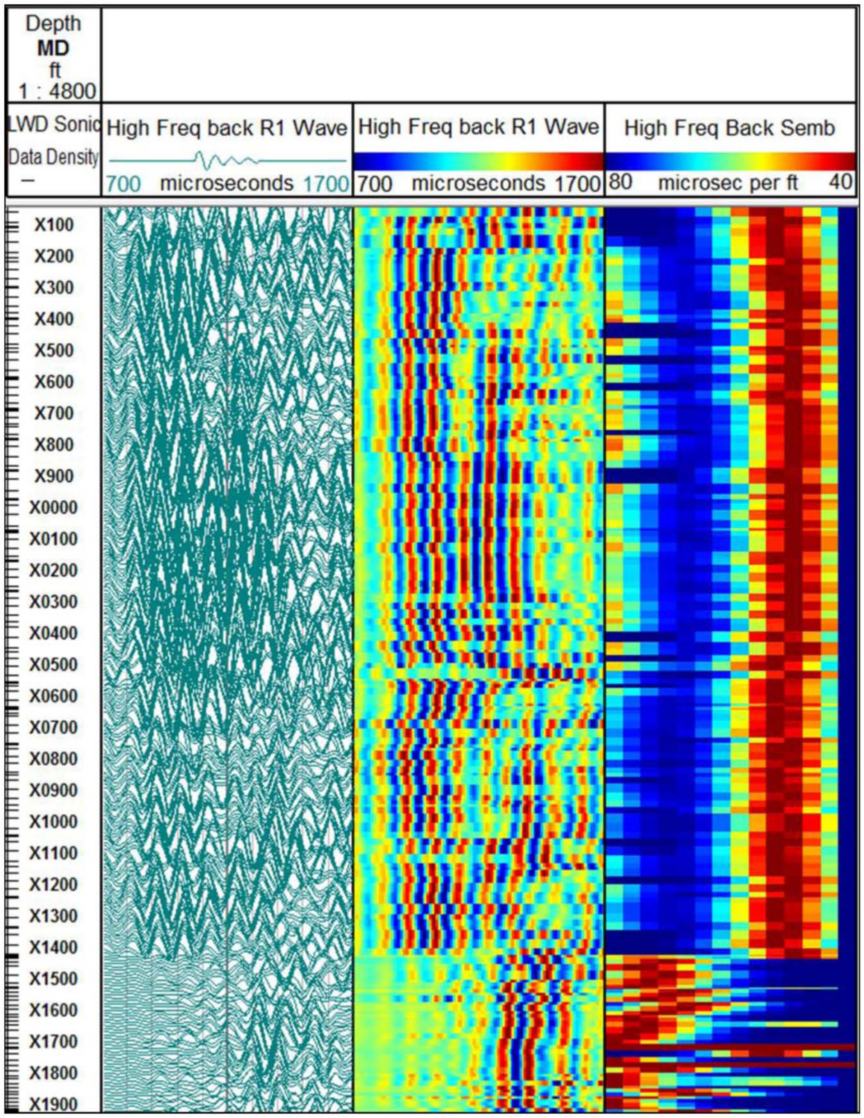

Figure 2—Log example from Case Study No. 1. A clear transition can be observed at ~X1,400 ft.

- Track 1, Measured depth (MD) markings in feet and LWD memory sonic data density tick marks for the raw waveforms acquired from the logging pass presented.
- Track 2, Raw waveforms presented as a waveform trace.
- Track 3, Raw waveforms presented as a variable density log (VDL) trace.
- Track 4, Processed acoustic semblance presented as a VDL trace.

In **Fig. 3,** two waveforms are presented from the two different intervals mentioned previously. The casing arrival can clearly be observed on the waveform for the shallower depth non-bonded interval, with a well pronounced ringing effect of the casing being recognized. In comparison, the waveform from the deeper depth well bonded interval shows evidence of the formation arrival with a non-existent or attenuated casing arrival. Representative sample waveforms from cased-hole logging when compared with a representative sample waveform from an open hole **(Fig. 4)** show the formation compressional signal observed on the waveform from the cased-hole well bonded interval.

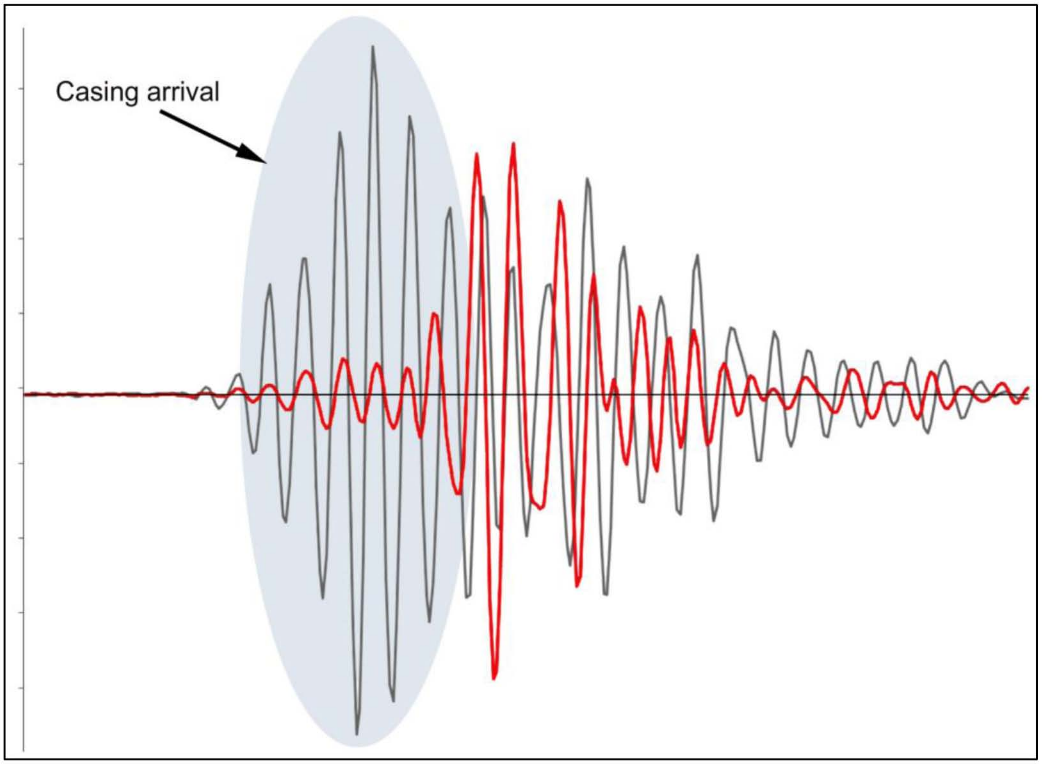

Figure 3—Representative acoustic waveforms from the LWD acoustic data acquisition presented in Fig. 2. The waveform as the gray trace was acquired at X1,238 ft. The waveform as the red trace was acquired at X1,703 ft.

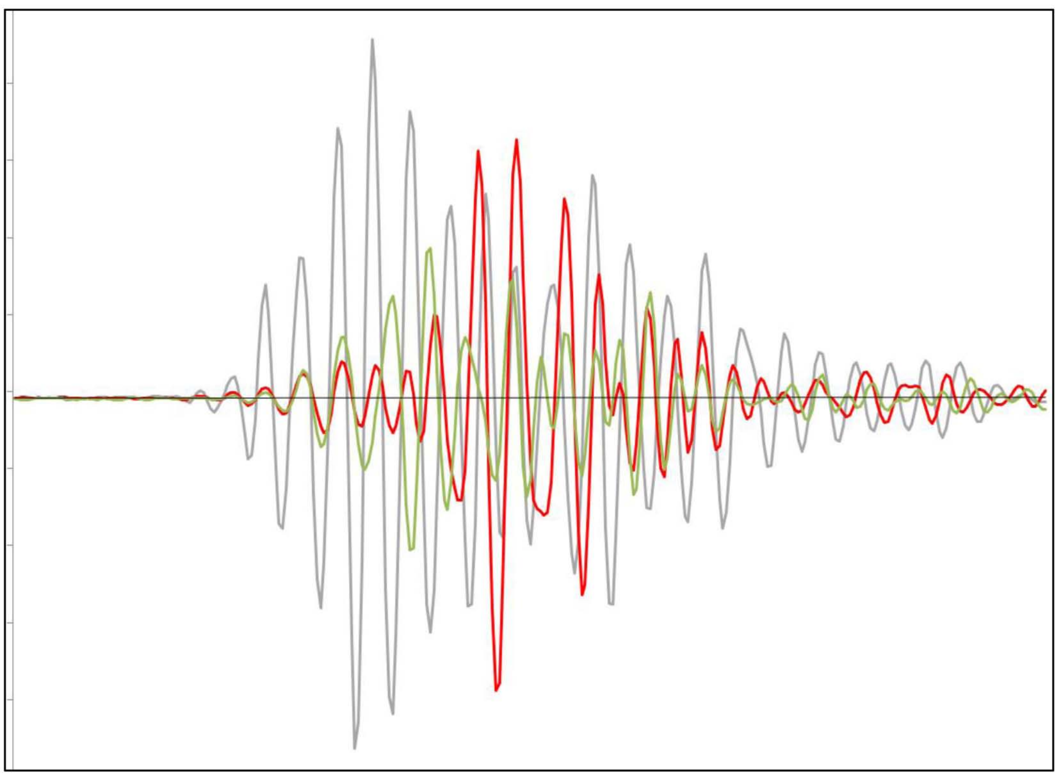

Figure 4—Same waveforms as in Fig. 3 are presented, along with a representative waveform shown as the green trace, which was recorded in the openhole environment from the same closest receiver to the transmitter tool arrangement.

In common practice, there is no automatic method for determining the TOC. The raw acoustic waveforms are analyzed and reviewed to identify where their character changes.

A common TOC analysis using LWD acoustic recorded data relies on different techniques that complement each other to provide more confidence in the analysis results.

1. Review of the raw waveforms recorded by the closest receiver to the transmitter for a high-frequency monopole firing to identify intervals where the casing was or was not ringing.
2. From an unfiltered processed acoustic semblance for a high-frequency monopole firing dataset, determine if formation compressional arrival is visible. This would indicate that the casing is bonded to the cement and the cement is bonded to the formation.
3. From an unfiltered semblance for a high-frequency monopole firing dataset, process the casing arrival based on a specific narrow slowness window (suggested 53 to 62 usec/ft) to obtain a "casing energy" response to make an assessment from such response, which is considered as the closest indicator comparable to a qualitative cement amplitude measurement.
4. Compare multiple passes (from trip-in and trip-out, based on a change in environments, such as mud weight change, and when using different frequency monopole firing datasets) for repeatability.

Based on actual design features of an LWD acoustic tool, the data transmission of downhole computed peaks from predefined real-time slowness windows (e.g., up to three peaks per window) is possible. The real-time slowness window can be pre-defined to cover the anticipated formation compressional slowness range as well as the casing arrival. The peaks transmitted allow making the following assessments.

- If all of the peaks transmitted are for the casing arrival, then there is strong evidence that the casing is ringing (no bonding).
- If all of the peaks transmitted are for the formation compressional arrival, then there is strong evidence that the casing is bonded to the formation.

During the prelogging stage, it is important to consider configuring the real-time slowness windows for a TOC application as detailed previously. Having available openhole data or offset well data for the formation compressional slowness response expected across the cased-hole section where the TOC is to be identified will greatly assist in the configuration planning.

The data analysis can be more credible with a higher confidence level if the depth interval logged covers a clear contrast between free pipe and good bond, which can be interpreted from the data acquired.

Fig. 5 presents a suggested LWD acoustic TOC analysis plot format. This example shows a nonbonded zone transitioning to a well bonded zone behind a single string of casing at ~X9,600 ft.

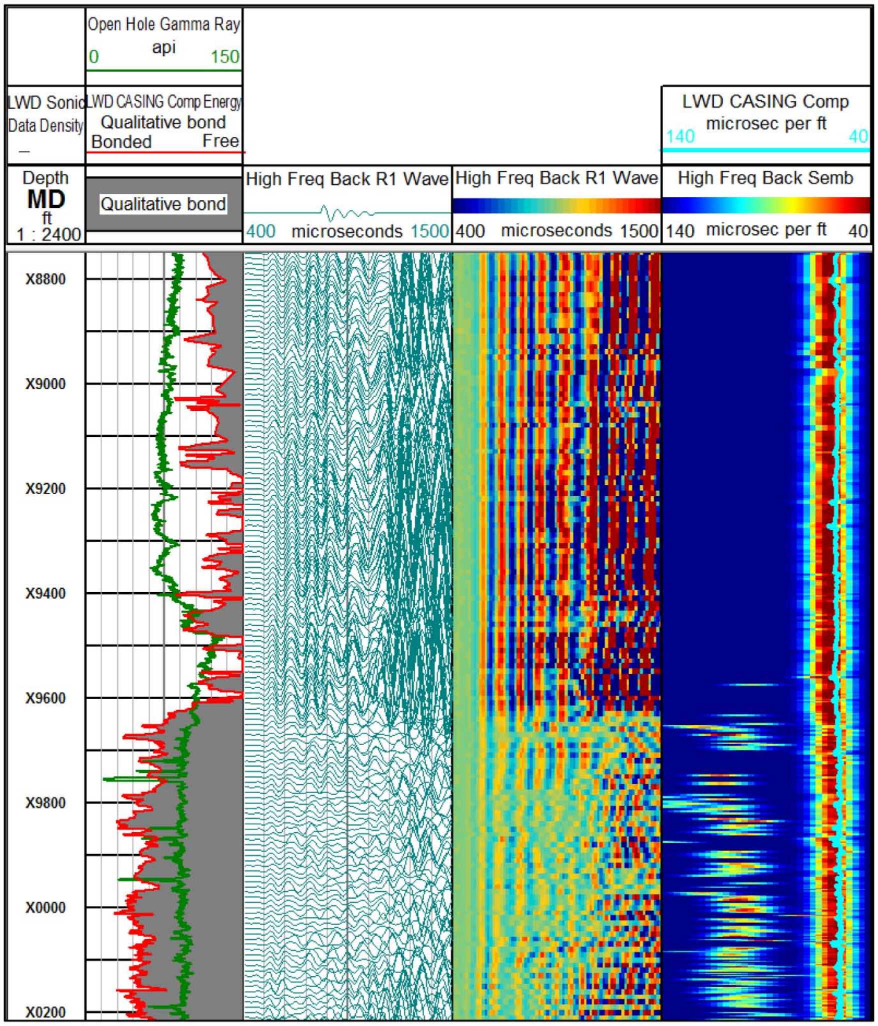

Figure 5—Analysis plot format presenting data from Case Study No. 2 discussed in this paper.

- Track 1, MD markings in feet.
- Track 2, Openhole gamma ray response as a scalar trace and casing mode energy presented as a qualitative bond response with shading illustrating the bond magnitude.
- Track 3, Raw waveforms presented as a waveform trace.
- Track 4, Raw waveforms presented as a VDL trace.
- Track 5, Processed acoustic semblance presented as a VDL trace and interpreted casing mode as a scalar trace.

Case Studies

Table 2 summarizes the key points for the different case studies presented in detail in this section.

Table 2—Key points for the case studies presented.

	Case Study No. 1	Case Study No. 2	Case Study No. 3
Primary objective	LWD sonic open hole data acquisition	Determine LWD TOC from memory data	Determine LWD TOC from memory data
Secondary objective	Confirm TOC behind 13 5/8-in. casing in previously drilled hole section	Acquire data for proof of concept for the real-time LWD TOC solution	Apply real-time LWD TOC solution
Casing string settings	13 5/8-in. Casing	7 5/8-in. Liner	7 5/8-in. Liner inside 9 5/8-in. liner
Cement information	Class Hconventional cement design	Class H (TXI lightweight 13.8 lbm/gal) conventional cement design	Class H (TXI lightweight 13.8 lbm/gal) conventional cement design
Fluid in the casing	Synthetic oil-based mud	Synthetic oil-based mud (with a change in mud weight half way during the run)	Synthetic oil-based mud
Extent of the prejob planning	Data acquisition sequence planned for openhole logging only	Data acquisition sequence planned for cased-hole logging	Data acquisition sequence planned for cased-hole logging
Run details where LWD acoustic was used	Drill 12 1/4- × 14 1/2-in. hole after FIT acquiring waveform data during trip-in and trip-out to confirm estimated TOC from cement lift pressure	Dedicated clean out run for drilling cement and mud displacement to different mud weight	Dedicated clean out run for drilling cement and mud displacement keeping same mud weight
LWD Real-time and/or memory analysis	TOC from memory analysis	TOC from memory analysis	TOC from real-time and memory analysis
Wireline comparison	None	Wireline CBL was run after LWD, but those results were inconclusive	Wireline CBL was run after LWD and both complemented each other
Outcome of TOC results from LWD	Conclusive	Conclusive as trip-in matching trip-out results	Conclusive

Case Study No. 1: 13 5/8-in. Intermediate Casing String, Deepwater GOM

One of the major challenges while drilling wells in the young formations of the deepwater GOM is zonal isolation of the intermediate casing strings. Often during cementing operations, mud losses are encountered to the weaker formation, leaving uncertainty about the placement of the cement at the conclusion of the job. Operators analyze the cementing lift pressures from the job chart and calculate the TOC behind the casing, then drill out the casing shoe and perform a formation integrity test (FIT) or leakoff test (LOT) to verify the integrity of the isolation. In many instances, LWD sonic tools are included in the deepening runs and a battery powered tool allows acquiring recorded waveform data while the drilling BHA is tripping in the hole to drill out ahead. In these cases of uncertain cement placement, the raw waveform data are often capable of determining a TOC by using a macro-log presentation to locate the contrast of free ringing casing and the bonded casing to the formation. Without any impact or effort other than ensuring the sonic tool was on and sampling, the TOC is often identified and noted for possible future needs.

Fig. 6 demonstrates a typical macro-log for a case study involving a 13 5/8-in. intermediate casing job. Mud losses while running the casing, cementing, and displacing plug of 55 bbl, 349 bbl, and 1,423 bbl, respectively, were recorded. With a planned lift pressure of 700 psi, the final differential pressure was 650 psi, putting the calculated TOC at X1,430 ft.

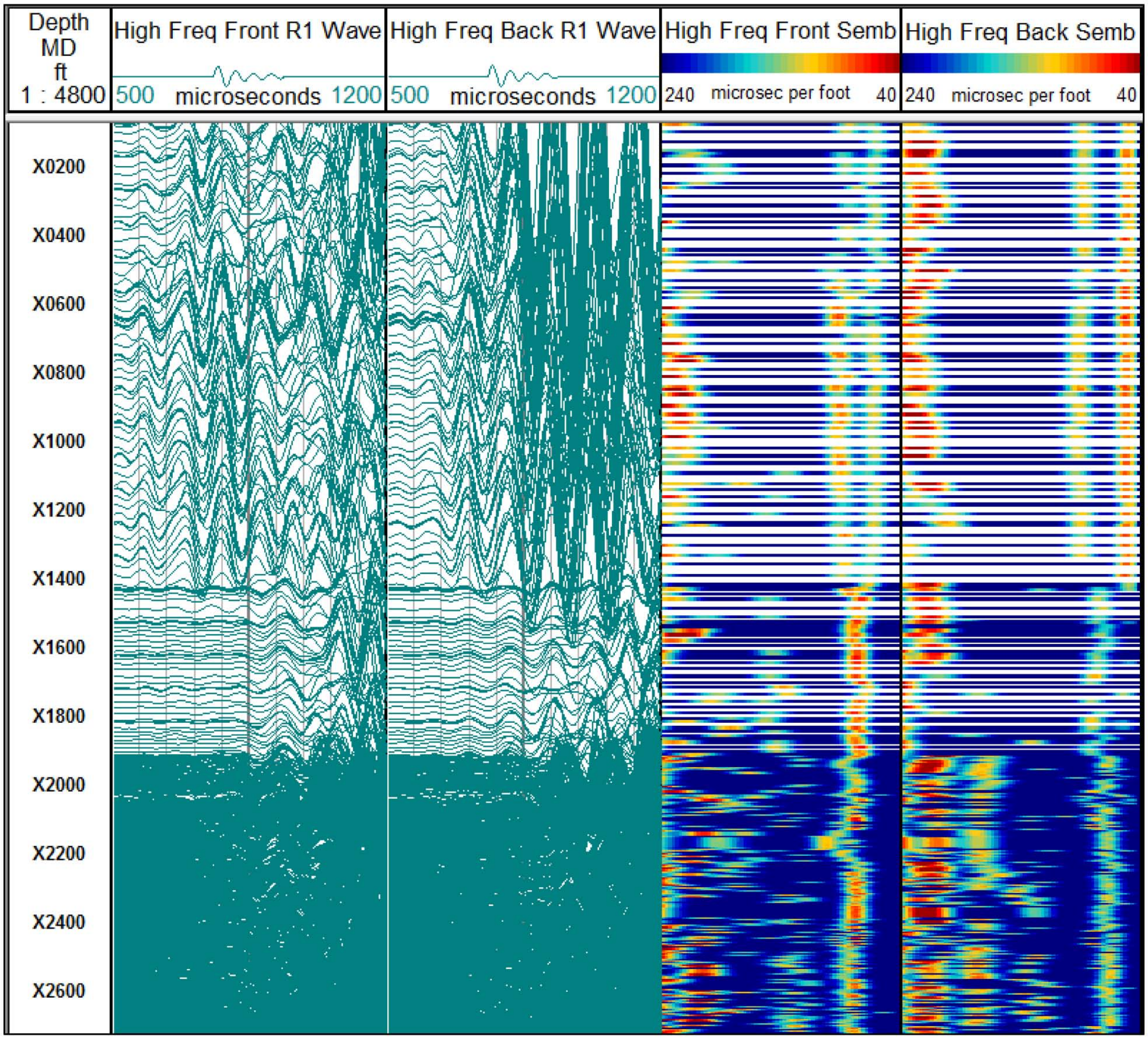

Figure 6—TOC analysis plot presenting memory raw waveforms acquired during the trip-in pass. A clear contrast can be identified at ~X1,420 ft for the TOC.

Tracks 1 and 2 of the macro-log show the raw waveform data of the high-frequency monopole firing nearest to the transmitter, and Tracks 3 and 4 are the processed semblances using the waveforms from all of the receivers. The LWD sonic sensor was in the drilling BHA downloaded for openhole logging for real-time pore pressure guidance and seismic tie-in and recording waveforms with a 12-second sample rate. The gaps in the semblance tracks on the right side of the figure represent the time between samples at regular tripping speeds. The change in the waveforms representing the TOC is clearly noticeable around X1,420 ft, but depth resolution is limited by sample period and tripping speed. These results supported the calculations made from the final lift curve and place emphasis for further opportunities to evaluate TOCs without conventional wireline operations.

This case study is typical of LWD acoustic openhole logging, where the measurements acquired inside the casing while tripping are used for a TOC analysis.

Note the difference between the behaviors of the front and back set of waveforms in the free interval. This is caused by the tool not being centralized inside the casing with no tool rotation. The back receiver array appears to be closer to the casing wall than the front receiver array based on the data quality of each dataset acquired independently.

Case Study No. 2: 7 5/8-in. Liner, Ultradeepwater GOM

On this well (**Fig. 7**), the drilling fluid was displaced during a dedicated clean out run soon after the cement job of the casing was performed. The purpose of the clean out run was to drill the cement inside the casing and perform a complete drilling fluid displacement. The mud weight difference before and after mud displacement allowed the LWD acoustic logging while trip-in and while trip-out to occur while the casing was pressurized differently. A cased-hole wireline logging run for cement evaluation was also performed after the clean out run. During the wireline run, it was not possible to perform a pressurized pass for micro-annulus confirmation.

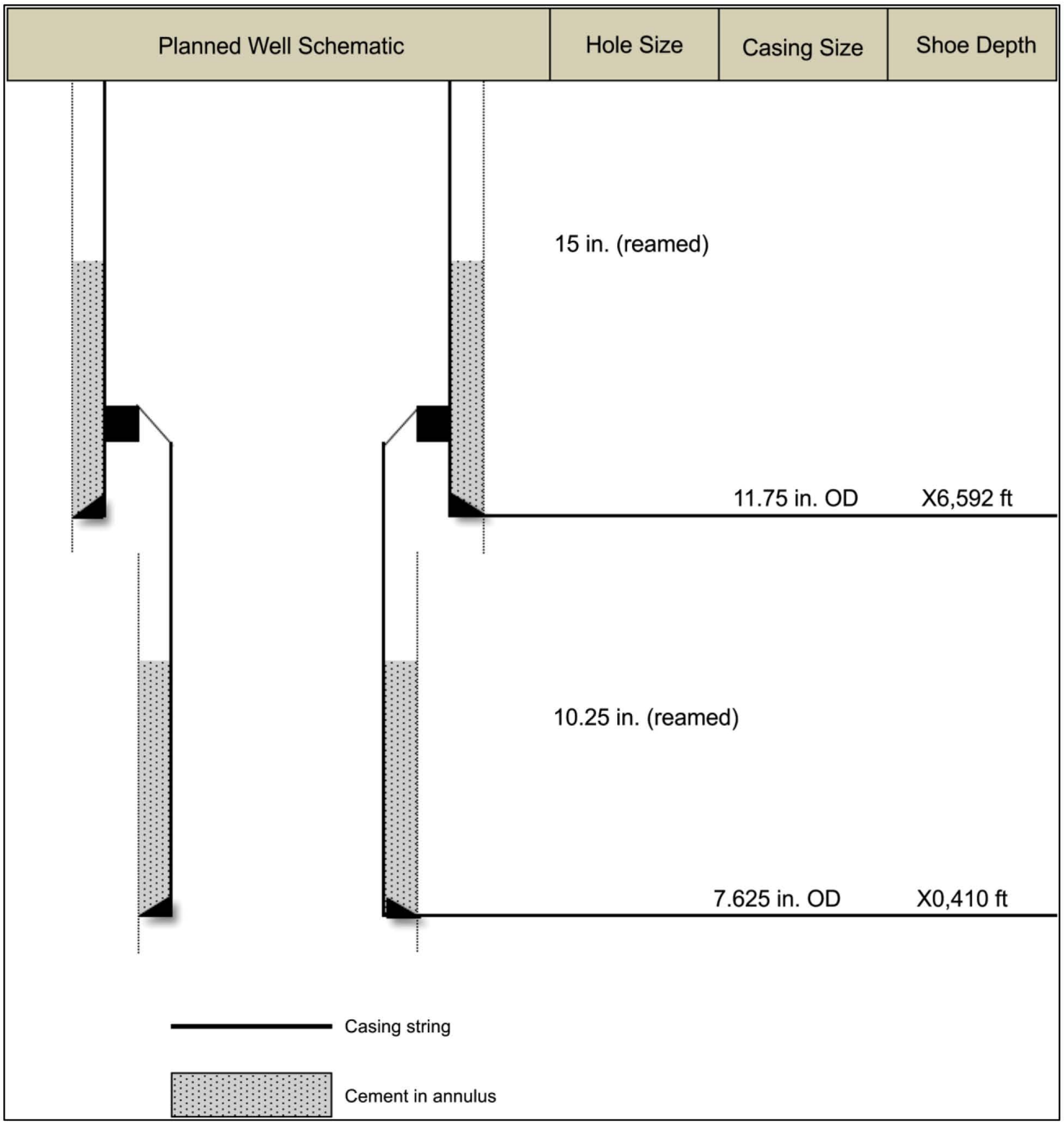

Figure 7—Planned well schematic for the zones of interest.

Challenges.

- Following the cementing of the 7 5/8-in. liner, the client expected cement integrity issues and planned to perform a squeeze job.

- A clean out run for drilling through the cement inside the 7 5/8-in. liner occurred, followed by wireline cement bond log (CBL) to be run on tractor logging to confirm the TOC.
- Facts:
    - Liner was reamed to total depth (TD)
    - Could not establish returns during the cementing pumping operations
    - Final differential (150 psi) during cementing was less than planned (180 psi)
    - Based on cement lift pressure, expected cement column to be less than planned by ~150 ft

Solutions.

- The LWD sonic tool was used to acquire acoustic waveforms inside the liner during the clean out run. This was to assist with identifying and confirming the TOC from wireline CBL.
- The LWD tool was optimized to operate by firing two monopole high-frequency modes and to acquire data in memory at a fast sample rate for sufficient data density without slowing tripping operations.

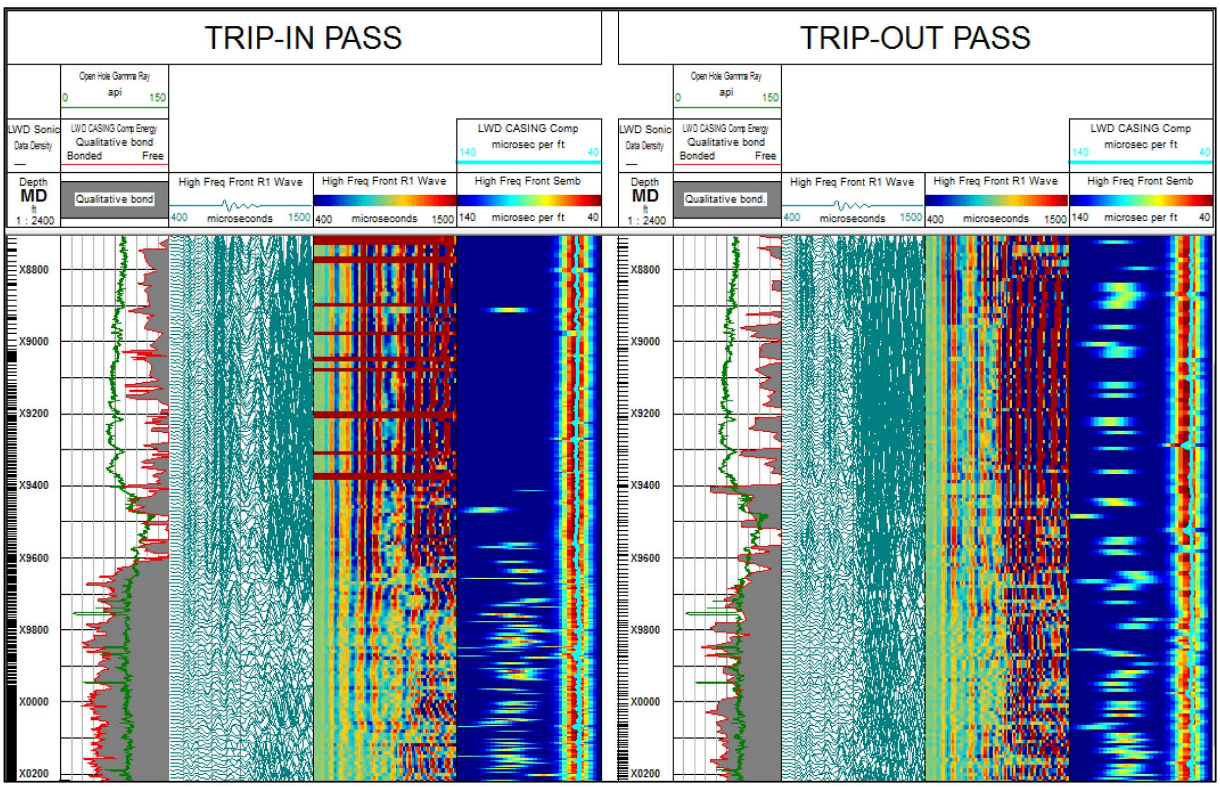

Figure 8—These two plots side by side show the TOC analysis comparison before and after mud displacement. The trip-out logging occurred with a lighter mud weight than during the trip-in logging.

Results and Value Added.

- Quality LWD acoustic data were acquired **(Fig. 8)**. Identification of a TOC inside the 7 5/8-in. liner was possible at ~X9,650 ft MD. The TOC was confirmed based on four different datasets acquired from two different firing modes, and from trip-in and trip-out data acquisitions. Both waveform analysis and casing arrival interpretation methods complemented each other in providing the analysis results.

- Wireline CBL was not conclusive, indicating no cement was present behind the liner, possibly resulting from a micro-annulus.
- Analysis of the LWD acoustic data helped identify a micro annulus and the TOC. As a result, it was decided not to perform a squeeze job. This allowed resuming normal drilling operations and to drill ahead the remaining hole section for the well.

Case Study No. 3: 7-5/8-in. Liner Inside 9-5/8-in. Liner, Ultradeepwater GOM

The main objective was to confirm the TOC of the 7 5/8-in. inner pipe inside the 9 5/8-in. liner (**Fig. 9**). On this well, LWD real-time application for determining the TOC was required for allowing quick operational decisions and was eventually followed by wireline segmented bond tool (SBT) logging. During the cementing of the 7 5/8-in. pipe, the primary cement job had full returns with an estimated TOC at X7,501 ft.

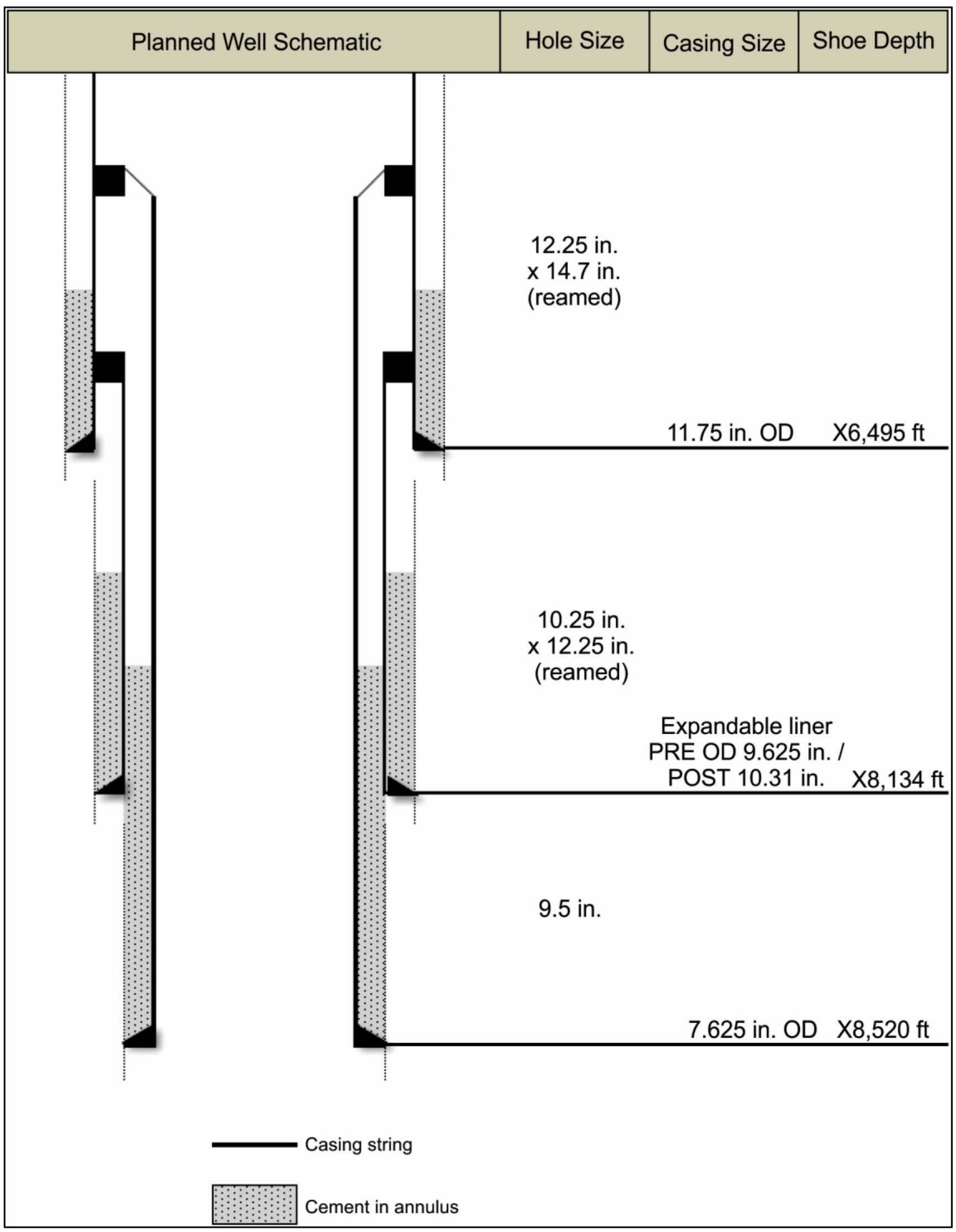

Figure 9—Planned well schematic for the zones of interest.

Challenges.

- Determining TOC of the inner pipe
- Real-time cement evaluation during LWD logging
- Quick decisions on the cased-hole wireline logging run

Solutions.

- Proof of concept using available LWD acoustic openhole tool
- Optimize LWD data acquisition to meet the objectives and allow for normal tripping speed with limited impact on the critical path

Results and Value Added.

- An LWD sonic log was run 5 days after the cement job during the clean out trip. The LWD sonic run yielded a clear indication of cement below and above the liner overlap, with TOC at approximately X7,500 ft.
- A wireline SBT log was run after the 3,800-psi casing test (~9 days after the cement job) and provided a more ambiguous indication of cement in the liner overlap, but TOC was still observed at approximately X7,490 ft.
- The difference in results between LWD and wireline SBT might be attributable to a micro-annulus through the overlap interval.

The SBT analysis is presented in **Fig. 10.** The log shows bonding consistent with the designed cement compressive strength and no channels from X8,258 ft to the log first reading at X8,412 ft. The interval from the 9 5/8-in. casing shoe at X8,134 to X8,258 ft shows the presence of a channel in the cement. The log response alternates between a free pipe reading and that of poor bonding from X7,490 to X8,134 ft. All of the logged footage above X7,490 ft reads free pipe. Of note is that the interval in the 7 5/8- by 9 5/8-in. annulus from X7,490 to X8,134 ft was so close to the free pipe response that a TOC call was difficult to make with certainty.

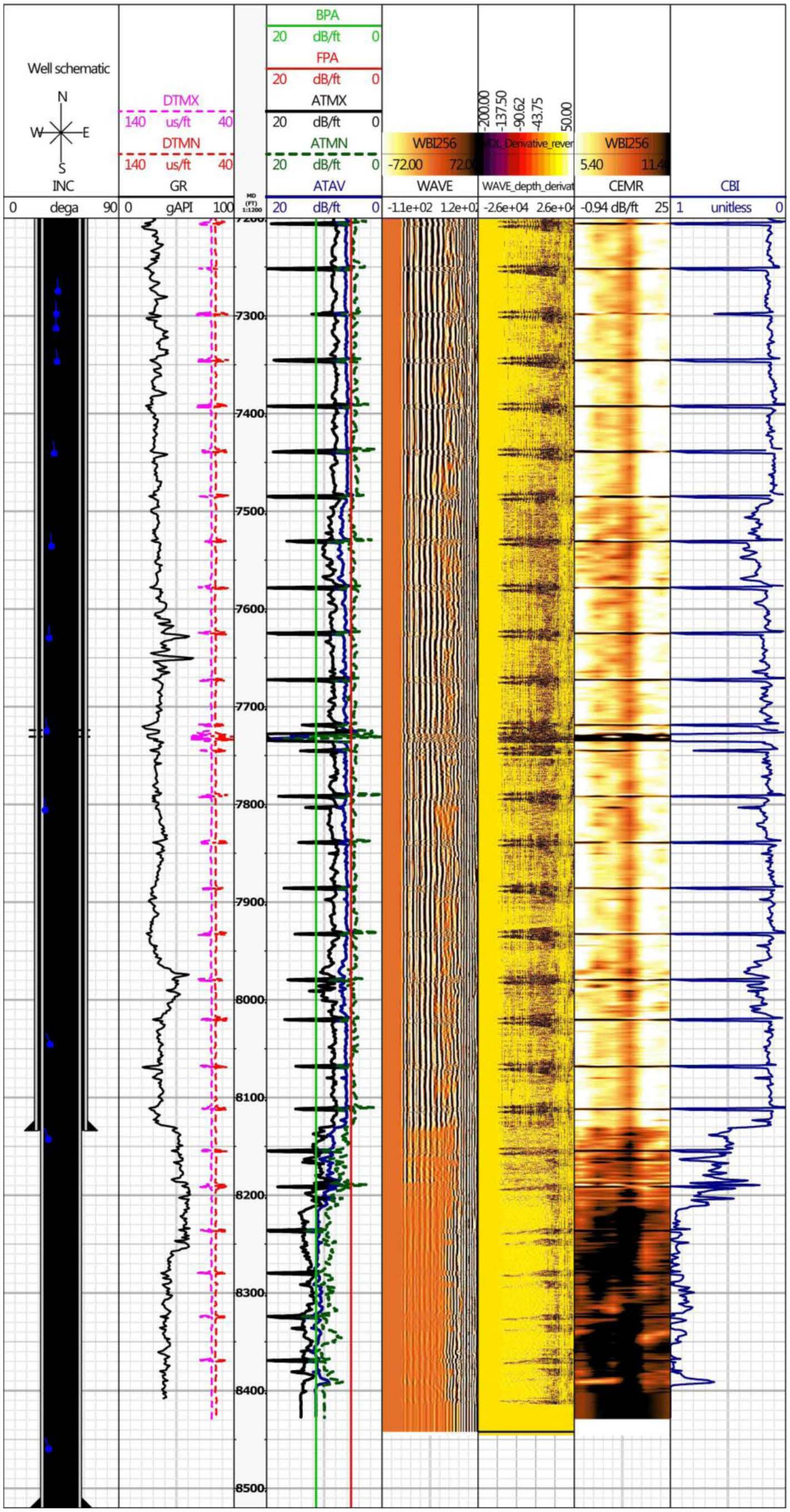

Figure 10—SBT log with corresponding analysis. Green and red lines in Track 3 correspond to bonded and free pipe response, respectively.

While TOC from wireline SBT was not as clear, TOC from LWD was more easily discerned. Both LWD and wireline cement evaluation results complemented each other greatly, and analysis of the wireline results on their own would have been difficult.

Figs. 11 and 12 show a TOC in the 7 5/8- by 9 5/8-in. annulus at approximately X7,500ft.

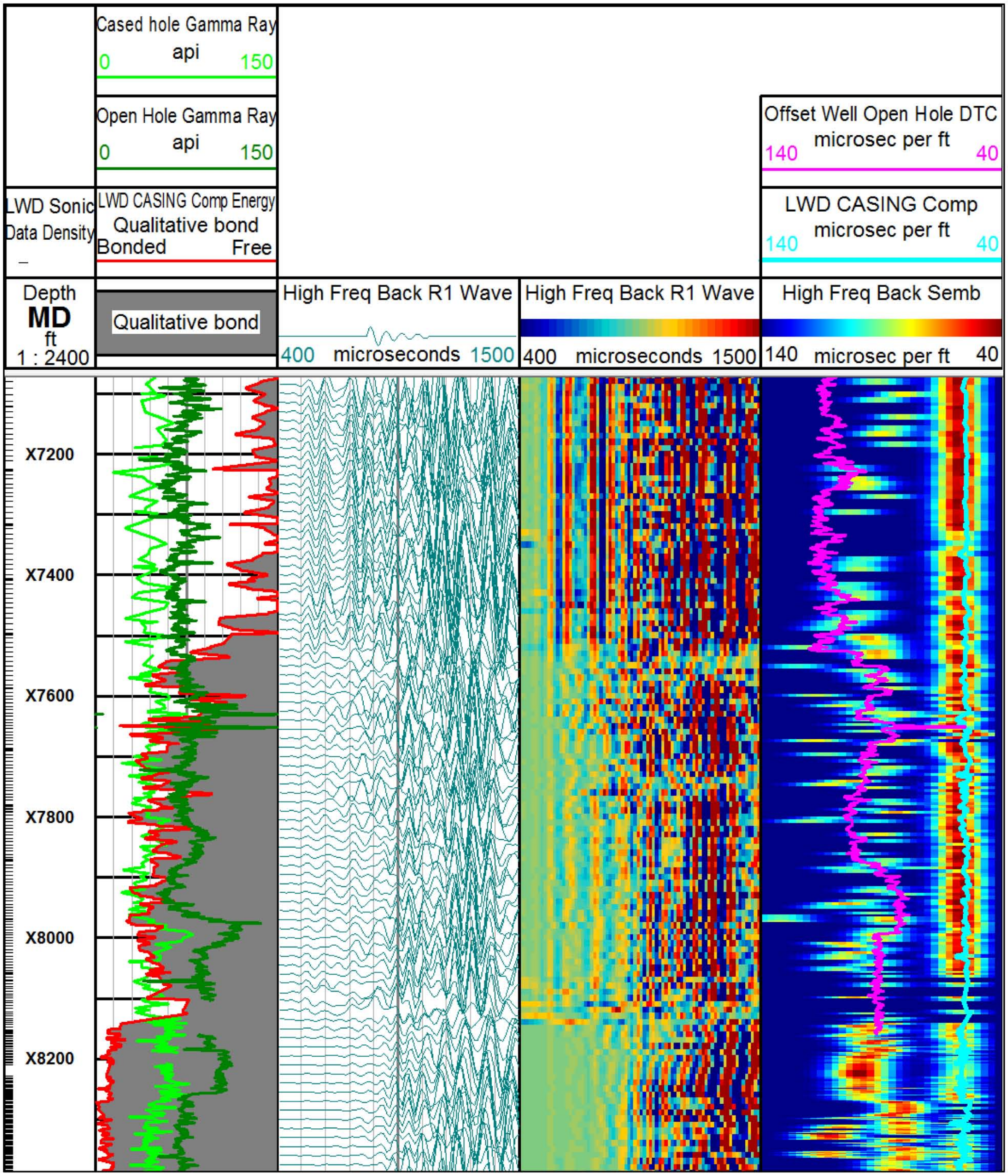

Figure 11—LWD memory acoustic analysis results for the trip-out pass, identifying the TOC in the 7 5/8- by 9 5/8-in. annulus at ~X7,500 ft, with a transition at the 9 5/8-in. casing shoe at X8,150 ft.

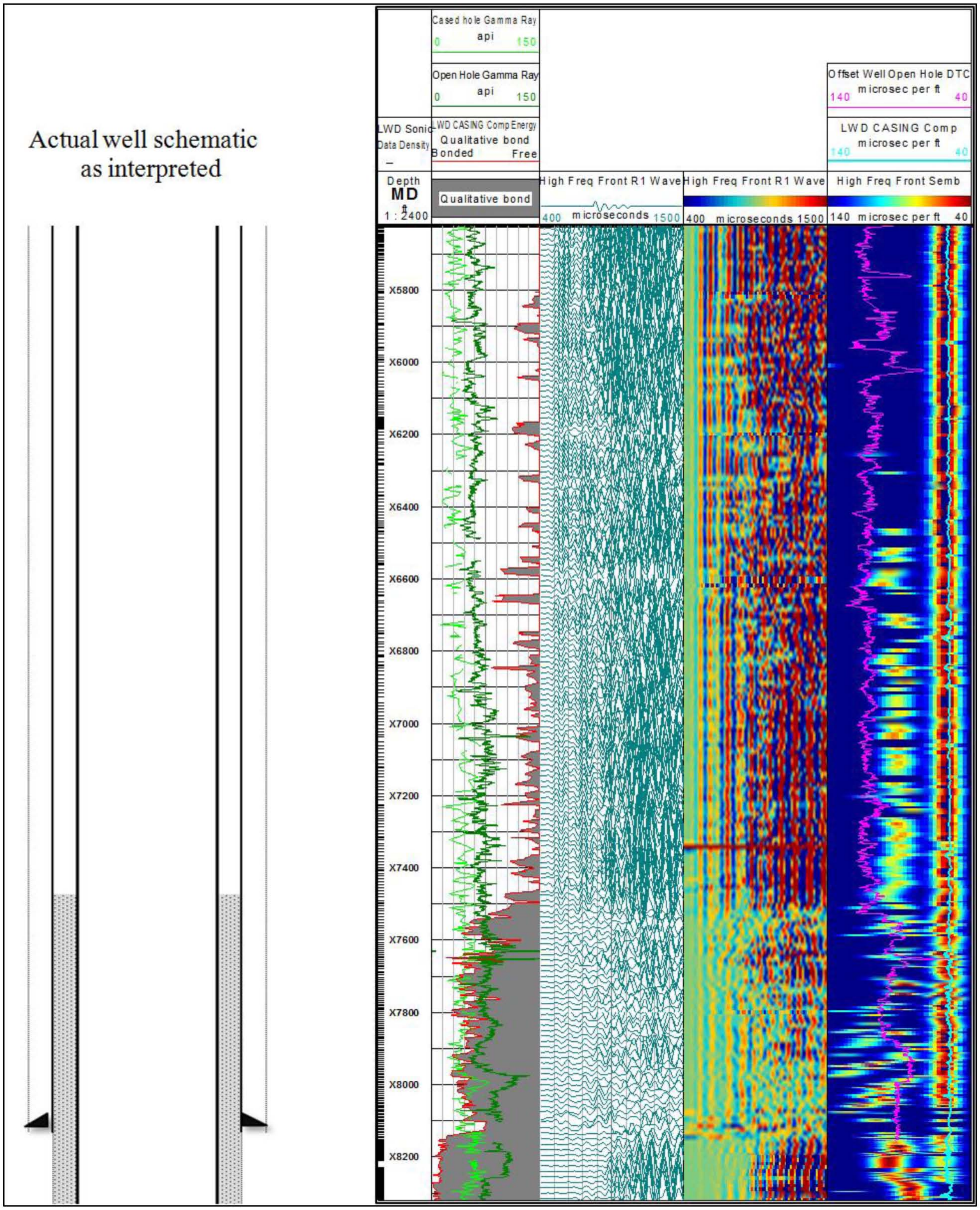

Figure 12—Overview of the entire cased-hole logging pass for TOC analysis correlated with the interpreted actual well schematic.

The raw waveforms plotted in **Fig. 13** compare representative waveforms for a zone interpreted as not bonded and another deeper zone interpreted as fully bonded, referring to the bonding between the inner pipe and the outer pipe, as per the schematic in Fig. 9. The casing mode can be observed on both waveforms, with a stronger ringing of the casing on the waveform acquired in the shallow zone above the TOC.

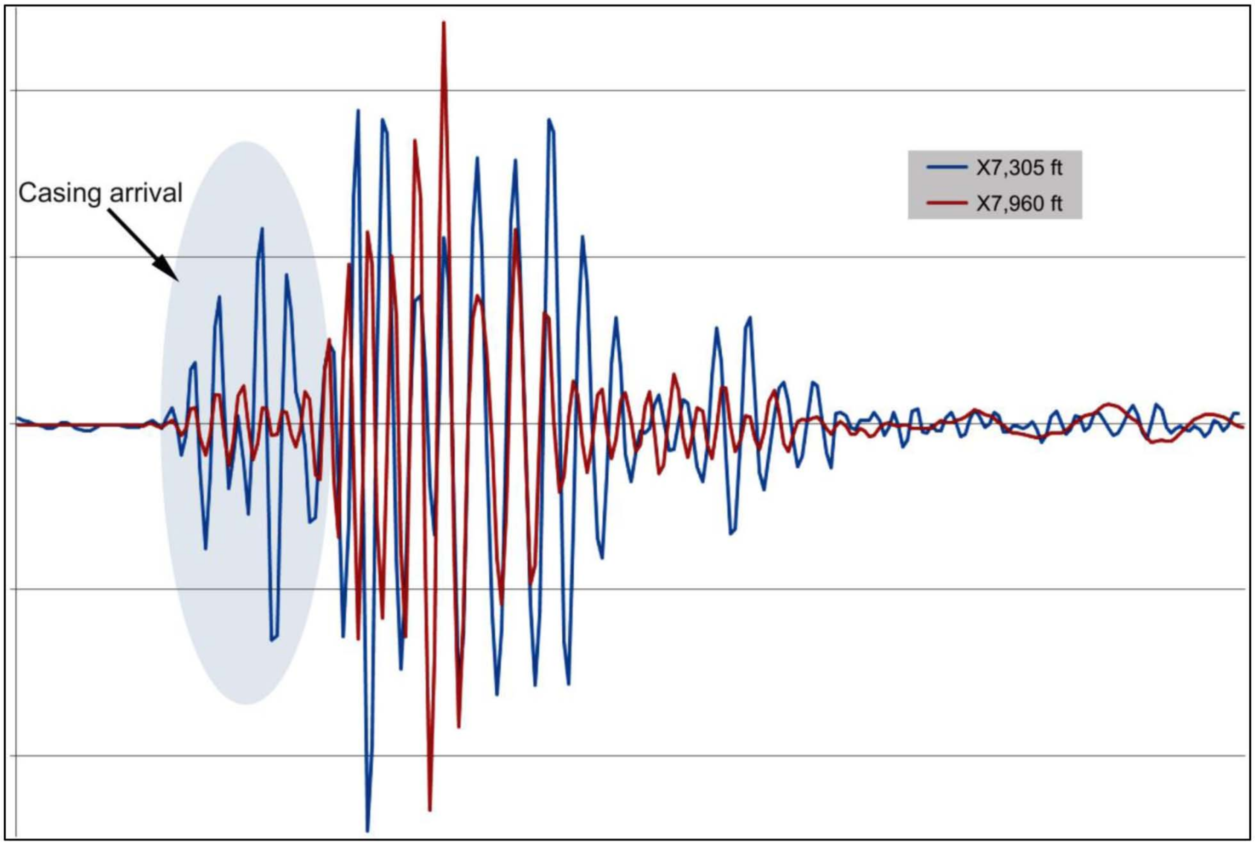

Figure 13—Representative raw waveforms illustrating the contrast in response from non-bonded and bonded zones.

Conclusion and Lessons Learned

LWD TOC determination can provide significant value by complementing analysis of the wireline results. It should be noted that, when possible, correlation with a gamma ray tracer response (based on add-on of radioactive material in the cement at a controlled volume before the cement is pumped) can assist with the cement bond analysis from LWD acoustic.

Lessons Learned

- Real-time LWD sonic reduced the rig time required for these TOC applications and decreased risks associated with wireline logging.
- The LWD logging service discussed in this paper, along with the results from the case studies, demonstrate that during the different stages of such services, accountability is important for critical decision making inputs, such as the following:
    - Eliminating a planned cement squeeze operation
    - Removing a dedicated wireline cement evaluation logging service
    - Validating the cement integrity behind pipe before drilling a new hole section
- Wireline CBL evaluation is still industry preferred, with the solutions discussed in this paper being strong viable alternatives for complementing the evaluation.

Acknowledgement

The authors acknowledge Shell, BP, Chevron, and Halliburton for their permission to publish this paper.

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