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Optimization of Spacer Train for Use on Wolfcamp D Production Strings

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Abstract

The Wolfcamp D formation in the Midland Basin poses many challenges when cementing production casings. High formation pressures require the use of heavy oil-based drilling fluids compared to most other formations in the area, often in the 12.5-13.5 lb/gal range. Multiple wells cemented in this formation showed poor cement bond log (CBL) response in the vertical section on the production casing. An investigation was performed to identify the causes of these poor CBL responses, and the spacer train was optimized to displace the oil-based fluid and improve cement bonding on these production casing cement jobs more efficiently.

Using an industry-standard mud displacement simulator, the previous jobs were analyzed to determine the possible causes of poor CBL response. Centralization, pre-job circulation, fluid properties, and pump rates were all taken into consideration during this process. The recommendations were made to optimize the densities and rheologies of the spacer fluids to enhance mud displacement, and to minimize static time prior to cementing to maximize mud mobility during cementing. Four production strings were cemented with the new design in this case study.

Cement bond log response was improved in the wells cemented with the optimized spacer design. Side-by-side results of simulations with the previous spacer design and new spacer design are presented, along with side-by-side comparisons of cement bond logs.

Introduction

Drilling a horizontal well in the Wolfcamp D formation in the Midland Basin poses many not typically seen with shallower formations in the basin. This formation often shows significant hole stability problems, and the most effective way of combatting these issues is to drill with heavy oil-based mud. While this helps to make the drilling and casing running operations more efficient, this makes it much more difficult to achieve acceptable zonal isolation when cementing the production casing. Not only cement properties such as stability and compressive strength are important to the success of the cement job, but the wellbore preparation and placement mechanics during the cement job are also critical to the operation. Mud properties must be optimized to minimize gelation but also ensure solids carrying capacity is not diminished. Casing must be properly centralized to allow for uniform displacement through the annulus, spacers must be designed with proper density and rheological properties for displacement, and the correct surfactant package must be selected to ensure compatibility with the oil-based drilling fluid and to ensure complete water-wetting of the casing and formation surfaces so cement can form a seal against these faces. When designing production casing cement jobs such as these, a holistic approach must be taken to the design to ensure the best chance of success. This paper describes the use of this approach to improve production cement job outcomes during a recent drilling campaign in Glasscock County, TX.

Problem Background

An operator drilling in the Midland Basin has historically drilled Wolfcamp D horizontal sections on heavy oil-based mud (12.5 to 13.5 lb/gal). The additional hydrostatic head was necessary to ensure hole stability while drilling the lateral. To keep this heavy mud from fracturing weaker Spraberry and Wolfcamp zones above the target formation, a deep intermediate casing was set into the Wolfcamp C and cemented in two stages with the stage tool just below the San Andres prior to drilling the curve and lateral. Depending on the well configuration, this intermediate casing would be either 8 5/8”, 32 lb/ft or 9 5/8”, 40 lb/ft casing. The production casing on these wells was 5 ½” 20 lb/ft casing. On the wells with 8 5/8” intermediate casing, the curve and lateral were 7 7/8” open hole through the curve and lateral, and wells with 9 5/8” intermediate casing had an 8 ½” curve and lateral. The 5 ½” casing was equipped with a flotation tool to aid in minimizing drag while casing was run through the lateral. As the stage tool on the intermediate was placed just above a zone known to contain H_2S, target top of cement on the production string was planned to be approximately 2000 feet above this to provide a second layer of protection against potential casing corrosion.

Offline cementing is an operational feature of many of these production casing cement jobs that poses an interesting challenge. In recent years, offline cementing has become increasingly popular due to the efficiency gains operators have seen. Offline cementing allows for the drilling rig to skid to the next well on the pad and begin the process of drilling the next hole section while the primary cement job is completed on the previous well. While there are some differences from rig to rig, typically depending on wellhead provider and surface equipment layout, the process generally goes as follows. Once the drilling rig reaches TD, it will perform its normal cleanup cycles, pull out of hole, and run casing. Once the casing is on bottom, the rig will perform any additional circulation, the packoff will be set, and the rig will move to the next well. An adapter is installed onto the wellhead with a changeover to a casing coupling that will allow for a traditional cement head to be attached, and the cement job can be pumped through the casing and returns will be taken through the casing valves on the wellhead. While this moves cementing from the “critical path” and allows for the rig to drill the next well while cementing is occurring simultaneously, this can cause issues for cementing. Without a rig over the well being cemented, there is no way to move the casing, if needed in the event of annular bridging, or to improve cement job quality through casing rotation or reciprocation. Also, after the casing is landed and while the rig is being moved, the well is static with no circulation. This static period can cause issues with mud gelation, barite sag, and possible cuttings settling if the hole wasn’t properly cleaned prior to running casing (Nelson et al, 2007).

The standard centralization program was to run one solid centralizer per joint through the curve and lateral, and then one bow spring centralizer per 1000 ft inside the previous casing. In the wells with 7 7/8” open hole sections, the centralizers were 7 3/8” in diameter, and in the wells with 8 ½” open hole sections, the casing was fitted with 8 ¼” outer diameter centralizers. This centralization program offered reasonable centralization throughout the curve and lateral sections, but less than ideal standoff in the vertical portion of the well inside previous casing. If standoff is insufficient, there will be uneven flow through the annulus, i.e., more of the fluid will tend to flow along the wider side of the annulus instead of the narrow side. This difference in flow around the eccentered annulus can lead to uneven mud removal and cement coverage. While there is no industry standard for minimum standoff for cementing, it is widely accepted that standoff should be maximized where possible for optimal mud removal and cement placement (Nelson et al, 2007, Sabins et al, 1990).

The drilling fluid for the production intervals for these wells ranged from 12.5 to 13.5 lb/gal. As the drilling fluid was oil-based, a surfactant spacer was required ahead of cement to ensure compatibility between the water-based and oil-based fluids, and to ensure water-wetting of all surfaces for proper cement adhesion. To reduce drilling fluid costs, a second fluid was added to displace the remaining OBM from the wellbore. Some of these wells were cemented with a weighted, viscosified surfactant spacer followed by a weighted, viscosified OBMR, or oil-based mud recovery fluid to displace the remaining OBM ahead of cement. Other wells were cemented using a flush of gelled water-based mud with surfactant, followed by produced water or brine with surfactant and corrosion inhibitor to displace the remaining OBM from the wellbore.. While the latter option is more economical, it presents the risk of poor mud displacement due to mud dilution and channeling spacer through the viscous, heavy weight oil-based mud (Guillot et al, 2007). Typically, for optimal displacement with a viscosified, weighted spacer, the density and rheological properties of the spacers should lie between those of the drilling fluid and the cement slurry to minimize channeling of a less viscous fluid through a more viscous fluid ahead of it in the wellbore (Nelson et al, 2007).

To evaluate the quality of the primary cement jobs performed on the production casing strings, the operator performed a radial cement bond log after each job. On the first four wells in this study targeting the Wolfcamp D formation, while the CBL showed isolation through the curve and into the lateral, there were large portions of the vertical section of the well that showed little to no cement bond. While the zonal isolation provided by these cement jobs is likely sufficient to support a hydraulic fracturing completion, the lack of cement bond in the vertical section means that the production casing likely has little protection from corrosion throughout the life of the well. Even though the designed top of cement was consistent through the four cement jobs, the tops of cement seen on the CBLs were inconsistent. To improve the CBL quality through the vertical section, the entire casing running and cementing process were evaluated from start to finish to identify possible ways to improve cement quality, and these recommendations were implemented on the next four wells.

Analysis and Recommendations

The four wells cemented in the first part of this study had very erratic CBL responses. All four wells showed good cement bond through the curve and into the lateral, but the vertical portions of the wells showed spotty cement bonding and inconsistent cement tops. The logs were reviewed and assigned a score from 1 to 10. This score was a subjective interpretation of the quality of the bond. The results of these four CBLs are presented in Table 1. Based on TOC seen on the logs and the scores given, the CBLs from Jobs #1 and #4 were clearly better than those from Jobs #2 and #3.

Details for the four cement jobs analyzed are presented in Tables 2-4. To make the best recommendation to cement the next round of Wolfcamp D production strings, the following were considered:

- Mud/Spacer/Cement Rheologies and Density
- Fluid Volumes
- Centralization
- Static Time Before Cementing
- Cement Online/Offline
- Pre-Job Circulation

The first four jobs had significant variation in how they were designed and executed. Three were performed offline, and one was performed online. There was a large variance in static time between landing casing and performing the pre-job circulation, from less than one hour on the online job to up to 12 hours for one of the offline jobs. One bottoms-up volume of mud was circulated after bursting the casing flotation tool on all four jobs. Two of the jobs used a gelled spacer and brine OBMR provided by the operator, and two of the jobs used weighted, viscosified spacer and OBMR fluids; however, even in these cases the spacer and OBMR densities were lower than that of the oil-based drilling fluid. Mixing and displacement rates were largely consistent across the cement jobs, and all four jobs showed full returns during the cementing operation. The cement design was the same on all four jobs, a single tail slurry mixed at 13.2 lb/gal.

The first issue noted with these jobs was the poor density hierarchy between the mud, spacer, and cement slurries. Jobs #1 and #2, on which an 8.8 lb/gal spacer and 9.5 lb/gal brine were used, had the worst densities for mud displacement. Even on Jobs #3 and #4, where a weighted spacer and OBMR were used, the mud density ranged from 13.1 lb/gal to 13.4 lb/gal and the spacer densities were 13.0 lb/gal. The rheological properties were also not appropriate for optimal displacement on Jobs #1 and #2. Using industry standard simulation software, the expected pressure drop in psi/ft was plotted for all fluids in the annulus at expected cementing rates. This is presented in Figure 1. As can be seen from this graph, the spacer is more “viscous” than the mud, brine, and even the tail slurry at expected cementing rates, while the brine pumped between the leading spacer and cement is less “viscous” than all other fluids. With these rheological properties, there is significant risk of channeling and intermixing between the fluids as they are being circulated through the annulus. Based on these results, the recommendation was made to use only weighted spacers and OBMR for the next batch of Wolfcamp D wells. The recommendation was also made to improve the rheological profile of the OBMR so it fell closer to the rheologies of the spacer slurry. The expected pressure drop for the original weighted spacer and OBMR design and the optimized OBMR designs are also presented in Figure 1.

Another potential issue that was noted was possible inadequate centralization in the vertical section. With the current centralization program of one rigid centralizer per joint in the curve and lateral, and one rigid centralizer per 1000 ft in the vertical section, the average vertical section centralization was 38% in the wells with 8 5/8” intermediate casing, and 41% in the wells with 9 5/8” intermediate casing. The recommendation was made to increase centralization frequency to one centralizer per three joints in the vertical section, which improved centralization to approximately 60% in both cases.

Using the same industry standard simulation software mentioned previously, two-dimensional displacement efficiency modeling was performed at anticipated cementing rates to verify the efficacy of the proposed changes. The first run was made with the original 8.8 lb/gal spacer and 9.5 lb/gal brine flush. The second run was made with the same viscosified spacer at 13.0 lb/gal, and with an OBMR fluid that had optimized rheologies to ensure correct rheological hierarchy. The third run was made with the recommended improved centralization program. All three cases shown are based on Job #1 depths, volumes, and an assumed cement mixing rate of 6 bbl/min and displacement rate of 7 bbl/min. These results are presented as Figures 2-4. As can be seen from the fluid concentration maps, each step change made an improvement in reducing fluid mixing and improving cement concentration through the vertical section, with the switch to the weighted, viscosified spacer train making the largest improvement.

The other clear issue noted was static time between landing casing and circulation prior to cementing. This was primarily due to time it took to move the rig to the next well prior to beginning the offline cementing operations. The two jobs with the better CBLs had less static time between landing casing and beginning the cementing operation. Even with the poor density and rheological hierarchy seen in Job #1 from the unweighted spacer and brine used for OBM recovery, the CBL still showed reasonable bond through the vertical section. Jobs #2 and #3 showed extended static time between landing casing and beginning pre-job circulation, with only one bottoms-up pumped prior to cementing. These jobs showed the worst CBLs of the group. The recommendation was made based on these results to make every effort to minimize flat time while moving the rig, and once the rig was moved, to increase the circulation volume to two to three bottoms-up volumes prior to cementing to help minimize the mud gelation and improve mud displacement and cement placement.

Execution and Results

The following changes were made for all four of the subsequent Wolfcamp D production casing cement jobs. All four jobs were performed with a 13.0 lb/gal weighted spacer and OBMR spacer train. The combined spacer and OBMR volume was kept at a fixed 150 bbl. The surfactant concentration was kept constant from the previous four wells, as it was confirmed to be acceptable for water-wetting by both an API wettability test and no adjustments were made to the centralization program from what was previously used. Five percent excess cement over the open hole volume was used in jobs, #5, 6, and 7, but due to washout caused by issues while drilling the lateral, Job #8 called for 40% excess cement on the open hole volume. All four jobs were performed at approximately the same mixing and displacement rates, no lost circulation was noted and no cement was seen at surface in any of these cases. OBM density fell between 13.0 and 13.2 lb/gal on all four jobs. Details from these four jobs are summarized in Tables 2-4. The CBLs were given a subjective quality score from a 1-10 scale, and these are summarized in Table 1. Snips from the CBLs at TOC and at the approximate depth of the corrosive San Andres formation are shown in Figures 5-8.

Job #5 was performed online. As it was performed online, there was no static time to wait on a rig move, the pre-job mud circulation was kept to 1 bottoms-up volume. The spacer volumes were 60 bbl of surfactant spacer followed by 90 bbl of the original OBMR slurry. As this well had 9 5/8” intermediate casing, the surfactant spacer length was 1,293’ in the casing-by-casing annulus. The CBL on this well showed a clear top of cement at approximately 800’ and good cement to 4,500’, at which point the CBL response showed poor cement coverage until approximately 8,000’. Where there was coverage, it appeared to be uniform around the circumference of the casing with no apparent channeling. It is worth noting that this job had the shortest time between cement job and CBL run of any of the wells in the case study. The time between cement job and CBL for this job was only three days. The next shortest time was Job #1 from the first set, at eight days. It is possible that slightly contaminated cement was in the void space from 4,500' to 8,000', causing lower early compressive strength. Additional curing time may have helped this material appear more clearly on a CBL.

Job #6 was performed offline. The pre-job circulation volume was increased to 1.6 bottoms-up due to the static time. In this case, the volume of leading surfactant spacer was increased to 90 bbl, while the OBMR volume was reduced to 60 bbl to see if increasing the contact time with weighted spacer would improve CBL response. As this well had 8 5/8" intermediate casing, the surfactant spacer length was 2,852' in the casing-by-casing annulus. Again, this used the original OBMR slurry used in two of the previous four wells. Even though no cement was seen at surface by the cement crew, this CBL showed top of cement at surface, with solid bond from surface all the way to the curve with no voids in coverage. The radial map showed that the coverage was uniform around the entirety of the casing string.

Job #7 was performed offline. Pre-job circulation volume was limited on this job to only 1 bottoms-up volume. The spacer volumes were identical to job #5, with 60 bbl of leading surfactant spacer and 90 bbl of OBMR. Again, as this well had 9 5/8" intermediate casing, spacer length was only 1,293' in the casing-by-casing annulus. This well used the new OBMR with improved rheological properties. This well showed a top of cement at 1050' with uniform coverage from this point to the curve.

Job #8 was performed offline. Pre-job circulation volume was again increased to 1.6 bottoms-up volumes due to the static time. This job was nearly identical to Job #6, as it was performed on a well with 8 5/8" intermediate casing and with 90 bbl of leading spacer and 60 bbl of OBMR, so the leading spacer length was 2,852' in the casing-by-casing annulus. Due to issues while drilling the lateral, there was significant washout through the open hole section, so the excess cement volume was increased to 40%. Again, even though no cement was noted at surface during the job, the CBL showed TOC to be at surface, with excellent bond and no voids from surface all the way to the curve.

Conclusions

From the results presented here, it is apparent that pre-job mud circulation, spacer density, rheology, and, if a well is drilled with OBM, contact time with the surfactant-laden spacer all have a significant impact on the CBL quality immediately after a primary cement job. Jobs #6 and #8 had the best CBLs of any of the 8 jobs in the study, and they had the best chances of success based on the adjustments made – replacing the lightweight spacer and brine preflushes with weighted, viscosified spacers, increased surfactant spacer volume, increased pre-job mud circulation, and job #8 had optimized OBMR rheologies. The optimized OBMR rheologies also appear to have had an effect in comparing the quality of Jobs #5 and #7, as this was the only difference in design between these two jobs. While we would have liked to have compared results between the 8 5/8" and 9 5/8" intermediate casing scenarios with equal volumes and pump rates to evaluate the influence of spacer length and annular velocities, this was not possible during this study.

We would make the following recommendations for any future Midland Basin Wolfcamp D two-mile horizontal production string where CBL response through the vertical section is critical. First, maximize centralization through the curve and lateral. Without sufficient centralization in the lateral, the fluid interfaces between mud, spacer, and cement will begin to channel and intermix much earlier in the cement job, making it nearly impossible for these fluid interfaces to recover higher up in the wellbore. Second, the minimum pre-job circulation immediately prior to cementing should be 1.5 to 2 bottoms-up volumes, pumped at or above expected cement displacement rates. This increased volume of pre-job circulation is critical for offline operations. Third, the fluids introduced should follow a rheological hierarchy, i.e., each subsequent fluid should be more viscous than the fluid it is displacing. A similar density hierarchy is ideal, but it is understood that this is not always feasible given limitations around frac gradient. Finally, if the well is drilled with an oil-based drilling fluid, the volume of surfactant-laden spacer should be sufficient to yield a minimum of 2,000' of fill in the widest annulus to be cemented.

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Nomenclature

Define symbols used in the text here unless they are explained in the body of the text. Use units where appropriate.

CBL = Cement Bond Log
OBMR = Oil Based Mud Recovery Fluid
TOC = Top of Cement
MD = Measured Depth
TVD = True Vertical Depth
OH = Open Hole

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Table 1– CBL Results Summary

Job #	Target TOC	CBL TOC	CBL Score
1	3000	1850	6
2	2500	4200	5
3	2000	4000	3
4	2000	1200	7
5	2000	800	5
6	2000	Surface	10
7	2000	1050	8
8	3000	Surface	10

Table 2 – Operational Summary for All Jobs

Job #	MD	OH Size	TVD	Target TOC	Average Mix Rate	Average Disp. Rate	Cement to Surface	Full Circulation?	Cement Online/Offline	Static Time	Circulation Volume Before Cementing	Circulation Rate/Pressure
1	20700	7.875	9987	3000	5 bpm	5 bpm	None	Yes	Online	<1 hour	1 bottoms up (rig)	Unknown
2	20770	7.875	10202	2500	5.5 bpm	6 bpm	None	Yes	Offline	12 hours	605 bbls (NexTier)	5 bpm/1300 psi
3	20685	8.5	9970	2000	7 bpm	6 bpm	None	Yes	Offline	5 hours	1 bottoms up (offline)	Unknown
4	20775	8.5	10108	2000	7 bpm	7.5 bpm	None	Yes	Offline	4 hours	1 bottoms up (offline)	Unknown
5	20776	8.5	10065	2000	7.5 bpm	7.5 bpm	None	Yes	Online	<1 hour	1 bottoms up (rig)	Unknown
6	20778	7.875	10065	2000	7.5 bpm	7.5 bpm	None	Yes	Offline	5.5 hours	1035 bbls (NexTier)	6 bpm/1700 psi
7	23640	8.5	10205	2000	8 bpm	5.5 bpm	None	Yes	Offline	2 hours	1 bottoms up (offline)	Unknown
8	23626	7.875	10204	3000	6 bpm	6 bpm	None	Yes	Offline	4.75 hours	1200 bbls (NexTier)	7 bpm/2100 psi

Table 3 – Mud and Spacer Properties for All Jobs

Job #	Mud Type	Mud Weight	PV (cP)	YP (lb/100ft2)	10 sec gel	10 min gel	Spacer Density	Spacer Volume	Spacer Length	PV (cP)	YP (lb/100ft2)
1	OBM	13.4 ppg	31	10	13	16	8.9 ppg	60 bbl	1901 ft	7	43
2	OBM	12.8 ppg	32	13	11	22	8.8 ppg	60 bbl	1901 ft	7	43
3	OBM	13.1 ppg	25	12	13	24	13.0 ppg	60 bbl	1293 ft	49	10
4	OBM	13.4 ppg	33	9	13	31	13.0 ppg	60 bbl	1293 ft	54	13
5	OBM	13.0 ppg	36	14	17	40	13.0 ppg	60 bbl	1293 ft	62	15
6	OBM	13.2 ppg	29	12	12	20	13.0 ppg	90 bbl	2852 ft	62	15
7	OBM	13.0 ppg	27	9	13	28	13.0 ppg	60 bbl	1293 ft	57	12
8	OBM	13.2 ppg	36	13	14	24	13.0 ppg	90 bbl	2852 ft	49	15

Table 4 – OBMR and Cement Properties for All Jobs

Job #	OBMR Density	OBMR Volume	PV	YP	Cement Density	Cement Volume	Cement Excess
1	9.5 ppg	100 bbl	2	0	13.2 ppg	608 bbl	16%
2	9.5 ppg	100 bbl	2	0	13.2 ppg	605 bbl	10%
3	13.0 ppg	100 bbl	25	4	13.2 ppg	833 bbl	5%
4	13.0 ppg	100 bbl	25	4	13.2 ppg	826 bbl	5%
5	13.0 ppg	100 bbl	25	4	13.2 ppg	831 bbl	5%
6	13.0 ppg	60 bbl	25	4	13.2 ppg	831 bbl	5%
7	13.0 ppg	100 bbl	43	6	13.2 ppg	953 bbl	5%
8	13.0 ppg	60 bbl	43	6	13.5 ppg	818 bbl	40%

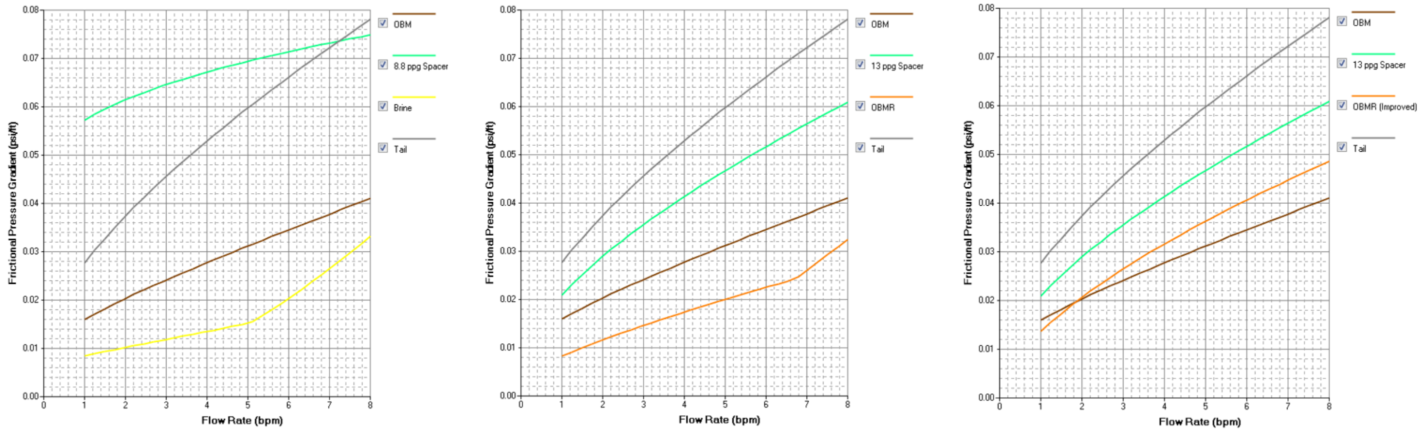

Figure 1 – Friction pressure plots of the following scenarios, from left to right: Original scenario with lightweight spacer and brine, original scenario with weighted spacer and OBMR, proposed scenario with weighted spacer and OBMR.

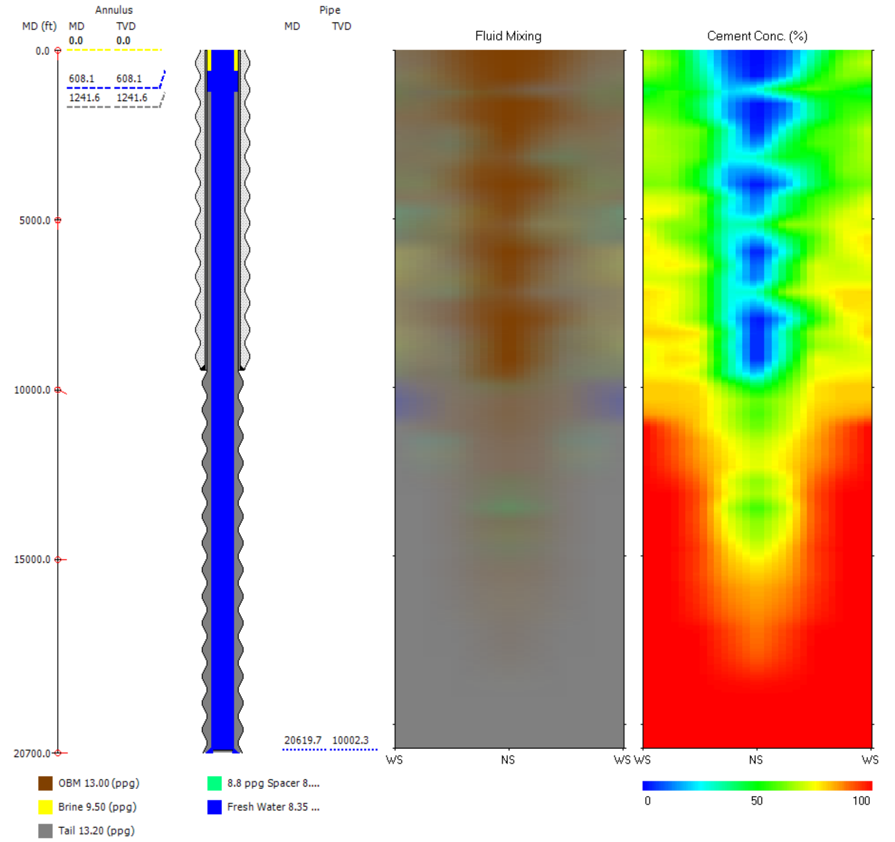

Figure 2 – Expected fluid concentrations at the end of the job with original lightweight spacer and brine pumped ahead of cement.

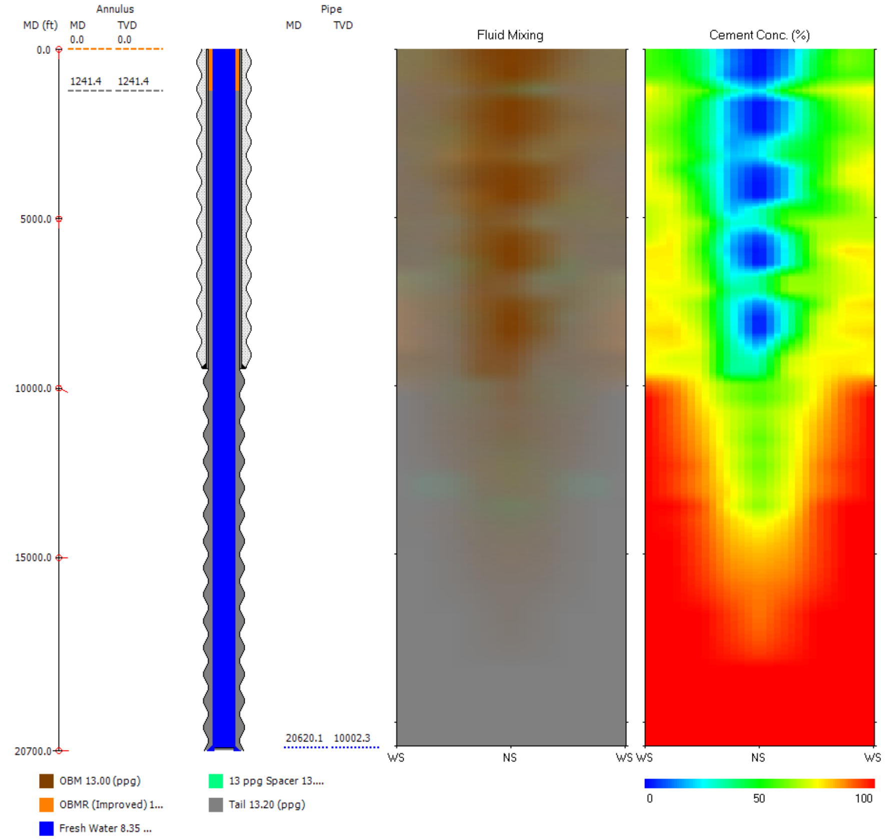

Figure 3 – Expected fluid concentrations at the end of the job with weighted spacer and optimized OBMR rheologies

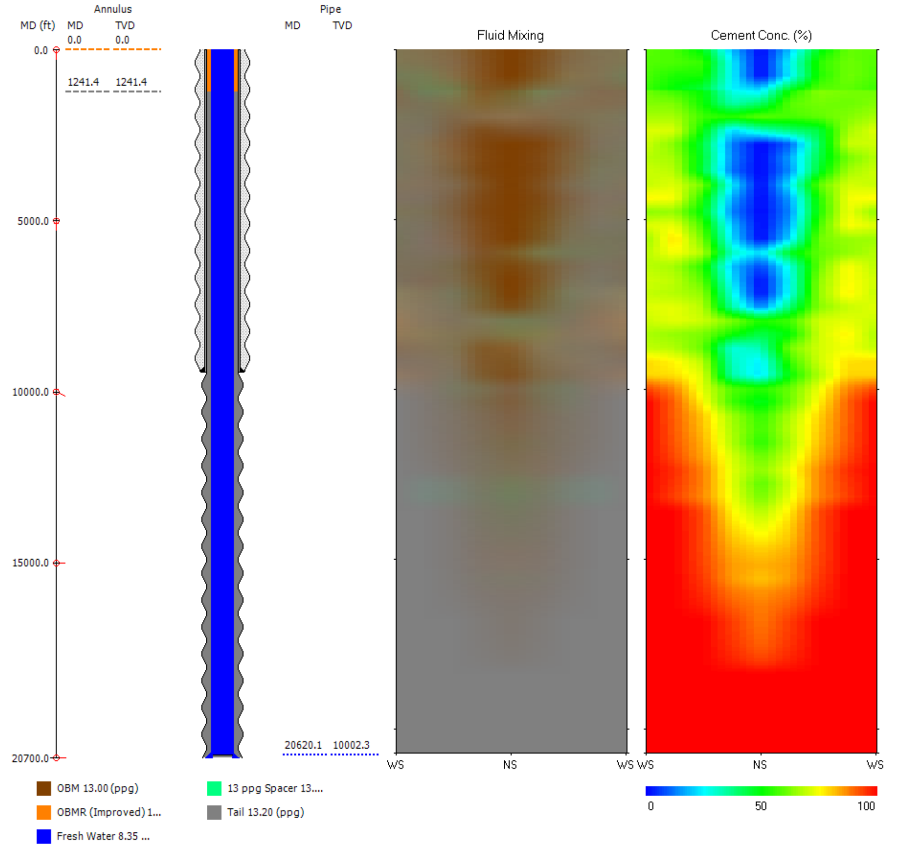

Figure 4 – Expected fluid concentrations at the end of the job with weighted spacer, optimized OBMR rheologies, and improved centralization

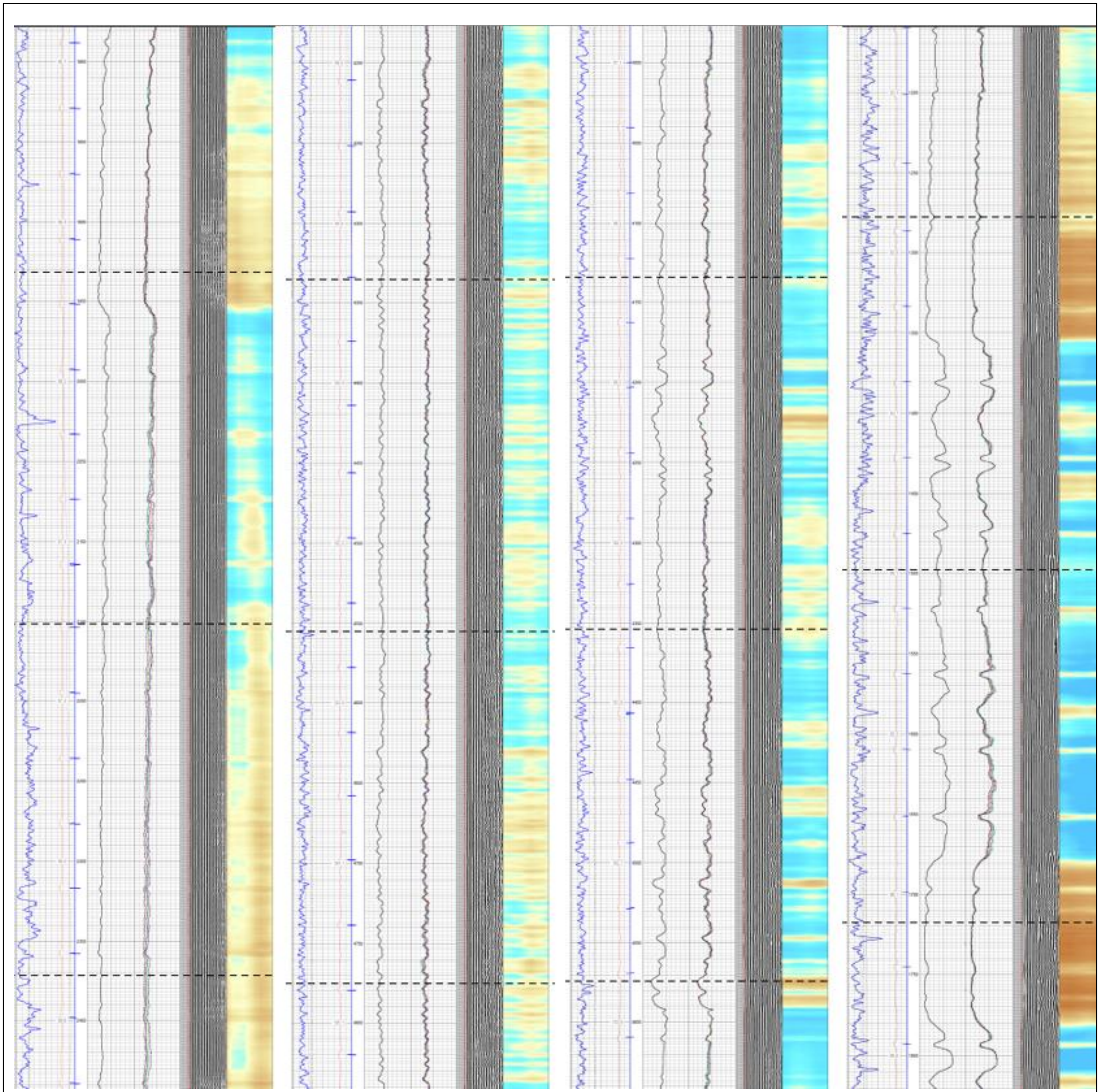

Figure 5 – From L to R, CBL Snips of TOC for Jobs #1 to #4

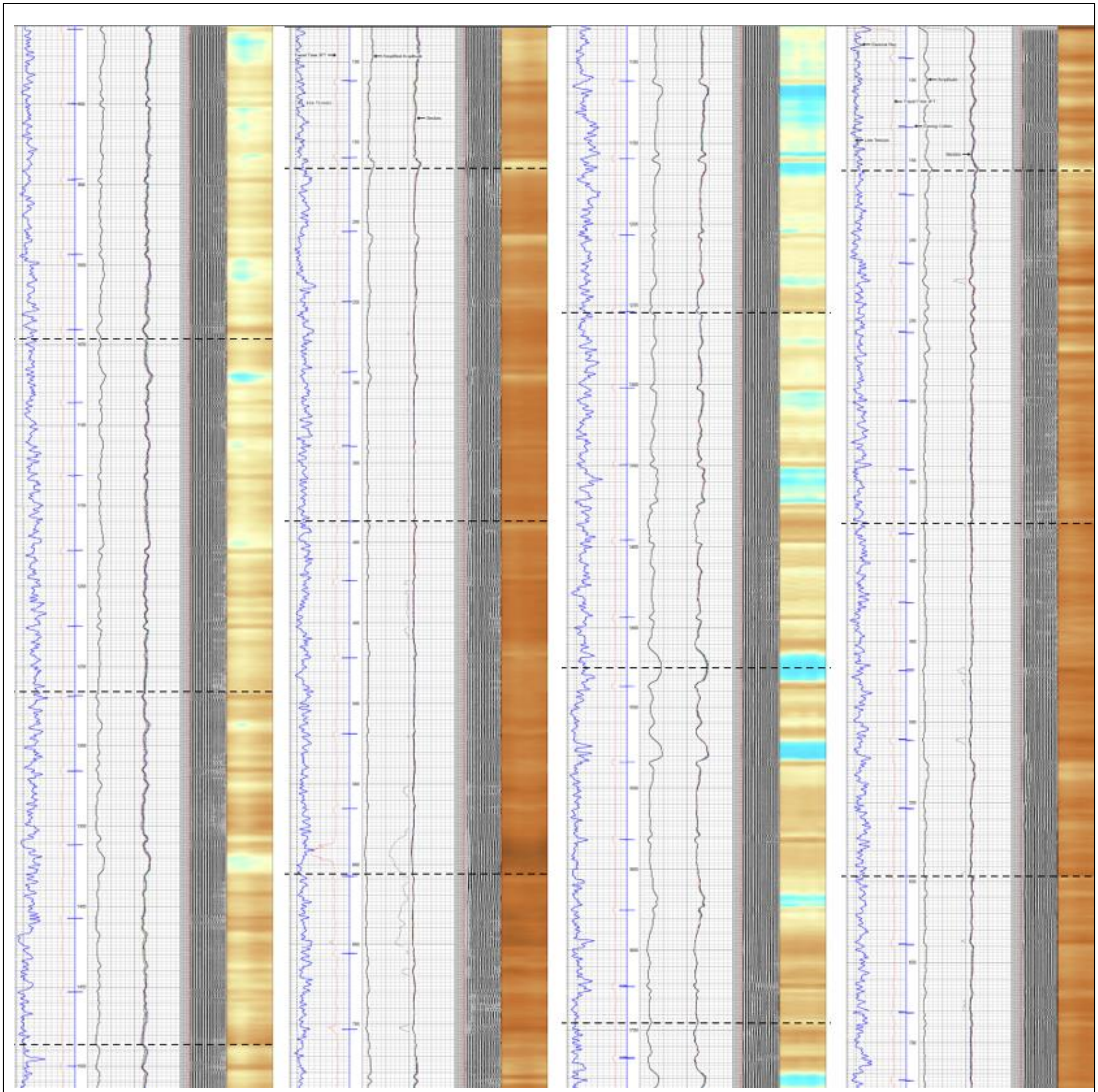

Figure 6 – From L to R, CBL Snips of TOC for Jobs #5 to #8

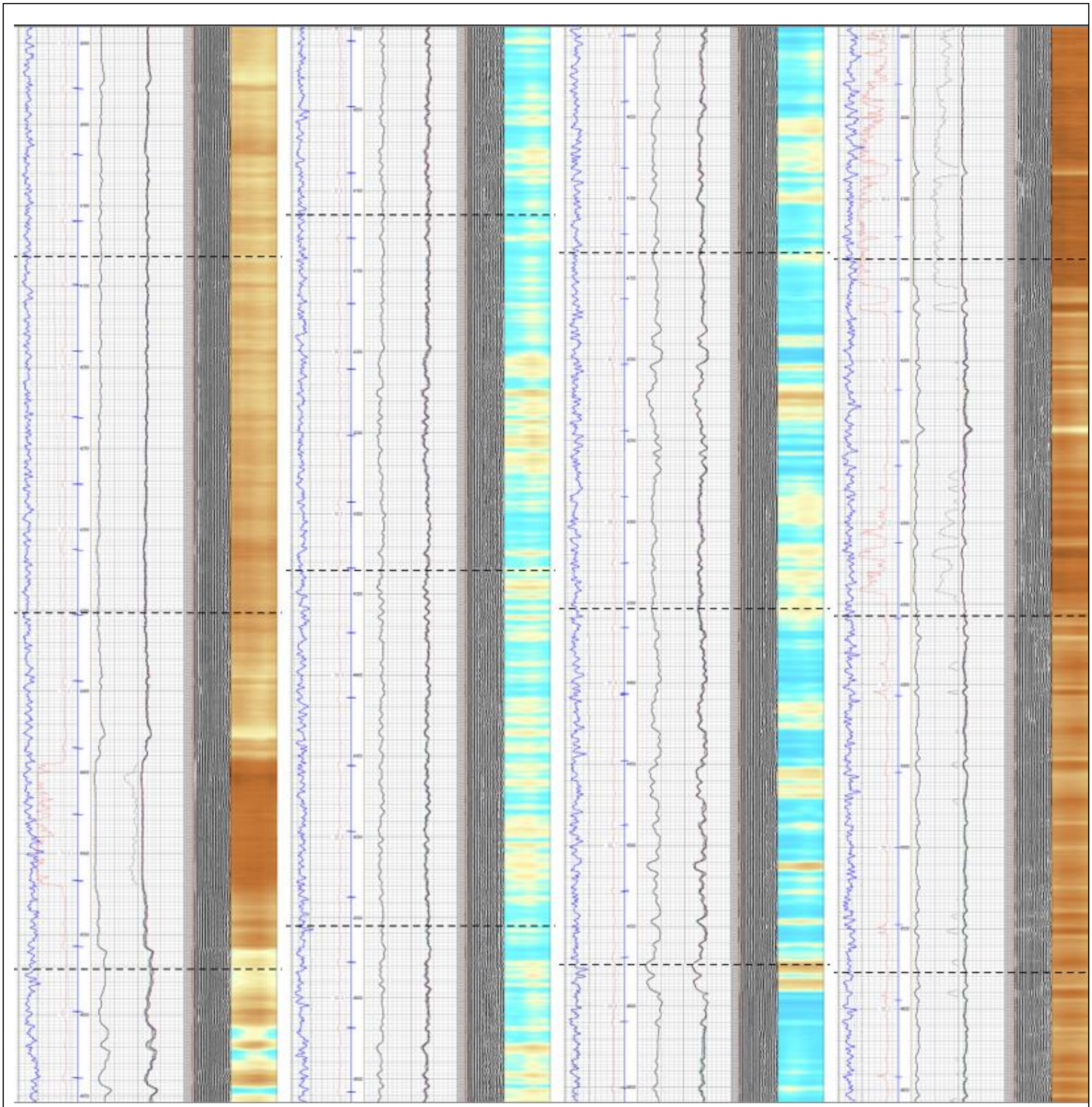

Figure 7 – From L to R, CBL Snips of 4,000 – 4,500' for Jobs #1 to #4

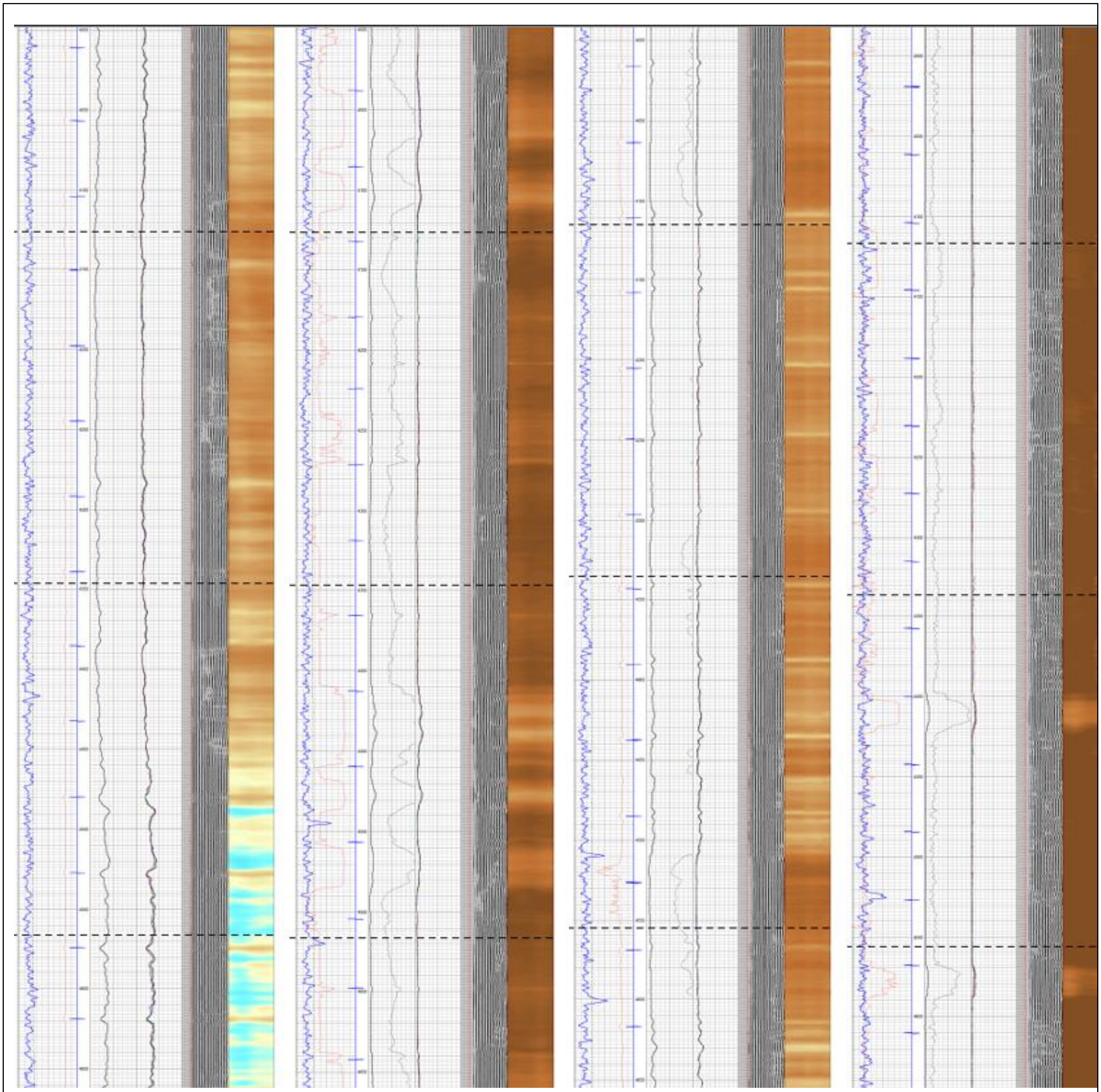

Figure 8 – From L to R, CBL Snips of 4,000 – 4,500’ for Jobs #5 to #8