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The efficient and economical application of a cement slurry programme for sandstone and carbonate reservoirs. A case study of the Zubair, Mauddud, and Mishrif formations in a supergiant oilfield, in southern Iraq

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ABSTRACT This study was accomplished in oil drilling wells located in the Mishrif and Mauddud carbonate formations and in the Zubair sandstone formation to ensure safer, efficient, and economical cementing operations, a better bond between the cement, casing, and formation, and a better isolation between the zones. Moreover, it was also undertaken to obtain competitive cement at the shoe. The study developed a cement slurry programme of 1.55 lead and 1.9 SG tail slurry for both the primary and secondary stages in well WQ1-XX0, as well as a new programme for the wells that would follow (the same primary stage, and 1.45 and 1.75 SG for the secondary stage), so as to improve the casing and cementing stability and reduce costs. The results indicated that well problems were gradually reduced in wells WQ1-XX1 and WQ1-XX2 and were entirely eradicated in well WQ1-XX3. The reduction in cement cost was 62% (from 0.756 to 0.47 barrels per metre), and the cement shows good bonding at the top of productive formations (Mishrif, Mauddud, and Zubair). The problems and costs in the Zubair sandstone and Mauddud carbonate formations were higher than in the Mishrif formation, and the programme adopted would prove to overcome them all. The lightweight high-performance slurry, with a specific gravity of 1.45, achieved the objectives of liner cementing in the Mishrif wells without involving any losses.

Key words: slurry, casing, Mishrif, Mauddud, Zubair, VDL logs.

1. Introduction

Cement casing quality is essential to guarantee safe and extended operations of various types of wells, obtained with different drilling criteria, such as oil/gas production wells, water injection wells, CO_2 injection wells, and CO_2 sequestration wells (Zhang *et al.*, 2010). There is an optimal density difference in mud-cement density to provide the best displacement efficiency (E_D) at a given inclination and eccentricity under laminar flow conditions (Bu *et al.*, 2016). During cementing, the bottom-hole pressure is even greater than during drilling due to the cement slurry density being higher than that of mud. In order to overcome the loss of circulation and the related consequences, it is necessary to apply suitable drilling and cementing processes with acceptable methods and to carefully select materials to plug the loss zones (Gaurina-Međimurec *et al.*, 2021). The factors that influence E_D are effective standoff and the effective mud properties prior to the cement job, caliper log and deviation profile, flow rates during the cement job, and spacer composition in accordance with the effective mud properties (Lavrov and Torsater, 2016).

Wellbore construction practices are complex. Documented challenges posed by sustained casing pressure, related to poor zonal isolation, can affect production and may require significant well reconditioning interventions (Maganga, 2011). Being typical processes to prevent fluid migration, slurry designs should be gas-tight (Kwatia *et al.*, 2019). Well cement shrinks when tested under high temperature and pressure. Such shrinkage may result in a loss of cement hydrostatic pressure, conceivably driving gas seepage to the surface. Specific compositions increase the slurry yield of the cement and/or will reduce the water content and decrease shrinkage (Chenevert and. Shrestha, 1987; Bu *et al.*, 2018). In deviated wells, solids, settling from the drilling fluid to the low side of the hole, may adversely affect mud displacement during cementing (Mahmoud *et al.*, 2020). Large-scale laboratory cementing experiments confirm that, in a deviated wellbore, solids settling from the drilling fluid can cause a continuous mud channel, which will remain along the low side of the cemented annulus (Assi and Almehdawi, 2021). Highly deviated and horizontal wells of offshore oil fields require much consideration and pose challenges in relation to cementing quality, which is greatly influenced by the E_D of cement slurry (Sabins, 1990). Highly deviated wells are considerably significant compared with conventional vertical wells, which are not always feasible in reaching the reservoirs. In addition, highly deviated wells can save investments by reducing the number of wells and increasing productivity by improving the contact area between the wellbore and reservoir (Bu *et al.*, 2016). The improved quality of the cement slurry and set cement were tested in different types of cement of the American Petroleum Institute classification in horizontal wells, and the results were compared to conventional pozzolanic materials, which are currently used to increase the cement properties. Innovative micromaterials provide excellent slurry stability, free water control, particulate suspension, and additional fluid loss control in order to obtain superior set cement properties, including high early compressive and tensile strengths, extremely low permeability, and zero shrinkage (Pernites *et al.*, 2018). The reasonable placement of casing centralisers is the key to controlling casing eccentricity and ensuring E_D, especially in highly deviated wells (Renteria *et al.*, 2019).

Cementing has faced many problems with carbonate zones (Brandl *et al.*, 2014). Improving the cement bond across carbonate reservoirs is critical for future drilling in order to avoid remedial cement works and production problems (Velayati *et al.*, 2015). The finding of the most suitable type of cement, formula, properties, and cementing tools for cementing carbonate zone sections must be considered (Quan *et al.*, 2016).

The field tests proved that the eccentricity limit model helped increase the cementing quality in highly deviated wells, indicating that the casing eccentricity was reasonably controlled (Wang *et al.*, 2022). The design aspects of the horizontal wells include the selection of bit and casing sizes, detection of setting depths and drilling fluid density, casing, hydraulics, well profile, and construction of drill string simulators (AL-Jawad *et al.*, 2014). Experience and best practices established in order to deal with drilling challenges in the West Qurna-2 field, such as Tanuma shale instability, loss of circulation, and high vibration, provided the technical and operational recommendations for performing within a large integrated contract that includes logistics and communication difficulties (Vedernikova *et al.*, 2016).

Formation arrival, the acoustic signal passing through the formation, gives an indication of the bonding between casing and cement, and cement and formation (Kadhim *et al.*, 2022). A variation of the formation arrival trend represents lithology variance (Reijmer *et al.*, 2022). A weak formation signal occurs in washout or high porous zones. Poor bonding between cement and formation could create a connection between the top and bottom of the zone (Bai *et al.*, 2022).

The fried egg, or galaxy, patterns are created by the interference between casing resonance and reflections from the outer casing or solid formation due to casing decentralisation (Harris, 2021). The sign of patterns shown in the tool response, such as a high amplitude reading and visible casing signal, on the Variable-Density Log (VDL), are shown for conditions like thin cement sheath, partial or no cement bond. The Circumferential Acoustic Scanning Tool (CAST) response is low acoustic impedance showing channels or void space for partial or no cement bond on the impedance map (Alvarado *et al.*, 2021).

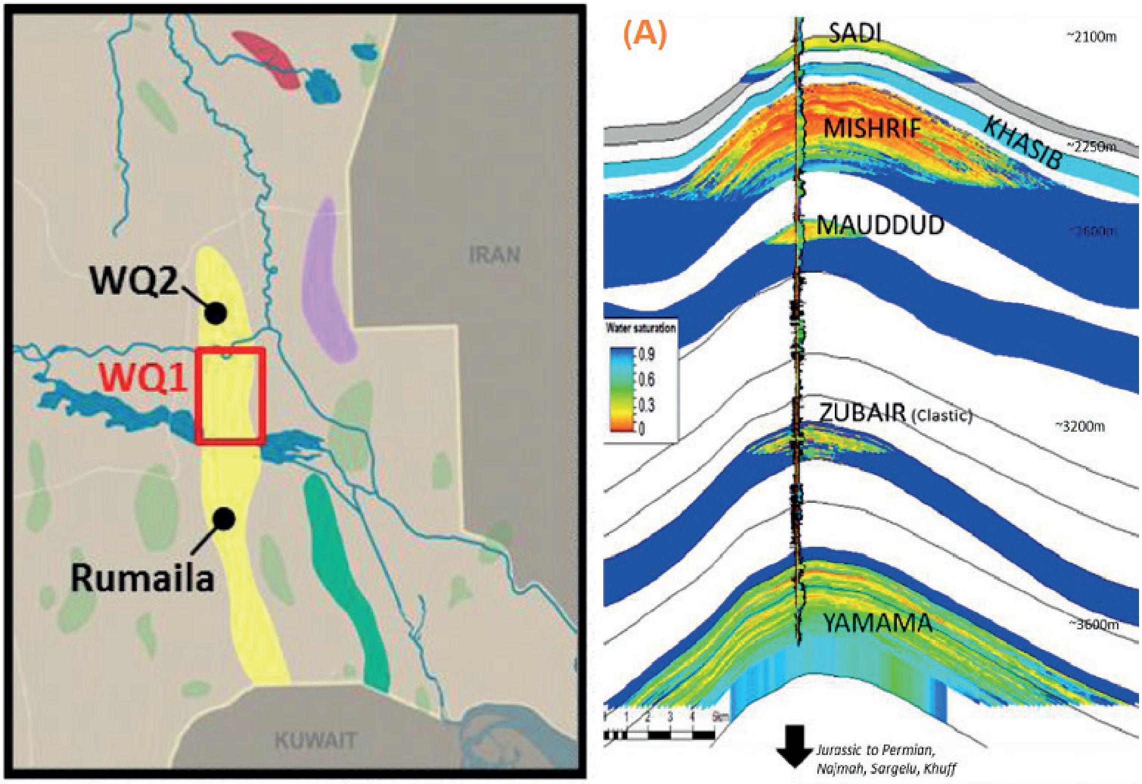
This study tried to investigate the best cement programme for wells located in carbonate and sandstone formations to improve efficiency and cost-effectiveness by studying different types of cement slurry. The previous applications of the cement programme in wells, earlier to WQ1-XX0, depended on the first-stage slurry with a specific gravity of 1.9 and the second-stage of 1.55, which led to a higher cost and loss of circulation.

2. Geological setting

The studied area covers southern Iraq, and is included within the Mesopotamian zone (Fig. 1B). The West Qurna oilfield covers an area of 340 km² (Ali and Al-Zaidy, 2020). Mishrif is the most prolific reservoir of the West Qurna 1 (WQ1) field, located approximately 50 km NW of Basra city in south-eastern Iraq (Fig. 1A). The oilfield is part of a large anticline, which is oriented north-NW and extends over 120 km (Al-Dujaili *et al.*, 2021a).

The Basra Oil Company has previously divided the Mishrif formation into five stratigraphic zones, two of which are caprocks with poor reservoir quality (Al-Dujaili *et al.*, 2021b). This study has translated this zonation into a sequence-stratigraphic framework (Fig. 2). The main producing intervals, from the oldest to the youngest, are the mB2, mB1, and mA. Caprock intervals (associated with sequence boundaries) are present at the top of the mB1 and mA intervals (Al-Dujaili, 2023; Al-Dujaili *et al.*, 2023c). The Rumaila formation corresponds to the mC zone at the Mishrif base. Pressure data show that most Mishrif zones (including the mC zone) are in pressure communication in response to primary depletion, with the exception of lower mB2 and mC in the south-western part of the field (Aqrawi *et al.*, 2010; Al-Dujaili *et al.*, 2023a). The electro and lithofacies model indicated that the Mishrif formation consists of 62% carbonates, 24% shale, and 14% coarse sand (Al-Dujaili *et al.*, 2023b).

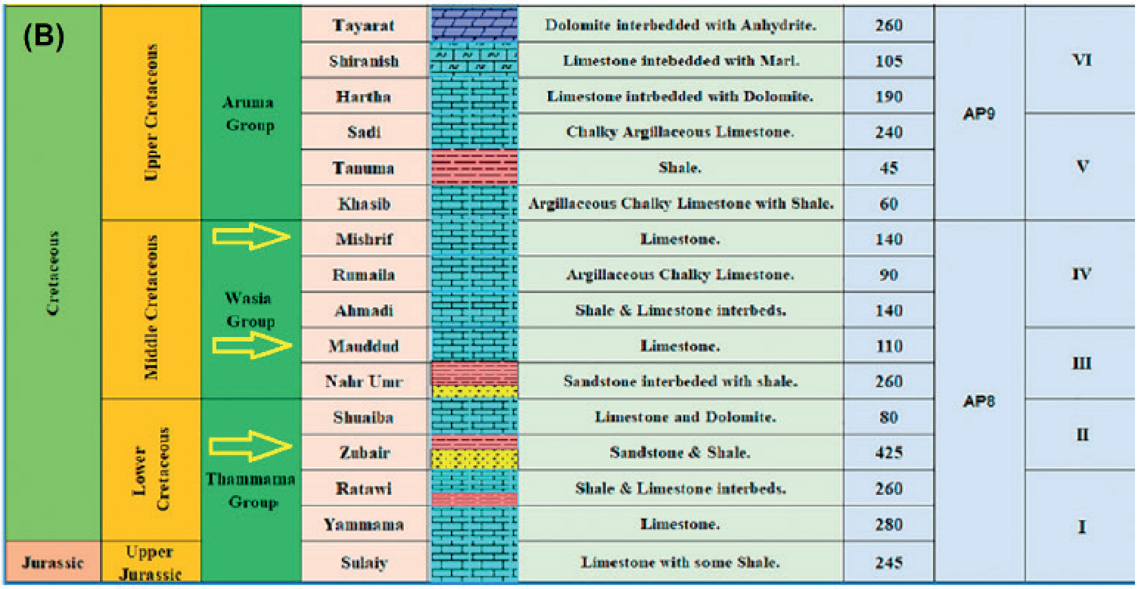
The Mauddud formation (of the Albian-Early Cenomanian age) is dominated by bioclasts (approximately 23%) and peloids (approximately 60%), whereas intraclasts are less abundant (approximately 2.3%). The sedimentary microfacies of the Mauddud formation include lime mudstone, wackestone, wackestone-packstone, packstone, packstone-grainstone, dolostone lithofacies, and green shale lithofacies. The formation displays various extents of dolomitisation and is cemented by calcite and dolomite. It has gradational contact with the underlying Nahr Umr formation but is unconformable and overlain by the Ahmadi formation, despite local conformity (Al-Dabbas *et al.*, 2012). Several shales, acting as seal rocks, were deposited during the Cretaceous period. Only some of the compacted shales formed efficient seals, leading to no producible oil from the Mauddud formation in some of the southern Iraq oilfields. However, the formation is an essential reservoir in the Middle East due to the inefficiency of the Ahmadi shale formation as a caprock or due to the presence of shale beds in the upper part of the Nahr Umr formation, which act as caprocks and which may, generally, prevent vertical charging of overlying reservoirs (Abeed *et al.*, 2013).



Mishrif
- **OOIP= 42 GBO,**
- Production Rate ~450 kbd;
- ~270 producers (~170 active) , 100 injectors
- GOR 500, API 23

Mauddud (Undeveloped)
- **OOIP= 2 GBO**
- Perm 1 to 10; Dead Oil GOR 50 ; API 25
- 1 horizontal producing appraisal well (~1 kbd production)

Zubair
- **OOIP= 1.4 GBO**
- Prod Rate: ~30 kbd ; 10 active producers
- Water Injection recently initiated
- Variable GOR, API 24/32



(B)								
Cretaceous	Upper Cretaceous	Aruma Group	Tayarat		Dolomite interbedded with Anhydrite.	260	AP9	VI
			Shiranish		Limestone intebedded with Marl.	105		
			Hartha		Limestone intrbedded with Dolomite.	190		
			Sadi		Chalky Argillaceous Limestone.	240		V
			Tanuma		Shale.	45		
			Khasib		Argillaceous Chalky Limestone with Shale.	60		
	Middle Cretaceous	Wasia Group ⇨	Mishrif		Limestone.	140	AP8	IV
			Rumaila		Argillaceous Chalky Limestone.	90		
			Ahmadi		Shale & Limestone interbeds.	140		
		⇨	Mauddud		Limestone.	110		III
			Nahr Umr		Sandstone interbeded with shale.	260		
	Lower Cretaceous	Thammama Group	Shuaiba		Limestone and Dolomite.	80		II
		⇨	Zubair		Sandstone & Shale.	425		
			Ratawi		Shale & Limestone interbeds.	260		I
			Yammama		Limestone.	280		
Jurassic	Upper Jurassic		Sulaiy		Limestone with some Shale.	245		

Fig. 1 - A) Location and the main reservoirs of the field (by researchers). B) Stratigraphic column for southern Iraq (Mahdi and Aqrawi, 2014).

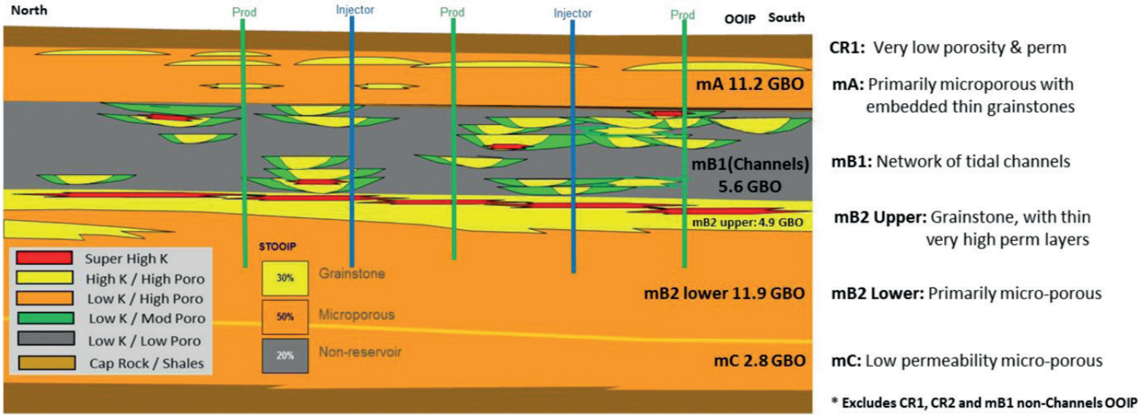


Fig. 2 - Depositional environment and properties of the Mishrif units (by researchers).

The Mauddud highstand sequence displays a lateral change in lithology, ranging from good quality grainstones, in the northern and central part of the field, to lower quality peri-tidal packstone/wackestone facies, in the southern part of the field (Fig. 3). Most Mauddud lithofacies present moderate porosity and low permeability, with microporosity as the dominant pore type. Intervals with enhanced reservoir quality can be related to fracturing and faulting or to the presence of rudist floatstone to rudstone facies (Al-Dabbas *et al.*, 2012) (Fig. 3).

The proposed sequence-stratigraphic framework and the sequence-stratigraphy-keyed facies scheme result in a predictable distribution of reservoir and seal facies and allow for a better prediction of the vertical and lateral distribution of reservoir quality and reservoir continuity both on a field scale and regional scale (Van Simaeys *et al.*, 2015).

The Zubair formation is a large part of the Lower Cretaceous sequence in Iraq, extending in Iraq, the Persian Gulf region, Syria and Iran, and designated as the prevalently terrigenous clastic and oil-bearing sequences of the southern oilfields of Iraq (Ali and Nasser, 1989; Al-Ameri *et al.*, 2011).

The Shuaiba formation corresponds to the upper limit of the Zubair formation (the Albian sequence), which is predominantly a conformable and gradation surface, while the Ratawi formation is the lower contact with an unconformable surface (Ali and Al-Zaidy, 2020) (Fig. 4).

The Zubair formation consists of 55% of shale, which represents almost 70% of wellbore problems due to incompatibilities between drilling fluids and shale formations. The design and selection of appropriate drilling fluids are the most common and effective solution to solve shale instability (Abbas *et al.*, 2018). Chronologically, wellbore problems in the Zubair formation were related to wellbore instability and represented over 90% of the problems (Abbas *et al.*, 2018). The upper sandstone consists of various sandstone units isolated by shale units (Al-Jaberi and A-Jafar, 2020).

An unconsolidated sandstone reservoir is an essential and unconventional oil and gas resource with the characteristics of low porosity, low permeability, high heterogeneity, and many interlayers (Wang *et al.*, 2020). The main challenge posed by an unconsolidated sandstone formation is sand production in oil wells, and in the more severe situations, the occurrence of high-pressure oil and gas escaping, blowout accidents, environmental pollution, and the safety of operators (Zeng and You, 2021). To solve the sensitivity problem of loose sandstone, a low-density admixture was developed. A new low-density cement has been prepared to overcome

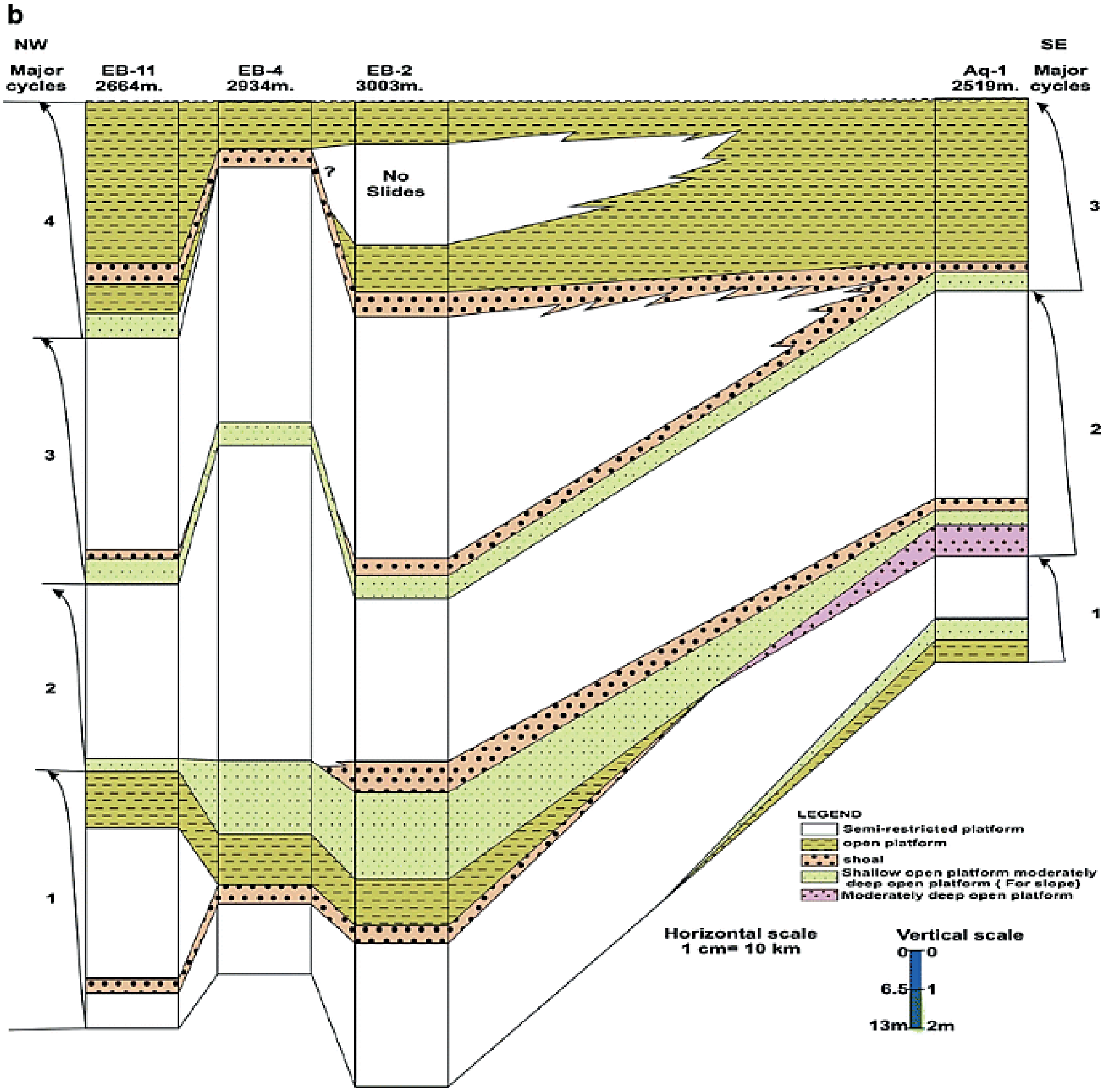


Fig. 3 - Lithology, facies distributions, depositional environments of the Mauddud formation (according to Al-Karadaghi, 2001).

the sensitivity issue of loose sandstone at 1.4- to 1.7-g/cm3 density. The cement slurry exhibits good rheological properties, less thickening time, less than 50 ml of water loss, and a 24-hour compressive strength of over 12 MPa (Zeng and You, 2021).

3. Materials and methods

The current study included the Mishrif, Mauddud, and Zubair deviated and horizontal produced wells (WQ1-XX0, WQ1-XX1, WQ1-XX2, and WQ1-XX3). The only changes expected in the new wells will be the number of centralisers, which depend on the actual well profile and cement slurry volumes, based on the actual well depth and hole size. Calculations were

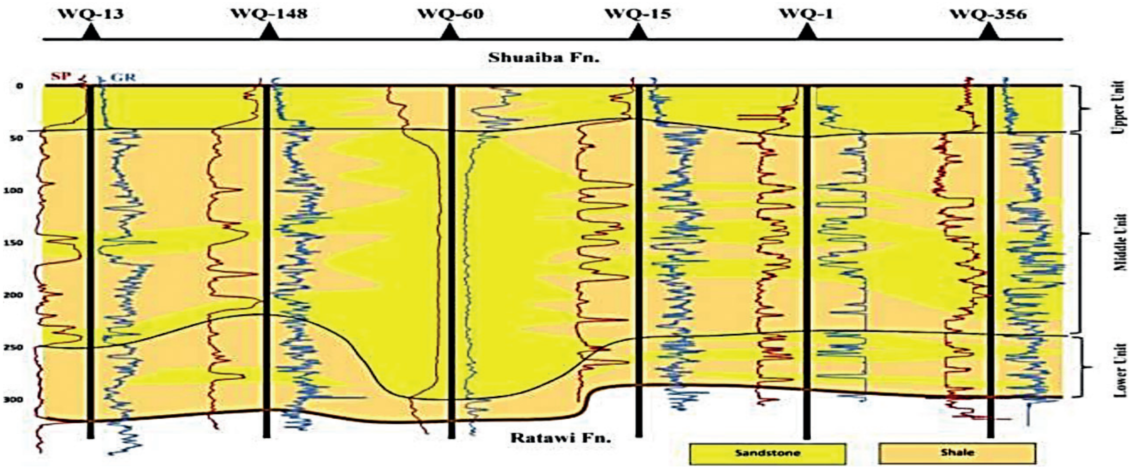


Fig. 4 - Cross-section of the main Zubair formation units (Ali and Al-Zaidy, 2020).

based on the drilling process of the new deviated well (WQ1-XX7 oil producer well). Each well studied in this work has four casings (20” conductor, 13.3/8” surface, 9.5/8” production casings, and 7” production liner strings) cemented into the reservoir. A 4.5” additional un-cemented production liner was applied to the Mishrif horizontal well and Mauddud horizontal well with the same cementing process. Lost circulation of the slurry, in the Dammam and Hartha formations, and sulphurous water, present in the Tayarat formation, must be considered for a successful drilling and cementing process. This study provides the primary decision that will affect the design of the slurry programme and selection process, and the elements that provide assurance for such design in carbonate and sandstone reservoirs. The justification for the cement design will be based on the risk associated with reaching the primary job objectives.

To ensure that all pre-job cement designs, laboratory testing, and job preparations were completed in time to perform the job, it was essential to provide the time-sensitive data. Pressurised or atmospheric conditioning was testable below 190 °F. The appropriate heat-up schedule for the wells was followed (Fig. 5 and Table 1).

Fig. 5, drawn by Powerdraw^{TM}, indicates that well WQ1-XX0 followed the previous slurry programme (1.9 and 1.5 SG). Wells WQ1-XX1, WQ1-XX2, and WQ1-XX3 were experimented with a new programme having different specific gravities of lead, tail slurry, and mud.

Fluid loss tests were performed at a differential pressure of 1,000 psi against a 325-mesh screen at the Bottom Hole Circulating Temperature (BHCT) of the well. Free water, or free fluid, tests were carried out on the vertical or deviated wells at 45 degrees. Free water is the fluid separated from the cement slurry during the test. A spacer compatibility test with muds and (or) cement slurries was limited to the rheological determination of the various fluids and performed at the BHCT or at 180 °F, whichever the lower value. A minimum of three systems were tested consisting of fluid ratios of 95/5, 50/50, and 5/95 for fluid1 and fluid2 and other combinations of spacer and mud according to the results of the rheology testing. A thickening time, for the mixture consisting in 50% drilling mud and 50% spacer, for spacers with oil-based or non-aqueous muds, was recommended.

An ultrasonic cement analyser (UCA) was utilised to determine the strength development of a cement sample while it was being cured under downhole temperature and pressure conditions. In addition, the duration that cement slurry remains in a fluid state and is capable

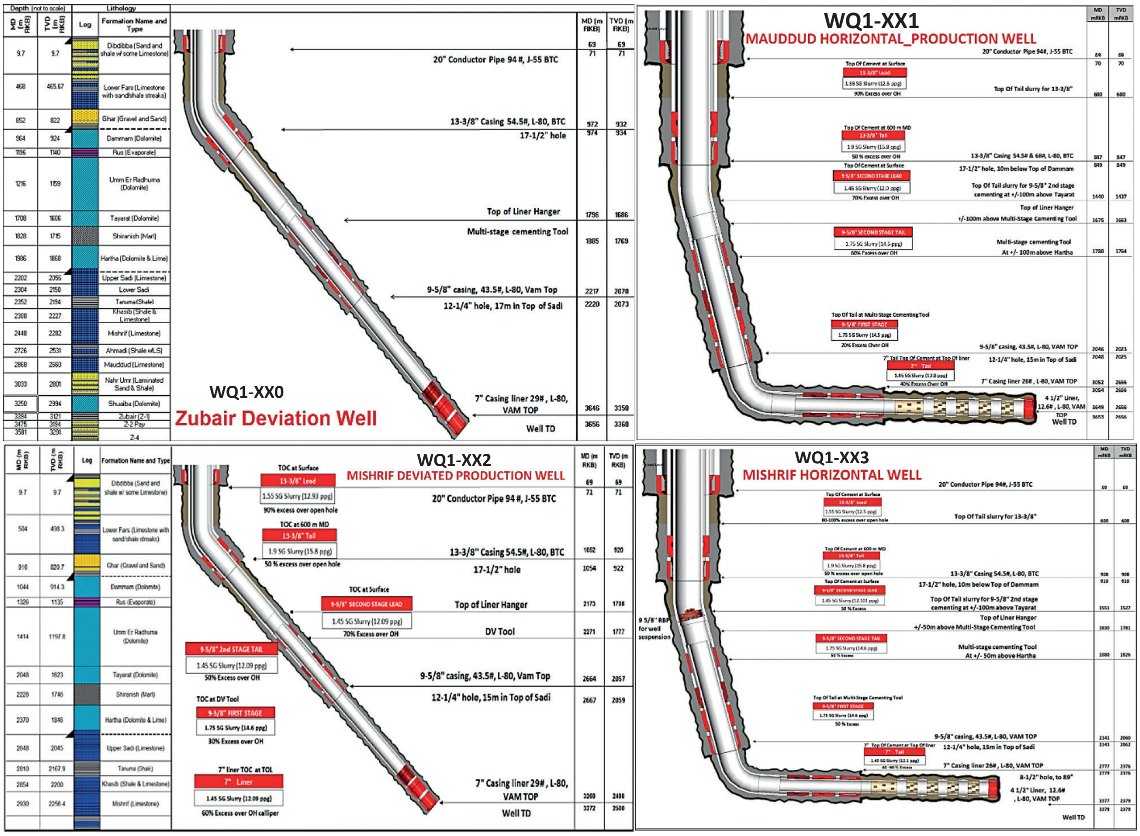


Fig. 5 - Well scheme and lithology by Powerdraw^{TM}.

of being pumped was identified. Thickening time is assessed under downhole conditions using a pressurised consistometer that plots the viscosity of slurry over time under the anticipated temperature and pressure conditions. The rheology, static gel strength, and fluid loss of the cement slurry were calculated and recommended.

In general, the acquisitions of Cement Bond Log (CBL) and CAST data are the best data quality. There is no indication of poor tool centralisation or observed bad shots influenced by the borehole or fluid behind the casing that will affect the tool reading.

CBL VDL and amplitude (AMP) data seem to be affected by micro-annulus, such as casing signal and high amplitude readings, which were observed throughout the whole log interval.

Advanced Cement Evaluation (ACE) processing was conducted to analyse data using the variance technique on waveform [message (MSG)/VDL] acoustic impedance (ZP) to help evaluate cement bond profiles in detail among top formations and zonal isolation in between formations.

The ZP is fragmented into nine segments and five variances per segment. The high variation activities indicated solid, which was observed throughout the whole log interval.

3.1. Changes in WQ1-XX3 plans

The cementing programme for well WQ1-XX3 was changed according to the drilling problems in wells WQ1-XX0, WQ1-XX1, and WQ1-XX2.

Table 1 - Casing sections for the wells under study.

Well no.	Casing strings	Conductor pipe from the rotary kelly bushing	17.1/2” hole section	13.3/8” hole section	12.1/4” hole section	9.5/8” casing	8.1/2” hole section	7” liner	6.1/8” horizontal hole	4.1/2” prediller liner
WQ1-XX0	3	69 m	drilled across the Dibdibba, Lower Fars, Ghar, and Dammam	run and cemented at 972 m measured depth (MD)/931 m TVD, 9 m into Dammam	drilled across Dammam, Rus, UER, Tayarat, Shiranish, and Hartha	run and cemented at 2,217 m MD/2,070 m TVD, 17 m into Sadi	drilled across Sadi, Tanuma, Khasib, Mishrif, Ahmad, Mauddud, Nahr Umar, Shuaiba and Zubair (3,656 m MD)	run and cemented at 3,646 m MD, with top of the liner hanger at 1,796 m MD		
WQ1-XX1	3	69 m	drilled across the Dibdibba, Lower Fars, Ghar, and Dammam	set and cemented at 846.6 m MD/ 846.6 m TVD, 9 m into Dammam	drilled across Dammam, Rus, UER, Tayarat, Shiranish, Hartha, and Sadi	run and cemented at 2,046 m MD/2,022.7m TVD, 19 m into Sadi	drilled across Sadi, Tanuma, Khasib, Mishrif, Ahmadi and Mauddud	run and cemented at 3,052 m MD with the top of the liner hanger set at 1675 m MD	drilled across Mauddud with well total depth (TD) at 3,653 m MD/2,656 m TVD	with 6 Swell Packers was run and set across horizontal hole section with Bull plug set at 3,649 m MD and top of 4 ½” liner set at 2,995 m MD
WQ1-XX2	3	69 m	drilled across Dibdiba, Lower Fars, and Ghar and into the Dammam formations	run and cemented at 1,052 m MD/922 m TVD, 10 m below the top of Dammam	drilled across Dammam, Rus, UER, Tayarat, Shiranish, and Hartha	was run and cemented in two stages at 2,664 m MD/2,054 m TVD, 15 m into Sadi	drilled across Sadi, Tanuma, Khasib, and Mishrif up to 3,272 m MD/ 2,500 m TVD	was run and cemented at 3,269 m MD with top of the liner hanger at 2,173 m MD		
WQ1-XX3	4	32 m	drilled across Dibdiba, Lower Fars, and Ghar and Dammam	set and cemented at 914.5 m MD	drilled across Dammam, Rus, UER, Tayarat, Shiranish, Hartha, and Sadi	run and cemented at 2,006 m MD/2,001 m TVD		was run and cemented at 2,398 m MD with the top of the liner hanger set at 1,413 m MD	drilled across Mishrif with well TD at 2,466 m TVD /3,281 m MD	run and set across horizontal hole section with Bull plug set at 3,289 m MD and top of liner set at 2,349 m MD

The well landing point (7’’ shoe) changed from -2,779 m to -2,708 m. The 6.1/8’’ hole trajectory changed the azimuth of the well from 4° to 16° and increased the section length. According to the new directional plan, the true vertical depth of the well became -2,368 m, and, then, the depth was changed again to -2,369 m due to difficulty in turning the well. The well depth was at -3,200 m [-2,370 m true vertical depth (TVD)]. A bypass bottom plug was placed in the first stage of the cementing process. Liquid chromatography (LC) material (Steel Seal 400) was added to the lead slurry and lead XS cement (Slumberger MUDPUSH family) to apply the effective laminar flow technique, combining several criteria to achieve optimum mud removal at low flow rates for salt systems, which were increased from 60% to 132% when cement losses occurred during circulation once the casing was at the bottom. A suitable sleeve was used (fitted in the landing joint before rigging the cement head).

4. Results

After the slurry programme was used for well WQ1-XX0 as shown in Table 2, the programme was changed according to lost circulation, high flow rate, additional duration time, and high slurry volume (Table 3). After hydro-jet, casing inspection was performed to evaluate the casing (Fig. 6).

Table 2 - Slurry programme for well WQ1-XX0. SG=Specific gravity, bbl=barrel.

Well no.	Description	Density (SG)	Rate (bbl/min)	Volume (bbl)	Duration (min)
WQ1-XX0- 1st stage	Lead slurry Tail slurry Mud	1.55 1.9 1.11	6 4-6 2-6	513 222 599	90 66 98
WQ1-XX0 2nd stage	Lead slurry Tail slurry Mud	1.55 1.9 1.1	4 4 4	367 174 457	91.8 57 102.2

Table 3 - Drilling problems in well WQ1-XX0.

Well no.	Formation	Drilling problems
WQ1-XX0	Shuiba and Mishrif	Encountered losses
	Nahr Umr	Hole instability

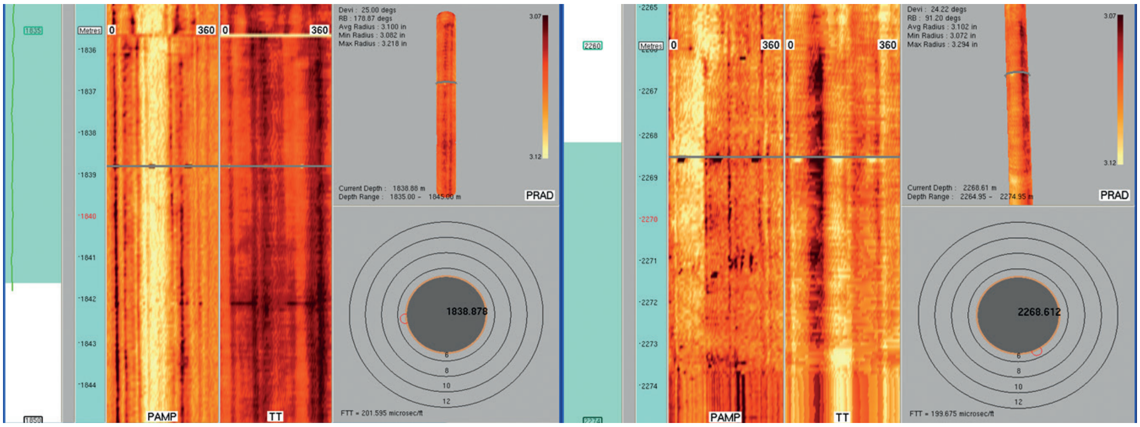


Fig. 6 - WQ1-XX0 casing inspection after hydro-jet at 1,838.8 m and 2,668.6 m.

The cement programme failed due to circulation losses, hydra-jet perforation failure (following 25 hours of non-productive time), and pressure test problems with cement lines and pressure sensors. Although the casing was perforated, there was no indication of a 100% slurry penetration into the annulus. The total damage across the joint section was 31% (top interval) and 49.5% (bottom intervals), which was calculated by the Chime™ software by the Halliburton company.

A new programme was conducted on the following wells to overcome these problems. This new programme was based on the experimental results of two kinds of slurry (1.75 and 1.9 SG) design in well WQ1-XX1, performed to find the best E_D and equivalent circulating density (ECD) (Table 4 and Fig. 7). The cementing problems were reduced in wells WQ1-XX1 and WQ1-XX2 and were eradicated in well WQ1-XX3 (Table 5). Both 1.75 and 1.9 SG slurry designs increase the E_D up to ± 95%, and both 1.75 and 1.9 SG slurry designs have approximately the same ECD (with a 0.01 SG difference), E_D with 1.55 SG = 90%, and 1.45 SG = 85% (Figs. 8 and 9).

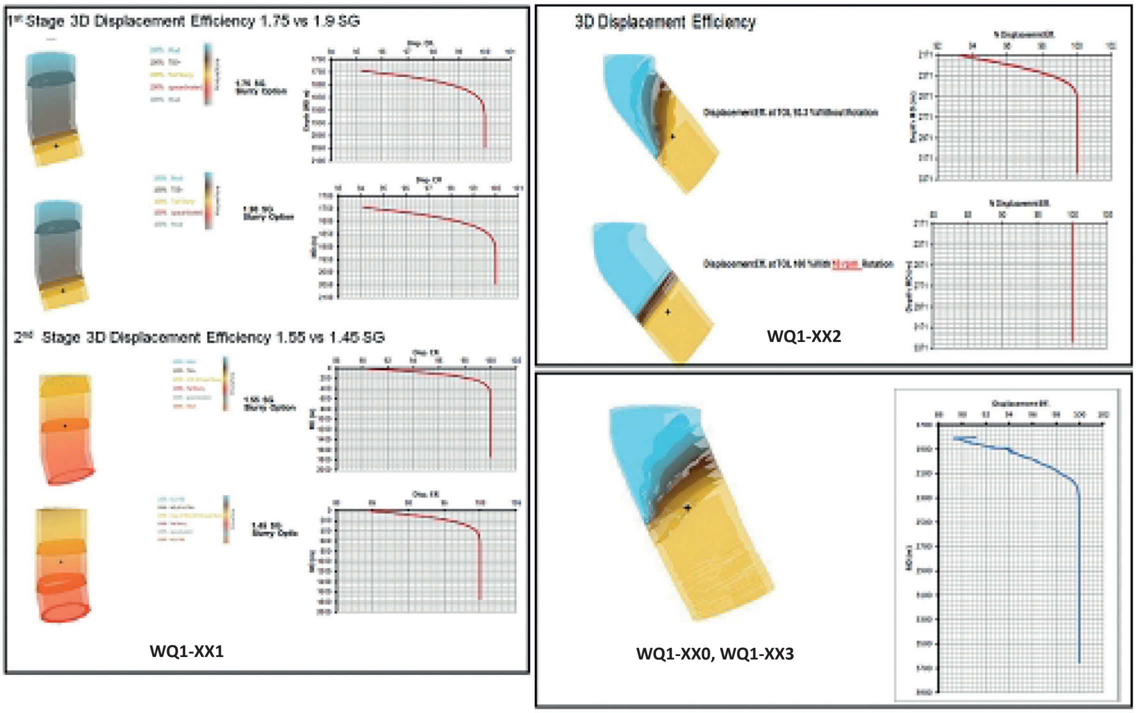


Fig. 7 - Left: the 3D E_D comparison for well WQ1-XX1. Right: the 3D E_D for wells WQ1-XX2 and WQ1-XX3.

According to Figs. 8 and 9, no significant changes in Down Hole Pump (DHP) and ECD occurred in the first stage between the 1.75 and 1.9 SG cement, while changes were clearly observed in ECD in the second stage only with 1.75 SG tail slurry and 1.55 versus 1.45 SG lead slurry.

The CBL-CCL (Casing Collar Locator)-GR (Gamma Ray) CAST tool suite was run with TPL operation in the WQ1-XX0 well, in a seven-inch liner. According to well WQ1-XX0, the CBL-VDL CAST log showed good results (Fig. 10).

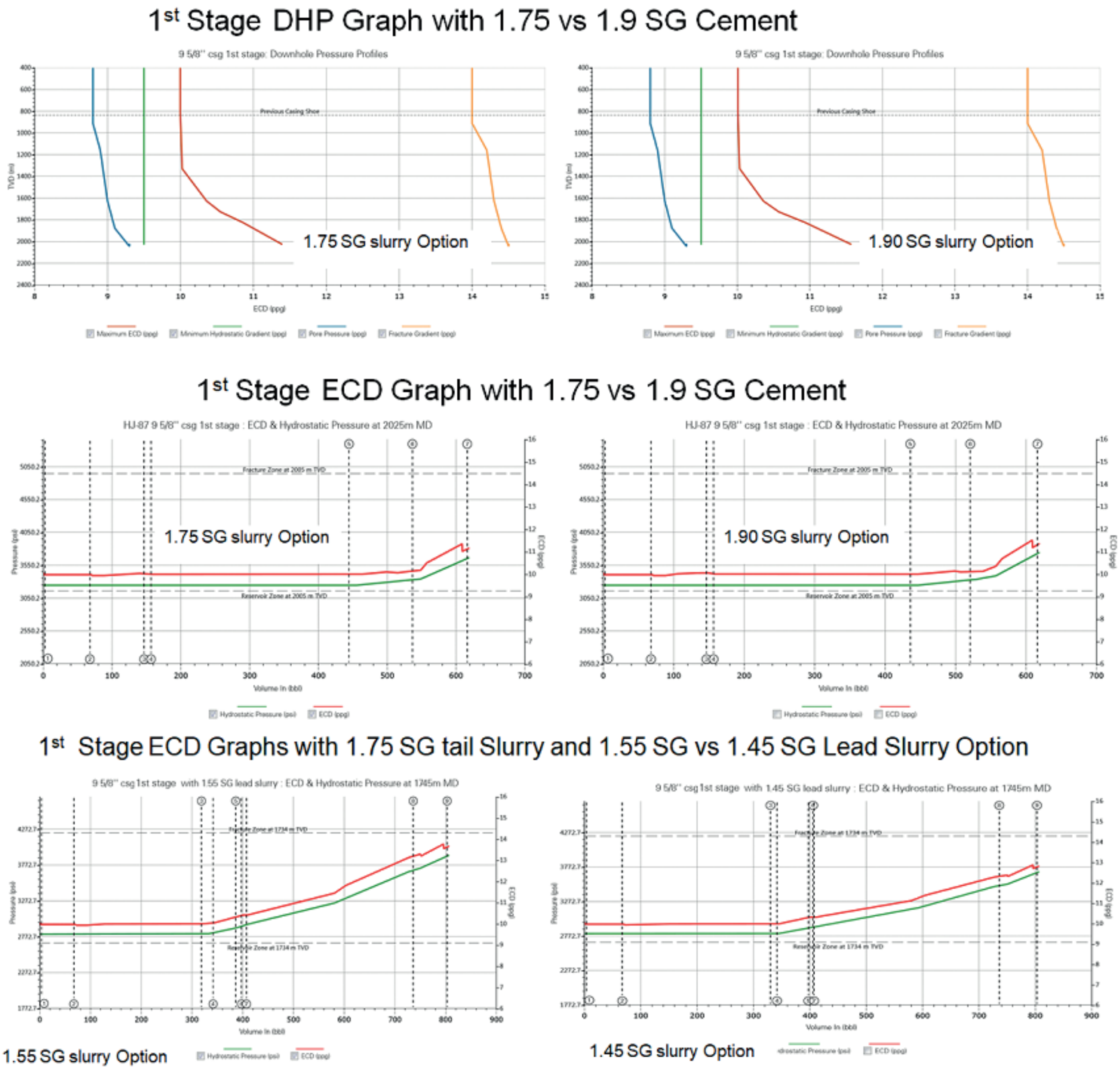


Fig. 8 - DHP, ECD and hydrostatic pressure (slurry in the 1st stage) for well WQ1-XX1.

Fig. 10 shows that the cement bond graded from free to poor bonding at the top section above 2,450 m, and the low cement activity above 2,300 m, indicates less solid bonding, with a squeeze interval in the depth interval between 1,800 and 2,350 m.

Table 6 shows that the percentage of the total volume of slurries to the depth of the well decreased according to the new cement programme. The type of cement bonding was improved as the drilling of new wells continued.

In washout or highly porous zones, poor bonding between the cement and formation could create a connection between the top and bottom of the zone. Casing resonance interference and reflections from the outer casing or solid formation could lead to ‘fried egg’ or galaxy patterns due to casing decentralisation. Thin cement layers and partial or no cement bonding may result in a high amplitude reading and visible casing signal on the VDL log. Low acoustic impedance indicates the presence of channels or void space due to partial or no cement bonding (Fig. 10).

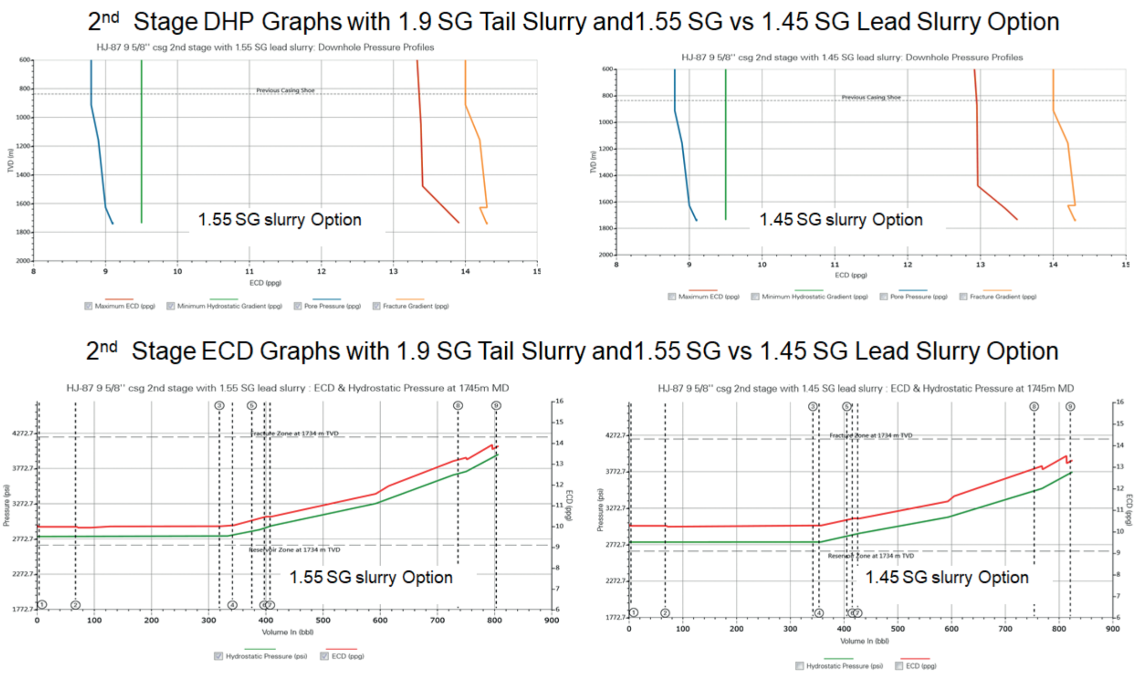


Fig. 9 - DHP, ECD and hydrostatic pressure (slurry in the 2nd stage) for well WQ1-XX1.

Table 4 - Slurry programme for wells WQ1-XX1, WQ1-XX2, and WQ1-XX3.

Well no.	Description	Density (SG)	Rate (bbl/min)	Volume (bbl)	Duration (min)
WQ1-XX1- 1st stage	Lead slurry Tail slurry Mud	1.55 1.9 1.23	4-5 5 6	451 164 399	115 44 81
WQ1-XX1 2nd stage	Lead slurry Tail slurry Mud	1.45 1.75 1.14	3.5 3-5 2-7	357 105 150	102 34 76
WQ1-XX2 1st stage	Lead slurry Tail slurry Mud	1.55 1.9 1.23	5 5 3-8	452 283 496.15	90.33 56.58 82.88
WQ1-XX2 2nd stage	Lead slurry Tail slurry Mud	1.45 1.75 1.12	5 5 2-7	600.1 509.39 547.35	120.02 24.68 93.62
WQ1-XX3 1st stage	Lead slurry Tail slurry Mud	1.55 1.9 1.1	5 5 2-6	429.05 204.73 428.77	85.81 40.87 78.92
WQ1-XX3 2nd stage	Lead slurry Tail slurry Mud	1.45 1.75 1.14	5.6 5 2-8	108 87.02 208	22.74 17.4 56

Table 5 - Drilling problems in wells WQ1-XX1, WQ1-XX2, and WQ1-XX3.

Well no.	Formation	Drilling problems
WQ1-XX1	Dammam and Hartha	Encountered losses
WQ1-XX2	Dammam and Hartha	Encountered losses
	Saai	0.50 degree/30 m drop while drilling
WQ1-XX3		No problems (LC cement plugs were used)

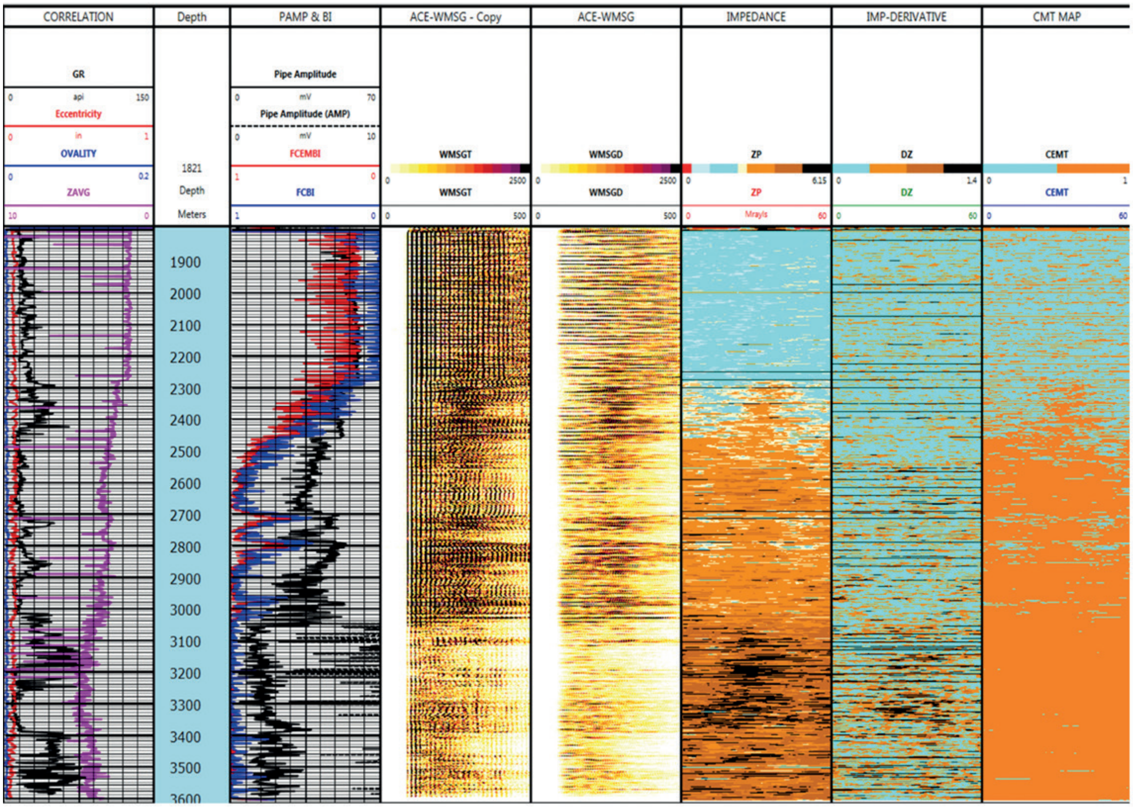


Fig. 10 - Cement evaluation by CBL-VDL CAST log for 7” open hole (WQ1-XX0).

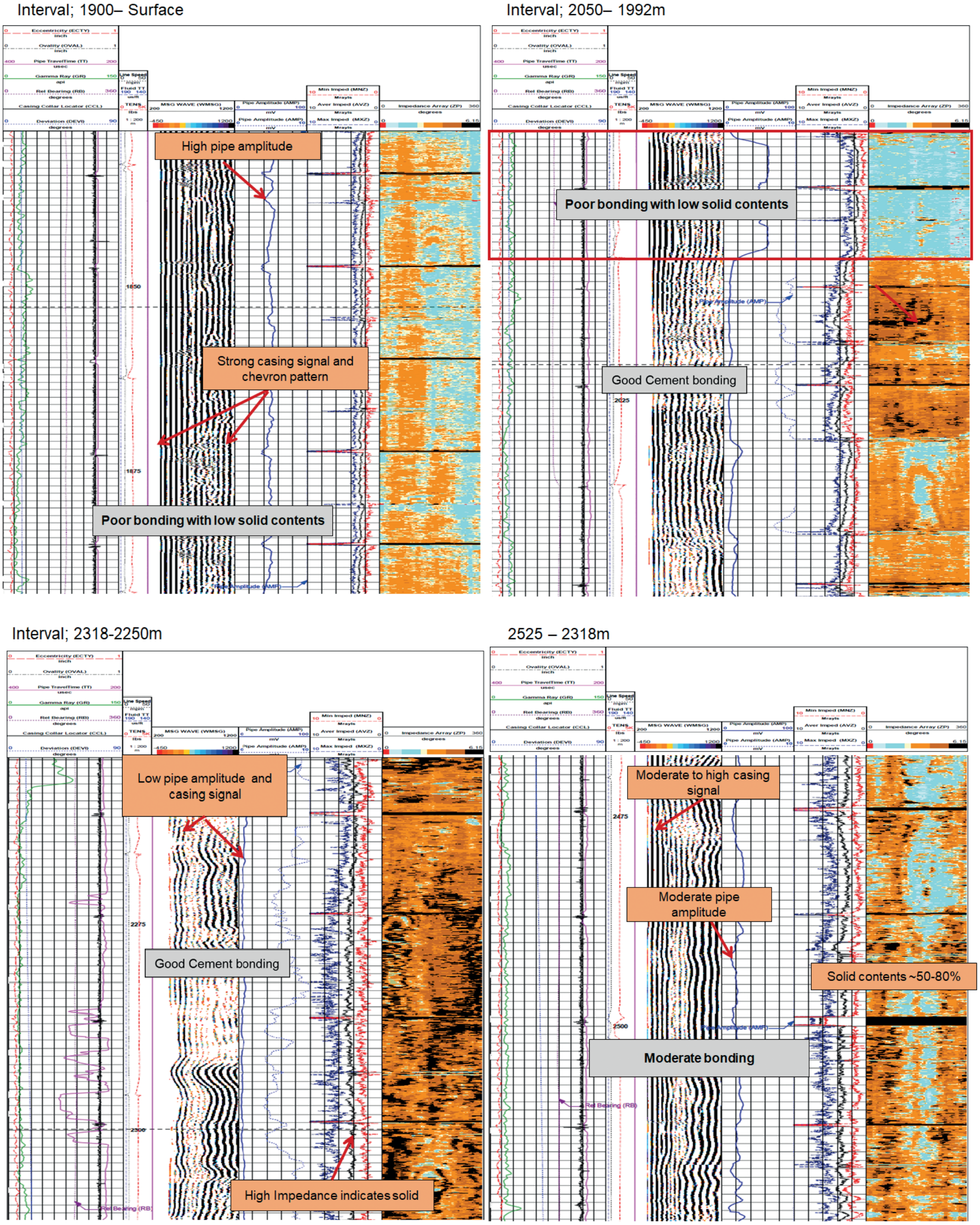
Table 6 - The volumes of slurries used in the 17.5’’ hole section for the wells under study.

Well no.	Depth (m)	Excess, lead/tail (%)	Volume of lead (bbl)	Volume of tail (bbl)	Total volume of slurries (bbl)	Volume of pure cement on the surface (bbl)	Total slurries volume to depth (bbl/m)
WQ1-XX0	972	100/60	513	222	735	140	0.756
WQ1-XX1	847	90/50	451	164	615	113	0.726
WQ-XX2	1052	90/50	452	289	741	180	0.50
WQ-XX3	914.5	80/50	429	204.4	633.4	182	0.47

Good bonding with moderate to low pipe amplitude, high impedance in CAST, and formation arrival, according to a VDL between 2,950 and 3,150 m, was noticed in well WQ1-XX1. Partial bonding with moderate pipe amplitude and impedance map showed a solid content of approximately 40% to 70%, at depths from 1,650 to 1,850 m. Poor bonding to free pipe showed high amplitude, low impedance, and strong resonance in VDL at depths from 2,200 to 2,275 m. High pipe amplitude and solid contents in the impedance map were observed in the transition zone at depths from 2,275 to 2,475 m (Fig. 11).

According to Fig. 12, the 9.625” casing for well WQ1-XX2 presents a strong casing signal and chevron pattern, high pipe amplitude, and solid contents (circa 10% to 30%). Insufficient bonding with low solid contents is noticeable at the surface and up to a depth of 750 m.

From the 750-metre depth to the differential valve (DV) tool, moderate to high pipe amplitude, solid contents of approximately 40% to 80%, partial bonding, DV to total depth (TD) with medium pipe amplitude and casing signal, were observed. A solid content of approximately 80-90% and


Interval; 1900– Surface

High pipe amplitude

Strong casing signal and chevron pattern

Poor bonding with low solid contents

Interval; 2050– 1992m

Poor bonding with low solid contents

Good Cement bonding

Interval; 2318-2250m

Low pipe amplitude and casing signal

Good Cement bonding

High Impedance indicates solid

2525 – 2318m

Moderate to high casing signal

Moderate pipe amplitude

Solid contents ~50-80%

Moderate bonding

Fig. 11 - Cement evaluation by CBL-VDL CAST log for 7” open hole (WQ1-XX1).

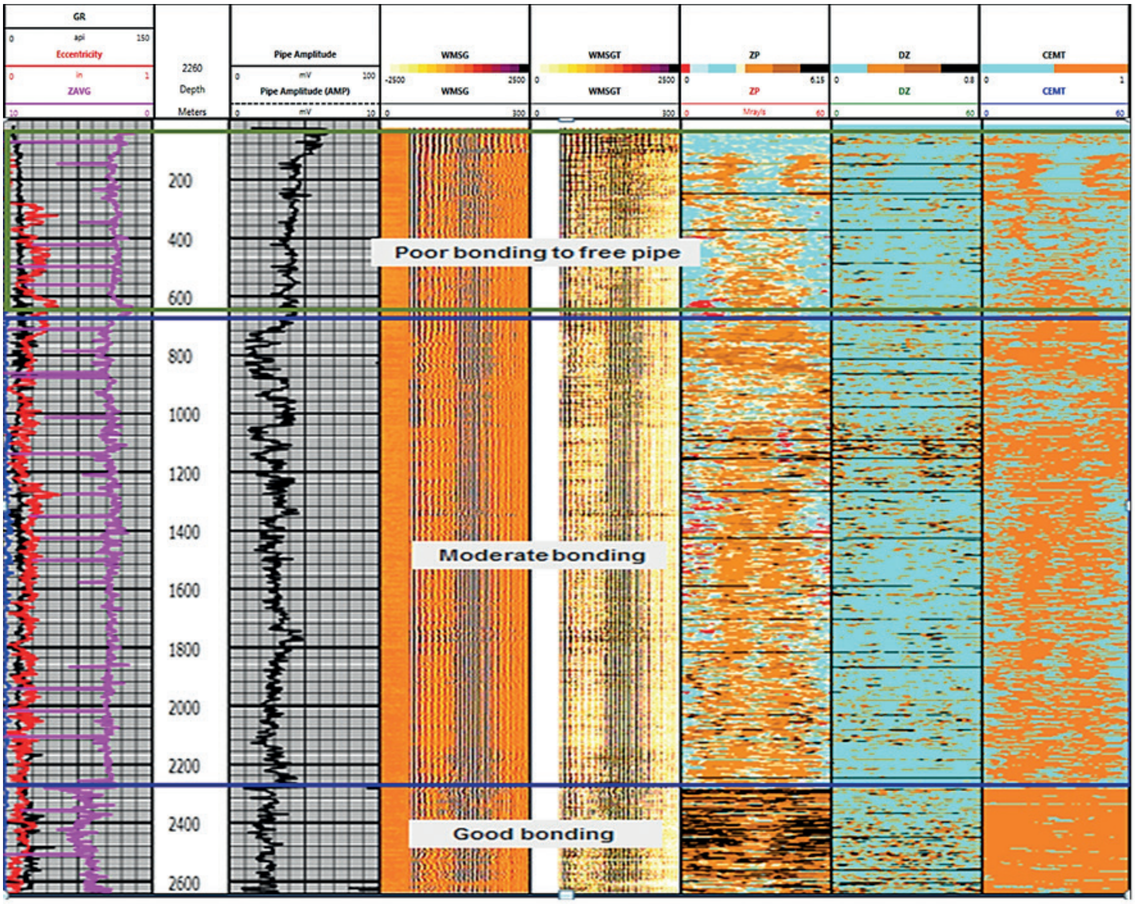


Fig. 12 - Cement evaluation by CBL-VDL CAST log for 9.625” open hole (WQ1-XX2).

good bonding were noticed (Fig. 13). At depths from 2,200 to 2,400 m, partial bonding with solid contents covers 60% to 80%. Moderate bonding is evident at depths from 2,400 to 2,600 m. Partial bonding with solid contents covers 80-90% at depths from 2,600 to 2,750 m. Good cement bonding is noticed at depths from 2,750 to the TD.

For well WQ1-XX3, good bonding and formation arrival were observed at depths from 2,400 to 2,410 m and moderate bonding, moderate pipe amplitude, and solid contents of approximately 30-70% at depths from 2,410 to 2,505 m were observed according to the impedance map, while depths from 2,505 to 2,700 m also showed good bonding (Fig. 14).

5. Discussion

Circulation rates are to be established in accordance with the ECD and annular velocity, and lost circulation cement plugs with 1.44, 1.5, and 1.62 SG were used in case of losses in Dammam, Hartha, and Mishrif, respectively, for well WQ1-XX3 (Table 5), to assist in overcoming the losses.

Based on the statistics of this study (Table 6), well WQ1-XX3 provides the best results with the minimum problems, leaving 70% in the lead interval and decreasing it to 40% in the tail cement

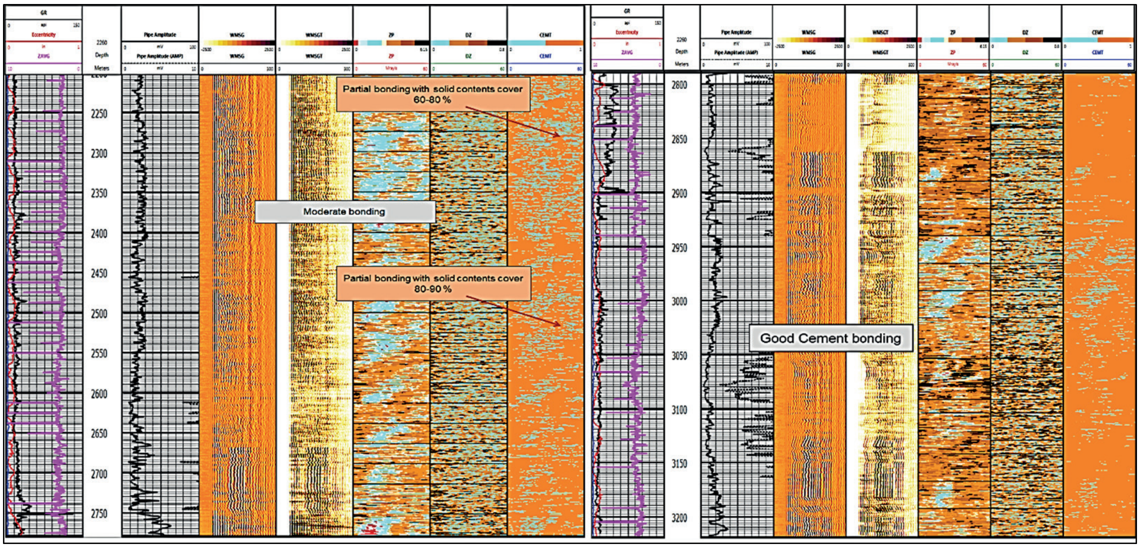


Fig. 13 - Cement evaluation by CBL-VDL CAST log for 7” open hole (WQ1-XX2).

interval. Such results will be beneficial for the purpose of optimising excess for open holes for future drilling wells.

To check the log quality of well WQ1-XX0 (section 9.625) and overcome all possible errors during the logging process, additional logging was performed. Overall, the data quality for well WQ1-XX0 was good. The tool was centred along the interval as indicated by the eccentricity curve (less than 0.2”), except for some intervals with high dog-leg severity (Fig. 15).

The log shows very good repeatability between the main and repeated log (Fig. 16).

The lead XS type was increased from 60% to 132% when losses were observed during circulation once the casing was on the bottom to ensure the lead covered the required interval. This increases the cost in wells WQ1-XX0 and WQ1-XX2.

LC material (Steel Seal 400 type) has been used with lead slurry as losses were observed during circulation once the casing was on the bottom, and this action led to overcome the losses. A suitable sleeve has been fitted in the landing joint before rigging up the cement head, to help the plugs set without sticking inside the collar part of the landing joint for well WQ1-XX3. In addition, the T-bar is used to ensure that the plugs pass the cement head and casing collar below the cement head.

The liner could not run to the designed measured depth (MD) for well WQ1-XX0 (Zubair deviation well) due to the condition of the hole in the last 5 m, so the shoe was set to the MD of 3,646 m, and hole circulation and mud conditioning undertaken prior to the cement job.

The variance of the Z segments (A-I) indicates high activities for solids (cement), and flat variance for no/less cement-free pipe (free pipe) above 1,627 m for well WQ1-XX1 (Fig. 11).

The fried egg, or galaxy, patterns may occur due to the interference between casing resonance and reflections from the outer casing or solid formation. This will be clearly shown in well WQ1-XX3.

A balanced cement plug with 10 bbls of 1.44 SG slurry at 2,276 m and a squeeze job were performed for wells WQ1-XX1, WQ1-XX2, and WQ1-XX3 to overcome all problems encountered in well WQ1-XX0. Moderate pipe amplitude and casing signal are possible due to micro-annulus in well WQ1-XX2.

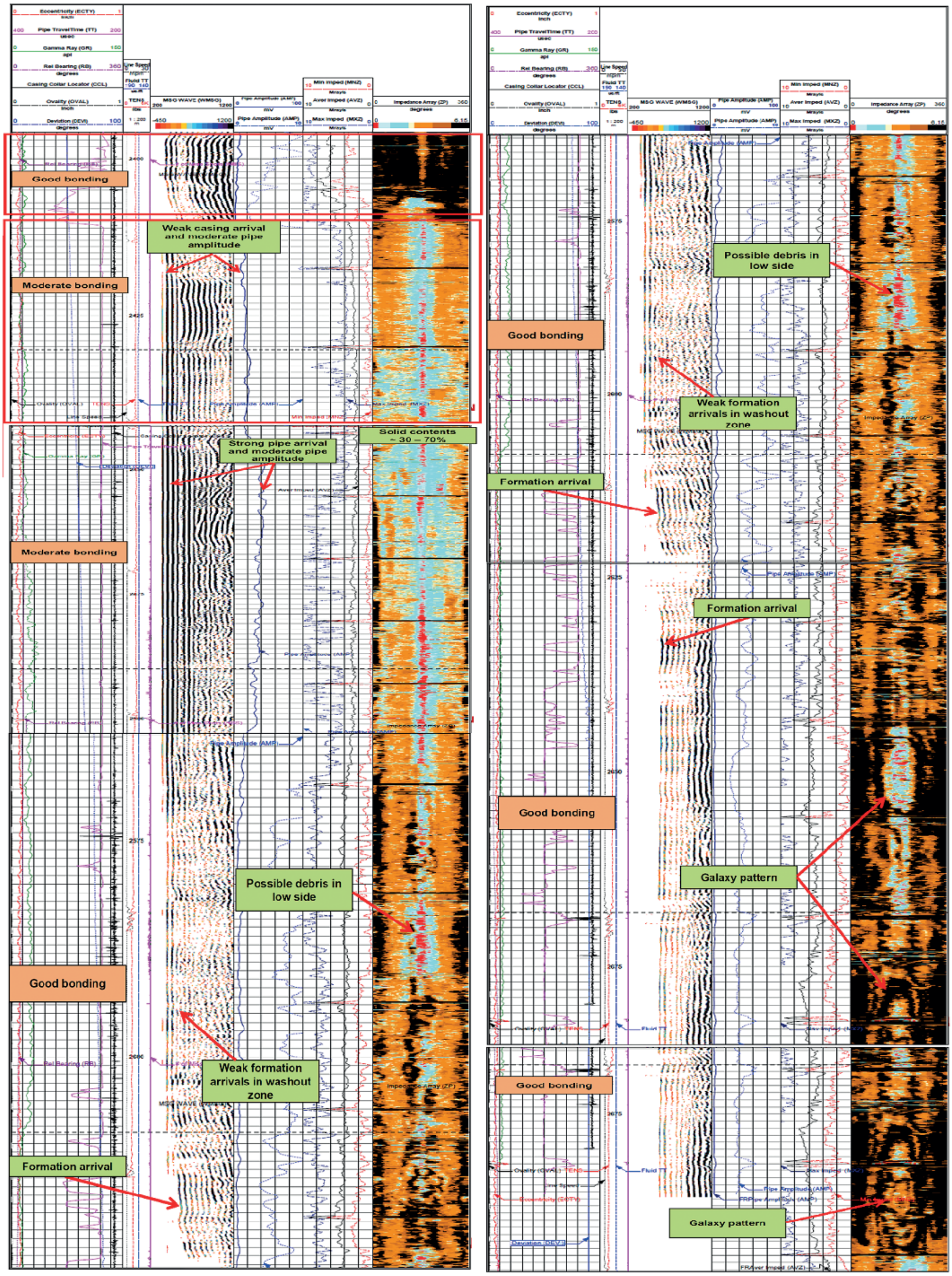


Fig. 14 - Cement evaluation by CBL-VDL CAST log for 7” open hole (WQ1-XX3).

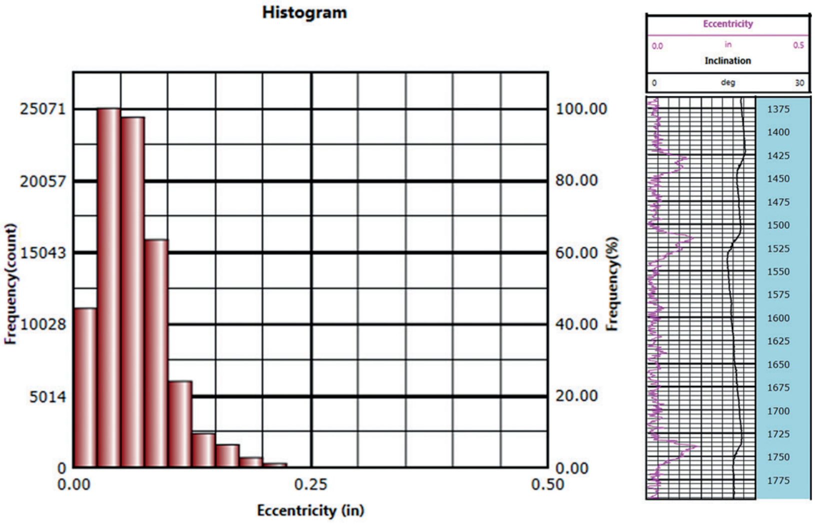


Fig. 15 - The eccentricity of the logging tool for well WQ1-XX0: left) the histogram showing the frequency and right) showing the log.

In well WQI-XX0, the rotary bottom hole assembly (BHA) in the 12.25'' hole used a 12.18'' near bit and 11.25'' string stabiliser that provided 0.4-0.5 degree/30 m build and continuous right turn of 0.6-1 degree/30 m, while in well WQI-XX2, the rotary BHA in the 12.25'' hole used a 12.00'' near bit and 11.75'' string stabiliser which provided a 0.8 degree/30 m drop and average tendency to right turn of 0.8-1 degree/30 m, which led to a reduction in the cementing issues.

Caliper log information may be beneficial, but an impact on the rig time may, then, need to be applied due to the need for supplementary time possibly for preparing an additional cement blend, laboratory testing, and delivery to the location.

When no pressure is applied to the wells when acquiring data and strong pipe arrival is observed from the VDL in the zone that CAST shows to have high ZP, there is higher uncertainty to include CBL data (AMP and VDL) in the interpretation.

6. Conclusions

The 1.75 SG cement was tested in the Rumaila field for carbonate and sandstone formations, which gave better bond log results and no significant metal loss in the condition of the casing with the new cement programme in both fields. This led to the experiment with this programme in the West Qurna field:

1. when the slurry designs changed SG from 1.9 and 1.75 to 1.55 and 1.45, the E_D varied by only -5%, which will be beneficial in reducing the cost with approximately the same efficiency;
2. the excess percentage of the lead/tail will be beneficial in optimising the excess for the open holes for future drilling wells when it will be adjustable to 70/50%;
3. the well-hole for all wells was in excellent condition, and economic issues were the only limit;
4. in the deviated wells, when the rotary bottom hole assembly drops with an average tendency to right turn of 0.8–1 degree/30 m, this will lead to a reduction in the cementing issues. Highly deviated wells require a standoff to be higher than 90%, and the use of a pre-flush spacer (unweighted space) will help to dilute the mud and increase its mobility;

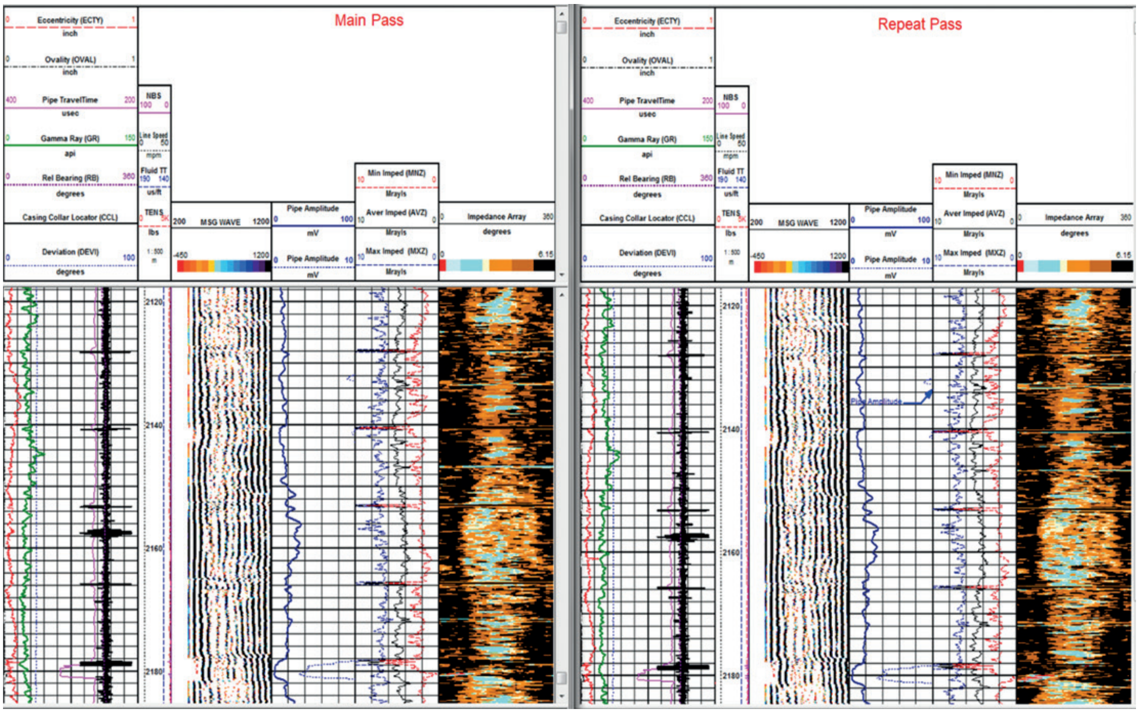


Fig. 16 - CBL-VDL CAST log for 7” open hole for well WQ1-XX0 (main and repeat pass).

5. lightweight high-performance 1.45 SG slurry achieved the objectives of cementing the liner in the Mishrif wells without losses. Circulation rates must be established in accordance with the ECD and annular velocity and LC 1.44, 1.62, and 1.50 SG cement plugs must be used in case of losses in Dammam, Hartha, and Mishrif, respectively;
6. a bypass bottom would help decrease cement contamination and improve shoe track. A sufficient length of the shoe track would isolate and keep the cement from being contaminated with wiped mud inside the shoe;
7. good results were indicated when displacement by higher-pressure rig pumps was utilised, and the discharge line was always opened.

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