AADE-19-NTCE-103

Review and Strategies to Aid in Trouble-Free Drilling of Carbonate Formations Globally Recognized as Problematic

Patrick Bijjani, ADNOC Sour Gas; Mark Luyster, Kim Tresco, Craig White, and James W. Dobson, Jr., TBC-Brinadd, LLC; Ahmed S. Amer, Newpark Fluids Systems, Raoul G. Razzouk, Energy M.E., Marcos Anez, Global Chemical Company LLC.

Abstract

A review of lost circulation plans, contingencies, recaps, and actual materials used to prevent losses in the upper-hole sections drilled in the regions of the Brazil, Egypt, Middle East, North America, and Southern Europe was compiled in an effort to ascertain which lost circulation treatments and/or combinations were historically effective or ineffective for regaining circulation, especially with regards to total losses in known troublesome carbonate formations. In addition, this data was evaluated to ascertain if total planned interval depth was achieved with the lost circulation treatments.

These evaluations highlighted numerous materials, inconsistencies, and excessive time committed to combating losses whereby the critical path was marginalized. Many were drilled through known troublesome formations identified by previous offsets, often with the same result. It was surmised that certain types of lost circulation material (LCM), concentration, volume applied, and frequency of use contributed little to no benefit. Numerous wells were reviewed to ascertain if time could be saved with more prudent utilization tactics when incorporating LCM as well as the potential to identify a pill, system, LCM or combination that consistently succeeded in stopping losses or regained circulation, or to identify tactics that were less than acceptable in specific circumstances.

These reviews showed LCM was supplied in a myriad of sizes, textures, types, and applied in varying concentrations, combinations, and volume. Data were compiled and contrasted versus the formation, borehole, and area, and included fluid-loss systems that were utilized. While selected attempts were successful in stopping losses in the upper boreholes, this success was sometimes temporary. In some intervals where returns were lost, operations would continue to fill the borehole with seawater and/or inexpensive drilling fluid while drilling ahead, only to realize additional problems later.

The ensuing discussion provides a synopsis of the challenging carbonate formations, the LCM types employed, the field results, and finally, lessons learned and strategies are proposed to assist with improving success rates when drilling in these challenging formations.

Introduction

This paper focuses on the use of LCM as incorporated into fluid-loss pills or systems to mitigate, control, and stop losses when drilling through known troublesome matrices, channels, vugs, and/or fractured carbonates as well as their effectiveness to even regain lost circulation. This topic was originally introduced at the ADIPEC Conference in November 2018 (Bijjani 2018a) and then expanded to include additional areas discussed in this paper. LCM is not only utilized for mitigating losses but for maintenance or wellbore strengthening (Guo et al. 2014; Growcock et al. 2009; Barrett et al. 2010), however this paper focuses only on mitigation of losses.

Controlling and mitigating fluid loss while drilling upper boreholes and/or the target reservoir is well documented in the literature. Excessive fluid loss and failure to control to manageable rates can subsequently lead to, among other things: well control issues, excessive NPT, cost overruns, inability to run planned logging tools and casing, and in the case of the target/producing formation, damage such that production rates are less than planned thereby requiring workover or stimulation operations.

In cases of severe losses and lost circulation, especially in the upper-hole sections, several options, in lieu of LCM, fluid-loss systems and pills, include: pumping cement, employing a floating cap (Davidson et al. 2000), employing underbalance drilling, liner drilling (Rosenberg et al. 2010), or drilling ahead and accepting losses. ECD management techniques have proven viable in avoiding or mitigating lost circulation events with pre-planning in a fractured formation (Murray et al. 2013). All of these options may prove successful; however, these options typically generate additional costs and NPT (Ferras et al. 2002).

Other pills and methods include reverse gunk pills (Ryan et al. 2015), chemically activated crosslinking pills (Ferras et al. 2002), borate crosslinking pills (Al Habsi et al. 2017; Bijjani et al. 2018b) defluidizing pills (Scorsone et al. 2010), limiting drilling parameters to limit losses (Al-Hameedi et al. 2017), resin (Knudsen et al. 2015), and the use of brine and viscosifiers to create pseudoplastic fluids which can control fluid loss using an exponential viscosity increase that is realized with increasing radial distance from the borehole (Howard and Anderson 2017).

The use of LCM to control losses is prevalent and judicious with many shapes available (e.g., flakes, grains, and fibers) as well as varieties of composition such as fiberglass, graphite, calcium carbonate, mica, nut shells, wood, rubber, swelling polymers, and foam, to name a few. Recent and novel materials, such as foam and nanoparticles (Savari et al. 2016; Akhtarmanesh et al. 2016), are of interest however as recently introduced case histories are forthcoming. Many of these LCM have been contrasted and compared using laboratory simulations (Loeppke 1990; Waldmann et al. 2014; Wang 2011).

Alsaba et al. (2014) proposed a classification of LCM, including nanoparticles, using physical and chemical properties as well as their application. Of note is the application of LCM as a continuous and controlled addition to a drilling fluid system whereby this background material enhances bridging, plugging, and strengthening thus reducing the loss rate in known problematic zones (Sanders et al. 2003).

Our prior literature investigation (Bijjani 2018a) revealed nearly 1,900 publications which document LCM type and use for combating losses and borehole stability. While these articulately document the potential use of LCM, only a limited number of papers document field experiences in troublesome zones especially vugular and/or fractured carbonate formations (Davidson et al. 2000; Sanders et al. 2003; El-Hassan et al. 2003; Mofunlewi et al. 2014; Rastogi et al. 2015; Urdaneta et al. 2015; Alkinani et al. 2018). The literature searches demonstrate a substantial contrast between the myriad of available LCM, fluid-loss pills, laboratory simulations, and methods versus successful case histories (and even unsuccessful case histories) in problematic carbonate formations, especially when NPT and costs are mitigated.

In summary, attempts to mitigate partial, severe, and lost circulation can be divided into the following:

- Treatments where losses are resolved through the addition of solid to semi-solid materials (i.e. LCM) to the drilling fluid system or pill
- Treatments where losses are resolved through use of a non-drilling fluid system or pill
- Limiting drilling parameters to reduce losses
- Unconventional methods such as floating cap or underbalance drilling
- Finally implementing a contingency or worse-case plan – pumping cement, filling a borehole with inexpensive fluid or sidetracking

The following sections summarize the LCM identified in the case histories and subsequently applied in troublesome formations in the aforementioned areas as well as their published characteristics and limitations. The results and learnings from those case histories are summarized to offer the drilling community fluid-loss materials and/or systems whereby the learnings postulated could improve success and potentially reduce failure rate and subsequently rig time. The intent is that this information may benefit not only future wells in these areas but potentially global operations in troublesome channeled, vugular, and/or fractured carbonate formations.

Loss Circulation Materials Applied in Troublesome Carbonate Formations

The following LCM were utilized in the water-based drilling fluid systems and fluid-loss pills for mitigating or controlling losses in the aforementioned formations, wells and areas studied (**Table 1**). These LCM vary in texture (e.g., fibrous, platelets, sub-angular to rounded grains, etc.), size (e.g., up to several mm), chemistry, and functionality. A relatively broad range of particle size is conducive for forming effective bridges on matrix-dominated rock. However their use to potentially bridge inherent openings in vugular and/or fractured carbonate formations can be suspect as relatively large fractures, channels, even vugs may well exceed the size necessary to establish a bridge while maintaining the ability to pump the LCM through the drillstring and BHA. For example, fractures greater than 5 mm would require a particle as large as 4.5 to 5 mm to initiate a seal (Dick et al. 2000). Conversely, the Abrams' Rule (1977) states that the median particle size of the LCM should be equal to ⅓ of the median pore size. However, when LCM is applied in insufficient concentration, distribution, or combinations thereof, plugging may be temporary, fail, and/or additional pills may be required.

LCM Shape and Texture

Granular (High to Moderate Sphericity)

Organic: Nut shell, ground walnut, and pecan shells, are organic and typically available in a range of gauged sizes such as fine, medium, coarse, and extra coarse.

Inorganic: Common selections include calcium carbonate and sodium chloride which are typically classified in specific size ranges by their median and maximum size which is stated in micrometers (μm), commonly known as "microns". These materials are readily degraded with typical breakers (e.g., acid, chelates, etc.). Uncommon particles, not found in these case histories, include perlite (i.e., volcanic glass) and magnesium oxide.

Non-Granular (Low to Elongated Sphericity)

Organic and Novel: Of note, but not used in these case histories, are date or palm seeds, a flowering plant species in the palm family, *Arecaceae*. The seeds contain a single stone about 2 to 2.5 cm (0.8 to 1.0 in.) in length and 6 to 8 mm (0.2 to 0.3 in.) in thickness. Evaluations for resistance to mechanical impact/force showed these seeds to be comparable to conventional LCM in drilling fluids (Amanullah et al. 2017). The seeds provide a beneficial application of an otherwise waste product in the Middle East region which is inexpensive, available, and ecologically sustainable for use as LCM. After washing and drying, the seeds can be ground and sized. This material also incorporates relatively small amounts of water thus possessing the ability to swell when applied in a water-based drilling fluid.

In addition, other organic materials include the ground peanut hulls used in this study.

Inorganic: Graphite and graphite-based materials are primarily used to help seal highly permeable formations while improving wellbore stability as well as reducing the risk of differential sticking when drilling depleted zones. There are several qualitative grades available.

Diatomaceous Earth. **"**DE", as diatomaceous earth is common as nearly pure siliceous material with medians from 25 to >100 µm that exhibits both inter- and intra-porosity.

Flakes. Typically, flakes are composed of mica, or even calcium carbonate. Mica is a phyllosilicate that visually resembles sheets and is ground to various sizes. Other flake products include cellophane and thermoset plastics.

Fibers. Cellulose derivatives or polysaccharides are linear chains of several hundred to many thousands of monomers in length and typically used to reduce seepage losses through the filtercake. Some of these materials, depending on preparation and treatment, are preferentially oil-wet as opposed to water-wet. Thus, when added to a water-based pill or drilling fluid system, the oil-wet material may absorb other products, such as lubricants. Cellulosic fibers have proven effective when applied to relatively high-permeability, matrix-dominated rocks. These are not readily degraded with typical breakers. They are also available as micro-sized, thus minimizing the impact on rheological properties in the drilling fluid system.

Expandable. Sodium polyacrylates are high-molecular-weight particles and unique in that the material will swell in water and low-density brine as much as 200 times the original weight (e.g., 30 to 60 times its original volume). As swelling is not instantaneous, these particles, when pumped into a matrix-dominated rock, swell in-situ as opposed to serving as a primary bridging mechanism. As they incorporate water and swell, these particles function to reduce the permeability of the invaded matrix. This material will be nearly completely removed at the shaker screens and thus must be re-introduced at the suction line to ensure coverage of a zone or formation.

Fluid-Loss Systems

Mixed-metal oxide (MMO) is a water-based drilling fluid system (Richard and Enriquez 2018) that is also used to mitigate fluid loss when pumped as a pill. Inherent high viscosity at low shear rates results in a near-static condition after the fluid traverses radially from the borehole. Dewatering systems primarily use combinations of sized lime, silica, barite, fibers, and diatomaceous earth at elevated concentrations. A relatively high-fluid-loss pill rapidly dewaters (e.g., defluidizes) and forms and/or deposits a filtercake on a matrix. Crosslinked systems utilize borate to generate hydrogen bonding (i.e., cis-hydroxyls) with a biopolymer (Powell et al. 1991). These systems can include, but are not limited to, barite, calcium carbonate, cellulosic fibers, and/or additional borate grades.

Contingency systems include cement with fibers, bentonitic cement, and gunk pills with polymers, bentonite, and/or fibers. Contingency systems are so named because they are an option that is typically applied when all other pills and systems fail to control losses sufficiently to allow drilling/operations to continue.

LCM Sizes

The LCM particle sizes as shown in **Table 1** reflect published data. Most of these materials exhibit a maximum size of less than 2000 µm with the exception of ground peanut hulls.

LCM Concerns

When fluid-loss pills, prepared with LCM, are utilized in a drilling fluid system or as a pill in appropriate concentration and preparation, the materials promote rapid filtercake formation or defluidizing of the drilling fluid system or fluid-loss pill against a medium (e.g., matrix-dominated rock/formation). However, there are limitations, and these include dilution of the drilling fluid system or fluid-loss pill during events with high-rate losses, as well as, ineffective bridging when fractures or vugs are much larger than the maximum size of the LCM.

Once a filtercake forms with positive pressure, as during drilling or even due to the static or dynamic fluid column, the residual filtercake is prevented from "lifting-off" or extricating as long as the fluid pressure remains positive keeping the filtercake in place. Thus a residual filtercake is subject to removal, due to swabbing or lost returns, thereby compromising its ability to persist and maintain fluid-loss control. Also, one must consider that these additives do not adhere or bond to the matrix, nor do they amalgamate loose particles and fragments as they can only bridge at effective concentrations and combination.

In summary these LCM, in combination or as a single additive, may exhibit the following:

- Do not adhere or bond to a matrix nor do they amalgamate loose particles and fragments as they only function as a bridging mechanism
- Once a filtercake is deposited (e.g., defluidization), positive pressure is required to maintain the residual filtercake in place; swabbing, surging, or loss of the fluid column may eradicate the filtercake as LCM does not inherently adhere or bond to the rock. In addition, running a casing string with centralizers may physically remove the filtercake.
- May be ineffective for bridging fractures or vugs in a troublezone if the maximum particle size and distribution is incorrectly sized
- Dilution of the drilling fluid system or fluid-loss pill is more common during high loss scenarios thus reducing their initial/target concentration as well as viscosity
- Continuous shearing and circulation can degrade the LCM particle size, especially marble (Scott et al. 2012) and graphite (Growcock et al. 2012)
- Scalping at the shakers requires continuous addition of larger grades or adjustment of screen mesh to mitigate their loss, or even temporarily by-passing the screen

In contrast, an advantage of the aforementioned LCM (**Table 1**) is the ability to pump through a BHA, MWD/LWD, and bit with low risk of plugging when used in a reasonable concentration and can even enhance borehole stability. This eliminates a trip-out/trip-in thus open-ended drillpipe is not required. Their use also eliminates the need for dropping a ball to open/close a fluid-loss valve if installed. In addition, the ability of the LCM to supplement a fluid-loss system, such as a dewatering pill, can further reduce fluid losses from matrix-dominated formation or rock.

Fluid-loss pills prepared with these LCM are typically viscous, even thixotropic, thus this mechanism also mitigates fluid loss by reduction in shear rate. As the pill moves away from the borehole, higher viscosity develops with lower shear where the shear rate is inversely proportionate to the distance into the formation. This is particularly notable in highly thixotropic fluids such as mixed-metal oxide. However, some dispersants and anionic additives, such as calcium chloride, interfere with a mixed-metal oxide complex, thus mitigating the ability for the fluid-loss pill to develop low-shear-rate viscosity.

Stratigraphy and Lithology of Troublesome Carbonate Formations

Case histories, recaps, and drilling reports provided from several global areas for wells drilled through known troublesome carbonates were carefully reviewed. These areas included Brazil, Egypt, Middle East, North America, and Southern Europe. The following provides a brief background of the stratigraphy, lithology, and age of the formations known for losses.

Brazil

Wells drilled in offshore Brazil in the Campos and Santos Basins (**Figure 1**) can transect the Barra Velha Formation and lost circulation is expected. This pre-salt rock is Aptian age, approximately 113 to 125 mya (**Figure 2**), and is predominantly a microbial heterogeneous carbonate as such misnamed the "Microbialite" reservoir (Wright and Tosca 2016).

This formation is up to 1804 ft (550 m) thick and its geological fabric is complex. Several textures/fabrics and pore types are found in the Barra Velha formation (**Figure 2**) and appear to have no direct analogue with other carbonate successions and reservoirs (Wright and Barnett 2017). The formation is unique in that three lacustrine distinct facies are defined – calcite shrub framestones, calcite spherulite floatstones, and laminated calcimudstones. It is theorized that the main rock fabrics resulted from the dissolution of matrices of magnesium silicates, thereby creating most of the porosity. **Figures 3a** and **3b** show selected petrographic images of the shrub and spherulite textures and inherent porosity. Thus matrix or vugular porosity predominates in this formation versus fractures. This formation serves to demonstrate the broad diversity of matrices inherent with carbonates and subsequently the challenges posed when mitigating fluid loss in this area.

Egypt

Wells drilled in Egypt transect the Alamaein, Apoll, Kharita, and Alam El Baueib Formations (**Figure 4a**). However drilling the Alamaein Dolomite Formation, early Cretaceous age (e.g., from 115 to 125 mya), was challenging with respect to controlling losses. This formation overlies the Alam El Bueib Formation and exhibits an average thickness of 250 ft (76 m). It is composed almost entirely of dolomites. These dolomites are honey brown, light brown, or tannish white, and properties range from micro to cryptocrystalline, hard to moderately hard, pyritic and sandy near the base (Abu Khadrah et al. 2018). However, the Alamein Dolomite is known for its vugular and fractured texture/fabric as well as crystalline dolomite (Barakat 2017). Dolomitization took place in a shallow, warm, Mg-rich environment under favorable pH, salinity, and temperature conditions. The relatively low $Si0_2$ content, absence of fossils, and the association of anhydrites with dolomites reflects a restricted, shallow-marine, low-energy environment, interrupted in parts, by high-energy environment in which microsparites and sparites were formed. (Zein El-Din et al. 1982).

The Kharita Formation overlies the Dahab shale and Alamein Dolomite and is younger, but still early Cretaceous (**Figure 4a**). This formation extends over the western desert and comprises fine to coarse-grained sandstone with subordinate shale and carbonate beds (Aboelhassan et al. 2016). A neutron-density crossplot confirms that calcareous cement is present as well as the interbedding of sandstone, shale and carbonate (**Figure 4b**). This formation was deposited as an extensive shallow marine shelf in a high-energy environment. As such, it is an example of a formation where carbonate rock is interbedded versus fractured or dominated by vugular porosity.

Middle East

Wells drilled in the Arabian Gulf (**Figure 5**) transect the geologic formations shown in **Figure 6**. These range in age from the more recent Neogene-Paleogene to early and late Cretaceous (approximately 90 to 100 mya) to the Upper Permian (e.g., 255 to 260 mya). The UER, Diyab, Mishrif, Thamama, Arabs, Gulailah, Suedair, and Khuff Formations are notorious for loss events. These formations comprise oolitic-peloidal, packstones, grainstones, mixed carbonate, terrigenous limestones and dolomites with anhydrite and shale streaks (Alsharhan 1989; Schlumberger 1991). However, these rocks also include inherent fractures as well as karst, vugular matrices, and even faults and occasional unconformities, all of which can provide conduits for drilling fluid invasion thus their problematic structure and lost circulation concerns. Starting with the Cretaceous and succeeding formations, the upper boreholes are typically drilled with inexpensive bentonite-polymer fluids and high-temperature water-based fluids are used for the lower boreholes (i.e., Permian). We reviewed the intervals drilled after setting the surface casing which subsequently transect the aforementioned problematic fractured formations that are commonly plagued with fluid-loss events.

As an example of the inherent fractures, an FMI recorded after controlling a series of fluid loss events in an 8⅜-in borehole (**Figure 7**), confirmed that the losses in this interval were the result of a fracture system. Thus, these fractures provide the preferential path for fracture losses versus a matrix as is common with clastic formations. This suggests that the LCM and bridging material typically used to develop and deposit filtercakes as a mechanism of reducing fluid loss, are less effective in these formations due to the aforementioned size limitations. Furthermore, multiple fracture patterns as seen in **Figure 7** present an even more difficult challenge to control losses due to the increased open area, varying fracture widths, and their cumulative volume. Multiple fracture patterns are representative of rock masses with complex regional deformational histories where fractures are produced by two or more modes in a sequential manner (National Research Council 1996). In some cases, regional distributions of joint and fault patterns mimic the trends of mountain belts, suggesting a causative relationship between the formation of fracture systems and a specific tectonic event.

North America

Wells drilled in North America, in the Saltville field (**Figure 8**) transected the very-late Cambrian formation shown in **Figure 9**. The Copper Ridge Dolomite (Knox Group) is late Cambrian age (e.g., 485 to 498 mya) and lies above folded younger rock due to the overturning of their southeastern limb of the Greendale syncline by overthrusting along the Saltville fault (**Figure 10**) (Whisonant et al. 1996). The Copper Ridge Dolomite comprises quartzose and cyclic peritidal dolomites (Read and Eriksson 2012) which vary in color from light to dark (McGuire 1970).

While this rock includes inherent fractures, it is notorious for loss events due to channels which are active conduits for fresh water flows with negligible pore pressure; as such, losses are unpredictable as any well can transect several or no channels.

Southern Europe

The wells drilled in Southern Europe transected very-early Tertiary formations as shown in **Figure 11**. Historically, wells assessed in this study were drilled in the Ionian Zone and suffered partial to total losses when drilling their upper boreholes. These transected Eocene-Paleocene carbonate formations. These carbonates are pelagic with low matrix porosity; however large inherent fractures and vugs are prevalent (Vilasi 2009). These pelagic facies are associated with slumping horizons and turbidites. These carbonates overlie an unstable and tectonically stressed shale formation. Fluid losses persist within the relatively thick interval from surface to as deep as 3600 m (11,800 ft).

Offset Wells – Prior Lost Circulation Incidents

Previous offset well information was provided for a few of the areas reviewed. This section summarizes the associated fluid-loss problems, volumes lost, LCM and types of systems applied to combat losses. In all offset wells, the results were unsuccessful. This information serves as a reference to contrast with the succeeding case histories.

Middle East

Two offset wells, A and B, drilled in offshore UAE encountered numerous lost circulation problems. Well A was unable to attain quality logs across planned intervals, Upper and Lower Khuff Formations, to assist with interpretation for planned well testing, due to the relatively high loss rates.

As an example, Well A lost approximately 11,000 bbl of drilling fluid while utilizing the following lost circulation pills/systems:

- Approximately 3,000 bbl of LCM pills pumped
- Total of 46 LCM pills pumped
- 7 cement plugs pumped
- Several $CaCO_3$-based, bentonite-based, and crosslinked systems pumped

In addition:

- Drillpipe and annulus plugged
- Cemented BHA in hole and sidetracked
- Employed managed pressure drilling (MPD), however losses persisted
- Finally, cemented liner 170 ft above planned depth

After drilling-out of the liner:

- 44 days spent curing losses in the 8⅜-in. hole

In Well B, drilling the 12¼-in borehole required the following:

- Total Cement Pills - pumped 700 bbl
- Total Drilling Fluid Pills - pumped 600 bbl
- Total Gunk Pills - pumped 100 bbl
- Total XL Pills - pumped 200 bbl
- Total LCM Pills - pumped 2,234 bbl
- Total high-viscosity pill or brine - pumped 700 bbl

whereby:

- Total Seawater lost 10,571 bbl
- Total Kill Drilling Fluid lost 8,065 bbl
- Total Brine lost 650 bbl

In total approximately 23,820 bbl were pumped to combat losses. The time required pumping and mixing these fluids and materials resulted in excessive NPT in both wells.

North America

Prior to the wells reviewed from the Saltville field, a previous offset, Well A, experienced an additional 51 days to achieve the same TD. **Figure 12** shows the days to TD for this offset versus Well 22, a well that was reviewed and also experienced losses. Approximately 40 days or 38% additional days were used combatting losses in the offset using fluid loss pills. The drilling fluid losses were surmised due to channels as six (6) water flows were apparent before attaining a measured depth of 800 ft.

Southern Europe

Downhole losses in the fractured carbonate formation occurred in four previous offset wells (designated A through D). The loss rate varied from seepage to total losses. The lack of field-proven fluid-loss pills or systems resulted in arbitrary use of LCM and techniques. This approach yielded little success where in some cases LCM partially cured losses, in other situations they were ineffective. In the scenario of lost returns, cement plugs and gunk remediation pills were used. When these proved inadequate, blind drilling was used. For these offsets, blind drilling required swapping from a gel polymer fluid to water and supplemented with viscous pills until returns were established. Offset wells A and D lost returns whereby blind drilling was implemented. It was surmised that the heterogeneous and fractured texture/fabric of the carbonate formation was responsible. In contrast, offset wells B and C, experienced downhole losses, but did not lose returns. This implies low matrix porosity and less fractures due to their location in the Ionian Zone contributed to these differences.

While drilling the top-hole section for Well A, from surface to 1,621 m (5,318 ft), downhole losses ranged from partial to severe. The most severe interval, 45 to 850 m (148 to 2,790 ft), experienced a maximum loss rate of 103 bbl/hr (16.4 m^3/hr) and an average loss rate of 32.1 bbl/hr (5.1 m^3/hr). A downhole camera was utilized and revealed large vugs at a depth of approximately 485.6 ft (148 m). The estimated average width of the vug ranged from 3 and 4 centimeters (1.2 to 1.5 in.). This well lost a total of 50,583 bbl (8042 m^3) of fluid.

While drilling offset Well B, losses ranged from partial to total for the interval 308 to 482 m (1,010 to 1,580 ft) while drilling with foam. At 335 m (1,100 ft), excessive water influx lead to an increase in the density of the fluid and subsequently losses occurred. After several attempts to cure losses, included using a combination of aerated fluid treated with LCM, losses continued. From 482 to 875 m (1,580 to 2,870 ft) floating cap drilling was used which reduced the average loss rate to 50.3 bbl/hr (8 m^3/hr). From 875 m (2,870 ft) to the top of shale formation, approximately 3,465 m (11,369 ft), seepage losses prevailed. In total, this well realized total losses of 13,479 bbl (2,141 m^3).

Offset Well C experienced partial losses from 430 m (1,410 ft) to the top of the shale at 3,913 m (12,838 ft). However, excessive losses occurred from 590 to 1,200 m (1,936 to 3,937 ft), 2,047 to 2,215 m (6,716 to 7,267 ft), and at 3,418 m (11,214 ft). The maximum loss rate recorded was 74 bbl/hr (11.8 m^3/hr) with an average losses rate of 11 bbl/hr (1.7 m^3/hr). This well realized 22,540 bbl (3582 m^3) of losses.

The succeeding case histories further expand the information on types of LCM and systems and their success or failure.

Case Histories

We reviewed, in total, 30 wells from five areas where boreholes less than 20-in. in diameter were drilled and transected known troublesome carbonates as previously described. Their lithology and aforementioned offsets showed that the majority suffered excessive losses due to fractures while one, the Barra Velha Formation, suffered losses into a matrix-dominated dolomite and another, the Kharita Formation, suffered losses through an interbedded carbonate, sand and shale sequence. After reviewing the offset information provided, we then reviewed case histories that implemented fluid loss plans and contingencies specifically tailored to each formation. The following sections discuss the type and success or failure of the implemented fluid loss plans.

Brazil

One well, drilled in the Santos Basin, transected the Barra Velha Formation. The initial plan was to drill a 12¼-in. borehole using an impregnated bit with turbine from 4,863 to 5,298 m (15,955 to 17,382 ft) or approximately 435 m (1,427 ft) in distance. However due to a narrow pressure window, an MPD system was used to mitigate the risk of kicks and loss circulation. In the event of losses, fluid-loss pills consisting of calcium carbonate and dewatering pills were planned as contingencies. As such, a fluid-loss valve was included above the BHA to mitigate plugging the MWD/LWD.

During drilling of the interval at 5,065 m (16,617 ft) with 8.9-lb/gal synthetic-based drilling fluid, several stuck pipe and fishing events transpired resulting in an increase in the drilling weight. Subsequently losses approached 200 bbl/hr dynamically. A 100-lb/bbl calcium carbonate pill was pumped as per the contingency, as well as reducing the flow rate, and the loss rate decreased to 80 bbl/hr. To reduce the loss rate further, a 50-lb/bbl dewatering pill was pumped and squeezed using hesitation cycles in steps of 25 psi. A dynamic flow check was performed and drilling with circulation continued with zero losses. At a measured depth of 5,134 m (16,844 ft), losses again increased to 30 bbl/hr. A 100-bbl pill using 40-lb/bbl calcium carbonate was pumped and the loss rate increased to 45 bbl/hr. Drilling ceased and before pulling out of hole (POOH), a 120-bbl pill using 40-lb/bbl calcium carbonate was spotted on bottom and the loss rate decreased to 25 bbl/hr. To reduce the loss rate further, a 50-lb/bbl dewatering pill using the aforementioned squeeze method was pumped and the loss rate decreased to zero. Drilling continued and for the interval 5,134 to 5,219 m (16,844 to 17,123 ft), losses increased, ranging up to 60 bbl/hr dynamically. A 145-bbl pill using 40-lb/bbl of calcium carbonate was pumped and the loss rate persisted. Drilling continued with the losses increasing to 120 bbl/hr. At this loss rate, a third dewatering pill, 100 bbl, was pumped again using the hesitation squeeze technique. Losses were reduced to zero and drilling continued to TD.

All of the dewatering pills were pumped using the BHA and MPD system. In total four fluid-loss pills were pumped prior to the dewatering pills. These totaled 465 bbl and included approximately 18,600 lb of sized calcium carbonate (i.e., 40 lb/bbl). All failed to reduce the loss rate such that drilling could proceed, thus the combination of volume and concentration was ineffective. In summary, this combination of sized calcium carbonate was ineffective for sealing the matrix-dominated porosity of the Bella Velha Formation.

Egypt

Three wells transected the Alamein Dolomite where 9.8 to 11.0-lb/gal KCl polymer fluid was used to drill boreholes ranging from 8½ to 12¼-in. diameter. All three experienced drilling fluid losses ranging from 120 to 260 bbl total. Sweep pills, approximately 40 bbl, were used to mitigate losses. These pills used fine, medium and coarse grades of calcium carbonate and all failed to reduce losses below the target. For these three wells, a crosslinked system was applied as the contingency. For the 8½-in. borehole, a 30-bbl volume was mixed and pumped; and for the 12¼-in boreholes, 50-bbl and 80-bbl volumes were mixed and pumped. For each well, the losses were reduced to less than 5 bbl/hr.

Two wells transected the Kharita where 10.2-lb/gal and 10.5-lb/gal KCl polymer fluids were used to drill 6-in. and 8½-in. boreholes, respectively. While washing and reaming, the 6-in. borehole realized partial returns and, after spotting 35 bbl of crosslinked system, experienced a loss rate of 140 bbl/hr while pumping at 210 gal/min. A 40-bbl fluid loss pill consisting of fine, medium, and coarse grades of calcium carbonate, 120 lb/bbl total, was pumped but failed to reduce the losses. A second crosslinked system was pumped, and the static losses were reduced to 1 bbl/hr. However after returning to washing and reaming, the loss rate increased to 240 bbl/hr while pumping at 250 gal/min.

Middle East

Twenty-one wells were assessed for fluid loss and LCM type in intervals during drilling only, however intervals such as 24-in. and 20-in. and larger where spud mud or saltwater is sometimes used were not included in the review. **Table 2** shows a summary where fluid-loss events are compared to the borehole size and formation. If losses occur however returns are apparent, this is deemed “Partial” and for intervals/formations where returns are lost the term “Total” is applied. If neither event occurred, the term “None” is applied.

These findings for these wells are summarized in **Figures 13, 14,** and **15**. **Figure 13a** shows a comparison of total loss events versus fractured formations. The Khuff and UER Formations accounted for greater than 50 percent of events where total losses were prevalent. **Figure 13b** shows a comparison of partial loss events versus formation. Again, the Khuff and UER Formations accounted for nearly 50 percent of events where partial losses were prevalent. The Thamama Formation was responsible for 12 percent of the total loss events and 25 percent of partial loss events. As field experience has demonstrated, the UER (lower Paleogene), Thamama (Middle Cretaceous), and Khuff (Upper to Middle Permian), which account for nearly 70 to 75 percent of all loss events in this area, as previously noted, are all fractured limestone and dolomitic rocks.

When normalizing the data for intervals where no loss events occurred, the analysis shows, statistically, that approximately one-third of the intervals in this study exhibited no loss events while two-thirds of the intervals exhibited a loss event that was addressed with either fluid-loss pills with LCM, non-LCM, cement, or required a sidetrack (**Figure 14**). Using selected wells as reviewed, the unanticipated effect of a sidetrack and resulting extra rig time due to the event of uncontrollable losses, is compared and shown in **Figure 15**. In this comparison, Wells 16 and 17 exhibited no loss events while Wells 2, 19 and 20 exhibited total and partial loss events which were mitigated to allow drilling to continue. However, Well 10 required a sidetrack due to uncontrollable losses, and as such exceeded the planned time to achieve TD.

Figure 16 shows a selected comparison of loss events where total losses were realized in the Arabs, Hamlah and Khuff Formations. A total of 82 pills or fluid-loss systems were pumped and averaged 11 to 12 per well in these formations. Using an average of 6.5 hr to prepare and pump each, this approximates 3 days of NPT per well. For this comparison, the borehole diameters ranged from 14½ to 8½-in. except for the 8⅜-in. which was drilled in the Khuff Formation. The losses were stopped in two wells, 11 and 21, using a crosslinked system after only two attempts. In addition, Wells 1 and 10 were successful utilizing several LCM pills where the total solids loading and volume were increased (e.g., >250 lb/bbl and 250 bbl) and multiple grades of calcium carbonate were used. With respect to Well 11, approximately 240 bbl of a crosslinked system was pumped after the loss rate exceeded plan. Upon TIH the top of the residual crosslinked system was tagged high. After accounting for the volume of the crosslinked system that set in the wellbore, it was determined that approximately 206 bbl flowed into the fracture network as shown in **Figure 7**. As the loss rate increased after a drill break and drilling continued for another 84 ft., this length of fractured carbonate necessitated approximately 2.5 bbl/ft to seal. The loss rate stabilized dynamically at 2 bbl/hr after drilling out the residual system, thus operations deemed safe to continue with plan. In summary, approximately 85 percent by volume set in the formation with 15 percent excess. Well 21 required only two LCM pills to stop losses in the Arabs Formation in the 14½-in. by 16-in. borehole. In contrast, three of the wells required a sidetrack or running and setting the liner high after multiple attempts using both LCM pills and various fluid loss systems.

In summary, fluid-loss LCM pills or systems that exhibited the greatest failure rate in these formations include:

- pills incorporating all calcium carbonate grades <200-250 lb/bbl
- pills incorporating combinations of calcium carbonate and sodium polyacrylate
- pills incorporating combinations of calcium carbonate and mica and/or nut shells
- pills incorporating combinations of calcium carbonate and cellulose
- dewatering type systems
- MMO systems

North America

Wells drilled in this area utilized inexpensive caustic gel fluid for the upper hole. Typically, a 19¼-in. interval is drilled through the Copper Ridge Dolomite after setting surface casing. For Wells 22 and 23, lost returns were realized and were not cured after each event. Attempts to cure losses included several LCM pills where the total solids loading and volume were increased from 50 to 100 lb/bbl and 25 to 75 bbl, respectively. The selected LCM types included combinations of nut shells, cellulose fibers (fine and medium grades) and sodium polyacrylate. After losing returns, the fluid level equalized (i.e., static) in the borehole due to low pore pressure in this area/formation. After losing returns in the second well, a downhole camera was run in hole (RIH) (**Figure 17**) and showed that the borehole transected a relatively large channel, estimated at approximately 3 in. (8 cm) in diameter, which functioned as the preferential path for losses as no other feature was observed. The diameter of this channel suggests that the fluid-loss pill and LCM failed to bridge, deposit a filtercake, and/or plug the channel.

Thus, the aforementioned combination of LCM type, size, concentration, and volume were ineffective to reduce or stop fluid loss through the estimated 3-in. channel. Cement, as the contingency, was successful for each well however, Well 23 required three additional days and two separate cement jobs. For these two wells, the discernible root cause for lost returns was inherent channels.

Southern Europe

One well was reviewed that was drilled near Offset A in the Ionian Zone. As previously described, the loss zone in the pelagic Eocene-Paleocene carbonate formations which are known for low matrix porosity; however, inherent large natural fractures and vugs serve as fluid conduits. The 22-in. borehole was drilled to approximately 1,305 m (4,281 ft) using a drilling fluid with viscoelastic properties; only minor losses occurred and did not impact the drilling program. However, during the subsequent casing run, losses prevailed such that the casing string was pulled and the centralizers removed. The casing string was re-run and cemented with complete losses. It was surmised that the filtercake was removed by the centralizers during the first casing run. The 17½-in. borehole was drilled to approximately 3,338 m (10,951 ft). During drilling, returns were lost at approximately 1,540 m (5,052 ft) and the wellbore was filled with water. A total of six fluid-loss pills were pumped ranging in volume from 50 to 80 bbl that included combinations of fibers, graphite, medium and coarse calcium carbonate, sodium polyacrylate, and elastomeric polymers/sealants. All six pills failed to reduce the losses. In an attempt to regain control of losses, two fluid-loss pills were pumped sequentially. The first, 15 bbl included sodium polyacrylate and was followed with an 80-bbl pill consisting of medium and coarse calcium carbonate and fibers. After pumping the loss rate slowed to 50 bbl/hr (8 m^3/hr) which was considered safe to continue drilling. Upon drilling to TD, the 13⅜-in. casing was successfully run to TD and cemented.

Lessons Learned

The relatively wide range in geologic age, depositional environment, and lithology of the carbonate formations reviewed showed several textures/fabrics which provided a preferential path or conduit for fluid losses. These can be grouped as:

- Fractures and vugs dominated
- Channel dominated
- Matrix and vug dominated
- Matrix and interbedded dominated

In summary, when a fluid-loss event occurred in a fracture, channel and/or vug, multiple fluid-loss pills with a variety of ineffective LCM and/or fluid-loss systems were pumped in increasing concentration and volumes. The numerous attempts yielded little to no success. As a result, cement, bentonitic cement, kill fluid, combinations of these, or a sidetrack, were required; all resulting in excessive NPT as related to fluids. The failure mechanism is the misapplication of LCM by combination, size, concentration, and/or volume in the identified carbonate textures/fabrics. To further, the failure mechanisms and successful LCM or systems are expanded in the next sections by their specific carbonate textures.

Carbonate Formations Dominated by Fractures, Vugs, and Channels

Ineffective fluid-loss control was realized with fluid-loss pills that utilized combinations of non-granular (e.g., cellulose, micro-cellulose, and polycellulose fibers, diatomaceous earth, polyacrylates, and graphite) as when these pills were pumped, losses slowed, however they did not stop. Attempts to squeeze these pills after spotting realized no success. In addition, fluid-loss systems generated relatively high low-shear-rate viscosity, even when applied during total loss events. While losses slowed, these systems did not stop the losses completely. In addition, defluidizing-type systems were not successful. Crosslinked pills exhibited success in four wells reviewed. In loss events where marginal to severe losses were apparent, multiple LCM pills were pumped/spotted and realized variable success. Fluid-loss LCM pills that exhibited the highest failure rate where total losses were apparent in a fracture and vugular texture/fabric include:

- Using only calcium carbonate grades (fine, medium and coarse) at a concentration less than 200-250 lb/bbl
- Using combinations of calcium carbonate grades with sodium polyacrylate, mica and/or nut shells, cellulose, diatomaceous earth, or graphite.
- Using volumes less than 250 bbl
- Using sweep pills

Fluid-loss LCM pills that exhibited the highest failure rate where total losses were apparent in a channel texture/fabric include:

- Using combinations of sodium polyacrylate, mica and/or nut shells or cellulose to seal/plug channels

Fluid-loss LCM pills that exhibited success in a fracture and vugular texture/fabric include:

- Using only calcium carbonate grades (fine, medium, and coarse) at a concentration greater than 250 lb/bbl and at a volume of 250 bbl or greater
- Using crosslinking pills

Based on the carbonate texture/fabric dominated by channels (e.g., 3-in diameter), the identified LCM pills and cement failed to mitigate the losses as when pumping cement multiple attempts were required.

Carbonate Formations Dominated by Matrix Porosity

Ineffective fluid-loss control was realized with fluid-loss pills that utilized combinations of granular and sized calcium carbonate. These were applied using volumes less than 150 bbl consisting of 40 lb/bbl of calcium carbonate in 12¼-in. boreholes. The grade of the calcium carbonate was not known. However, dewatering pills pumped using a volume of 50 bbl with a hesitation squeeze reduced the losses to zero. This application supports the use of dewatering pills to mitigate the losses in this texture/fabric (i.e. matrix porosity).

Carbonate Formations Dominated by Interbedded Carbonate, Shale, and Sandstone

Ineffective fluid-loss control was realized when drilling 6-in. and 8½-in. boreholes. Fluid-loss pills utilizing fine, medium and coarse calcium carbonate at a concentration of 120 lb/bbl failed to reduce the losses. Crosslinked systems, pumped at volumes of 35 bbl reduced the static loss rate to 1 bbl/hr; however, when increasing the pump rate, losses increased to the previous rate. It is theorized that a more external filtercake formed and was removed with subsequent washing and reaming. This application supports the use of a crosslinked system; however, the volume and size as utilized was considered inadequate.

Strategies

These strategies are predicated on using economical LCM and/or systems with the objective of spotting such that the loss rate is reduced below the manageable loss-rate target or completely stopped for each event/interval. Multiple events are possible, based on the 30 wells reviewed. The following strategies are recommended:

- Incorporate a higher concentration of granular calcium carbonate as well as a greater volume of the fluid-loss pill. In addition, consider a particle as large as the problematic fracture or channel if possible. If this is not possible, apply Abrams Rule (1997) and determine if this particle is pumpable.
- Consider utilizing a lead viscous pill, in combination with a fluid-loss pill (as above), whereby a large grade of granular material can effectively bridge and embed inside a fracture or vug.
- Incorporate a fluid-loss valve above the BHA that accommodates multiple cycles to allow spotting larger particles as well as multiple or sequential pills.
- When utilizing crosslinked systems in fractured carbonates, consider pumping a minimum of 2.5 bbl/ft plus 15 percent excess volume to thus enhancing success to stop losses with the first attempt. In contrast, mitigate multiple attempts.
- When using dewatering pills to mitigate losses, consider the subsequent operations such as running casing with centralizers that could potentially remove the filtercake.

In summary, a fluid-loss plan should consider larger volumes (i.e., >250 bbl) and greater concentrations of calcium carbonate (i.e., >250 lb/bbl) to address a fluid-loss event as the initial strategy whereby a crosslinked or dewatering system is the contingency plan. The choice is also dependent on the carbonate textures/fabrics. Thus the use of a crosslinked system includes fractures, vugs, as well as interbedded carbonates with fractures, as the contingency. A matrix-dominated texture would dictate the use of a dewatering system. A channel dominated texture/fabric may dictate the use of the aforementioned large volume and concentration of calcium carbonate or a crosslinked system however the field/well, as reviewed, did not implement these, as such, only the volumes and type LCM that failed warrant caution.

Acknowledgments

The authors thank the management teams of Al Hosn Gas / Abu Dhabi Gas Development Company Ltd., Energy M.E., Newpark Fluid Systems, and TBC-Brinadd, LLC for their permission to publish the case history data. Our thanks to Mary Dimataris for her technical critique of our numerous drafts as well as editing and formatting the manuscript in such a short timeframe.

Nomenclature

BHA = *Bottomhole Assembly*
BHP = *Bottomhole Pressure*
LCM = *Lost Circulation Material*
MD = *Measured Depth*
MW = *Mud Weight*
NPT = *Non-Productive Time*
PBS = *Poly Borate Salt*
POOH = *Pull Out Of Hole*
RIH = *Run in Hole*
TD = *Total Depth*
TIH = *Trip in Hole*

References

Aboelhassan, N., Tarabees, E., and Alaa, M. “Subsurface Study and Petrophysical Analysis of Kharita Formation in Tut Field, North Western Desert, Egypt.” *Researcher* vol. 8, no. 7 (2016). www.doi.org/10.7537/marsrsj080716.08

Abrams, A. “Mud Design to Minimize Rock Impairment Due to Particle Invasion.” SPE-5713-PA, *Journal of Petroleum Technology*, vol. 29, no. 5 (May 1977) 586. https://doi.org/10.2118/5713-PA

Abu Khadrah, A.M., Refaat, A.A. and Omar, M. “Cyclo-Stratigraphy of the Lower Cretaceous Succession in Jade Field, North Western Desert, Egypt.” *IOSR Journal of Applied Geology and Geophysics*, vol. 6, no. 5 ver. II (September-October 2018) p.28-35. http://www.iosrjournals.org/iosr-jagg/papers/Vol.%206%20Issue%205/Version-2/C0605022835.pdf

Akhtarmanesh, S., Al-Saba, M., Cedola, A.E., Qader, R., Caldarola, V.T, Hareland, G. and Nygaard, R. “Barite Nano-Micro

Particles with LCM Seals Fractured Form Better in Weighted Water Based Drilling Fluids." ARMA 2016-306, 50th US Rock Mechanics / Geomechanics Symposium, Houston, June 26-29, 2016. Available from www.onepetro.org

Al Habsi, M., Bijjani, P., Dawson, G., McCurdy, P., Anez, M., Luyster, M., Tresco, K. and Dobson, J.W. "Multiple Key Operational Achievements Yield Major Economic Impact as a Result of Successful Controlling Fluid Losses in Troublesome Zones of Jurassic to Permian Age in Offshore United Arab Emirates." SPE 188862, Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi, November 13-16, 2017. https://doi.org/10.2118/188862-MS

Al-Hameedi, A.T., Dunn-Norman, S., Alkinani, H.H., Flori, R.E., Hilgedick, S.A. "Limiting Parameters to Control Mud Losses in the Shuaiba Formation South Rumaila Field, Iraq." AADE-17-NTCE-45, AADE National Technical Conference, Houston, April 11-12, 2017. Available from www.aade.org

Alkinani, H.H., Al-Hameedi, A.T.T., Flori, R.E., Dunn-Norman, S., Hilgedick, S.A., Amer, A.S., and Alsaba, M.T. "Drilling Strategies to Control Lost Circulation in Basra Oil Fields, Iraq." AADE-18-FTCE-059, AADE Fluids Technical Conference, Houston, April 10-11, 2018. Available from www. aade.org

Alsaba, M., Nygaard, R., Hareland, G., and Contreras, O. "Review of Lost Circulation Materials and Treatments with an Updated Classification." AADE-14-FTCE-25, AADE Fluids Technical Conference, Houston, April 15-16, 2014. Available from www.aade.org

Alsharhan, A.S. "Petroleum Geology of the United Arab Emirates." *Journal of Petroleum Geology*, vol. 12, no. 3 (July 1989) 253-288.

Amanullah, M.D., Al-Arfaj, M., Gadalla, A., Saleh, R., El-Habrouk, I., Al-Dhafeeri, B., and Khayat, A. "Date Seed-Based Particulate LCM 'ARC Plug' – Its Development, Laboratory Testing and Trial Test Results." SPE 187988, SPE Kingdom of Saudi Arabia Annual Technical Symposium, Dammam, Saudi Arabia, April 24-27, 2017. https://doi.org/10.2118/187988-MS

Barakat, M.: "Reservoir Modeling of Alam El Bueib Formation in the TUT Oil Field, Western Desert, Egypt" *International Journal of Scientific Engineering and Applied Science (IJSEAS)*, vol. 3, no. 2 (February 2017). http://ijseas.com/volume3/v3i2/ijseas20170203.pdf

Barrett, S., Manescu, G., Vasquez Cueva, G.E., and Growcock, F. "Wellbore Strengthening: Where Field Application Meets Theory." SPE 139167, SPE Latin American and Caribbean Petroleum Engineering Conference, Lima, December 1-3, 2010. https://doi.org/10.2118/139167-MS

Bijjani, P., Anez, M., Luyster, M., Tresco, K., White, C., and Dobson, J.W, Jr. "The Dichotomy of Lost Circulation Material – Is Their Application in Prolific and Troublesome Formations Mitigating Losses or Progressing as a Habitual Practice?" SPE-193308, Abu Dhabi International Petroleum Conference, Abu Dhabi, November 12-15, 2018. https://doi.org/10.2118/193308-MS

Bijjani, P., Dawson, G., McCurdy, P., Luyster, M., Tresco, K., and Dobson, J.W. "Successfully Controlling Fluid Losses in Troublesome Zones of Jurassic to Permian Age in Offshore United Arab Emirates Utilizing a Newly Optimized Crosslinked Borate Fluid Loss System." AADE-18-FTCE-019, AADE Fluids Technical Conference, Houston, April 10-11, 2018. Available from www.aade.org

Davidson, E., Richardson, L. and Zoller, S. "Control of Lost Circulation in Fractured Limestone Reservoirs." SPE 62734, IADC/SPE Asia Pacific Drilling Technology, Kuala Lumpur, September 11-13, 2000. https://doi.org/10.2118/62734-MS

Dick, M.A., Heinz, T.J., Svoboda, C.F. and Aston, M. "Optimizing the Selection of Bridging Particles for Reservoir Drilling Fluids." SPE 58793, SPE International Symposium on Formation Damage Control, Lafayette, Louisiana, February 23-24, 2000. https://doi.org/10.2118/58793-MS

El-Hassan, H.I., Abbas, R., Jarouj, H. and Munk, T. "Using a Novel Fiber Cement System to Control Lost Circulation: Case Histories from the Middle East and the Far East." SPE 85324, SPE/IADC Middle East Drilling Technology Conference, Abu Dhabi, 20-22 October 2003. https://doi.org/10.2118/85324-MS

Estrella, G. "Pre-Salt Production Development in Brazil." 20th World Petroleum Congress, Doha, Qatar, December 4-8, 2011.

Ferras, M., Galal, M., and Power, D. "Lost Circulation Solutions for Severe Sub-Salt Thief Zones." AADE-02-DFWM-HO-30, AADE 2002 Technology Conference, Houston, April 2-3, 2002. Available from www.aade.org

Gadallah, M.M., Samir, A., Nabih, M.A. "Integrated Reservoir Characterization Studies of Bahariya Formation in the Meleiha-NE Oil Field, North Western Desert, Egypt." *Journal of King Abdulaziz University: Earth Science*, vol. 21, no. 1 (2010). https://doi.org/10.4197/Ear.21-1.5

Growcock, F.B., Kaageson-Loe, N., Friedheim, J., Sanders, M.W., and Bruton, J. "Wellbore Stability, Stabilization and Strengthening." OMC-2009-107, Offshore Mediterranean Conference, Ravenna, Italy, 25-27 March 2009. Available from www.onepetro.org

Growcock, F.B., Mahrous, R., and Flesher, R. "Wellbore Stability, Shear Degradability of Granular Lost Circulation Materials." AADE-12-FTCE-27, AADE Fluids Technical Conference, Houston, Texas, April 10-11, 2012. Available from www.aade.org

Guo, Q., Cook, J., Way, P., Ji, L., Friedheim, J.E. "A Comprehensive Experimental Study on Wellbore Strengthening." SPE 167957, IADC/SPE Drilling Conference, Fort Worth, Texas, March 4-6, 2014. https://doi.org/10.2118/167957-MS

Howard, S. and Anderson, Z. "HPHT Formation Fluid Loss Control without Bridging Particles." AADE-17-NTCE-110, AADE National Technical Conference, Houston, April 11-12, 2017. Available from www.aade.org

Jain, B., Khattak, M.A., Mesa, A.M., Al Kalbani, S., Aghbari, S., Al-Salti, A., Hennette, B., Khaldi, M., Al-Yaqoubi, A., and Al-Sharji, H."Successful Implementation of Engineered Fiber Based Loss Circulation Control Solution to Effectively Cure Losses While Drilling, Cementing and Work Over Operations in Oman." SPE 166529, SPE Annual Technical Conference, New Orleans, September 30 – October 2, 2013. https://doi.org/10.2118/166529-MS

Knudsen, K., Leon, G.A., Sanabria, A.E., Ansari, A. and Pino, R.M. "First Application of Thermal Activated Resin as Unconventional LCM in the Middle East." SPE 177430, Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi, November 9-12, 2015. https://doi.org/10.2118/177430-MS

Loeppke, G.E., Glowka, D.A. and Wright, E.K. "Design and Evaluation of Lost-Circulation Materials for Severe Environments." SPE 18022-PA, *Journal of Petroleum Technology*, (Mar. 1990) p.328-337. https://doi.org/10.2118/18022-PA

McGuire, O.S. "Geology of the Eagle Rock, Strom, Oriskany, and Salisbury Quadrangles, Virginia." *Commonwealth of Virginia Department of Conservation and Economic Development Division of Mineral Resources. Report of Investigations* 24,

(1970) p. 9.

Mofunlewi, S.S., Okeke, C., Bankole, A. and Ighodaro, O. "Field Case Histories: Countering Lost Circulation with Monofilament Polypropylene Fiber." SPE 172385, SPE Nigeria Annual International Conference, Lagos, August 5-7, 2014. https://doi.org/10.2118/172385-MS

Murray, D., Sanders, M.W., Houston, K., Hogg, H., and Wylie, G. "Case Study – ECD Management Strategy Solves Lost Circulation Issues on Complex Salt Diapirs/Paleocene Reservoir." SPE 166134, SPE Annual Technical Conference, New Orleans, September 30 – October 2, 2013. https://doi.org/10.2118/166134-MS

National Research Council. "Chapter 2: Physical Characteristics of Fractures and Fracture Patterns." In: *Rock Fractures and Fluid Flow: Contemporary Understanding and Applications.* National Academies Press, Washington, DC. 1996. https://doi.org/10.17226/2309

Powell, J.W., Stagg, T.O., Reiley, R.H., Dobson, J., "Thixotropic, Crosslinking Polymer/Borate/Salt Plug: Development and Application." SPE 22068, SPE International Arctic Technology Conference, Anchorage, 29-31 May 1991. https://doi.org/10.2118/22068-MS

Rastogi, R., Lal, K., Singhal, R., Sinha, M.P., and Pratap, K.K. "An Innovative Approach for Curing Severe Loss Control Problems in Mumbai Offshore While Drilling – A Case Study." SPE 178119, SPE Oil & Gas India Conference, Mumbai, November 24-26, 2015. https://doi.org/10.2118/178119-MS

Read, J.F. and Eriksson, K.A. "Chapter 3: Paleozoic Sedimentary Successions of the Virginia Valley & Ridge and Plateau." https://vtechworks.lib.vt.edu/handle/10919/19078

Richard, D.J. and Enriquez, F.P, Jr. "30 Years of Mixed-Metal Technology (MMH/MMO): Where Are We Now?" AADE-18-FTCE-027, AADE Fluids Technical Conference, Houston, April 10-11, 2018. Available from www.aade.org

Rosenberg, S.M., Gala, D.M., and Xu, W.J. "Liner Drilling Technology as a Mitigation to Hole Instability and Loss Intervals: A Case Study in the Gulf of Mexico." SPE 128311, IADC/SPE Drilling Conference, New Orleans, February 2-4, 2010. https://doi.org/10.2118/128311-MS

Ryan, J., Akyabi, K., Saleh, M., Omgbu, J., Kustanto, S., Ivan, C. and Mihalic, B. "Successful Application of Reverse Gunk Pill to Cure Losses in Basinal Limestone with Interbedded Marl and Shale Formation Drilling Offshore Abu Dhabi." SPE 177720, Abu Dhabi International Exhibition and Conference, Abu Dhabi, November 9-12, 2015. https://doi.org/10.2118/177720-MS

Sanders, W.W., Williamson, R.N., Ivan, C.D. and Powell, D. "Lost Circulation Assessment and Planning Program: Evolving Strategy to Control Severe Losses in Deepwater Projects." SPE 79836, SPE/IADC Drilling Conference, Amsterdam, February 19-21, 2003. https://doi.org/10.2118/79836-MS

Savari, S. and Whitfill, D.L. "Managing Losses in Naturally Fractured Formations: Sometimes Nano is Too Small." SPE 173062, SPE/IADC Drilling Conference, London, March 17-19, 2015. https://doi.org/10.2118/173062-MS

Savari, S., Rolfson, J., Williams, R., Whitfill, D.L. and Wang, H.M."Reticulated Foam Enhanced High Fluid Loss Squeeze LCM for Severe Lost Circulation Management in Highly Fractured Formations." SPE 180306, SPE Deepwater Drilling and Completions Conference, Galveston, Texas, September 14-15, 2016. https://doi.org/10.2118/180306-MS

Schlumberger. "Middle East Well Evaluation Review." (1991). http://www.slb.com/~/media/Files/resources/mearr/wer11/rel_pub_mewer11_2.pdf

Scorsone, J.T., Dakin, E.S. and Sanders, M.W. "Maximize Drilling Time by Minimizing Circulation Losses." AADE-10-DF-HO-42, AADE Fluids Conference, Houston, April 6-7, 2010. Available from www.aade.org

Scott, P.D., Beardmore, D.H., Wade, Z.D., Evans, E., Franks, K.D. "Size Degradation of Granular Lost Circulation Materials." SPE 151227, IADC/SPE Drilling Conference, San Diego, California, March 6-8, 2012. https://doi.org/10.2118/151227-MS

Taufik, M., Panjaitan, R.A., and Djambek, A. "Fibrous Organic Cellulose Application to Combat Seepage Losses in Fractured Limestone Formations, Offshore East Kalimantan, Indonesia." SPE 145763, SPE Asia Pacific Oil and Gas Conference, Jakarta, September 20-22, 2011. https://doi.org/10.2118/145763-MS

Urdaneta, J.A., Ravi, K., Delgado Gonzalez, F.E., Viera, J.M., Liaño Marinkovi, R. and Pedrazas Castillo, O. "Novel Low-Solids Shear-Dependent Cement System Used to Cure Severe Lost Circulation While Drilling: A Case History." SPE 177788, Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi, 9-12 November 2015. https://doi.org/10.2118/177788-MS

Vilasi, N. "Study of Reservoir Analogues in Foreland Fold-and-Thrust Belts: Sedimentology, Diagenesis, Deformation and Fracturing of the Upper Cretaceous-Eocene Carbonate Systems of the Ioanian Zone (Southern Albania)." PhD Thesis, École Nationale Supérieure des Mines de Paris, 2009. https://pastel.archives-ouvertes.fr/pastel-00006128

Waldmann, A.T.A., de Lima, V.A.R.M.P., Souza, E.A., D'Almeida, A.R., Teixeira, G.T., Geraci, A.C.M., Magalhães, S., Neto, O.A.D., Scheid, C.M. and Calçada, L.A. "Efforts to Control Fluid Losses in Offshore Drilling." AADE-14-FTCE-26, AADE Fluids Technical Conference, Houston, April 15-16, 2014. Available from www.aade.org

Wang, H. "Is it Really Possible to Efficiently Form a Strong Seal inside Subterranean Openings without Knowing Their Shape and Size?" AADE-11-NTCE-25, AADE National Technical Conference, Houston, April 12-14, 2011. Available from www.aade.org

Whisonant, R.C. "Geology and the Civil War in Southwestern Virginia: The Smyth County Salt Works." *Commonwealth of Virginia, Dept of Mines, Minerals, and Energy. Division of Mineral Resources. Virginia Minerals*, vol. 42, no. 3 (August 1996). https://www.dmme.virginia.gov/commercedocs/VAMIN_VOL42_NO03.pdf

Wright, P. and Barnett, A. "Classifying Reservoir Carbonates When the Status Quo Simply Does Not Work: A Case Study from the Cretaceous of the South Atlantic." AAPG 2017 Annual Convention, Houston, April 2-5, 2017. http://www.searchanddiscovery.com/pdfz/documents/2017/51419wright/ndx_wright.pdf.html

Wright, P. and Tosca, N. "A Geomechanical Model for the Formation of the Pre-Salt Reservoirs, Santos Basin, Brazil: Implications for Understanding Reservoir Distribution." AAPG Annual Convention, Alberta, June 19-22, 2016. http://www.searchanddiscovery.com/documents/2016/51304wright/ndx_wright.pdf

Zein El-Din, M.Y., Abul-Fetouh, M.A. and Sadek, R. "Petrographic Studies of the Alamein Dolomite (Lower Cretaceous) in El-Razzak Oil Field, Western Desert, Egypt." *Qatar University Science Bulletin*, vol. 2, no. 1 (1982) p.169-206. http://qspace.qu.edu.qa/handle/10576/7910

Tables and Figures

Table 1 – Summary of LCM

Common Name/Grade	Typical Particle Size Range
Mineral Flakes	
Fine	1.0-30% is 14-100 mesh (1400-150 µm)
Medium	30-85% is 10-20 mesh (2000-850 µm)
Coarse	0.1-20% is 16-100 mesh (1180-150 µm)
Graphite	
Plus	300-500 µm
Plus Coarse	500-800 µm
Calcium Carbonate	
Fine	<20 µm
Medium	<40 µm
Coarse	<300 µm
Sodium Chloride	D_{50} approximately 5 µm-30 µm (Common Grades) up to 10,000 (Rock)
Borate	D_{100} approximately 20 µm- 8,000 µm
Diatomaceous Earth	D_{50} approximately 25 µm
Nut Shells	
Fine	400-500 µm
Medium	1200-1500 µm
Coarse	1600-2000 µm
Ground Peanut Hulls	
Fine	1-500 µm
Coarse	< 6.3 mm
Cellulose	
Ground Fine	90% finer than 100 mesh (150 µm)
Ground Medium	80% greater than 50 mesh (300 µm)
Ground Coarse	80% is 8-100 mesh (2360-150 µm)
Organic cellulose[1]	Blend of various sizes
Micro Fibers	
Fine	7-13% is 28-100 mesh (650-150 µm)
Coarse	30-40% is 28-100 mesh (650-150 µm)
Blends of fiber, flake and granular material	
Fine	approx. 20% retained on 10-mesh screen (2000 µm)
Medium	approx. 12% retained on 10-mesh screen (2000 µm)
Coarse	approx. 8% retained on 10-mesh screen (2000 µm)
Sodium polyacrylate	Various grades ranging from 80-100 µm
Novel LCM not used in these Case Histories	
Date Seeds[2]	Approx. 2 to 2.5 cm long by 6 to 8 mm thick. Can swell in the presence of water-based fluid.
Reticulated Foam[3]	Utilized as a two components, foam and particles.
Engineered Fibers[4]	Maximum 5 mm and 2,000 psi
MM LCM[5]	One sack material with three ranges of particles: 7-15 µm, 200-800 µm and 1,500-3,500 µm.

[1] Taufik et al. 2011
[2] Amanullah et al. 2017
[3] Savari et al. 2016
[4] Jain et al. 2013
[5] Savari and Whitfill 2015

Table 2 – Summary of Fluid Loss Issues by Well, Interval, and Formation for the Middle East Wells in this Study (Bijjani 2018a).

Well Number	Size of Interval (in.)	Formation	Type of Losses	Action or Result
1	12¼	Arabs	Total	After numerous pills with LCM pumped cement and finally kill mud
2	17½	Thamama	Total	Required three cement plugs
3	17½	UER	Total	Cuttings not circulated out
4	17½	UER	Partial	Spot fluid loss pills
5	8⅜	Khuff	Total	Spot several pills with LCM however no returns.
6	16	UER	Total	Drilled with SW
7	16	UER	Total	Used sweep pills every stand to remove cuttings
8	16	UER	Partial	Continued drilling SW using Hi-Vis sweeps
	12¼	Thamama	Total	Spot several pills with LCM
9	12¼	Gulialah	Partial	Spot several pills with LCM
	8½	Khuff	Partial	Spot several pills with LCM, squeezed and then stuck
10	16	Arab	Partial	Spot several pills with LCM and squeezed.
	12¼	Upper Khuff	None	
	8⅜	Khuff	Total	Spot several pills with LCM. Pump cement then stuck.
	6	Khuff	Total	Spot bentonitic cement plug. Pump cement again.
11	8½	Khuff	Partial	Spot two crosslinked pills. Losses reduced to manageable
12	12¼	Diyab	Total	Spot several pills with LCM
	8⅜	Upper Khuff	Total	Spot several pills with LCM. Stuck DP/Core barrel
13	12¼	Sudair	Total	Spot several pills with LCM
	8⅜	Upper Khuff	None	
14	12¼	Diyab & Sudair	Partial & Total	Spot several pills with LCM
	8½	Upper Khuff	Partial	Spot several pills with LCM
15	8½	Upper Khuff	Partial	Spot several pills with LCM
16	17½	Thamama	None	
	12¼	Sudair-Diyab	None	
	8½	Khuff	None	
17	17½	Thamama	None	
	12¼	Sudair-Diyab	None	
	8½	Khuff	None	
18	8½	Upper Khuff	Partial	Spot several pills with LCM
19	17½	Thamama & Mishrif	Partial	Spot several pills with LCM and squeezed
	12¼	Sudair-Diyab	None	
	8½	Upper Khuff	Partial	Spot several pills with LCM
20	17½	Thamama	Partial	Resume drilling with controlled parameters
	12¼	Arabs	None	
	8½	Khuff	Partial	Spot several pills with LCM. Ran openhole log suite
	6	Khuff	None	
21	12¼	Arabs	Total	Spot two crosslinked pills. Losses stopped
	8½	Khuff	None	None
	6	Khuff	None	None

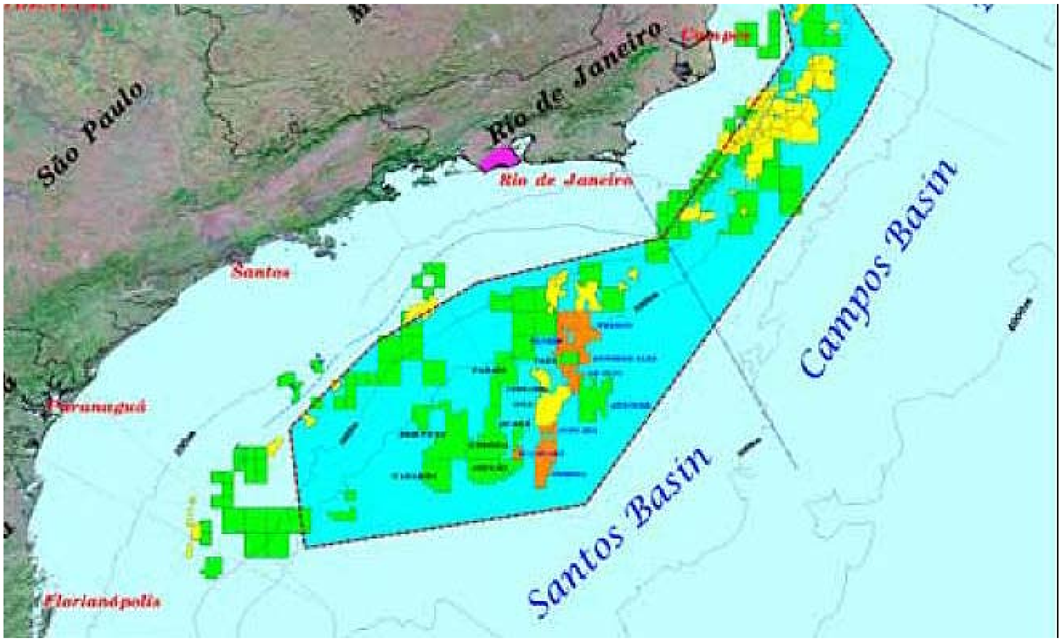


Figure 1 – Pre-salt cluster area in the Santos and Campos Basins, offshore Brazil (Estrella 2011).

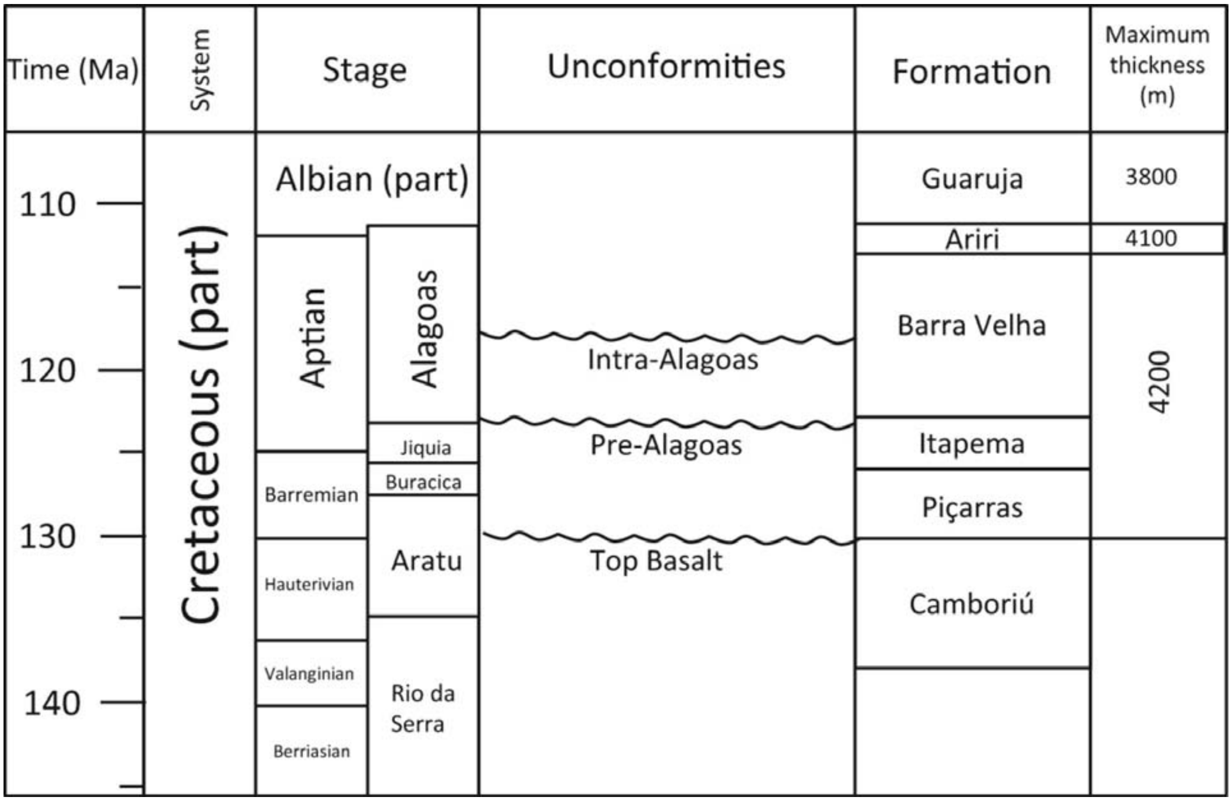


Figure 2 – Approximate sequence, relative thickness and age of the early Cretaceous (Aptian) Barra Velha Formation, found offshore Brazil (Wright and Barnett 2017.

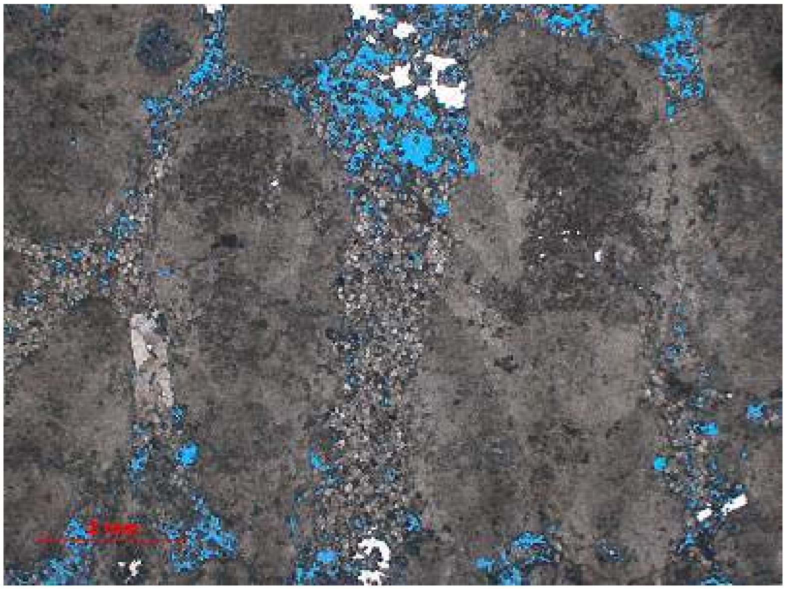


Figure 3a – In-situ shrubs with open inter-shrub typically with “floating” dolomite rhombs and resulting porosity (Wright and Barnett 2017).

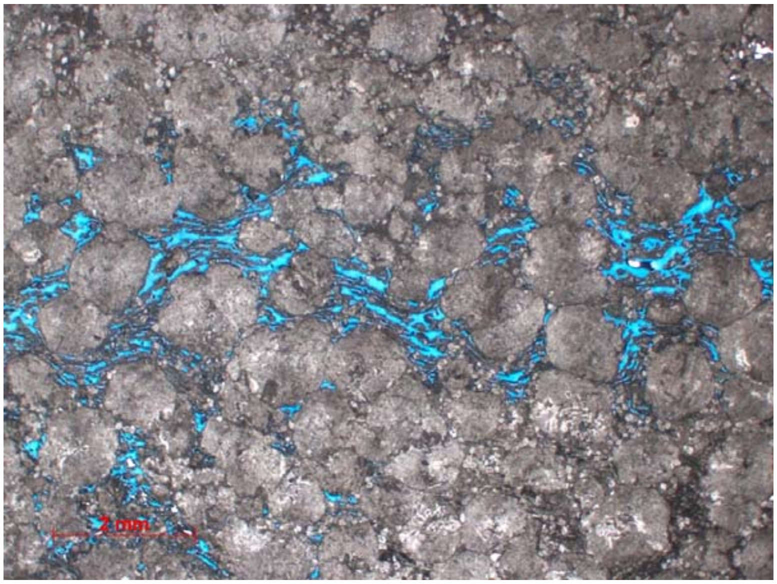


Figure 3b – Spherulite texture with Mg-silicate matrix dissolved and resulting porosity (Wright and Barnett 2017).

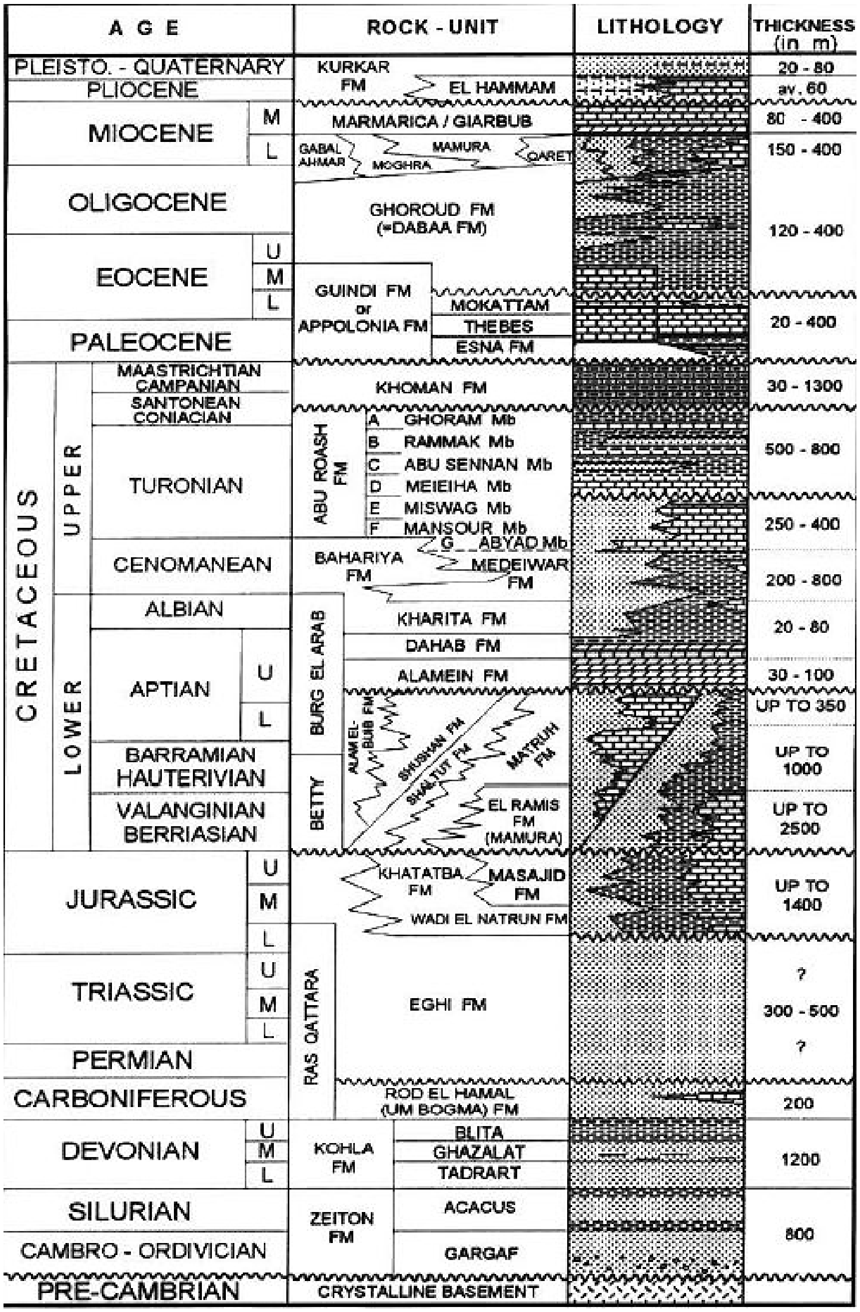


Figure 4a – Approximate sequence, relative thickness and age with lithology for formations in Egypt (Gadallah 2010).

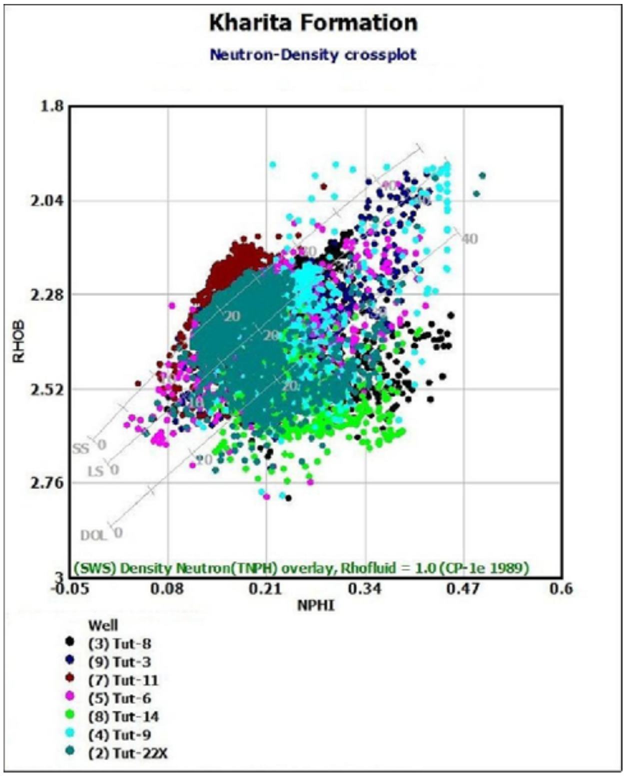
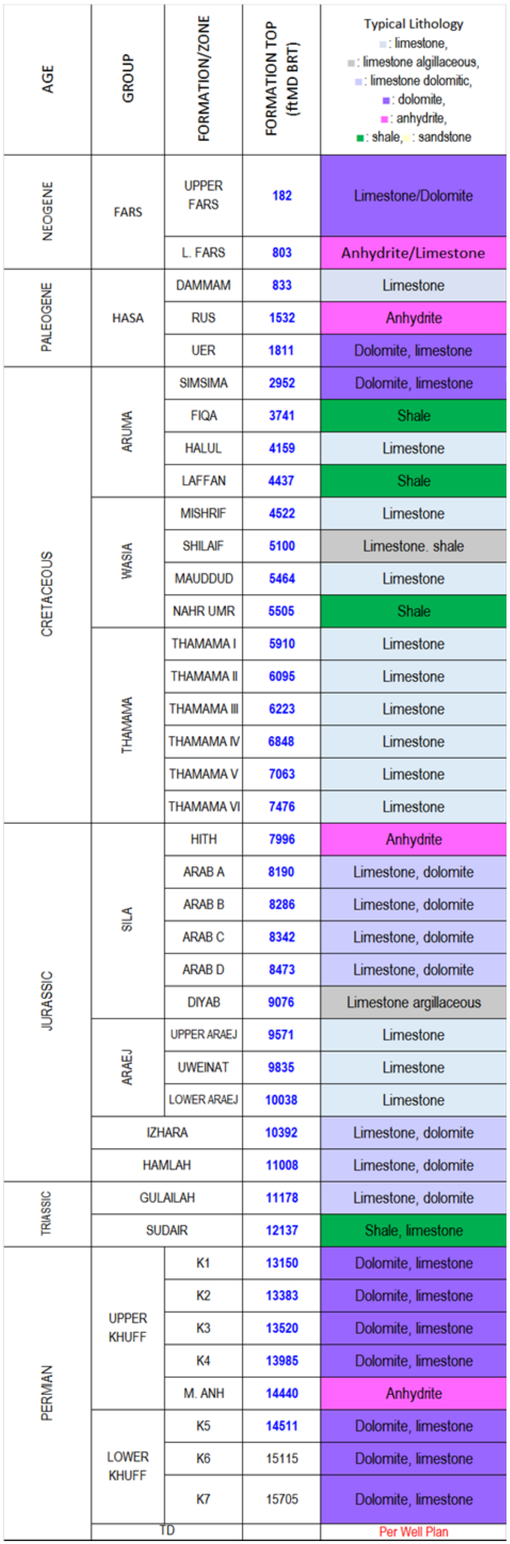


Figure. 4b – Neutron-density crossplot of the Kharita formation. Points plotted between sandstone and limestone lines indicate calcareous cement is present as well as interbedded carbonate (Aboelhassan et al. 2016).

Figure. 5 – Offshore UAE fields.



AGE	GROUP	FORMATION/ZONE	FORMATION TOP (ftMD BRT)	Typical Lithology ▫: limestone, ▪: limestone algillaceous, ▫: limestone dolomitic, ■: dolomite, ■: anhydrite, 🟩: shale, ▫: sandstone
NEOGENE	FARS	UPPER FARS	182	Limestone/Dolomite
		L. FARS	803	Anhydrite/Limestone
PALEOGENE	HASA	DAMMAM	833	Limestone
		RUS	1532	Anhydrite
		UER	1811	Dolomite, limestone
CRETACEOUS	ARUMA	SIMSIMA	2952	Dolomite, limestone
		FIQA	3741	Shale
		HALUL	4159	Limestone
		LAFFAN	4437	Shale
	WASIA	MISHRIF	4522	Limestone
		SHILAIF	5100	Limestone. shale
		MAUDDUD	5464	Limestone
		NAHR UMR	5505	Shale
	THAMAMA	THAMAMA I	5910	Limestone
		THAMAMA II	6095	Limestone
		THAMAMA III	6223	Limestone
		THAMAMA IV	6848	Limestone
		THAMAMA V	7063	Limestone
		THAMAMA VI	7476	Limestone
JURASSIC	SILA	HITH	7996	Anhydrite
		ARAB A	8190	Limestone, dolomite
		ARAB B	8286	Limestone, dolomite
		ARAB C	8342	Limestone, dolomite
		ARAB D	8473	Limestone, dolomite
		DIYAB	9076	Limestone argillaceous
	ARAEJ	UPPER ARAEJ	9571	Limestone
		UWEINAT	9835	Limestone
		LOWER ARAEJ	10038	Limestone
	IZHARA		10392	Limestone, dolomite
	HAMLAH		11008	Limestone, dolomite
TRIASSIC	GULAILAH		11178	Limestone, dolomite
	SUDAIR		12137	Shale, limestone
PERMIAN	UPPER KHUFF	K1	13150	Dolomite, limestone
		K2	13383	Dolomite, limestone
		K3	13520	Dolomite, limestone
		K4	13985	Dolomite, limestone
		M. ANH	14440	Anhydrite
	LOWER KHUFF	K5	14511	Dolomite, limestone
		K6	15115	Dolomite, limestone
		K7	15705	Dolomite, limestone
		TD		Per Well Plan

Figure 6 – Approximate tops and age with brief description and rock type for formations in the Middle East (Bijjani 2018b)

Figure 7 – Selected image of an FMI log from Well 11, 8⅜-inch wellbore, as processed after controlling losses. Note the fracture patterns which most likely provided the preferential path for losses (Bijjani et al. 2018a)

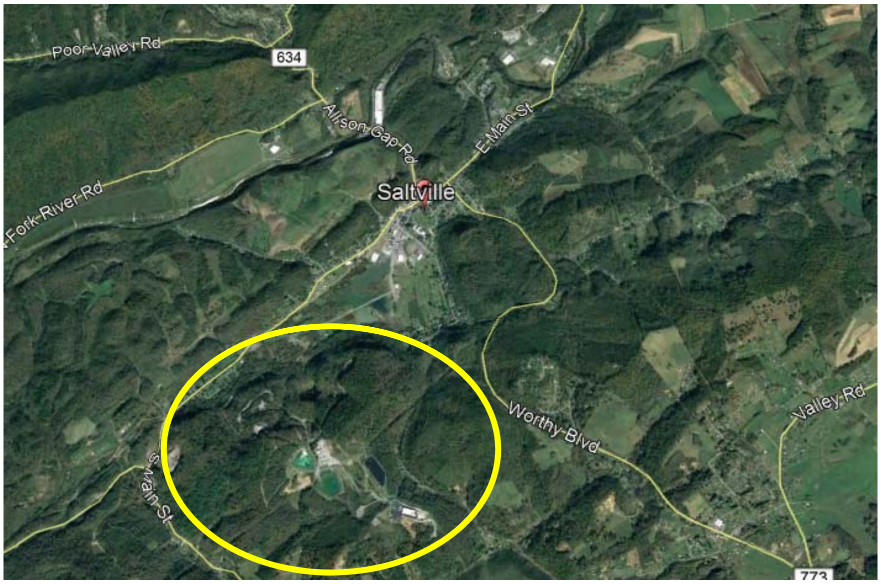


Figure. 8 – Saltville Field, North America circled in yellow.

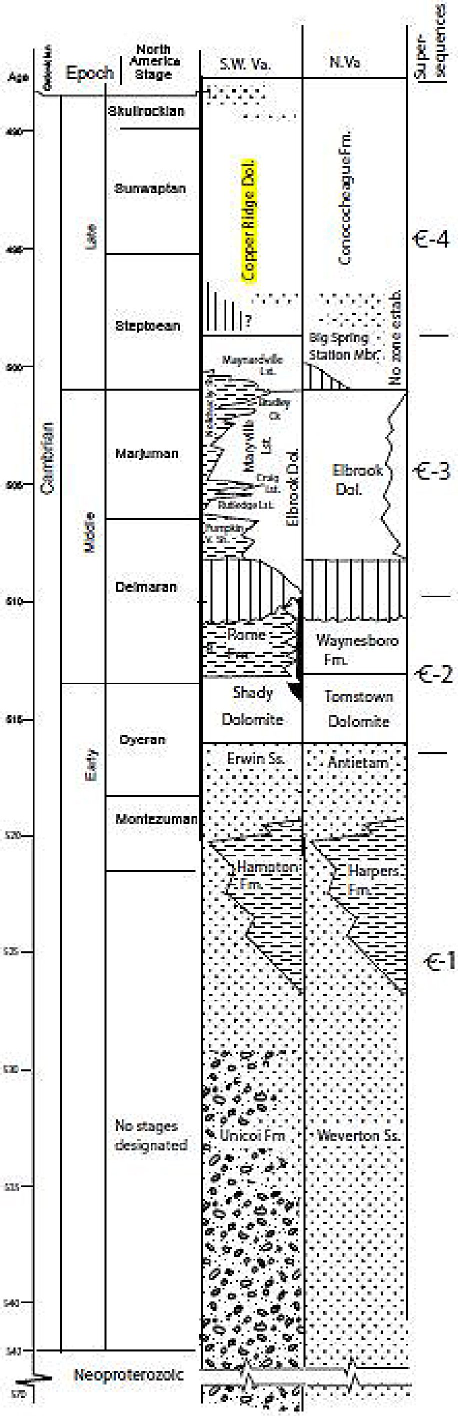


Figure 9 – Approximate formation rock type and age. The Copper Ridge Dolomite is very-late Cambrian (see yellow highlight).

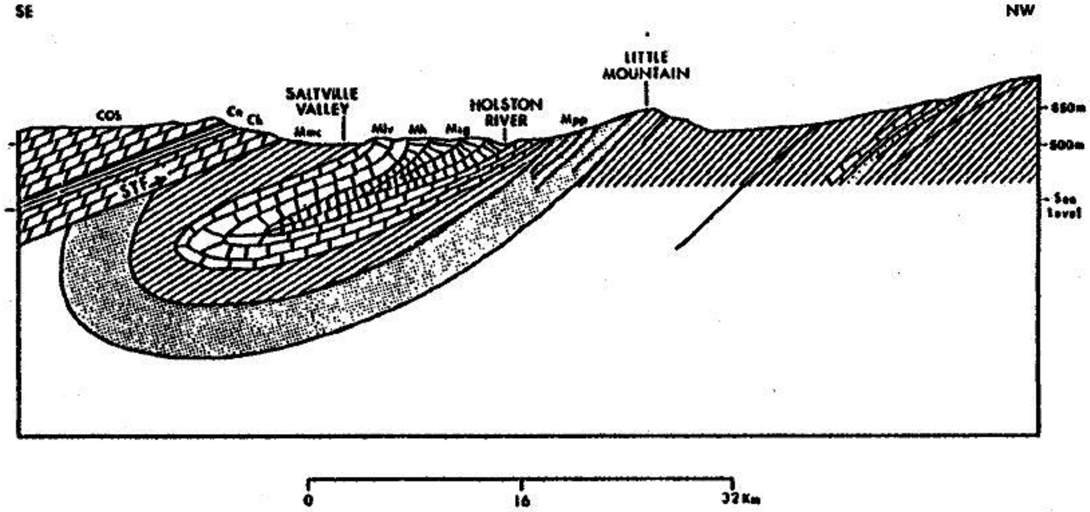


Figure 10 – Geologic cross-section of the Saltville region along the Smyth-Washington county line. The COk, Co and Ch denote Cambrian formations and the STF denotes the Saltville thrust fault whereby older rock overrides younger (McGuire 1970).

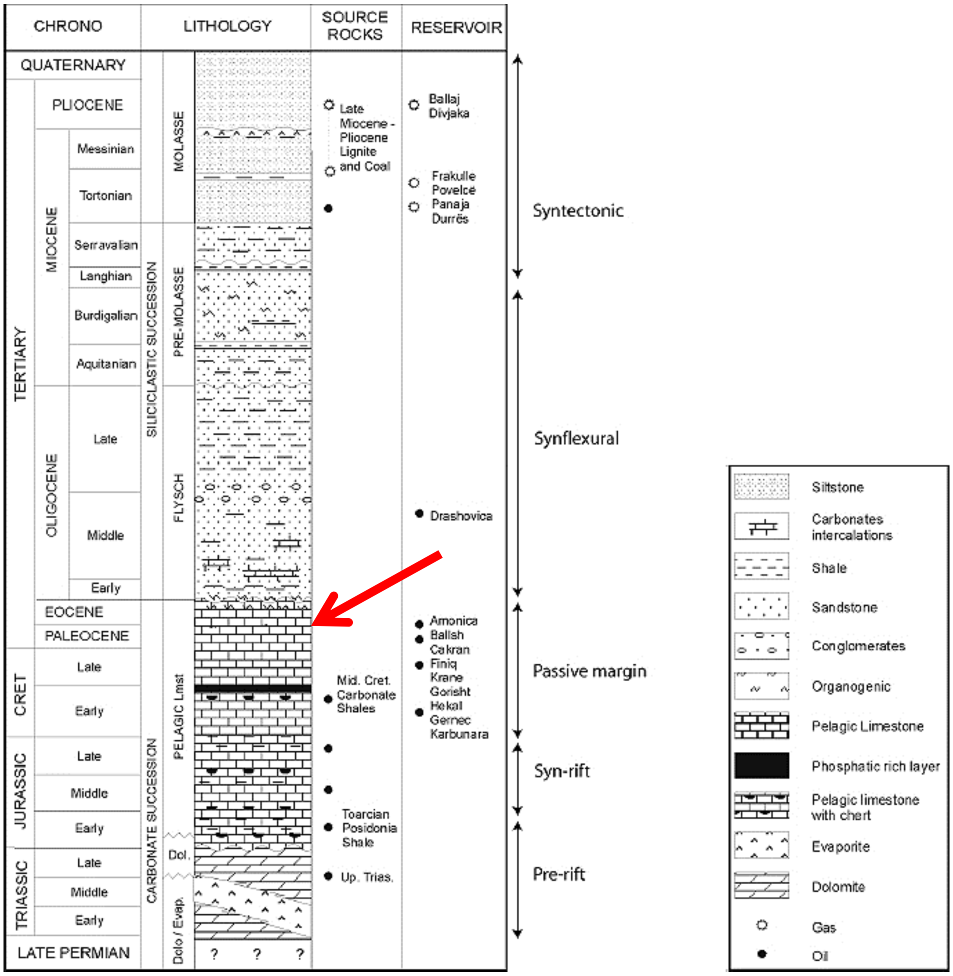


Figure 11 – Lithostratigraphic characterization of the Ionian zone in Southern Europe. Legend on right side depicts the rock types. The problematic carbonate for this area is the pelagic limestone of Eocene-Paleocene age per red arrow (Vilasi 2009).

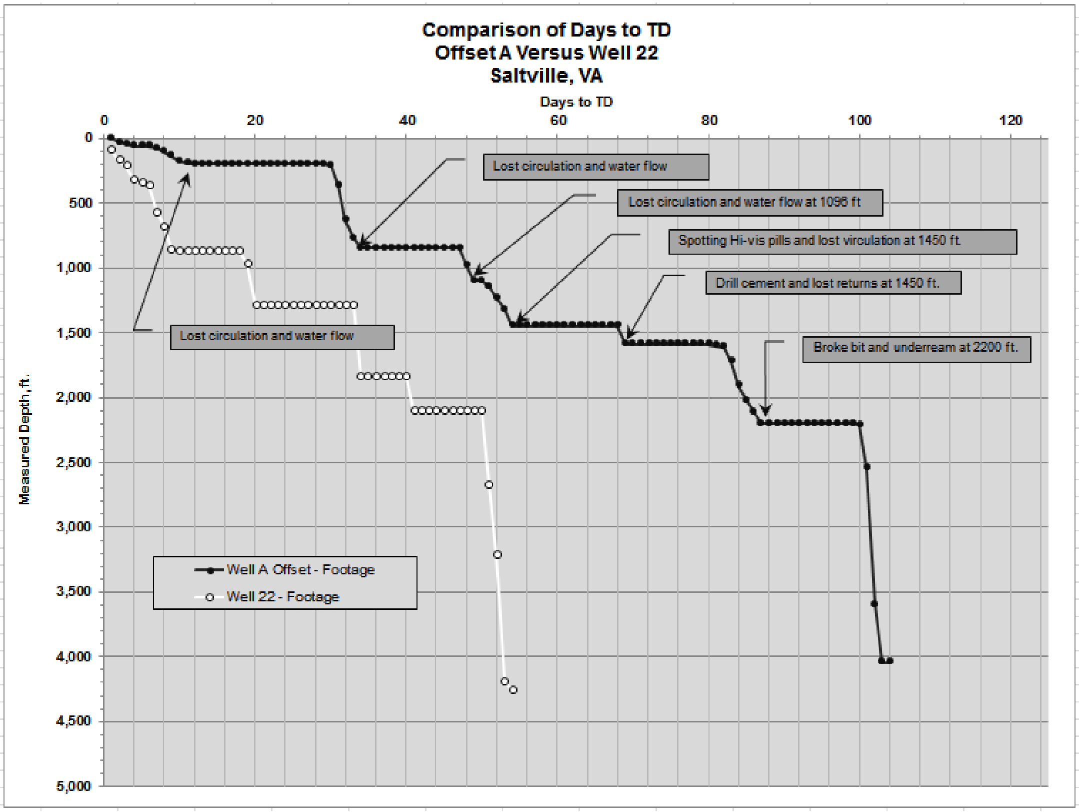
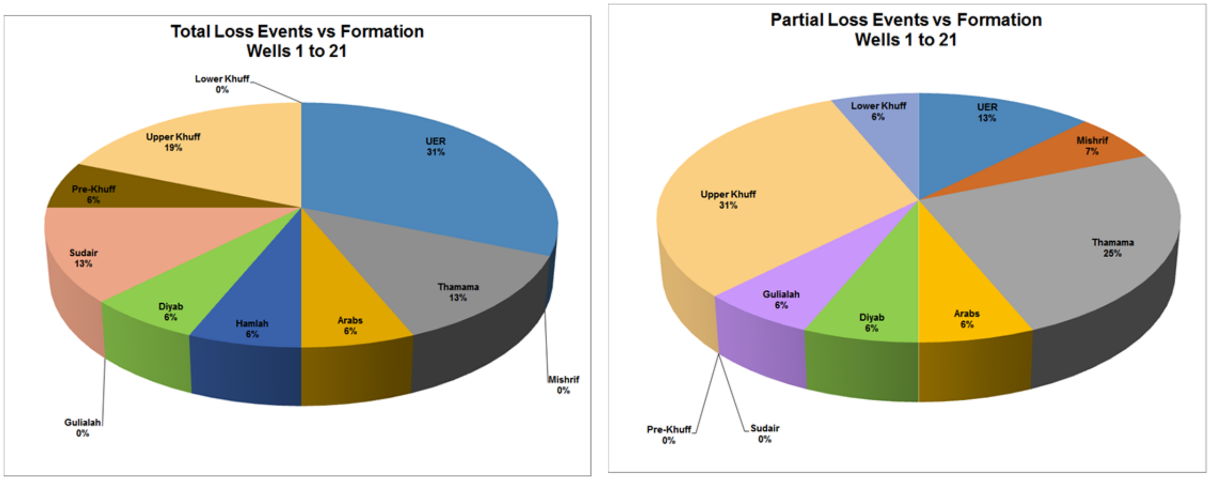


Figure 12 – A comparison of Days to TD for a previous offset Well A versus Well 22. Highlighted text denotes problem and depths where additional days were required to combat fluid losses. Note the water flows that occurred in the dolomitic carbonate, approximately 1,100 ft. and shallower.



Figures 13a and 13b – Comparison of formations and intervals where Total and Partial Losses were experienced in Wells 1-21 (Bijjani 2018a).

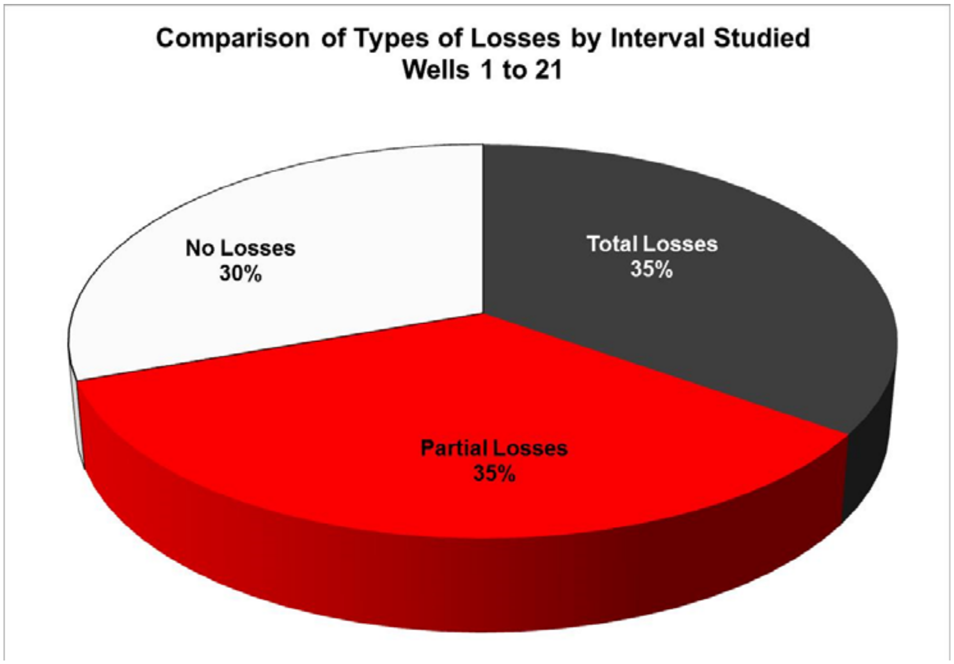


Figure 14 – Comparison of all intervals in wells studied exhibit a nearly equal statistical distribution for general loss type as each approximates one third. (Bijjani 2018a)

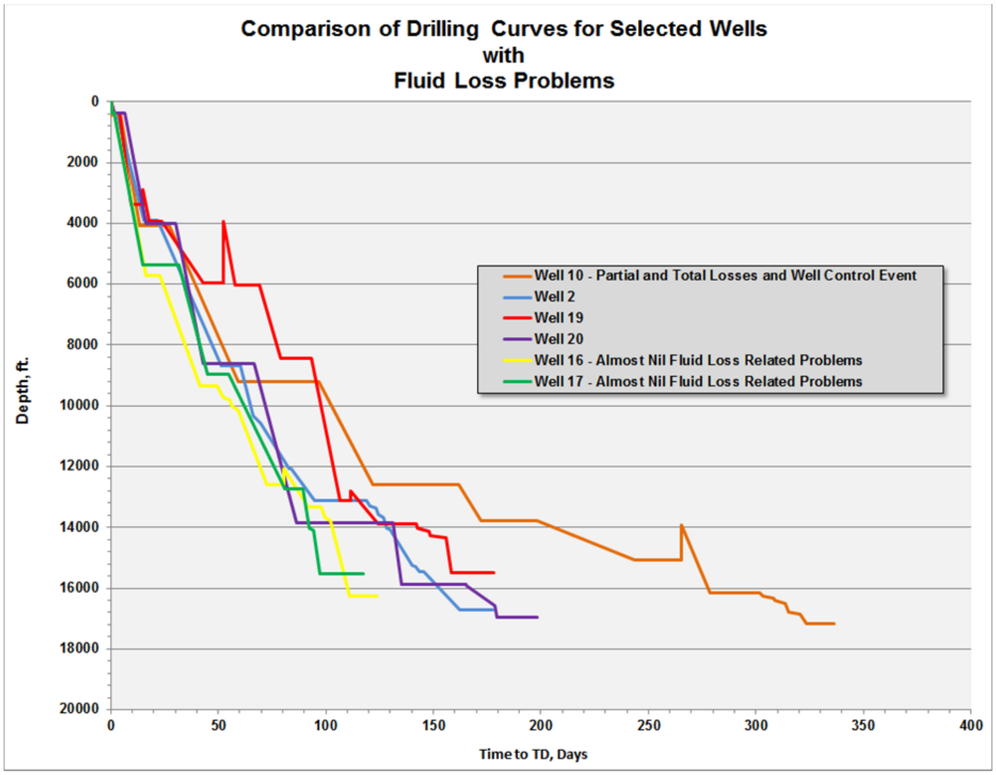


Figure 15– Comparison of selected wells with and without fluid loss events. Note that Well 10 is the offset. Wells 16 and 17 experienced little to no events. Wells 2, 19, and 20 experienced marginal events, and Well 10 numerous events. Thus, excessive rig time and a sidetrack were required to prevent/reduce fluid loss and their concurrent problems (Bijjani 2018a).

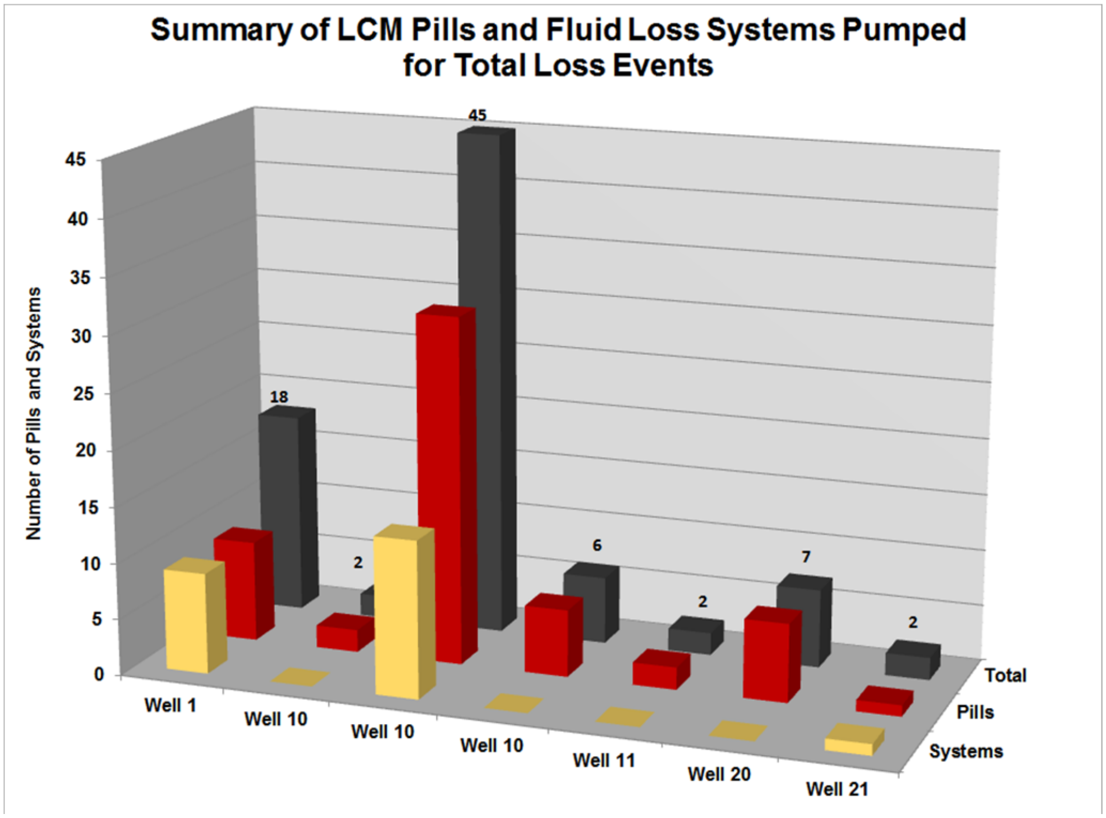


Figure 16 – Comparison of selected wells from Arabian Gulf where returns were lost versus types of pills, systems, and formation. A total of 82 pills/systems were pumped or an average of 11 to 12 per well (Bijjani 2018a).

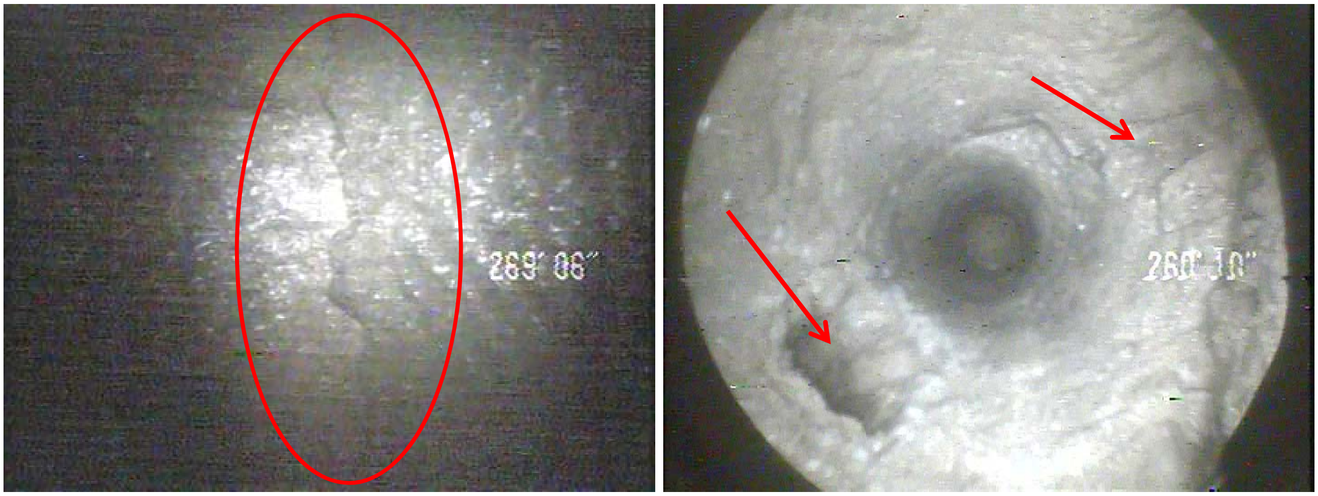


Figure 17 – Selected images from a downhole camera from Well 23 in the 19¼ -inch wellbore. While some fractures are most likely due to stress unloading (red circle in left image) others are inherent. The approximately 3-in. channel that transects the 19¼ -in wellbore is the cause of lost returns (arrows right image) (Bijjani 2018a).