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Application of Precipitating Aluminum Complex Drilling Fluids in Problematic Geological Formations

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ABSTRACT

Unconventional formations have been operationally complex and costly to drill. Shale, in particular, can prove challenging due to its heterogeneous nature, characterized by nano to micro sized pore distribution, low permeability, pre-existing natural (micro-) fractures and high in-situ stresses. Traditionally, O/SBM systems have been used to drill troublesome shales due to geological challenges. However, numerous unforeseen complications are just now being exposed while using O/SBM in specific geological areas, potentially worsening geomechanical effects. With the development of 'state-of-the-art' technical competencies in the utilization of novel product additives, these formations have become manageable to drill with advanced high performance water based mud (HP-WBM). Furthermore, these systems have proven to be successful in various challenging formations, such as highly reactive shales, micro-fractured shales, shales with geomechanical issues (e.g. weak bedding planes), lost circulation zones, tar-sands, and chalk.

These considerations have driven the advancement of an aluminum complex HP-WBM (Al-HP-WBM) containing a novel shale stabilizing package, where the main component is a 'precipitating aluminum complex' that unequivocally provides respectable pore plugging capabilities. Although 'precipitating' fluids are nothing new, this distinctive stabilizing function in drilling fluids can provide similar results to S/OBM and other precipitating mud (e.g. silicate muds). The wellbore stabilization mechanism is one of the most important considerations in this mud system that generates a three-domain archetype (chemical, physical, mechanical), therefore effectively improving shale membrane efficiency by maintaining wellbore stability via decreasing pore pressure transmission and managing osmotic pressure.

INTRODUCTION

Characteristically, in operations where wellbore instability or problematic shales might be encountered, oil based mud (O/SBM) systems have historically been the typical choice. In recent years, adaptions, primarily driven by environmental shortcomings, has presented HP-WBM as an attractive alternative option to replace O/SBM. Alongside this environmental quandary, operators face the issue of balancing performance specifications with other drivers such as economical and logistical factors. Naturally, it has been believed that O/SBM has proven to offer the better performance, but with recent advancements in chemical products, HP-WBM is closing the gap in the performance difference. Moreover, in recent years, certain cases in micro-fractured shales have shown that the use of O/SBM can prove detrimental to wellbore stability more than the use of HP-WBM (van Oort et al., 2017; Oleas et al., 2008). Furthermore, the disadvantages of O/SBM have been noted in numerous cases highlighting the necessity for properly choosing and assessing the fluid based on the formation (sub-surface), location (surface), and drilling operations with proper well construction strategies. Some of the less favorable characteristics of O/SBM include, but are not limited to (see van Oort et al., 2016):

1. Environmental limitations.
2. Not suitable in micro-fractured shale.
3. Logistics & economics.
4. Exacerbating lost circulation.
5. Gas kick detection.
6. Emulsion droplets impairing tight sand reservoirs.
7. Lower logging resolution.

Numerous papers have been written in the past decade exclaiming the benefits of using HP-WBM in place of O/SBM. One of these promising, mud systems is the 'Aluminum Complex HP-WBM' (Al-HP-WBM), a unique mud system that can deliver similar performance to O/SBM while still being economical and providing obvious advantages such as providing stability via chemical, physical, and mechanical factors as it is able to stabilize problematic shales by means of borehole pressure-management. This HP-WBM has emerged as a robust and adaptable mud system, apt for various applications, making it suitable to be deployed in challenging geological formations around the world.

In this paper, the use of Al-HP-WBM in challenging formations will be highlighted and identify the geological conditions where drilling troublesome areas has shown successful outcomes by using a precipitating, mechanically plugging, Al-HP-WBM.

Background – Aluminum Complex HP-WBM

The Al- HP-WBM has shown to be a robust and versatile mud system, fit for purpose for various global applications and has been field proven to give noticeable results, world-wide, including applications in Gulf Of Mexico, North Sea, Norway, Colombia, Ecuador, Venezuela, US onshore, offshore China, offshore ASIA-PAC, Australia, Libya, Saudi Arabia, UAE, Oman, Kuwait, Qatar, and Bahrain.

Key principles by which the Al-HP-WBM emulates the performance of O/SBM systems are listed below (Al-Ansari et al., 2005):

1. Chemical Stability: inhibition and suppression of swelling pressures in clay platelets, i.e. reactive minerals.
2. Mechanical Stability: wellbore stability by controlling fluid pressure transmission into the formation pore matrix, and potentially inducing osmotic back flow.
3. Physical Stability: sealing micro-pores and micro-fractures by means of specialized polymer.
4. Superior cuttings encapsulation.
5. Solids removal efficiency.
6. High penetration rate.
7. Minimizing torque and drag.

Key components that are required for the Al-HP-WBM to have its full functionality include:

- **Aluminum complex-** a dual resin / aluminum compound designed to stabilize reactive shale by reducing pore pressure transmission effects. The product will precipitate a solid aluminum compound on contact with the formation pore fluid by means of a drop in pH.
- **Polyamine -** a complex cationic amine additive designed specifically to provide high levels of ionic inhibition in HP-WBM systems. The product suppresses the swelling of clays.
- **Sealing polymer-** a deformable sealing polymer designed to stabilize shales by reducing pore pressure transmission effects in combination with the aluminum complex. The sub-micron sized sealing polymer deforms over micro-pores and micro-fractures in shale forming a framework to reduce pressure transmission via fluid invasion into the pore matrix.
- **Anti-Accretion additive-** an organic blend of surface active ingredients designed to form a hydrophobic coating on the bit face and BHA, thereby avoiding bit balling and drill-string accretion.
- **PHPA**- a partially hydrolyzed polyacrylamide designed to provide cuttings encapsulation.

Each of these products function are governed by different mechanisms. They may, function independently or synergistically, all dependent on the rock properties and obvious mineralogy. However, the specific mechanism that describes the stabilization of the Al-HP-WBM is portrayed in **figure 1** below. Further information on aluminum chemistry as precipitating agents can be found in Clark et al., 1993; Garcia-Mina, 2006, Benaissa et al., 1997; Zhang et al., 2013. Information on the effects of humic acid and crystallization of aluminum hydroxide and chelating agents can be found in Singer, 1990; Violante et al., 1980. For detailed information in regards to aluminum complex mud systems can be found at Dye et al., 2006; Ramirez et la., 2005/2006/ 2007a / 2007b; Ewy et al., 2009; Leaper et al., 2005.

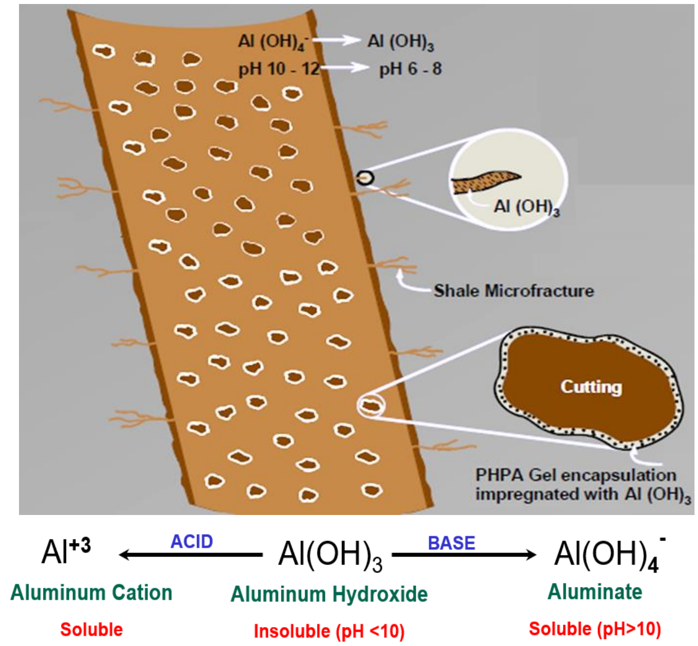

Figure 1 –Stabilization mechanism of the aluminum complex mud. Note – The aluminum hydroxide complex (AHC) is soluble in the mud (pH > 10), but will precipitate in the pore network where the pore fluids will have a pH <8, forming an $Al(OH)_3$ precipitate. The Aluminum Hydroxide can also precipitate due to hardness and create calcium or magnesium aluminate. Both precipitation mechanisms deliver a mechanism for decreasing pore pressure transmission into the wellbore and hence provide improved borehole stability.

Aluminate Muds vs. Silicate Muds

One of the main differences that distinguishes between a conventional WBM and a HP-WBM is effective wellbore stability via multiple stabilization mechanisms. Many WBM are chemically inhibitive but lack the mechanical stabilization factor that categorically differentiates them as HP-WBM. Typical HP-WBM that provide this type of multi-prong stabilization are 'precipitating complex' mud systems, such as silicate muds (see van Oort et al., 1996; van Oort and Hoxha et al., 2017), aluminum complex muds, and clouding glycol mud systems. The current general perception in the oil and gas industry is that the most effective mud systems for plugging pore throats and reducing pressure transmission in shale are silicate muds and precipitating aluminum complex muds {it is important to note that nanoparticles have also been extensively studied in recent years as suitable plugging additives, but Hoxha et al., 2017 and 2019 describes in detail the scientific limitations faced when using nano-particle based drilling fluids). Furthermore, for further reading, Ewy et al., 2005 has publicized pressure transmission data for silicate and aluminate mud systems.

Even though the governing mechanism of both these systems are very similar, there is a noticeable difference in their functioning specifications. The information presented in **table A1** depicts the advantages and disadvantages of these mud systems. Pressure transmission data for Al-HP-WBM are shown below (see **figure 2**).

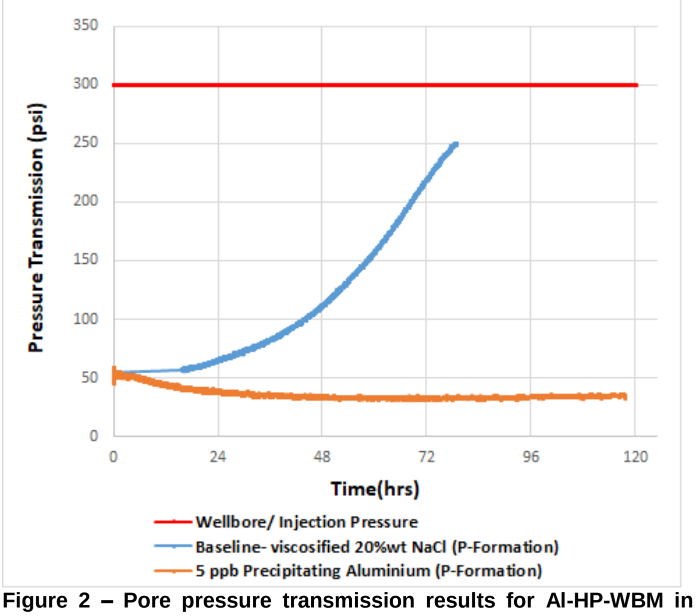

Figure 2 – Pore pressure transmission results for Al-HP-WBM in comparison to base fluid, clearly showing major reduction in pressure transmission. Note, further reproducibility results prove to be consistent and will be provided in future papers. The shale sample in this study is a 1''x 0.5'' Pierre Type II plug, plugged parallel to bedding, with differential pressure of 250 PSI at 150°F.

For reference to silicate mud pressure transmission performance, refer to van Oort (1996) and van Oort et al., 2017 on Tor/Ekofisk filed for the Lark & Horda shale, and van Oort & Hoxha et al., 2016 for fluid performance comparison in Mancos shale.

It has been stated that the primary role to the success of precipitating complex mud systems is in their ability to improve membrane efficiency by altering the mobility of solutes/ions through the shale pore network. Precipitating mud systems can influence this mobility by effectively plugging up the shale pore throats and preventing fluid transport through the pore network.

The difference between silicates and the aluminum complex muds is that the aluminum salts have the tendency to be soluble at lower pH in aqueous solution. However, aluminates produce highly alkaline solutions when dissolved in water, but not as high as silicate muds. Additionally, another unique feature of aluminum chemistry is the amphoteric nature of aluminum hydroxide. Aluminum hydroxide may react with base (OH^-) or acid (H^+) to produce water soluble aluminum species (see Dye et al., 2006; Ramirez et al., 2006).

It is important to note that this paper clearly recognizes that, at the moment, there is not enough substantial evidence in the industry to compare the pressure transmission performance of these two mud systems. It is necessary for future endeavors to directly test these mud systems in pressure transmission testing under the same conditions, avoiding indirect cross-reference comparisons.

CASE HISTORY

Fluid design is a bottom up approach, understanding the properties and characteristics of the formation being drilled will warrant the selection of proper additives for the HP-WBM fluid design. For development of the Al-HP-WBM, this methodical design is practiced by utilizing a systematic approach by focusing on the main key components which contribute to the stabilization mechanism by reducing pressure transmission. In contrast, conventional filtration additives cannot reduce pressure penetration in shales because shale has limited Darcy flow due to small pore throats and low permeability (micro-Darcy range). Therefore, the creation of a conventional filtercake in shales is unlikely. Hence, mitigating pressure penetration in shales can only occur by means of a pore-plugging mechanism. The aluminum complex is highly effective in precipitating as an insoluble Aluminum Hydroxide precipitate inside the shale pore matrix and preventing pressure transmission via pore throat connectivity. These mechanism has shown to be highly successful in different types of shale as well as other troublesome formations which will be described below.

Reactive Shales

Shales that are 'reactive' typically constitute of clay components that swell and cause wellbore instability, leading to poor drilling performance and necessary remediation to drill the well. There are two main forces which cause hydration of clays:

1. Surface Hydration – Results from adsorption of water on the basal surfaces (external and internal).
   - Swelling occurs because of hydrogen bonding of water molecules to the oxygen on the clay surfaces. In the case of smectite type clays several (10 – 20) layers of water surround the clay particles.
2. Osmotic Swelling – Occurs because the concentration of cations between layers is greater than bulk solution, drawing water between the layers.
   - Osmosis can occur because the concentrations of the cations on the clay surfaces are greater than in the brine phase of the drilling fluid. Therefore water will be drawn to the clay surface.
   - No semi-permeable membrane is involved.
   - Causes a large increase in bulk volume.

Historically the concern with using conventional WBM has been the inability to properly inhibit reactive clays, or effect of clays hydrating quickly and eventually dispersing, causing wellbore instability issues. Progress in HP-WBM development, the achievement of a higher degree of inhibition has allowed the clays to stay within the plastic phase of the Atterberg limits, whereas the WBM generally retain the clay cuttings in the liquid phase (see **figure 3**). The problem with HP-WBM keeping clay minerals in the plastic phase is that it promotes cuttings agglomeration and accretion; and even possibly bit-balling. The issue significantly worsens with the increase of reactive minerals in the shale.

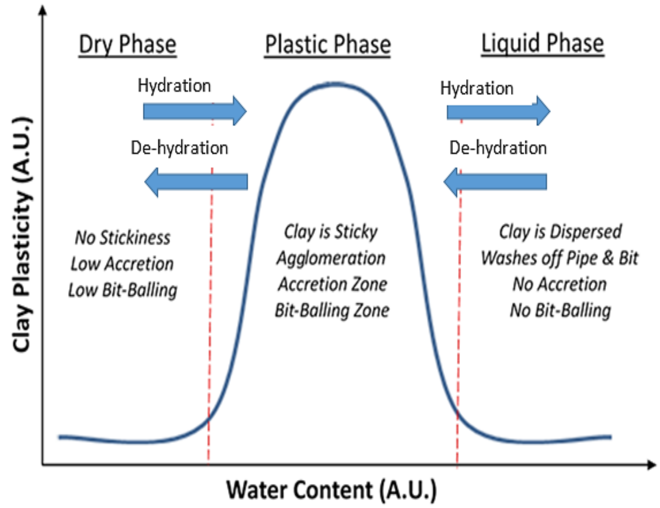

Figure 3 – Diagram of clay plasticity in shale-fluid interaction based on Atterberg limits of soil mechanics. *See Sridharan et al., 2004.*

As a result, a properly designed HP-WBM will provide optimal inhibition by promoting osmotic gradient to keep the shale hydration on the lower side of the plastic phase without totally entering the dry phase - this would be the optimal inhibition area, minimizing the possibility for accretion and to a certain degree, minimizing bit-balling. Field data has shown that the Al-HP-WBM, when properly designed, has a satisfactory ability to slow down the rate of hydration in shales by controlling chemical osmosis and managing the osmotic gradient between the shale and drilling fluid water activity, allowing for fluid inhibition to range between the dry and plastic phase without fully entering the plastic phase, thereby avoiding accretion and bit-balling. The Al-HP-WBM has shown superior inhibition even in the most reactive of shales, such as gumbo shale in the Gulf of Mexico (see **figure 4**).

Field	Quartz %	Illite %	Mixed Layer Clays %	Expandable %	Kaolinite %
West Delta	10-15	15-20	45-50	>95	10-15
Viosca Knoll	20-25	20-25	35-40	100	10-15

Figure 4– Gumbo shale cuttings drilled with a PDC bit, specifically in the West Delta and Viosca Knoll in the Gulf of Mexico, a reactive shale based on the mineralogy of the formation in the table above.

Understanding the mechanisms of reactive shales has been an ongoing topic of interest for many decades. An interesting project initiated by DEA-113 noted peculiar differentiation between the characteristic of Pleistocene 'gumbo' shale in GoM vs. Graben Shale in the North Sea. The report focused on testing to stabilize gumbo shale in GoM. Typically gumbo shale becomes extremely 'sticky' when wet and will adhere aggressively to drill pipe and the bottomhole assembly. The general misconception has been that since the shale hydrates it will be soft. This isn't (typically) always the case. The report mentions that the studies showed that the younger GoM gumbo shale from the west delta can have a moisture content of 12% with a hardness of 99 via durometer, while other older, deeper, North Sea (central Graben) shale with a moisture content that is 15% can display a lower hardness reading of only 50. Consequently, the shale characteristics can possibly be explained by the soil mechanism defined by the Attberg limits and plasticity index of the shale. These concept explains the hydration mechanisms as they interact with various drilling fluids. Simply put, internal moisture content, and the hydration kinetics of the shale-fluid interaction will justify its clay plasticity index and thus determine if the clay/shale will agglomerate and cause wellbore stability issues.

Subsequently, the study reports extensive borehole stability testing via a 'Downhole Simulation Cell', comparing various industry fluids. The Al-HP-WBM demonstrated to be in the top four water based mud systems (see **figure A2**).

The Al-HP-WBM has also shown to adequately inhibit highly reactive type shales like the 'Green Clay' and Draupne formation in Norway, North Sea. Proper salt/inhibition package provided no noticeable problems with agglomeration and bit-balling. The morphology of the cuttings were definite and dry with adequate integrity (see **figure 5**)

	Quartz	Feldspar	Calcite	Mixed Layer (I/S)	Illite	Chlorite	Kaolinite
Green Clay (North Sea)	10-15%	1-5%	5-10%	40-60%	5-10%	2-5%	4-7%

Figure 5 – Image of North Sea, green clay cuttings. Green clay is an arbitrary synonym used for reactive shale in the North Sea, the most prominent area of this clay is located in in Denmark, named Lillebaelt. Further information on the lithology of this clay can be accessed at Heilmann-Oausen et al., 1985.

On the complete opposite side of the hemisphere, the shale formations of the Arabian Peninsula have different characteristics to the GoM and North Sea shales. They are less reactive (moderately), with less mixed layer clays and a significantly higher Kaolinite content. A well-known problematic shale in the Middle East is the Nahr Umr shale. It covers a large portion of the Arabian Gulf and forms the cap rock to many major reservoirs. The clay minerals mainly consist of illite/smectite and kaolinite, and the content of smectite is low (see **figure 6**).

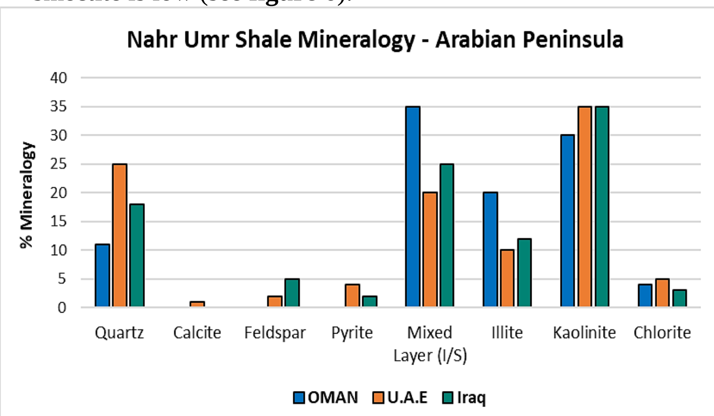

Figure 6 – Mineralogy of Nahr Umr shale in Oman, UAE, and Iraq.

A common observation experienced in this area is the use of KCl salt to control the shale swelling pressures in highly kaolinitic shales. Experience and extensive laboratory data has shown potassium to de-stabilize shale containing kaolinite (Bjorkum et al., 1988). The failure mechanism of shale containing kaolinite is associated with fluid invasion through micro-pores. This process is enhanced considerably by the potassium change in the shale structure. Illitization of kaolinite occurs when potassium cation is introduced to the clay platelets of the kaolinite mineral. This can produce two effects including the transformation of the relatively inert kaolinite into highly dispersible illite and structural changes in the shale, exacerbating the wellbore stability problems (see Ramirez et al., 2005; Mohammed et al., 2018; Xi et al., 2016; Nguyen et al., 2007). The destabilizing illitization process occurring during wellbore instability can be illustrated thus:

$$\underset{\text{(Kaolinite)}}{3Al_2Si_2O_5(OH)_4} + 2K^+ \rightarrow \underset{\text{(Illite)}}{2KAl_3Si_3O_{10}(OH)_2} + 2H^+ + 3H_2O$$

It is important to note that the illitization of kaolinite is based on many other factors such as the degree of the crystallinity of the Kaolinite structure, temperature, pressure etc. Nevertheless, this problem can be avoided by using other salts, such as NaCl, as an osmotic gradient generator. Field data reported back has shown that the use of Al-HP-WBM (with NaCl brine) proved to successfully inhibit and stabilize these problematic shales.

Other shales that have revealed to be problematic in the Arabian Peninsula are the Ahamdi and Wara shale. Nevertheless, Al-Ansari et al., 2005 showed that Al-HP-WBM replacement of O/SBM proved to be a successful alternative fluid design while drilling of Ahmadi, Wara, and Burgan shale in Kuwait, where previous offset wells exhibited high potential for losses to the cap rock and tight hole in the interbedded shale sections was experienced whilst drilling with O/SBM. Significant pre-planning was initialized for the project to be successful. However, with precise diligent planning, identifying risks and setting up mid-operation action plans, drilling with HP-WBM in problematic areas where O/SBM has shown to be ineffective, is possible. Furthermore, Al-Ansari et al., 2005 goes on to describe another challenging scenario where use of the Al-HP-WBM was used to drill onshore Bahrain, for a depleted reservoir zone in a deep gas field (see Hoxha et al., 2017 for depleted zone drilling). The drilling challenges included fluid invasion, differential sticking, and lost circulation if drilled with a substantial overbalance pressure. The outcome showed that, with proper bridging optimization, the aluminum complex in the HP-WBM showed to be effective at efficiently controlling the pressures while drilling and mitigated significant fluid invasion and pressure transmission into the depleted, low-pressured, reservoir

Micro-fractured Shale

Almost all shale formation contain some degree of fracturing. Shales that contain fractures will rapidly be destabilized by fluid invasion as pressure penetrates the pores and elevates the pore pressure, thus increasing stress to the wellbore. Consequently, the shale membrane efficiency is compromised and the destabilization is imminent; it is not a question whether it will happen, but when? The destabilization mechanism is time dependent, therefore, and fluid design needs to focus on providing suitable stability to delay this time dependent destabilization.

The common misunderstanding in the oilfield has been that fluid pressure penetration is not a concern with O/SBM systems because capillary entry pressures are high enough to restrict entry of the filtrate. However, many studies have proven that this is not the case when the shale is micro-fractured and/or if the shale is oil-wet with organic pore fluid (see van Oort et al., 2017b; Oleas and Chenevert et al., 2010; Montilva et al., 2007; Al-Bazali et al., 2009).

Some of the typical conditions for O/SBM to invade the shale pore space and destabilize the wellbore (can possibly be more unfavorable the WBM), are listed below (see **figure A1** and **table A2**):

1. Petro physical, chemo-physical properties of the shale:
   a) Porosity
      - Low capillary forces
   b) Permeability
      - Shale is (micro-) fractured in-situ and/or induced
   c) Mineralogical
      - Wettability
        - Mixed-wet or oil-wet with organic pore fluid.
        - Oil-wet minerals: Carbonates, Kaolinite, Chlorite
2. Surface Area of shale (mineralogy based)
3. Osmotic effects/pressure – membrane efficiency

Similar phenomenon can describe the issues associated in the Tuscaloosa Marine Shale where wellbore instability occurs due to pressure transmission into troublesome shale, generating large amounts of cavings and ultimately leading to packing-off in the well (see **figure 7**).

The Tuscaloosa Marine Shale (TMS) is a deep formation with natural (micro-) fractures, low permeability, brittle, calcareous laminated shale, and contains high gas content (Lu et al., 2016 and Moffett, 2015). The TMS is a mildly-moderately reactive with a composition predominantly quartz, calcite, and typically less than 20 % mixed layer (I/S) clay where the expandable clays range between 10-20% (Wilson, 2016). Accordingly, the shale is vulnerable to fluid invasion due to capillary effects which results in massive wellbore instability from cavings to pack-offs. Thus, mechanical stabilization is inevitability an obligation.

Figure 7 – Image of cavings from the Tuscaloosa Marine Shale.

Al-HP-WBM is suitably designed to replace O/SBM in these types of drilling operations in order to reduce and delay the pressure transmission of the drilling fluid into the pore matrix. The novel shale stabilizing package, with the main component being the 'precipitating aluminum complex' provides superior pore plugging by counterbalancing hydraulic flow into the shale via osmotic back flow mechanism (see **figure 2** for example. Refer to van Oort 2019 for more detail).

Other shales that experiences similar phenomenon is the Lark & Horda shale in the North Sea (see van Oort et al., 2017). These types of instances are not just recently becoming prevalent, they are simply being exposed and more deeply understood as operators are performing in depth analysis for determining root cause problems. Therefore, in these types of formation the use of O/SBM will demonstrate more unfavorable results than the use of HP-WBM. Accordingly a HP-WBM with mechanical plugging and sealing additives is the most suitable option to prevent wellbore instability and possible lost circulation.

A study performed by the drilling engineering association, describes another type of phenomenon where O/SBM usage proved more unfavorable results than WBM. This case was thoroughly explained in the DEA-13 testing for fracture propagation studies between WBM and O/SBM. The study showed that for WBM, the full pressure that is exerted onto the borehole is largely shielded from the fracture tip by deposited solids in the external filter cake. In O/SBM, the full pressure is exerted at the tip of the fracture with little to no shielding to lessen fracture propagation (see **figure 8**).

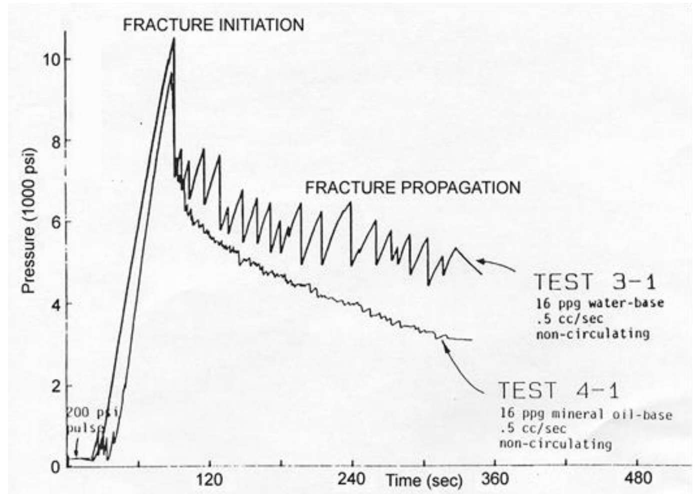

Figure 8 – Fracture pressure data showing difference between FIP and FPP in WBM vs O/SBM. Based on DEA-13 testing.

Therefore the pressure needed to crack and initiate a fracture is the same for WBM and O/SBM since this is a function of rock strength, but the amount of pressure needed to propagate a fracture is lower with O/SBM.

O/SBM can additionally be problematic when drilling along natural fractures or faults, where the equivalent circulating density pressures exceed the borehole pressures and induce shear failure along the natural fracture or faults, resulting in seepage, losses, or lost circulation. Accordingly, the use of O/SBM is the least suitable option in drilling these challenging geomechanical operations.

Bedding Plane Failures

Bedding plane failure is experienced when the borehole is drilled through weak to strong formation beds, resulting in anisotropic destabilization of the formation (see **figure 9**).

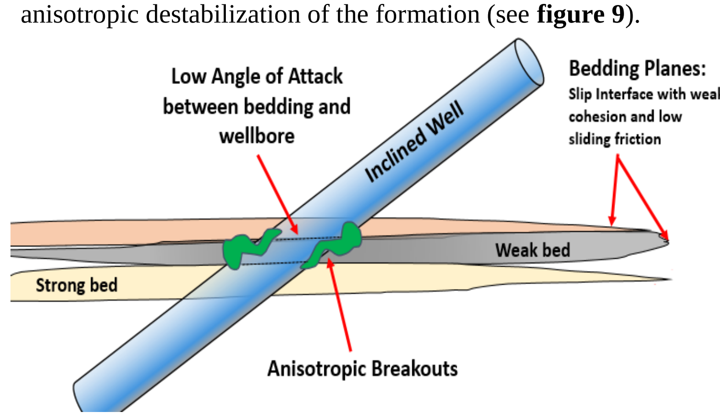

Figure 9 – Diagram of weakened bedding planes in an inclined well. Note the anisotropic destabilization of the bedding formation, resulting in breakouts. Bedding plane instability is extremely dependent on 'angle of attack' when drilling through weak formations (e.g. shales, clay etc.).

Bedding plane failure typically depends on the actual field stress, pore pressure, bedding dip, dip azimuth, cohesion between the beds, and the sliding friction along the bedding planes (Aadnoy et al., 2009. Dokhani et al., 2013. Wu et al., 2010). This geomechanical destabilization is usually experienced when drilling through weak shales and eventually through strong formations underneath. This complex phenomenon is time-dependent and pressure dependent, eventually destabilizing the bedding planes by forcing fluids into the bedding plane interfaces; ultimately leading to expanded shear failure along bedding planes. Bedding plane failure generates formation breakouts anisotropically and produces blocky and planar cavings (see **table A2**) that can be large and difficult to remove during the hole cleaning process.

The ultimate factors influencing tendencies for bedding plane weakening/failure is mud weight and well trajectory (inclination and hole azimuth). Furthermore, pressure transmission via fluid invasion into the bedding plane interface, exacerbates the failure, splitting the beds and increasing the amount of cavings spalling into the borehole (see **table A2**).

The differential between the formation pressure and the borehole pressure (exerted by the drilling fluid) is the driving force which affects the fluid invasion into the shale pore matrix. In certain cases, raising the mud weight can potentially contribute to the shale destabilization.

These severe issues could lead to further problems such as tight hole, cavings, pack-off, stuck pipe, loss of fluid, fractures (Karimi, 2013; Han et al., 2017, 2018).

In most cases, bedding plane failure cannot be avoided due to the well trajectory planning. Therefore, it is imperative that an efficient 'sealing product package' is arranged in the fluid design when drilling through these challenging geological formations.

Historical cases have shown the Al-HP-WBM to perform well in sealing and plugging the weak bedding planes, preventing the drilling fluid from penetrating into the formation.

Tar Sands

A unique application for the use of the Al-HP-WBM was explored and proved effective in Saudi Arabia. A geological formation proved to be problematic in designing a proper mud system for drilling through TAR sands. TAR sands are sandstone formations saturated with bitumen or heavy oil and are soft and poorly consolidated.

Abahussain et al., 2019 describes the unique application where conventional drilling fluid systems, either water-based or oil-based, had proven to be ineffective. The reason being that drilling with an O/SBM fluid would lower the mechanical strength of the tar, exacerbating any tendency to mobilize into the wellbore (creeping). TAR is mostly hydrocarbon-based and thus swells, softens and/or dissolves in oil. In contrast, a conventional water-based mud with basic inhibition and poor management in pore pressure transmission will not prevent the challenges associated with wellbore stability, accretion, wellbore enlargement, and torque/drag impediments.

According to Abahussain et al., 2019, Al- HP-WBM was designed to drill the complicated intervals offering improved drilling performance and cuttings stability (see **figure 10**).

Figure 10 – Tar sand cuttings from KSA. From Abahussain et al., 2019.

Evaporites

Moroni, 2009 describe a case history where a unique application was utilized for the use of the Al-HP-WBM in multi-lithological zones. The mud system showed versatility and tolerance in the 'Sirte Basin' in Libya where the drilling environment typically involves drilling through the problematic Sirte and Rachmat shale and the Etel evaporite sequences, which are heavily pressured and mechanically unstable. Subsequently, the successful operations notes the versatility of the mud system to be used in challenging drilling operations, enhancing borehole stability and stabilizing challenging formations, allowing for enough time-dependent stabilization to set a single liner size.

CONCLUSION

Oilfield literature is heavily bombarded with papers describing the development of "new" HP-WBM. In this manuscript, the description of Al-HP-WBM system is not novel, it has been around for several decades. The information provided in this publication does not offer an evolution of the mud system but rather a revolution. HP-WBM have traditionally been designed to, primarily, apply in environmentally sensitive areas and combat reactive shales. But, in recent assessments, HP-WBM are being deployed in other types of drilling and geological conditions. In the case of the Al-HP-WBM, the new applications have further shown its versatility, robustness and effectiveness in various drilling environments. The mud system has been redesigned via performance testing such as cuttings stability and wellbore stability:

1. Cuttings Stability:
   - Cuttings Dispersion Test
   - Accretion Test
   - Linear Swell
   - Hardness Testing
2. Wellbore Stability:
   - Pore Pressure Transmission (PTT) test
     - Membrane Efficiency Testing
       - Diffusion and/or chemical osmosis
   - Borehole collapse:
     - Downhole Simulation Cell
     - Thick Wall Collapse
   - Cavings Analysis
   - Triaxial testing for failure envelope

Furthermore, field data has provided numerous case histories of successful stories in its redesign and re-deployment to various applications, such as:

- High drilling performance in Dingo shale in the Australian Northwest Shelf.
- Chalk formations: use of precipitating aluminum complex muds will react with the hardness cations (Ca^{2+} and Mg^{2+}) in the chalk and marl, thus stabilizing and preventing any potential fluid transport that would disperse the brittle formation.
- South China Sea – Pearl River Basin
- Ecuador- Yuralpa field
- Chile - Magallanes Strait

The novelty of the Al-HP-WBM lies in its ubiquitous ability to precipitate an aluminum complex into the shale pore throats and preventing water transport into the shale pore matrix. Ultimately, the time-sensitive destabilization mechanism is delayed allowing for essential time to set casing in problematic formations.

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NOMENCLATURE

AHC = *Aluminum Hhydroxide Complex*
Al-HP-WBM = *Aluminum complex HP-WBM*
CEC = *Cationic Exchange Capacity*
DEA = *Drilling Engineering Association*
HP-WBM = *High Performance Water Based Mud*
O/SBM = *Oil/Synthetic Based Mud*
PPT = *Pore Pressure Transmission*
TMS = *Tuscaloosa Marine Shale*
WBS = *Wellbore Stability*

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APPENDIX

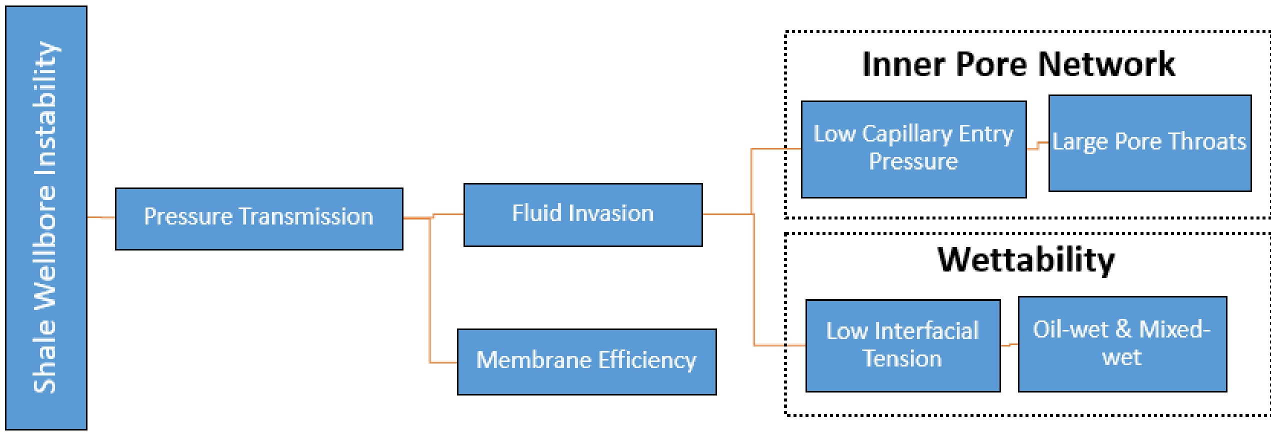

Figure A1- Conditions and characteristics for O/SBM to invade shale pore network.

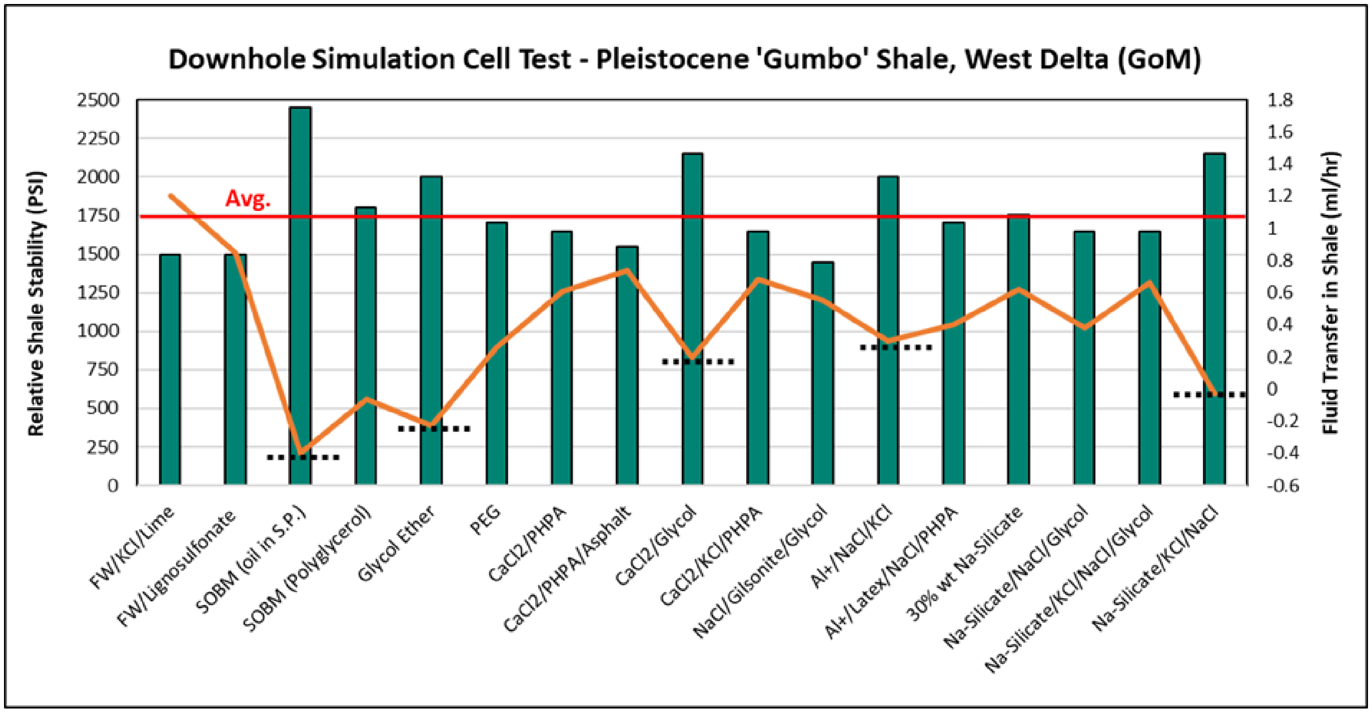

Figure A2 – Borehole stability testing of various industry muds performed by DEA-113 study and GRI study, 2001. Testing conditions at 150°F, axial stress at 3450 psi, confining pressure at 2650 psi, injection pressure at 2200 psi, and sand-pack pressure at 2000 psi.

Table A1- Comparison between Aluminum mud vs. Silicate mud system

	Aluminum Complex	**Silicate**	**Explanation**
Operating pH	10.5 +	12 +	
Product Concentration	3-5 ppb	1-3 %v	Silicate requires approximately 2 to 3 x higher concentration
Pressure Transmission	---	Slightly superior	Depends on shale properties
Effect on Polymers	less	More	High pH will degrade bio-polymers
Effect on Rheology	Less	More	Silicates will impact rheology
Effect on Environment	More	Less	Depends on environment
Effect on Accretion	Less	More	Silicates possibly contribute to “sicky-ness/ plasticity” factor of bit-balling.
Contamination	Less	More	Depending on the contamination
Engineering & Maintenance	Less	More	Difficulty controlling pH, rheology and fluid loss. Even more so impact lubricant compatibility.
Effect from Black Powder	Less	N/A	MAX-PLEX includes lignite carrier
Effect from Hardness	Less	More	Silicates highly sensitive to hardness. Over time, even slight solubility of CaCO3, will attribute to precipitation of silicates.
Effect on elastomers	Less	More	High pH will impact elastomers.
Salt Tolerance	---	---	MAX-PLEX can function at conct of 7-10 lb/bbl in 20% wt sat NaCl. Silicates can tolerate salt only at lower concentrations.
Lubricant compatibility	more	less	Historically, lubricant compatibility with silicate muds has limited options.

Table A2- Cavings analysis and description of failure. Caving Images adopted from Baker Hughes Geomechanics Institute. Angular caving from *Walter Aldred, 1993.*

Types	**Description**	**Cause/Failure**	**Mud Types**	**Solution**	
Splinter	Long, concave shape	Enlarged wellbore, Tensile failure, Stress in massive shale	O/SBM, WBM	Increase mud weight, Change trajectory. a.k.a - splintery “pressure” cavings	
Tabular & Platy	Flat & parallel surface	Rubble zones, Brittle rock-weak, Fissile bedded, Rock anisotropy	O/SBM, WBM	Mud weight & Mud type, Reduce surge & swap, Increase angle of attack to bedding	
Blocky & Rubble	Blocky, circular, symmetrical	Mud penetration (time-dependent), Stress-fractured rocks, salts, faults	***O/SBM is worse than WBM***	Mud weight, Mud type, Reduce surge & swap, HP-WBM to reduce fluid invasion	
Angular	Rough surface & non-parallel edges	Borehole breakout, Shear failure		Increase mud weight, Flow rate/ pump rate