A Review of the Continuing Application of Aluminium Chemistry in Drilling Fluids

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Abstract

The drilling of clay, claystones and shales has always placed great demands on drilling fluids in terms of wellbore stability and drilling efficiency. The drilling fluids industry has been striving to understand the mechanisms involved and apply the knowledge gained to improving drilling fluid design.

The application of aluminium chemistry in drilling fluids was first described in 1973.The early experiences with this aluminium chemistry led to enhancements in the chemistry of the products being used. These in turn led to the products being more widely used with great success.

Various theories were postulated as to the mechanism by which aluminum chemistry benefited drilling fluid performance. It was not until techniques for the measurement of pore pressure transmission in shales were developed that the mechanism for the success of aluminium chemistry was identified. The mechanism will be described and recent laboratory test data will be provided. This same mechanism has been used in the development of other drilling fluids, including silicate and glycol based fluids. Several pore pressure transmission studies have been published and these will be reviewed.

Aluminium chemistry has been successfully applied in numerous wells in various parts of the world. Experience has been gained in the integration of this chemistry into drilling fluid systems. The aluminium chemistry is also a viable alternative for salt inhibited systems in areas where environmental regulations discourage the use of chlorides, but where shale mineralogy dictates the use of an inhibitive fluid. This paper will present several case histories demonstrating the development of the application of aluminium chemistry. This aluminium chemistry has been further refined in recent years as an integral part of a new high performance water based drilling fluid (HPWBM). Fluid design features of this fluid will also be described.[1]

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Key words: Shale, geomechanical, stability, interaction.

Introduction

Recent research work performed by the industry shows that several mechanisms are involved, and that their relative importance can be estimated.[2-6]

- Pore pressure transmission into the formation rock, in the vicinity of the wellbore appears to be of major importance in very low permeability rocks as confirmed by experimental and analytical work.
- Plasticity models better simulate the actual behavior of a wellbore as seen in hollow cylinder tests.
- Anisotropy of the rock can influence failure either by its impact on stress redistribution, or through rock strength anisotropy.

- Capillary effects can help greatly in oil-based muds by effectively supporting the borehole wall. Pressure invasion is controlled by the extremely high capillary entry pressure required for an oil to enter shale pore throats.
- Osmosis, although a well understood phenomenon, is only part of the physico-chemical interactions between borehole and drilling fluid. The role of osmosis as part of the complex effect of drilling fluids on wellbore stability has been discussed by other authors.
- Physico-chemical interaction between shale and water-based drilling fluids leads to dissolution of a mineralogical phase of the rock, as demonstrated by laboratory experiments and observed in field cases. The subsequent alteration of rock cohesion can explain shale failure or dispersion.
- Thermal effects (cooling of the bottom part of the well and heating of the upper part), although not specific to shales, can also be significant.
- The aluminum chemistry approach to shale stability is based on changing the physico-chemical behavior of the shale, in contrast to the widely applied ionic exchange approach.

Shale interaction with the drilling fluid is a major cause of decreased drilling efficiency and increased well cost. Laboratory studies of shale interaction with drilling fluids have been, for the most part, limited to the observation of reactivity. Routinely, cuttings taken from shale shakers are washed, dried, and weighed or, in some cases, the recovered cuttings are pressed into pellets. The cuttings or pellets are then placed into test fluids and observed for their tendency to soften, disperse or disintegrate. The fluid's effects on the cuttings or pellets are evaluated by measuring changes in sample weight and hardness, as well as physical condition.

Other methods such as triaxial test devices have been built at very high cost to test cores under confinement pressures. The large supply of shale cores needed for these devices are difficult to obtain in their native state.

One major characteristic of shales is their very low permeability. As has been reported by several authors, shale permeability has to be expressed in nanodarcies. This is due to the small size of the shale pores, which are in the 0.01-0.001 um range. When using conventional water-based muds, a filter cake cannot form on a shaly formation. Thus, water will enter the rock through pore openings or microfractures. However, before a significant amount of water enters the rock matrix, pore pressure will diffuse into the rock. Eventually, this pore pressure increase will result in an increase of average effective stress at the wellbore, and thus induce rock failure. This failure is time-dependent, due to the low permeability of the shale.

The most important factor in maintaining borehole stability is the prevention of fluid invasion into the shale matrix, thus mainitaining hydraulic pressure support of the borehole wall. An ideal drilling fluid, with respect to shale stability, will allow no fluid invasion. Measuring the pressure increase across a shale core as small amounts of fluid enter into the core is an alternative method of measuring borehole stability. Shell, BP and Agip have developed devices for measuring pore pressure transmission (PPT). A test device was designed and built by a fluid service company to measure pore pressure transmission through native cores. The custom-built PPT apparatus has been in operation for seven years and has been used to evaluate numerous drilling fluids systems. In fact, the device has been a keystone in the development of aluminum products, and HPWBM systems.[7-9]

The PPT device is designed primarily to measure membrane efficiency and osmotic effects of fluids on shale samples. When these aspects of wellbore stability are isolated by laboratory testing, it has been found that chemicals that are capable of reducing rate of pore pressure transmission are most effective when they are used with a high concentration of a salt to

reduce water activity of the simulated drilling fluid. Several chemicals have been found to reduce pore pressure transmission including glycols, silicates, and aluminum complexes. Glycols are reported to reduce pore pressure transmission by cloud point effects while precipitation processes allow silicates[10] and aluminum complexes to control pore pressure transmission. Although these chemicals are most effective when tested in highly saline solutions, field experience has proven that some of the same chemicals can be used effectively in combination with other shale stabilizers and sealing agents in land applications. Several years ago preliminary PPT testing of aluminum complexes revealed that aluminum compounds could be used effectively to reduce rate of pore pressure transmission in the laboratory device. PPT plots of water-based mud systems are shown in **Fig. 1**. A PPT plot for an AHC fluid and an oil-based mud are shown for comparison.

Aluminum Chemistry

The versatility of aluminum chemistry can be discussed in the context of general characteristics of this element. Various aspects of aluminum chemistry[11-12] featured in drilling applications include:

- Aluminum can exist as compounds that may be soluble or insoluble in water (**Table 1**) depending on the counter ion and solution pH.
- Aluminum ions, formed by the dissolution of soluble aluminum salts, exist as hexahydrate ions in an octahedral configuration (**Fig. 2**). The high charge of aluminum ions results in the loss of hydration shell protons that produces a series of hydrolysis products (**Fig. 3**). Aluminum induced hydrolysis produces acidic solutions for virtually all water-soluble salts.
- Aluminum exhibits a complex, pH-dependent chemistry in aqueous systems and the ability to produce important effects from either acidic or alkaline aluminum sources. Solutions of aluminum salts contain only $Al(H_2O)_6^{3+}$ at pH values below 3. When pH values are between three and five, aluminum species are distributed between a mixture of hydroxo species including $Al(OH)^{2+}$, $Al(OH)_2^{+}$, and various polynuclear (containing two or more aluminum atoms) cations. At pH values between 5 and 6, $Al(OH)_3$ appears. As the pH becomes more alkaline, $Al(OH)_4^{-}$ becomes dominant.
- Under appropriate conditions, aluminum forms an amphoteric hydroxide which at higher pH forms soluble tetrahydroxyaluminate anion (**Fig. 4**).
- Aluminum hydroxides exist in several crystalline or amorphous forms (**Fig. 5**).
- Wellbore stability is enhanced by precipitation of aluminum hydroxides within shale pore throats and microfractures.

Aluminum Chemistry Mechanism for Stability

The aluminum chemistry approach to shale stability is based on changing the physico-chemical behavior of the shale. Contrary to the widely investigated ionic exchange between fluid and shale, this approach is based on aluminum chemistry designed to precipitate as aluminum hydroxide which may eventually become incorporated into the mineral matrix of the formation. This aluminum precipitate greatly enhances the stability and physical strength of a sensitive shale section and forms a physical barrier to further filtrate invasion of the shale.

The aluminum hydroxide complex (AHC) dissolves in the aqueous drilling fluid and generates tetrahydroxyaluminate ions, $Al(OH)_4^-$. Chemical literature implies that the tetrahydroxyaluminate anion is the dominant soluble species for the drilling fluid environment.[14] As AHC is added the drilling fluid, aluminate immediately enters solution. AHC treatments will generate a mud pH of 10 to 12, depending on the quantity added. The mud pH will determine the distribution of tetrahydroxyaluminate and aluminum hydroxide.

If sufficient AHC is maintained in the mud, excess tetrahydroxyaluminate will be present in the filtrate. When exposed to a lower shale pH, aluminum hydroxide [$Al(OH)_3$] will precipitate from the filtrate. Precipitation is accelerated when the alkaline mud filtrate is exposed to connate water, possessing pHs as low as 4 to 5, in the shale microfractures. Aluminum hydroxide may exist as an amorphous precipitate or in a variety of crystalline forms such as: gibbsite, bayerite, nordstrandite, boehmite or diaspore. The type of aluminum hydroxide that forms is dependent on many factors including temperature as well as other ingredients in the fluid such as electrolytes and organic acids.[15-20] Under certain conditions, the aluminum hydroxide may initially precipitate in one form but later change to another form or allotrope.

Because hydroxides and aluminate are the most common aluminum species at typical drilling fluid pH levels, the generation of aluminum hydroxides from aluminate is the critical process in AHC mud systems. This prevents hydration and enhances borehole stability. This same hypothesis explains the stabilizing effects of mud filtrate on shale cores. The filtrate is exposed to a lower pH environment when it penetrates into the shale wall and microfractures, causing the excess AHC in the mud filtrate to precipitate as hydroxides along the filtrate front (**Fig. 6**). The precipitated hydroxides may eventually change to crystalline forms. Subsequently, the aluminum hydroxides may become part of the shale crystal structure, helping stabilize the shale. This chemical process would greatly reduce the induced pore pressure transmission inside the shale microfractures.

Various chemical factors are involved in controlling clay hydration and stability. **Fig. 7** illustrates the use of aluminum complex as part of a strategy to control dispersion of kaolinite. Aluminum complex is shown precipitating in micro-fractures of Colombian Villeta shale

Shale Studies and Aluminum Chemistry Mechanism for Stability

Several shale studies have been conducted that demostrate the ability of Aluminun complex product for stabilizing formations. They include Join Industry Project conducted by O'Brien Going and Simpson to evaluate different water-based muds by using Downhole simulation cells, and study related to fluid rock interaction by using formations located in Venezuela.

The lab results of Downhole Simulation Cells indicate fluid containing aluminum complex had one of the lowes flitration values (ml/min) among the water base mud tested **(Fig. 7)**

The Young module obtained with a core simple saturated with water base mud containing aluminun complex indicates that the rock strenght should be increased through precipitation of aluminum hidroxide. This value is close to the value obtained for a dry core**. (Fig. 8)**

Pore Pressure Transmission Testing

A number of devices have been developed to study shale failure mechanisms. One such class of instruments measures pressure transmission through a shale specimen from fluid invasion. These instruments are called Pore Pressure Transmission (PPT) instruments.

Shale permeability is extremely low, 10^{-6} to 10^{-12} Darcy[1]. An instrument capable of accurately measuring the very small water volume displaced out of shale by filtrate invasion is required.

The PPT test exposes a preserved shale core to drilling fluid at high pressure at one end, and to synthetic pore fluid at lower pressure on the other end. The shale pore spaces are filled with connate water. As filtrate enters one end of the core, connate water is driven out the other end into the synthetic pore fluid reservoir.

This reservoir is low volume, liquid filled and isolated from the rest of the system. Since water is highly incompressible, a very small liquid influx results in a large pressure rise, which provides the necessary sensitivity to measure minute fluid invasion. The pressure rise over time is a measure of the pore pressure transmission rate. The invasion rate is so slow that filtrate rarely travels all the way through the shale sample.

The volume change in the reservoir due to temperature variation is on the order of the flow volume so these devices are extremely temperature sensitive. On the service company device a 1°F temperature rise will raise the pressure 10 - 15 psi. Precise temperature control is crucial for meaningful data.

The temperature and pressure equilibration processes occur slowly. A good measure of the pressure transmission through the core requires about 48 hours.

PPT Cell Types

There are two basic PPT cell styles differentiated by the seal around the core between the higher pressure mud upstream and the lower pressure synthetic pore fluid downstream. One is the sleeve seal and the other the O-ring seal. With the sleeve seal, the core and the steel piston on each end are enclosed in a tubular rubber sleeve (Fig. IV). A confining pressure is applied around the outside of the sleeve to effect a seal exert radial confining stress on the core. Sleeve type cells are generally capable of forming a good seal around the core and have the advantage of applying confining stress to the core.

The three basic sleeve sealed PPT cell types are fixed sleeve, floating sleeve and cartridge loaded. The fixed sleeve is the classic Hassler cell where the sleeve is held fixed in each end of the cell with hollow conical bushings. The drawback to this design is the sleeve must be stretched between the bushings. This stretch must exceed elongation from heating and pressurizing during the test to avoid the sleeve becoming loose and breaking the pressure seal.

Sleeve type cells must have the pistons flush against the core on both ends. A drainage pattern is machined into the piston face to provide a fluid passage **(Fig. 10).** These passages are small to keep the face contact area large enough to support the shale end. To avoid clogging these passages, barite and viscosifying polymers are generally not run in sleeve PPT test muds.

Field Experience

The aluminum chemistry was introduced in the challenge wells of Cusiana field located in the foorhills of Colombia in 1996. The reason behind the application was to improve drilling efficiency while drilling intermediate hole sections containing Leon and Carbonera shales. The introduction of aluminum complex in drilling fluid formulation improved drilling performance as indicated by average feet per day along the 17 ½" hole section combined with cost per foot reduction. **(**Fig. 11).

The aluminum-based drilling fluid was used to drill a difficult exploratory wells in the middle Magdalena River of Colombia. The system was proposed as alternative for emulsion based systems to control Villeta shale instability. **Tables 2,3,4,5** ilustrates shale mineralogy, fluid formulation and fluid properties.

The aluminum complex has also applied in the Maracaibo Lake by major operator. The introduction of the system surpasses the performance of conventional water-based muds used in the area. Generally speaking oil emulsion systems have not been solution for the wellbore problema besides the environmental restrictions. **Fig. 12** shows improvement as indicated by key performance indicators improvement.

The wells located in the eastern part of Ecuador presented significant challenge while drilling the Napo shale formation. Aluminun-Based fluid were introduced in 2000 by operator to replace salt inhibited drilling fluid that caused severe wellbore instability problems. Since ten more than sixteen(16) wells including directional and horizontal have been drilled very successfully. The figure demostrated the learning curve of the application of the system as compared with conventional inhibited potassium system. **(Fig. 13)**

Finally the system has been introduced successfully in Argentina to drill wells in Comodoro Rivadavia and Neuquen areas. **Fig. 14,** illustrates the well performance. Excellent caliper logs have been achieved by using aluminum chemistry as indicated by **Table. 6** and **Fig. 15**

The ecological and toxicity data of AHC is presented in **Tables. 7,8.**

The New Frontier - from aluminum chemistry to HPWBM

The high performance term suggest that a HPWBM will deliver a high level of performance that is currently attainable using conventional water base mud. Researches and engineers often focus on delivering a single ,specific performance attribute when designing water-based alternatives to emulsion –based fluids.The addition of ROP enhancer to a water-based mud may deliver drilling rates equivalent to those of an OBMSBM;however,it is likely that it alone will match the overall drilling performance of emulsion muds.

In departure from conventional approaches,the design team focused on delivering a high performance system rather a novel product.The first step of the development process centered on identifying the drilling attributes of emulsion systems that make them so attractive for drilling challenging wells. The key attributes of emulsion systems were identified as: 1) shale stability. 2) clay stability. 3) cuttings stability. 4) rates of penetration. 5) bit balling and accretion. 6) torque and drag.

The next stage was research and identify the mechanisms by which the emulsions delivered these attributes, and then to duplicate them in a HPWBM. It was immediately recognized that

simply combining existing products would not work and step-change in design approach was required to achieve the desired results. The design team regconized and accepted that some required technology may not be available in current oilfield chemical use and would be acceced from non-oilfield industries. This lead to a very time-consuming of research,product screening,system compatibility and environmental compliance testing specifically for the new system.

The outcome of this work is a new HPWBM based on a system design approach whereby state-of-the art technology combined in a system designed to emulate the key drilling attributes of emulsion base muds. The system is based on a novel “total inhibition” concept,whereby shale,clay and cuttings stability are systematically provided along with benefits in key such as ROP,accretion control and torque and drag reduction..The uniqueness and properity of the system is such that it has been awarded a US patent. The new system deliveres performance approaching that of emulsion muds systems,while offering environmental acceptance in key areas around the world.

Conclusions

1.The water-based mud used along the Andean Mountains of south American basin consisted of aluminum complex for shale stability, amine compound for clay stability, blown asphalt to improve sealing effect on micro fractures, a high pressure lubricant and ROP enhancer.

2. The aluminum hydroxide precipitate effectively reduces pore pressure transmission through the micro-fractured brittle shales and provided wellbore stability while drilling the troublesome shales, such as Carbonera, Napo, Chonta and Los Monos.

3. Because aluminum chemistry is very effective for controlling the rheology of high density muds, no dispersants are required. The improved viscosity control enhanced gas removal efficiency during kicks.

4. The mud system is environmentally friendly in two ways: 1) no chloride salts are used for inhibition, and 2) since the aluminum hydroxide precipitates are compatible with formation geology, the precipitates incorporate into the shale crystal structure formed by alumino-silicates.

5. Although further improvements to this new water-based system are anticipated, this system is a first step toward changing the paradigm of oil-based mud as the only solution for wellbore problems.

6. Operators must balance the environmental benefits and more reliable formation evaluation with the increased operational risks associated with a water-based mud. The environmental benefits and more reliable formation evaluation in exploratory wells led the operator to take some risk.

7. A new generation of HPWBM based in the same chemistry has been developed to emulate the performance of oil emulsion systems.

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SI Metric Conversion Factors

bbl × 1.589873	E–01	= m^3
gal × 3.785412	E–03	= m^3
cp × 1.0	E–03	= Pas
inch × 2.54	E+00	= cm
lbm × 4.535924	E–01	= kg
ft × 3.04	E–01	= m
psi × 6.894757	E+00	= kpa
psi × 6.894759	E–02	= bar
ppg × 2.853	E+00	= kg/m^3
lbm/gal × 1.198264	E+02	= kg/m^3
lb/100 ft^2 × 4.788026	E–01	= Pa
(°F-32) ÷1.8	E+00	= °C

TABLE 1 - Examples of Aluminum Compounds

Name	Formula	Water Solubility	Aqueous Solution pH
Aluminum Chloride	$AlCl_3$	S	<7
Aluminum Sulfate	$Al_2(SO_4)_3$•16 H_2O	S	<7
Potassium Alum	$KAl(SO_4)_2$•12 H_2O	S	<7
Aluminum Lactate	$Al(C_3H_5O_3)_3$	S	<7
Aluminum Stearate	$Al[O_2C(CH_2)_{16}CH_3]_3$	I	?
Sodium Aluminate	$NaAlO_2$ or Na_2O•Al_2O_3	S	>7
S=Soluble I=Insoluble			

TABLE 2 - Typical Well Mineralogical Profile

Depth, ft	% Quartz	% Feldspar	% Calcite	% Dolomite	% Pyrite	% Illite	% Kaolinite	% Chlorite	% Mixed Layer
4800	5-10	–	–	–	3-5	20-25	50-55	–	15-20
6200	5-10	1-2	–	–	3-5	20-25	45-50	–	15-20
8350	5	–	30-35	tr	–	5-10	25-30	5-10	15-20
8700	10-15	–	–	–	–	5-10	45-50	–	30-35
9550	5-10	–	–	–	–	5-10	55-60	–	25-30
9700	20-25	–	5	–	–	5-10	45-50	–	20-25
9950	5-10	–	5	–	–	5-10	40-45	10-15	25-30
10100	5-10	–	25-30	–	–	10-15	55-60	–	20-25
10300	5-10	–	–	–	5-10	5-10	55-60	–	20-25
10430	10-15	–	15-20	–	5-10	5-10	50-55	–	25-30
10570	5-10	–	2-3	–	5-10	5-10	55-60	–	20-25
10590	5-10	–	5-10	–	5-10	10-15	55-60	–	15-20
10620	5	–	5-10	–	5-10	10-15	45-50	10-15	15-25
10640	5-10	–	5	–	5-10	5-10	55-60	-	20-25

TABLE 3 - Mud Formulation for Monicongo Well

Component	Concentration
Bentonite	9.0 lb/bbl
PHPA	1.5 lb/bbl
Aluminum Complex	3.5 lb/bbl
Amine	5.0 lb/bbl
Low Vis PAC	1.0 lb/bbl
Regular PAC	0.7 lb/bbl
Blown Asphalt	4.0 lb/bbl

TABLE 4 - Typical Properties for Monicongo Well Muds

Hole Size, in	17 ½"	12 ¼"
Property		
Density, lb/gal	10.7	15.7
Plastic Viscosity, cP	24	36
Yield Point, lb/100 ft^2	22	25
Gel Strengths, lb/100 ft^2	6/15/18	8/15/19
API Filtrate, cm^3/30 min	4.8	4.0
pH	10.8	10.7
250°F HTHP, cm^3/30 min	15.0	12.5
MBT, lb/bbl	22.5	20.0
LGS, % by volume	7.49	6.2

TABLE 6 – Caliper and aluminum complex concentration			
Well	**Depth,m**	**Aluminum Complex, Kg/M3**	**Caliper, in 8.75” bit**
A	2,626	12.3	8.74
B	2,231	11.4	8.62
C	2,101	10.8	8.89
D	2,625	11.6	8.96
E	2,530	11.5	8.68
F	2,650	12.5	9.01
G	2,350	14.2	8.95
H	2,350	12.8	8.77
I	2,140	15.5	8.75

TABLE 5 – Fann 75 Model Results for 10.3 lb/gal Field Mud									
Test Conditions		**RPM Readings @**						**PV, cP**	**YP, lbf/100ft²**
Temp (°F)	**Pressure (psi)**	**600**	**300**	**200**	**100**	**6**	**3**		
75	?	145	81	58	42	20	19	64	17
87	3,493	105	59	47.4	33.2	17.8	15.8	46	13
100	3,887	87.6	53	43.9	30.6	12.3	10.1	34.6	18.4
112	4,280	77.3	49.2	41.7	28.6	13.8	15.6	28.1	21.1
4,673		70.3	44.5	38.2	28.1	14.5	15.6	25.8	18.7
136	5,066	64.4	44.7	36.9	25.7	12.3	14.5	19.7	25
149	5,460	64.5	44.5	36.2	25.1	16.2	14.5	20	24.5
161	5,853	61.5	42.7	35.7	24.8	15.1	17.3	18.8	23.9

TABLE 7 - Seawater Mud Formulation for US EPA *Mysidopsis bahia* bioassay	
Component	**Concentration**
AHC	6 lb/bbl
Bentonite	20 lb/bbl
Carboxymethyl Cellulose	0.5 lb/bbl
Lignite	3.0 lb/bbl
Sulfonated Styrene Copolymer	0.5 lb/bbl
Xanthan Gum	5.0 lb/bbl
Chrome-free Lignosulfonate	1.0 lb/bbl
Sodium Hydroxide	1.0 lb/bbl
Soda Ash	1.0 lb/bbl
Barite	137 lb/bbl

TABLE 8- Ecological and Toxicological Data for AHC	
Test Method	**Result**
US EPA *M. bahia* LC_{50} for 6 ppb in Chrome-Free Lignosulsonate System (See Table 9)	>1,000,000 ppm suspended particulate phase
72hr EC_{50} *Skeletonema costatum*	1250 mg/L
Acartia tonsa 48 hour LC_{50}	>1000 mg/L
96hr LC_{50} *Scophthalamus maximus* (mg/l)	>1800
5 day EC_{50} *Abra alba* (ppm total medium)	289
28 day Aerobic Biodegradation (OECD 306), %	21 (Organic component)
Bioaccumulation Potential (Octanol/water partition co-efficient – log P_{ow})	2.4
HQ Band	Gold (No Substitution Warning)

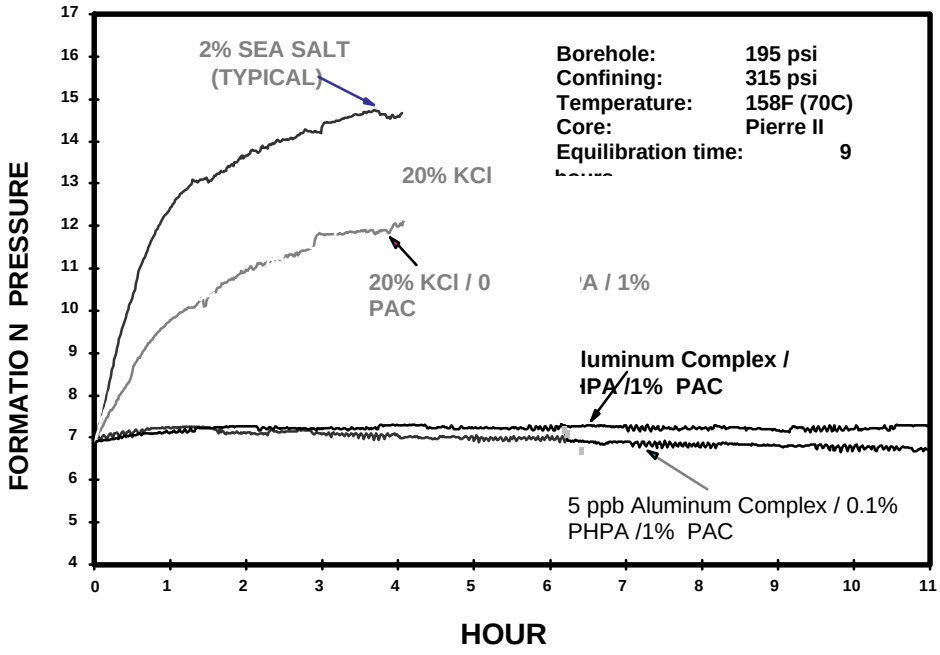

Figure 1 – Pore Pressure Transmission of aluminum based drilling fluid

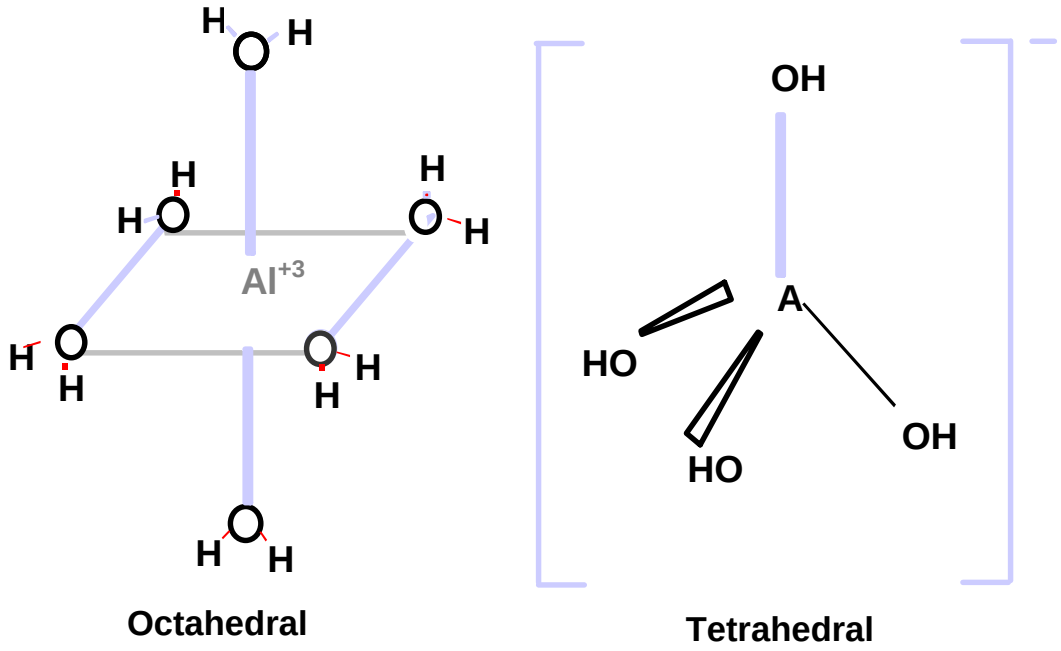

Figure 2 – Configuration of soluble aluminum salts

$$Al^{+3} + H_2O \longrightarrow Al(OH)^{+2} + H^+$$

$$Al^{+3} + 2H_2O \longrightarrow Al(OH)_2^{+} + 2H^+$$

$$Al^{+3} + 3H_2O \longrightarrow Al(OH)_3 + 3H^+$$

$$Al^{+3} + 4H_2O \longrightarrow Al(OH)_4^{-} + 4H^+$$

Figure 3 – Hydrolysis of aluminum cations

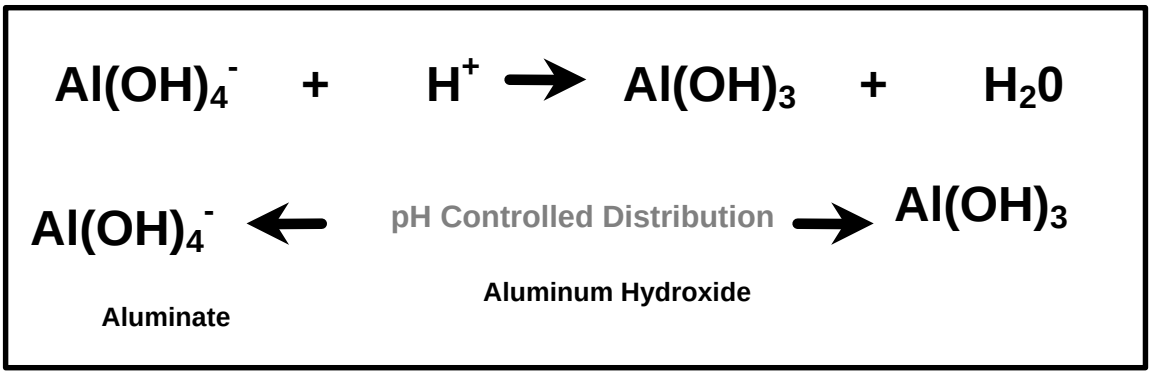

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Figure 4– Hydrolysis of aluminum cations and precipitate formation

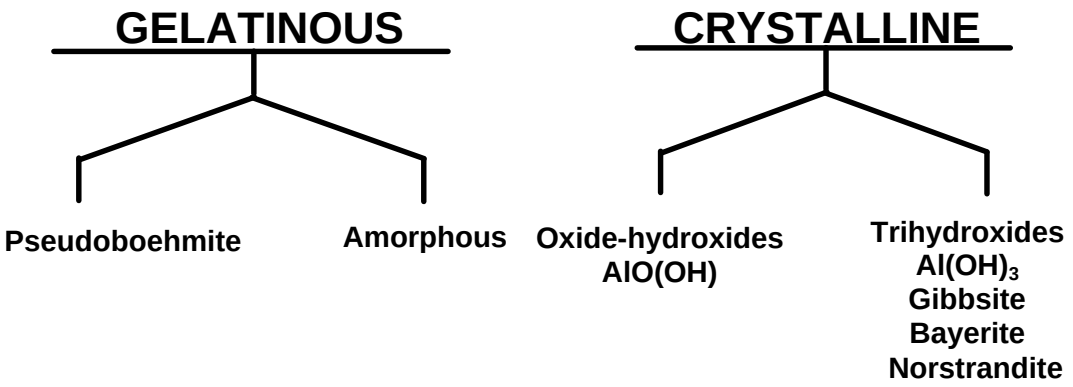

Figure 5 – Crystalline and non-crystalline or gelatinous forms of aluminum hydroxide

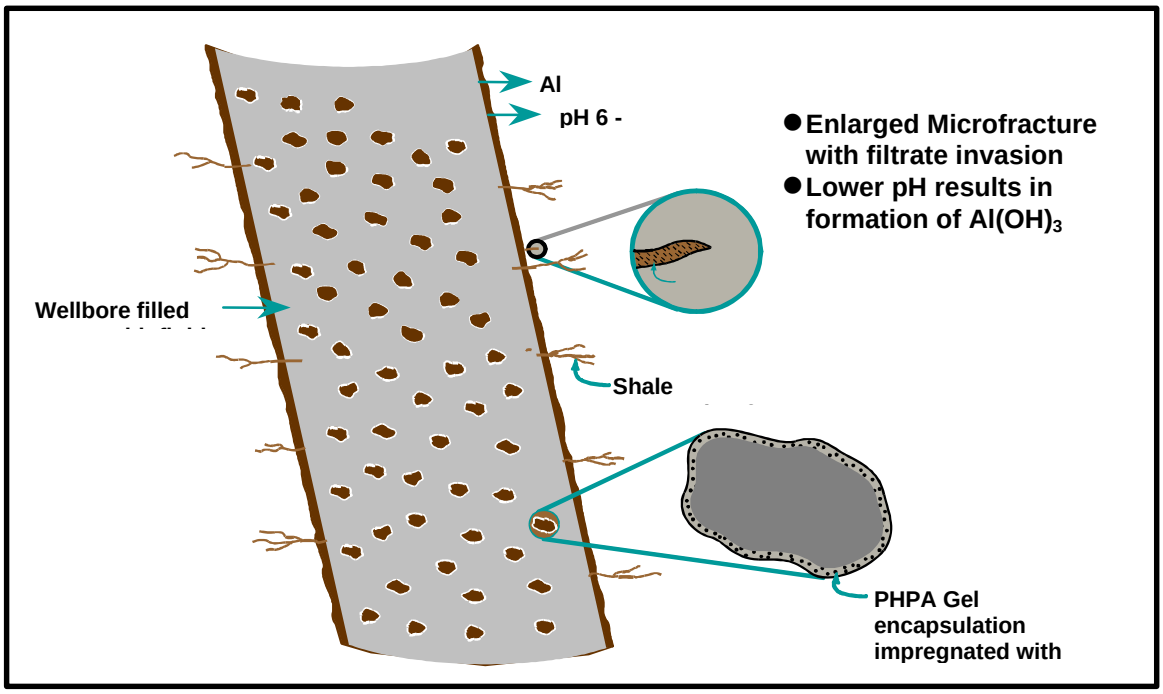

Figure 6 - Wellbore stability is enhanced by precipitation of aluminum hydroxides within shale pore throats and microfractures. Drill solids integrity is maintained by a combination of partially hydrolyzed polyacrylamide and aluminum complex.

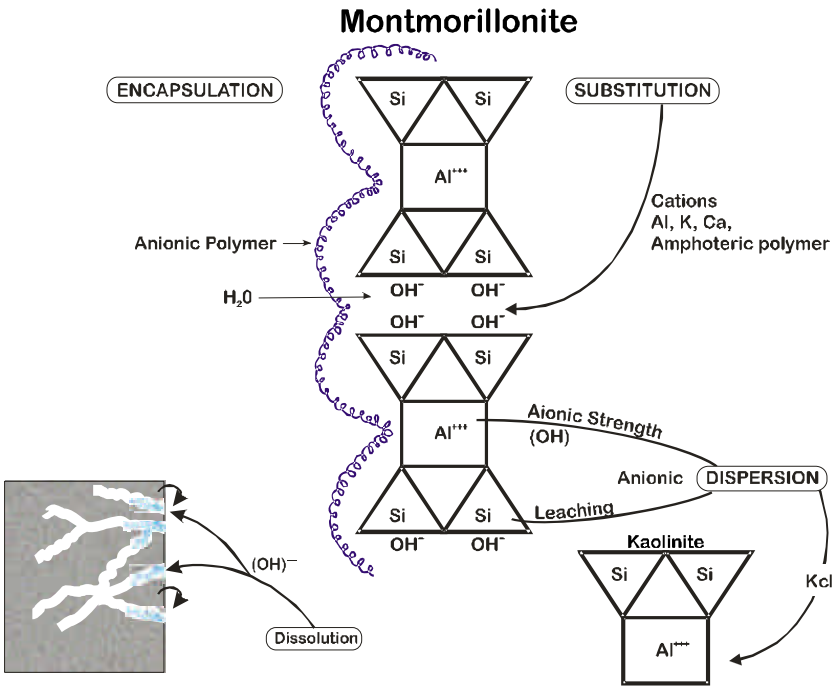

Figure 7 – Crystalline and non-crystalline or gelatinous forms of aluminum hydroxide

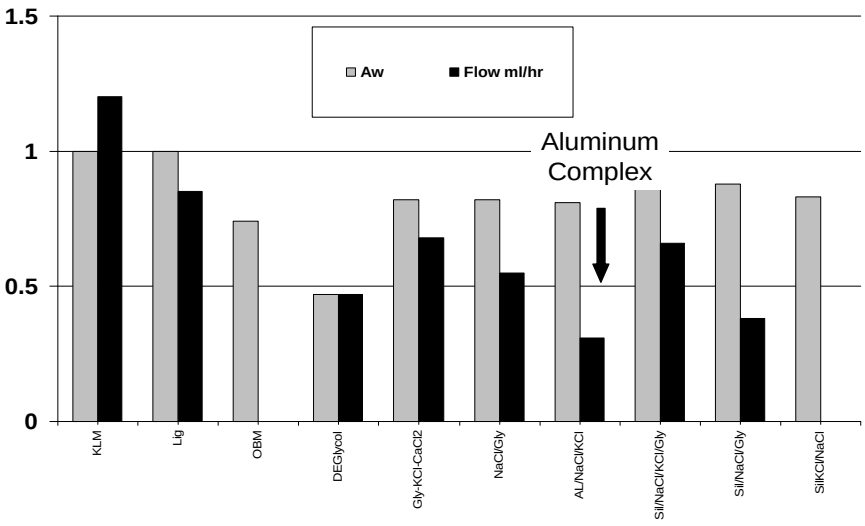

Figure 8 – Results of fluid filtration in DSC

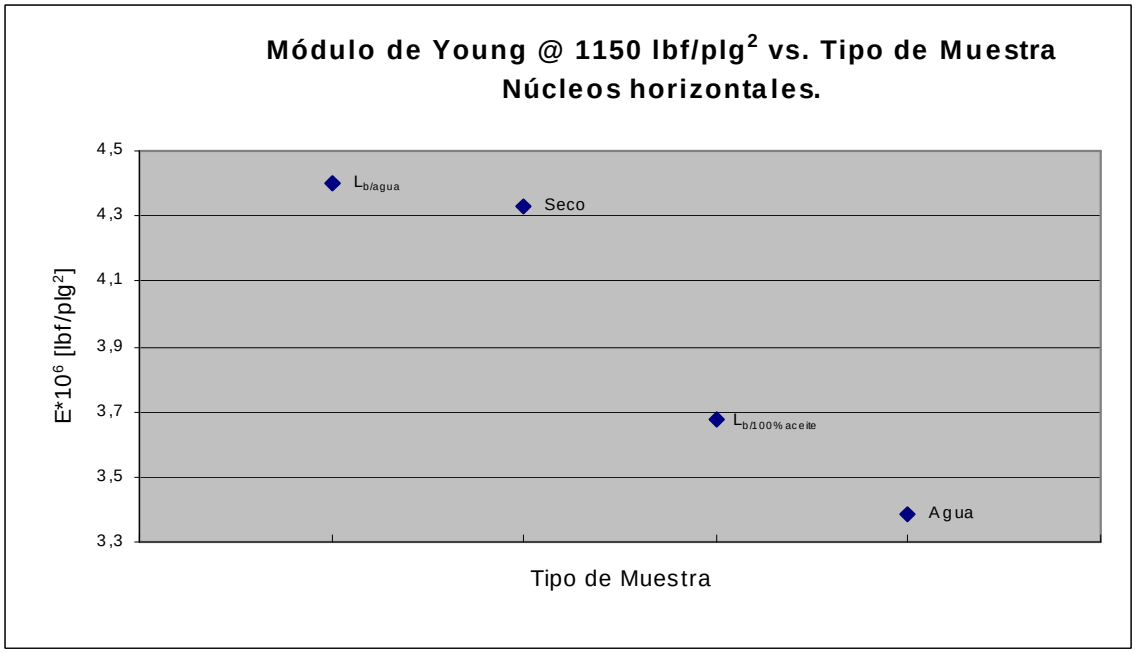

Figure 9 – Young modules of cores saturated with aluminum based fluids

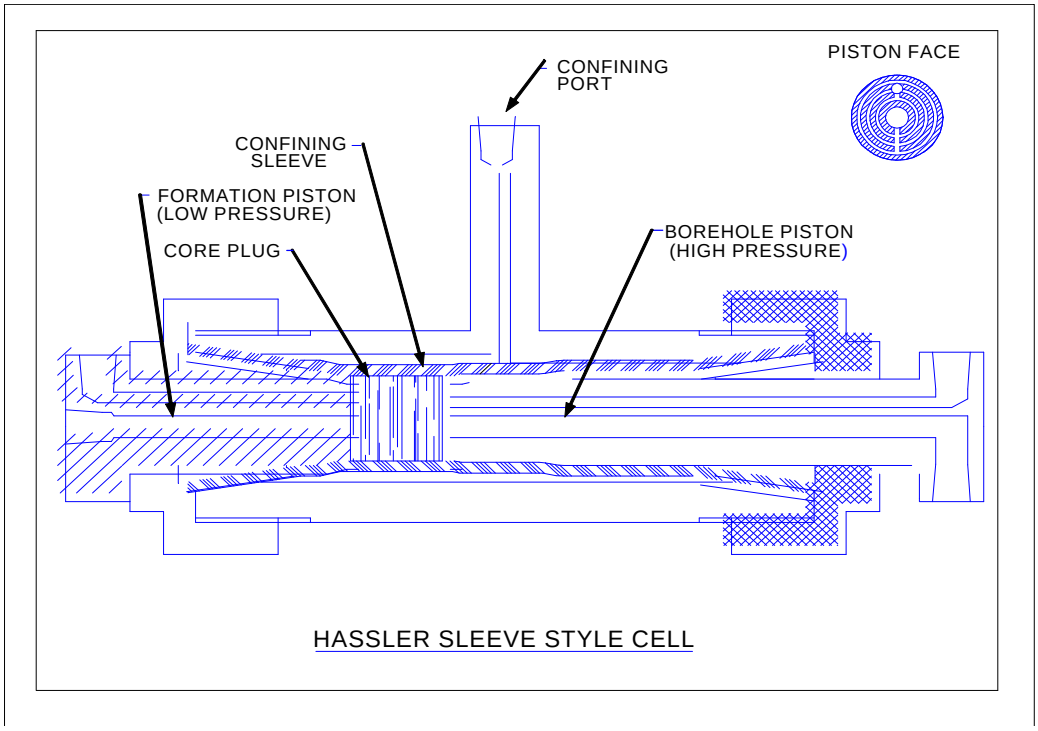

Figure 10 – Pore Pressure Transmission Tester

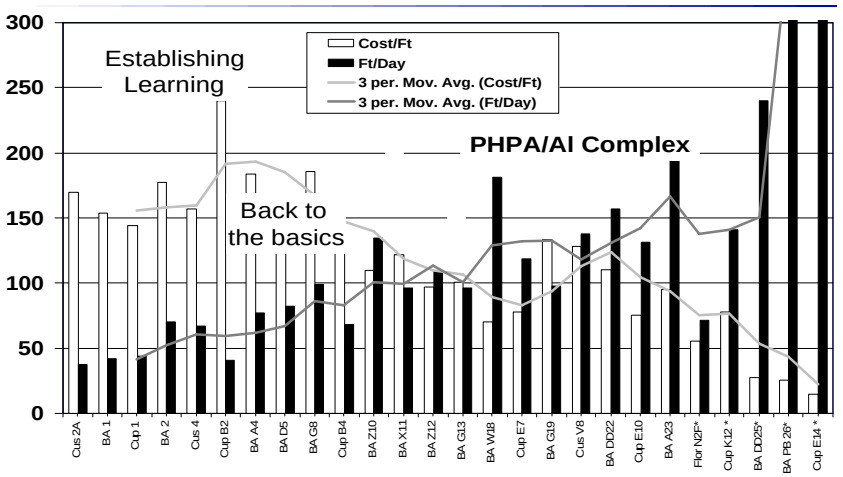

Figure 11 – Field application of aluminum-based drilling fluid in the Cusiana field of Colombia

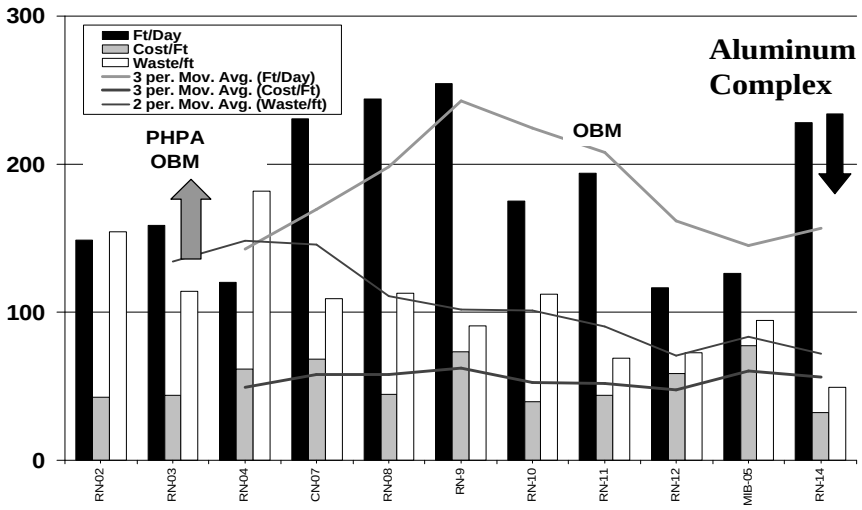

Figure 12 – Field application of aluminum-based drilling fluid in Venezuela Maracaibo Lake

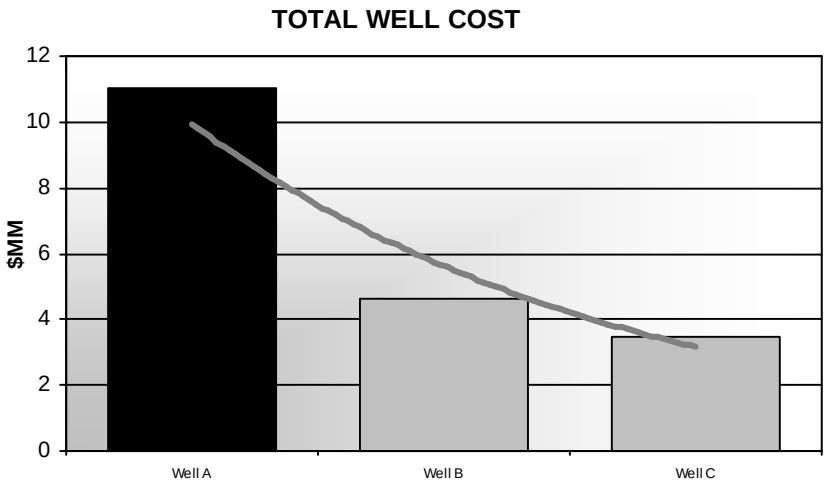

Figure 13 – Field application of aluminum-based drilling fluid to replace potassium Inhibited fluid system in the Yuralpa field-Ecuador

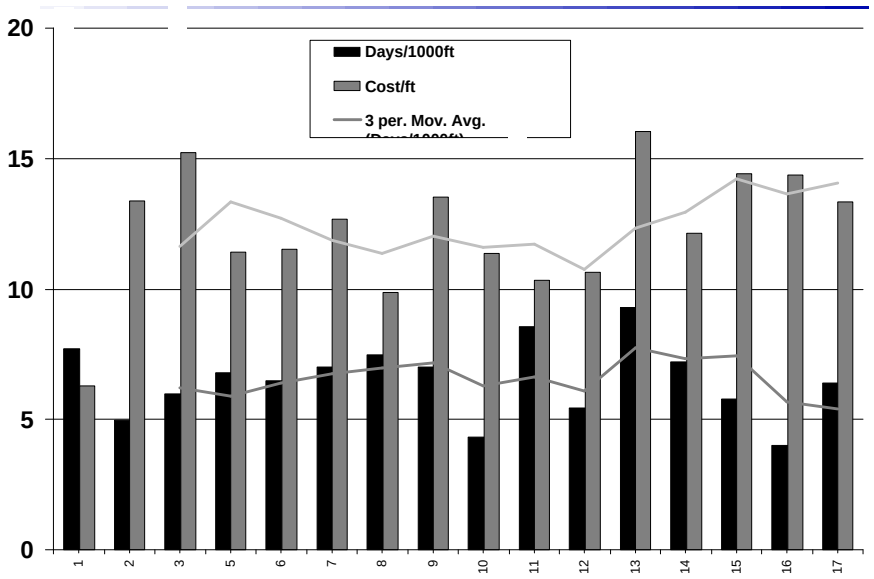

Figure 14– Performance review of application aluminum-based drilling fluid in Argentina

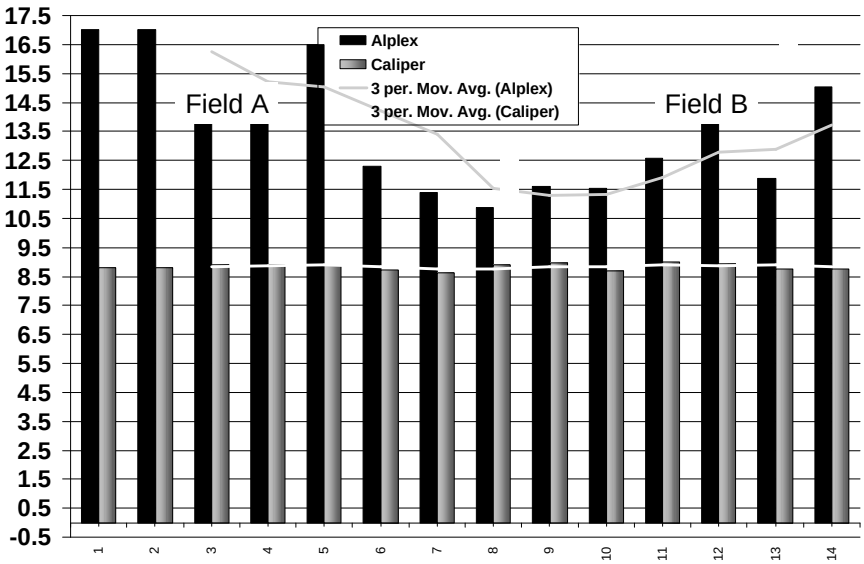

Figure 15 – Field application of aluminum-based drilling fluid in Argentina
Average caliper log and aluminum complex concentration