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Sodium Silicate Fluids Improve Drilling Efficiency and Reduce Costs by Resolving Borehole Stability Problems in Atoka Shale

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Abstract

Maintaining borehole stability while drilling the Atoka shale in the Arkoma Basin of Eastern Oklahoma has historically posed a number of technical challenges. Typically, the 12¼-in. surface holes and ±7000 ft of the following interval are drilled relatively trouble-free with air, after which the hole is displaced with either water- or oil-based drilling fluid for the remainder of the interval. However, a review of the drilling history in this area reveals very few instances in which water-based mud was used successfully. Consequently, oil-based mud traditionally is used to drill the Atoka Shale. Nevertheless, even using oil-based fluids has resulted in enlarged wellbores with corresponding drilling and logging problems.

This paper reviews a unique technical collaboration between a service company and major operator that led to the development and successful application of a sodium silicate drilling fluid for use in these stressed shale sections. After an extensive testing program, the uniquely engineered fluids were applied successfully in the Atoka Shale. When compared to their water- and oil-based counterparts, the sodium silicate drilling fluids significantly improved drilling efficiency and dramatically reduced trouble-related downtime while displacing the air system. Furthermore, the authors will document the environmental and economic benefits of the new system, particularly in the areas of disposal, clean up, base fluid cost, and improvements in drilling performance parameters such as volume handling, dilution rates, competitive ROP, logging efficiency, and reduction of mud related non-productive time.

Introduction

Silicate drilling fluids have established very successful track records over the last few years in different areas of the world. Hole stability is one of the great challenges for any drilling operation in Southeastern Oklahoma. Several fluids were investigated, with the ultimate goal of finding a drilling fluid system that could provide a stable borehole and comply with the local environmental regulations. On the basis of its proven performance, a silicate drilling fluid was proposed as a potential solution to the problems encountered drilling the Atoka shale.

Pre-Planning and Product Selection

Cutting Analysis

As a starting point, a wide range of samples representing the Atoka shale was collected from various wells in the field. XRD analysis was performed to identify the mineralogy and the required inhibition mechanism for this highly dipped formation, (Fig. 1). The XRD data, in addition to cation exchange capacity (CEC) equivalent, indicated relatively moderate type clay minerals (Fig. 2). These results tend to orient the testing program towards mechanical inhibition and surface-acting agents to enhance the borehole strength, as well as increasing the integrity of both the drilled cuttings and the exposed formation surface. Overall this strategy should lower the stress levels on the rock and deliver less problematic drilling conditions. The final conclusion indicated the silicate-based system could mechanically enhance the formation integrity by reconsolidating the shallow invaded zone. This conclusion was the reason behind displacing the hole with ±15% silicate fluid for an initial trial well.

Fluid Selection Analysis

As a comparative analysis for fluid selection, shale recovery tests were conducted using API procedures (RP 13I; Shale Particle Disintegration Test by Hot Rolling). The results from these tests (Fig. 3), show the superior performance of the silicate fluid for the specific clay minerals in the Atoka shale.

The inhibition provided by the silicate fluid had also been assessed using bulk hardness testing. It was evident that for the formulated fluids tested, good shale recovery was possible provided the fluid had some type of inhibitive property. In order to differentiate between these fluids further testing was conducted.

The Bulk Hardness Tester is a device designed to assess the hardness of shale cuttings exposed to a drilling fluid. In this test, shale cuttings are hot rolled in the test fluids for 16 hours at 100°C. After hot rolling, the shale cuttings are recovered on a screen, washed with brine and placed into the Bulk Hardness Tester. Using a torque wrench the cuttings are extruded through a plate with holes. Depending upon the hydration of the cuttings, the torque may reach a plateau region or may continue to increase during the extrusion; The harder the cuttings, the higher the torque reading and the more inhibitive the mud system (Fig. 4).

To compensate for inadequate solids-control equipment that might be encountered on the rig, additional testing was carried out to assess the stability of the silicate mud to solids contamination. It was observed from the tests that the fluid was largely unaffected by solids contamination (Rev-Dust) and produced acceptable results. Other contaminants such as divalent cations were not tested, as they were unlikely to occur in this particular region.

Field Performance

Due to rig-site limitations, the required volume was mixed in three separate batches. The resultant fluid properties for the initial volume are given in Table 1. All of the initial properties were in the programmed range with the exception of fluid rheology. The rheology was adjusted after the first few circulations to avoid any unexpected response from additives prior to the fluid stabilizing.

Performance Assessment

The silicate fluid was primarily chosen for its ability to inhibit the soft, brittle, and fragile shale of the Atoka formation. This formation commonly causes severe tight hole and frequent pack-offs followed by massive mud losses. It was believed that running a silicate system would also help limit the dispersion of cuttings and preserve shale cementation. The enhanced borehole stability and formation integrity would help minimize the rapid increase in the solids content of the mud and severe hole deterioration, in addition to several other hole problems that were commonly encountered even when drilling with oil-based mud.

The initial silicate well produced the greatest improvement in drilling performance ever seen in the area. All the cuttings generated were solid and firm instead of the usual mushy, sticky type cuttings (commonly referred to as toothpaste). In addition, the fluid parameters were very stable throughout the entire interval. Typically the water-based mud would deteriorate into thick, unstable fluid (peanut butter water based fluid).

The sodium silicate section was drilled with almost no problems. Minor subsurface losses were encountered while drilling the sand section, which were cured by reducing the mud weight by 0.4 lb/gal and incorporating a small amount of loss-circulation material into the mud. A caliper log was run which indicated the highest quality wellbore ever recorded in the entire field, even better than that obtained with oil-based fluids. The casing was run to TD and cemented successfully.

Drilling Performance (ROP)

The penetration rates in Eastern Oklahoma have been significantly higher with the silicate-based fluids than any other mud system, including invert emulsion fluids. Subsequent to this initial and highly successful field trial, five additional hole sections have been drilled in Eastern Oklahoma with similar improvements in drilling performance (Fig. 6). Data also indicates the rate of penetration was not affected by bit type.

Lubricants

On previous water-based mud sections in this field, glycol had been utilized as a lubricant. In most cases, very little improvement in torque and drag was observed. The glycol also had limited impact on torque and drag when used with the silicate-based mud system. Development work is currently underway to identity the most suitable lubricant for the silicate drilling fluid.

Formation Damage

Standard field procedure is to run casing across the entire production zone, perforate, and then fracture the reservoir sands before initiating production. Accordingly, formation damage was not a major concern since the depth of invasion would be limited because of the deposition of precipitated silicate immediately inside the sand formation.

Pick-up Weight vs Measured Depth

The pick-up weights from offset wells drilled with the same or similar rigs indicate that there were no issues relating to torque and drag (Fig. 7).

Logging with Silicate

Historically, the normal logging program for the Arkoma basin utilized a ‘Triple Combo’, incorporating induction resistivity, compensated density, and a neutron log. A temperature survey was normally added when drilling with air. Additional logging opportunities might include sonic, formation imaging, sidewall cores, and pressure testing.

Deeper drilling and complex structural components initiated a conversion from air drilling to oil-based mud (OBM) for many wells. While each drilling environment offers its own advantages, air or conventional OBM eliminated many useful log measurements and tools that could be applied in a water-based fluid. The application of silicate fluid has made many of those tools available again.

However, two complications with the use of silicates have arisen. The first is a requirement to convert from induction resistivity to laterolog resistivity on deep wells.

This is necessitated because of the need for higher resistivity values in deeper horizons and the higher conductivity (apparent salinity) of the silicate mud. The second complication is the as yet untested possibility that the membrane developed by a silicate mud on the borehole wall may interfere with pressure sampling. Concerns raised regarding the pad devices on the logging tools appear to have been unfounded.

Caliper and Hole Condition

Significant improvement was also achieved on data acquisition and logging performance. Having drilled a stable near-gauge hole provided an opportunity for advanced formation evaluation tools to be utilized. Figs. 8, 9 and 10 provide borehole diameter comparisons of a silicate mud system alternative water-based and an oil-based drilling fluid.

- Charlie 1-8, silicate mud
- Reed-A-6, oil-based mud
- Smallwood, alternative water-based mud

Conclusion and Remarks

The silicate drilling fluid system performed as expected, achieving most of the goals outlined in the mud program, including:

- More efficient drilling and tripping operations
- Greatly improved hole condition and bore hole stability (as determined from caliper data)
- Stable fluid properties that were simple to maintain
- Environmental compliance

In addition to the specified goals, further value is derived with the silicate system through an expanded pore pressure and fracture gradient window. The low viscosity profile of the silicate system provides a significant improvement over alternative water-based systems that have been used to drill through the Atoka shale. Previously, all offsets drilled in this region with water-based mud relied primarily on excessive rheology for hole cleaning, which often resulted in excessive equivalent circulating density (ECD) values. These excessive ECD values limited the pore pressure/fracture gradient window.

Fig. 5 demonstrates the above point, indicating a maximum of 0.5 lb/gal difference between static and circulating density provided the flexibility to increase the mud weight to 13.0 lb/gal (considered relatively high for this region) with minimum impact on the formation integrity. This strategy minimized the potential for fluid losses and contributed to the successful drilling of the section.

Acknowledgments

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Appendix – Main Fluid Properties and System Keys

Fluid Density

The required fluid density for hydrostatic control was unknown prior to drilling this section. There was potential for a gas kick, but the pressure gradient had not been established. It was decided to commence drilling with a 9.6 lb/gal then increases the mud weight gradually to +/- 13.0 lb/gal. Fluid rheology played a very important part in this process. With a relatively low ECD, there was a certain degree of flexibility to adjust the fluid density with a minimum impact on the formation integrity.

Silicate Concentration

Since this was the first field trial in the area, it was necessary to establish a reference for the formation activity and subsequent interaction with the drilling fluid. There are some variables that may affect the hole stability such as; silicate depletion rate, level of inhibition required for the entire section, and formation integrity. It was essential to start the section with a high silicate concentration for these reasons. It should also be mentioned that possible rig equipment failures, poor mixing facilities, and many other reasons should also be considered as strong reasons for commencing with a high silicate concentration. While drilling the section, the depletion rate varied from very low to moderate.

Filtration, (API WL)

Fluid loss is unique in the silicate mud system and as such it should be treated differently. The filtration process measured in the lab does not truly reflect the process that is occurring downhole. The active soluble silicate in the filtrate reacts immediately with any divalent cations forming a solid precipitate and is also precipitated out of solution once it is exposed to a low pH environment. This by itself is part of the stabilization mechanism and cannot easily be simulated in the laboratory using an API filter press. For this reason, the filtration values were relaxed to 8-mL/30 min.

High-End Rheology

The yield point was actually the main driver for controlling the high-end rheology (600- & 300-rpm Readings) to ensure optimum hydraulics and hole cleaning. In general the fluid behavior was relatively stable while drilling the section. Solids loading associated with increasing the mud weight to 13.0 lb/gal adversely affected the high-end rheology. This is a typical fluid response for all systems with any additional solids incorporated into the system. Adequate dilution proved to be an efficient method for cutting the rheology back at ± 8300 ft.

Low-End Rheology

The low-end rheology was not a major factor for the fluid design. The low-end rheology was elevated when barite was added to the system. An increase in the LSRV values occurred when the reactive drilled solids were incorporate into the system while drilling the section. As presented in the chart these values were maintained using dilution at the end of the section.

Alkalinity

Alkalinity is one of the main engineering factors while running a silicate system. In a low salt concentration system, where the silicate is fully soluble, there is a direct relationship between mud and filtrate alkalinity readings, with both being affected by active silicate concentration.

General Comments

Cuttings condition and bit balling were the most important benchmarking tools for this particular job. Drill cuttings were subject to close monitoring, with specific attention paid to volume, shape, condition and integrity. This close monitoring provided a quick indication of fluid performance and borehole condition. Bit and BHA balling was used as a secondary indicator of borehole condition. The following pictures are self explanatory, depicting BHA quality during and after the Atoka shale was drilled.

Table 1 - Initial Silicate System Formulation	
Sodium Carbonate (lb/bbl)	1.0
Biocide (lb/bbl)	0.5
Potassium Sulfate (lb/bbl)	14.0
Polyanionic Cellulose (lb/bbl)	2.0
Xanthan (lb/bbl)	1.0
Barite	To 9.5 lb/gal
Sodium Silicate	15% by vol

Table 2 - Initial Formulation and Fluid Properties			
Density (lb/gal)	9.6	6-rpm Reading	3
Funnel Viscosity (sec)	43	3-rpm Reading	2
600-rpm Reading	22	PV (cP)	7
300-rpm Reading	15	YP (lb/100 ft^2)	8
200-rpm Reading	12	10-sec/10-min Gels (lb/100 ft^2)	3/5
100-rpm Reading	9	API FL (mL)	5.2
pH	10.9	Pf/mf	35/41
Pm	45	Silicate v/v	15.5 %
** Rheology measurements @ 120°F*			

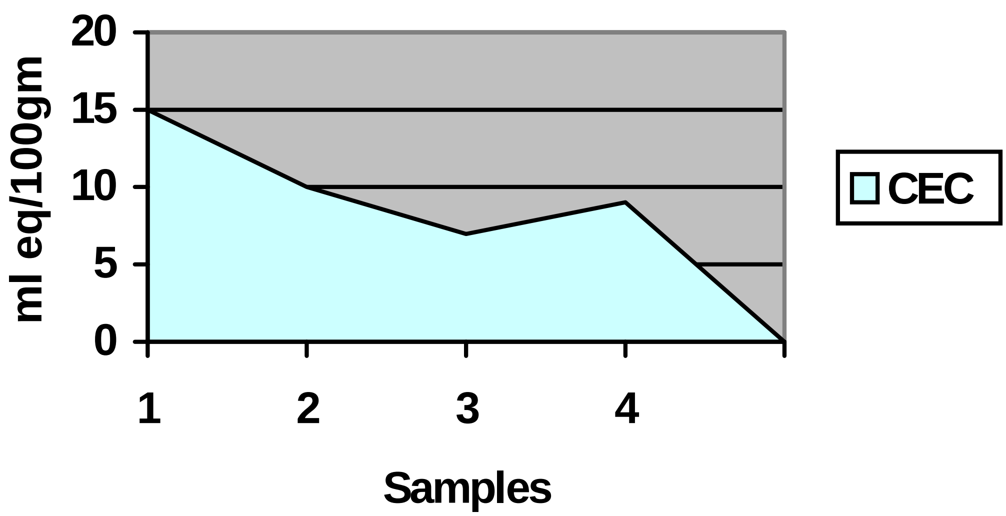

Fig. 1 – Average CEC equivalent of Atoka shale.

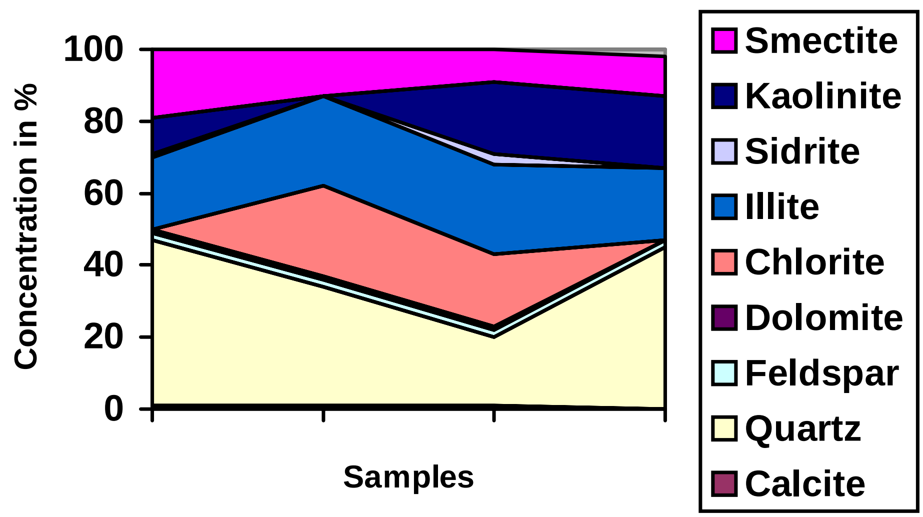

Fig. 2 – Mineralogy of Atoka shale.

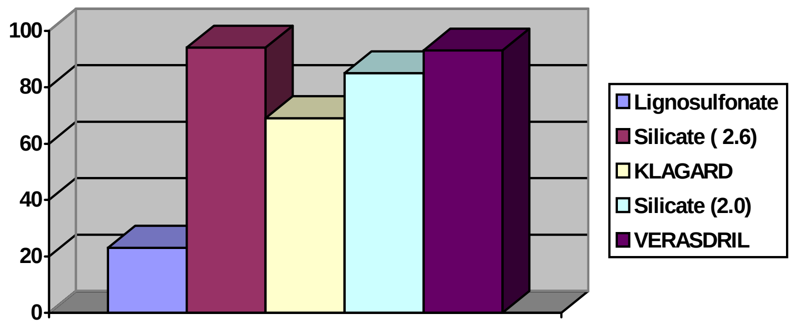

Fig. 3 - Comparative analysis of the tested fluids.

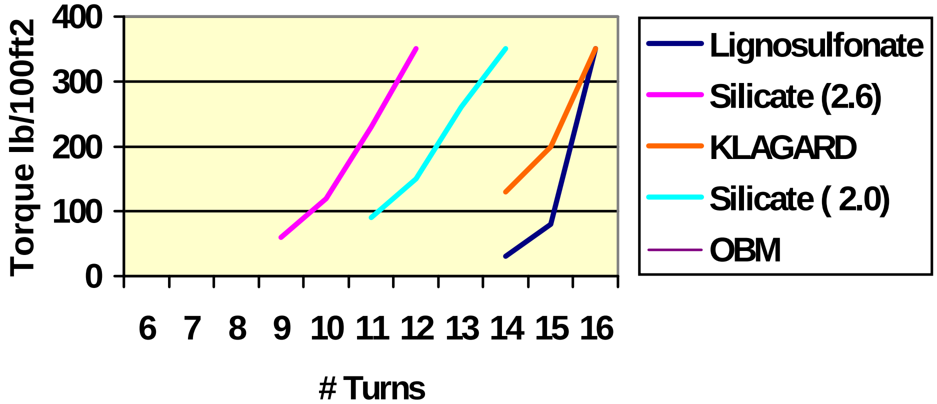

Fig. 4 - Bulk hardness test results.

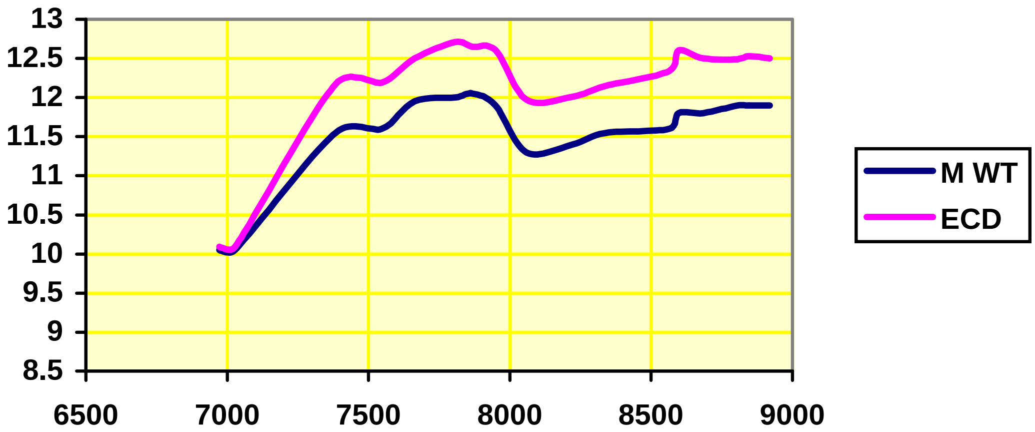

Fig. 5 – Mud weight and ECD trend.

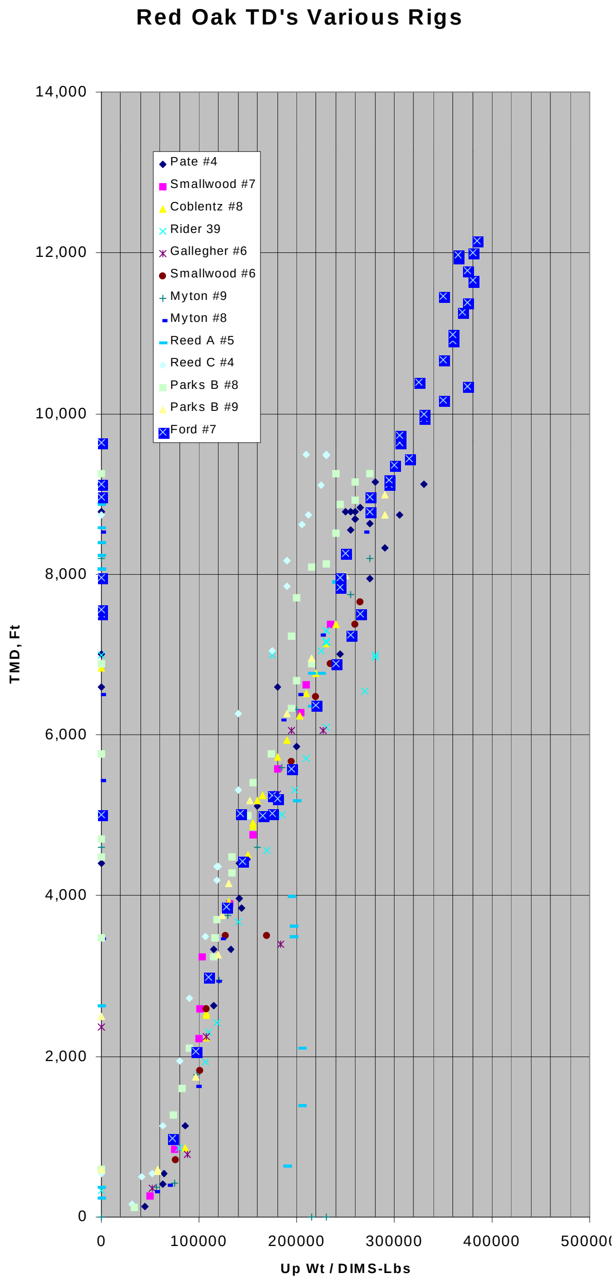

Fig. 6 - ROP comparison for tri-cone and drag bits in the same lithology, similar directional profile and mud weights.

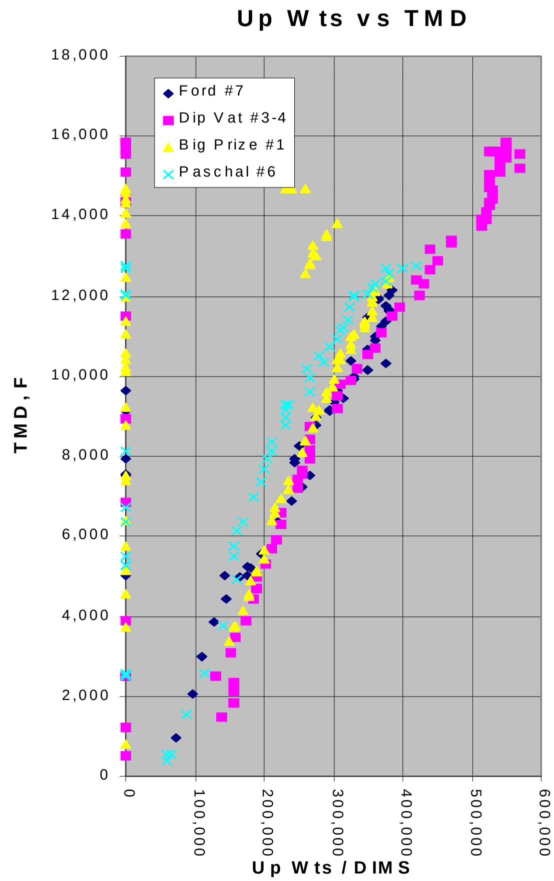

Fig. 7 - Area wells drilled with same rig fleet, indicating no torque and drag problems

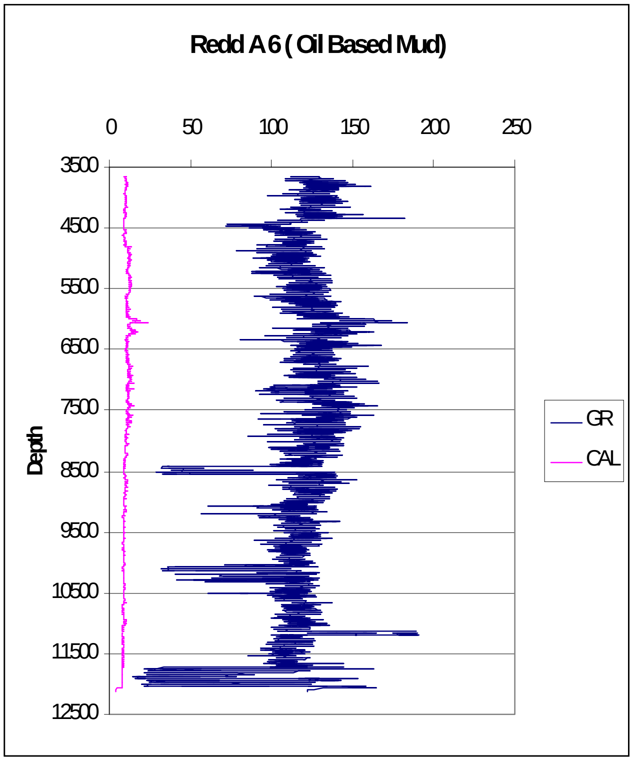

Fig. 8 – Caliper and gamma-ray log of OBM.

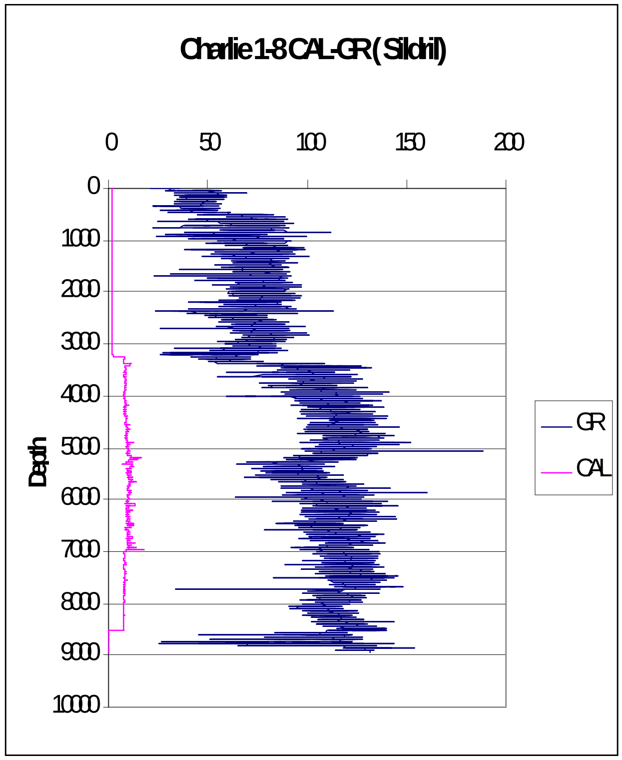

Fig. 9 – Caliper and gamma-ray log of silicate-based mud.

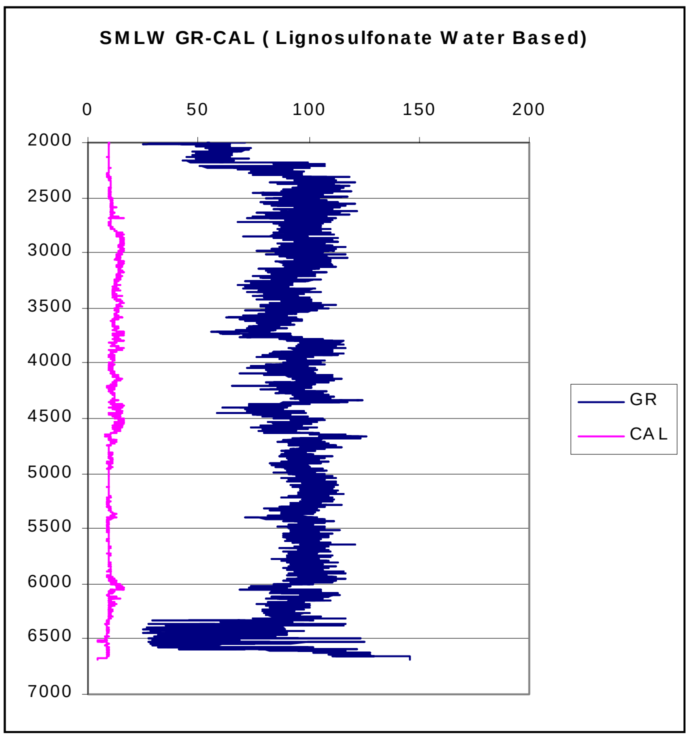

Fig. 10 – Caliper and gamma-ray log for lignosulfonate WBM.

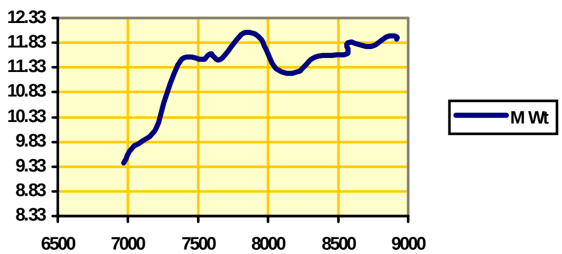

Fig. A1 - Fluid density trend

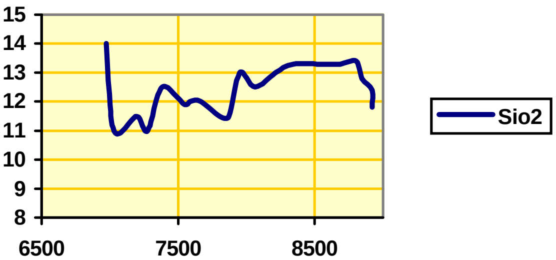

Fig. A2 - Silicate concentration.

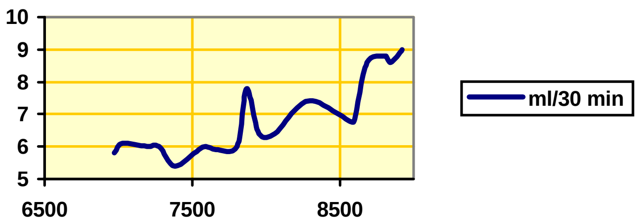

Fig. A3 - Filtration trend (API WL).

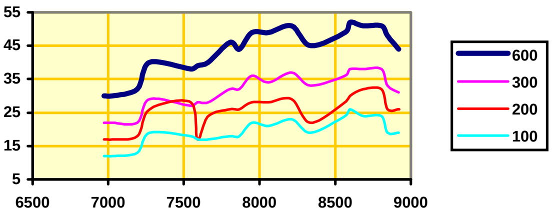

Fig. A4 – High-end rheology trend.

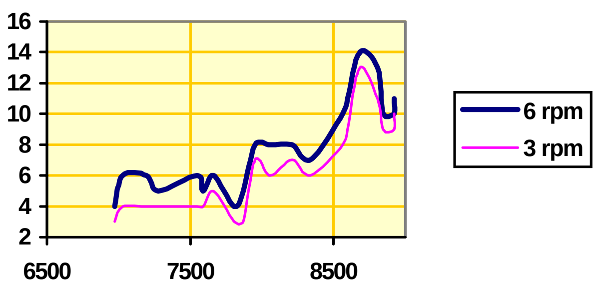

Fig. A5 – Low-end rheology trend.

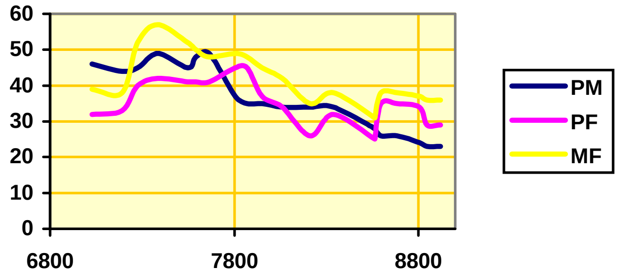

Fig. A6 - Alkalinity profile.

Fig. A7 - Bit condition after finishing the Atoka shale section.

Fig. A8 - Typical cuttings shape and volume on the shaker through Atoka shale.