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Prevention of Dynamic Sag in Deepwater Invert Emulsion Fluids

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Abstract

Controlling weight material sag in invert muds is difficult in deviated wellbores, where the phenomenon of sag is not completely understood and simultaneous optimization of all hydraulics variables is complex. The fluid must be designed with a specific rheological profile over the entire temperature range encountered in the drillpipe and wellbore. This is particularly difficult for deepwater wells, where temperatures may vary from near freezing to greater than 250^{o}F. Organophilic clays are especially well suited for this purpose. In this work, a blend of specific organophilic clays was used to provide the rheology necessary to minimize dynamic sag in two deepwater wells in the Mississippi Canyon, Gulf of Mexico. Reduction of the sag potential was accomplished without an increase in the viscosity profile of the mud.

Introduction

Sag is defined as a "significant" variation in mud density (>0.5 to 1 lbm/gal) along the mud column, which is the result of settling of the weight material. Often this occurs during the first bottoms-up circulation after a trip, and in inclined wellbores, sag can result in formation of a bed of the weighting agent on the low side. Barite is the most common weighting agent, but the same phenomenon occurs with other materials, *e.g.* hematite and calcium carbonate.

Several distinctively different phenomena can contribute to sag: static settling, dynamic settling and slumping.[1] Because of the complexity of the mechanism, control of sag requires an integrated approach. Control methods usually involve improved mud formulation and preparation, monitoring and maintenance, and adequate operational practices. Staging into the wellbore, increasing the flow rate and rotating the drillpipe are operational techniques to reduce the sag potential. Controlling the rheology of the drilling fluid is another key to minimizing sag potential. It is well established that static settling is related to the development of gel structure and viscoelastic properties. Dynamic sag is more complex, but it appears to correlate primarily with the low-shear rheology. Two accepted descriptors of low-shear rheology are the yield stress (extrapolated from the Herschel-Bulkley model) and the low-shear-rate yield point (LSRYP), given by:[2]

$$LSRYP = (2x\ \theta_3) - \theta_6 \quad (1)$$

where θ_3 and θ_6 are the Fann 35 Viscometer Readings at 3 and 6 rpm, respectively.

It has been shown that control of the low-shear rheology -- and therefore of the dynamic sag -- can be achieved more effectively with organophilic clays than with fatty acid based low-shear viscosity enhancers.[2] The situation is more difficult when high-angle wells are drilled in deepwater environment. The increase in rheology required to minimize the sag is restricted here by the low temperature of the fluid in the riser, thus generating high viscosities and consequently high equivalent circulating densities (ECDs).

A sag-preventing organophilic clay (SPOC) was recently developed. The product was initially tested in laboratory fluids and compared with standard organoclays, where it showed very good control of low- shear rheology and barite sag. To minimize the effect on low-temperature rheology, a combination of conventional organoclay and the new product was found to be optimum. Further testing was conducted in the M-I Sag Flow Loop to study the effects of varying concentrations of the new additive and shear on barite sag.

The new product was introduced in a field application, while drilling the last interval of a high-angle "S" shaped well in the Gulf of Mexico. The main treatment was made to the premix that is added to the drilling fluid to increase the synthetic/water ratio (SWR) and reduce the amount of low-gravity solids (LGS). The resulting fluid had higher SWR, less LGS concentration, similar rheology yet lower sag potential.

A second field application was just completed. The SPOC was used to reduce significantly the barite sag, but it was necessary to use a higher concentration of product for the desired effect.

Laboratory Studies

Preliminary Laboratory Evaluation. In an initial screening test, the new organophilic clay demonstrated the ability to develop superior low-shear-rate viscosity (LSRV) and reduce the sag tendency. LSRV was measured with a Brookfield viscometer at 0.0636 sec^{-1}. Sag tendency was evaluated by a laboratory procedure,[3] which is described below. The fluid used for comparison was a 14-lbm/gal synthetic-based drilling fluid, with a synthetic/water ratio (SWR) of 80:20. Using 4 lbm/bbl of the new product, similar LSRV and sag were measured as with 6 lbm/bbl of conventional organophilic clay supplemented by 0.5-lbm/bbl of organic gelling agent (see **Figs. 1 and 2**). The new organoclay was also much more effective in improving the LSRV after a 2-lbm/bbl increase, as shown in **Fig. 2**.

An undesirable effect of the SPOC, especially for deepwater environments, was a higher rheology at cold temperature (40-60^oF), compared to that provided by a conventional organophilic clay (**Fig. 3**). To reduce this impact, a combination of the two species was recommended for further testing.

Sag Flow Loop Test (SFLT) and Viscometer Sag Test (VST). Before testing the SPOC additive in the field, effects of additive concentration and shear on sag potential were evaluated in the SFLT and VST.

The Sag Flow Loop is a device that can measure directly the decrease in mud weight (MW) which results from barite sag.[1] The test mud is circulated through a 6-ft long tube at various flow rates and rates of pipe rotation. Density of the mud is measured continuously during the test and is corrected to a constant temperature of 120^oF. In general, sag is most likely at an angle of 45-60 degrees. At this angle, the maximum density decrease is often observed to occur at an annular velocity of 25 ft/min without pipe rotation. No drop in MW should occur at maximum flow rate and pipe rotation. The operating conditions used are given in **Table 1**.

In contrast, the VST is used to make a quick evaluation of the sag potential by measuring the increase in MW at the bottom of a rotational viscometer thermocup.[3] In order to promote sag, the viscometer is rotated at 100 rpm for 30 minutes. The difference between the final and the initial density is used as an indication of the dynamic sag potential.

The experimental conditions for the two sag tests are not the same; hence the specific values obtained from the VST usually do not agree with the SFLT results. However, the trends observed with the two devices usually agree very well. A fluid is considered to have moderate-to-low sag tendency when the density change is less than 0.15 - 0.2 lbm/gal measured by the SFLT and less than 1 lbm/gal on the VST.

The SPOC was tested as a treatment of a 14.3-lbm/gal synthetic-based mud at concentrations of 2 and 4 lbm/bbl (see Table 2 for the composition of the base mud). The base mud and the treated mud were each sheared at 6000 rpm for 30 min with a Silverson shearing device (Model # L4RT) and hot-rolled at 150^oF for 16 hr prior to the SFLT. After the first round of SFLT's, each test fluid was sheared again for a total time of 1 hr and 2 hr (including the initial 30 min) and re-tested.

Effect of Shear. The effect of shear on barite sag tendency is illustrated in **Fig. 4**. An initial shear of 30 min resulted in a maximum MW drop of 0.27 lbm/gal. After a total shear of 1 hr, the MW drop was reduced to 0.22 lbm/gal, and it was further reduced to 0.19 lbm/gal after a total shear of 2 hr. The shear helped to tighten the emulsion and improve particle size distribution, thus enhancing suspension quality and reducing sag tendency of the mud. The reduction in sag tendency was also indicated by the VST results. SFLT, VST and Electrical Stability (ES) Test results as a function of shear are compared in **Fig. 5**. The rheology of each tested fluid was measured with Fann 35A and Chandler 3500 viscometers at 75, 120, and 150^oF. The latter instrument is equipped with an F-0.2 spring for measuring viscosity at shear rates as low as 0.1 rpm. **Fig. 6** shows the rheology measured at 120^oF for different periods of shear. The changes in rheology due to shear appear to be insignificant; however, a general trend of increasing viscosity with increasing period of shear is discernible. The changes at low shear rates also correlate well with SFLT and VST results. One of the authors does not agree on what is more effective in sag reduction: increasing the duration of shear or finding the optimal way of transferring energy to the fluid (*i.e.* cavitation, extension or shear).

Effect of Sag-Preventing Organophilic Clay. The impact of organophilic clay on sag prevention was found to be more significant and effective than that of shear. This is clearly illustrated in **Fig. 7**. The fluids in **Fig. 7** all had been sheared for a total of 2 hr. After each treatment of 2-lbm/bbl organophilic clay, the maximum MW drop measured with the SFLT was reduced 50%, *e.g.*, from 0.38 lbm/gal for the base mud to 0.18 lbm/gal with 2 lbm/bbl, and to 0.07 lbm/gal with 4 lbm/bbl of organophilic clay. This rapid decrease in sag tendency can be directly associated with addition of the organophilic clay.

Rheological measurements using Fann 35 and Chandler 3500 viscometers showed a rapid increase in viscosity after treatment with organophilic clay, particularly at the lower end of the shear rate. Such an effect was also observed with shear, but this one was apparently much more significant in magnitude. The rheograms from the base mud before and after organophilic clay treatment are shown in **Fig. 8**. A good correlation between the treatment level of organophilic clay and the results from VST and ES measurements was also obvious (see **Fig. 9**).

Field Applications

Case History #1. A complex geometry well was being drilled from a deepwater platform in the Mississippi Canyon - Gulf of Mexico. The operator was concerned that while drilling the $10^5/_8$-in. final section, a barite bed might form on the extended high-angle portion preceding this interval (see **Fig. 11**). The use of a blend of conventional organoclay and SPOC was recommended to minimize sag and maintain optimal rheology while drilling the last part of this well.

The initial properties of the drilling fluid after it was weighted up to 13 lbm/gal are presented in **Table 2**. The plastic viscosity (PV) was considered high for the given MW and SWR. This was related to the increased LGS concentration observed at the beginning of the drilling interval. The VST density difference was 0.75 lbm/gal, indicating a moderate-to-low sag tendency.

One of the main goals after the drilling began was to increase the SWR and to reduce the LGS concentration. Adding a premixed fluid with synthetic oil, emulsifier, surfactant and lime is typically an easy way to do this. Barite is added to maintain the MW. To counter the increase in sag tendency that the dilution treatment was expected to bring about, 1.5-lbm/bbl conventional organoclay and 0.5-lbm/bbl SPOC were added to the premix. These concentrations were thought to be low enough to produce minimal impact on rheology and still minimize the sag potential.

The treatment was applied during a conditioning trip. The properties of the treated fluid are presented in **Table 2**. LGS concentration was reduced by 3%, from 12.3% to 9.3%, and as a consequence PV was reduced from 35 to 27 cP. SWR was increased from 70:30 to 73:27. The sag potential determined with the VST was not just maintained, but it was actually reduced after this treatment, from 0.74 to 0.37 lbm/gal. After conditioning the mud, a trip was made to pick up a PDC bit and drilling assembly. When circulation resumed – after approximately 24 hours – no significant MW variation that could be related to sag was observed.

The premix was added almost continuously to the system, and the well was drilled to TD without any problems. Not only was there no evidence of barite sag, but the large amount and high integrity of the cuttings indicated excellent hole cleaning; for such a difficult well geometry, these results were considered very successful. The treatment with premix using the blend of two organophilic clays proved to be efficient in controlling rheology while minimizing the sag potential.

Case History #2. The SPOC was considered a viable alternative in a highly deviated deepwater production well drilled in the Mississippi Canyon area of the Gulf of Mexico, relatively close to the previous well but from a different platform. The operator was concerned that sag might occur after an extensive logging period. An initial concentration of 0.5-lbm/bbl SPOC was maintained in the system prior to logging. The drilling fluid properties after this treatment are presented in **Table 3**. The wellbore was logged via toolpush, and it took two attempts and over 76 hours to finalize the operation. After circulation resumed, some barite sag was observed, with 0.4 to 0.6-lbm/gal reduction in mud density at the flowline for the initial flow during the first bottoms-up trip and 1.0-lbm/bbl increase in mud density for the tail-end flow.

The drilling fluid was circulated and conditioned at this point. An addition of SPOC was made to increase the total concentration to 1 lbm/bbl. The fluid was also treated with organic gelling agents to reduce the static settling. As presented in **Table 3**, the treated fluid had higher YP, higher gels and low-shear rheology. YP was increased from 20 to 23 lbf/100 ft^2, 10-sec/10-min/30-min gel strengths were increased from 16/21/21 to 21/25/26 lbf/100 ft^2 and the 3-rpm reading was increased from 9 to 12. The sag potential measured by VST was 0.5-lbm/gal MW differential, which indicated that no major sag should occur. After logging again for over 45 hours, when circulation was resumed before drilling ahead, the MW variation during the first bottoms-up trip was only $\pm$0.3 lbm/gal.

The system was weighted up to 14.0 lbm/gal and the well drilled to its final planned depth. After logging for 52 hours, the well was circulated, and it showed a MW variation again of only $\pm$0.3 lbm/gal. The SPOC concentration was increased from 1.0 to 1.2 lbm/gal. VST density difference was 0.1 lbm/gal. While circulating prior to running liner, sag was within the same limits, 0.3 lbm/gal on the light side, and 0.3 on the heavy side. This density variation was considered manageable for the given conditions, and sag was considered minimal. The use of SPOC at 1 lbm/bbl was considered successful, while a concentration of 1.2 lbm/bbl was considered too high, inasmuch as it generated high viscosity at the flow-line temperature. At a temperature of around 75°F, the Marsh funnel viscosity was increased from 90 to 108 sec (see **Table 4**). This re-enforces the idea that excessive SPOC treatment may affect the rheology at cold temperature.

An optimal treatment to minimize sag should consider the rheology throughout the whole temperature range, from seafloor to bottomhole. It is also necessary to treat both dynamic and static settling, which requires optimizing the relative amounts of organophilic clays and organic gelling agents.

Conclusions

Sag is a complex process, involving static settling, dynamic settling and slumping. An integrated approach involving improved mud formulation and preparation, monitoring and maintenance, and adequate operational practices should always be used to minimize sag.

This paper describes a method of controlling the fluid rheology by use of a special organophilic clay in conjunction with other rheology modifiers. The following are the main conclusions derived from this work:

1. Initial laboratory work showed that 4 lbm/bbl of SPOC generated similar LSRV and sag -- with lower PV and gels – to those provided by 6 lbm/bbl of conventional organophilic clay supplemented by 0.5-lbm/bbl of organic gelling agent.
2. SPOC has tendency to increase cold temperature rheology more than conventional clays. A blend of conventional and sag-preventing clays is therefore recommended for deepwater applications.
3. As demonstrated by a flow-loop test, exposing the fluid to additional shear enhanced suspension quality and reduced sag tendency.
4. The use of SPOC in a field treatment caused a notable improvement in the attempt to minimize sag while decreasing LGS and increasing SWR. The treatment consisted of 1.5-lbm/bbl conventional clay and 0.5-lbm/bbl SPOC added to the dilution fluid.
5. A more aggressive field treatment was used to minimize a sag problem that occurred after extensive logging. The treatment consisted of 1-lbm/bbl SPOC supplemented by organic gelling agents.

Nomenclature

ECD = *Equivalent Circulating Density (lbm/gal)*
ES = *Electrical Stability (V)*
LGS = *Low-Gravity Solids (%v/v)*
LSRV = *Low-Shear Rate Viscosity (lbf/100 ft^2)*
LSRYP = *Low-Shear Rate Yield Point (lbf/100 ft^2)*
MW = *Mud Weight or Density (lbm/gal)*
PDC = *Polycrystalline Diamond Compact*
PV = *Plastic Viscosity (cP)*
rpm = *revolutions per minute*
SFLT = *Sag Flow Loop Test*
SPOC = *Sag-Preventing Organophilic Clay*
SWR = *Synthetic/Water Ratio*
VST = *Viscometer Sag Test*
YP = *Yield Point (lbf/100 ft^2)*
q_3, q_6 = *Fann 35 Viscometer Readings at 3 and 6 rpm*

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2. Bern, P. A., *et al.*: "The Influence of Drilling Variables on Barite Sag," SPE 36670, SPE Annual Technical Conf, Denver, Oct 6-9, 1996.
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Table 1
Operating conditions of Sag Flow Loop Test

Operating Conditions		**Comments**
Wellbore ID (in.)	2.0	Clear acrylic tube allows visual examination of barite sag
Pipe OD (in.)	¾	
Well Angle (degrees)	60	Maximum sag develops between 45 and 60 degrees
Pipe Eccentricity	0.80	
Flow Rate (gal/min)	2.8 - 28	
Annular Velocity (ft/min)	25 – 250	Max. sag develops at 25 ft/min annular velocity with no pipe rotation
Pipe Rotation (rpm)	0 - 250	Pipe rotation can reduce sag

Table 2
Composition of SBM Used in Sag Tests

Base Fluid (bbl)	0.563
Viscosifier (lbm/bbl)	2
Emulsifier (lbm/bbl)	8
Lime (lbm/bbl)	6
$CaCl_2$ Brine (bbl)	0.154
Barite (lbm/bbl)	363
SWR	80:20
Mud Weight (lbm/gal)	14.3

Table 3
Comparison of Fluid Properties Before and After Treatment
Case History #1

	Initial	Treated
MW (lbm/gal)	13	13
SWR	70:30	72:28
PV (cP)	35	27
YP (lbf/100 ft^2)	19	13
10-sec/10-min Gels (lbf/100 ft^2)	21/23	17/20
LGS (%)	12.3	9.3
VST ΔMW (lbm/gal)	0.75	0.37

Table 4
Comparison of Fluid Properties Before and After Treatment
Case History #2

	Initial 0.5-lbm/bbl SPOC	Treatment #1 1-lbm/bbl SPOC	Treatment #2 1.2-lbm/bbl SPOC
MW (lbm/gal)	13	13.1	14
SWR	75:25	75:25	76:24
PV (cP)	21	23	29
YP (lbf/100 ft^2)	20	23	22
10-sec/10-min/ 30-min Gels (lbf/100 ft^2)	16/21/21	21/25/26	19/21/18
Marsh Funnel Viscosity (sec)	85 @ 71^{o}F	90 @ 71^{o}F	108 @ 71^{o}F
LGS (%)	5.4	5.7	5.1
VST ΔMW (lbm/gal)	0.75	0.5	0.1
Max. MW @ bottoms up (lbm/gal)	14	13.3	14.3
Min. MW @ bottoms up (lbm/gal)	12.4	12.7	13.7

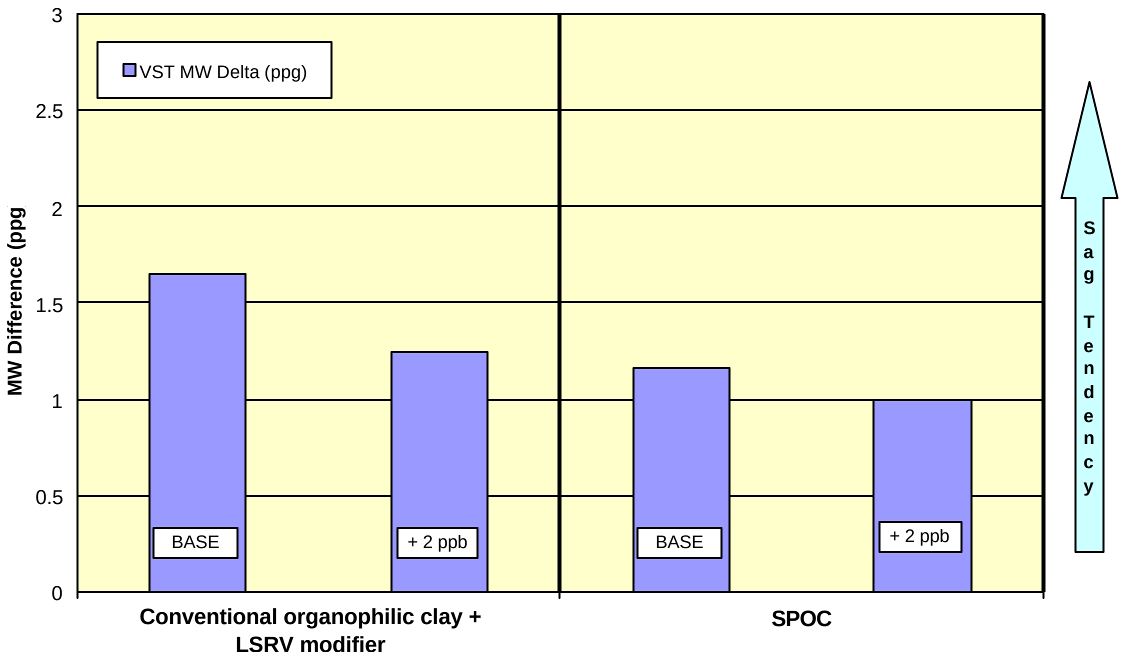

Fig. 1 – Effect of organophilic clays on sag tendency measured by VST in laboratory fluids.

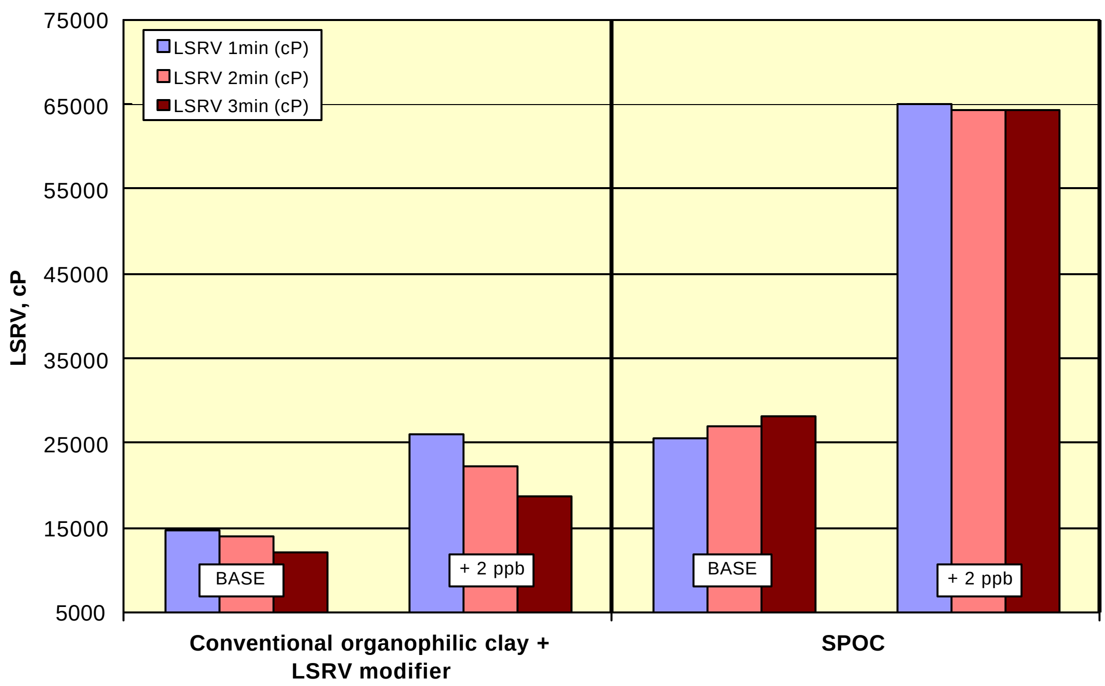

Fig. 2 – Effect of organophilic clays on Brookfield LSRV in laboratory fluids.

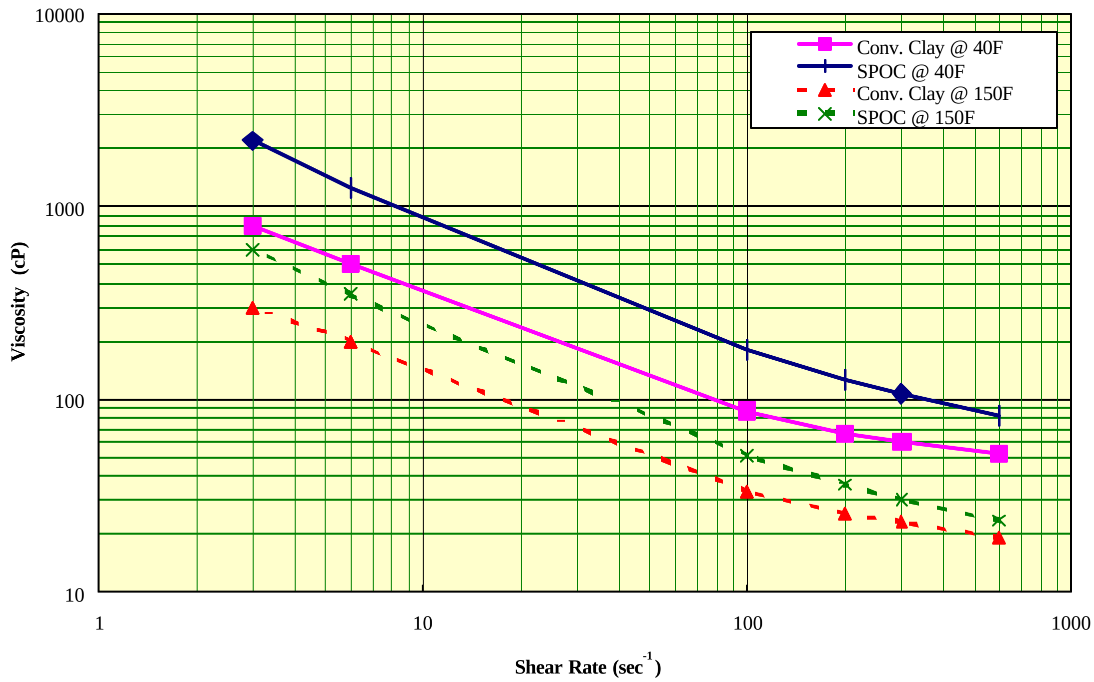

Fig. 3 – Effect of 4-lb/bbl organophilic clays on rheology of SBM at different temperatures.

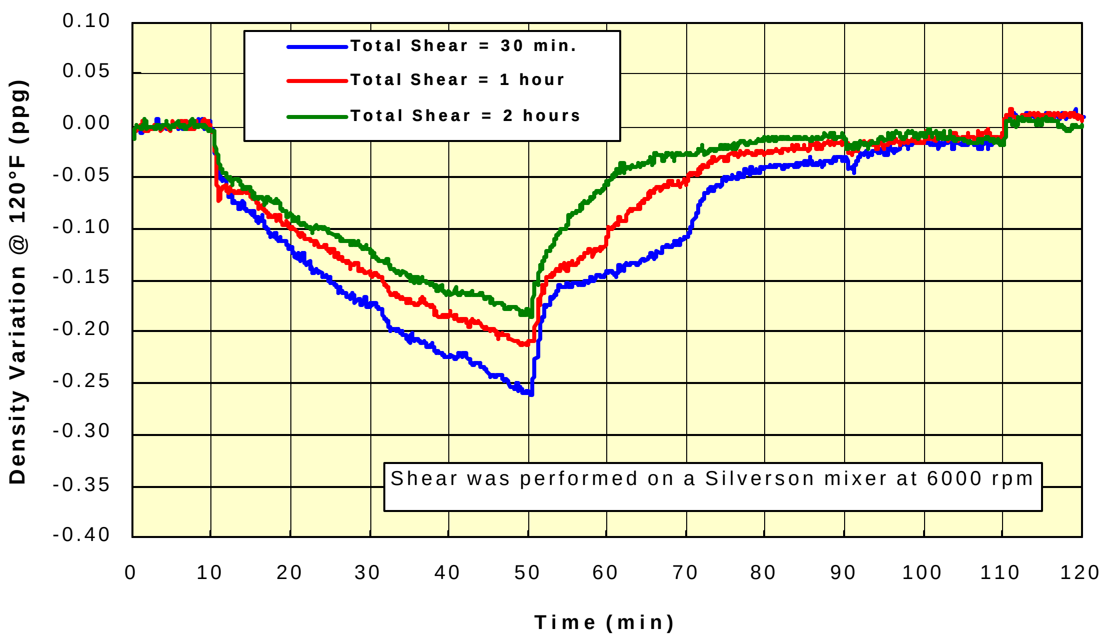

Fig. 4 – Density variation curves with 2-lbm/bbl treatment of organophilic clay and three stages of shearing with a 14.3-lb/gal SBM.

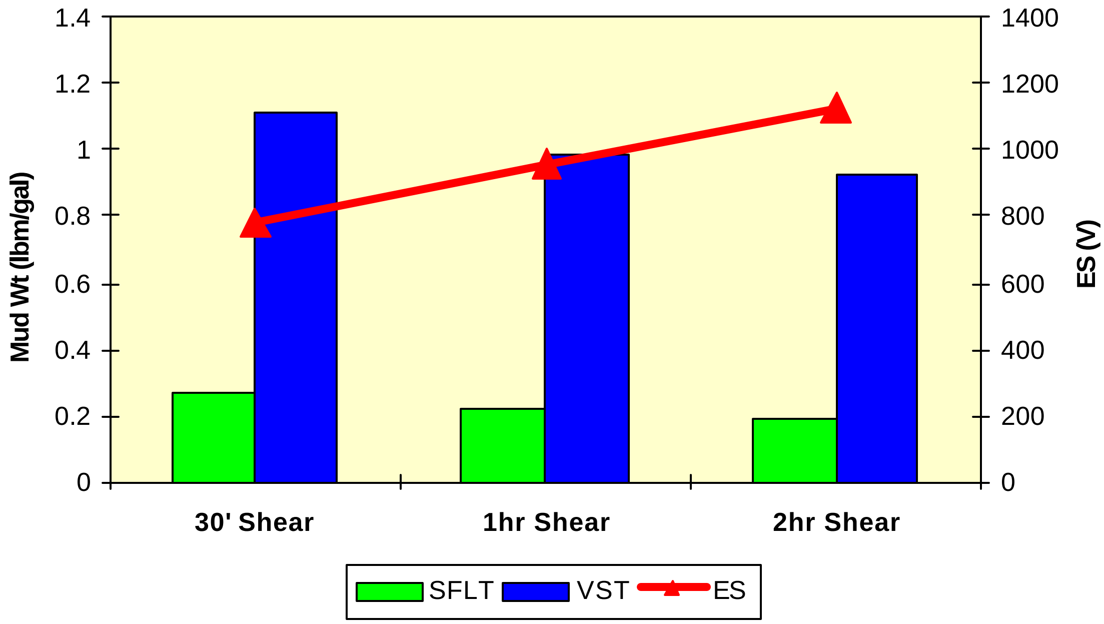

Fig. 5 – Effect of shear on SFLT, VST and ES results.

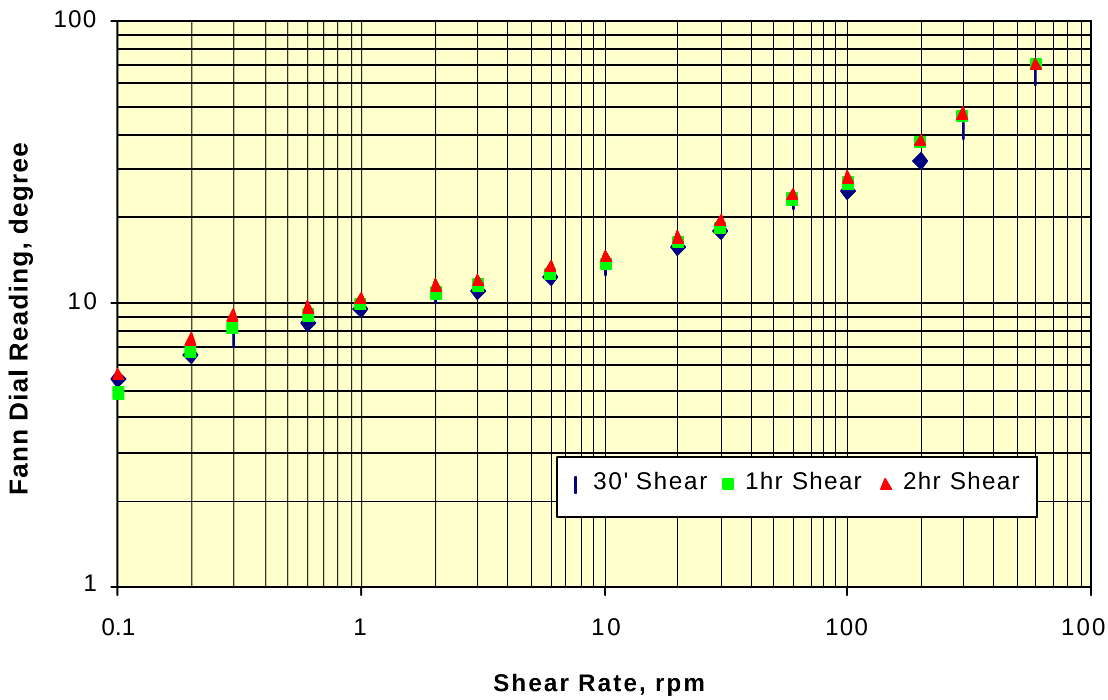

Fig. 6 – Effect of shear on rheology of 14.3-lb/gal SBM treated with 2-lbm/bbl organoclay.

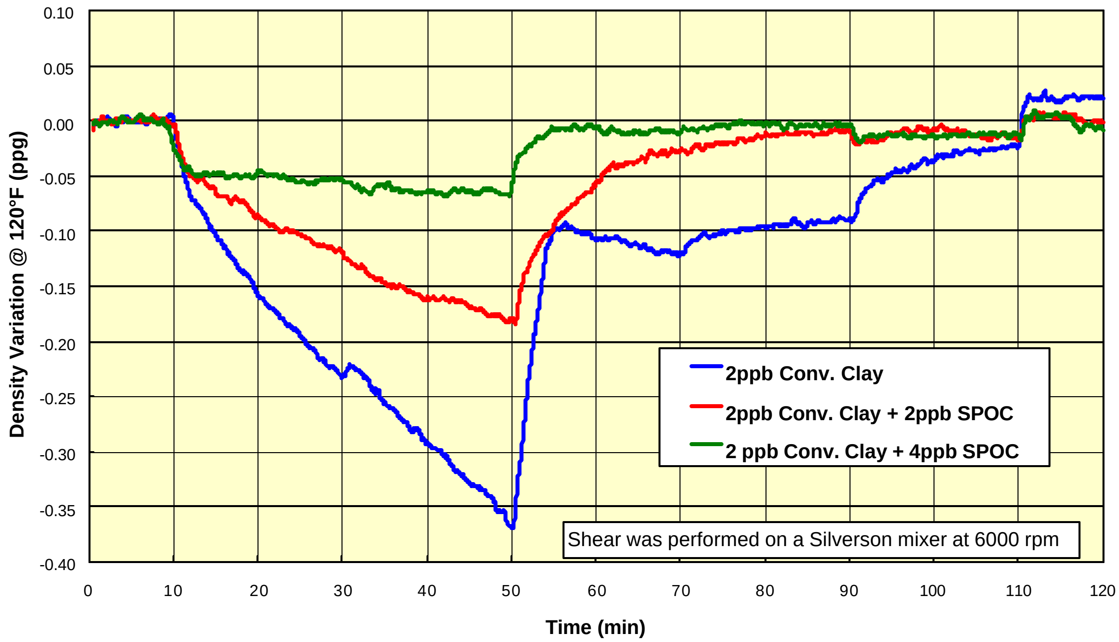

Fig. 7 – Effect of SPOC addition to 14.3-lb/gal SBM illustrated by SFLT density variation curves.

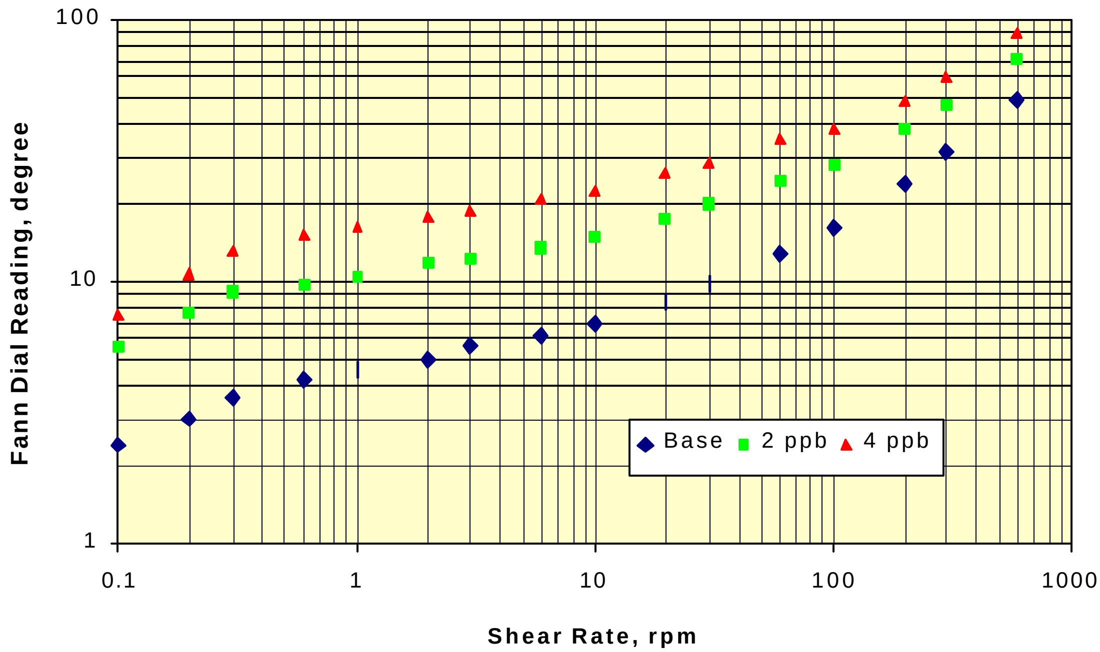

Fig. 8 – Effect of organophilic clay content on rheology of 14.3-lb/gal SBM sheared for 2 hours.

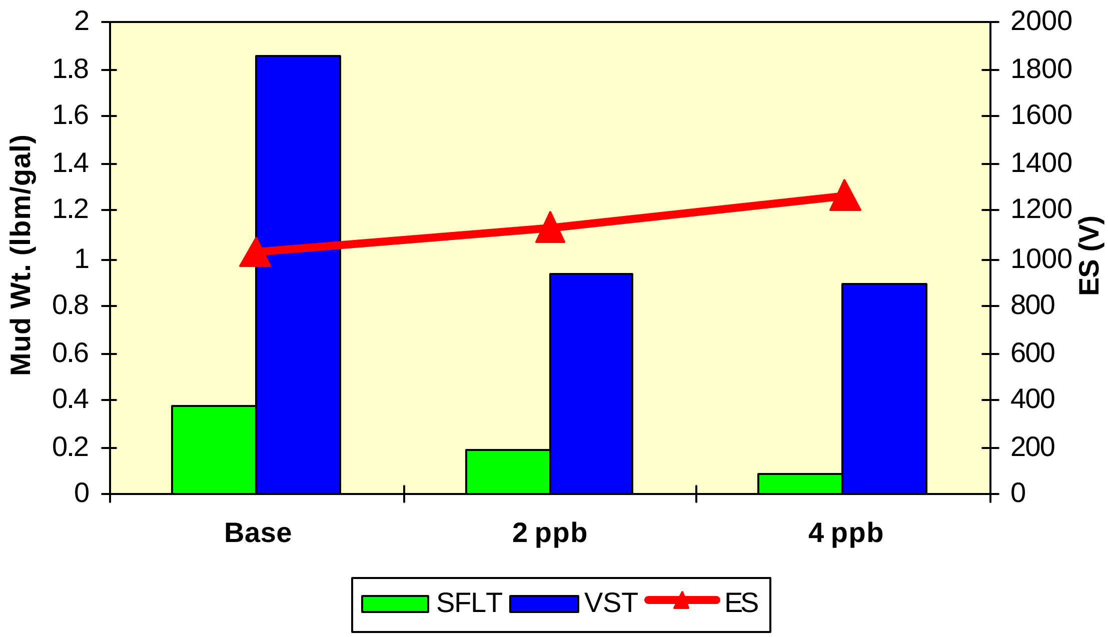

Fig. 9 – Effect of SPOC Addition on SFLT, VST, and ES results.

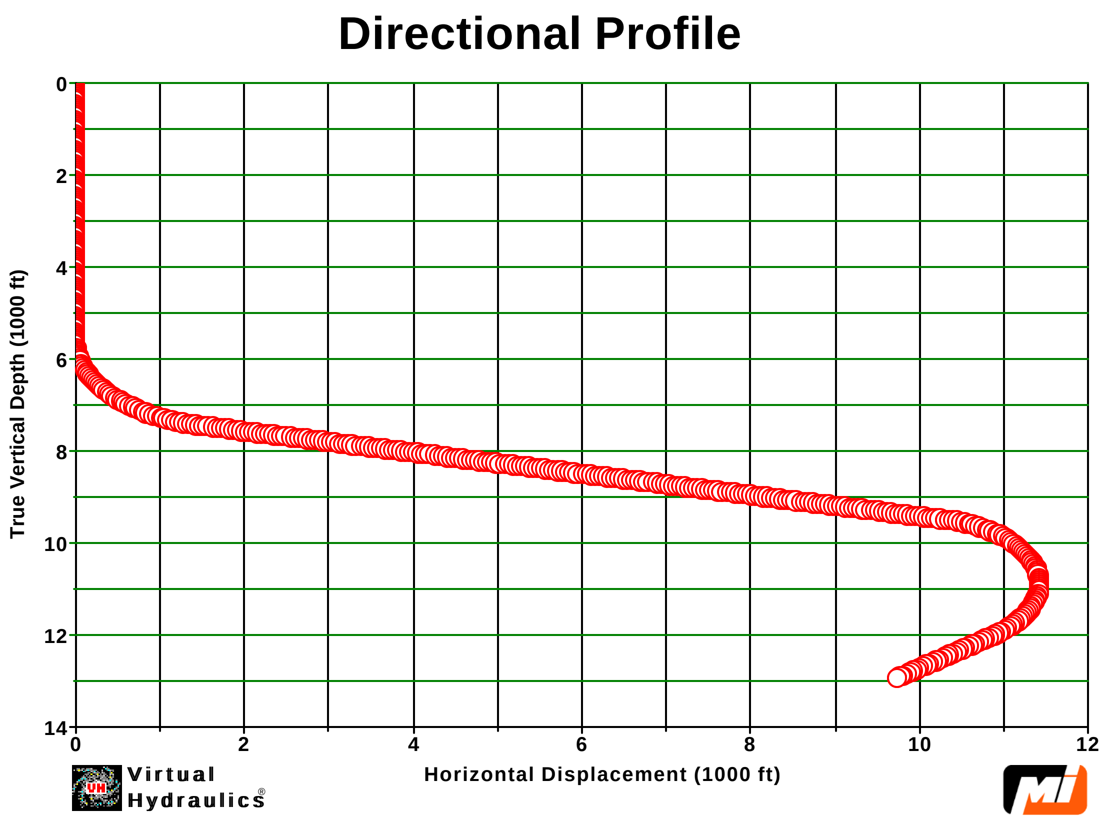

Fig. 10 – Directional profile of the well described in Case History #1.