



## Role of Rheology in Barite Sag in SBM and OBM

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### Abstract

Barite sag in SBM and OBM is affected by drilling fluid properties and drilling parameters such as flow rate, hole geometry, pipe trips, and others. Of these, fluid rheology has received the most attention and is perceived to be a dominant and complex factor affecting sag.

Available guidelines for mitigating sag, derived mostly from measurements under laboratory conditions, relate barite sag to the low-shear-rate rheology of the fluid as measured by oilfield-type rotational viscometers. The guidelines have been used with varying degrees of success to reduce sag in invert emulsion fluids. Frequently, however, they are inadequate for eliminating or reducing sag to acceptable levels. Apart from other non-rheology related parameters, a main reason for this is the inadequacy of current rheology guidelines for application across a wide range of fluids. This may be due to the fact that the low-shear-rate characteristics of some fluids are poorly defined by conventional oilfield viscometers, or that the fluid structures responsible for solids suspension are better defined by linear viscoelastic properties.

This paper discusses rheological properties that characterize the degree of structure in invert drilling fluids. It presents steady shear data at very low shear rates and linear viscoelastic properties for a range of fluids formulated with different viscosifiers. The data show that dynamic sag best correlates with certain viscoelastic properties. Such correlation is not evident from the steady shear data.

### Introduction

Barite sag is the settling of weight material, which results in significant drilling fluid density variations seen at the flow line. Barite sag is more severe in synthetic-based drilling fluids (SBM) and oil-based drilling fluids (OBM) and can occur over a relatively wide fluid density range, 11.7-20.0 lb/gal. It can lead to density variations as high as 4.0 lb/gal. Occurrence of sag can lead to potential drilling complications such as well-control problems, lost circulation, induced wellbore instability, and stuck pipe.

The symptoms of sag are observed when circulating the fluid out of the hole after the fluid column has been static for some time. This observation had previously led

to the belief that static settling was the main mechanism for barite sag. However, flow-loop tests and field experience have shown that dynamic sag is more likely to produce the large-scale density variations seen at the flow line. Hanson *et al.*<sup>1</sup> and Jefferson<sup>2</sup> emphasized the potential for dynamic sag occurring while circulating the drilling fluid and observed that prevention of dynamic sag is more difficult than static sag.

The overall potential for barite sag is highest when the drilling fluid experiences low shear rates.<sup>1,3</sup> Flow-loop data and field observations suggest that severe sag occurs under the combined influence of low viscosity and low annular velocity and can lead to the formation of a barite bed. Bern *et al.*<sup>3</sup> and Dye and Mullen<sup>4</sup> suggested a critical mean annular velocity of 100 ft/min above which barite bed formation was minimized.

Accelerated settling can occur in an inclined wellbore through the well-known Boycott effect. This can lead to "slumping" which is the sliding downward of a bed of solids deposited on the lower side of an inclined wellbore. The barite bed may be disturbed by high annular velocities and with drillpipe rotation. Flow-loop tests and field experience show that sag is worst when drillpipe is stationary.<sup>3</sup>

Barite sag is related both to the drilling fluid properties and the drilling conditions and practices. The fluid properties affecting sag include rheology, solids content, particle size and distribution, and the interfacial chemistry of the dispersed solid and aqueous phases.

It is generally agreed that the low-shear-rate (LSR) rheology of the fluid affects the sag performance of the fluid.<sup>3</sup> An increase in the LSR rheology is thought to be beneficial for mitigating dynamic sag.<sup>3,5</sup> The LSR rheology has been variously defined by the low-shear-rate viscosity (*LSRV*), yield stress or gel strength. The LSR environment can typically be thought of as the shear rate created by the particle as it settles under gravity in an otherwise quiescent fluid. This may be estimated from Stokes' Law:

$$V_s = 430.2 \frac{(SG_{solid} - SG_{liquid}) g d^2}{\mu} \quad (1)$$

$$\dot{\gamma}_{LSRV} = \frac{2V_S}{d} \quad (2)$$

For a typical barite particle [ $d = 1.968 \times 10^{-3}$  inch (50 micron), s.g. = 4.25], fluid density (s.g. = 1.4), a given LSRV (say,  $\mu = 2 \times 10^4$  cP), and with  $g = 32.8$  ft/s<sup>2</sup>, Eq. (1) predicts:

$$\dot{\gamma}_{LSRV} = 0.008 \text{ s}^{-1} \quad (3)$$

Dye, *et al.*<sup>6</sup> suggested that the viscosity value at a shear rate of  $0.5 \text{ s}^{-1}$  could be used as sag indicator, while others (e.g. Herzhaft, *et al.*<sup>5</sup> and Saasen<sup>7</sup>) argued that considerably lower values in the range  $10^{-2}$  to  $10^{-3} \text{ s}^{-1}$  may be more appropriate. Thus, a conventional oilfield viscometer such as the Fann 35, which has a low-shear-rate restriction of  $5.1 \text{ s}^{-1}$ , is inadequate for direct LSRV measurements.

More recently, Dye and Mullen<sup>4</sup> used a field viscometer, capable of measuring at shear rates as low as  $0.0017 \text{ s}^{-1}$ , to characterize the LSR properties of several invert drilling fluids. From these data and dynamic sag measurements in a flow-loop, they produced a sag prevention window of viscosity vs. shear rate, where the viscosity limits are imposed by the constraints of poor sag performance (lower viscosity limit) and formation fracture pressure (upper viscosity limit). However, little detail is provided in their paper, making it difficult to substantiate their claims.

Herzhaft, *et al.*<sup>5</sup> investigated the LSR characteristics of invert drilling fluids. They identified two distinct regimes: a regime at very low shear rates where the fluid exhibited quasi-Newtonian behaviour and one at higher shear rates where the fluid had shear-thinning characteristics. The transition between the two regimes appeared to occur at a "critical" shear rate which increased with increasing temperature. They also performed cryomicroscopic observations, which suggested that interaction of organoclay (usually used in the formulation of invert muds for rheology control) with emulsion droplets is responsible for a solid-like structure at very low shear rates. This structure, which breaks down rapidly upon shearing, is responsible for the yield stress of the fluid. The yield stress required for preventing the settling of a barite particle in a quiescent fluid can be estimated from a balance of buoyancy and viscous forces:

$$\tau_y = 2.70 (SG_{solid} - SG_{liquid}) g d \quad (4)$$

For the barite particle and the drilling fluid of the previous example, Eq. (4) gives an estimate of 0.50 lb/100 ft<sup>2</sup>. Unfortunately, accurate measurement of the yield stress is achievable only with sophisticated rheometers capable of operating in the controlled stress

or creep modes. Without such instruments, only estimates of the yield stress can be produced. Bern, *et al.*<sup>3</sup> suggest the Herschel-Bulkley yield value  $\tau_y$ , and predict that sag may be minimized if  $\tau_y > 7$  lb/100 ft<sup>2</sup>. For field application, they define an alternative low-shear-rate yield point (LSYP) as the minimum yield stress required to prevent sag. This value is estimated from the 6- and 3-rpm data on the Fann 35 viscometer (shear rates of  $10.2$  and  $5.1 \text{ s}^{-1}$ , respectively):

$$LSYP = 2\theta_3 - \theta_6, \quad (5)$$

where  $\theta$  is the Fann 35 reading in Pa. Based on available data, they suggest a value of 7–15 lb/100 ft<sup>2</sup> for LSYP.

Viscoelastic behaviour may also be important for reducing sag.<sup>3</sup> In particular, static sag is thought to be related to the viscoelastic properties of the fluid.<sup>8</sup> Herzhaft, *et al.*<sup>5</sup> performed oscillatory measurements on a number of oil-based drilling fluids viscosified with organoclay. They concluded that, at rest or in the absence of appreciable shear, the viscoelastic properties of the fluid may influence sag. These and many other observations point to the possibility of structure formation in the fluid at ultra-low shear rates, and hence to the existence of a gel strength. Bern *et al.*<sup>3</sup> observed that static settling can be controlled by appropriate development of gel strength and suggested this as the reason why clay-type products are more effective at sag reduction than fatty-acid rheology enhancers. Jamison and Clements<sup>9</sup> studied the static settling of barite in an inclined tube. They observed a tendency of increased sag potential with reduced viscosity or gel strength.

In addition to the rheology, other properties of the fluid also affect barite sag. The effect of high solids content in the drilling fluid is to increase the resistance to the settling motion. Hindered settling in a concentrated suspension of particles has been the subject of many studies, most of which have treated the effect of the solids as an increase in the bulk density and rheology of the continuum. In oil-based drilling fluids, the settling is further reduced if gel structure develops and improves suspension.<sup>1</sup> The interfacial chemistry of the dispersed phases, *i.e.* the solids and emulsion droplets, can also influence barite sag in invert drilling fluids. The type and concentration of the emulsifier and wetting agent affect emulsion stability and the wettability of the solids, including organoclays, and may have an effect on sag.<sup>3,7</sup>

Barite sag in SBMs and OBMs is related both to the mud properties and the drilling operation and, as such, they should not be treated independently of one another. However, understanding the effect of each variable on sag will help define an appropriate course of action to minimize sag. From the standpoint of drilling fluid properties, rheology is a key parameter for controlling sag. The studies reported to date have produced useful

guidelines for reducing sag in invert drilling fluids, nevertheless there remains a need for a clearer understanding of the link between sag and fluid rheology. This paper describes work aimed at determining the effect of rheology and structure on barite sag. It presents steady shear data at very low shear rates, and linear viscoelastic properties for a range of fluids formulated with different viscosifiers. This is achieved by measuring dynamic sag under viscometric flow conditions so that rheological properties become the dominant parameter in the sag phenomenon.

## MATERIALS

The invert drilling fluids used in this work differed only in the type and concentration of the rheology control additive. The fluids were formulated to the same oil-water ratio, density and brine-phase salinity, and hot rolled at 250°F for 16 hours. The concentration of the rheology additive was adjusted to produce a Fann 35 reading of 5–14 lb/100ft<sup>2</sup> at 3 rpm. The formulation is shown in Table 1. The concentration of the additives and the 3-rpm data are summarized in Fig. 1.

The rheology additives consisted of organoclays and polymeric materials, with some of the fluids containing a combination of the two types of additives. The organoclays differed in the clay type (*i.e.* bentonite, hectorite, attapulgite), particle size, the chemistry of the organic treatment (*i.e.* quaternary ammonium salt), the degree of treatment, and the type of process used for the treatment, *e.g.* wet or dry process. The type and extent of treatment affect the polarity and temperature needed for the clays to yield. Since all clays were used in similar formulations and were subjected to the same temperatures, they produced different rheological performance. The polymeric additives included non-functionalized block copolymers and polymer blends with some functionality.

In Fig. 1, the test fluids are denoted as OB1 – OB14 (containing organobentonite), OH1 – OH2 (containing organohectorite) and OA (containing organoattapulgite). Fluids containing polymeric materials are shown as P1 – P7. The data are sorted in the ascending order of lb/bbl of material used. The polymeric additives are most efficient at generating the targeted 3-rpm Fann reading, thus requiring the lowest amounts. The organoattapulgites are at the opposite end, requiring the highest concentration. The more common organoclays (the modified bentonite and hectorite types) fall across the middle.

## METHODS OF MEASUREMENT

**Rheology** - Rheological measurements were carried out on a Fann 35 viscometer and a Bohlin C-VOR rheometer. The Bohlin characterization consisted of steady shear measurements in the controlled stress mode, and dynamic oscillatory measurements in the linear viscoelastic region. The test fluids were stabilized

by a 5-minute shearing period on a high-shear mixer prior to transfer of the sample to the measuring geometry. The measurement protocol included pre-shearing at 1000 s<sup>-1</sup> for 5 minutes, followed by a 5-minute equilibration time before measurements began.

Concentric-cylinder geometry was used for the steady shear measurements, in preference to the conventional cone-plate geometry, in order to avoid loss of fluid by centrifugation at higher shear rates. The fluid contact surfaces of the geometry were roughened to minimize slip. The truncated cone-plate geometry was used for the oscillatory measurements.

The steady shear measurements were performed over a shear stress range that covered shear rates in the range 1000 s<sup>-1</sup> to 10<sup>-3</sup> s<sup>-1</sup>. Shear stress was ramped both up and down. Dynamic oscillatory measurements consisted of a strain sweep to establish the linear viscoelastic region, followed by a frequency sweep (0.01-100 Hz) to measure the elastic (or storage) and viscous (or loss) moduli.

Fann 35 measurements were carried out at 122°F (50°C), while the Bohlin measurements were performed at 68°F (20°C) and 122°F to correspond to temperatures of the dynamic sag measurements used in this study.

**Dynamic sag** - Laboratory measurement of dynamic sag is commonly performed in one of two ways; in a viscometer sag test<sup>2</sup> device (VST) where the sag performance of the fluid is investigated in a relatively well-defined shear field (where the dominant effect is that of fluid rheology), or in a flow loop where other parameters such as flow rate, eccentricity, pipe rotation and inclination are also effective.

Available data show that the sag performance of fluids in a flow loop is closer to how drilling fluids perform in the field than results obtained by the VST method.<sup>4</sup> Nevertheless, to investigate the effect of rheology on dynamic sag, to the exclusion of all other effects, it was decided to perform the sag tests under conditions where rheological properties are the dominant factor, *i.e.* in a well-defined, or viscometric, shear field.

Two viscometric sag devices were used in this work. VST1 was a modified version of the original VST method developed by Jefferson.<sup>2</sup> It utilizes the heating cup of the Fann 35 rotational viscometer to apply shear at a fixed rate of 170.3 s<sup>-1</sup> (100 rpm). Dynamic sag was measured as the change in fluid density after 30 minutes. The modifications were similar to those described by Dye and Mullen,<sup>4</sup> who allowed the fluid in the heating cup to be circulated through a densimeter for continual density and temperature measurements. The test temperature in the VST device was 122°F.

A drawback of the VST device is that it has two distinct fluid volumes experiencing different shear rates.<sup>4</sup> A high-shear volume of about 0.61 in<sup>3</sup> (10 cm<sup>3</sup>) between the rotating sleeve and bob where the fluid is sheared at 170.3 s<sup>-1</sup>, and a low-shear volume of 7.14 in<sup>3</sup> (117 cm<sup>3</sup>) between the sleeve and the heating cup where the fluid

is sheared at about  $39 \text{ s}^{-1}$ . This duality in shear fields makes it difficult to determine which is the main contributor to the measured sag. The uncertainty increases to some extent in the modified version of the VST as the design introduces additional volume and different shear fields in the densimeter, the pump and the connecting tubing.

The second device (VST2) is another modification of the conventional VST, which eliminates the uncertainty in shear rate of the conventional VST in the region between the rotating sleeve and the heating cup. The sheared fluid consists solely of the volume between a rotating inner cylinder and a stationary cup. The bottoms of the inner cylinder and the cup are conical and form a funnel-shaped gap of the same width as the vertical cylindrical gap. The sample of the fluid is removed for density measurement from a port drilled into the tip of the conical base. Dynamic sag was measured after the fluid had been subjected to a shear rate of about  $12 \text{ s}^{-1}$  for 30 minutes. This device was used at ambient temperature close to  $68^\circ\text{F}$ , because the fluid cannot be heated in this device. In the remainder of this paper the two sag test methods are referred to as VST1 and VST2.

## RHEOLOGY

Steady shear measurements – Fig. 2 shows the Fann 35 rheology profiles of the fluids at  $122^\circ\text{F}$ . It is evident that although the 3-rpm data are relatively close, the fluids have markedly different stress values at higher rotational speeds. This is particularly true for polymeric additives P5/1 and P5/2 which were styrene-butadiene block copolymers. These materials produced much higher plastic viscosity values than other additives, as shown in Fig. 3.

The test fluids showed varying degrees of time dependency in the steady shear measurements on the Bohlin rheometer. The time dependence was more pronounced at lower stress values, indicating the existence of some structure in the fluids. A waiting time of 2 minutes per point was found to be adequate for producing an equilibrium flow curve.

The viscosity profiles of some of the fluids, obtained by the controlled stress measurements, are shown in Fig. 4. It is interesting to note that although the fluids were formulated to a relatively narrow 3-rpm Fann reading (equivalent to a shear rate of  $5.1 \text{ s}^{-1}$ ), their low-shear-rate viscosities showed wide variations.

The more common types of organoclays, *i.e.* modified bentonite and hectorite, produced similar rheology under steady shear flow conditions. An example of this is given in Fig. 5 for fluid OB2. In the range of shear rates considered, the fluid showed evidence of two Newtonian regimes, at very low and at high shear rates. These regimes were followed, or preceded, by two shear-thinning regions which in turn were connected by a quasi-Newtonian region at intermediate shear rates. For fluid OB2 the first

Newtonian regime occurred at shear rates below  $0.0005 \text{ s}^{-1}$ , while the second regime emerged above  $100 \text{ s}^{-1}$ . In the intermediate region the fluid exhibited evidence of several structural changes. For most of these fluids the quasi-Newtonian region occurred in the  $0.01\text{--}1 \text{ s}^{-1}$  shear-rate range. It is generally believed that both the clay particles and the emulsion droplets are involved in the gelling mechanism in invert drilling fluids. The existence of the quasi-Newtonian region is thus likely to be due to a strong interaction between the organoclay particles and emulsion droplets. As such, it depends on the type and extent of organic treatment of the clay, as observed in this study. These observations are in agreement with previous observations, including those reported by Herzhaft.<sup>5</sup>

Fig. 5 also shows the flow curve for fluid OA2 containing an organoattapulgit. With these needle-shaped particles, the particle-emulsion droplet interactions are weaker than with organophilic smectites and, as a result, a higher concentration of clay is required. The weaker interaction results in a smoother transition between the two Newtonian regimes. A distinctly different behaviour is shown by fluid P5/2 containing a block copolymer as the rheology additive. The complete absence of the quasi-Newtonian region is indicative of little or no interaction with emulsion droplets. Fig. 5 illustrates clearly that, when used as the sole rheology additive, the block copolymer produced poor low-end rheology and excessive high shear viscosity.

All fluids exhibited a degree of thermal-thinning at higher temperatures. Fig. 6 shows the rheology of the above fluids at  $122^\circ\text{F}$ . The flow curves are shifted to the right but their overall shape remains unchanged. This suggests that the behaviour of the additives and the nature of any particle-droplet interaction were not affected by temperature change in the  $68\text{--}122^\circ\text{F}$  ( $20\text{--}50^\circ\text{C}$ ) range.

Viscoelastic measurements – These measurements are used to characterize the structural properties of fluids. The measurements involve application of a small, oscillatory deformation (or strain) of frequency  $f$  to the fluid, and measurement of the in-phase and out-of-phase components of the stress. The component of stress that is in phase with the strain gives the elastic (or storage) modulus  $G'$ , while the out-of-phase component of stress gives the viscous (or loss) modulus  $G''$ . For purely Newtonian fluids, the stress is completely (*i.e.*  $90^\circ$ ) out of phase with the applied strain and  $G''=0$ , while for fully elastic materials, such as rubber,  $G''=0$ . Viscoelastic fluids have non-zero  $G'$  and  $G''$ . For these, the relative value of the moduli becomes important and gives a measure of the viscoelastic properties of the fluid. The ratio  $G''/G'$  is equal to the tangent of the phase angle  $\delta$  between the stress and strain (*i.e.*  $\tan \delta = G''/G'$ ). Since the viscoelastic properties of fluids are frequency

dependent, the moduli are measured by performing a frequency sweep. Several pieces of information can be extracted from the frequency sweeps. The absolute values of  $G'$  and  $G''$  and the ratio  $G''/G'$  provide information on the viscous and elastic properties of the fluid, and determine if the fluid behaves like a viscous liquid or a viscoelastic material at different frequencies. The frequency at the crossover point, *i.e.* the point at which  $G'=G''$ , is an indication of the relaxation time of the fluid. At frequencies below the crossover, where  $G'' > G'$ , the fluid behaves as a viscous liquid, whereas above its crossover point it has viscoelastic characteristics. Finally, the combined effect of the viscous and elastic moduli is reflected in the complex viscosity  $V^*$  defined as:

$$V^* = \frac{(G'^2 + G''^2)^{1/2}}{2\pi f} \quad (6)$$

Viscoelastic measurements are commonly performed at small deformations, *i.e.* a region of strain where the relationship between stress and strain is linear. Thus, prior to any frequency sweep, the linear viscoelastic region of the fluid has to be established. This is achieved by performing a strain sweep at a suitable frequency, often 1 Hz, and measuring the moduli. Then, a strain within the region where  $G'$  and  $G''$  are non-changing is chosen for the subsequent frequency sweep. Fig. 7 illustrates typical strain sweeps obtained for the clay-based and polymer-based fluids of these tests. Both types of fluid produced a linear response below 1% strain.

Examples of the viscoelastic responses of the test fluids are given in Figs. 8 and 9. The response of an organophilic hectorite (OH1) is compared with that of attapulgite (OA2) in Fig.8. The attapulgite fluid has slightly higher  $G'$  and  $G''$ , but its  $\tan \delta$  is also higher at different frequencies. Furthermore, the crossover frequency of OA2 is higher than OH1, giving it a shorter characteristic relaxation time. Overall, the attapulgite fluid has more dominant viscous properties than the hectorite fluid OH1. Fig. 9 presents a similar comparison between organophilic bentonite fluid OB14 and fluid P5/1 containing a block copolymer. Fluid OB14 has a higher crossover frequency than the polymeric fluid and higher  $\tan \delta$  below 5 Hz, making it less viscoelastic than the polymeric fluid at lower frequencies. However, at frequencies above the crossover, its  $G'$  rises rapidly to impart greater viscoelasticity to the fluid.

An example of the effect of temperature on the viscoelastic response of invert fluids is given in Fig. 10. Comparison of data for fluid OB14 at 68°F and 122°F shows that the crossover frequency increases with increasing temperature, while the elastic modulus  $G'$  decreases. Both of these indicate that the fluid became less viscoelastic as temperature increased.

## SAG MEASUREMENTS

A summary of the dynamic sag measurements is shown in Fig. 11. The sag values measured by the two methods are different. This is due to differences in temperature, shear rate and, in particular, the geometry of the sag test device. Further, the two methods do not show the same sag trend among the fluids. Since VST1 and VST2 measurements were at two different temperatures, this suggests that the fluids have different rheology-temperature relationships.

Both methods show a wide variation in the sag performance of the fluids. This is attributable to the significant differences in the LSR rheology of the fluid as evidenced by the viscosity profiles of Fig. 4. Fig. 11 shows that barite sag was higher in the polymer-based fluids, *i.e.* the fluids to the left of the chart. This reflects their poorer LSR rheology and suggests a lack of structure in these fluids.

Dynamic sag data obtained with VST1 at 122°F show strong trend with the 100 – 600-rpm Fann data. Fig. 12 shows such correlation for the 100-rpm reading, which is the rotational speed at which the VST1 sag test was conducted. The data suggest an inverse relationship between dynamic sag and shear stress at 100 rpm ( $170.3 \text{ s}^{-1}$ ). Fig. 13 shows the sag data of VST2 against shear stress at  $12 \text{ s}^{-1}$ , which is the shear rate of the VST2 tests. The shear stress data were obtained from the controlled stress measurements on the Bohlin rheometer at 68°F.

In general, for all the fluids investigated, dynamic sag correlates with fluid rheology at the prevailing shear rate. This is an interesting observation, albeit obvious, in that it explains why the sag performance of fluids in the field is often different from the results obtained in the laboratory.

Dynamic sag for all the fluids, including those containing polymeric additive, correlated well with viscosity at shear rates down to around  $10^{-2} \text{ s}^{-1}$ . Data for the organoclay-based fluids, measured with VST2 at 68°F, showed strong trend with viscosity at low shear rates down to  $10^{-4} \text{ s}^{-1}$ . Fig. 14 shows the correlation with viscosity at a shear rate of  $10^{-3} \text{ s}^{-1}$ .

Dynamic sag at 122°F, as measured by VST1, did not correlate well with low-shear-rate viscosity when plotted for all the fluids. For clay-based fluids good correlation was seen down to  $10^{-2} \text{ s}^{-1}$ , as shown in Fig. 15. Correlation of dynamic sag with rheology at very low shear rates may be suggestive of the existence of a structure in the clay-based fluids. The reverse seemed to be true for the polymer-based fluids.

Variations in the dynamic sag data showed trend with the crossover frequency, the storage modulus  $G'$ ,  $\tan \delta$  and complex viscosity  $V^*$ . The trends were considerably stronger when only the clay-based fluids were considered. Examples of such correlation are given in

Figs. 16 and 17. Fig. 16 illustrates the relationship between VST2 dynamic sag and elastic modulus in clay-based fluids at 1 Hz. Fig. 17 shows that the VST2 dynamic sag for the organoclay-based fluids correlates well with  $\tan \delta$  at 1 Hz. Both sets of data suggest that dynamic sag decreases as the elastic properties of the fluid increase. Correlation of dynamic sag with viscoelastic properties in organoclay-based fluids is an indication of the structure-dependence of barite sag. The lack of such correlation for polymer-based fluids suggests that such structure does not exist in these fluids.

A further example is given in Fig. 18 where the VST1 dynamic sag in clay-based fluids is plotted against the complex viscosity at 122°F and 1 Hz. Complex viscosity reflects the effects of both viscous and elastic components of stress and, as such, is the oscillatory equivalent of shear viscosity. It is perhaps for this reason that the strongest correlation obtained for all the fluids was with the complex viscosity at frequencies above the crossover frequency. Fig. 19 shows the VST2 sag data plotted against  $V^*$  at 68°F and a frequency of 5 Hz.

## Conclusions

The link between rheology and dynamic barite sag was investigated in a range of invert emulsion fluids formulated with different organoclays and polymeric additives:

- The organoclay-based fluids produced a multi-region rheogram that suggests the existence of a structure resulting from interaction of clay particles and emulsion droplets. This was not observed for the polymer-based fluids.
- For all the fluids investigated, dynamic sag correlated with fluid rheology at the prevailing shear rate. It also correlated with Fann data at higher speeds.
- For all the fluids considered, the correlation continued down to shear rates around  $10^{-2} \text{ s}^{-1}$ . The organoclay-based fluids showed good correlation down to  $10^{-4} \text{ s}^{-1}$ .
- Dynamic sag correlated with viscoelastic properties of the fluids. This was more pronounced for the clay-based fluids, suggesting the existence of a structure at very low shear rates.
- Although the fluids were formulated to a relatively narrow range of 3-rpm Fann reading, dynamic sag showed wide variations. This was clearly due to the wide differences in the low-shear-rate rheology and structural characteristics of the fluids.

- Dynamic sag was lower in the clay-based fluids tested than those formulated with polymeric additives.

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## Nomenclature

- OBM* = oil-based mud  
*SBM* = synthetic-based mud  
*lb/bbl* =  $lb_m$ /barrel  
*lb/gal* =  $lb_m$ /gallon  
*rpm* = revolutions per minute

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Table 1 – Invert Emulsion Formulation Used in the Tests	
Product	lb/bbl
Base fluid	167.30
Invert emulsifier	4.55
Wetting agent	4.55
Lime	7.70
Rheological additive	2.5 – 30
Brine	66.50
Barite	304.50

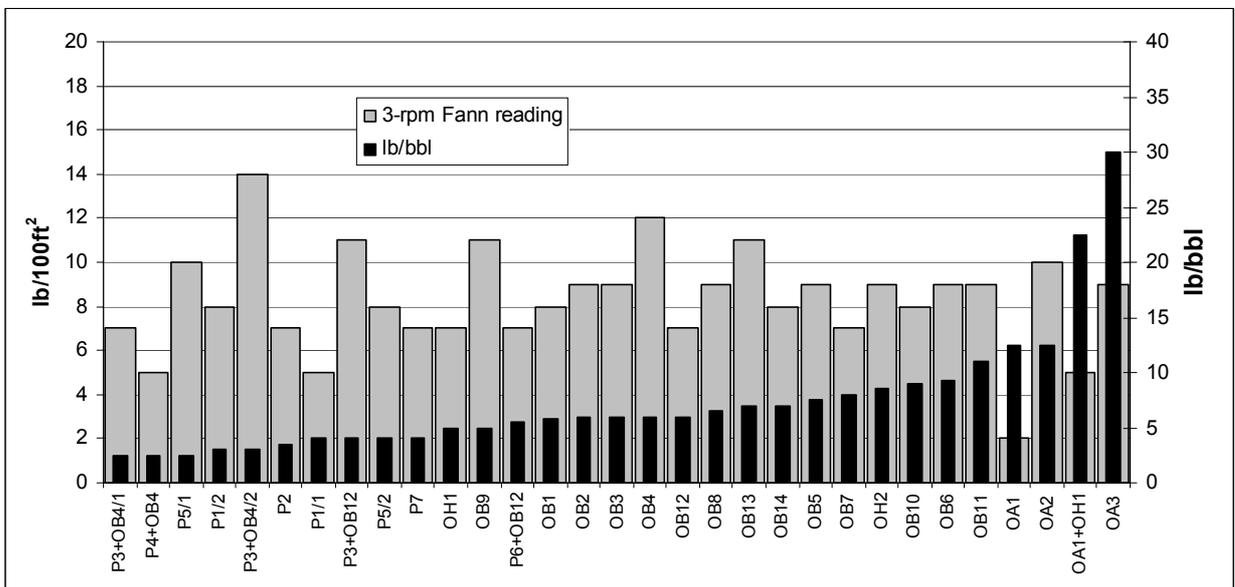


Fig. 1- The rheology additives and their concentration used in the test fluids.

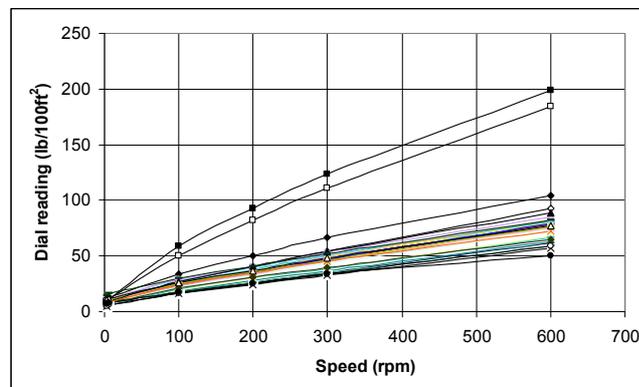


Fig. 2 – Fann 35 profiles of the test fluids at 122°F.

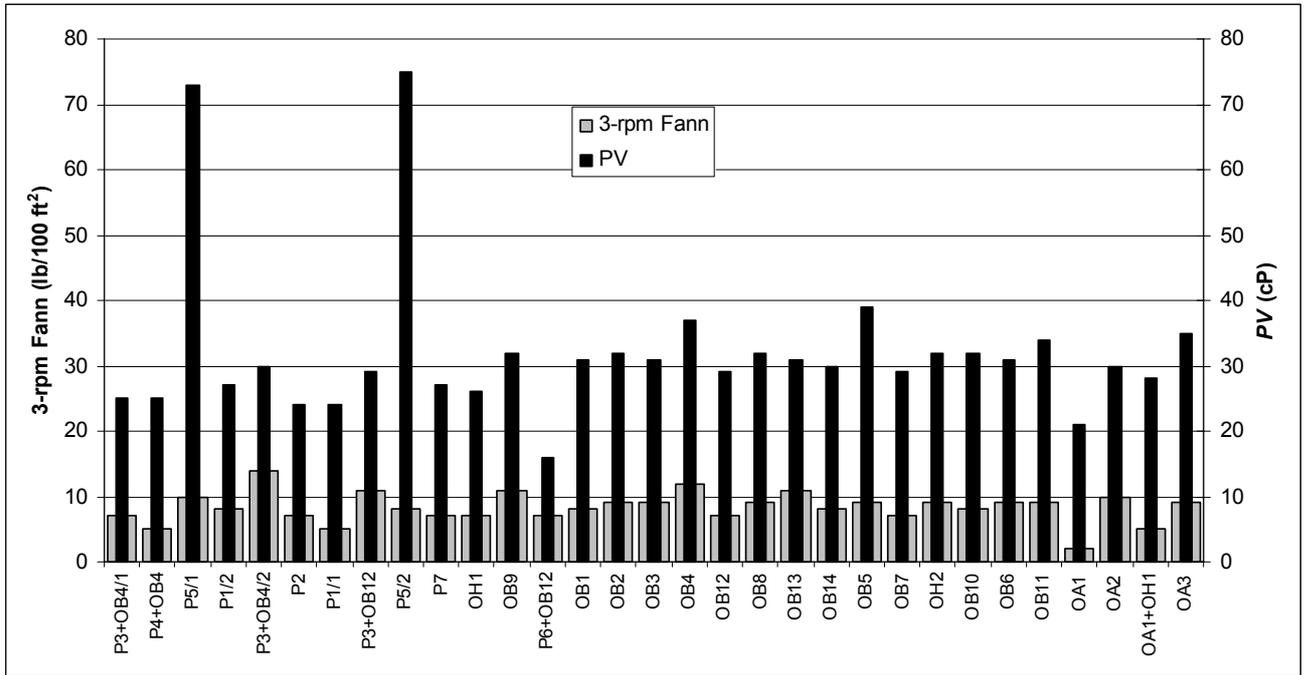


Fig. 3 – Comparison of 3-rpm Fann readings and PV values of the test fluids at 122°F.

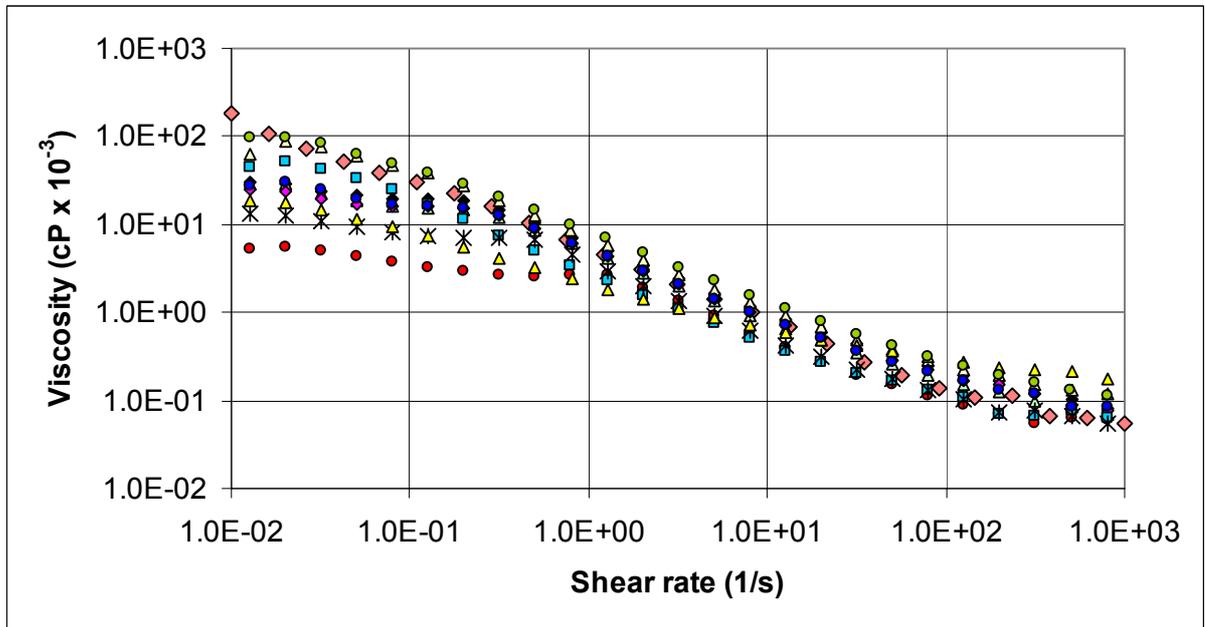


Fig. 4 – Viscosity profiles of some of the test fluids obtained by controlled stress measurements at 68°F.

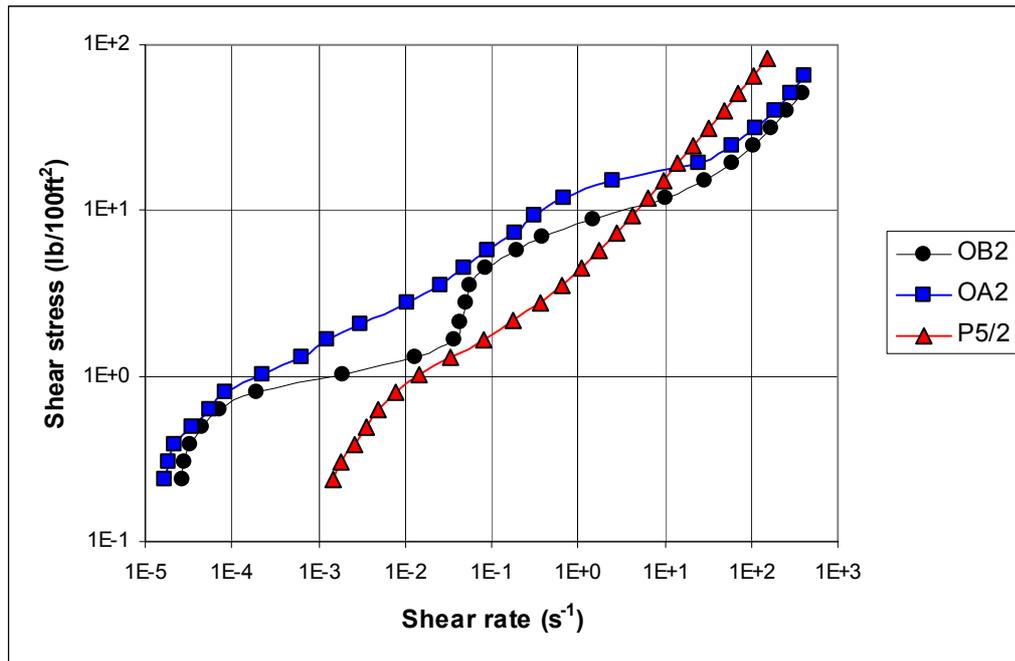


Fig. 5 – Equilibrium flow curves at 68°F for invert fluids containing different rheology additives.

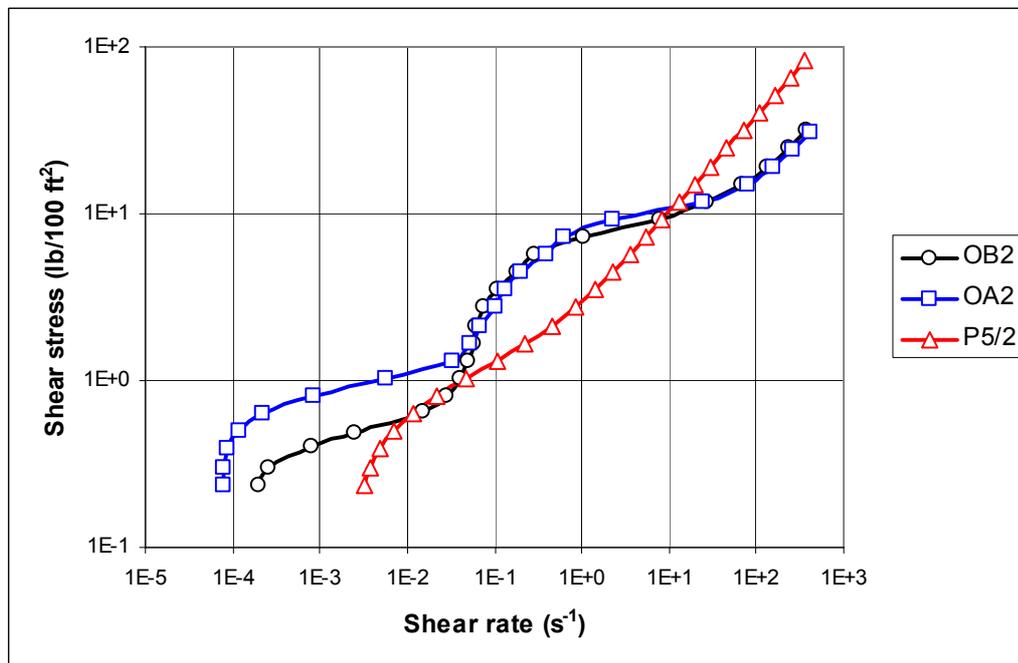


Fig. 6 – Equilibrium flow curves at 122°F for invert fluids containing different rheology additives.

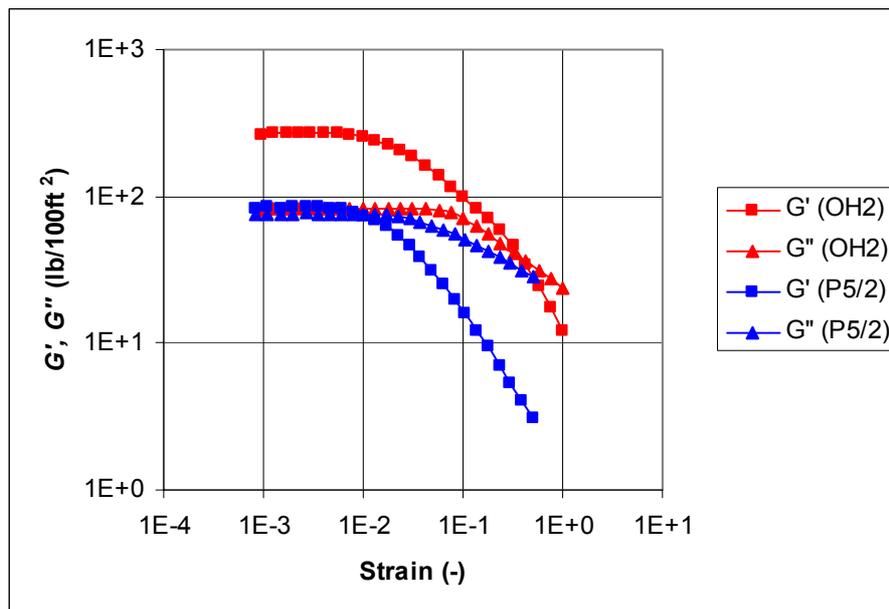


Fig. 7 – Examples of strain sweep for organoclay-based and polymer-based test fluids at 1 Hz and 68°F.

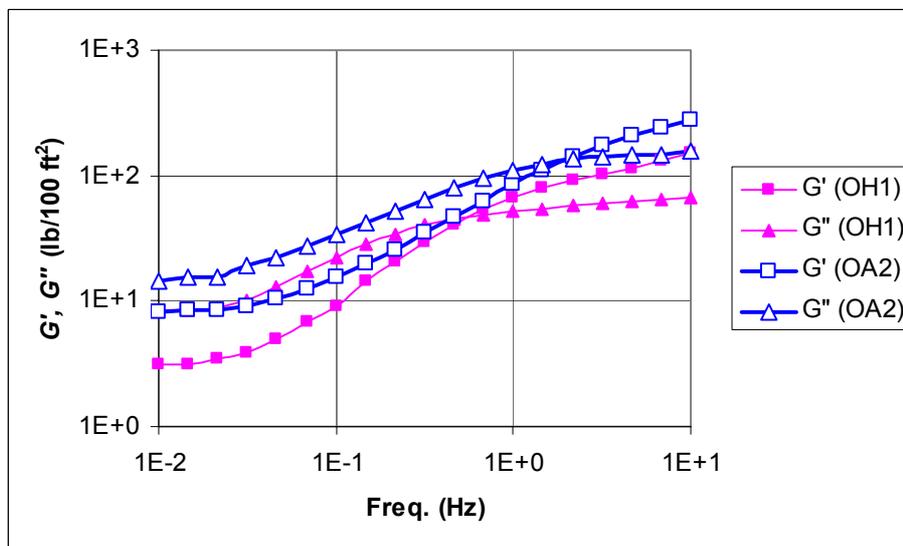


Fig. 8 – Comparison of viscoelastic responses of invert fluids containing organophilic clays; hectorite (OH1) and attapulgite (OA1) at 68°F.

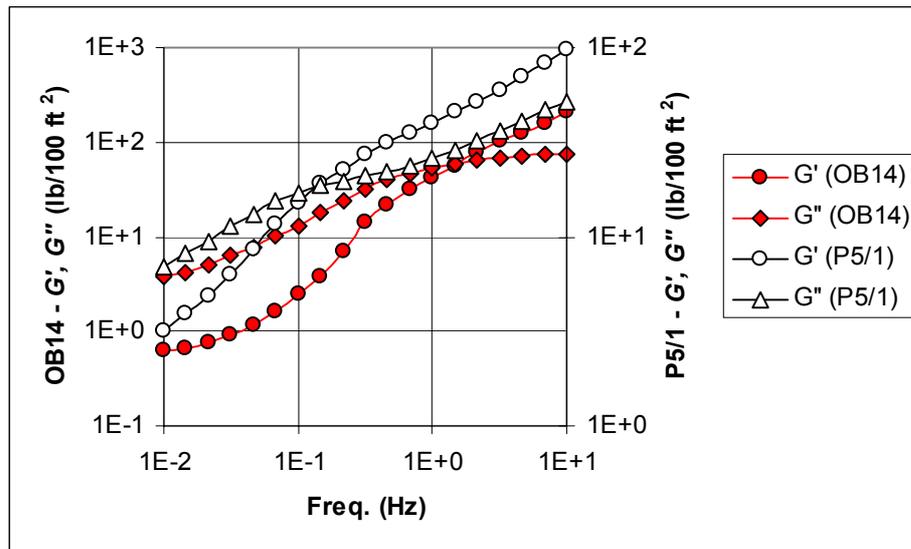


Fig. 9 – Comparison of viscoelastic responses of invert fluids containing organophilic bentonite (OB14) and a polymeric additive (P5/1) at 68°F.

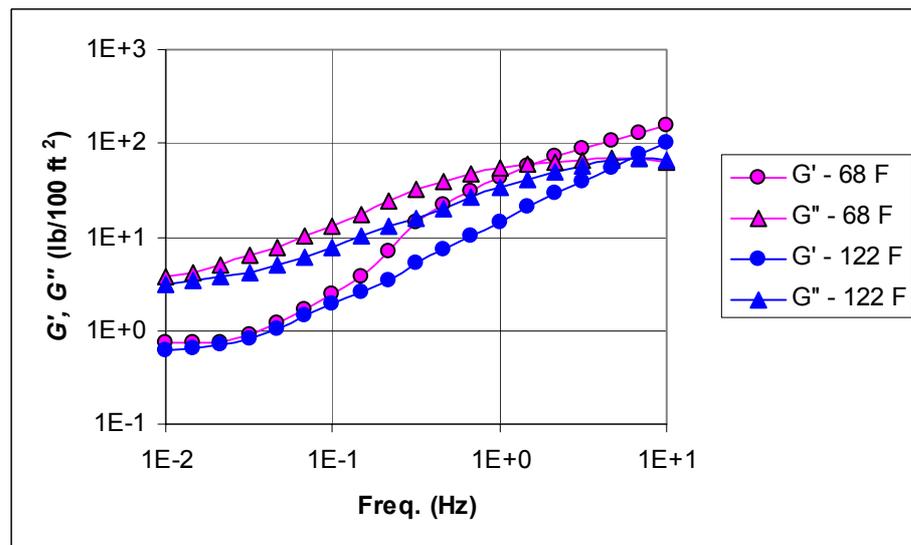


Fig. 10 – Effect of temperature on viscoelastic characteristics of invert fluid containing organophilic bentonite OB14.

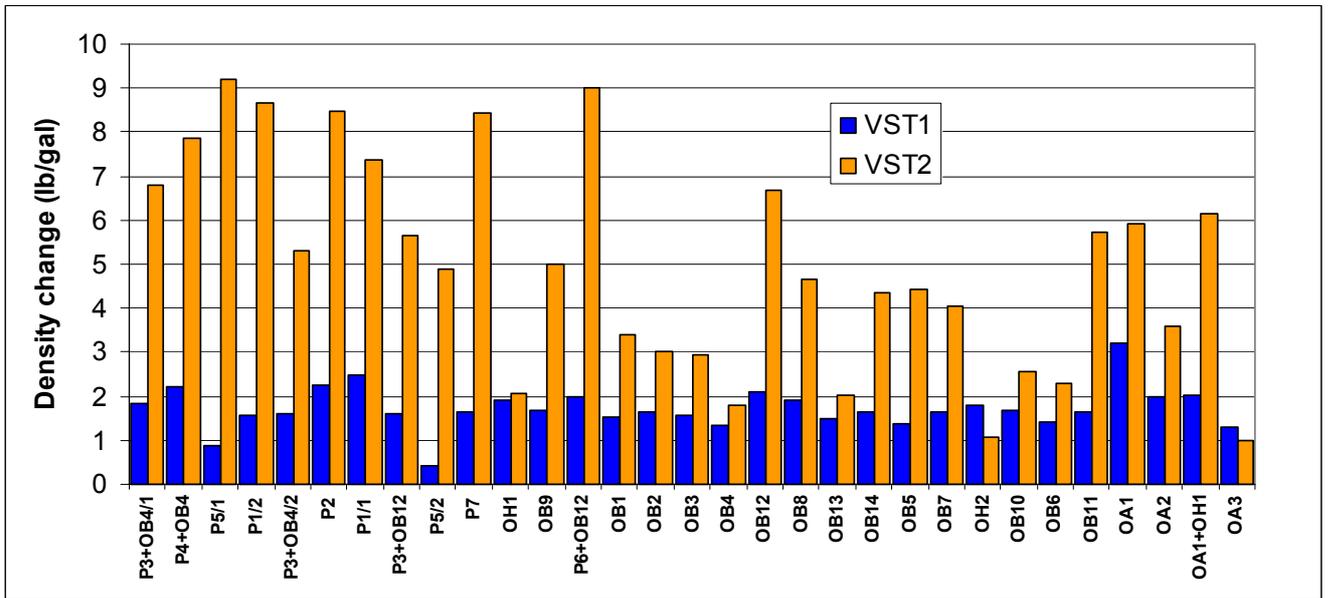


Fig. 11 – Dynamic sag measured by the two viscometer sag test devices at 68°F (VST2) and 122°F (VST1).

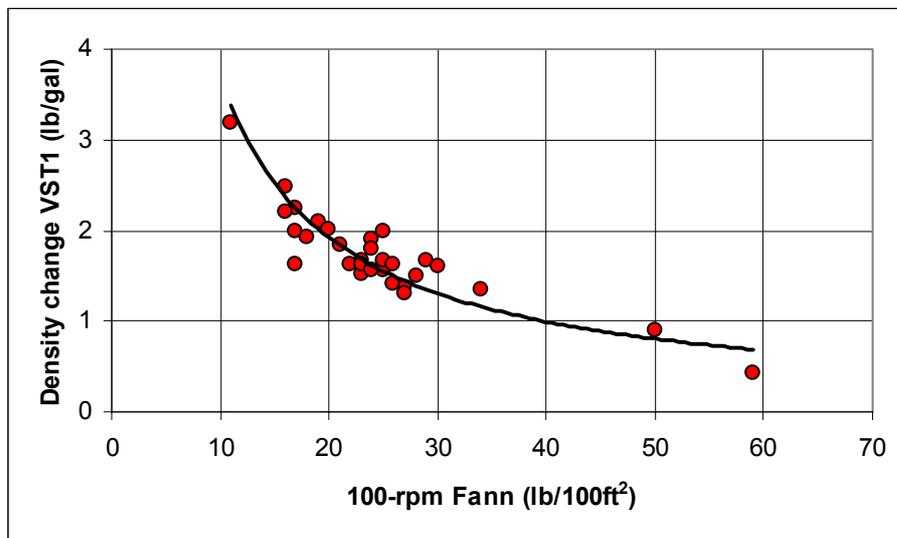


Fig. 12 – Dynamic sag measured by VST1 varies inversely with 100 rpm Fann data at 122°F.

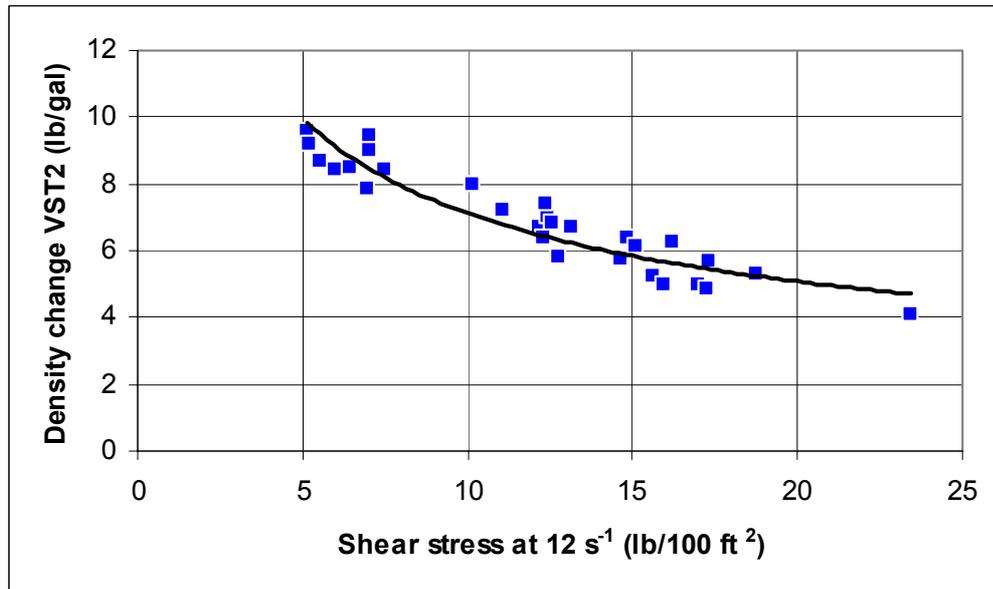


Fig. 13 – Dynamic sag measured by VST2 at 68°F vs. shear stress under conditions of the test.

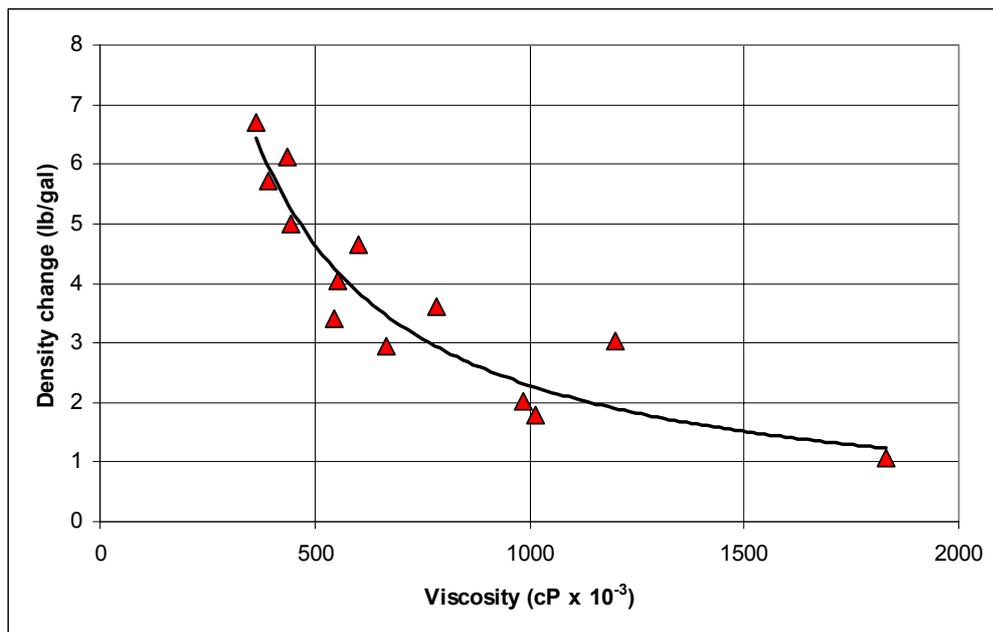


Fig. 14 – Dynamic sag in clay-based fluids vs. low-shear-rate viscosity at  $10^{-3} \text{ s}^{-1}$  (sag data measured by VST2 at 68°F).

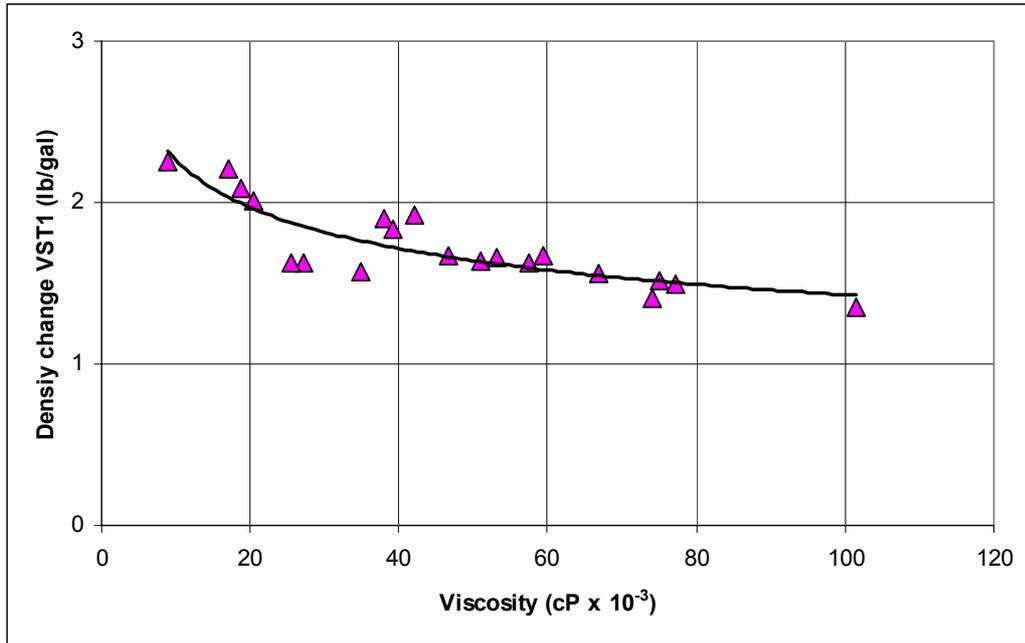


Fig. 15 – Dynamic sag vs. low-shear-rate viscosity at  $10^{-2} \text{ s}^{-1}$  (sag data measured by VST1 at 122°F).

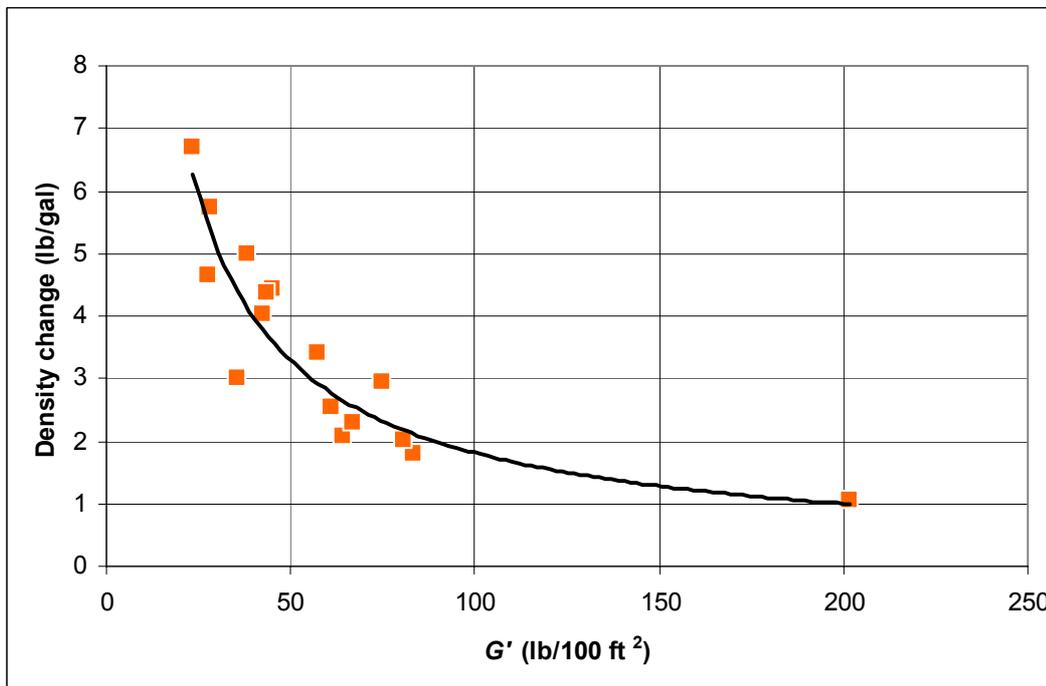


Fig. 16 – Dynamic sag for clay-based fluids vs.  $G'$  at 1 Hz (sag data measured by VST2 at 68°F).

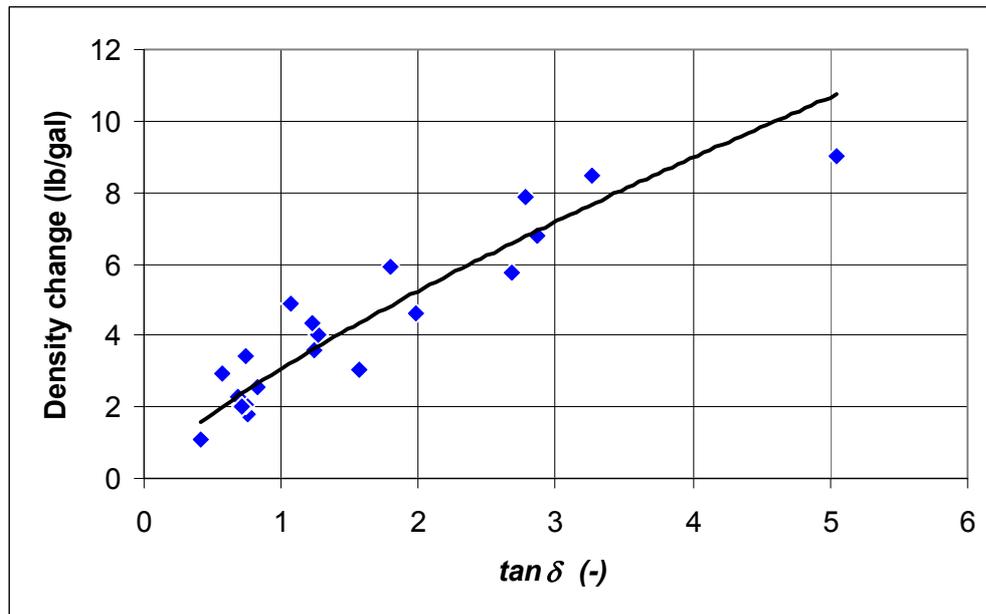


Fig. 17 – Dynamic sag for clay-based fluids vs.  $\tan \delta$  at 1 Hz (sag data measured by VST2 at 68°F).

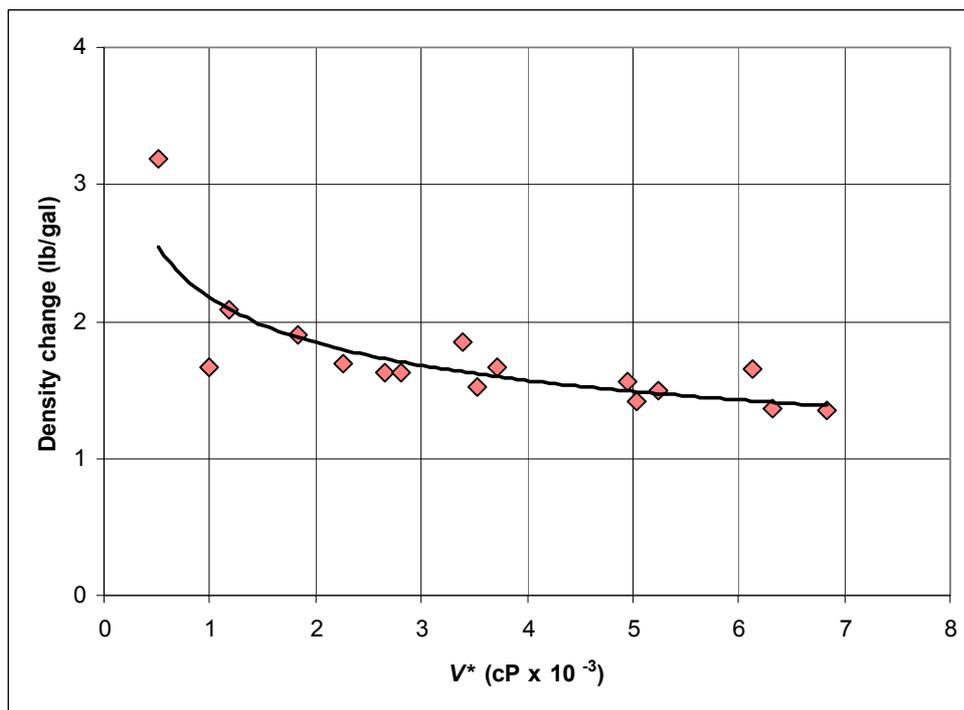


Fig. 18 – Dynamic sag for clay-based fluids vs. complex viscosity at 1 Hz (sag data measured by VST1 at 122°F).

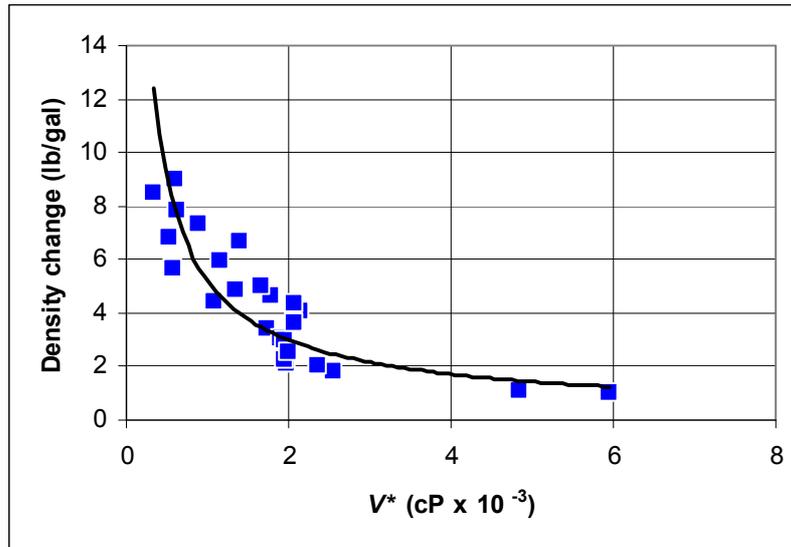


Fig. 19 – Dynamic sag vs. complex viscosity at 5 Hz (sag data measured by VST2 at 68°F).