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Barite Segregation in Inclined Boreholes

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Abstract

Settling and sagging of barite in inclined boreholes may lead to safety and operational problems. To study the effect of rheology on settling, a laboratory tool was designed, consisting of two connected tubes, one inclined and one vertical. The hydrostatic pressure was measured at the bottom of each pipe. Stable and unstable muds can clearly be differentiated through their pressure behaviour.

Several muds were studied at simulated static and dynamic conditions. The results show that sagging is most severe during laminar flow and also indicate that the rheological parameters may be used for predicting stability problems.

Introduction

In weighted drilling mud barite tends to segregate slowly. In directional drilling operations the settling process is accelerated. Barite settles in the lower side of the borehole and starts sliding when the borehole has an inclination above 30˚. This phenomenon is known as barite sagging. Sagging can lead to drilling and completion problems; a density variation or non-linear hydrostatic pressure gradients which can lead to pressure control problems, while thick and tight barite beds can lead to high torque and drag, stuck pipes and plugged boreholes, and even lost circulation.

The sag problem is related to the so called Boycott effect(1), first described in 1920. Hanson et al.(2) have investigated the phenomenon and found that most of the sagging occurs while the mud is circulating. The same conclusion was reached by Bern et al.,(3) the sagging tendency is highest at low annular velocities. Zamora and Jefferson(4) presented a method for tracking drilling fluid density variations, which helps to detect, but not to predict drilling mud instability. Jamison and Clements(5) developed a test method to characterise settling and sag tendencies in static drilling fluids, however their equipment was not able to distinguish between settling and sliding. They also found that their data, based upon standard API rheological parameters like PV and YP, were unsuitable for prediction of sagging behaviour. It is apparent from previous works that the most difficult part of the problem is the prediction of drilling mud instabilities for both static and flowing drilling fluids. To date there are no API test procedures for sag testing.

A new simple laboratory tool was therefore designed for the purpose to study and develop a method to predict sagging.

Drilling Mud Separation

Settling of Particles

In vertical wells the settling of weighting material is generally not a problem due to the long settling distance. In horizontal wells the distance to the lower side of the wall is only about 0.2 m, which leads to rapid generation of solids beds. The settling velocity of a single spherical particle, $v_{s,l}$, in a fluid is expressed by Stoke's law(6):

$$v_{s,l} = d_p^2\left(\rho_p - \rho_{fluid}\right)g/18\mu \qquad (1)$$

A barite particle (ρ_p = 4,200 kg/m^3) with a diameter (d_p) of 20 μm in a fluid of density (ρ_{fluid}) 1,500 kg/m^3 and a viscosity (μ) of 40 cP will settle at a rate of 53 mm/h. With an increase in particle concentration or volume fraction, c, the settling velocity at low concentration (c < 0.01) will decrease only due to the reduced cross-sectional flow area(7). At higher concentrations hydrodynamic interference will arise. Based on geometric considerations for dispersed particles in laminar flow, the slip velocity at higher concentration, $v_{s,c}$, can be expressed as(6):

$$v_{s,c}/v_{s,l} = 1/\left(1+1.5c^{1/3}\right) \qquad (2)$$

A concentration of 10 vol% barite (c = 0.1) in water results in a settling velocity $v_{s,c}$ = 0.59 $v_{s,l}$, i.e. the slip velocity is reduced by 41%. Agglomeration/clustering, collision, flow regime at particle/fluid interface, particle shape and size distribution will also affect settling velocity, but the above equations will give a fair estimate.

The problem of barite and cuttings settling have been investigated extensively during the last two decades and there are several empirical equations and approaches in use for calculating settling velocities in vertical wells. The correlations of Chien(8) and Walker and Mayers(9) still benefit from widespread acceptance.

A drilling fluid at rest will develop a gel structure with a certain mechanical strength. Equation (3) expresses equilibrium between gravitational forces acting on the volume of a particle, $4/3\pi r_p^3$, and gel strength τ_g which acts on the surface of a sphere, $4\pi r_p^2$;

$$4\pi r_p^2\tau_g = \left(\rho_p - \rho_{fluid}\right)g4/3\pi r_p^3 \qquad (3)$$

Expressed in terms of gel strength and particle diameter;

$$\tau_g = d_p\left(\rho_p - \rho_{fluid}\right)g/6 \qquad (4)$$

In a 1,500 kg/m^3 mud, the gel strength necessary to suspend a spherical barite particle with a diameter of 60 μm, and a rock cutting of 12.5 mm are according to Equation (4) equal to 0.26 Pa and 55 Pa respectively.

TABLE 1: Composition and control parameters of the field mud.

Additive	Amount kg/m³	Shear rate rpm	Shear stress Pa	Shear stress lb/100ft²
Antisol Fl 10	12	600	36.5	76.2
Xanvis	2	300	24.8	51.8
KCl	153	200	19.2	40.1
Barite	542	100	13.6	28.4
Cuttings	58	6	4.5	9.4
Fresh water	733	3	3.6	7.5
Mud	1,500	$3_{10''}$	3.6	7.5
		$3_{10'}$	4.8	10.0
		3_{2h}	5.5	11.5
		3_{3h}	5.7	11.9

At static conditions in vertical wells barite settling will therefore never or seldom occur. For inclined wells the settling process is more complex, as first described by Boycott. In static, inclined conditions, a gel will develop, but experience shows that separation occurs nevertheless, which indicates that the gel strength cannot be a good indicator for predicting sagging tendencies. Some operators and service companies(3) are basing evaluation of static sagging on the 3 and 6 rpm shear stress readings. The low shear rate yield point is defined by(3):

$$YP_{low} = 2\tau_3 - \tau_6 \qquad (5)$$

Since the relative error is large at such low shear stress readings, it was decided to apply the plastic viscosity and yield point in our investigations. Saasen et al.(10) also found that it was difficult to relate the 3 rpm Fann reading to prediction of static sagging. The 10 min. gel strength gave a closer fit. They found an even better fit by applying an oscillary viscometer (Carri-Med CSL 50) and the viscoelastic energy storage properties of the drilling fluid.

For flowing conditions the fluid is constantly being sheared, the gel is destroyed, and will therefore behave like a power law fluid without yield point. Under such conditions barite will settle at a slow but steady rate. The effective viscosity of the fluid is determined by the shear rate prevailing in the pipe. The shear rate is calculated from the well geometry and fluid flow rate, i.e. standard API methods. As an example, the field mud in Table 1 produces viscosities and settling rates [from Equations (1) and (2)] for a 60 μm barite particle as shown in Table 2. Assuming the shear rate corresponds to the 100 rpm reading it would take a barite particle one hour to settle a vertical distance of 0.14 m in slow laminar flow.

TABLE 2: Settling parameters for a 60 μm barite particle in a flowing field mud with 10% solids concentration.

Shear rate rpm	Eff. viscosity cP	Hindered settling rate m/h
600	36	0.32
300	49	0.23
200	56	0.20
100	80	0.14
6	440	0.026
3	700	0.016

It was shown by Bern et al.(3) that rotation of the drill pipe will counteract barite separation. When the particles are brought to the high side of the borehole through rotational flow they will settle towards the centre of the borehole, i.e., in the opposite direction of the transported particles.

Sliding of barite beds

The sliding of accumulated, submerged beds on the lower side of the borehole is initiated at a lower critical slip or slide angle than the corresponding slide angle of similar material beds in air. The onset of sliding is mainly influenced by:

1. Borehole inclination. Sliding occurs at angles from 30 – 60 degrees and is predominant at 40 – 50 degrees(4).
2. The nature of the drilling mud determines the wetting of the particle surfaces. This will influence the critical slide angle.
3. The size and shape of the weighing material will also influence the internal friction and the critical angle at which sliding is initiated.

A slick pipe at 45˚ inclination will therefore promote sagging.

Laboratory Studies of Sagging

Experimental Set-up

For instability evaluation of a drilling mud a Sag Tester was developed as shown in Figure 1. The Sag Tester consists of an 1.5 m long inclined pipe with ID = 45.2 mm, a collector pipe, two pressure transducers and a data acquisition system. The inclined pipe angle is 45˚, which is the worst case from a sagging point of view. At 0.5 m from the bottom of the inclined pipe a vertical collector pipe is attached (ID = 27.2 mm). The pressures at the bottom of each pipe were measured and denoted bottom and collector

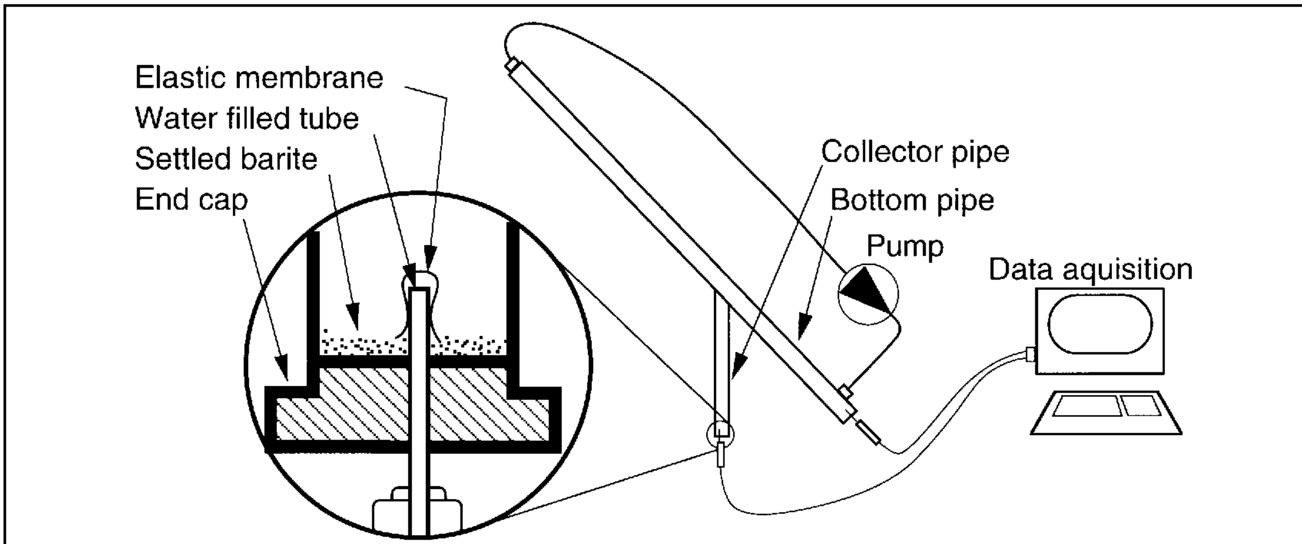

FIGURE 1: Experimental set-up of the Sag Tester.

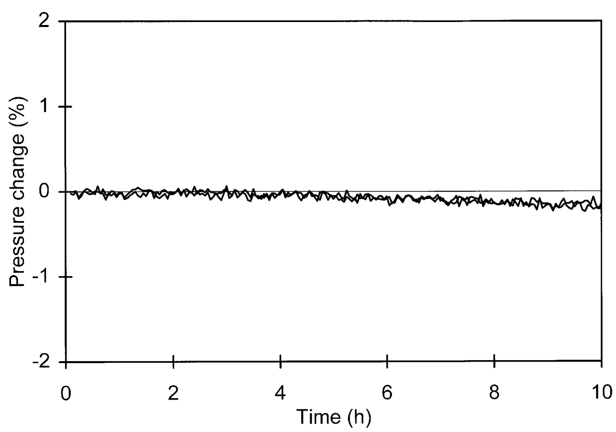

FIGURE 2: Pressure changes for a stable mud (mud A) under static test conditions. The pressures in both pipes are identical.

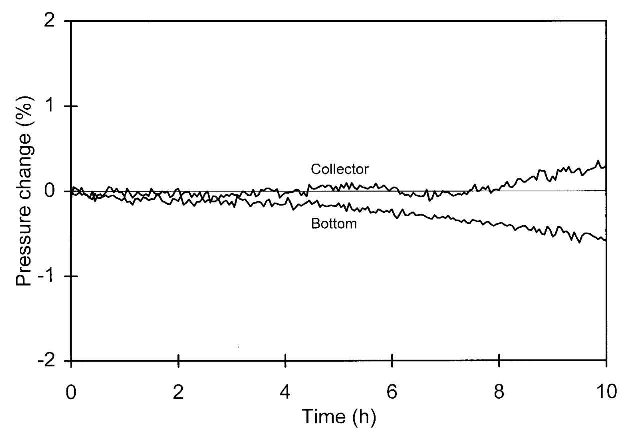

FIGURE 3: Pressure changes for a slightly less stable mud (mud B) under static test conditions.

pressures, respectively. The pressure range of the high precision transducers (Honeywell ST 3000) was 25 kPa with an accuracy of ± 0.1%. Filled with a 1,500 kg/m^3 mud the hydrostatic pressure was 15.5 kPa, meaning that the accuracy for the Sag Tester was approximately 0.2% when filled with this mud. Data measured from both sensors were taken at time intervals from one to 10 minutes, for periods up to 15 hours.

The experimental set-up is based on the idea that changes in the drilling mud density as a result of segregation will cause pressure changes in the mud column. If the mud is stable, the hydrostatic pressure will remain constant, and there will be little or no difference between the collector and the bottom pressures.

In the case of an unstable drilling mud, even though it had gel strength higher than the minimum to avoid settling, a barite bed will form on the lower side of the inclined pipe. This process will cause a reduction of the drilling mud density, and a corresponding reduction in bottom and collector pressures. The pressures measured at the bottom of the two pipes will decrease in a similar way and will be nearly equal for both. If the solid particles accumulated on the lower side start to slide, they will fall into the collector pipe due to gravity and stay in suspension for up to several hours because the settling distance is large. The increase of the weighing material concentration in the collector pipe will increase the mud density and thus the hydrostatic collector pressure. The pressure in the collector pipe will differ from that in the inclined pipe; it will decrease less than the bottom pressure or it will remain constant or even increase if the mud is very unstable. A difference between the collector and bottom pressures will indicate an unstable mud.

The stability behaviour in the sag tester will then be:

- Stable mud: collector and bottom pressures are almost constant and close to each other. Stable, static mud behaviour is plotted in Figure 2 and 3.
- Unstable mud: collector pressure is higher than bottom pressures and both are decreasing with time. Typical pressure behaviour of an unstable drilling mud under static conditions is shown in Figure 4.

As seen from the two plots the stable muds show no changes in the measured collector and bottom pressures, while the unstable drilling mud shows a pressure difference around 2% after three hours, and a collector pressure that is nearly constant.

As a quality control, the sag tester was initially calibrated with water which, as expected, showed constant pressures.

Laboratory Test Procedures

For most of the tests a commercial mud, supplied by Saga Petroleum was used. Its data are shown in Table 1. This mud was treated with water, prehydrated bentonite, Na_2CO_3 and barite in different portions to vary rheology and thus stability. Prior to tests the treated mud was aged for 24 hours. Static tests were run for up to 12 hours while the flow tests were run for 2 hours, which was

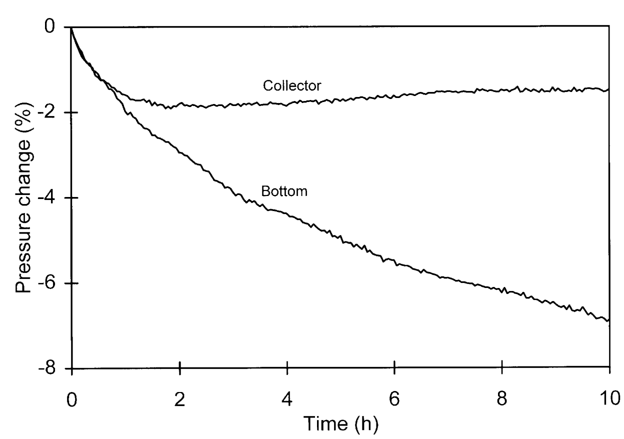

FIGURE 4: Pressure changes for an unstable mud (mud C) under static test conditions.

found to be sufficient to characterise the mud. The rheology and gel strength parameters were measured with a Fann rheometer[11], and the density with an API mud balance[11].

Four different tests were run; static, pressure pulsing, piston agitation and pumping of mud. In the static tests, the mud was poured into the sag tester and then left undisturbed. To simulate the effect of pressure surges which in the wellbore are caused by an accelerating and decelerating drill string, a pressure pulse of 0.1 MPa was applied to the top of the tester. Sharp pulses were applied every 2.5 min during the time frame from 1.5 to two hours. To simulate tripping operations and the effect of drill pipe, tool joints, stabiliser and bit movement along the wellbore, a metal rod with a piston (OD = 30 mm) in front was moved out and in of the inclined pipe every 2.5 min. starting 1.5 hours after mud was poured into the Sag Tester and lasting for 0.5 hour. The purpose of pulse testing was to investigate if barite sag would be accelerated by small disturbances in the mud. During the flow tests the mud was circulated from the bottom of the inclined pipe using a centrifugal pump at a constant flow rate giving a speed of about 0.15 m/sec. In all flow tests the Reynolds number ranged between 500 – 1,500.

Results

In all, more than 200 tests were carried out and the pressure plots presented here are typical behaviour of stable and unstable muds. All data from the experiments with the Sag Tester are plotted as per cent pressure change from the initial pressure versus

TABLE 3: Control data for the treated field fluids. Composition of the muds are similar to the field mud in Table 1; to mud A mainly barite is added, to mud C mainly water is added.

Fluid #	Characterisation at static conditions	Density kg/m^3	PV cP	YP lb/100ft^2	"$\tau_{3,10}$" lb/100ft^2	$\tau_{3,10'}$ lb/100ft^2
A	Stable	1,600	51	35	8.2	11.1
B	Semistable	1,500	29	16	2.0	2.7
C	Unstable	1,400	11	10	1.8	2.4

time. Fluid properties for the test results presented in the graphs are shown in Table 3.

Static Tests

Typical examples of static tests are those given in Figures 2, 3 and 4. Based on all tests, it was concluded that after three hours in the Sag Tester a stable mud should exhibit less than 0.2% pressure loss in the collector tube and less than about 0.7% in the bottom tube. Thus, muds A and B are stable while mud C is unstable. Although the 10 min. gel supposedly is high enough to carry the barite particles, the dynamic "Boycott" process causes sagging even at much higher levels of gel.

Flow Tests

The flow tests were performed to study sagging during circulation. Both the settling rate and sliding increased significantly compared to static conditions, and settling and sliding was observed in muds that were stable at static conditions. The same conclusion was reached by Hanson et al.(2) and Bern et al.(3) This is borne out in Figures 5 and 6. The reason behind the increased settling rate is that under circulation the drilling mud is continuously sheared and there is no time for gel development.

All flow test results are gathered and presented in Figures 7 and 8, where the pressure data are plotted as a function of the two rheological parameters PV and YP. Note that settling is decreasing with increasing rheological parameters, however, settling will never quite cease when drilling fluid is flowing in laminar flow regime.

Dynamic Tests

The muds were also tested under dynamic conditions. Neither pressure pulses, Figure 9, nor piston agitation, Figure 10, did influence the results significantly, only minor pressure changes were noted during the tests. Disturbances like the ones simulated were not sufficient to alter the stability of the muds in question. This is clearly seen in Figures 11 and 12.

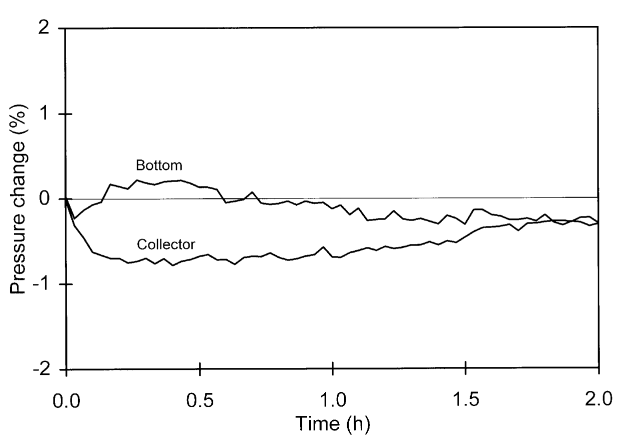

FIGURE 5: Pressure changes for laminar flow conditions of a stable mud (mud A).

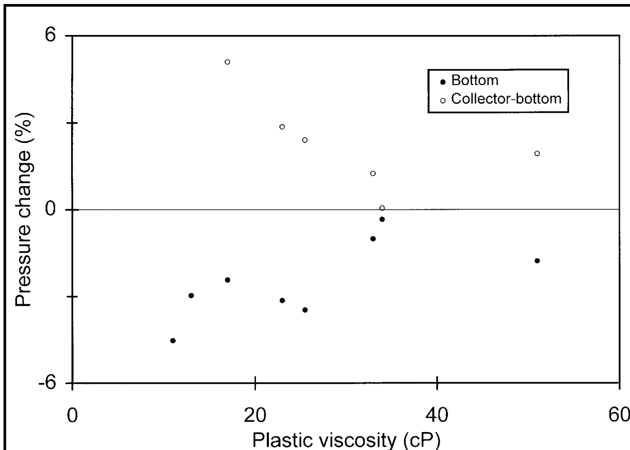

FIGURE 7: Pressure changes after two hours under laminar flow conditions as a function of plastic viscosity. "Collector-bottom" is the pressure difference between the collector and bottom pipes.

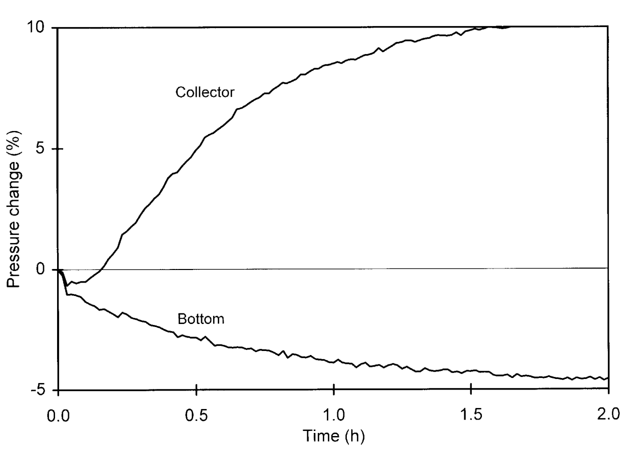

FIGURE 6: Pressure changes for laminar flow conditions of an unstable mud (mud C).

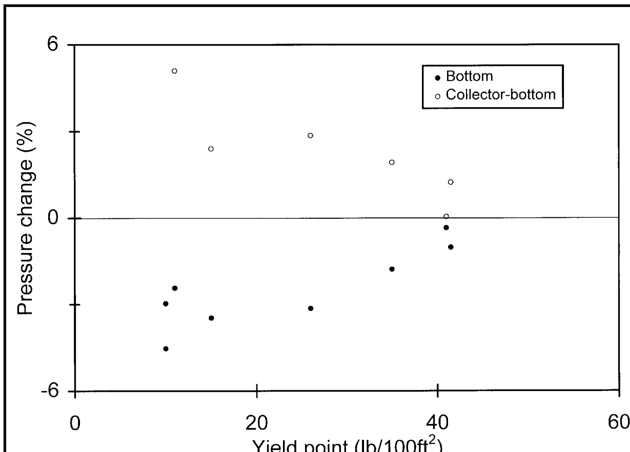

FIGURE 8: Pressure changes after two hours under laminar flow conditions as a function of yield point.

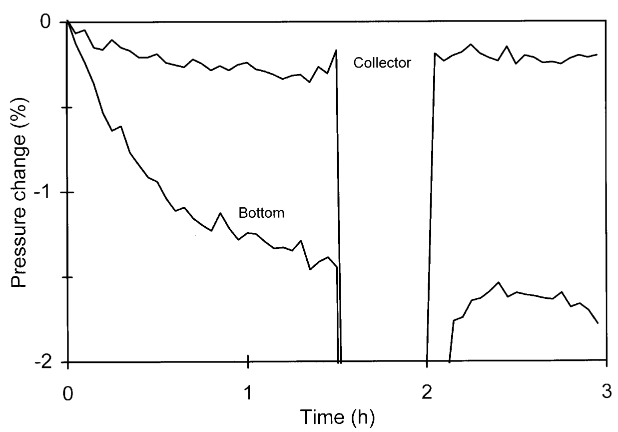

FIGURE 9: Pressure changes for an unstable mud (mud C) when a pressure pulse was applied every 2.5 min between 1.5 and two hours.

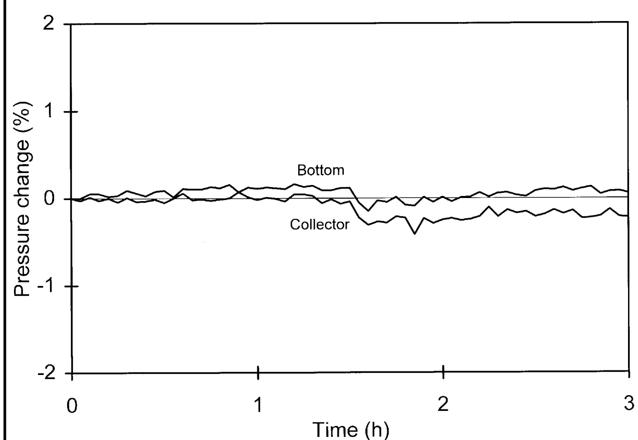

FIGURE 10: Pressure changes for a stable mud (mud A) when a piston was run up and down once every 2.5 min between 1.5 and two hours.

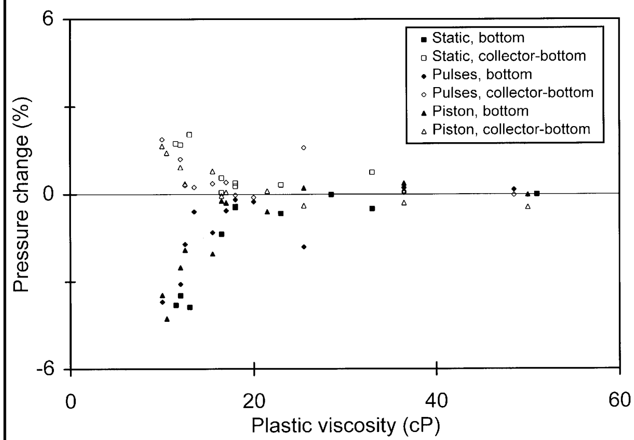

FIGURE 11: Pressure changes after three hours for the static, pressure pulses and piston tests as a function of plastic viscosity.

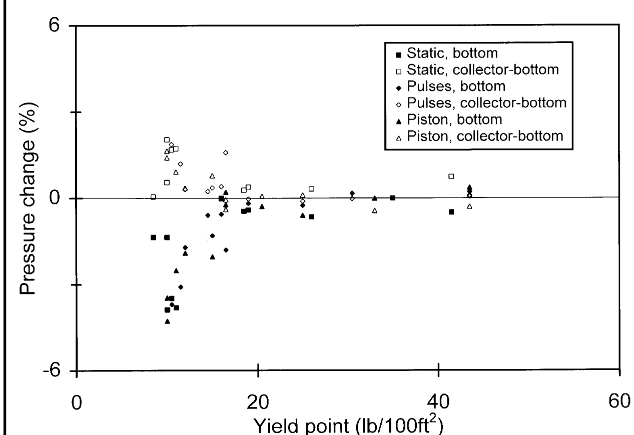

FIGURE 12: Pressure changes after three hours for the static, pressure pulses and piston tests as a function of yield point.

Discussion

All the static tests are plotted in Figure 11 and 12. By varying the rheology and keeping the density within 1,400 to 1,600 kg/m^3, it is seen that this particular field mud will exhibit static stability, i.e., no settling in inclined pipes when the plastic viscosity is higher than 20 cP and/or when the yield point is higher than 20 lb./100ft^2. The rheological parameters can thus be applied for predicting stability problems.

When flow and static tests are plotted together as in Figure 13, it is seen that settling and sliding will occur at higher YP and PV in flowing muds than muds at rest.

Conclusions

The following conclusions may be drawn from this work:

1. A laboratory apparatus was developed to investigate drilling mud instability leading to barite sag in inclined holes. It differentiates between settling and sliding and between static and flowing conditions, and can be applied to determine when sagging will be initiated at static conditions.
2. Settling in static and flowing fluids is different. In flowing fluids the settling process will be exacerbated during laminar flow conditions. Since the fluid has no gel strength when sheared it will behave like a power law fluid without yield point, and as such produce a high effective viscosity at low shear rates. At high viscosity, settling can be slowed down but never fully avoided. Common API rheological parameters are necessary and suitable to estimate rheology for particle settling.
3. It has been shown that pressure pulses and piston agitation, simulating tripping, did not significantly influence the process of barite sagging.
4. The 3 and 6 rpm Fann readings are unreliable because of the viscometer's high relative error at those low speeds. PV and

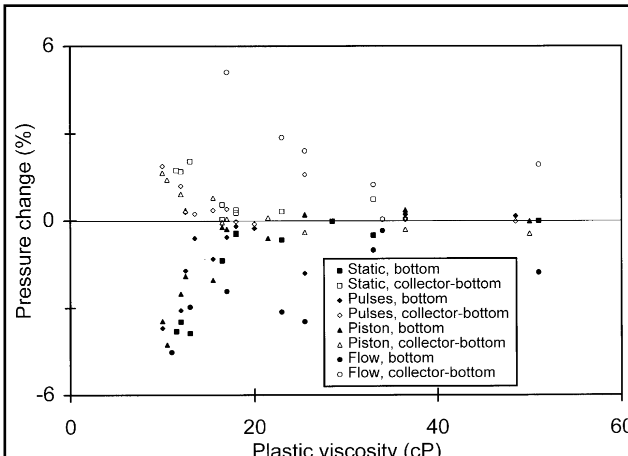

FIGURE 13: Pressure changes at two or three hours as a function of PV for all tests.

YP however, have in this study proven to give reproducible information on barite sagging.

5. A highly viscous fluid (PV and/or YP above 20) will slow down the settling rate but will at the same time cause high friction and suppress turbulence in the annulus. High friction is in conflict with ECD while suppressed turbulence will promote settling. A qualified suggestion of how to handle the sag problem is therefore:
   a. Avoid static settling by designing a mud with minimum necessary rheology; for this specific field mud a PV and/or YP of 20 is required.
   b. During laminar circulation hindered settling is a very slow process. Segregating particles in the annulus can be redistributed through creating short lasting (seconds) turbulent flow at regular intervals. Intermittent turbulent flow in the annulus will homogenise the suspension and thus counteract the segregation effect. The necessary interval must be determined through laboratory or field tests.

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NOMENCLATURE

c	=	particle volume concentration, fraction
d_p	=	particle diameter, m
g	=	gravitational acceleration, m/s^2
PV	=	plastic viscosity, Pa•s (cP)
r_p	=	particle radius, m
$v_{s,l}$	=	particle settling velocity, m/s
$v_{s,c}$	=	particle slip velocity, m/s
YP	=	yield point, Pa (lb/100ft^2)
YP_{low}	=	low shear rate yield point, Pa (lb/100ft^2)
ρ_{fluid}	=	fluid density, kg/m^3
ρ_p	=	particle density, kg/m^3
τ	=	shear stress, Pa (lb/100ft^2)
τ_3	=	Fann reading at 3 rpm, Pa (lb/100ft^2)
τ_6	=	Fann reading at 6 rpm, Pa (lb/100ft^2)
τ_g	=	gel necessary to suspend particle, Pa (lb/100ft^2)
μ	=	viscosity, Pa•s (cP)

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Metric Conversion Factors

cp	× 1.0*	E–03 = Pa•s
ft	× 0.3048*	= m
lb	× 4.535 924	E–01 = kg
lb/100ft^2	× 4.788 026	E–01 = Pa

*Conversion factor is exact.

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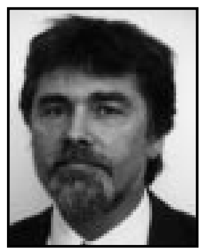

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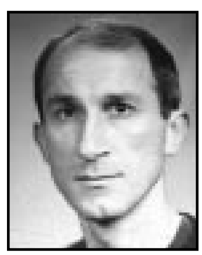

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