

# Behaviour of Suspensions and Emulsion in Drilling Fluids

Nordic Rheology Society

14-15 June 2007

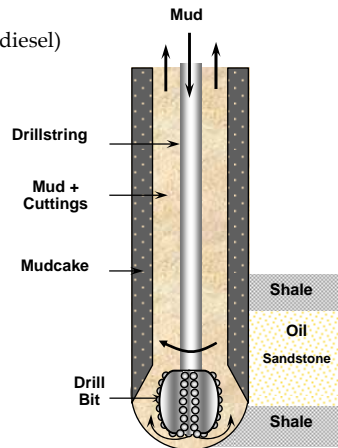
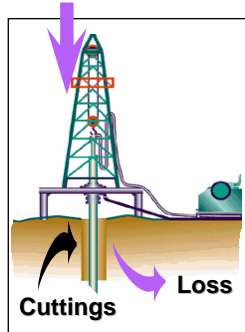


## Overview

- Introduction to drilling fluids
- Role of fluid rheology in the drilling operation
- Drilling fluid rheology; measurement & control
- Effect of rheology on hole cleaning
- Effect of rheology on barite sag
- Concluding remarks

## Drilling Operation & Drilling Fluid

- A drilling fluid (mud) is a fluid containing one or more of the following, such that the objectives of the well or section to be drilled are achieved:
  - Aqueous phase (water, brine)
  - Non-aqueous phase (mineral oil, synthetic, diesel)
  - Solids (barite, clay, carbonate)
  - Gas (air, nitrogen)



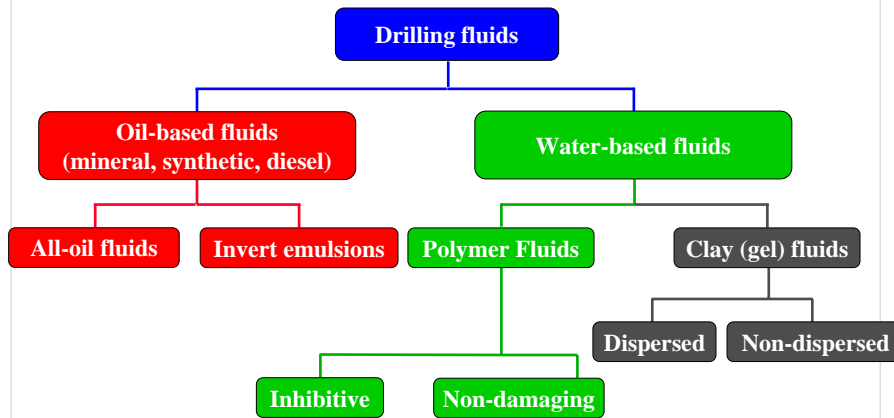
## Functions of Drilling Fluids

Drilling fluids **MUST** be able to provide the following functions:

- Cooling & lubrication
- Cuttings suspension & removal (hole cleaning)
- Weight material (barite) suspension
- Balance formation pressure
- Maintain wellbore stability
- Minimise damage to formation
- Transmit hydraulic energy to tools & bit
- Control corrosion
- Allow formation evaluation
- Facilitate cementing & completion
- Minimise impact on environment

Typical OBM Formulation	
Product	Kg/m <sup>3</sup>
Base oil	478
Invert emulsifier	13
Wetting agent	13
Lime	22
Rheology additive	10 – 40
Fluid loss control additive	8.5
Brine	190
Barite	870

## Drilling Mud Classification



## Some Measured Mud Properties

- Drilling fluids are complex multi-phase, multi-component systems whose properties undergo continuous change during the drilling operation
- Change is caused by liquid lost to formation, addition of drill cuttings, chemical reactions, and temperature and pressure variations
- To maintain their ability to perform, their properties must be monitored throughout the drilling operation so that corrective actions can be taken.
- The properties routinely measured are:
  - Rheology
  - Fluid loss
  - Oil/water ratio and emulsion stability for OBM
  - pH (WBM)
  - Density – lb/gal (ppg) or s.g.
  - High gravity & low gravity solids contents (HGS / LGS)
  - Salt content - usually as chlorides (WBM & OBM)
  - Inhibitor concentrations - K+, PHPA, glycol etc (WBM)

## Rheology & Its Impact on Drilling Operation

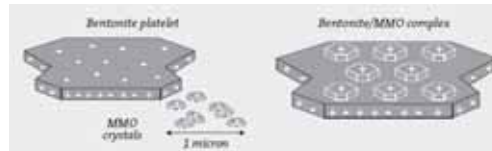
- Pressure drop
- Hole cleaning (during flow)
- Cuttings suspension (during trips)
- Weight material suspension (barite sag)
- Hole stability
- Stuck pipe
- Swab & surge pressures
- Signal transmission (logging & measurement while drilling, well testing)
- Waste management

## Rheology Additives for Drilling Fluids

- Clay-based WBM
  - Bentonite (platey)
  - MMO/MMH
  - Occasionally sepiolite or attapulgite (fibres)
- Polymer-based WBM
  - Xanthan gum
  - Celluloses
  - Occasionally guar gum, welan gum or polyacrylamide
- Invert emulsion fluids
  - Organophilic clay
  - Synthetic polymers
  - Aqueous emulsion

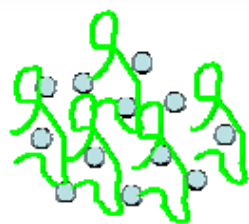
## Clay-Viscosified Water-Based Fluids

- Bentonite clay: negative surface charge and positive edge charge of platelets produces highly shear-thinning house-of-cards structure.

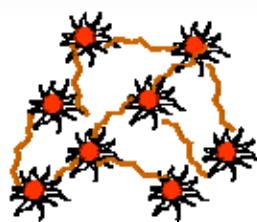


- Mixed-metal oxide (MMO) has an electron-deficient lattice and, when added to water, the particles bond to the cation-exchange sites on bentonite, forming a strong complex, which in turn structures the fluid and provides gels and shear-thinning behaviour.

## Polymer-Viscosified Water-Based Muds



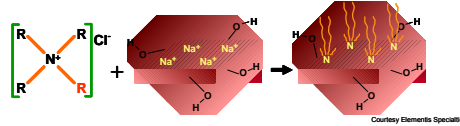
- In conventional polymer muds, high MW polymers in aqueous solution generate rheology capable of suspending dispersed solids.



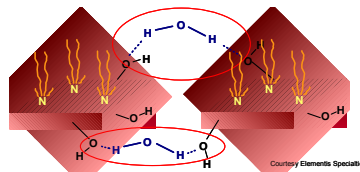
- In a novel high-temperature polymer mud, medium MW polymers adsorb on dispersed solids and interact with dissolved polymers to produce highly shear-thinning rheology.

## Organoclay in Oil-Based Muds

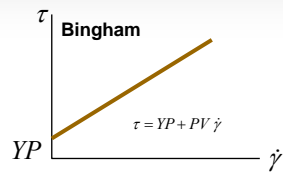
- Organoclays are hydrophobically modified clays such as bentonite, hectorite, etc.



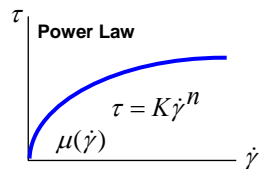
- In an invert emulsion fluid, hydrogen bonding between water molecules and OH<sup>-</sup> groups of organoclay produces a weak network to enhance rheology in OBM.



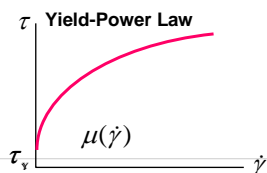
## Rheology Models Used for Drilling Fluids



$$\tau = YP + PV \dot{\gamma}$$



$$\tau = k \dot{\gamma}^n$$



$$\tau = \tau_y + k' \dot{\gamma}^{n'} \quad (\text{Herschel-Bulkley})$$

$$\tau^{1/2} = k_0 + k_1 \dot{\gamma}^{1/2} \quad (\text{Casson})$$

## Rheology Measurement in Drilling Fluids

### Rig-site measurements

- Marsh Funnel
  - Funnel viscosity (seconds/quart)
- Fann-type viscometer
  - Fixed rotational speeds
  - Shear rate range  $5.11 - 1022 \text{ s}^{-1}$
  - Used to derive Bingham model parameters
    - Yield Point (*YP*)
    - High-shear-rate (HSR) viscosity, Plastic Viscosity (*PV*)
  - Some measure of thixotropy (10-sec & 10-min gel strength)
- Low-shear viscometer



Marsh Funnel

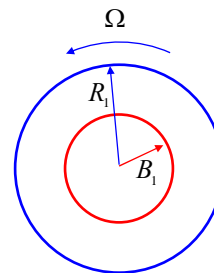
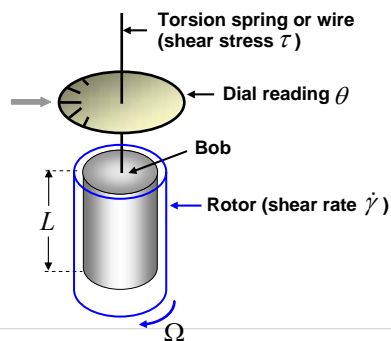
### Laboratory measurements

- Controlled rate and/or stress rheometers for in-depth study and characterisation of fluids

13

## Rheology Measurement in Drilling Fluids: Fann-35 Viscometer

- Concentric cylinder (Couette)
- Outer cylinder rotates (rotor or sleeve)
- Inner cylinder measures torque (bob)



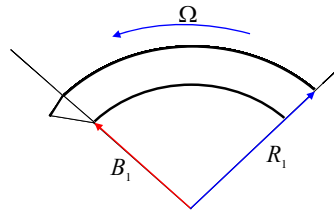
$R_1 = 1.8415 \text{ cm}$   
 $B_1 = 1.7245 \text{ cm}$   
 $L = 3.800 \text{ cm}$

## Measurement of Rheology: Fann 35

- For a curvilinear shear field, the shear rate at inner cylinder is given by:

$$\dot{\gamma} = \frac{2R_1^2}{R_1^2 - B_1^2} \Omega$$

$$\dot{\gamma} = 1.703 N$$



- Shear stress is given by the deflection ( $\theta$ ) of the torsion spring which measures torque:

$$\tau = 5.11 \theta \text{ dyne/cm}^2 = 0.511 \theta \text{ Pa}$$

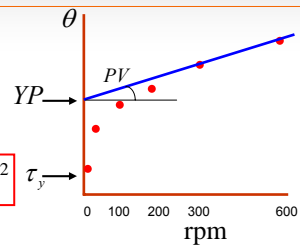
$$\tau = \theta \text{ lb}_f / 100 \text{ ft}^2$$

## Oilfield Definitions for Rheology: Fann 35

- For a Bingham fluid ( $\tau = YP + PV \cdot \dot{\gamma}$ )

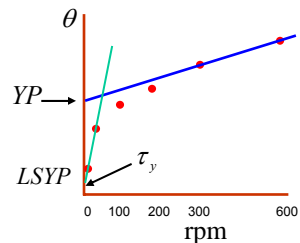
$$PV = \theta_{600} - \theta_{300} \text{ cP}$$

$$YP = 2\theta_{300} - \theta_{600} = \theta_{300} - PV \text{ lb}_f / 100 \text{ ft}^2$$

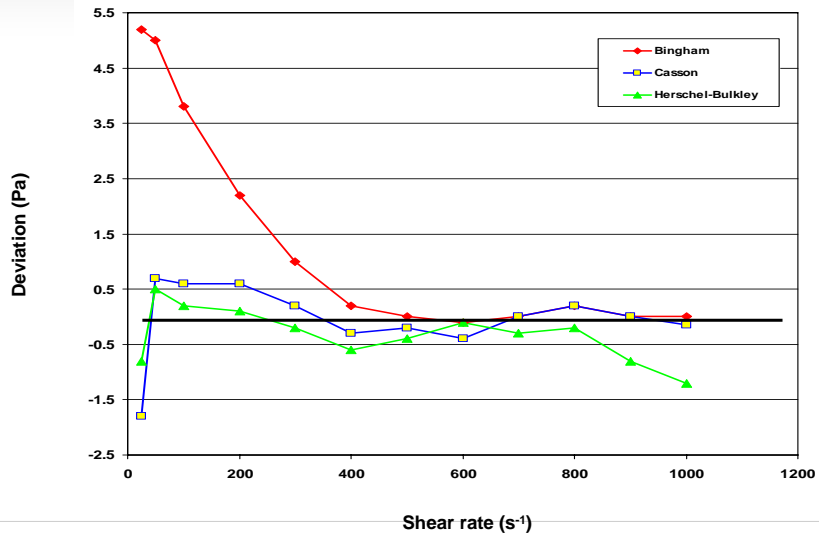


- LSR rheology is an important property of drilling fluids – it affects the solids bearing capacity of the fluids
- The Bingham model overestimates LSR rheology (in Fann-35 terms  $\leq 10 \text{ s}^{-1}$ )
- A more realistic YP can be defined by using the 6 & 3 rpm readings (the LSYP):

$$LSYP = 2\theta_3 - \theta_6$$



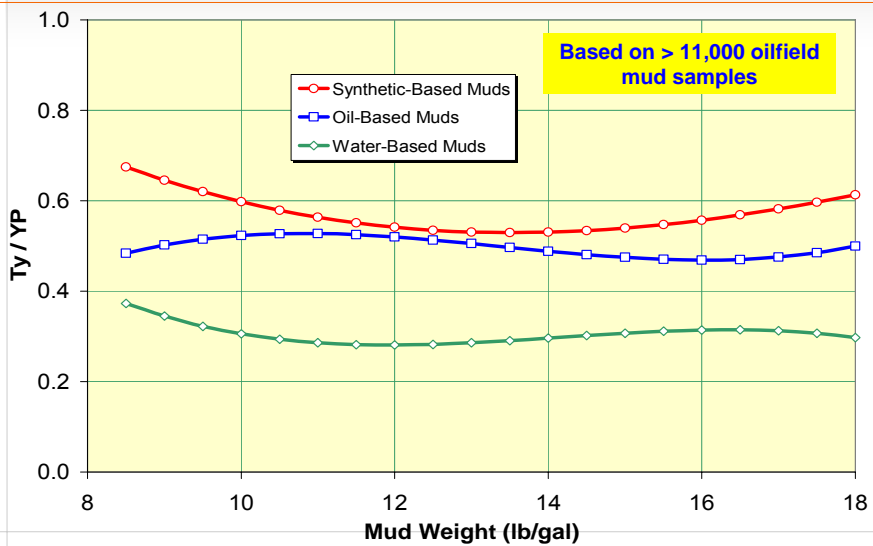
## Comparison of Rheology Models



Deviation = Model - Measurement

## Normalized Yield Points ( $\tau_y / YP$ )

(M. Zamora, *et al.*, AADE-03-NTCE-35)

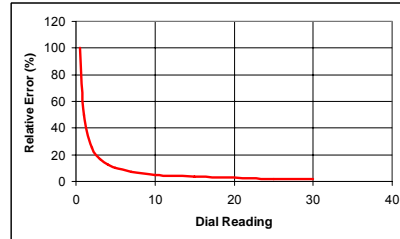


## Fann-35 Measurements – Error Analysis

- Errors generally attributed to measurements of shear stress

- Relative error of measurements: 
$$\frac{\Delta\tau}{\tau} = \pm \left[ 1.9 \times 10^{-5} + \frac{1}{4\theta^2} \right]^{1/2}$$

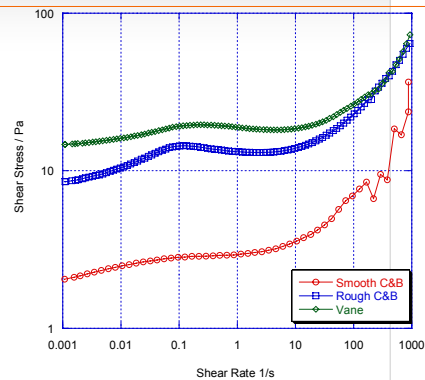
- A Fann reading of 5 may be in error by  $\pm 10\%$ 
  - A reading of 2 may be in error by  $\pm 25\%$
- Minimum error is  $\pm 0.5\%$



- Low readings and wall slip are major sources of error in Fann measurements

## Wall Slip

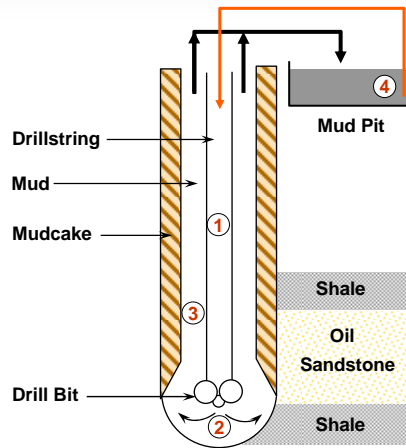
- Fluid adjacent to a solid surface normally moves with velocity of that surface
- But, a velocity difference can occur through “wall slip”, caused by:
  - Depletion of solid particles in the layer near the wall (oil, water film), etc
  - Alignment of polymer molecules near the wall
- Slip gives erratic torque readings through stick-slip, and low stress
- Some drilling fluids are prone to wall slip during rheological measurements – e.g. bentonite muds, high viscosity pills, etc
- Where slip is present, measurements with different geometries will produce different flow curves
- To rectify:
  - Use roughened, grooved or cross-hatched metal surfaces
  - Alternatively, use the vane rheometer



## Shear Rate

Drilling fluids experience a wide range of shear rates:

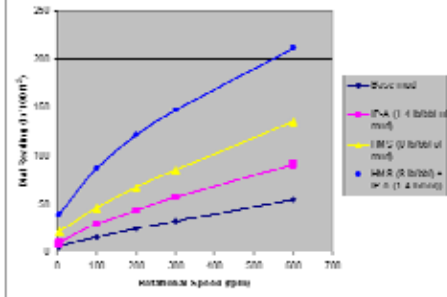
1.  $O 10^3 \text{ s}^{-1}$  in drillpipe
  - Where low HSR viscosity is needed to reduce frictional pressure
2.  $O 10^5 \text{ s}^{-1}$  through bit nozzles
  - Where high shear-thinning is needed to give high impact velocity
3.  $O 10^2 \text{ s}^{-1}$  in annulus
  - High LSR viscosity and good shear-thinning needed for hole cleaning and solids support
4. Low in mud tank
5.  $\sim 0$  in hole when flow interrupted



## Rheology Control in Drilling Fluids

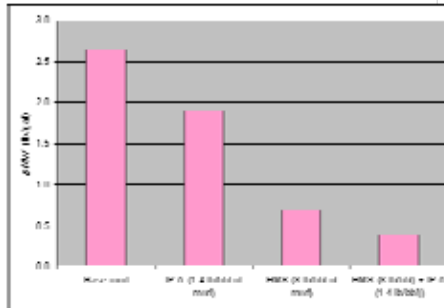
- All properties influenced by mud type and condition
  - Plastic viscosity influenced by solids content
  - Yield point influenced by chemical environment
- In OBM, there are contributions to rheology from:
  - Rheology additives (organoclays, polymeric viscosifiers) affect  $PV$  and  $YP$
  - Dispersed solids (weight material, drill cuttings) affect  $PV$
  - Emulsified brine phase affects  $PV$
- In addition
  - Treatment of brine phase in OBM can increase droplet rigidity and modify its surface chemistry, leading to enhancement of LSR rheology
  - Use of surface treated, micro-fine weight material can impart steric stabilisation to suspension, thus reducing dependence on LSR rheology for solids suspension and sag mitigation.

## Brine Phase Treatment in OBM



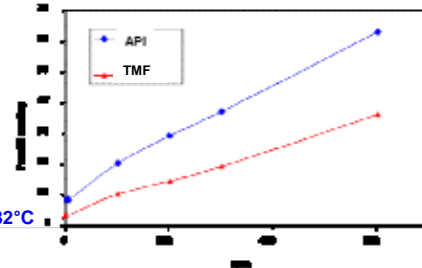
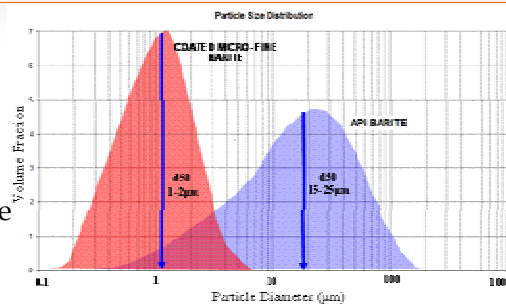
- Brine viscosifiers can improve LSR rheology
- They can show synergistic effect with some oil-phase viscosifiers

- Improved LSR rheology reduces settling of weight material



## Treated Micro-Fine Barite vs. API Barite

- Comparison of particle size distributions
- Treated micro-fine barite creates lower rheology than conventional OBM of same mud weight
- Steric stabilisation improves resistance to settling

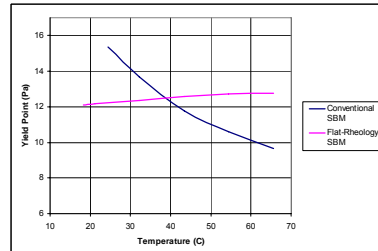


Comparison of rheology profiles at 82°C and 5000 psi for 1.32-SG fluids

## Effect of Temperature on Rheology

- Drilling fluids are exposed to a wide range of temperatures
  - In deepwater drilling temperatures can range from ~ 4°C at seabed to well above 100°C downhole.
- This places major demands on fluid rheology:
  - Maintain low HSR viscosity at low temperatures in order to reduce pumping pressures
  - Provide adequate LSR rheology at high temperatures to suspend solids and reduce barite sag downhole.
  - *A tough challenge to meet for conventional fluids*
- One solution is a synthetic-based invert emulsion fluid, which
  - uses high-performance polymeric additives, a small amount of organoclays, and emulsifiers
  - generates a temperature-stable rheology over the range frequently encountered in deepwater drilling (4-120°C).

Comparison of YP of conventional and "flat-rheology" SBM as measured during field application.

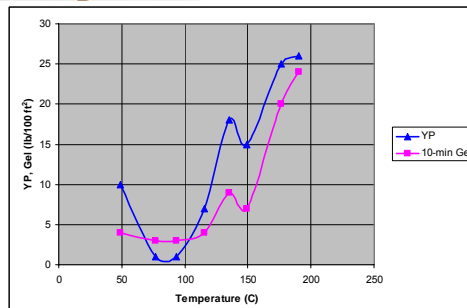


## HTHP Rheology

- The HTHP rheology of drilling fluids is important for their performance downhole
- High-temperature gelling can occur as a result of
  - breakdown of additives
  - interaction of products
- HTHP rheology is characterised in Fann 70 or 75 viscometers which allow measurements at up to 250°C and 1360 bar.



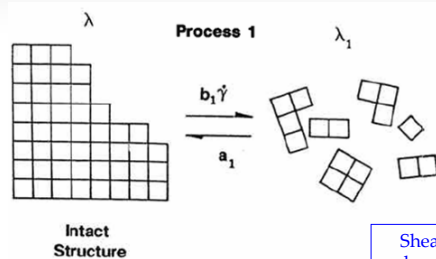
Temp C	Press bar	YP	Gel 10 min
49	0	10	4
77	483	1	3
93	552	1	3
116	690	7	4
135	828	18	9
149	1034	15	7
177	1103	25	20
191	1172	26	24



## Thixotropy in Drilling Fluids

- In some drilling fluid systems, clay particles with surface charge, or cross-linkable polymeric materials, form a gel that helps support the weight material and drill cuttings.
- At higher shear rates the network breaks down and the fluid flows with low viscosity.
- This thixotropic characteristic is an optimal type of rheology for conventional drilling fluids
  - *Provided that the time scales for buildup and breakdown of structure are small*

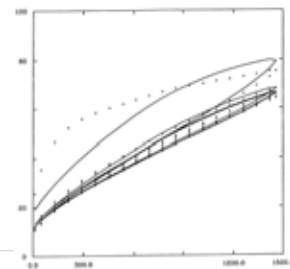
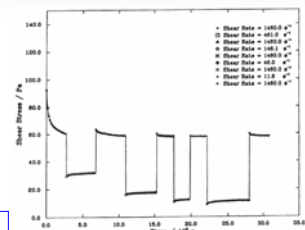
## Thixotropy in Drilling Fluids



Shear rate step-change tests and hysteresis loops for a bentonite WBM

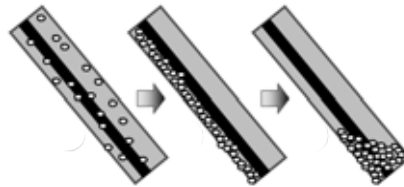
$$\frac{d\lambda(t)}{dt} = \underbrace{a[1 - \lambda(t)]}_{\text{build-up}} - \underbrace{b\lambda(t)\dot{\gamma}}_{\text{breakdown}}$$

$$\tau(t) = \lambda(t)\tau_y + [\mu_\infty + c\lambda(t)]\dot{\gamma}^m$$



## Hole Cleaning

- Removing cuttings from the wellbore during drilling is an essential function of the drilling fluid
- Hole cleaning is difficult in long, inclined, tangent sections due possible accumulation of cuttings beds on the low side of the hole
- Possible consequences of poor hole cleaning
  - reduced rate of penetration
  - high torque
  - stuck pipe
  - lost circulation
  - difficulties running and cementing casing



## Factors Affecting Hole Cleaning

**Mud:** flow rate  
rheology  
density

**Cuttings:** size  
density  
shape  
stickiness

**Hole:** ROP  
size  
quality

**Drillpipe:** diameter  
eccentricity

## Role of Rheology in Hole Cleaning

- To transport the particle out of the inclined section before it settles out we must have:

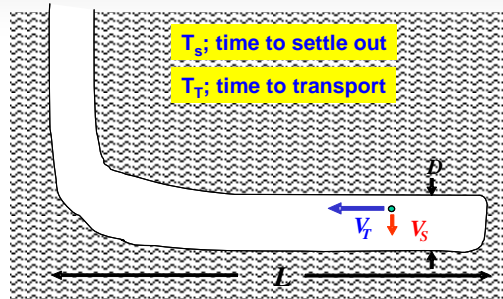
$$T_s \gg T_T, \quad \text{or} \quad \frac{D}{V_s} \gg \frac{L}{V_T}$$

- $V_s$  can be estimated from Stokes' settling velocity:

$$V_s = \frac{\Delta\rho g d^2}{18\mu}$$

- Giving:

$$\mu \gg \frac{L}{DV} \frac{d \Delta\rho g}{18}$$



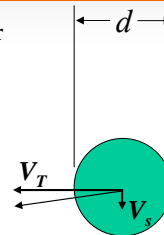
For:  $V_T = 1 \text{ m/s}$        $L = 1000 \text{ m}$   
 $D = 20 \text{ cm}$        $d = 1 \text{ mm}$   
 $\Delta\rho = 1200 \text{ kg/m}^3$        $g = 10 \text{ m/s}^2$

$$\mu \gg 3.3 \text{ Pa}\cdot\text{s} \text{ (3300cP)}$$

## What Shear Rate?

- For non-Newtonian fluids, viscosity is a function of shear rate
- Effective shear experienced by the particle is net of those due to translational and gravitational flows, but, the dominant component is due to flow

$$\dot{\gamma} = \frac{4V_T}{w} \quad (w \text{ is width of annulus})$$

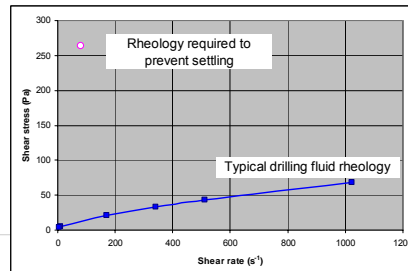


- For  $V_T = 1 \text{ m/s}$  &  $w = 5 \text{ cm}$ , shear rate is;  $\dot{\gamma} = 80 \text{ s}^{-1}$  (47 rpm on Fann 35)

- Fluid with  $3.3 \text{ Pa}\cdot\text{s}$  viscosity at  $80 \text{ s}^{-1}$  has a shear stress of  $264 \text{ Pa}$ , equivalent to a Fann value of  $550 \text{ lb/100 ft}^2$

- An unrealistically high value for drilling fluids

- Thus, rheology alone cannot be utilised to prevent particle settling during flow



## Can Rheology Prevent Settling in Stationary Fluid?

- To prevent settling when flow is interrupted, the gravitational force must be balanced by viscous forces:

$$\tau_y \times 4\pi \left(\frac{d}{2}\right)^2 = \frac{4}{3}\pi \left(\frac{d}{2}\right)^3 \Delta\rho g$$

- For the 1-mm particle with  $\Delta\rho = 1200 \text{ kg/m}^3$ :

$$\tau_y = 2 \text{ Pa}$$

- This is “true” yield stress.
- Based on Zamora, *et al.*'s analysis, the required YP would be 4 - 10 Pa. This gives a realistic range of 8 - 20 lb/100 ft<sup>2</sup> for YP.

## Mud Flow Regime Options

### Turbulent

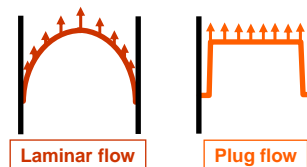
- Most efficient for hole cleaning
- Prevents formation of cuttings beds and disturbs/re-suspends any cuttings beds which do form
- Can erode weak formations
- Pump capacity may be limiting factor
- Gives large pressure drops (can use drag reducers)

### Laminar

- Carries cuttings effectively but does not easily re-suspend cuttings beds
- Cuttings beds transported by sliding and saltation
- Hole cleaning can be augmented by low viscosity pills and drill pipe rotation

### Plug

- Fluids in plug flow give good hole cleaning in large holes at low pump rates
- Examples are MMO/MMH and polymer muds with high (>2 ppb) concentrations of Xanthan gum
- Fluids have low PV, high YP and high, flat gels

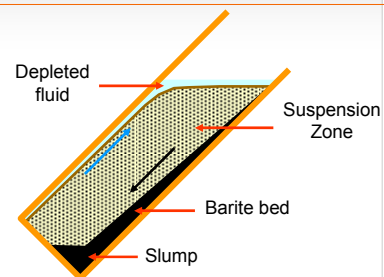


## Barite Sag

- Sag is the settling of weight material under gravitational forces, leading to density segregation of the drilling mud
- Sag can occur
  - with any solid weight material; Barite, haematite, calcium carbonate, salt crystals
  - in both OBM and WBM, but is seen more often in OBM
  - over a wide density range (1.4 – 2.4 s.g.)
  - through Dynamic and/or Static settling
- Can result in variations up to 0.5 s.g.
- Is observed in circulating fluid after a static period

## Barite Sag

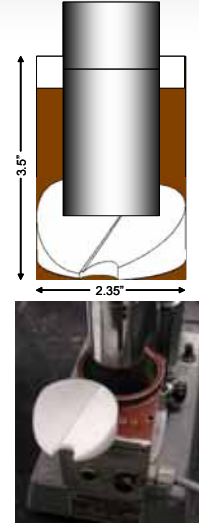
- Sag is more problematic in deviated wellbores where:
  - gravity induced settling forms density gradient or barite bed on low side of hole
  - barite beds can slide down the low side of the hole (depends on hole angle and strength of bed), further increasing the density contrast in the hole, a process known as the “Boycott Effect”
- Problems caused by sag
  - Poor control of bottom-hole pressure
    - inhomogeneous mud weight
    - fluctuations in the equivalent circulating density
    - induced fractures (lost circulation problems)
    - possible influx of formation fluids (well control problems)



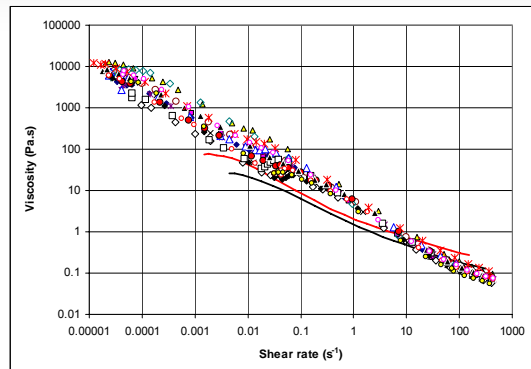
- wellbore instability
- Problems while tripping & running casing
- Stuck pipe & logging tools
- Poor cement placement

## Techniques to Study and Measure Sag

- Jefferson (1991), Zamora & Jefferson(1994)
  - method based on Fann viscometer (VST)
  - static/dynamic & up to 85°C
- Saasen et al (1995)
  - variable inclination coaxial cell - inner reciprocator
  - static & dynamic sag
- Zamora & Bell (2004) – modified VST with “sag-shoe”
  - Measures dynamic sag

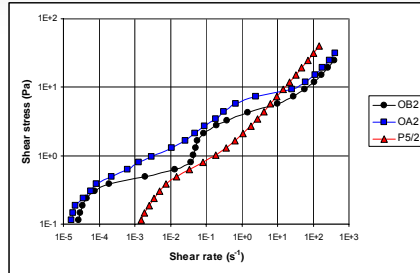


## Effect of Rheology Additives on OBM Viscosity – Tehrani, *et al.* (2004)



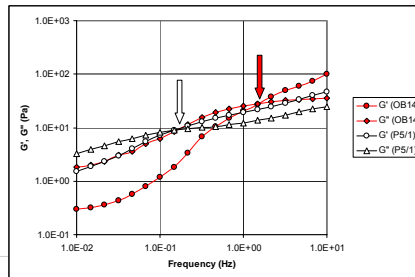
- Measurements at 50°C
- Solid lines represent polymeric OBM viscosifiers
- Markers represent organoclay viscosifiers

## Effect of Rheology Additives on OBM Rheology

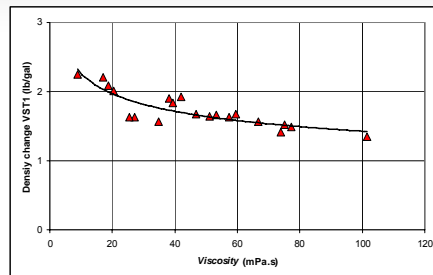


- Measurements at 50°C
- OB2: hydrophobically modified bentonite
- OA2: hydrophobically modified attapulgite
- P5/2: diblock styrene-ethylene/propylene copolymer

- Measurements at 50°C
- OB14: hydrophobically modified bentonite
- P5/1: linear styrene-ethylene/propylene copolymer

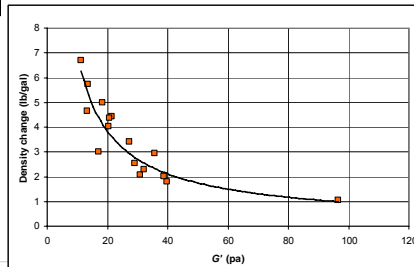


## Effect of LSR Viscosity on Dynamic Sag

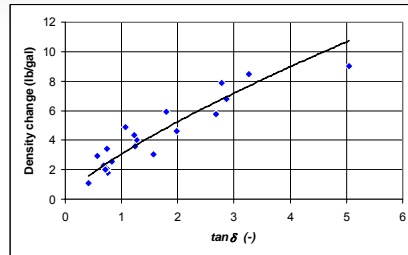


- Dynamic sag measured by VST + sag-shoe" method at 50°C
- Viscosity at 10<sup>-2</sup> s<sup>-1</sup> and 50°C
- Clay and polymeric additives

- G' measured at 1 Hz and 20°C

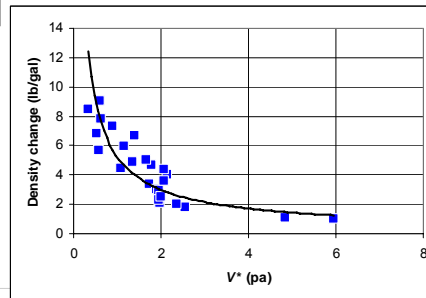


## Effect of $\tan \delta$ on Dynamic Sag



- $\tan \delta = G''/G'$
- $\tan \delta$  at 1 Hz and 20°C

- $$V^* = \frac{(G'^2 + G''^2)^{1/2}}{2\pi f}$$
- Complex viscosity at 5 Hz and 20°C



## Conclusions

- Drilling fluids are complex, multi-component suspensions and emulsions designed to perform a variety of functions during the drilling operation.
- The continuously changing environment to which the fluids are exposed means that their properties must be monitored and controlled throughout the drilling operation.
- Rheology is a key parameter that affects many functions of drilling fluids, e.g. friction pressure, hole cleaning, barite sag, etc
- Low HSR viscosity favours the hydraulics of the drilling operation, while sag prevention and hole cleaning benefit from high LSR rheology.
- Thus, the optimum *conventional* fluid is one which has thixotropic characteristics with short structure breakdown/buildup time scales.
- *Novel* fluids are now available which use steric stabilisation to reduce dependence on LSR rheology for sag prevention and hole cleaning.