# Predicting HP/HT Effects on the Flow Properties of Field Water Based Muds: Trials & Tribulations

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Drilling Fluids

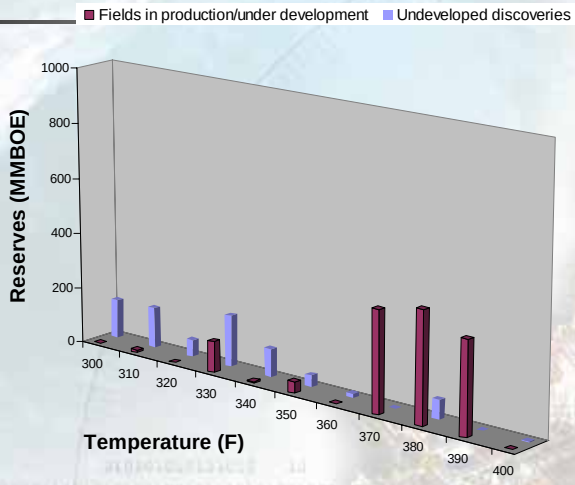
## Presentation Outline

- Description of HP/HT wells
- Viscometers Available
- Issues with rig site & laboratory use
- Average flow properties
- Water and Saline solution Viscosities
- Field example
  - Circulating Casing
- Conclusions

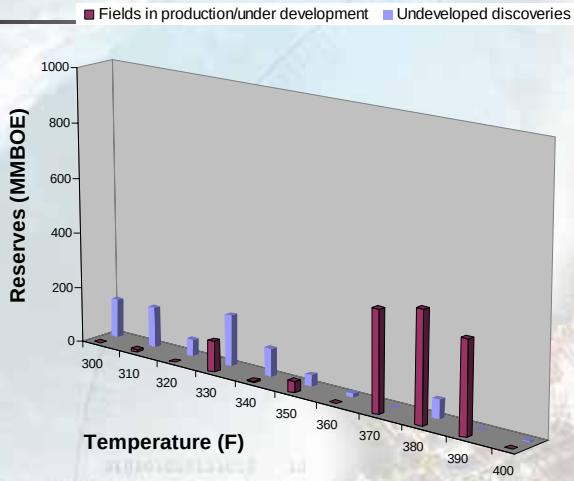
# High Pressure High Temperature Wells – HP/HT

- Originally defined by the UK Dept of Trade & Industry as wells where temperatures exceed 150°C and pressures exceed 18,000 Pa/m
- Some completion engineers have now segmented these wells into 3 tiers based on increasing temperature and pressure...
  - However, geological environments can vary significantly
  - Often not possible to conveniently assign some wells into pre-determined neat criteria
- The example well had static pressures of ±117 MPa and a bottom hole temperature of 256°C

## UK North Sea HP/HT Field Temperatures



## UK North Sea HP/HT Field Temperatures




Subject well
493°F

## Current Field Viscometer

- Fitted with a heating cup the couette viscometer can measure at a selected temperature (typically 48.9-65°C) and produce 6 dial readings at 600,300,200,100 6,3 RPM – taken manually
  - Some models in Norway can provide 60 and 30 rpm readings
- Dial readings are converted into a stress value and the rpm converted to shear rate in software

# Field Viscometer

- Robust and economic
- Wide gap of 1170 micron with typical R1B1 combination
- Set many years ago when muds were dirtier due to less efficient solids control
- Prone to reading & measurement errors especially at the lower rpm of 6 and 3

# Current HP/HT Viscometers

- Various models currently on the market- but not rig friendly
- Some have high pressure capability up to 275 MPa although 172 MPa is typical
  - (high pressures not really required for water based muds)
- Other viscometers are available that have high temperature capability but with limited pressure (typically 6.9 to 13.8 Mpa)

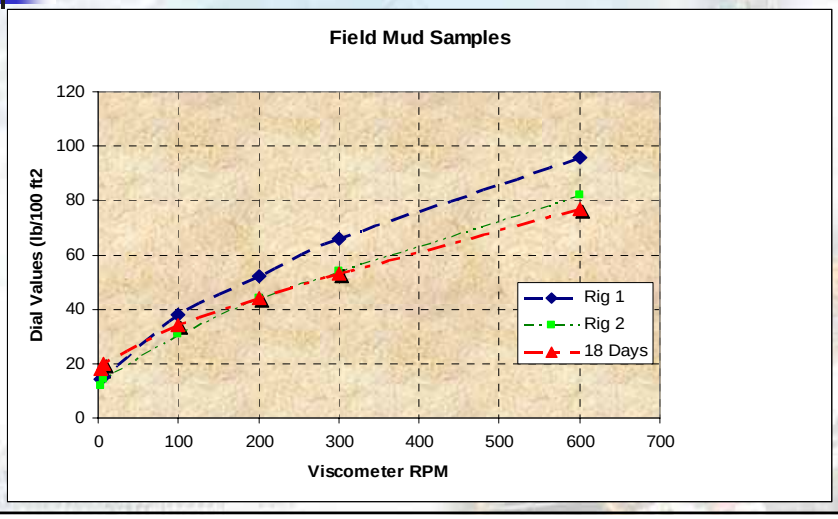
# LP/HT Viscometers

| | |
|---|---|
| Sample Size: | 13~73 ml (B5-52 ml API) |
| Speed Range: | 0.0001~1100 RPM continuous |
| Shear Stress Range: | 1-10,000 dyn/cm² |
| Shear Rate Range: | 0.00004~1870 1/S |
| Repeatability: | ±0.05% of full scale range |
| Resolution: | 0.5 dyn/cm with standard |
| Viscosity: | configuration |
| Pressure Range: | 0.5~5,000,000 Centipoise |
| Temperature Range: | Vacuum to 1000 psi -40~500 °F |
| Dimensions: | 8.5"x12.5"x24" (with bath) |
| Weight: | 55 lbs (with bath) |
| Construction: | Hastelloy C |

# Test Mud in the Lab?

| RPM | Rig 1 | Rig 2 | 18 days | 30 days sheared | Stirred |
|---|---|---|---|---|---|
| 600 | 96 | 82 | 77 | 79 | 88 |
| 300 | 66 | 54 | 53 | 58 | 63 |
| 200 | 52 | 44 | 44 | 45 | 52 |
| 100 | 38 | 31 | 34 | 40 | 41 |
| 6 | 15 | 14 | 20 | 22 | 21 |
| 3 | 14 | 12 | 18 | 21 | 20 |
| Gels | 14/25 | 14/21 | 27/56 | 30/93 | 38/81 |

# Variable Flow Properties!

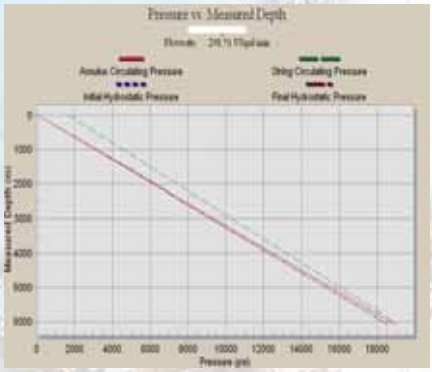



# Average Flow Properties

- The measurement of flow properties at surface conditions (defined temperature and ambient pressure) will only be correct for modelling purposes if these conditions represent the average condition
  - For many wells with shallow depths these flow properties may be adequate
- For HP/HT or deep offshore wells it is usually necessary to take into account both the pressure and temperature gradients that can affect flow properties and of course density

## Pressure Effects

- These are the combined values of hydrostatic density and pumping pressure required to circulate
- While pressure effects on water viscosity are relatively small they are significant for hydrocarbons




## Estimating Circulating Temperatures

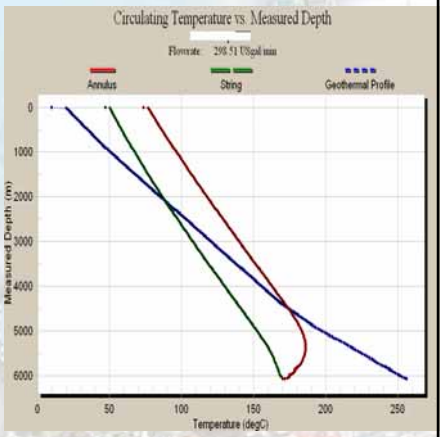
- Required are:
  - Some idea of geothermal gradient
  - Surface temperature
- Some software models use hard coded values for mud Thermal Conductivity and Specific Heat Capacity – others use flexible values
- An Empirical equation proposed by Kutasov can quickly derive the approximate average well circulating temperature
  - Satisfactory for predictive purposes

# Kutasov Empirical Equation

- Given well depth in feet
- Estimated bottom hole temperature (from gradient) in °F (B)
- Surface temperature °F
- Geothermal gradient deg f/ft (C)
- 4 coefficients
  - A1—102.1; A2-3354; A3-1.342; A4-22.28
- Quickly calculates the estimated circulating temperature
  - A1*(A2*C)+(A3-A4*C)*B

# Temperature Effects

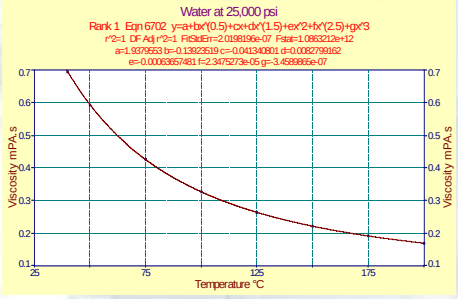
- Utilising the empirical equation for the subject well with a surface circulating temperature of 57°C and a bottom hole temperature of 256 °C gives a maximum bottom hole circulating temperature of ±188°C and an average well temperature of ±122°C
  - Not the temperature of the mud check at 60°C!

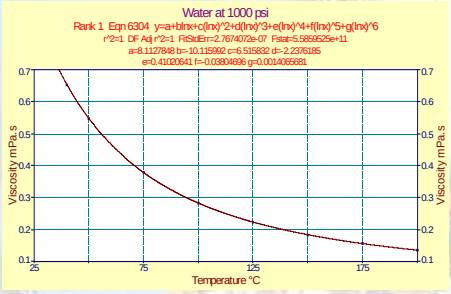


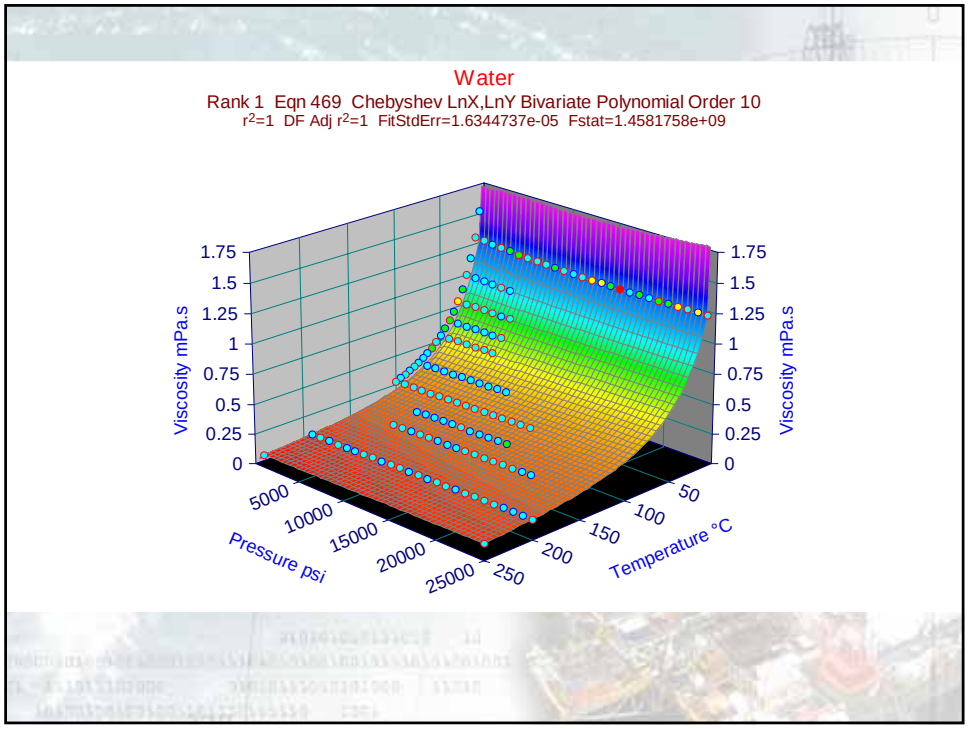
# Mud Composition

- Muds may be composed of three main components (oil, water and solids) and for most water based muds just two
- Solids contents are derived from retort analysis – accurate at best to 0.5%
- In this example we have 38% solids, 42% water
- Chemical additives will increase the viscosity of the external phase but may also reduce the system rheology

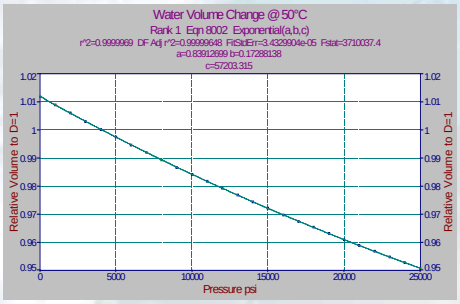
# Water Viscosity

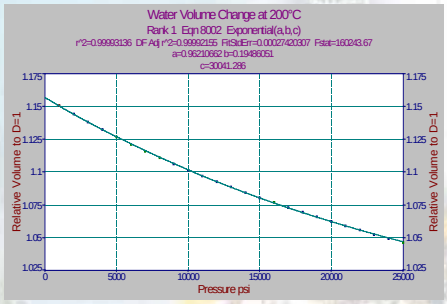





# Water Relative Volume



# Water Mud Matrix

Table 1. Comparative Dial Values Derived for Water and Solids at Varying T&P

| water vis mPa.s | ratio to test temp | volume ml/g | Solids % | Temp °C | Pressure psi |
|---|---|---|---|---|---|
| 0.468 | 1.000 | 1.017 | 38 | 60.0 | 14.5 |
| 0.718 | 1.533 | 1.006 | 38.419 | 35 | 14.5 |
| 0.249 | 0.531 | 1.028 | 37.599 | 120 | 9500 |
| 0.174 | 0.372 | 1.049 | 36.846 | 185 | 20000 |

| RPM | RPM | RPM | RPM | RPM | RPM |
|---|---|---|---|---|---|
| 600 | 300 | 200 | 100 | 6 | 3 |
| Dial | Dial | Dial | Dial | Dial | Dial |
| 91 | 55 | 40 | 25 | 8.0 | 7.0 |
| 139 | 84 | 61 | 38 | 12.2 | 10.7 |
| 49 | 29 | 21 | 13 | 4.3 | 3.7 |
| 34 | 21 | 15 | 9 | 3.0 | 2.7 |

# Salt Water Viscosity

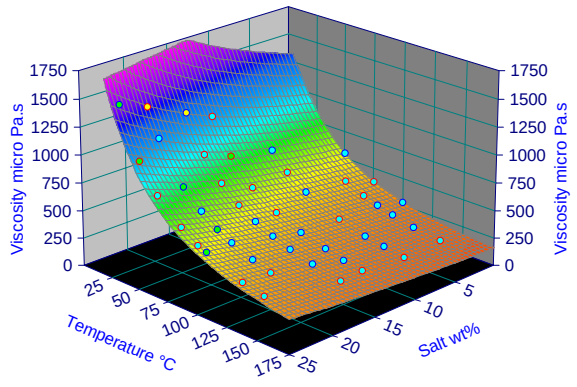
NaCl Brine Viscosities Ambient Pressure

Rank 11 Eqn 1302 $z=(a+cx+elny+gx^2+i(lny)^2+kxlny)/(1+bx+dlny+fx^2+h(lny)^2+jxlny)$

$r^2$=0.99993435 DF Adj $r^2$=0.99991483 FitStdErr=2.9609714 Fstat=57879.245

a=1371.585 b=-0.0074468289 c=12.712265 d=-0.34518 e=-479.36862 f=-0.00014296779

g=0.035511701 h=0.042333734 i=43.511729 j=0.0027296206 k=-2.076433



# Salt Water Viscosity

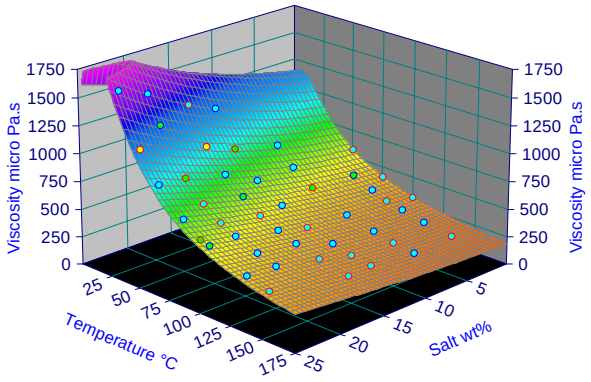
NaCl Brine Viscosity at 18,000 psi

Rank 16 Eqn 1125 $z=(a+bx+cx^2+dx^3+elny+f(lny)^2)/(1+gx+hx^2+ilny+j(lny)^2)$

$r^2$=0.99967659 DF Adj $r^2$=0.99959148 FitStdErr=6.8544403 Fstat=13394.615

a=1022.5566 b=-0.30447697 c=0.13945847 d=-0.0031523277 e=-303.1182

f=24.280144 g=-0.0058069874 h=-1.1254369e-05 i=-0.40273984 j=0.061328412




# NaCl Brine Volume Change

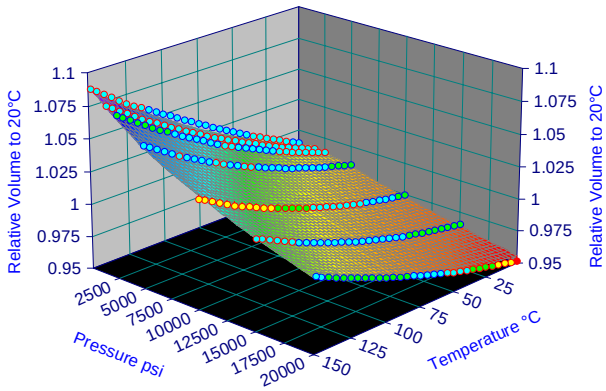
19.2% NaCl Relative volumes

Rank 19 Eqn 313 $z=a+bx+clny+dx^2+e(lny)^2+fxlny+gx^3+h(lny)^3+ix(lny)^2+jx^2lny$

$r^2$=0.99842731 DF Adj $r^2$=0.99835097 FitStdErr=0.0012589927 Fstat=14601.635

a=1.0847414 b=0.00033183968 c=-0.061743752 d=5.7314434e-07 e=0.011568836

f=0.0001044212 g=1.5328683e-09 h=-0.00067142615 i=-1.2473995e-05 j=4.9352116e-08



# No Significant Change!

- Compared to the fresh water mud matrix a mud matrix based on 13% NaCl shows very little difference
- As expected, when a salt water mud matrix is used in the HP/HT hydraulics software, calculated surface pressures are lower than actuals – indicating that the mud in the well is thicker than these predictions
- The solution is then to use predictions at increasing (or decreasing) temperatures from the SWP in an iterative process so that a data set when input as the average flow properties produces accurate outputs
  - At most 3 iterations may be required

# A more realistic picture

Table 5. HP/HT Matrix Dial Values Derived from SWP and average well condition

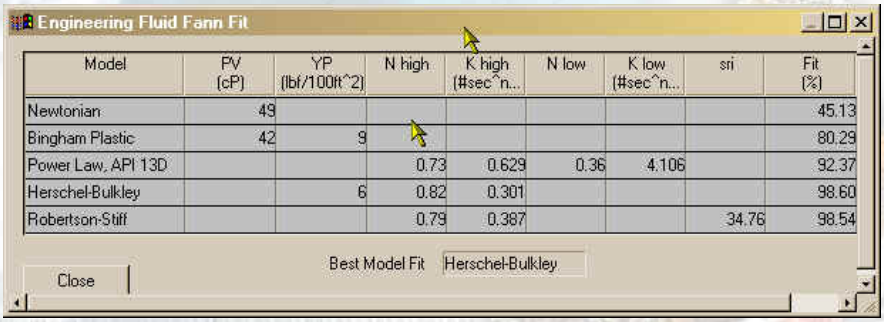
| T °C | Press. Psi | 600 rpm | 300 rpm | 200 rpm | 100 rpm | 6 rpm | 3 rpm |
|---|---|---|---|---|---|---|---|
| 60 | 14.5 | 91 | 55 | 40 | 25 | 8.0 | 7.0 |
| 35 | 14.5 | 136 | 82 | 60 | 37 | 12 | 10 |
| 122 | 9500 | 78 | 47 | 34 | 21 | 6.8 | 6.0 |
| 50 | 5000 | 94 | 57 | 42 | 27 | 9.2 | 8.2 |
| 60 | 6000 | 92 | 56 | 41 | 26 | 9.2 | 8.2 |
| 70 | 1000 | 89 | 54 | 39 | 25 | 8.0 | 7.0 |
| 80 | 8000 | 88 | 54 | 40 | 25 | 9.3 | 8.3 |
| 200 | 20000 | 65 | 41 | 31 | 21 | 9.5 | 8.8 |
| 100 | 3000 | 83 | 50 | 37 | 23 | 7.9 | 7.0 |
| 110 | 12000 | 83 | 51 | 38 | 25 | 9.5 | 8.6 |
| 120 | 13000 | 81 | 50 | 37 | 24 | 9.5 | 8.7 |
| 130 | 8000 | 78 | 48 | 35 | 23 | 8.3 | 7.5 |
| 140 | 15000 | 77 | 48 | 36 | 23 | 9.6 | 8.8 |
| 150 | 11000 | 74 | 46 | 34 | 22 | 8.6 | 7.8 |

# Is this the true picture?

- Perhaps!
  - What is known is that the calculations agree with surface pressures being recorded. The mud may be slightly thicker or thinner than predicted for a set temperature and pressure condition, but overall use of a synthetic matrix is better than just using surface measured flow properties

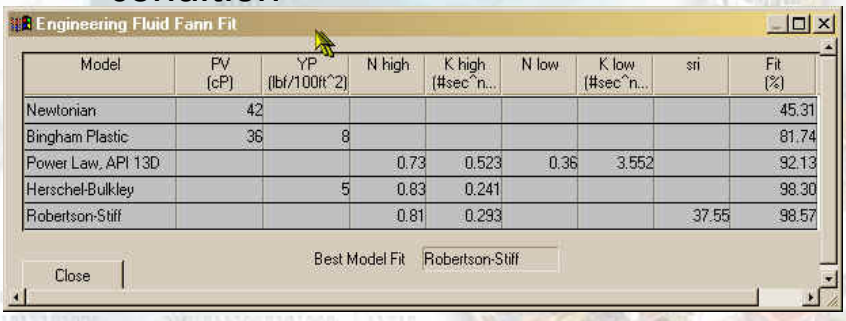
# Flow Model Selection

- These fits are based on actual surface dial readings (Line 1 of Table 5) corrected for stress



# Flow Model Selection

- These fits are based on the synthetic derived flow values at the average condition




# Level of Accuracy

- Use of the Herschel Bulkley flow model in calculating flow circuit pressure drops always gives a higher total pressure loss than the Robertson Stiff model
- An error of +1 in both 6 and 3 rpm readings to Table 5 values changes the best fit model to Robertson Stiff and increases calculated pressure loss by 6% or 14% if staying with the Herschel Bulkley model

## Level of Accuracy

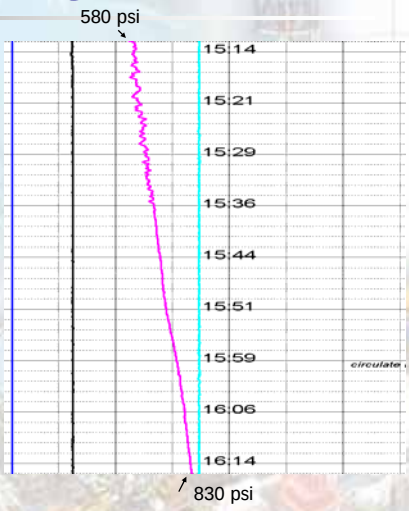
- Since the flow model fits are very close, coupled with the inherent errors in viscometer readings, inadequate data points and then mathematical manipulation of these values, use of either flow model could be correct
  - A level of accuracy has been reached that we have to accept when all the engineering unknowns are also considered

## Circulating casing

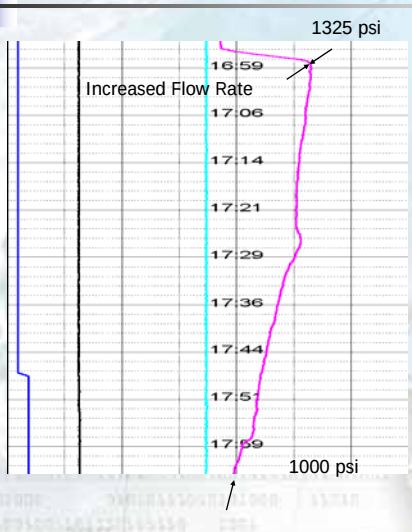
- The casing was equipped with Turbolisers to help mud removal
- It is felt these could have become partly plugged with gelled mud and filter cake
- The mud could also have been significantly thixotropic by this time

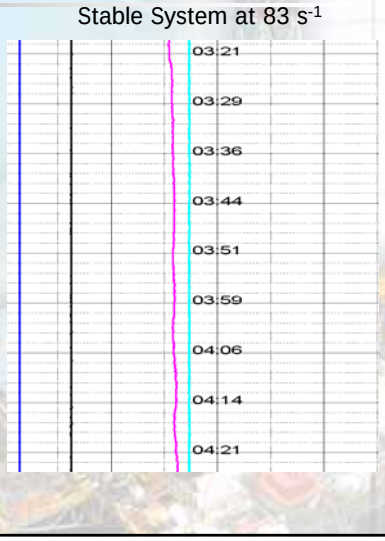
# Reverse Circulating

- At a low flow rate the pump pressure was seen to increase
- This was due to the mud structuring at Newtonian shear rates above 64 $s^{-1}$ but below 83 $s^{-1}$



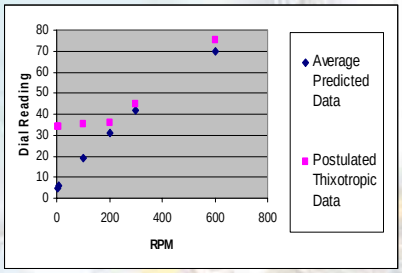

# Structural Collapse



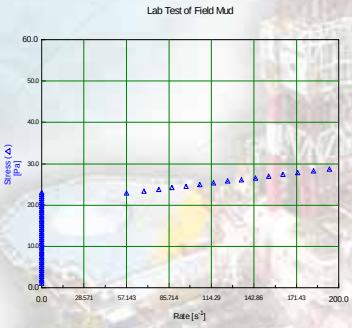
# Flowing Structure?

- An educated guess would be of a fluid exhibiting a high up curve yield stress
- A fluid with postulated average flow properties as in the graph gives pressure values close to measured
- Not all the mud would be like this as this is likely a temperature effect and would not be seen in the upper portions of the well



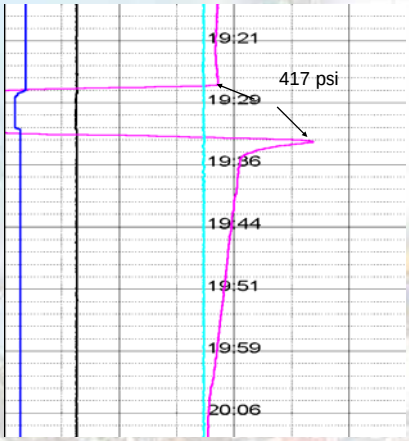

# Lab Test

- A sample of field mud taken prior to the cementing operation was tested months later
- While it has also increased in Thixotropy with time from the circulating condition, the result after a 15 minute wait shows similar response to the field mud in the prior slide



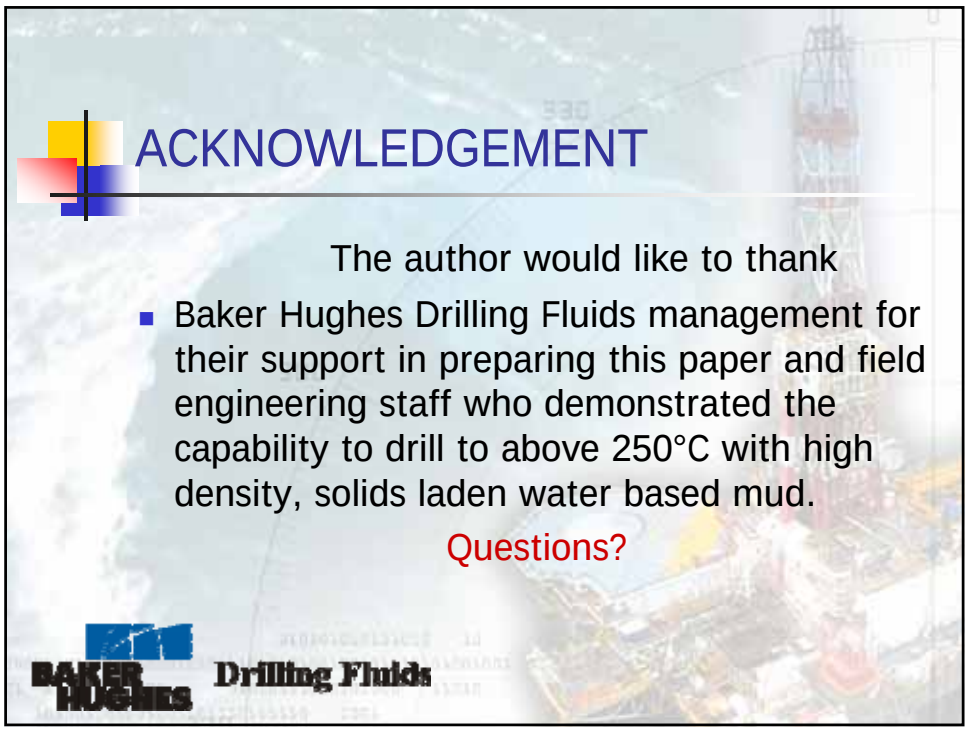
## Gel Peak

- The peak often described as due to “gel breaking” is really a combination of the stress required to initiate movement of the mud column and the rate of deformation being applied (Strain rate)
- Laboratory tests at 60 °C show that the mud linear viscoelastic region only extends up to 1% strain




## Conclusions

- A methodology has been established to determine the downhole flow properties of water based muds
- Use of a high temperature viscometer with limited pressure capabilities at a wellsite would allow verification of current modelling
- This would also allow monitoring of structure build up at low shear rates and elevated temperatures that current standard viscometers are unable to evaluate


ACKNOWLEDGEMENT
The author would like to thank
Baker Hughes Drilling Fluids management for their support in preparing this paper and field engineering staff who demonstrated the capability to drill to above 250°C with high density, solids laden water based mud.
Questions?
BAKER HUGHES
Drilling Fluids