**Lesson I**
- **Introduction and Objectives**
  - Technical/Scientific Aspects
- **Function and Properties**
  - Wellbore Hydraulics, Cuttings Transport
  - Fundamentals of Rheology
  - Drilling Fluids and Borehole Stability
  - Filtration Properties
  - Balancing Formation Pressure
  - Lost Circulation Problems
  - Lubrication/Friction Reducing
  - Corrosion Prevention
- **Testing Methods/Equipment**
- **Mud Additives Controlling Properties**

**Lesson II**
- **Solids Control**
  - Unweighted/Weighted Muds
- **Types of Drilling Fluid Systems**
  - Waterbased Mud
  - Oilbase Mud/Emulsion Systems
- **KTB-Experiences**
  - Strategy
  - Pilot Hole
  - Ultradeep Hole
- **Conclusions**
Drilling Mud – Why do we deal with?

Drilling Tasks

- Bottomhole Cleaning
- Cuttings Transport
- Borehole Wall Support
- Balancing Formation Pressure
- Cooling the Bit
- Hydraulic Power Transmission
- Data Transmission (MWD)
- Reducing Friction
- Corrosion Protection

Engineers

Mud

Scientists

Information Carrier

Mud/Fluids
- Gas
- Tracers
- Cuttings

Gas
- Fluids
- Cuttings
- Cores

Aiding Scientific Evaluation

Borehole Logging

Aiding Scientific Evaluation

Aiding Scientific Evaluation
Technical Key Functions of Drilling Fluids

Mud Circulation System

- Swivel
- Kelly
- Rotary Table
- Annulus
- Casing
- Drillstring
- Standpipe
- Shale Shaker
- Mud Pumps
- Mud Pits
- Charging Pumps

- Transport of Cuttings to Surface
- Support of Borehole Wall
- Transmission of Data/Hydraulic Power
- Cooling Bit
- Balancing Formation Pressure
- Reducing Friction Torque/Drag
- Aiding Solids Removal
- Protection against Corrosion
- Hydraulic Optimization

Pump Pressure = f(Pumprate, MudViscosity)

Cleaning the Bottom of the Hole

Reducing Friction Torque/Drag

Support of Borehole Wall

Transmission of Data/Hydraulic Power
Mud Properties Controlling Technical Key Functions

Functions:
- Cleaning the Bottom of the Hole
- Transport of Cuttings to Surface
- Hydraulic Power
- Data Transmission
- Cooling the Bit
- Borehole Wall Support/Stabilization
- Balancing Formation Pressure
- Reducing Friction/Torque and Drag
- Protection against Corrosion
- Aiding Cuttings Removal and Solids Control

Properties:
- Rheological Parameters
  - Viscosity
  - Thixotropy
- Density
- Filtration Parameters
- Free Water Capacity
- Lubricity Coefficient
- Chemical Composition
- pH
- physico-chemical Parameters
- Solids Content
  - weighted/unweighted
**Fundamentals of Cutting Transport**

Transporting of Cuttings to Surface

V\(_{\text{ann}}\): Mud Velocity in Annulus
- Pumprate,
- Annular Geometry

V\(_{\text{sett}}\): Cutting Settling Velocity
- Mud Parameters
  - Rheology (Viscosity)
  - Density
- Cutting Parameters
  - Density
  - Diameter
  - Shape

V\(_{\text{ann}}\) >> V\(_{\text{sett}}\)

**Basic Law of Cuttings Transport**
\[
\frac{(V_{\text{ann}} - V_{\text{sett}})}{V_{\text{ann}}} > 50\%
\]
Fundamentals of Cutting Transport

Drilling/Mud Circulation

Roundtrip/Circulation Break

Holding Cuttings in Suspension

\( \tau_0 \): Yield Strength of Mud depends on:
- Rheological Behaviour
- Gel Strength, Thixotropy

\( \tau_{\text{cutt}} \): Tangential/Normal Stress due to Cutting Weight depends on:
- Cutting Diameter \( (d_c) \)
- Cutting Density \( (\rho_c) \)
- Cutting Shape
- Mud Density \( (\rho_m) \)

\[
\tau_{\text{cutt}} = \left( d_c g (\rho_c - \rho_m) \right) / 6
\]

\( \tau_{\text{cutt}} < \tau_0 \)
Cuttings Transport – The Role of Drilling Fluid Rheology

Circulation/Drilling Dynamic Carrying Capacity

Rheological Behaviour while Flowing
Viscosity dependent on Shear Rate

Circulation Break/Roundtrip Static Carrying Capacity

Rheological Behaviour while Stationary
Thixotropy: Fluid $\rightarrow$ Gel reversible
Shear Stress - Shear Rate Diagram

Shear Rate $\gamma$

Shear Stress $\tau$

Theory of Fluid Rheology

Typical Drilling Muds are Shear Thinning. Viscosity decreases with increasing Shear Rate.

- **Pseudoplastic Fluid (Drilling Mud)**: Viscosity dependent on Shear Rate.
- **High Newtonian Viscosity**: Apparent Viscosity. Slope $= \mu$
- **Low Newtonian Viscosity**: $\Delta \gamma$
- **Newtonian Fluid (Water, Mineral Oil)**: Straight Line with Constant Slope $= \mu$.
Drilling Mud Viscosity – Measuring Equipment

Rotational Viscosimeter

Marsh Funnel

Determination of Shear Dependent Viscosity by Measuring Flow Curve at different Rotational Speeds

Measuring Outflow time (s)
Water: 26 s
Measuring Rheological Behaviour of Drilling Fluids

Rotational Viscosimeter

Determination of Flow Model

Measuring Points
Flow Curve

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Gel Strength

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<tr>
<td>3 after 10 min</td>
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Rotational Speed (RPM)
Flow Models Describing Pseudoplastic Drilling Fluid Rheology

Shear Stress – Shear Rate Diagram

- **Bingham Fluid**
  - $\text{YP: Yield Point} = 2R_{300} - R_{600}$
  - $\text{PV: Plastic Viscosity} = R_{600} - R_{300}$
  - $\tau = \text{YP} + \text{PV} \times \gamma$

- **Power Law Fluid**
  - $\text{K: Konsistency Index} = R_{300}/511^n$
  - $n: \text{Power Law Coefficient} = \log(R_{600}/R_{300})/0.301$
  - $\tau = K \times \gamma^n$
Shear Thinning of Drilling Fluids – Impacts on Drilling Process

\[ \mu_{\text{app}} = \frac{\tau}{\gamma} \]

\( \mu_{\text{app}} = \mu = \text{const} \)

Low Shear-Range
High Viscosity
Annulus \( \rightarrow \) Cuttings
Transport

High Shear-Range
Low Viscosity

Bingham Asymptotic Line for high Shear Rates \( \mu_{\text{app}} \rightarrow PV \)

Drillpipe \( \rightarrow \) Pressure Loss
Bit Nozzles \( \rightarrow \) Hydraulic Power at Bit
Solids Control \( \rightarrow \) Cutting Removal

Apparent Viscosity \( \mu_{\text{app}} \) (mPas)

Shear Rate \( \gamma \)
Influence of Yield Point on Cuttings Transport Efficiency

Annular Geometry: 5" Drillpipe/12 ¼" Hole

- Cutting Density: 2.9 kg/dm³
- Cutting Diameter: 15 mm
- Mud Density: 1.25 kg/dm³
- Plastic Viscosity: 30 mPa.s
**Impact of Mud Rheology on Cutting Lag Depth Correction**

- **Hole Diameter:** 8 ½“
- **Drillpipe Diameter:** 5“
- **Hole Depth:** 10 km
- **Mud Density:** 1,01 kg/dm³

**Mud Rheology:**
- Rotational Viscosimeter: \( R(300) = 16; R(600) = 21 \)
- Bingham (\( YP = 5,3 \) Pa; \( PV = 5 \) mPas)
- Power Law (\( K = 0,68; n = 0,39 \))

**Typical Density Ranges of Rock Minerals**
- Quartz/Feldspars
- Amphiboles
- Corundum
- Zircon
- Magnetite
- Mica
- Garnets

**Cutting Density (kg/dm³)**

**Cutting Diameter:** 1 mm
**Cutting Shape:** Sphere
**Gel Building Properties of Drilling Fluids**

**Time dependent Gel Strength**

- Drilling Fluids show thixotropic properties
- Thixotropy: GS@10min-GS@10s
  - Measured with Rotational Viscosimeter @ 3 RPM
  - Initial GS after 10s

**Gel Strength GS (Pa)**

- fragile Gel desirable
- progressive Gel dangerous

- GS too high ➔ high Surge/Swab Pressures ➔ Excessive Pump Pressures ➔ Formation Fracturing/Lost Circulation ➔ Borehole Instability ➔ Uncontrolled Influx of Formation Fluids

- GS too low ➔ Insufficient Static Carrying Capacity for Cuttings

**Pump Pressure necessary for Breaking Gel**

- Mining Drilling 5 ½” DP/6” Hole KTB Pilot Hole
- Narrow Annulus

- Rotary Drilling 5 ½” DP/12 ¼” Hole
- Rotary Drilling 5 ½” DP/17 ½ “Hole
Objective: Maximizing Hydraulic Power at Bit

Rule of Thumb for Rotary Drilling: 2/3 of total Pressure Loss at Bit

Jet Nozzles in a Roller Cone Bit

Minimizing Parasitic Pressure Losses
- PV as low as possible,
- YP as high as necessary for Cuttings Transport

Impact Parameters on Parasitic PL
- Annular Geometry
- Surface Equipment
- Drillpipe Size
- Mud Rheology (YP and PV)
Mud Additives Controlling Rheology

**Viscosifiers**

- **Clays**
  - Bentonite
  - Attapulgite
  - Sepiolite
  - Hectorite

- **Polymers**
  - Biopolymers
    - Xanthan
    - Guar Gum
  - Polyacrylate/Polyacrylamides
  - HEC (Hydroxyethylcellulose)
  - CMC (Carboxymethylcellulose)

**Dispersants/Deflocculants**

- Lignosulfonates
- Lignites
- Phosphates
- **SSMA** (Styrene Sulfonate Maleic Anhydride)
  (important for High Temperature Applications)
State Diagram of Colloidal Montmorillonite Suspension in Water

Clay Platelets

- Dispersed
- Aggregated
- Face to Face
- Face to Edge

Dispersed and Flocculated

Increasing Plastic Viscosity (PV)
- Decreasing filtration rate, reduced water bonding

Aggregation

Flocculation

Increasing Yield Point (YP) and Gel Strength

Dispersion

Decreasing Plastic Viscosity (PV)
- Increasing filtration rate, reduced water bonding

Irreversible

Reversible
Support of the Borehole Wall – Balancing Formation Pressures

While Drilling Open Hole
Mud Column should act as „Hydraulic Casing“

Sufficient Mud Density
Good Filtration Properties

Insufficient Mud Density
Bad Filtration Properties

- Uncontrolled Fluid Entry
- Borehole Instabilities
- Differential Sticking
Balancing Formation Pressures

Normal Drilling (overbalanced)
Mud Pressure > Formation Pressure

Pressure of Mud Column
\[ P_{\text{mud}} = \text{Density}_{\text{mud}} \times g \times \text{Depth} \]

Formation Pressure Profile

Pressure (MPa)

EXCESS PRESSURES
overhydrostatic
SUBNORMAL PRESSURES
subhydrostatic

INTAKE AREA

PIEZOMETRIC SURFACE

GROUND LEVEL

PRESSURE HEAD

DISCHARGE AREA

RESEVOIR ROCK

OIL POOL

geopressed Aquifer

hydrostatic

petrostatic:

Sub hydrostatic

Frac Gradient: Mud
Instruments for Measuring Mud Density

Hydrometer

Mud Balance
Weighting Materials for Drilling Muds

Mud Density (kg/dm³)

- Calcium Carbonate
- Barite
- Ilmenite
- Iron Powder
- Lead Oxide
- KCl
- NaCl
- Sodium Formate
- CaCl₂
- NaBr
- K₂CO₃
- Potassium Formate
- CaBr₂
- ZnBr₂

Solids Free Salt Solutions
Inert Solids
Solids Content and Mud Density for Various Weighting Materials

- Calcium Carbonate (2.7 kg/dm³)
- Barite (4.2 kg/dm³)
- Ilmenite (4.8 kg/dm³)
- Iron Powder (7.9 kg/dm³)
- Lead Oxide (9.1 kg/dm³)

Mud Density (kg/dm³)

Solids Concentration (Volume Fraction)
Supporting the Borehole Wall – Hydraulic Casing Effect

Mud Properties
- Mud Density -> Pressure Support
- Filtration Characteristics -> Wall Sealing
- Free Water Activity -> Interaction Rock

Beginning Filtration
Buildup of Filtercake

Invasion of:
- Mud Filtrate
- Mud Particles

Wall sealed

Filter Cake

Impermeable Formation

Good Filtration Characteristics
- Quick Filtercake Buildup
- Low Filtration Rate
- Filtercake
  - thin
  - impermeable
  - slick

Minimizing Formation Damage
Filtercakes and Differential Sticking Mechanism

Overpull required to unstick BHA

Thick Mudcake

OVPL (tons) vs Pore pressure (SG)

- 4 mm
- 7 mm
- 1 mm

Max. OVPL = 130 tons

MW=1.69
h=75% of 74 m

Sticking Area
Sticking Force
Measuring Filtration Properties

Parameters measured:
- Filtrate Volume (ml) after 30 min
- Cake Thickness (mm)

Normal Conditions
- T: Room Temperature
- $\Delta P$: 100 psi (7 bar)

HTHP Conditions
- T: 300°F (149°C)
- P: 500 Psi (35 bar)
- $\Delta P$: 100 psi (7 bar)
Principle of Capillary Suction Timer

Mud sample

Filter Paper

Electrode

Spreading of Free Water


time spreading time \rightarrow CST Value

\Delta T: seconds

high CST \rightarrow low free water

low CST \rightarrow high free water
Destabilisation of Red Shale Caused by Contact with Water

Original Sample

Sample after 20 min in Water

Sample after 24h in Dehydrl HT (2%)

Destabilisation Process is favoured by High Free Water Activity

High Free Water Activity <-> Low CST
Low Free Water Activity <-> High CST
Additives Controlling Filtration Properties and Free Water Activity

Bentonite ↔ Polymers

Polymers act as Protection Colloids
Preventing Aggregation of Clay Particles

- Starch
- Polyanionic Cellulose (PAC)
- Sodium Carboxymethylcellulose (CMC)
- Hydroxyethylcellulose (HEC)
- Polyacrylates/Polyacrylamides
- Vinilsulfonate/Vinylamide-Copolymers (VS/VA)
### Prevention of Lost Circulation – Factors to Consider

#### Types of Lost Circulation Zones

<table>
<thead>
<tr>
<th>Types of Lost Circulation Zones</th>
<th>Preventive Methods</th>
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<tbody>
<tr>
<td>High Permeable Gravel</td>
<td>• Reducing Mud Density</td>
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<tr>
<td></td>
<td>• Avoiding Pressure Surges</td>
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<tr>
<td></td>
<td>• Lowering Gel Strength</td>
</tr>
<tr>
<td></td>
<td>• Lowering Equivalent Circulation Density (ECD)</td>
</tr>
<tr>
<td>Natural/Artificial Fractures</td>
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<tr>
<td></td>
<td><strong>Fighting Against Lost Circulation</strong></td>
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<tr>
<td></td>
<td>Application of Sealing Material</td>
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<tr>
<td></td>
<td>Sealing at Fracture Face</td>
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<tr>
<td></td>
<td>Sealing within The Fracture</td>
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<td>Proper Size Distribution</td>
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<tr>
<td>Caverneous Formation</td>
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</tbody>
</table>

#### Types of Materials used:

- Fibrous (Raw Cotton, Mineral Fibers, Glass Fibers)
- Flaky (Cellophane, Mica, Cotton Seed Hulls)
- Granular (Perlite, Ground Plastic, Nut Shells, Wood)
- Thick Slurry Pills (Bentonite/Polymer, Cement)
Reducing Friction – Controlling Torque/Drag

Borehole Curvature
Dogleg Severity: deg/m

Rotating Drillstring

Trip In/Out Drillstring

Normal Force $F_N$

Friction Force $F_R$

$F_R = \mu * F_N$

Drag (Trip In/Out)
Torque (Rotation)

Mud Lubricity Coefficient

Rotating Drillstring Trip In/Out
Inhibiting Corrosion

Forms of Corrosion
- Uniform Corrosion
- Localized Corrosion (Pitting)
  - Bimetallic Corrosion
  - Oxygen Concentration Cells
    - Crevice Corrosion
    - Air/Water Interface
    - Oxygen Tubercles
    - Scaling/Sludges
- Corrosion Fatigue
- Stress Corrosion
  - Sulfide Cracking
  - Hydrogen Embrittlement

Measures
- Raising pH of Mud
- Reducing dissolved Oxygen in Mud
  - Vacuum Degassing
  - Oxygen Scavengers
    - Sodium Sulfite
    - Sodium Nitrite
- Addition of Corrosion Inhibitors
  - Filming Amines
  - Sulfide Scavengers
  - Zinc Carbonate
  - Sodium Molybdate

Corrosion is the Major Cause of Drillpipe Failures
<table>
<thead>
<tr>
<th>Product Name</th>
<th>Trivial Name</th>
<th>Formula</th>
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Mud Properties Must Aid Effective Cuttings Removal

Solids Control Equipment Is the Base for Cutting Sampling