Hydraulic Testing and Fluid Sampling

Lesson I

- **Introduction and Objectives**
  - Technical/Scientific Aspects
- **Geohydraulic Properties of Rocks**
  - Permeability/Transmissivity/Storage Coefficient
  - Fractured Rocks
  - Dual Porosity Models
- **Theory of Test Evaluation**
  - Horner‘s Method
  - Wellbore Storage
  - Skin Effect
- **Fundamentals of Drill Stem Testing**
  - Test Assemblies
  - Open Hole/Cased Hole

Lesson II

- **Testing Equipment**
  - Principle of Packers
  - Data Recording/Transmission
  - Sampling Equipment
- **KTB-Experiences**
  - Pilot Hole
  - Ultradeep Hole
- **Conclusions**
Hydraulic Testing/Fluid Sampling - Why do we deal with?

Primary Scientific Objectives

- Heat
- Fluids
- Stress
- Transport Processes

Key Parameters

- Heat Sources
- Permeability
- Fluid Chemistry
- Stress State
- Pore Pressure
- Mineralization
- Stress
- Earthquakes
- Temperature Profile
- Heat Transport
- Quatz
- Calcite
- Graphite
- Flow Barriers
- Diffusivity
- Driving Forces
- Fluid Properties
- Density
- Compressibility
- Chemistry/Salinity
- Viscosity
Planning Considerations Hydraulic Testing/Fluid Sampling

**Hydraulic Testing**

**Scientific Goals**

Representative Data about:
- Geohydraulic Properties
- Pore Pressure
- Permeability/Transmissivity
- Storativity

Achieving Goals Depends on:
- Type of Formation
- Magnitude of Permeability
- Wellbore Storage/Skin effect
- Test Duration
- Test Design/Equipment
- Hole/Well Condition
- Open Hole/Cased Hole

**Fluid Sampling**

**Scientific Goals**

Representative Fluid Samples

Chemical Composition of Fluids/Gases

Achieving Goals Depends on:
- Delay Time since Detection of fluid zone
- Contamination with Mud
- Wellbore Damage/Skin
- Sampling Equipment
- Test Duration
- Magnitude of Permeability

**Interruption of Drilling Process**

Hydraulic Isolation of Test Interval

Technical/Borehole Stability Risks

Successful Planning Requires Close Cooperation of Geoscientists and Engineers
Permeability and Hydraulic Conductivity

Permeability is a Measure of the Ability of a Rock Mass to Transmit Fluids

Darcy’s Law

\[ \frac{Q}{A} = q = -K \frac{(h_2 - h_1)}{L} = -K \frac{\partial h}{\partial l} = -KJ \]

1 Darcy = 10^{-12} m^2 = 10^{-5} m/s

K (Rock + Fluid): Hydraulic Conductivity (m/s)

k: (Rock): intrinsic Permeability (m^2 or Darcy)

\[ K = k \frac{\rho g}{\mu} \]
## In situ Hydraulic Conductivity of Rock Masses

**K**: Conductivity, $\text{m/s}$

<table>
<thead>
<tr>
<th>Degree of conductivity</th>
<th>V. high</th>
<th>High</th>
<th>Moderate</th>
<th>Low</th>
<th>V. low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil type</td>
<td>Gravel</td>
<td>Sands</td>
<td>V. fine sands, silts, glacial tills, stratified clays</td>
<td>Homogeneous clays</td>
<td></td>
</tr>
<tr>
<td>Rock type</td>
<td>Fractured</td>
<td>Sandstone</td>
<td>Soln.Cavities</td>
<td>Limestone &amp; Dolomite</td>
<td>Unfractured</td>
</tr>
<tr>
<td></td>
<td>Cavernous/Fractured</td>
<td>Basalt</td>
<td>Dense</td>
<td>Fractured/Weathered</td>
<td>Volcanics excl. Basalt</td>
</tr>
<tr>
<td></td>
<td>Weathered</td>
<td>Metamorphics</td>
<td>Bedded Salt</td>
<td>Weathered</td>
<td>Granitic Rocks</td>
</tr>
</tbody>
</table>
Types of Fluid Pathways in Rocks

- Homogeneous Porous Continuum
- Fractured/Fissured Continuum
- Homogeneous Porous Continuum
- Fractured/Fissured Continuum
- Fault Zone
- Rock Matrix
- Joints
- Fractures
- Carbonates
- Permeability depends on Scale
  - Core Sample
  - Field (Rock Mass)

- Sand/Sandstone
- Crystalline Rocks
- Fault Zone
- Rock Matrix
- Joints
- Fractures
- Cavernous/Carst

- Continuum
  - Single
  - Dual Porosity
- Discrete Network
  - Simple Fractures
  - Stochastic
  - Fractal
Principles of Hydraulic Testing

A Hydraulic Test is an Experiment which creates a Pressure/Flow-Signal by
- withdrawal
- injection of fluid

Pressure/Flow-Response of the Formation is evaluated by means of a Conceptual Model with distinct Geohydraulic Properties

The Test Procedure depends on:

- Type of reservoir
  - homogeneous
  - fractured
- Magnitude of Permeability
  - high
  - low
- Main objectives
  - fluid sampling
  - geohydraulic properties
- Borehole/Well Status
  - open hole
  - cased hole

Test Interval hydraulically isolated by packers
Characteristic Pressure Diagrams of Hydraulic Test Methods

Constant Head Test

- \( P \) (MPa)
- \( q \)
- Closed
- Open
- Time \( t \)
- \( P_{stat} \)
- Testvalve

Constant Flowrate Test

- \( P \) (MPa)
- \( q \)
- Time \( t \)
- \( P_{stat} \)

Slug Test

- \( P \) (MPa)
- \( q \)
- Time \( t \)
- \( P_{stat} \)

Drill Stem Test (DST)

- \( P \) (MPa)
- \( q \)
- Time \( t \)
- \( P_{stat} \)

Pulse Test

- \( P \) (MPa)
- \( q \)
- Time \( t \)
- \( P_{stat} \)

Combined Pulse/Slug Test

- \( P \) (MPa)
- \( q \)
- Time \( t \)
- \( P_{stat} \)

Increasing Permeability

- very low to low
- low to medium
- medium to high
- very high to high
**Theory of Hydraulic Test Evaluation**

**Diffusivity Equation:**

\[
\frac{\partial^2 p}{\partial r^2} + \frac{1}{r} \frac{\partial p}{\partial r} = \frac{\phi \mu c_t}{k} \cdot \frac{\partial p}{\partial t}
\]

Based on:
- Continuity Equation
- Darcy’s Law
- Equation of State

\[c_t = c_f + c_p\]

\[\Delta V_f = -c_f V_p \Delta p\]

\[\Delta V_p = -c_p V_p \Delta p\]

\(\phi\): Porosity
\(\mu\): Fluid Viscosity
\(k\): Permeability
\(c_t\): Total Compressibility
\(c_f\): Fluid Compressibility
\(c_p\): Pore Compressibility

**Solving the Diffusivity Equation:**

\[
p_{r,t} = p_i + \frac{q \mu}{4 \pi k h} E_i \left( - \frac{\phi \mu c_t r^2}{4 k t} \right)
\]

\[-E_i(-x) = \int_x^\infty \frac{\exp(-u)}{u} \, du\]

**Boundary Conditions**

- uniform initial pressure \(p_i\)
- infinite reservoir
  - with \(p \to p_i\) as \(r \to \infty\)
- constant flow rate: \(q\)
- infinitesimal well radius

**Logarithmic Approximation**

If \(\frac{\phi \mu c_t r^2}{4 k t} < \frac{1}{100}\) \(\Rightarrow\)

\[
p_{r,t} = p_i + \frac{q \mu}{4 \pi k h} \ln \frac{\gamma \phi \mu c_t r^2}{4 k t}
\]
Superposition Principle

\[ p_{ws}(\Delta t = 0) = p_{wf}(t_p) \]

Semilog Straight Line Equation
Horner Plot

\[ p_i - p_{ws}(\Delta t) = \frac{21.5 q B \mu}{k h} \log \left( \frac{t_p + \Delta t}{\Delta t} \right) \]

Logarithmic Approximation
of Solution of Diffusivity Equation

\[ p_i - p_{ws}(\Delta t) = [p_i - p_{wf}(t_p + \Delta t)] - [p_i - p_{wf}(\Delta t)] \]
Evaluation of Pressure Buildup Test - Horner's Method

\[ p_i - p_{ws}(\Delta t) = \frac{21.5 \, qB\mu}{kh} \log \frac{t_p + \Delta t}{\Delta t} \]

Increasing \( \Delta t \)

Extrapolated \( p_i \): undisturbed formation pore pressure

\[ m = \frac{21.5 \, qB\mu}{kh} \]

Transmissivity

\[ kh = \frac{21.5 \, qB\mu}{m} \]

Extrapolated \( p_i \) as \( r \to \infty \)

Infinite reservoir

Distortion by Wellbore Storage

Skin Effect

S: Skin Effect determined after 1 h of Pressure Buildup

Radius of Investigation

\[ r_i = 0.038 \sqrt{\frac{k \Delta t}{\phi \mu c_i}} \]
Pressure Buildup Analysis - Skin Effect

S > 0 \( k_s < k_{or} \) plugged (Mud)
S < 0 \( k_s > k_{or} \) enhanced (Fractures)

\[ S = 1.15 \left( \frac{p_{1h} - p_{wf}(t_p)}{m} + \log \frac{t_p + 1}{t_p} - \log \frac{k}{\phi \mu c_t r_w^2} + 3.10 \right) \]
Hydraulic Testing - Effect of Wellbore Storage

Due to Compressibility of Wellbore Fluid
Surface Shut In is not Transmitted Instantaneously to Bottomhole

Wellbore Storage: $C = -\Delta V_{\text{well}}/\Delta p$

Early Time Pressure Buildup Data are affected by Wellbore Storage

Wellbore Storage Orders of magnitude
Downhole Shut In (DST): $10^{-4} - 10^{-3} \text{ m}^3/\text{bar}$
Surface Shut In: 0.1 to 1 m$^3$/bar

Flow Rate

- Surface
- bottomhole

Bottomhole pressure

Time

Flowmeter and/or Pressure Gauge
No Downhole Shut In Valve
DST is a Slug-Withdrawal Test with 2 Flow Phases combined with 2 Pressure Buildup Phases. Tools are run into the well on the Drill Stem. In situ Fluid Samples can be obtained.
Drill Stem Test - Typical Operation Diagram

Rev. Circ. Sub
Dual CIP-Circ. Ports
Dual CIP-Valve
Tester-Valve
ByPass-Ports
Pressure Recorder
ByPass-Ports
Packer
Perforated Anchor
Pressure Recorder

Running In  Flow Phase  Shut In  Press. Equal.  Reverse Circ.  Running Out
(water, nitrogen)
Downhole Sampling during DST - Operational Diagram

Running In

Tester-Valve

Multiple Sampler

ByPass-Ports

Extension Joint

Pressure Recorder

Safety Joint

Packer

Perforated Anchor

Pressure Recorder

Running Out

Flow Period

Flow Through Sample Chamber

Shut In

Sample Trapped In Situ Pressure

Running Out
Basic Types of Test Assemblies

Packers are Rubber-Elements designated for Hydraulic Isolation of Test Interval

Open Hole Test

Single Packer  Straddle Packer

Cased Hole Test

Hook Wall Packer

RTTS TESTING PACKER

TESTED INTERVAL

COLLAR

PERFORATED TAILPIPE

B.T. PRESSURE RECORDER (BLANKED OFF)

HT-500 TEMPERATURE RECORDER
Working Principle of Mechanically Expandable Packers

Running in Hole

Setting the Packer by Slacking off Weight

Anchor Pipe perforated

Support for weight to set the packer

Anchor Pipe

Anchor Shoe

Bottom of Hole

Side Wall Anchor

Used below straddle packers
Working Principle of Hydraulically Inflatable Packers

Inflatable Packer
Open Hole

Inflating Hydraulically

Closed

Open

Slacking off DP

Flow Period

Mud

Steel ball

Auto-J moved down

Inflating port is closed

Stinger unssets ball

Fluid flows through packer
Pressure/Temperature Recorders for Drill Stem Testing

Bundle Carrier for Electronic Pressure Gauges

Bourdon Tube (BT) Pressure-Recorder

Temperature Recorder

BT Running Case

Pressure Entry Passage
Hydraulic Test Tool with Online Data Acquisition

Advantages
- Realtime Downhole P/T-Information during the Test
- Realtime Interpretation
- Withdrawal/Injection Option
- Control of Packer Seal (P1-P3)

Disadvantages:
- Packer Inflated via Test String
- String has to be Emptied before Test for Pressure Drawdown
- Limited Depth Capacity
- Transmission Cable clamped outside of Test String (Risk of Damage in Crooked Holes)
Procedures for Fluids Withdrawal/Injection

Pumping
- Tubing String
- Submersible pump

Swabbing
- Swab winch
- Swab Line
- Swab Elements
- Packer

Injection
- HP Injection pump
- Straddle Packer
- Packer

Gas/Air-Lift
- Compressed nitrogen
- Packer
## Planning a Hydraulic Test - Factors to Consider

<table>
<thead>
<tr>
<th>Hole Conditions</th>
<th>Mud Conditions</th>
<th>Test Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Borehole Caliper</td>
<td>• Mud Weight</td>
<td>• Max. Differential Pressure</td>
</tr>
<tr>
<td>• Borehole Trajectory</td>
<td>• as high as necessary</td>
<td>• Water or Nitrogen cushion</td>
</tr>
<tr>
<td>Keyseats, Doglegs</td>
<td>• as low as possible</td>
<td></td>
</tr>
<tr>
<td>• Borehole Wall</td>
<td>• Mud Solids, Viscosity</td>
<td>• Duration of Test</td>
</tr>
<tr>
<td>Stability</td>
<td>• Gel Strength</td>
<td>(Flow and Shut-In Periods)</td>
</tr>
<tr>
<td></td>
<td>• as low as possible</td>
<td>• Radius of Investigation</td>
</tr>
<tr>
<td></td>
<td>• Sufficient Thixotropy</td>
<td></td>
</tr>
<tr>
<td>• Caliper Log</td>
<td>• Mud Conditioning</td>
<td>• Sampling Strategy</td>
</tr>
<tr>
<td>• Inclination</td>
<td>• Sufficient Circulation</td>
<td>Min. Inside Diameter of Test String</td>
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<tr>
<td>• Azimuth</td>
<td>• Complete cutting removal</td>
<td></td>
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<tr>
<td>• Dogleg Severity</td>
<td></td>
<td>• Data Recording</td>
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<tr>
<td></td>
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<td>Pressure/Temperature Gauges (Mechanical,</td>
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<td>Electronical)</td>
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### Selection of Test Equipment