Subsurface Pressure and Stress

Stress

Stress = force / area
Units = Pascals, psi

= N/m²
= kg/(m . s²)

Force = 50 kg * 9.8 m/s²
Area = 1 cm² = 0.0001 m²
Stress = 4,900,000 Pascals = 686 psi

How much is 1 Pascal?

• 1 Pa = 0.00014 psi
• Car tire ~230,000 Pa
• 1 Megapascal (1 MPa) = 1 million Pa
  = 1 x 10⁶ Pa
  = 145 psi

Stress/pressure

• What is the difference?
• Pressure - Scalar quantity
• Stress - Tensor quantity
• Pressure – in fluids
• Stress – in solid bodies

Stress Tensor

On-in convention:

ON the x-plane
IN the y-direction

2D Stress Tensor

Normal and Shear components
Lithostatic stress/ hydrostatic stress

- Lithostatic stress
- Tectonic stress
- Fluid Pressure
  - Hydrostatic
  - Hydrodynamic

Lithostatic Stress

- Due to load of overburden
- Magnitude of stress components is the same in all directions

\[ \sigma_{\text{Lith}} = \rho \cdot g \cdot z \]

- Density
- Gravity
- Depth

Lithostatic Stress Gradient

\[ \sigma_{\text{Lith}} = \rho \cdot g \cdot z \]

Rock density = 2000 to 3000 kg/m³

\[ \sigma_{\text{Lith}} = 2500 \text{ kg/m}^3 \times 9.8 \text{ m/s}^2 \times 1000 \text{ m} \]

\[ \approx 25 \text{ MPa/km} \]

\[ \approx 1 \text{ psi/ft} \]

Pressure/stress gradients

- 22 to 26 Mpa/km
- 1 psi/ft
- 10 Mpa/km
- 0.43 psi/ft

What about horizontal stress?

Rocks are elastic solids
Horizontal stress depends on rock compressibility

Poisson’s Ratio \( \nu = \frac{|e_{yy}|}{e_{xx}} \)

\( \nu = 0.5 \) incompressible material (no volume loss)

Rocks \( \nu = 0.1 \) to 0.3

Horizontal Stress

\[ \sigma_{\text{Hor}} = \nu / (1 - \nu) \cdot \rho \cdot g \cdot z \]

If \( \nu = 0.5 \), \( \sigma_{\text{Hor}} = \rho \cdot g \cdot z \)

If \( \nu = 0.25 \), \( \sigma_{\text{Hor}} = 0.33 \rho \cdot g \cdot z \)

Horizontal stress is about 1/3 of vertical if rocks are lithified
Comparison of vertical and horizontal stresses

Suppe, 1985

Vertical Min horizontal

ρgz

ρgz

Borehole Wall Breakouts and Stress

Horizontal Stresses

Caliper log measures the shape of the borehole

Pressure/stress gradients

22 to 26 Mpa/km
1 psi/ft

10 Mpa/km
0.43 psi/ft

Overpressure = more than hydrostatic

Spindletop, 1901 Deepwater Horizon, 2010

What about these?

Why more than 0.43?
Shale Porosity vs. Depth Curve

Shale compacts as water is expelled

Schmoker and Halley, 1982

Shale Compaction

Wet Mud
Compacted Sediment (water expelled)

Over Pressure Zone

Pressure seal inferred to exist in region of high fluid pressure gradient

Fluid pressure as a function of depth, Cook Inlet Alaska - Hunt, 1990

Reservoir Compartments

Pressure barrier

Characteristics of Overpressure Zones

- Under-compacted shale
- Low density, low sonic velocity
- Rapid Drilling Rate
- Low Thermal Conductivity, high T
- Low Salinity

Controlling Reservoir Pressure

- Drilling Mud
- Casing
- Blow-out preventers
**Blow Out Preventers**

How to measure formation pressure

Formation Tester
Schlumberger

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How to measure reservoir pressure?

**Drill Stem Test**

![Drill Stem Test Diagram](image)

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**Drill Stem Test Pressure Results**

![Drill Stem Test Pressure Chart](image)

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**Drill Stem Test (DST)**

1. **Initial Flow Period (IFP)** removes effect of mud filtrate “supercharge.”
2. Initial Shut-in is used to determine reservoir Pressure (ISP).
3. Final Flow Period (FFP) is used to collect a fluid sample and create a pressure disturbance beyond any damaged zone.
4. Final Shut-in is used to test permeability, production rate and well damage.

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**Initial Reservoir Pressure**

Leduc Fields, Alberta (Canada)

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Leduc #1 Gas flare
Phase Behavior for a single hydrocarbon

- Liquid
- Critical point
- Supercritical fluid
- Gas

Supercritical: density like a fluid, viscosity like a gas

Phase Behavior of Gas-Oil Mix

- Reservoir
- Critical Point
- Separator
- Stock Tank
- Bubble Point
- Gas

Phase Behavior of Wet Gas or Condensate

- 100% Liquid
- Gas

Pressure vs. Temperature graph showing phase transitions.

Summary

\[ \sigma = \rho g z \]

- Hydrostatic gradient = 0.43 psi/ft or 1 Mpa/km
- Lithostatic gradient= 1 psi/ft or 25 MPa/km
- Overpressure forms when water cannot escape
- Pressure gradient defines reservoir compartments
- Artesian aquifers can produce anomalous P
- Methods to control P during drilling
- Hydrodynamic reservoirs lead to tilted oil-water contacts
- Physical state of hydrocarbons depends on P-T regime
- Bringing oil to the surface cools and depressurizes it