GEOMECHANICS FOR GEOPHYSICISTS

Borehole Stability

Rune M Holt

Trondheim, 26 April 2012

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Borehole Stability Problems

- **Tight hole / Stuck pipe incidents**
  - Responsible for 5-10% of drilling time
  - Most frequently occurring in shale
  - Often high pore pressure, and in presence of swelling clay minerals (e.g. smectite)
  - Often in deviated wells
- **Lost circulation / Mud losses**
  - May lead to kick / blow-out
  - Caused by fluid lost into natural fractures or by new fractures generated

Tight hole / Stuck pipe

- **Causes:**
  - Mechanical borehole collapse (often by shear failure)
    - Increased hole size by brittle failure; stuck because of accumulated cavings (”sloughing shale”)
    - Reduced hole size by large (plastic) hole deformations (”gumbo shale”)
  - Inappropriate hole cleaning
  - Differential sticking (only in permeable zones with mud cake)
  - Difficult hole trajectory: Key-seat, dog-legs

Tight hole / Stuck pipe

- **Consequences:**
  - Lost time, reaming, side-track $\propto$ € (or $)
  - Problems in further well operations (logging, cementing; continued drilling)
- **Solutions:**
  - Overall well design i.e.
    - Casing programme
    - Mud weight
    - Mud composition
    - Drill somewhere else..
- ***Note: The solution depends on the cause $\Rightarrow$ Need for diagnostics***

Lost circulation / Mud losses

- **Consequences:**
  - Dangerous situation, a major safety issue
  - Risk of life and equipment
- **Solutions:**
  - Overall well design i.e.
    - Casing programme
    - Mud weight
    - Lost circulation material (LCM)

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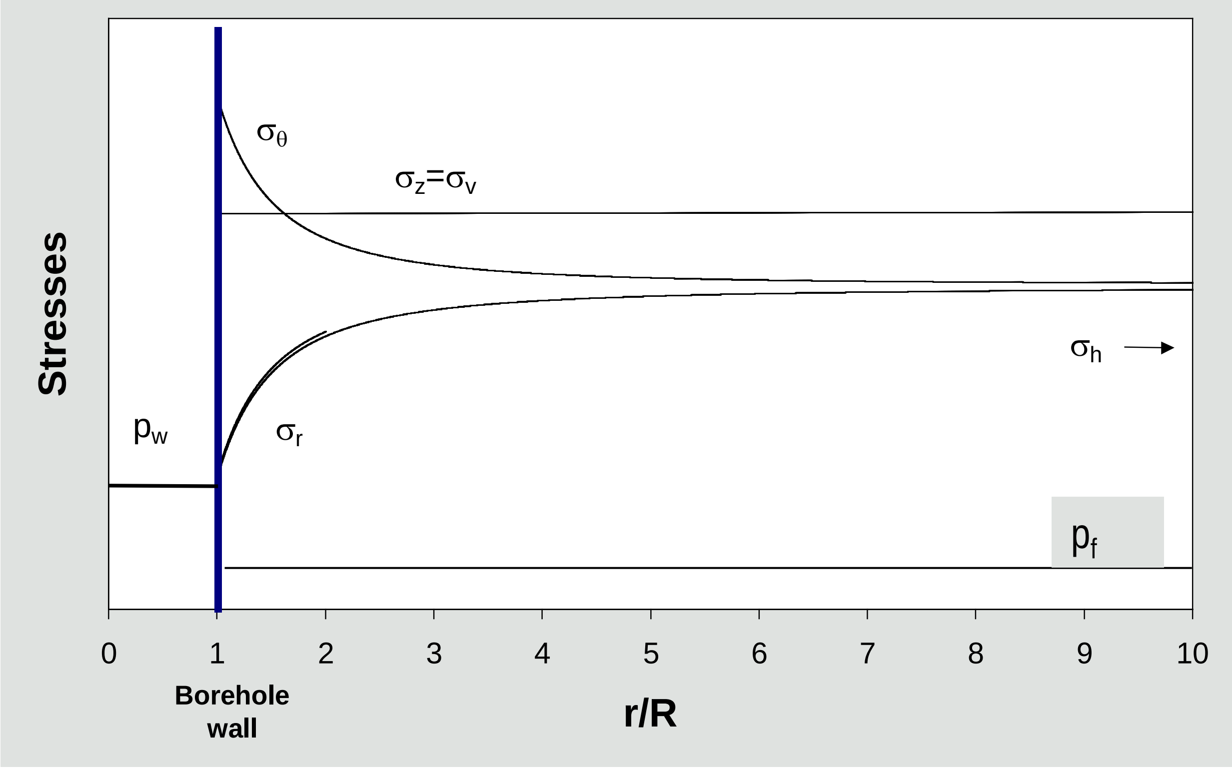
Borehole Stress Analysis

Stresses at vertical impermeable borehole wall (based on linear elastic rock and isotropic horizontal stresses):



$$\sigma_r = p_w$$
$$\sigma_\theta = 2\sigma_h - p_w$$
$$\sigma_z = \sigma_v$$

Case a: $\sigma_\theta > \sigma_z > \sigma_r$

Impermeable wall means:

- Perfect mud cake, or
- During drillout in shale

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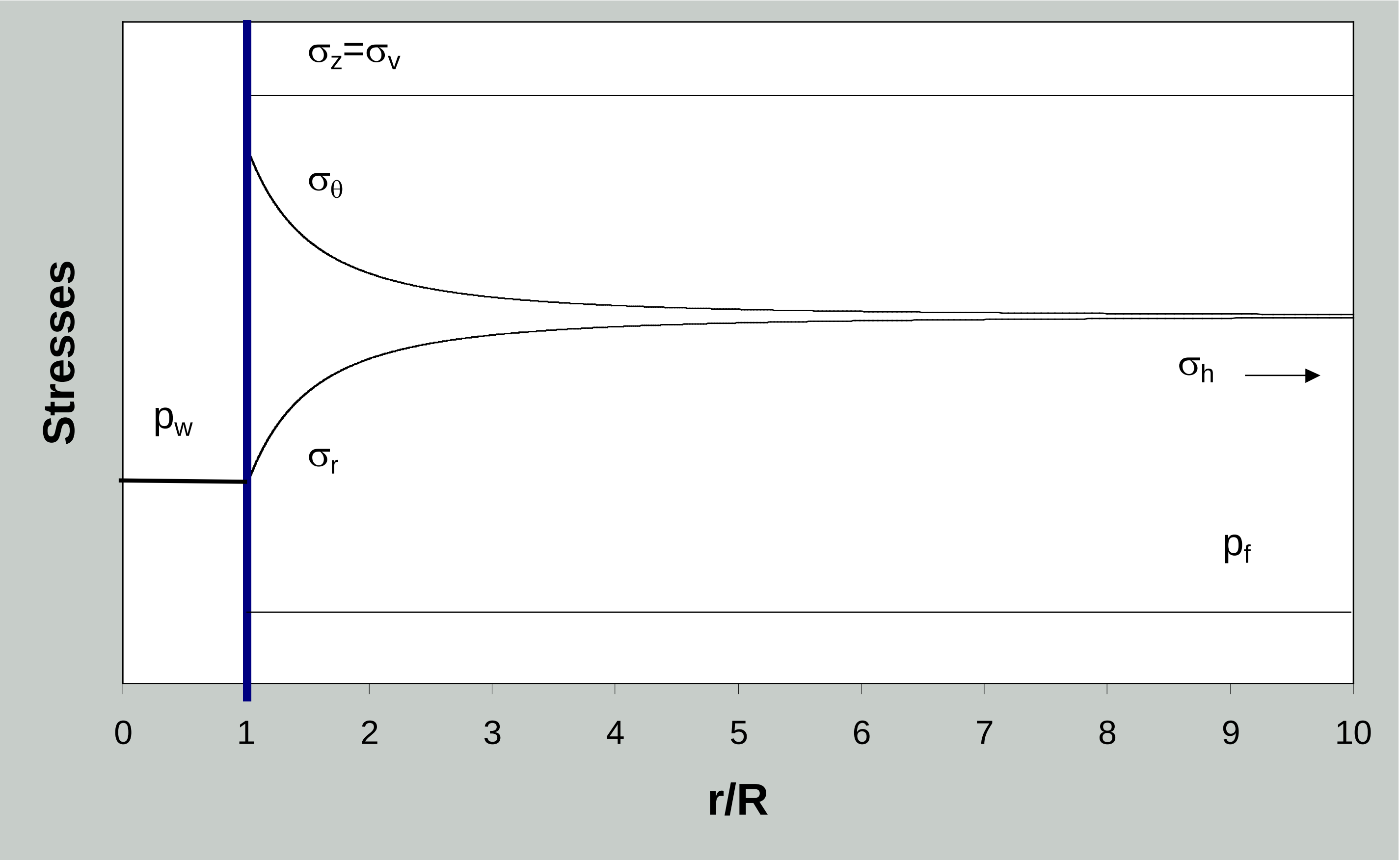
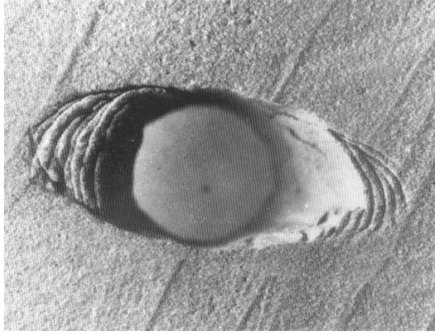
Borehole Stress Analysis



Case b: $\sigma_z > \sigma_\theta > \sigma_r$

Borehole Failure Analysis



- Borehole stresses + Mohr-Coulomb failure criterion

$$\Rightarrow \quad \sigma_1' = C_0 + \sigma_3' \tan^2 \beta$$

- Minimum permitted well pressure to prevent shear failure at borehole wall (hole collpase)

$$p_{w,\min}^{(a)} = p_{f0} + \frac{3\sigma_H' - \sigma_h' - C_0}{\tan^2 \beta + 1}$$

or

$$p_{w,\min}^{(b)} = p_{f0} + \frac{\sigma_v + 2|\nu_{fr}|(\sigma_H - \sigma_h) - C_0}{\tan^2 \beta}$$

$$\Rightarrow \quad p_{w\min} = \rho_{w\min} g D$$

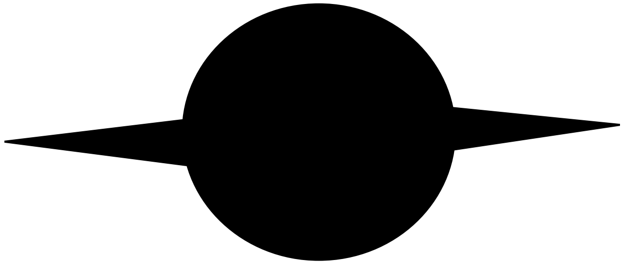
Minimum mud weight

Borehole Failure Analysis

- Tensile failure at the borehole wall may occur at high well pressure (Hydraulic fracturing => mud losses):

$$\sigma_\theta^{'} = -T_0 \quad \Rightarrow$$

$$\boxed{p_{w,\max}^{frac} = 3\sigma_h - \sigma_H - p_{f0} + T_0}$$

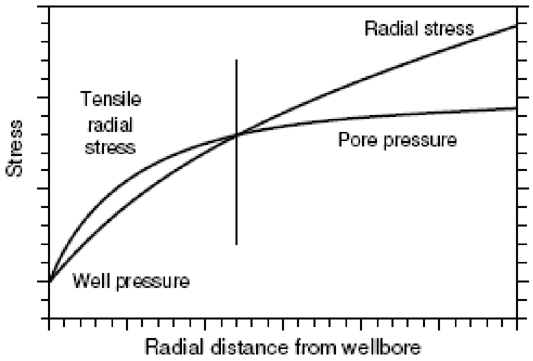


- Tensile failure may also occur at low well pressure (in underbalance):

$$\sigma_r^{'} = -T_0$$

$$\Rightarrow$$

$$\boxed{p_{w,\min}^{rad,tens} = p_{f0} - T_0}$$



Gives sharp (blade-shaped cavings

The Mud Weight Window

- **Minimum mud weight**
  - Hole collapse in shale (shear failure case a or b)
  - Radial tensile failure in shale
  - Pore pressure (in case underbalanced drilling is prohibited)
- **Maximum mud weight**
  - σ_h (minimum horizontal stress) in case of pre-existing natural fractures
  - Fracturing of borehole wall

Boreholes in anisotropic stress fields

- If hole axis is parallel to a principal stress, then we can use the borehole stresses for a vertical hole also for horizontal holes, but we need to rotate the coordinate system first.

- In general: Holes are most stable towards shear failure initiation when drilled along a direction with low stress anisotropy and with low stress level in the plane perpendicular to it.

- Deviated holes are usually less stable because of shear stresses at the borehole wall.

Stability vs. Hole Angle

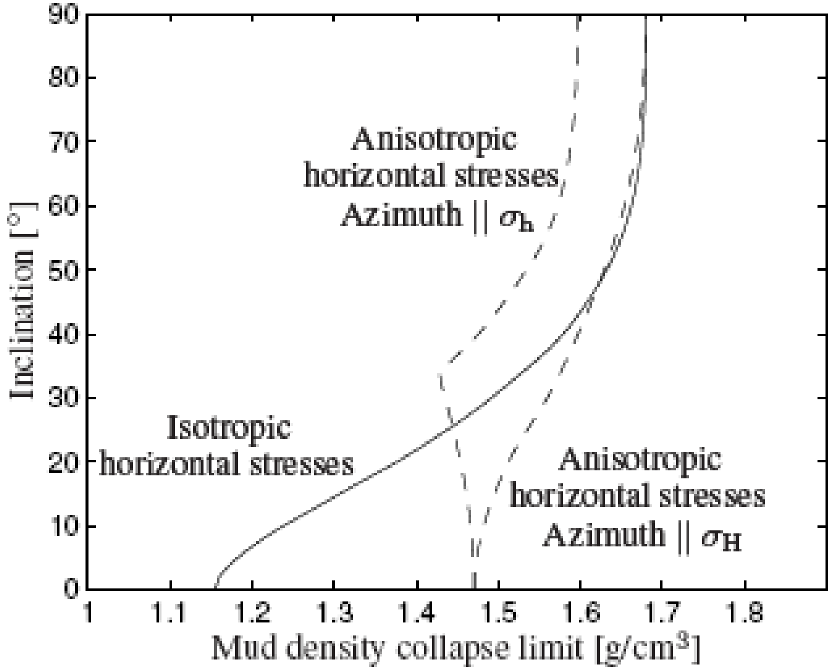
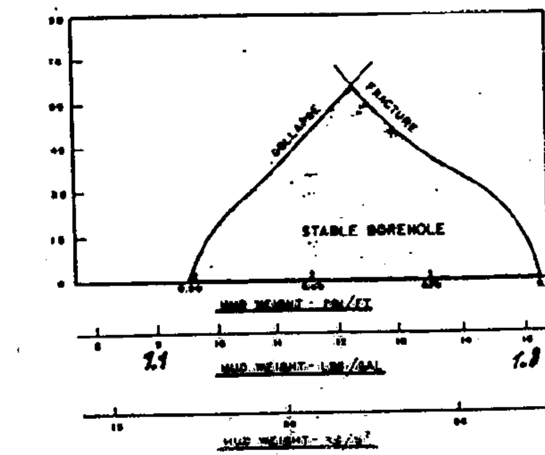


Illustration of stability analysis for a deviated wellbore at 1500 m depth, with vertical stress 30 MPa, isotropic horizontal stresses 25 MPa, and pore pressure 15.5 MPa. The unconfined strength is set to 10 MPa, the friction angle is 30°, the Biot coefficient 1, and Poisson's ratio 0.25. Also included is a case with anisotropic horizontal stresses, where all parameters are kept the same as above, except the maximum horizontal stress 28 MPa.



From Bradley, 1979: Impossible to pass 60˚?

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Well Design

c: Collapse

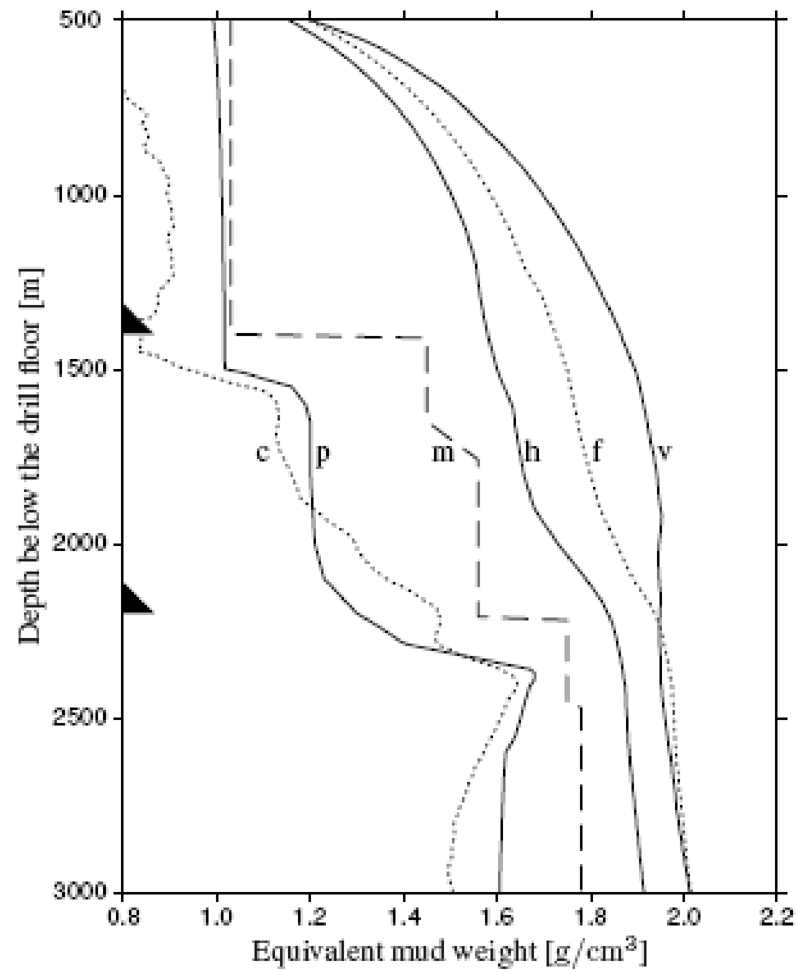
p: Pore pressure

m: Mud weight

h: Horizontal stress

f: Fracture

v: Vertical stress



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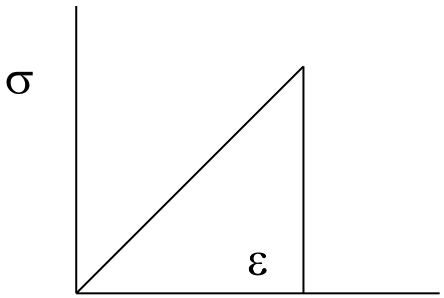
Borehole Stability

... so far elastic behaviour + brittle failure

But: Note the following field observations:

- Boreholes are often stronger than predicted by elastic+brittle theory
- Hole collapse is often time-delayed (~ days) with respect to drill-out
- Oil-based mud gives better stability than water-based mud
- Addition of salt (in particular K+) may improve stability

Borehole Stability: Plasticity

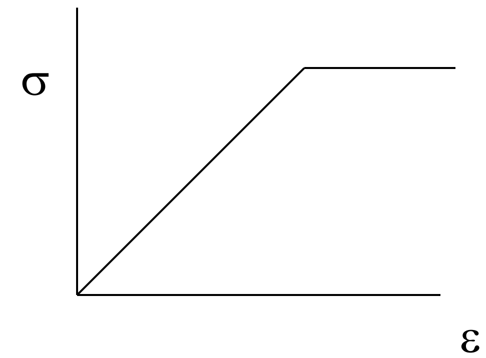


Stress-strain curves for

☐ Elastic-brittle

Elasto-plastic ☐

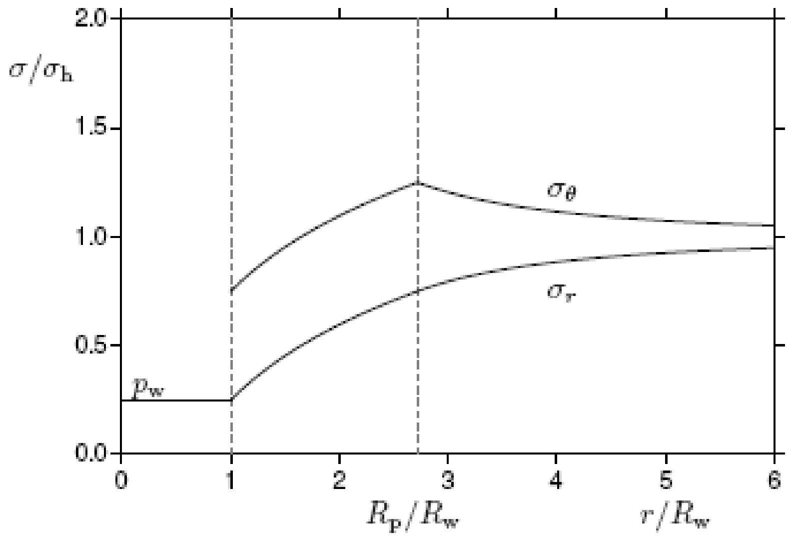
material behaviour



- Elastic-brittle: No load-bearing capacity after failure initiation
- Elasto-plastic: Can still sustain load after failure initiation

Borehole Stability: Plasticity

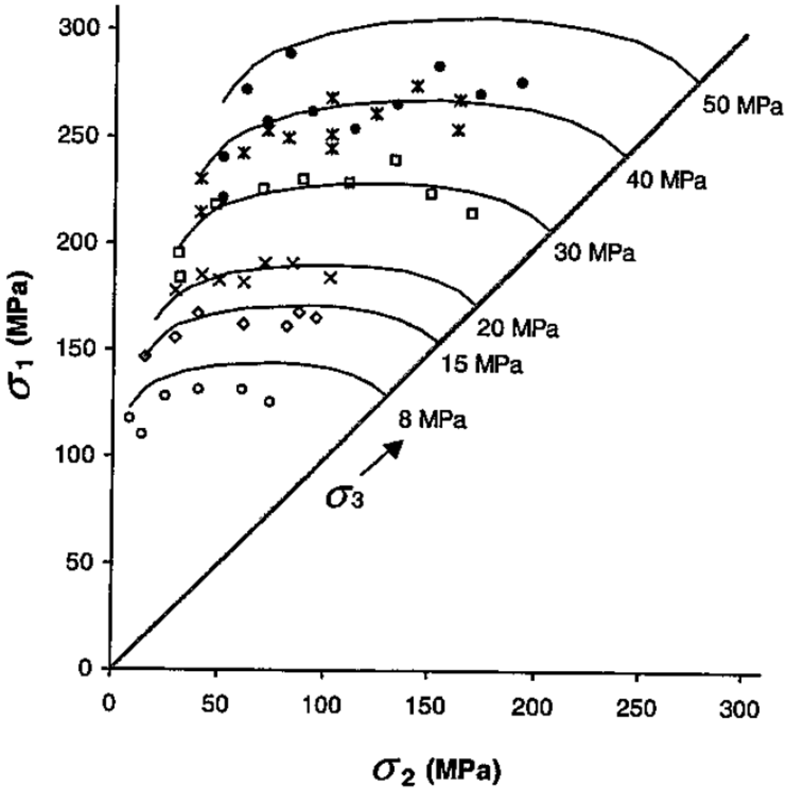
- Plastic zone around a borehole
  - Leads to softened zone around the hole, but may serve as a support to rock behind



1. Stresses around a borehole with a plastic zone, according to the Tresca model. Parameters are $C_0 = 0.5\sigma_h$, $p_w = 0.25\sigma_h$.

- ❑ Borehole failure criterion can be specified by a critical amount of plastic strain, or by a critical extent of a plastic zone.
- ❑ Using the elastic-brittle equations with an upscaled strength gives acceptable results…

Borehole Stability:
Effect of intermediate principal stress



Takahashi & Koide, 1989

Mohr-Coulomb predicts same strength independent of σ_2.

- Lab experiments show that this may underestimate strength
- There are failure criteria (Drucker-Prager, Lade a.o.) that account for σ_2.
- Borehole stress state is true triaxial!

Drucker-Prager

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = C'(\sigma_1 + \sigma_2 + \sigma_3 + A)^2$$

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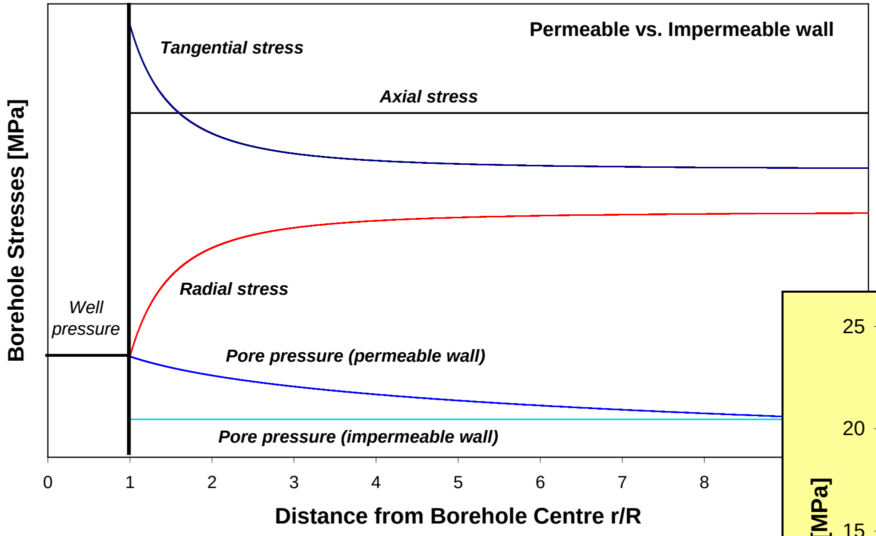
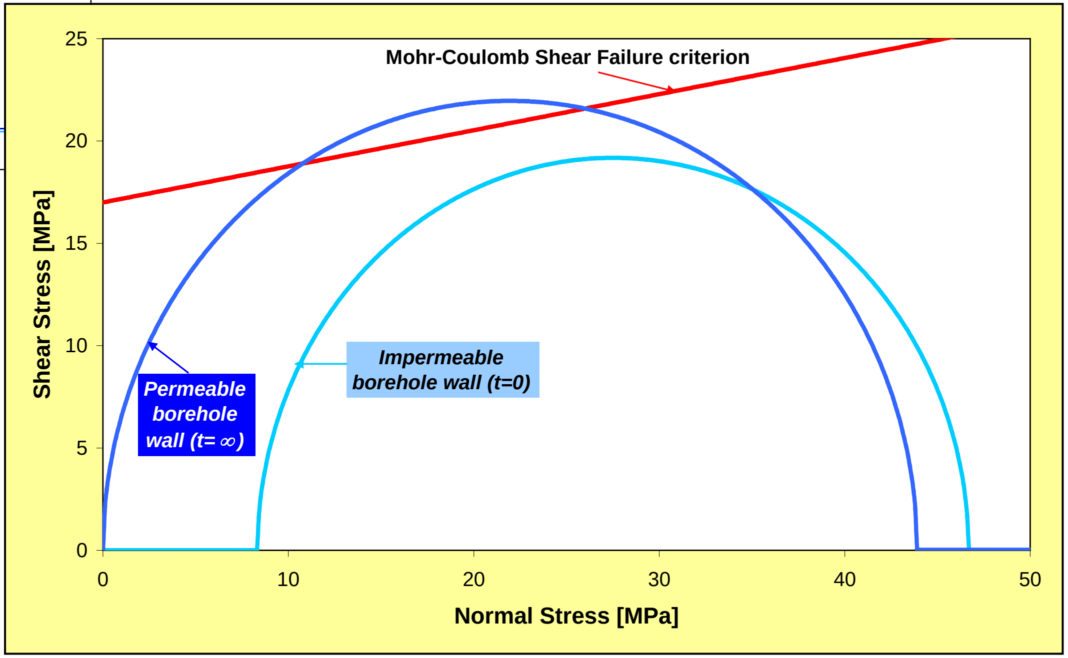
Time-delayed borehole failure: Consolidation





Hole collapse occurs after some time; i.e. when the Mohr-circle touches the M-C failure line.

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Time-delayed borehole failure: Cooling

- The thermal stress contribution may be very significant!
- Temperature equlibrates with surroundings over time, so improved stability is temporary.
- The effect on collapse pressure is:

$$\Delta p_{w,\min}^{(a)} = \Delta\sigma_T \frac{1}{1+\tan^2\beta};$$

$$\Delta p_{w,\min}^{(b)} = \Delta\sigma_T \frac{1}{\tan^2\beta}$$

$$\Delta\sigma_T = \alpha_T \frac{E_{fr}}{1-\nu_{fr}}\left(T_w - T_f\right)$$

α_T is the thermal expansion coefficient of the rock

Practical Advantages Of Mud Cooling Systems For Drilling

Vincent Maury, SPE, and Alain Guenot, SPE, Elf Aquitaine

SPE Drilling & Completion, March 1995

Mud Support

- **Capillary support by non-wetting fluid (e.g. oil):**

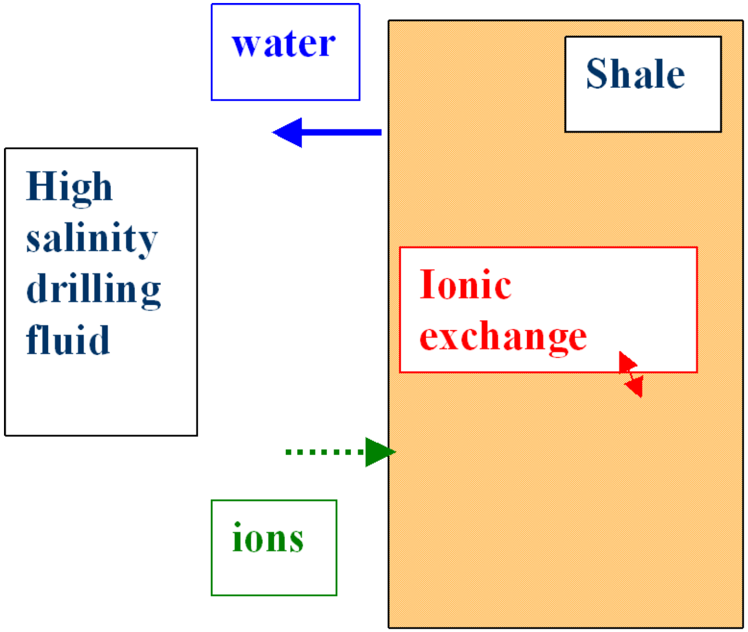
$$p_c = \frac{2\gamma}{r}$$

γ: surface tension; $\gamma_{oil\text{-}water}$ = 50·10^{-3} N/m
r: pore size; r_{shale} ~ 10 nm
⇨ p_c ~ 10 MPa

- **So: An overbalance of 10 MPa is required for oil to penetrate into an intact shale. Since there is always an impermeable membrane, the t=0 stability will prevail.**

- **Oil-based muds are not pure oils (so chemical effects could play a role; cf. osmosis)!**

Mud Chemistry: Osmosis



Osmotic potential acts like an excess pore pressure:

$$\Delta\Pi = \sigma \left(\frac{RT}{V_w} \right) \ln \frac{a_{w,df}}{a_{w,sh}}$$

$\Delta\Pi$ is reduced by membrane efficiency σ<1.

Ionic transport & exchange affects shale properties.

$a_{w,df}$: chemical activity of water in drilling fluid
$a_{w,sh}$: chemical activity of pore water in shale
a_w=1 (fresh water) a_w<1 (salt water)

R: molar gas constant = 8.31 J mol^{-1} K^{-1};
V_w: molar volume of water = 0.018 l / mol;
T: absolute temperature in K (=273 + ˚C)

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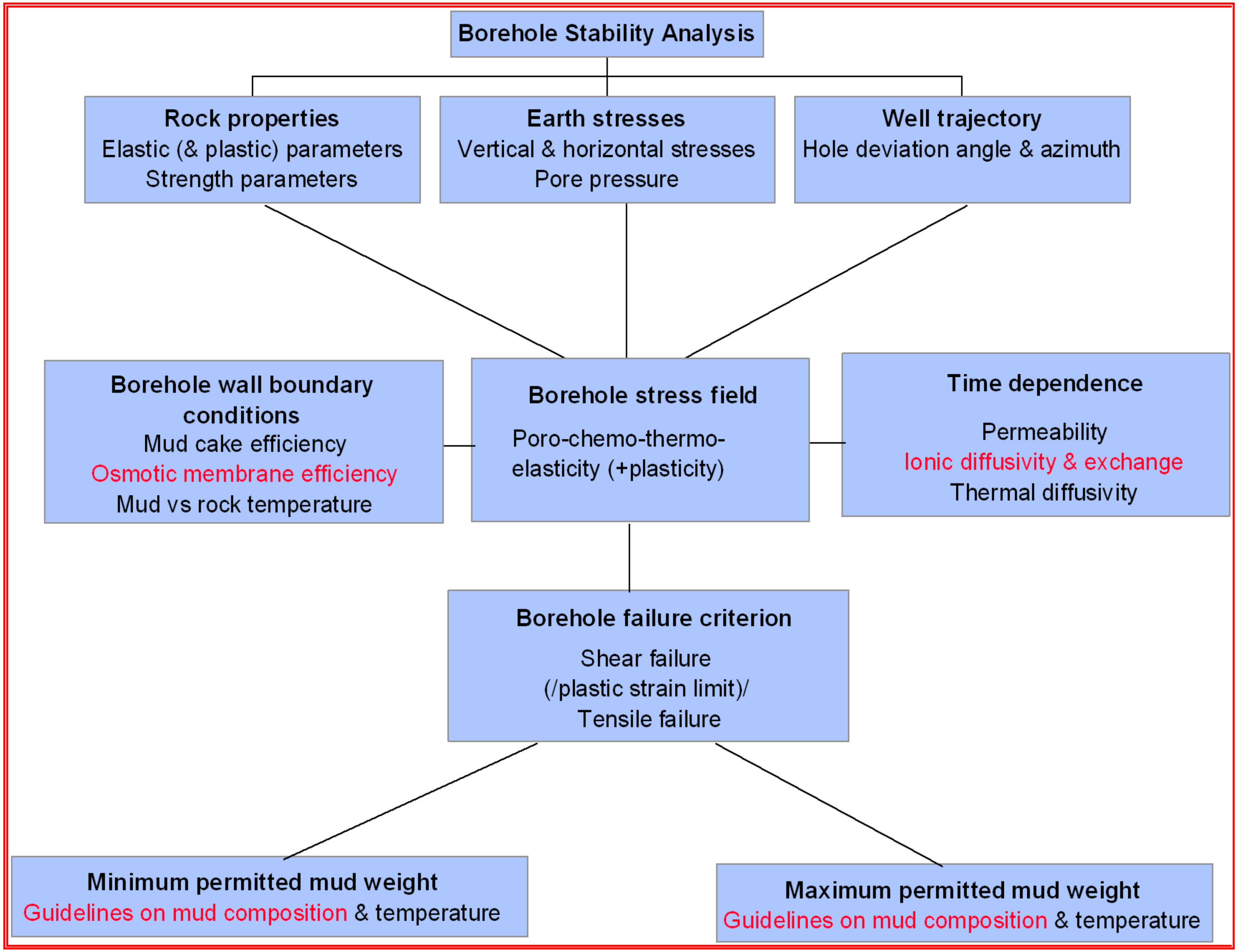
Borehole Stability Analysis
Rock properties
Elastic (& plastic) parameters
Strength parameters
Earth stresses
Vertical & horizontal stresses
Pore pressure
Well trajectory
Hole deviation angle & azimuth
Borehole wall boundary conditions
Mud cake efficiency
Osmotic membrane efficiency
Mud vs rock temperature
Borehole stress field
Poro-chemo-thermo-elasticity (+plasticity)
Time dependence
Permeability
Ionic diffusivity & exchange
Thermal diffusivity
Borehole failure criterion
Shear failure
(/plastic strain limit)/
Tensile failure
Minimum permitted mud weight
Guidelines on mud composition & temperature
Maximum permitted mud weight
Guidelines on mud composition & temperature

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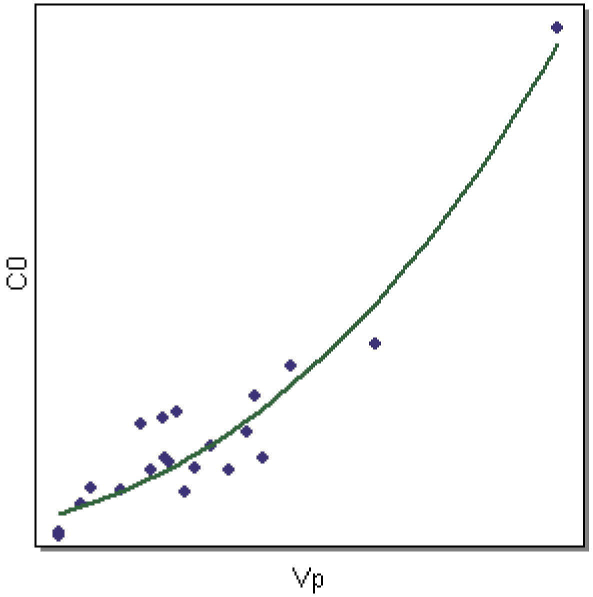
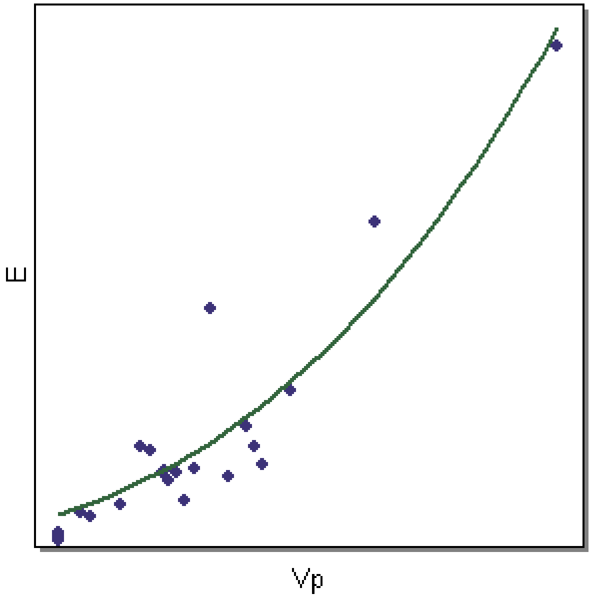
Geophysics for Borehole Stability?

Key parameters are:
- Rock strength (C_0 and β)
- Rock stresses
- Pore pressure

What do we have?

Correlations – based on lab data
Controlled experiments, but needs corrections for stress, temperature, frequency etc.





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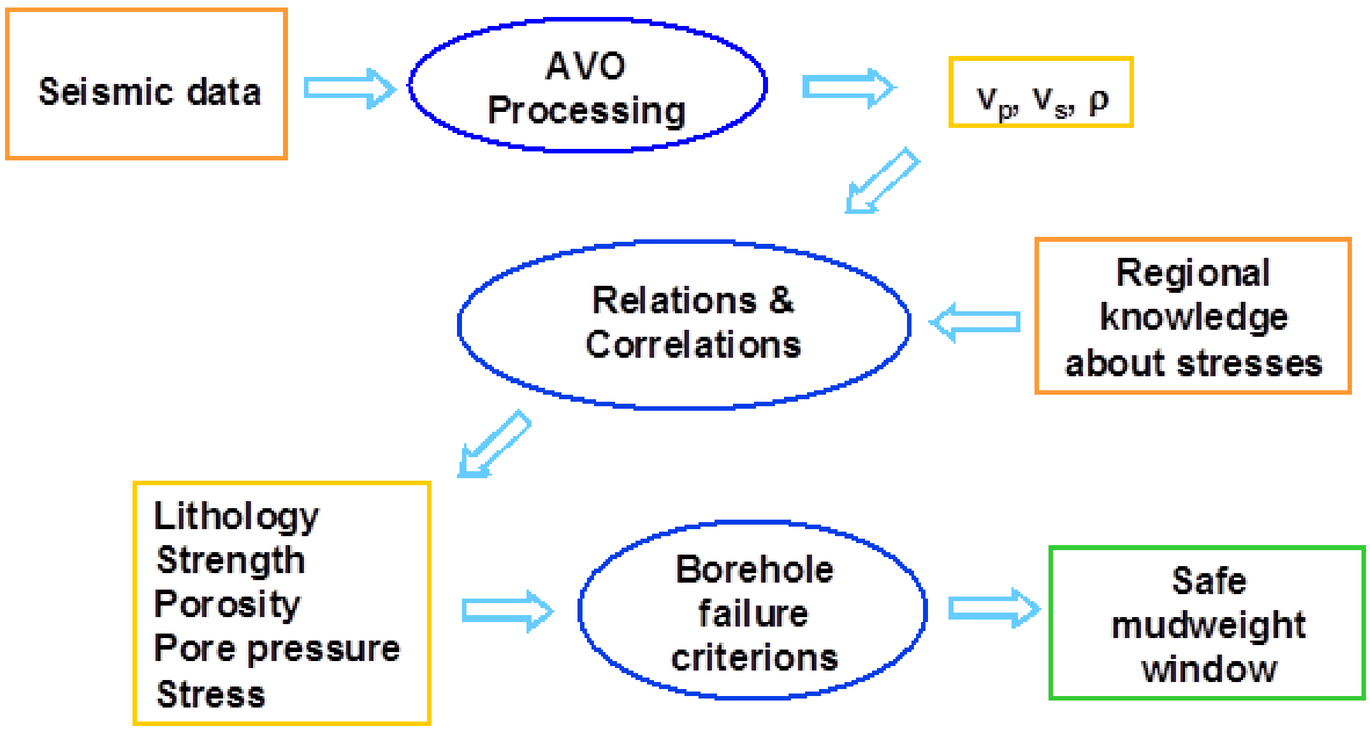
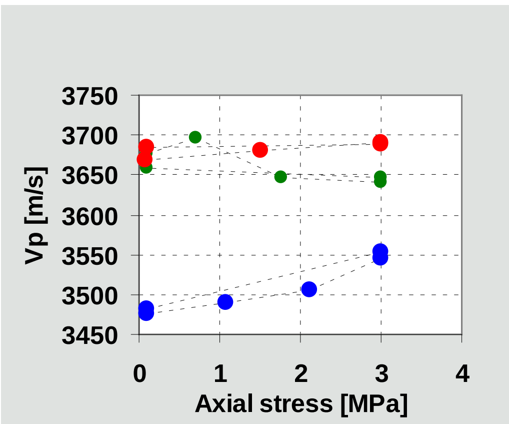
Well planning from seismics

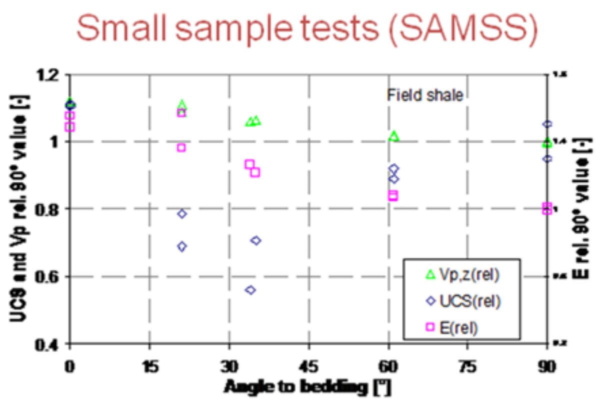


Small Sample Shale Testing

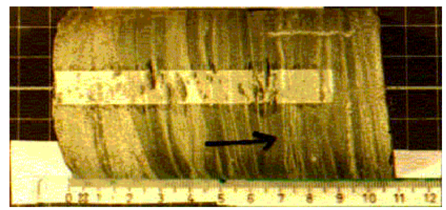
- We have developed techniques to measure static mechanical behaviour and stress dependent velocities in shale samples from cm to mm size
  - Full size shale cores are rarely available
  - Tests on small samples are fast



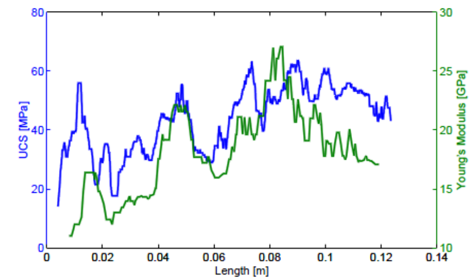
Anisotropic P-wave velocities *vs*. stress, measured on sub-mm shale samples (⇔ drill cutting size!)

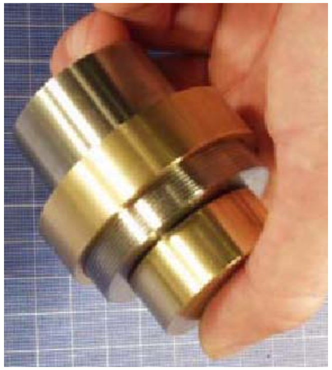


Strength & Elastic Anisotropy on cm size shale samples

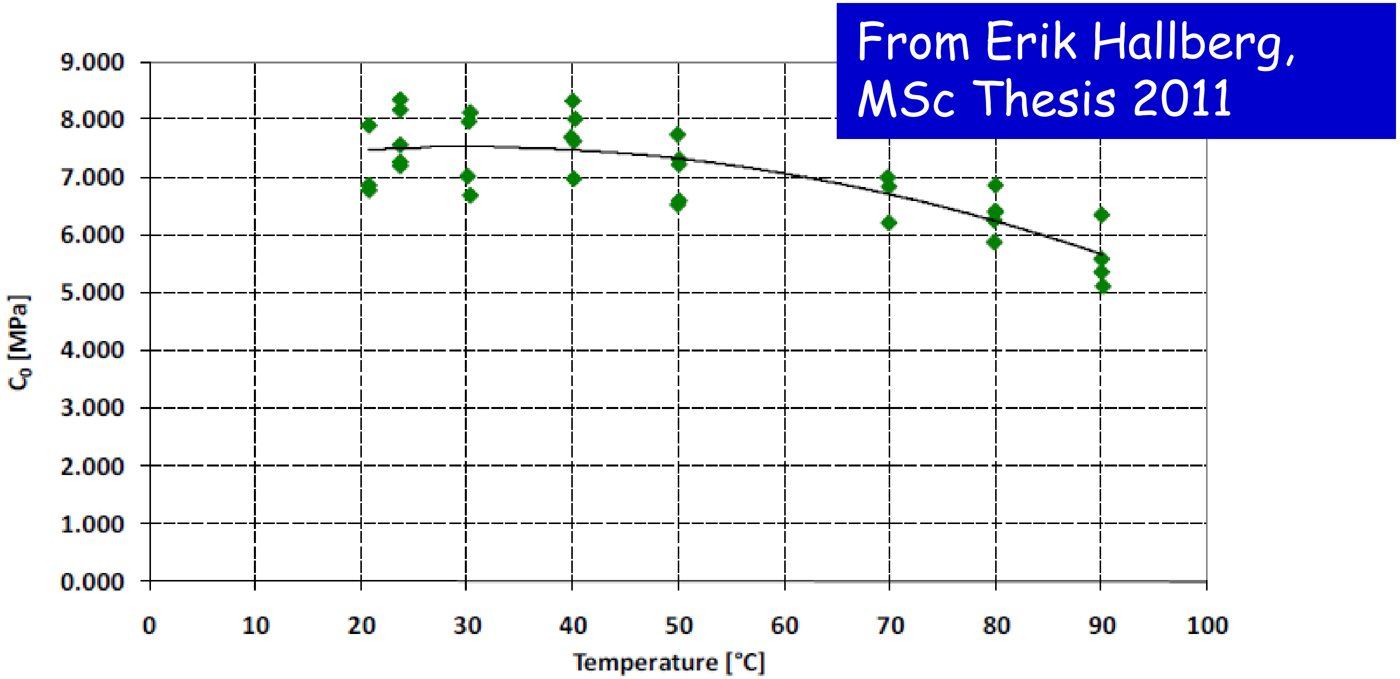


Strength & Stiffness from core scratch





Shale puncher



Temperature dependent strength of Pierre shale