Underground stresses and pore pressure

ROSE

Rock Physics and Geomechanics

Course 2012

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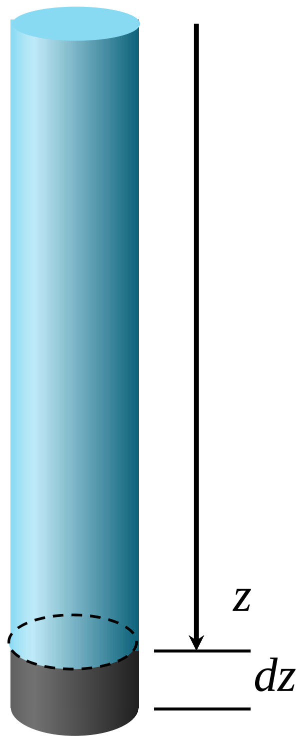
SINTEF NTNU

Vertical stress:
given by the weight of the overburden

$$\sigma_v = \int_0^D d\sigma_z = \int_0^D \rho(z) g dz$$



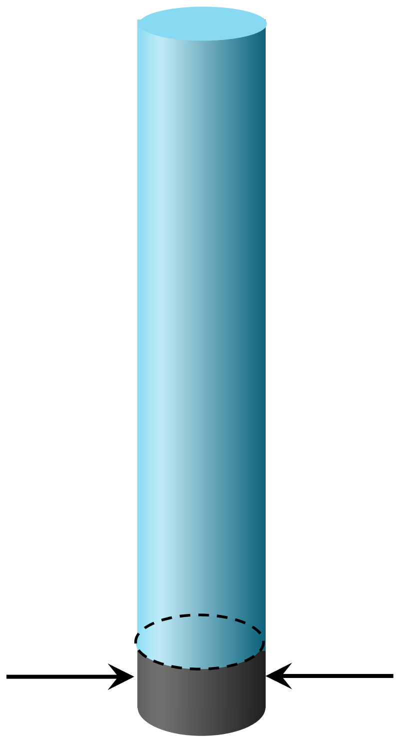
Average density ~ 1.8 – 2.3 g/cm^3

→

typical vertical stress gradient ~ 20 MPa/km or 1 psi/ft

Horizontal Stress

- is largely a consequence of compression under restricted lateral deformation



Hooke's law:

$$E\Delta\varepsilon_h = 0 = \left(1-\nu_{\mathrm{fr}}\right)\Delta\sigma'_h - \nu_{\mathrm{fr}}\Delta\sigma'_v$$

$$\Rightarrow$$

$$\Delta\sigma'_h = \frac{\nu_{\mathrm{fr}}}{1-\nu_{\mathrm{fr}}}\Delta\sigma'_v$$

Horizontal Stress

In general: $$\sigma_h' = \kappa \sigma_v'$$

Typically in relaxed sedimentary basins $\kappa \sim 0.5$, normally $\kappa < 1$, but $\kappa > 1$ (near surface)

Note:

$$\kappa \neq \frac{\nu_{\mathrm{fr}}}{1-\nu_{\mathrm{fr}}}$$

(common mistake, however)

$$\kappa \neq \frac{\nu_{\mathrm{fr}}}{1-\nu_{\mathrm{fr}}}$$

Why not?

Example:

Consider a loose sediment with ν = 0.45 that is gradually being buried.
Using the relation

$$\Delta\sigma_h' = \frac{\nu_{\mathrm{fr}}}{1-\nu_{\mathrm{fr}}}\Delta\sigma_v'$$

- what is the horizontal stress at 1000 m depth?

The sediment is further buried until the depth reaches 2000 m. Then the rock undergoes a diagenetic process which implies that $\nu \to$ 0.20.
After that, some of the overburden is eroded, and the rock experiences uplift until the depth is again 1000 m.

What is now the horizontal stress at 1000 m depth? What is κ?

Example:

Burial $\nu_{\mathrm{fr}} = 0.45$ $\dfrac{\nu_{\mathrm{fr}}}{1-\nu_{\mathrm{fr}}} = 0.82$

at 1000 m $\sigma_v' = 10\ \mathrm{MPa}$ $\sigma_h' = 0.82 \cdot \sigma_v' = 8.2\ \mathrm{MPa}$ $\Rightarrow$ $\kappa = 0.82$

at 2000 m $\sigma_v' = 20\ \mathrm{MPa}$ $\sigma_h' = 0.82 \cdot \sigma_v' = 16.4\ \mathrm{MPa}$

Cementation & Uplift $\nu_{\mathrm{fr}} = 0.20$ $\dfrac{\nu_{\mathrm{fr}}}{1-\nu_{\mathrm{fr}}} = 0.25$

at 1000 m $\sigma_v' = 10\ \mathrm{MPa}$ $\sigma_h' = 16.4\ \mathrm{MPa} + 0.25 \cdot \left(\sigma_v' - 20\ \mathrm{MPa}\right) = 13.9\ \mathrm{MPa}$

$\Rightarrow$ $\kappa = 1.39$

However, if $\nu_{\mathrm{fr}} = 0.5$

then $\kappa = \frac{\nu_{\mathrm{fr}}}{1-\nu_{\mathrm{fr}}} = 1$ Example: salt

Shales tend to have a high Poisson's ratio,
and also high horizontal stress.

Note: High Poisson's ratio in salt and shale are related to *creep*.
Standard laboratory tests may not give the right values.

Horizontal stress:

Alternative approach:

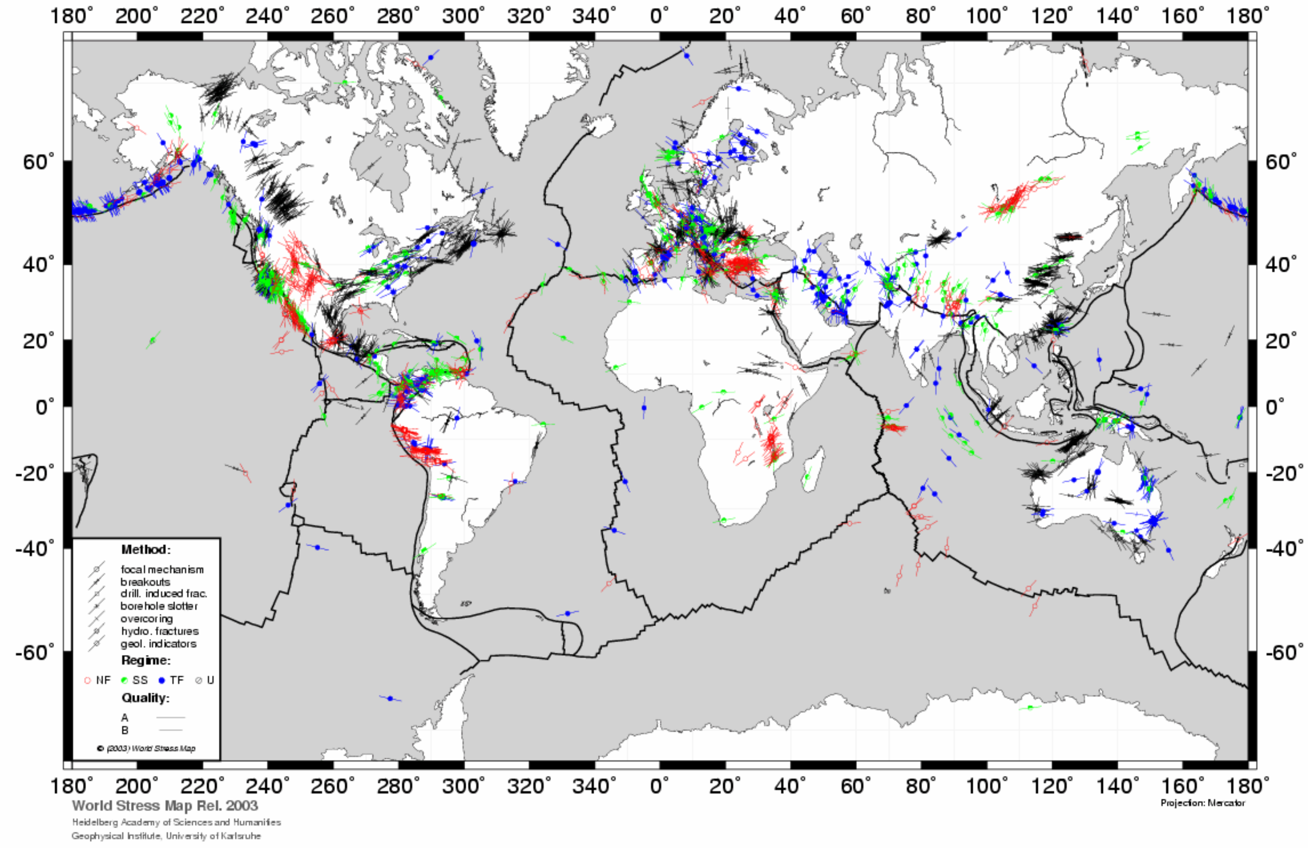
Assume that the rock is in a continuous state of failure
Mohr-Coulomb:

$$\sigma_v' = C_o + \sigma_h' \tan^2\beta \rightarrow \sigma_h' \tan^2\beta$$

$\Rightarrow$

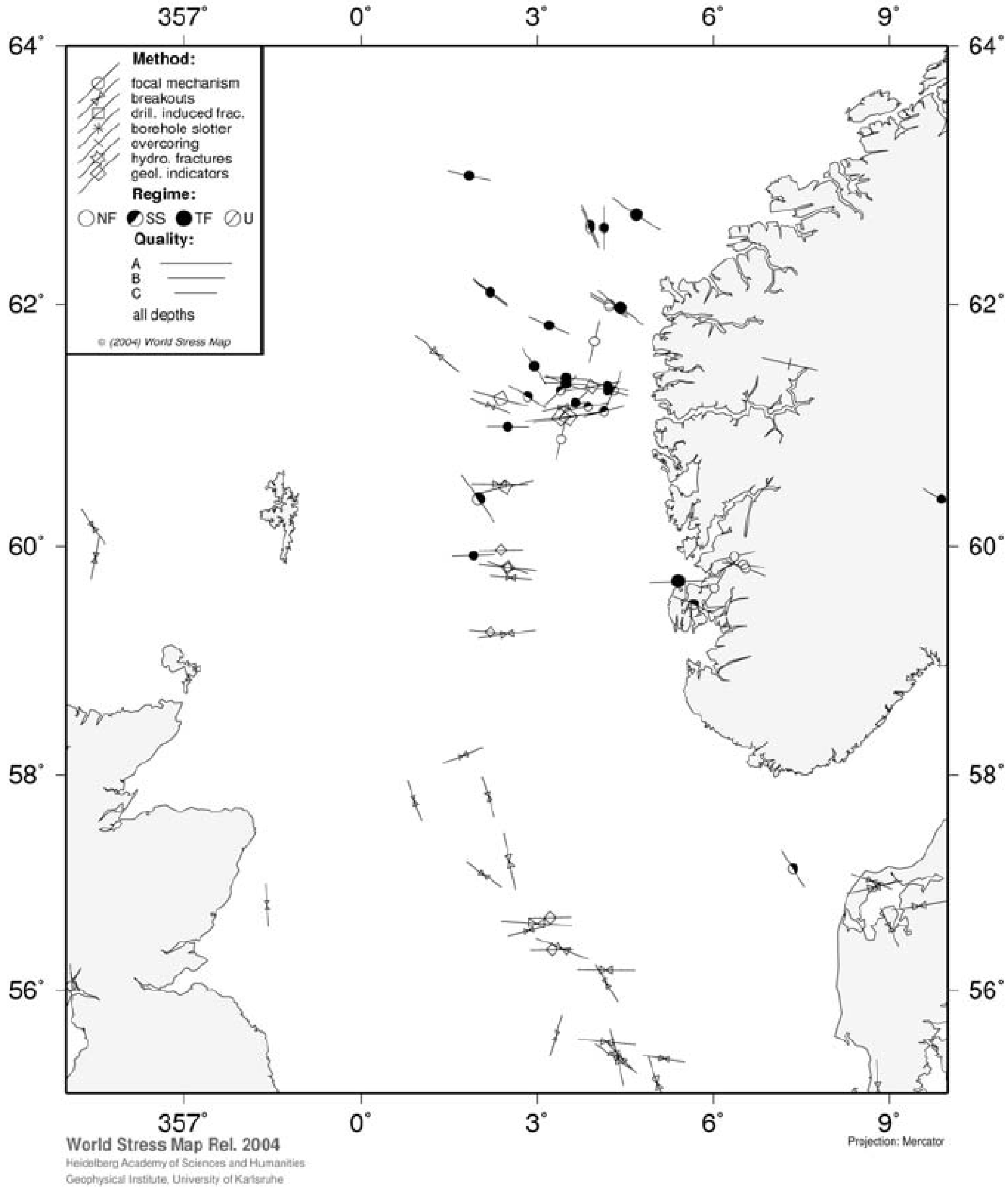
$$\kappa = \frac{1}{\tan^2\beta}$$

World Stress Map



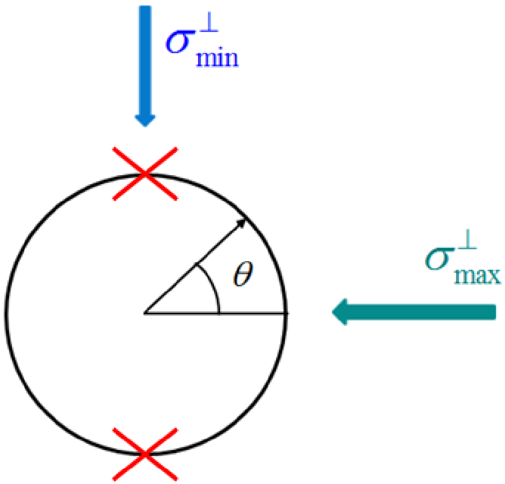
http://dc-app3-14.gfz-potsdam.de/

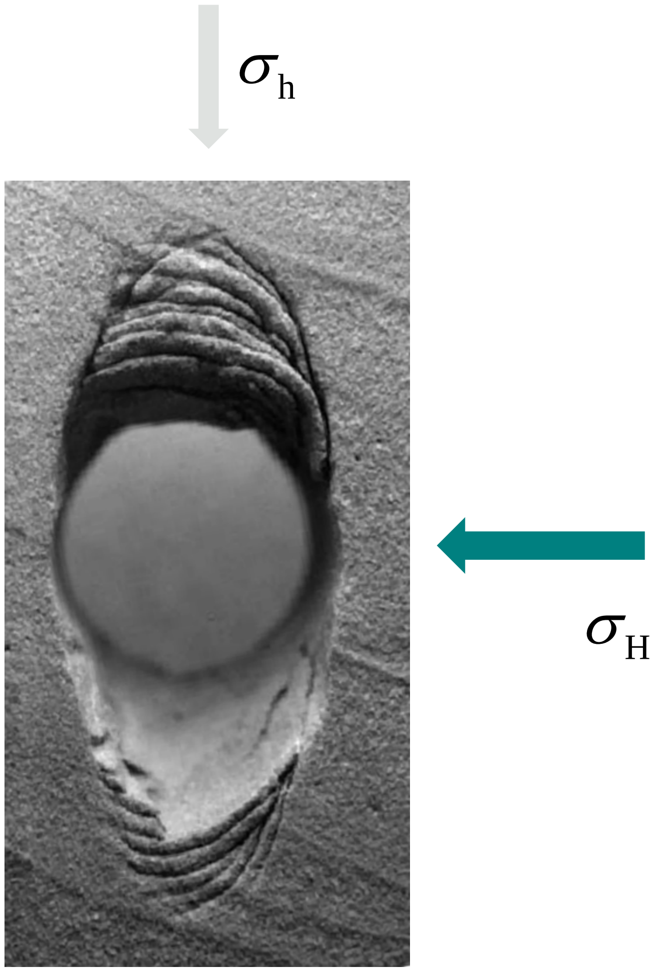
World Stress Map



Orientation of in situ stresses

Borehole breakouts

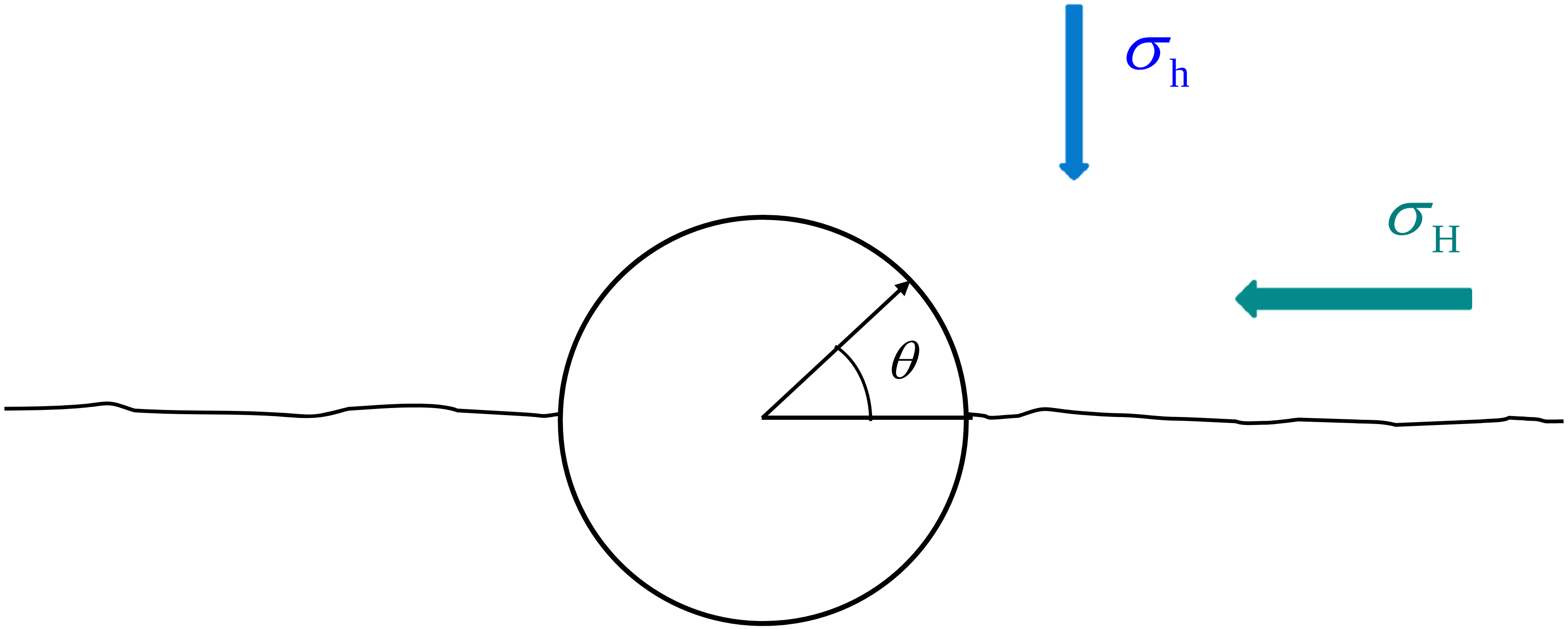




Vertical well, σ_v is a principal stress

Orientation of in situ stresses

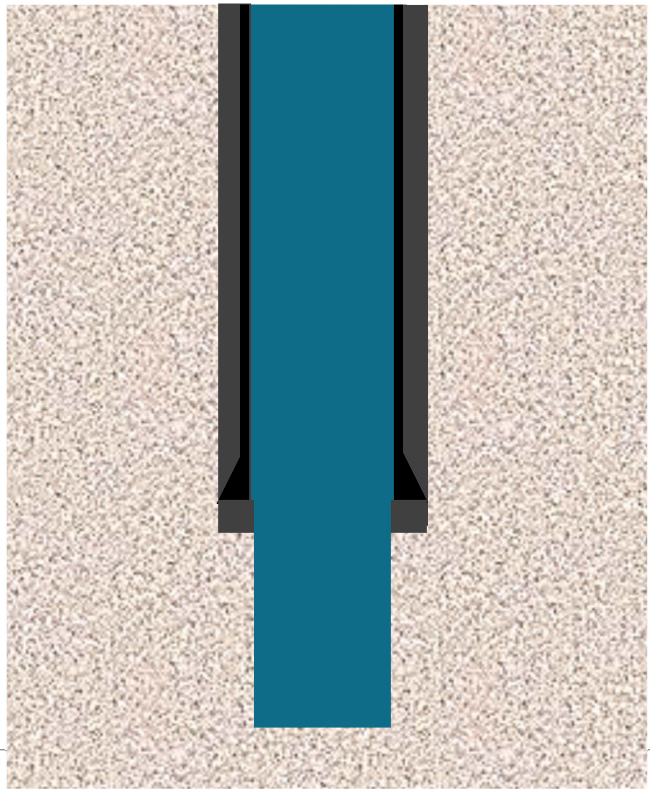
Hydraulic fracturing



Vertical well, σ_v is a principal stress

LOT – Leak Off Test

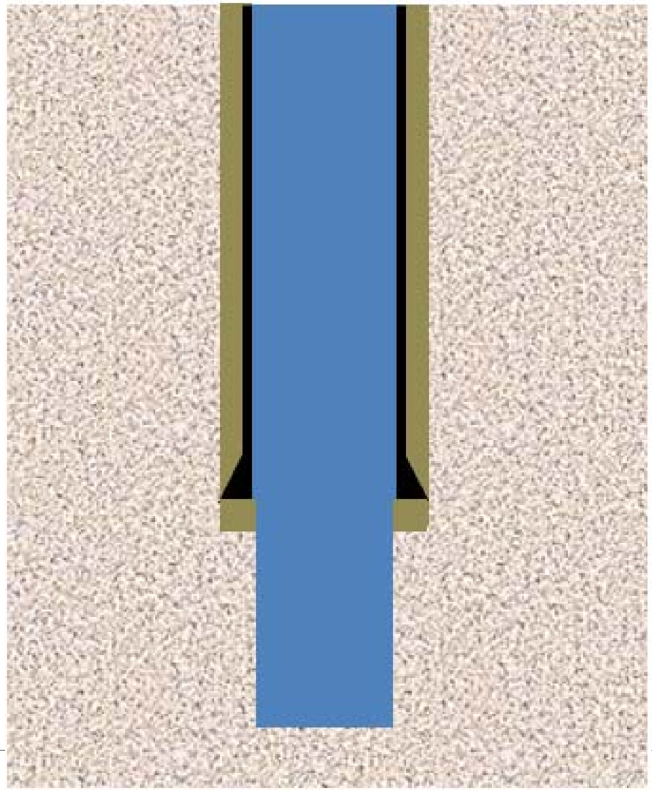
Purpose: To determine the maximum well pressure a new section of the well can take without fracturing

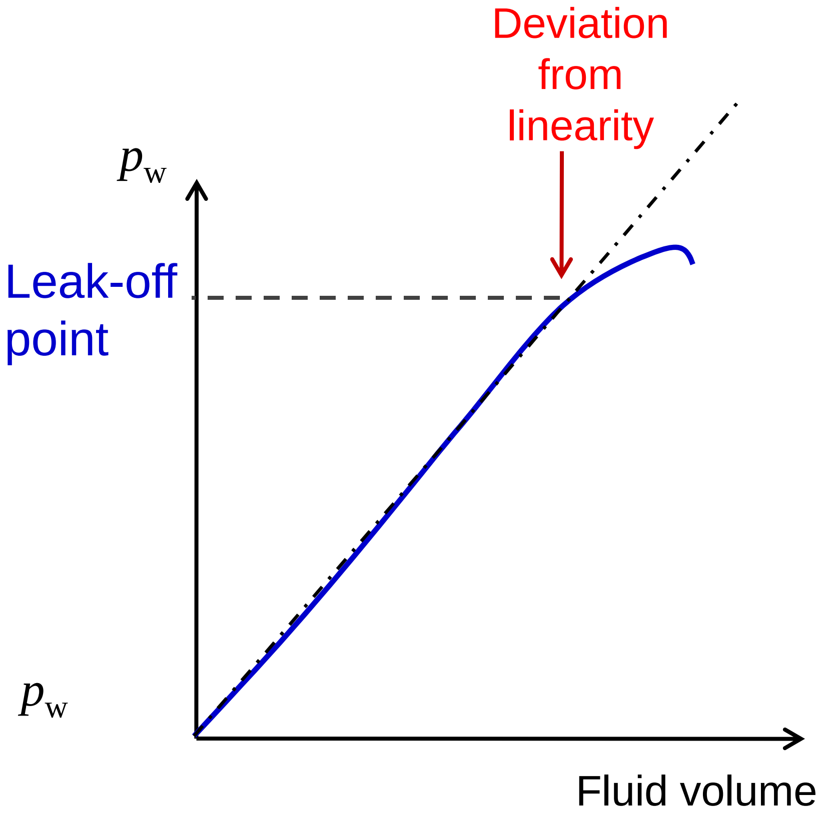


Performed during the drilling phase, immediately below the casing shoe

LOT – Leak Off Test

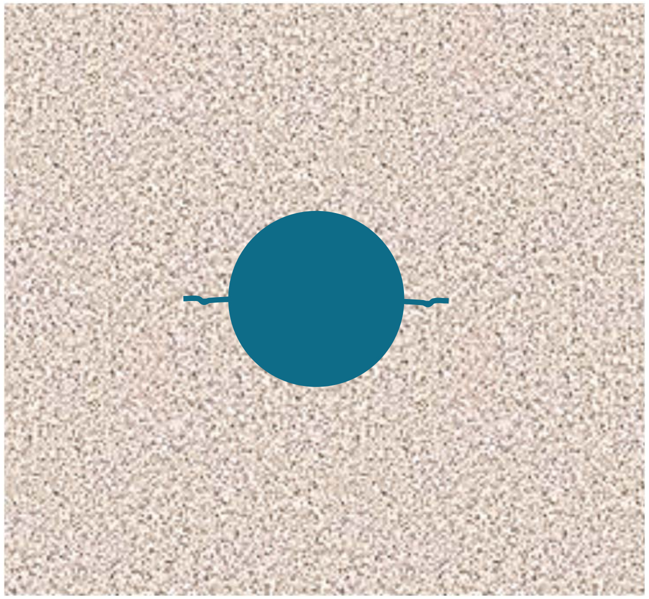
Procedure: the open hole section is pressurized, by pumping in mud at a constant volume rate

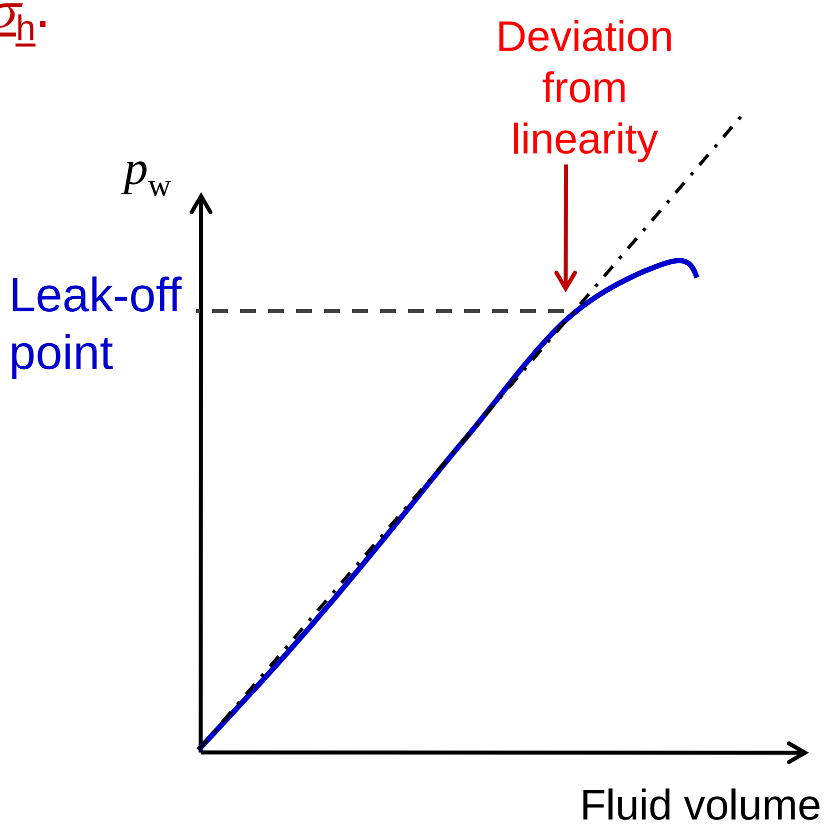




LOT – Leak Off Test

The leak-off point is where a fracture is starting to initiate. However, it is not directly related to the smallest in situ stress, hence it is not a good measure for σ_h.

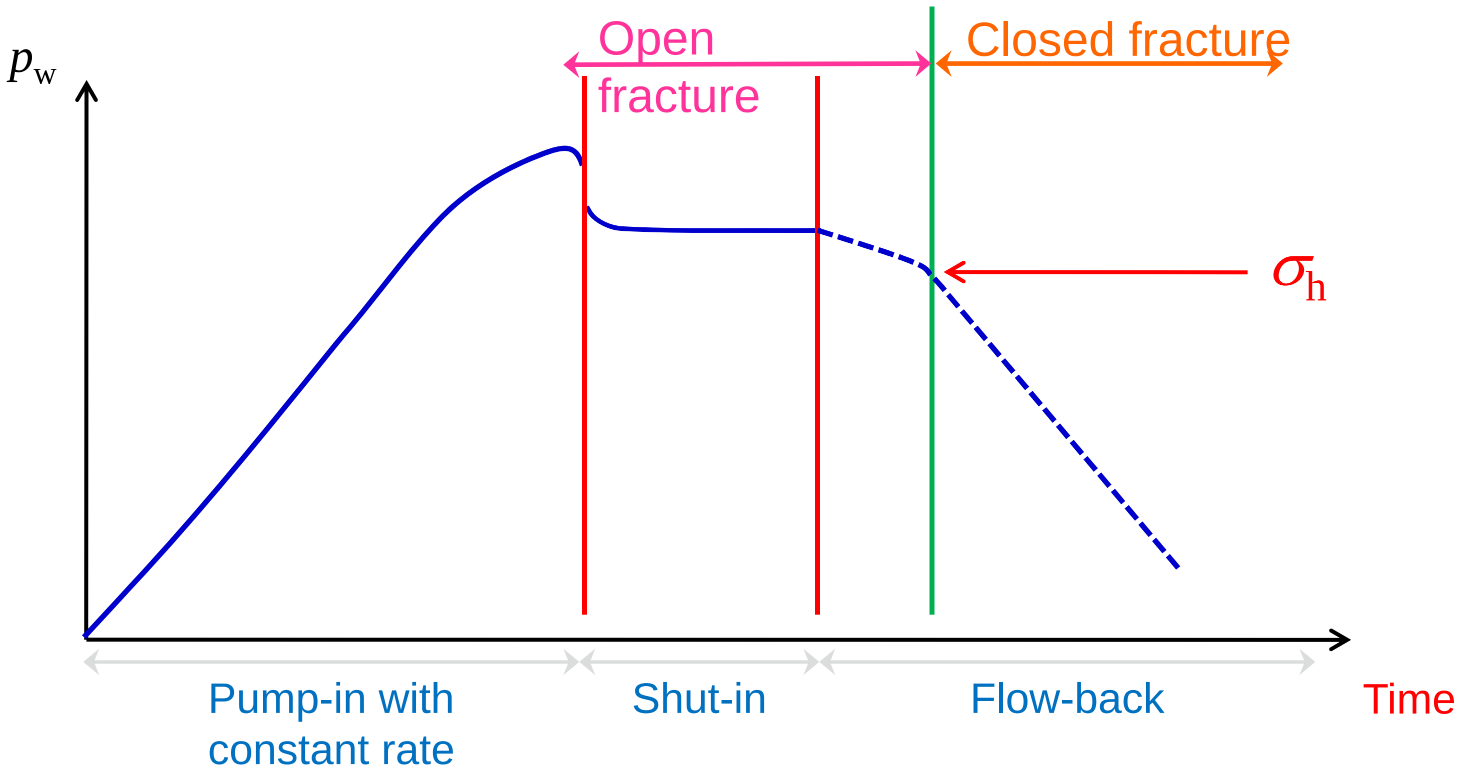




The leak-off point is controlled by the stress state at the borehole wall, which differ from the in situ stress state.

XLOT – Extended Leak Off Test

The test continues beyond breakdown, and pressure is monitored after shut-in and during flow-back



Pore pressure

Pore pressure

<u>Normal pore pressure</u> is caused by the weight of the fluid column above the actual depth:

$$p_{\mathrm{fn}} = \int_0^D \rho_{\mathrm{f}}(z) g dz = \langle \rho_{\mathrm{f}} \rangle g D$$

For brine: $\langle \rho_{\mathrm{f}} \rangle \simeq 1.05 \text{ g/cm}^3$

Abnormal pore pressure may occur in sealed or (nearly) impermeable zones.

Potential causes:

- Burial faster than drainage

- Chemical processes related to diagenesis

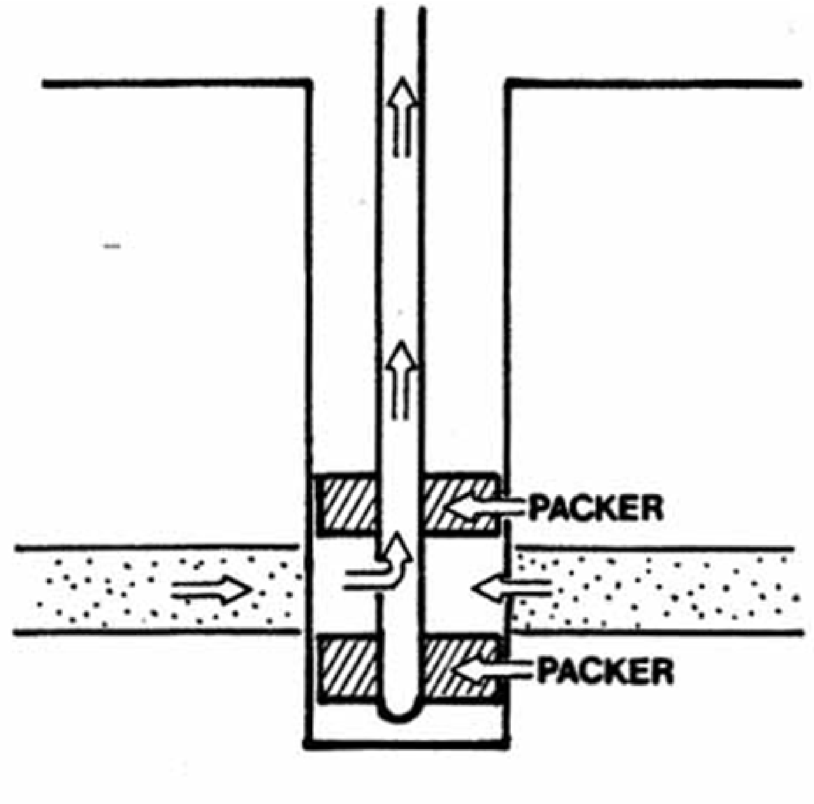
- Large deformations due to tectonic stresses

- Migration of high pressure fluid from other zones

- There is a need to measure the pore pressure

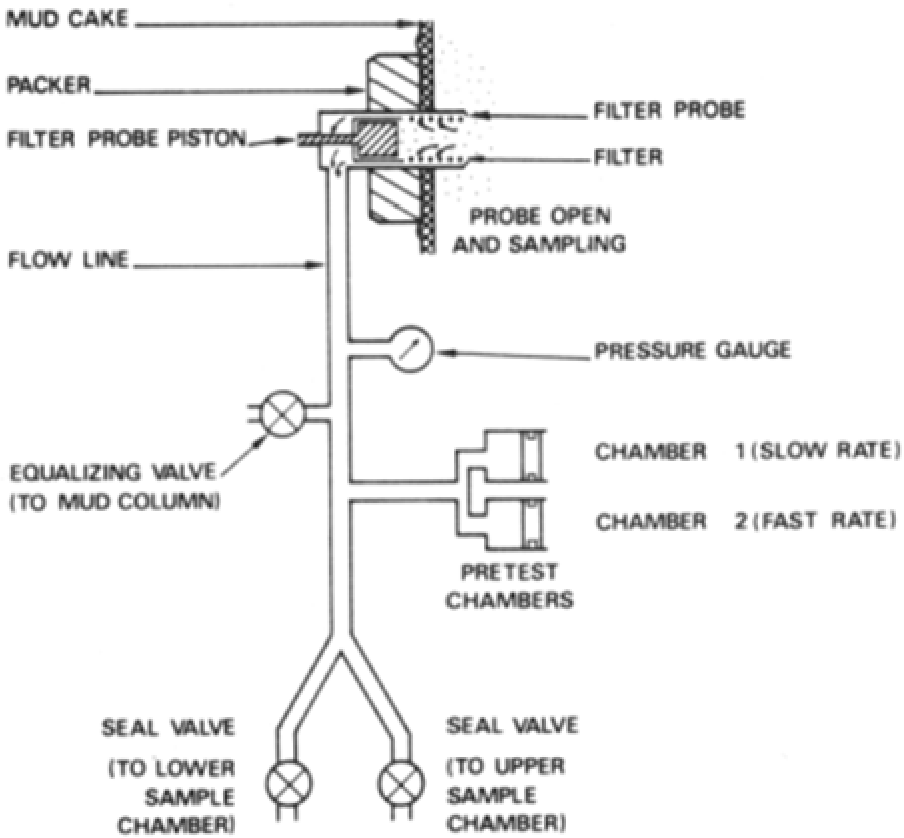
Recommended procedures
(if time and cost allows for it)

Drill stem test



Recommended procedures
(if time and cost allows for it)

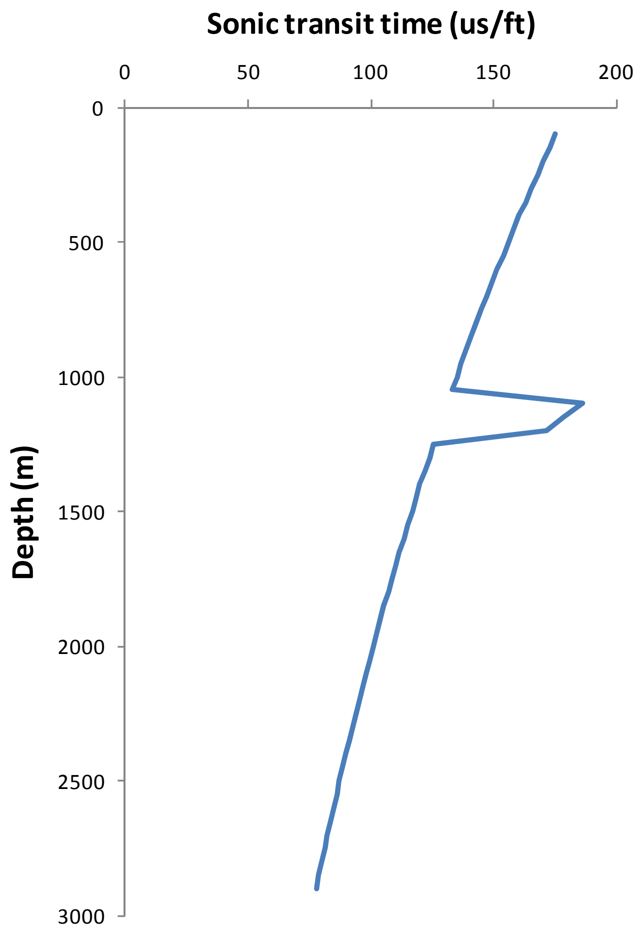
RFT tester



The Eaton method

1. Identify the normal trendline for sonic transit time in shale sections

$$\Delta t_{norm} = \Delta t_{sh}^{o} \left(\frac{\Delta t_{sh}^{1}}{\Delta t_{sh}^{o}} \right)^{\frac{D-D_0}{D_1-D_0}}$$



The Eaton method

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$$\Delta t_{norm} = \Delta t_{sh}^{o} \left(\frac{\Delta t_{sh}^{1}}{\Delta t_{sh}^{o}} \right)^{\frac{D-D_0}{D_1-D_0}}$$

2. Find the pore pressure gradient in the overpressured section from the observed transit time Δt_{obs} in this section, using the vertical stress, the normal pore pressure gradient, and the Eaton exponent E:

$$\frac{p_{\mathrm{f}}}{D} = \frac{\sigma_{\mathrm{v}}}{D} - \left(\frac{\sigma_{\mathrm{v}}}{D} - \frac{p_{\mathrm{fn}}}{D} \right) \left(\frac{\Delta t_{norm}}{\Delta t_{obs}} \right)^{E}$$

Typically, $E \approx 2-3$

May also be used for S-waves (E = 2) and for resistivity (E = 1.2)

Pore pressure estimation from seismics

Assumptions:

1. Interval velocity is a known function of effective vertical stress

$$V_i = V_o + \alpha \left(\frac{\sigma_v - p_f}{\sigma_o} \right)^{\beta}$$

2. Vertical stress is a known function of depth

$$\sigma_v = \gamma D$$

$\Rightarrow$

$$p_f = \gamma D - \sigma_o \left(\frac{V_i - V_o}{\alpha} \right)^{\frac{1}{\beta}}$$

Typical values:

$\alpha = 132$ m/s

$\beta = 0.62$

$\gamma = 0.021$ MPa/m

$\sigma_o = 1$ MPa

$V_o = 1500$ m/s

Pore pressure estimation from seismics

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$$V_i = V_o + \alpha \left(\frac{\sigma_\mathrm{v} - p_\mathrm{f}}{\sigma_o} \right)^\beta$$

Not unique!

2. Vertical stress is a known function of depth

$$\sigma_\mathrm{v} = \gamma D$$

Velocity depends on

- Lithology
- Porosity
- Horizontal stress
- Stress history

……. in addition to the vertical stress

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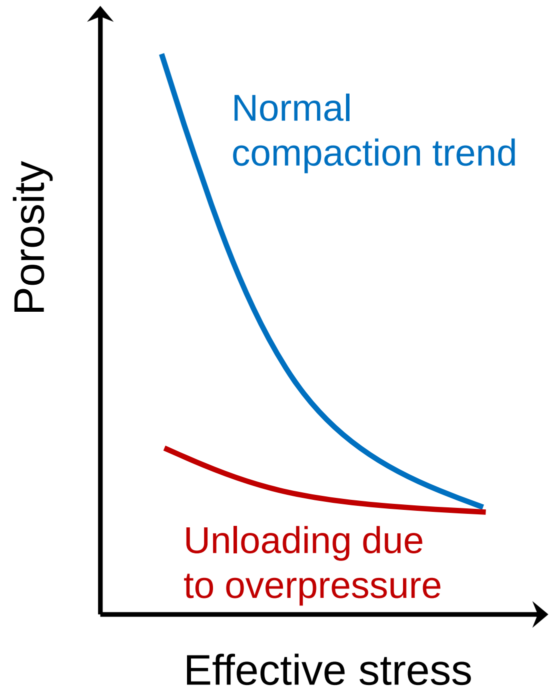

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$$V_i = V_o + \alpha \left(\frac{\sigma_\mathrm{v} - p_\mathrm{f}}{\sigma_o} \right)^\beta$$

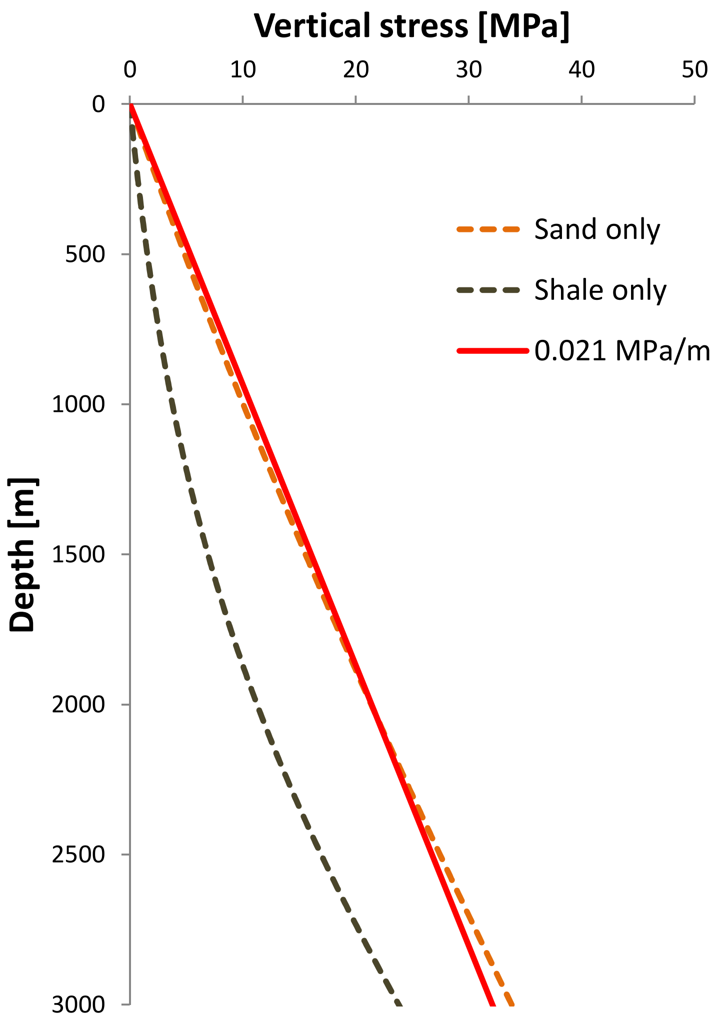
Not unique!

2. Vertical stress is a known function of depth

$$\sigma_\mathrm{v} = \gamma D$$

Not unique!

The vertical stress at a given depth depends on the weight of the overburden, even in simple compacting sediments



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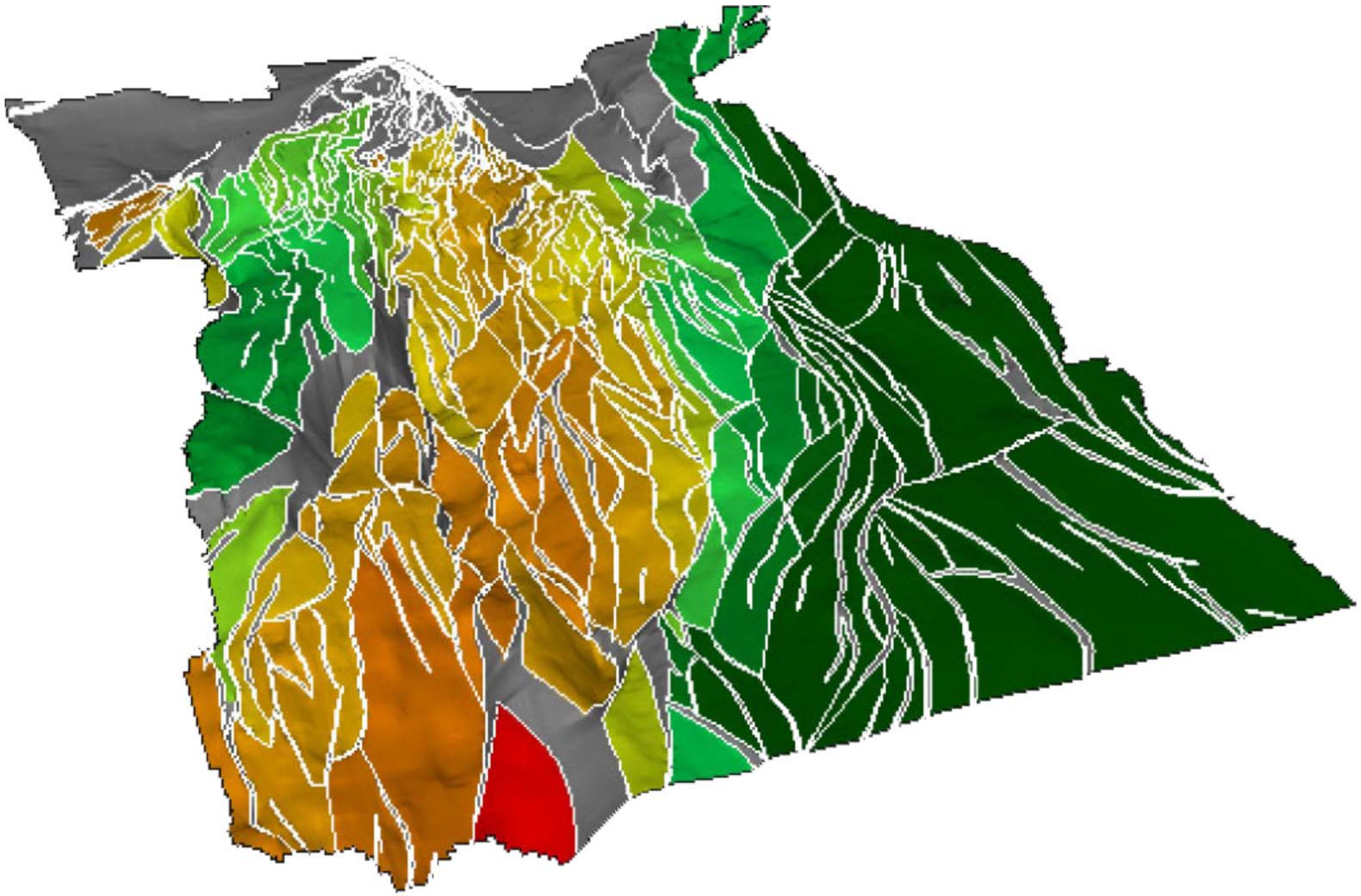
Alternative method:

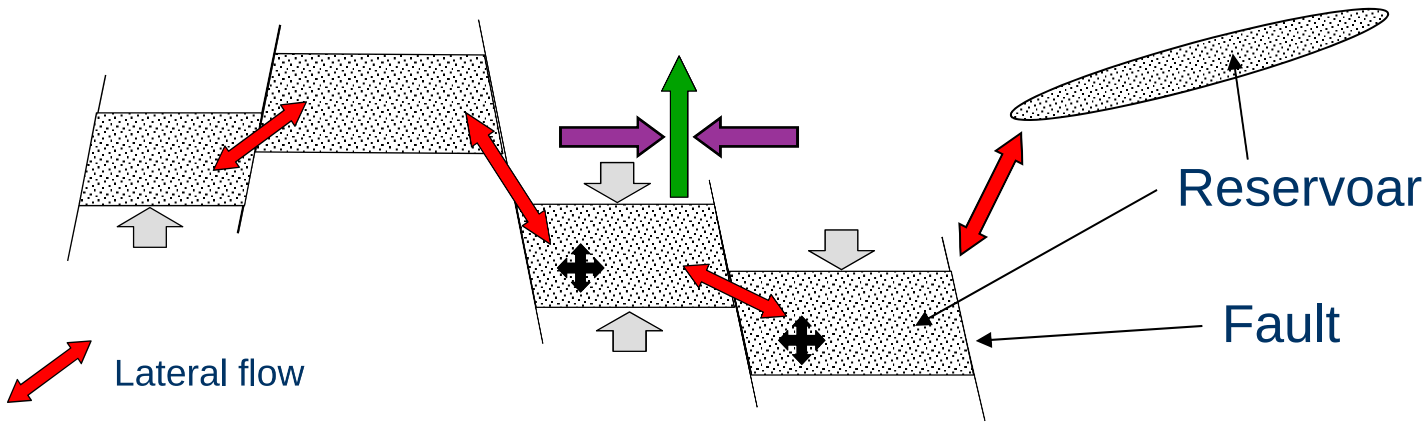
$$V_P = V_P(\sigma')$$
$$V_S = V_S(\sigma')$$
$$\Rightarrow$$
$$V_P : V_S = f'(\sigma') \rightarrow f(p_f)$$
$$\Rightarrow$$
$$p_f = f^{-1}\left(\frac{V_P}{V_S}\right)$$

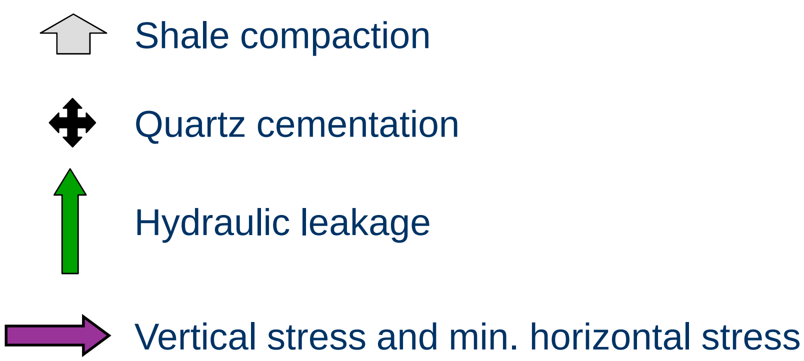
Not a unique relation either,
but it may work when the relations
are sufficiently well known

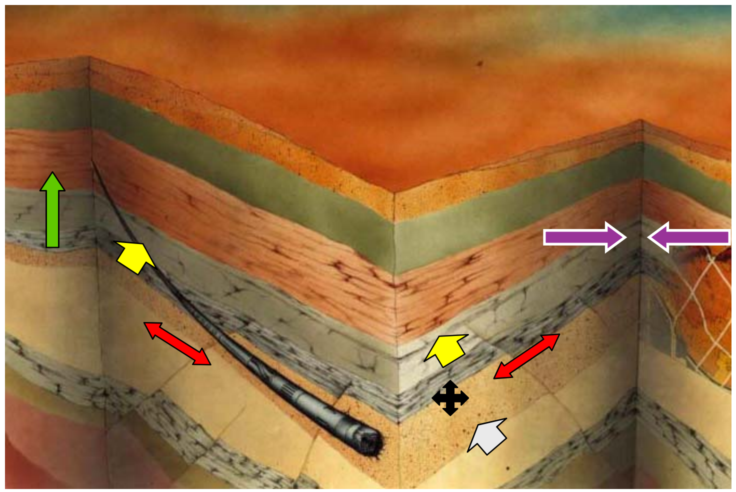
Pressure modelling based on basin modelling



pressim - a tool developed by SINTEF Petroleum Research

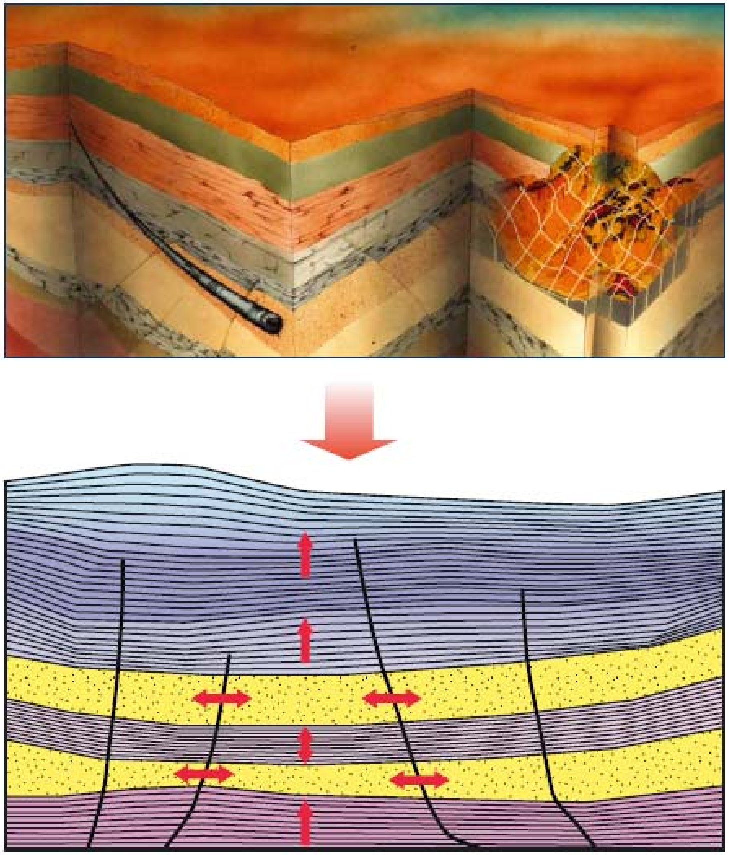






Pressim models all processes for pressure generation and dissipation – *unique features related to modelling of 3D fluid flow*

Pressim3D – Flow units



- Decompacted depth maps (from seismic) define a geological model
- The sealing layers are split into a vertical resolution typically 10m-50m
- The reservoir units are only divided laterally by fault traces/polygons
- Mixed lithologies can be used to describe the sealing and reservoir layers

References:

Fjær, E., Holt, R.M., Horsrud, P., Raaen, A.M. and Risnes, R. (2008) "Petroleum Related Rock Mechanics. 2nd Edition". Elsevier, Amsterdam

World Stress Map, http://dc-app3-14.gfz-potsdam.de/

Zoback, M.D. (2007) "Reservoir Geomechanics". Cambridge University Press, New York