WORKSHOP

PHOTONICS FOR DEEP GEOTHERMAL
ENERGY HARVESTING

Physical rock properties relevant for deep drilling

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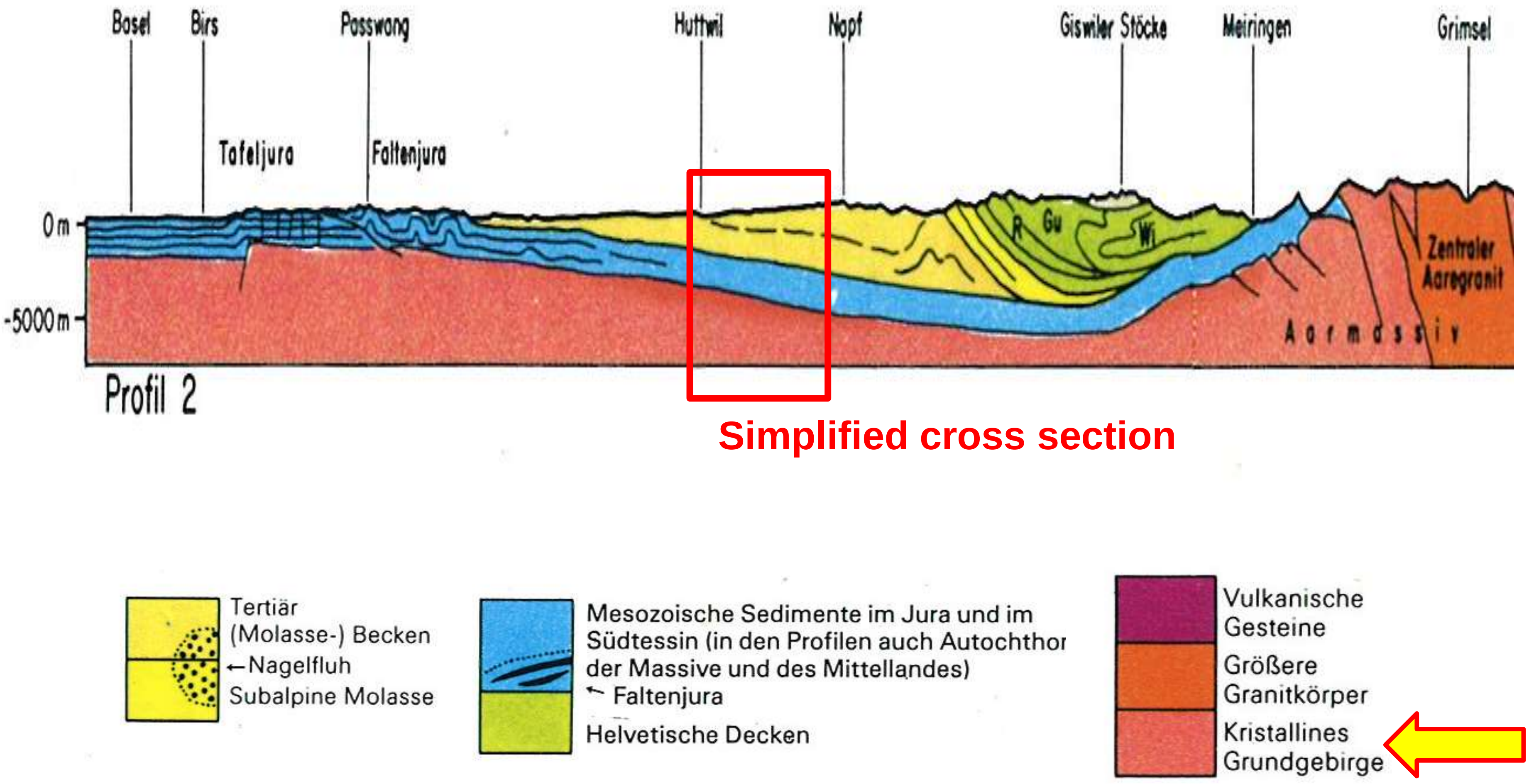
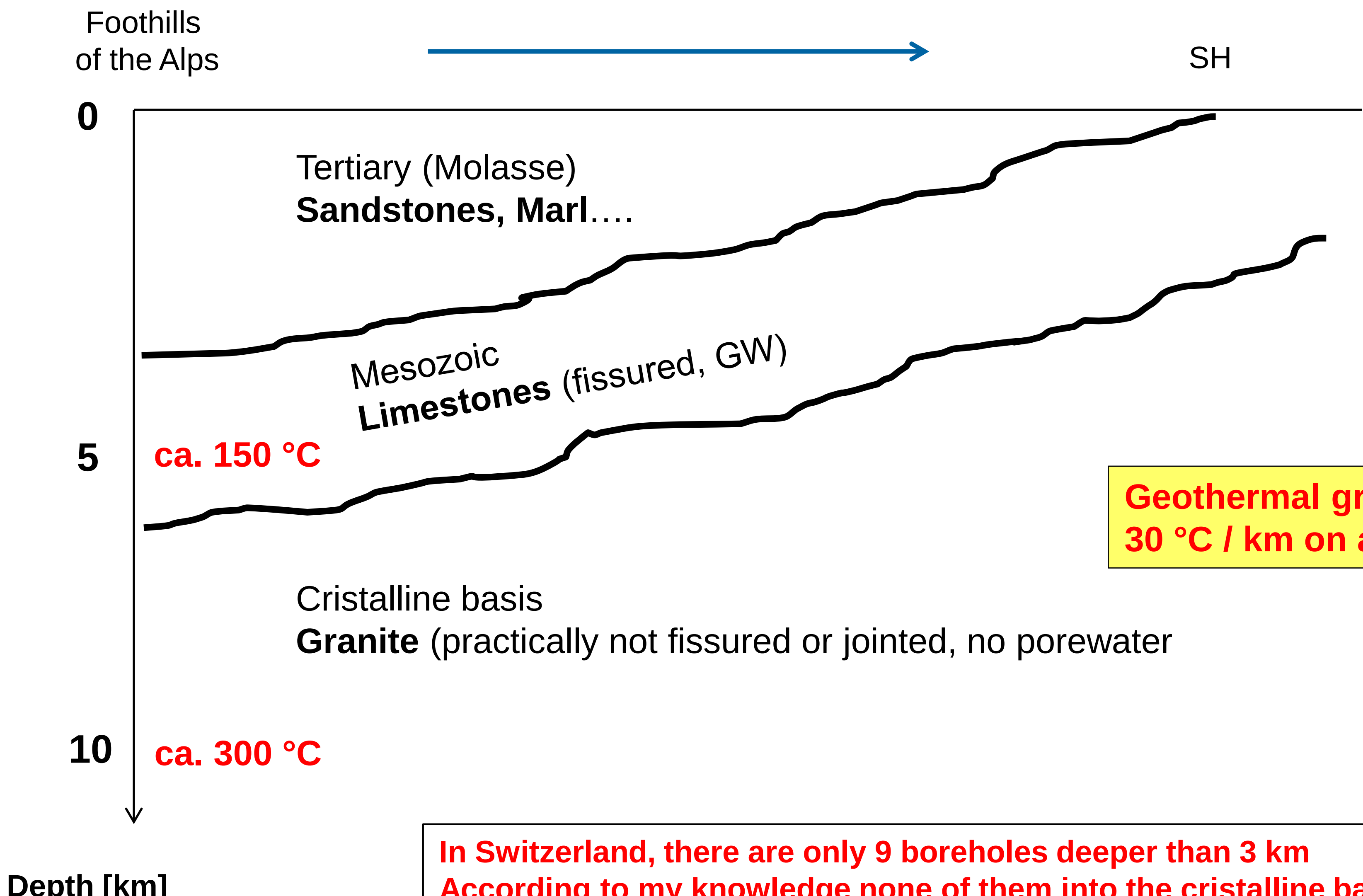
HSR
HOCHSCHULE FÜR TECHNIK
RAPPERSWIL
FHO Fachhochschule Ostschweiz

Geological-tectonic cross section for Switzerland

(from Labhart T. P.: Geologie der Schweiz, 1992)



Simplified cross section for conceptual considerations



Geothermal gradient
30 °C / km on average

In Switzerland, there are only 9 boreholes deeper than 3 km
According to my knowledge none of them into the cristalline basis

What do we need to know to estimate the borehole stability

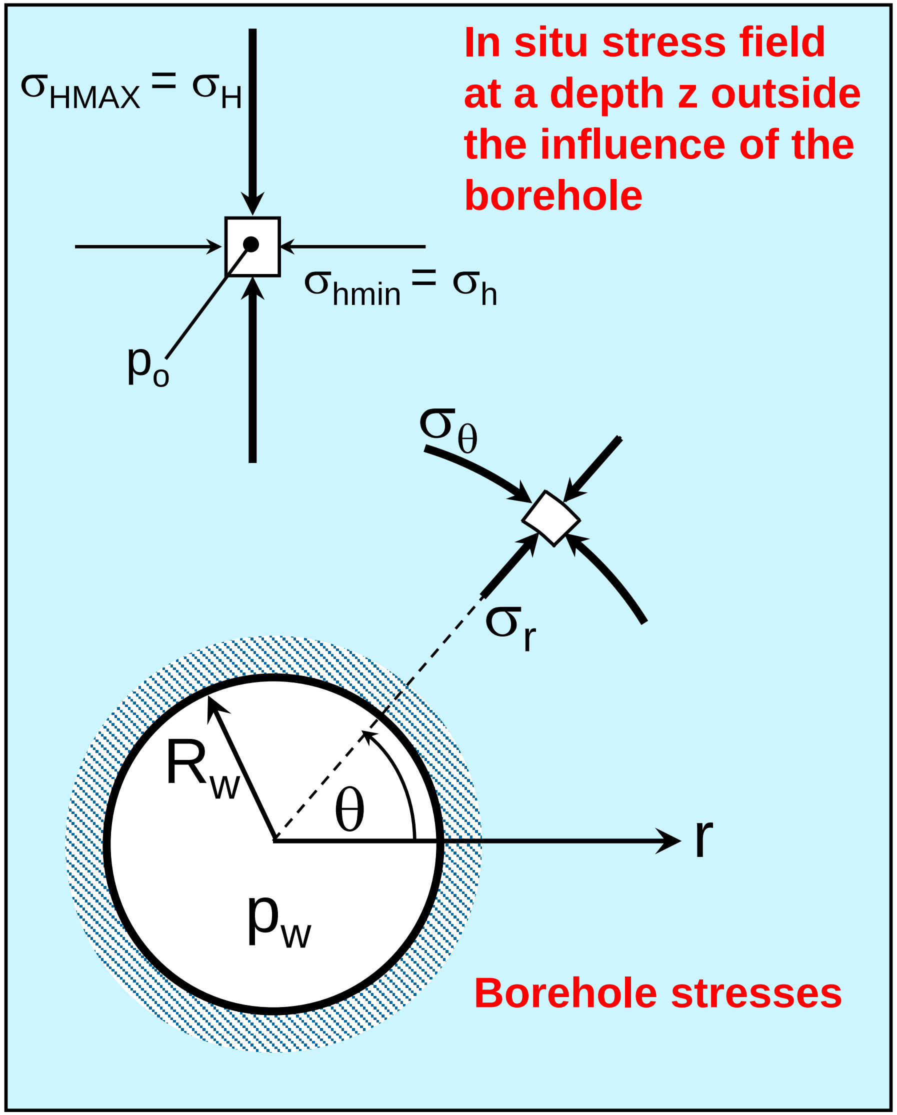
- **Rock stresses *in situ***
  - vertical overburden stresses σ_v
  - horizontal (tectonic) stresses σ_{Hmax} and σ_{hmin}
  - Pore pressures p_0
- **Rock failure strength**
  - Shear strength parameters such as
    - angle of internal friction and
    - cohesion
- **Pressure p_w inside the borehole**
    - from some kind of casing
    - mud pressure

As a function of rock temperature and the existing In situ stresses

Insitu stresses in the rock and borehole stresses

- **The in situ stress field consists of natural earth stresses and pressures, generated by gravity, tectonics…**
- **A reason for different horizontal stresses at a certain depth z (= anisotropic stress state) is tectonic stresses.**
- **Borehole stresses are generated by creation of an opening in a natural stress field**

As a result, a stress concentration is produced around the borehole, and so the *in situ* stresses are modified. This could lead to rock failure



In situ stresses in the rock

- **The vertical principal in situ stress σ_v is usually assumed to be equivalent to the weight of the overburden, i.e.**

$$\sigma_v = \mathrm{z} \cdot \gamma$$

- **Generally the ratio of the minimum horizontal stress $\sigma_{h\,min}$ to the vertical stress σ_v is within the limits of:**

$$\frac{\sigma_{h\,min}}{\sigma_v} = 0.3 \text{ to } 1.5$$

- **and the ratio of the maximum horizontal stress $\sigma_{H\,max}$ to the minimum horizontal $\sigma_{h\,min}$ stress ranges from:**

$$\frac{\sigma_{H\,max}}{\sigma_{h\,min}} = 1 \text{ to } 2$$

1 = isotropic stress field

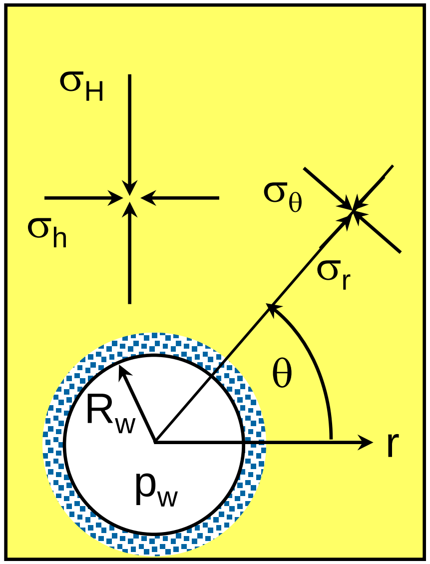
Stresses around vertical boreholes in anisotropic stress field

Stress calculation approach for Linear Elastic rock behavior based on the “Kirsch” Equations

$$\sigma_r = \frac{\sigma_H + \sigma_h}{2}\left(1 - \frac{R_w^2}{r^2}\right) + \frac{\sigma_H - \sigma_h}{2}\left(1 + 3\frac{R_w^4}{r^4} - 4\frac{R_w^2}{r^2}\right)\cos 2\theta + p_w \frac{R_w^2}{r^2}$$

$$\sigma_\theta = \frac{\sigma_H + \sigma_h}{2}\left(1 + \frac{R_w^2}{r^2}\right) - \frac{\sigma_H - \sigma_h}{2}\left(1 + 3\frac{R_w^4}{r^4}\right)\cos 2\theta - p_w \frac{R_w^2}{r^2}$$

$$\sigma_z = \sigma_v - 2\nu_{fr}(\sigma_H - \sigma_h)\frac{R_w^2}{r^2}\cos 2\theta$$



At the wall of the borehole ($r = R_w$) the equations simplify to:

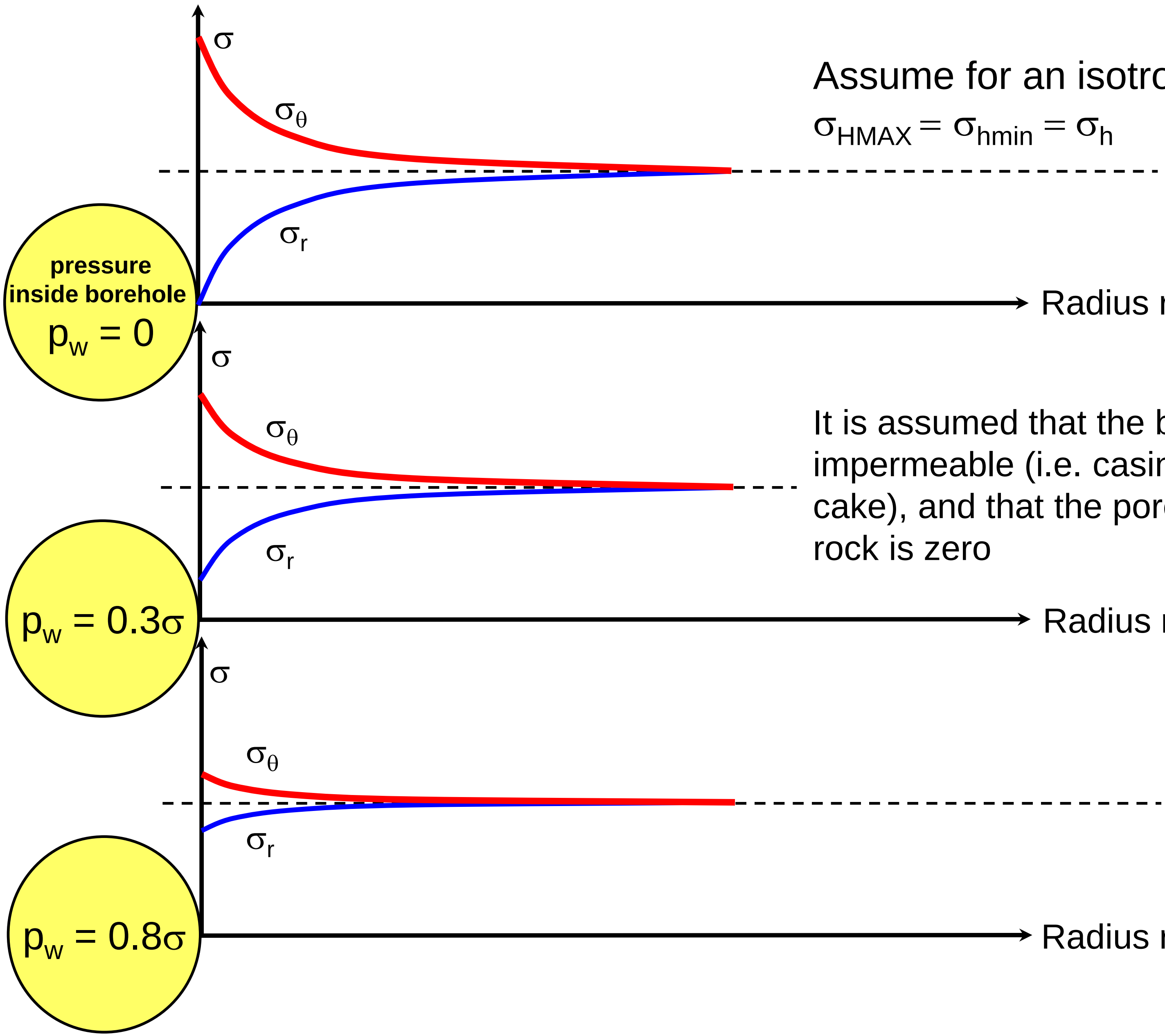
$$\sigma_r = p_w$$

$$\sigma_\theta = \sigma_H + \sigma_h - 2(\sigma_H - \sigma_h)\cos 2\theta - p_w$$

$$\sigma_z = \sigma_v - 2\nu_{fr}(\sigma_H - \sigma_h)\cos 2\theta$$

θ is measured relative to the direction of the major horizontal stress σ_H

Stresses around vertical boreholes

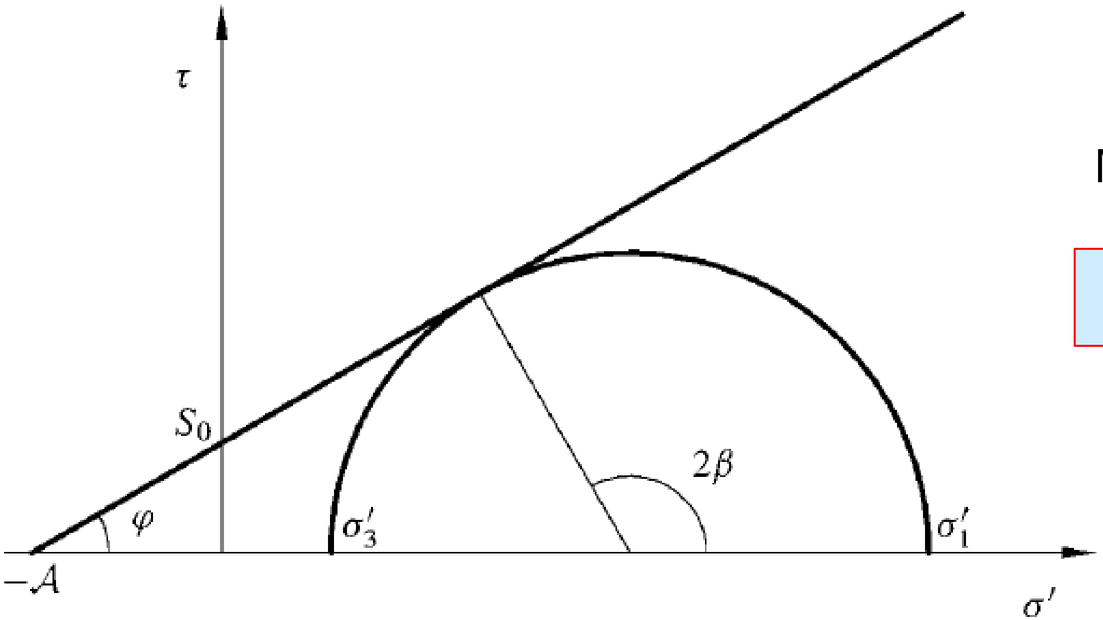


Assume for an isotropic stress field

$\sigma_{HMAX} = \sigma_{hmin} = \sigma_h$

It is assumed that the borehole wall is impermeable (i.e. casing or perfect mud cake), and that the pore pressure in the rock is zero

Borehole failure criteria based on Mohr-Coulomb



Mohr-Coulomb failure criterion

$$\tau = S_0 + \sigma \cdot \tan \varphi$$

S_0	=	cohesion [kPa]
φ	=	angle of internal friction [°]

redefining

$$\beta = \frac{\pi}{4} + \frac{\varphi}{2}$$

$$C_0 = 2 \cdot S_0 \cdot \tan \beta$$

$$\boldsymbol{\sigma_1 = C_0 + \sigma_3 \cdot \tan^2 \beta}$$

reformulated
Mohr-Coulomb failure criterion

Conditions for shear failure in vertical borehole for isotropic stress field and impermeable borehole wall

$\sigma_1 \geqslant \sigma_2 \geqslant \sigma_3$	Borehole failure occurs if
$\sigma_\theta \geqslant \sigma_z \geqslant \sigma_r$	$p_w \leqslant p_f + \dfrac{2(\sigma_h - p_f) - C_0}{1 + \tan^2\beta}$
$\sigma_z \geqslant \sigma_\theta \geqslant \sigma_r$	$p_w \leqslant p_f + \dfrac{\sigma_v - p_f - C_0}{\tan^2\beta}$
$\sigma_z \geqslant \sigma_r \geqslant \sigma_\theta$	$p_w \geqslant p_f + 2(\sigma_h - p_f) - \dfrac{\sigma_v - p_f - C_0}{\tan^2\beta}$

and hydraulic fracturing occurs at $p_{w,max} = 2 \cdot \sigma_h - p_f + T_O$

where T_O = tensile strength of the rock

The principal stresses at the borehole wall are

$$\sigma_r = p_w$$

$$\sigma_\theta = 2\sigma_h - p_w$$

$$\sigma_z = \sigma_v$$

Source: Fjaer, E., Holt R.M., Horsrud P., Raaen A.M. and Risnes R., 2008,

In summary we can state

- **σ_θ is the tangential stress, also called the hoop stress**
- **σ_θ lies parallel (tangential) to the borehole wall**
- **The magnitude of σ_θ is affected by:**
  - In situ stresses
  - Stabilizing pressure inside the borehole
  - Temperature and rock behavior
- **The most critical stress conditions are around a borehole**
  - High σ_θ values can lead to rock failure or yield
  - Lower σ_θ values usually imply stability

What information do we need to successfully lower a deep borehole and keep it open

- **First, we need stresses around the borehole**
  - In **situ stresses** are vital
  - Temperature profile; thermally induced changes in stress affect both the tangential and the axial stress.
  - In some cases, rock properties are also needed
- **Then, we must compare the maximum shear stress with the rock strength**
  - We need to know the **rock strength for the in situ temperature, creep behavior for long term stability and deformation properties**

- **If stress exceeds strength, the rock will yield or "fail"**

What information do we need to successfully lower a deep borehole and keep it open

- **The only possibility to stabilize a borehole from failing or yielding is by providing some kind of lateral support p_w from within the borehole. This could be:**
  - some casing
  - fluid pressure
- **It is of greatest importance to estimate/calculate/control this stabilizing support during all phases of drilling. If a fluid pressure is used, care has to be exercised to be within the pressure band of possible minimum and maximum values**

References

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Thank you

Questions?