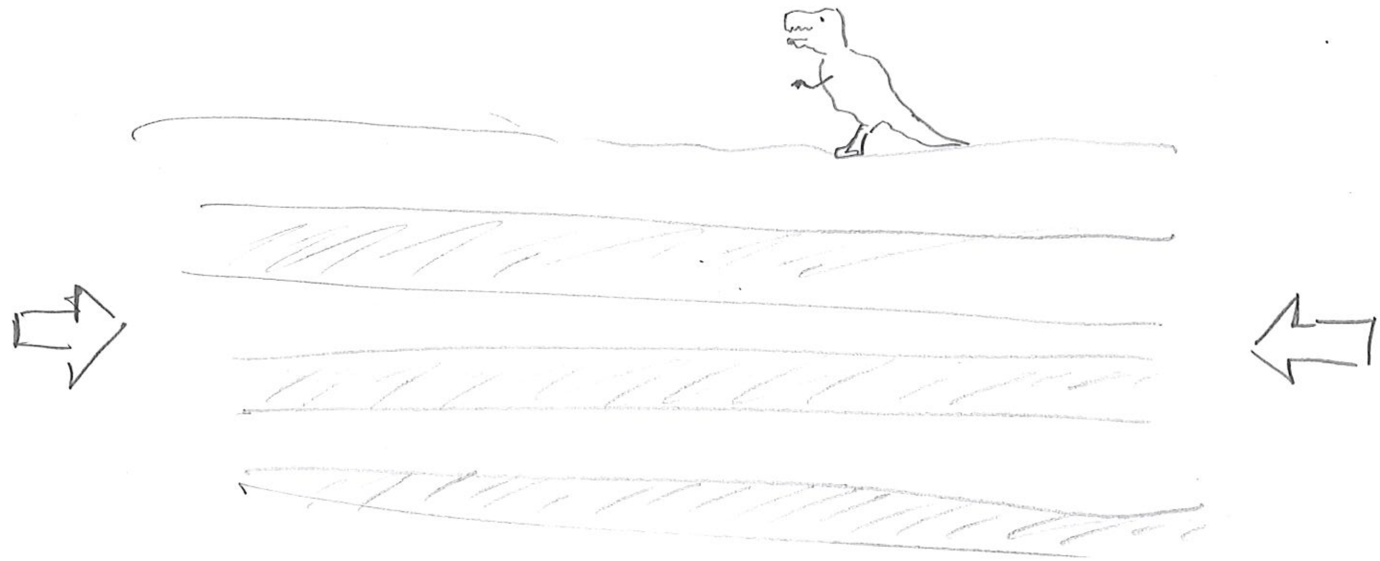
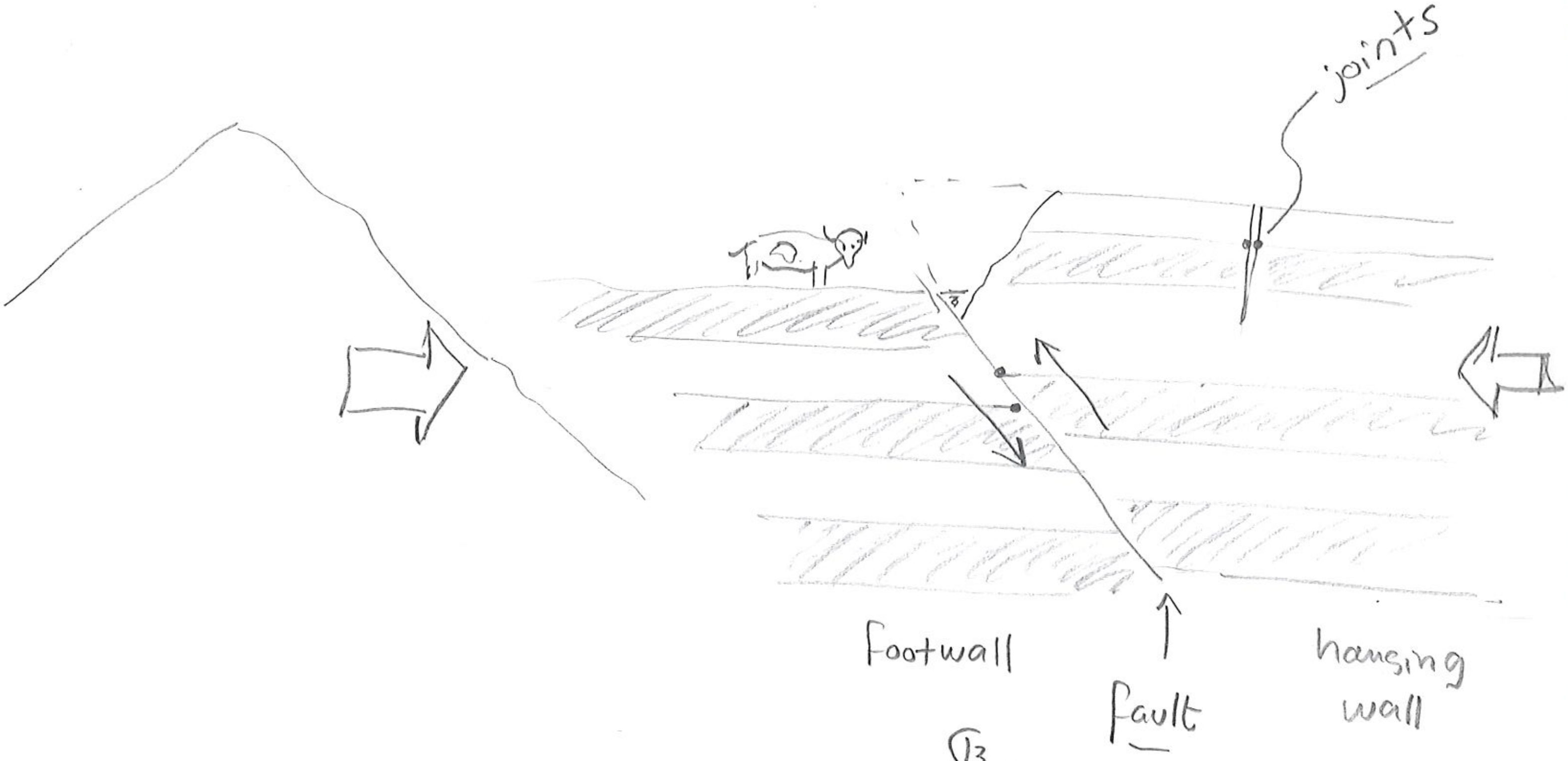
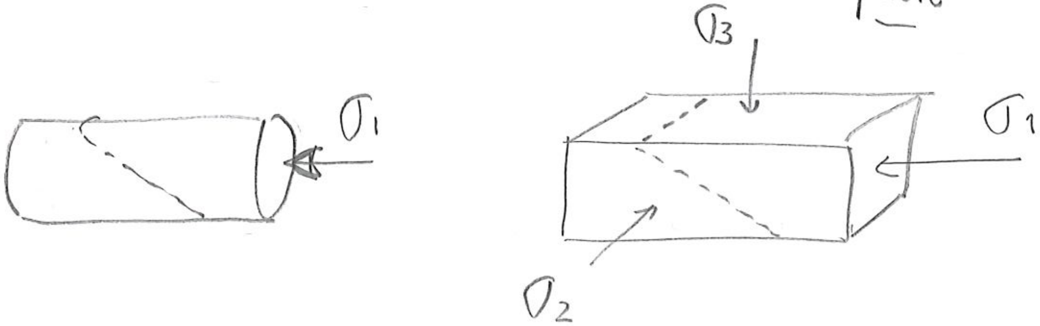
Faults and fractures (shear)

- crème brûlée
- frade oil field

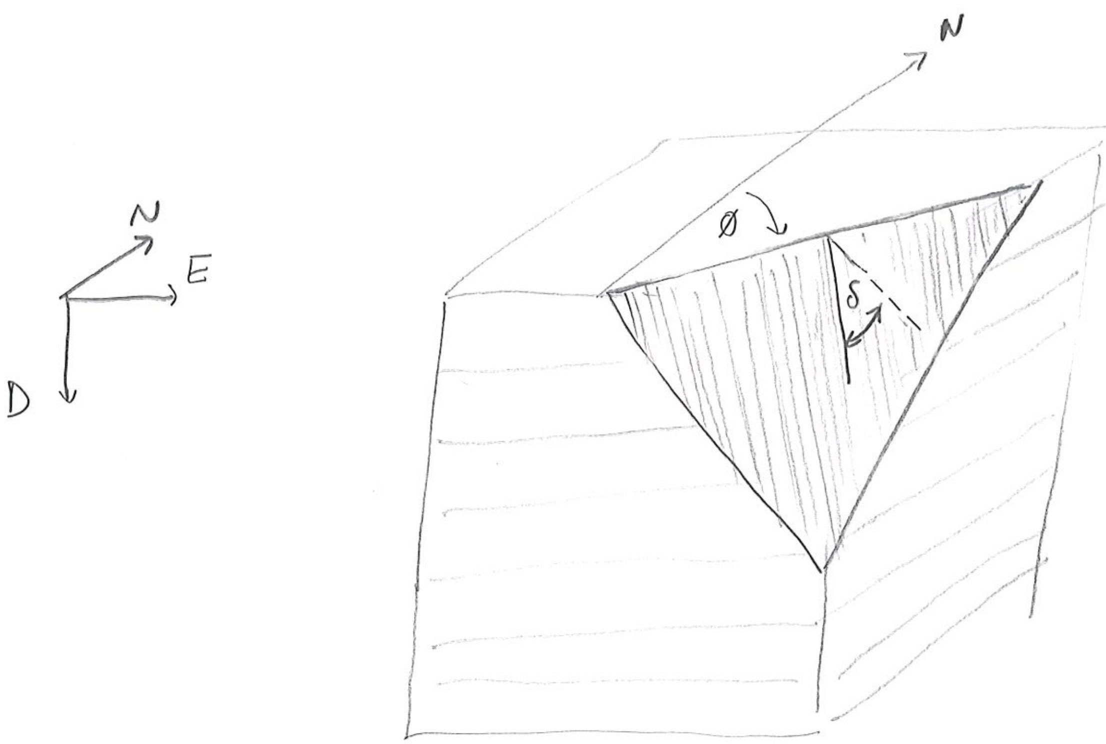






Methods to map faults and fractures

- seismic | big faults
- well bore imaging | big and small faults
- ...



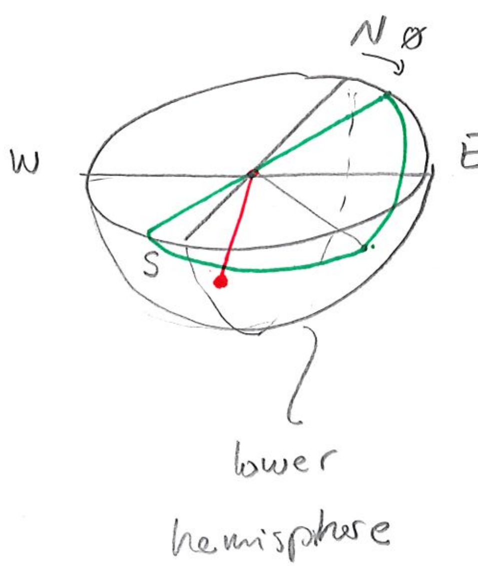
Ø: strike

δ: dip

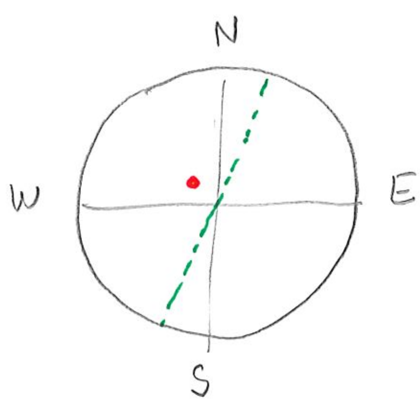
δ: | 0 – 90°
| = 45°

Ø: | Quadrant convention
| = N 40° E
| = E 50° N } field
| Azimuth convention
| = 040° (clockwise) } computations

stereonets : 3D → 2D

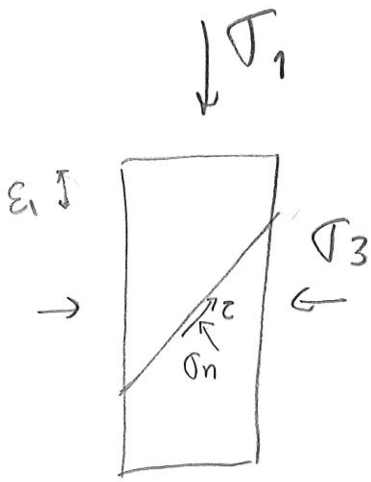


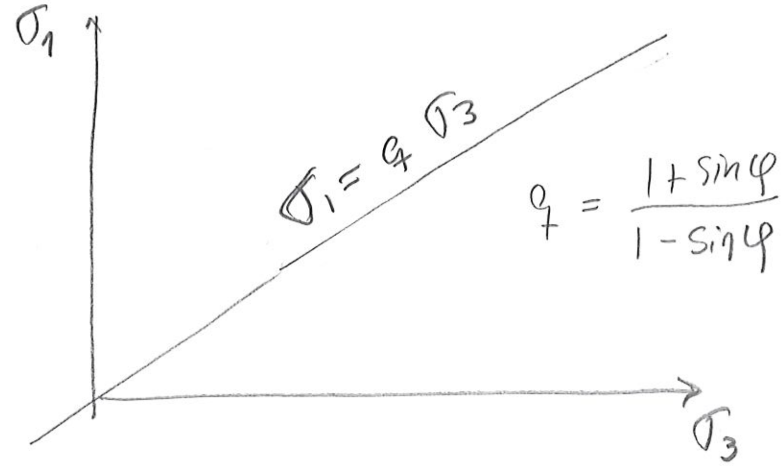
3D



2D

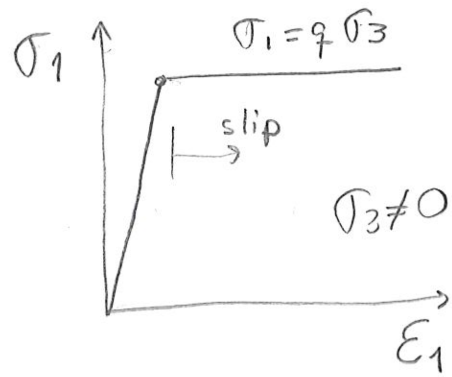
Strength of faults



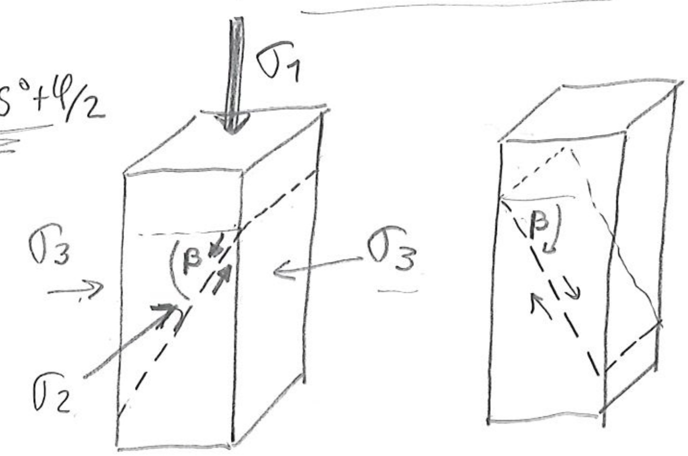


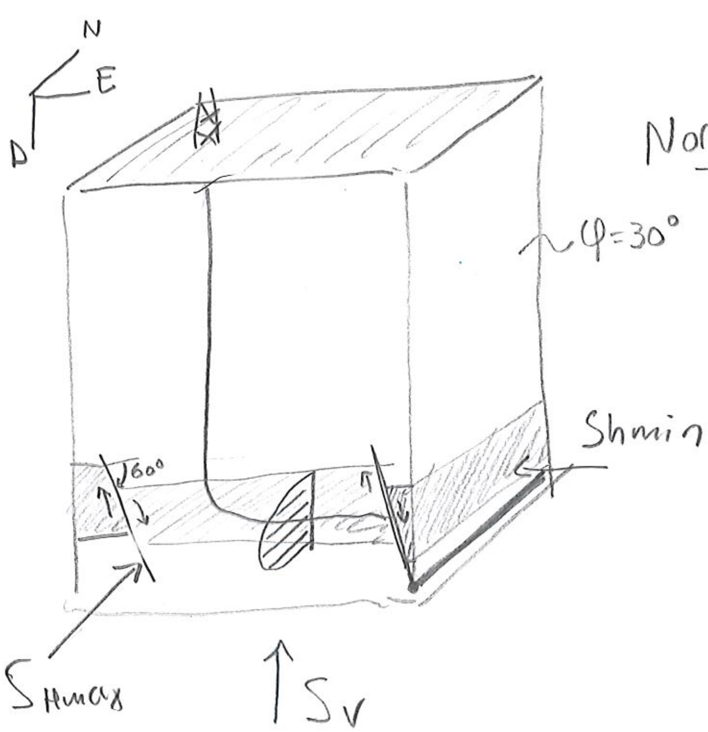
interface
- no cohesion
- frictional strength

$\varphi = 30^\circ \Rightarrow q = 3$



$\beta = 45^\circ + \varphi/2$





Normal faulting ($S_v > S_{Hmax} > S_{hmin}$)

Faults

strike ϕ: 000°

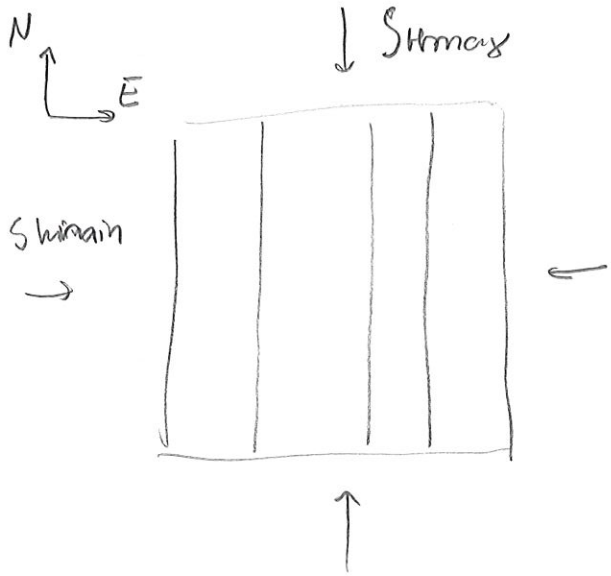
dip δ: 60°E

HF

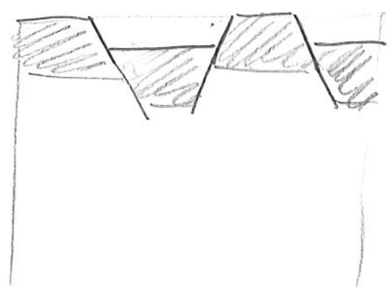
strike: 000°

dip: 90°

Top view (Normal faulting



side view



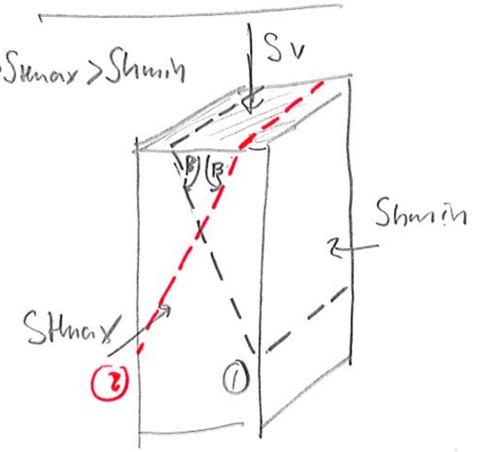
Ideal orientation of faults

$\varphi = 30°$ all cases

$\beta = 60° = 45° + \varphi/2$

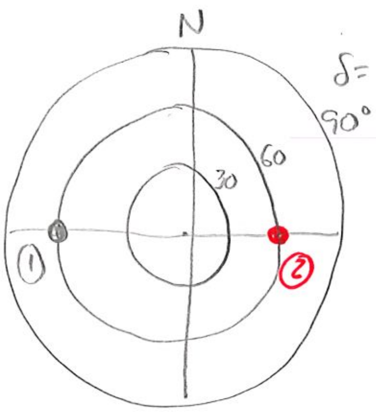
Normal Faulting

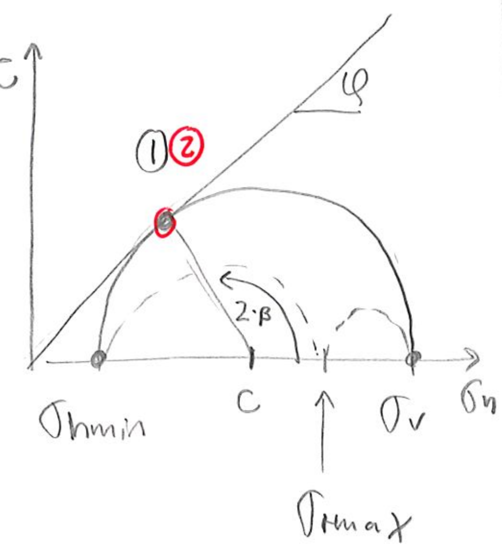
$S_v > S_{Hmax} > S_{hmin}$



① Ø = 000°
δ = 60°E

② Ø = N-S
δ = 60°W

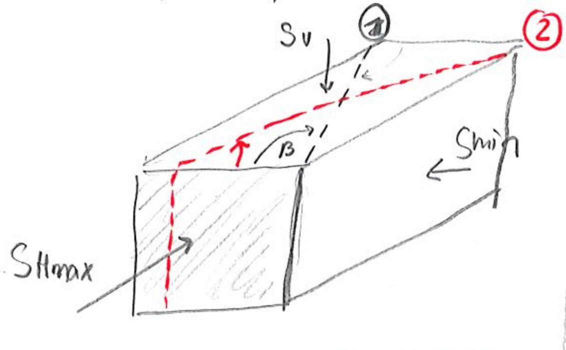




where $B = 45° + \varphi/2$
all cases

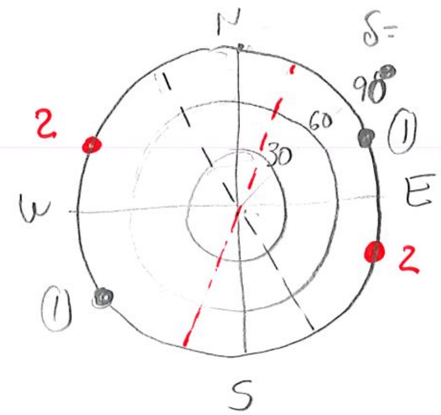
Strike Slip

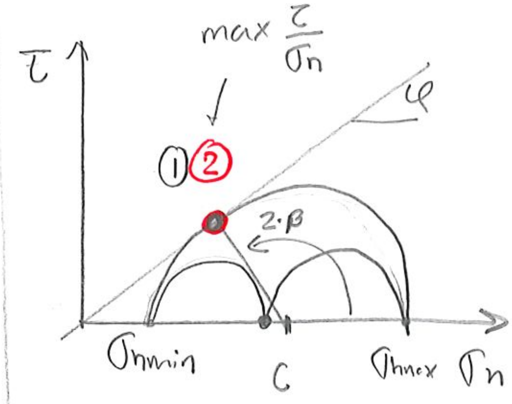
$S_{Hmax} > S_v > S_{hmin}$



① Ø = N 30°W
δ = 90°

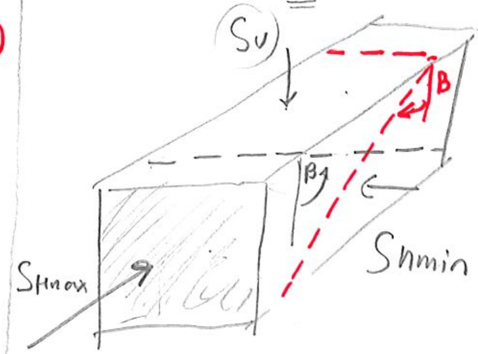
② Ø = 030°
δ = 90°





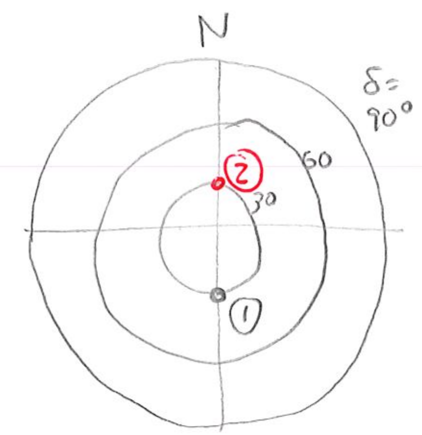
Reverse Faulting

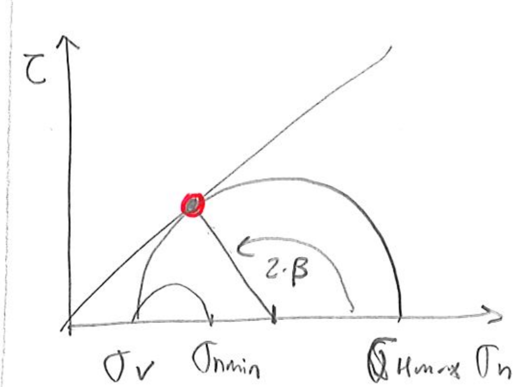
$S_{Hmax} > S_{hmin} > S_v$



① Ø = 090°
δ = 30°N

② Ø = E-W
δ = 30°S





Applications:

① Ideal orientation of faults

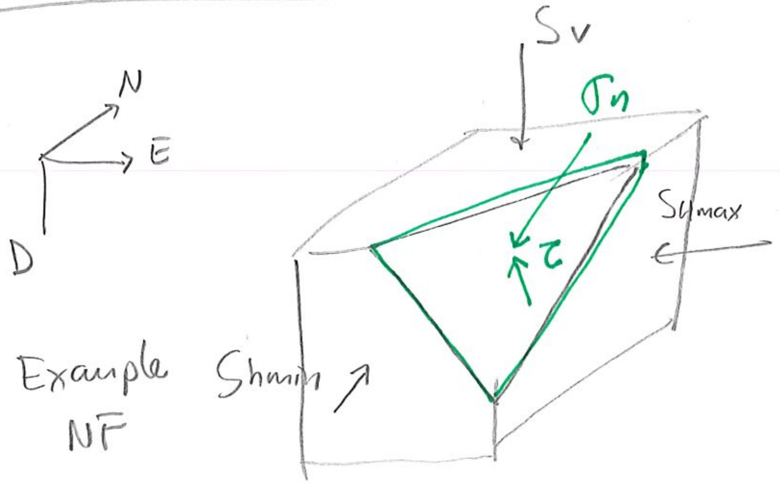
$\Updownarrow$

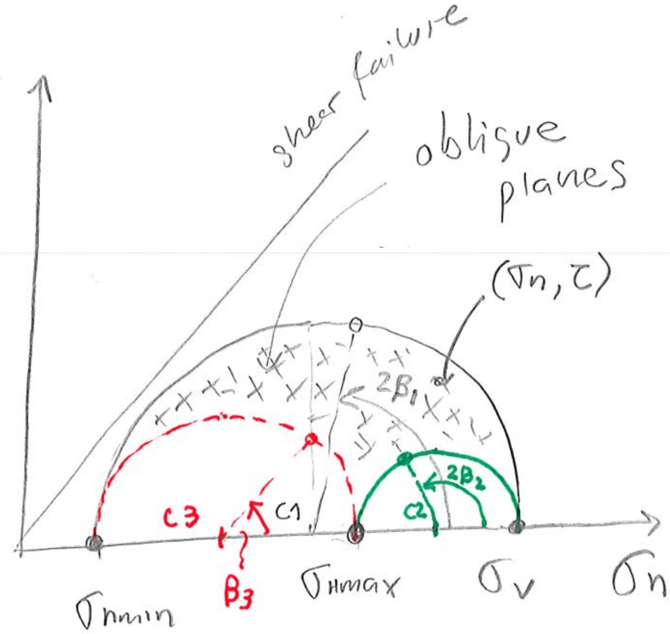
orientation of principal stresses

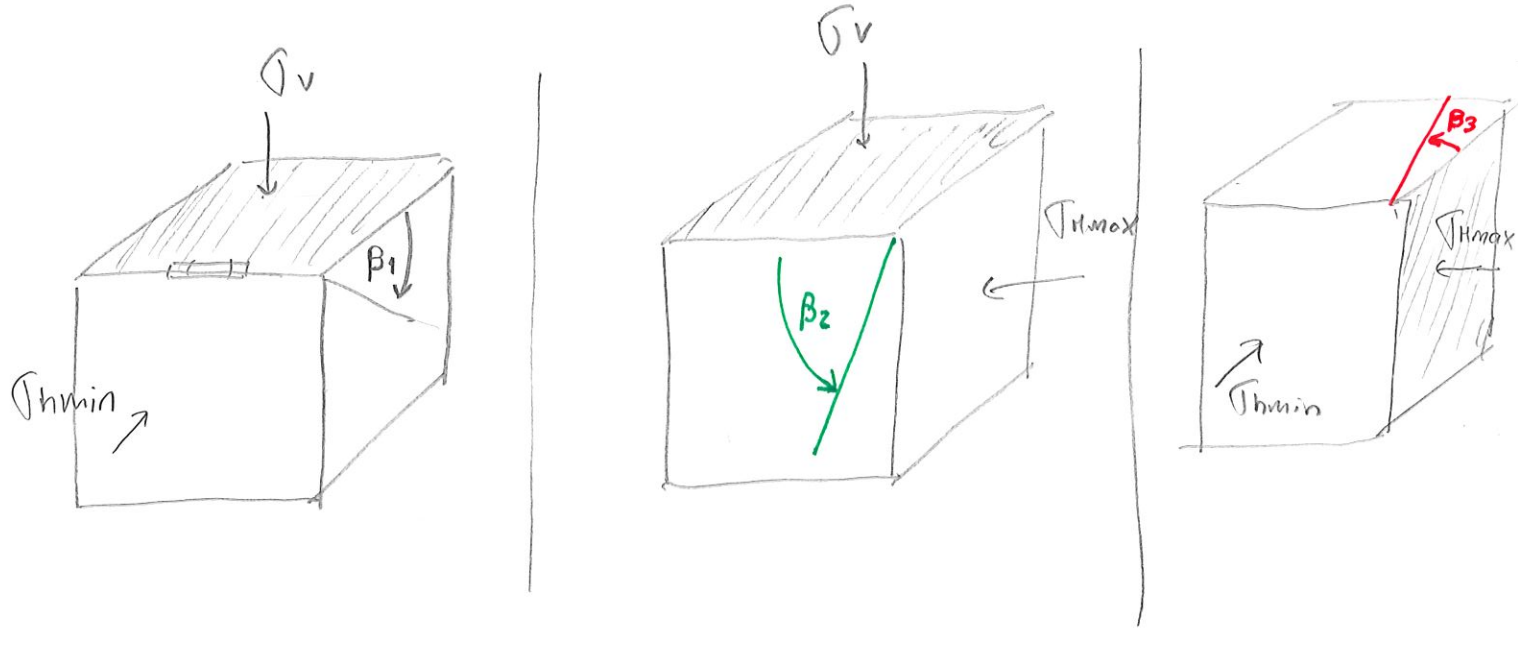
② Fracture reactivation (shear) or fault reactivation due to large τ / σ_n

$\hookrightarrow$ calculate τ and σ_n

3D Mohr-circle







Problem

Stress:
- $S_v = 23$ MPa
- $P_p = 10$ MPa
- $S_{Hmax} = 20$ MPa
- $S_{hmin} = 13.8$ MPa (Azimuth = 090°)

→
- $\sigma_v = 13$ MPa
- $\sigma_{Hmax} = 10$ MPa
- $\sigma_{hmin} = 3.8$ MPa

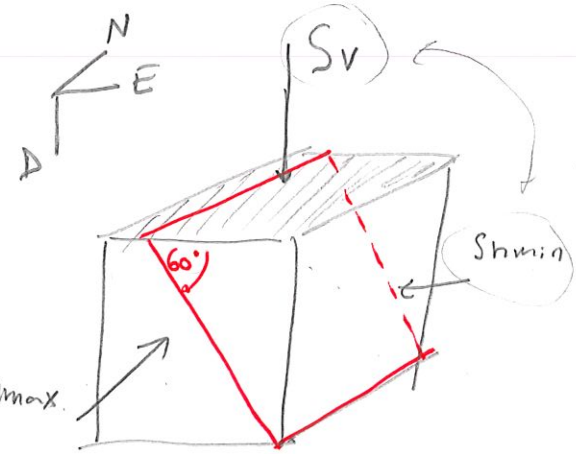
Fault:
- strike = 000°
- dip = 60°E

Calculate:
- σ_n, τ
- τ / σ_n

---

1) Identify stress regime → NF

2) Draw block diagram or top view



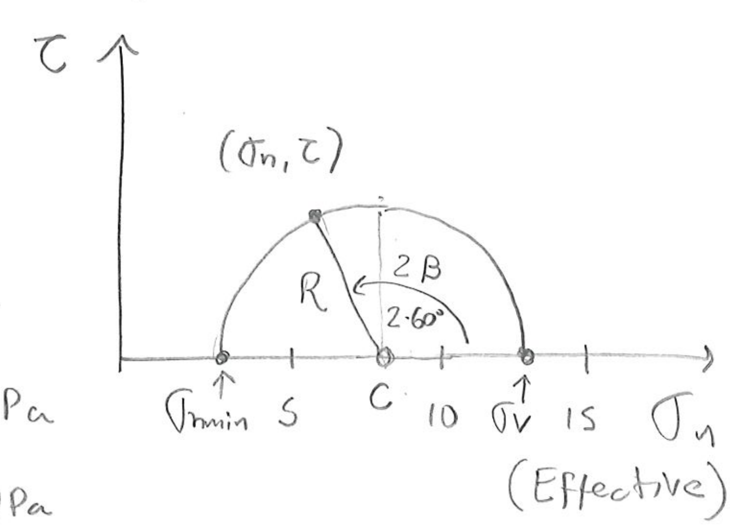
3) Identify fault and corresponding (circle, angle)

$$C = \frac{13\text{ MPa} + 3.8\text{ MPa}}{2} = 8.4\text{ MPa}$$

$$R = \frac{13\text{ MPa} - 3.8\text{ MPa}}{2} = 4.6\text{ MPa}$$

$$\sigma_n = C + \cos(2B) \cdot R = 6.1\text{ MPa}$$

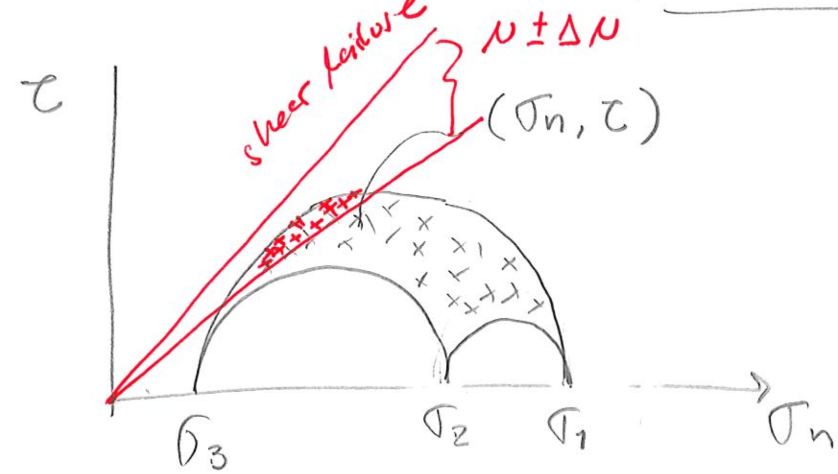
$$\tau = R \cdot \sin(2B) = 4.0\text{ MPa}$$



Applications of stress projection on a plane

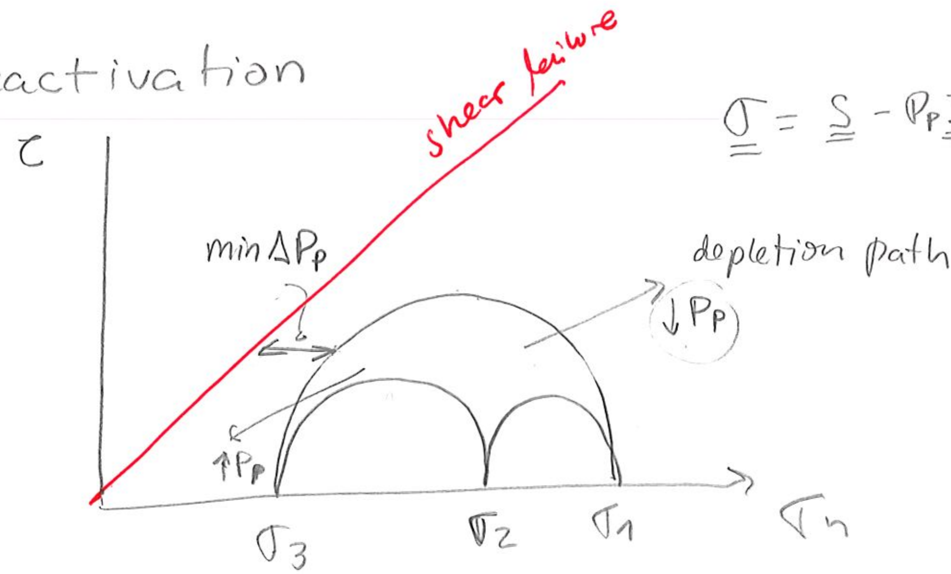
brittle rocks

1. Critically stressed fractures $\longleftrightarrow$ $\boxed{K_{frac} \propto \frac{\tau}{\sigma_n}}$



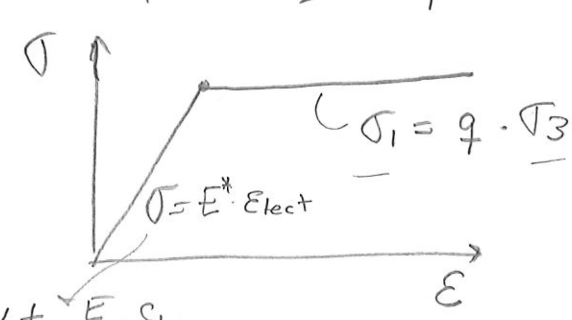
2. Fault reactivation

$\underline{\underline{\sigma}} = \underline{\underline{S}} - P_p \underline{\underline{I}}$



$\min \Delta P_p$ = distance between Mohr circle and shear failure line

3. Determination of limits/bounds of Horizontal stress



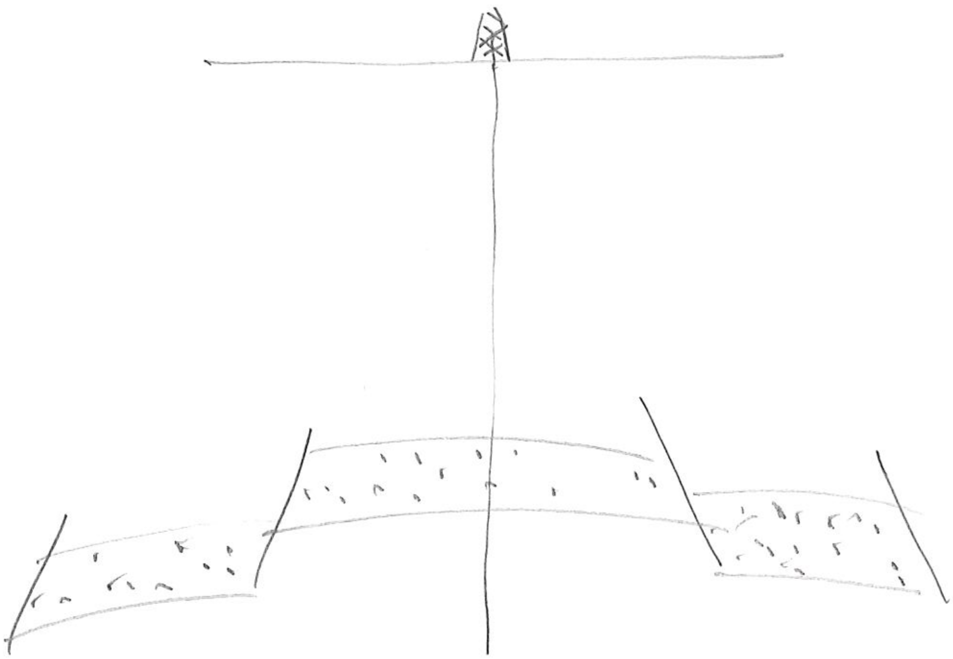
$\sigma_n = \frac{\nu}{1-\nu}\sigma_v + \frac{E}{1-\nu^2}\varepsilon_{hmax} \ldots$

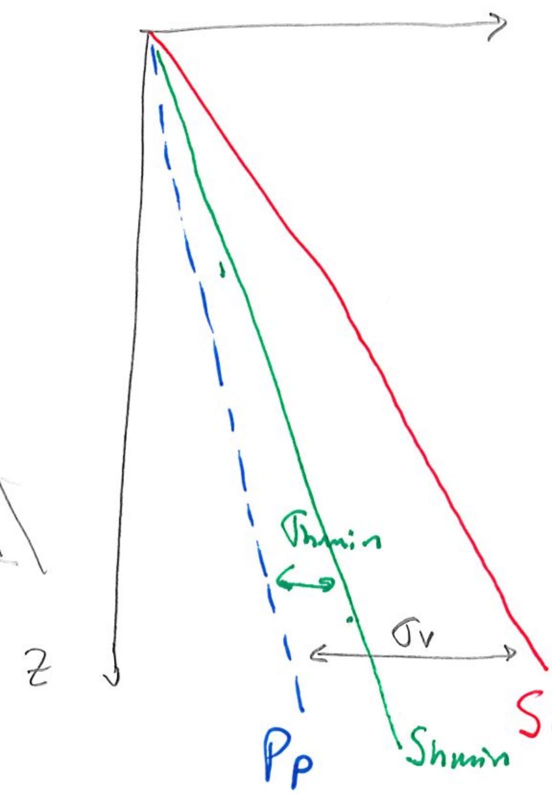
Normal faulting : $\sigma_1 = q\,\sigma_3$

$$\boxed{\sigma_v = q\,\sigma_{hmin}}$$

usually known

$\sigma_{hmin} = \dfrac{\sigma_v}{q}$





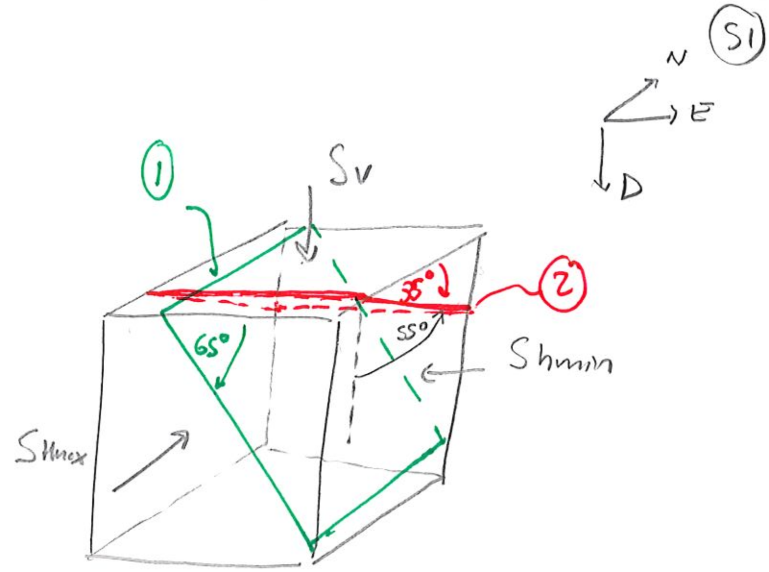
assume

$$\boxed{q = 3}$$

(S1)

HW 7

5) • Draw Block diagram



$S_{Hmax} > S_v > S_{hmin}$

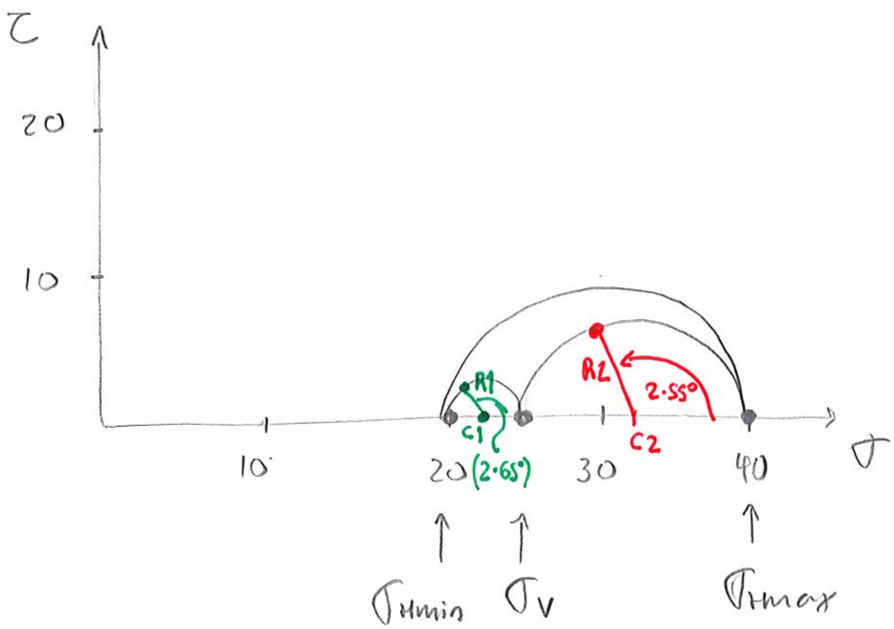
$P_p = 20\ MPa$

• Calculate effective principal stresses

$\sigma_{Hmax} = 40\ MPa$; $\sigma_v = 25\ MPa$] Principal stresses

$\sigma_{hmin} = 20\ MPa$

• Draw Mohr circles



① { $\tau =$

$\sigma_n =$

S2

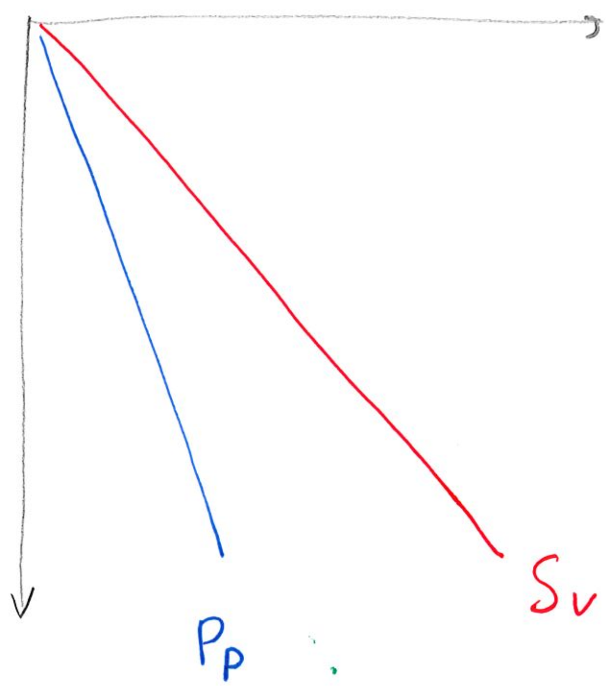
7) limits of S_1 and S_3 for NF and RF

→ S_v —

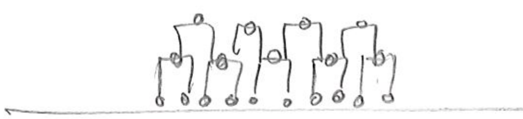
NF: $\sigma_{hmin} = \dfrac{\sigma_v}{q}$

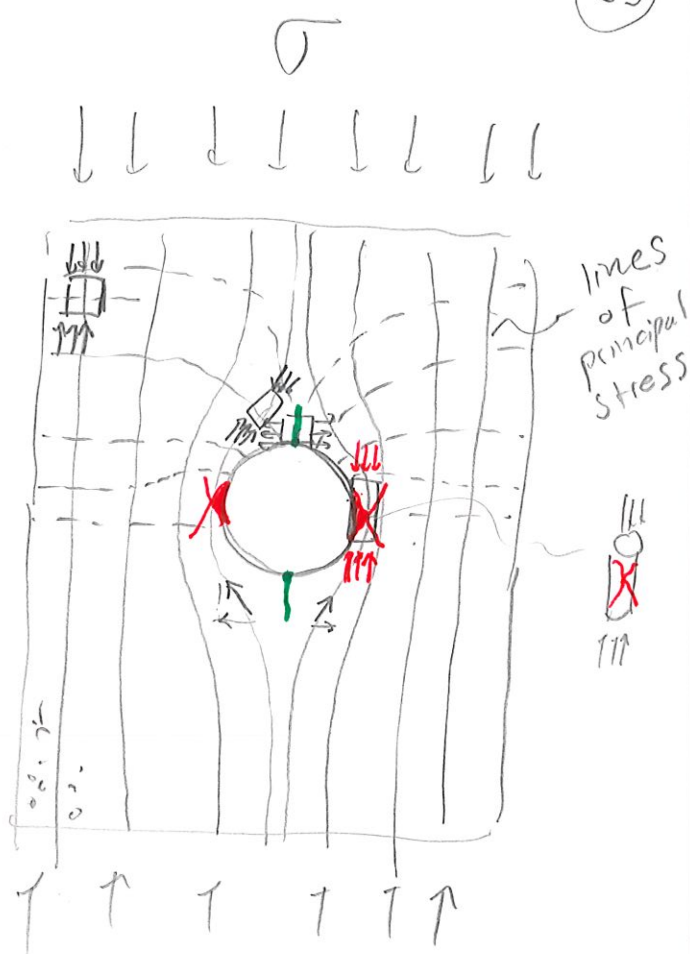
RF: $\sigma_{Hmax} = q \cdot \sigma_v$

$$\sigma_1 = q\,\sigma_3$$



Wellbore Stability





- Generalized solution of continuum mechanics problem

$$(\lambda + G)\,\nabla \cdot (\nabla \underline{U}) + G\,\nabla^2 \underline{U} = 0$$

↓

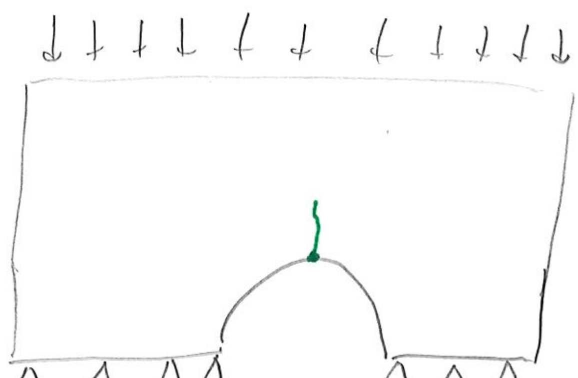
analytical

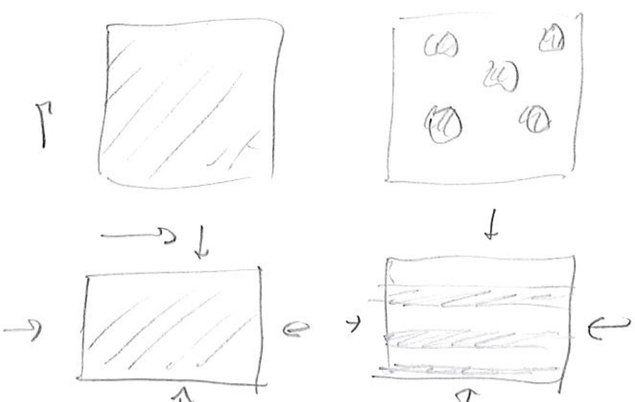
↓

<u>Kirsch solution</u>

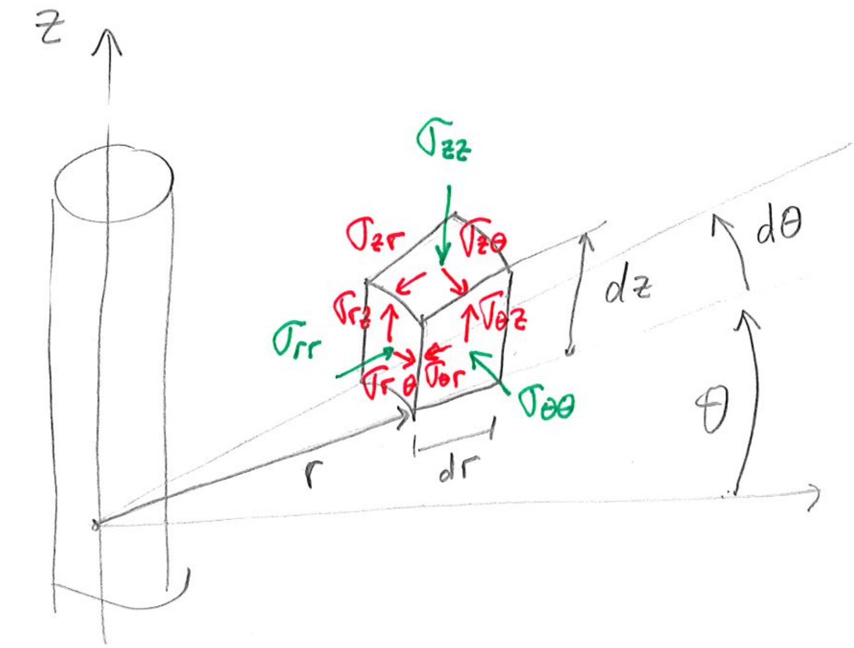
- linear elastic solid
- homogeneous
- isotropic

≡



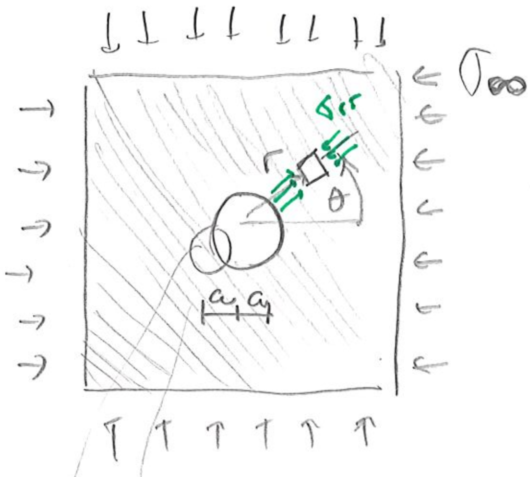


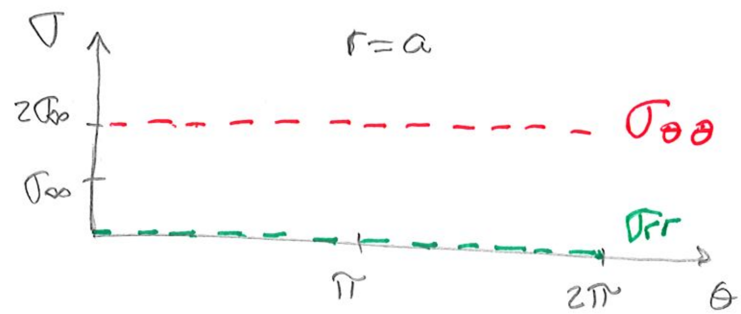
cylindrical coordinates

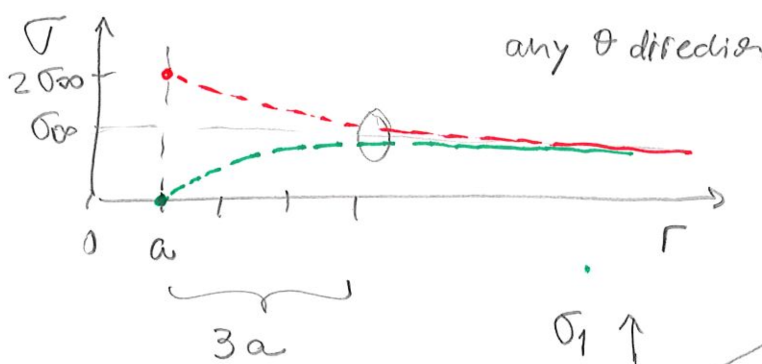


normal
- σ_{zz} : axial stress
- σ_{rr} : radial stress
- $\sigma_{\theta\theta}$: tangential, circumfe..., hoop stress

shear stresses
- σ_{zr}
- $\sigma_{\theta r}$
- ⋮

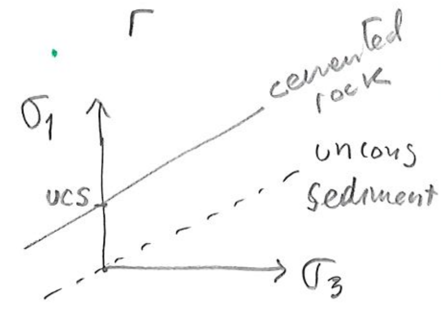




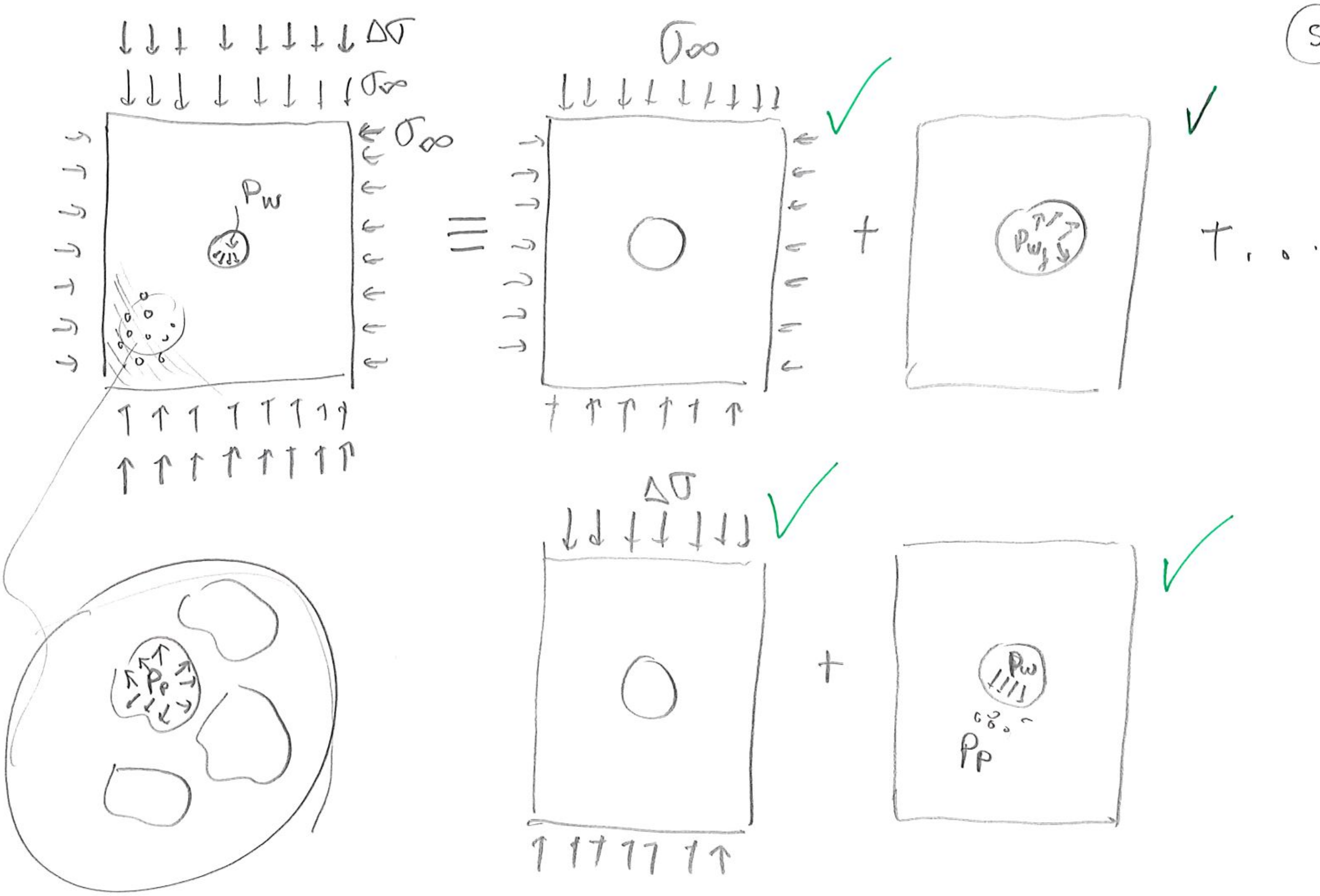


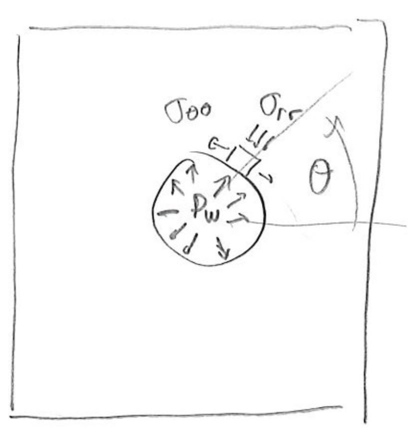
$$\sigma_{rr} = \left(1 - \frac{a^2}{r^2}\right)\sigma_\infty$$

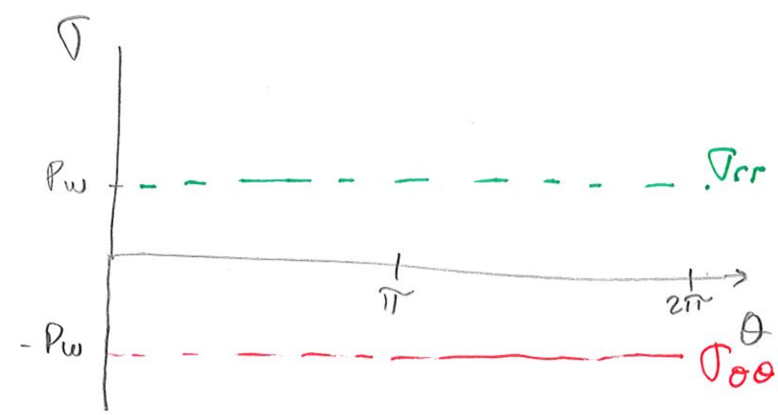
$$\sigma_{\theta\theta} = \left(1 + \frac{a^2}{r^2}\right)\sigma_\infty$$

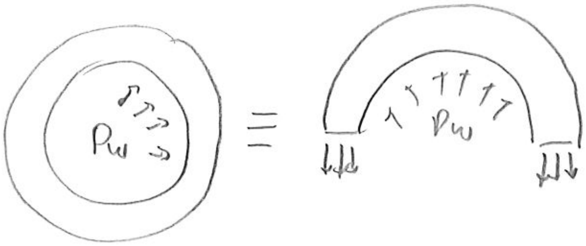


$$\underbrace{\frac{\sigma_{\theta\theta}(r=a)}{\sigma_\infty}}=2 \quad ; \quad \left.\frac{\sigma_{\theta\theta}}{\sigma_{rr}}\right|_{r=a} = \infty$$

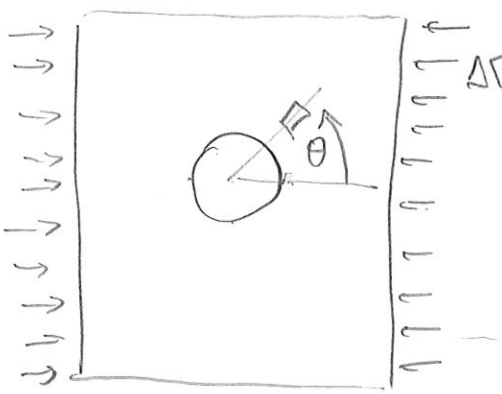

ΔΣ
σ∞
σ∞
Pw
≡
σ∞
+
Pw
+ . . .
ΔΣ
+
Pw
Pp
Pp

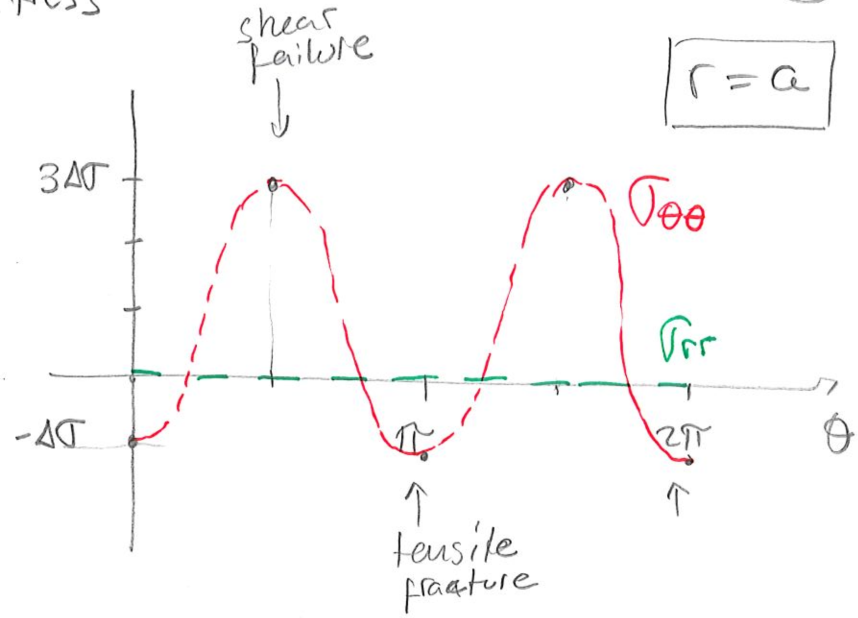

σθθ
σrr
Pw
θ


σ
Pw
σrr
π
2π
θ
-Pw
σθθ

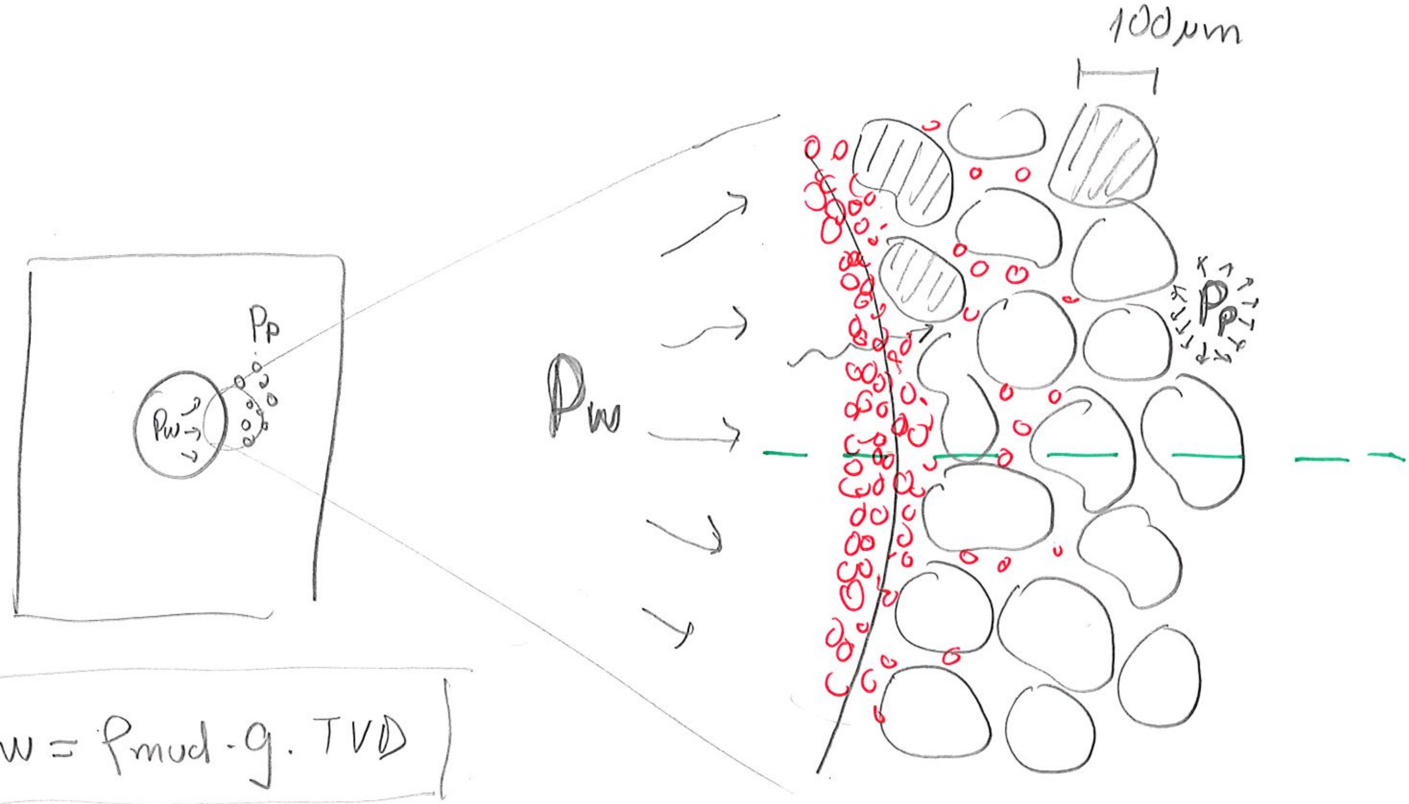

Pw
=
Pw

$\Delta\sigma$: differential stress



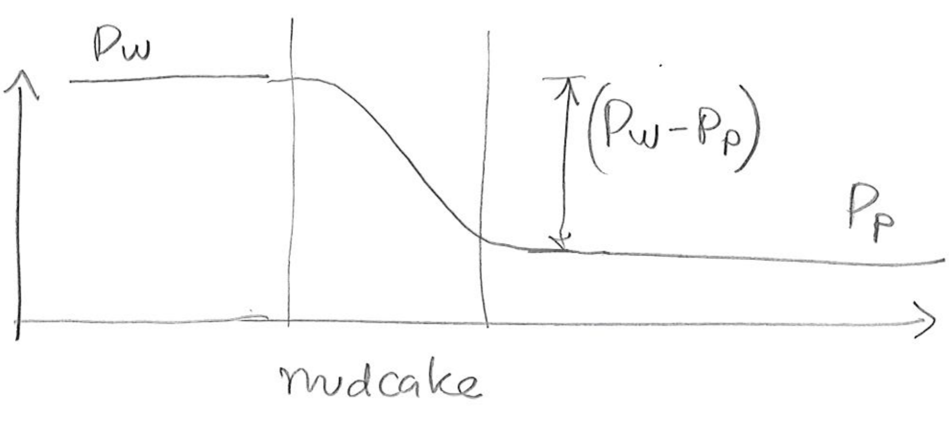


$$\left.\frac{\sigma_{\theta\theta}}{\Delta\sigma}\right|_{r=0,\,\theta=\pi/2} = 3$$



$$\boxed{P_w = \rho_{mud} \cdot g \cdot TVD}$$

↳ hydrostatic



Stresses at the well bore wall

$$r = a \quad \left| \begin{array}{l} \sigma_{rr} = (P_w - P_p) \\ \sigma_{\theta\theta} = -(P_w - P_p) + (\sigma_{Hmax} + \sigma_{hmin}) - 2(\sigma_{Hmax} - \sigma_{hmin})\cos 2\theta \\ \sigma_{\theta r} = 0 \end{array} \right.$$

Tensile failure ; Breakdown Pressure P_b

$$\theta = 0^\circ \text{ or } 180^\circ$$

$$\sigma_{\theta\theta} = -T_s$$

$$-T_s = -(P_w - P_p) + (\sigma_{Hmax} + \sigma_{hmin}) - 2(\sigma_{Hmax} - \sigma_{hmin})$$

thermal stress

$$\boxed{P_w = P_b = \underbrace{P_p}_{\text{pore press}} + \underbrace{3\sigma_{hmin} - \sigma_{Hmax}}_{\text{stress anisotropy}} + \underbrace{T_s}_{\text{tensile strength}} \; \Big| - \sigma^{\Delta T}}$$

pore press } field   stress anisotropy } field   tensile strength } lab

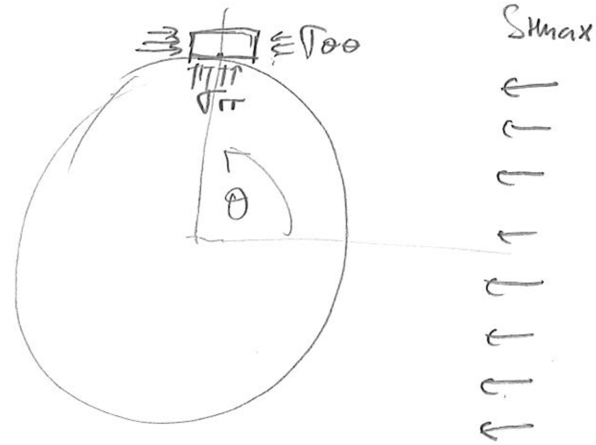
$$P_w > P_b \Rightarrow \left| \begin{array}{l} \text{tensile fracture} \\ \text{wellbore breakdown} \end{array} \right.$$

Sheer failure: Wellbore breakouts

$$\theta = 90^\circ \text{ or } 270^\circ$$

$$\sigma_{\theta\theta} = -(P_w - P_p) + 3\sigma_{Hmax} - \sigma_{hmin}$$

$$\sigma_{rr} = (P_w - P_p)$$



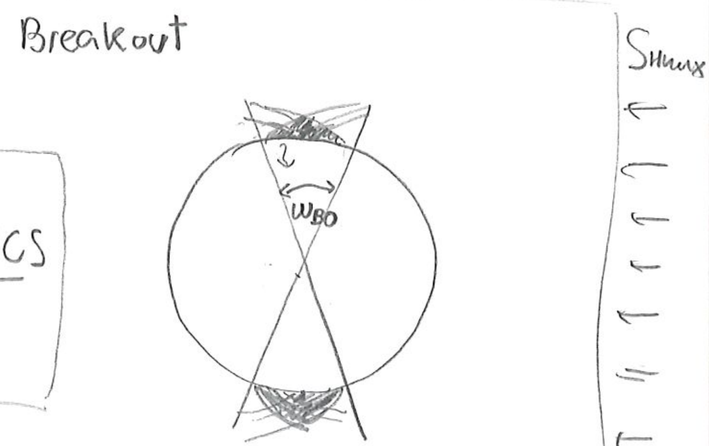
sheer failure: $\boxed{\underbrace{\sigma_1}_{\sigma_{\theta\theta}} = UCS + \underbrace{\sigma_3}_{\sigma_{rr}} \cdot q}$

$$\boxed{P_{w\,shear} = P_p + \frac{3\sigma_{Hmax} - \sigma_{hmin} - UCS}{1+q}}$$

$$\boxed{P_{wBO} = P_p + \ldots \frac{(\sigma_{Hmax} + \sigma_{hmin}) - 2(\sigma_{Hmax} - \sigma_{hmin})\cos(\pi - w_{BO}) - UCS}{1+q}}$$

valid for

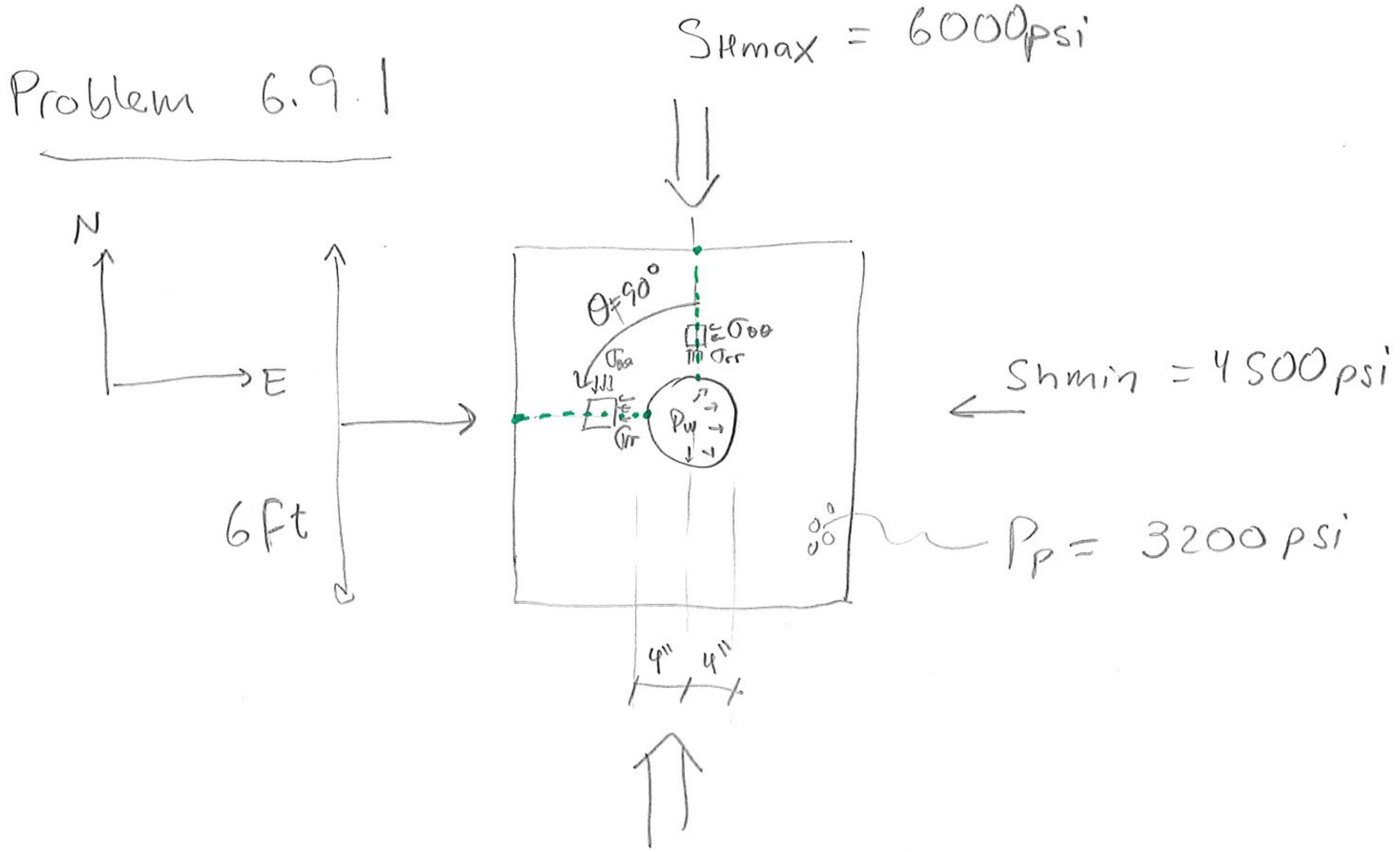
$w_{BO} \lesssim 70^\circ$



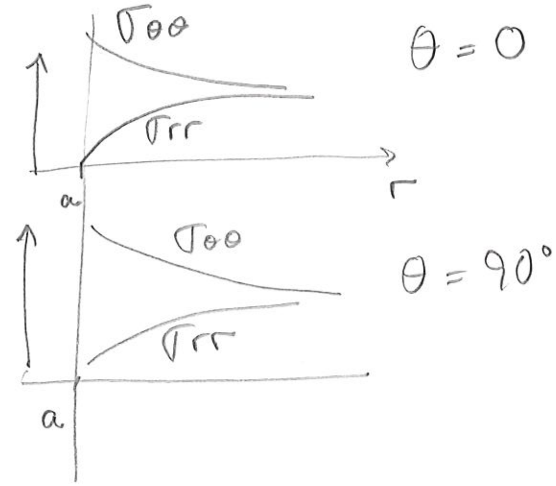
↳ back-calculate $\boxed{S_{Hmax}}$ for a vertical wellbore

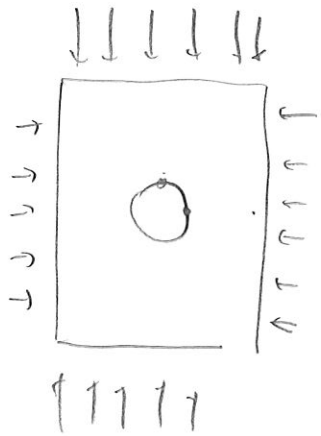
HW #8

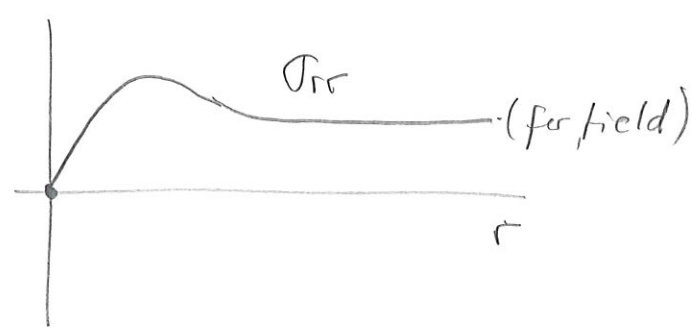
Problem 6.9.1



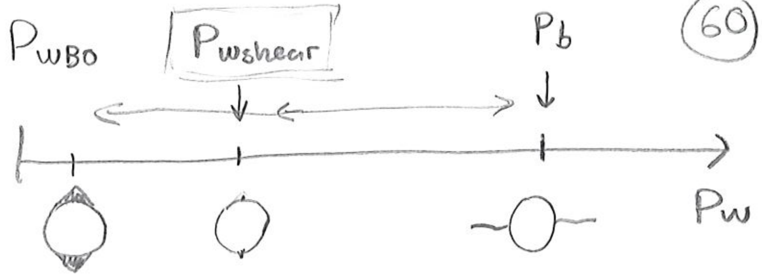
1) $P_w = 3200$ psi
2) $P_w = 4000$ psi

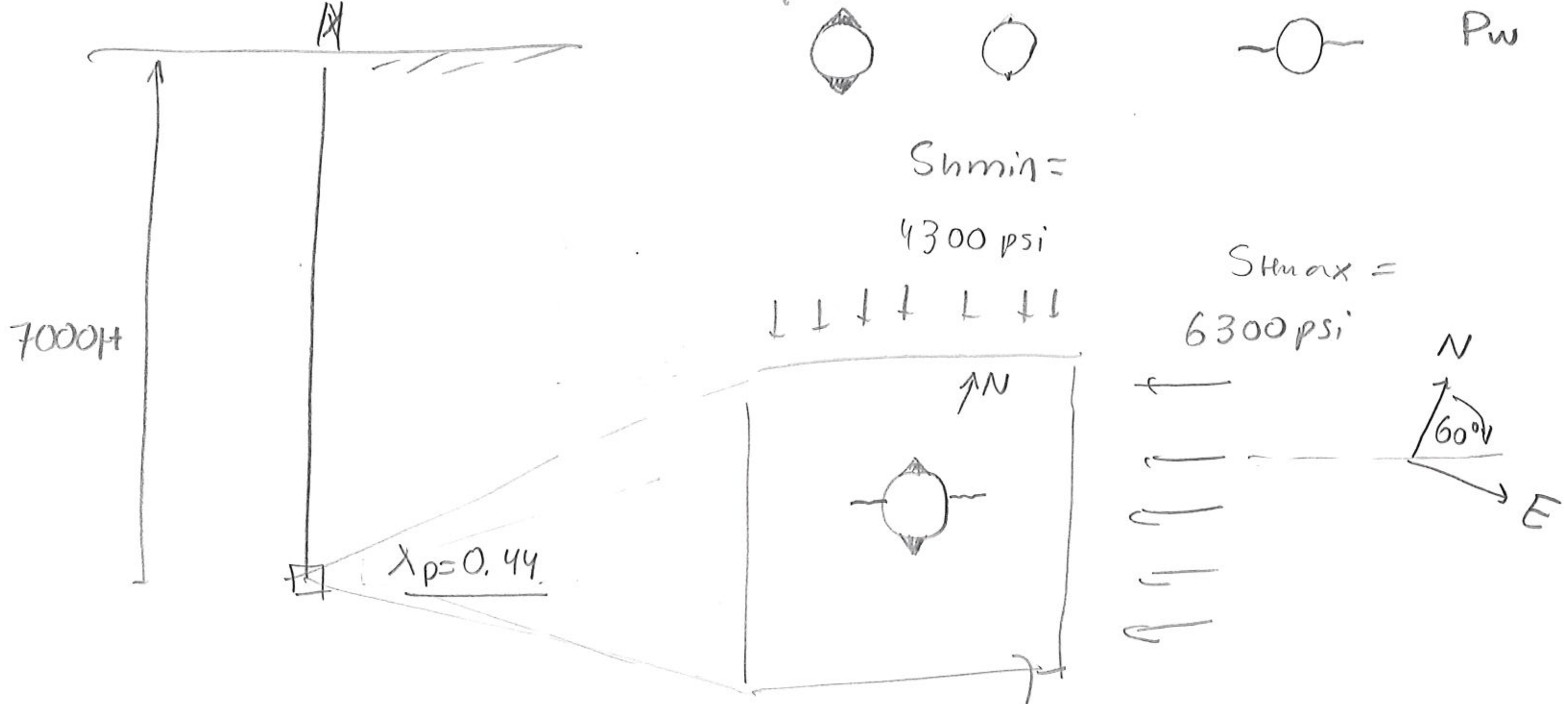






Problem 6.9.2



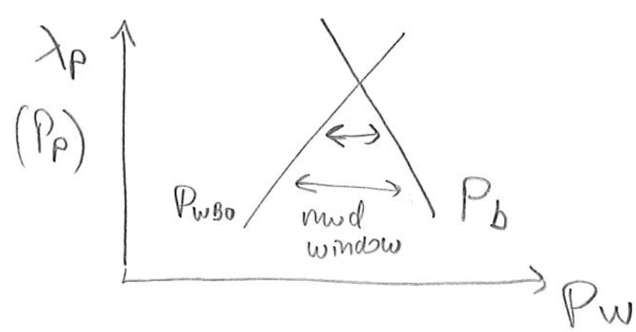


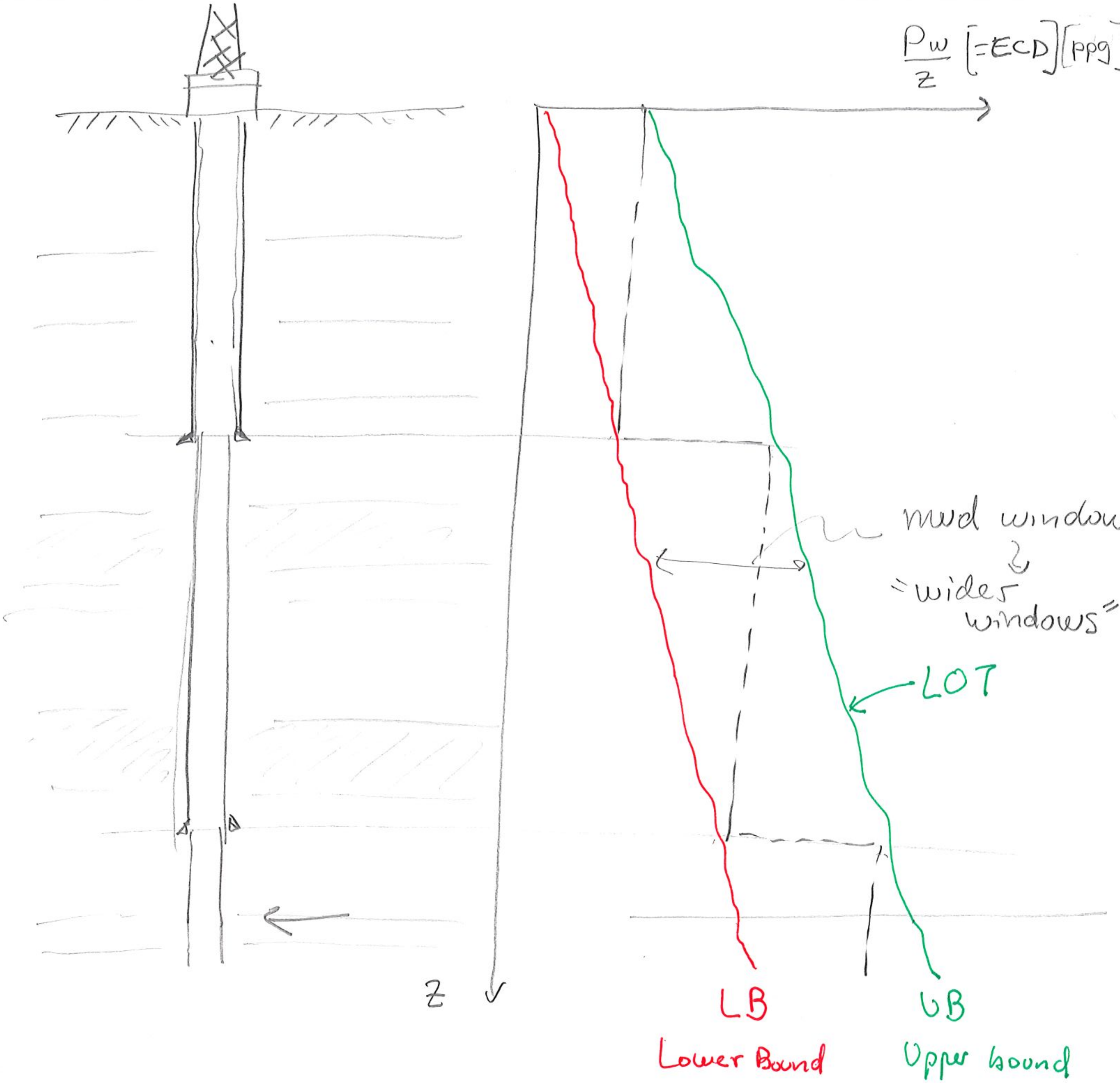
$T_s = 800$ psi
UCS = 3500 psi ; $\nu = 0.6$

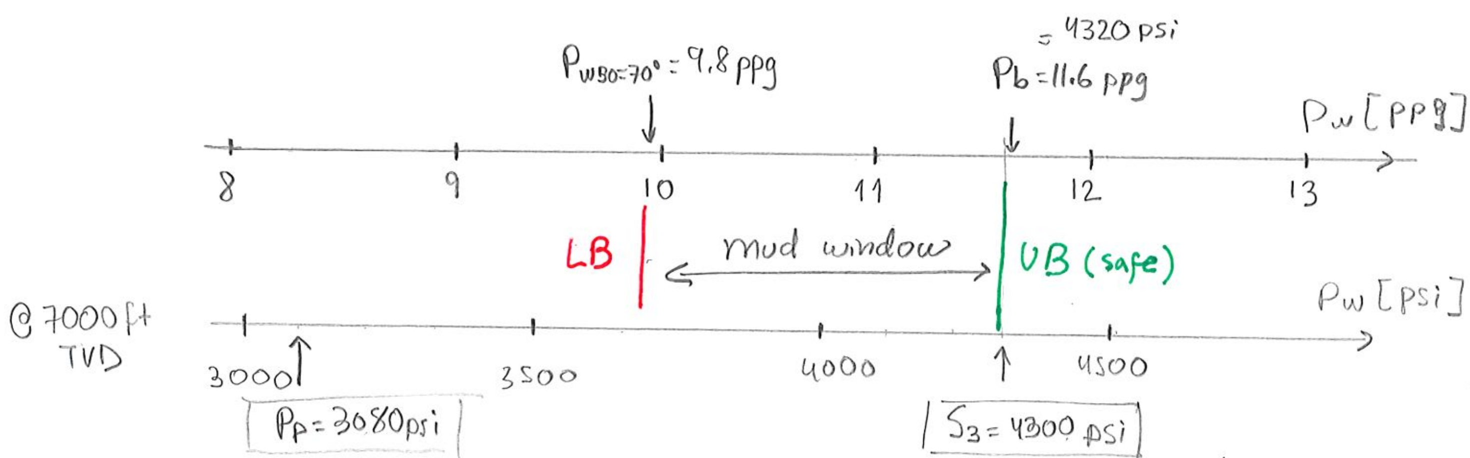
$$P_b = 3080\,psi + 3\cdot 1220\,psi - 3220\,psi + 800\,psi = \boxed{4320\,psi}$$
$= 11.60$ ppg

$$P_{wshear} = 3080\,psi + \frac{3\cdot 3220\,psi - 1220\,psi - 3500\,psi}{1 + 3.12} = \boxed{4280\,psi}$$
$= 11.53$ ppg

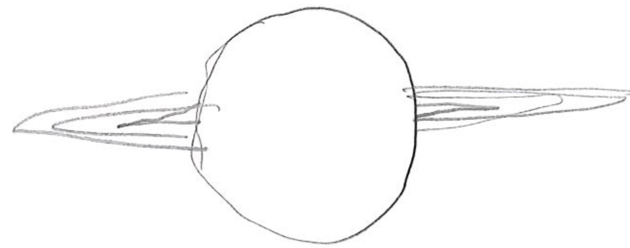
$$P(w_{BO} = 70°) = \ldots = \boxed{3640\,psi} = 9.8\,ppg$$




Pw/z [=ECD] [ppg]
mud window
"wider windows"
LOT
Z
LB
Lower Bound
UB
Upper bound


Pwβ0=70° = 9.8 ppg
= 4320 psi
Pb = 11.6 ppg
Pw [ppg]
8
9
10
11
12
13
LB
mud window
UB (safe)
@ 7000 ft TVD
Pw [psi]
3000
3500
4000
4500
Pp = 3080 psi
S3 = 4300 psi

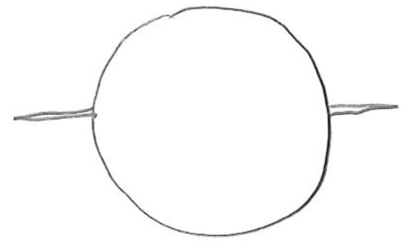
$\boxed{P_b > S_3}$; $P_w > P_b$



large hydraulic fracture

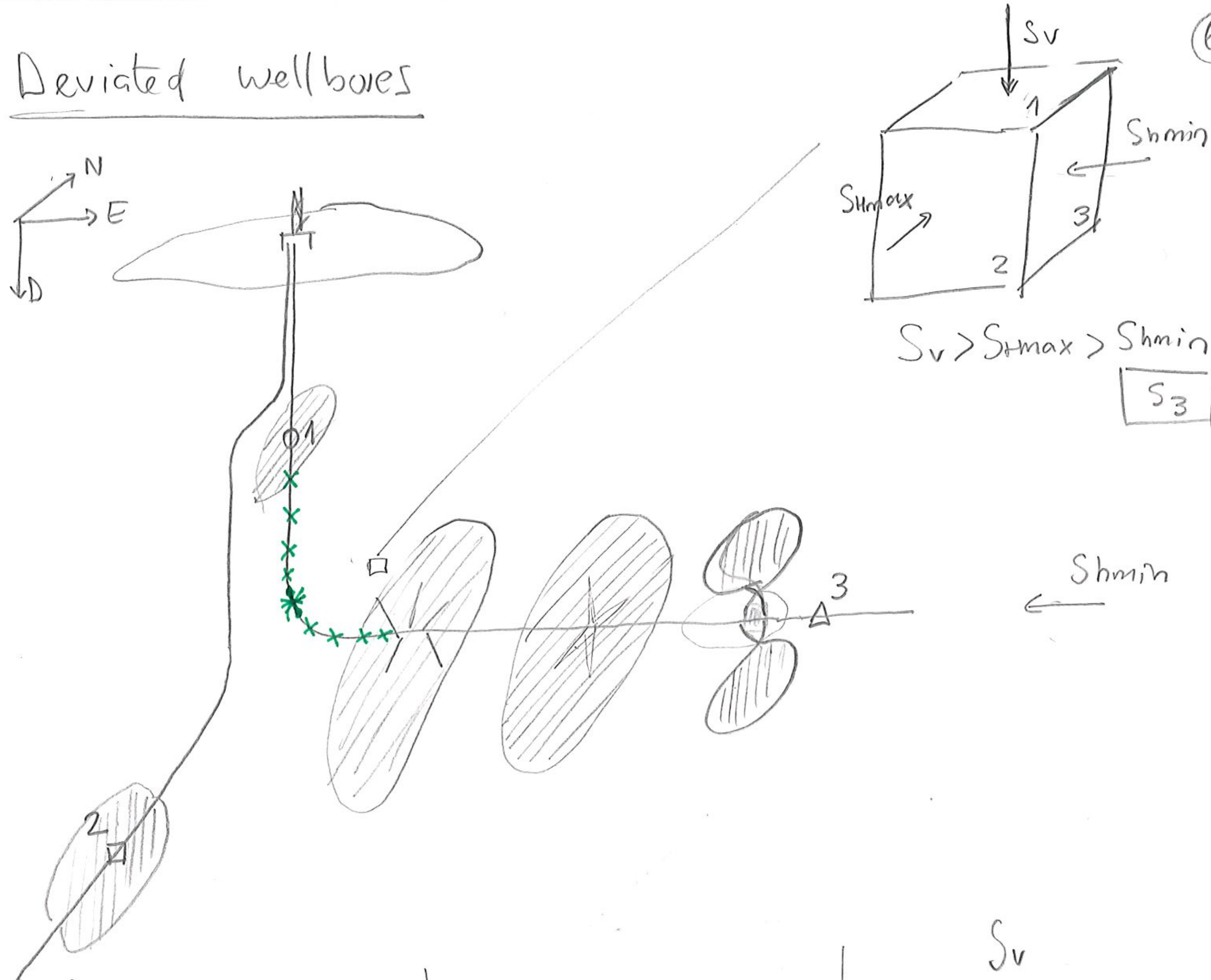
$\boxed{S_3 > P_b}$; $P_w > P_b$

$P_w < S_3$



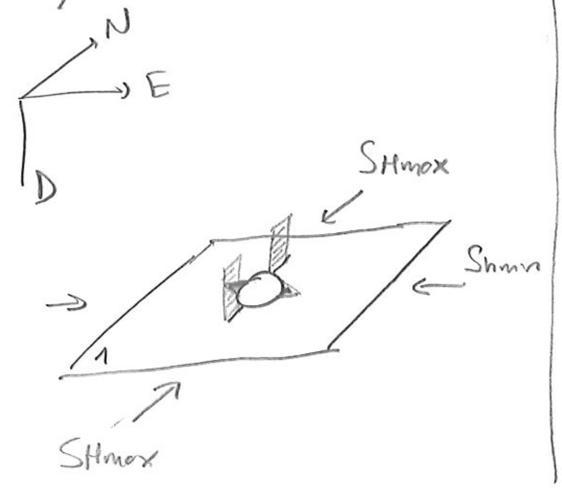
small tensile fracture

Deviated wellbores

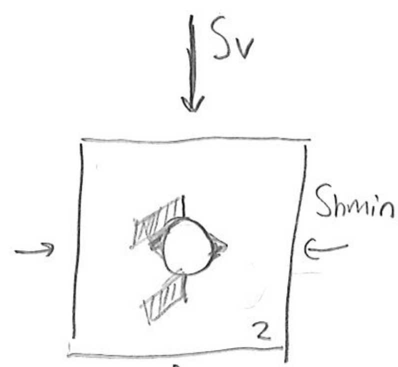


$S_v > S_{Hmax} > S_{hmin}$

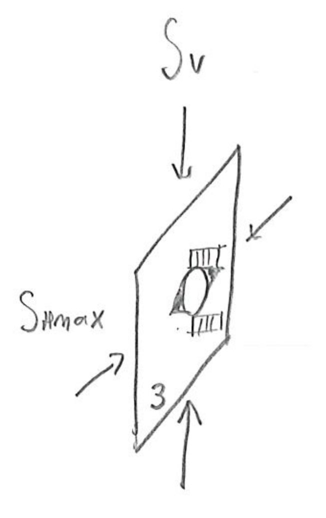
$\boxed{S_3}$



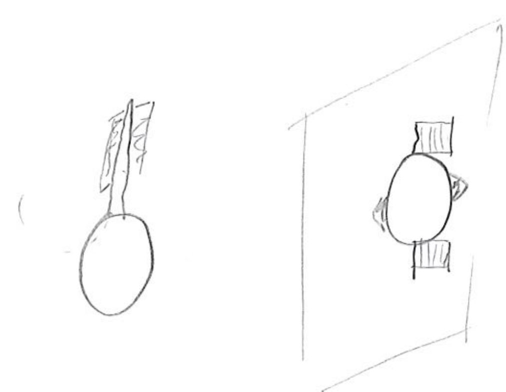
$S_{Hmax} > S_{hmin}$

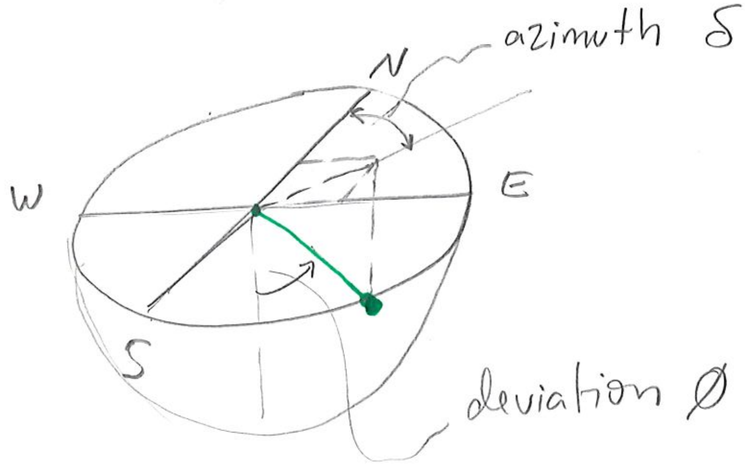


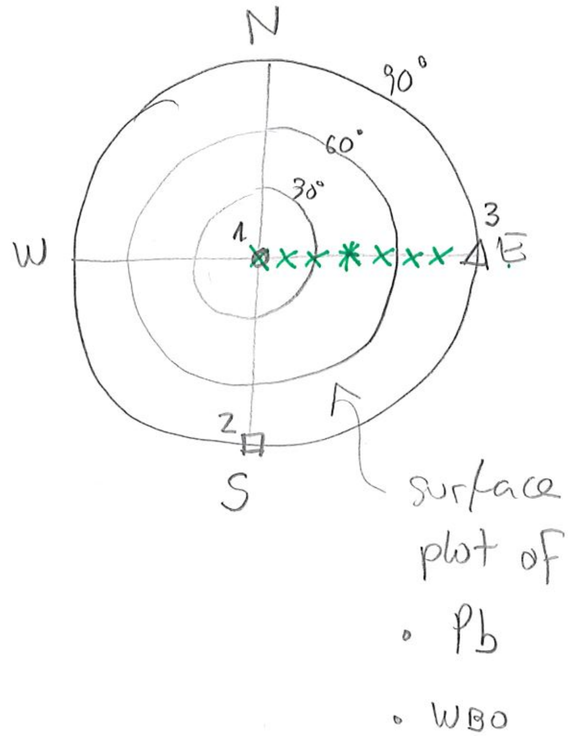
$S_v > S_{hmin}$



$S_v > S_{Hmax}$





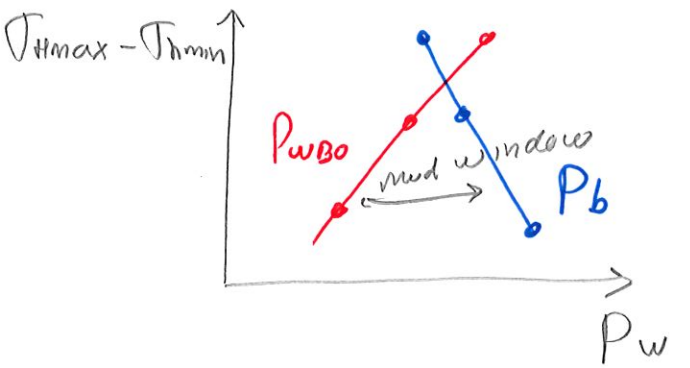


Calculation of wellbore stability for an arbitrary deviation

↳ see book notes

HW #9

6.9.3 → P_{wBO} , P_{wshear} , P_b



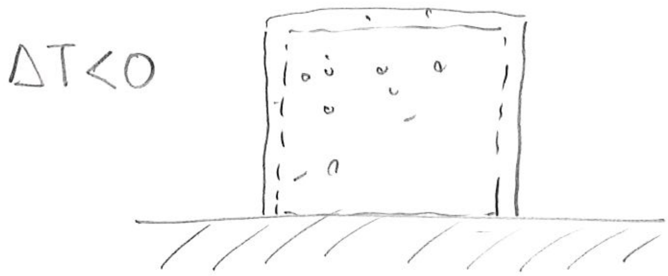
6.9.4 → Offshore

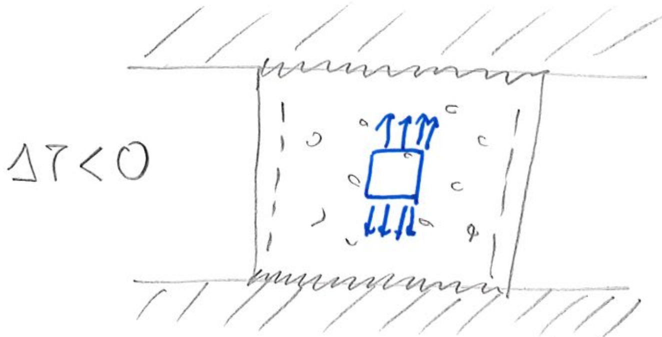
6.9.5 → Laterals : Hz wellbores

↳ $\underline{w_{BO} = 45°}$

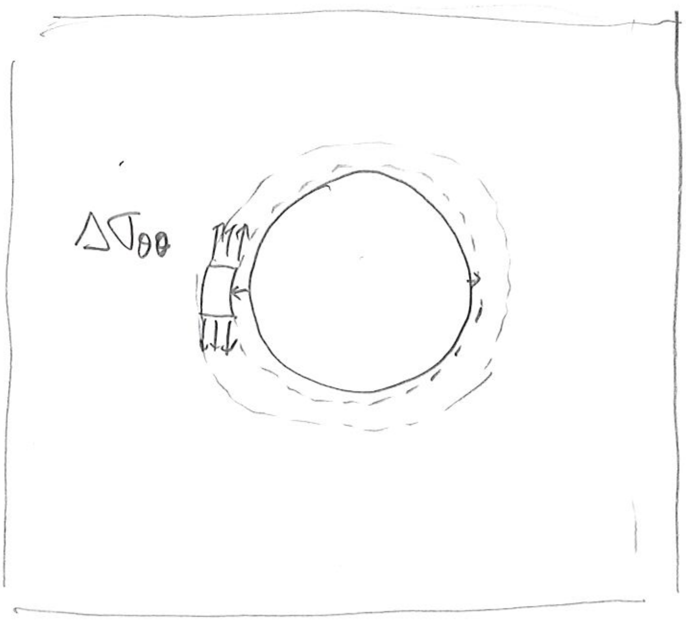
Other factors that affect wellbore stability

(1) Temperature





$$\frac{\Delta L}{L} = \alpha_T \, \Delta T \quad \text{(1D experiment)}$$



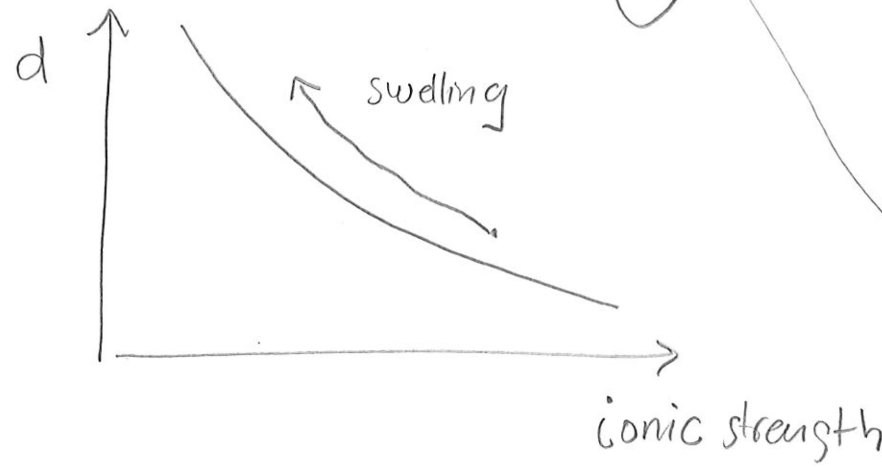
thermoelasticity

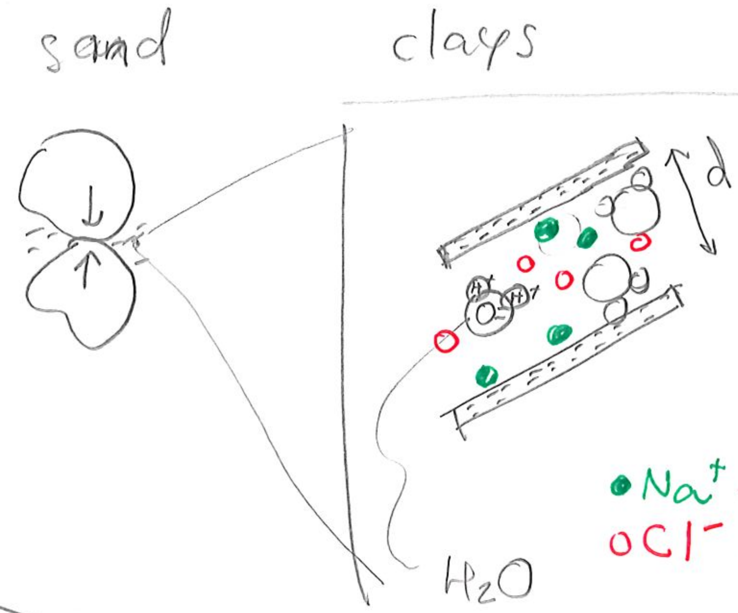
$$\Delta \sigma_{\theta\theta} = \frac{E}{1-\nu} \alpha_T \, \Delta T$$

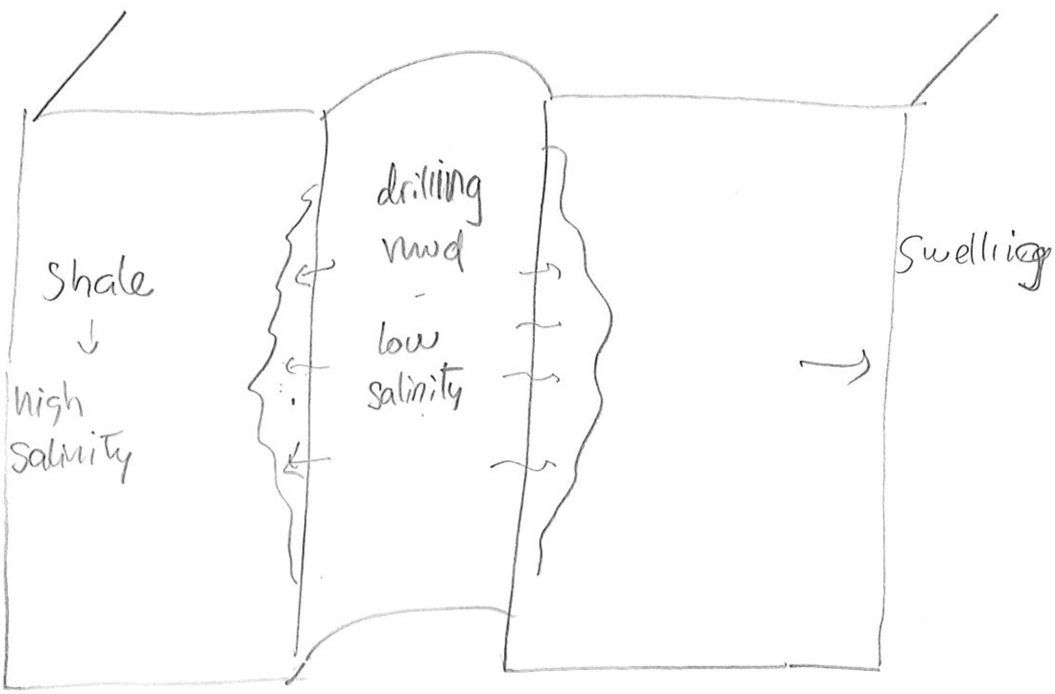
$\hookrightarrow \sigma^{\Delta T} \rightarrow$ use in $\underline{P_b}$

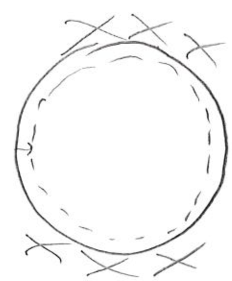
(2) Shale instability

shale ⟷ clays





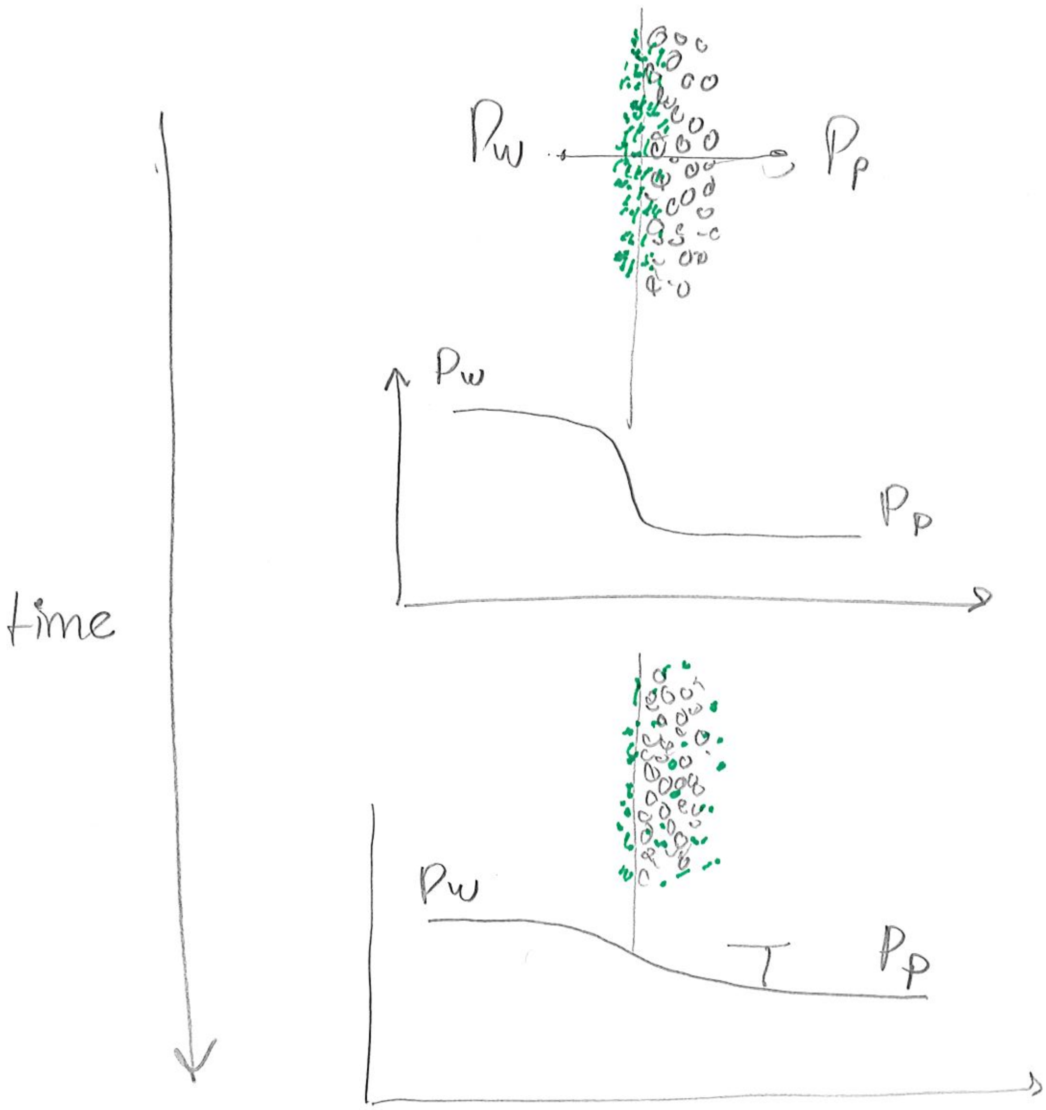




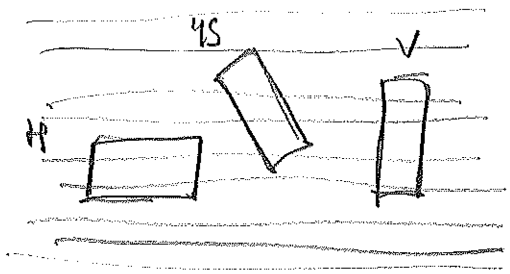
Solutions
- oil-based mud
- high-salinity – KI
- underbalanced drilling (no filtrate water)

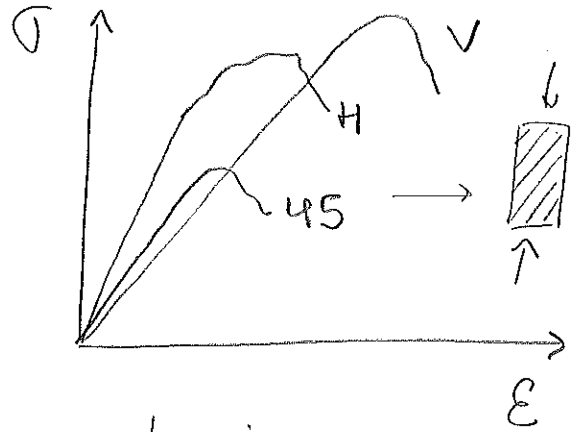
3 Loss of mud support

$\sigma_{rr} = (P_w - P_p) \Leftarrow$ filter cake, mudcake ✓

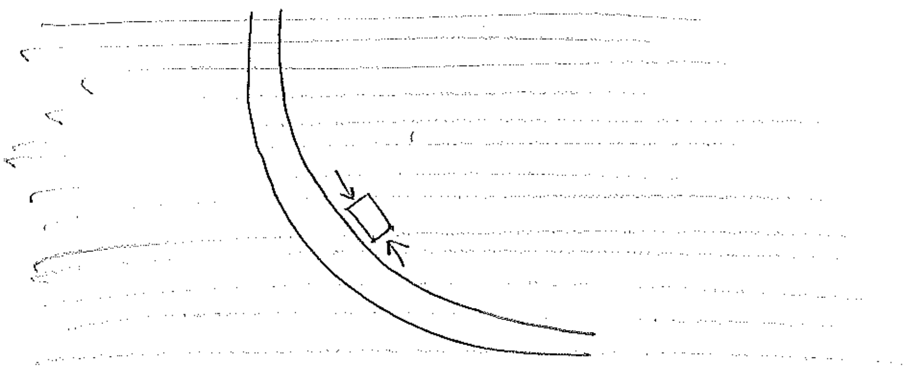


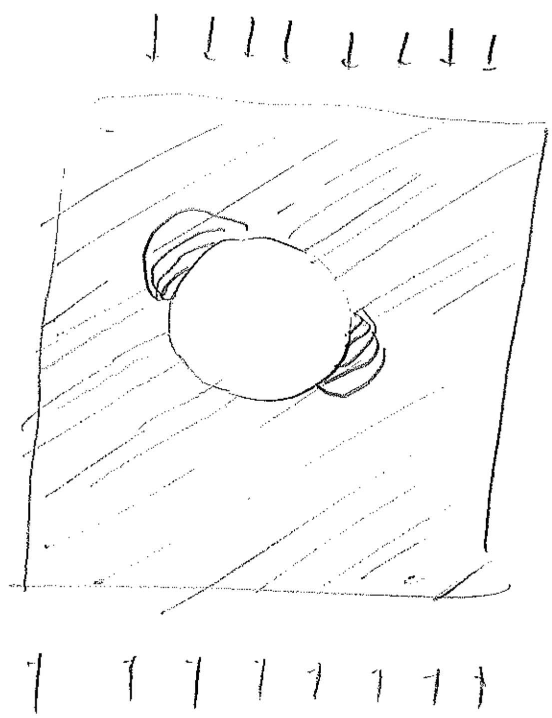
4) Strength anisotropy ⟷ deviated wellbores





→ tension
↳ tensile strength





→ breakouts in directions / locations different from the ones in isotropic rock