Shear and tensile earthquakes caused by fluid injection

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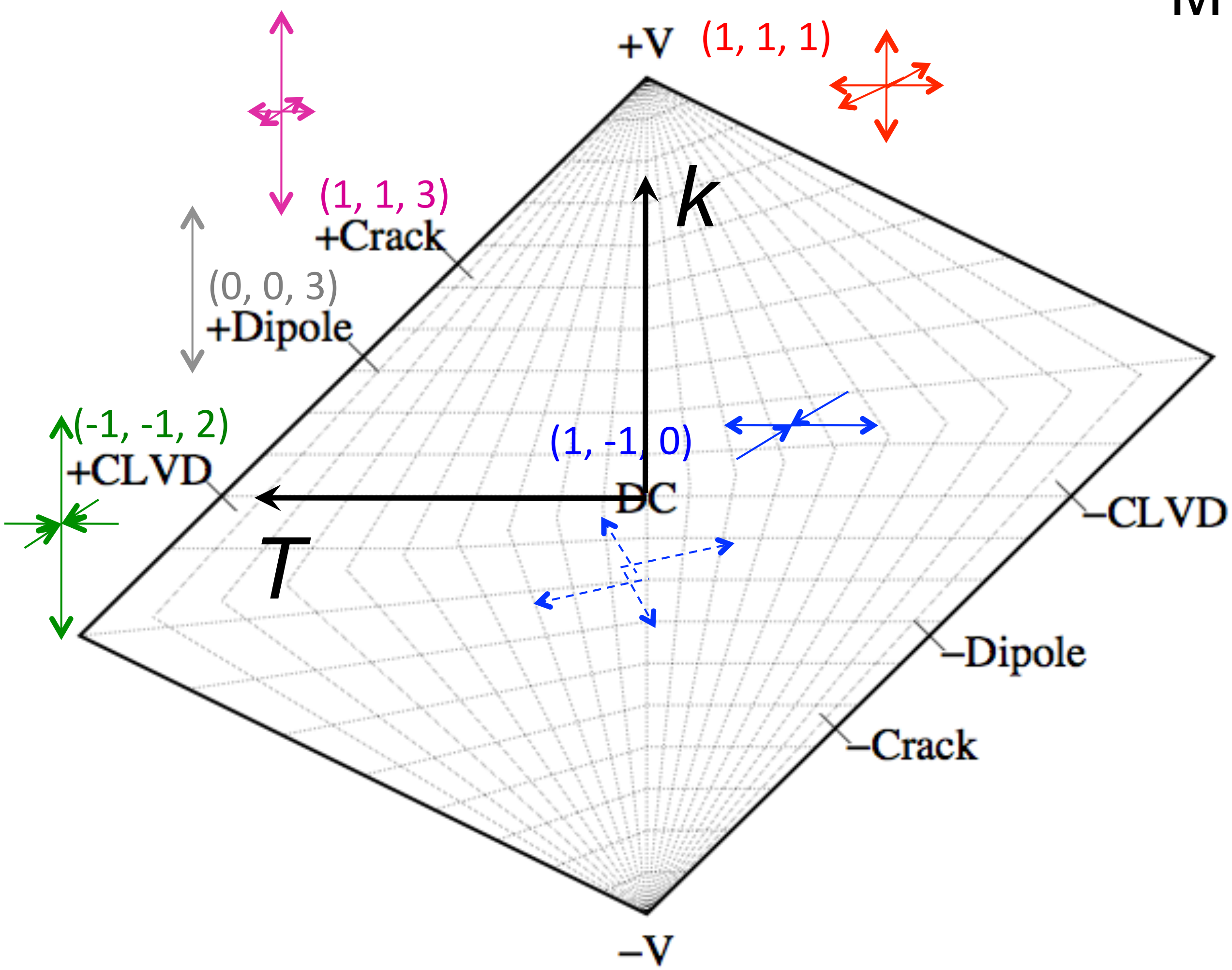
Outline

- Moment tensors of swarms and injection-induced earthquakes
- Moment tensor of Tensile earthquake
- Stress conditions for shear and tensile failure
- Differential stress and depth
- Application on data – Soultz-sous-Forets, Cotton Valley

Source-type plot (Hudson, 1989)



MT eigenvalues (abs)
$M'_1 < M'_2 < M'_3$

Isotropic part :

$$k = \frac{tr(M)}{|tr(M)| + |M'_3|}$$

CLVD part :

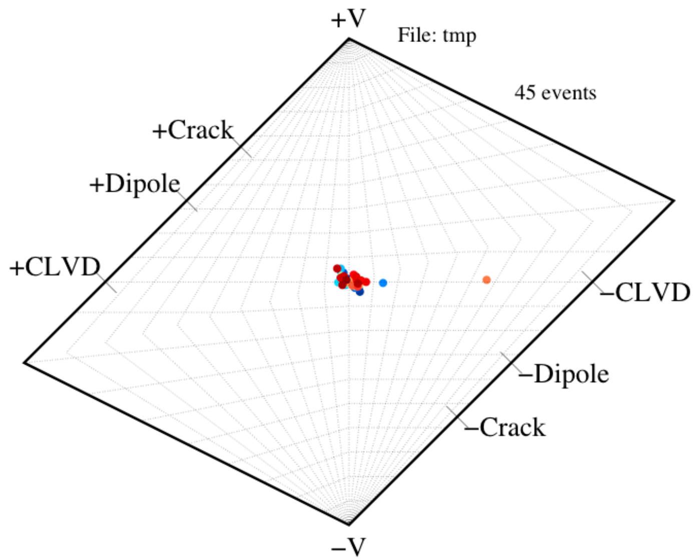
$$T = 2\frac{M'_1}{|M'_3|} = -2\varepsilon$$

Moment tensors of injection-induced microearthquakes

Soultz-sous-Forets geothermal field

(Horálek et al., 2010)

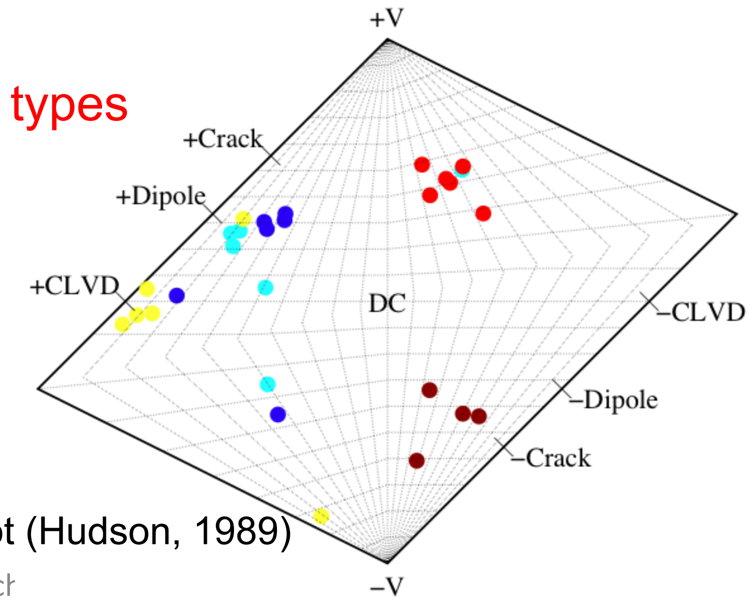
pure DC



Cotton Valley, gas field

(Šílený et al, 2008)

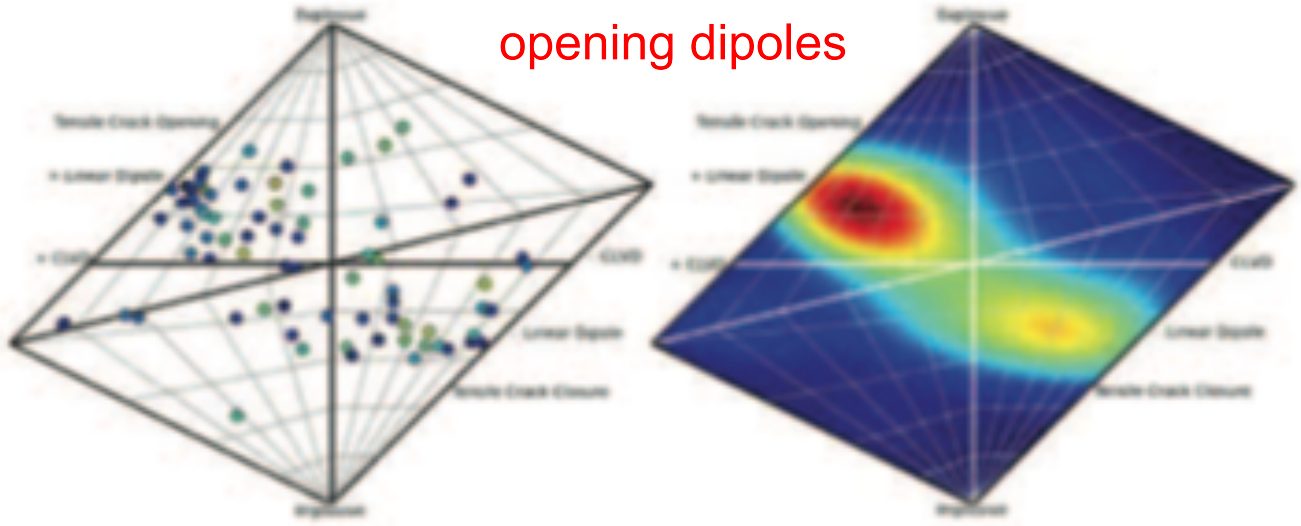
various types



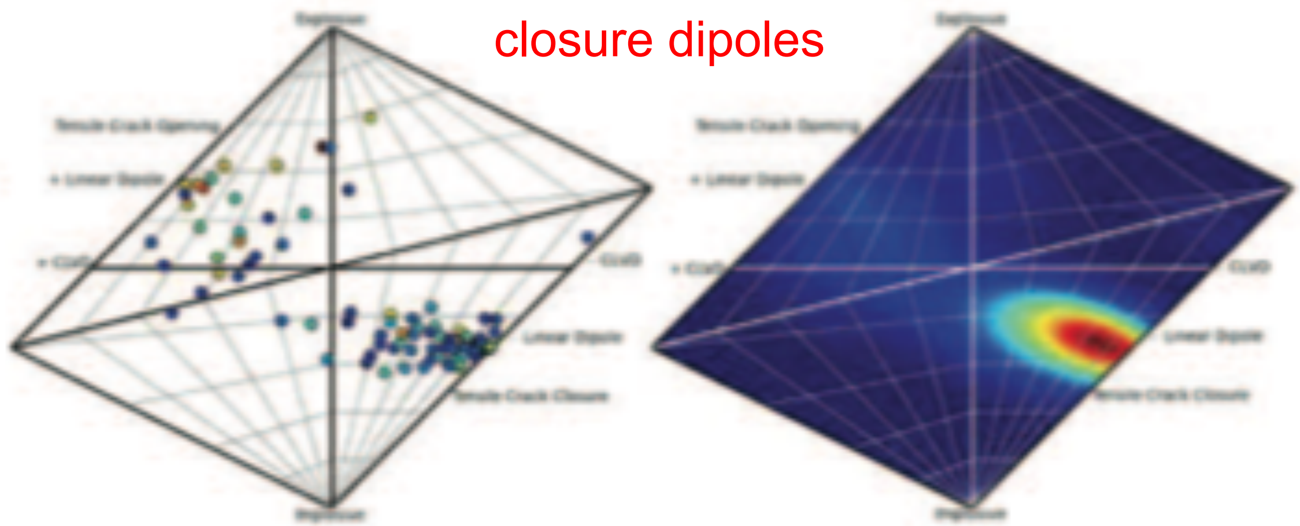
Source-type plot (Hudson, 1989)

Hydraulic fracturing in sediments
(Baig & Urbancic, 2010)

co-injection

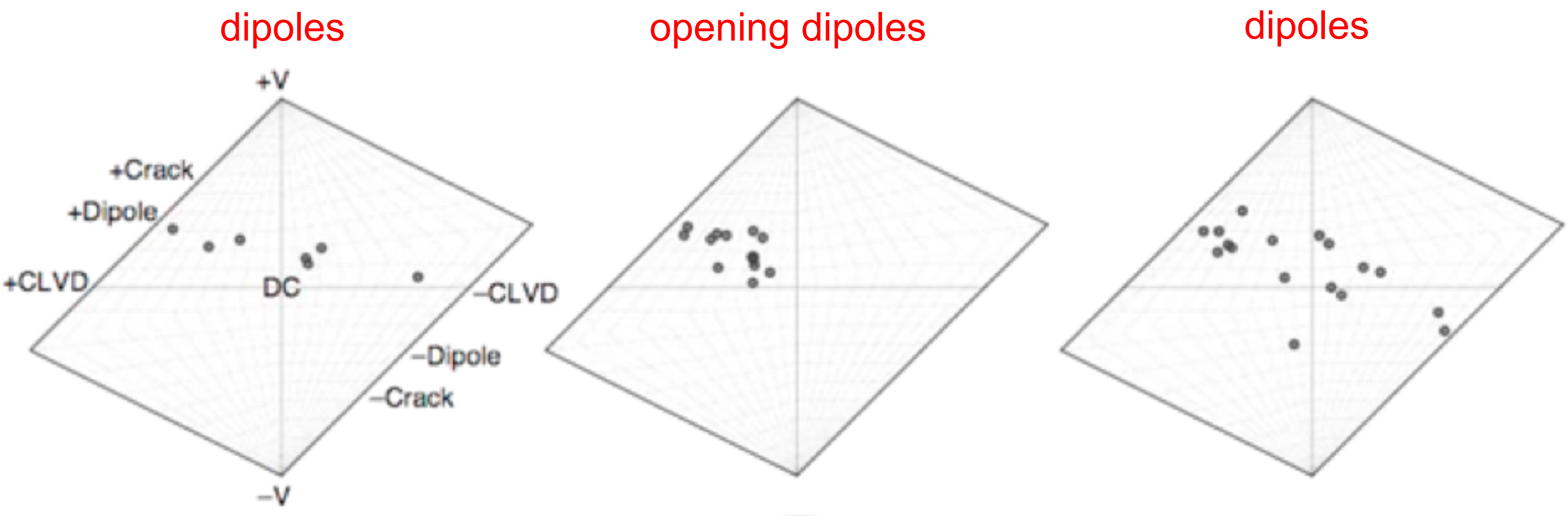


post-injection



Injection in Coso geothermal field

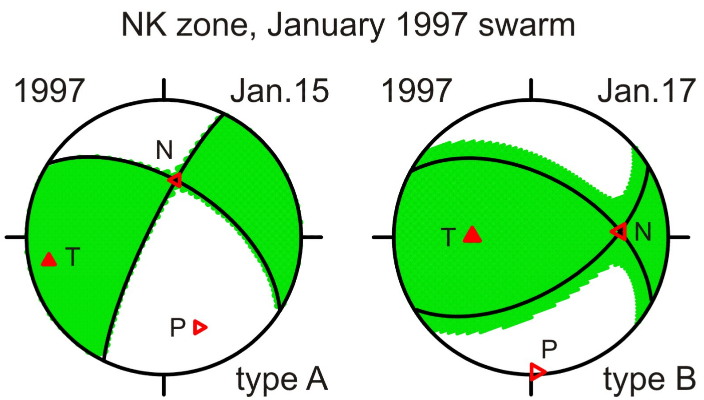
(Julian et al., 2010)



pre-injection co-injection post-injection

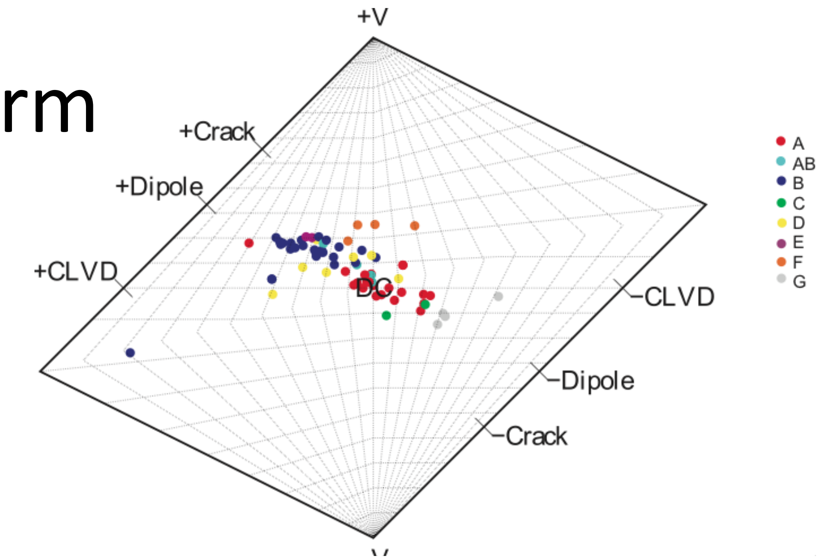
Earthquake swarms in West Bohemia

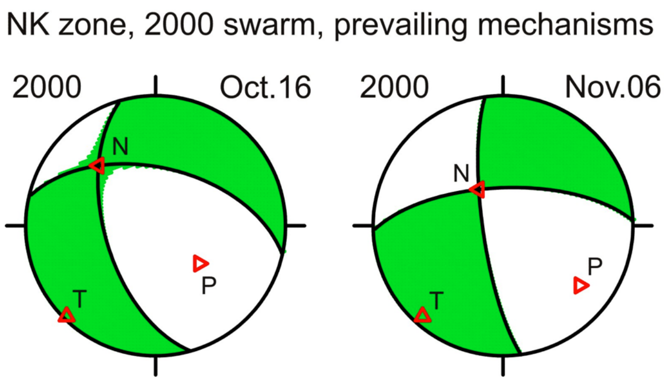
(Horálek et al., 2002; Horálek et al, submitted)



1997 swarm

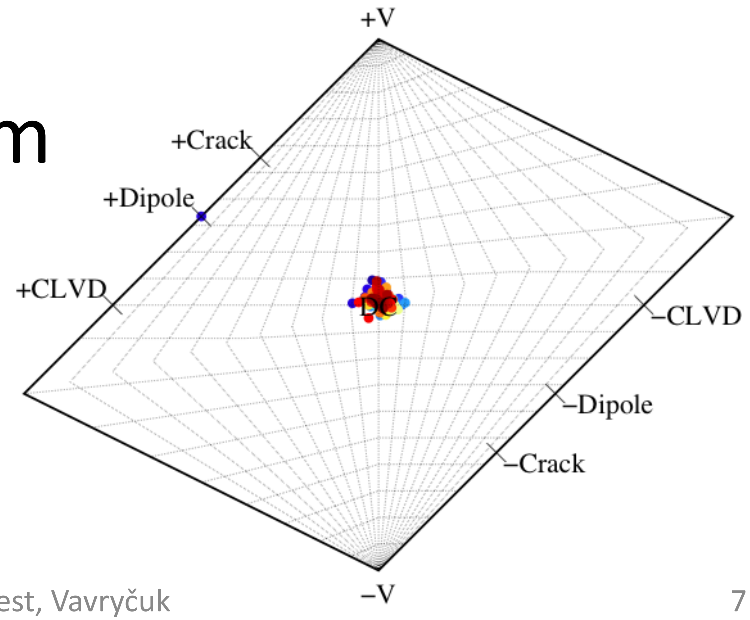
dipoles





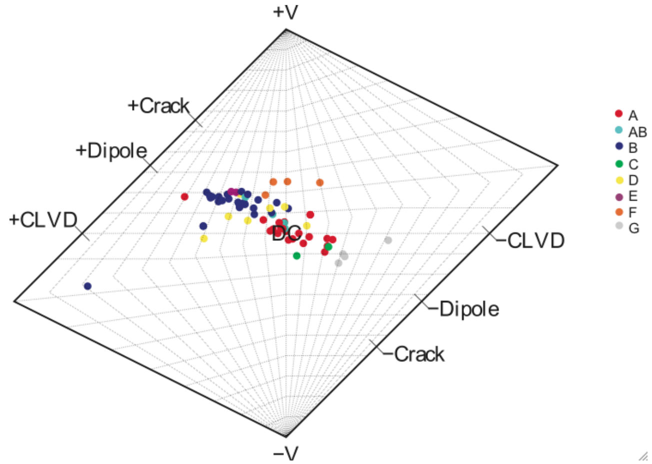
2000 swarm

pure DC

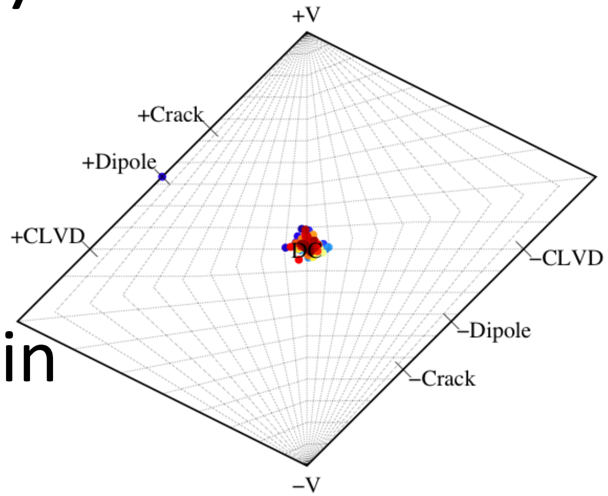


Motivation

- Ambigous non-DC components of MT of high-pressure related earthquakes



- Some are dipoles (opening, closure)
  – Coso geothermal field, gas fields, 1997 swarm in West Bohemia

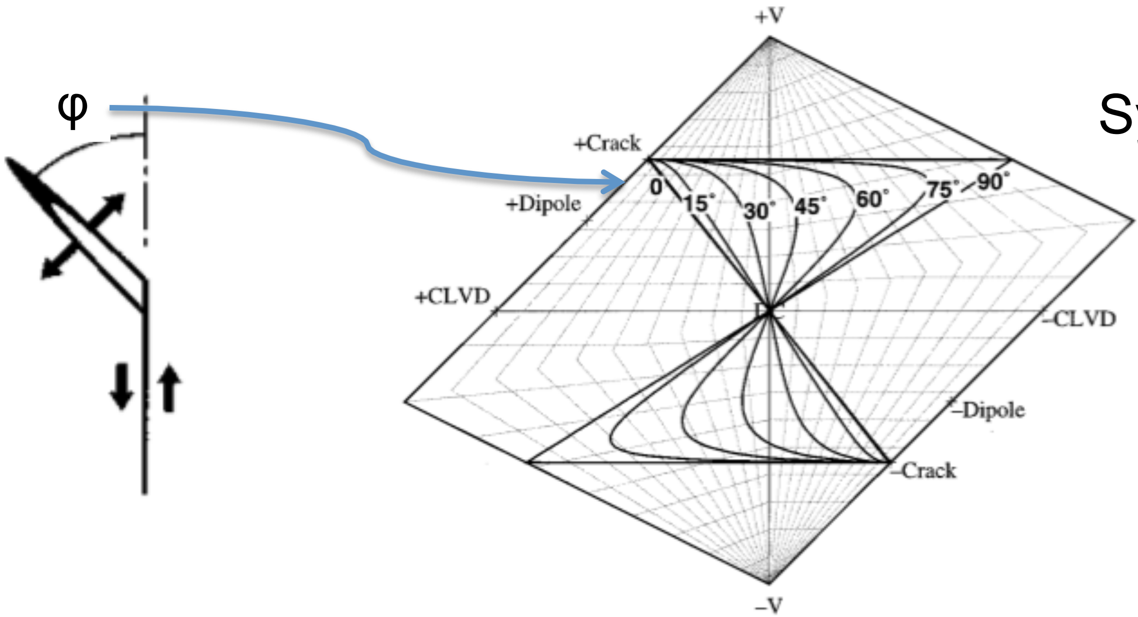


- Some are pure DC
  – Soultz geothermal field, 2000 swarm in West Bohemia

=> what is the role of high-pressurized fluid ?

Interpretation of non-DC components

- Combined pure tensile and pure shear faulting
  (Julian et al., 1998)

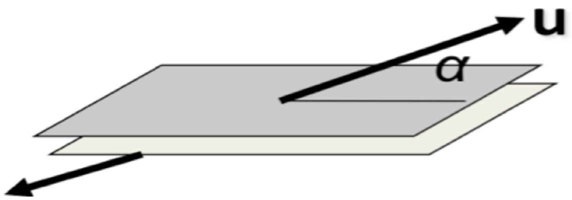


Synthetic moment tensor

- Shear wing crack (Julian et al, GRL 2010)
  pure shear+pure tensile

Interpretation of non-DC components

- Tensile earthquake
  (shear+opening – close to reality)
  (Dufumier & Rivera, 1997; Vavrycuk, 2001)



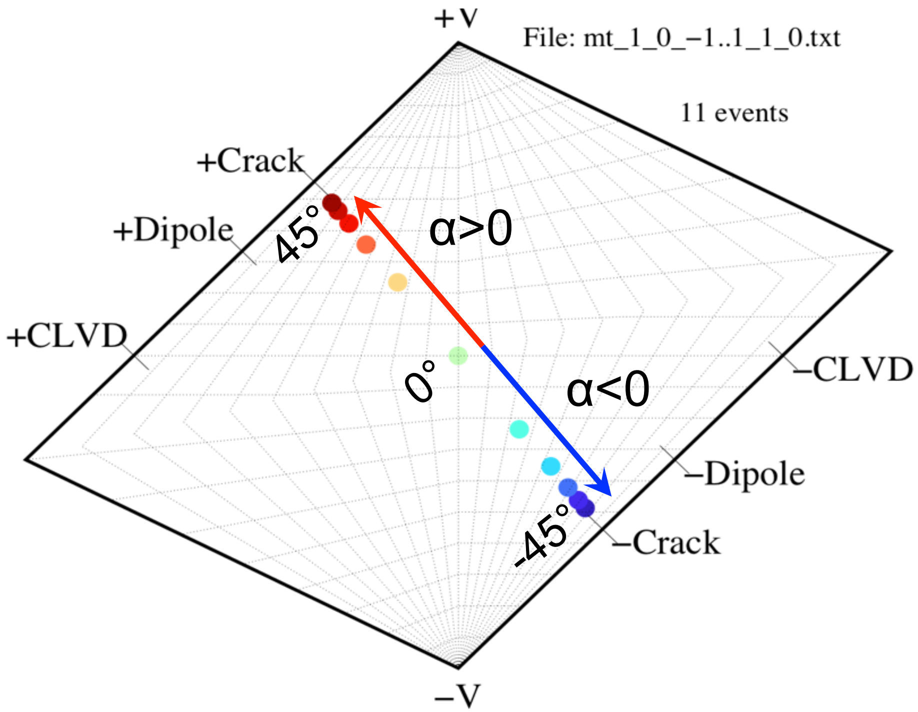
Synthetic moment tensor

$$\mathbf{M} = \begin{bmatrix} \lambda \sin\alpha & 0 & \mu\cos\alpha \\ 0 & \lambda\sin\alpha & 0 \\ \mu\cos\alpha & 0 & (\lambda+2\mu)\sin\alpha \end{bmatrix}$$

Slip is deviated from the fault

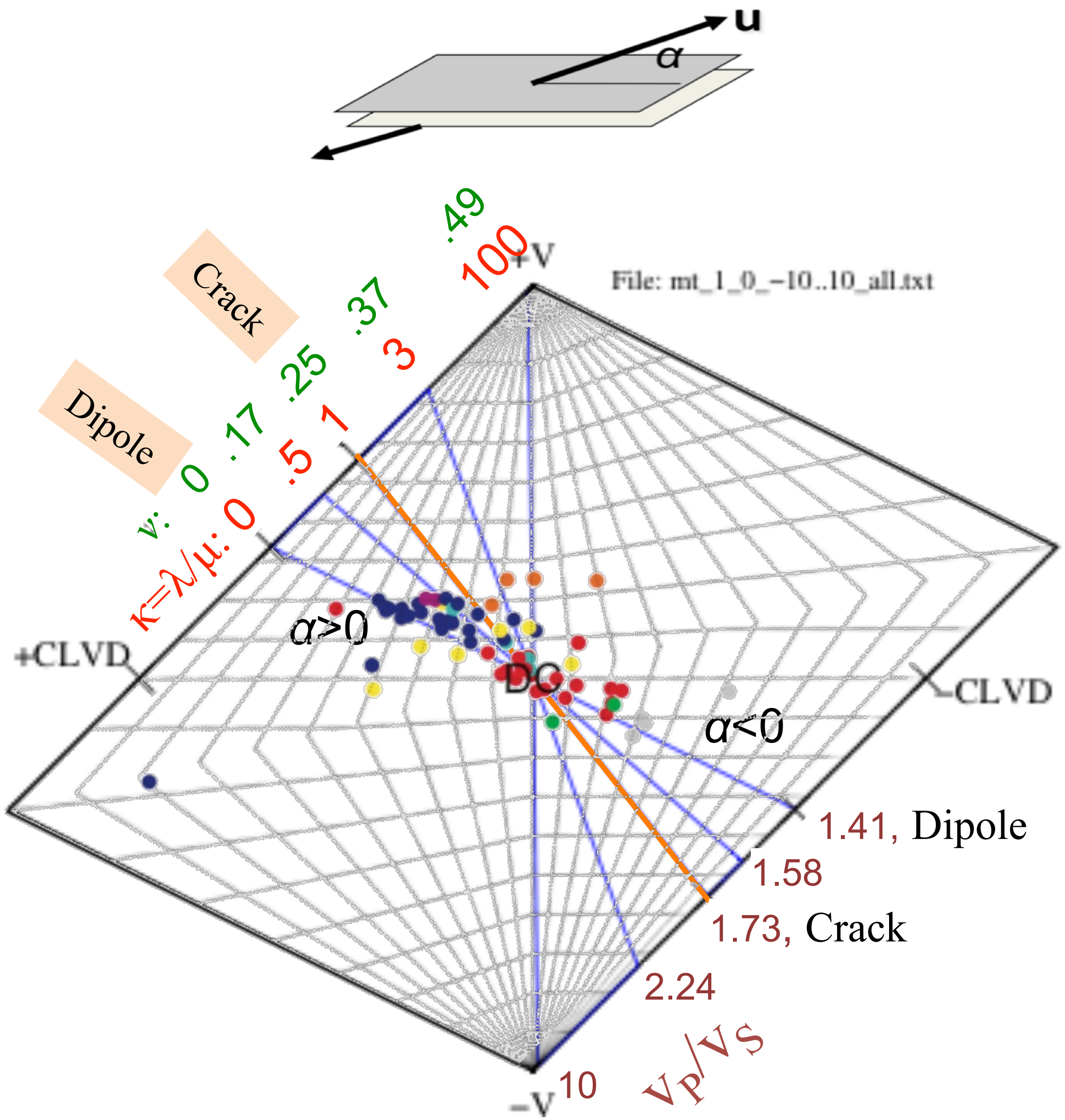
Moment tensor is non-DC (DC+CLVD+ISO)

Normal stress is extensive



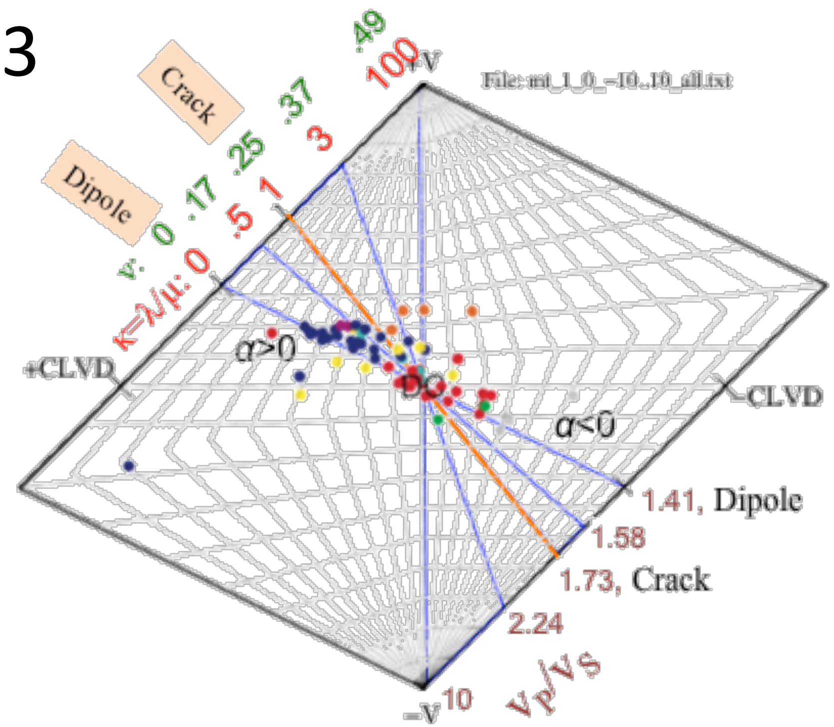
MT of Tensile earthquake

- Poisson solid, λ=μ gives crack faulting (MT=[1 1 3])
- Dipole faulting (MT=[0 1 1]) possible for λ/μ-->0 (fully compressible)
- Pure volumetric for only λ/μ-->∞



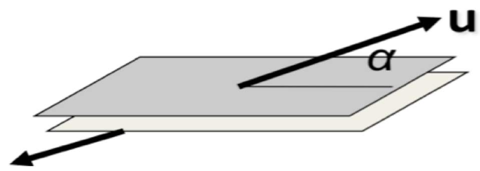
Non-DC components and elastic properties

- Smaller volumetric component (dipole faulting, MT=[0 1 1])
  possible for λ/μ-->0, i.e. ν-->0, v_P/v_S --> 1.41
- Higher volumetric component possible for $\lambda/\mu > 1$, i.e. $\nu > 0.25$, $v_P/v_S > 1.73$



- Literature:
  - v_P/v_S depends on pore pressure

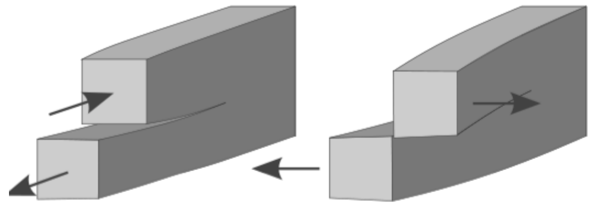
Tensile earthquake



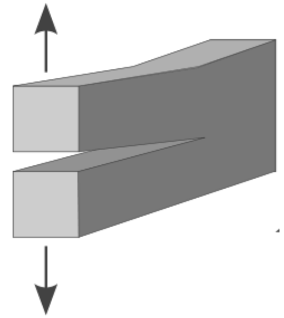
- Simultaneous shear and opening
- Explains MT of injection-induced earthqaukes
- Dipole faulting requires small v_P/v_S (non-physical?)
- What are the static-stress conditions for shear+opening?

Moment tensors -> geomechanics

- DC component of MT
  –> shearing (Mode 2 and 3 fractures)

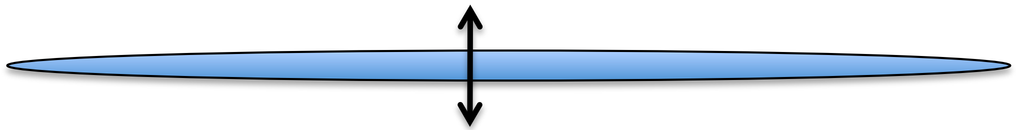


- Volumetric component of MT
  –> explosion or opening crack (Mode 1 fracture)

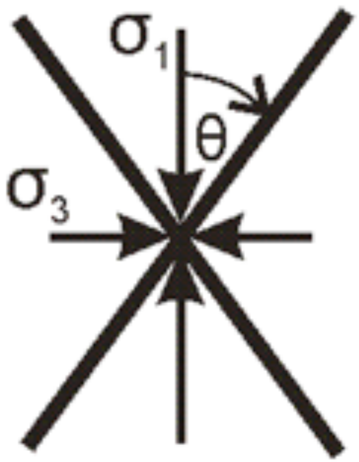


Fracture opening needs extensive normal stress

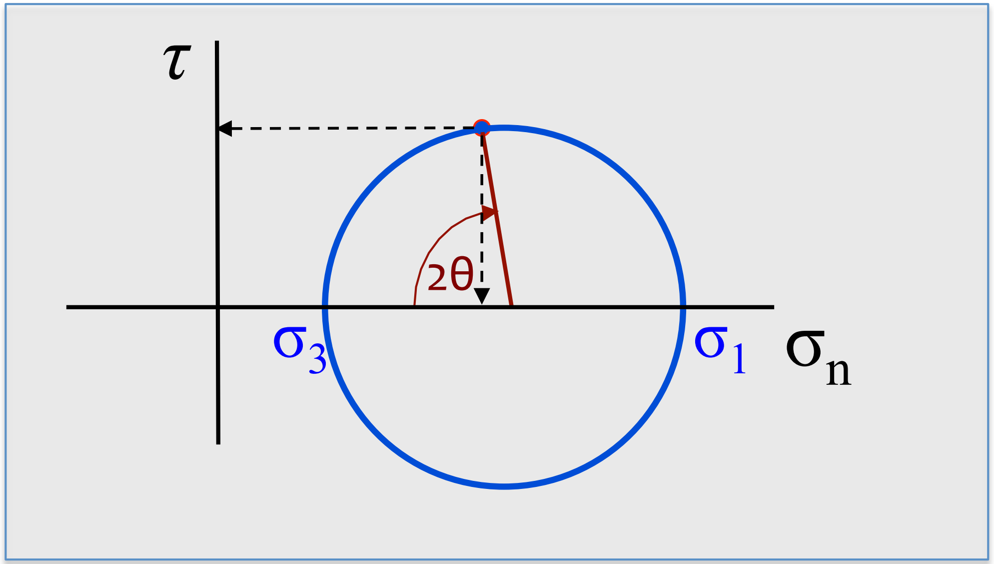
=> explore the conditions for static tensile stress



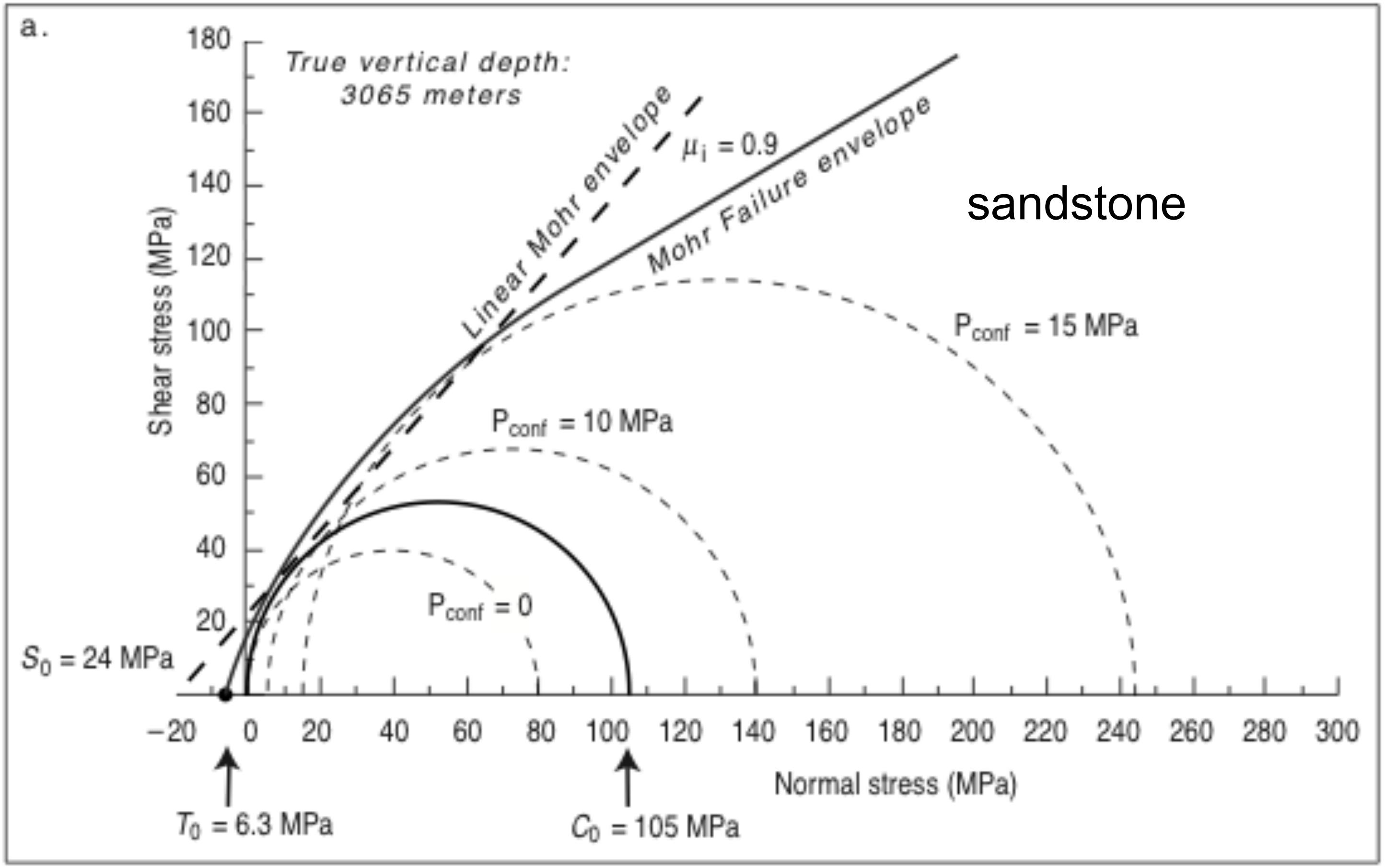
Stress and fractures in Mohr diagram



- Stress state
- ♦ Fracture
- ♦ Traction on a fracture



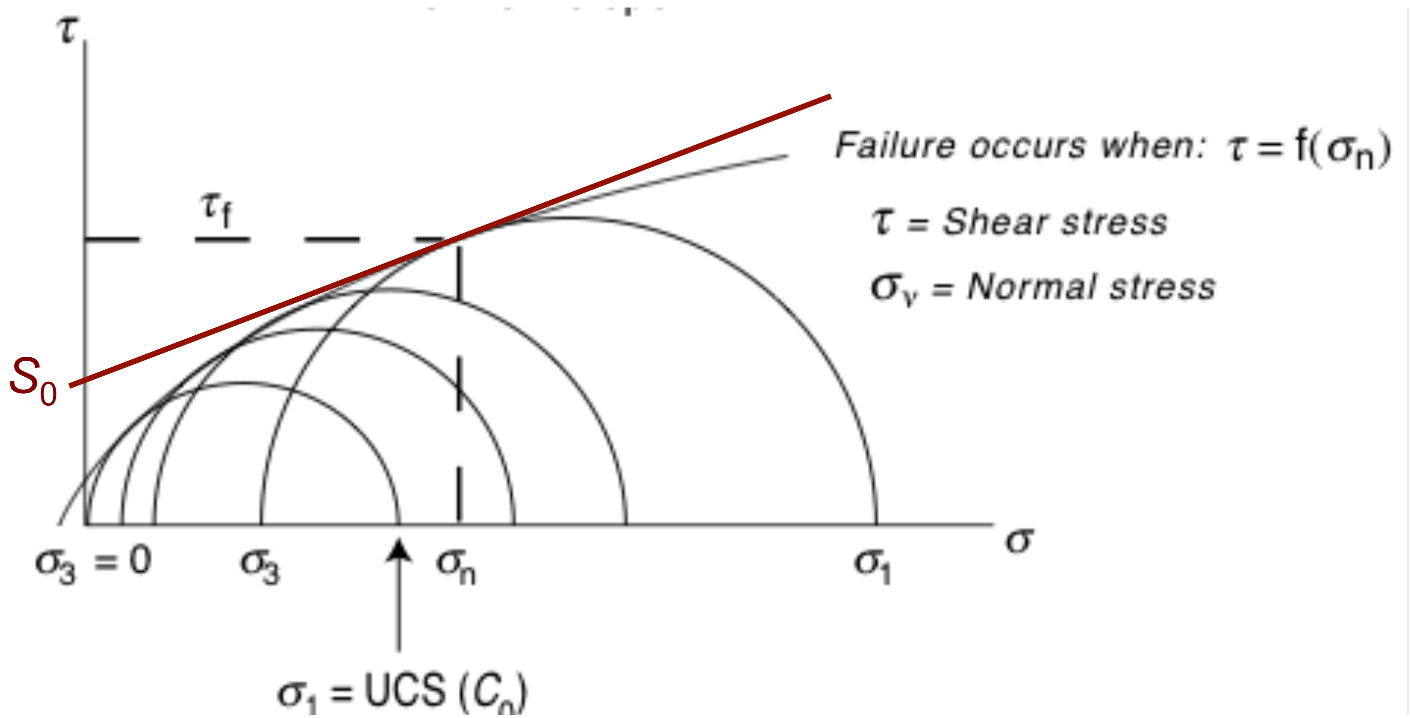
Failure envelope



(Zoback, 2007)

- nonlinear for small and negative normal stress
- linear for larger positive normal stress

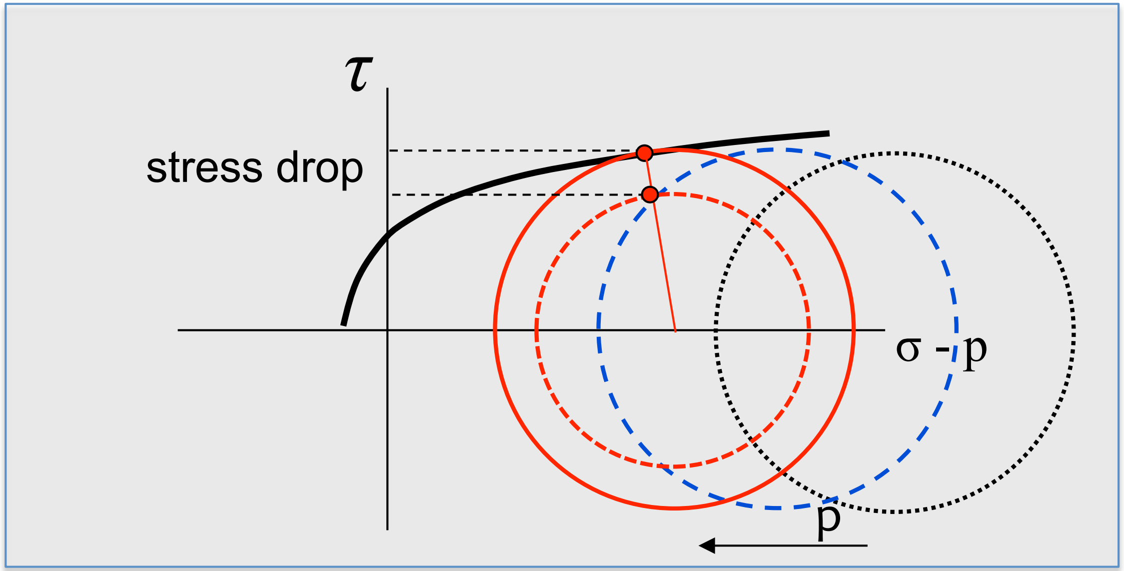
Failure envelope



- real failure envelope is non-linear
- linearized form

$$\tau_f = S_0 + \mu_i\,(\sigma_n - \text{P})$$

Rock failure, stress drop

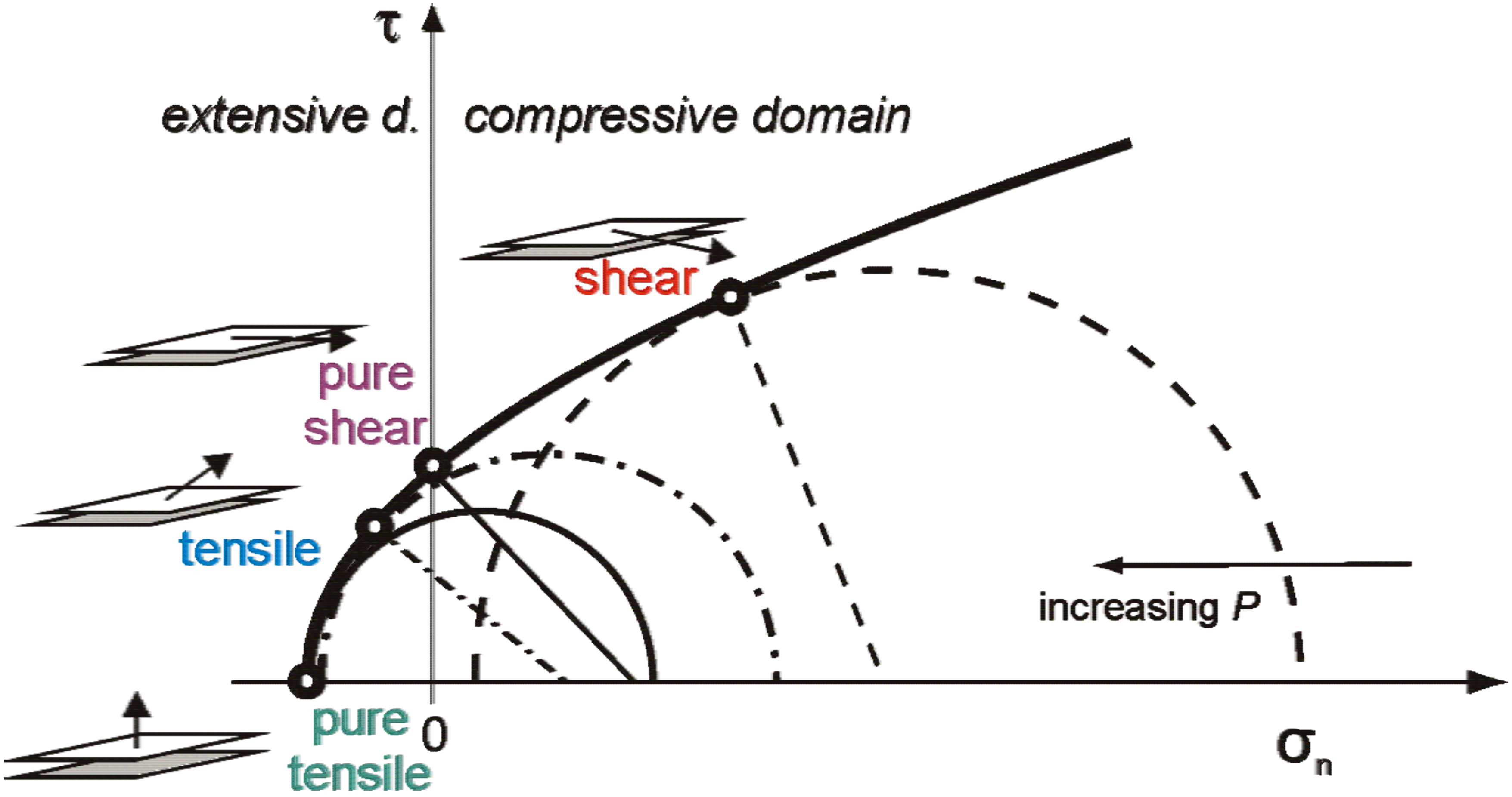


Failure: release of accumulated shear stress

=> stress drop $\Delta\sigma$ (depends on the available τ)

=> decrease of differential stress σ_1-σ_3

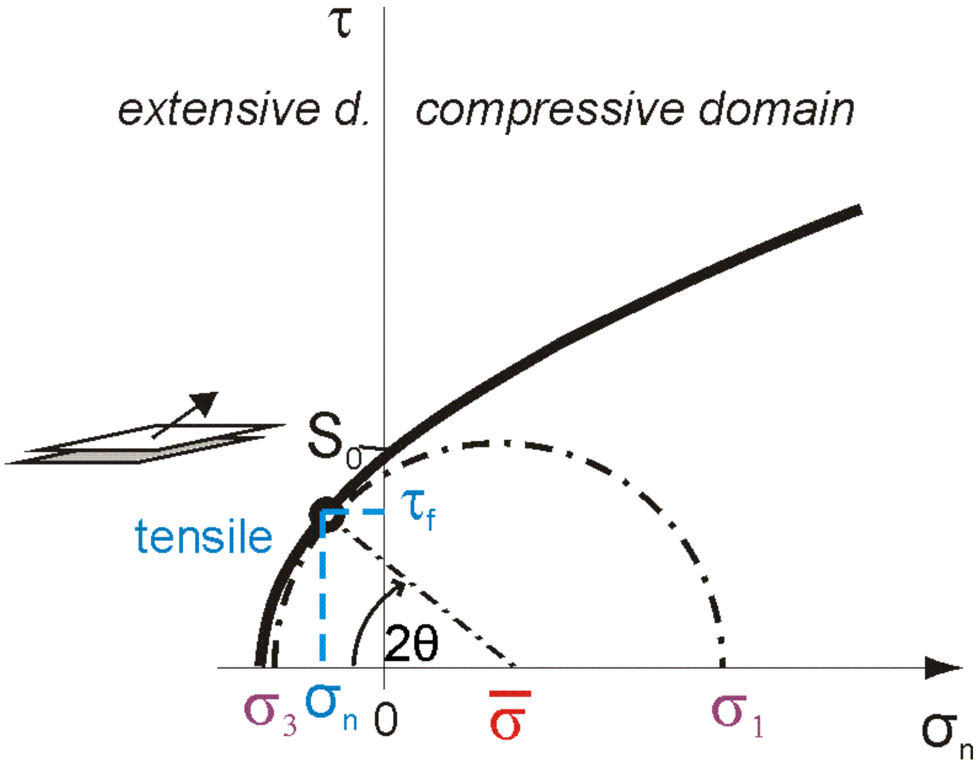
Failure types



Tensile failure possible only for

- small angle θ
- small diferential stress σ_1-σ_3

Failure stresses and fracture orientation



Griffith's failure envelope:

$$\tau_f^2 = S_0\left(2\sigma_n + S_0\right)$$

gives the following relations between

- tractions σ_1 and σ_3
- mean and differential stress
- fracture orientation θ

$$\sigma_n = \frac{1}{2}S_0\left(\tan^2(2\theta) - 1\right)$$

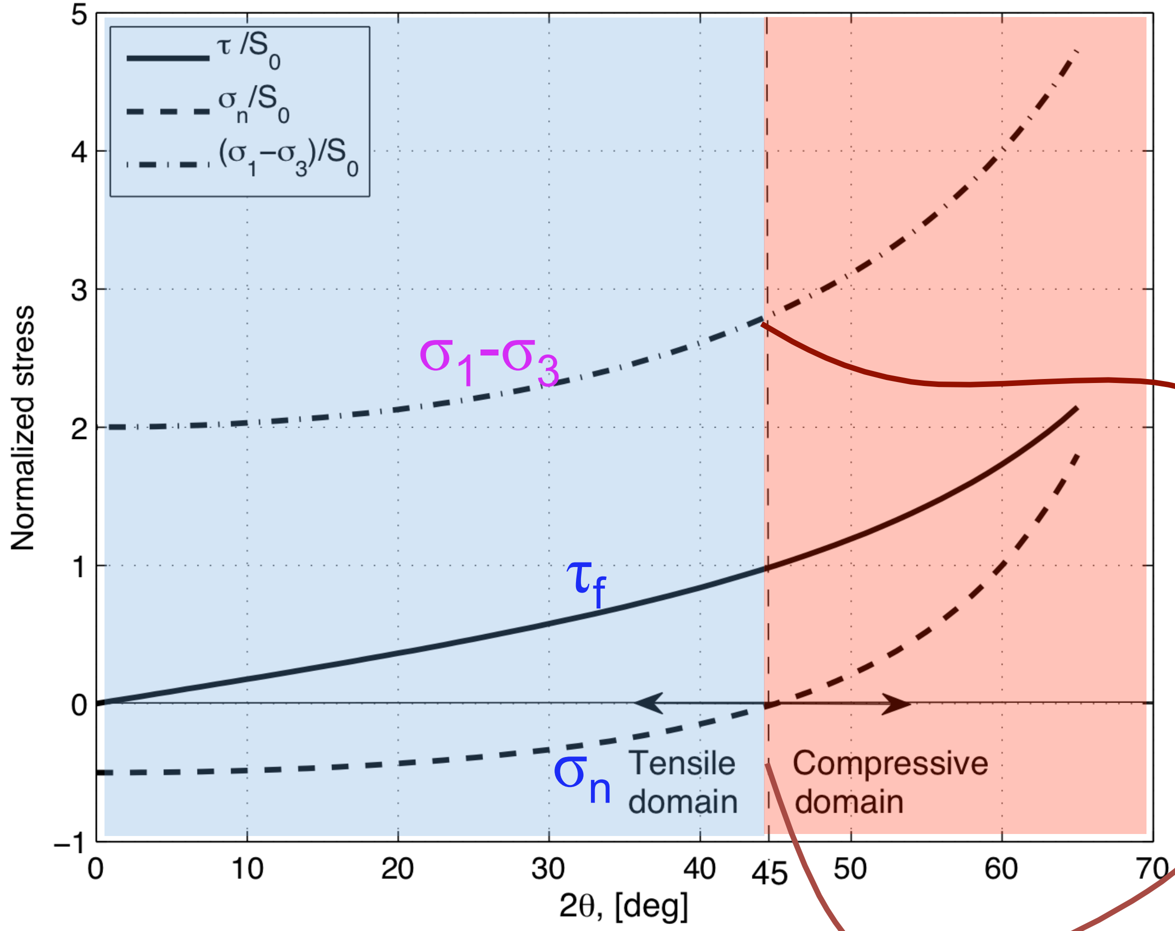
$$\tau_f = S_0\tan\left(2\theta\right)$$

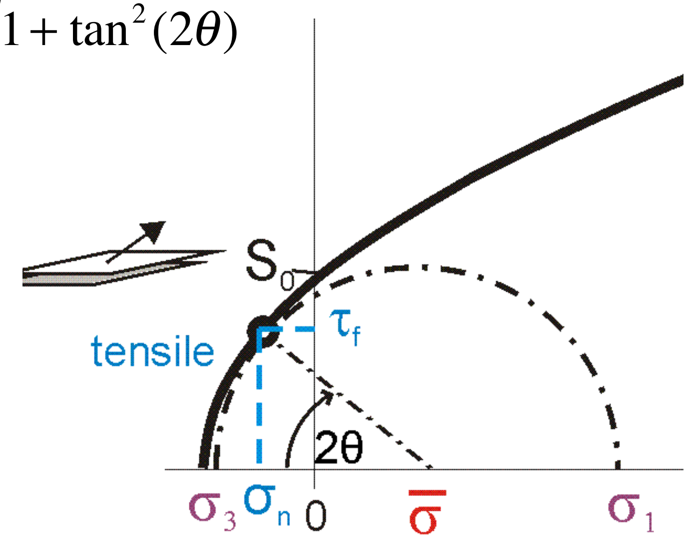
$$\bar{\sigma} = \frac{\sigma_1 + \sigma_3}{2} = S_0 + \sigma_n$$

$$\sigma_{DIFF} = \sigma_1 - \sigma_3 = 2S_0\sqrt{1 + \tan^2(2\theta)}$$

Failure stresses and fracture orientation

$$\sigma_n = \frac{1}{2}S_0\left(\tan^2(2\theta)-1\right) \quad \tau_f = S_0\tan\left(2\theta\right) \quad \sigma_1-\sigma_3 = 2S_0\sqrt{1+\tan^2(2\theta)}$$





$(\sigma_1-\sigma_3)_{MAX} \approx 2.8S_0$

$\theta_{MAX} = 22.5°$

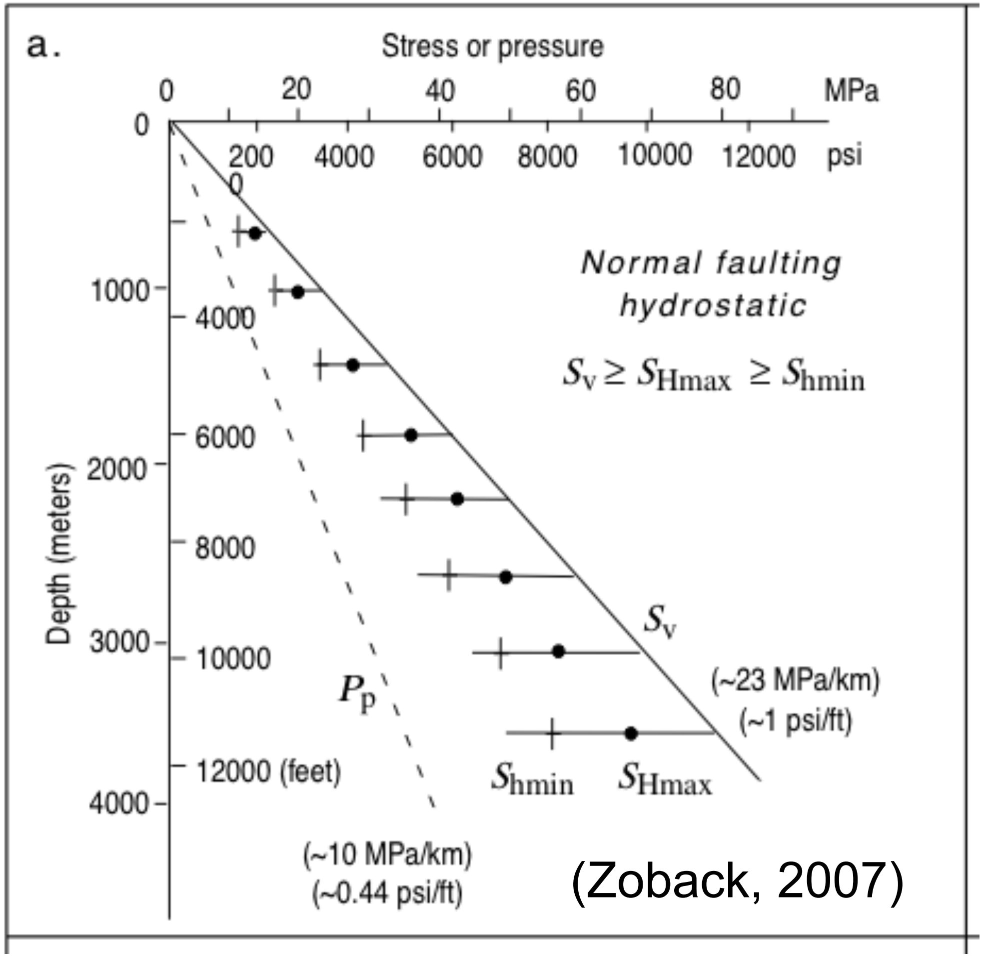
Tensile failure occurs only
- If diff. stress is small
- On fractures striking less than 22.5° to σ_1

Differential stress σ_1-σ_3 (in depth)

Tensile earthquakes:

- $(\sigma_1\text{-}\sigma_3)_{MAX} \approx 2.8S_0$
- Intact sandstone: $S_0 \approx 20$ MPa
  => $(\sigma_1\text{-}\sigma_3)_{MAX} \approx 56$ MPa
- Pre-existing fractures:
  $S_0 \approx 0..4$ MPa
  => $(\sigma_1\text{-}\sigma_3)_{MAX} < 10$ MPa
- σ_1-σ_3 increases with depth

Soultz: $S_{hmin} \approx 14.06\ z$ [km]
$S_V \approx 25.50\ z$ [km]



(Zoback, 2007)

S_{diff}: 11 MPa@1 km; 55 MPa@5km

=> depth limit of tensile earthquakes?

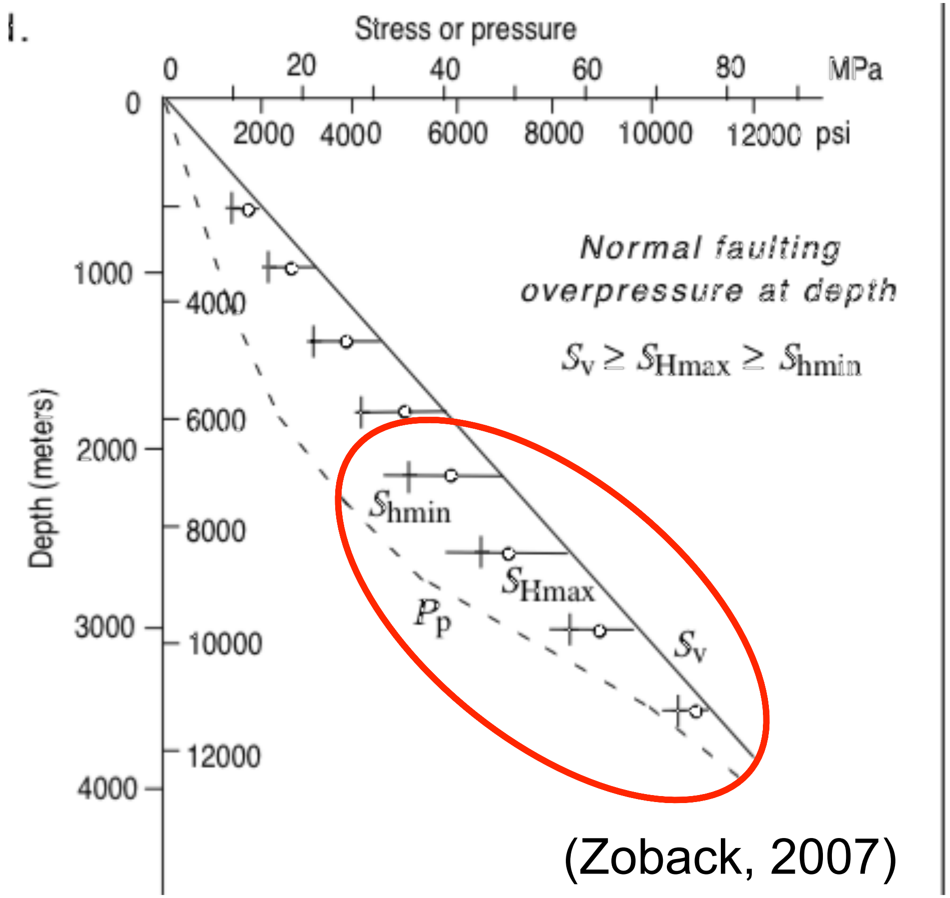
Differential stress σ_1-σ_3 in depth

Overpressurized formations:

- stepwise release of differential stress during pressure buildup
- $P < S_{hmin}$ to avoid hydrofracturing

=> small differential stress at present time !

=> NO LIMIT of depth occurrence of tensile events in overpressurized formations !!



(Zoback, 2007)

$$\sigma_{diff} = \sigma_1 - \sigma_3 = S_1 - P - (S_3 - P)$$
$$= S_1 - S_3$$

Small differential stress σ_1-σ_3 in overpressurized formation

How it happened?

- sealed formations - pressure buildup in geological past
- step-wise release of stress on optimally oriented fractures

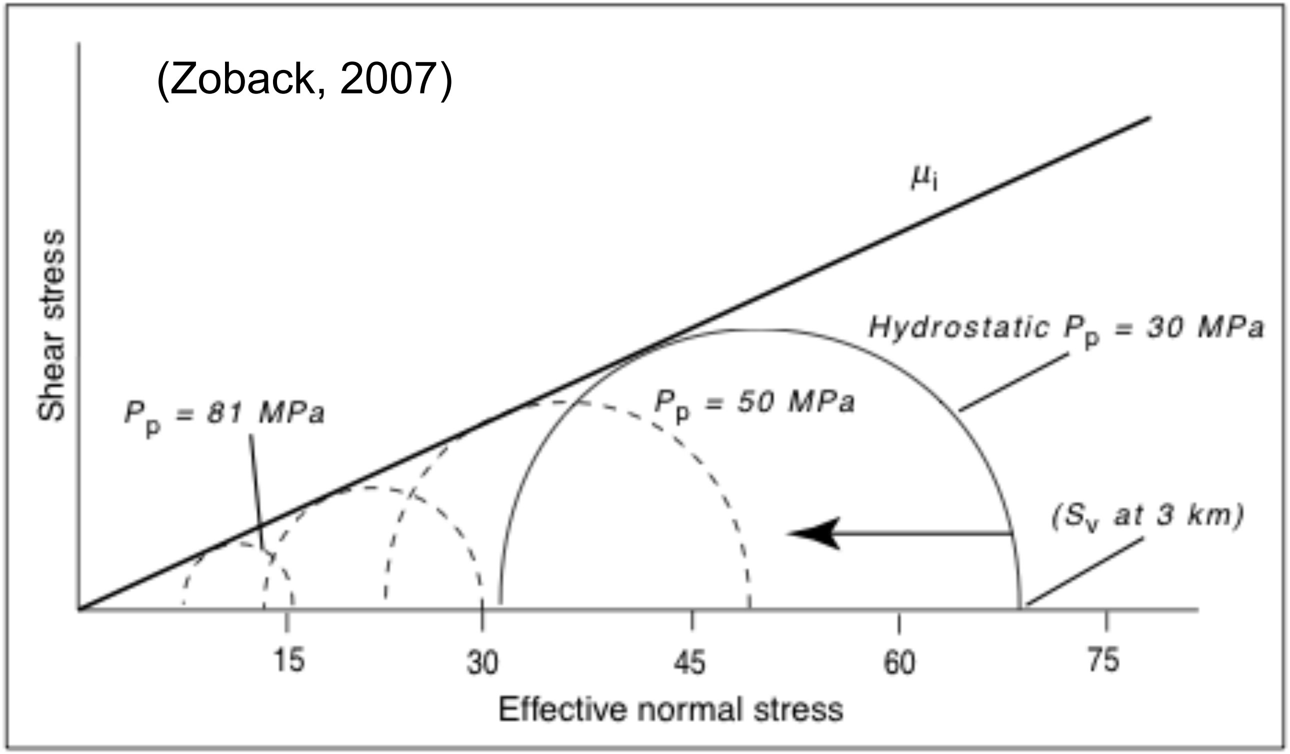


Figure 4.30. In terms of frictional faulting theory, as pore pressure increases (and effective stress decreases), the difference between the maximum and minimum effective principal stress (which defines the size of the Mohr circle) decreases with increasing pore pressure at the same depth.

Scenario

Fluid injection in

- Hydrostatic conditions
  - tensile failure is limited to small depths only on fractures trending <22.5°off SHmax
  - other fractures fail in shear mode
- Overpressured formation
  - tensile failure is possible at any depth for fractures trending <22.5°off SHmax
  - other fractures fail in shear mode

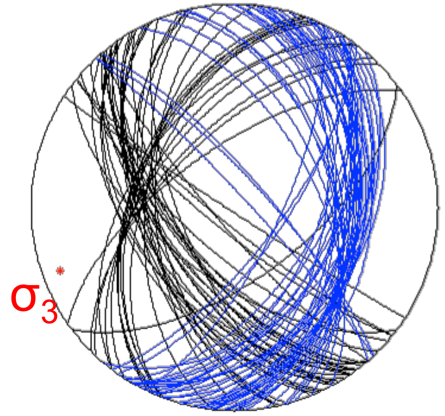
Example 1: Soultz-sous-Forets
focal mechanisms

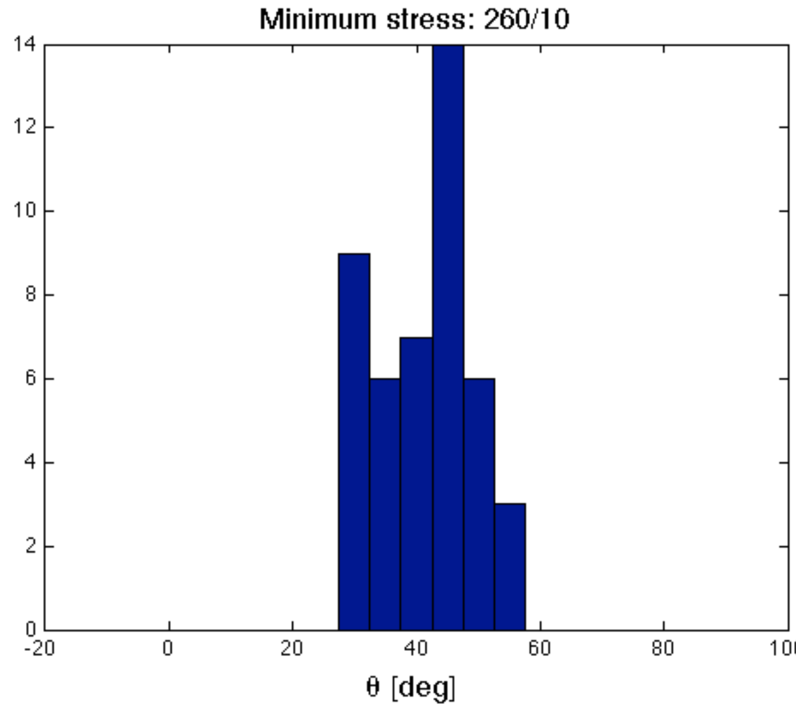
- Horálek et al. (2010) – 2003 injections
  - 45 full MT – dip slip/strike slip
- Valley & Evans (2007)
  - 0.90·Sv ≤ SHmax ≤ 1.05·Sv
  - SHmax 169°; unconstrained plunge
- Cuenot et al. (2005)
  - stable subhorizontal σ_3, NE-SW

=>

- use σ_3 of 260°/10°
- get θ between σ_3 and fault normal

θ ≈ 41°





Example 1: Soultz-sous-Forets
stress and fault failure

Stress @ 4.7 km depth (Valley & Evans, 2007):

- $P_{formation}$ = 47 MPa (hydrostatic)
- S_{Hmin} = 64 MPa
- S_V = 118 MPa
- S_{Hmax} = 0.9 .. 1.05 S_v
- P_{net} < 15 MPa (Tischner et al, 2007)

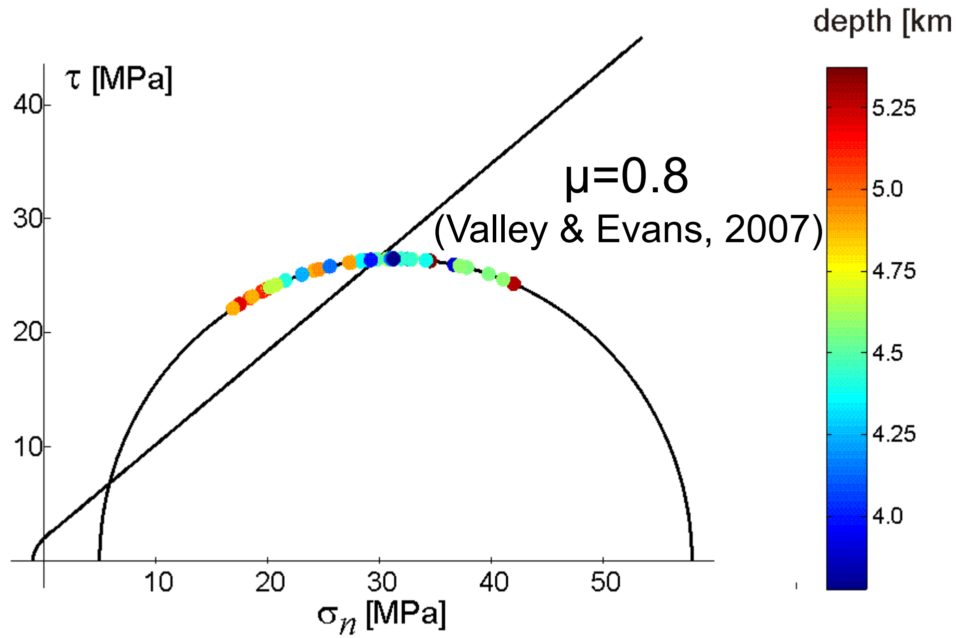
=>

σ_{mean}^{eff} = 31 MPa
σ_{diff} = 53 MPa
(? smaller near fractures?)

=> shear faulting, because

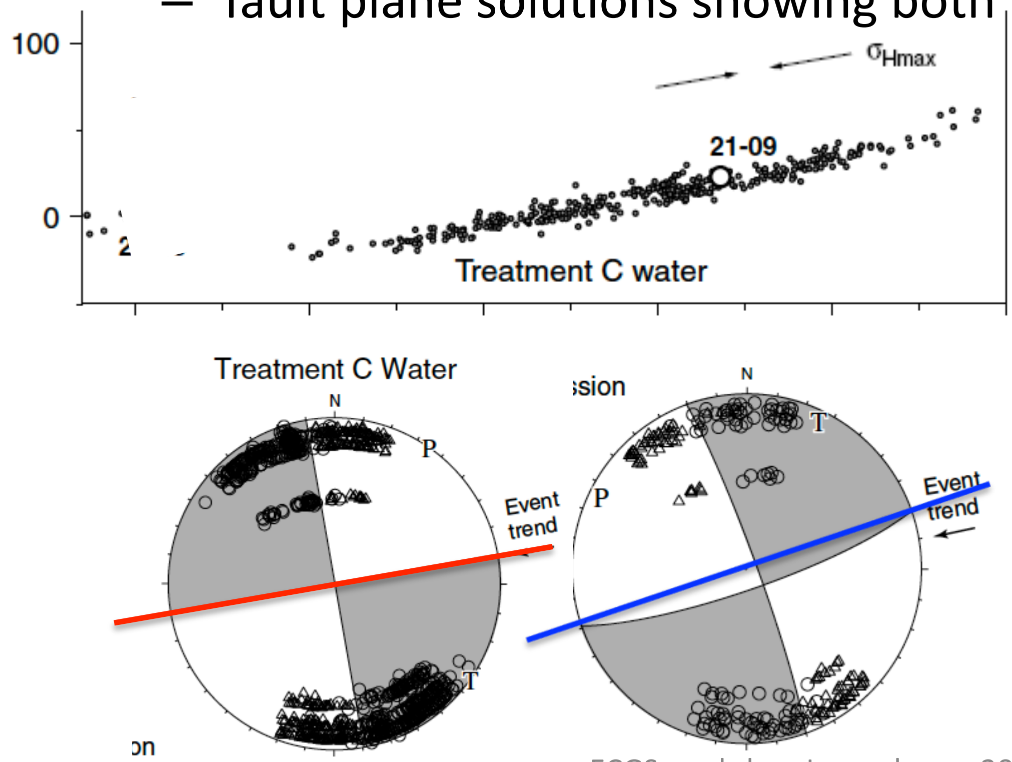
- σ_3 = 5 MPa (positive)
- σ_{diff} too large
- $\theta \approx 41°$ too large

Shear faulting agrees with pure-DC events of Horálek et al. (GJI 2010)



Example 2: Cotton Valley injection
focal mechanisms

- Sandstone formation with many natural fractures, shale interbeds
- Gas reservoir => probably overpressured
- Rutledge et al. (2004):
  - narrow bands of seismicity along vertical fractures trending close *SHmax*
  - fault plane solutions showing both left- and right- lateral strike-slips



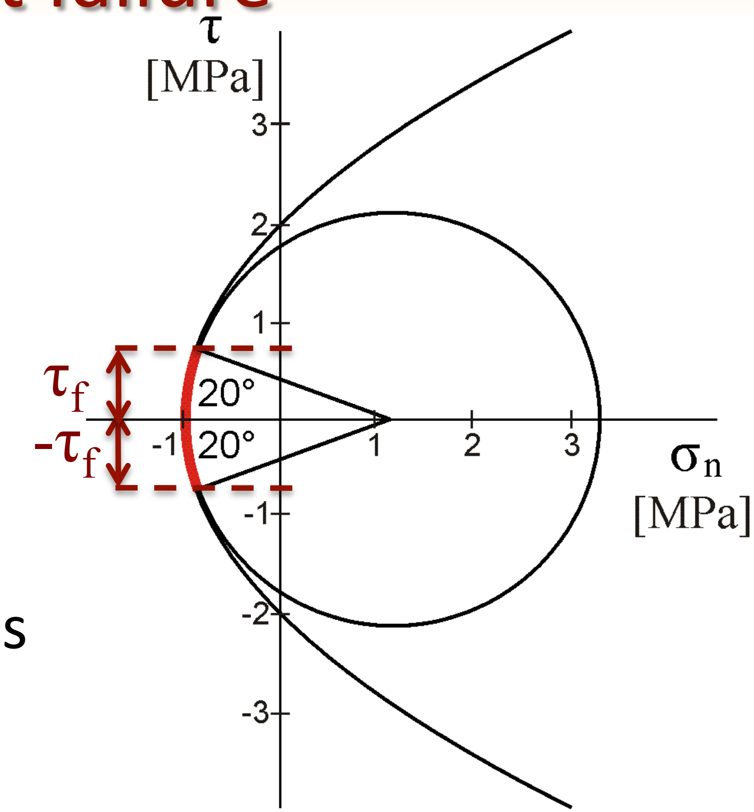
Alternating opposite slip on sub-parallel fractures (<10°difference in strike)

=> small shear stress
=> negative normal stress?

Example 2: Cotton Valley injection
stress and fault failure

- Opposite shears on faults striking within ±10° possible only if $\sigma_n<0$

- Assuming cohesion S_0=2 MPa
  - $|\tau_f|<0.7$ MPa => small stress drops
  - -1 MPa < σ_n < -0.97 MPa

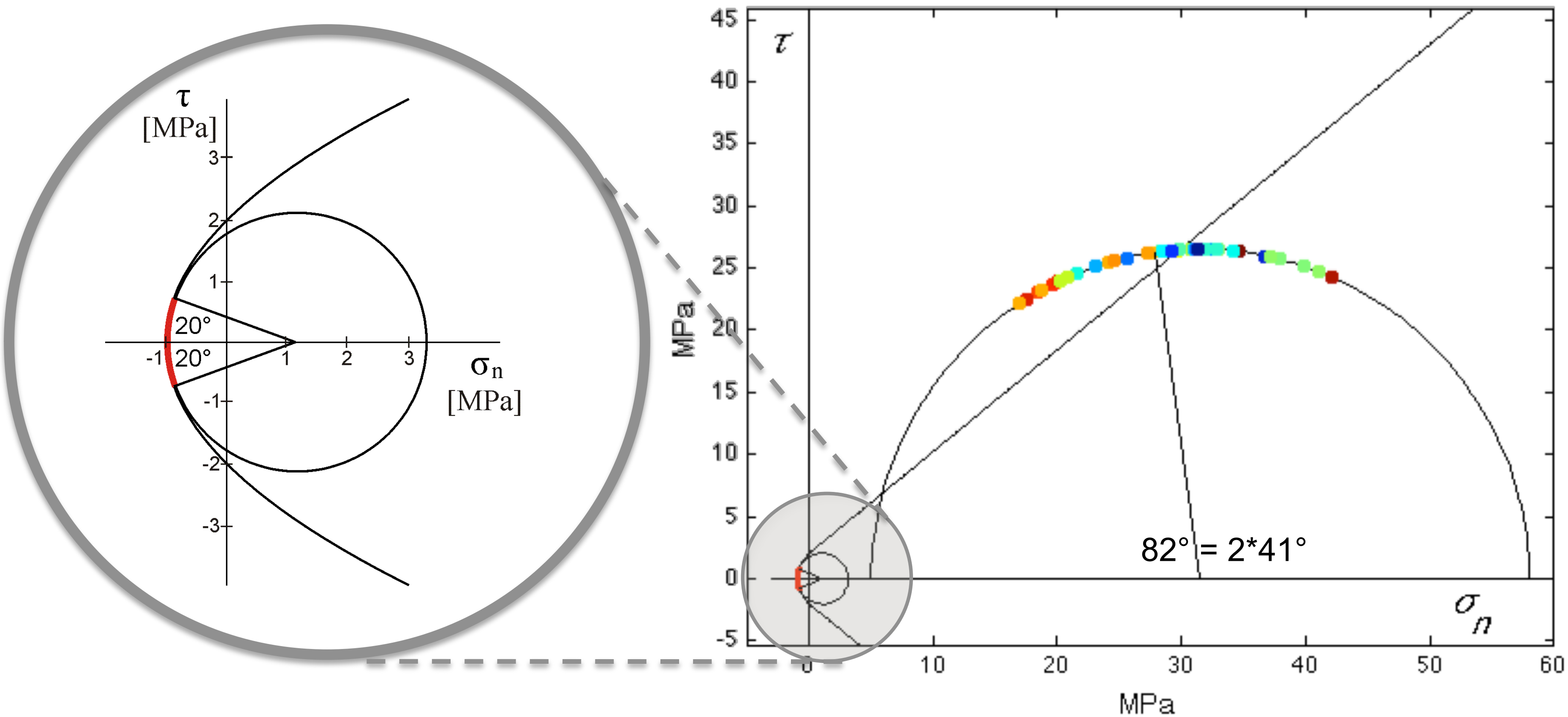


=> Opposite shears in DC-constrained mechanisms prove extensional failure mode and suggest large non-DC component of induced events

Confirmed by Šílený et al. (2008):
full MTs of Cotton Valley events show up to 50% of non-DC

Cotton Valley x Soultz-sous-Forets

overpressured x hydrostatic



small shear stress τ

small stress drop Δσ ?

large shear stress τ

large stress drop Δσ ?

Conclusions

- Tensile earthquake explains crack and dipole MTs and fits the stress components resolved
- Non-linear failure envelope explains stress for non-DC events
- Any fracture with σ_n<0 shows shear component, "tensile earthquake"
- Tensile eq. is possible only for fracs within small angles and small σ_1-σ_3 (θ<22.5°off S_{Hmax} and σ_1-σ_3 < 2.8 S_0)
- Small σ_1-σ_3 possible in small depths or in naturally overpressurized formations
- Tensile earthquakes should have small stress drops (verify by observations)
- The pure-DC character of the Soultz-sous-Forets events in caused by high differential stress and/or fractures oriented optimally for shear
- The non-DC character of the Cotton Valley events is due to the small differential stress and/or fractures oriented optimally for tensile opening

References

Acknowledgements

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Rutledge, J.T., Phillips, W.S., and Mayerhofer, M.J. (2004), Faulting induced by forced fluid injection and fluid flow forced by faulting: An interpretation of hydraulic-fracture microseismicity, Carthage Cotton Valley gas field, Texas, *Bull. Seismol. Soc. Am*, **94**, 1817–1830.

Valley, B. & Evans, K. F., 2007. Stress state at Soultz to 5km depth from wellbore failure and hydraulic observations, *Thirty-Second Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 22-24, 2007 SGP-TR-183.*

More details in

Fischer T. and Guest A. (2010). Shear and tensile earthquakes caused by fluid injection, *Geoph. Res. Lett.,* submitted.