EFFECTS OF COMPOSITION AND TEXTURE ON STRENGTH OF ANHYDRITE CAPROCK

Implications of lateral variations for long-term CO_2 storage

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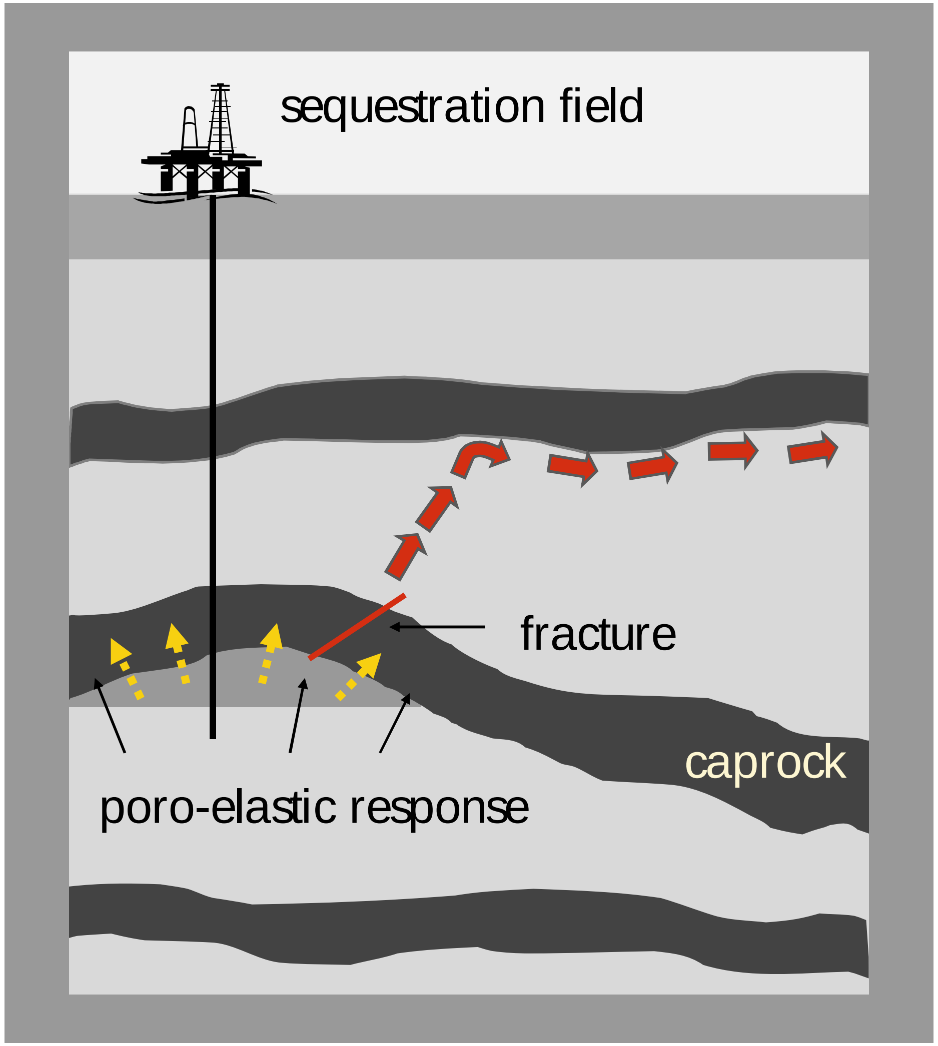
OUTLINE

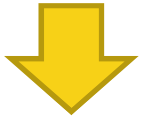
- CO_2 storage & caprock integrity
- Anhydrite caprock
- Rock properties & effect of texture
- Implications
- Conclusions

CO_2 STORAGE
CAPROCK INTEGRITY - NO SEAL, NO DEAL!



Potential issues:

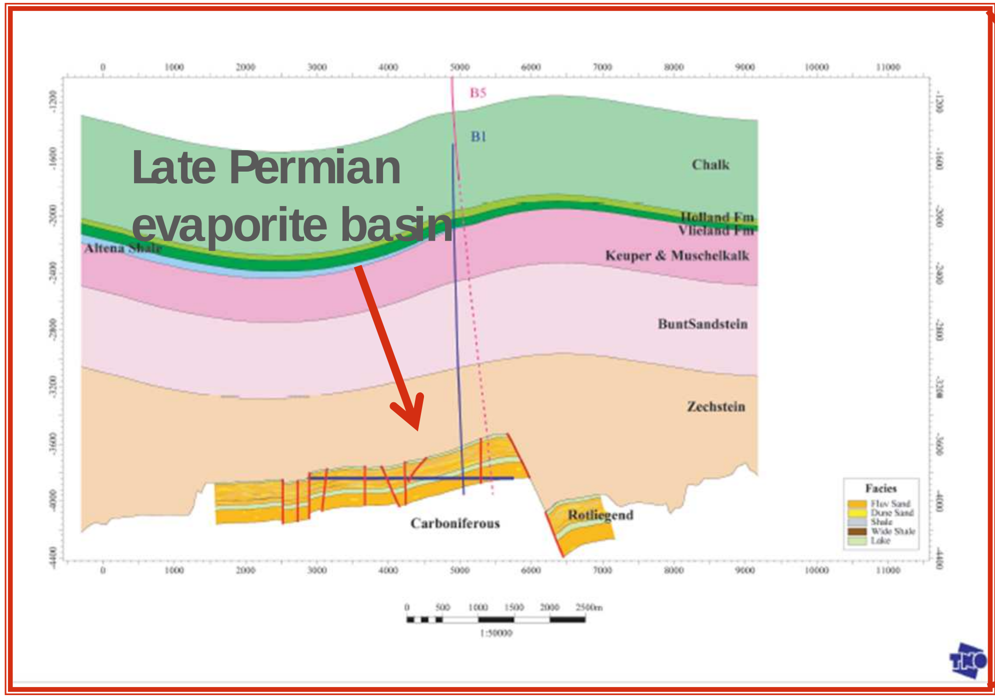
- Reservoir heave (poro-elastic response) or compaction (potential framework weakening through reaction)

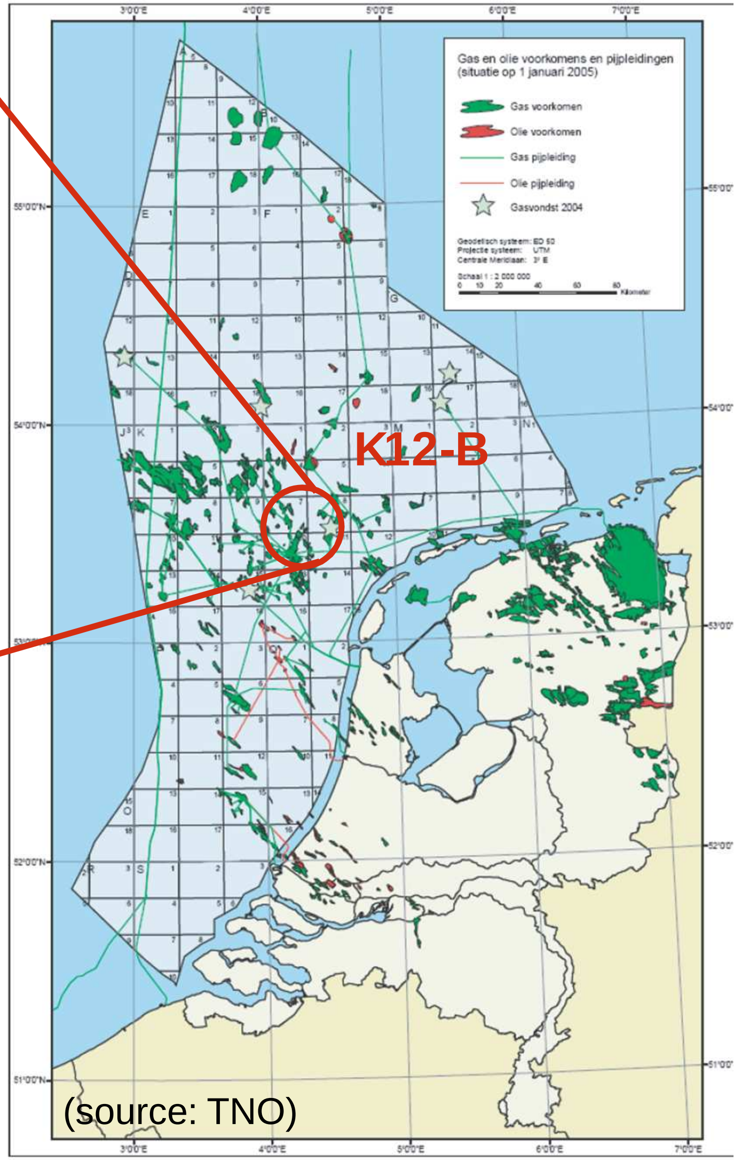


- Caprock flexure – permeability development or failure
- (Chemical) interaction with caprock - mechanical weakening?

Creation of leakage pathways?
Loss of containment??

ANHYDRITE CAPROCK
THE NETHERLANDS





Anhydrite – Basal unit Zechstein Group

$$CaSO_4 + CO_2 + H_2O \leftrightarrow CaCO_3 + H_2SO_4$$

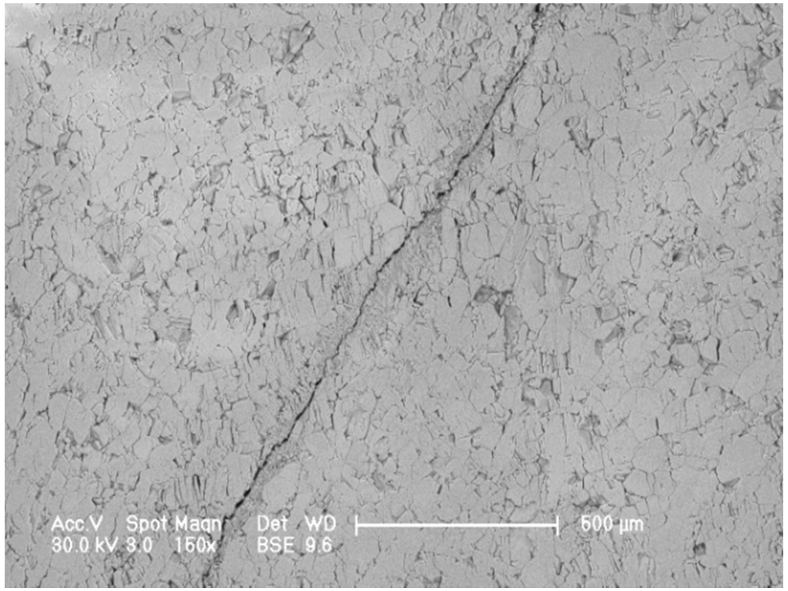
Of interest to the Netherlands, but also to the USA (Teapot Dome), Canada (Weyburn) and Middle East!

ANHYDRITE CAPROCK
ZECHSTEIN FORMATION

Acicular anhydrite

- Bimodal distribution:
  acicular grains (60%), *d* =1000-2000 µm; matrix (40%), *d* < 50 µm
- 15-25 wt% dolomite
- Φ = 0.1-0.3%
- $\kappa < 10^{-21}$ m^2

Euhedral anhydrite



- *d* = 100 µm
- 15-25 wt% dolomite
- Φ = 0.2-0.5%
- $\kappa < 10^{-21}$ m^2

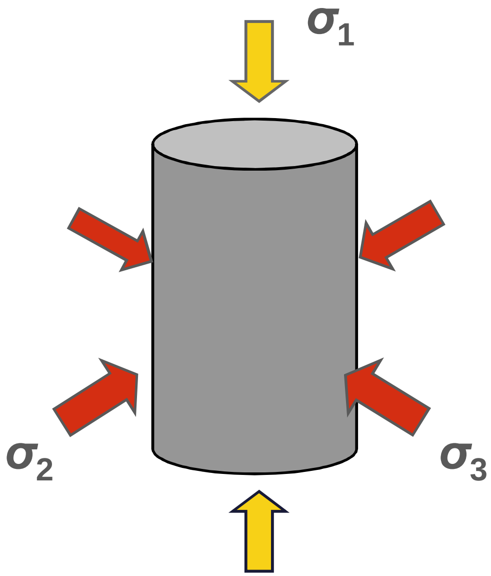
Well locations are ~10 km apart

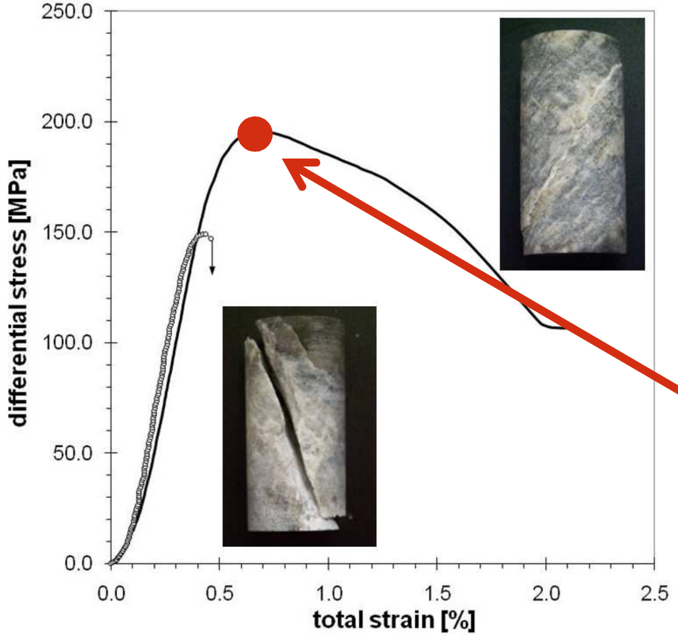
EXPERIMENTAL METHODS
COMPRESSION EXPERIMENTS

Hangx, Spiers, Peach [JGR; Geofluids,2010]

Experimental conditions:

- P_c^{eff} = 1.5 - 50 MPa
- P_f = 0 – 15 MPa
- fluids: $CaSO_4$/ CO_2-saturated solution
- T = 80°C
- $\dot{\varepsilon}$ = ~ 10^{-5} s^{-1}





$\sigma_2 = \sigma_3 = P_c$

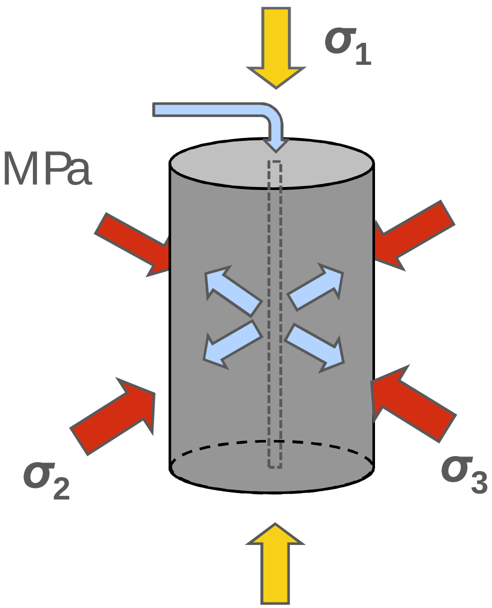
peak stress:
differential stress at which failure/ loss of strength occurs

EXPERIMENTAL METHODS
HYDROFRACTURING EXPERIMENTS

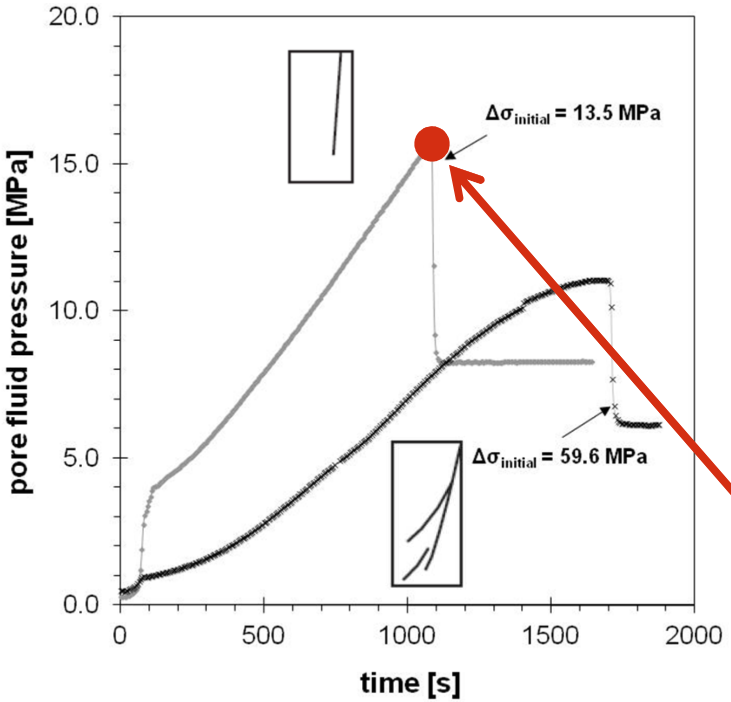
Hangx, et al. [in prep.]

Experimental conditions:

- P_c = 3.0-15.0 MPa
- $\Delta\sigma_{initial} = \sigma_{1,initial} - \sigma_{3,initial}$ =13.5-93.6 MPa
- T = 80°C
- Pump rate = ~0.34 µl/ s



$\sigma_2 = \sigma_3 = P_c$

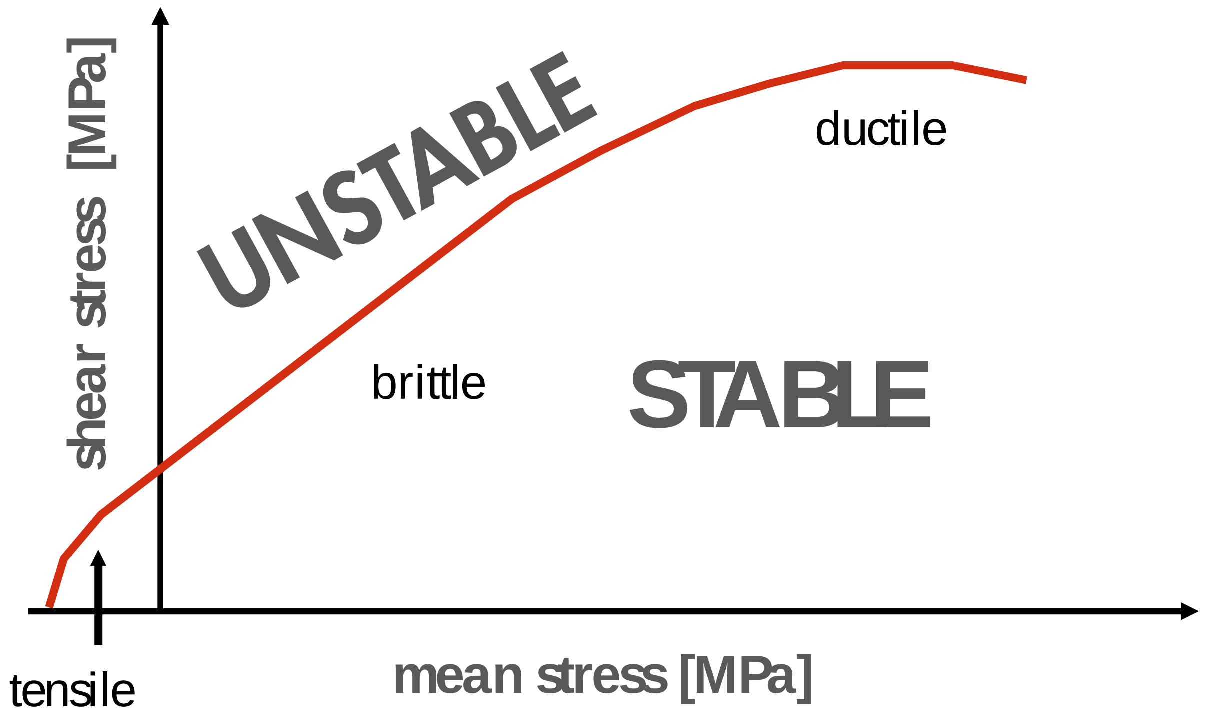


pore fluid pressure @ failure; P_p drop

KEY AIM: FAILURE ENVELOPES

MOGI FAILURE CRITERION

General failure envelope



MOGI FAILURE CRITERION:

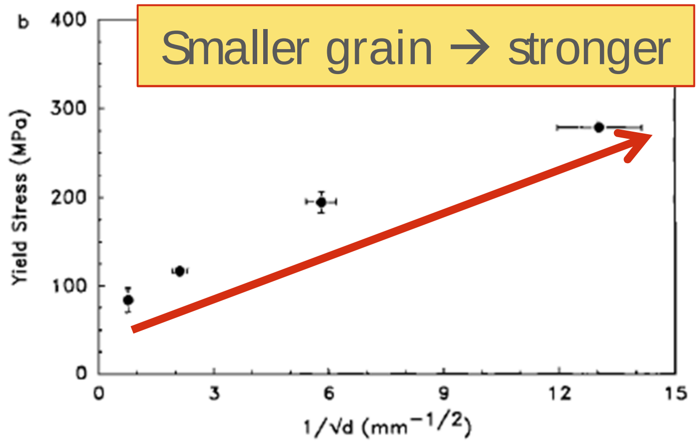
Octahedral shear stress: $\tau_{oct} = 1/3 \sqrt{[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]}$

Mean stress: $\sigma_{m,2} = (\sigma_1 + \sigma_2 + \sigma_3)/3$

EFFECT OF TEXTURE ON STRENGTH

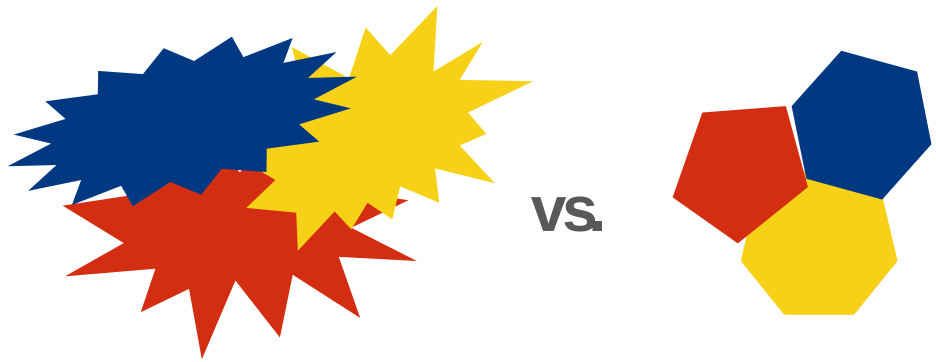
Grain size:

Smaller grain → stronger

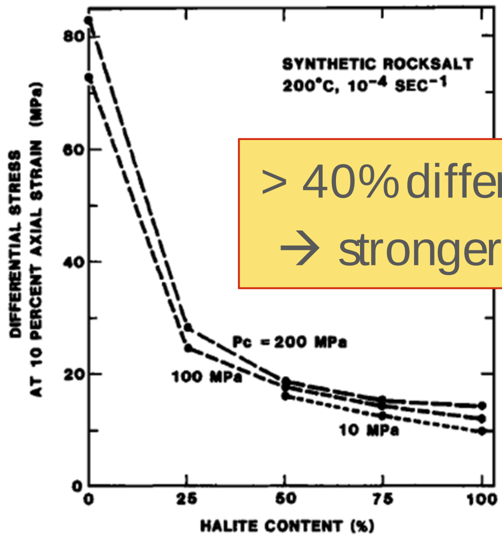


Fredrich etc al. [JGR, 1990]

Grain shape: Interlocking grains → stronger



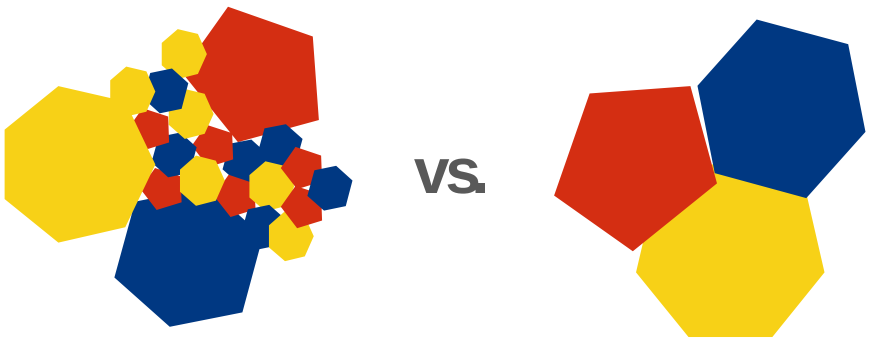
Composition:



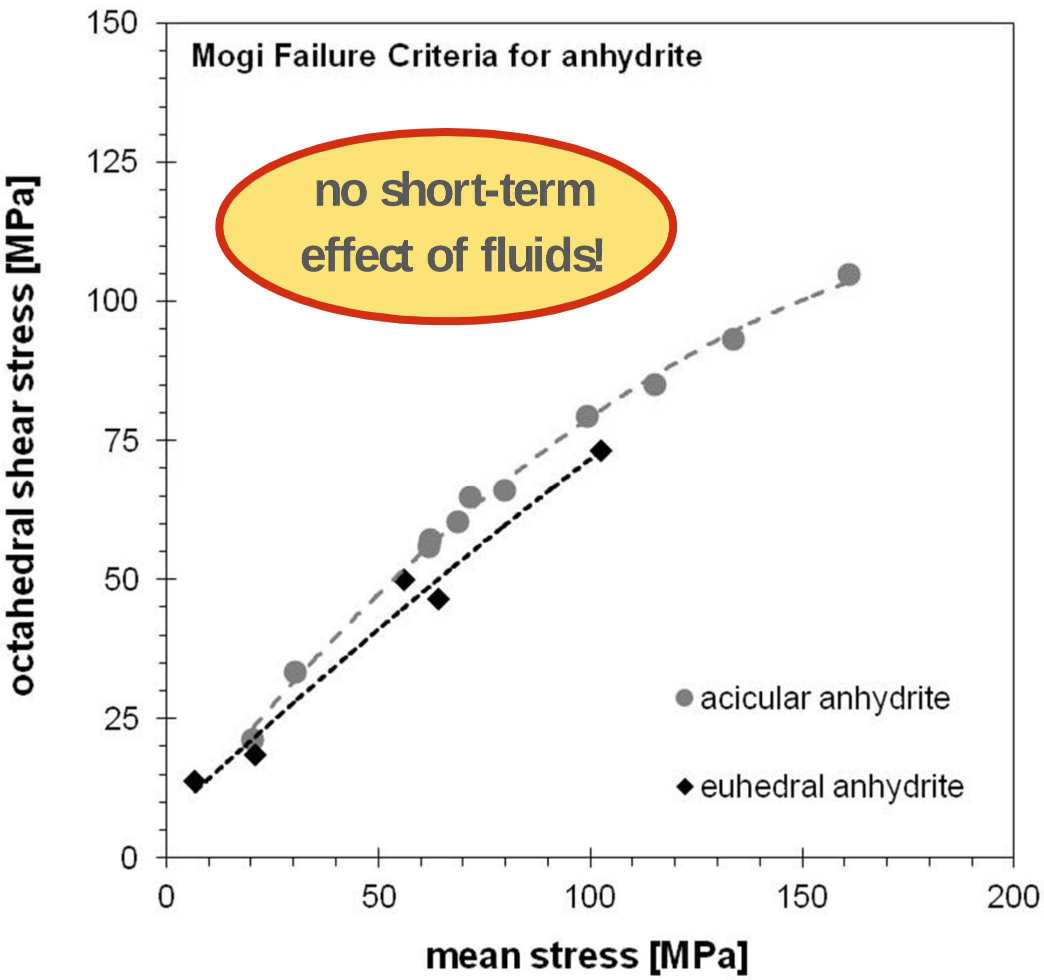
> 40% different phase
→ stronger/ weaker

Price [JGR, 1982]

Size distribution: wider range → stronger



MECHANICAL STRENGTH



Acicular anhydrite:

Irregular grains; bimodal *d*-range;

d = 1000 µm

- C_0 = 124 MPa
- μ = 0.5
- T_0 = 5 MPa
- E = 50 GPa

Euhedral anhydrite:

Regular grains; equigranular;

d = 100 µm

- C_0 = 55 MPa
- μ = 0.9
- T_0 = 8 MPa
- E = 41 GPa

Overall, euhedral anhydrite 15-30% weaker than acicular anhydrite

INITIAL FLAW SIZE

Acicular anhydrite

- Intragranular cracks
- E = 50 GPa
- σ_T = 5 MPa
- γ = 0.902 J/ m^2

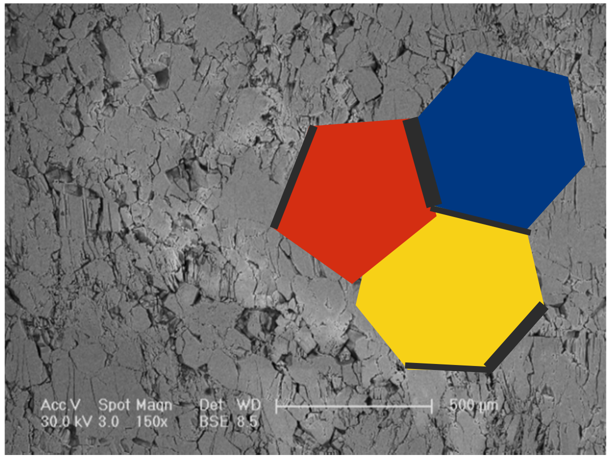
[*Tromans & Meech*, 2002]

- Initial flaw size,
  c = 2200 µm (~ grain size)

Griffith criterion

$$\sigma_T = \sqrt{\frac{2\gamma E}{\pi c}}$$

Euhedral anhydrite



- Grain boundary cracks
- E = 41 GPa
- σ_T = 8 MPa
- γ = 0.255 J/ m^2

[*Tromans & Meech*, 2002]

- Initial flaw size,
  c = 200 µm (~ 2x grain size)

FLEXURAL BENDING OF A CAPROCK
POTENTIAL FOR SHEAR FAILURE DUE TO RESERVOIR DEFORMATION

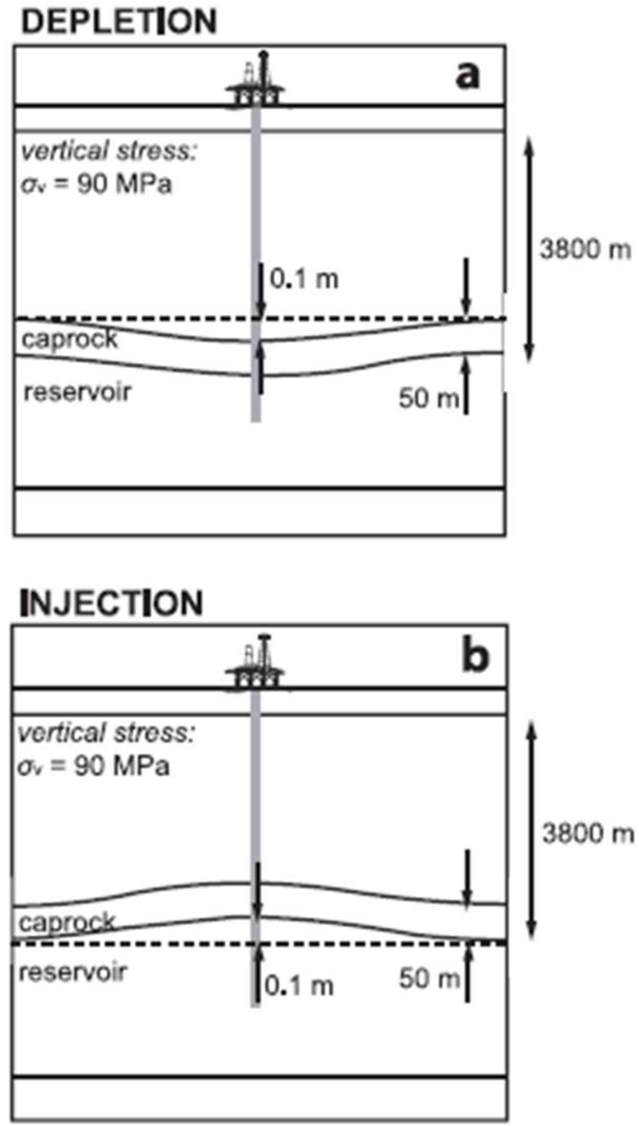
Model assumptions:

- circular reservoir, disc-shaped plate of caprock
- homogeneous, isotropic, elastic, uniform in thickness, and initially flat-lying; fixed edges, uniform load
- no fluid penetration
- all stress changes → poroelastic contraction or expansion of the reservoir

1. **hydrostatic**, where $\sigma_v = \sigma_1 = \sigma_2 = \sigma_3$
2. **compressive**, where $\sigma_v = \sigma_3$ and $\sigma_1 = \sigma_2 = 1.5\ \sigma_3$
3. **extensional**, where $\sigma_v = \sigma_1$ and $\sigma_3 = \sigma_2 = \frac{2}{3}\ \sigma_1$

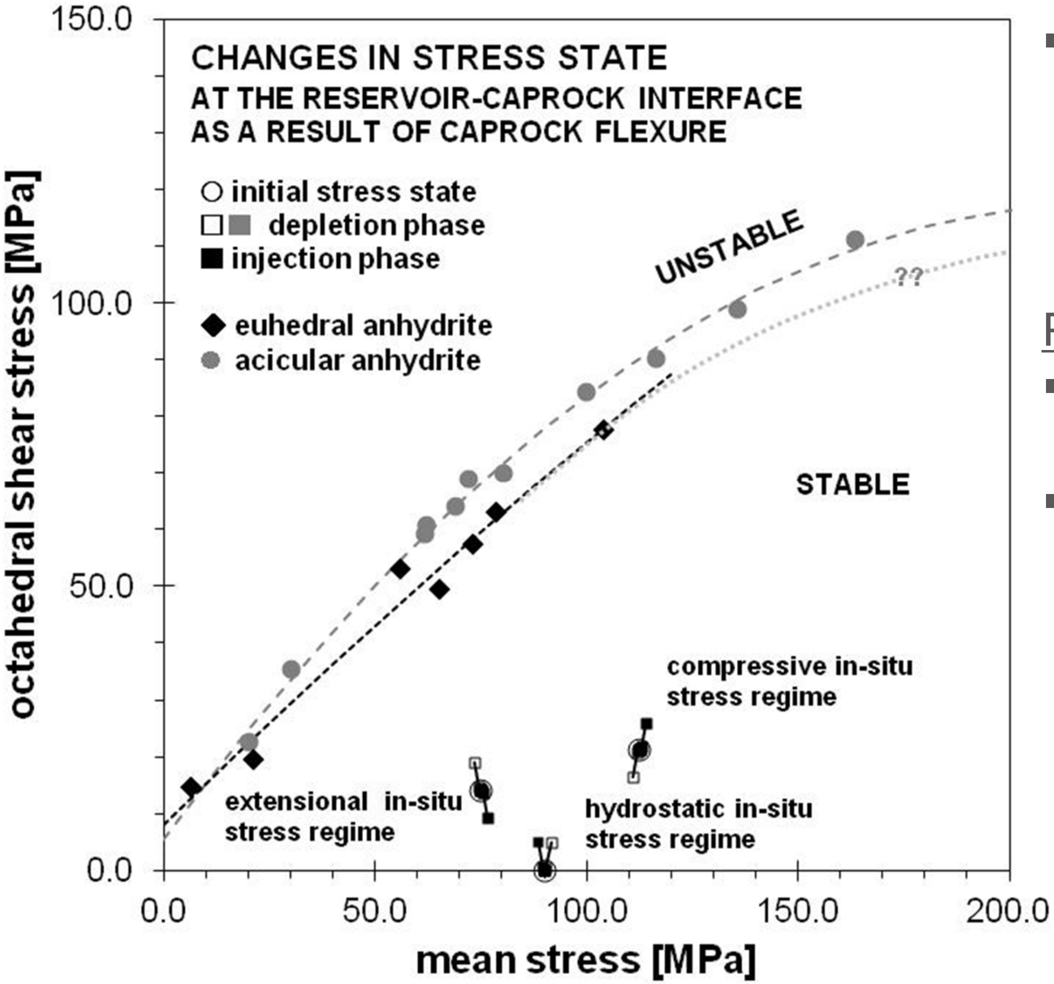
Model parameters:

- E = 5 GPa (upscaling of measured E)
- ν = 0.25
- t = 50 m
- y = ± 0.1 cm
- d = 100 m – 5 km



Hangx, Spiers, Peach [JGR,2010]

FLEXURAL BENDING
SHEAR FAILURE



- Loss of caprock integrity though permeability development and/ or damage → unlikely

<u>Failure may occur only for:</u>

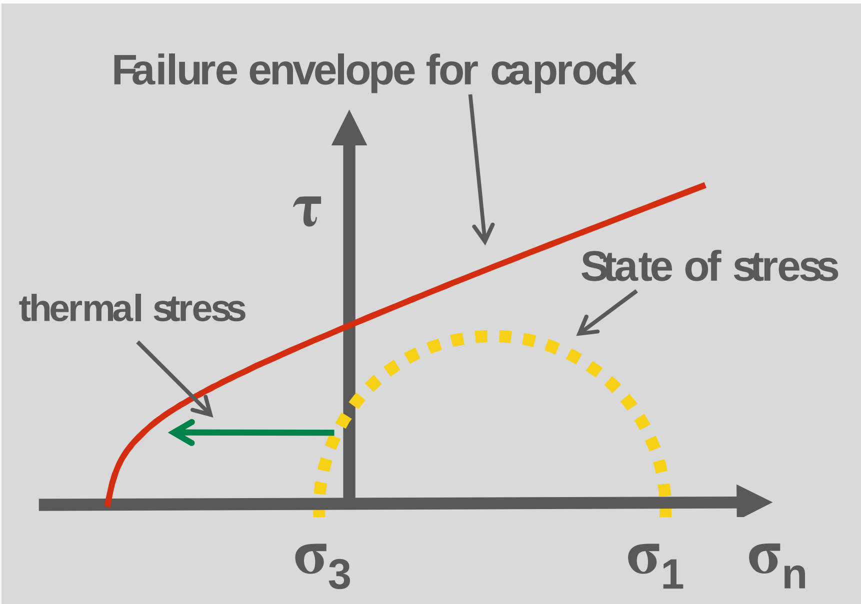
- Strong doming near the wellbore (e.g. d = 100 m, y = 1m)
- Higher values for *E* (e.g. 50 GPa)

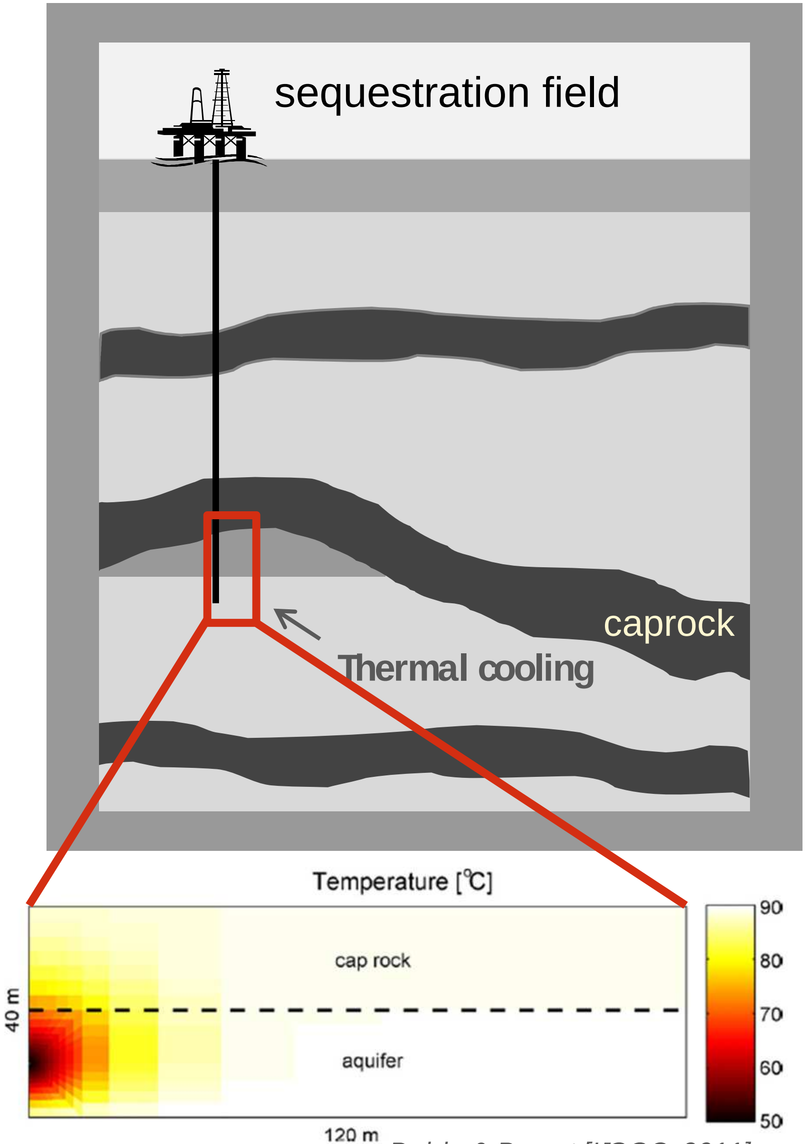
but: more complex numerical modeling needed to predict long-term behaviour!

THERMAL COOLING
POTENTIAL FOR TENSILE FAILURE DUE TO CO_2 INJECTION

Joule-Thomson effect: injection of HP CO_2 into LP reservoir → expansion of CO_2 → cooling

- Cooling near wellbore and base caprock (10's °C) → shrinkage of rock
- Thermally-induced stresses → tensile failure?

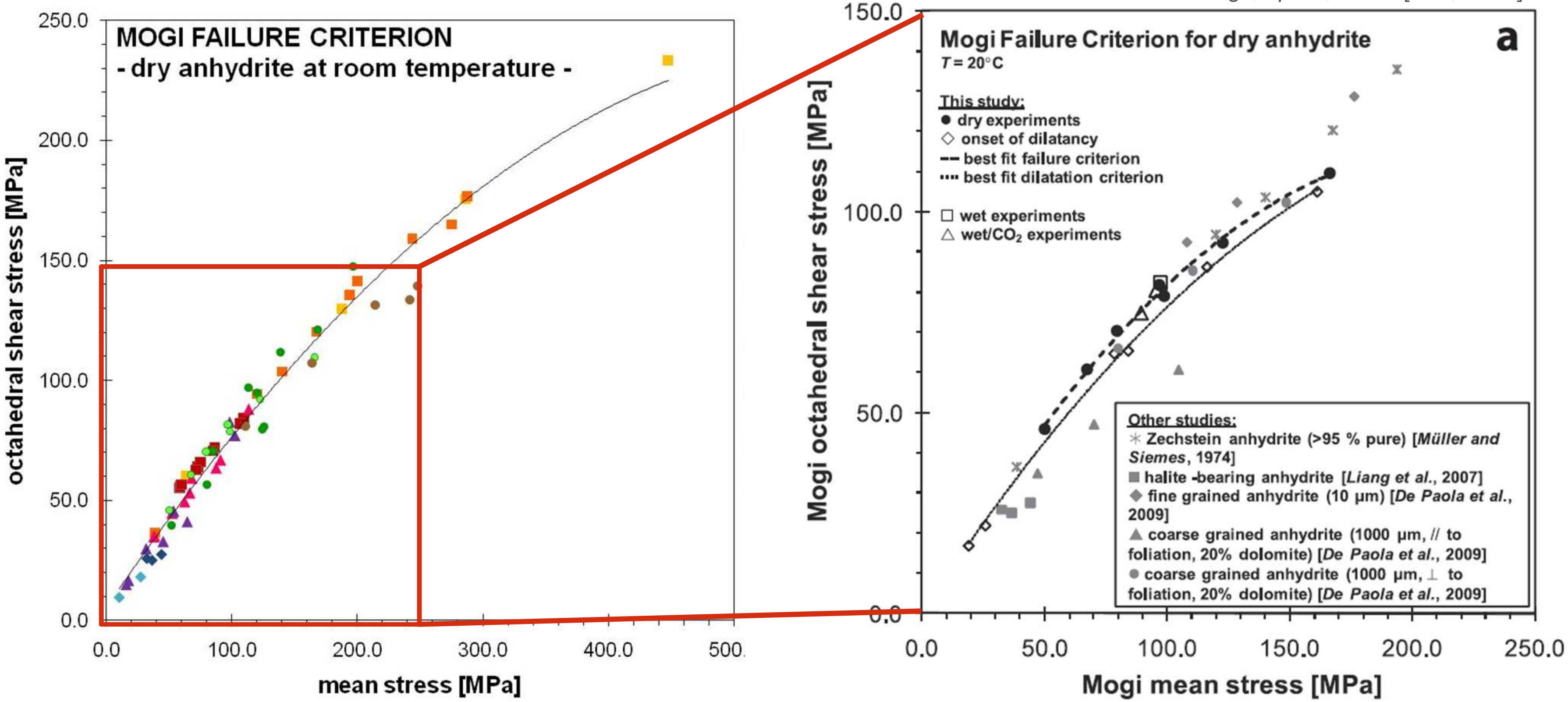




Preisig & Prevost [IJGGC, 2011]

CONCLUSIONS
SITE-SPECIFIC DATA IS NEEDED

Hangx, Spiers, Peach [JGR, 2010]



Rock texture and composition affect rock strength and mechanical properties
→ to properly asses caprock integrity, site-specific data is needed