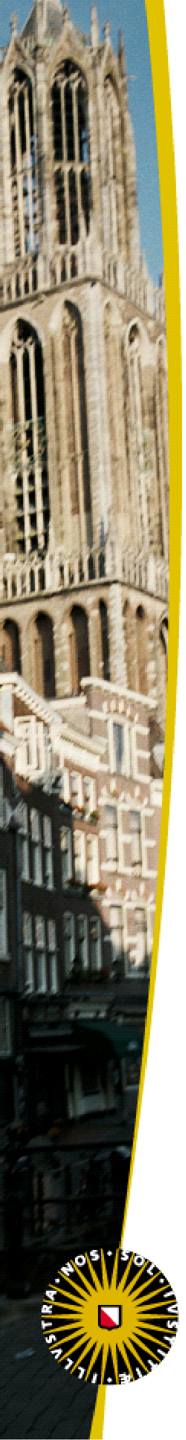

Salt Cavern Workshop:

"Proceedings in salt cavern uses and abandonment: Bridging the technical and social perspectives"

TNO Utrecht, 15 – 16 October 2024

Developments in salt mechanics research:
An overview

Chris Spiers

Emeritus Professor
Department of Earth Sciences
Utrecht University, The Netherlands

With thanks to: Suzanne Hangx,
Janos Urai, Pierre Bérest, Dieter Brückner

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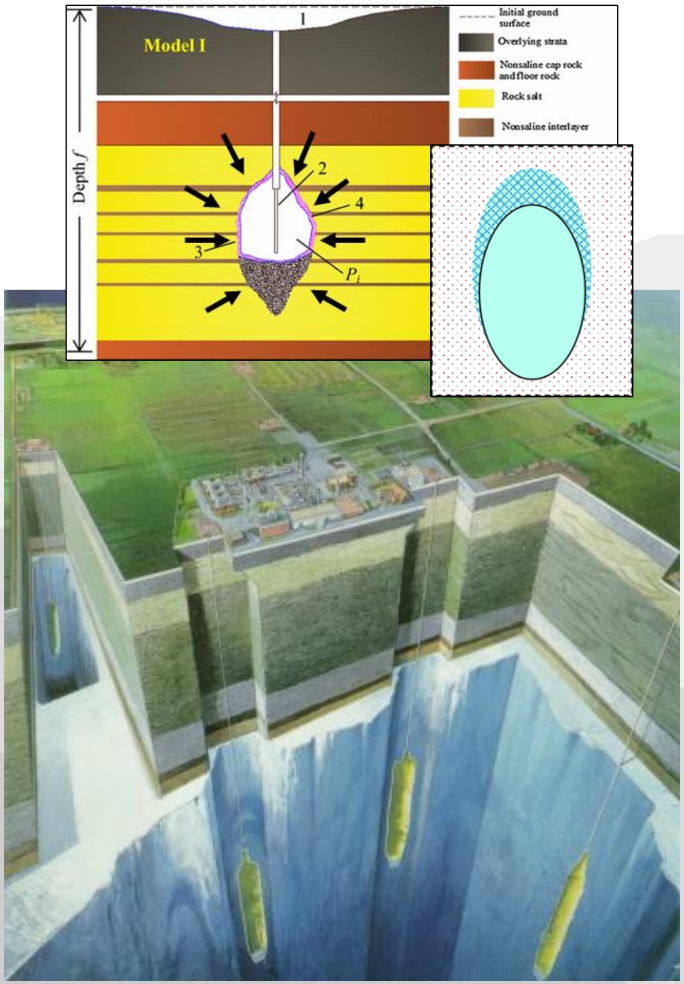
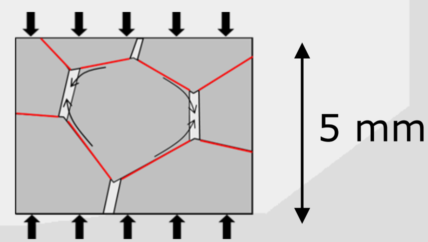
Summary – what's this talk about?



- Topic: Progress in understanding the *deformation behaviour* of rock salt
- Key for cavern closure, stability + subsidence
- Long term behaviour ≠ short lab tests
  (10-100-1000 yr) (weeks-months)
- Long term creep process (pressure solution) now in modelling (new!)



- Other key processes also in advanced models
- Much progress re abandonment – some remaining questions

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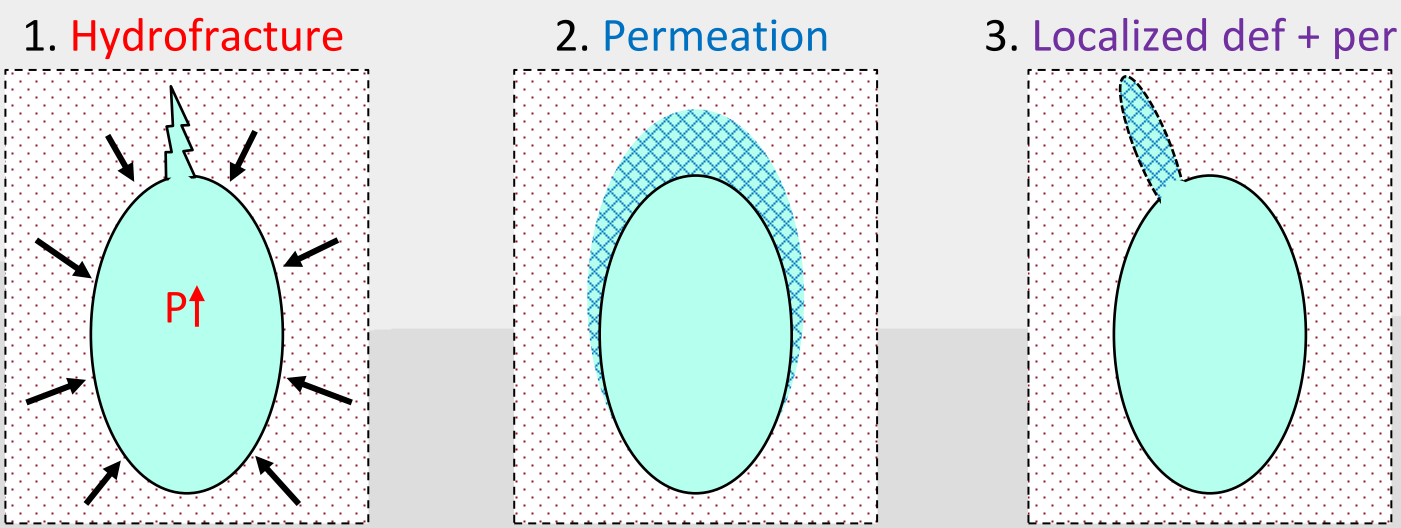
Key questions back in 2019

Will post-abandonment convergence and thermal equilibration lead to:

1) P-build up and ultimately hydrofracture of the salt cavern roof / cover?

2) Permeation of brine into the salt roof/cover preventing fracking?

3) Localized deformation/permeation?



Conclusions KEM-17: (2020)

A) Insufficient basis to answer question

B) Multiscale/multiphysics modelling needed (all known processes!)

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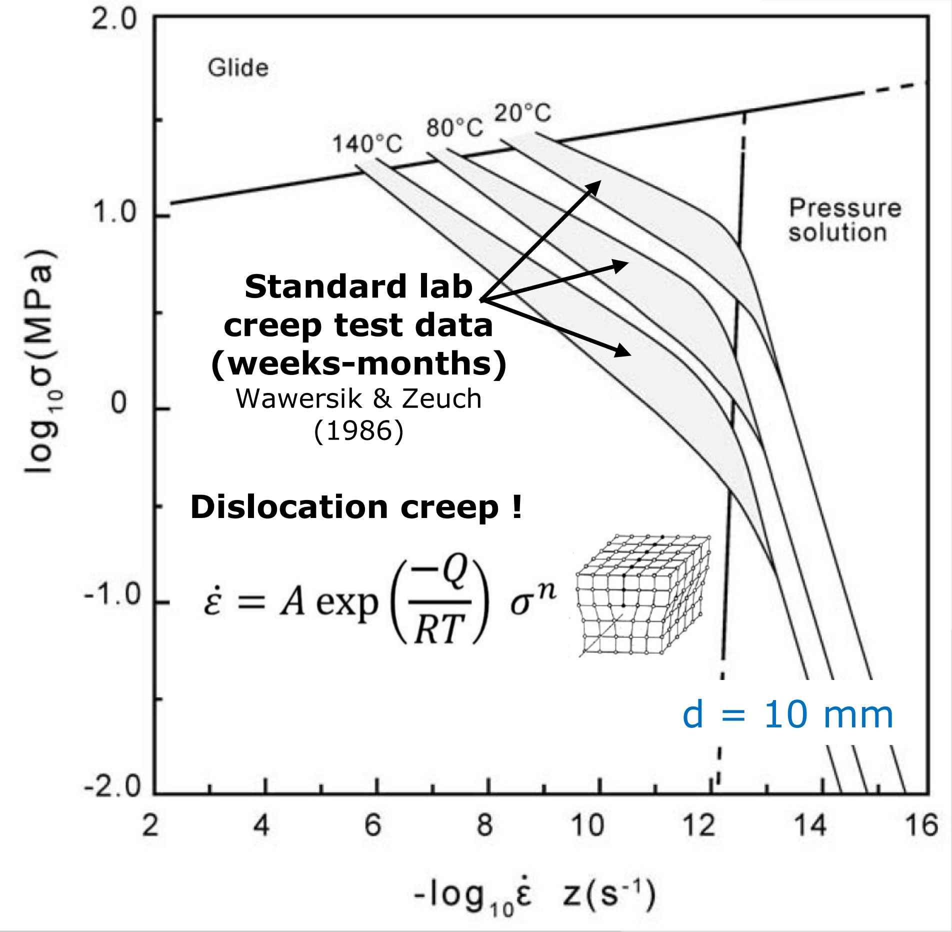
The central controversy (2019)

—

Known effects of grain boundary brine on creep not accounted for!

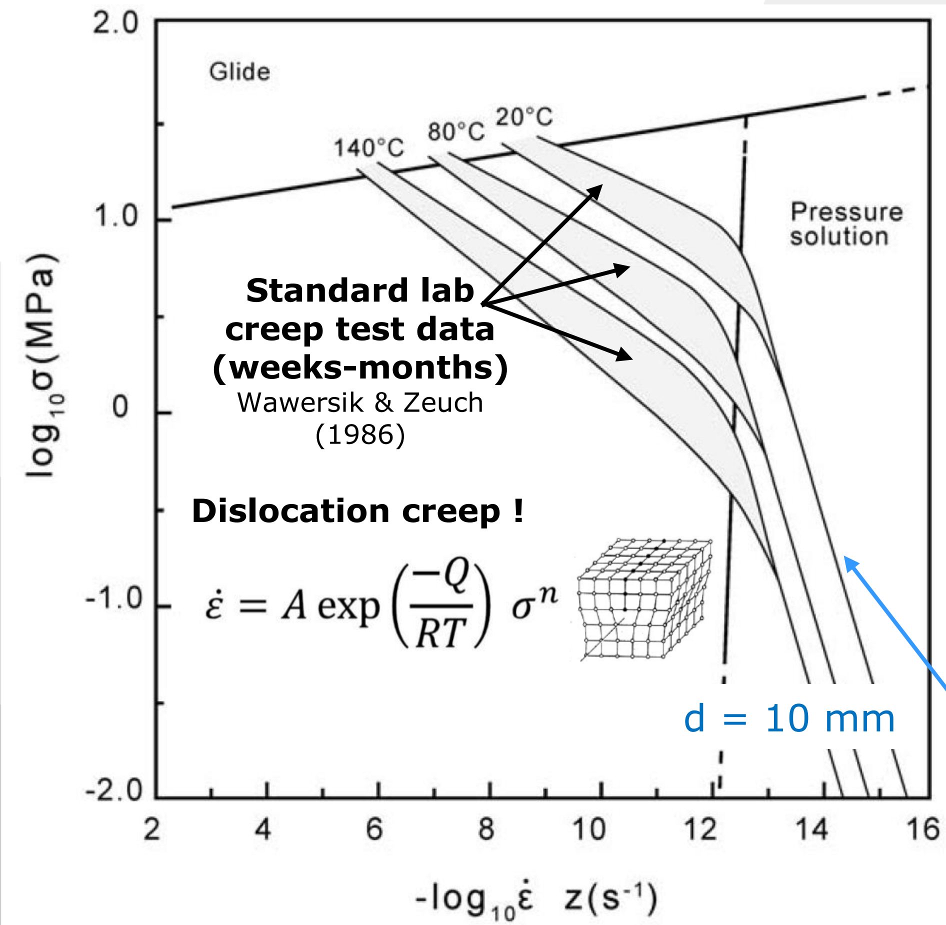


Urai et al. (1986), Spiers et al (1986, 1990), Urai & Spiers (2007)

The central controversy (2019)

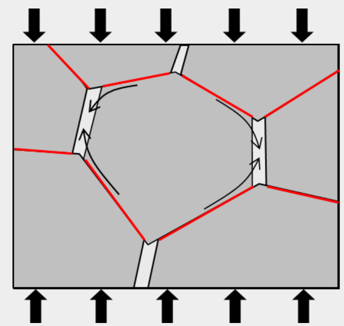
—

Known effects of grain boundary brine on creep not accounted for!



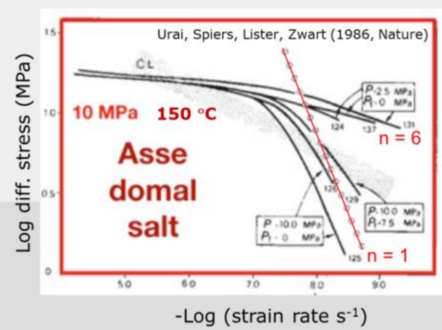
Urai et al. (1986), Spiers et al (1986, 1990), Urai & Spiers (2007)

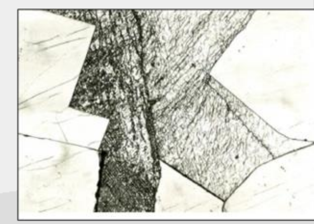
Lab tests on fine / recrystallized salt show "pressure solution" creep:



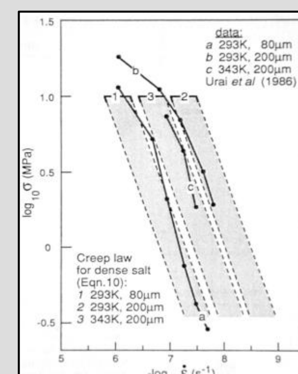
$$\dot{\varepsilon} = \frac{A\,DCS\,\Omega}{RTd^3}\,\sigma$$

Fast for fine grain size d !!





Pressure solution predictions for coarse natural rock salt

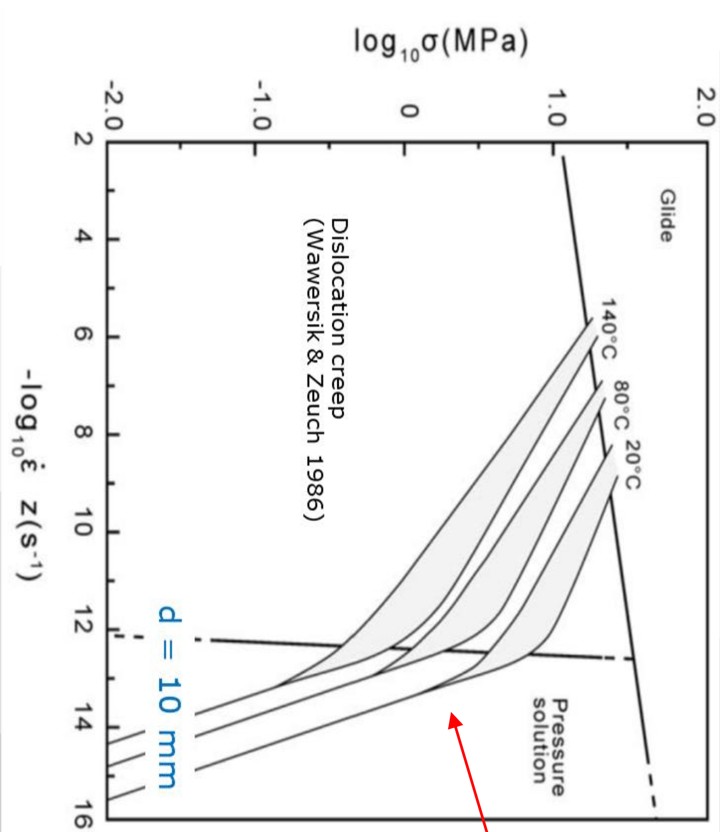


The central controversy (2019)

—

Effects of grain boundary brine long avoided in cavern modelling!

(except e.g. Breunese et al (2003), TNO Barradeel)



Why??

1) No lab data on natural salt at low stress and strain rate (test duration too long)
2) Sample microstructure not studied
3) Effects limited on short (op) time scales
4) Hard to estimate grain size at cavern or formation scale

No lab data in this range
until recently !!!

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The game-changer – also 2019! –

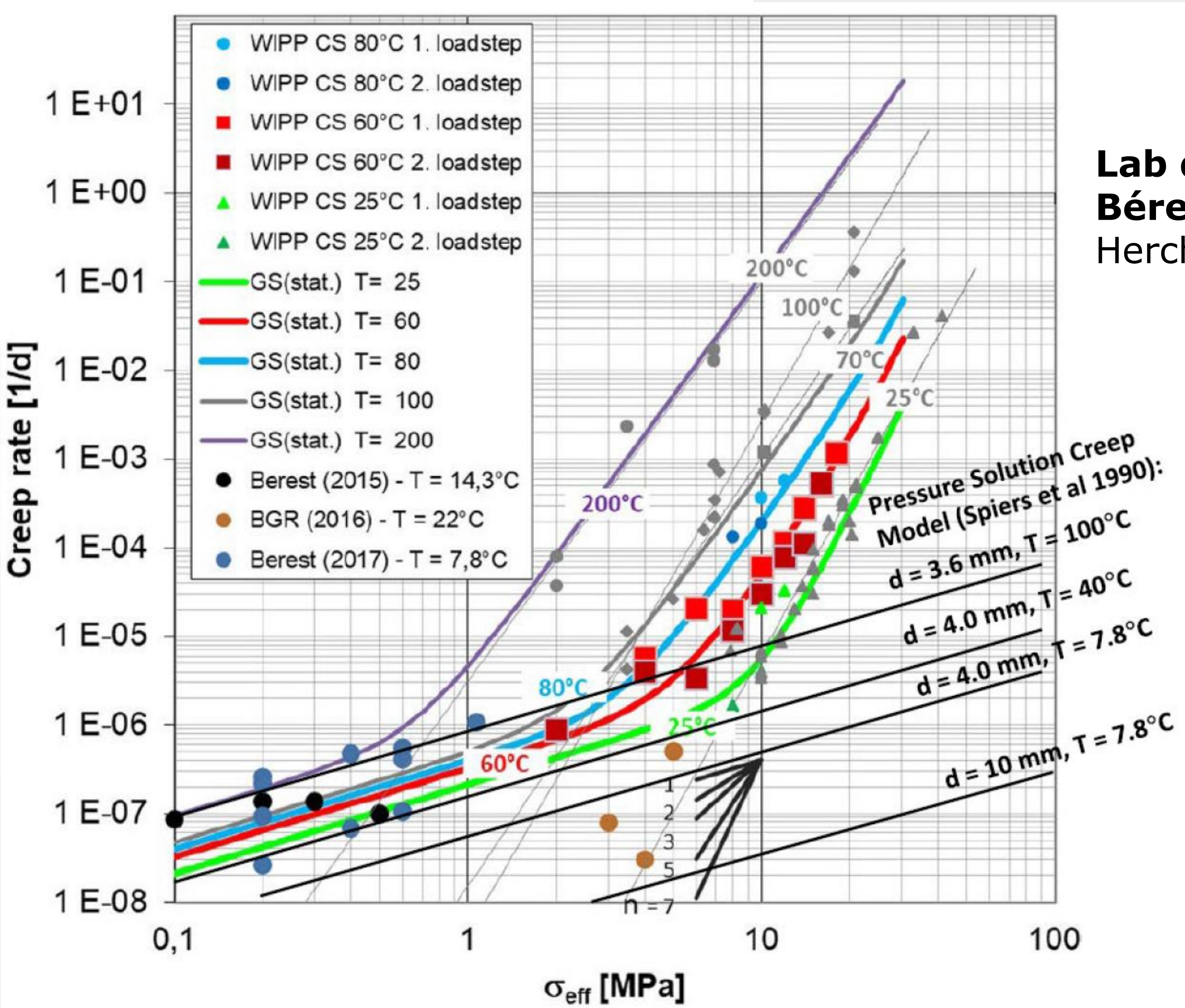

Fig. 4 Testing devices in a dead-end gallery at the Altaussee mine

Lab data from:
Bérest et al (2019)
Herchen et al (2018 WEIMOS)

- Linear creep confirmed at low deviatoric stress

- Berest et al:
  Creep rate slowest in coarsest + dried samples

- Linear regime reproduced in confined tests, see:

  Lüdeling et al. (2022,2023)
  Blanco-Martin et al. (2024)

- Lab protocol for testing established

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Impact on numerical modelling

Linear (p-solution) creep at low stress **now** widely included in modelling –

MECHANICAL BEHAVIOR OF SALT X, 2022
PROCEEDINGS (ISBN 978-1-032-28220-6)

30% SaltMech X papers 2022

Influence of THM process coupling and constitutive models on the simulated evolution of deep salt formations during glaciation

Florian Zill[1,2], Wenqing Wang[1], Thomas Nagel[2,3]*

Modeling of the 3D stress state of typical salt formations

Tobias S. Baumann[1,2], Boris Kaus[1,2], Anton Popov[1,2], Janos Urai[3]*

Influence of pressure solution and evaporate heterogeneity on the geo-mechanical behavior of salt caverns

Kishan Ramesh Kumar[1] and Hadi Hajibeygi[1]*

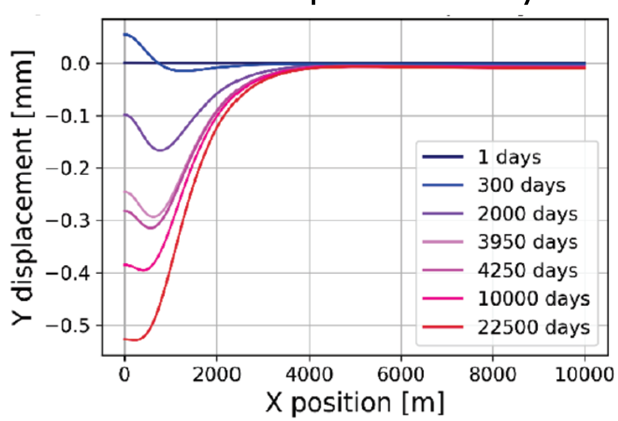
The influence of a threshold stress for pressure solution creep on cavern convergence and subsidence behavior – An FEM study

Luuk Hunfeld[1], Jaap Breunese[1], Brecht Wassing[2]*

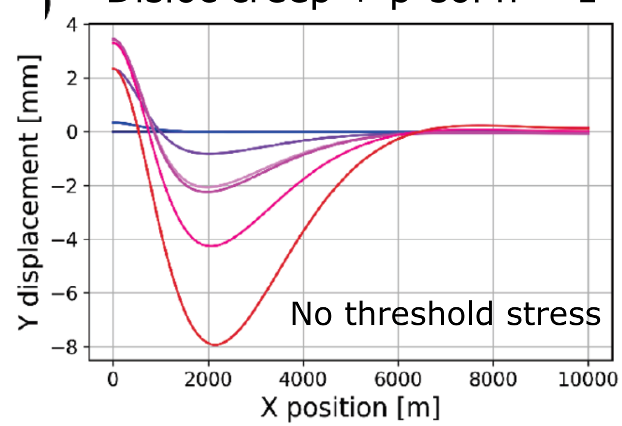
Subsidence predictions

after 10 yr operation + 50 yr shut-in

Disloc creep n = 5 only



Disloc creep + p-sol n = 1



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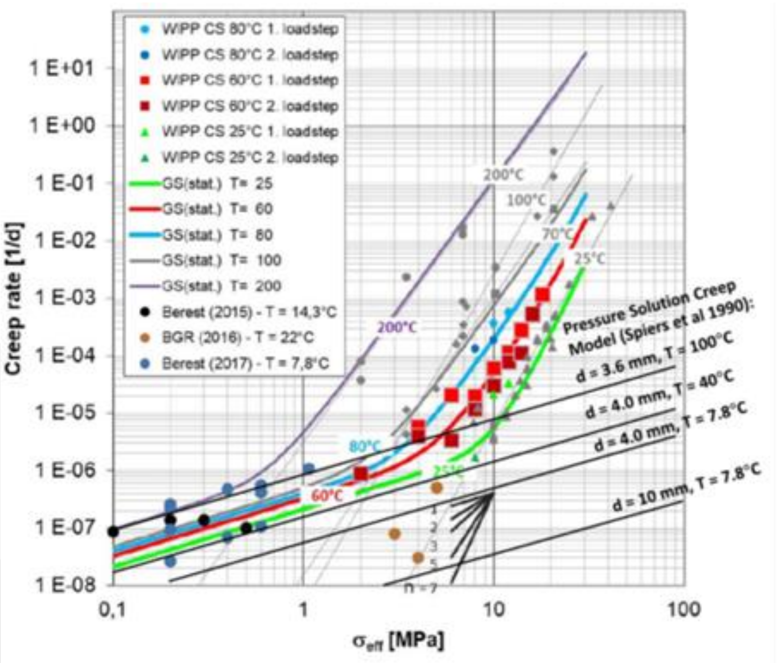
Impact on numerical modelling by 2024



Many codes now account for transition to linear (p-solution) creep at low stress:

- Cavern Closure Consortium / Nobian "SUM Law":

$$\dot{\epsilon} = \dot{\epsilon}_{\mathrm{dc}} + \dot{\epsilon}_{\mathrm{ps}} = A_{\mathrm{dc}} e^{-\frac{Q_{\mathrm{dc}}}{RT}} \sigma_{\mathrm{dev}}^{n} + A_{\text{ps-app}} e^{-\frac{\Delta H_{\text{ps-app}}}{RT}} \sigma_{dev}$$

  Calibrated vs field + geological data !!

- TNO – SUM Law

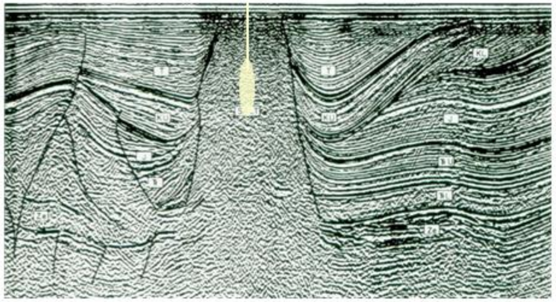
- Reedlunn (2022) SaltMech

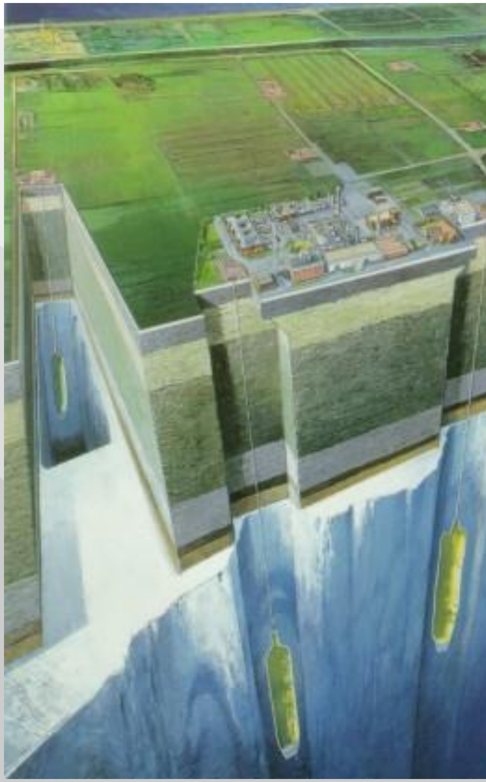
- IfG - Günther-Salzer Law

- Hannover University: Lubby2 (Zapf)

- Ecole des Mines: LeMaitre Law (Blanco-Martin et al 2024) ….and more

Geomechanical modelling needs

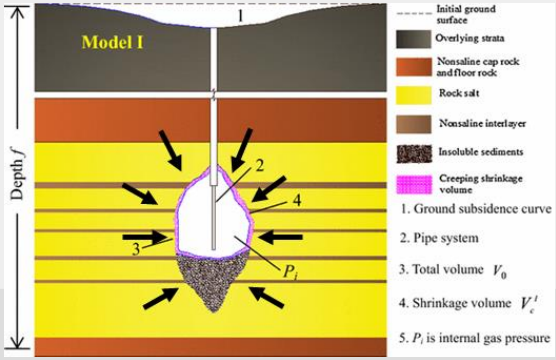


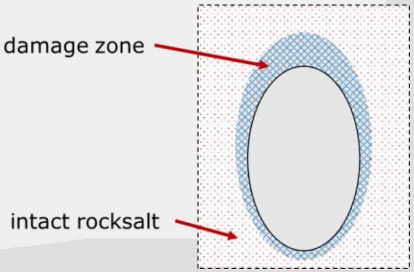


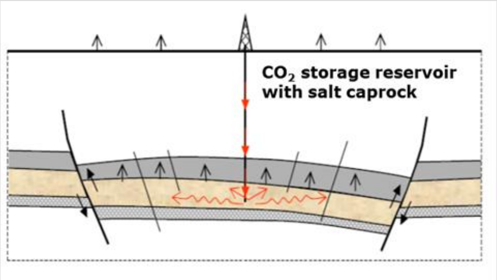
- Creep laws for short and long term

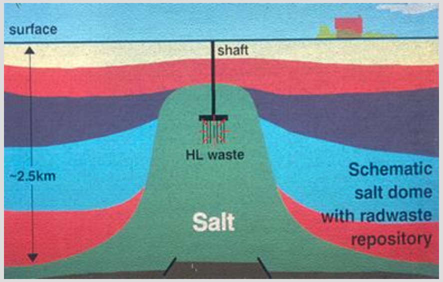
AND

- Damage / permeability / healing laws

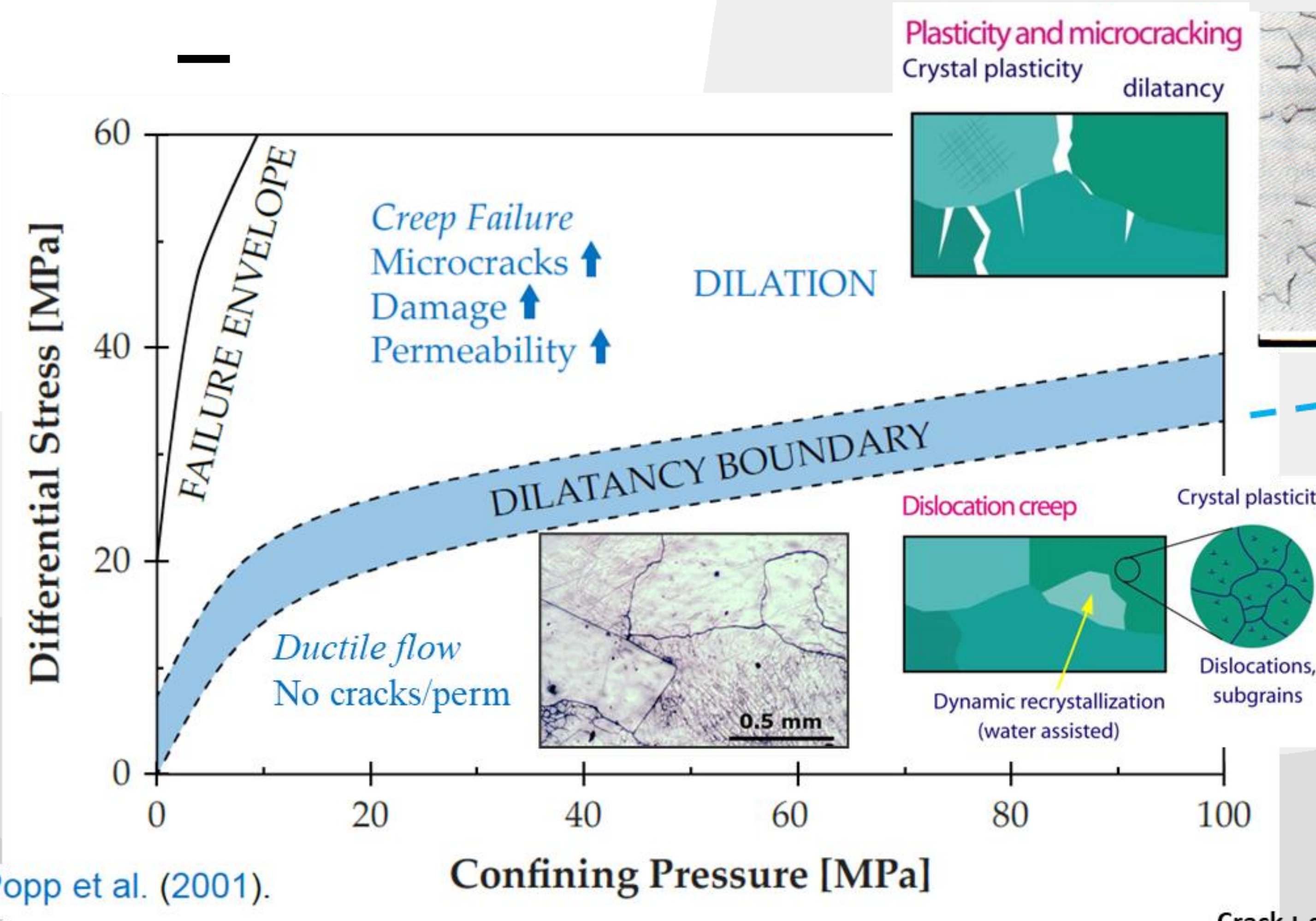




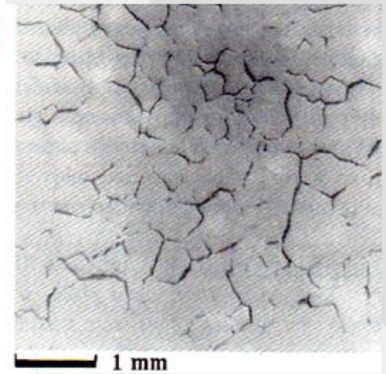


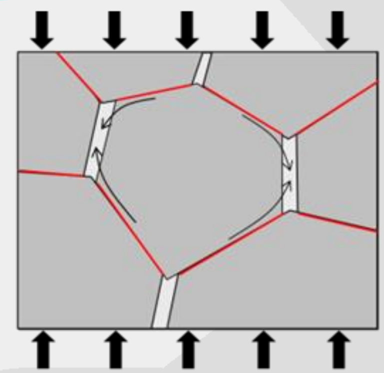


Dilatant Damage – Crucial in cavity walls



Popp et al. (2001).

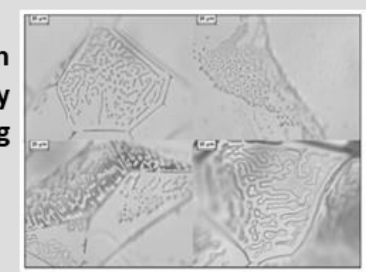




Stress-induced dissolution and precipitation

(Pressure Solution Creep)

Crack + grain boundary healing



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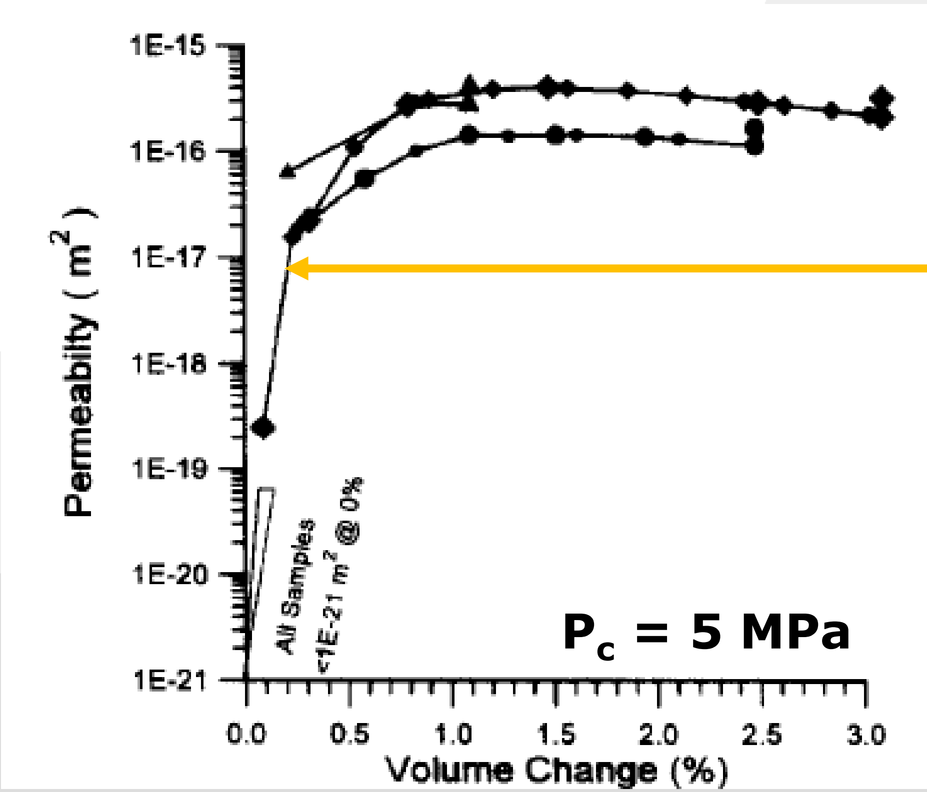
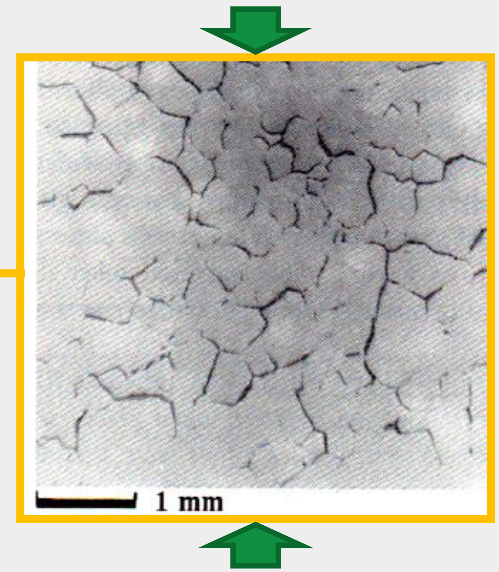
Permeability development: Dilatant field





Peach & Spiers (1996)

Synthetic rocksalt

Room T, 4 x 10^{-5} s^{-1}

- κ ↑ by 4 orders of magnitude @ ΔV = 0.1-0.2%
- ΔV > 0.25% only slight increase in κ

Minor dilatancy → huge increase in permeability

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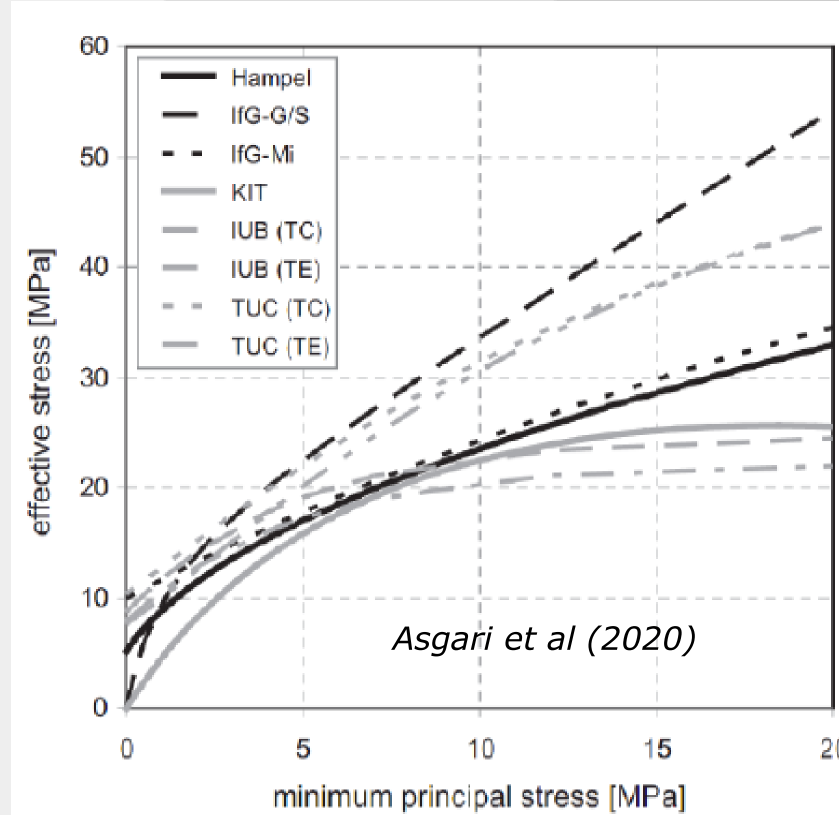
Dilatancy criteria

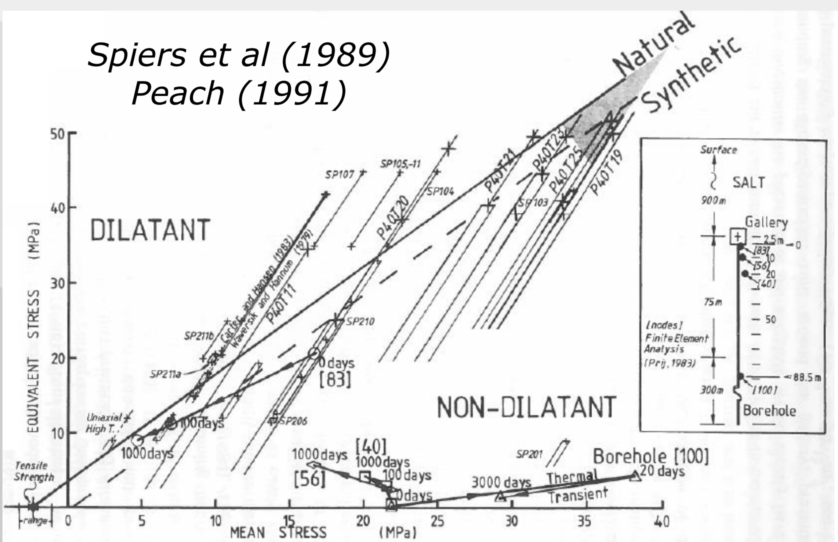
—

- Dilatancy occurs when

$$\sigma_{dev} \geq f(\sigma_{mean}) \quad or \quad \sigma_{dev} \geq g(\sigma_3)$$

- Many models + fits to data
- *Permeability* ↑ by 4-5 orders
- Use $(\sigma_{mean} - P_f)$ at fluid front





Dilatancy safety factor	Spiers et al. [32]	1989	$\sqrt{J_2} = 0.27I_1 + 1.9$
	Ratigan et al. [33]	1991	$\sqrt{J_2} = 0.27I_1$
	Hunsche [34]	1993	$\sqrt{J_2} = -2.286 \times 10^3 \times I_1^2 + 0.351 \times I_1$
	Spiers et al. [32]	2004	$\sqrt{J_2} = 12.04 - 9.104e^{-0.04931I_1}$
	Alkan et al. [35]	2007	$\sqrt{J_2} = \frac{0.54I_1}{1+0.013I_1}$
	Labaune and Rouabhi [36]	2018	$\sqrt{J_2} = 0.25I_1 + 1.44$

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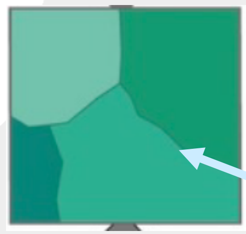
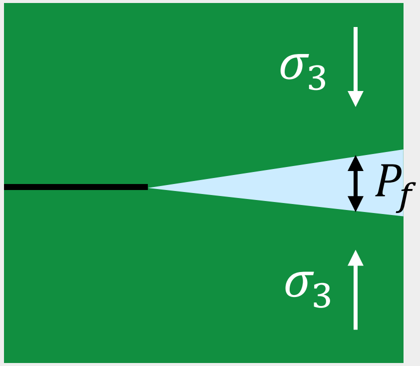
Tensile effective stress criterion

—

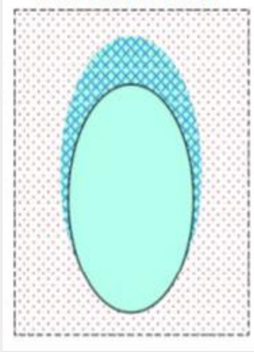
- Gas/brine can penetrate grain boundaries when

$$P_f \geq \sigma_3$$



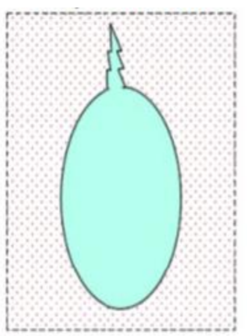


Cavern roof permeation



(e.g. Bérest et al 1999; Rokahr et al 2003; Lux 2005; Minkley et al. 2018)

Hydrofracture



Hydrofracture criterion

$$P_f \geq \sigma_3 + T_0 \leftarrow \textit{tensile strength of salt}$$

All three are accepted stability criteria for cavern ops/closure

All used in latest cavern modelling codes – e.g. CCC

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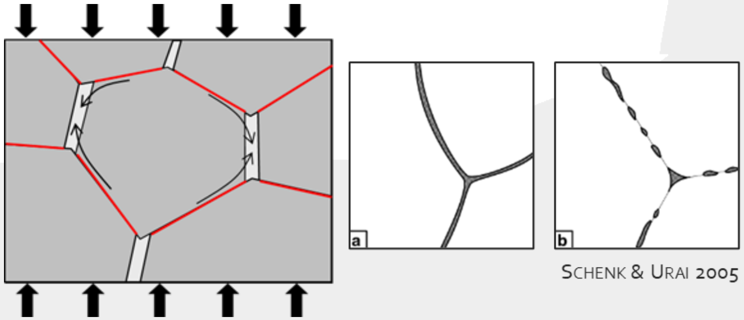
End of story? Not yet

Major advances since 2019 but several issues need resolving in future:

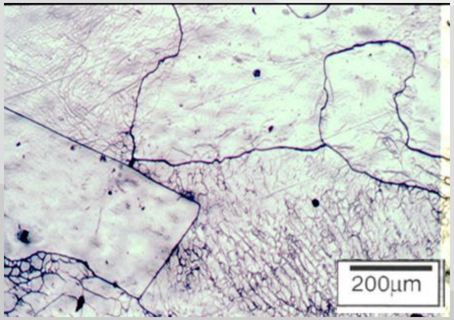
1) Is there a threshold stress for p-solution?



Brine-filled grain boundaries may heal stopping p-solution at very low stresses (< 0.2 MPa?)

Li et al (2012), Van Oosterhout et al (2022)

2) Brine-assisted recrystallization – effects on creep not yet quantified !



Peach et al (2001)

Significant effect on creep at small strains?

(Urai et al, JGR, 1986; Peach et al, JGR, 2001; Urai & Spiers, SaltMechVI, 2007)

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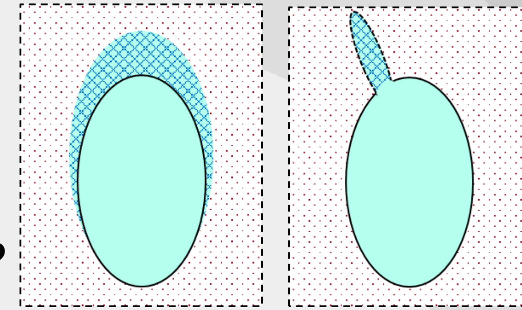
End of story? Not yet

—

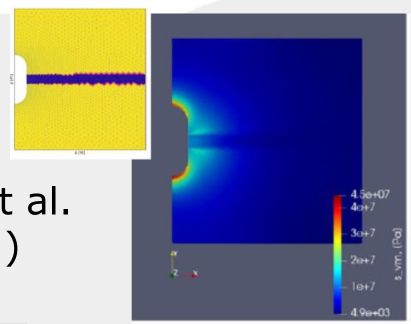
3) Deformation + damage + brine penetration can now be modelled !!

Chemical interactions not yet – feedback effects??

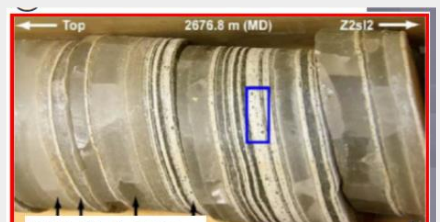


4) Effects of heterogeneities + anisotropy on deformation + permeation?

More work needed



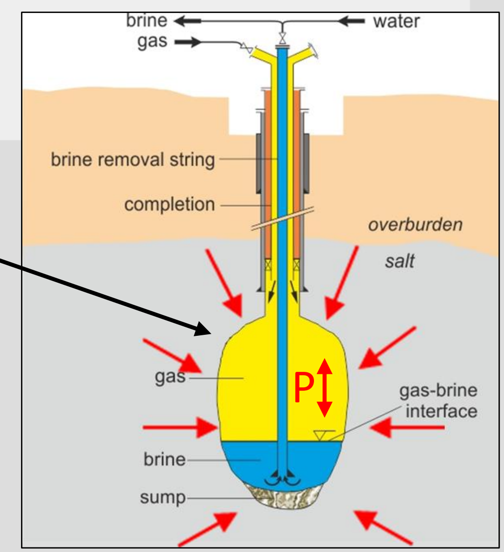
Kumar et al. (2021)



BAS-01 A Core
Biehl et al (2014)

Upscaling ??

5) H_2 storage and CAES: Effects of P-T-RH cycling on damage/permeation



Much lab and modelling research now in progress !!

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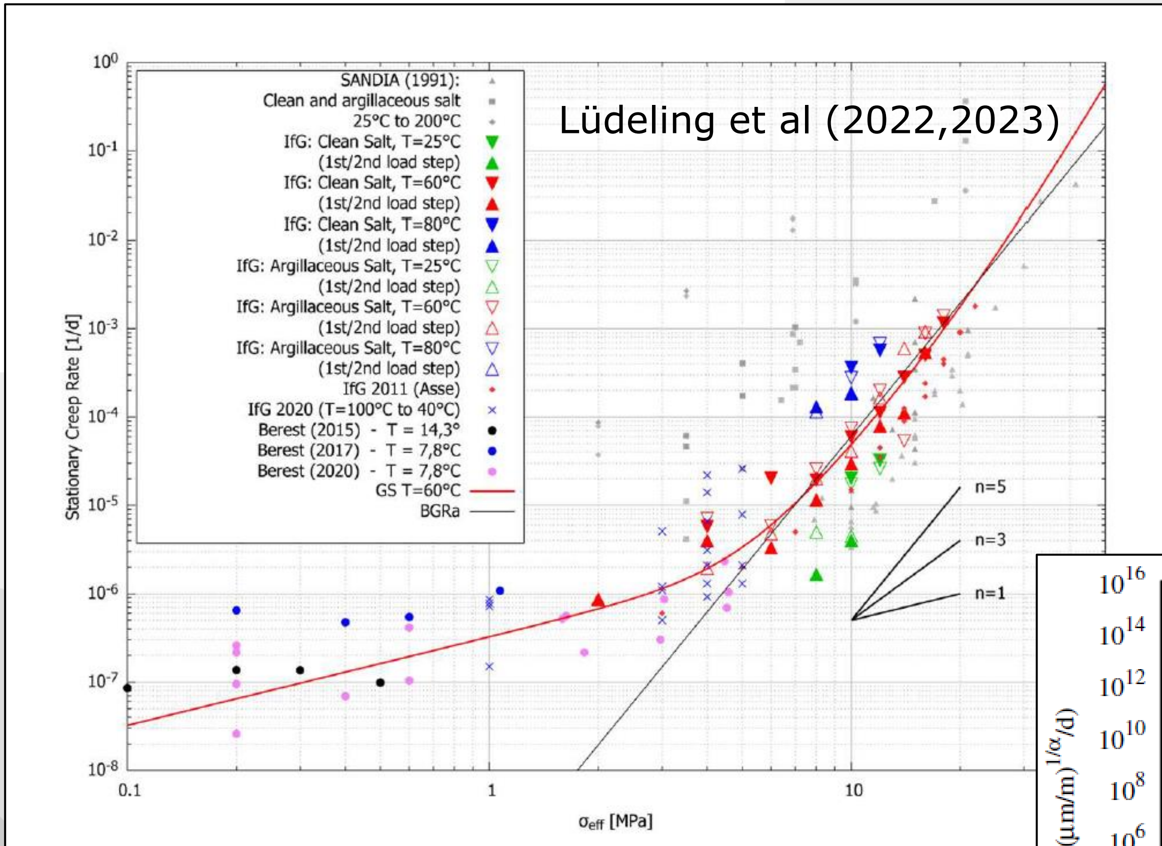
Conclusions

- Much progress in salt mechanics since 2019 (esp. relating to abandonment)
- Now recognized that classical power law creep transitions to linear viscous creep (p-solution) below a few MPa (Lüdeling et al., SMRI,2023)
- Especially important for far field, long term
- Linear p-solution creep plus main physical processes (incl. dilatancy, permeation) now entering cavern modelling (e.g. CCC/Nobian)
- Key: Validation/tuning/upscaling (effective grain size) using field data
- Research still needed on:
    - Threshold stress for p-solution
    - Effects of recrystallization on creep
    - Chemical coupling: damage, permeation and p-solution
    - Effects of heterogeneities / anisotropy … + P-T-Stress-Humidity cycling
- Lab tests: avoid dilatancy + water loss, measure grain size (Lüdeling et al., 2023)

EXTRA SLIDES

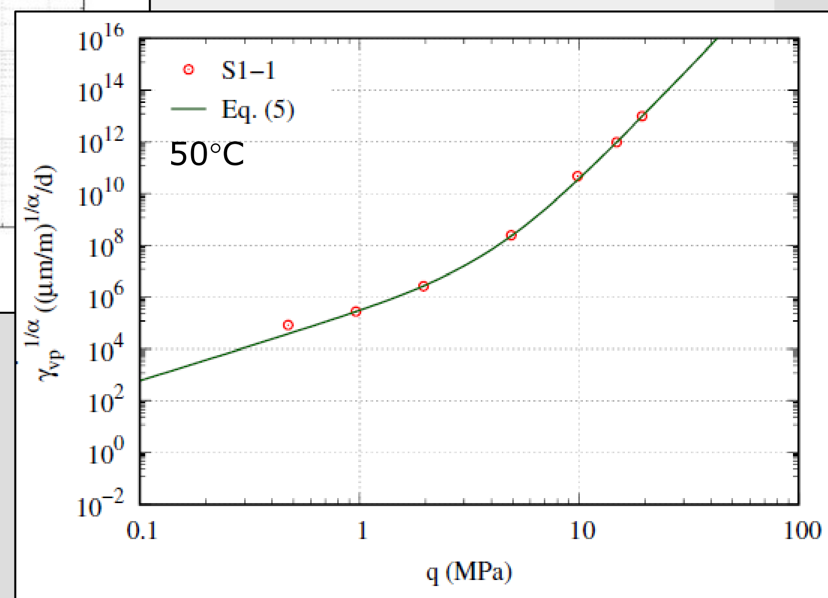
Findings confirmed 2022-2024!



Confined tests

(5-10 MPa)

Blanco-Martin et al. (2024)



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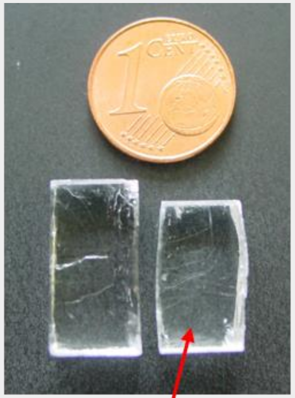
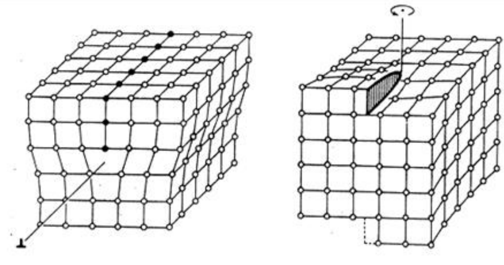
Rocksalt: A fantastic plastic seal

Pressure solution



Crystal plastic deformation

$\{110\}\langle 1\bar{1}0\rangle$ slip

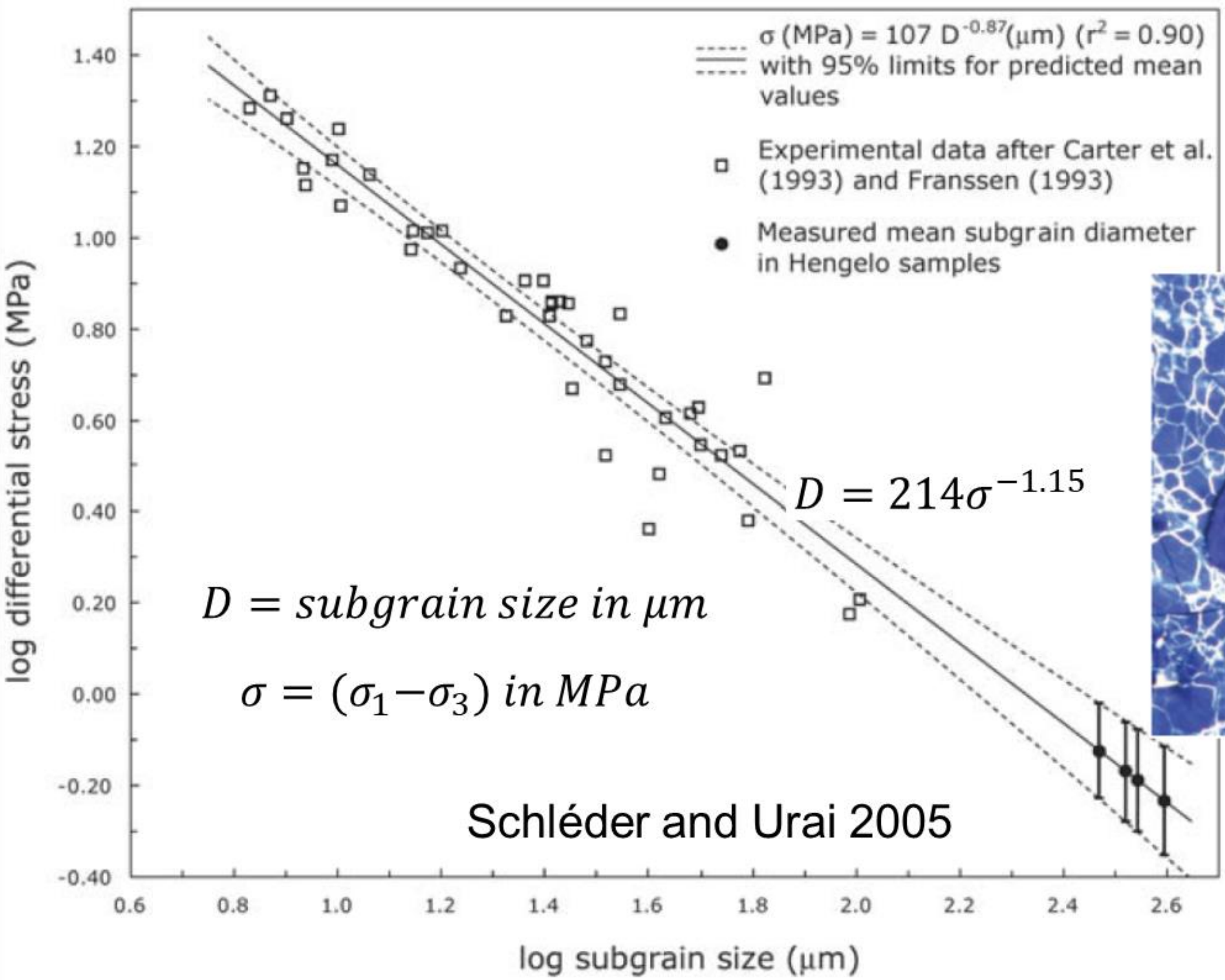


Edge and Screw Dislocations

Low porosity and permeability
High ductility + Low creep resistance
High solubility

Dislocation microstructures and mechanisms

Subgrain size systematically related to diff/dev stress (3-20 MPa):

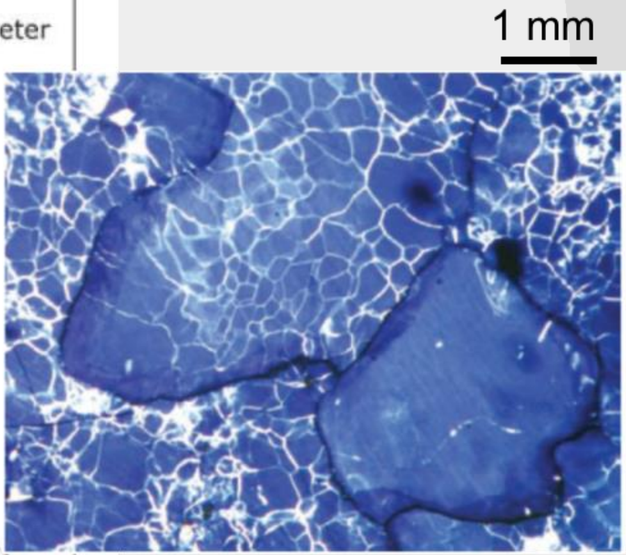


$D = 214\sigma^{-1.15}$

$D = subgrain\ size\ in\ \mu m$

$\sigma = (\sigma_1 - \sigma_3)\ in\ MPa$

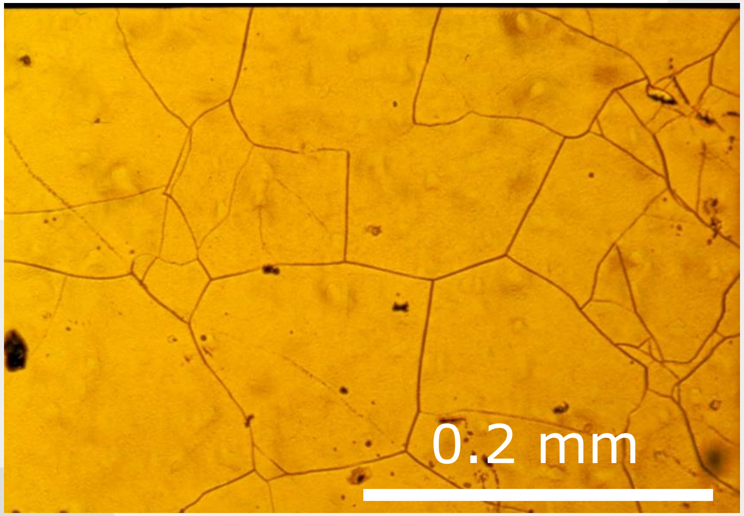
Schléder and Urai 2005

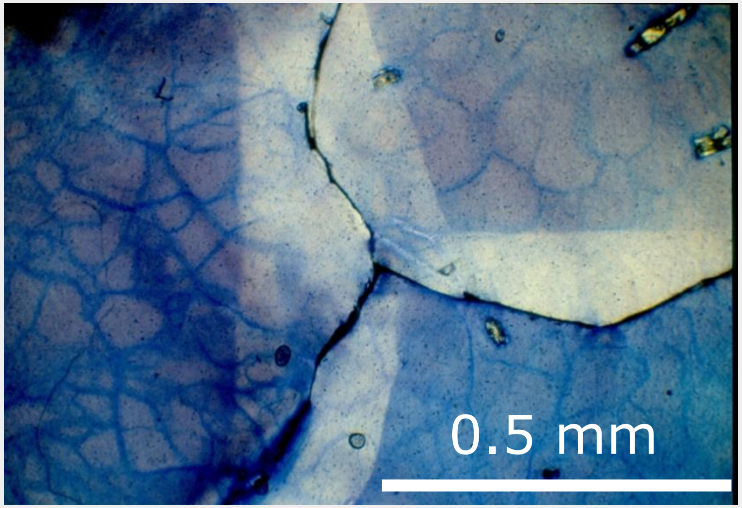


Subgrain size and flow stress recorded in bedded salt, Hengelo NL

SO: What controls creep at low stress?

Naturally deformed salt, Avery Island, USA





Reflection optics - Etched section

Subgrains:
climb controlled disloc creep?

Transmission optics - γ-irradiated

Subgrains:
climb controlled disloc creep?

Overgrowths:
dissolution-precipitation !!

(Spiers & Carter 1998; see Urai et al., 1987 on Asse salt)

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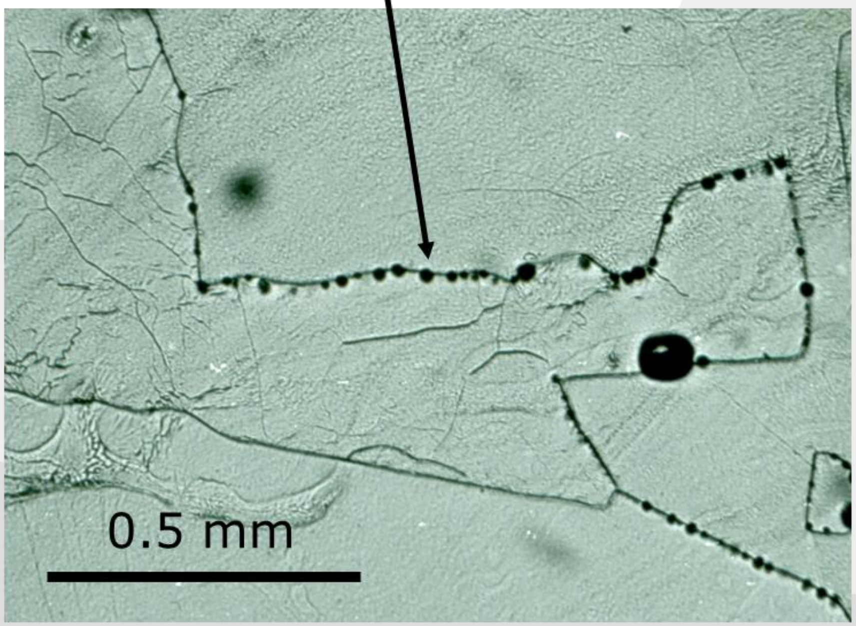
Grain boundaries in salt contain $H_2$0!

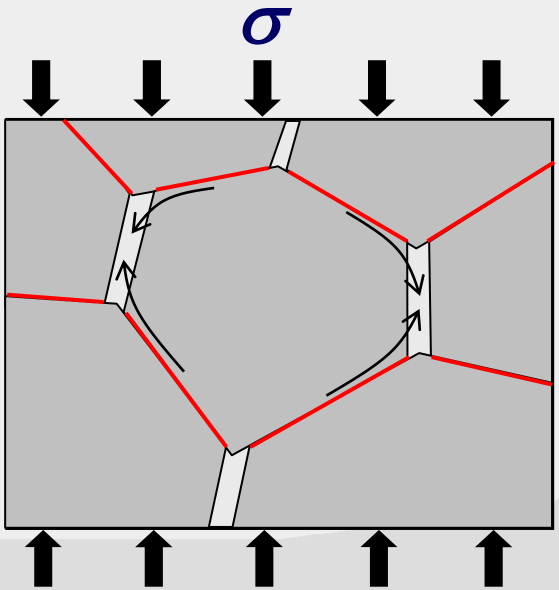
All natural salt contains grain boundary brine inclusions and films



Speizesalz, Asse Mine, Germany

100 ppm water at grain boundaries
+ grain size 5mm $\rightarrow$ 300 nm film

…..so creep by "pressure solution" (n = 1) should be possible…..



$$\dot{\varepsilon} = \frac{A.DCS.\Omega}{RTd^3}\sigma$$

Slow for natural grain size d

e.g. Rutter 1976 Spiers et al. 1990

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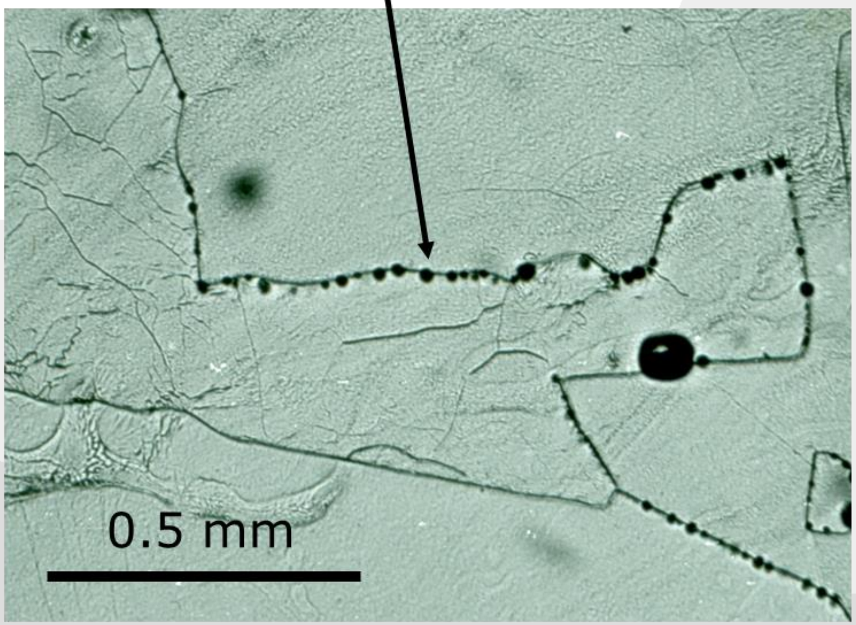
Grain boundaries in salt contain H_20!

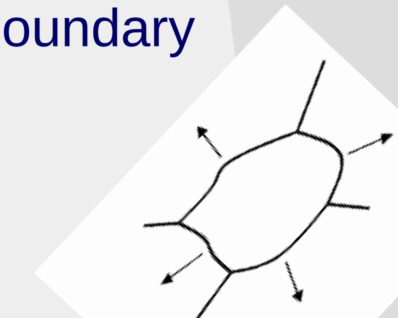
All natural salt contains grain boundary brine inclusions and films

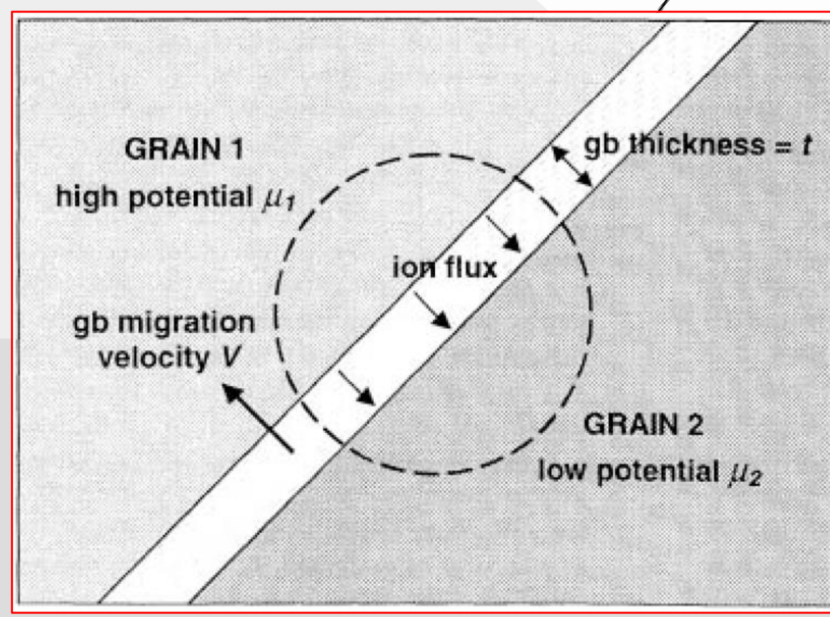


Speizesalz, Asse Mine, Germany

100 ppm water at grain boundaries
+ grain size 5mm $\rightarrow$ 300 nm film

…..and so should fluid-assisted grain boundary migration





(Urai et al, JGR, 1986; Peach et al, JGR, 2001; Urai & Spiers, SaltMechVI, 2007)

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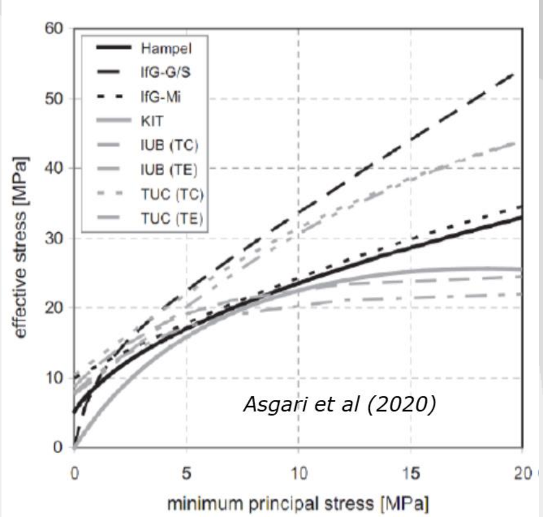
Key question:

—

How does P-T-stress cycling affect damage criteria and creep?



Lab studies to date suggest:

- Little effect of load cycling esp. in the non-dilatant field
- Limited damage enhancement in dilatant field (some cases)
- No effect of T-cycling, but T-gradients can produce damage

Arnold et al., 2011; Bauer et al., 2010, 2011; Bucholz et al., 2017; Düsterloh et al., 2013; Roberts et al., 2015; Song et al. 2013.

More work needed (also on humidity cycling)

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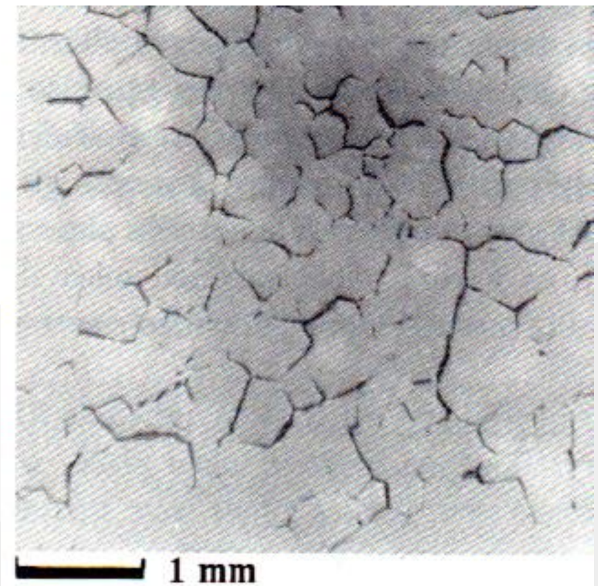
Crack growth vs. water-assisted healing



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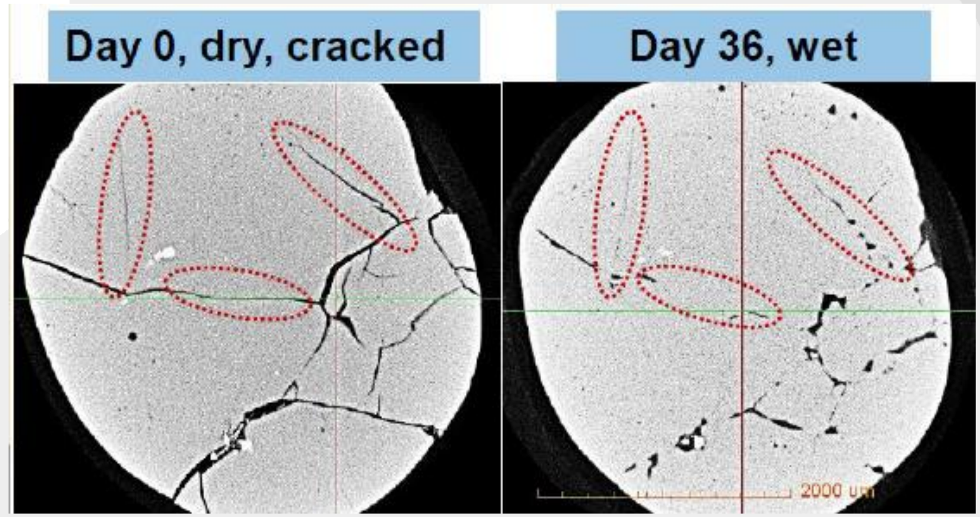
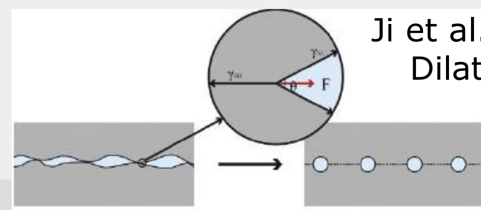


=?

Ji et al. (2022, SaltMech X)
Dilated Leine Steinsalz



Crack opening:
Enhanced by moisture / cycling?

Crack healing promoted by moisture

What is effect on rock strength, dilatancy criterion and permeability??

SUM Law (Spiers-Urai Mechanism-based Law)

$$\dot{\epsilon} = \dot{\epsilon}_{\text{dc}} + \dot{\epsilon}_{\text{ps}} = A_{\text{dc}} e^{-\frac{Q_{\text{dc}}}{RT}} \sigma_{\text{dev}}^{n} + A_{\text{ps-app}} e^{-\frac{\Delta H_{\text{ps-app}}}{RT}} \sigma_{dev}$$

BAS core data & fit

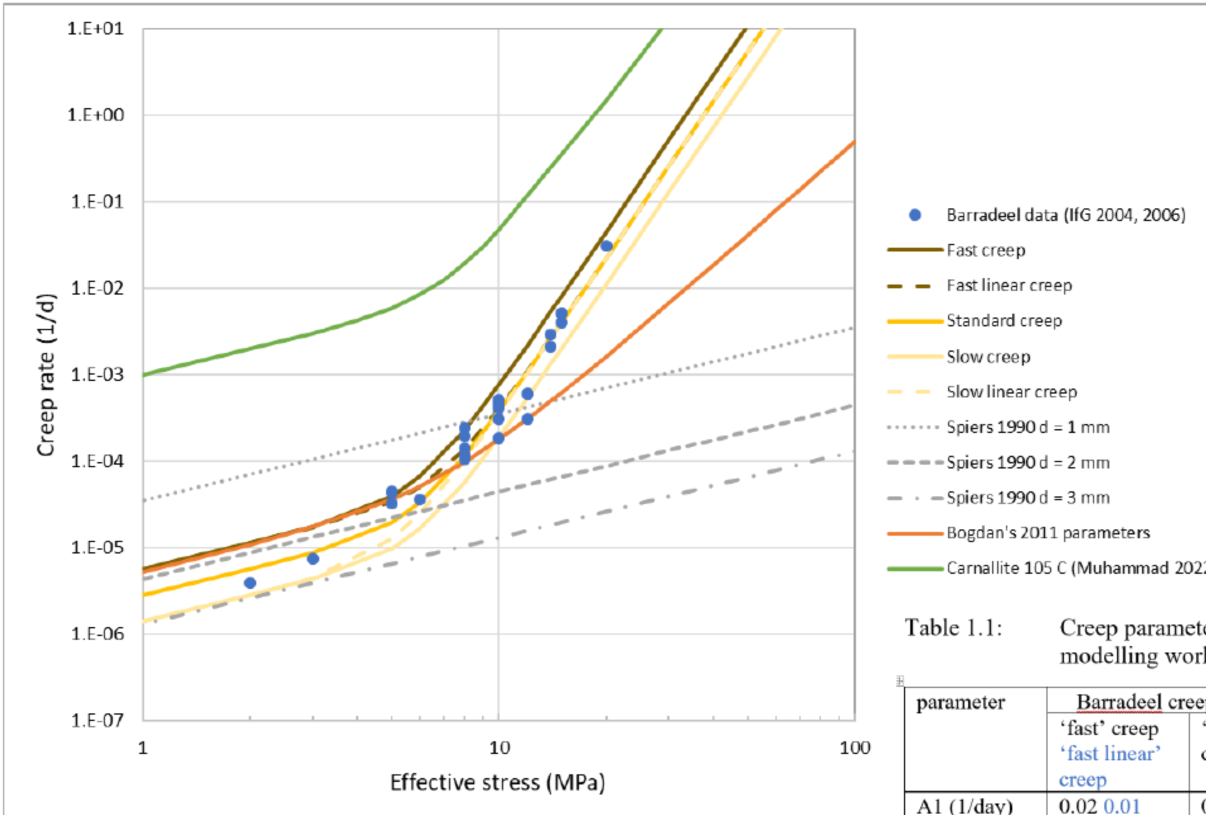


Table 1.1: Creep parameters for curves shown in Figure 1.5 and reported in previous Barradeel modelling work.

parameter	Barradeel creep models used in this study			Breunese et al. (2003[2])*	Orlic (2008-2012[5])	Carnallite** (Muhammad et al., 2022[13])
	'fast' creep 'fast linear' creep	'standard' creep	'slow' creep 'slow linear' creep			
A1 (1/day)	0.02 0.01	0.01	0.005 0.01	1.71	0.85-0.87	5.31
A2 (1/day)	0.016 0.016	0.008	0.004 0.004	1.2E-5 – 14.6E-3	14.8E-3	2.79
n1	6	6	6	3.6	3.6	5.3
n2	1	1	1	1	1	1
Q1/R (K)	6495	6495	6495	6206	6206	6495
Q2/R	3007	3007	3007	3007	3007	3007

* For grain seizes of 1.95-20 mm.

** Assuming the same activation energy as for halite, to extrapolate the carnallite flow law for 70 °C from Muhammad et al. (2022[13]) to higher temperatures.

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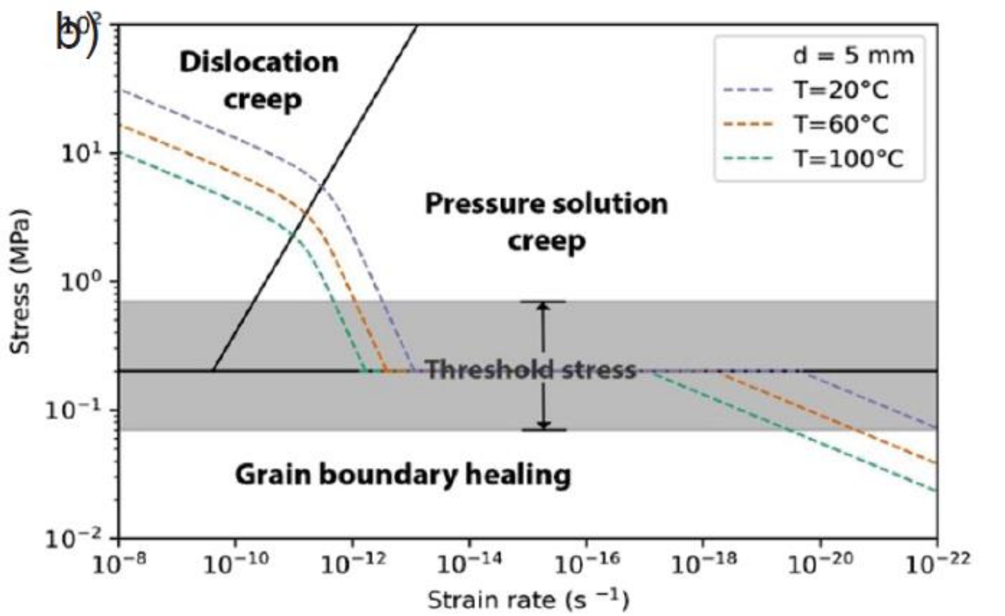
Grain boundary healing at low stress?

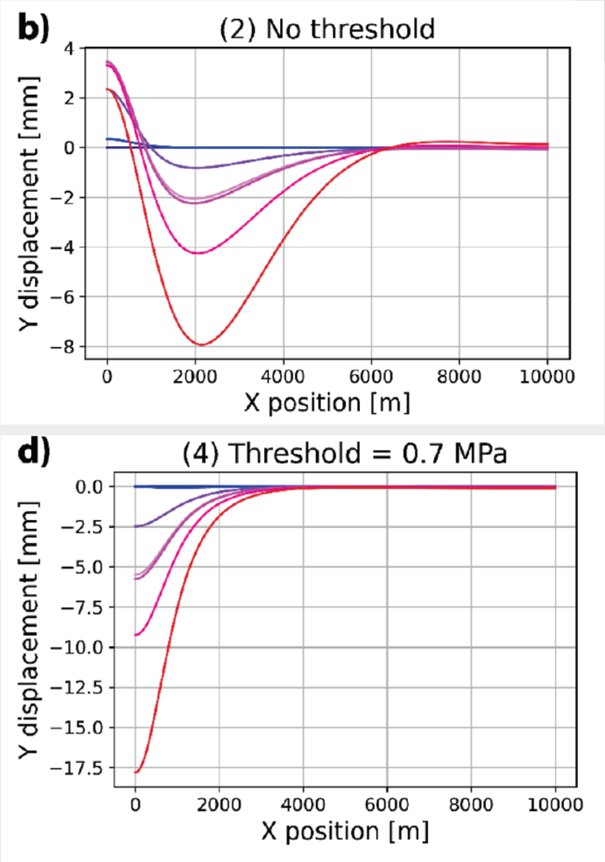
Threshold stress for p-sol in salt - Theory



Van Oosterhout et al (2022)

Theory needs experimental verification !!!

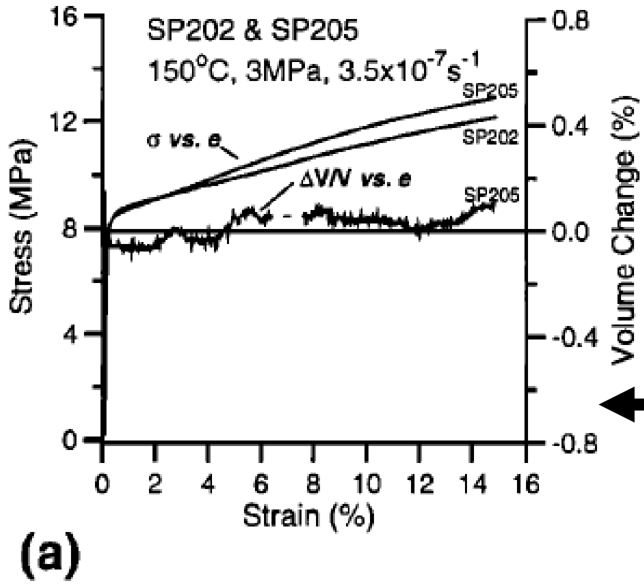
Threshold has large effect on numerical predictions of long term subsidence:

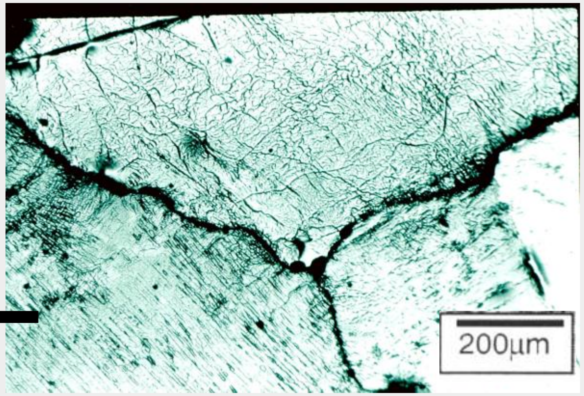


(TNO – Hunfeld et al. 2022)

Peach, Spiers & Trimby (JGR, 2001)

Effect of fliuid-assisted gbm on flow strength: Natural salt (Asse)

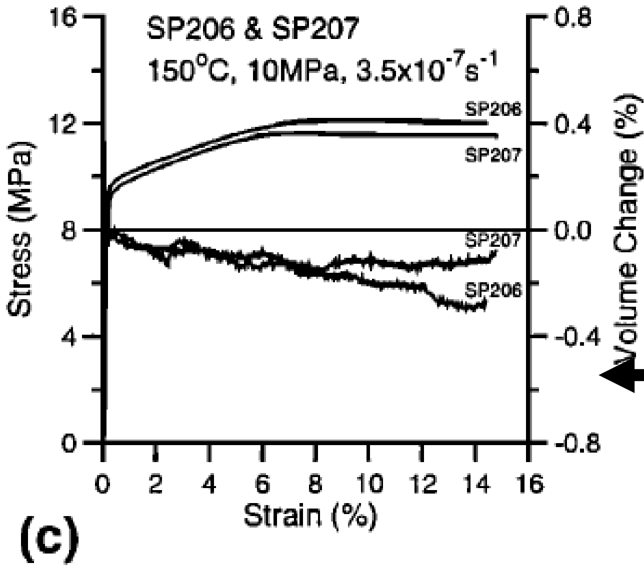


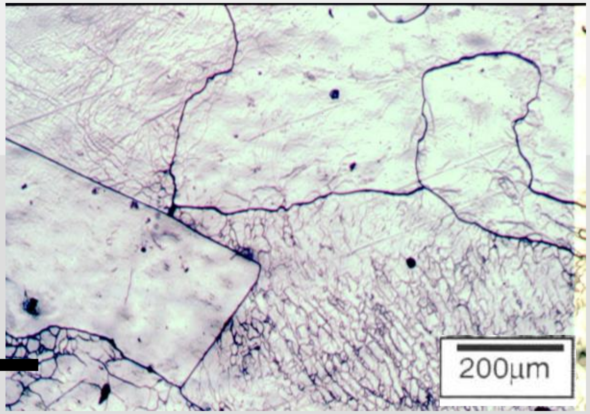


Dilated gb's

No gbm / recrystallization

Work hardening





Non-dilated

Widespread fluid-assisted gbm

Steady state flow beyond 7% strain

Threshold strain 5-10%? Effect on creep law?