Laboratory Tests on WIPP-Salt (Clean salt)

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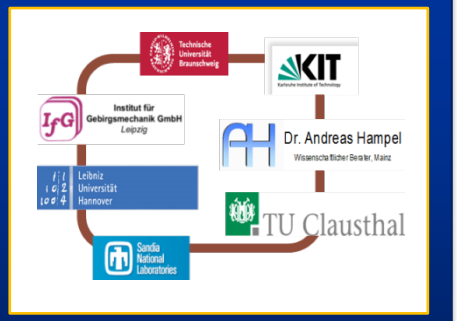


BMWi – Joint Project III: Comparison of current constitutive models salt

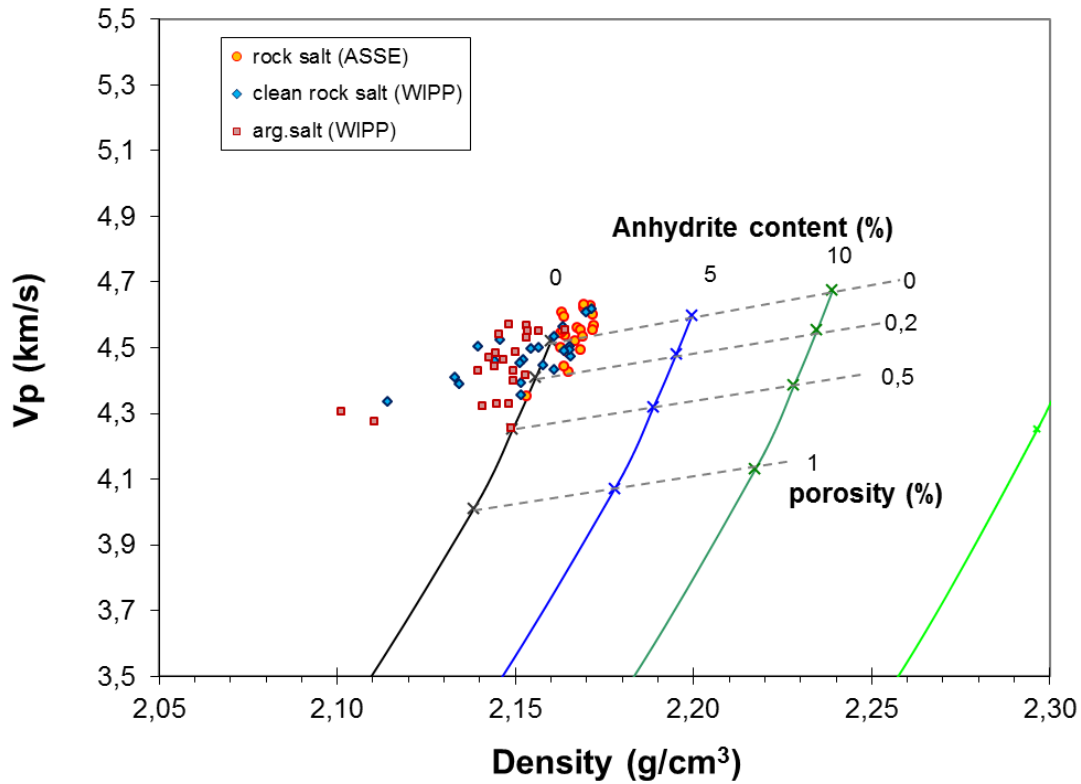
Sandia National Laboratories

Verantwortung für Generationen / Responsibility for Generations DBE TEC DBE TECHNOLOGY GmbH

PTKA Project Management Agency Karlsruhe
Karlsruhe Institute of Technology

- **Petrophyical characterisation**
- **Strength and dilatancy testing**
  - Confining pressure
  - Deformation rate
  - Temperature
- **Creep tests**
  - Creep test procedures
  - Results
- **Permeability-testing**
- **Summary**

Petro-physical characterization



- Clean salt ≈ argillaceous salt, but slightly different to pure „Asse-Speisesalz“:
  - $\rho_{WIPP\text{-}CS} \leq \rho_{Asse\text{-}Salz}$
  - The amount of impurities is very low (< 5%)
  - Initial porosity is low (<0.5%) , i.e. undisturbed salt

VELOCITY-POROSITY RELATIONSHIP

after Wyllie et al., 1956

$$\frac{1}{v_p} = \frac{\phi}{v_f} + \frac{1-\phi}{v_m}$$

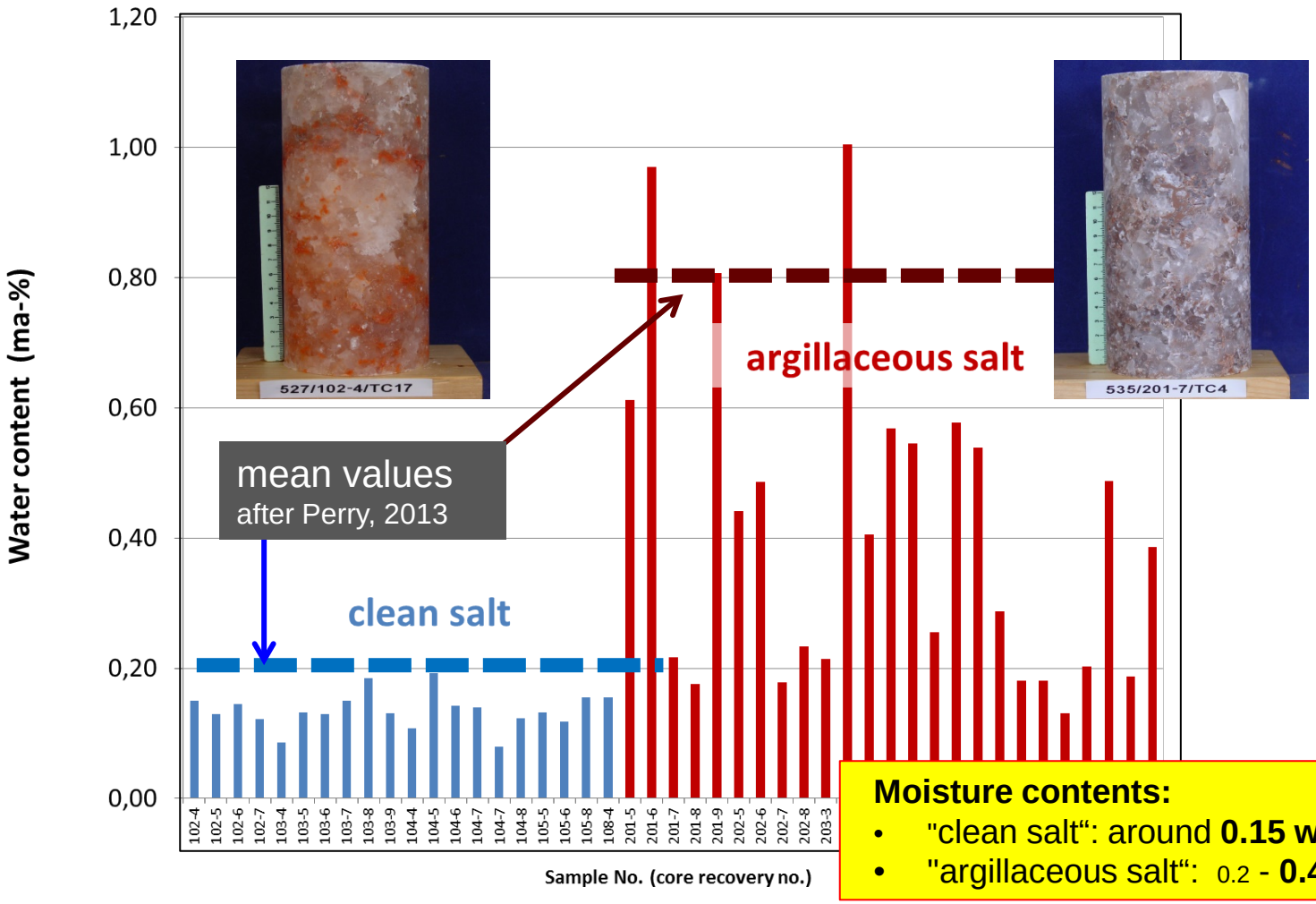
Pore space: air

Matrix: halite (2,16 g/cm³) + Anhydrite (2,96 g/cm³)

v_p- air (km/s) =	0,33
v_p- anydrite (km/s) =	6,05
v_p- halite (km/s) =	4,52

Excellent material!

Water content - drying 24 h 105°C



Moisture contents:

- "clean salt": around **0.15 wt. -%**
- "argillaceous salt": 0.2 - **0.4** - 1.0 **wt. -%**

Triaxial strength / onset of dilatancy

Factors influencing relevant failure strength and dilatancy strength

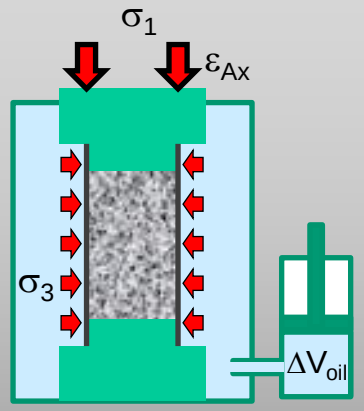
- Confining pressure
- Deformation rate
- Temperature

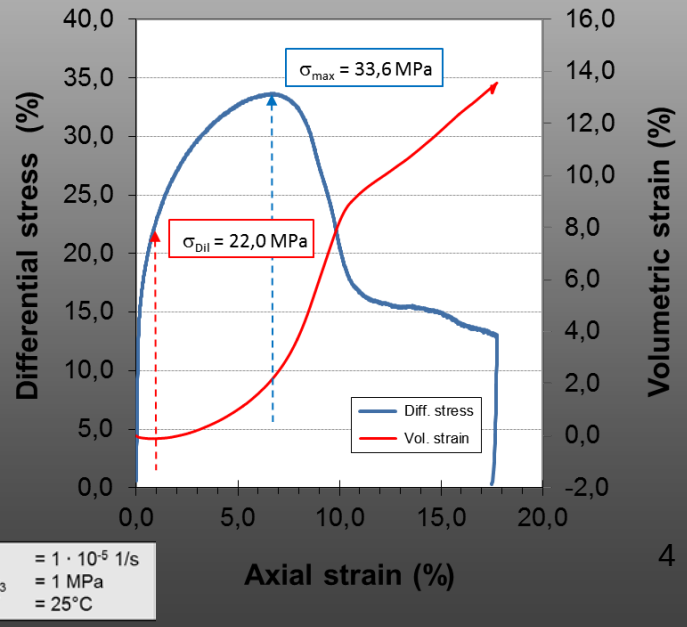
T	Eps-rate	σ_3 (MPa)							Σ CS
25°C	10^{-5} 1/s	0,2	0,5	1,0	2,0	3,0	5,0	20,0	7
60°C	10^{-5} 1/s	0,2	0,5	1,0	2,0	3,0	5,0	20,0	7
100°C	10^{-5} 1/s	0,2	0,5	1,0	2,0	3,0	5,0	20,0	7
25°C	10^{-6} 1/s	0,2	0,5	1,0	2,0	3,0	5,0	20,0	7
25°C	10^{-4} 1/s	0,2	-	1,0	2,0	-	5,0	20,0	5
								Σ Standard tests	33

Triaxial strength testing – state of art

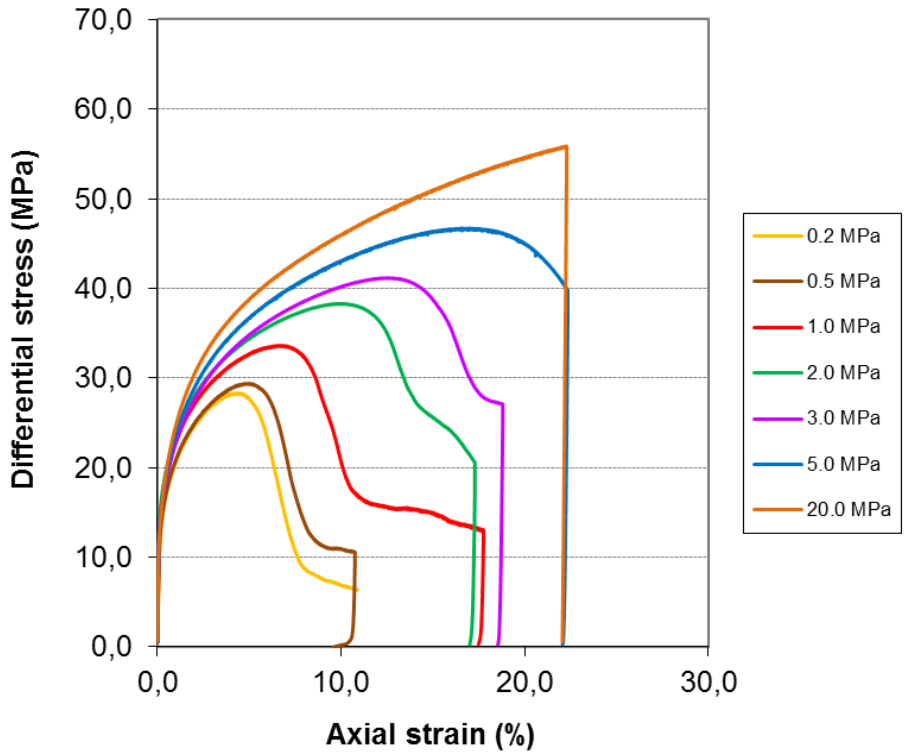
Strain-rate-controlled deviatoric deformation in a triaxial Kármán-cell

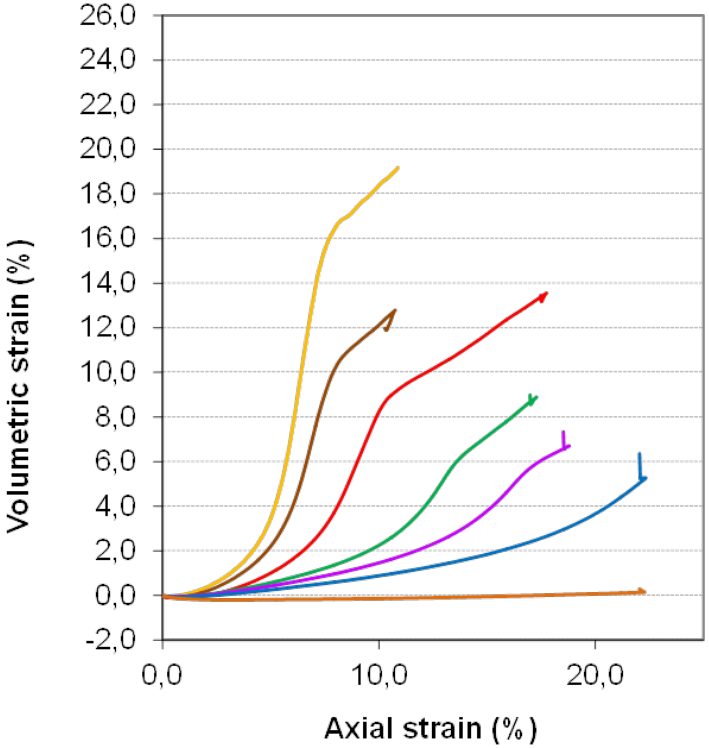
$\sigma_1 > \sigma_3$
$\Delta\sigma = f(\varepsilon_1)$
$\Delta V/V = f(\varepsilon_1)$





Triaxial strength tests ($1 \cdot 10^{-5} s^{-1}$, 25°C)

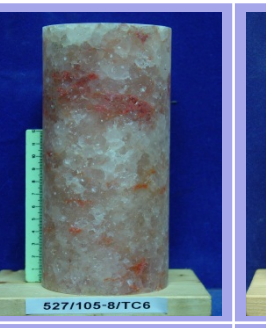
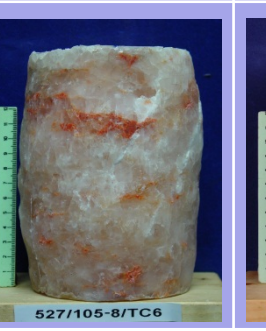




WIPP-site, clean rock salt; TC test @ room temperature and strain rate 1*E-05s^{-1}

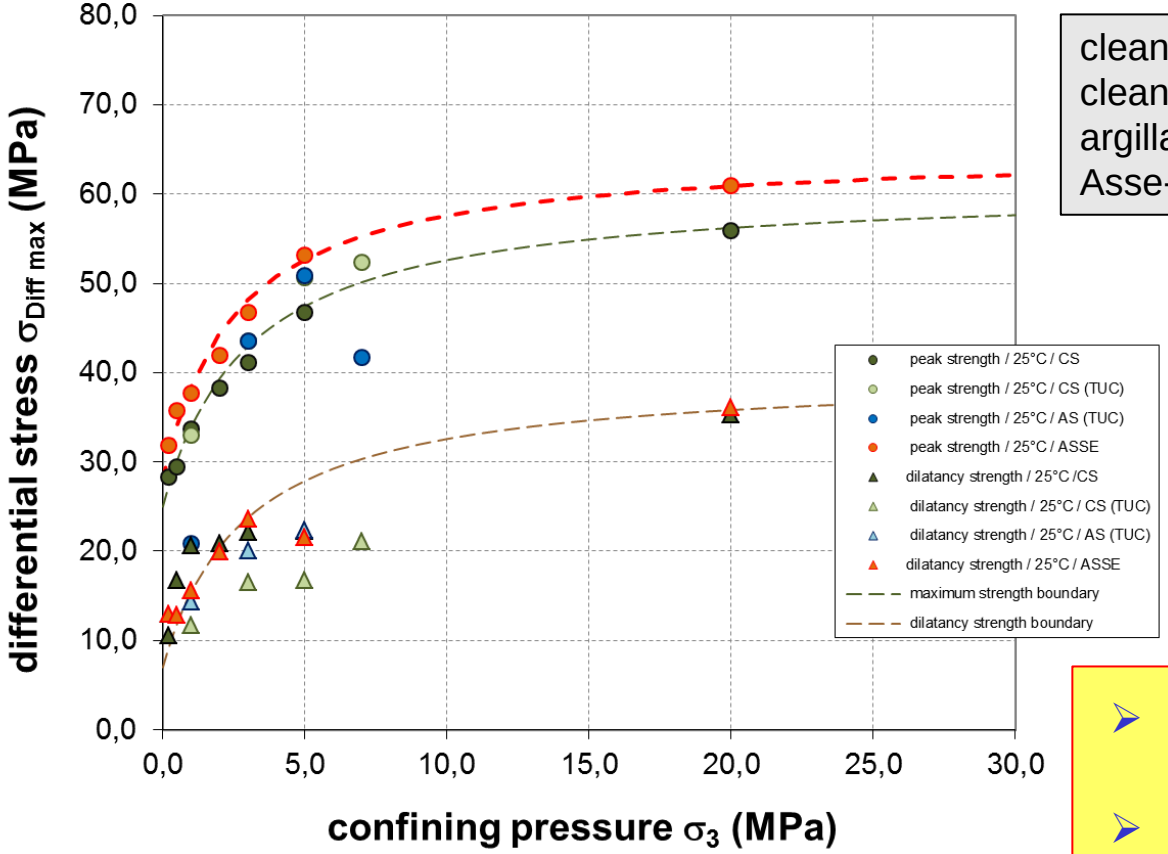
brittle ⇔ semi-brittle ⇔ ductile

Triaxial strength tests ($1 \cdot 10^{-5} s^{-1}$, 25°C)

0.2 MPa	0.5 MPa	1.0 MPa	2.0 MPa	3.0 MPa	5.0 MPa	20.0 MPa
						
						

brittle ⇔ semi-brittle ⇔ ductile

Strength testing - reliability of test results - Reference Asse-Speisesalz



clean salt	- large cores (IfG)
clean salt	- small cores (TUC)
argillaceous salt	- small cores (TUC)
Asse-Salz	- (Joint Project III)

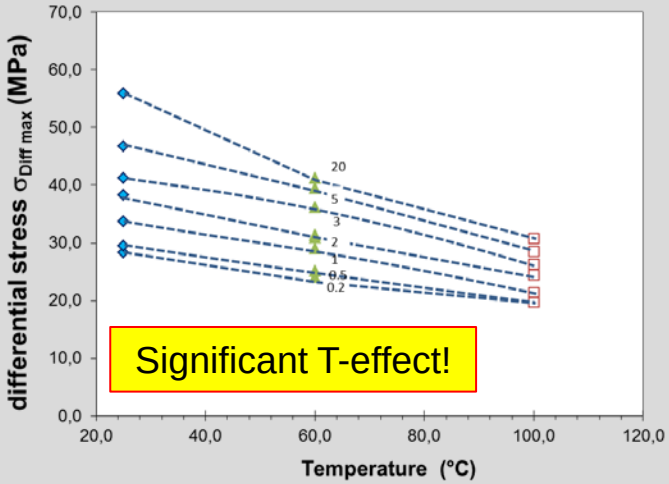
$$\sigma_{Diff,max} = \sigma_D + \frac{\sigma_{MAX} - \sigma_D}{\sigma_\phi + \sigma_3}\sigma_3$$

σ_D	σ_{MAX}	σ_ϕ
28	65	2,5
25	60,3	3
7	40	7

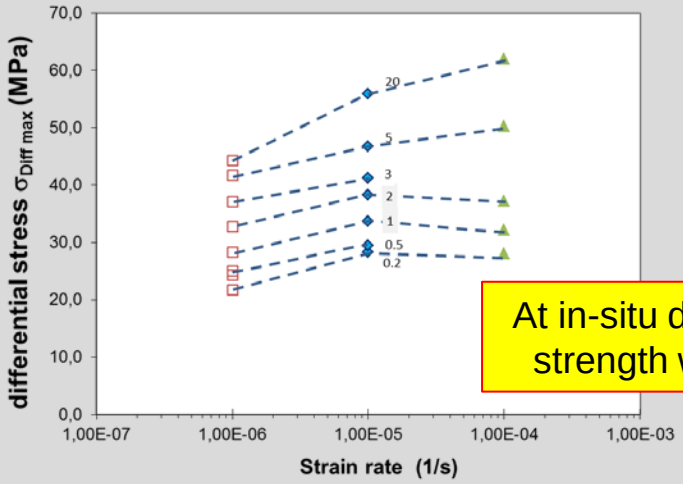
- Reliability of strength results depends on core quality
- Strength: slightly lower than for Asse salt
- Argillaceous salt (AS) higher scattering but comparable to CS
- Dilatancy boundary similar

Factors influencing relevant salt properties - Temperature / deformation rate

Strength

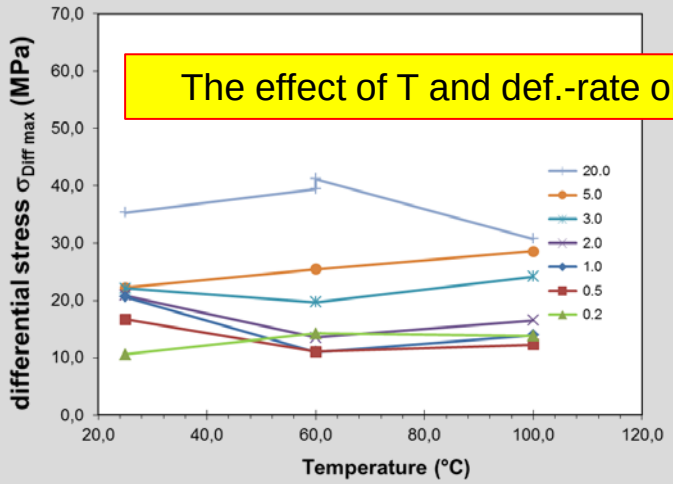


Significant T-effect!

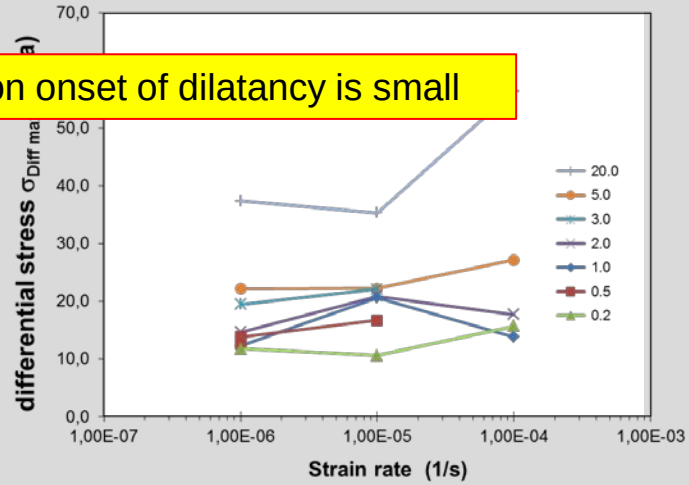


At in-situ deformation rates strength will be reduced!

Dilatancy



The effect of T and def.-rate on onset of dilatancy is small



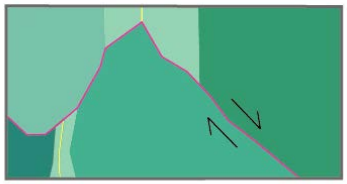
The challenge ..., how deforms the salt in the long term?

Boundary conditions:

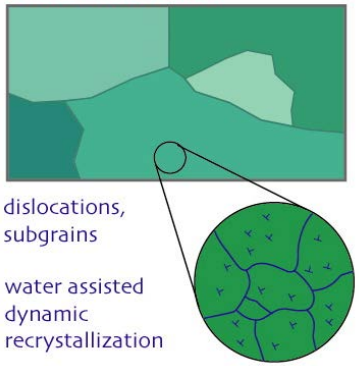
Fore cast period:	10^3 < time (years) < 10^6
Deformations:	$0.1 < \varepsilon < 1$
Temperatures:	20°C - 200°C
Def. Rates:	$3 \cdot 10^{-14} < \varepsilon\ (1/s) < 3 \cdot 10^{-11}$

Creep mechanisms:

Pressure solution creep vs. dislocation creep



grain boundary sliding, dissolution precipitation, no Xtal plasticity

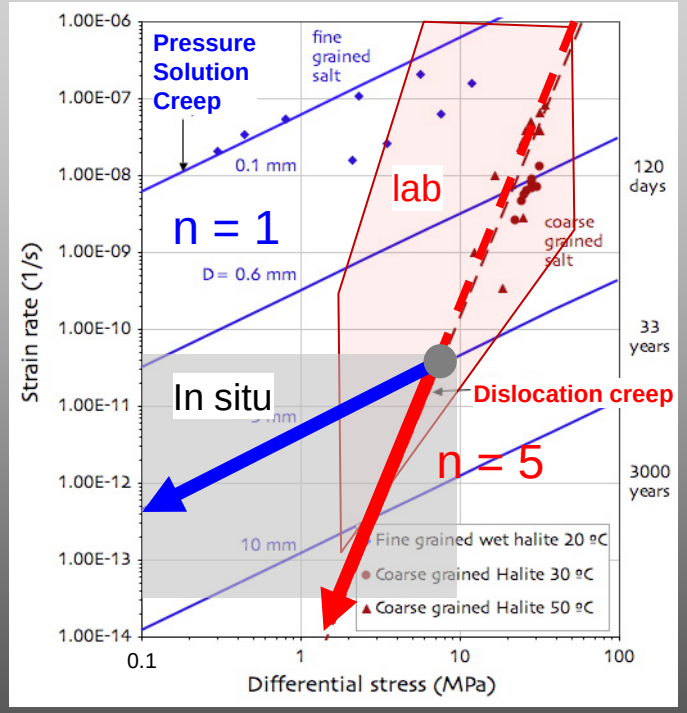


dislocations, subgrains

water assisted dynamic recrystallization

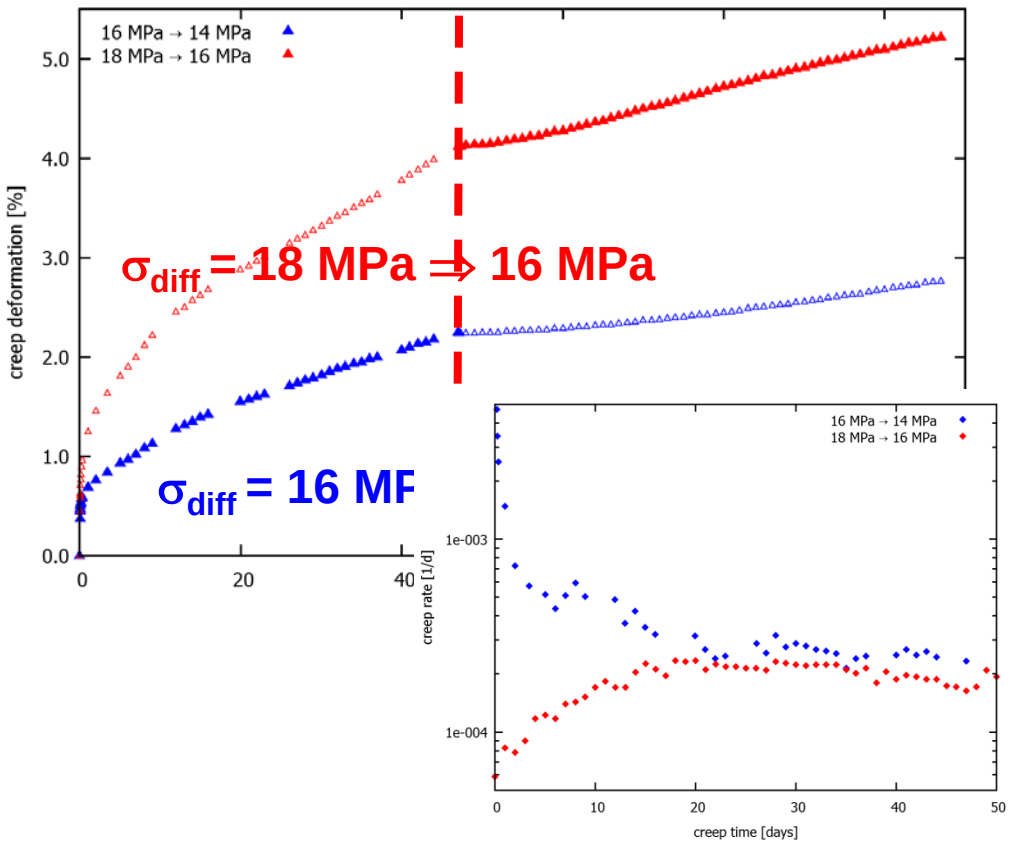
☹ ***Test duration is usually limited!***

Deformation-mechanism map



modified after Urai, 2012

Improved creep test procedures



Details: Günther, R.-M., Salzer, K., Popp, T. and Lüdeling, C., 2014. Steady state-creep of rock salt - Improved Approaches for Lab Determination and Modeling to describe transient, stationary and accelerated creep, dilatancy and healing. 48th U.S. Rock Mechanics Symposium, Minneapolis, Utah, USA, June 1 - 4, 2014. ARMA 14-7051.

IfG approach

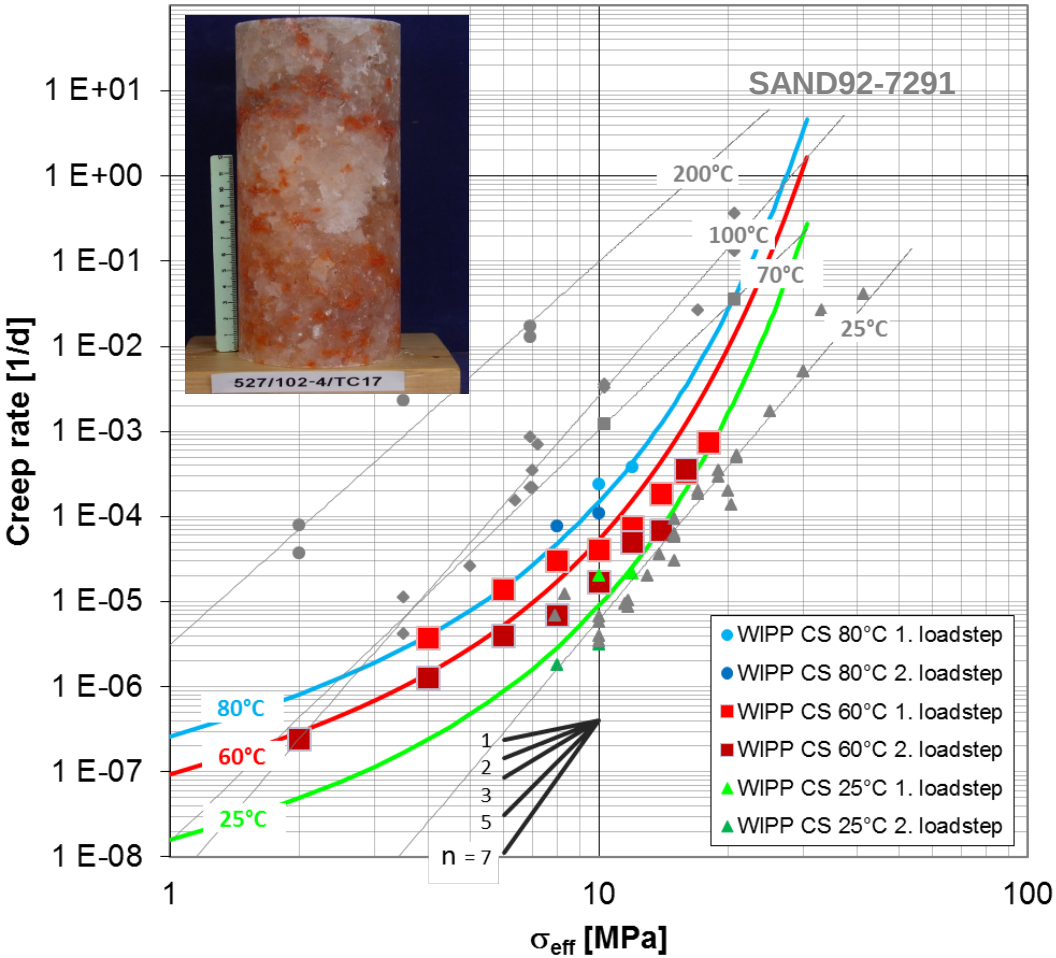
1. Raise temperature to e.g. 333 K (60°C) to speed up process and to involve recovery processes.
2. Use series of two-step tests with unloading, e.g.

(I.) σ_{diff} **= 16 MPa ⇒ 14 MPa,**
(II.) σ_{diff} **= 18 MPa ⇒ 16 MPa**

- transient and inverse transient creep **at 16 MPa**
- upper and lower bound on steady-state creep rate

3. Temperature stepping tests for the activation energy

Creep behaviour of clean salt – 25°C, 60°C, 80°C

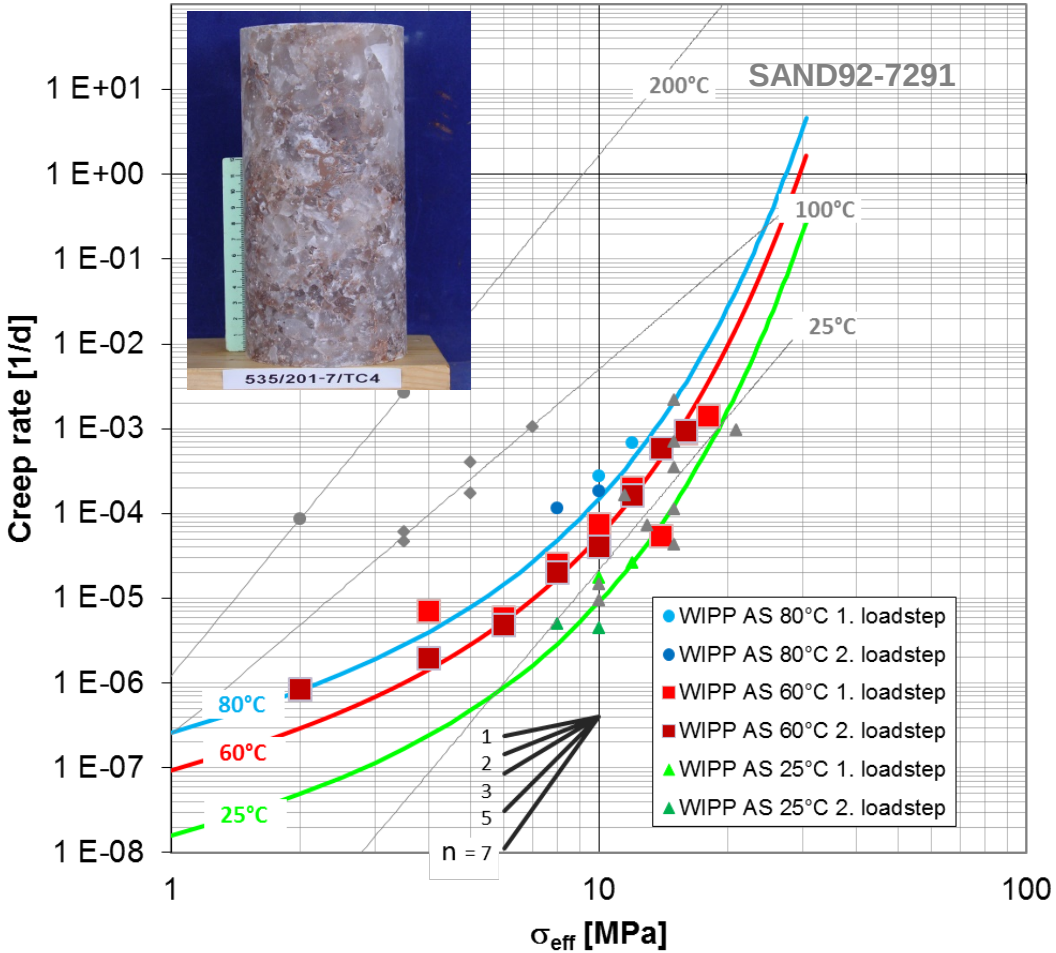


- Consistent data sets, but differences to earlier measurements (SAND92-7291) are obvious
- Mechanism change depending on stress state

IfG-Creep data sets (CS)

Creep test no.	σ_1 (MPa)	σ_3 (MPa)	$\Delta\sigma$ (MPa)	Duration (d)	T (°C)	creep rate (1/d)
Experimental data						
1 TCC1	30	20	10	50	24	2,04E-05
	28	20	8	50	24	1,81E-06
1a TCC3	30	20	10	50	24	1,43E-05
	28	20	8	50	24	3,39E-06
2 TCC5	32	20	12	50	24	2,16E-05
	30	20	10	50	24	3,12E-06
3 TCC15	24	20	4	50	60	3,68E-06
	22	20	2	50	60	2,43E-07
4 TCC13	26	20	6	50	60	1,37E-05
	24	20	4	50	60	1,26E-06
5 TCC6	28	20	8	50	60	1,94E-05
	26	20	6	50	60	3,31E-06
6 TCC2	30	20	10	50	60	4,05E-05
	28	20	8	50	60	6,80E-06
6a TCC4	30	20	10	50	60	1,67E-04
	28	20	8	50	60	5,63E-05
7 TCC7	32	20	12	50	60	7,42E-05
	30	20	10	50	60	1,70E-05
8 TCC9	34	20	14	50	60	1,86E-04
	32	20	12	50	60	4,92E-05
9 TCC11	36	20	16	50	60	3,29E-04
	34	20	14	50	60	6,85E-05
10 TCC12	38	20	18	50	60	7,50E-04
	36	20	16	50	60	3,62E-04
11 TCC16	30	20	10	50	80	2,41E-04
	28	20	8	50	80	7,74E-05
12 TCC19	32	20	12	50	80	3,76E-04
	30	20	10	50	80	1,09E-04

Creep behaviour of argillaceous salt – 25°C, 60°C, 80°C

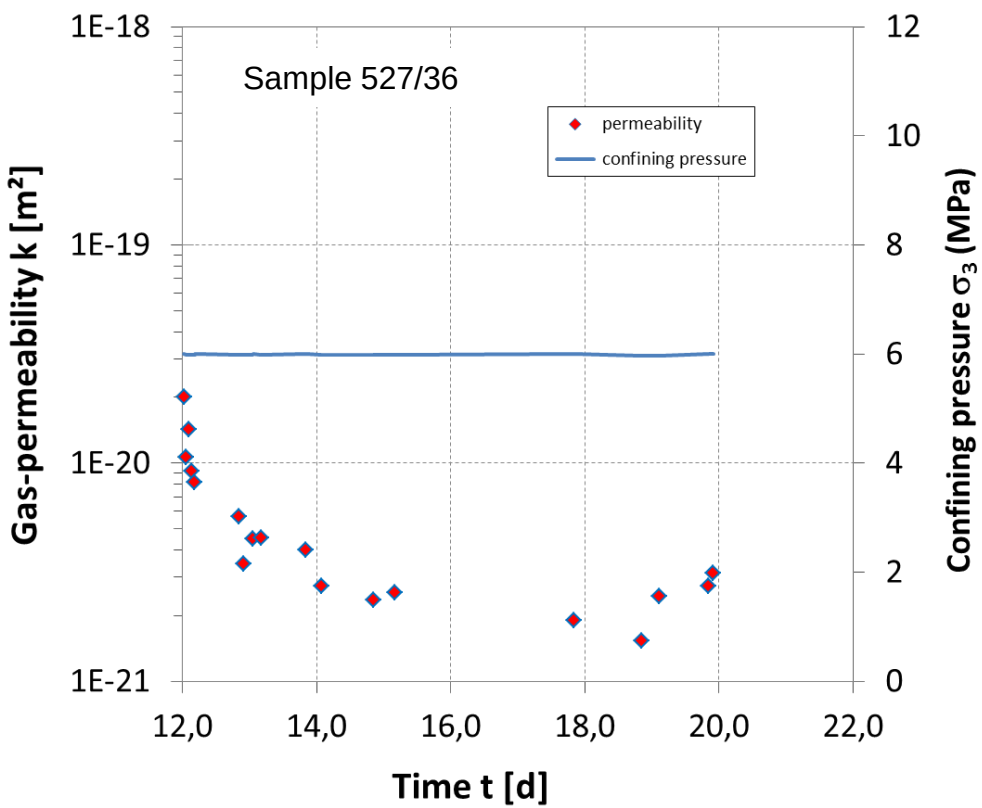


IfG-Creep data sets (AS)

Creep test no.	σ_1 (MPa)	σ_3 (MPa)	$\Delta\sigma$ (MPa)	Duration (d)	T (°C)	creep rate (1/d)
Experimental data						
TCC9	30	20	10	50	25	1,75E-05
	28	20	8	50	25	4,98E-06
TCC10	32	20	12	50	25	2,61E-05
	30	20	10	50	25	4,49E-06
TCC1	24	20	4	50	60	7,08E-06
	22	20	2	50	60	8,52E-07
TCC2	26	20	6	50	60	5,87E-06
	24	20	4	50	60	1,94E-06
TCC3	28	20	8	50	60	2,57E-05
	26	20	6	50	60	4,77E-06
TCC4	30	20	10	50	60	7,45E-05
	28	20	8	50	60	2,00E-05
TCC5	32	20	12	50	60	2,00E-04
	30	20	10	50	60	4,10E-05
TCC6	34	20	14	50	60	5,39E-05
	32	20	12	50	60	1,64E-04
TCC7	36	20	16	50	60	8,82E-04
	34	20	14	50	60	5,95E-04
TCC8	38	20	18	50	60	1,40E-03
	36	20	16	50	60	9,24E-04
TCC11	30	20	10	50	80	2,79E-04
	28	20	8	50	80	1,14E-04
TCC12	32	20	12	50	80	6,78E-04
	30	20	10	50	80	1,84E-04

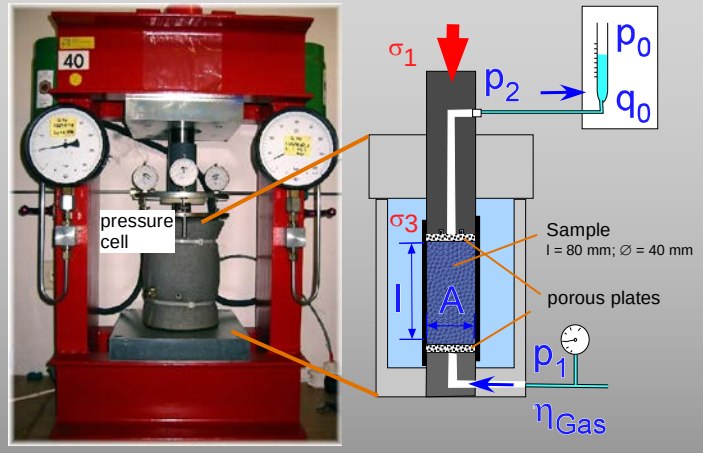
- Argillaceous salt creeps slightly faster (2x) than Clean Salt
- Generally WIPP-salt creeps faster than Asse Salt

Tightness of the geological barrier – permeability testing



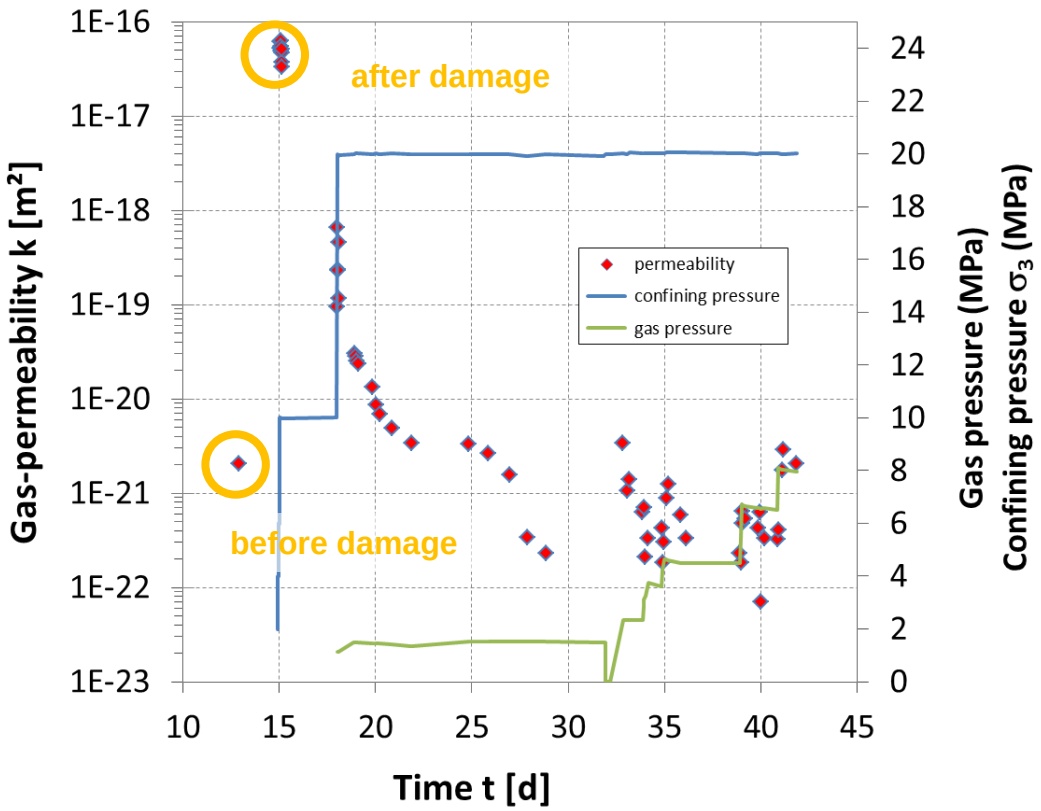
The permeability of the intact salt is very low!

Experimental setup



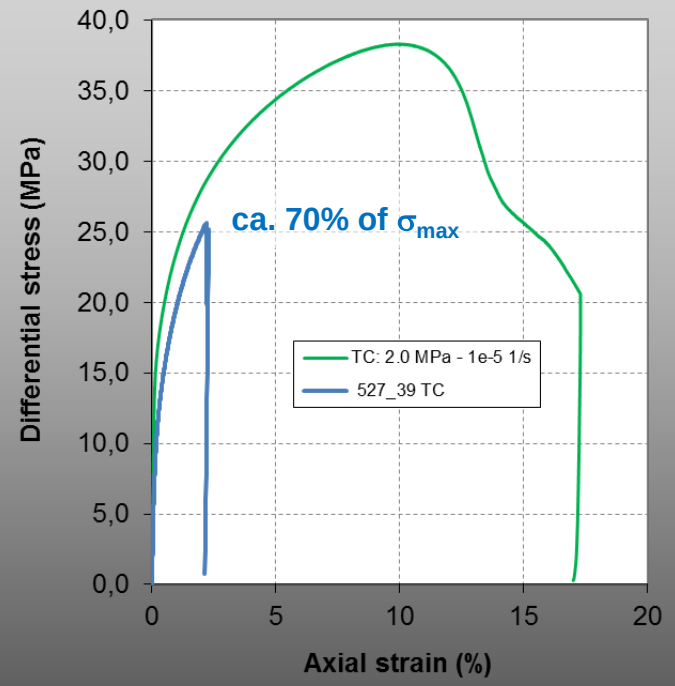
$$k = \frac{2 \cdot p_0 \cdot q_0 \cdot \eta \cdot l}{A(p_1^2 - p_2^2)}$$

Recovery of tightness after damage – crack closure / healing



After damage tightness is restored within some few weeks …

Pre-damage



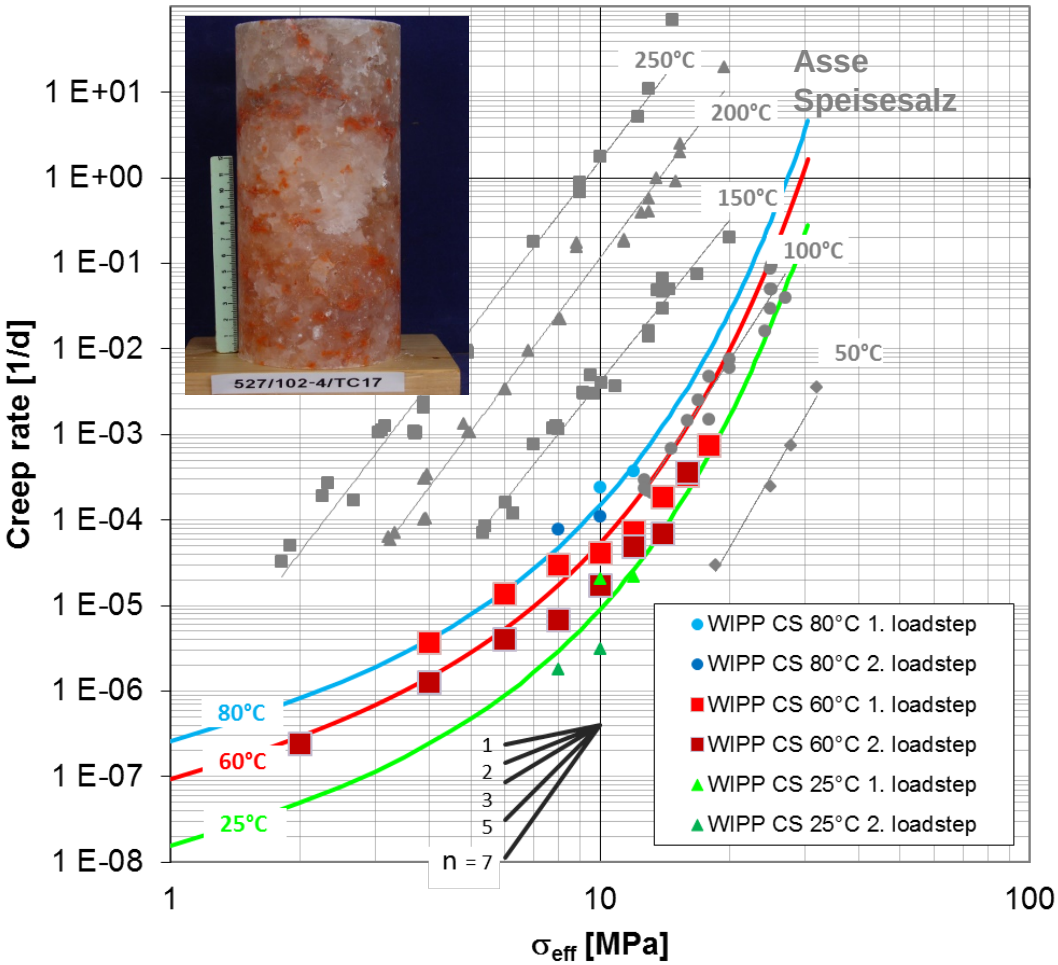
Sample 527/39

Summary laboratory investigations on WIPP salt

- **The "WIPP salt" is of excellent quality**, i.e. undisturbed and homogeneous.
  - Moisture contents:
    - "clean salt": around 0.15 wt. -%
    - "argillaceous salt": 0.2 - 0.4 - 1.0 wt. -%
  - ➢ *Lower than reported but generally higher than for domal rock salt*
- **The triaxial tests on "clean salt" are completed, resulting in a very consistent set of data** (strength and dilatancy):
    - Temperature-increase results in a significant strength decrease
    - Referred to in situ deformation rates ($<10^{-10}$ 1/s) strength will be reduced
    - Onset of dilatancy depends not on temperature and the deformation rate
  - ➢ *Comparison with the reference Asse salt shows generally somewhat lower strengths, but it fits into the known properties field of pure rock salt.*
- **Creep tests on "clean salt" and "argillaceous salt" are now also finished**
    - Unique data sets of high quality due to the new creep test approach, but differences to older results are obvious, especially at increased temperature
    - AS creeps slightly (2x) faster than CS, and both creep faster than Asse salt
  - ➢ *A creep mechanism change at lower stresses is obvious, i.e. no simple power law*
- **Gas tightness** of the salt is demonstrated, as well ist efficient sealing capability

thank you
for your attention!

Creep behaviour of clean salt – 25°C, 60°C, 80°C

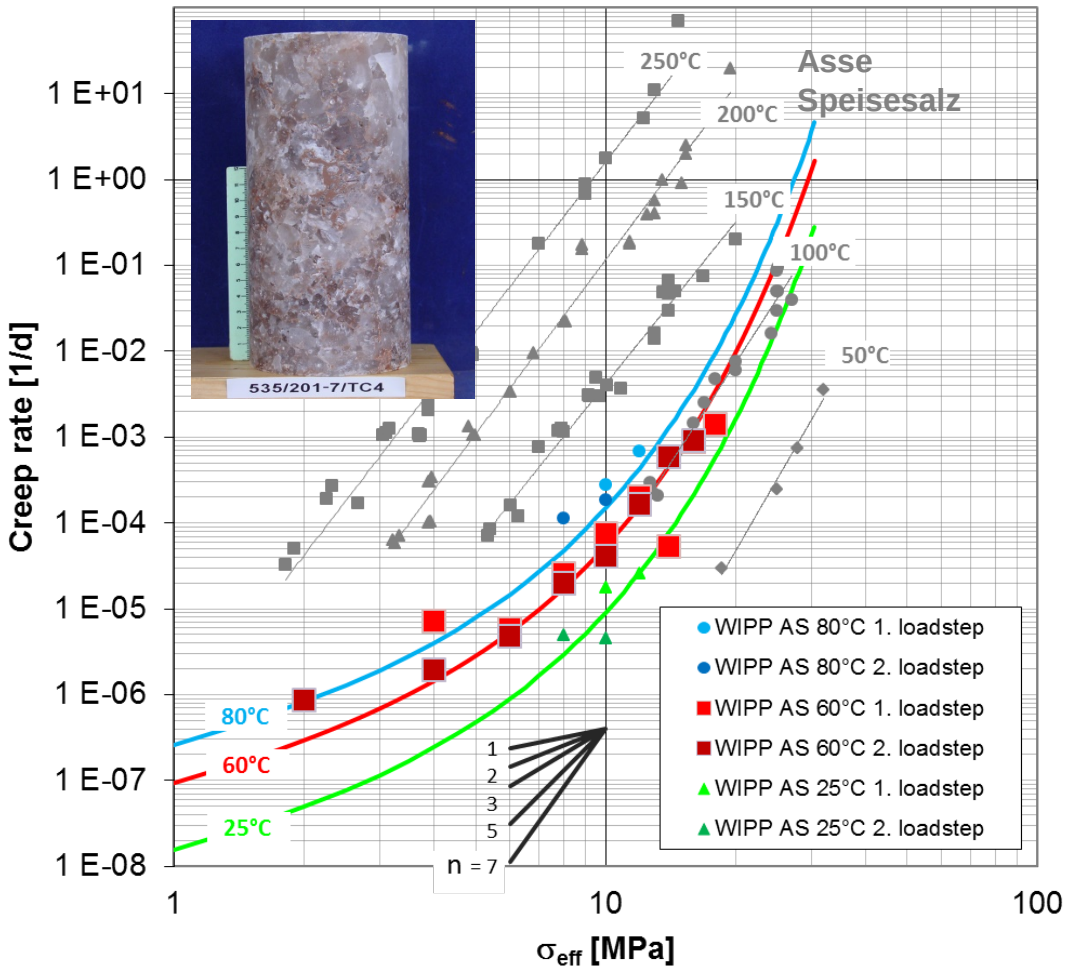


- Consistent data sets
- Mechanism change depending on stress state ⇒ a simple power law is not sufficient!

IfG-Creep data sets (CS)

Creep test no.	σ_1 (MPa)	σ_3 (MPa)	$\Delta\sigma$ (MPa)	Duration (d)	T (°C)	creep rate (1/d)
Experimental data						
1 TCC1	30	20	10	50	24	2,04E-05
	28	20	8	50	24	1,81E-06
1a TCC3	30	20	10	50	24	1,43E-05
	28	20	8	50	24	3,39E-06
2 TCC5	32	20	12	50	24	2,16E-05
	30	20	10	50	24	3,12E-06
3 TCC15	24	20	4	50	60	3,68E-06
	22	20	2	50	60	2,43E-07
4 TCC13	26	20	6	50	60	1,37E-05
	24	20	4	50	60	1,26E-06
5 TCC6	28	20	8	50	60	1,94E-05
	26	20	6	50	60	3,31E-06
6 TCC2	30	20	10	50	60	4,05E-05
	28	20	8	50	60	6,80E-06
6a TCC4	30	20	10	50	60	1,67E-04
	28	20	8	50	60	5,63E-05
7 TCC7	32	20	12	50	60	7,42E-05
	30	20	10	50	60	1,70E-05
8 TCC9	34	20	14	50	60	1,86E-04
	32	20	12	50	60	4,92E-05
9 TCC11	36	20	16	50	60	3,29E-04
	34	20	14	50	60	6,85E-05
10 TCC12	38	20	18	50	60	7,50E-04
	36	20	16	50	60	3,62E-04
11 TCC16	30	20	10	50	80	2,41E-04
	28	20	8	50	80	7,74E-05
12 TCC19	32	20	12	50	80	3,76E-04
	30	20	10	50	80	1,09E-04

Creep behaviour of argillaceous salt – 25°C, 60°C, 80°C



IfG-Creep data sets (AS)

Creep test no.	σ_1 (MPa)	σ_3 (MPa)	$\Delta\sigma$ (MPa)	Duration (d)	T (°C)	creep rate (1/d)
Experimental data						
TCC9	30	20	10	50	25	1,75E-05
	28	20	8	50	25	4,98E-06
TCC10	32	20	12	50	25	2,61E-05
	30	20	10	50	25	4,49E-06
TCC1	24	20	4	50	60	7,08E-06
	22	20	2	50	60	8,52E-07
TCC2	26	20	6	50	60	5,87E-06
	24	20	4	50	60	1,94E-06
TCC3	28	20	8	50	60	2,57E-05
	26	20	6	50	60	4,77E-06
TCC4	30	20	10	50	60	7,45E-05
	28	20	8	50	60	2,00E-05
TCC5	32	20	12	50	60	2,00E-04
	30	20	10	50	60	4,10E-05
TCC6	34	20	14	50	60	5,39E-05
	32	20	12	50	60	1,64E-04
TCC7	36	20	16	50	60	8,82E-04
	34	20	14	50	60	5,95E-04
TCC8	38	20	18	50	60	1,40E-03
	36	20	16	50	60	9,24E-04
TCC11	30	20	10	50	80	2,79E-04
	28	20	8	50	80	1,14E-04
TCC12	32	20	12	50	80	6,78E-04
	30	20	10	50	80	1,84E-04

- Argillaceous salt creeps slightly faster (2x) than Clean Salt
- Generally WIPP-salt creeps faster than Asse Salt