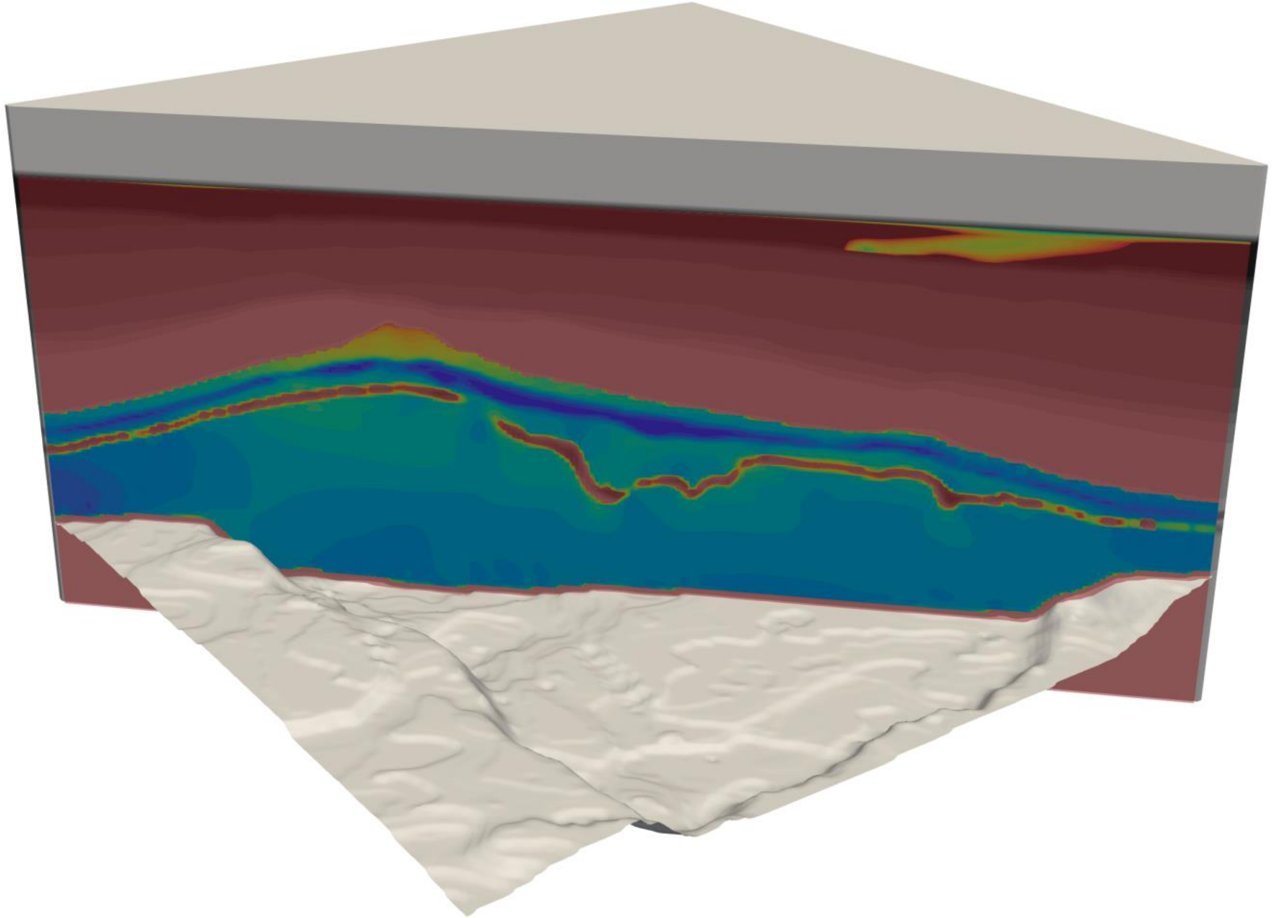
3D stress state within typical salt structures

Tobias Baumann, Boris Kaus, Anton Popov, Janos Urai

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

smart Tectonics

RWTH AACHEN UNIVERSITY



Summary

3D state of stress within typical salt structures

- This presentation outlines our contribution to the KEM 17-project **Over pressured caverns and leakage mechanisms – Dome scale report** https://www.kemprogramma.nl/blog/view/57979350/kem-17-over-pressured-salt-solution-mining-caverns-and-possible-leakage-mechanisms

- Stresses are the driving force of permeability evolution in rocksalt. In cavern engineering, it is usually assumed that the virgin state of stress in a salt formation is isotropic. **However, both micro scale and salt dome scale arguments show that differential stresses up to several MPa can be present.**

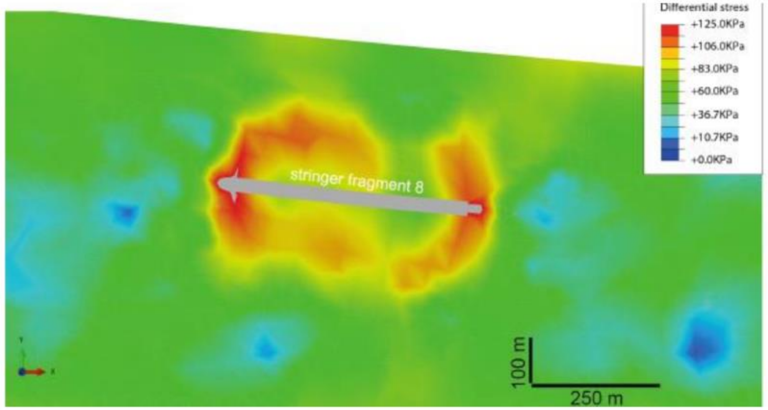
- Zones of heterogeneities (e.g. Anhydrite layers) and active deformation contribute to the far-field anisotropy of stress and have significant effects on the evolution of caverns, during operation and after abandonment. **For a given site, numerical computations allow assessing such initial deviatoric stresses, including their uncertainties.**

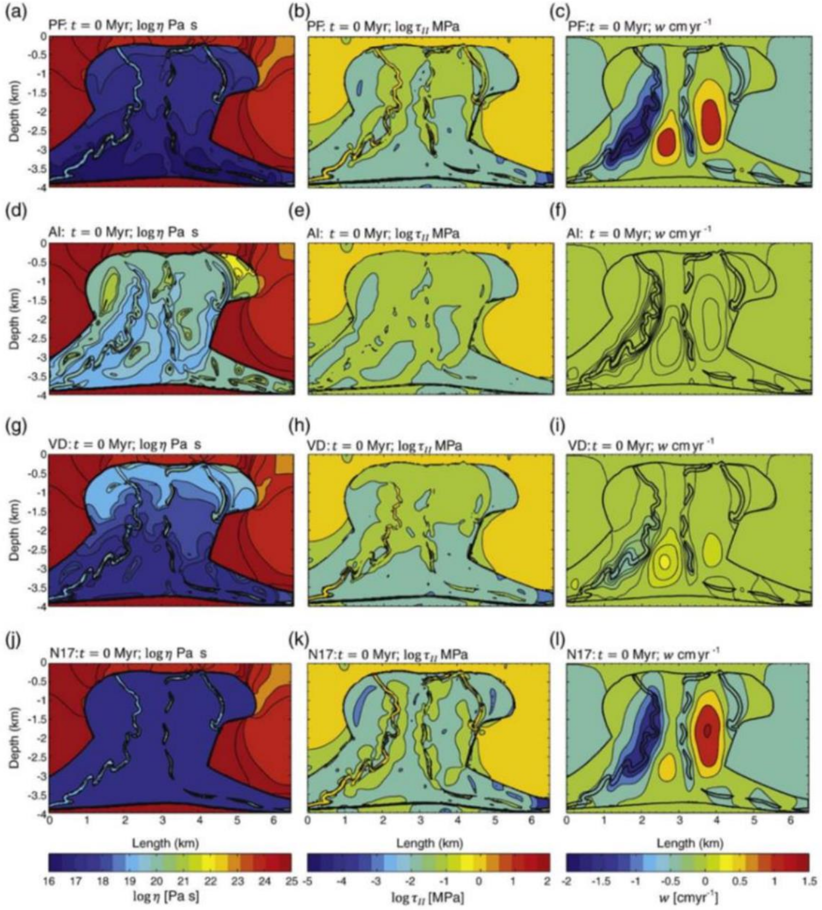
State of stress within salt structures

What is known about the stress state in salt formations?

- There is relatively little information about the stresses that are expected to occur within salt structures as a result of tectonic deformation of salt.
- **Analysis from microstructure: stresses are of the order of 1 MPa**
  Lower values for flat-lying salt layers and higher values occurring in salt domes, close to anhydrite layers and close to strongly deformed parts within the salt domes.
- **Published numerical models** on the dynamics of salt structures predominantly **focus on the external dynamics** and stresses of salt domes. **Very few studies exist that show the stress distribution within the salt**. They suggest that stress magnitudes can be quite heterogeneous.

➢ The literature on stress magnitudes and orientations within salt structures is not entirely conclusive. **We require more information about how stresses in salt are distributed as a function of geometry and as a function of salt rheology.**





Figures *Top: Fig. 2.1 - Li et al. (2012); bottom: Fig. 2.2 - Chemia et al. (2009)*

Salt rheology

Closing the gap between microscale and macroscale

Rheology of salt is controlled by interplay between the following two creep mechanisms:

Pressure solution creep (e.g. Spiers et al., 1990)

$$\dot{\varepsilon}_{ps} = A_{ps}\,\sigma \qquad A_{ps} = \frac{B_{ps}}{T\,d^3}\exp\left(\frac{-Q_{ps}}{RT}\right)$$

Dislocation creep (e.g. Urai et al., 2008)

$$\dot{\varepsilon}_{dc} = A_{dc}\,\sigma^n \qquad A_{dc} = B_{dc}\exp\left(-\frac{Q_{dc}}{RT}\right)$$

T: abs. temperature, R: gas constant, B: pre-exponential const., Q: activation energy, n: power-law exponent, d: mean grain size.

Total creep is the sum of the individual creeps

$$\dot{\varepsilon} = \dot{\varepsilon}_{dc} + \dot{\varepsilon}_{ps}$$

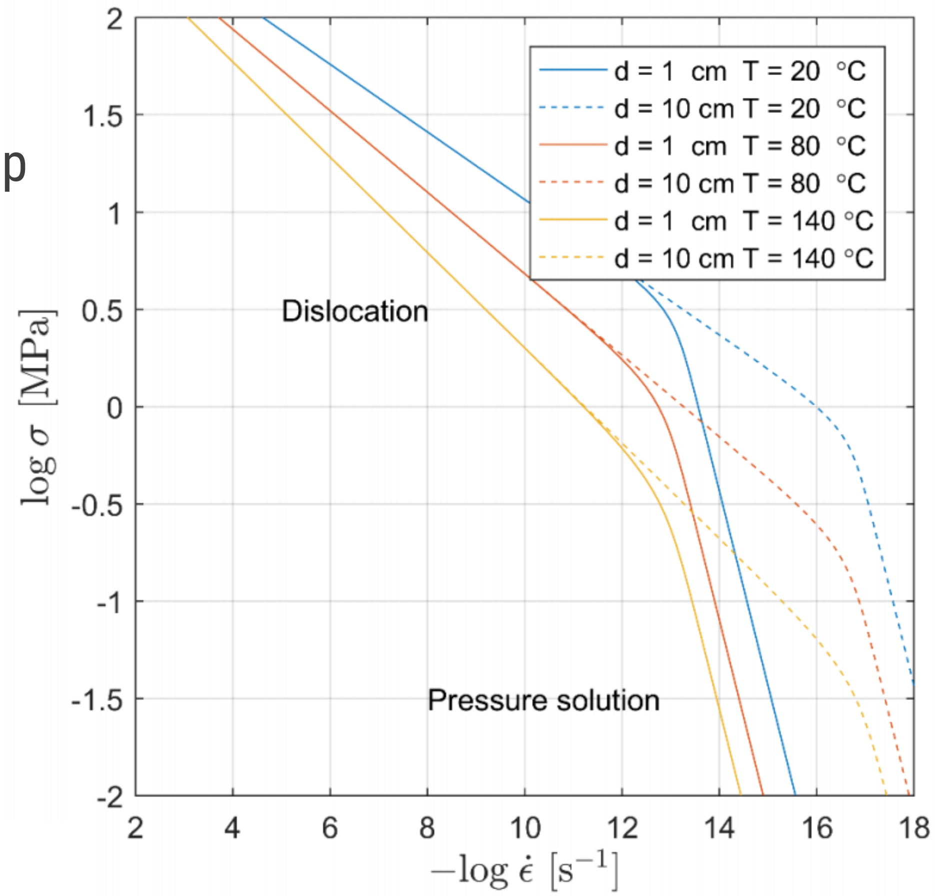


Fig. 3.4 – Dome-scale report

- ➢ DC creep is active in the high stress regime, while PS creep is dominant in the low stress regime.
- ➢ **The mean grain size has a decisive influence on the transition between the dislocation and pressure solution creep mechanisms.**

Salt rheology

Closing the gap between microscale and macroscale

- Netherlands: present-day strain rates of the order 10^{-17}-10^{-16} s^{-1}. Our models predict salt internal strain rates < 10^{-15} s^{-1}
- For rock salt with grain sizes < 1 cm, and active PS creep, we expect essentially zero differential stress.
- **The disintegration of continuous fluid films at grain boundaries** is well known to occur from microstructural observations of rock. This effect **needs to be quantified and to be considered in numerical models of salt domes within future studies.** Here, we consider models with DC creep only.
- The upper bound for the **mean grain size remains an essentially undetermined key parameter** that **requires additional constraints** from experiments and observations **in each particular case study**.

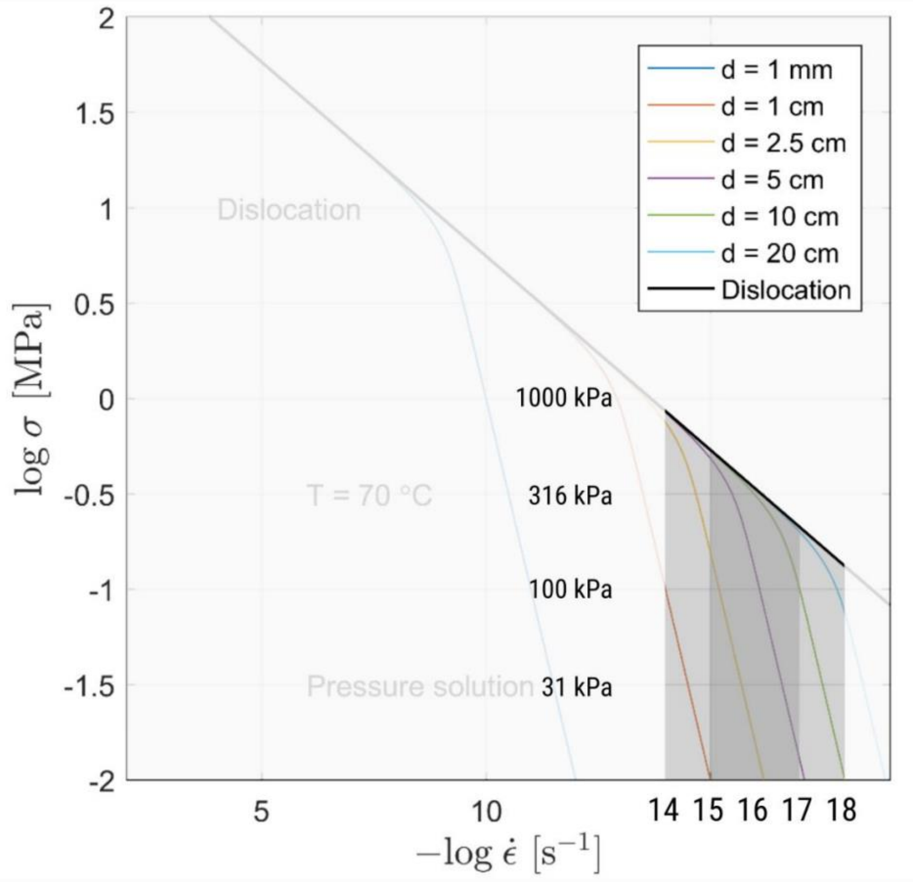


Fig. 4.8 – Dome-scale report

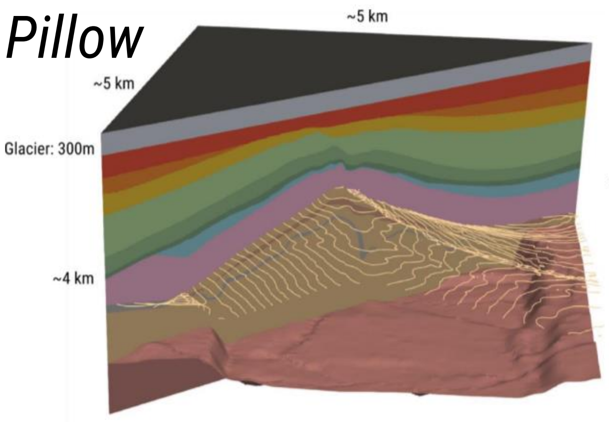
➢ Here we treat the grain size as a free parameter and vary it over a wide range

Modeling

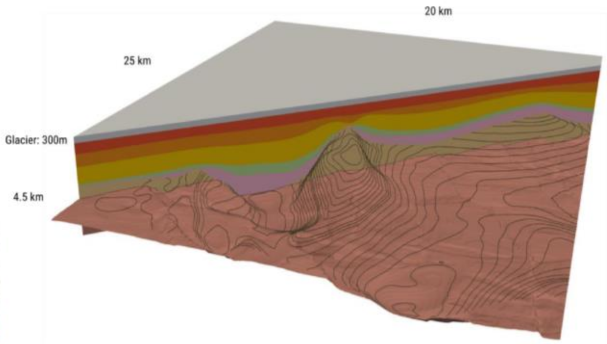
What stress magnitudes can we expect?

3D parametric study with three model geometries relevant for the Netherlands

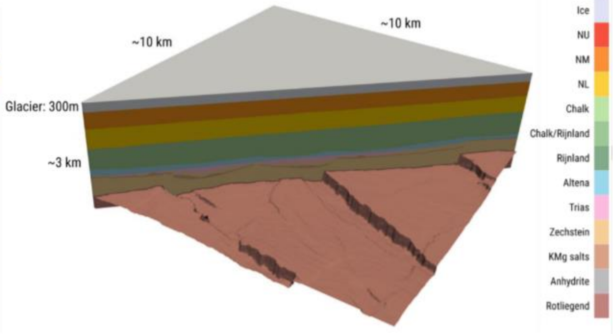
Salt Pillow



Salt Wall

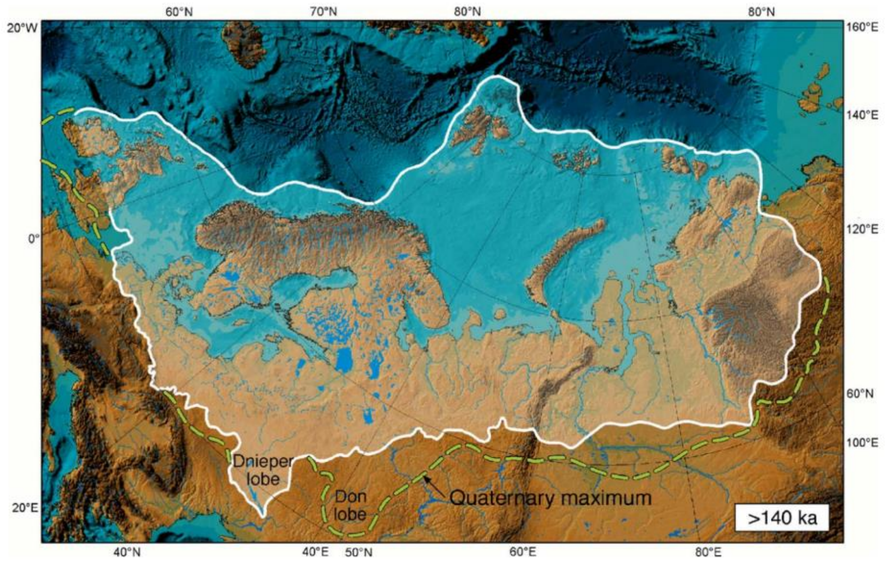


Flat-bedded salt



➢ We simulate the **full stress evolution over 300 kyrs** until the present day.

- We account for the additional loading of the ice shield during the Saalian ice age.
- Model calibration with data from literature (densities) and public data archives (temperature boundary conditions)



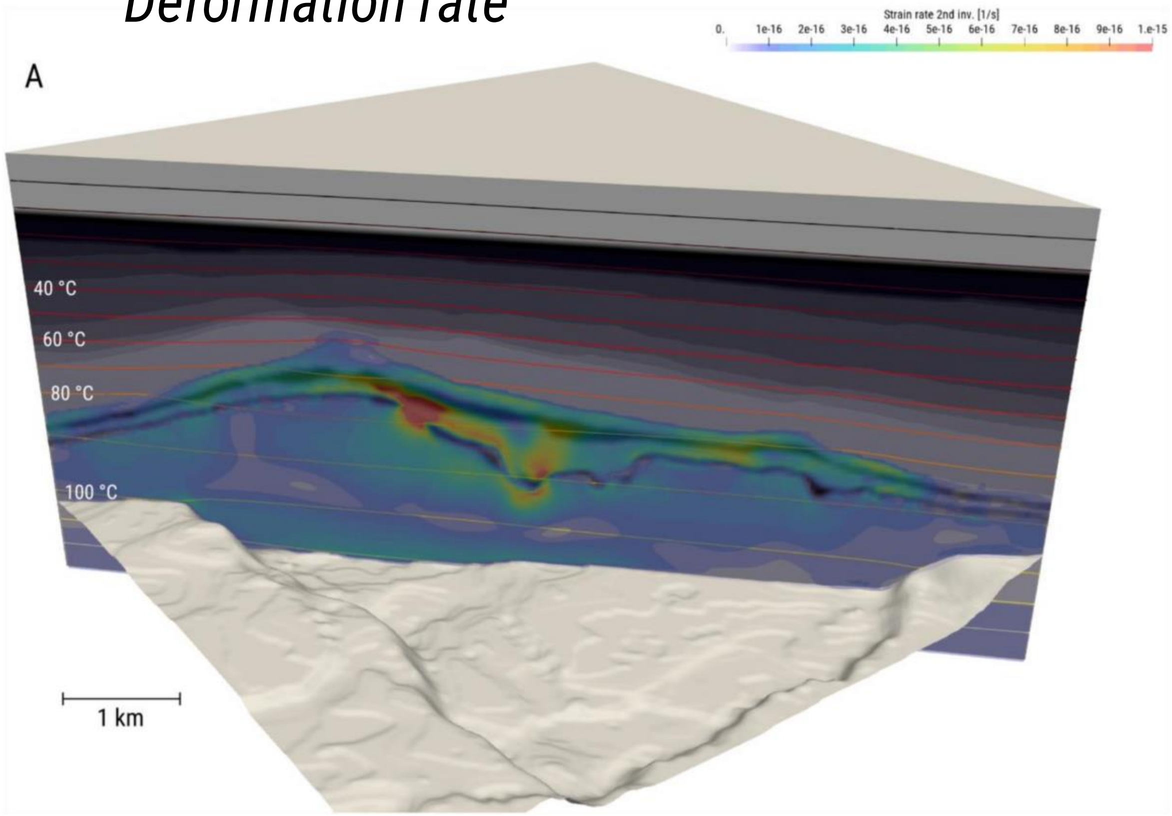
***Figures** Top Fig. 4.4-4.6 – Dome scale report; bottom: Svendsen et al. (2004)*

Modeling

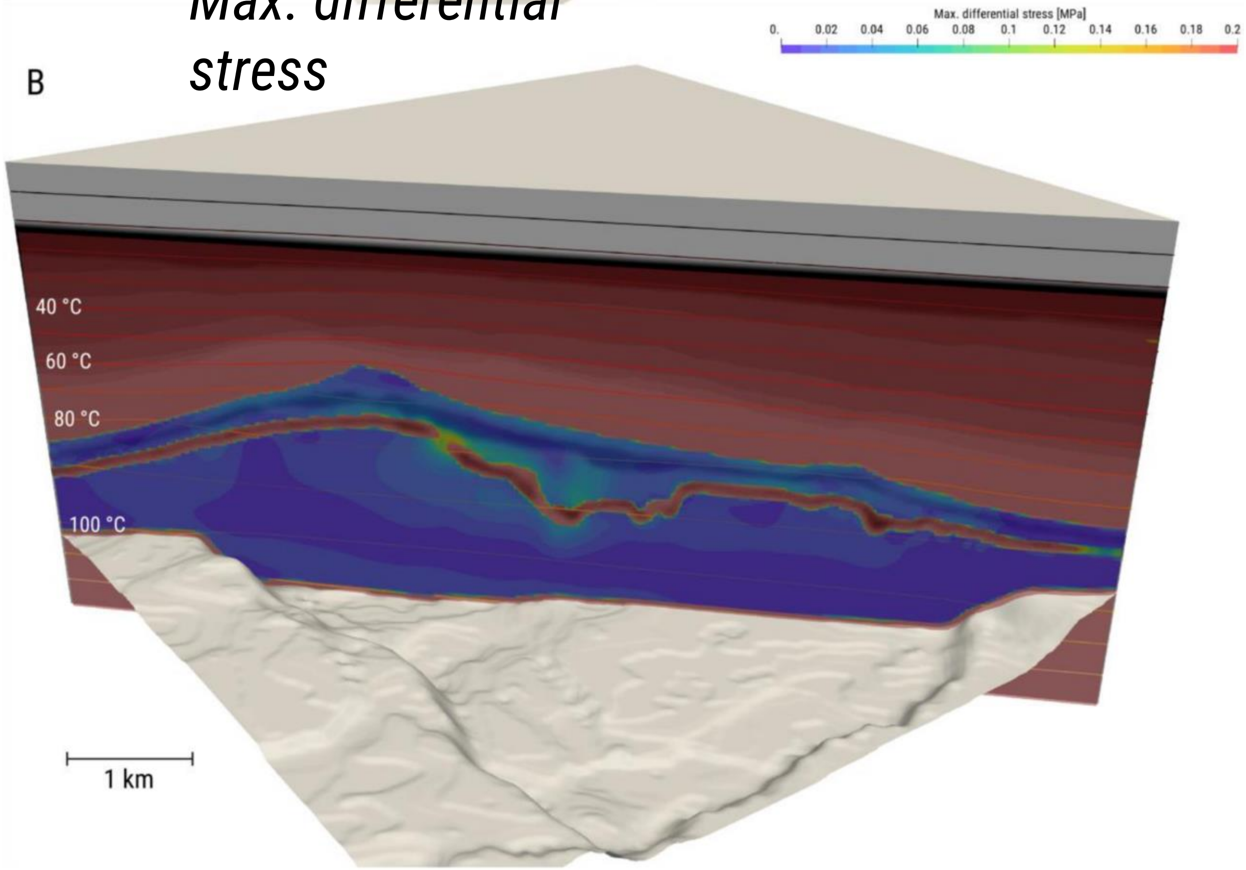
What stress magnitudes can we expect?

Example with coupled PS-DC creep and mean grain size of 2.5 cm

Deformation rate



Max. differential stress



Figures *Fig. 4.7 – Dome scale report*

Modeling

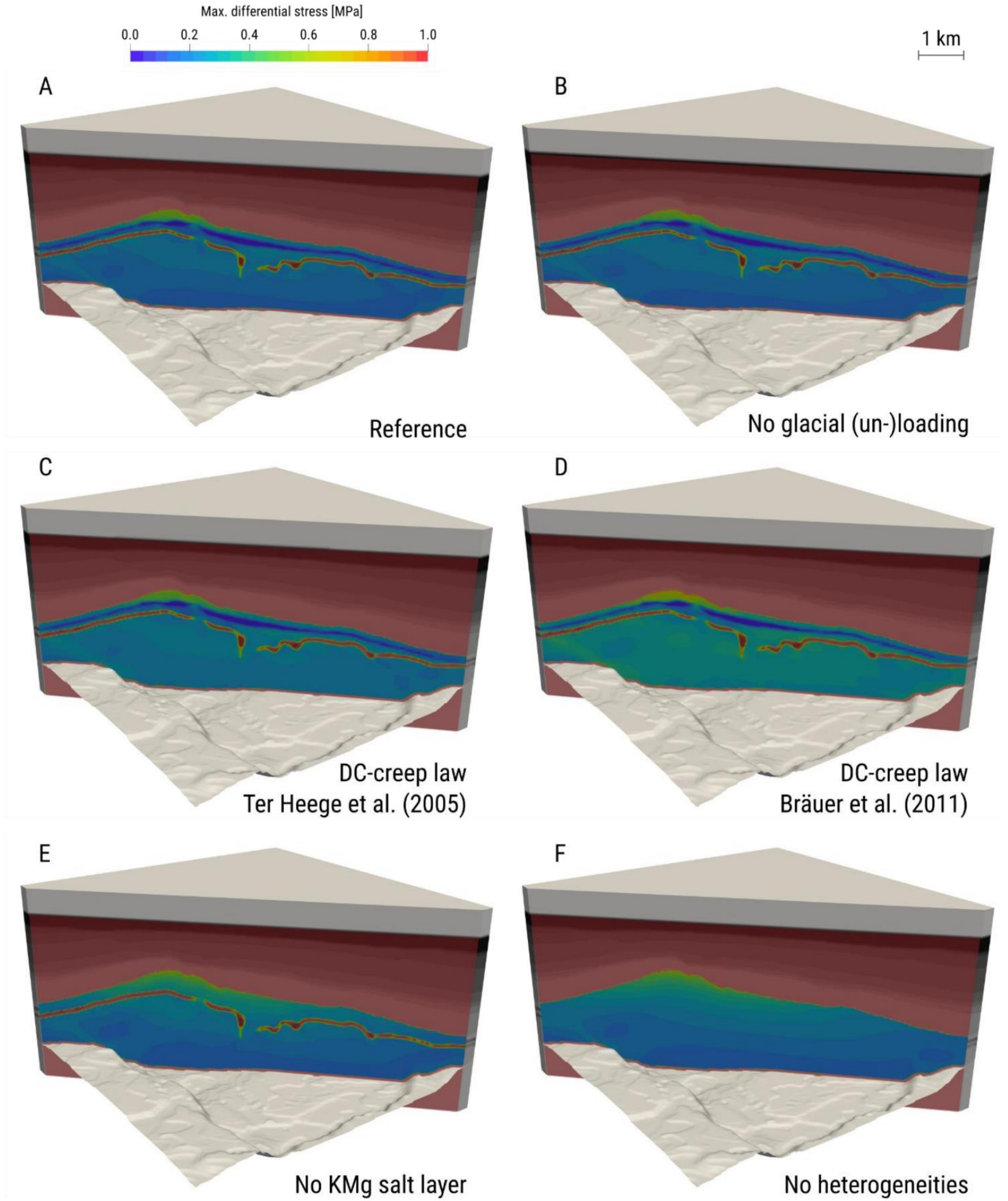
What stress magnitudes can we expect?

Example with salt pillow

Distribution of max. differential stress for various salt rheologies, and different levels of complexities (including anhydrite, KMg layers)

Robust findings

- High stress in the top of the pillow structure
- Higher stresses at the flanks of the pillow structure
- High stress around heterogeneities (stringers)
- Higher stresses associated with steps in the basement geometry (faults)



Figures *Fig. 4.10– Dome scale report*

Modeling

What stress magnitudes can we expect?

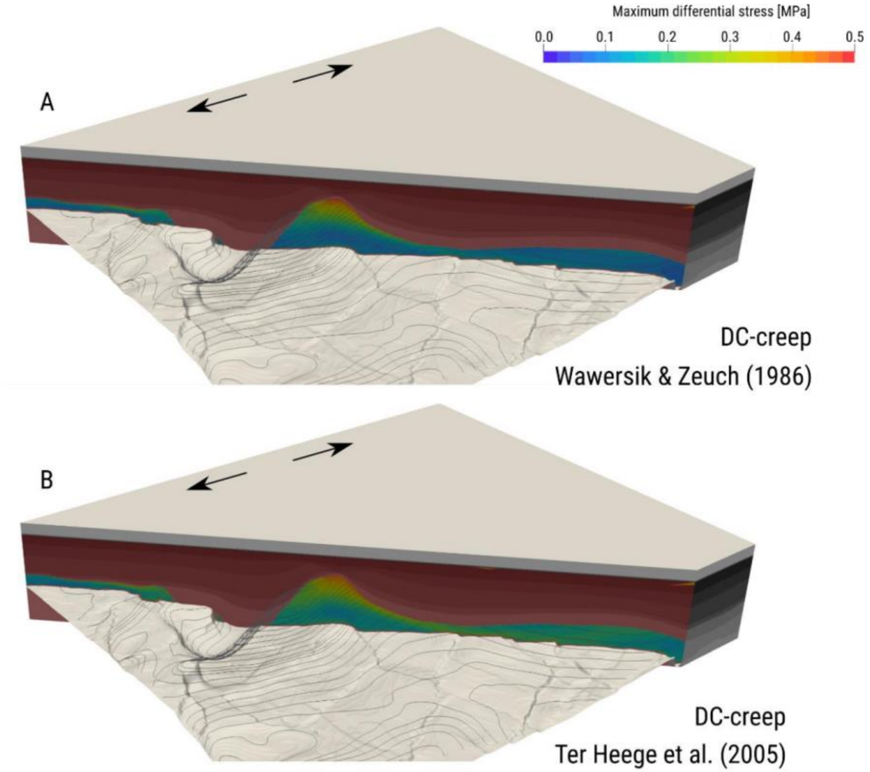
- For models of the salt pillow and wall structures with **coupled pressure solution and dislocation (PS-DC) creep**, we obtain maximum differential stresses that are typically **below 0.5 MPa.**
- Whenever **pressure solution creep is deactivated**, the resulting stresses are higher and reach up to **0.7-0.8 MPa**, depending on which creep law is employed.
- We obtain **maximum stress magnitudes near the top of the salt pillow/wall structure**, which is a robust feature, that was observed in all models.
- Stresses induced by **glacial (un-)loading may only contribute to the order of 100 kPa**, but **only if PS creep not active**, which is, in principle, testable using microstructural observations.
- Different DC-creep laws result in a change in the stress patterns.
- Changes in the tectonic rate amplify the stress magnitude but have almost no effect on the relative stress patterns within the salt body.
- **Internal heterogeneities induce local stress changes, as do faults in the basement**. Within the scope of the pillow model, we find that locally induced stress anomalies have **length scales of approximately 1km.**

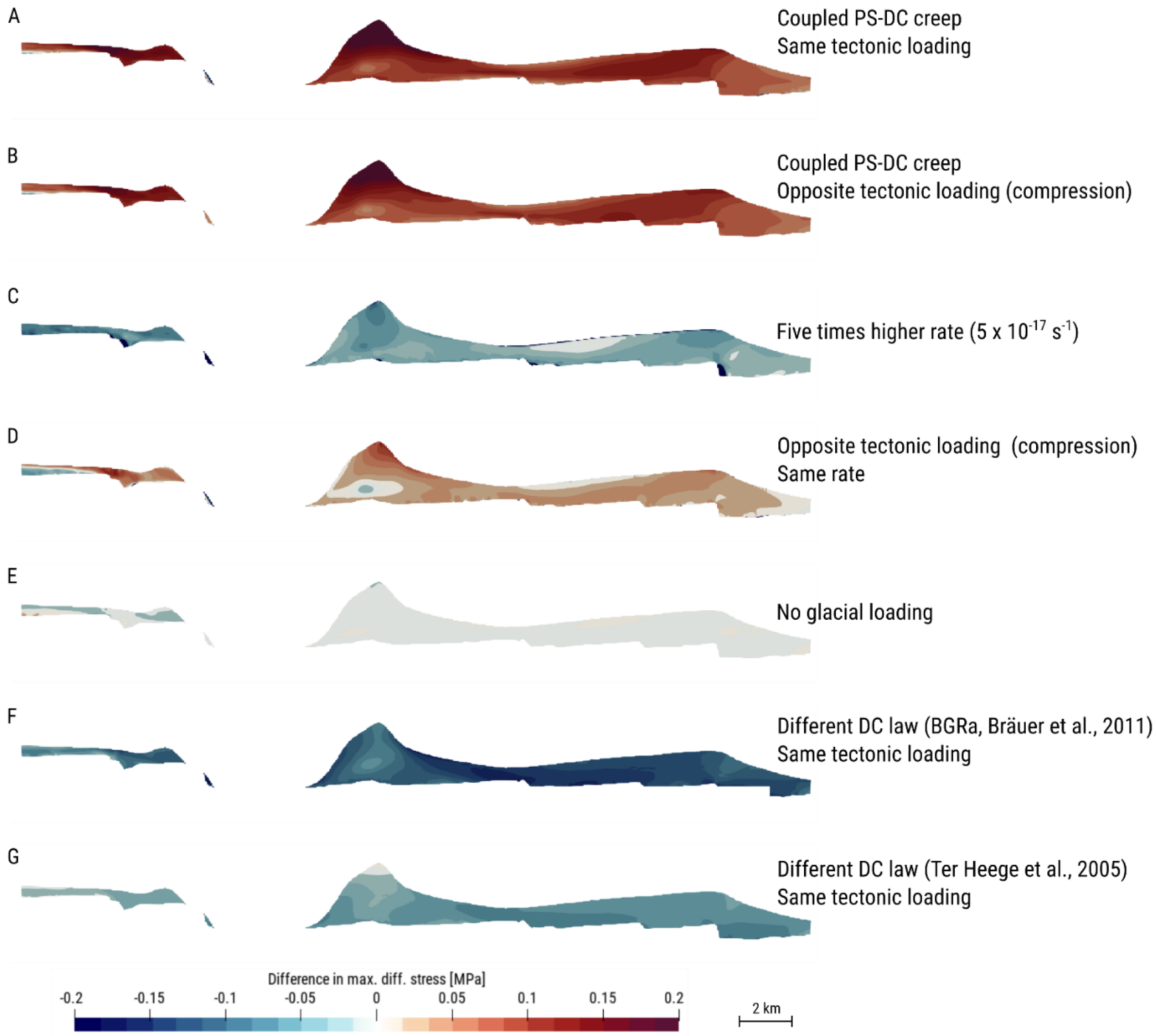
Modeling

What stress magnitudes can we expect?

- For **salt wall structures**, we observe similar stress magnitudes: High stresses at the flank and in the top of the structure

- Changes in DC-creep rheology have highest impact.



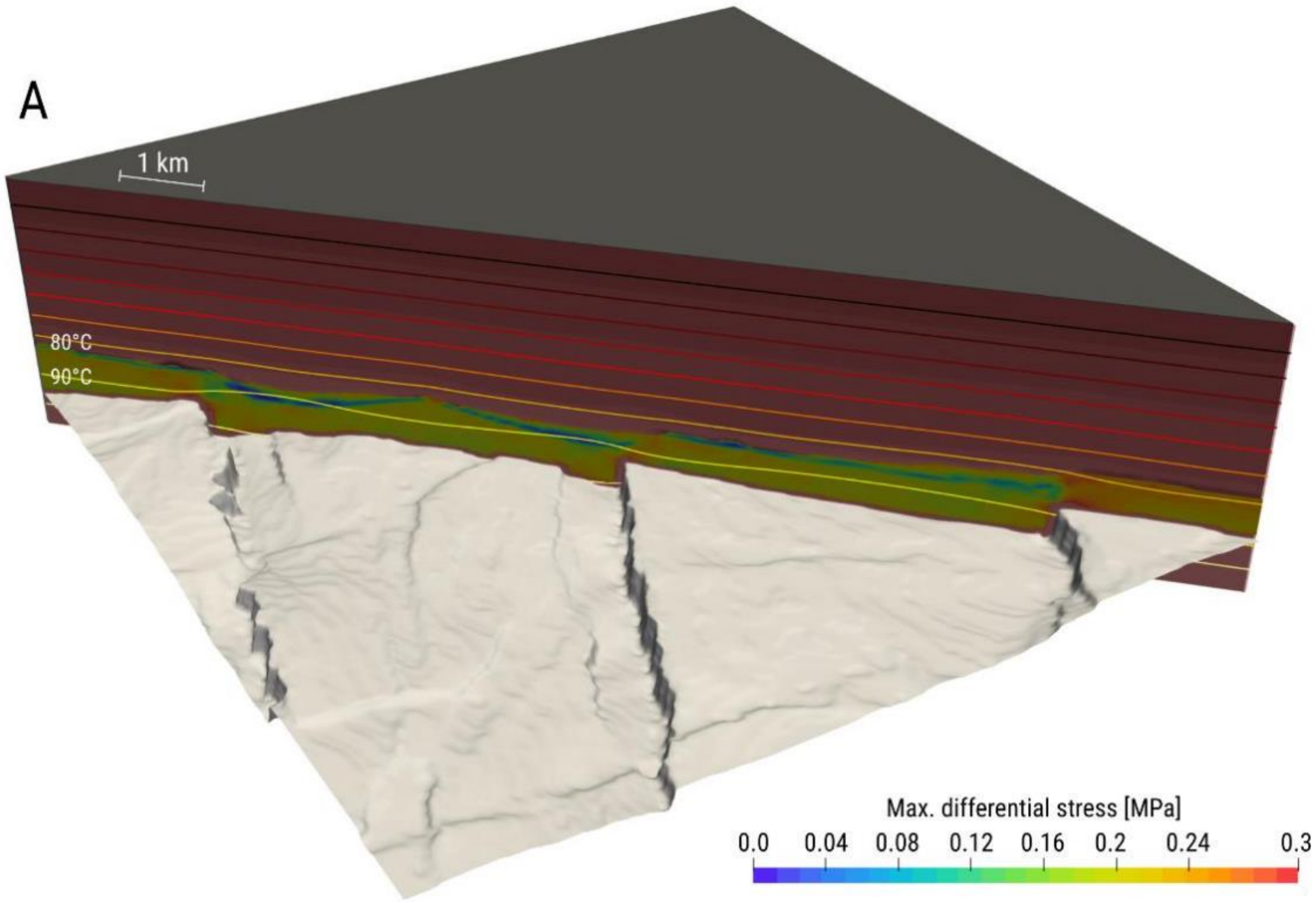


***Figures** left: Fig. 4.18; right: Fig. 4.17b – Dome scale report*

Modeling

What stress magnitudes can we expect?

- For **flat-bedded salt structures**, we observe lower differential stresses than for other geometries.
- High stresses in the vicinity of basement steps (faults).
- The stress pattern in the primary salt is influenced by “weak” inclusions (KMg layers).
- Here, we observe stresses up to **0.4 MPa.**
- Simulations with flat-bedded salt and a coupled PS-DC creep result in differential stresses smaller than 100 kPa.
- The effects of tectonic boundary conditions, glacial (un-)loading history, and moderate changes in grain size do not cause significant higher stresses.



Figures *Fig. 4.23 – Dome scale report*