

Improving Long-Term Predictions for Salt Cavern Abandonment **Constraining Rock Salt Creep and Coupled Dome-Scale Numerical Modeling**

Tobias Baumann, Joyce Schmatz, Benoit Brouard, Oskar Kottwitz, Anton Popov, Boris Kaus

Combined expertise from multiple scales

Combined expertise from multiple scales

Integrated multiscale concept

- Site-specific rock salt characteristics
- Current state of the salt dome
- Identification of key model parameters
- Optimized cavern operation and safe abandonment
- Uncertainty quantification

Modeling cavern abandonment

At what scale should we model the caverns?

2D, axis-symmetric?

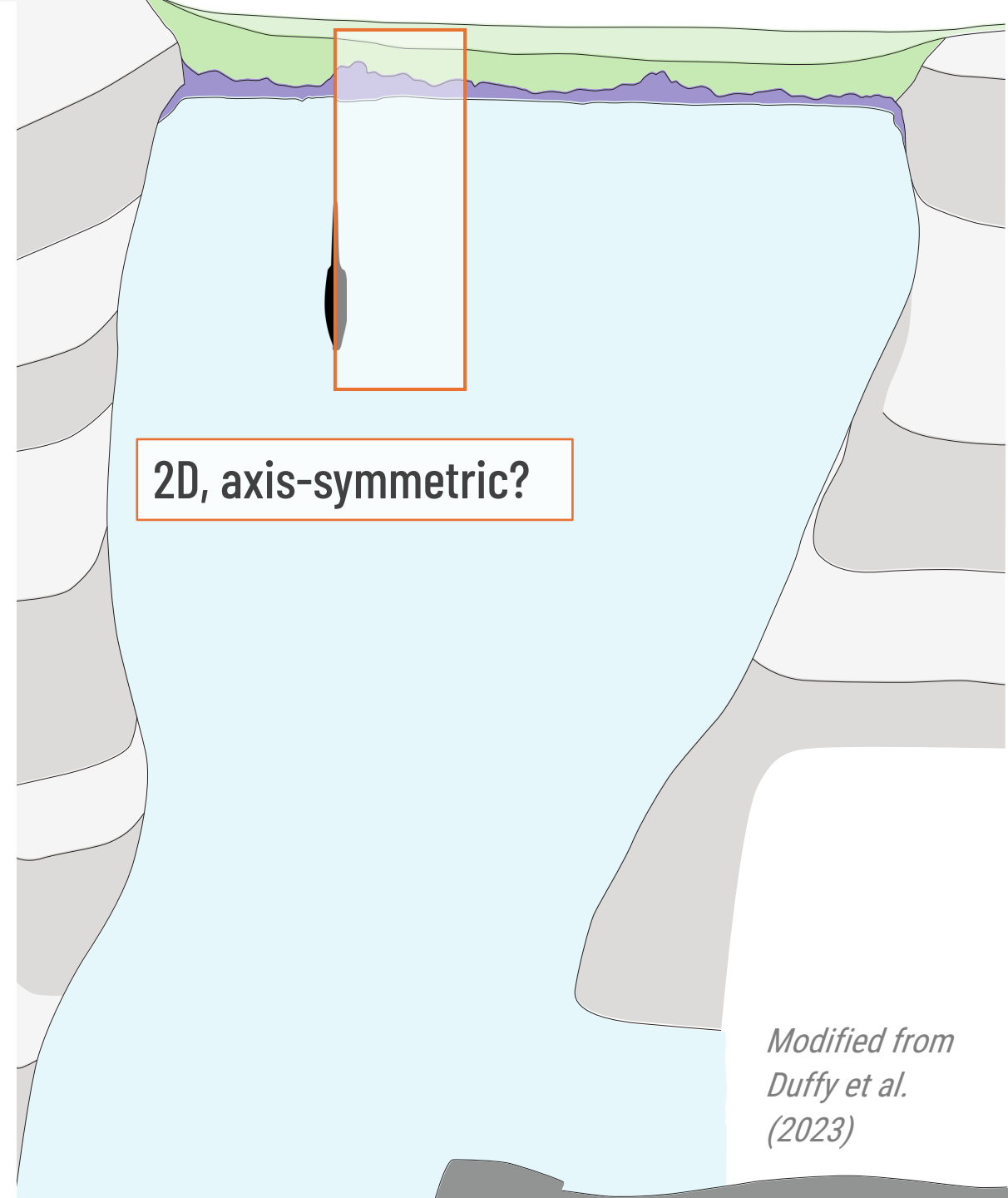


Modeling cavern abandonment

At what scale should we model the caverns?

What should be considered?

- Salt flows on long time scales
 - No infinite half-space of salt
 - 3D dome geometry, overburden

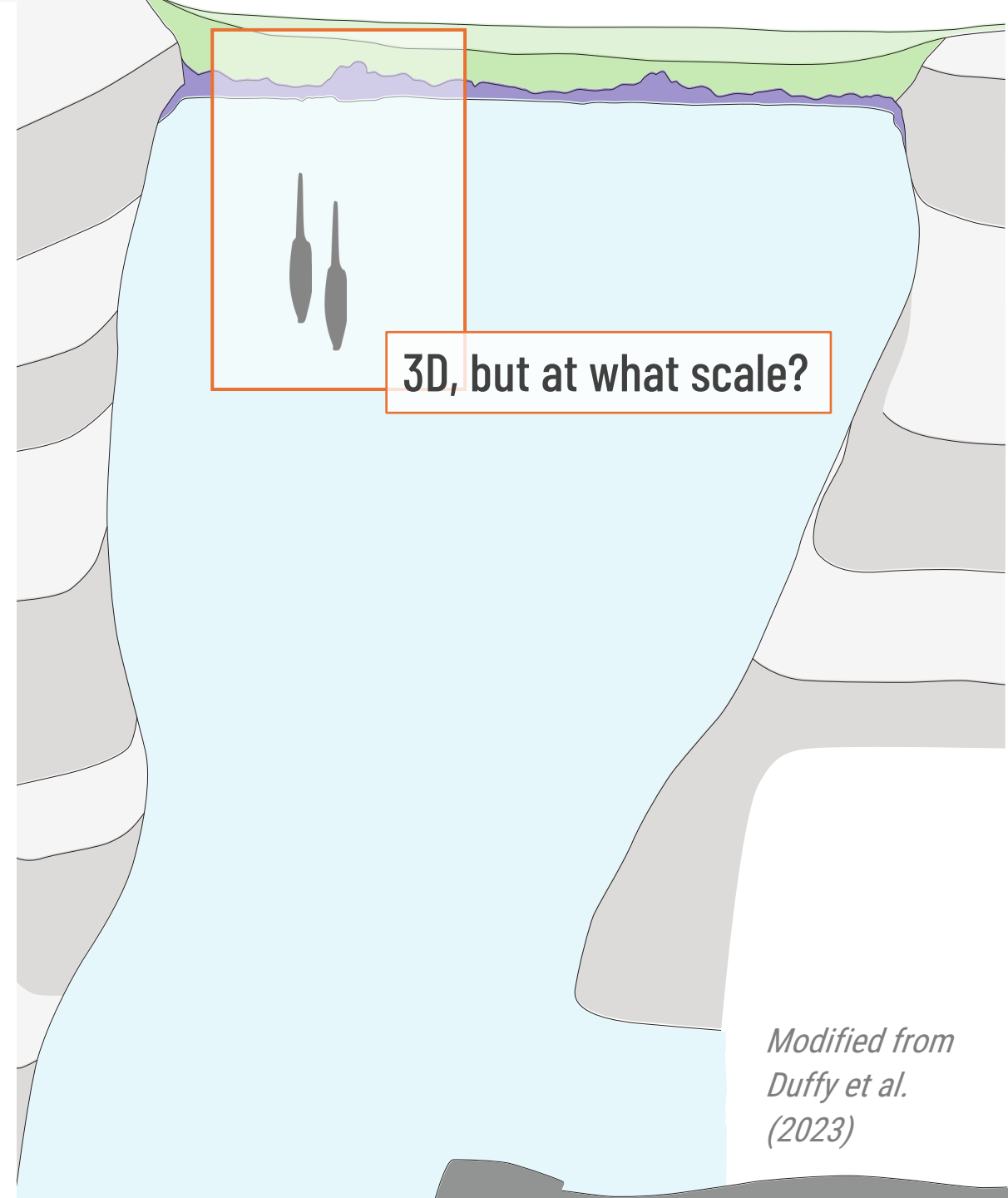


Modeling cavern abandonment

At what scale should we model the caverns?

What should be considered?

- Salt flows on long time scales
 - No infinite half-space of salt
 - 3D dome geometry, overburden

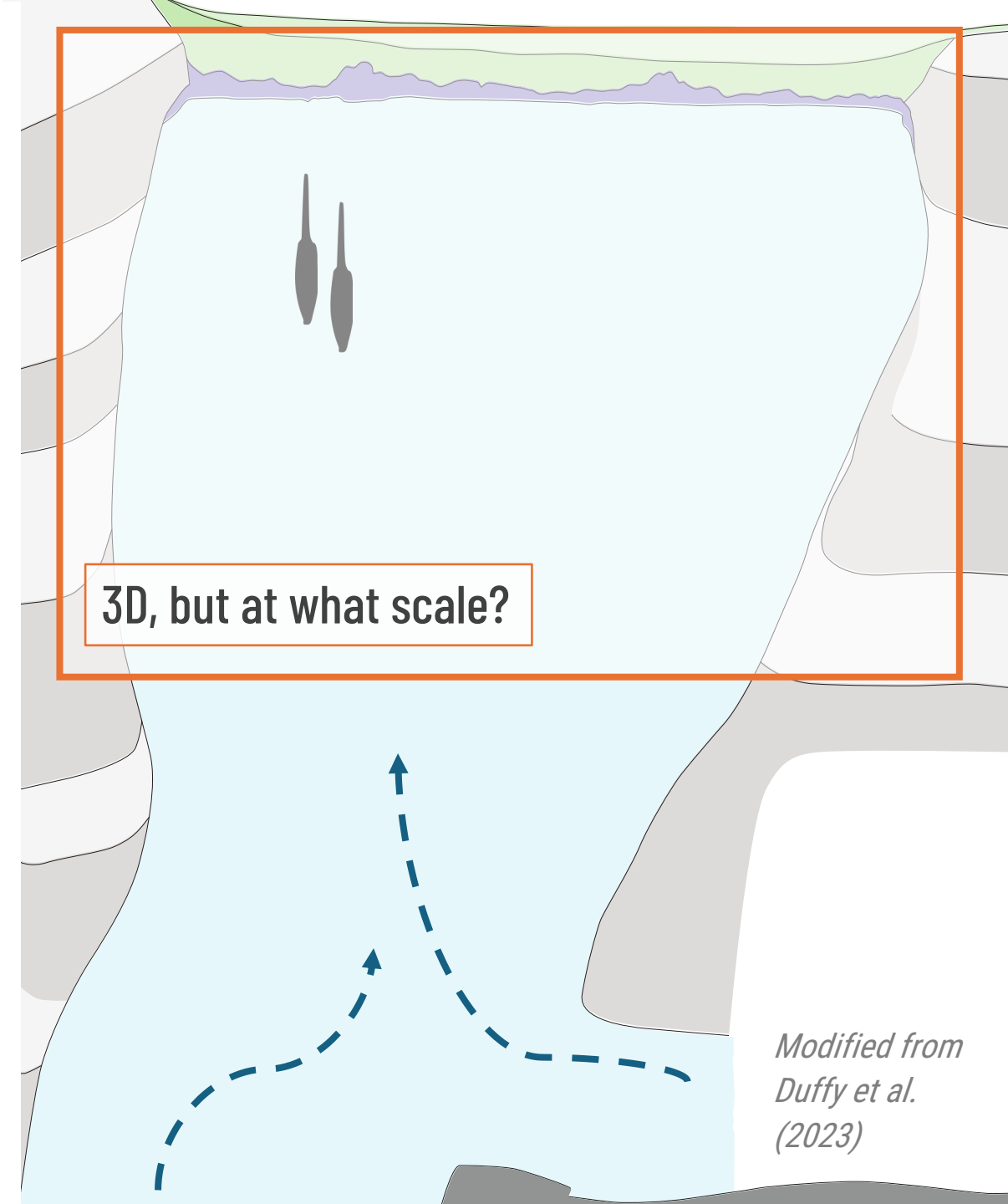


Modeling cavern abandonment

At what scale should we model the caverns?

What should be considered?

- Salt flows on long time scales
 - No infinite half-space of salt
 - 3D dome geometry, overburden
 - Basement, salt supply, welded?



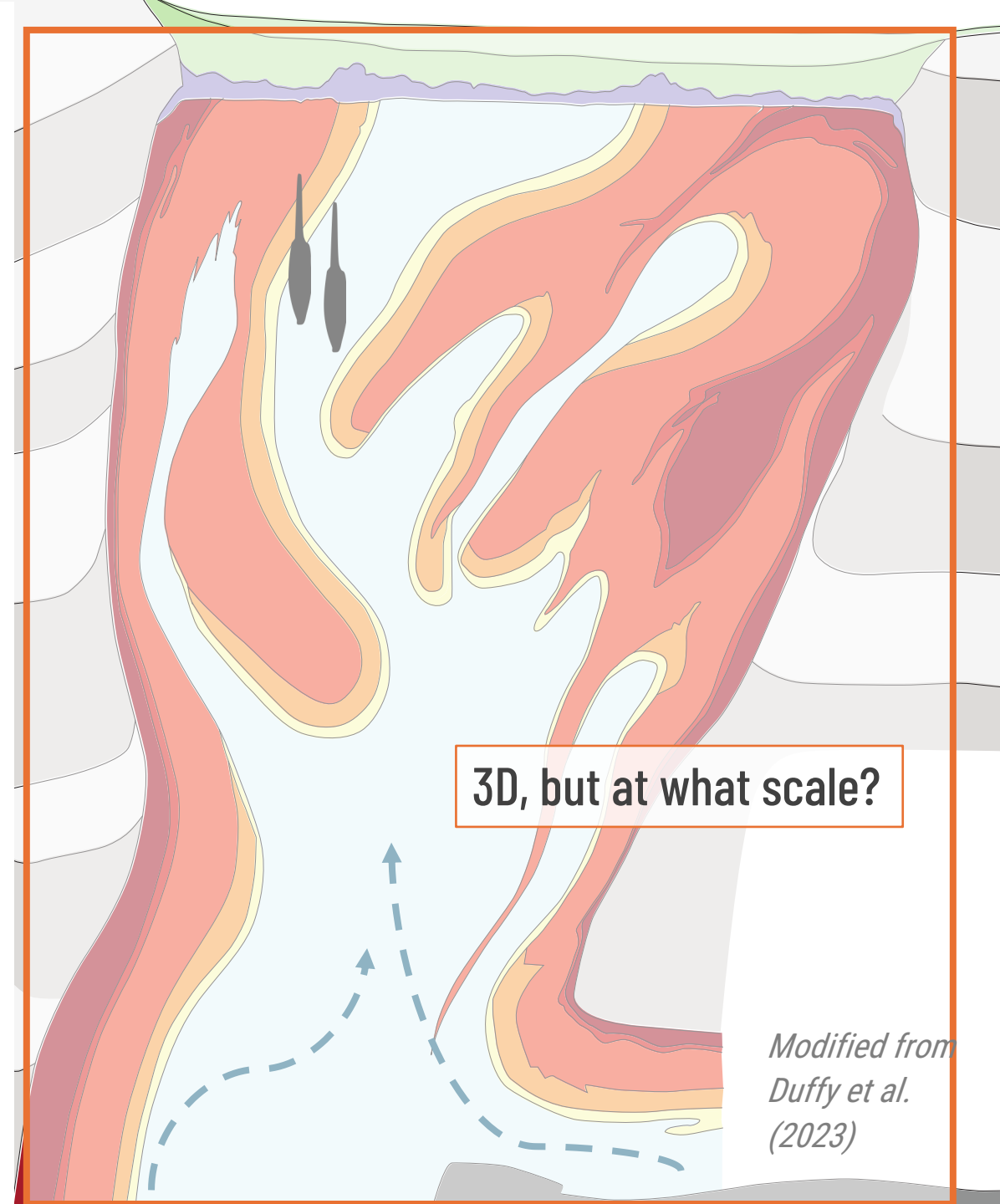
*Modified from
Duffy et al.
(2023)*

Modeling cavern abandonment

At what scale should we model the caverns?

What should be considered?

- Salt flows on long time scales
 - No infinite half-space of salt
 - 3D dome geometry, overburden
 - Basement, salt supply, welded?
- Multi-scale heterogeneities are present
 - Uncertainties -> model ensemble!
 - Site specific creep properties!

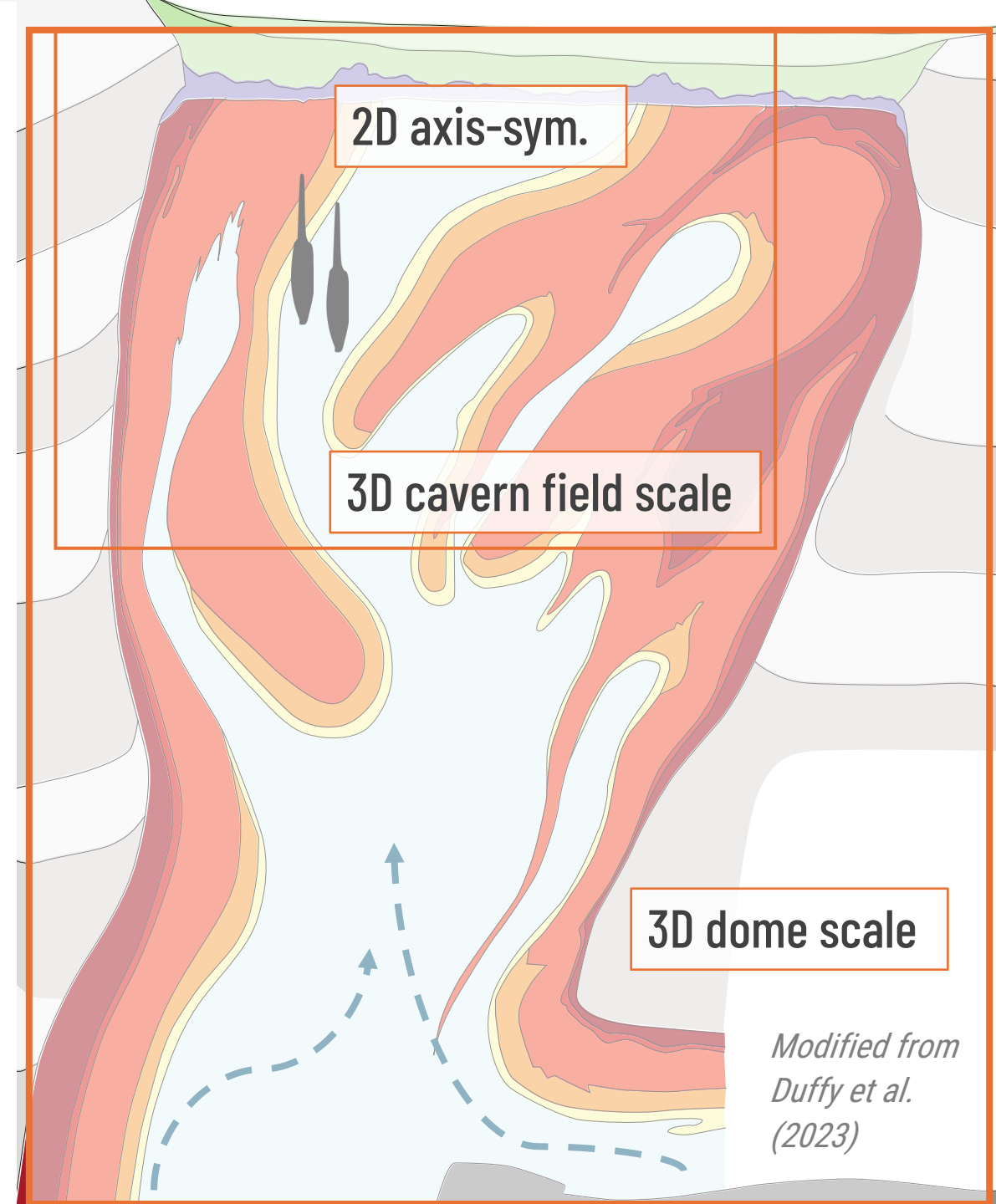


Modeling cavern abandonment

At what scale should we model the caverns?

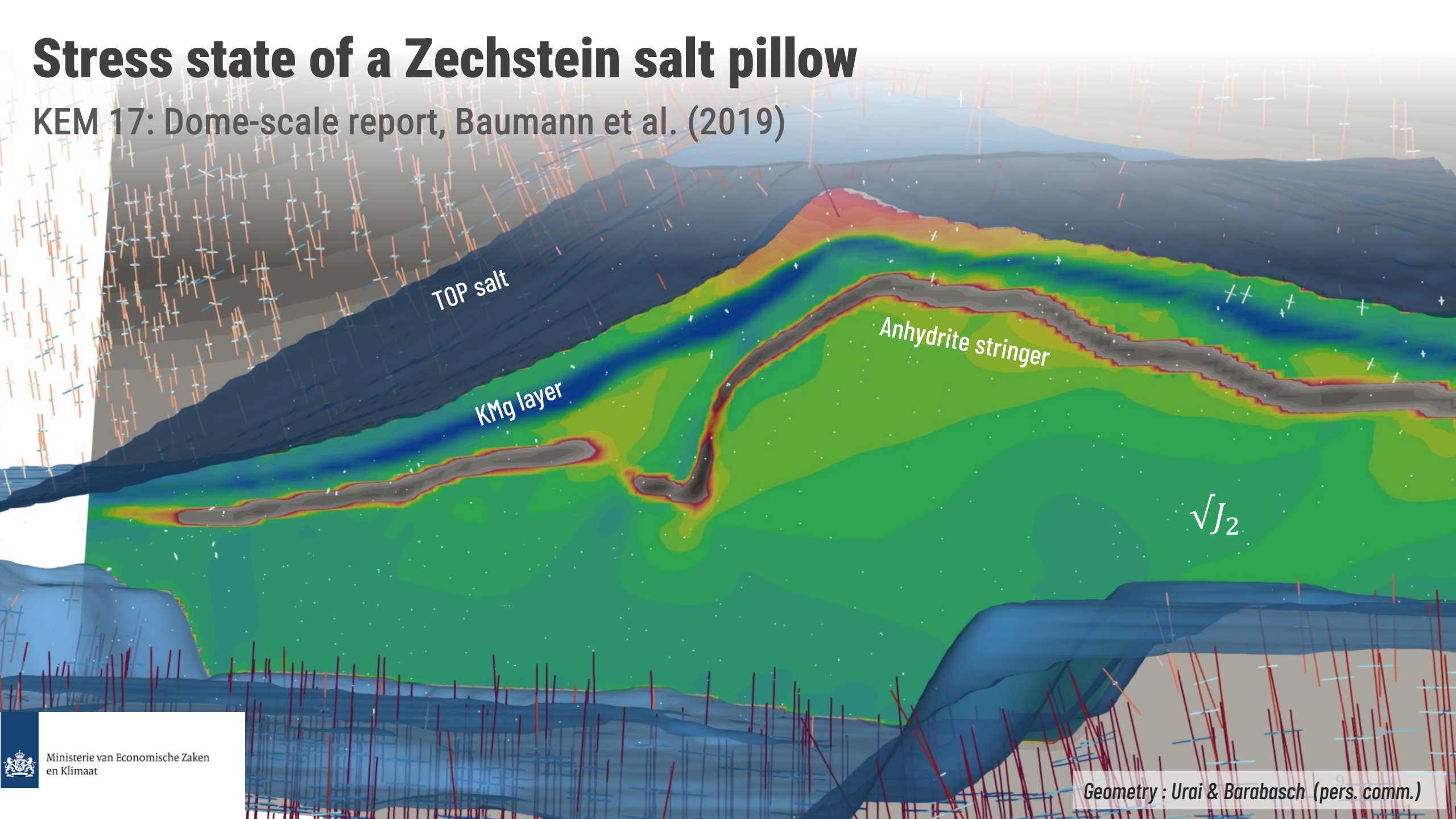
What should be considered?

- Salt flows on long time scales
 - No infinite half-space of salt
 - 3D dome geometry, overburden
 - Basement, salt supply, welded?
- Multi-scale heterogeneities are present
 - Uncertainties -> model ensemble!
 - Site specific creep properties!
- CCC:
 - Constrain site-specific creep properties at multiple scales
 - Coupled THM cavern modeling at two scales: Cavern- and dome scales focusing on near and far field effects



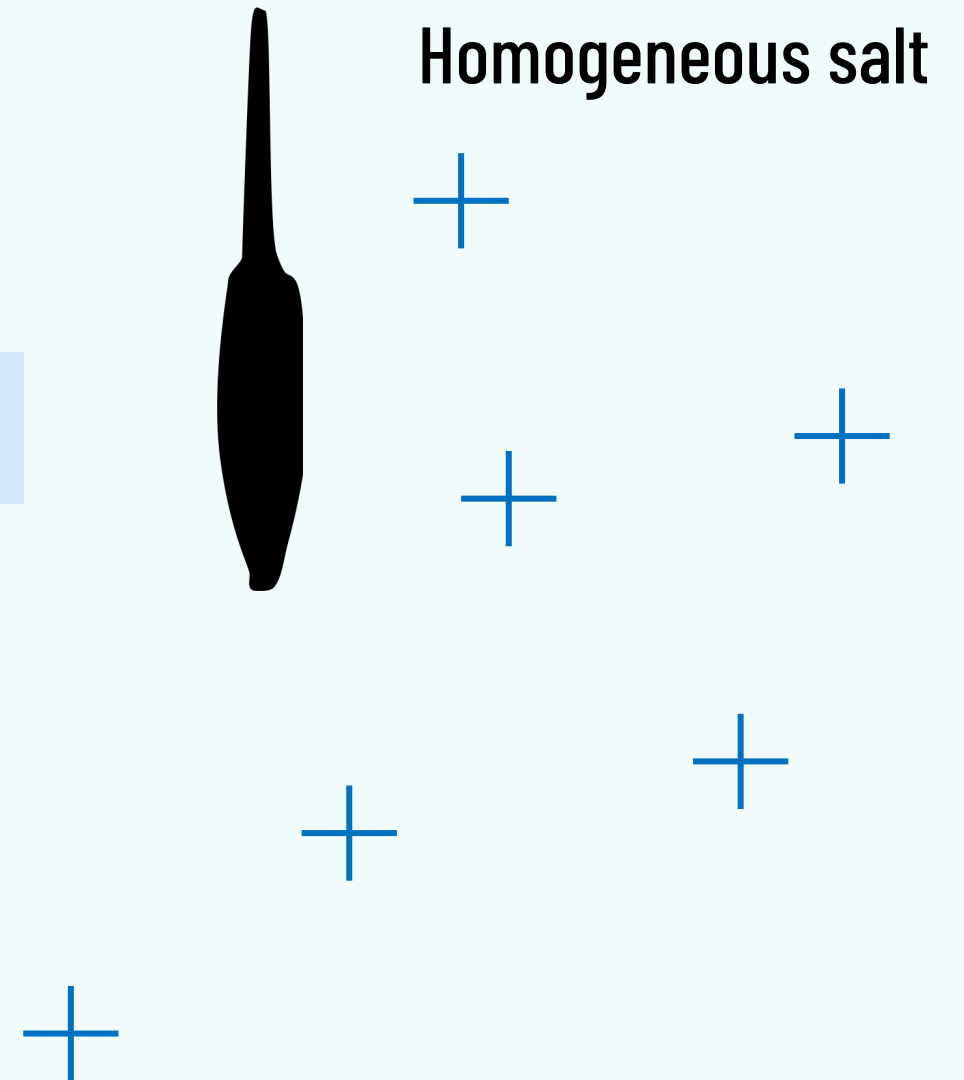
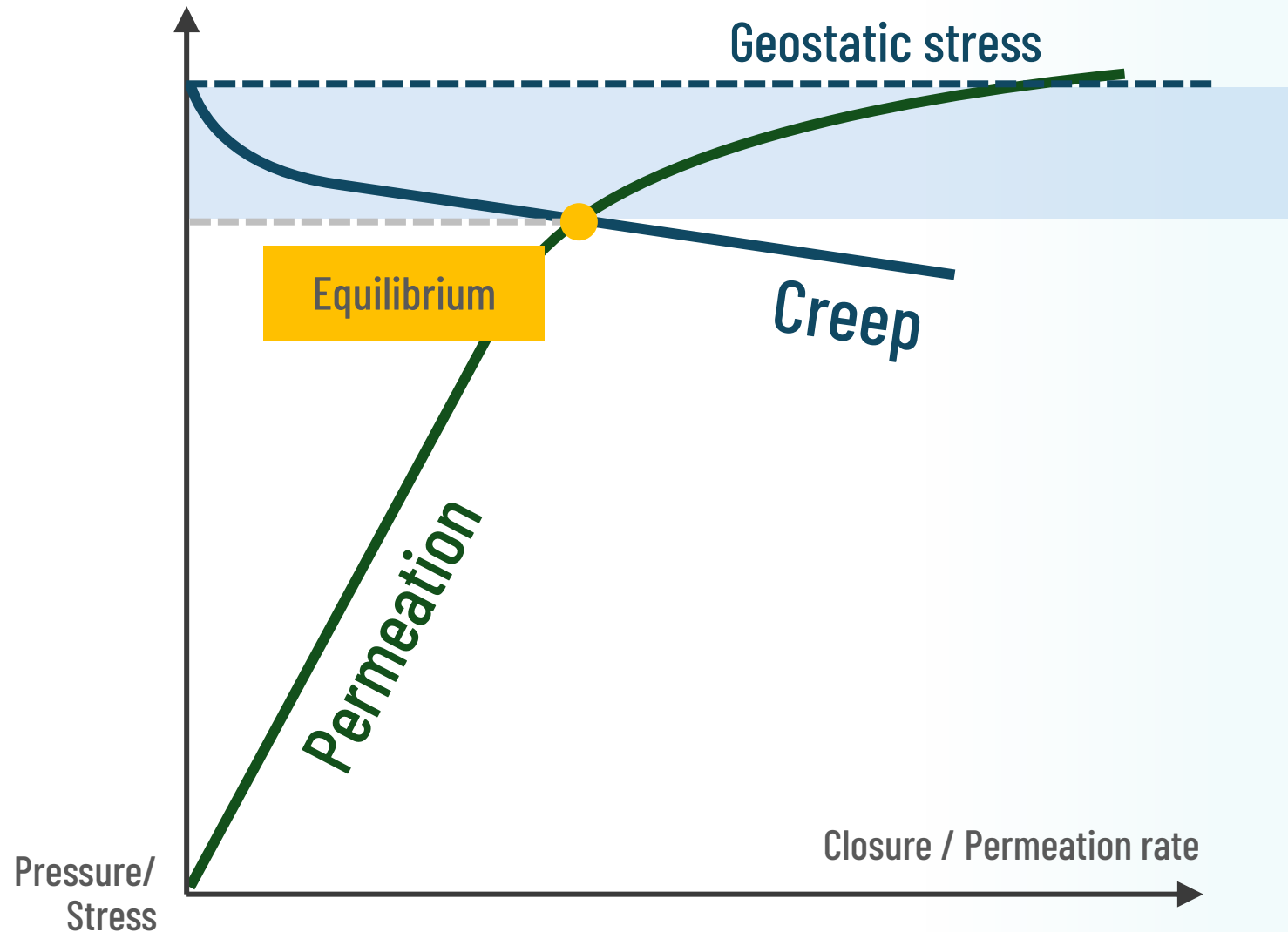
Stress state of a Zechstein salt pillow

KEM 17: Dome-scale report, Baumann et al. (2019)



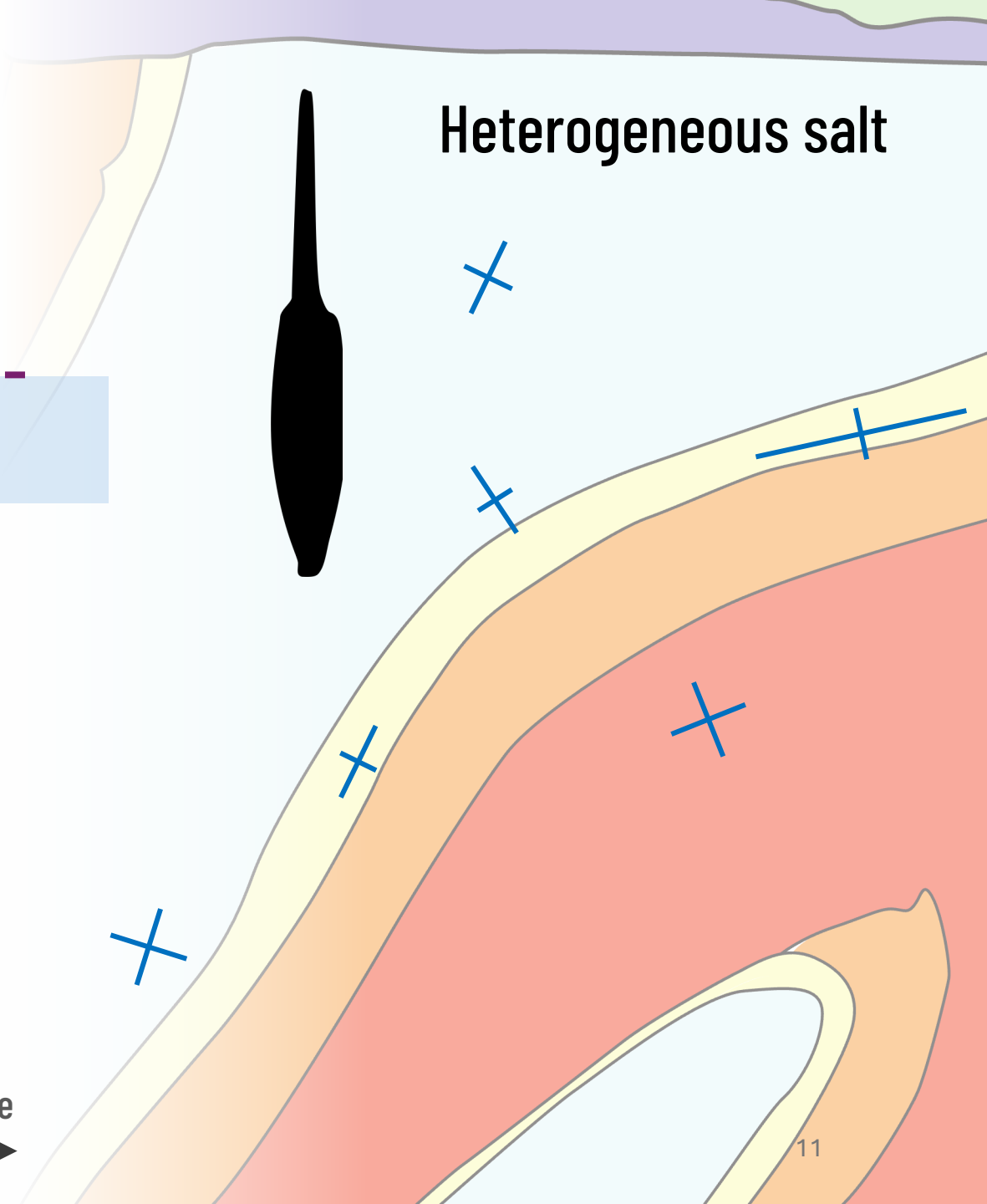
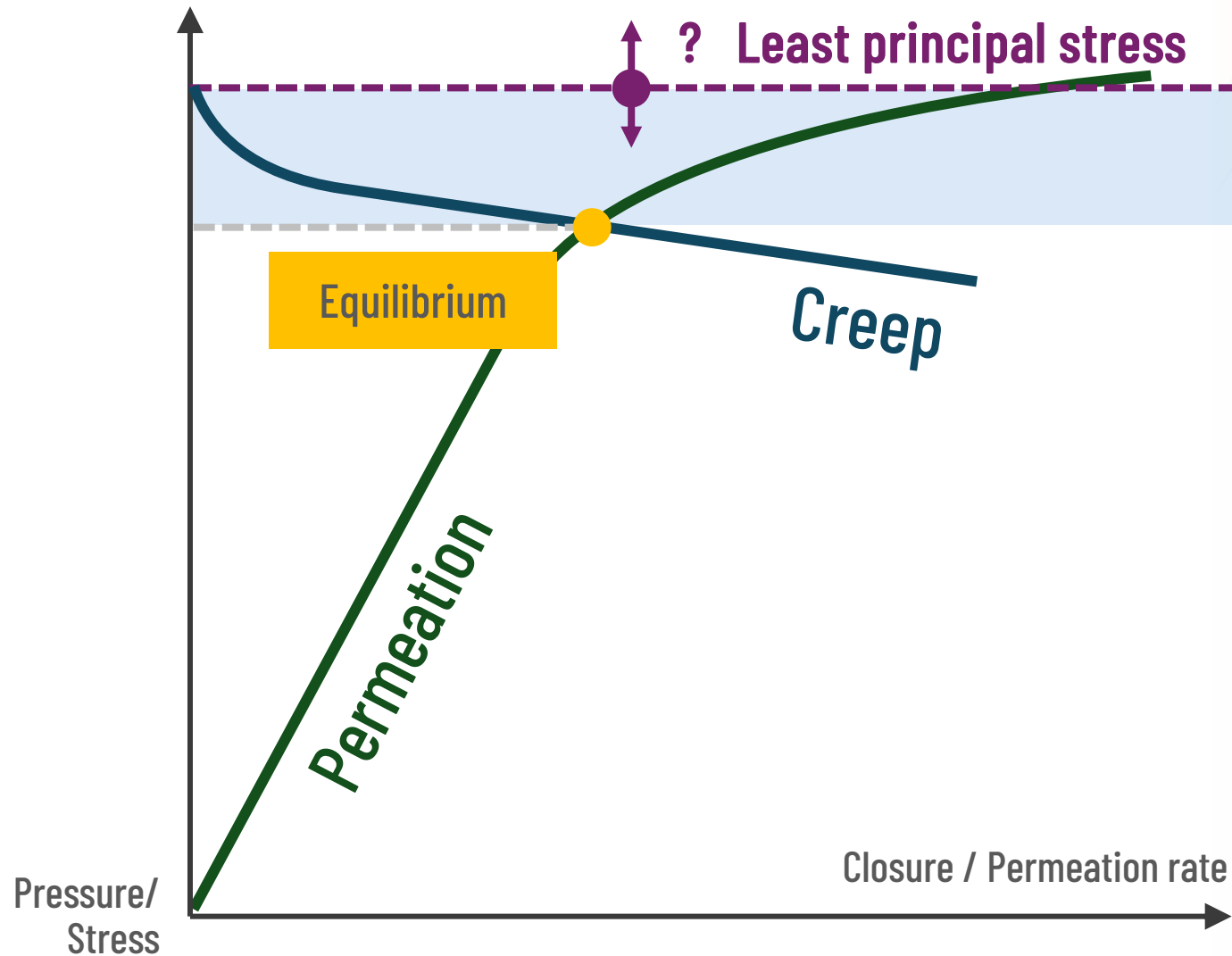
Modeling cavern abandonment

Geostatic vs. least principal stress




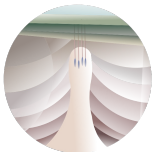
Modeling cavern abandonment

Geostatic vs. least principal stress

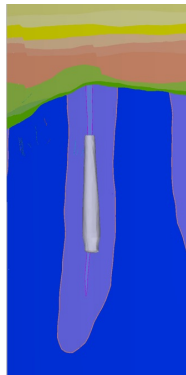


Multi-scale approach

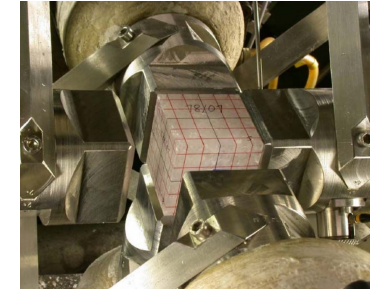
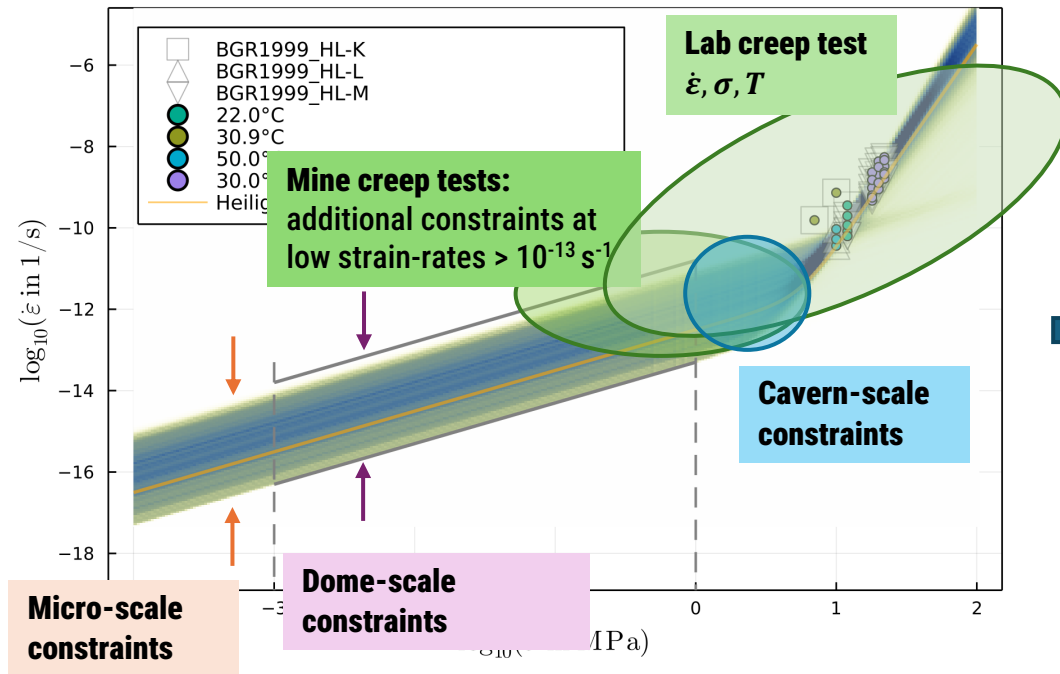
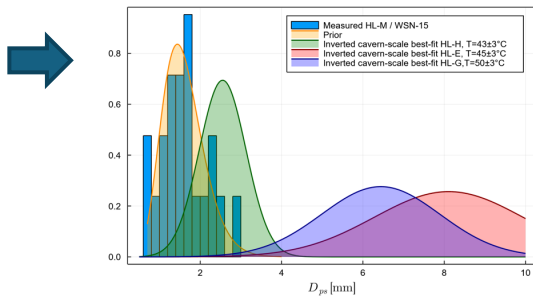
- 
- Micro-scale constraints**



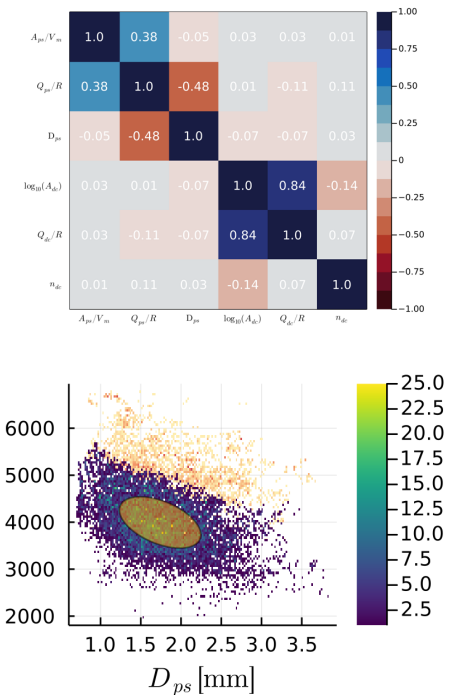
Cavern
Closure
Consortium



Cavern-scale constraints



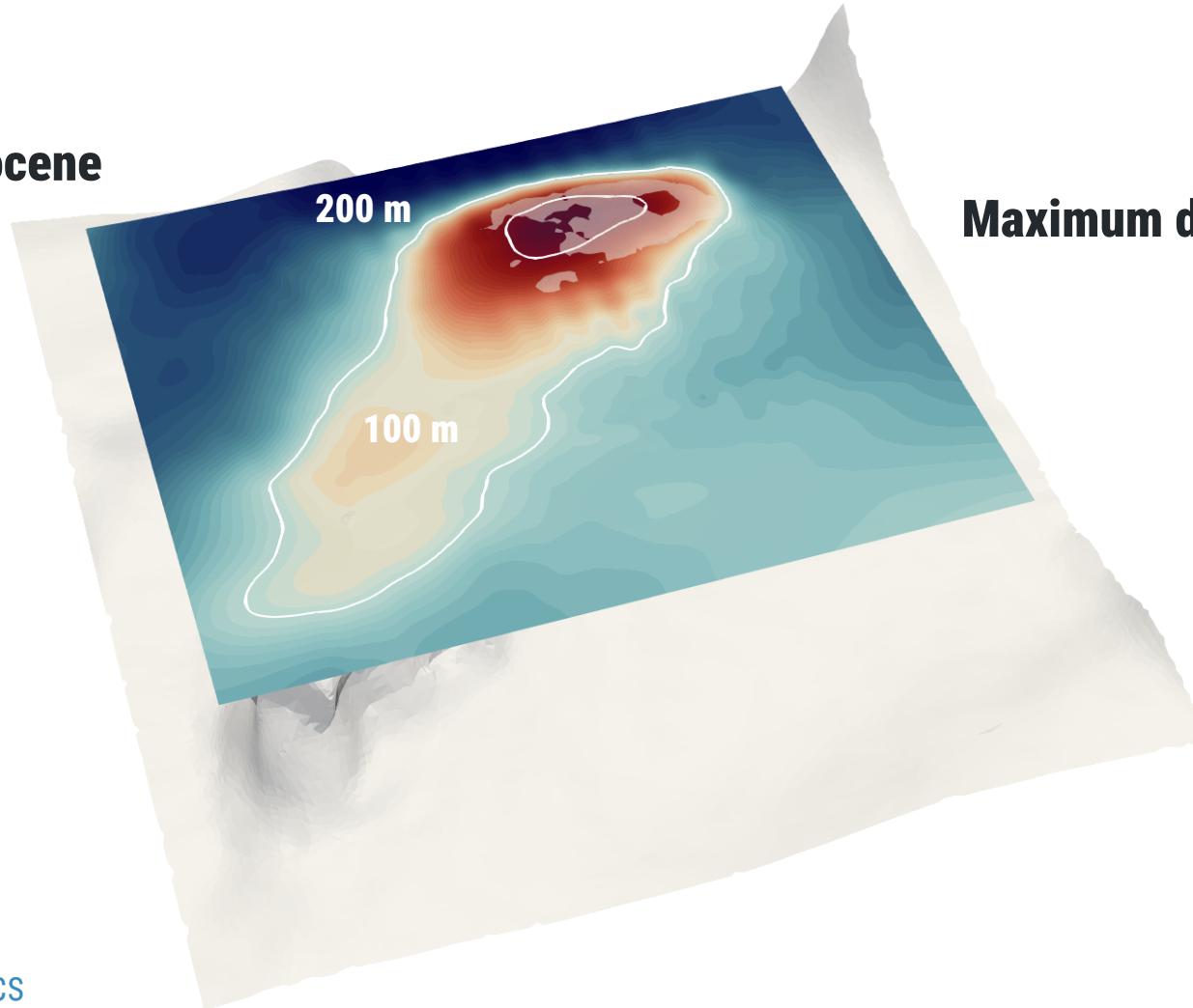
Lab-scale constraints



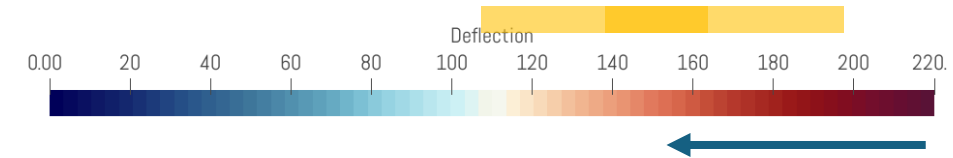
Site-specific creep model

Dome-scale constraints

Base Miocene



Maximum deflection: 200 m



← - 30%*

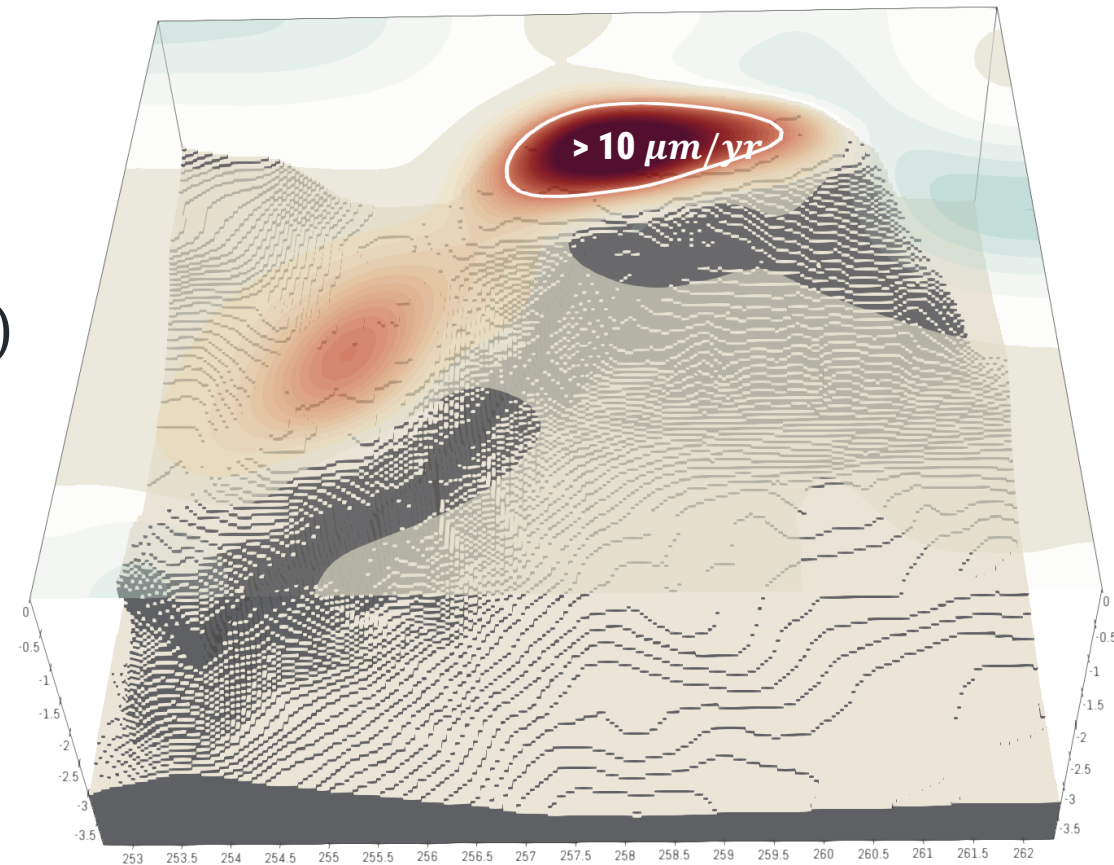
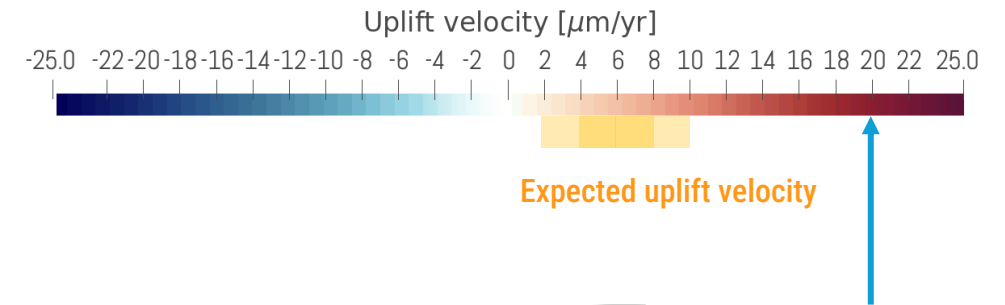
*Correction for diff. compaction

Site-specific creep model

Dome-scale constraints

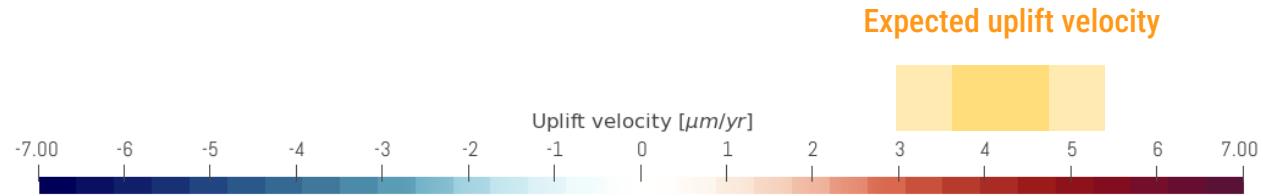
Systematic 3D TM simulations

- Find effective viscosity of salt dome that matches the expected uplift rates (grid-search)
- Result: first-order bounds for the creep model, but on the scale of the dome

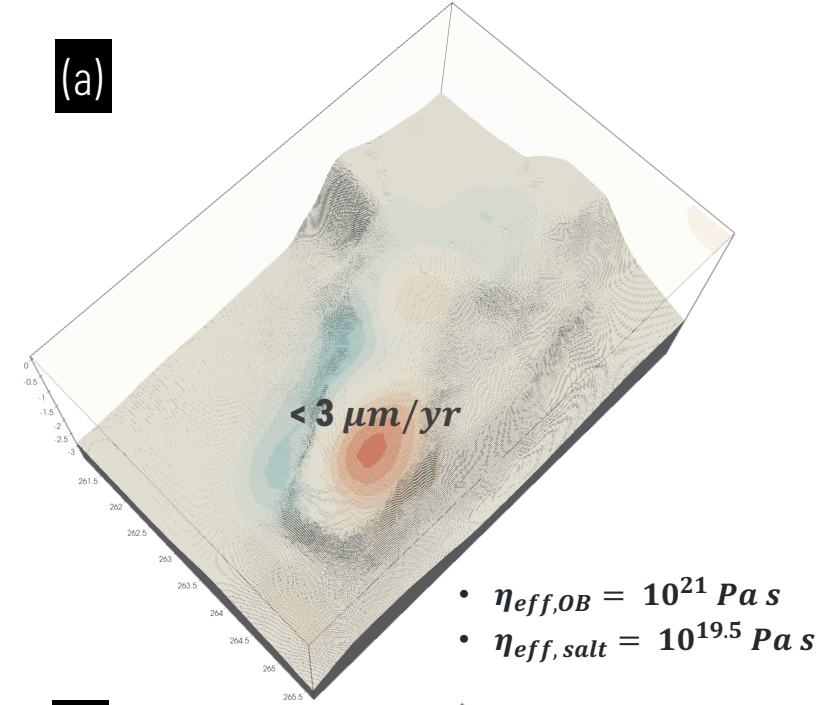


Site-specific creep model

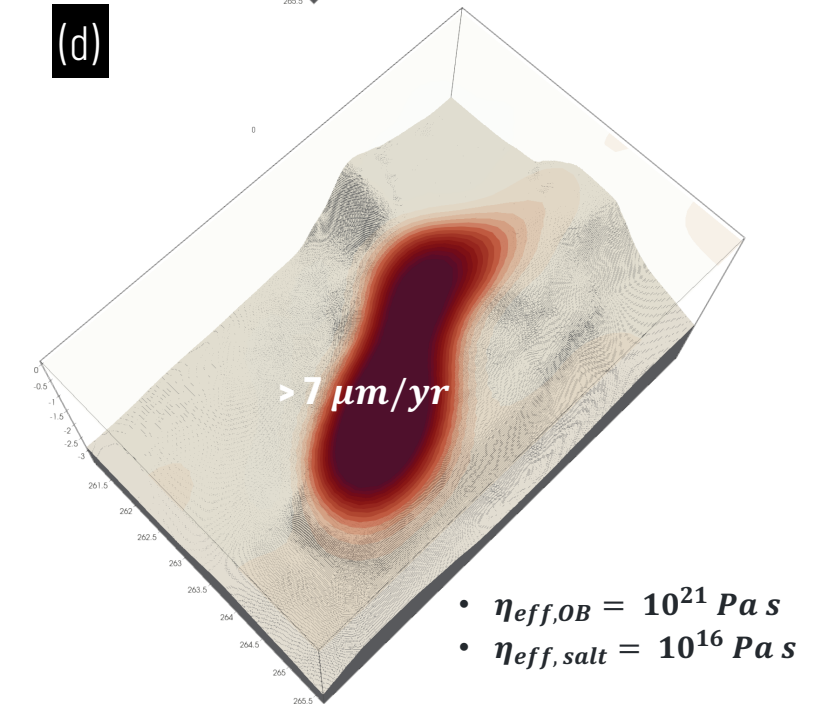
Dome-scale constraints



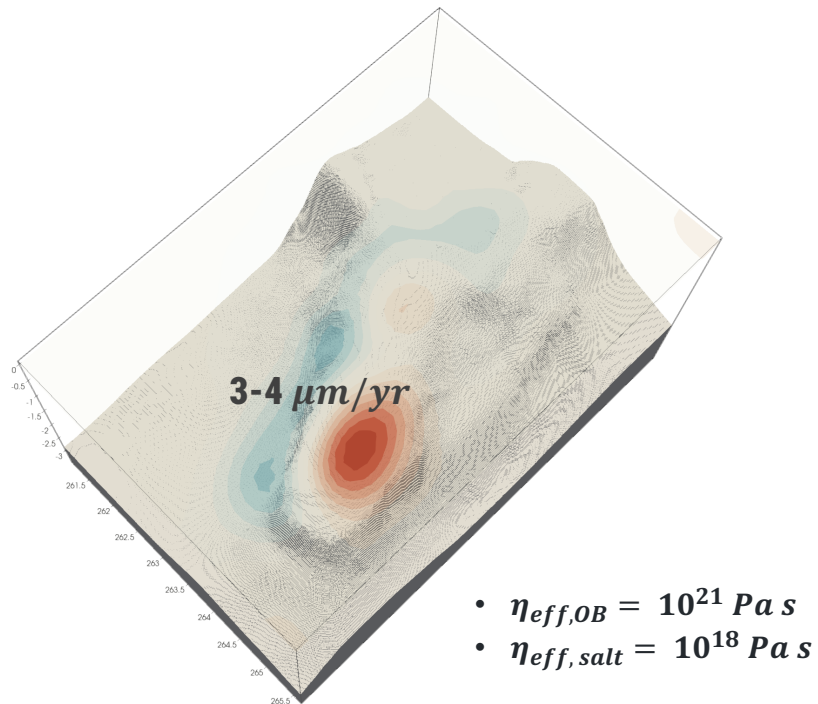
(a)



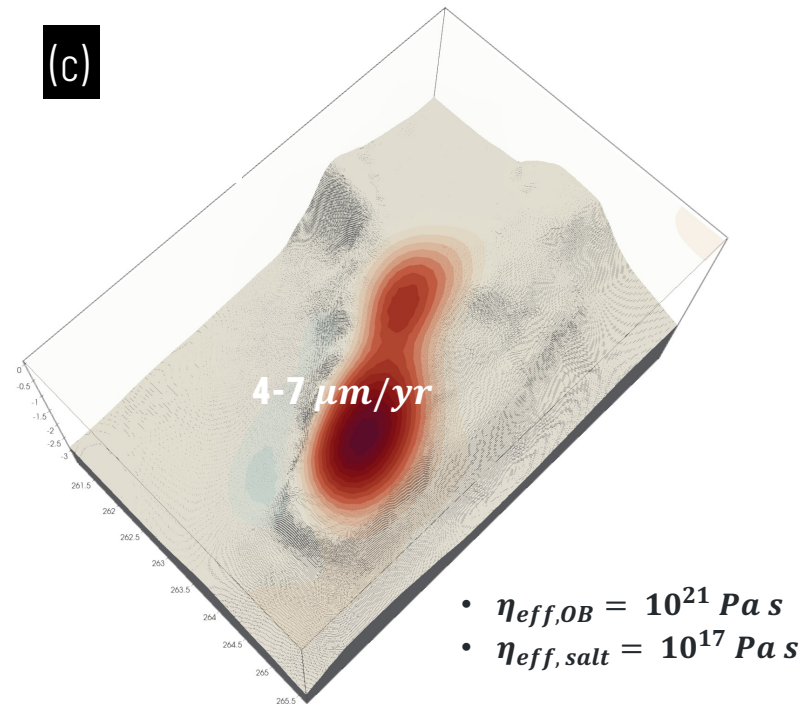
(d)



(b)

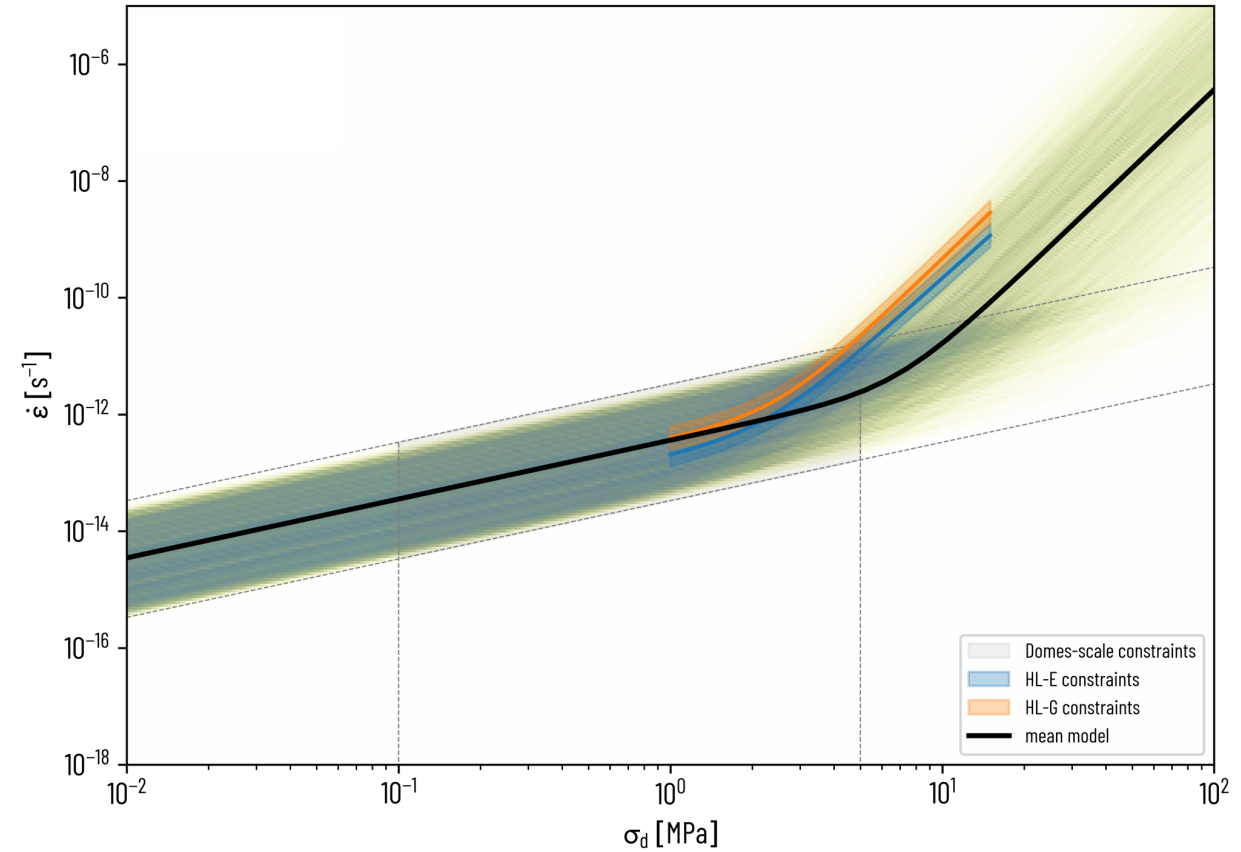
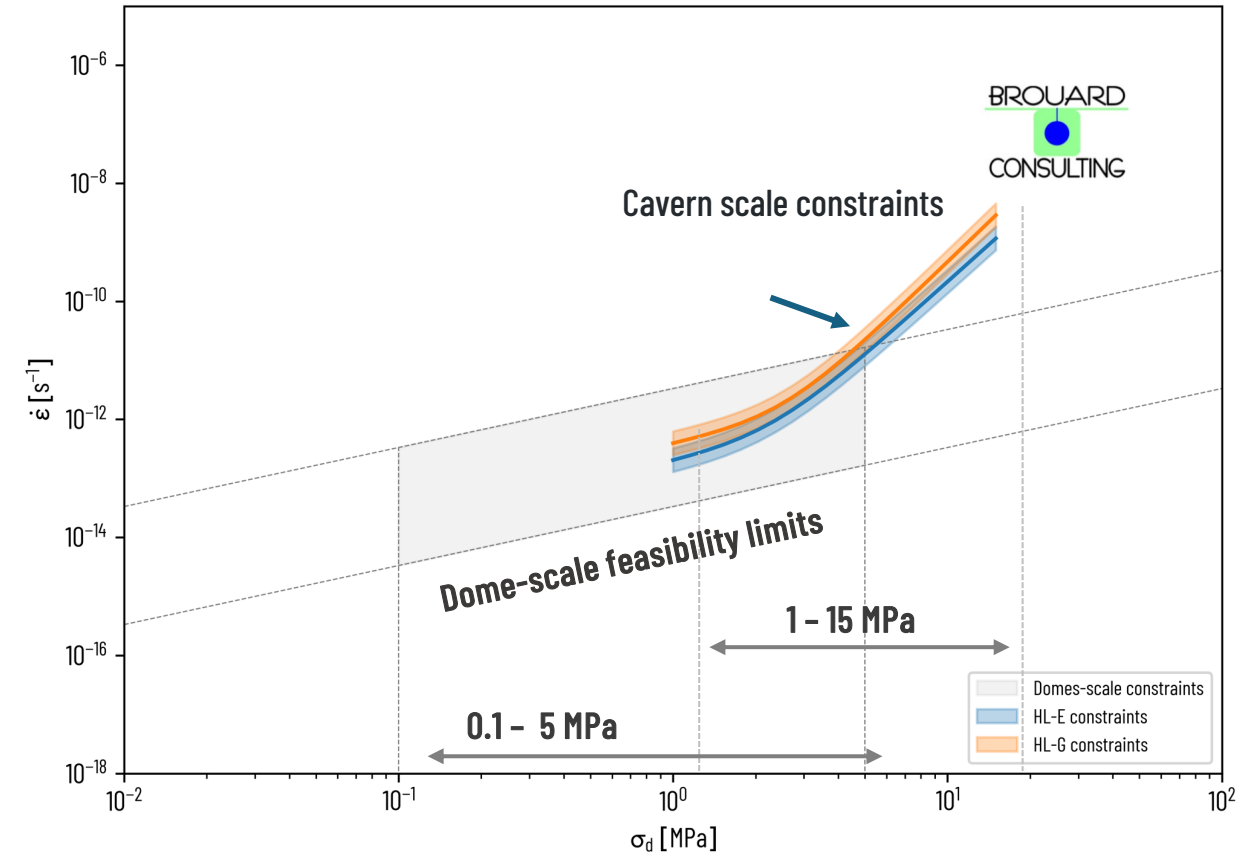


(c)



Site-specific creep model

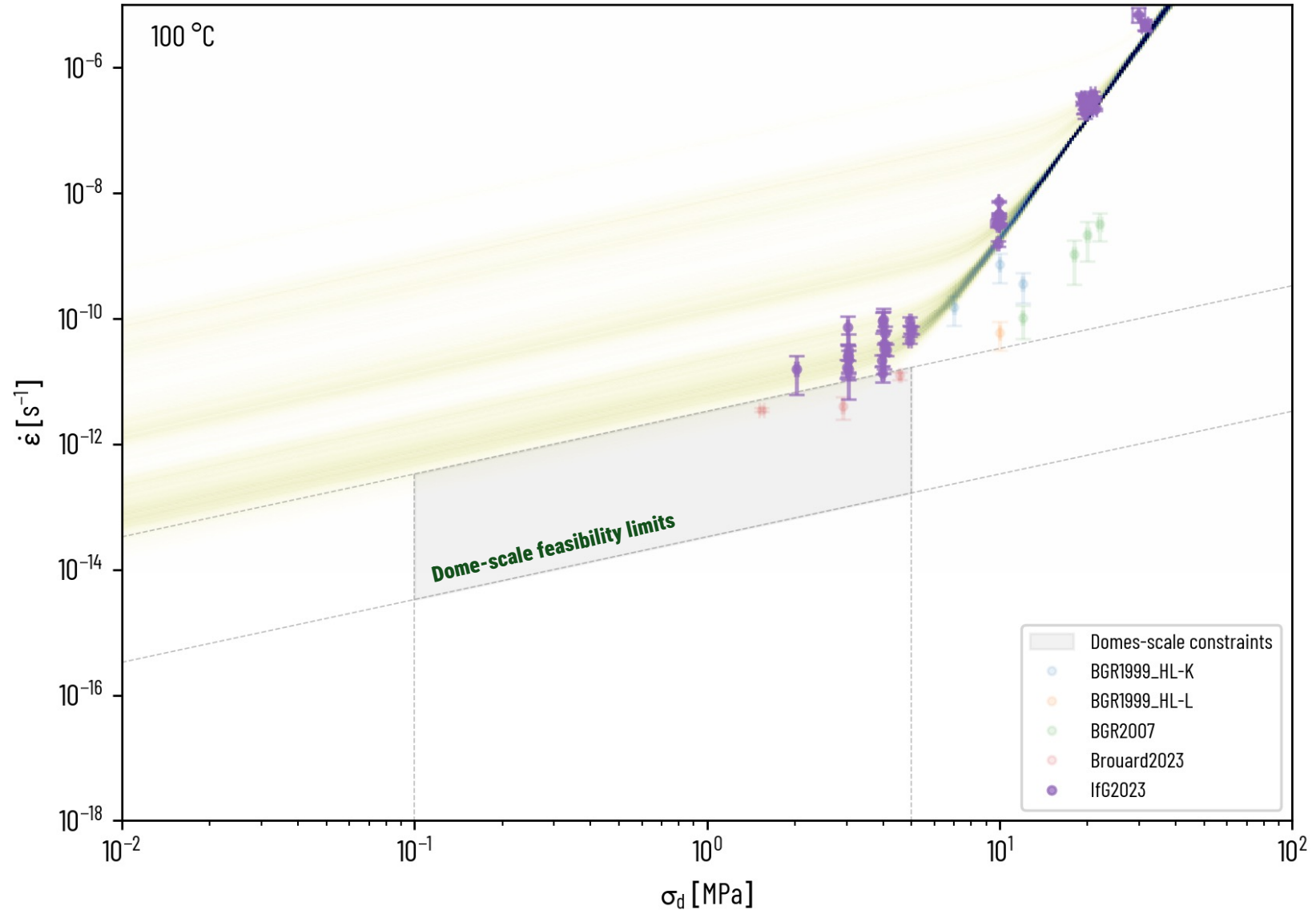
Combine constraints from dome- and cavern scale



Site-specific creep model

Lab-scale constraints

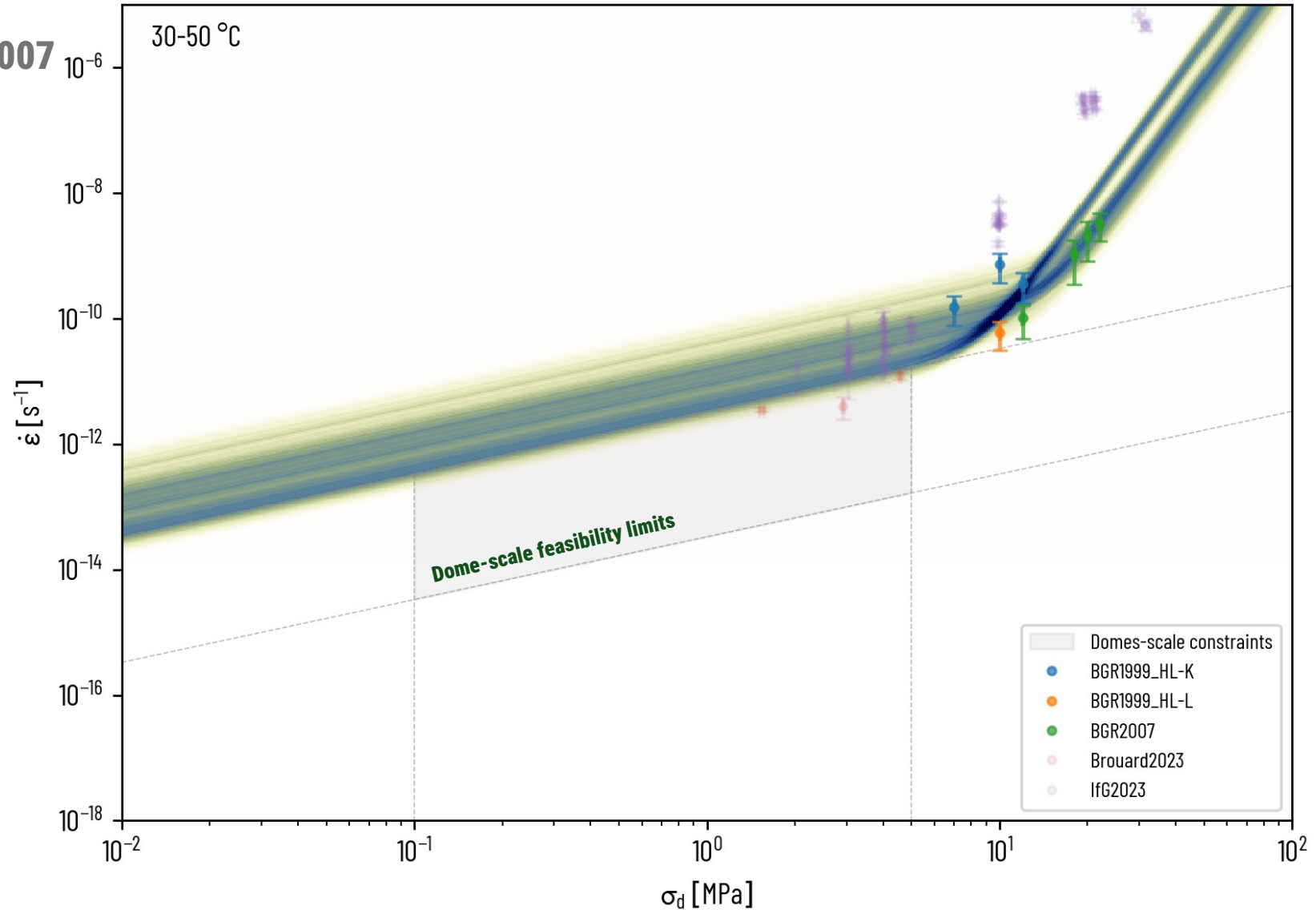
Strain rate prediction with IfG 2023
conditions ($T \sim 100^\circ\text{C}$, samples, ...)



Site-specific creep model

Lab-scale constraints

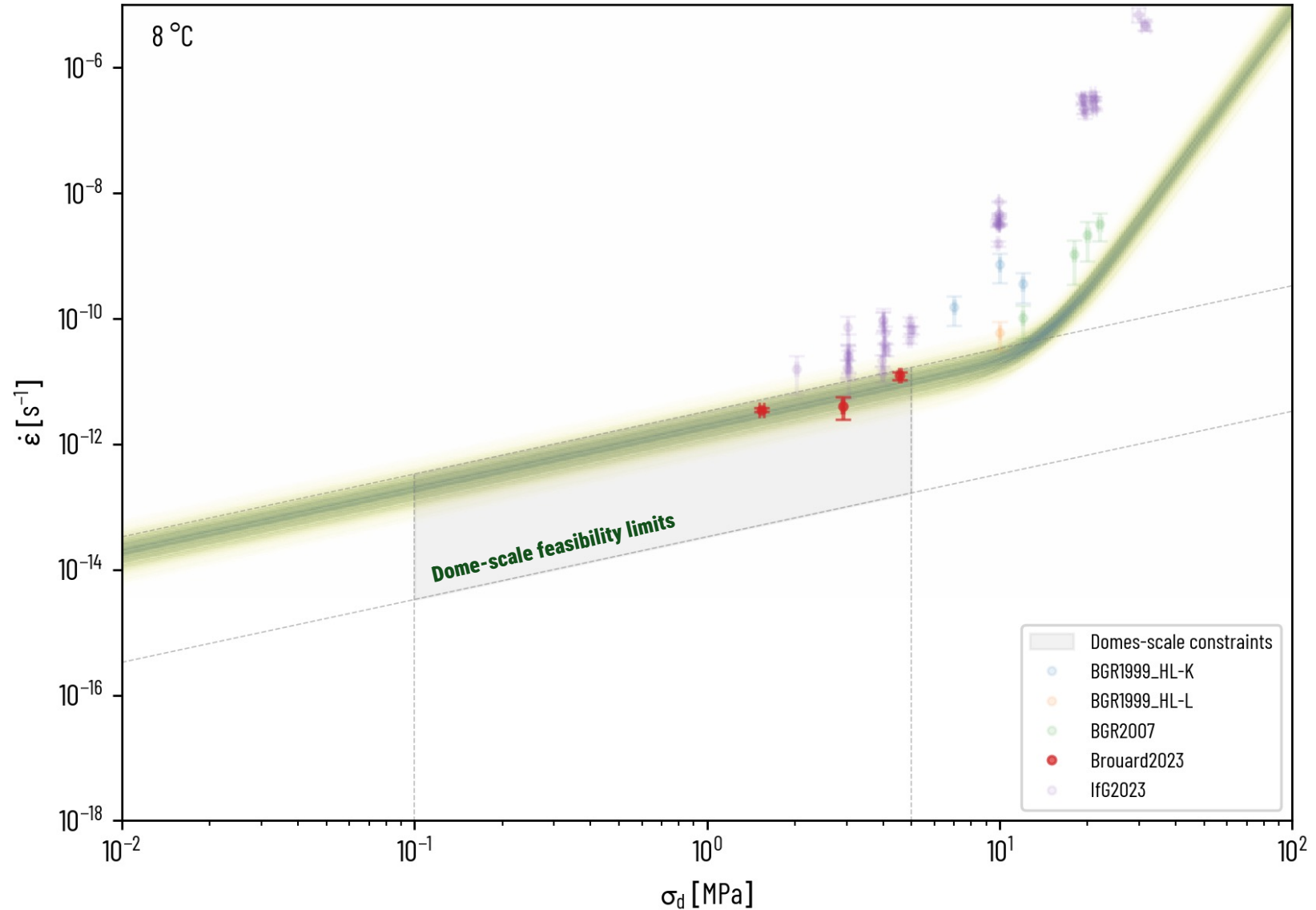
Strain rate prediction with BGR 1999ab, 2007 conditions ($T \sim 30\text{-}50^\circ\text{C}$, samples, ...)



Site-specific creep model

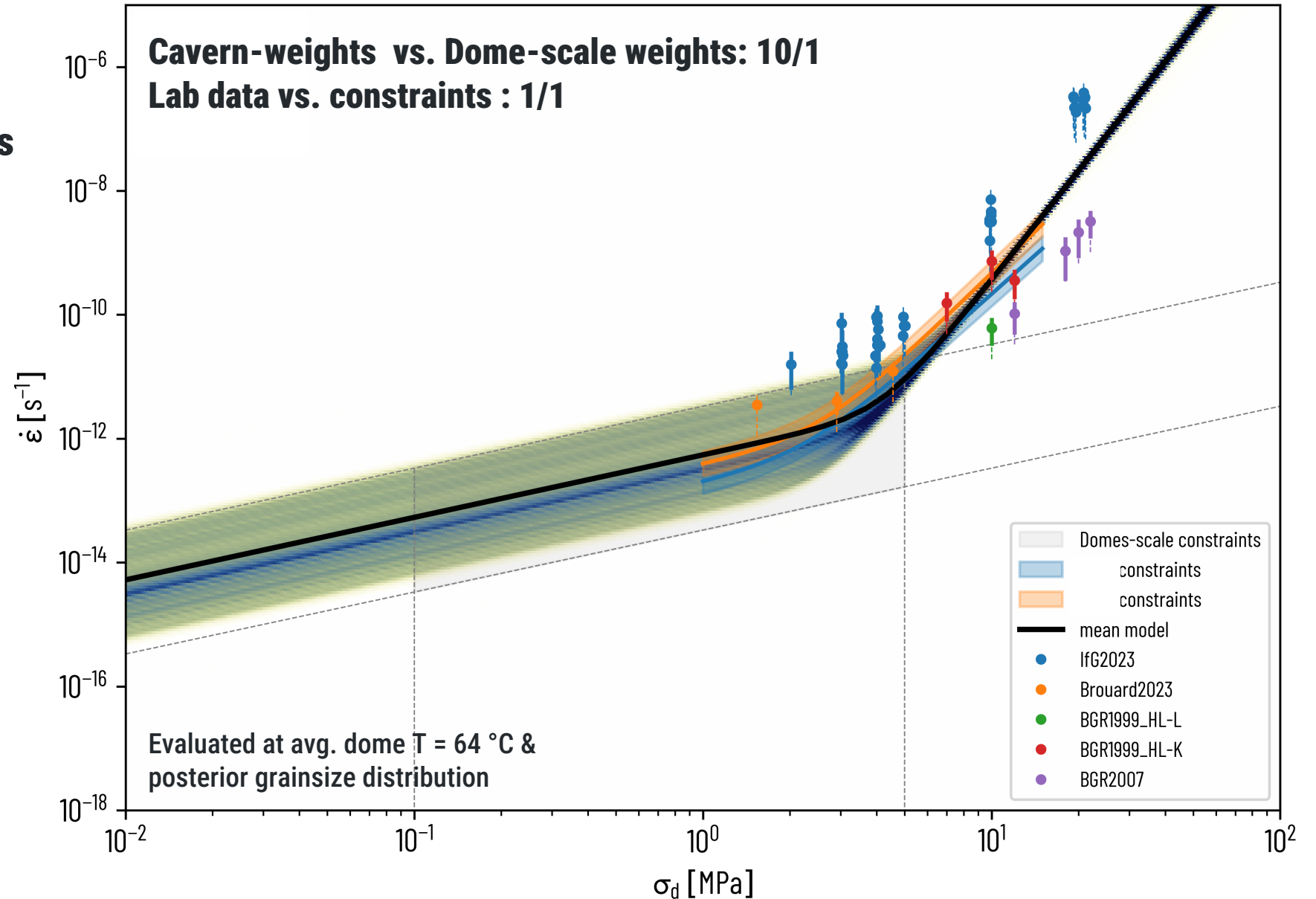
Lab-scale constraints

Strain rate prediction with Brouard 2023 conditions ($T \sim 8^\circ\text{C}$, samples, ...)



Site-specific creep model

Constrained at multiple scales



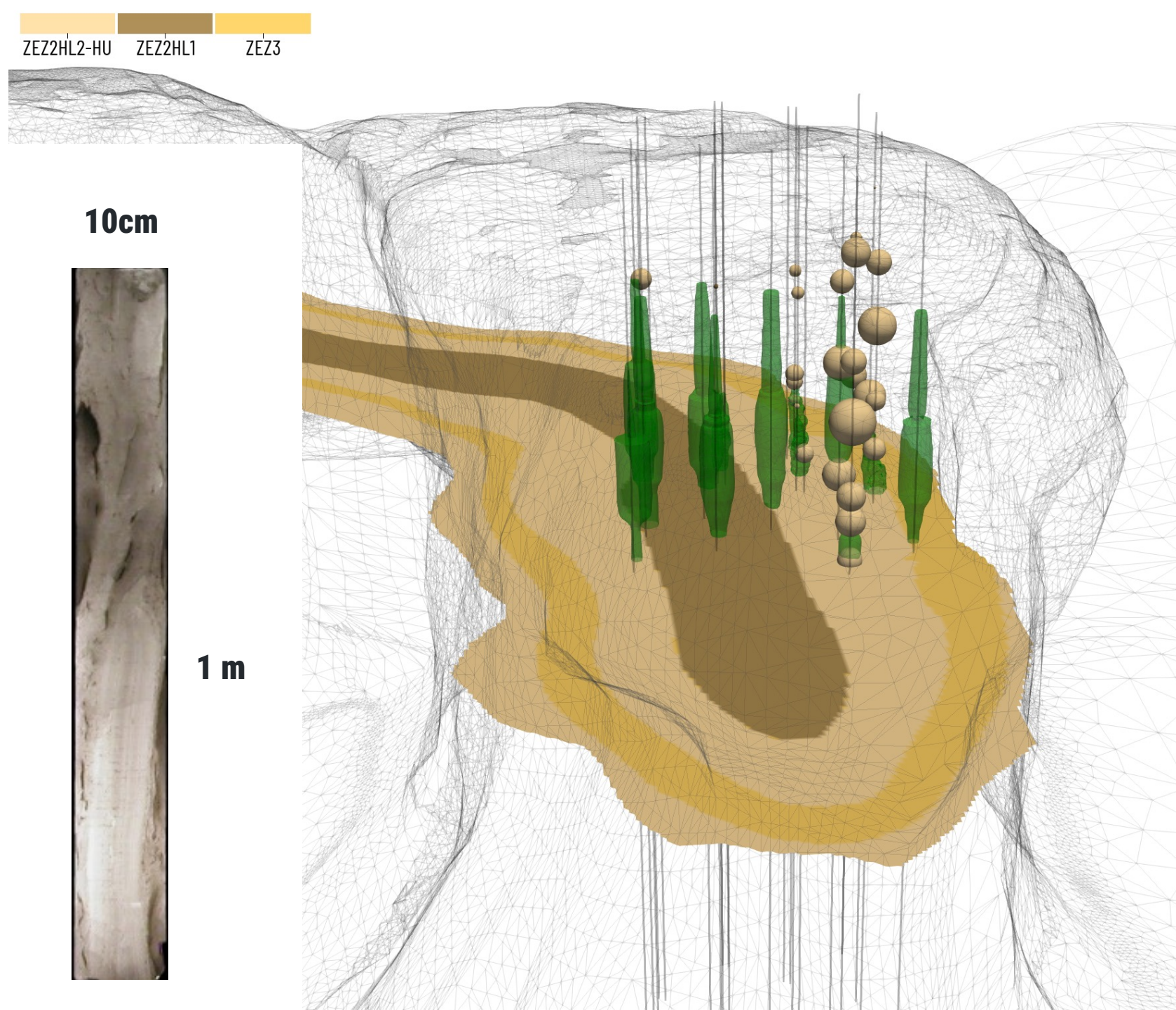
Site-specific creep model

Upscaling the multi-scale model

- Link between apparent grain size and megagrain volume fractions

Mega grain volume fractions

Mechanical unit	Average	STDEV
ZEZ2HL1	14,3%	6,3%
ZEZ2HL2/HM	33,1%	5,0%
ZEZ3	11,6%	6,8%



Creep of rock salt

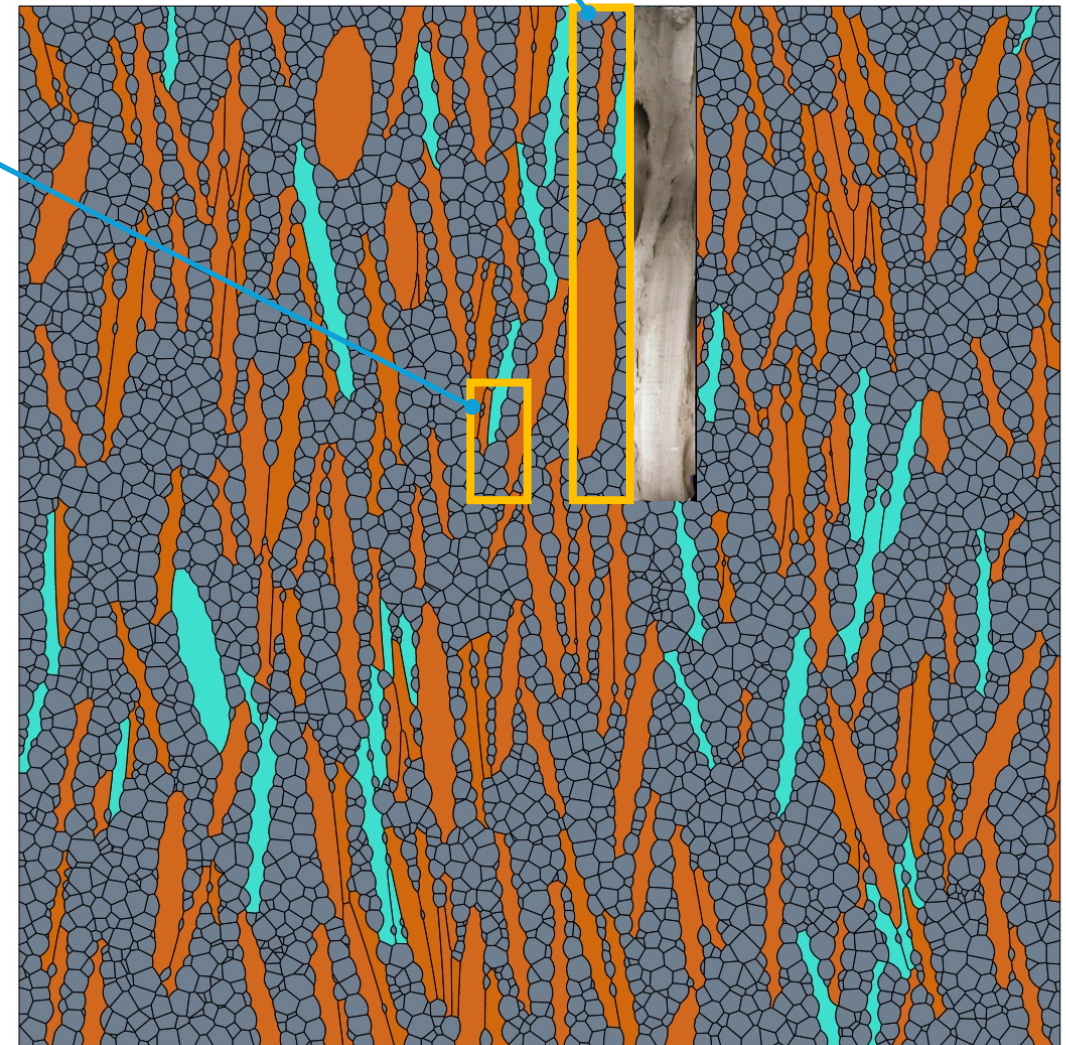
Numerical creep tests on REV scale

- Used values from available reports and literature
- Statistical model generator
- Define statistical properties of individual phases:
 - Major axis length
 - Aspect ratio
 - Orientation distribution

usual size of a
creep test
sample ~10 cm

usual width of a
drill core:
~10 cm

REV scale 2 x 2 m

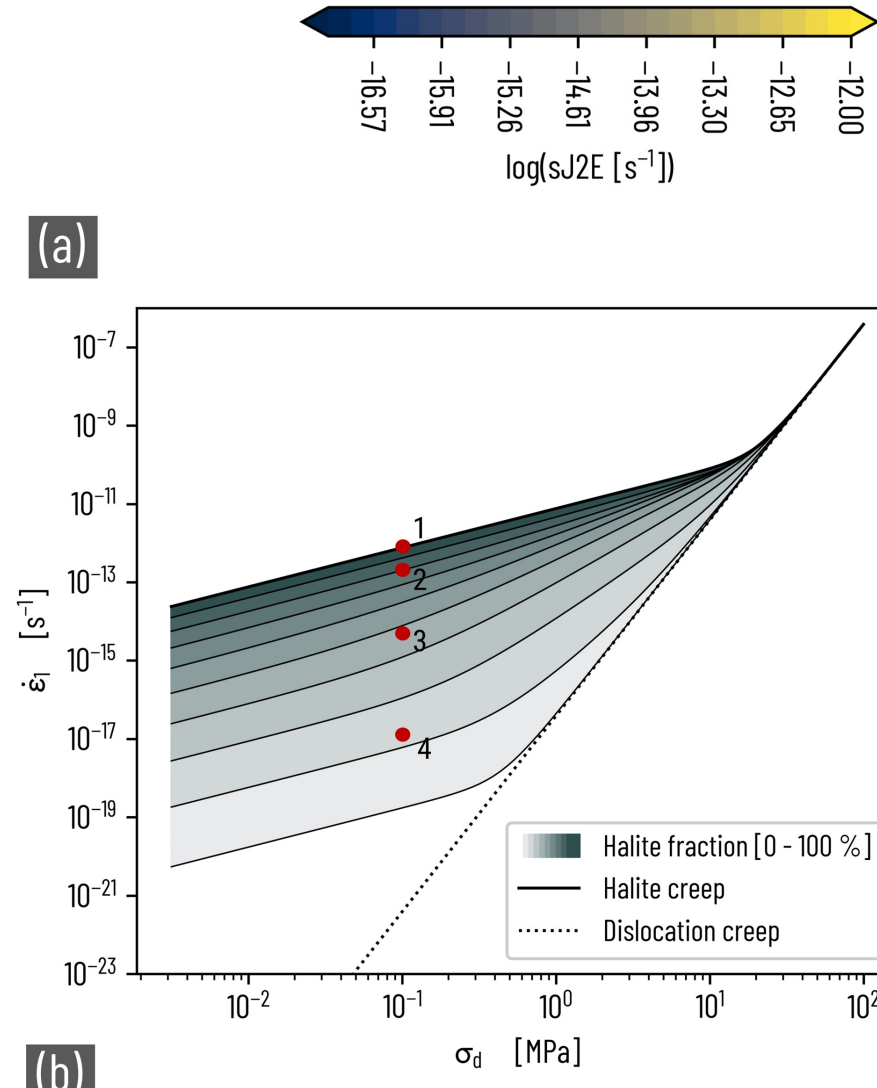


○ megagrain ○ anhydrite ● matrix

Creep of rock salt

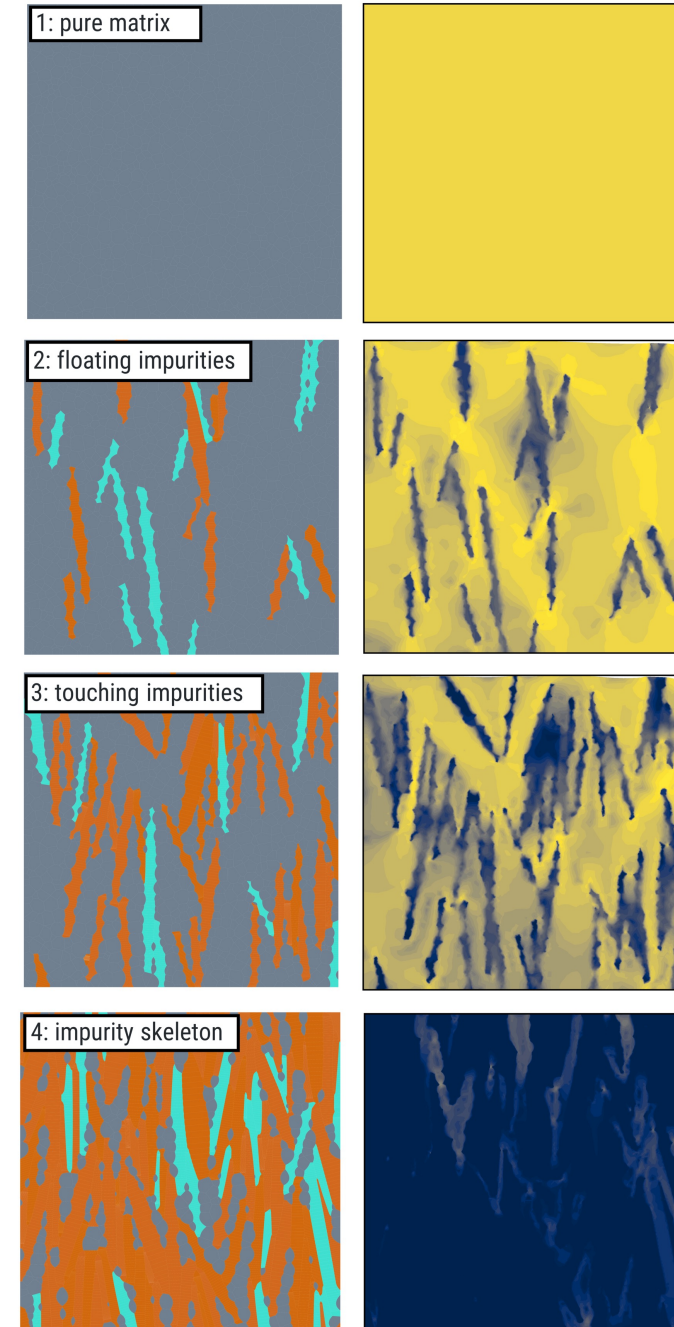
Numerical creep tests on REV scale

- High mega-grain contents may cause significant deviations from PS-creep behaviour at stresses below ~10 MPa



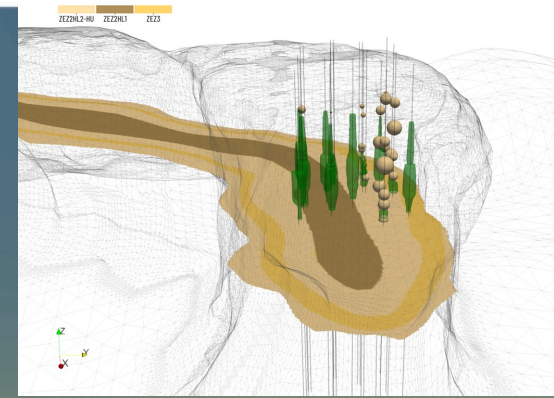
(b)

(c)



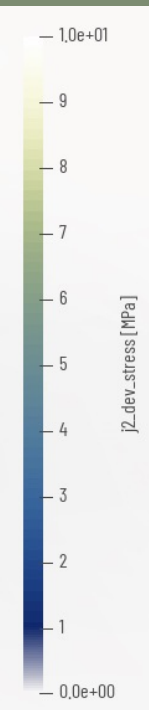
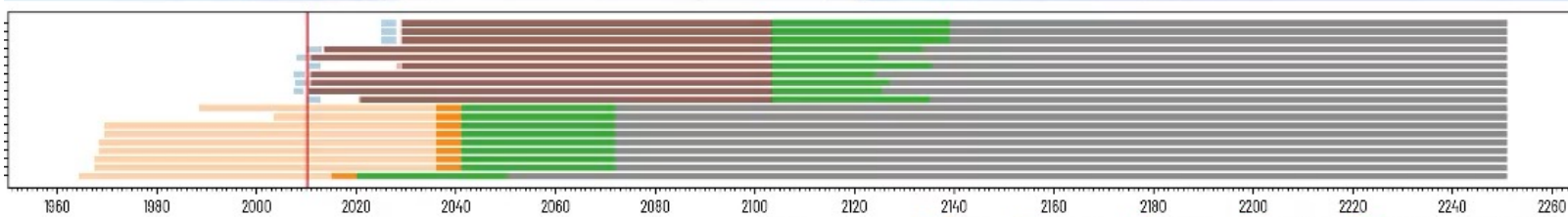
3D coupled THM model of cavern abandonment

The impact of heterogeneous rock salt on the scale of the cavern field



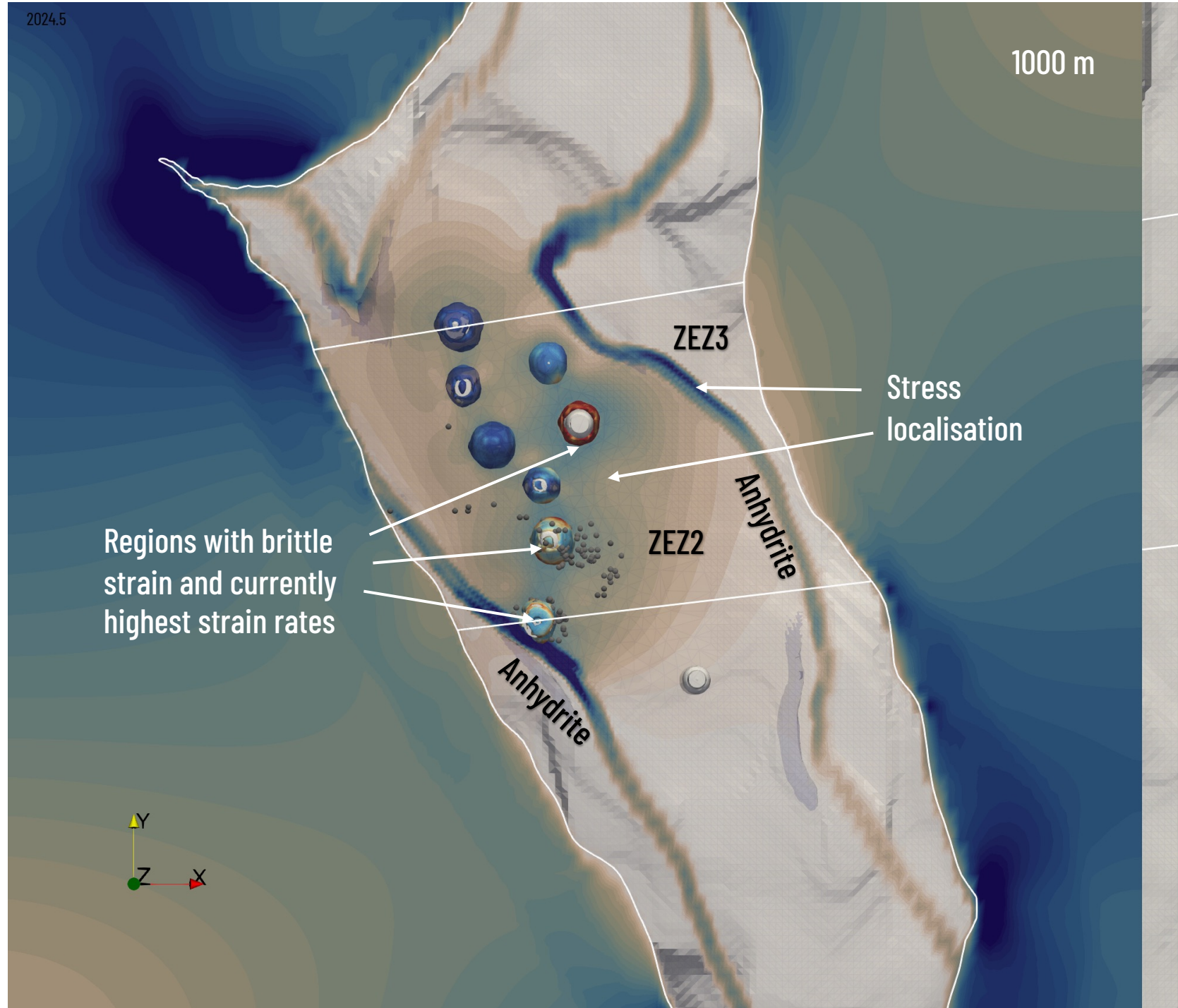
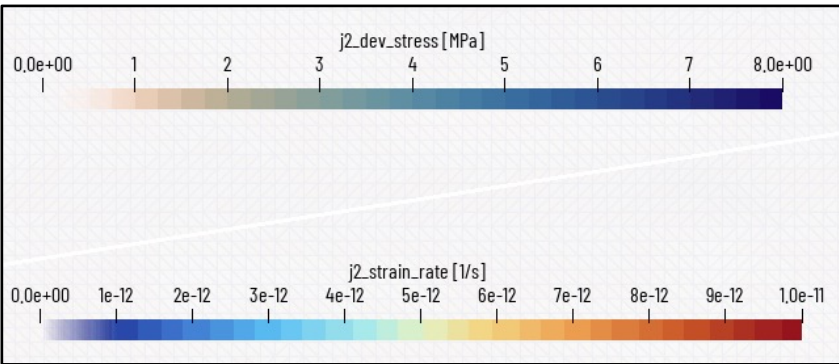
$\sqrt{J_2}$, 2nd inv. deviatoric stress

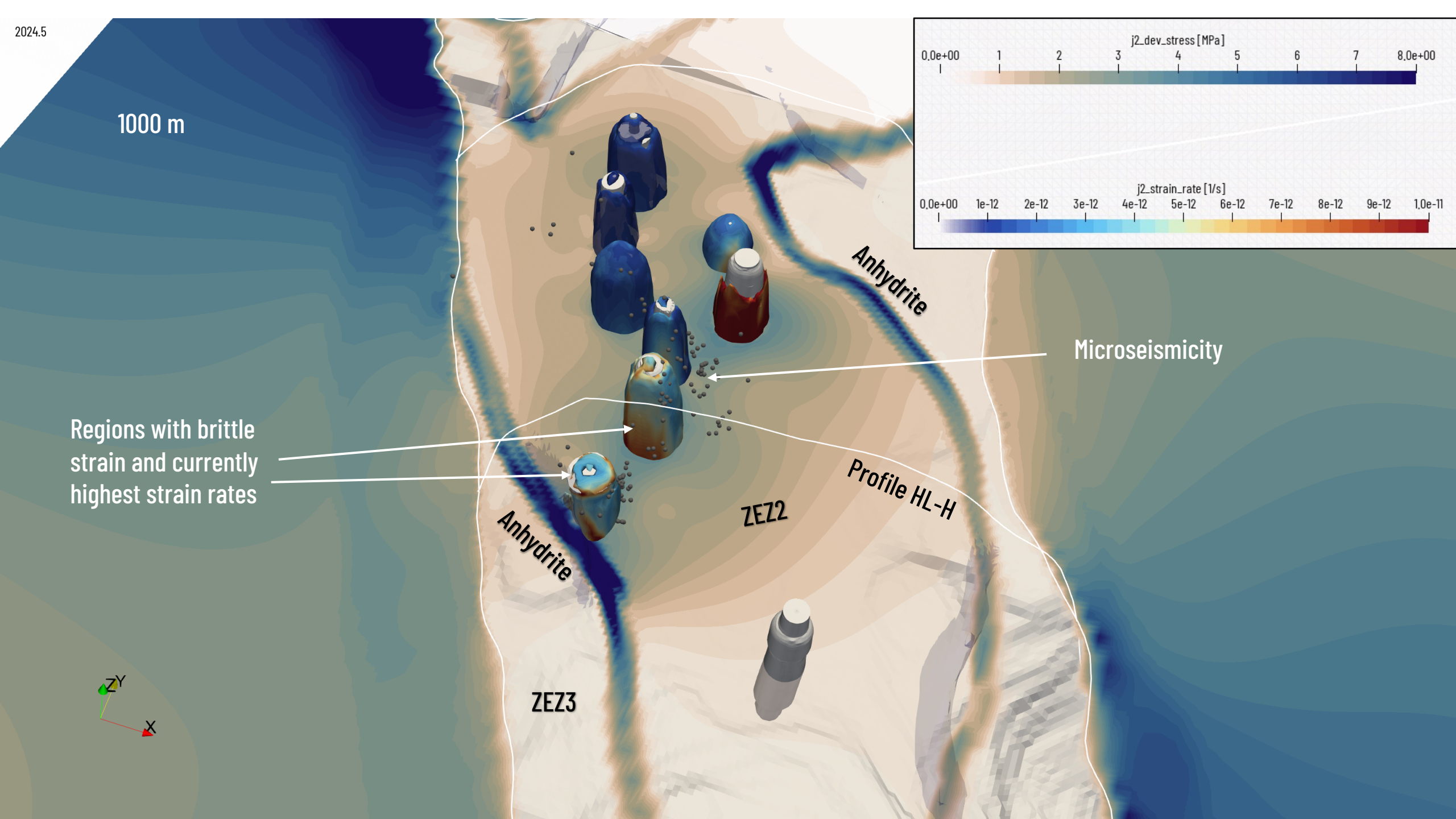
Hz. section at 1200 m depth



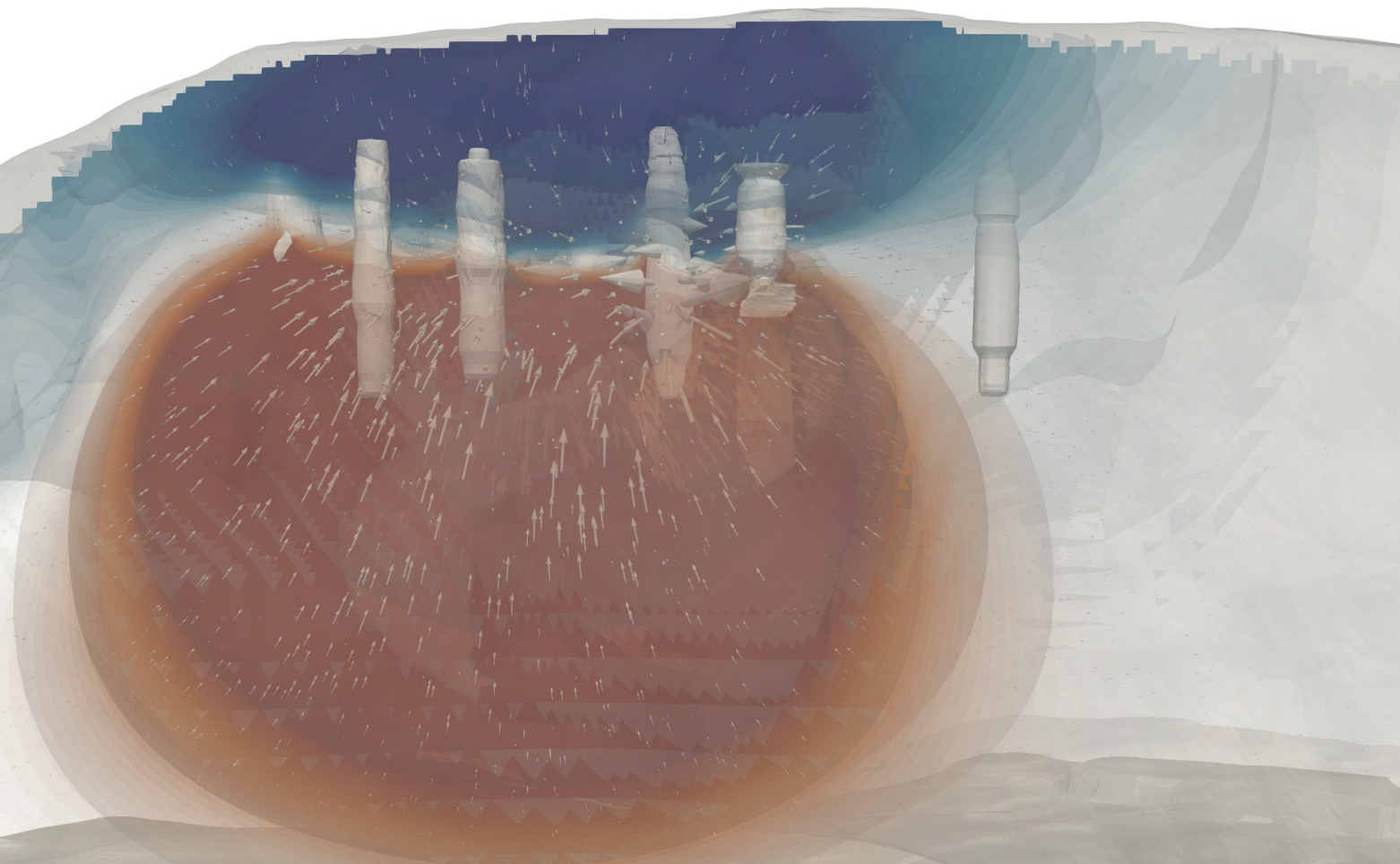
3D coupled THM model of cavern abandonment

The impact of heterogeneous rock salt on the scale of the cavern field

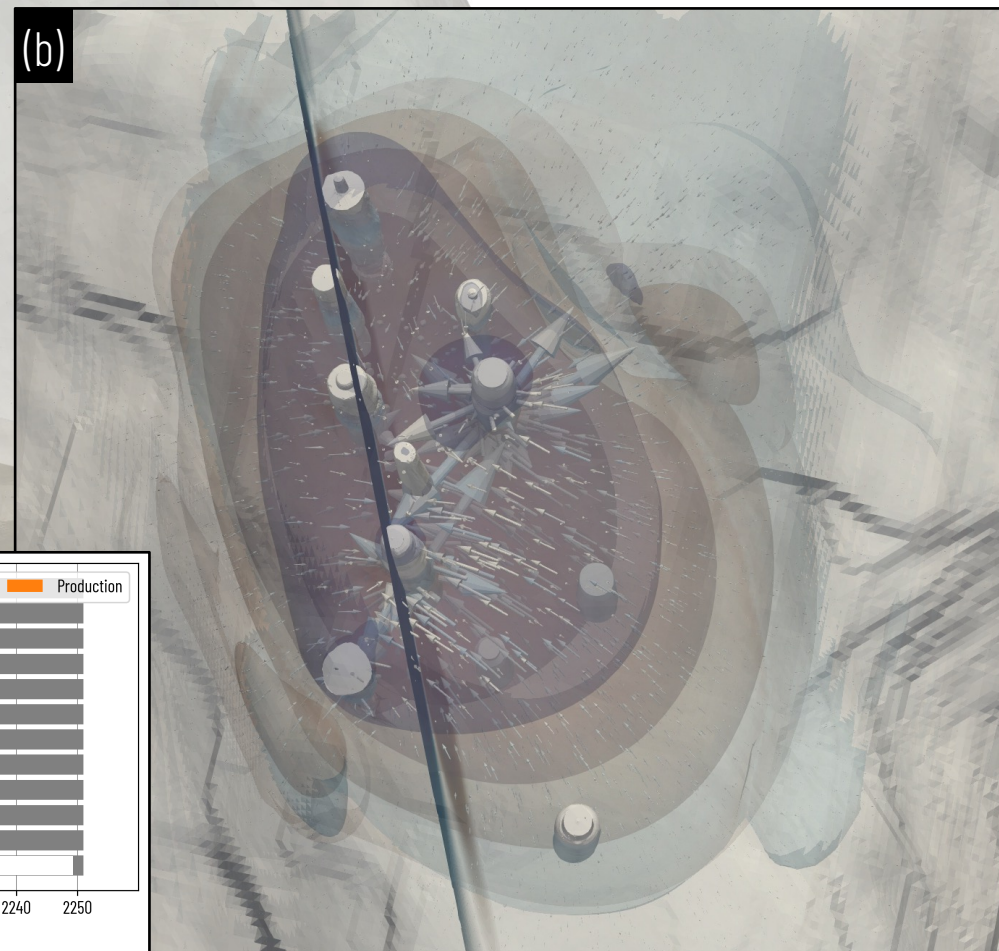




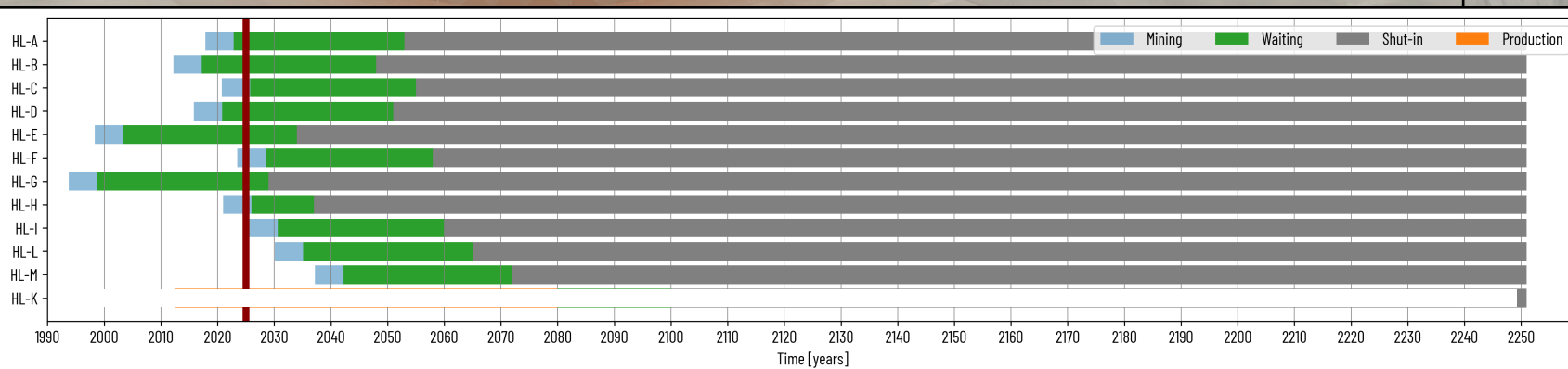
(a)



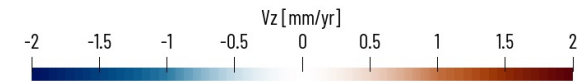
2025



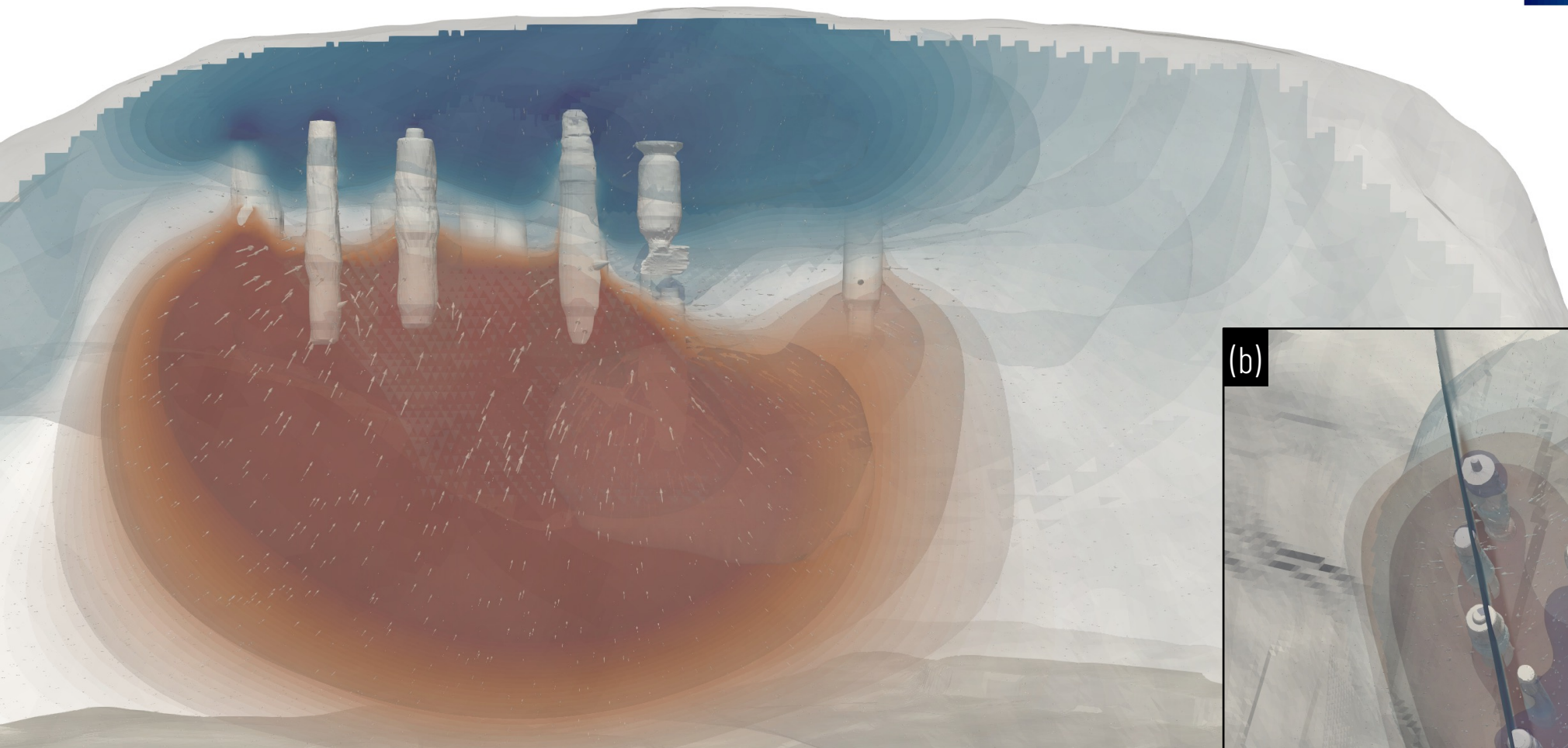
(b)



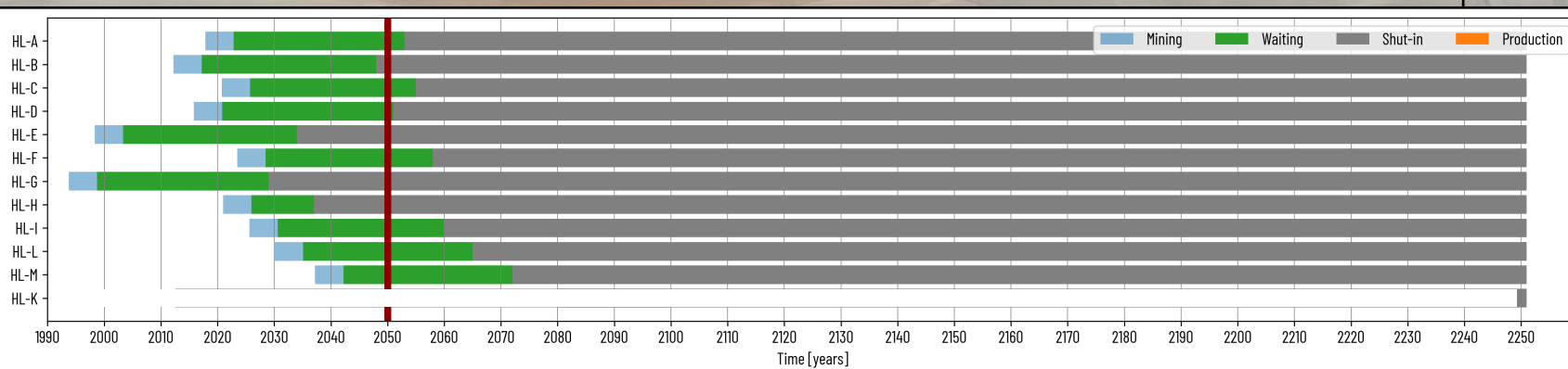
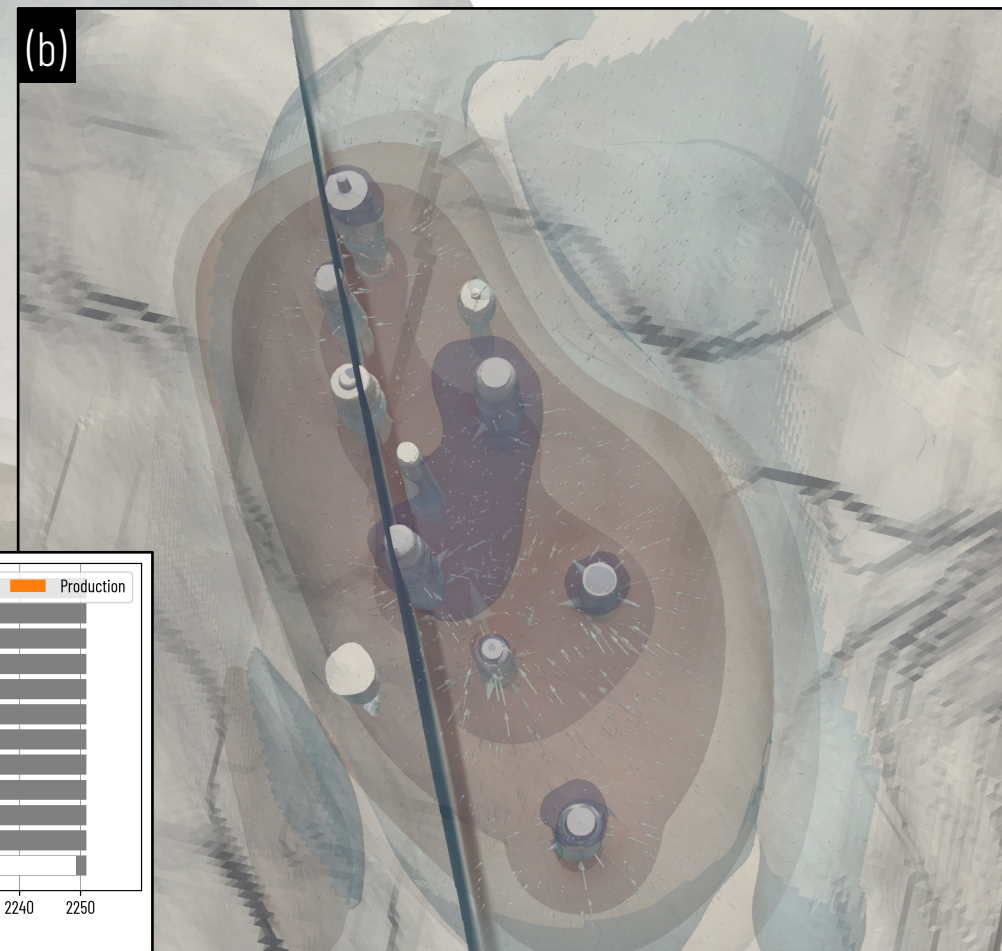
(a)



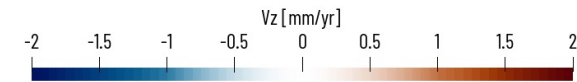
2050



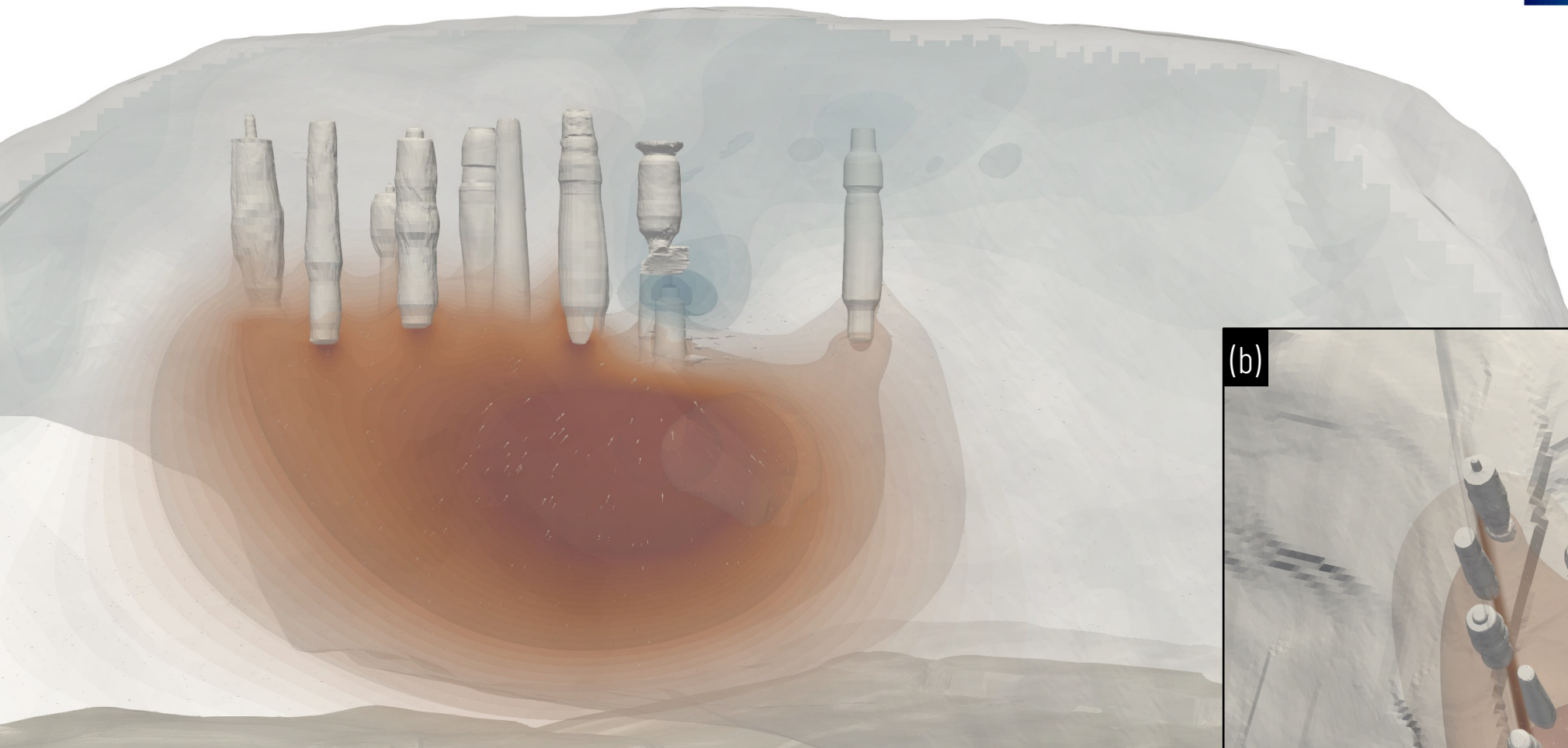
(b)



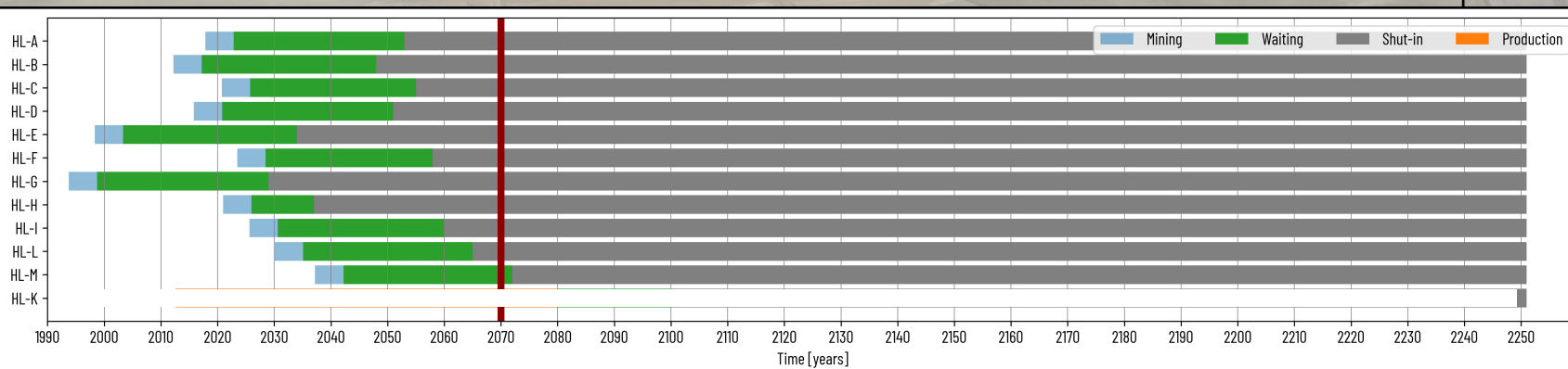
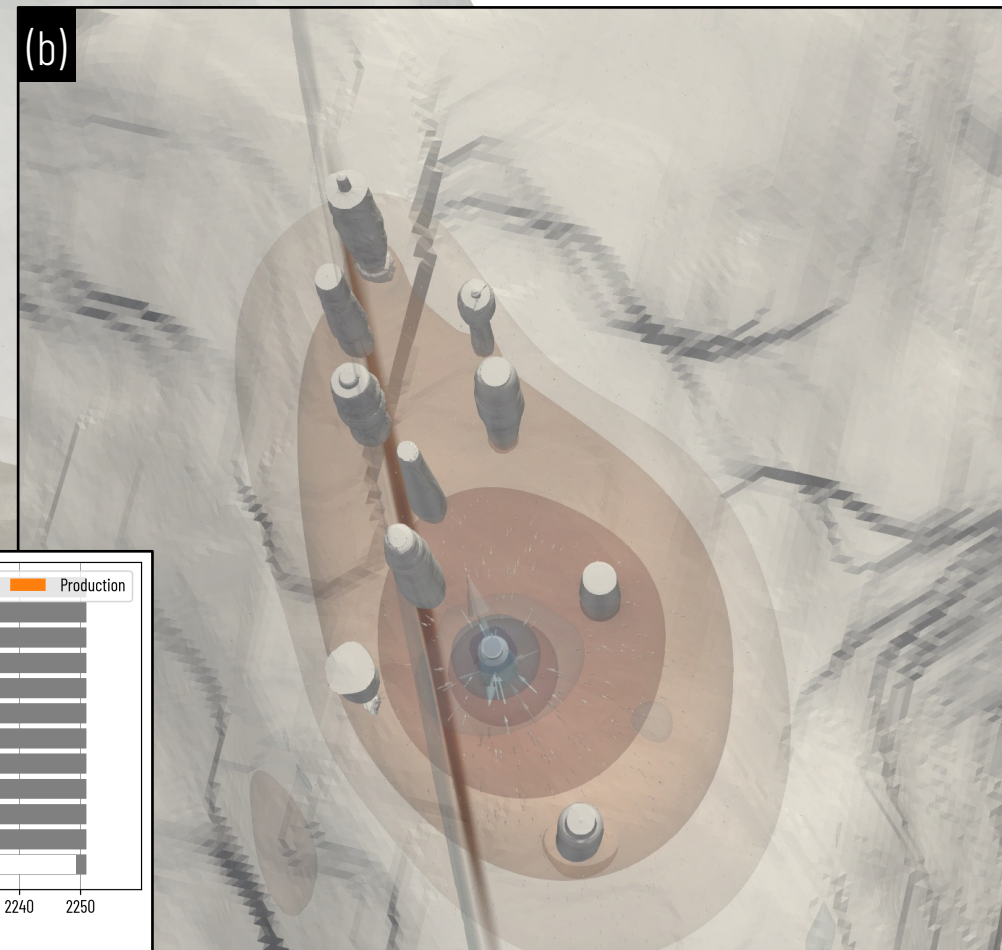
(a)



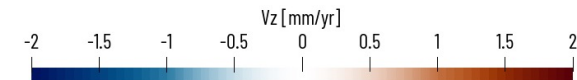
2070



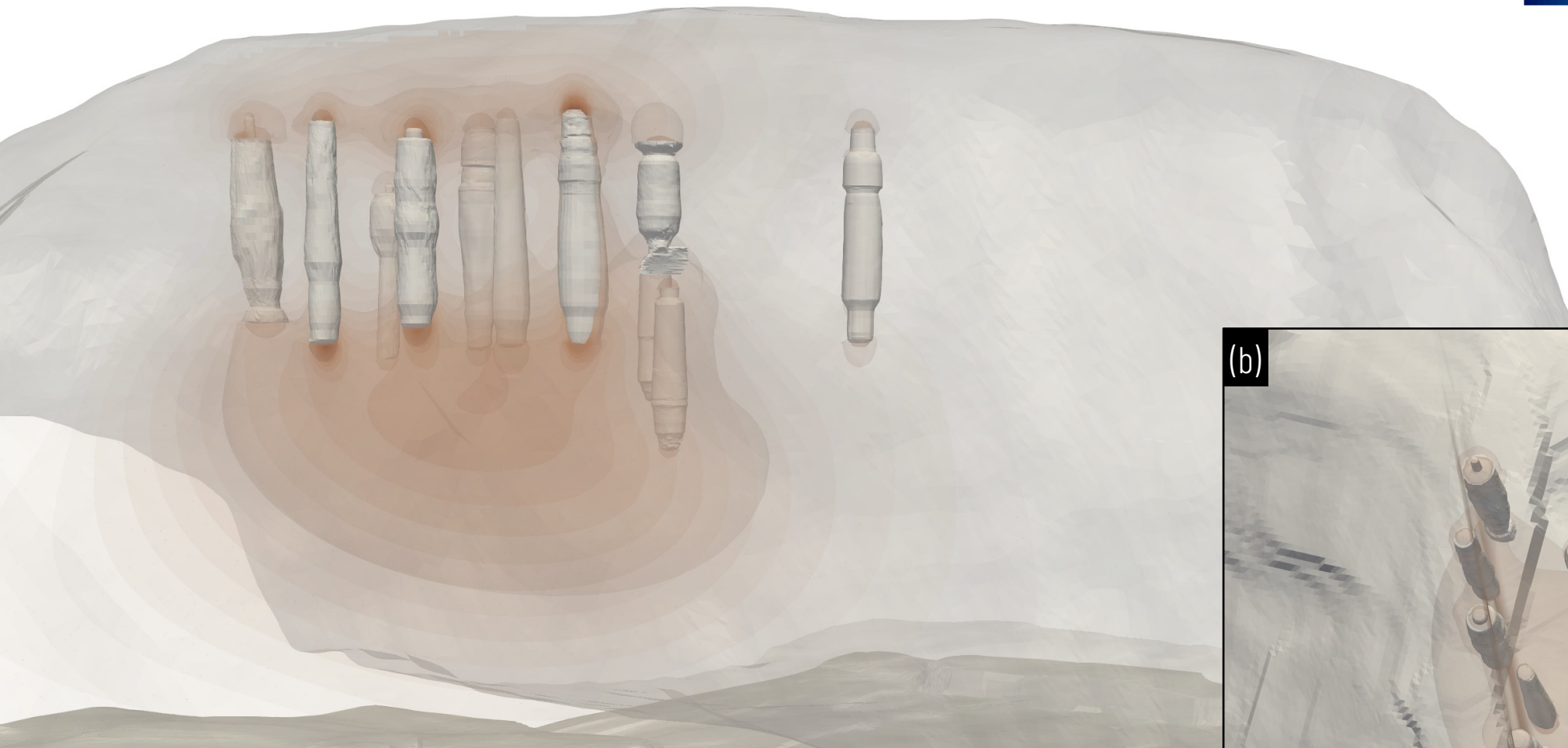
(b)



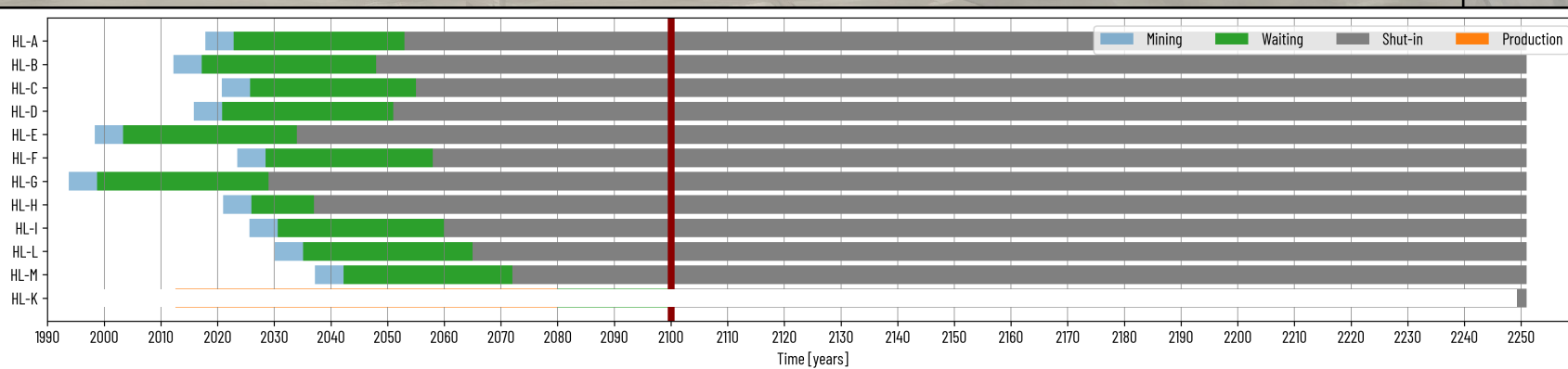
(a)



2100



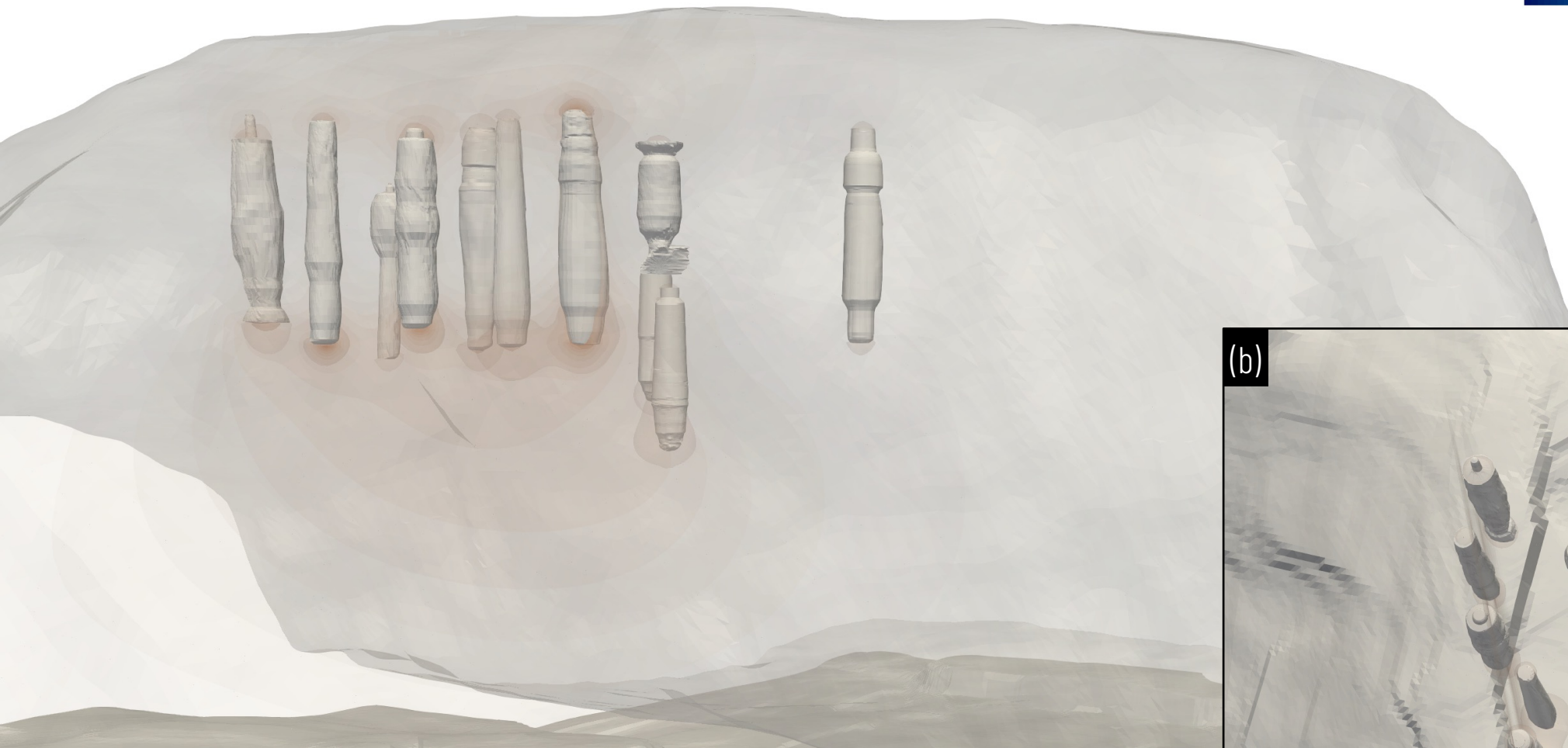
(b)



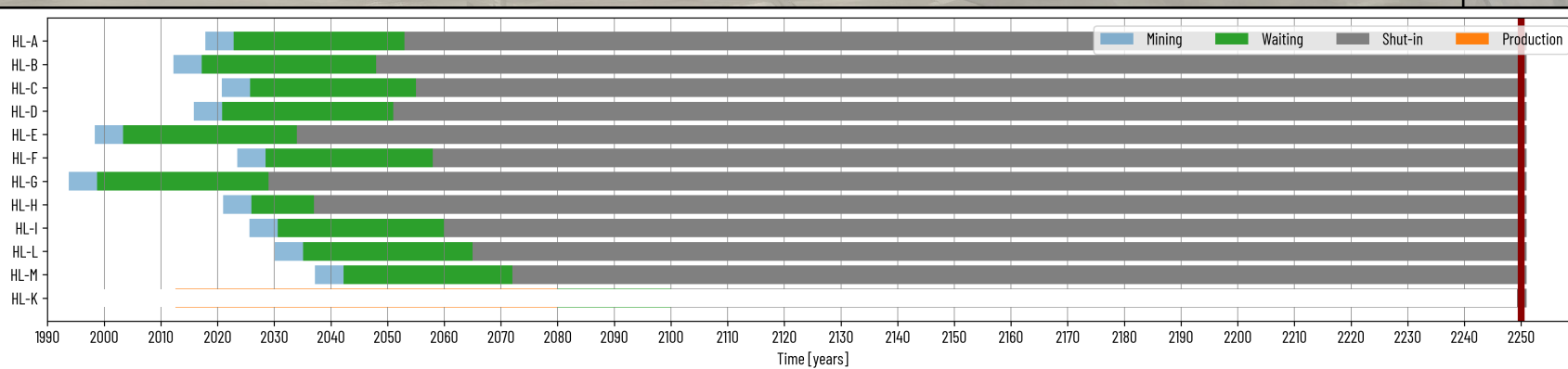
(a)



2250



(b)



Conclusions

- **Using constrained creep properties is crucial for THM numerical modeling of salt domes as host rock for operating caverns and their abandonment**
- **Probabilistic models have been proven to be very useful in determining uncertain creep properties by combining different constraints from multiple scales**
- **Upscaling is required.**
- **The longer the modeling timespan, the larger the model should be.**