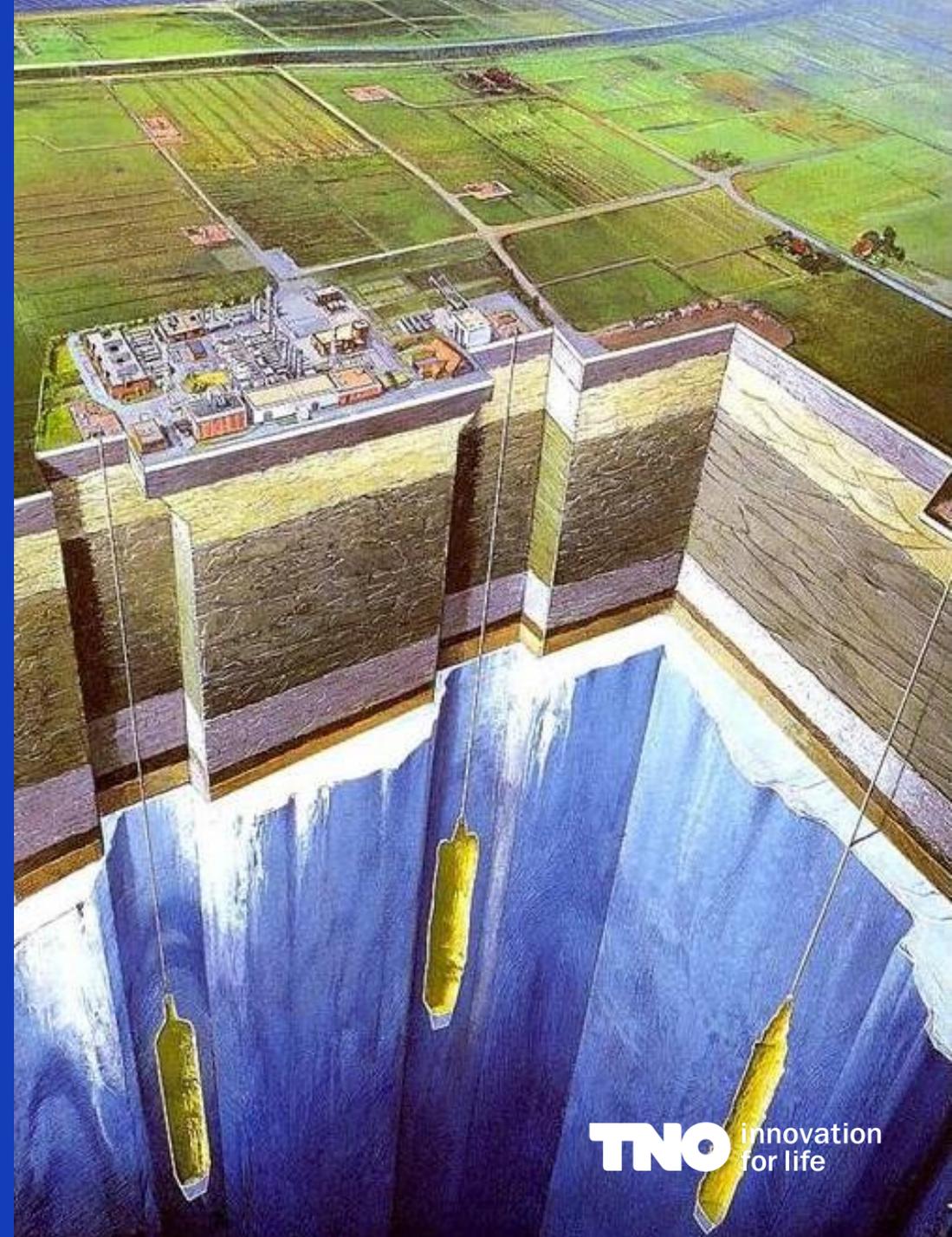


# Fingerprints of salt creep around caverns

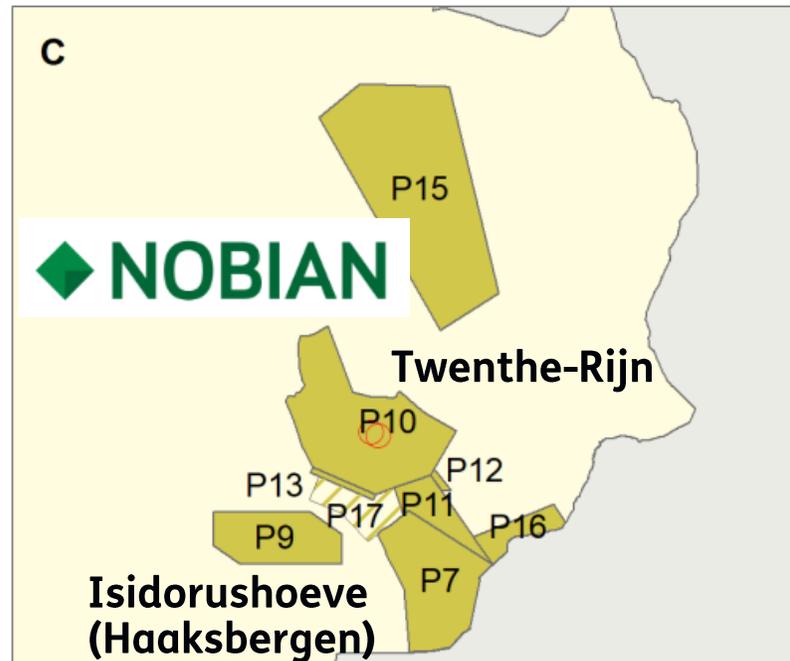
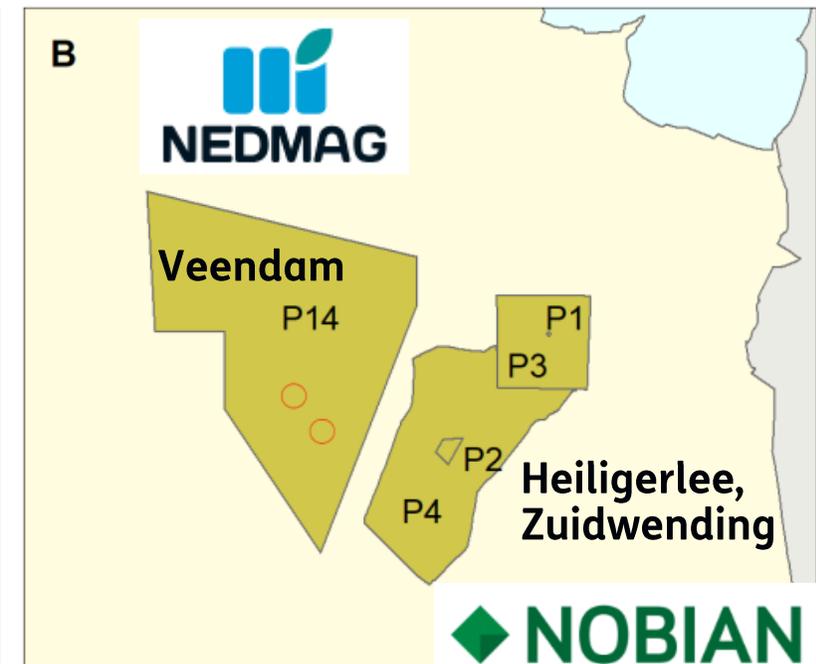
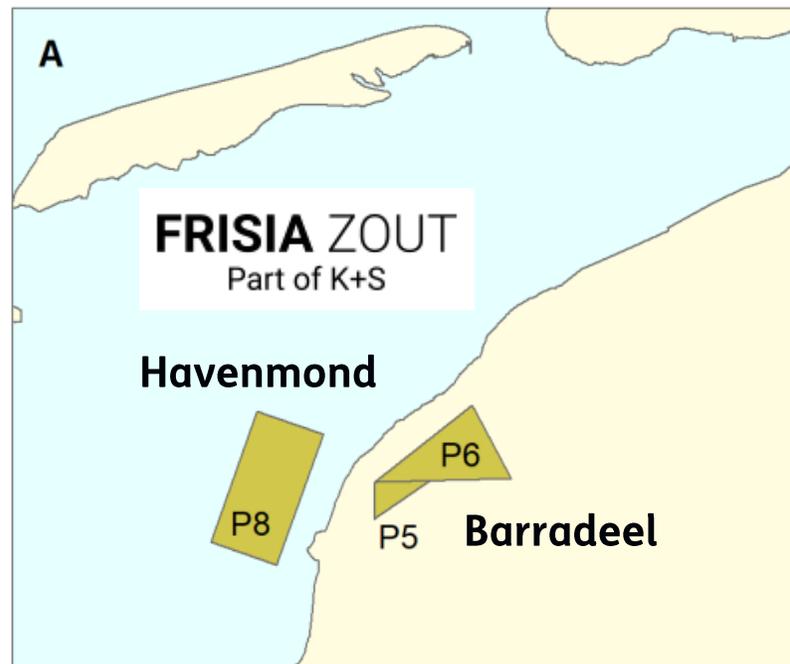
Dr. L.B. Hunfeld | TNO-AGE



# Salt Production in NL

## Solution mining

- Since 1919 (Boekelo, Overijssel)
- Twente, Groningen and Northwest-Friesland
- Varying from 350 m to 3 km depth



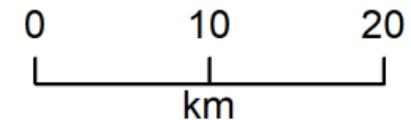
## Legenda

○ Boring 2022

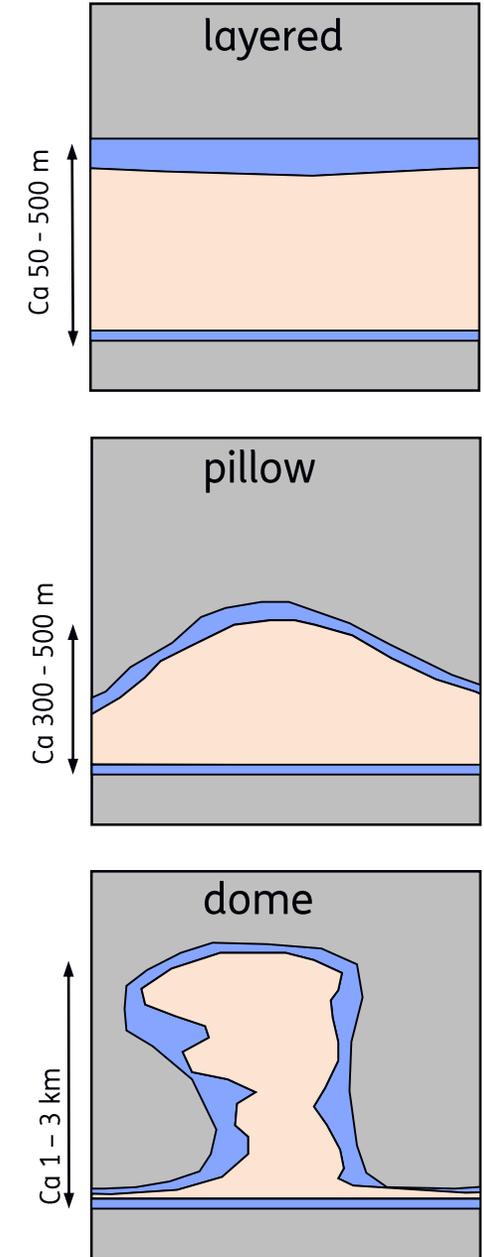
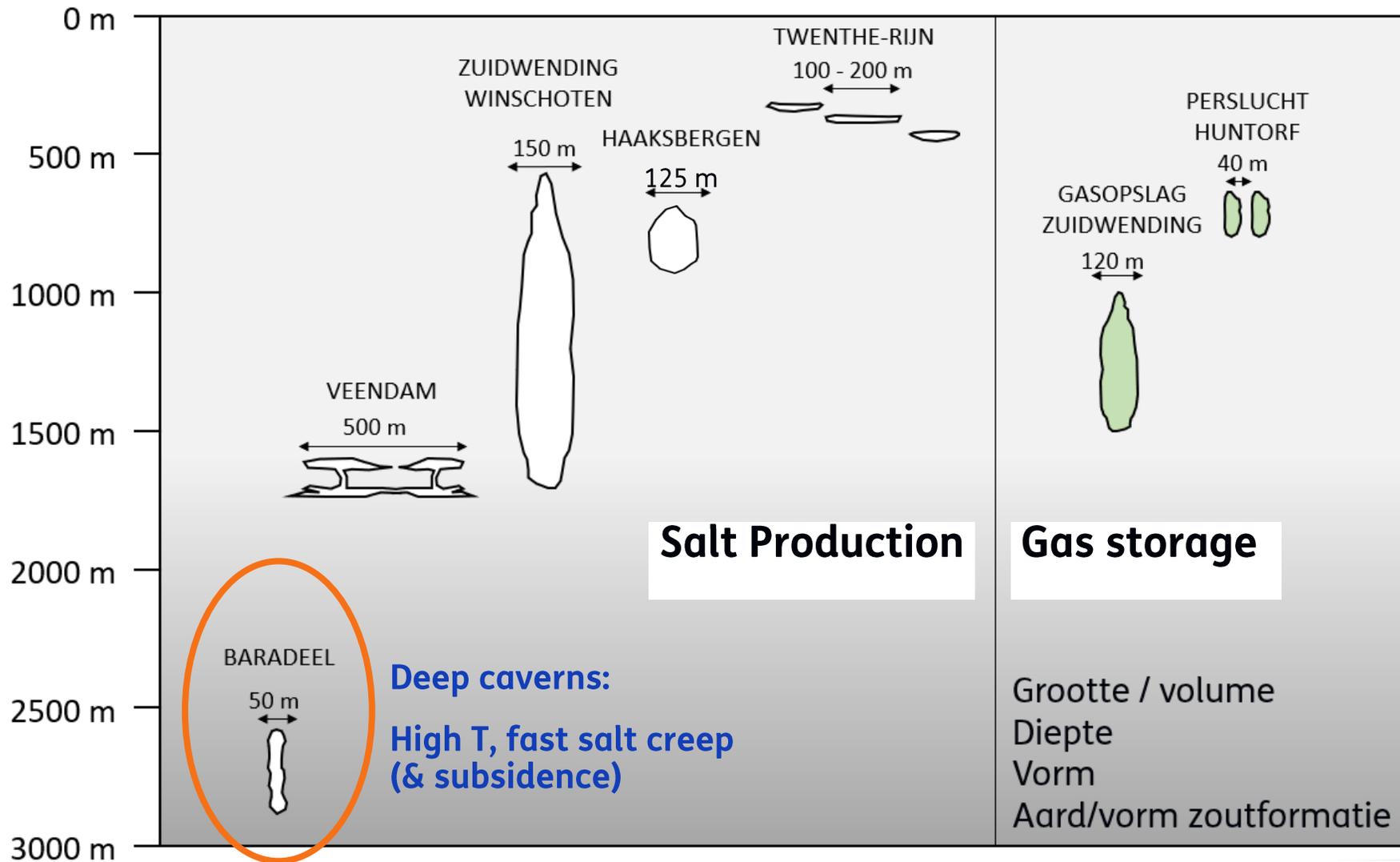
## Zoutvergunningen

■ Winning

▨ Winning, aangevraagd



# Cavern shapes & Sizes

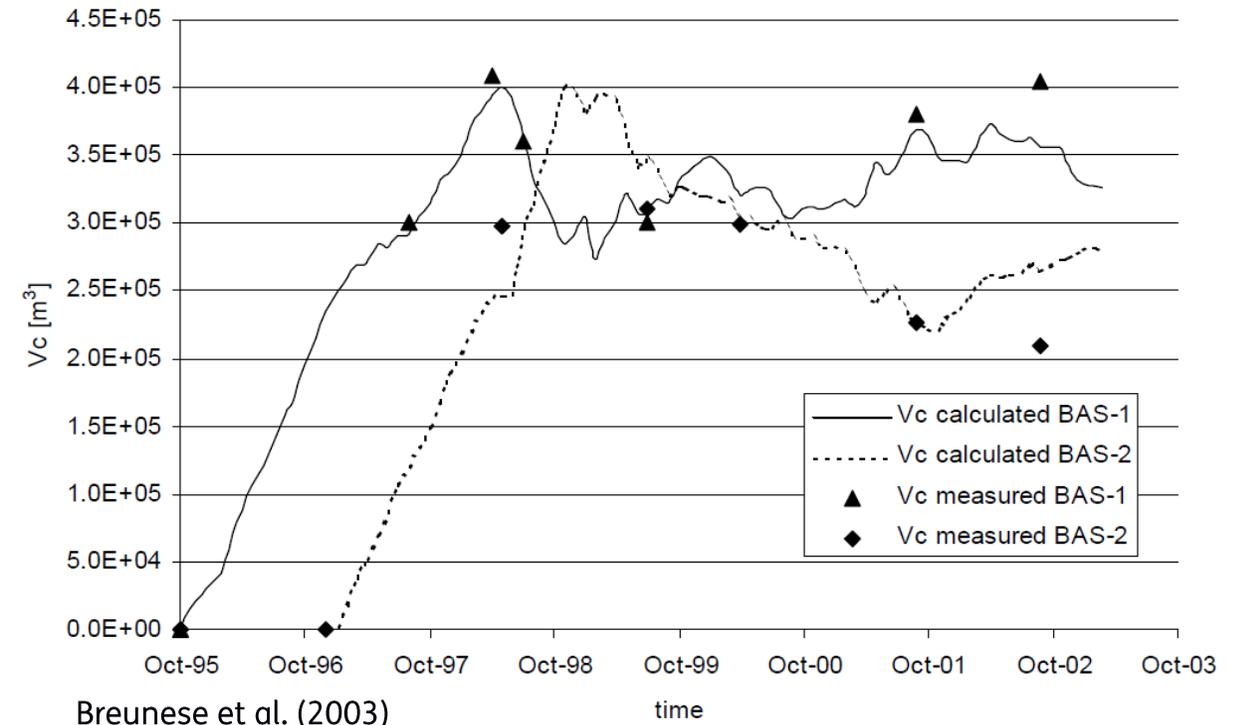
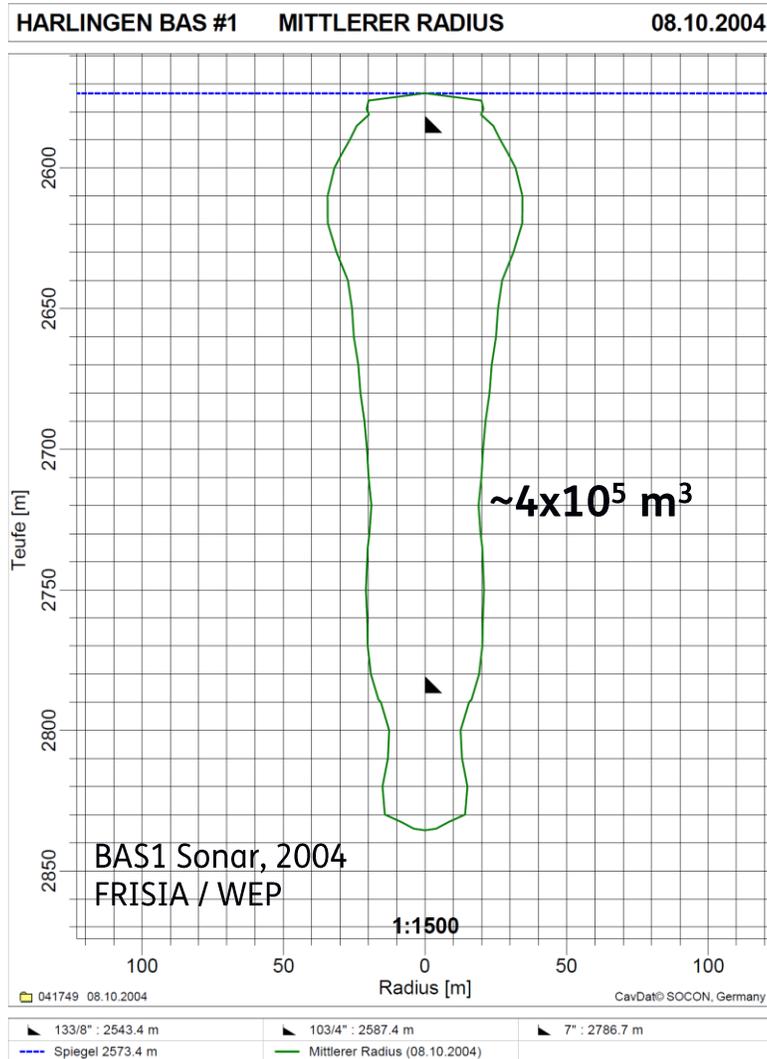


# Barradeel - cavern convergence

Mass-balance approach to estimate convergence based on:

- Sonar measurements
- Production data

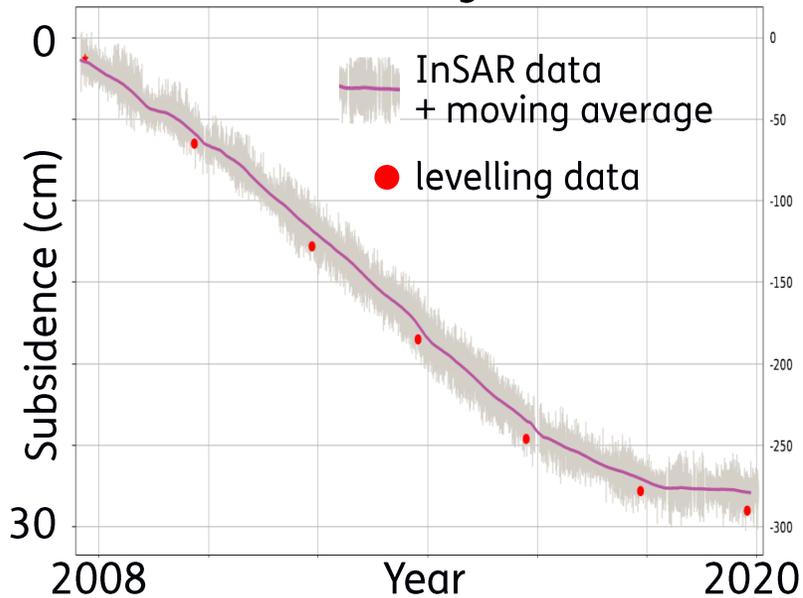
**Barradeel caverns 'loose' ~50-100% of the total cavern volume each year during production!**



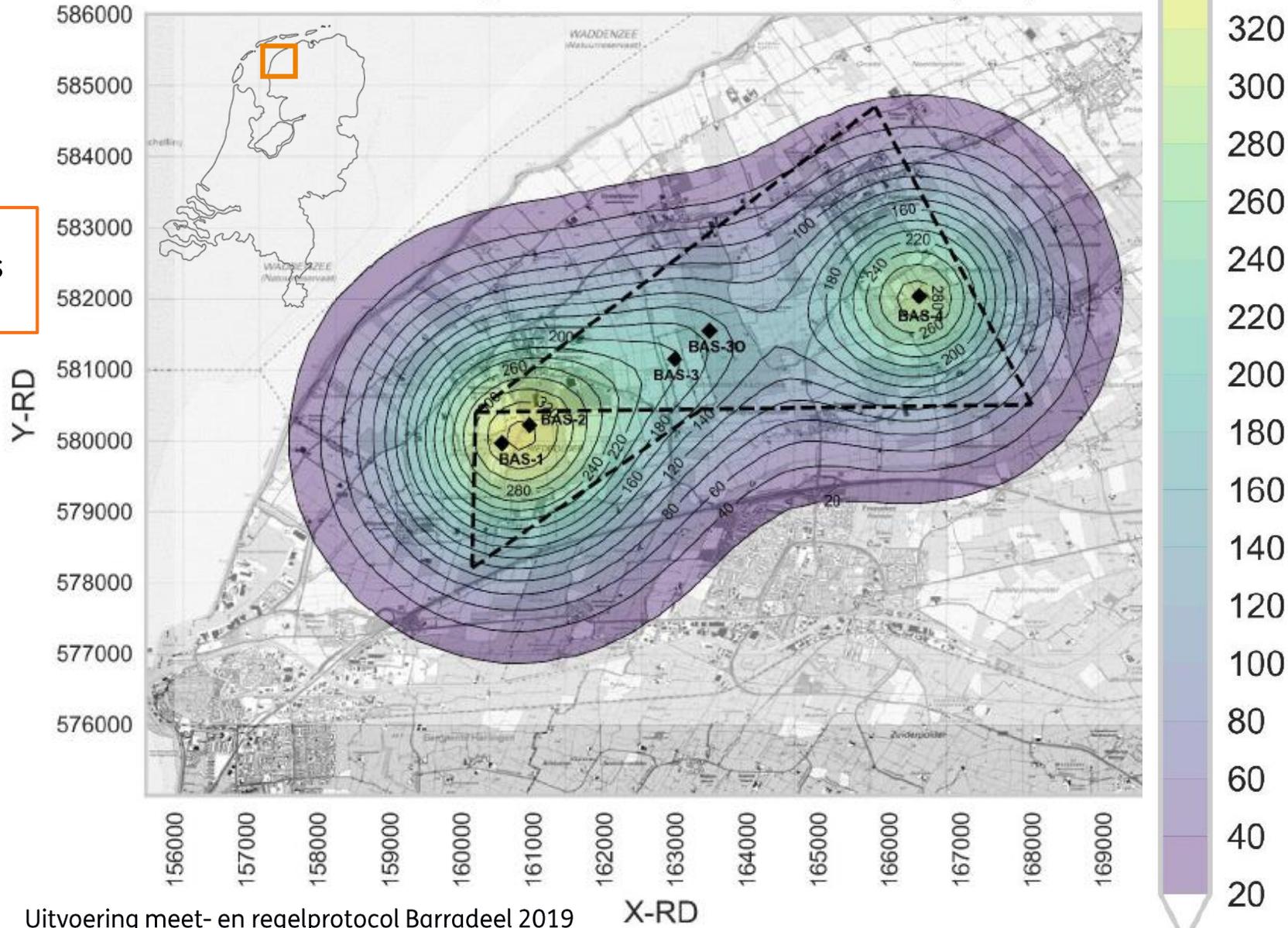
# Barradeel - Subsidence

~2.5 – 3 cm/year during production  
 Production stopped from all BAS caverns and started offshore (Havenmond)

Bodemdaling BAS-4



Contourenkaart bodemdaling periode 1995-2019  
 zoutwinning Barradeel en Barradeel II (mm)



Uitvoering meet- en regelprotocol Barradeel 2019

X-RD

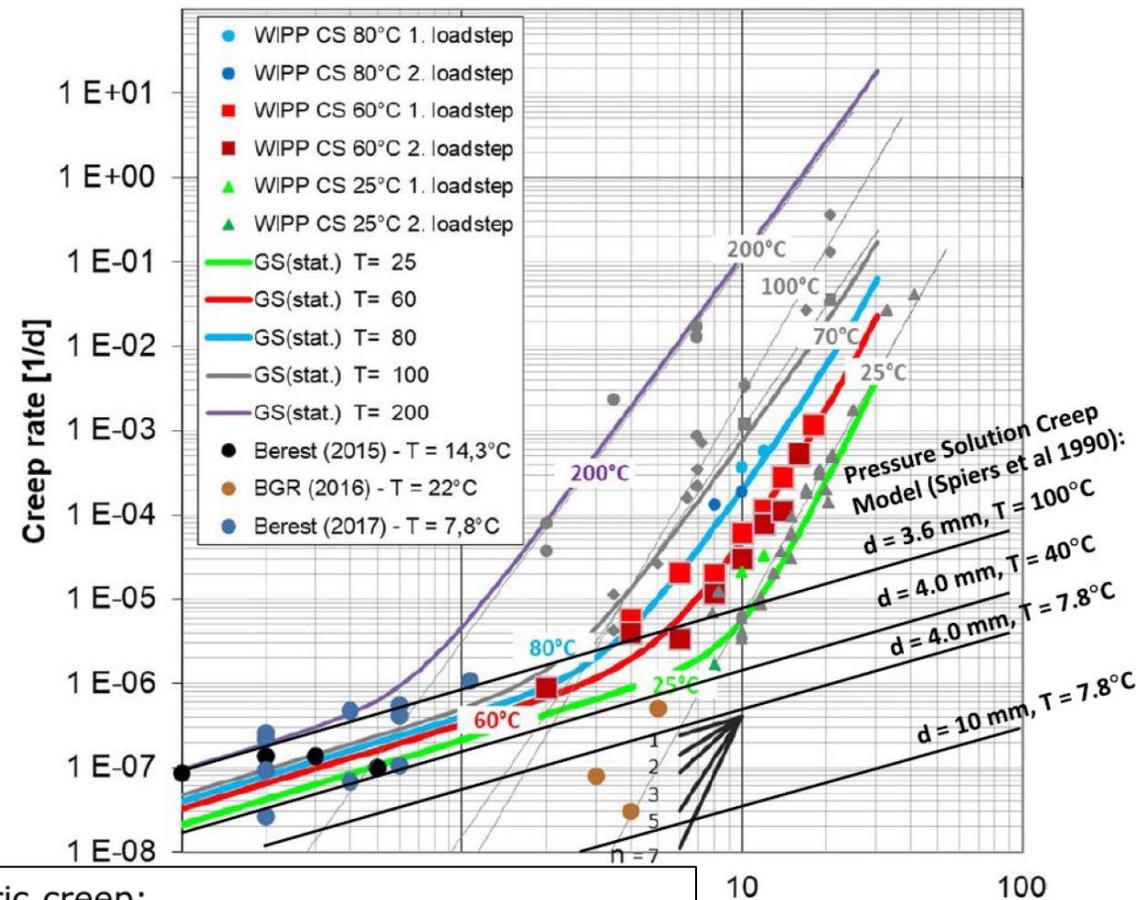
# Background: Salt Creep

## Deformation mechanisms in rocksalt

- Dislocation creep (**power-law, n=3-7**) at high stress
- Pressure Solution creep (**linear, n=1**) at low stress
  - Theory/exps synthetic rock salt (Spiers et al., 1990)
  - Confirmed in lab exps. on natural salt (Berest et al., 2019)

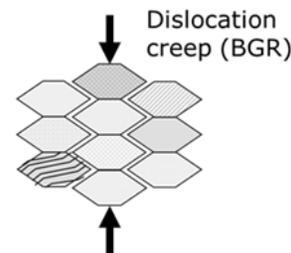
## Mechanism-based constitutive flow law for combined power law + linear creep

- Spiers & Carter (1998)
- Orlic et al (2016)
- Marketos et al (2016)
- Cornet et al (2017)

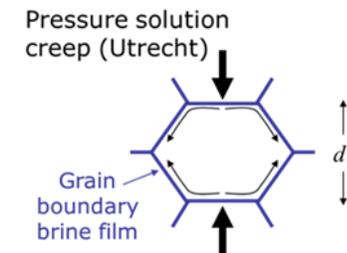


Deviatoric creep:

$$\dot{\epsilon} = A(T)\sigma^{5.5} + B(T)\frac{\sigma}{d^3}$$



High stress, high strain-rate,  
coarse grain size



Low stress, low strain-rate,  
fine grain size

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

# Barradeel - FE modelling

Breunese et al (2003)

- **power law + linear creep** can reproduce convergence and subsidence observations **during production**
- but predicts **'rebound'** following **'hard' shut-in**
- Such rebound has not been observed to date

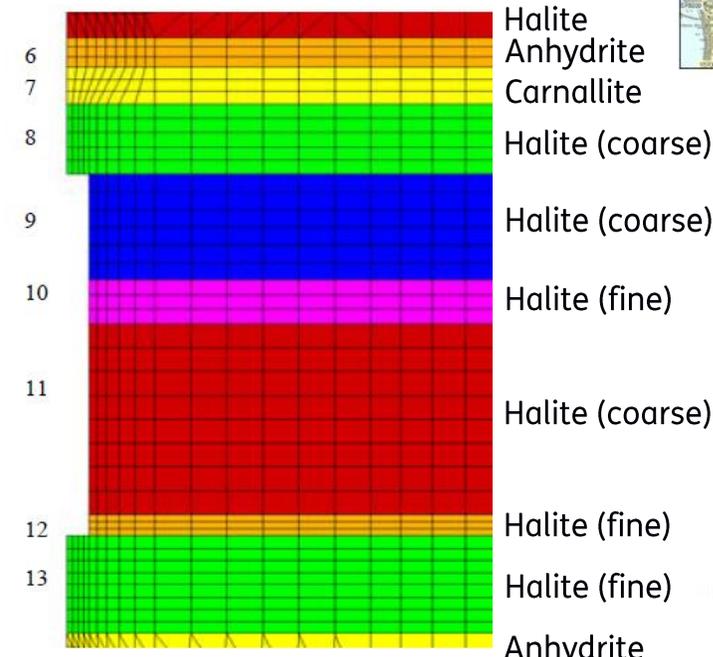
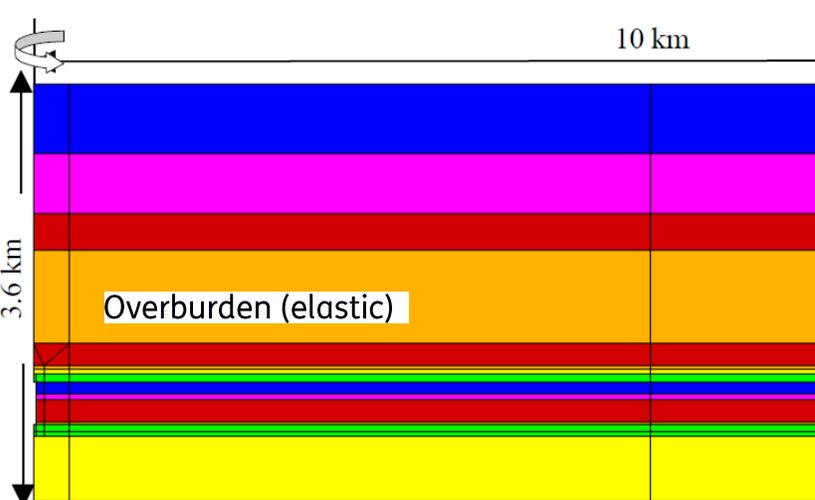
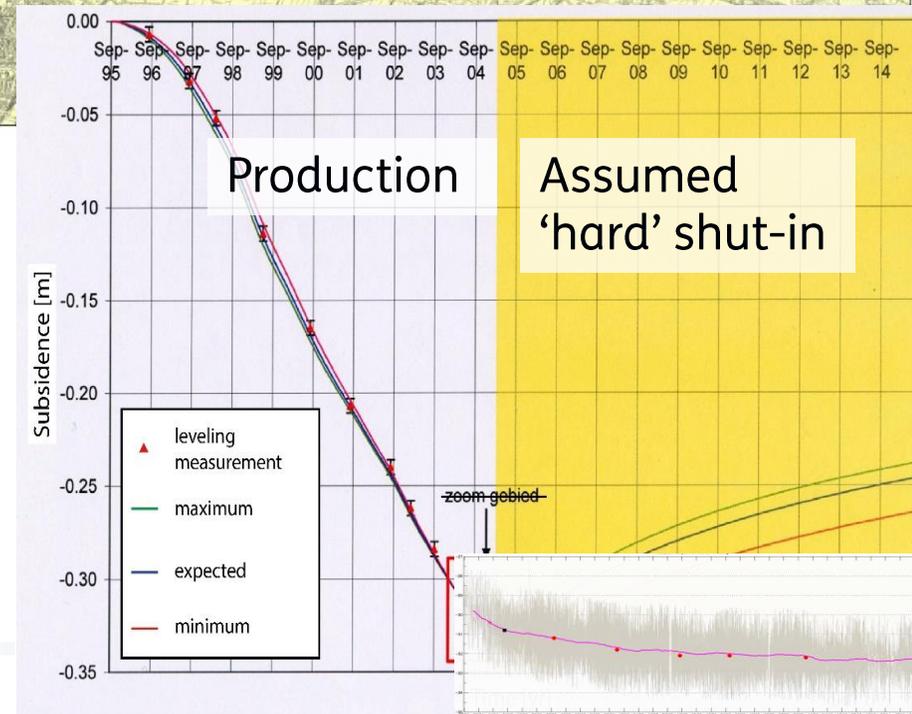
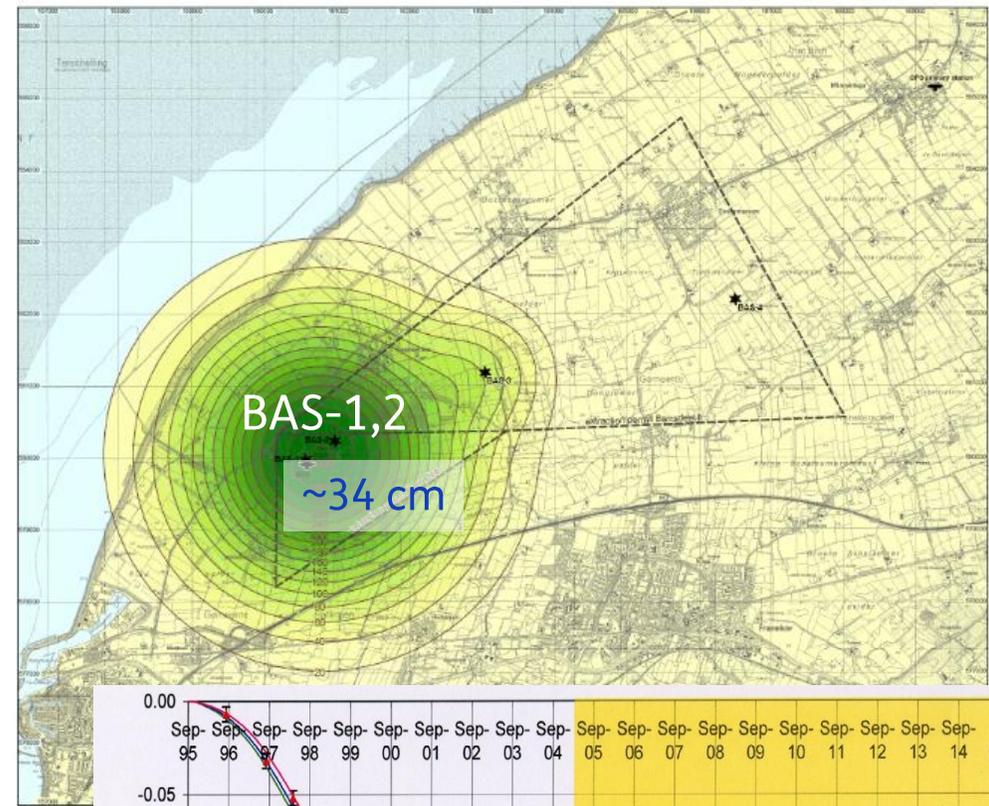
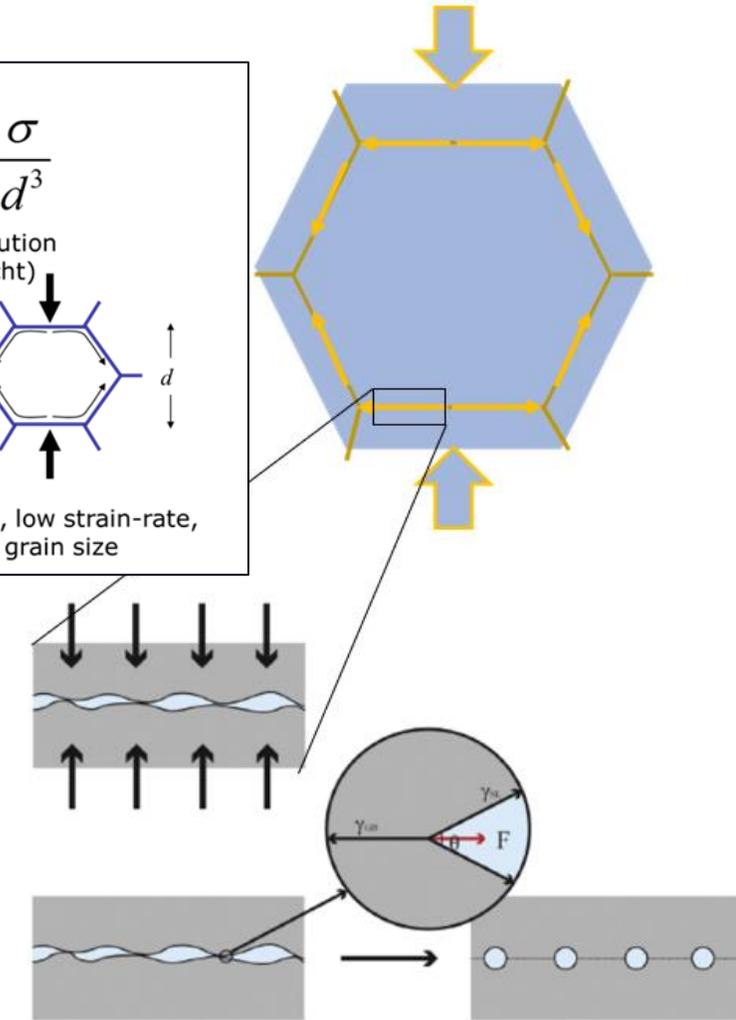
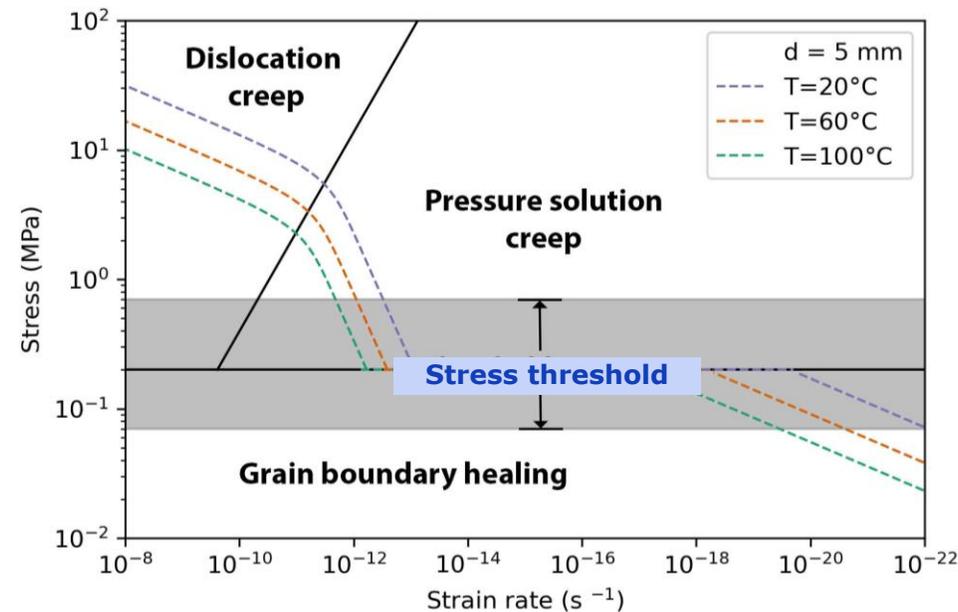
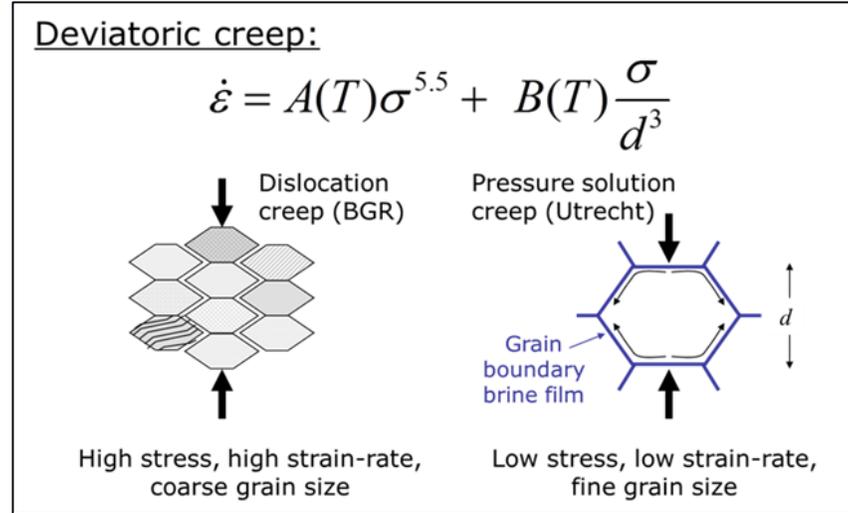


Figure 7a Geometry of the axi-symmetrical FE-model

# Background: New Insights

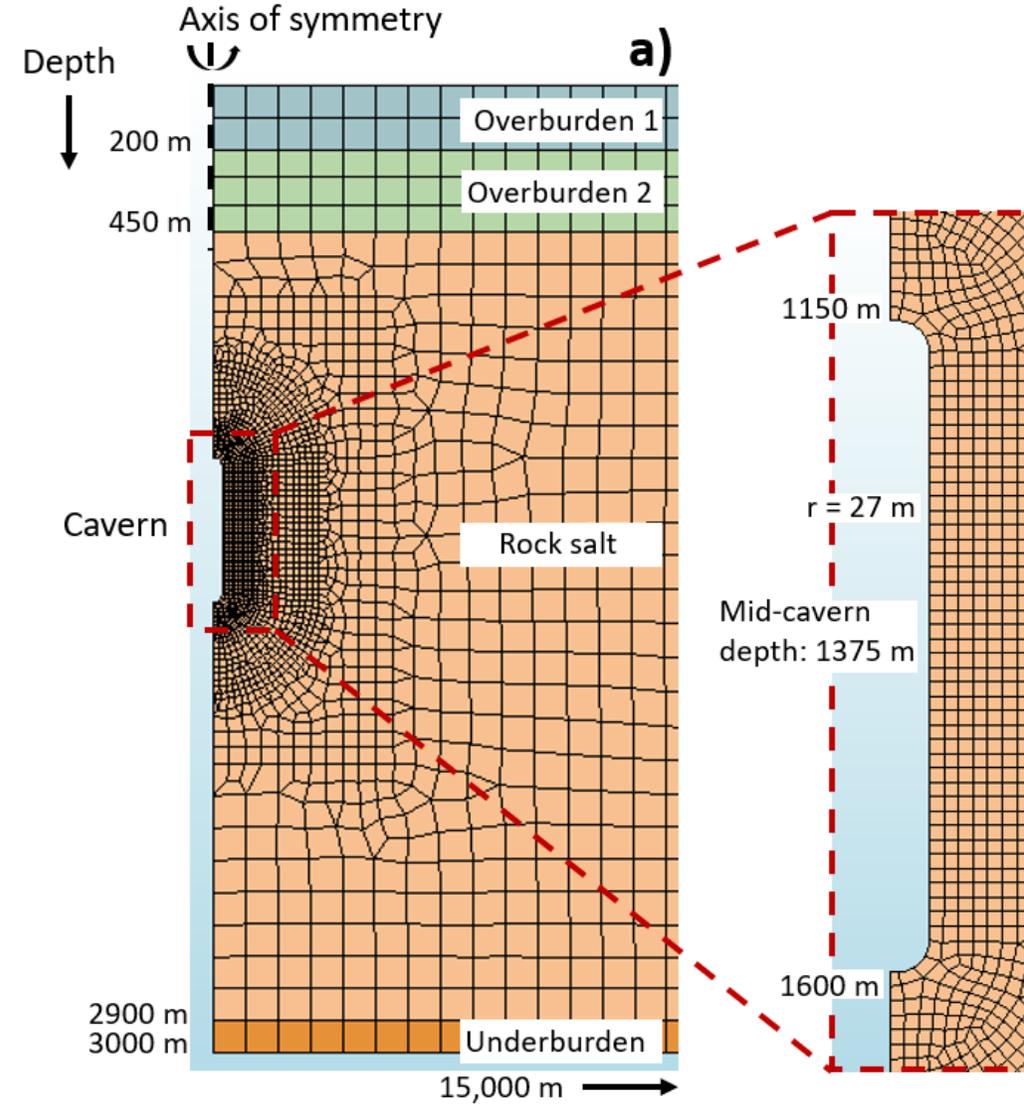
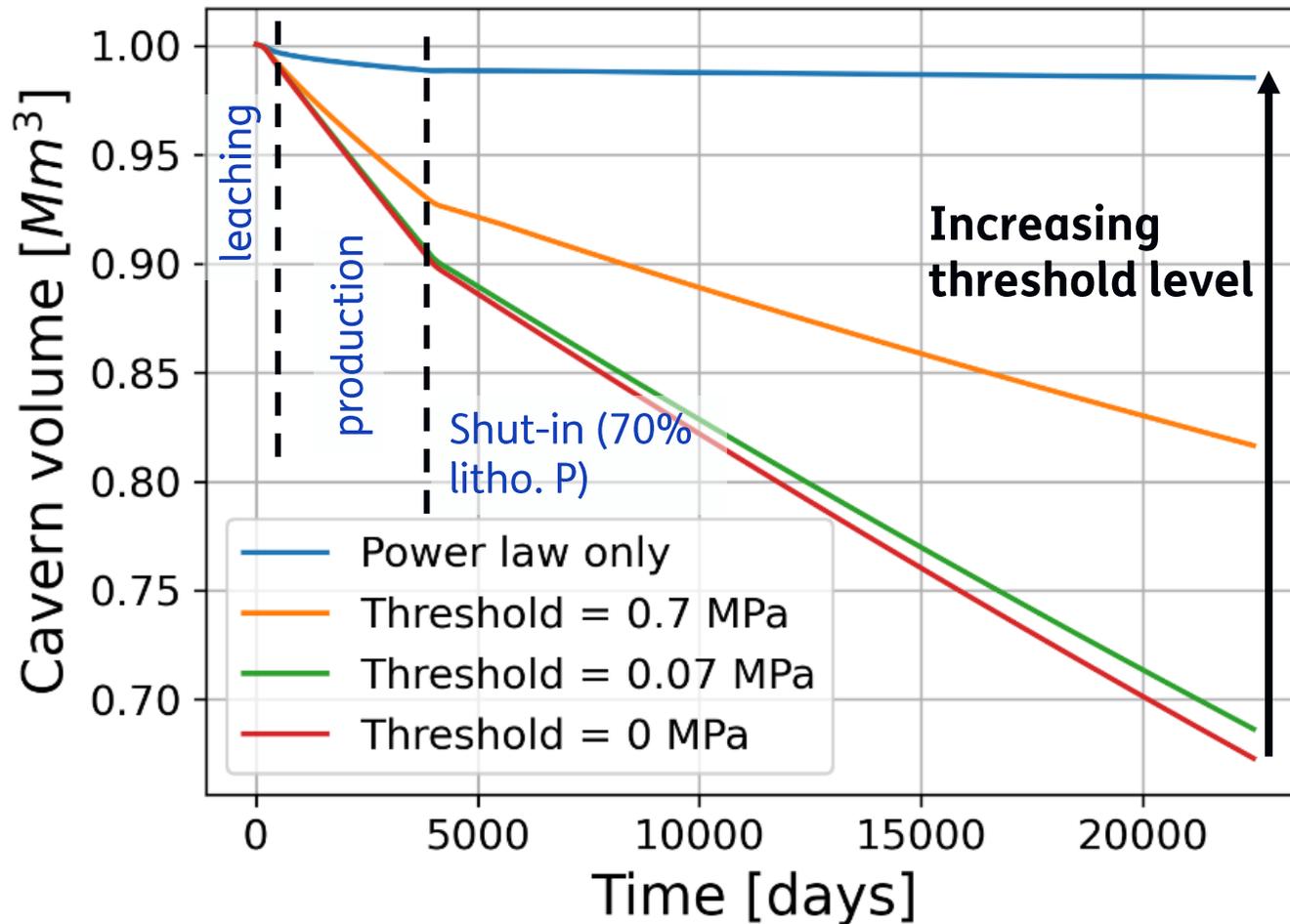
- Grain boundaries ‘heal’ at low stresses, stopping pressure solution (van Noort et al, 2008)
- Stress threshold for pressure solution in rock salt?  
**Theoretical prediction: 0.07-0.7 MPa**  
(Van Oosterhout et al, 2022)
- **Theory needs experimental verification!**  
UU + TNO Salt PhD research



After Houben et al. 2013; Van Noort et al 2008

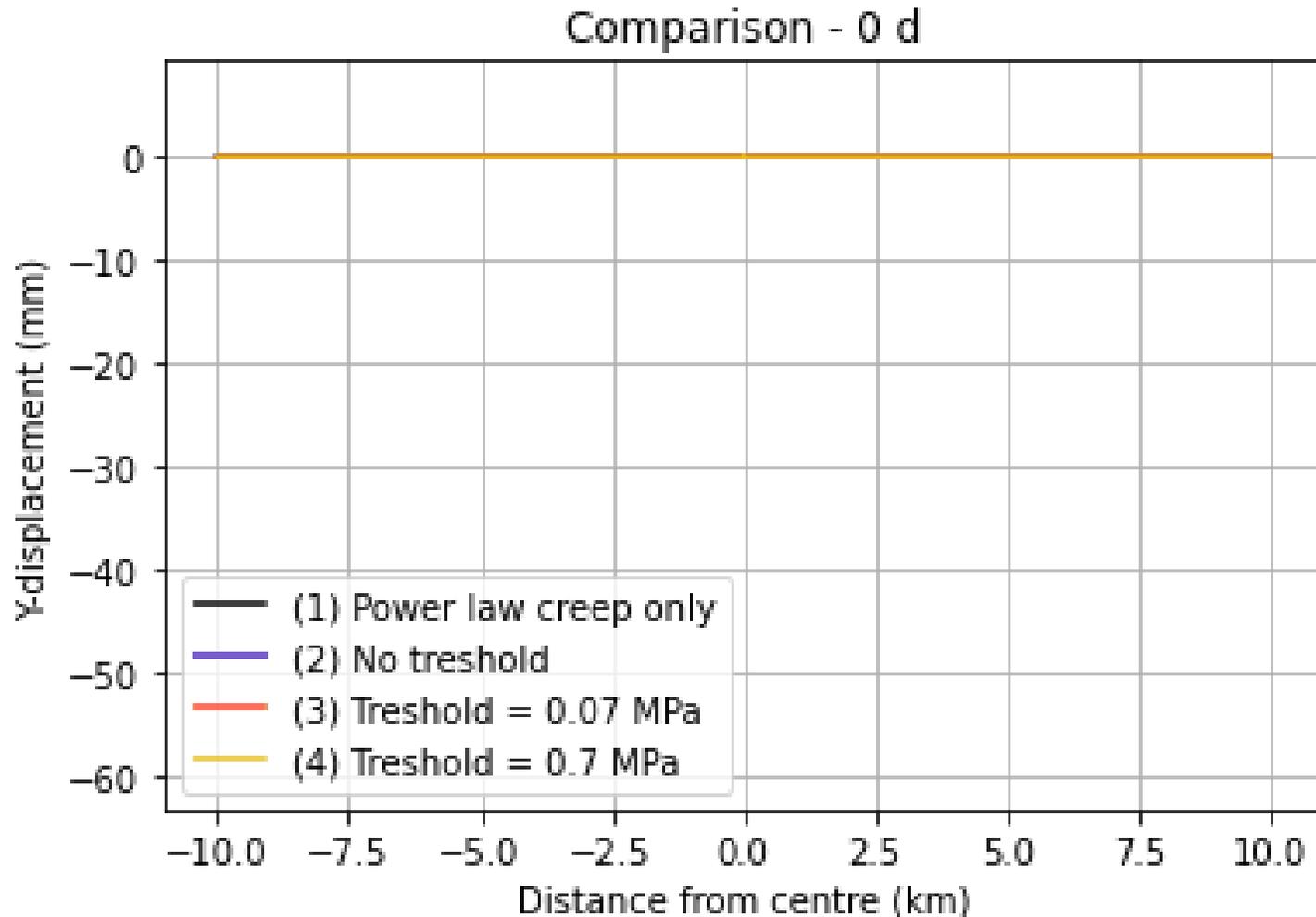
# Effects of linear creep threshold in cavern modelling

Hunfeld et al (SaltMech X, 2022)

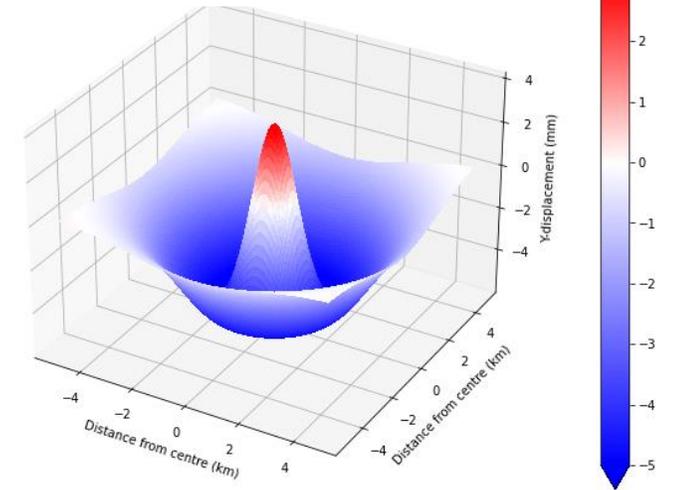


# Effects of linear creep threshold: surface displacements

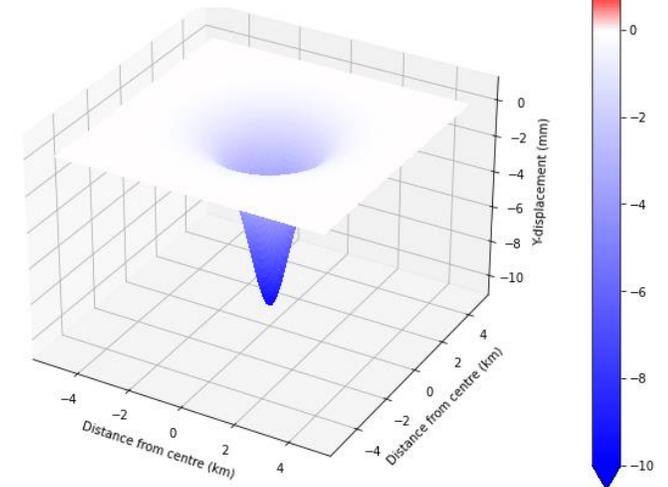
Hunfeld et al (SaltMech X, 2022)



(2) No threshold



(4) Threshold – 0.7 MPa

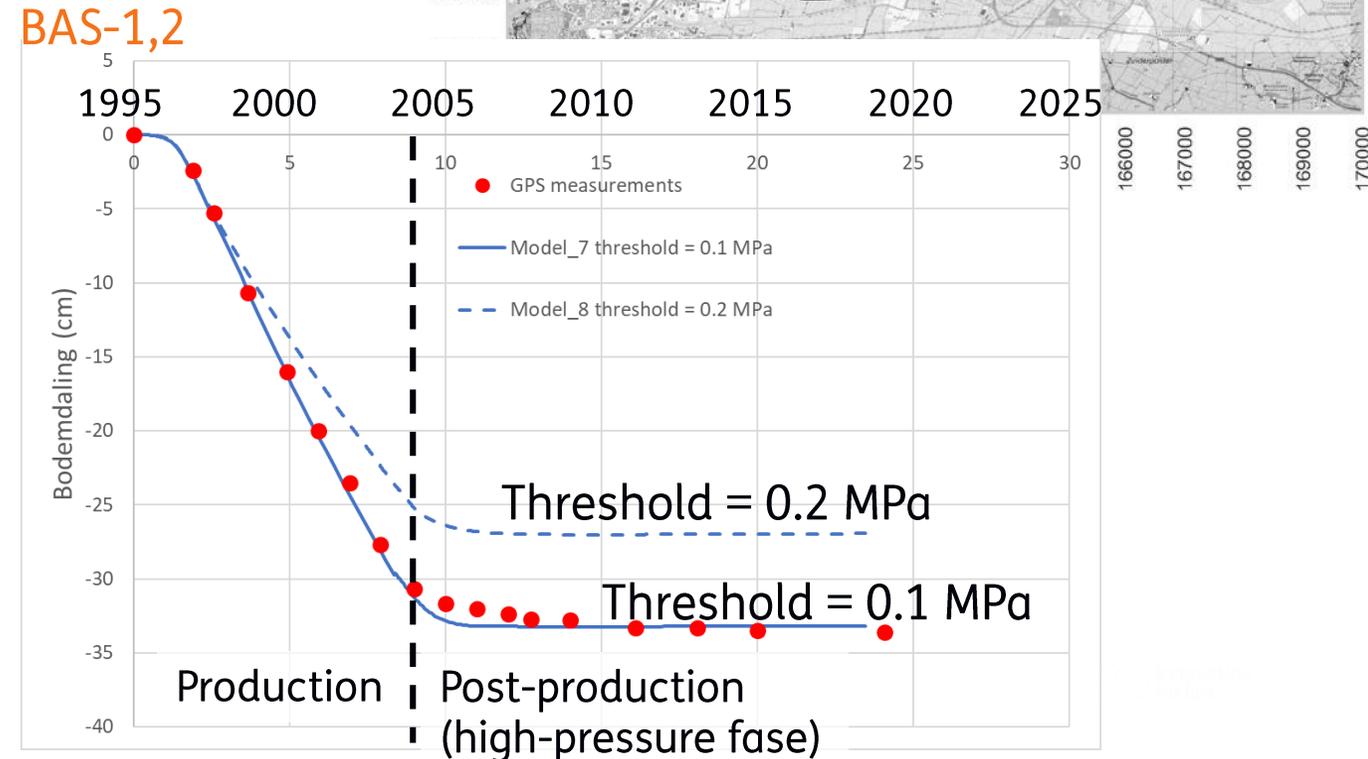
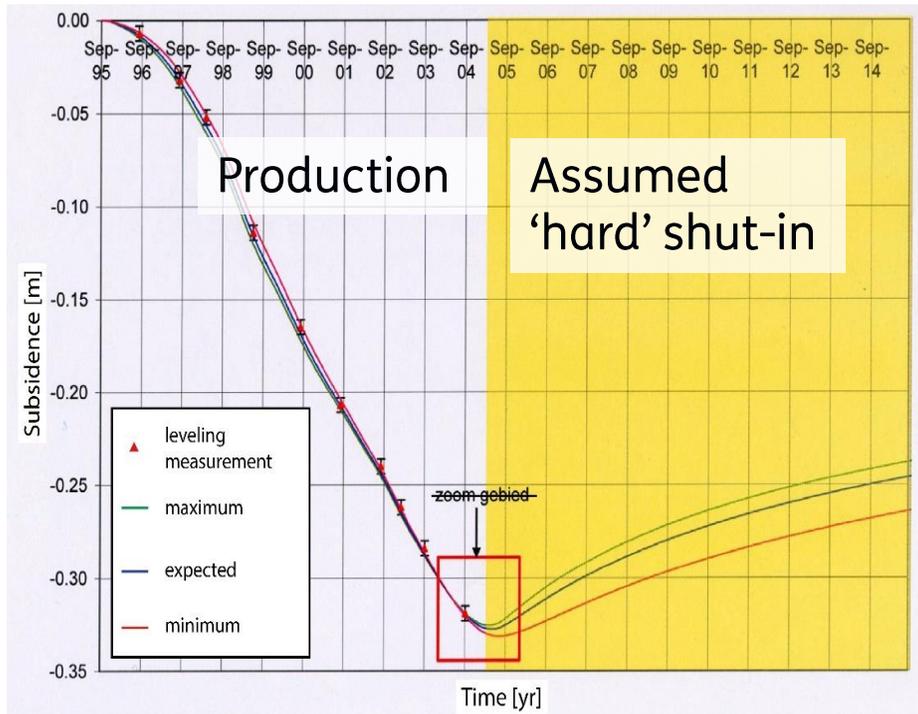
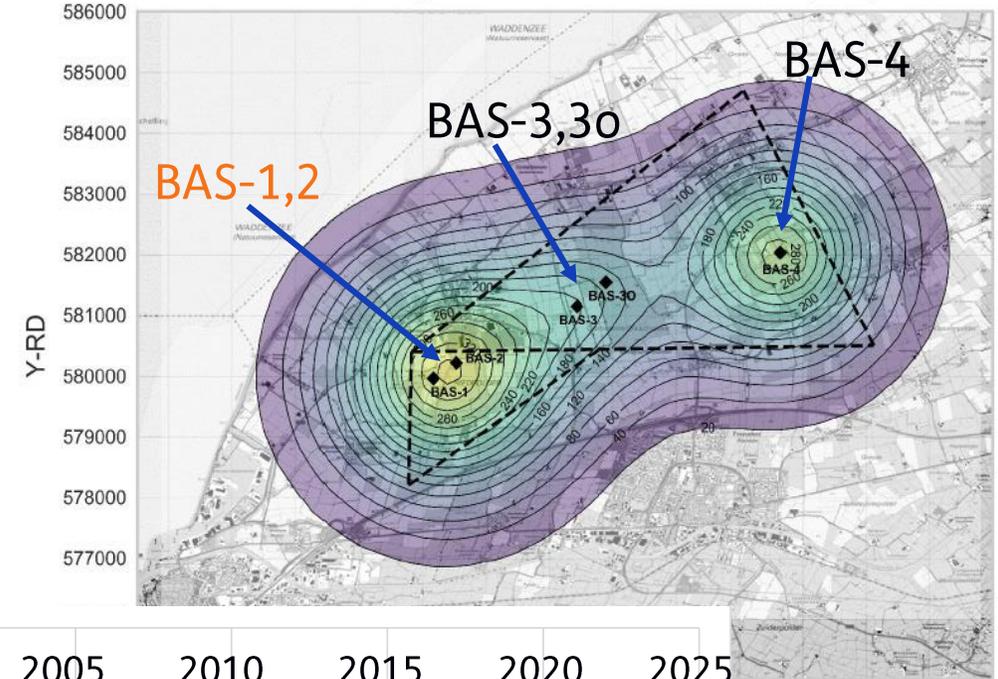


# Application to Barradeel

Work in progress

- Application of linear creep threshold removes 'rebound', but model outcome very sensitive to threshold value
- Field observations support threshold concept, but experimental verification needed!!

Contourenkaart bodemdaling periode 1995-2019  
zoutwinning Barradeel en Barradeel II (mm)



# Discussion

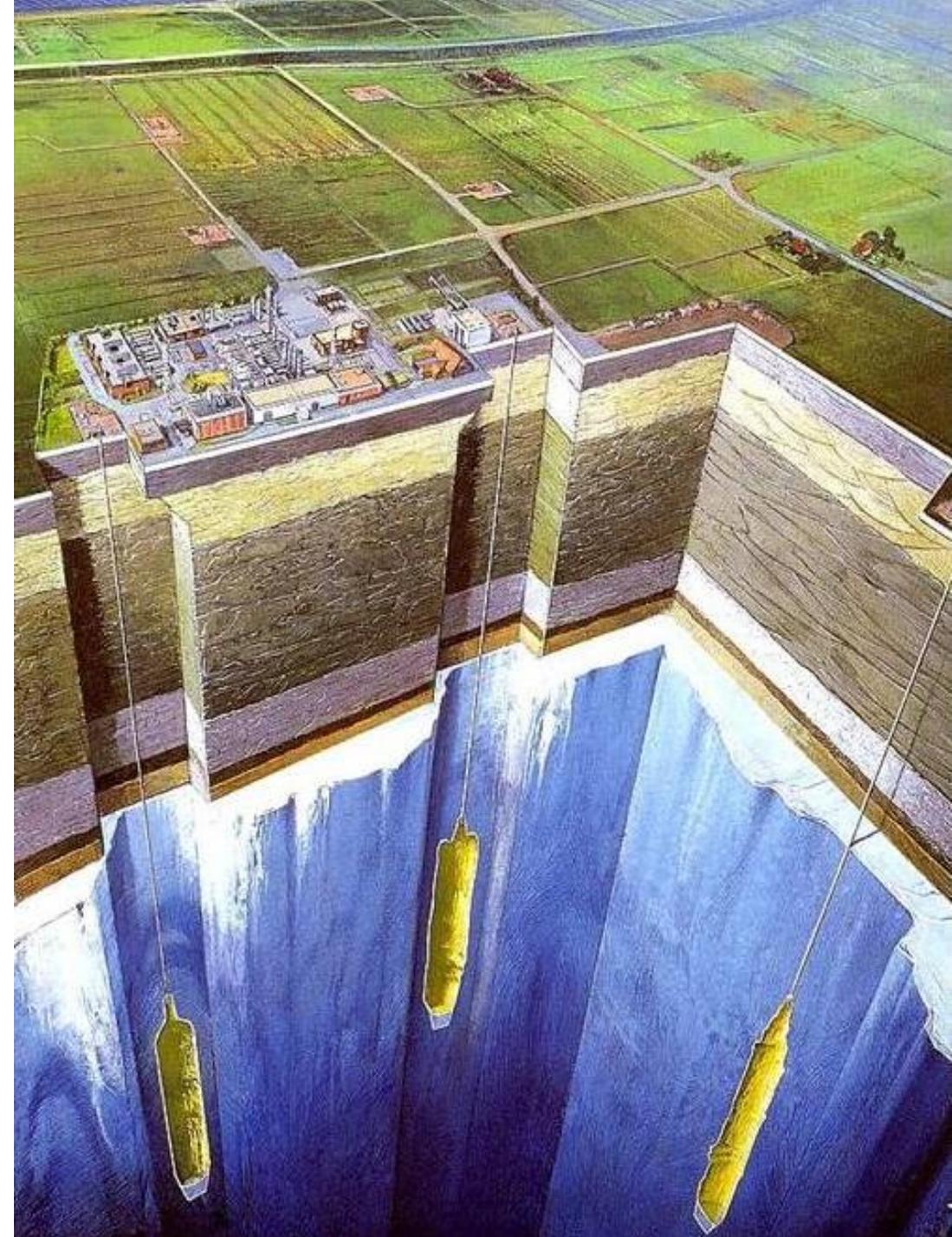
- Convergence & subsidence in single-cavern models is very sensitive to linear (pressure solution) creep & its threshold value
- Field observations are in agreement with limited linear creep (threshold hypothesis), but experiments needed to verify mechanism and stress values!!

## Outlook

- What about multi-cavern systems? Linear creep still dominant?
- Other processes not considered yet:
  - permeation
  - recrystallization at large strains
  - transient creep



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Utrecht



A woman with long blonde hair, wearing a light purple knitted sweater, stands in a field of tall grass. She is holding a small white model of a wind turbine in her right hand, looking at it with a slight smile. The background shows a coastline with waves and a sky filled with dramatic, grey clouds. A large blue circular graphic is overlaid on the left side of the image, partially framing the woman and the turbine.

**Thank you!**