Staatstoezicht op de Mijnen
Ministerie van Economische Zaken en Klimaat

KEM-17: Over-pressured caverns and leakage mechanisms

Gerco Hoedeman

Senior Inspector – State Supervision of Mines

KEM-17 - Two questions

1. What leakage mechanism is dominant when a salt cavern is closed?

   Permeation, hydraulic fracturing, localized leakage path?

   What happens when the brine pressure reaches the minimum principal stress?

2. How certain or uncertain can you be?

KEM-17 Team

Micro-scale

MAP Microstructure and Pores

Prof. Dr. Janos L. Urai
Dr. Joyce Schmatz
Dr. Job Klaver

Cavern-scale

BROUARD CONSULTING

Dr. Benoit Brouard
Prof. Dr Pierre Bérest

Salt dome-scale

smart Tectonics

Dr. Tobias Baumann
Prof. Dr. Boris Kaus
Dr. Anton Popov

Conclusions and Recommendations

KEM-17 - Two conclusions

1. With the current knowledge it can not be predicted with certainty if a deep cavern will leak via slow permeation, a localized leakage path or hydraulic fracture.

2. Knowledge of micro-, cavern- and salt dome-scale is not integrated enough. Processes on all three levels influence the leakage mechanism.

KEM-17 - Two recommendations

1. Integrate knowledge of micro-, cavern- and salt dome-scale.

2. Improve knowledge in areas with unceartainty. Mainly the upscaling of micro-scale behavior to cavern- and dome-scale.

Three thoughts about caverns

#full-life-cycle
#energy-transition

#all-realistic-scenarios
#salt-heterogeneity
#leakage-mechanisms
#anistropic-stress

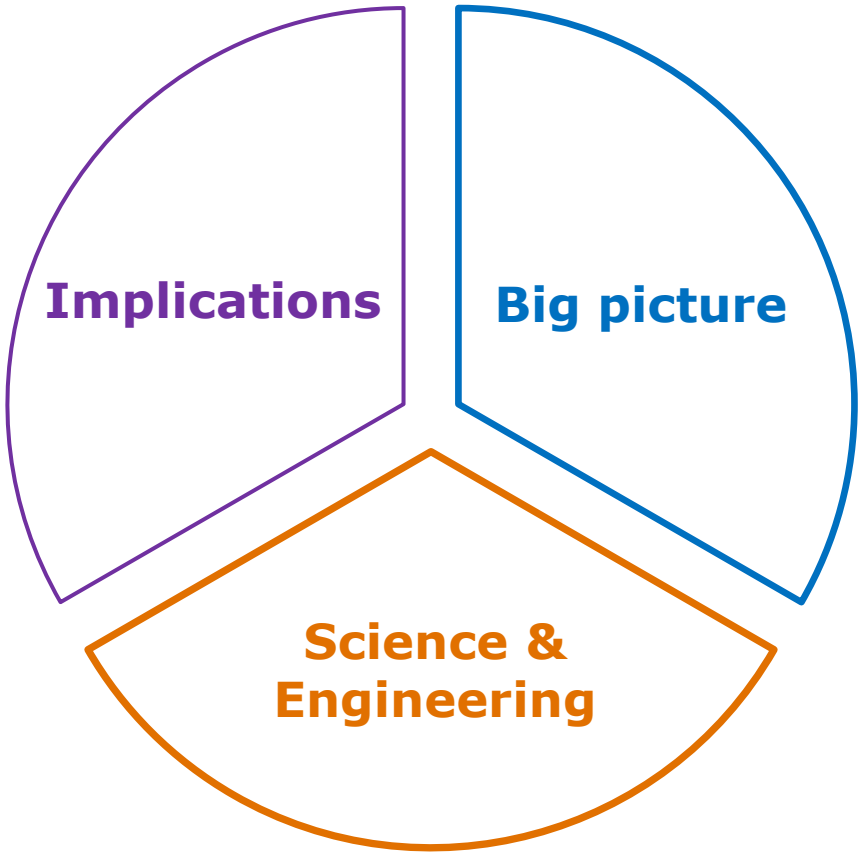
#cavern-interaction
#jungle-in-the-undergrond

Content

- State Supervision of Mines
- Salt mining in NL
- Why KEM-17?

- KEM-17 results
  - Micro-scale
  - Cavern-scale
  - Salt dome-scale
  - Conlusions

- KEM-17 implications
- Final thoughts



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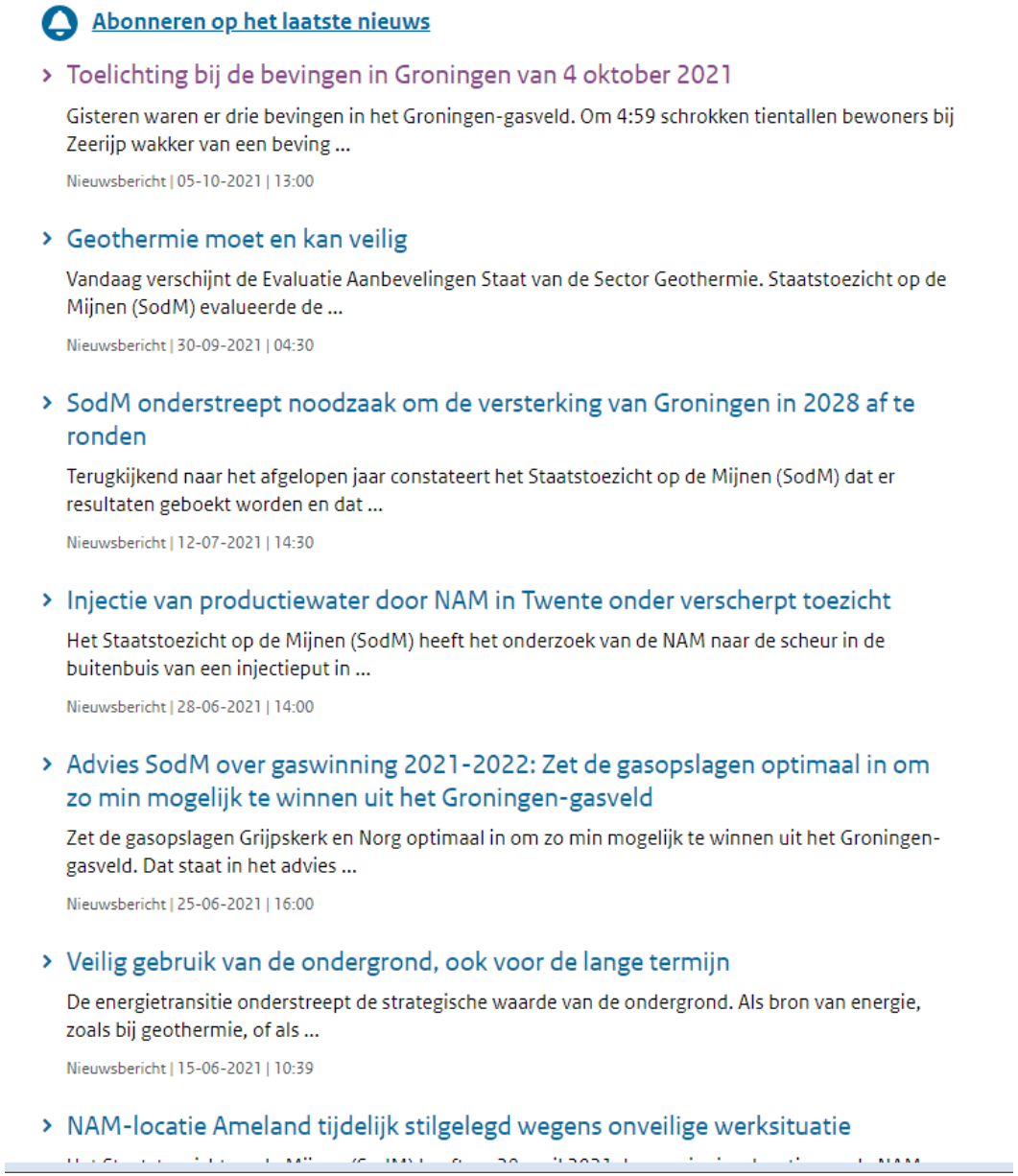

SodM Regulator:

Sector

- Production oil, gas and salt
- Geothermal energy
- Gas transportation network
- Underground storage
- Wind energy offshore

Where?

- Onshore and offshore
- Above ground, shallow subsurface and deep underground

Toezicht en handhaven

- Independent supervisor on copmliance to the laws and rules for mining and energy production.
- Inspections on safety and environment from a technical and social perspective.
- Goal is positively improving behavior of operators. If necessary SodM can enforce compliance.

Handhaven

- Warning
- Last onder dwangsom
- Shut-down installation
- Advice minister to withdraw license
- Administrative fine
- Criminal investigation by prosecutor ‘Openbaar Ministerie’

Advise minister EZK

- SodM has the assignment to advise the minister when asked or when SodM deemes it necessary.
- Asked: Assess competency of operator and risks in operational plans.
- When deeemed necessary: new insights in risks, suggestions to change policy/law.
- Minister in the final authority who takes the decision.

Scientific research

Coordinate research:

- SodM pays for specific research at institutes like TNO, KNMI, CBS, RIVM, etc...
- The ‘Kennisprogramma Effecten Mijnbouw (KEM)’ is a cooperation with the ministry EZK.
- KEM-17 in this presentation is one of those projects.

Salt mining in the Netherlands

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- KEM-17 results
- KEM-17 implications
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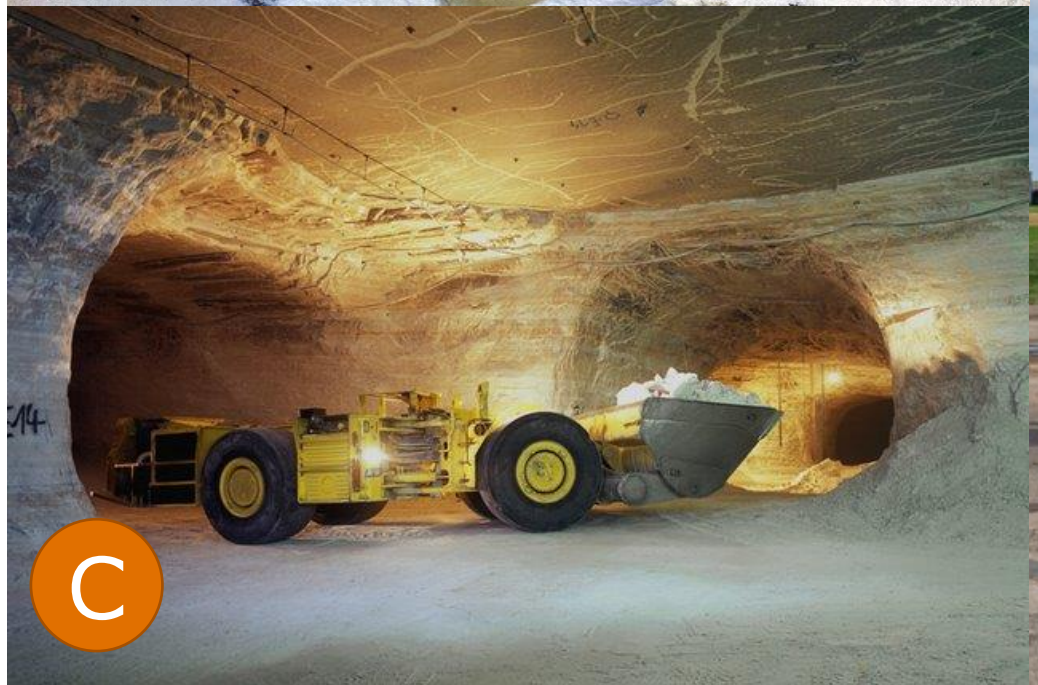
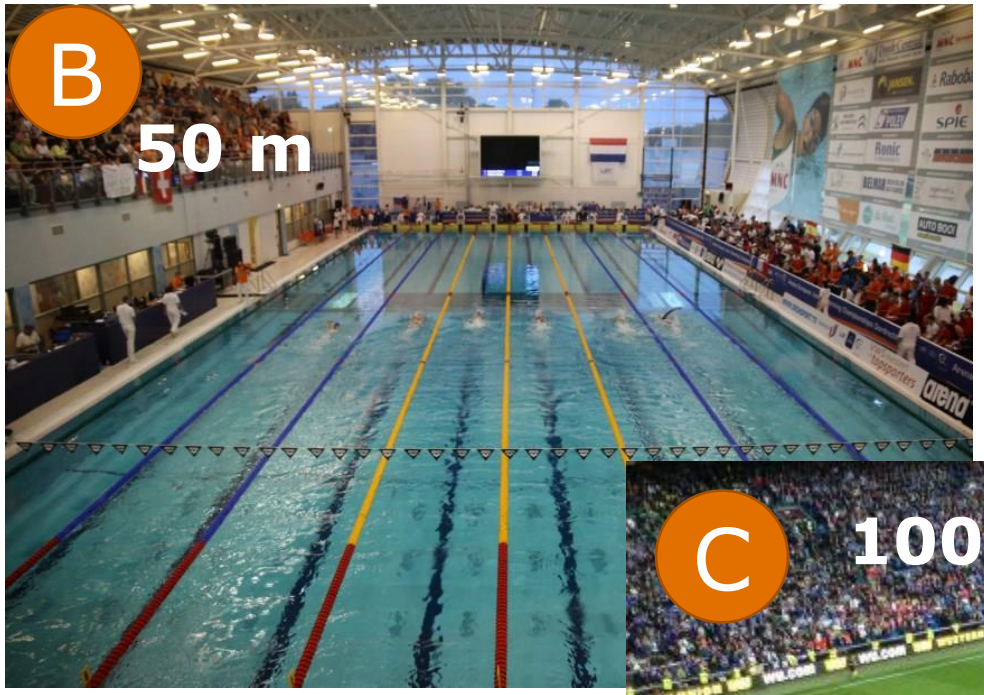
Q1: Salt mining Netherlands?



Q2: How small are the smallest caverns?



Q3: How large are the biggest caverns?

Euromast (185 m)

Eiffeltoren (324 m)

Burj Khalifa (829 m)

Q4: What is the price of a kilo salt?

Halite - NaCl

Minder dan € 1 /kilo

€ 10 /kilo

€ 5 /kilo

Alternative Silvite (KCl)

€ 70+ /kilo

€ 80-95 /kilo

€0,20 /kilo

Magnesium salts

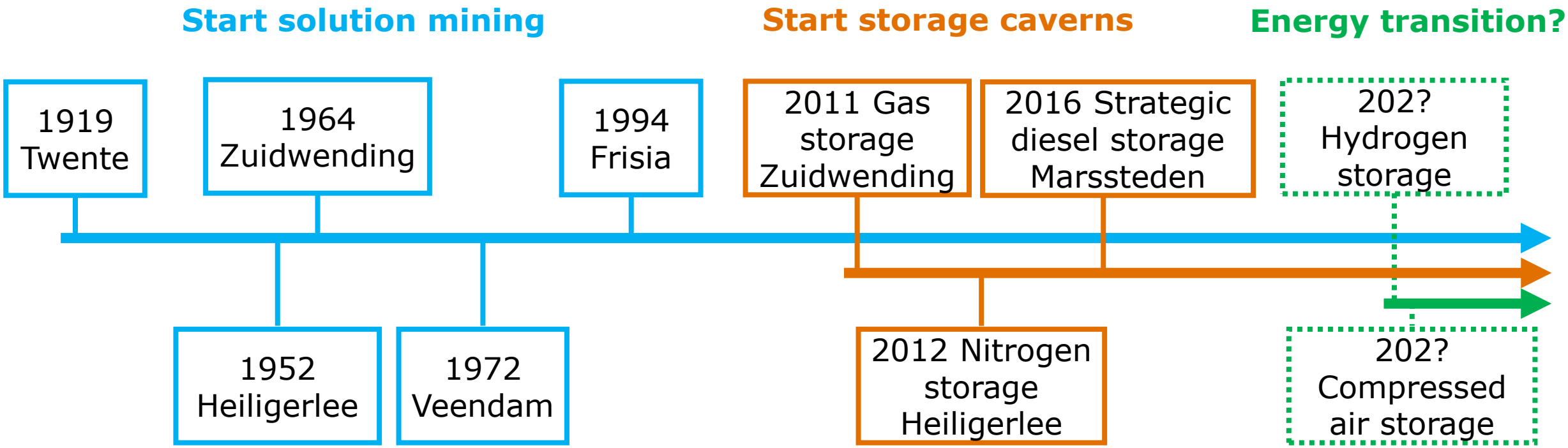
Bischofite: $MgCl_2 \cdot 6H_2O$
Carnallite: $KMgCl_3 \cdot 6H_2O$

€10 /kilo

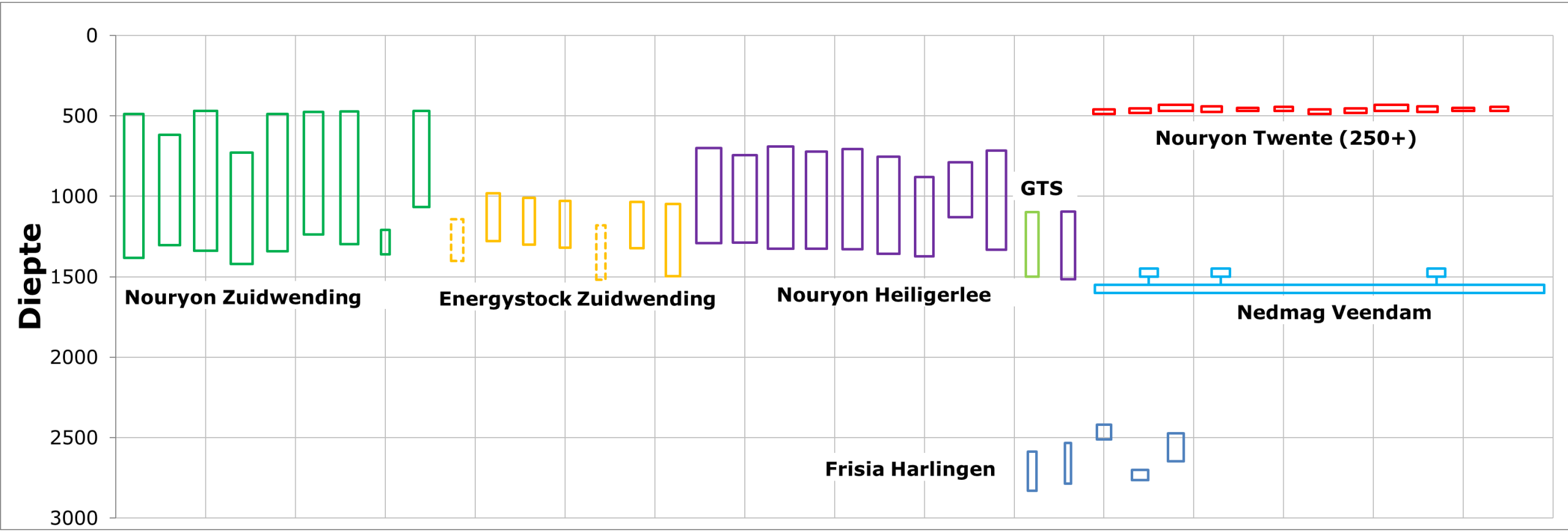
€16 /kilo

Minder dan €1 /kilo

Caverns in the Netherlands



Salt caverns in the Netherlands



Why KEM-17 Research?

1. State Supervision of Mines
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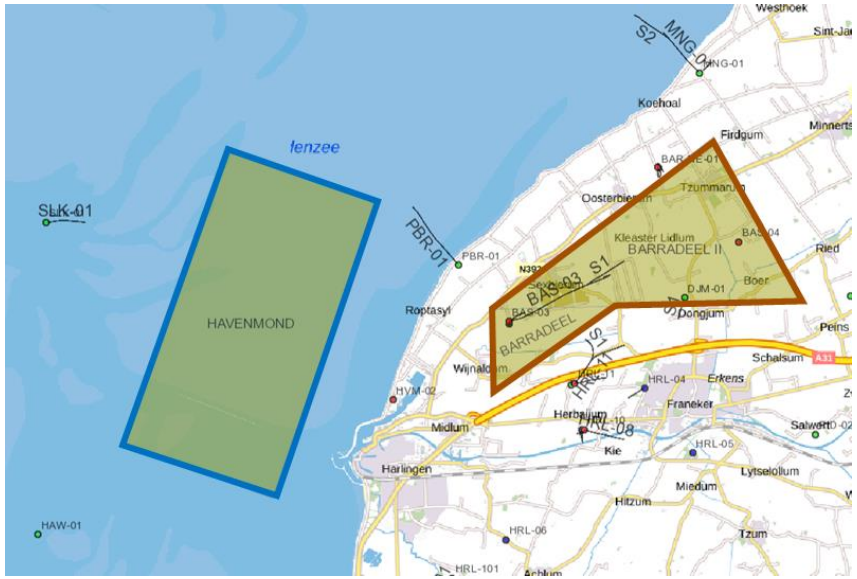
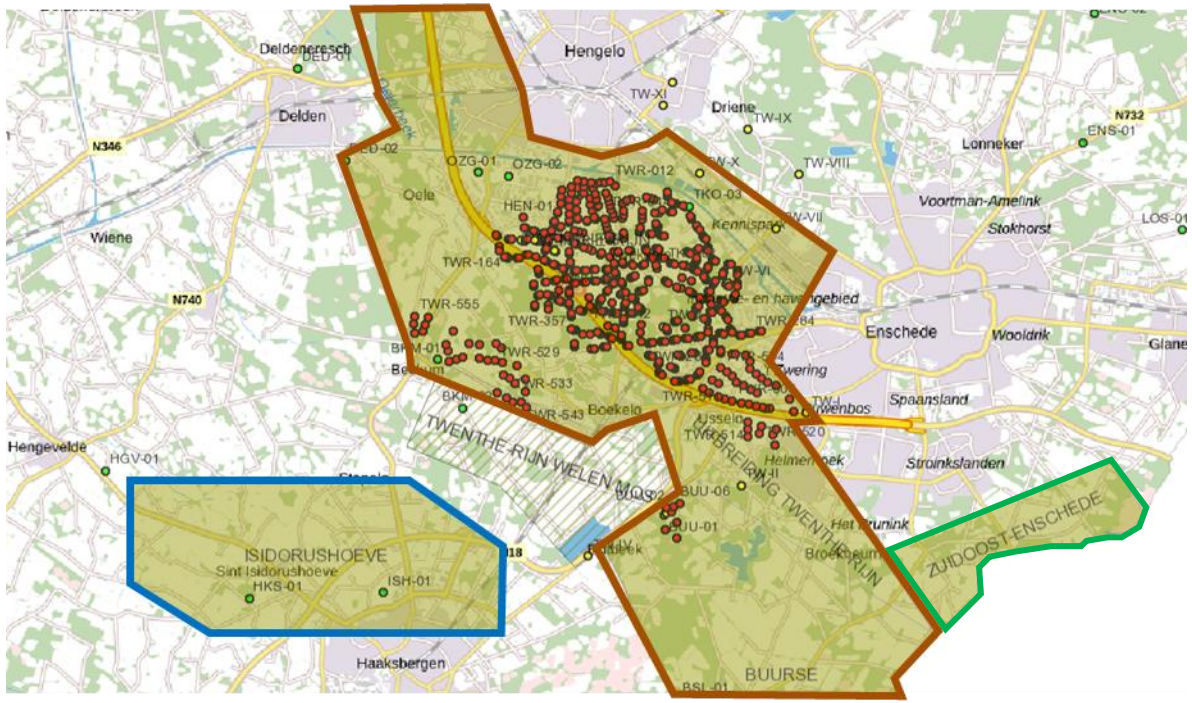
Solution mining – Legal requirements

- Operators need:
  - A concession (‘winningsvergunning’)
    - Show they are a capable operator
    - Area containing the salt





Solution mining – Legal requirements

- Operators need:
  - Mining plan ('winningsplan')
    - The way salt is mined
    - The risks: instability, seismicity, subsidence
    - How risks are taken away/minimized
    - The way caverns are abandonned

Mijnbouwbesluit, article 25, 1f

"… a description of the way caverns are abandonned after the end of production."

"…een beschrijving van de wijze waarop de holruimte na beëindiging van de winning buiten gebruik wordt gesteld."

Cavern closure – Leakage mechanism

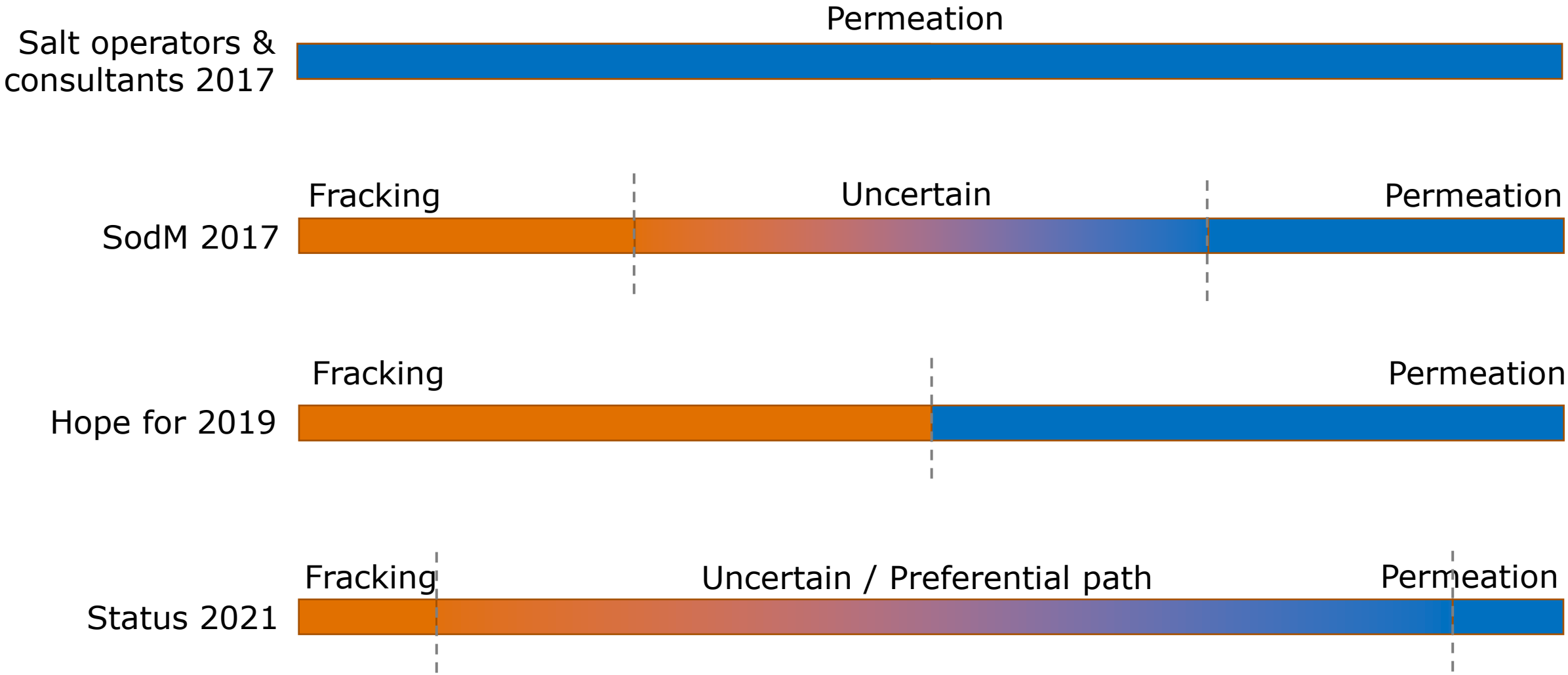
- Long-standing controversy in salt-solution mining community:

- What happens to a brine pressure in a cavern reaches local minimum principal?
  - Permeation/percolation
  - Preferential leakage path
  - Hydraulic fracturing

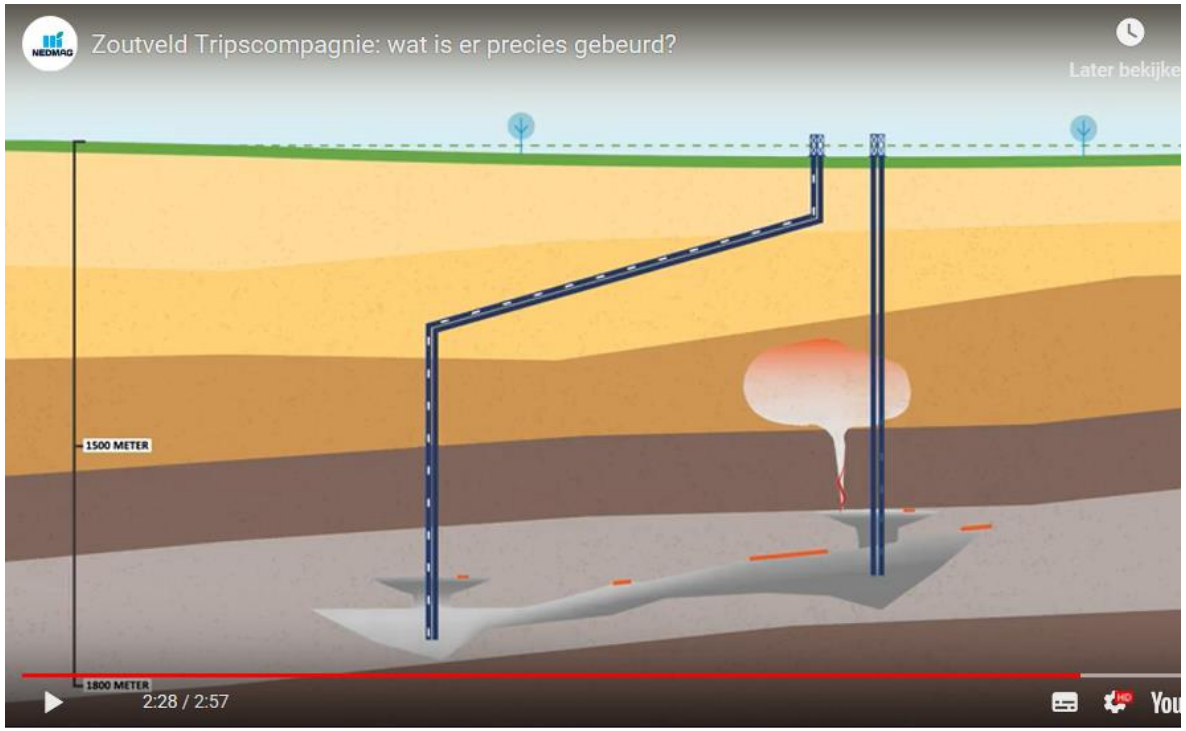
"Will it fizz or will it bang?"

Braniac, Discovery Channel

Cavern closure – Leakage mechanism

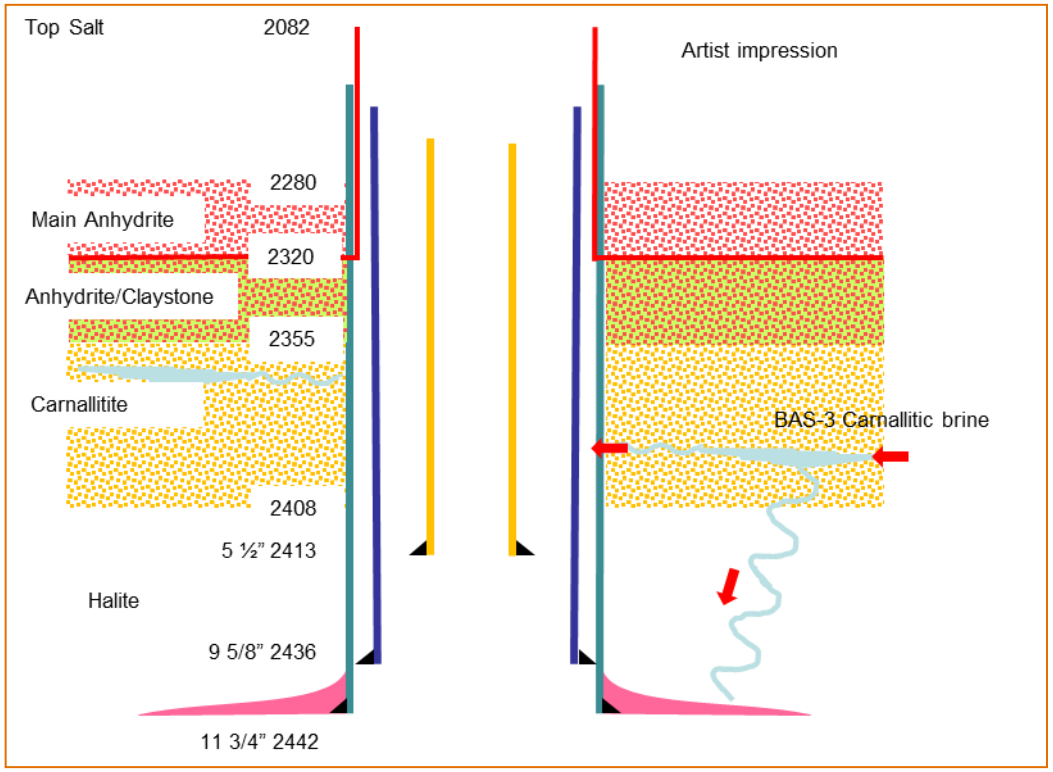


Reality catches up - Nedmag

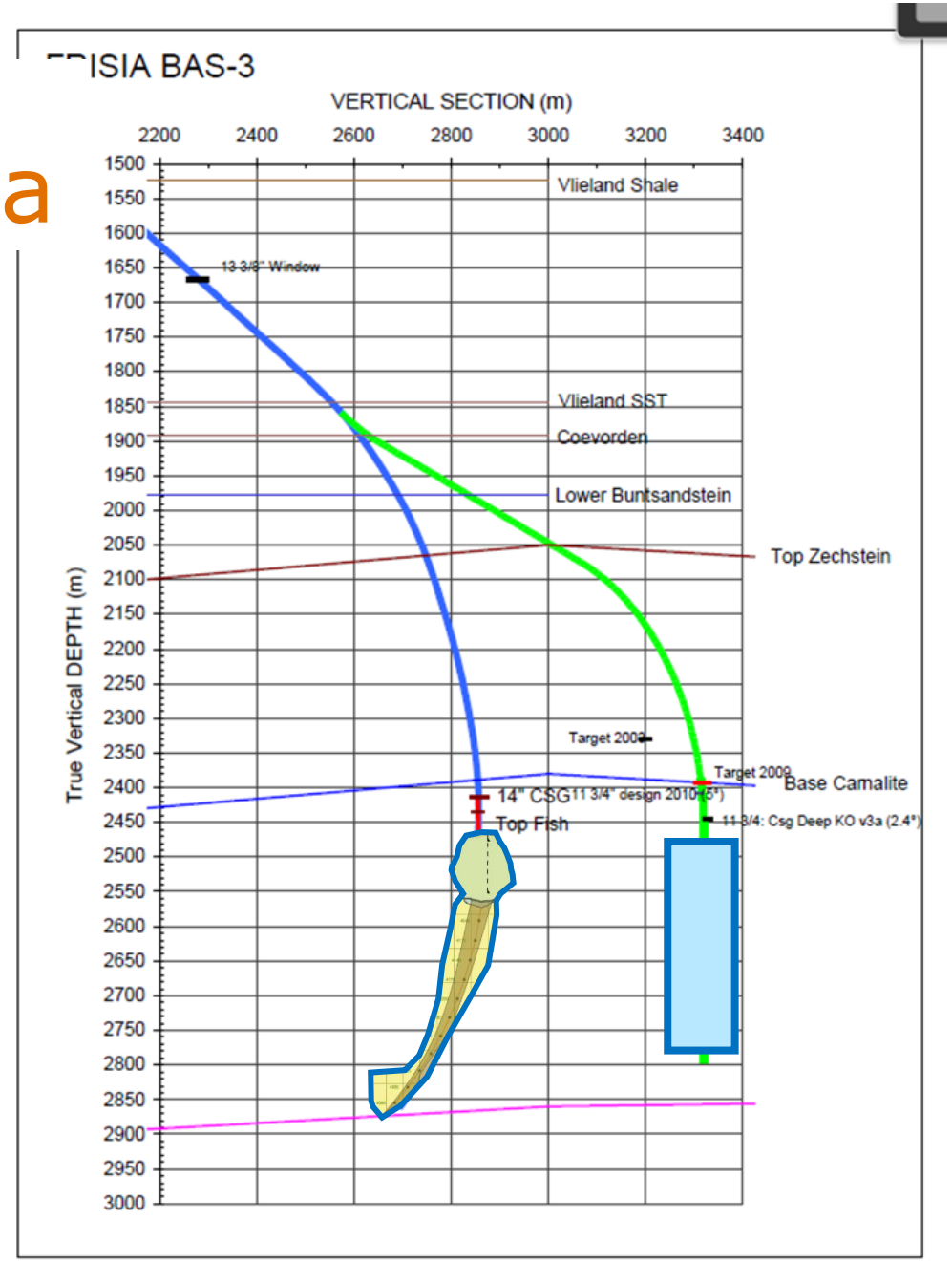


April 2018: outflow ~100.000 m^3 in ~2 days
Most likely frack from cavern to overburden

Reality catches up - Frisia



2018-2019: pulsing inflow from 1 to 100 m^3.
Brine migration through carnallite and halite



KEM-17 Micro-scale

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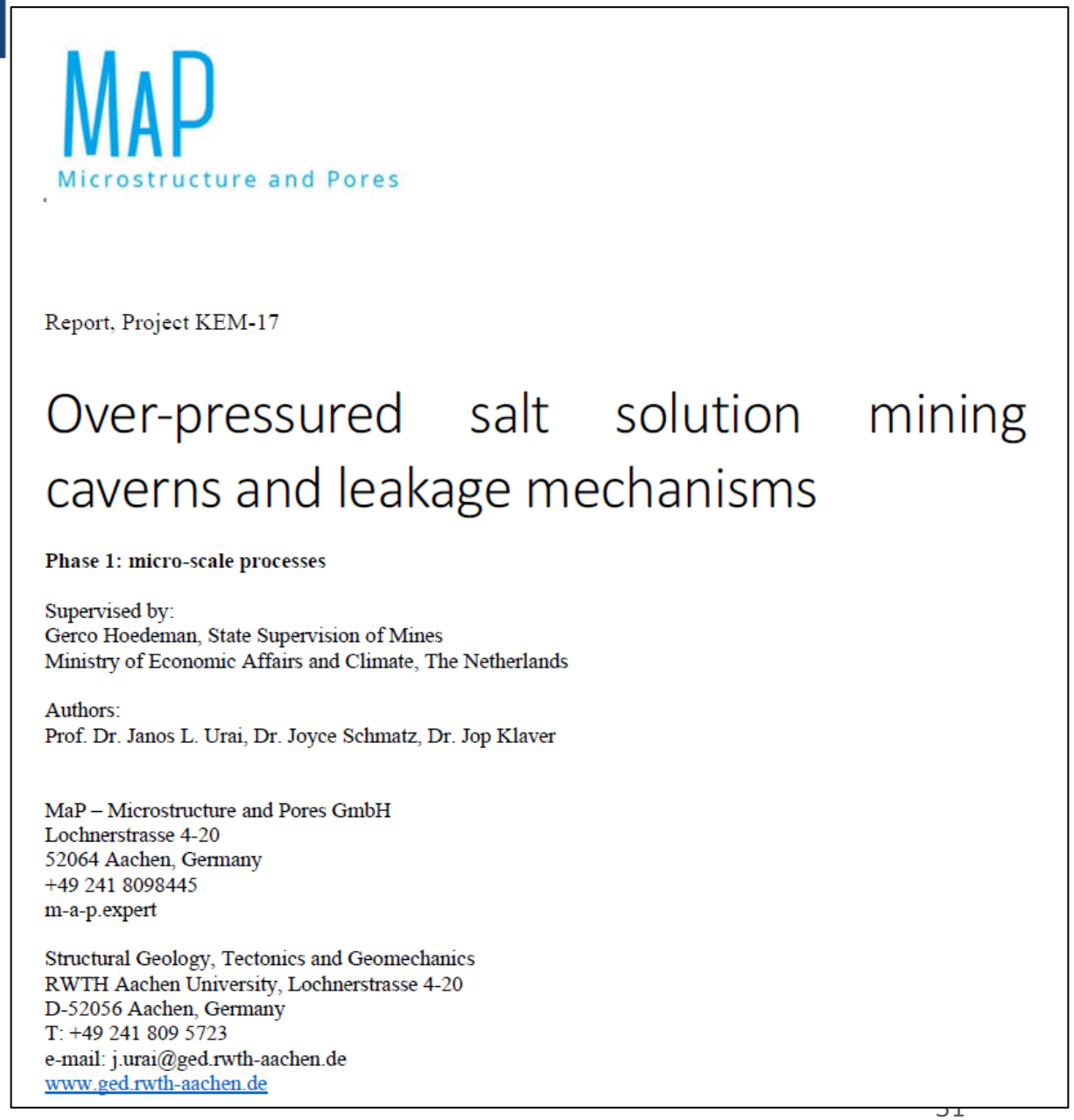
KEM-17 Micro-scale

- Questions
  - What are the initial mechanical properties of the salt?
  - How do mechanical and flow properties evolve during cavern life time?
  - How does the stress field evolve over time?
  - What is the role of heterogeneity/impurities?



MaP
Microstructure and Pores

Report, Project KEM-17

Over-pressured salt solution mining caverns and leakage mechanisms

Phase 1: micro-scale processes

Supervised by:
Gerco Hoedeman, State Supervision of Mines
Ministry of Economic Affairs and Climate, The Netherlands

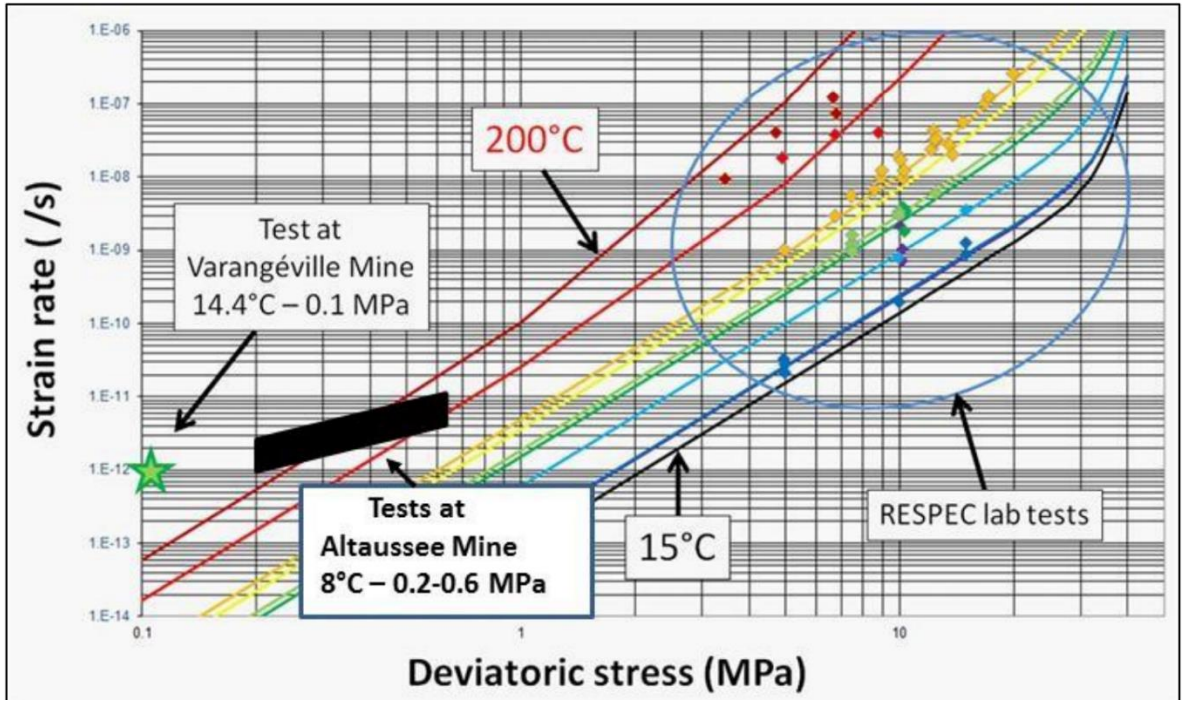
Authors:
Prof. Dr. Janos L. Urai, Dr. Joyce Schmatz, Dr. Jop Klaver

MaP – Microstructure and Pores GmbH
Lochnerstrasse 4-20
52064 Aachen, Germany
+49 241 8098445
m-a-p.expert

Structural Geology, Tectonics and Geomechanics
RWTH Aachen University, Lochnerstrasse 4-20
D-52056 Aachen, Germany
T: +49 241 809 5723
e-mail: j.urai@ged.rwth-aachen.de
www.ged.rwth-aachen.de

Micro-scale – Creep rate

- Micro-physical understanding required
  - Extrapolation of strain rates to much lower than laboratory.
  - Contribution of deformation mechanisms:
    - Dislocation creep
    - Pressure solution creep
    - Microcraking, dilatancy, permeability increase
  - Microstructure evolution is reasonably understood, but not integrated with large scale cavern behavior



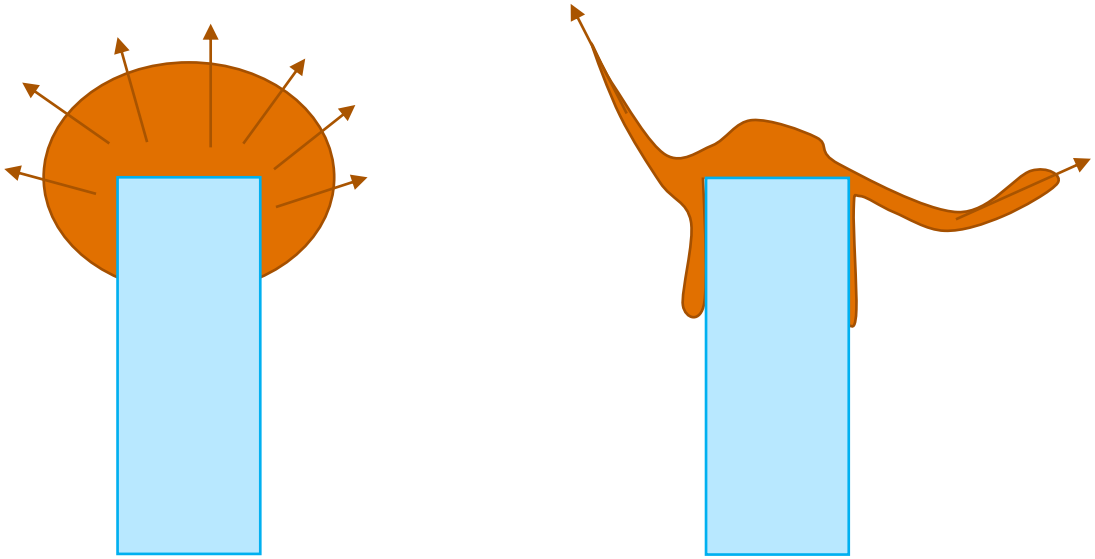
$$\dot{\varepsilon} = A(\Delta\sigma)^n = A_0 \exp\left(-\frac{Q}{RT}\right)(\sigma_1 - \sigma_3)^n$$

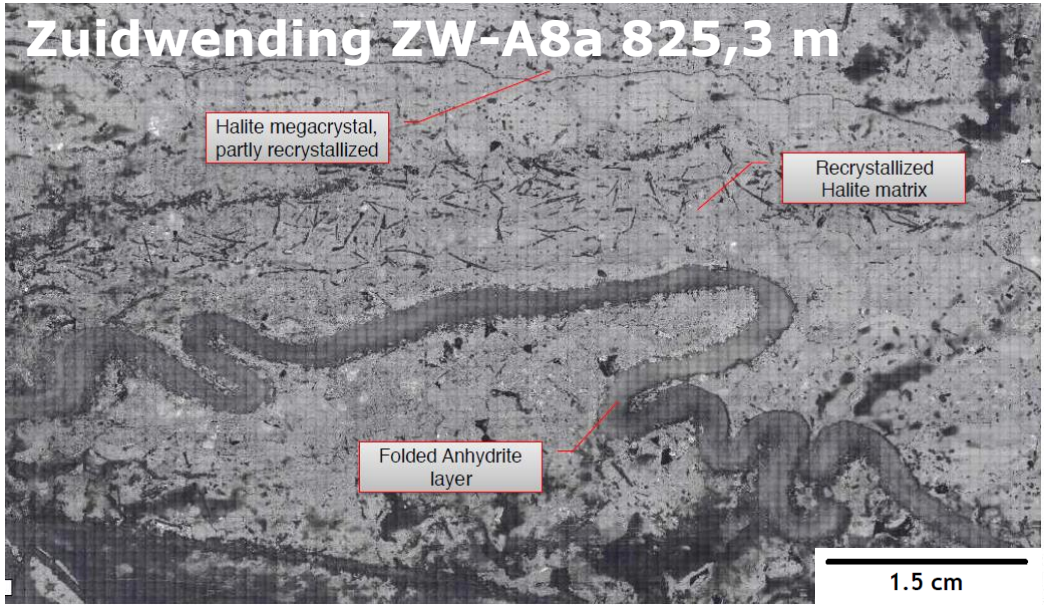
$$\dot{\varepsilon} = B(\Delta\sigma^1) = B_0 \exp\left(-\frac{Q}{RT}\right)\left(\frac{(\sigma_1 - \sigma_3)^1}{TD^m}\right)$$

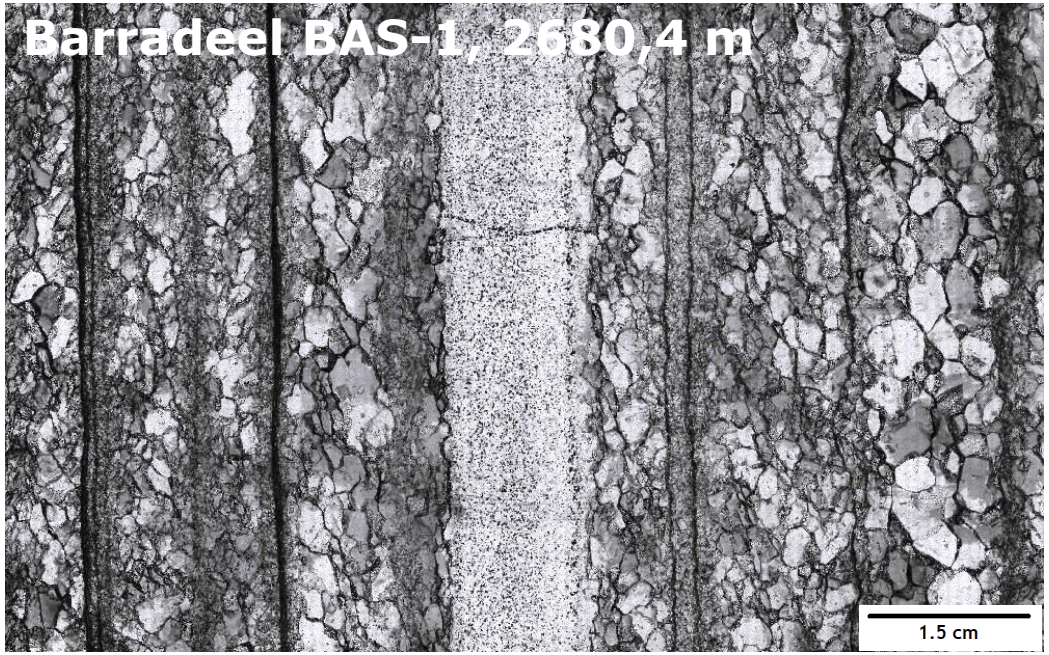
Top: SMRI Research Report RR2020-1: Very slow creep tests – A basis for cavern stability analysis – Phase 2

Micro-scale – Permeation

- Challenge permeation
  - Dependent on microstructure and impurities.
  - Permeation may be strongly heterogeneous and localized.







Micro-scale – Summary

1. A homogeneous permeation zone is not the most obvious leakage mechanism.

2. A localized leakage path seems more realistic based on differences in grain size and heterogeneity in composition.

3. Micro-physical understanding is required to upscale creep and flow properties to cavern and dome-scale.

KEM-17 Cavern-scale

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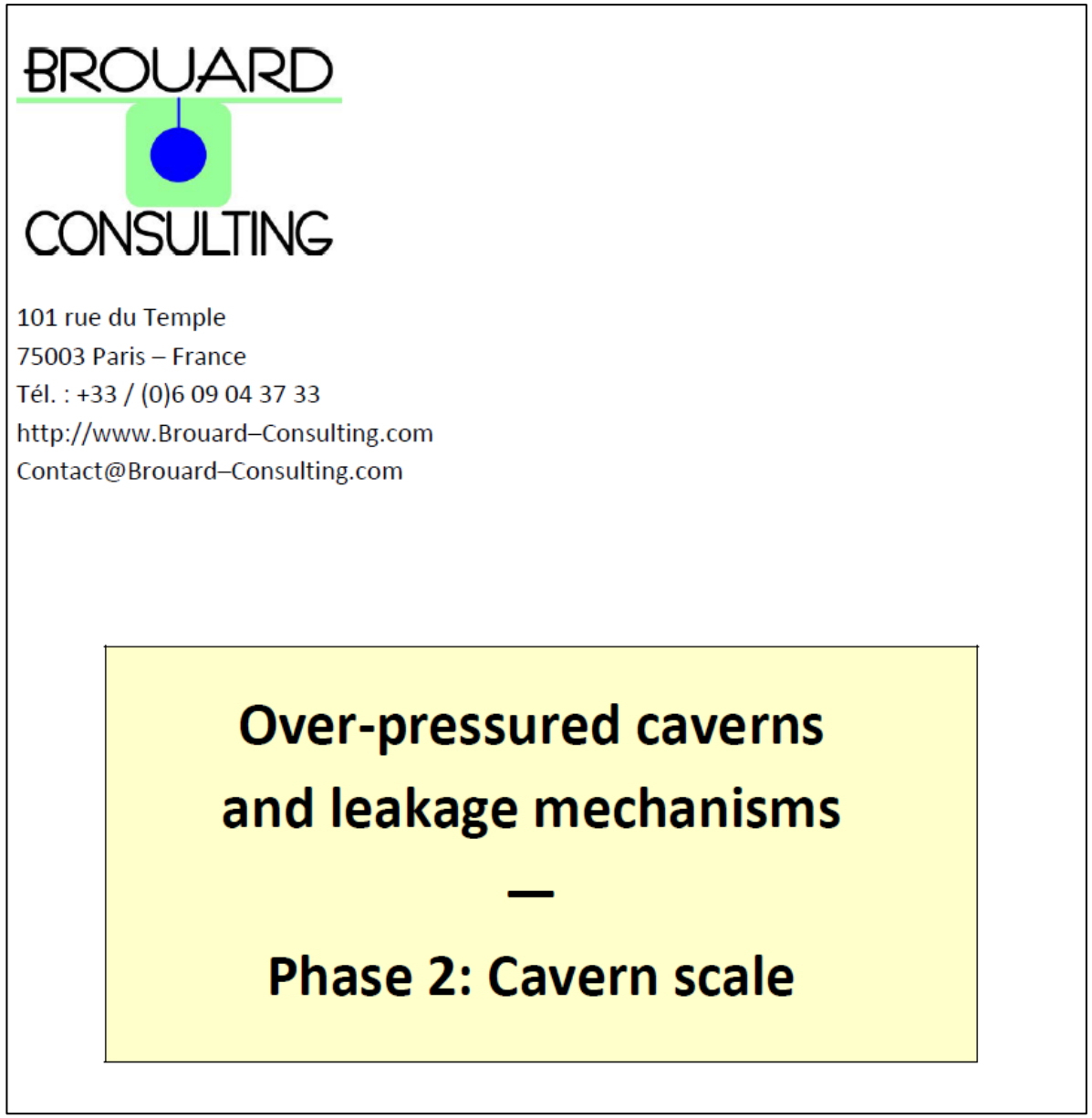
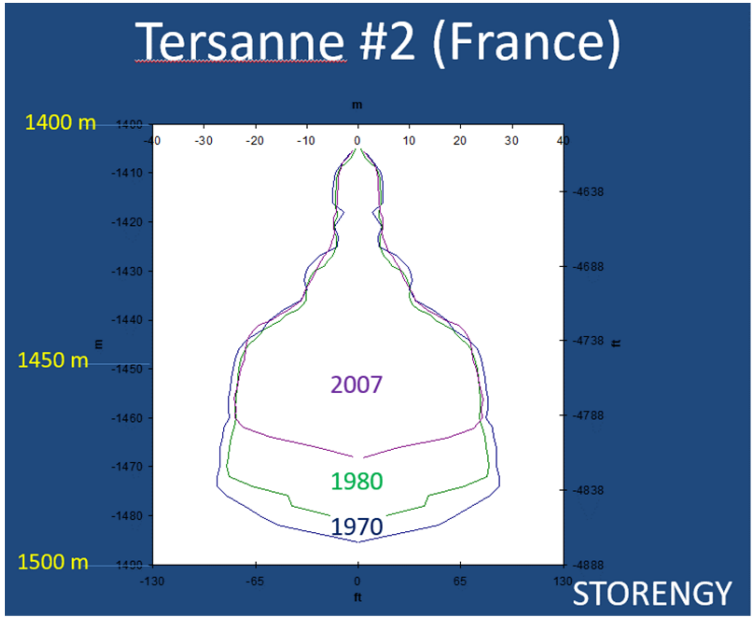
KEM-17 Cavern-scale

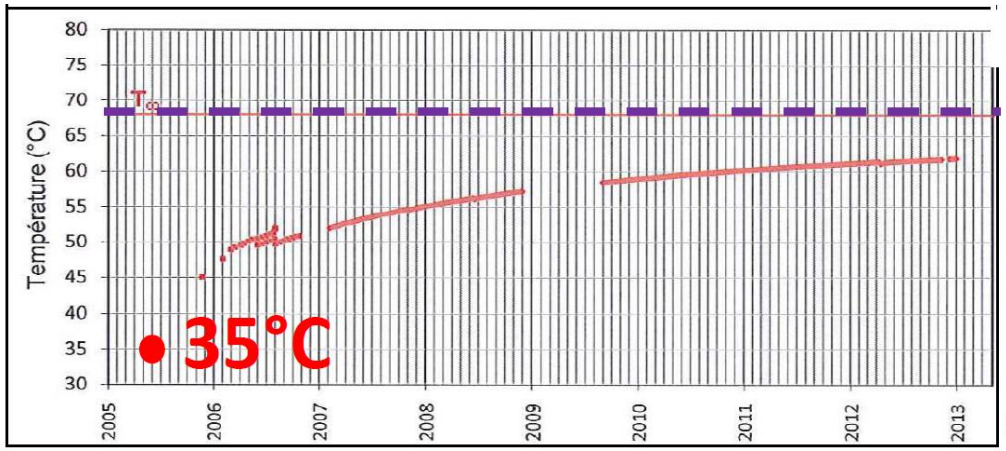
- Questions
  - How quickly does the pressure build up after closure?
    - Salt creep
    - Thermal expansion brine
  - Can permeation keep up with pressure build up?
  - What is the minimum principle stress?



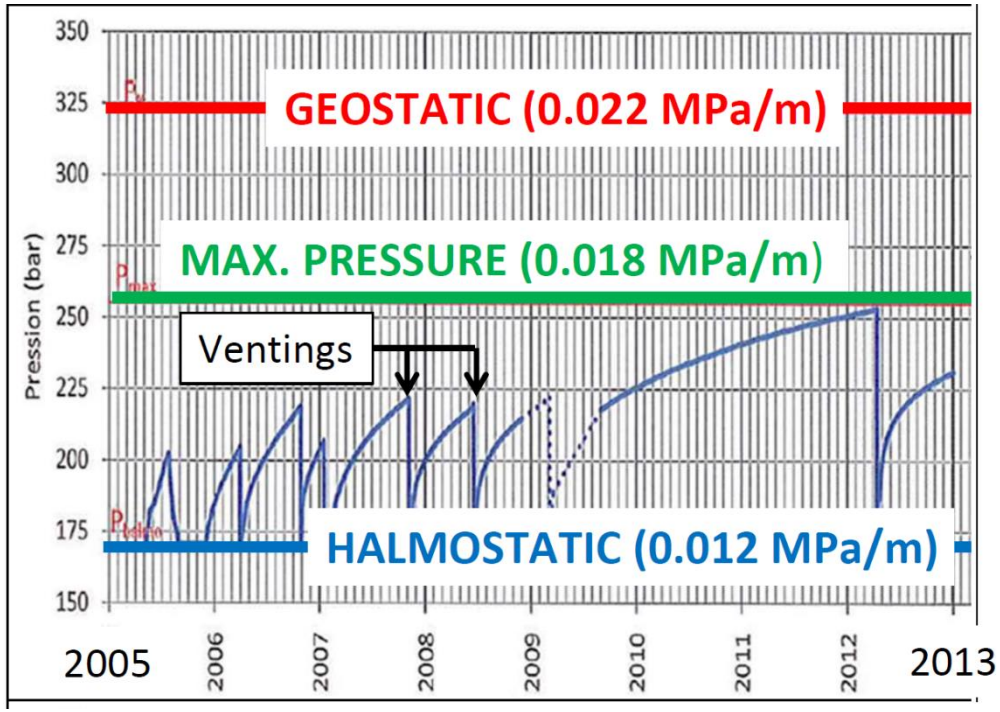
Why does pressure increase?

- Reason 1: Brine warming
  - Large influence 1 MPa per 1 ^{o}C!
  - In large cavernes it takes long time (low area vs volume)
  - Long waiting period is needed.





(Hévin & Rousset, 2013)



Why does pressure increase?

- Reason 1: Brine warming
  - Characteristic time for equilibrating 75% of temperature gap.
  - Cavern X:
    - H= 700 m, D= 100 m
    - Time = 40 years
  - Cavern Y:
    - H= 30 m, D= 100m
    - Time = 7 years

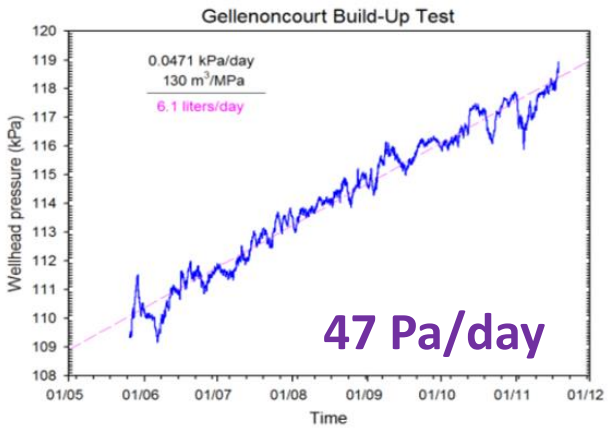
$$t_c \approx a \cdot \left[\frac{V_c(m^3)}{100{,}000}\right]^{2/3} \times \exp\left[-\frac{1}{2}\left(\frac{\ln(A/A_o)}{b}\right)^2\right]$$

$a = 4.67, b = 1.97,$ and $A_o = 0.91$. A=Height / Diameter

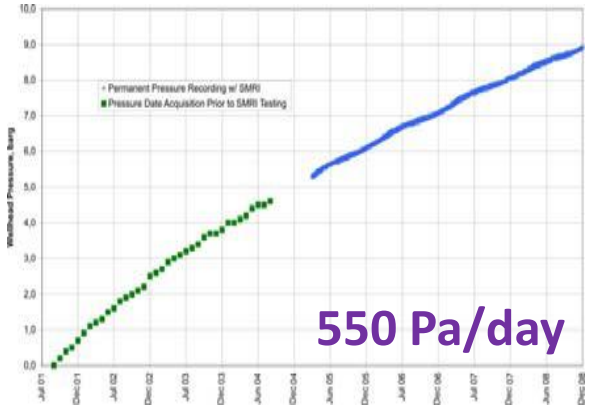
Karimi-Jafari et al (2007) Thermal effects in salt caverns

Pressure build-up rates

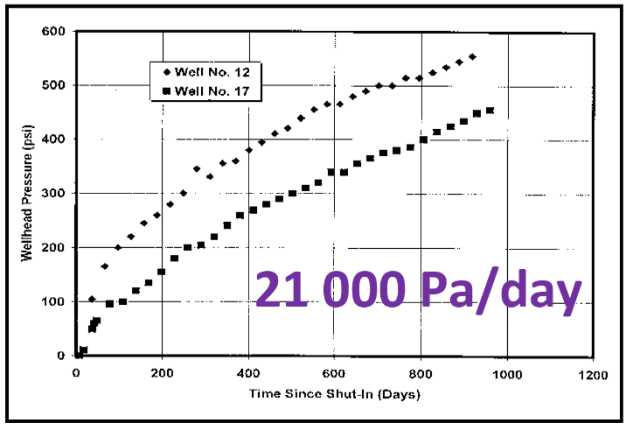
Gellenoncourt
300 m

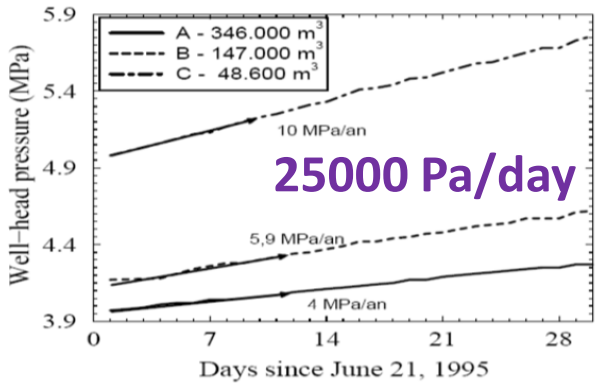


Stassfurt
600 m

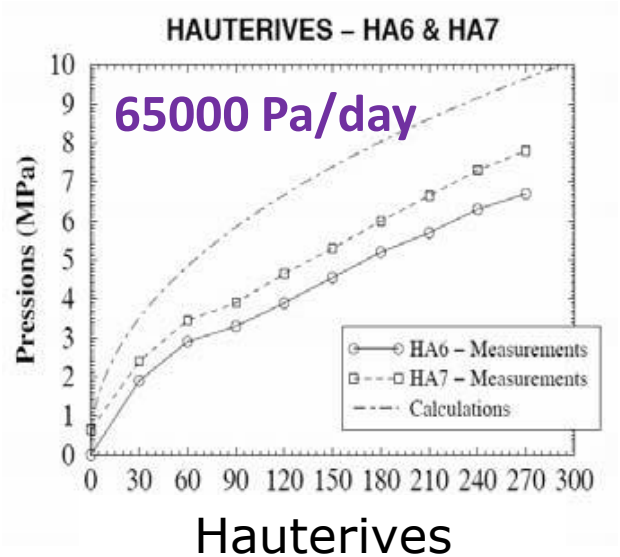


Mont Belvieu
600 m

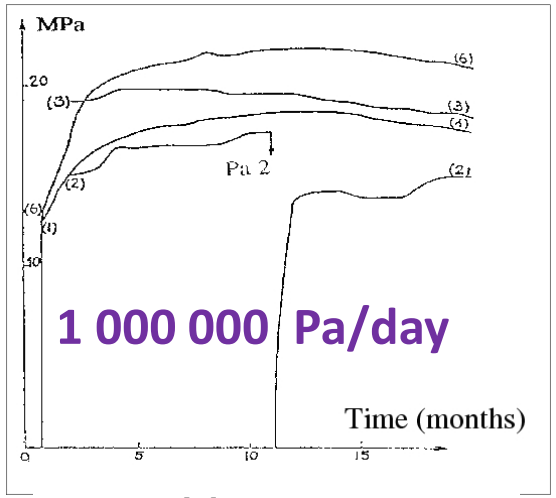




Etrez
1350 m



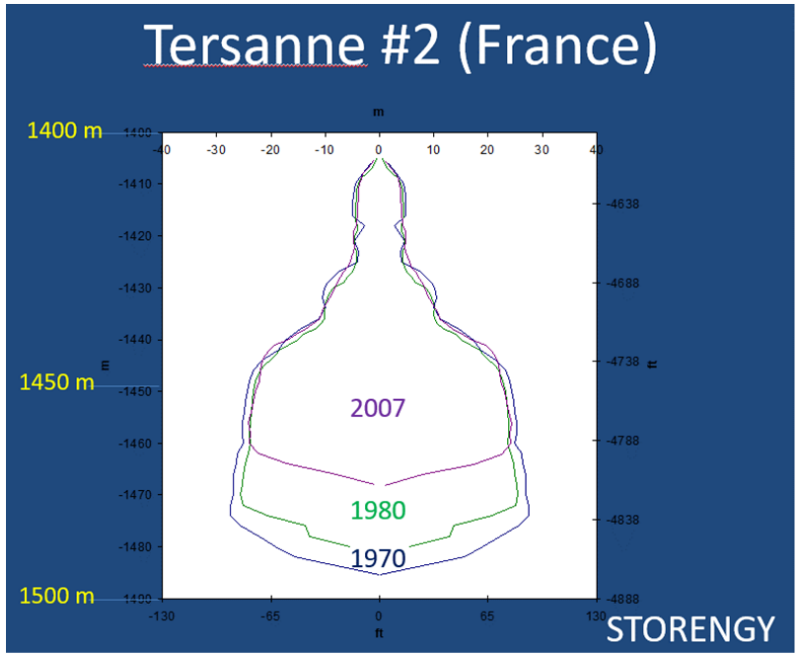
Hauterives
1500 m



Vauvert
2000 m

Why does pressure increase?

- Reason 2: Cavern creep closure
  - Salt is a viscous liquid
  - Cavern shrinks when brine pressure is smaller than stress in salt
  - Closure rate is highly non-linear dependent on pressure difference



$$\dot{\varepsilon} = A(\Delta\sigma)^n = A_0 \exp\left(-\frac{Q}{RT}\right)(\sigma_1 - \sigma_3)^n$$

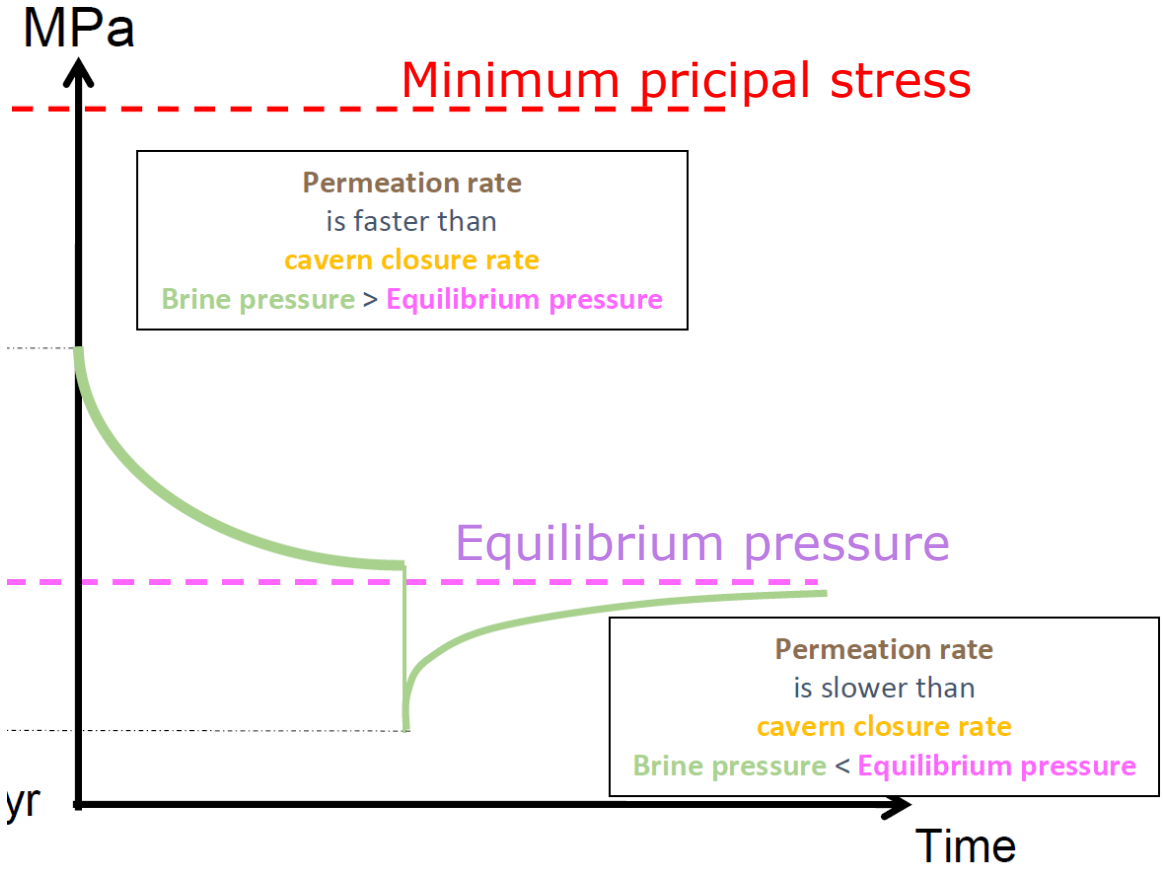
dislocation creep

$$\dot{\varepsilon} = B(\Delta\sigma^1) = B_0 \exp\left(-\frac{Q}{RT}\right)\left(\frac{(\sigma_1 - \sigma_3)^1}{TD^m}\right)$$

pressure solution creep

Shallow cavern abandonment concept

- P-decrease: Brine permeation
  - Tests in small, shallow cavern show an equilibrium pressure.
- Equilibrium pressure
  - $T_{brine} \approx T_{salt}$
  - Rate creep closure = Rate permeation
  - Equilibrium pressure smaller than critical minimum principal stress



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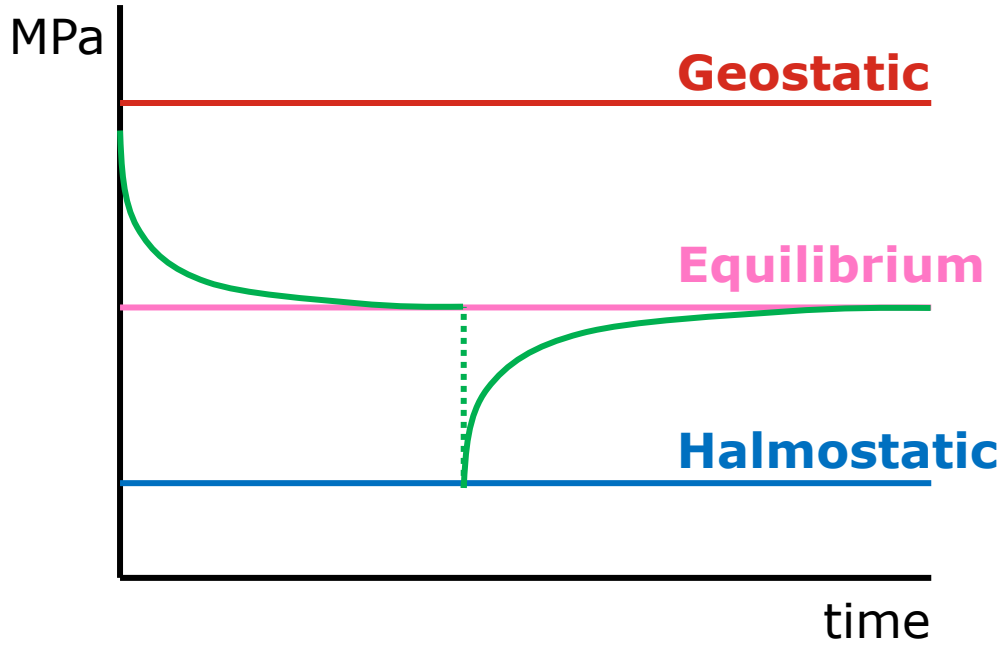
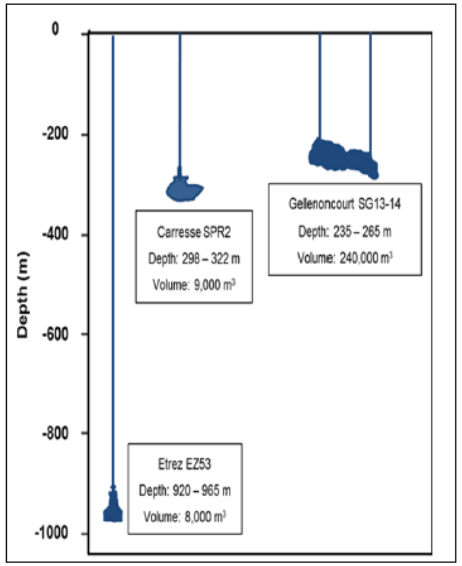
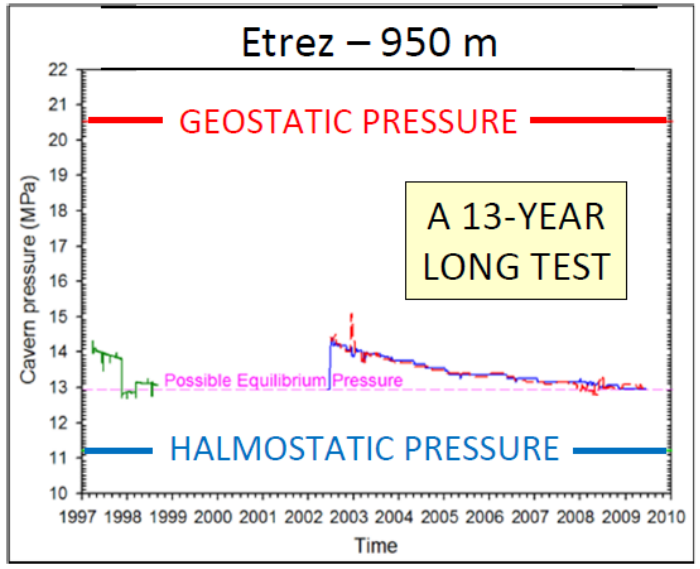
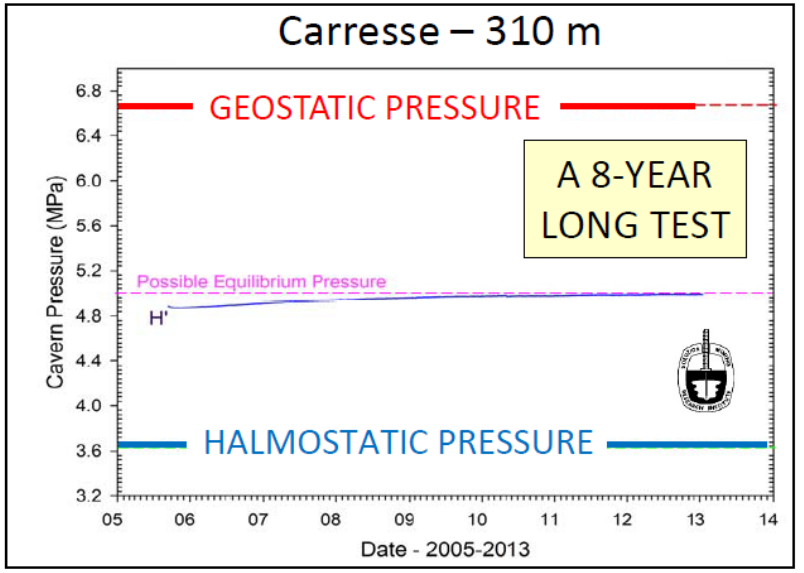
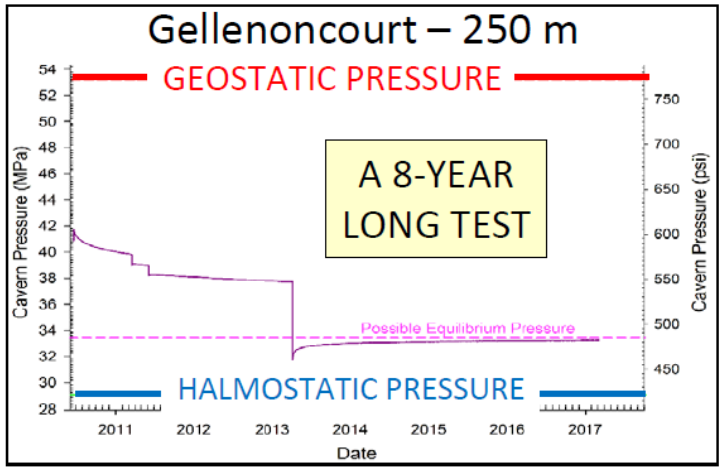


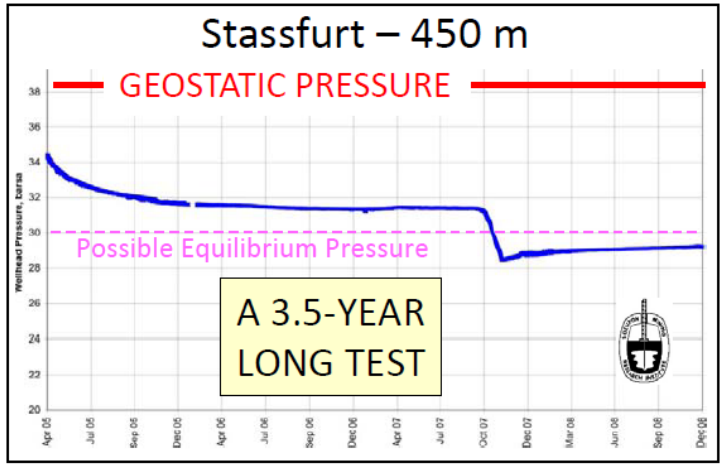
Shallow cavern abandonment concept

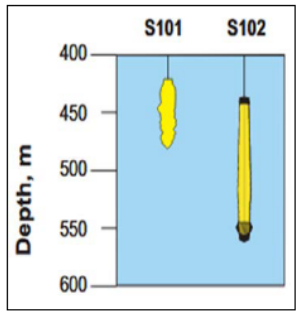








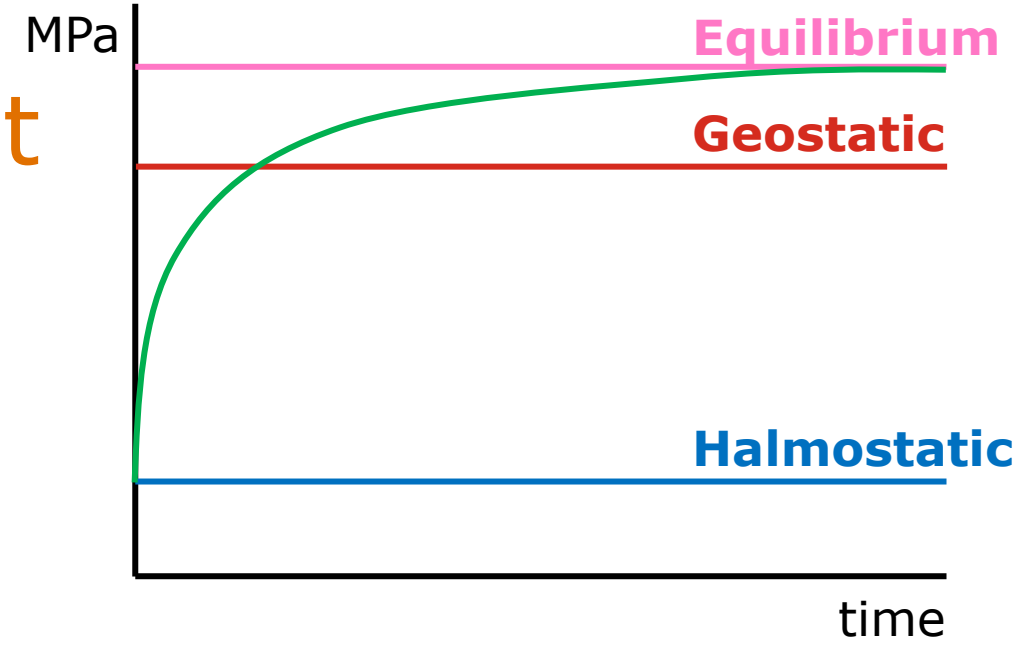


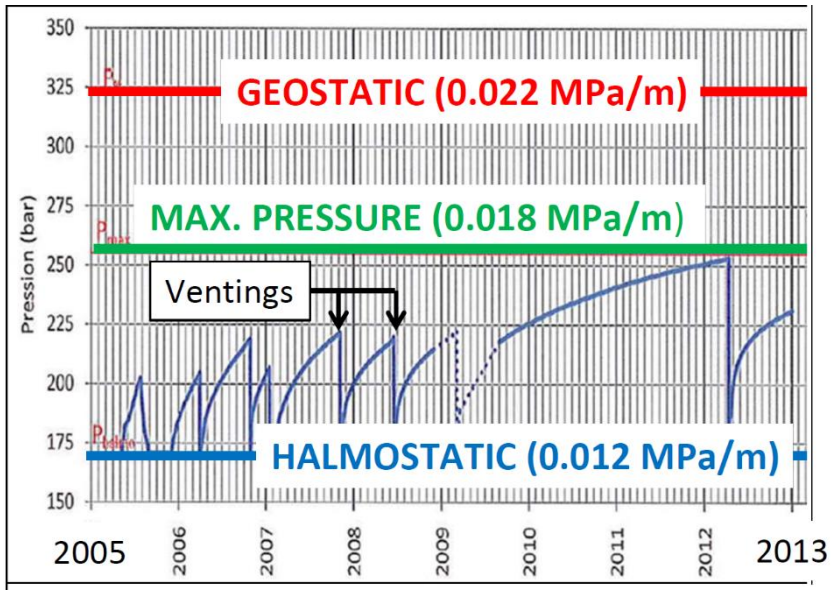


Deep cavern abandonment

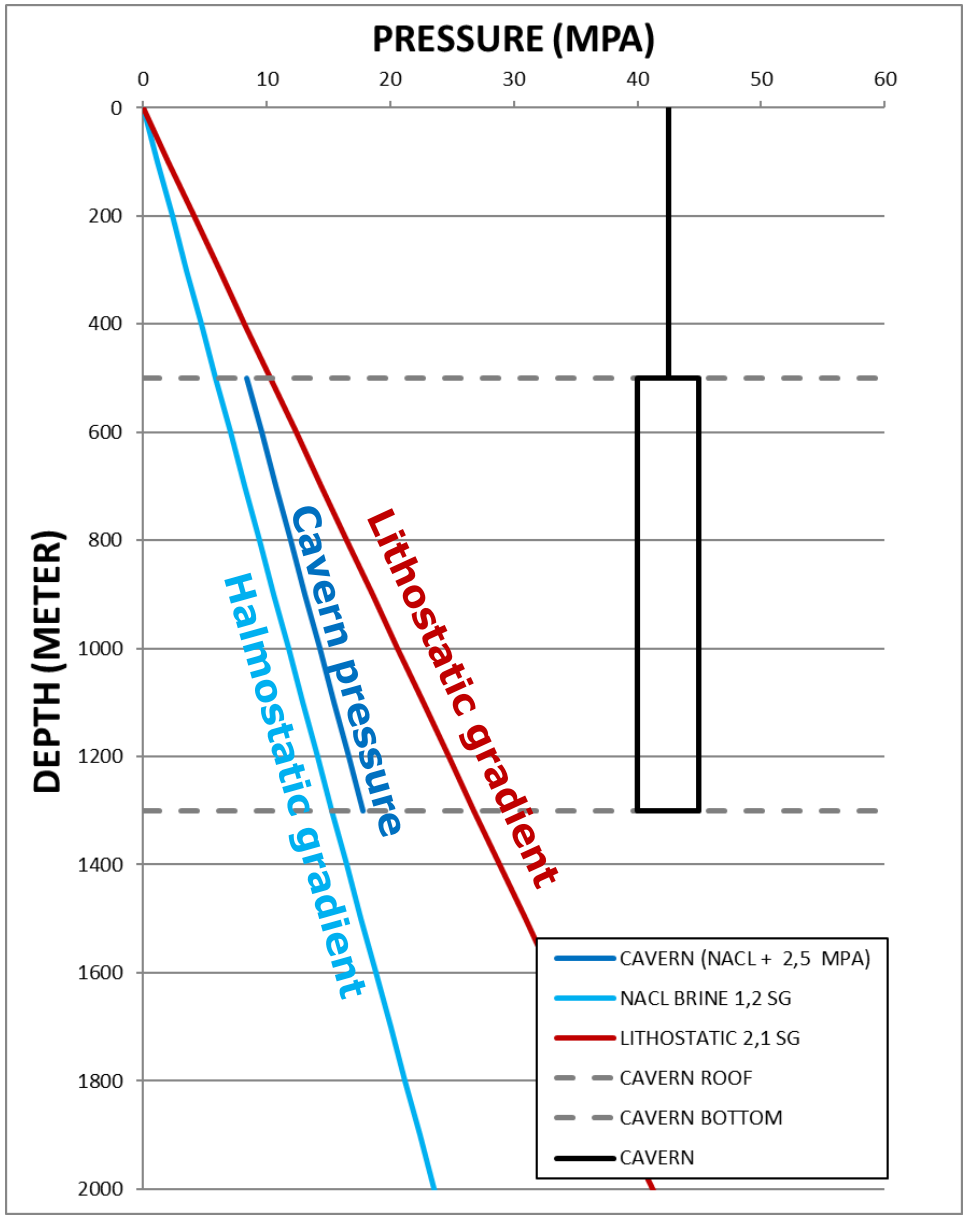
- More complex than shallow:
  - Higher temperatures cause higher creep and pressure build-up rates
  - Larger temperature gap to equilibrate
  - Tests more difficult, due to potential safety issues

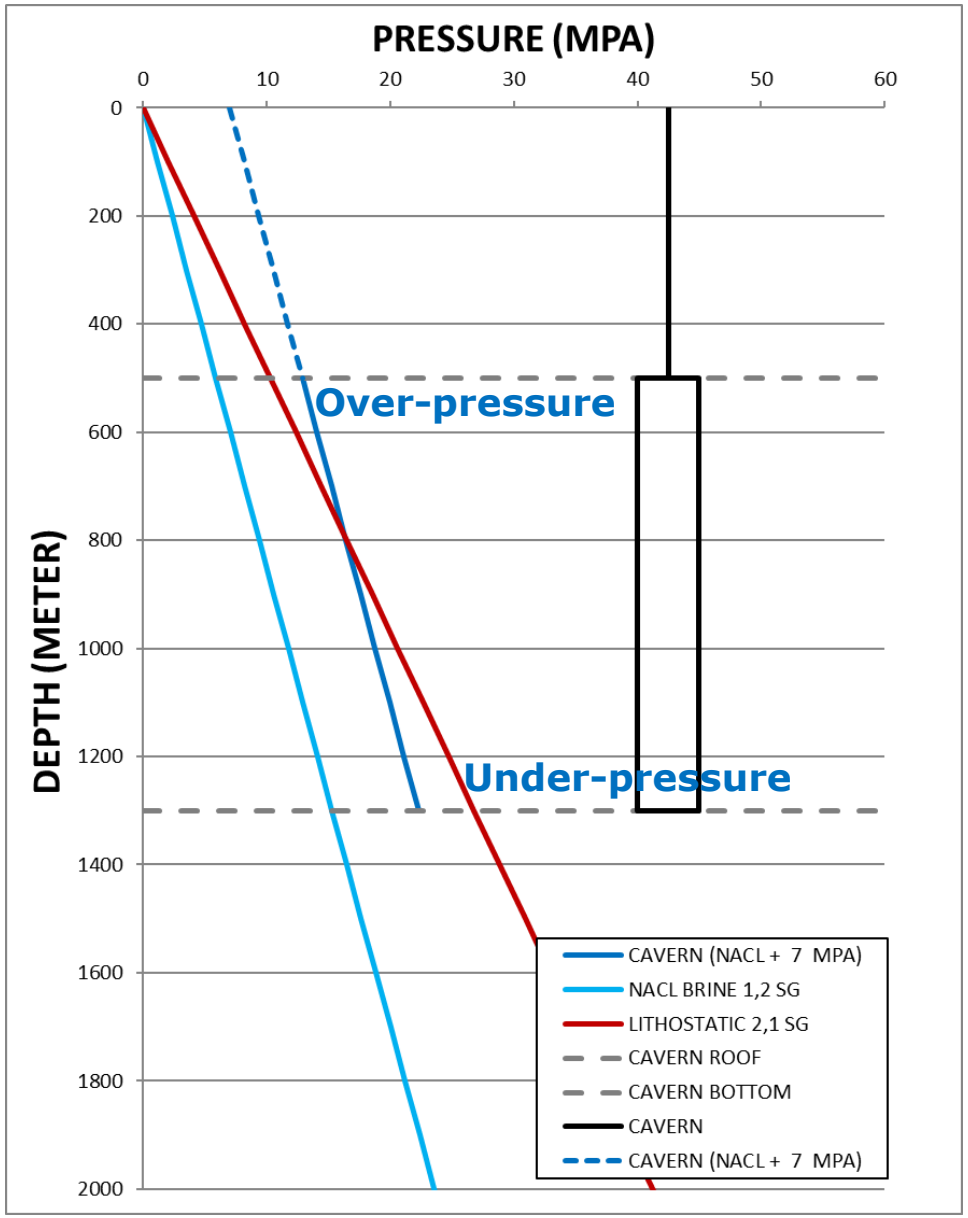
- Complexity *high* caverns:
  - Large potential for over-pressure at cavern roof due to density difference
  - Socalled "Wallner's margin"





High caverns – Wallner's margin





Cavern-scale - Summary

1. In shallow caverns a safe equilibrium pressure may be reached.
2. In deep caverns the pressure increase may be too rapid to accomodate by permeation.
3. In high caverns there is a large potential for overpressure.
4. SodM: The minimum principal stress may be lower than expected.

KEM-17 Dome-scale

1. State Supervision of Mines
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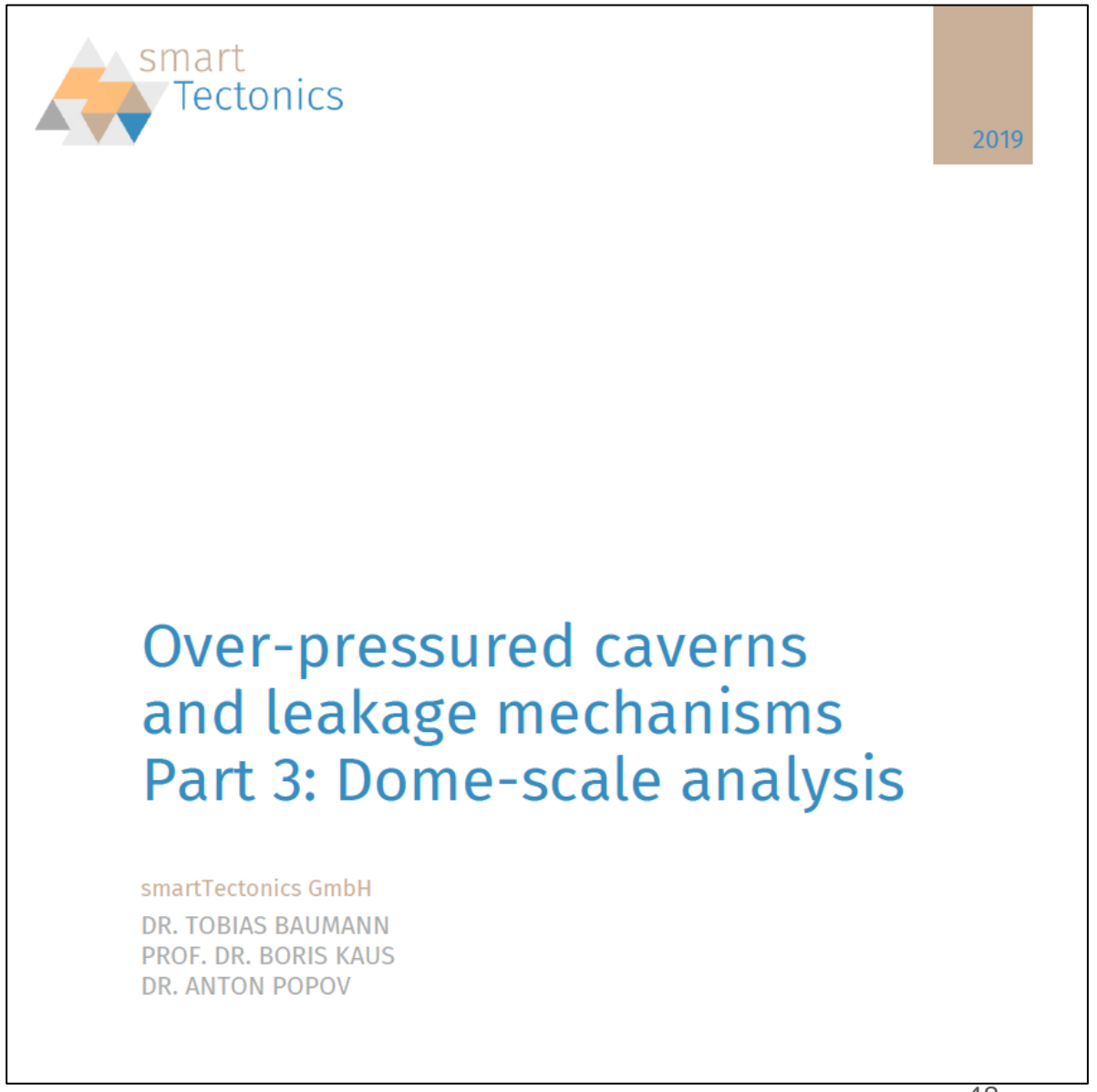
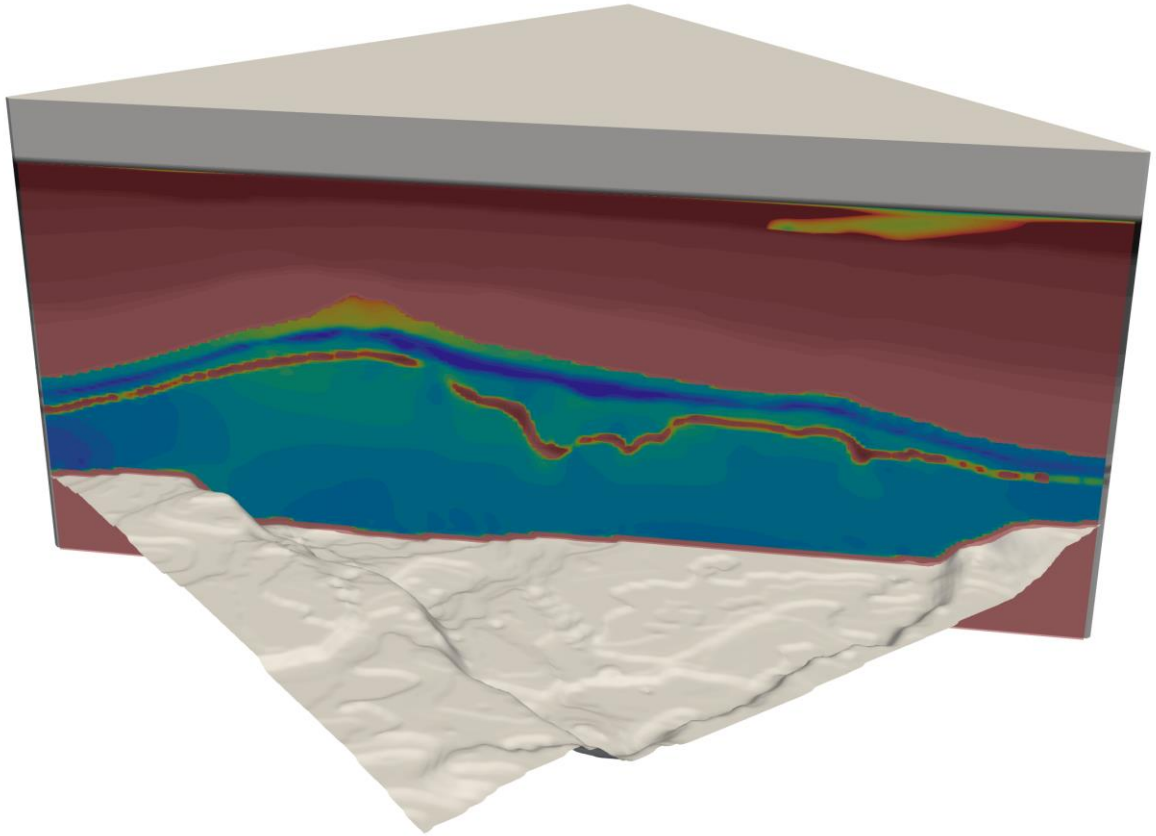
Dome-scale

- Literature: What is known about the stress state in salt formations?
- Rheology: How to close the gap between micro-scale and macro-scale?
- What initial stress magnitudes can we expect?



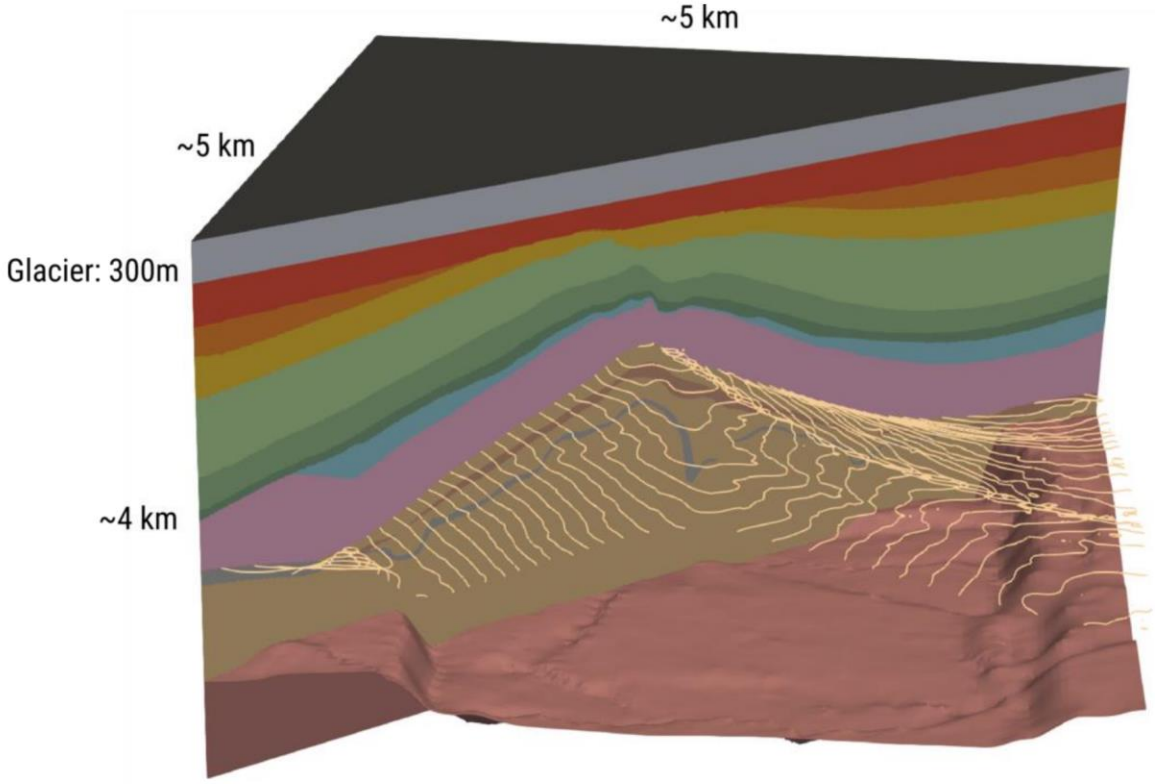
Dome-scale

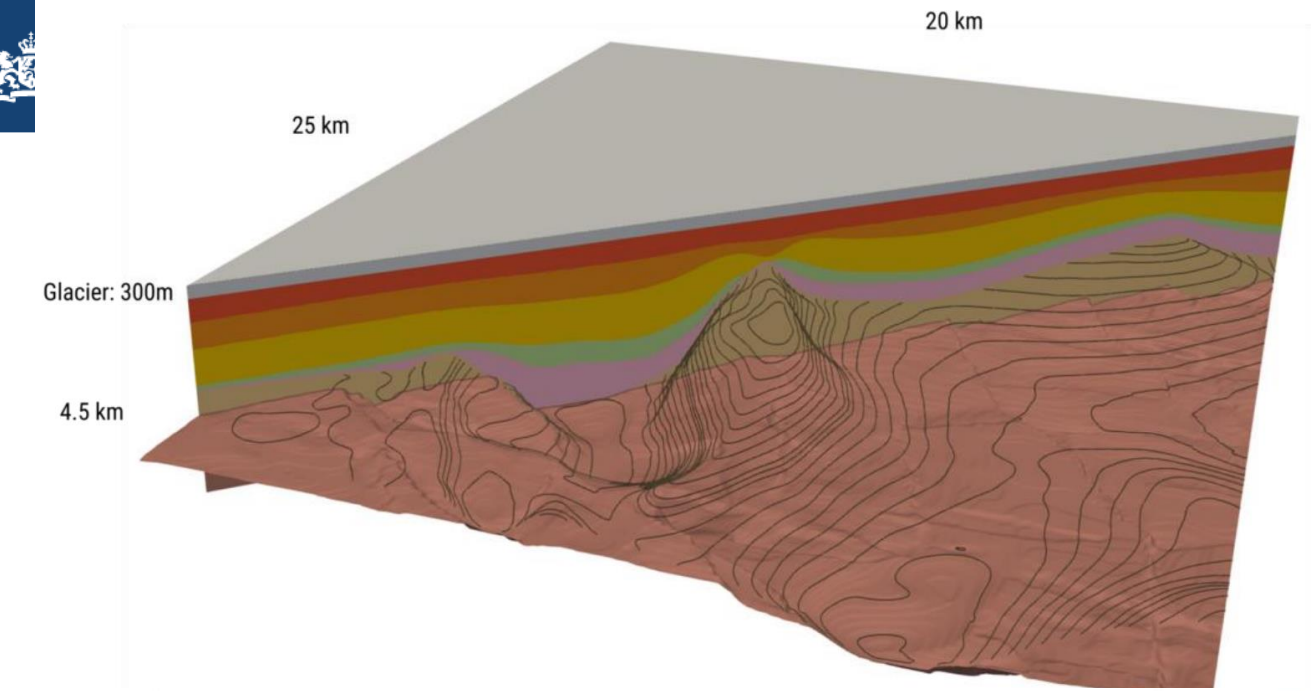
- Often the intial state of stres in a salt body is isotropic. How realistic is this?
- Numerical simulations were performed of relevant pillow and dome structures.
- Variations in salt rheology, glacial loading and anhydrite layers were simulated.
- Challenge: Realistically upscaling PS-DC creep behavior from lab to dome-scale.

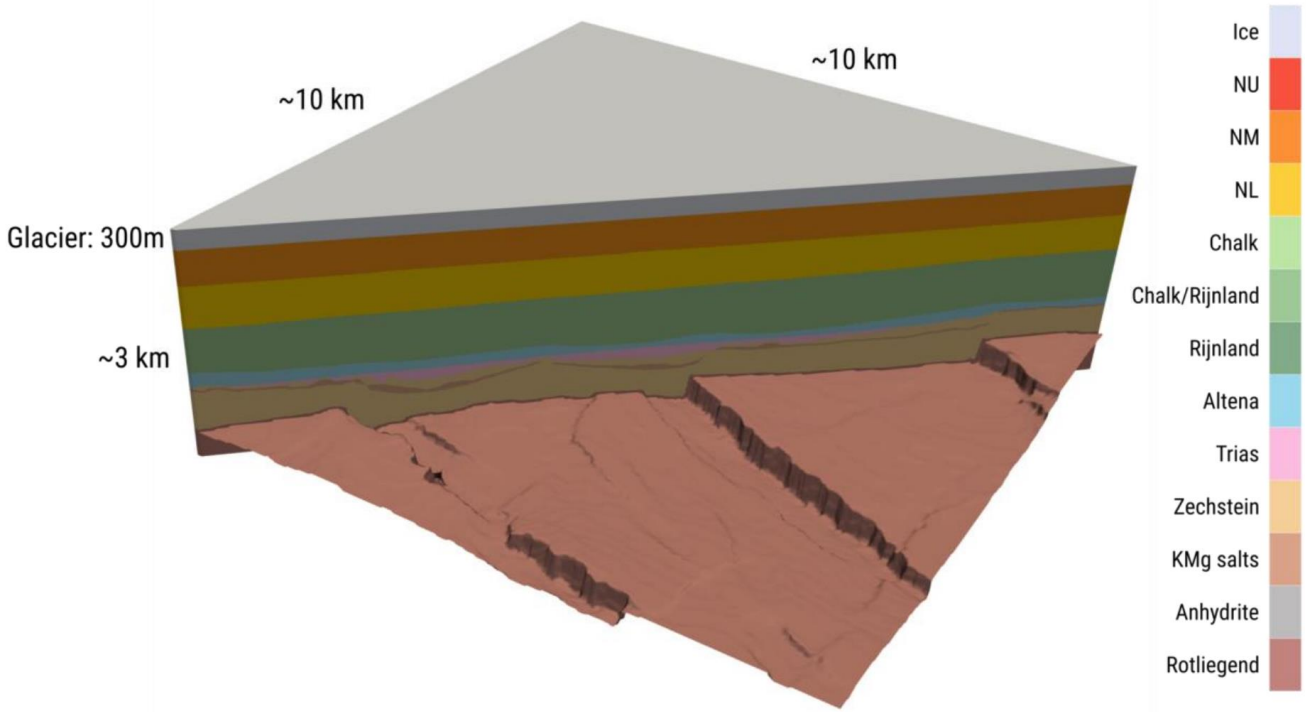


Dome-scale

- Simulation were done on salt pillow, flat-bedded salt and salt wall.

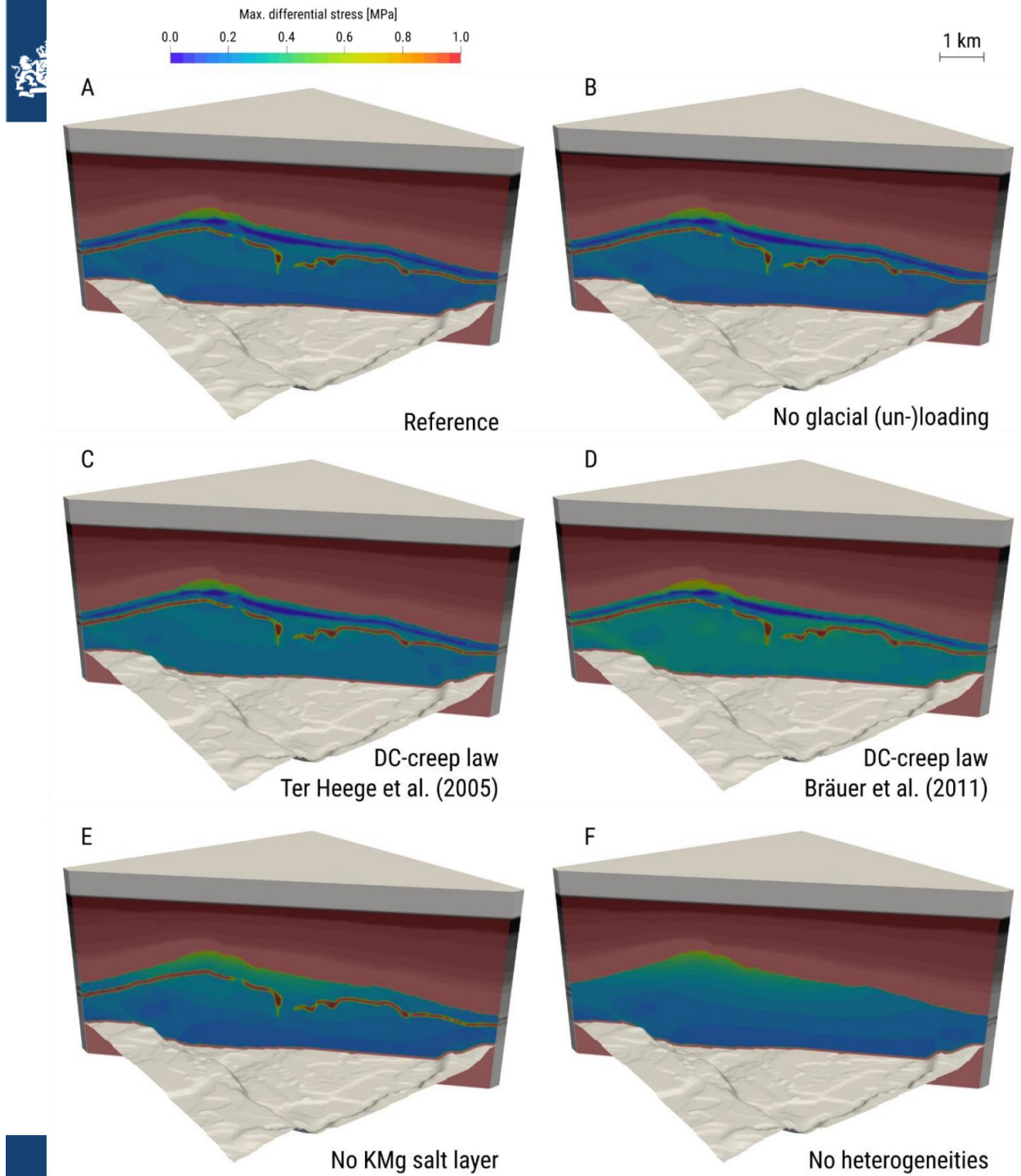






Dome-scale

- Simulations are run for:
  - Base case
  - No glacial (un-)loading
  - Different dislocation creep laws
  - No KMg-salt layers
  - No heterogeneities



Dome-scale – Summary

Conclusions

1. Flat-lying salt layers have the only small differential stresses.
2. Differential stresses are larger near:
    1. Top of salt structure
    2. Close to lateral edge of salt body
    3. Dense anhydrite stringers or weak KMg-salts.

Recommendations

1. Models can be calibrated with sonar and microstructural observations
2. Consider a range of creep rheologies to map bandwidth of uncertainty.
3. Simulate models including salt structure, overburden and cavern construction, operation and abandonment.

KEM-17 implications

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KEM-17 - Two conclusions

1. With the current knowledge it can not be predicted with certainty if a deep cavern will leak via slow permeation, a localized leakage path or hydraulic fracture.

2. Knowledge of micro-, cavern- and salt dome-scale is not integrated enough. Processes on all three levels influence the leakage mechanism.

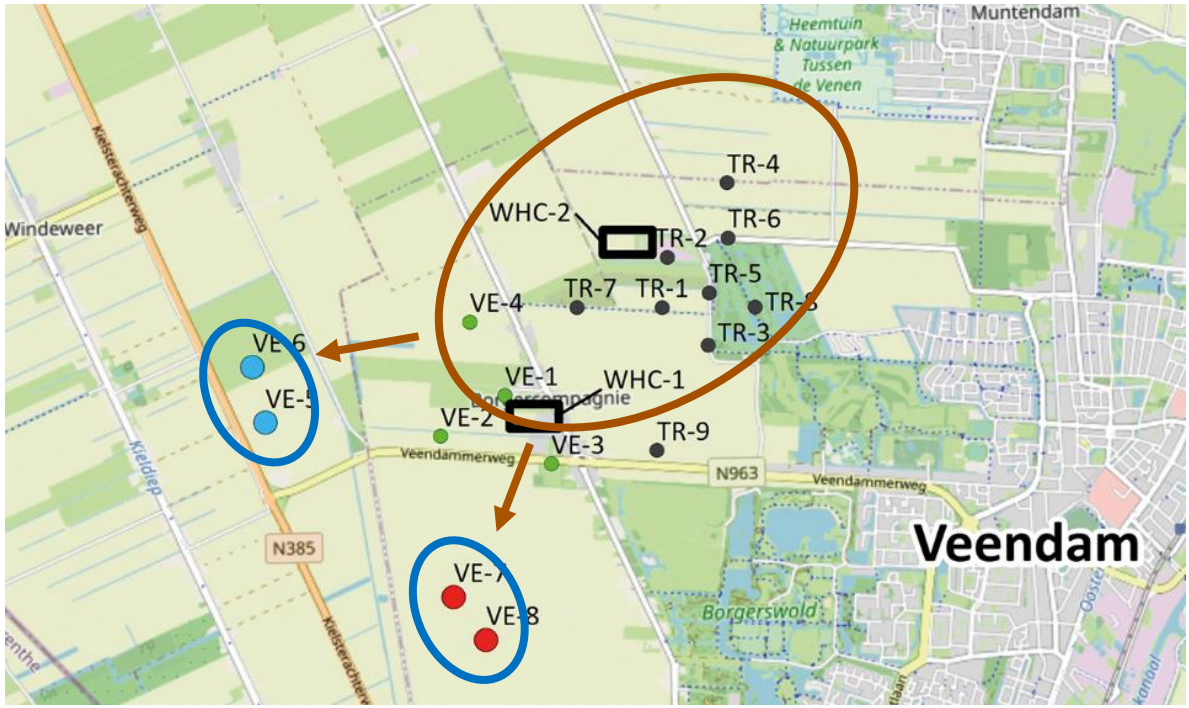
What options do we have?

Scenario	Advantage	Disadvantage
High pressure shut-in	If safe, least amount of impact/work	Chance of hydraulic fracture and rapid and more subsidence.
Safe, high brine pressure	Safe option	Very long period of pressure management required.
Drain as much brine as possible	Minimum risk for the future	Maximum subsidence
Fill caverns	Minimum risk for the future	Large operation required. Impact at surface.

Nedmag - Implications

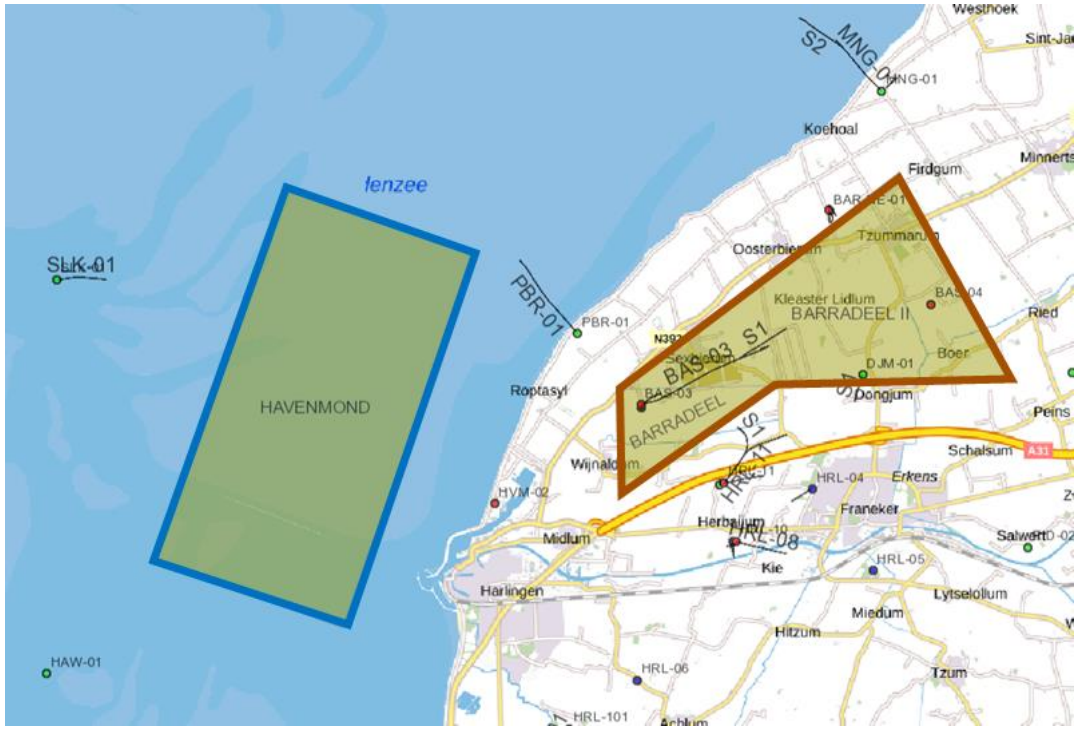
- New mining plan for 2022

1. Only small cavern pairs
2. Thick salt roof above caverns
3. No increase in pressure only decrease
4. Bleed off all brine after production
5. More environment-friendly blanket



Frisia - Implications

- Worst case: Hydraulic fracturing in multiple big caverns
- Onshore Barradeel
  - On land the total subsidence is what matters.
  - Subidence has to be compensated by measures ‘peilbeheer’ of the Waterschap.
- Offshore: Havenmond
  - Production is moving offshore
  - In the Waddenzee the subsidence rate is most relevant.
  - Can the rate of sedimentation keep up with the rate of subsidence?



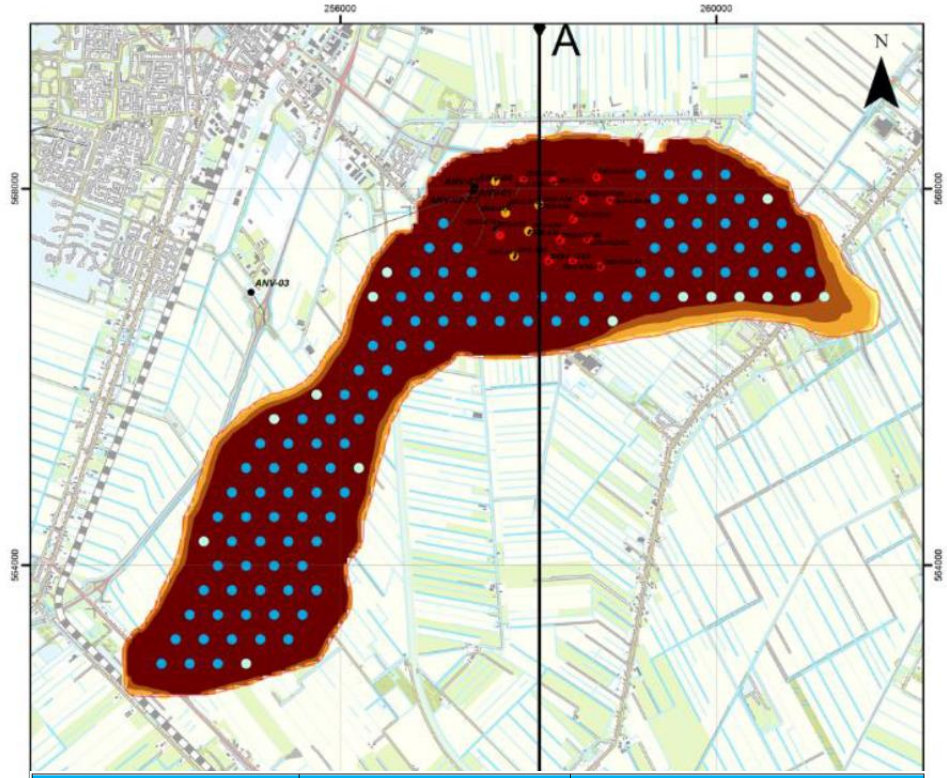
Storage caverns

- We may need storage caverns for the energy transition.

- Question regulator:
  - Are the caverns safe for the full life cycle, including abandonment?
  - What are the risks, uncertainties and control measures?

- Question ministry EZK:
  - Do the benefits outway the consequences?
  - Surface subsidence, impact surface facilities, etc…

TNO 2018 RR11372 – Ondergrondse opslag in Nederland – Technische verkenning



Naam	Aantal cavernes (50% theoretisch)	Effectieve energie opslagcap. perslucht (PJ)
GRONINGEN	**230**	**1,49**
Zuidwending	52	0,34
Winschoten	22	0,14
Pieterburen	39	0,25

'Mogelijk meer dan 200 opslagplaatsen van waterstof in zoutkoepels in Drenthe en Groningen. Gevaar voor bodemdaling'

PREMIUM

Voor de opslag van grote hoeveelheden waterstof zijn in de toekomst 50 tot mogelijk meer dan 200 cavernes in zoutkoepels in Groningen en Drenthe nodig. Bodemdaling ligt bij die opslag op de loer.

Dagblad van het Noorden, 4 oktober 2021

Final thoughts

1. State Supervision of Mines
2. Salt mining in NL
3. Why KEM-17?
4. KEM-17 results
5. KEM-17 implications
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Three last thoughts about caverns

#full-life-cycle
#energy-transition

#all-realistic-scenarios
#salt-heterogeneity
#leakage-mechanisms
#anistropic-stress

#cavern-interaction
#jungle-in-the-undergrond

KEM-17 reports

- Reports can be found a KEM-website and SodM.nl > Search > KEM-17

1. Micro-scale report
2. Cavern-scale report
3. Dome-scale report

4. Conclusions and recommendations
5. Practical measures
6. Dutch summary

Credits: KEM-17 Team

Micro-scale

MAP Microstructure and Pores

Prof. Dr. Janos L. Urai
Dr. Joyce Schmatz
Dr. Job Klaver

Cavern-scale

BROUARD CONSULTING

Dr. Benoit Brouard
Prof. Dr Pierre Bérest

Salt dome-scale

smart Tectonics

Dr. Tobias Baumann
Prof. Dr. Boris Kaus
Dr. Anton Popov

Conclusions and Recommendations