Underground Storage of CO2, H2, and more ...

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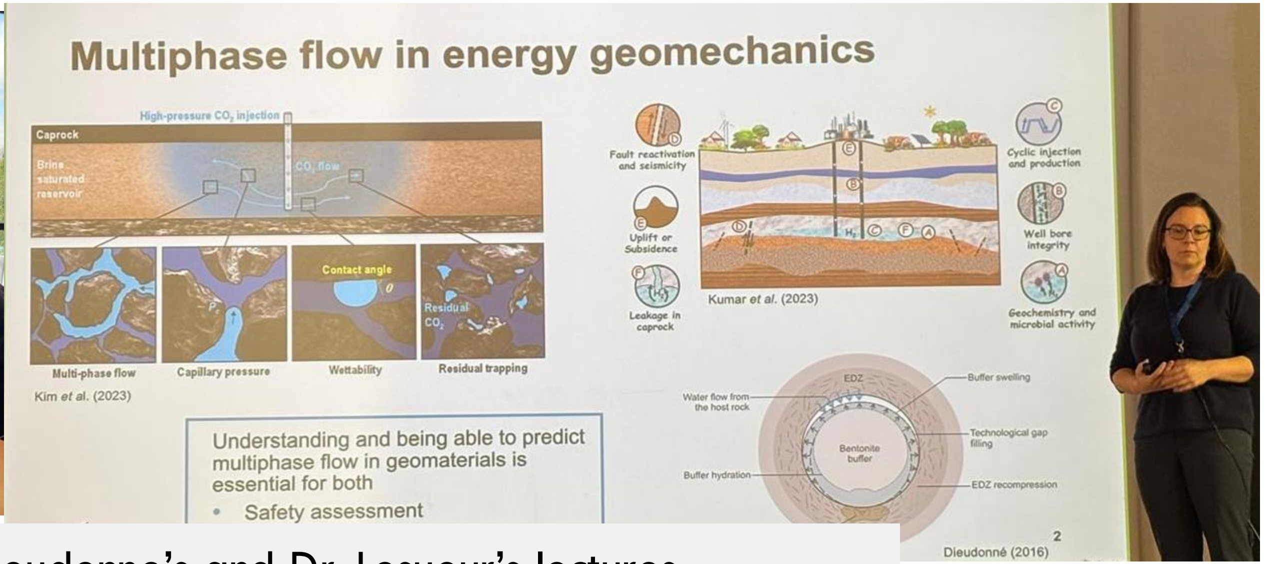
TU Delft 03 10 2025 energi SIMULATION

Goals for Today

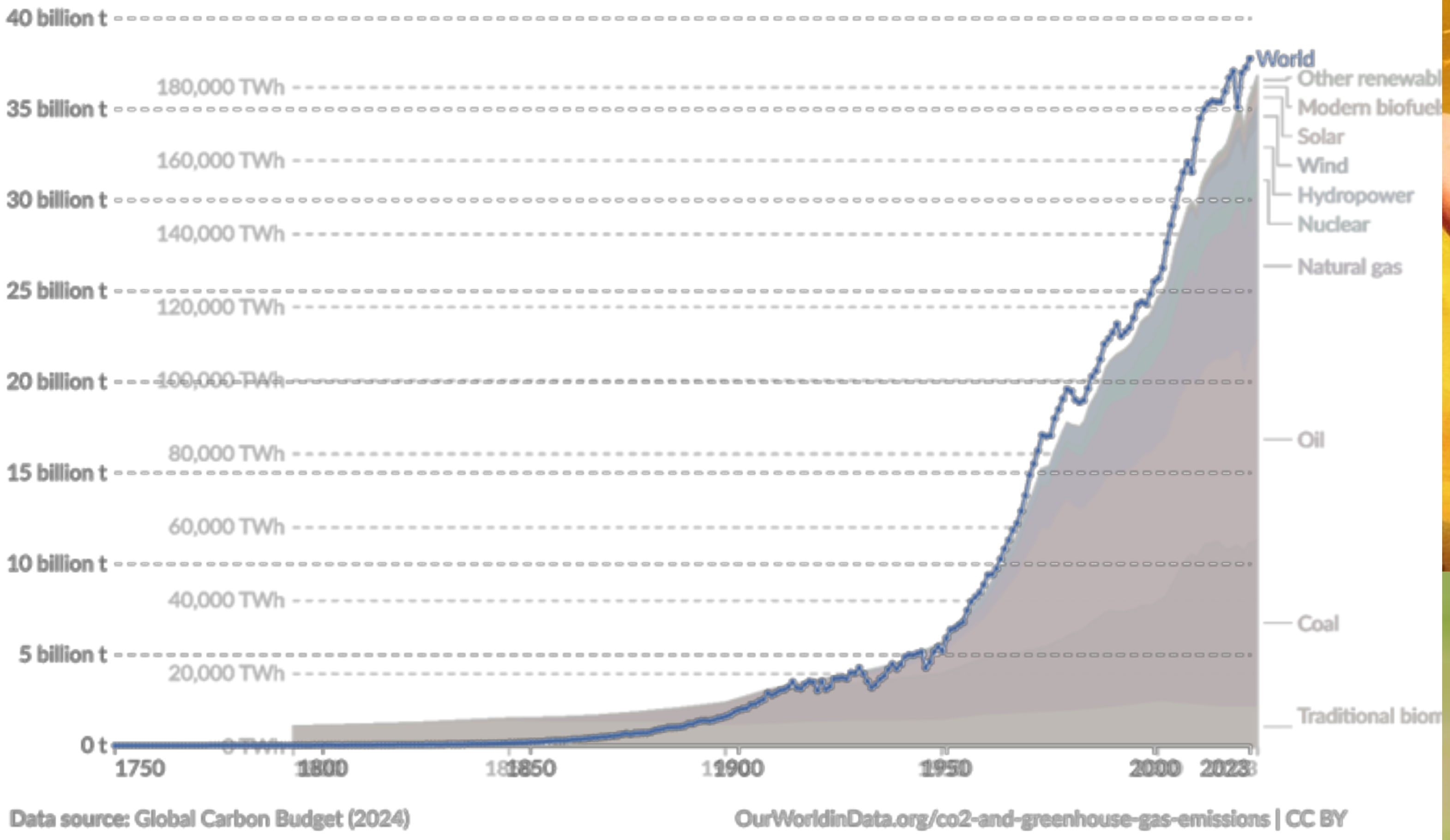
- What & Why CCS & UHS?
- Construct model & calibrate parameters for rocks under cyclic loading
  - Highlighted for Salt Caverns
- Multiscale modeling and simulation perspective for geolocial reservoirs



Direct link to Dr. Dieudonne's and Dr. Lesueur's lectures

Earth is home to 8.2 billion ppl (soon 10.4b)

180.000 TWh energy, ~40Gt CO_2 / year



Net-zero: CCS is essential

Netherlands

800 TWh
151 Mt of CO_2

USA

30.000 TWh
4.921 Mt of CO_2

China

37.000 TWh
9.528 Mt of CO_2

Canada

3.344 TWh
523 Mt of CO_2

180.000 TWh
0 Mt of CO_2

PORTHOS, Rotterdam
2.5 Mt/y x 15 years

CCS expected 3 – 10 Gt/y, currently ~30 Mt/y with 26 projects[1]

Port Rotterdam cut emissions from 30 to 20 Mt/y in 7 years, how?

New projects announced recently (PORTHOS, Northen Lights, …)

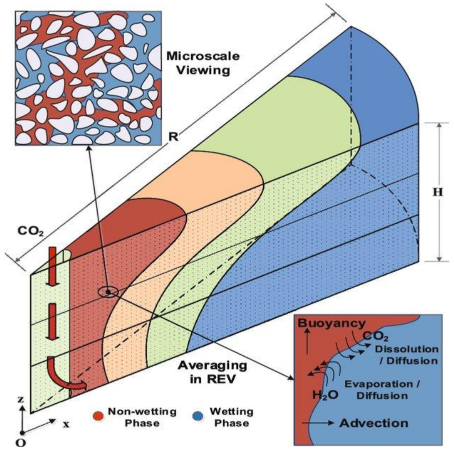
Will CCS deliver? → How can CCS deliver?

[1]: Krevor, …, Hajibeygi et al., Nature Reviews, 2023

CCS: CO2 geo-store concept

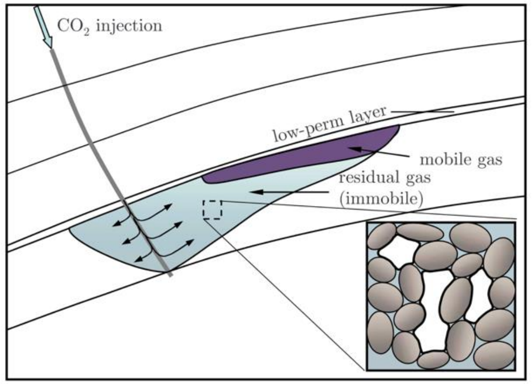
1Y → $+10^4$ Y

Injection & Pressure Manage



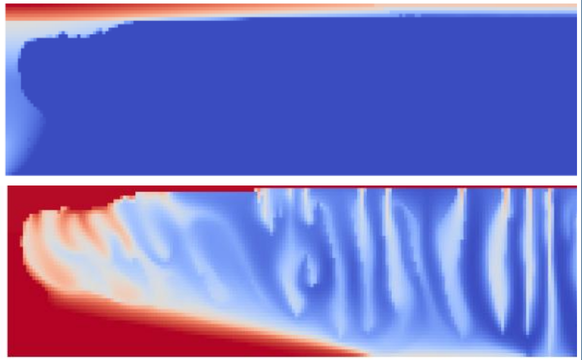
Env Earth Sciences (2019) 78:654

Post-Injection: migration!

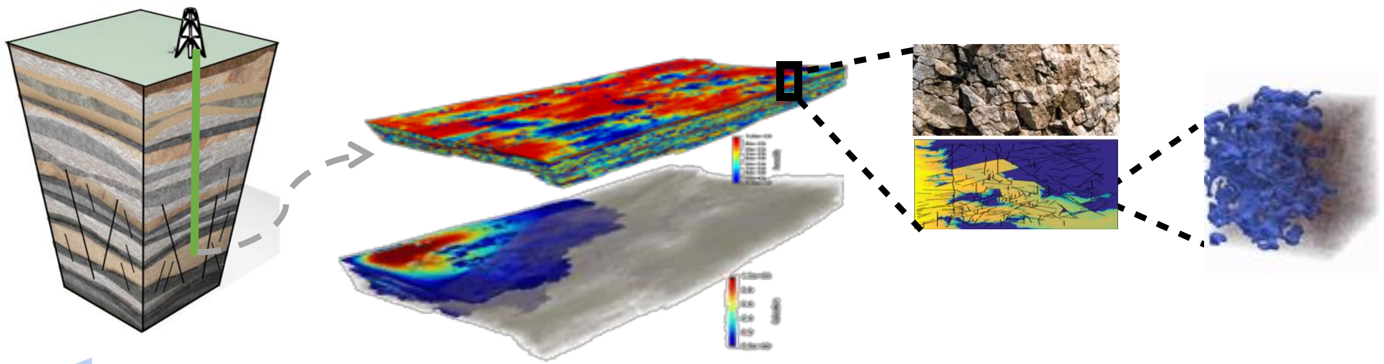


WRR 2006 10.1029/2005WR004806

Post-migration: Dissolution



Wang et al. 10.1016/j.ijggc.2021.103552



km ← μm

Multiscale Heterogeneous (fractured) & Uncertain, …

Net-zero: CCS is essential & large-scale energy storage

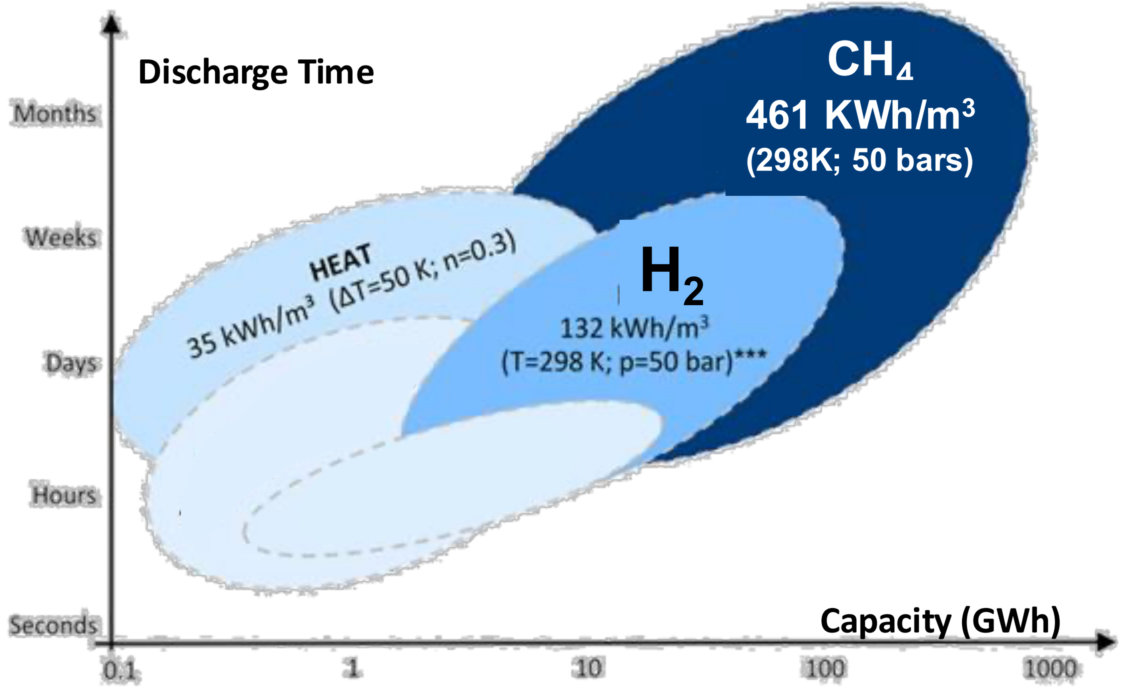
NL: 136 of 800 TWh stored in 4 gas fields

How much energy does France consume per year?

How much CO_2 emission is associated with it?

Hydrogen brings ‘hope’ that it may indeed …

→ EU 2030: 20Mt/y H_2 (world 125–600 Mt/y by 2050)



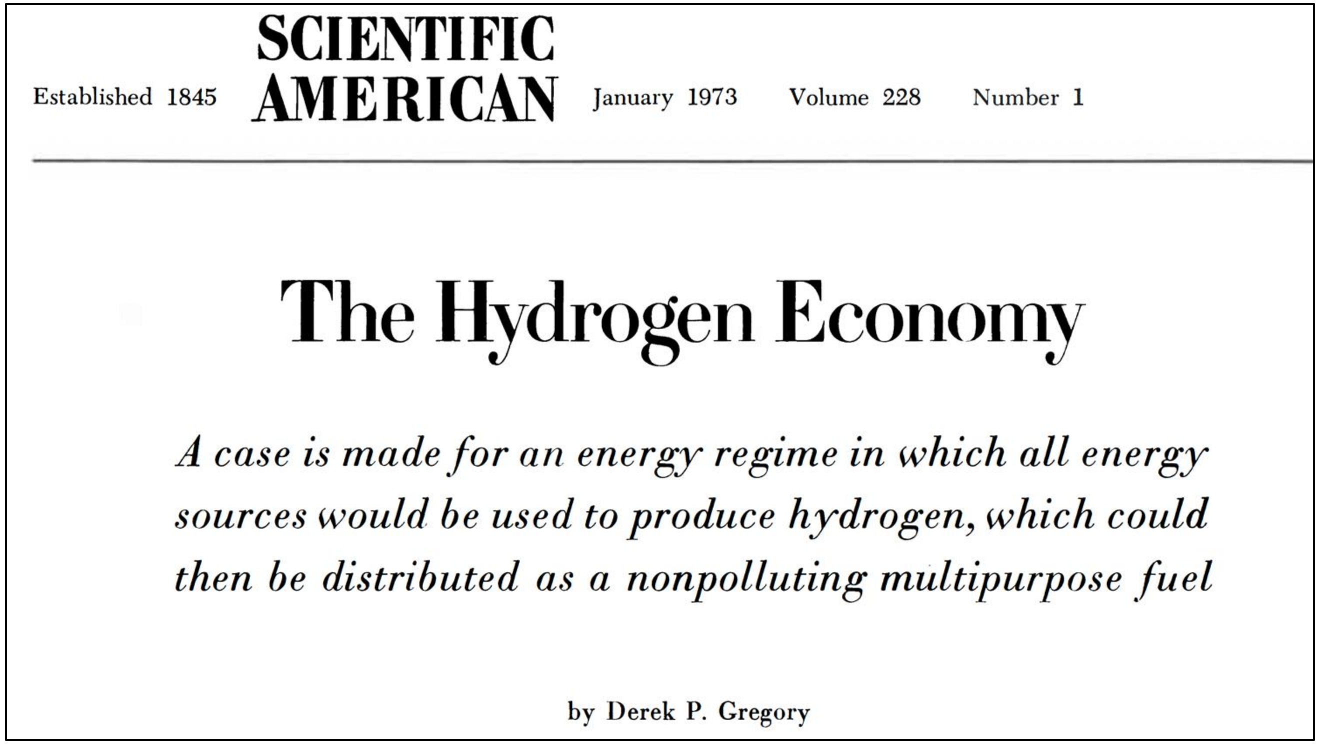
Q1: How many m^3 of CH4 at 50 bars & 25 °C is needed to store 10% of total energy supply of France? How about H_2?

Q2: How many m3 of water saturated sandstone is needed to be warmed 50 °C more, to store the same amount of energy?

Van Rooijen & Hajibeygi, 2025

Hydrogen brings ‘hope’ that it may indeed …

→ EU 2030: 20Mt/y H_2 (world 125–600 Mt/y by 2050)



Established 1845 **SCIENTIFIC AMERICAN** January 1973 Volume 228 Number 1

The Hydrogen Economy

A case is made for an energy regime in which all energy sources would be used to produce hydrogen, which could then be distributed as a nonpolluting multipurpose fuel

by Derek P. Gregory

Hydrogen is not new… but for the energy mix it is!

Van Rooijen & Hajibeygi, 2025

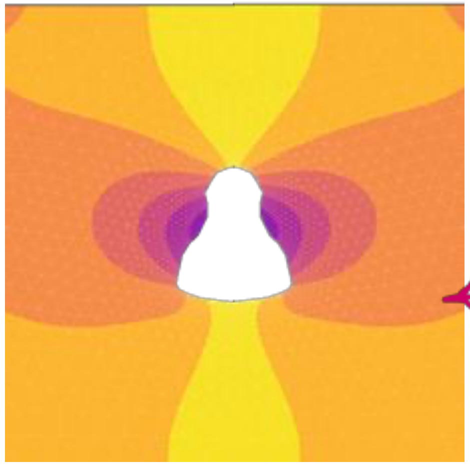
Underground Hydrogen Storage: going deep, to scale up!

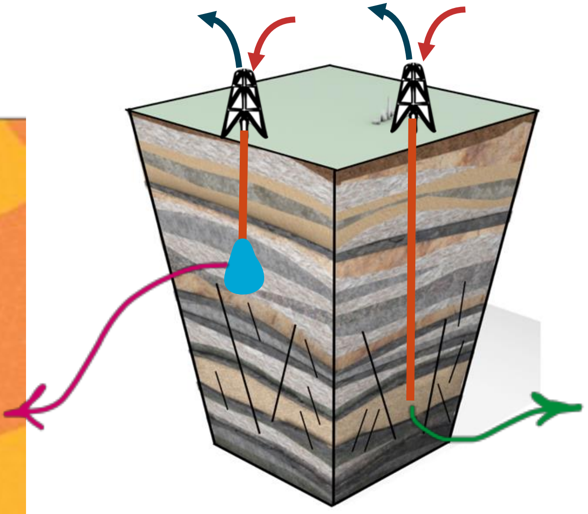
5 – 10 GWh

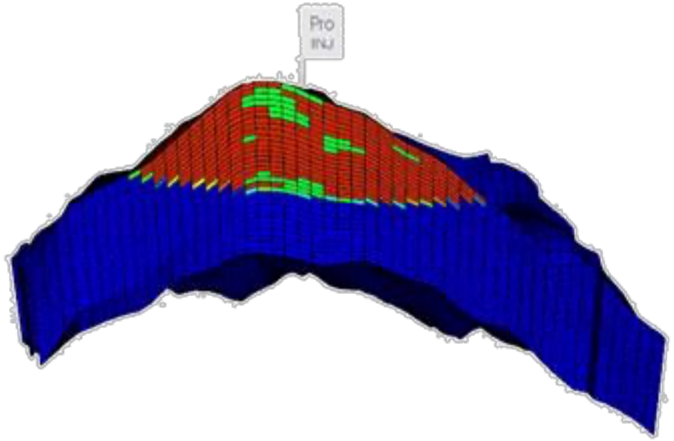
100 – 250 GWh

O (TWh)

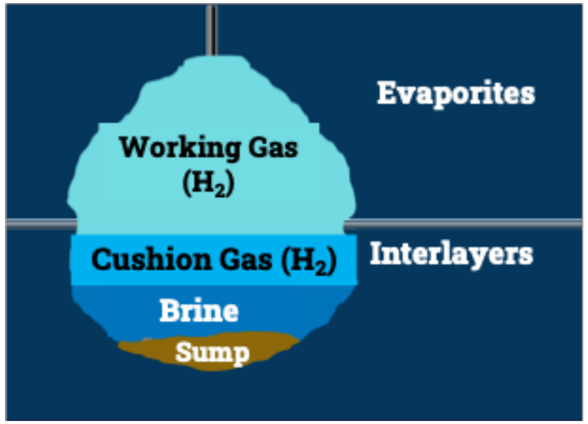
Space agency since 80's

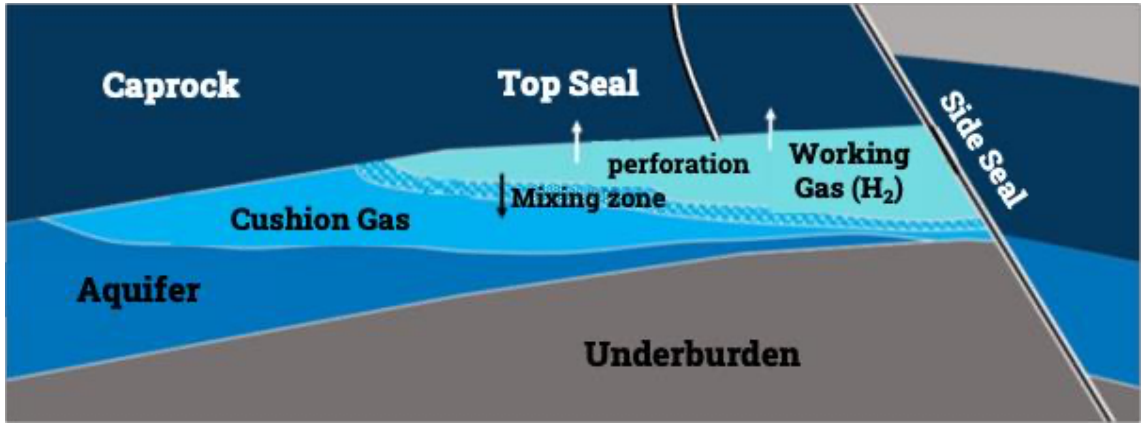






Objectives: Store inside, Maintain Purity, Operate below critical stress



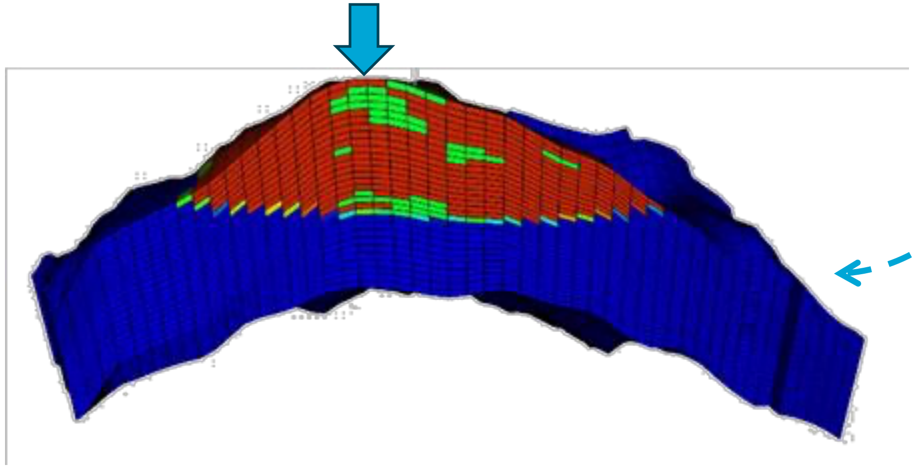


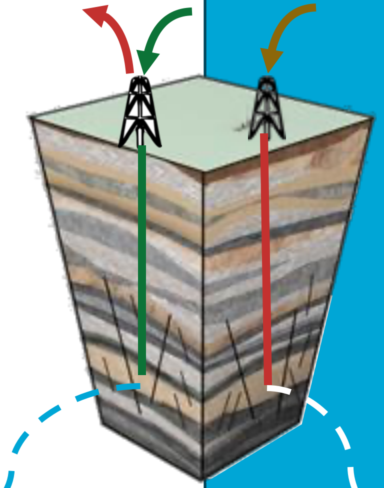
Objectives: UHS

Store inside the reservoir

Operate below critical stress

Reclaim Fully & Purely





Objectives: CCS

Store inside the reservoir

Operate below critical stress

Some key characteristics: CCS & UHS

(1) Temporal (H_2) vs permanent (CO_2) trap

(2) cyclic vs monotone loading (mechanics)

(3) cushion gas for UHS!

(4) Reservoirs: **salt caverns, depleted O&G, Aquifers**

(5) Thermodynamics

(6) Transport in porous media

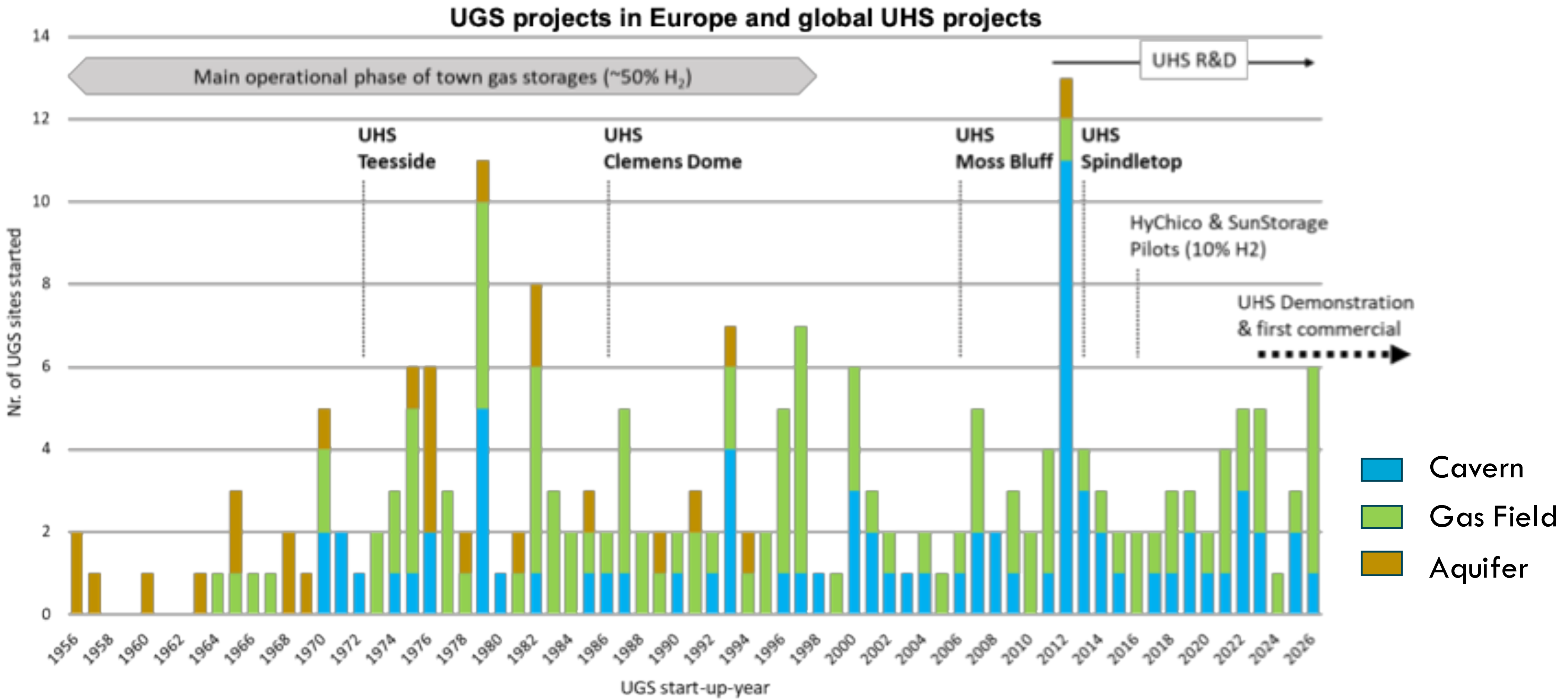
(7) Bio-geochemistry

(8) Techno-economics

(9) …

Build on what is known…

IEA TCP 42 – Final Report

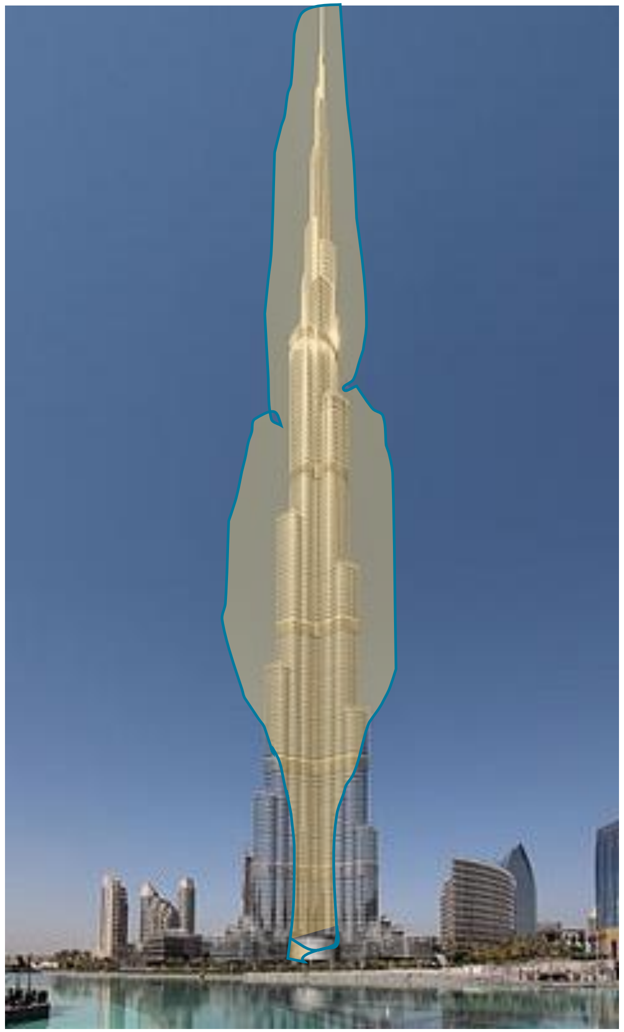


What do you learn from this historical statistics? Reservoirs for UGS, UHS & CCS?

How tall are the largest caverns (in NL)?

Euromast (185 m)

Eiffeltoren (324 m)



Burj Khalifa (829 m)

Courtesy of Heijn van Gent, State Supervision of Mines

gasunie
crossing borders in energy

NL will export H_2 to GE & import CO_2 to store under the North Sea

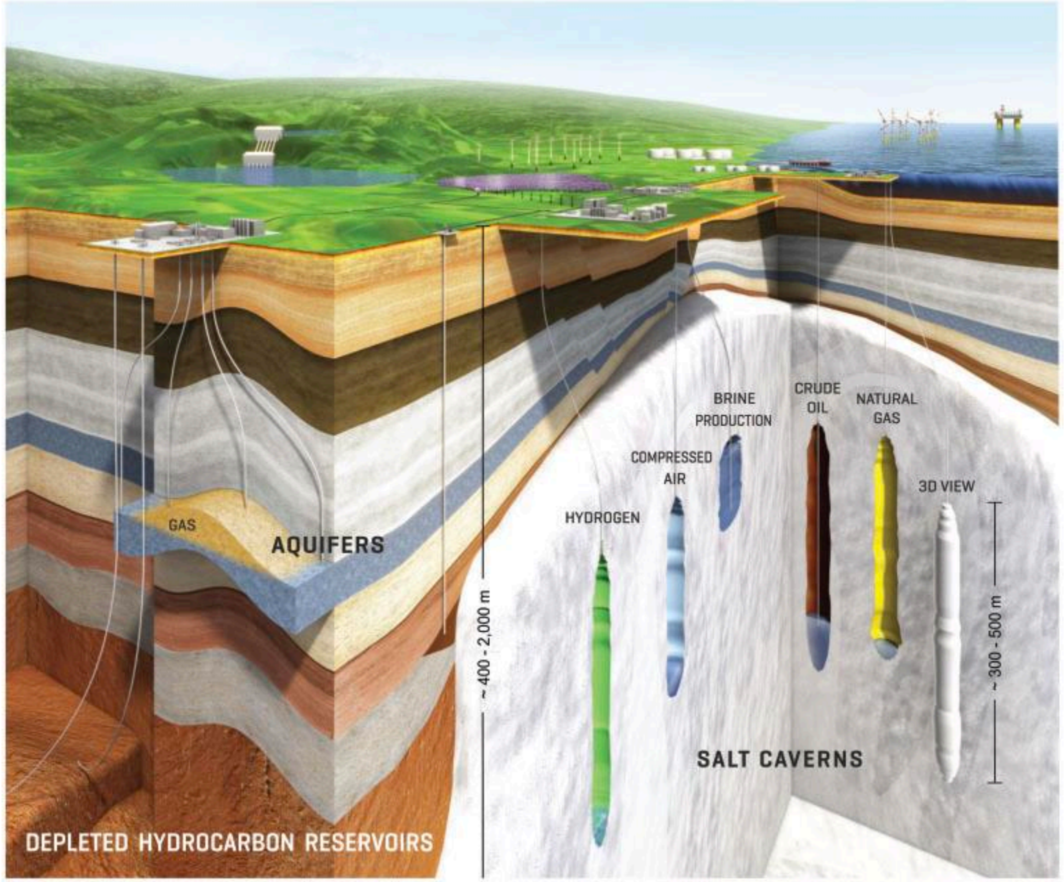
Salt Caverns: why for energy storage?

- Great seal (very low K, halite is chemically inert)
  - Halite (NaCl) crystal distance between lattice units 2.8E-10 m
  - Kinetic diameter: CH4 3.8E-10m, H_2 2.9E-10m, He 2.6E-10
  - H_2 may penetrate into Halite Lattice

- Rapid cycles possible (but be careful)!

- Competitive costs, decades of experience (since 70s)

- Many can be constructed in one dome, and big ones too!



Deep.KBB GmbH

Incidents: structural collapse & blowout

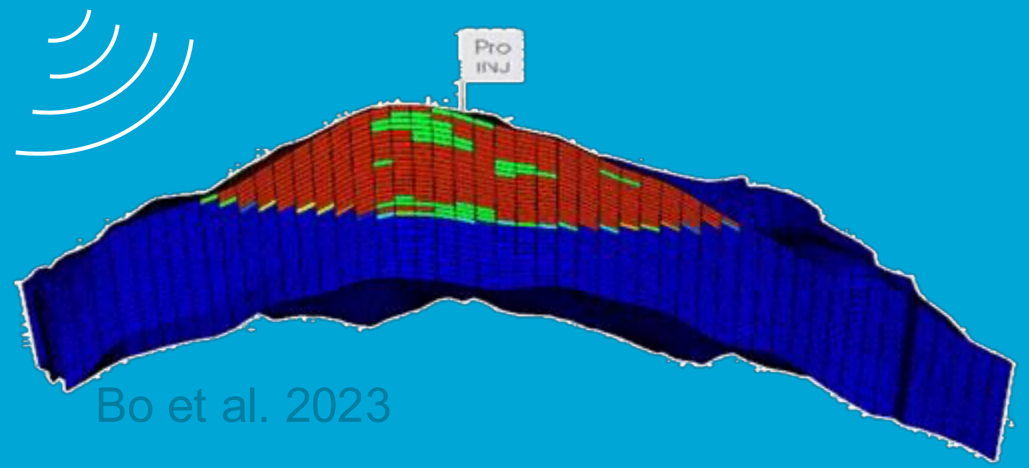
Rupture at a rock salt mine in NE Brazil in 2023

Sinkhole Hengelo/NL 1991: diameter 30m, 4.5m deep

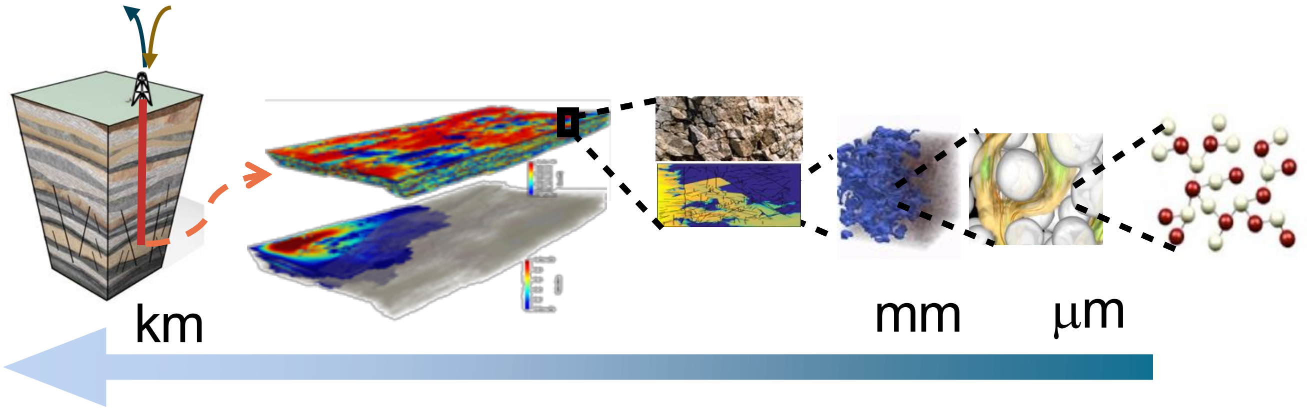
Geomechanics, Geology & Geometry

Porous Reservoirs: Site Selection, Operation & Abandonment

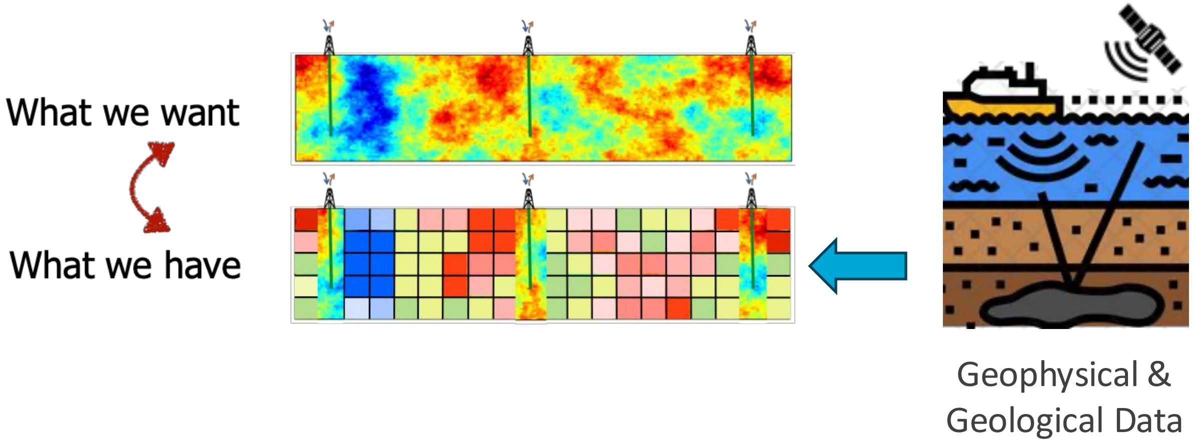
Monitoring



Multiscale & Heterogeneities

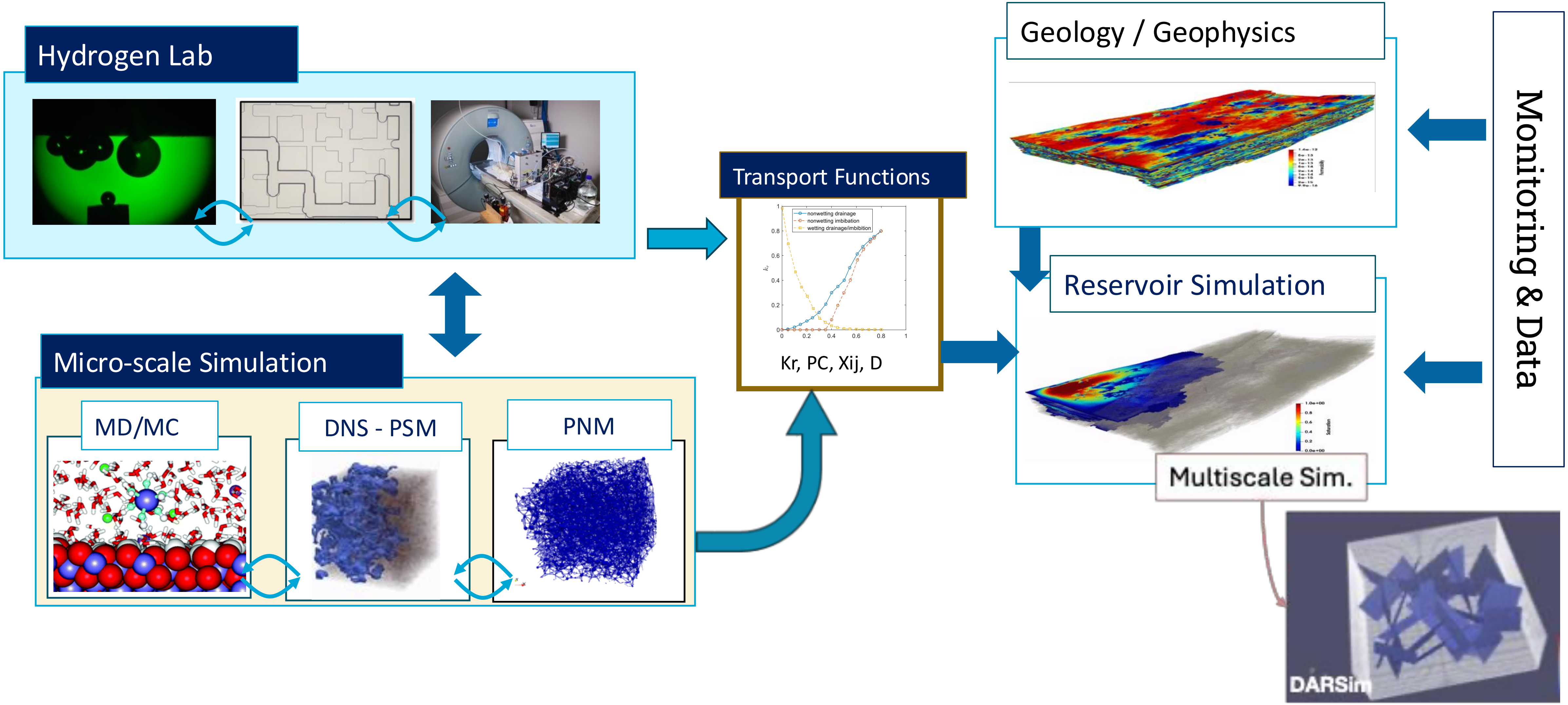


Uncertainties (increases with model complexities)

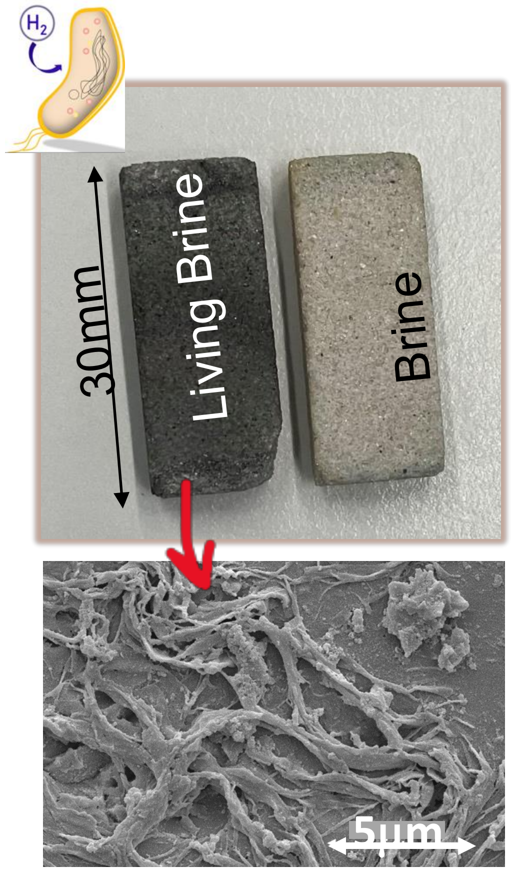


H2 Specific:
Cyclic/hysteretic solid/fluid mech., bio-geochemi, operation range (rates, stresses) …

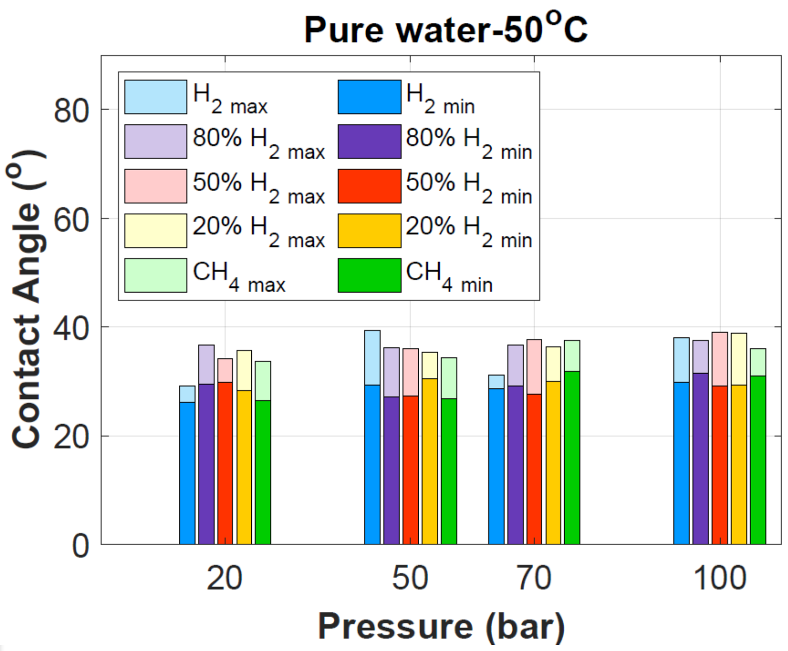
ADMIRE: Adaptive Dynamic Multiscale Integrated Reservoir Earth



Does it work?



Boon et al., 2024

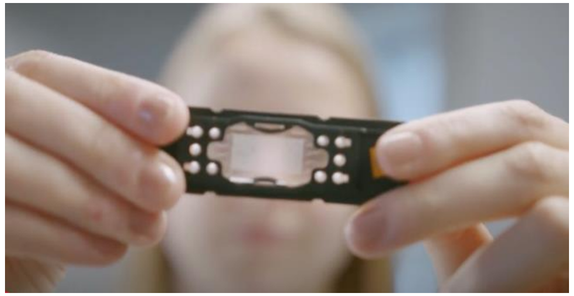


Hashemi et al. 2021 & 2022

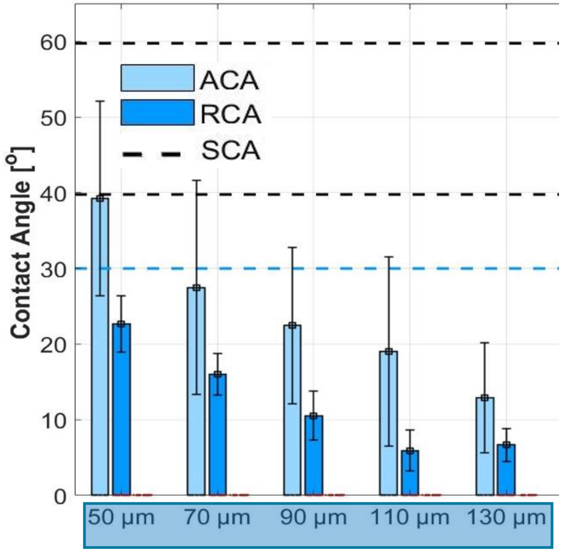
- H_2/Brine/Rock: Water Wet
- H_2 & CH_4 indifferent
- Microbes no general affect

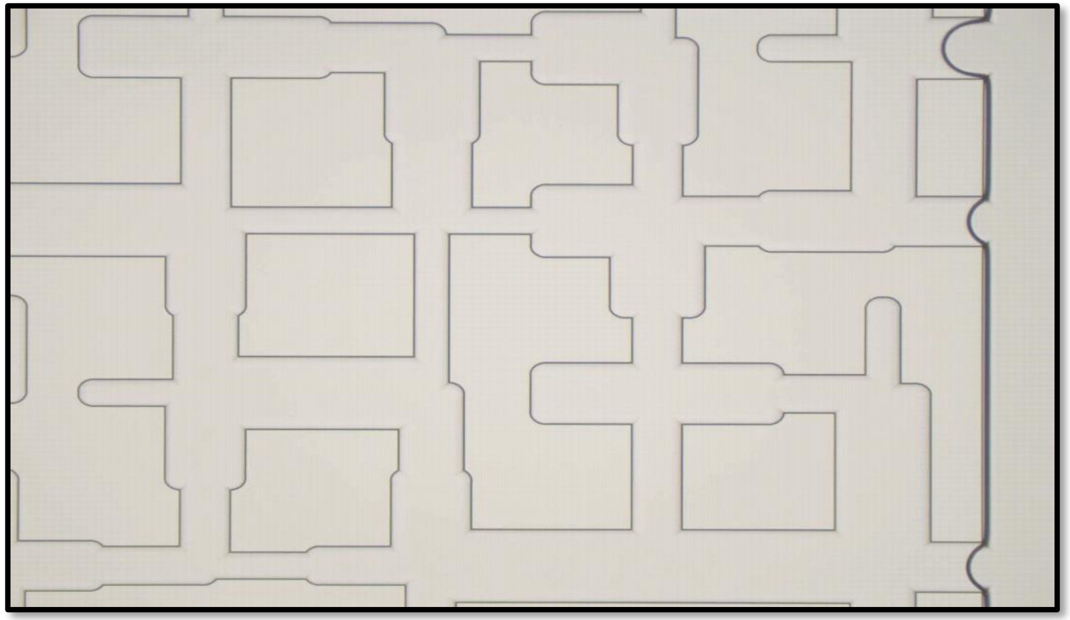
https://doi.org/10.1016/j.advwatres.2022.104165
https://doi.org/10.1016/j.advwatres.2021.103964

Transport & Trapping: Flow in ≠ Flow out



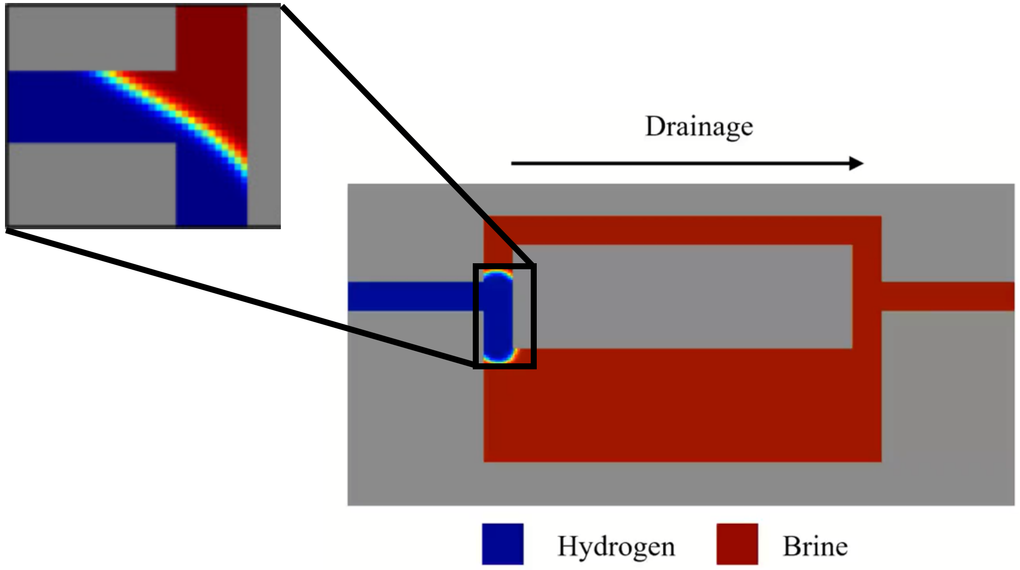
Theory matched this





Channels 50 – 130 μm

Van Rooijen et al. 2022



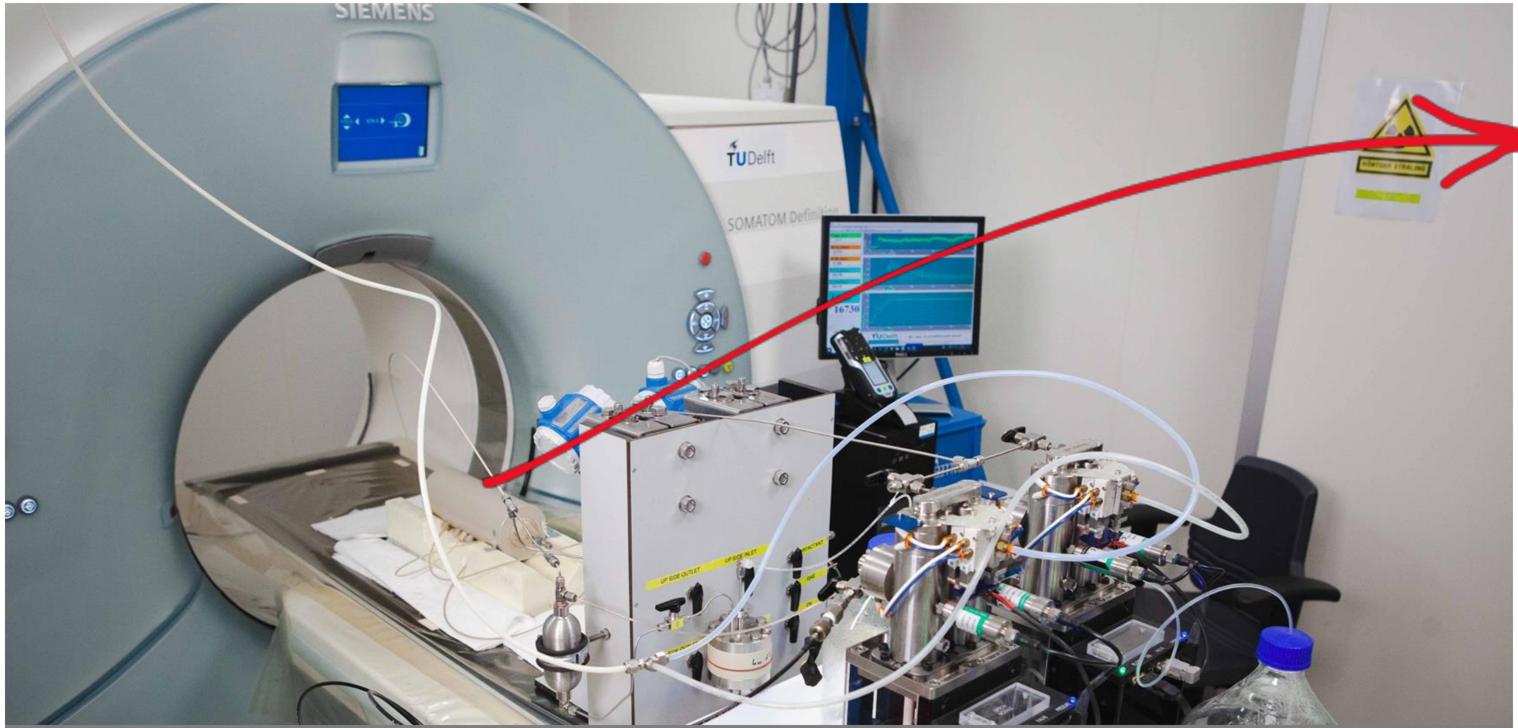
In-house LBM Simulations → Ca desaturation curves

Higher-aspect rations → more trapping

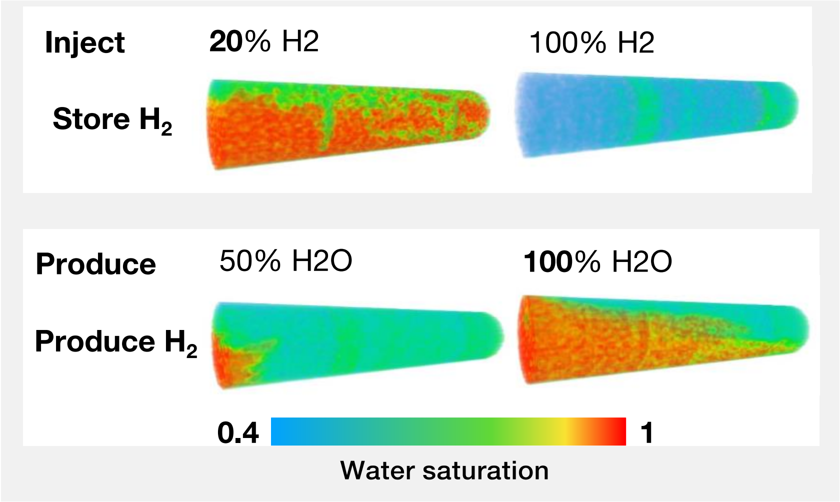
Van Rooijen et al., IJHE, 2025

Yu,…, Battiato AWR 2024: VOF for dead-end trapping.

Does it work at small rock scale?

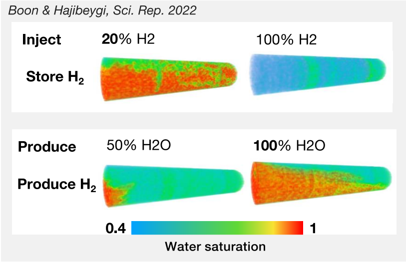


- Segregated fluids observed (Kr(S)?)
- UoB (Ferno et al.) matched ours, ~20% trapped H2 after 2nd imbibition
- ICL (Krevor et al.) found H2 & N2 the same in drainage, but H2 less trapped during imbibition (around 20%)
- Blunt et al. reported Ostwald ripening & we confirmed it too μCT (2024)



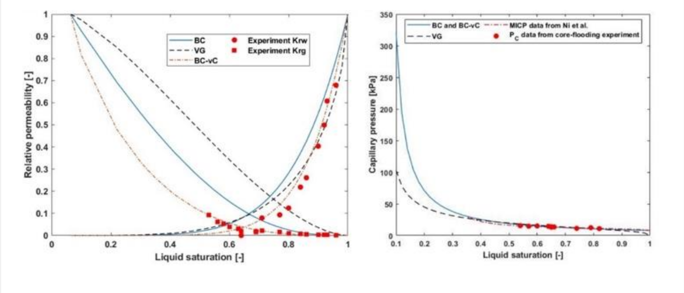
17cm core, 100 bar: *Boon & Hajibeygi, Sci. Rep.* ***2022*** *https://doi.org/10.1038/s41598-022-18759-8 & 2024*

The value of lab-based transport functions

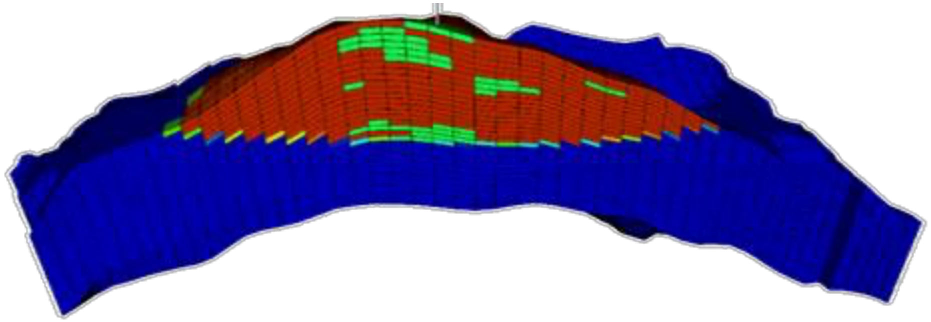


Boon et al., 2022 & 2024

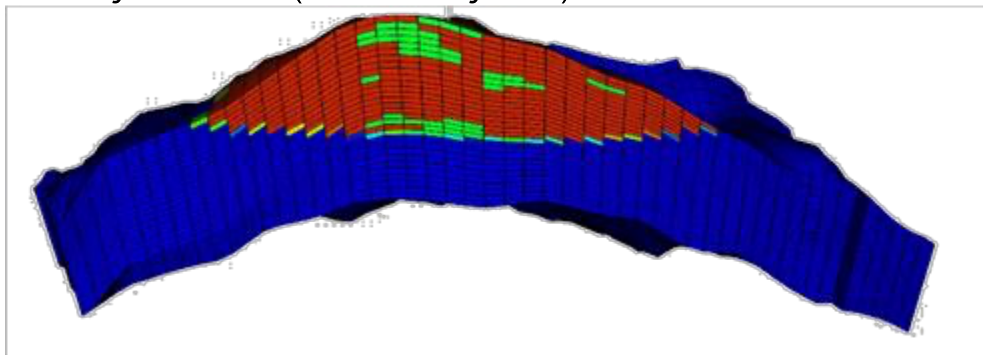
Lab-based reliable data



Ad-hoc functions (almost all literature)



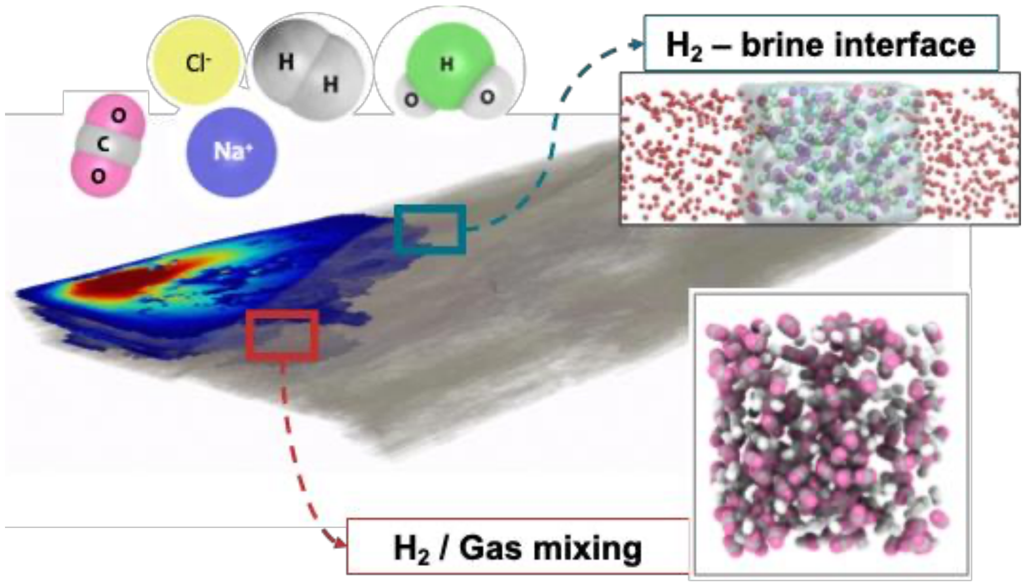
Experimentally-driven (our analyses)

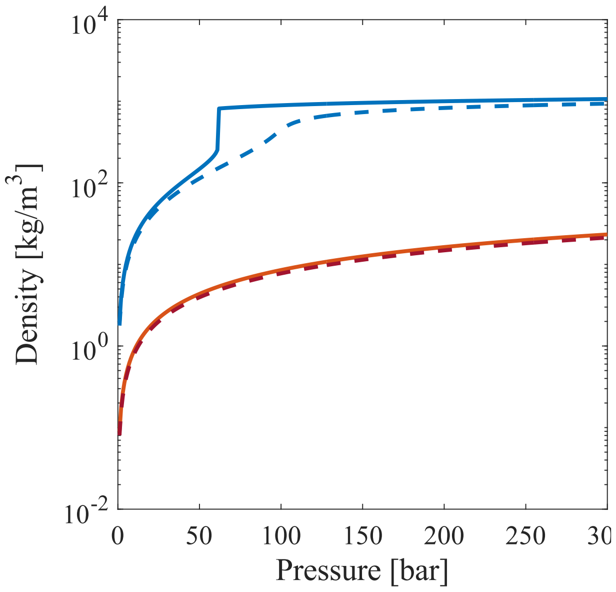


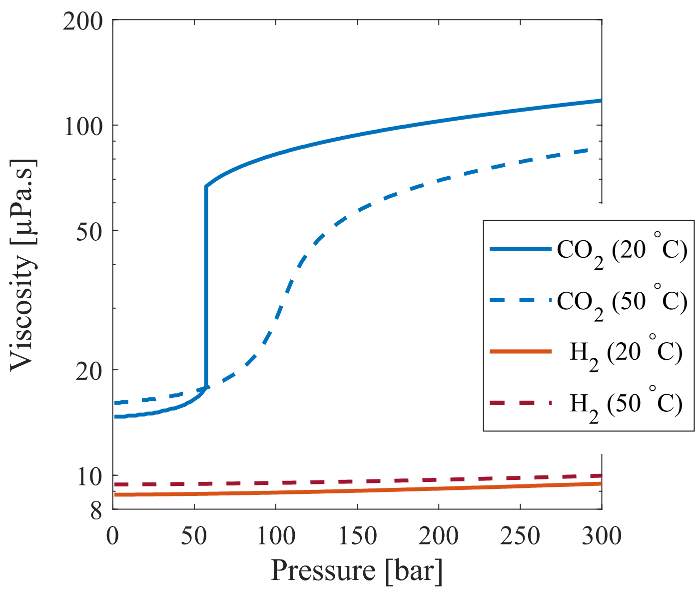
Shallower reservoirs (lower pressures) show less trapped H2.
Most trapping happens during 1st cycle!

Bo et al., Int J Hydrogen Energy, 2023

Thermodynamics: MD/MC for H2, H2-CH4, and H2-CO2 Mixtures

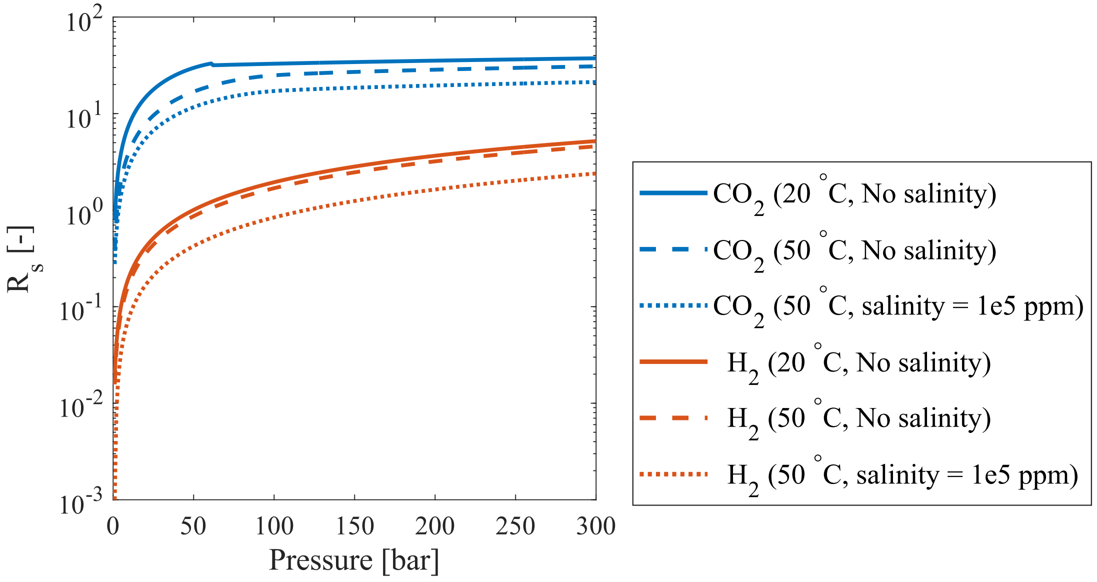






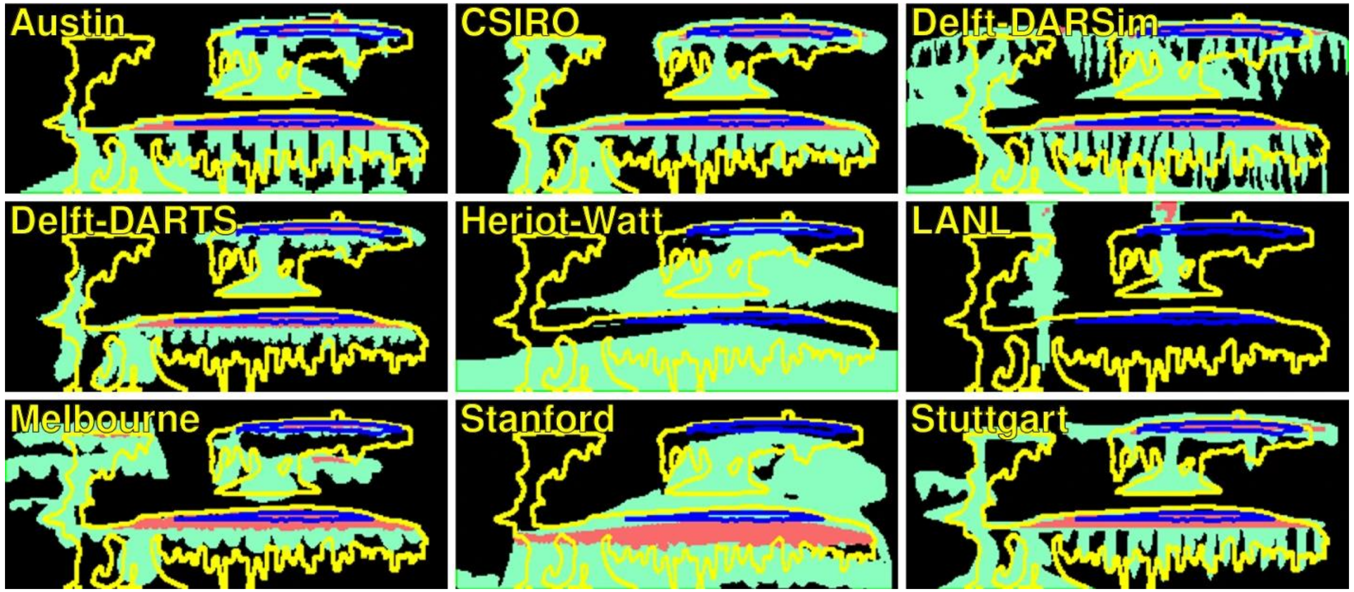
- Results matched LAB & REFPROP (if/when available)
- CO_2 is much more soluble than H_2, much denser too
- …

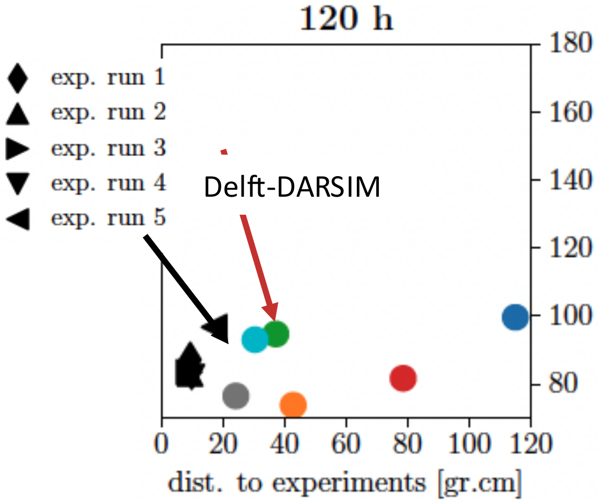
Rooijen et al. 2023 https://doi.org/10.1021/acs.jced.2c00707
Chakrapani et al. 2024 https://doi.org/10.1021/acs.iecr.4c01078



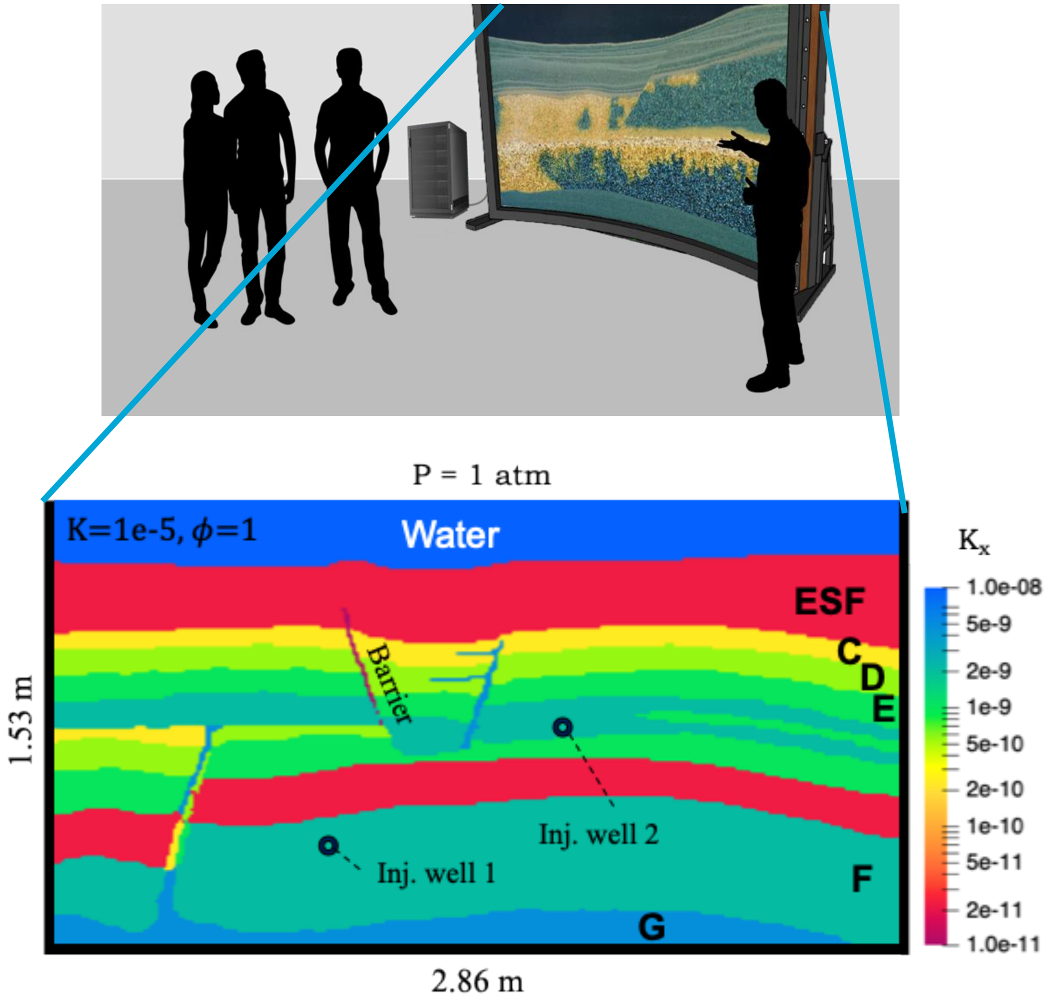
H2 & CO2 plume transport differently

CO2 vs H2, Low Pressure (FluidFlower Benchmark)





https://doi.org/10.1007/s11242-023-01977-7

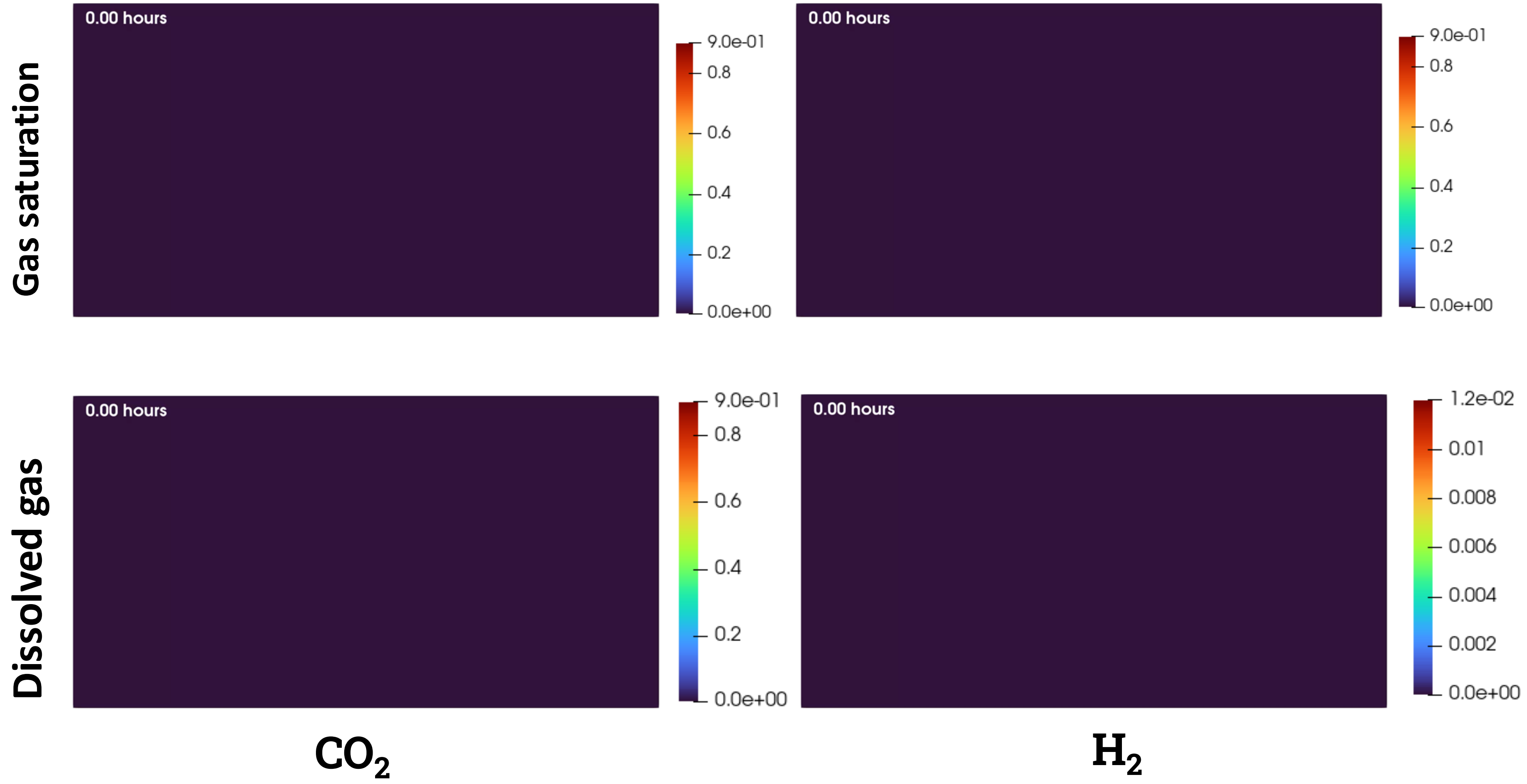


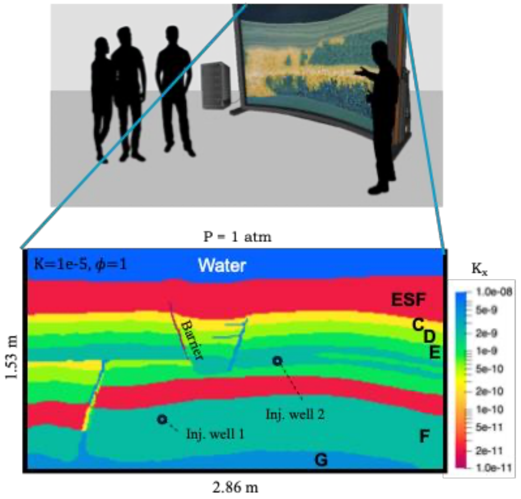
Limited system uncertainty, yet a wide simulation variations!

Lesson: validation is key to build confidence!

H2 & CO2 plume transport differently

CO2 vs H2, Low Pressure (FluidFlower Benchmark)





https://doi.org/10.1007/s11242-023-01977-7

Lower soluble H2 remains largely in gas phase, spreads widely and reaches farther (e.g. legacy wells)

Misaghi Bonabi et al. IJHE, 2025

Multiscale Strategy for Mechanics (Porous & Salt Rocks)

Altering pore-pressure leads to change of effective stress on rocks

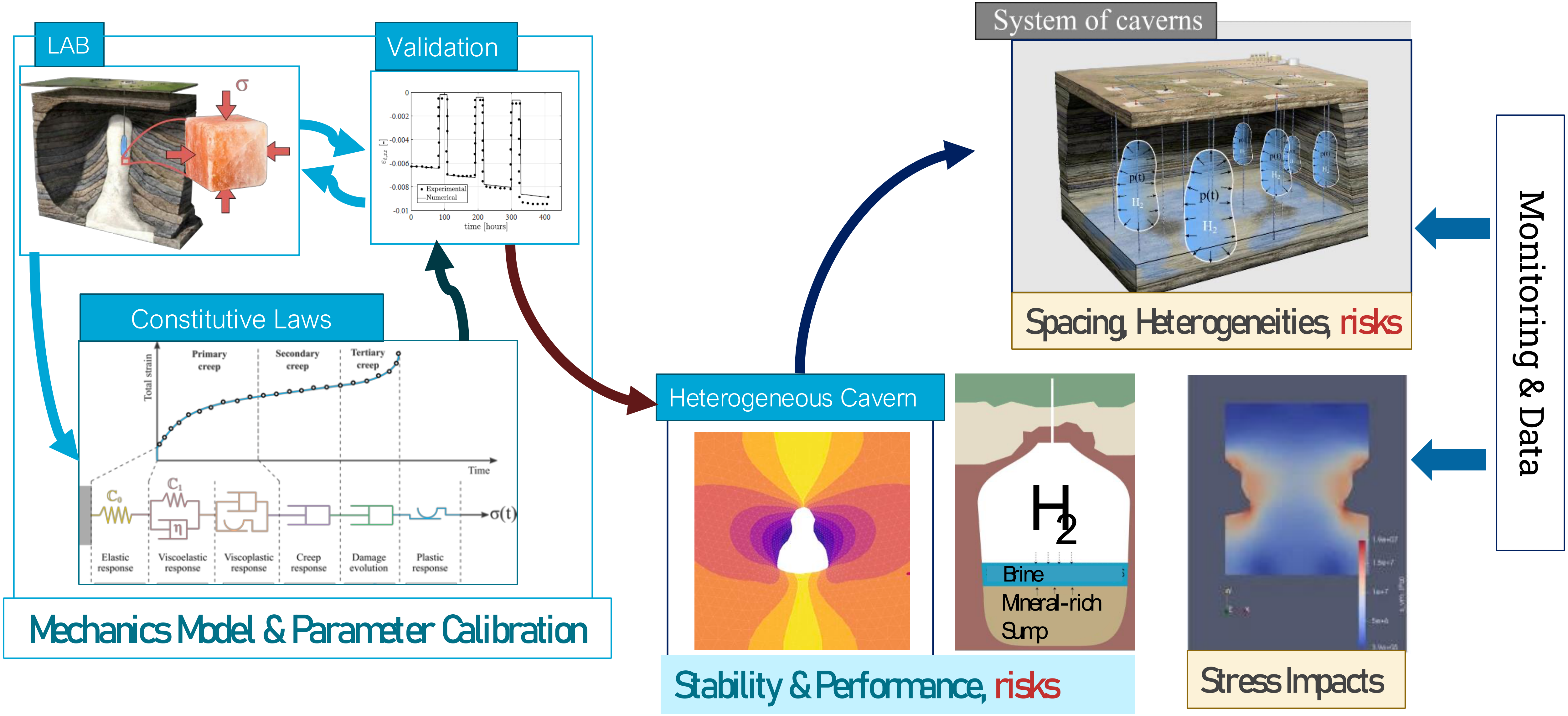
Stress change is globally felt, so nearby or far away consequences possible

Exposure to H_2 (&CO_2) can potentially alter the mechanical properties of rocks & faults

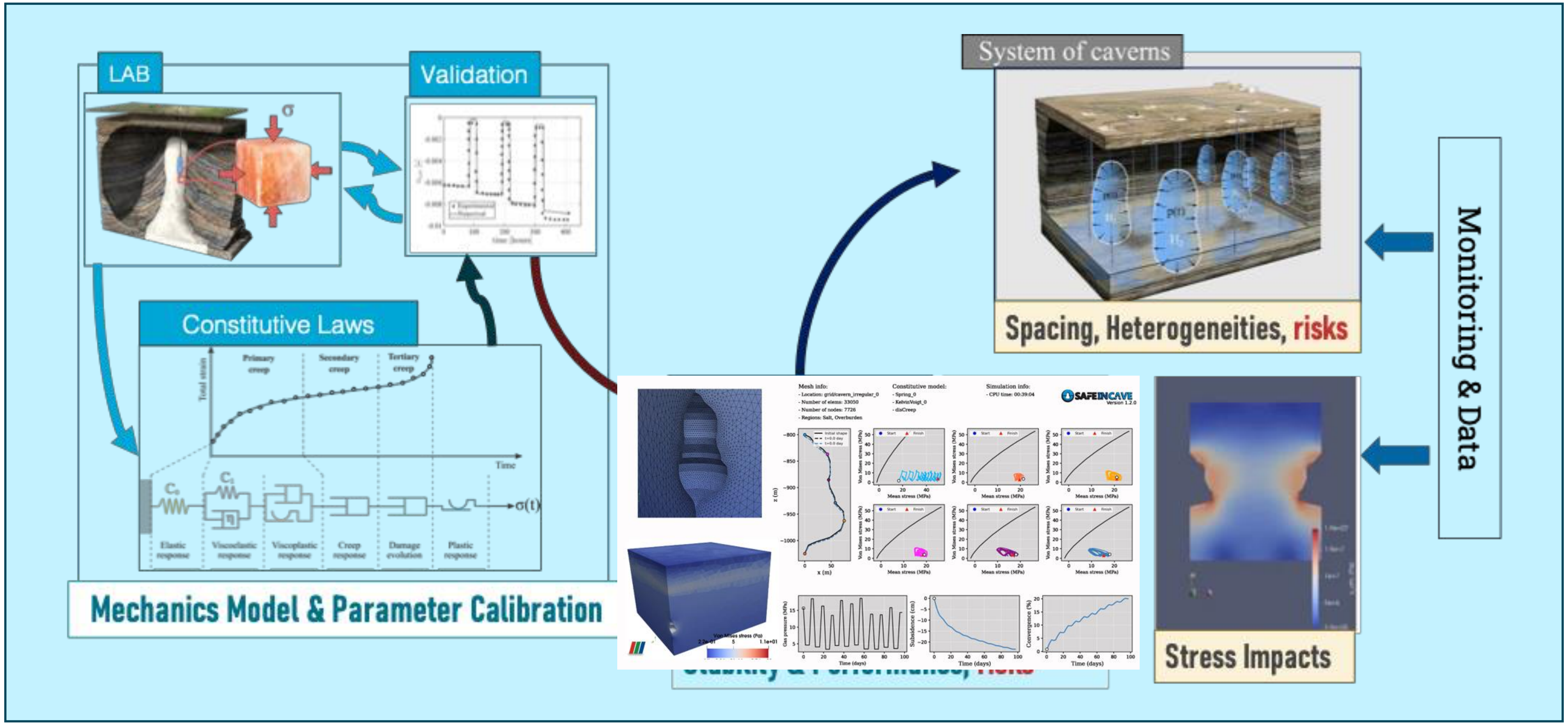
Geological systems enjoy ;) uncertain and heterogeneities properties

→ Model construction, parameter calibration, REV-scale … all ???

Multiscale Strategy for Mechanics (Porous & Salt Rocks)



Multiscale Strategy for Mechanics (Porous & Salt Rocks)



Open-Source Simulator for forward & inverse modeling:
Calibrate, Simulate, Optimize, Abandon!

Honório& Hajibeygi, Int J Hyd. Energy, 2024

Significant capacity for 'salt caverns' but not everywhere

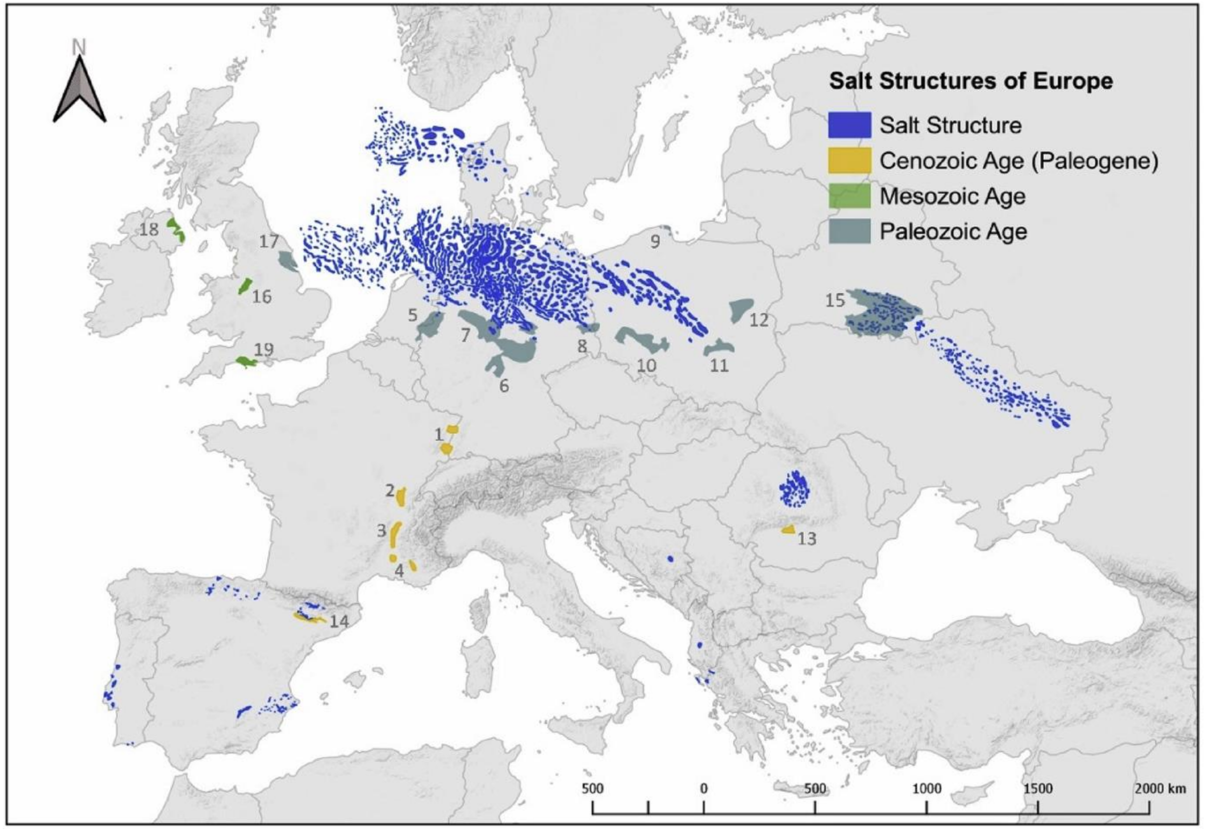
World salt rock deposit distribution (by S. Folle, 2008).

Significant capacity for ‘salt caverns’ but not everywhere

Do you see Austria?

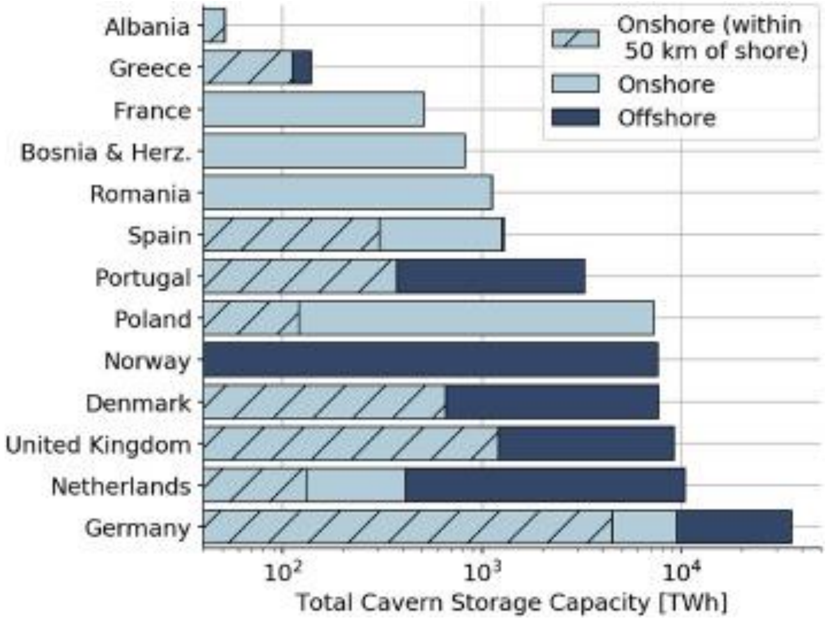
Why in NL & GE, salt caverns are under development for UHS?

Why in GE, a depleted reservoir is also under development for UHS?



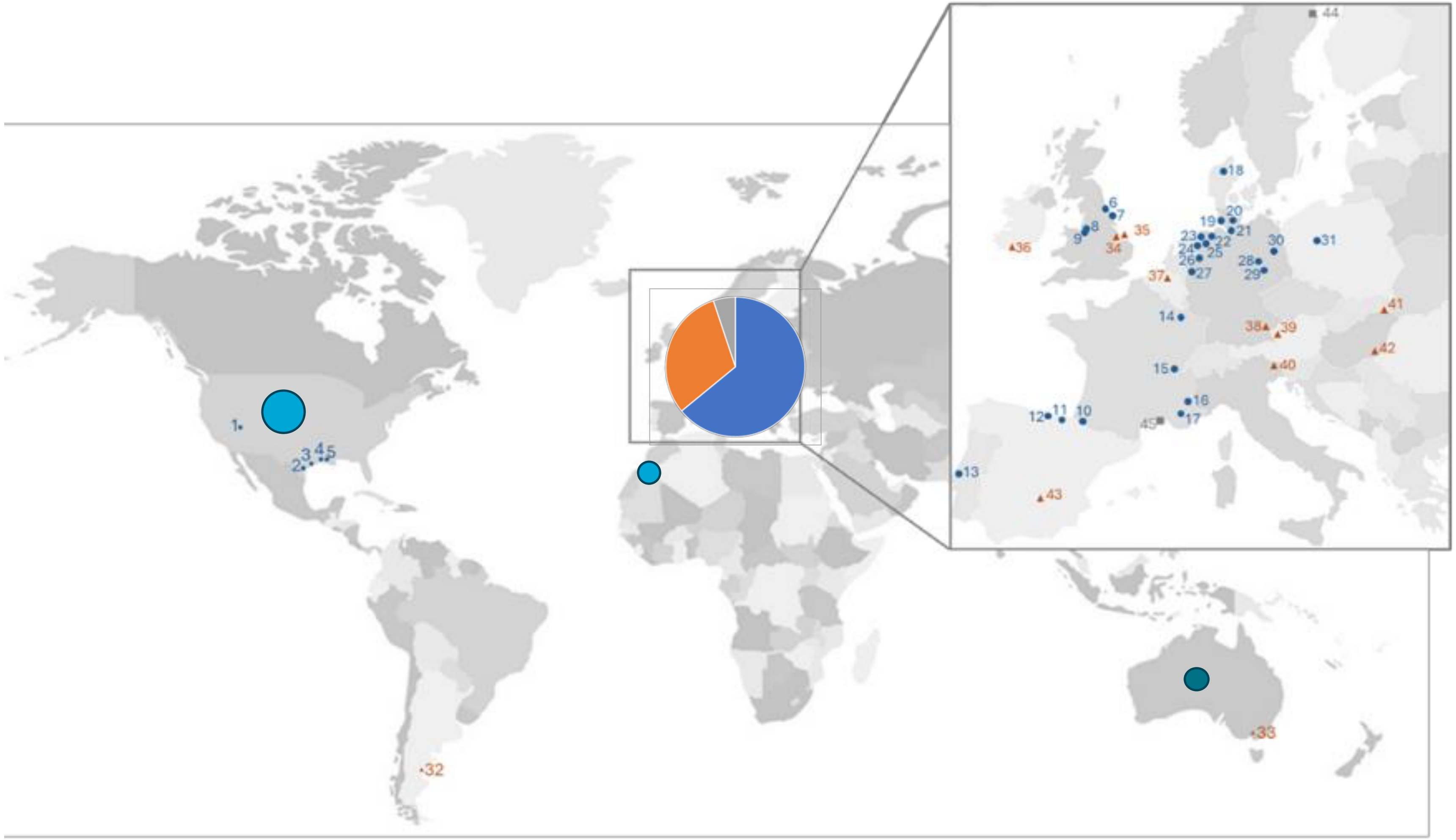
https://doi.org/10.1016/j.ijhydene.2019.12.161

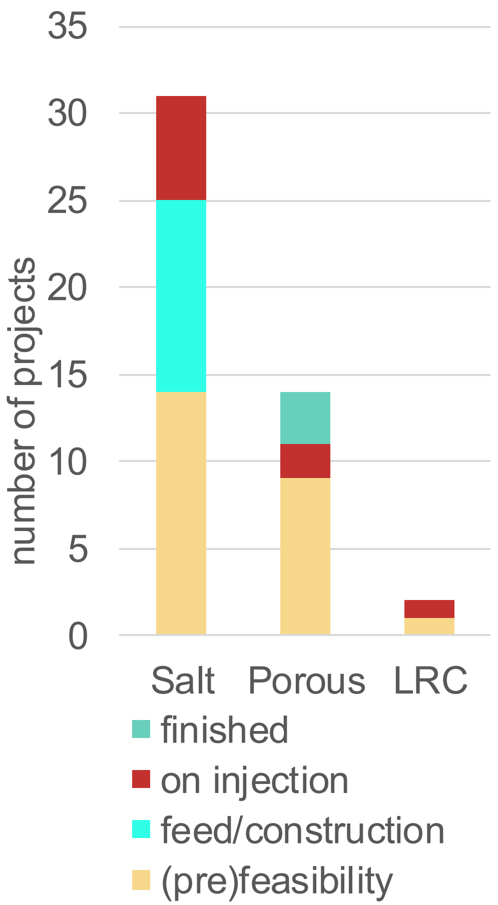
Europe most salty countries



https://doi.org/10.1016/j.ijhydene.2019.12.161

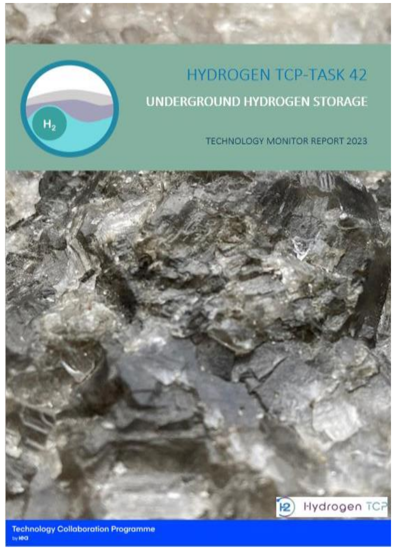
UHS for energy is focused on Salt Caverns, when available!



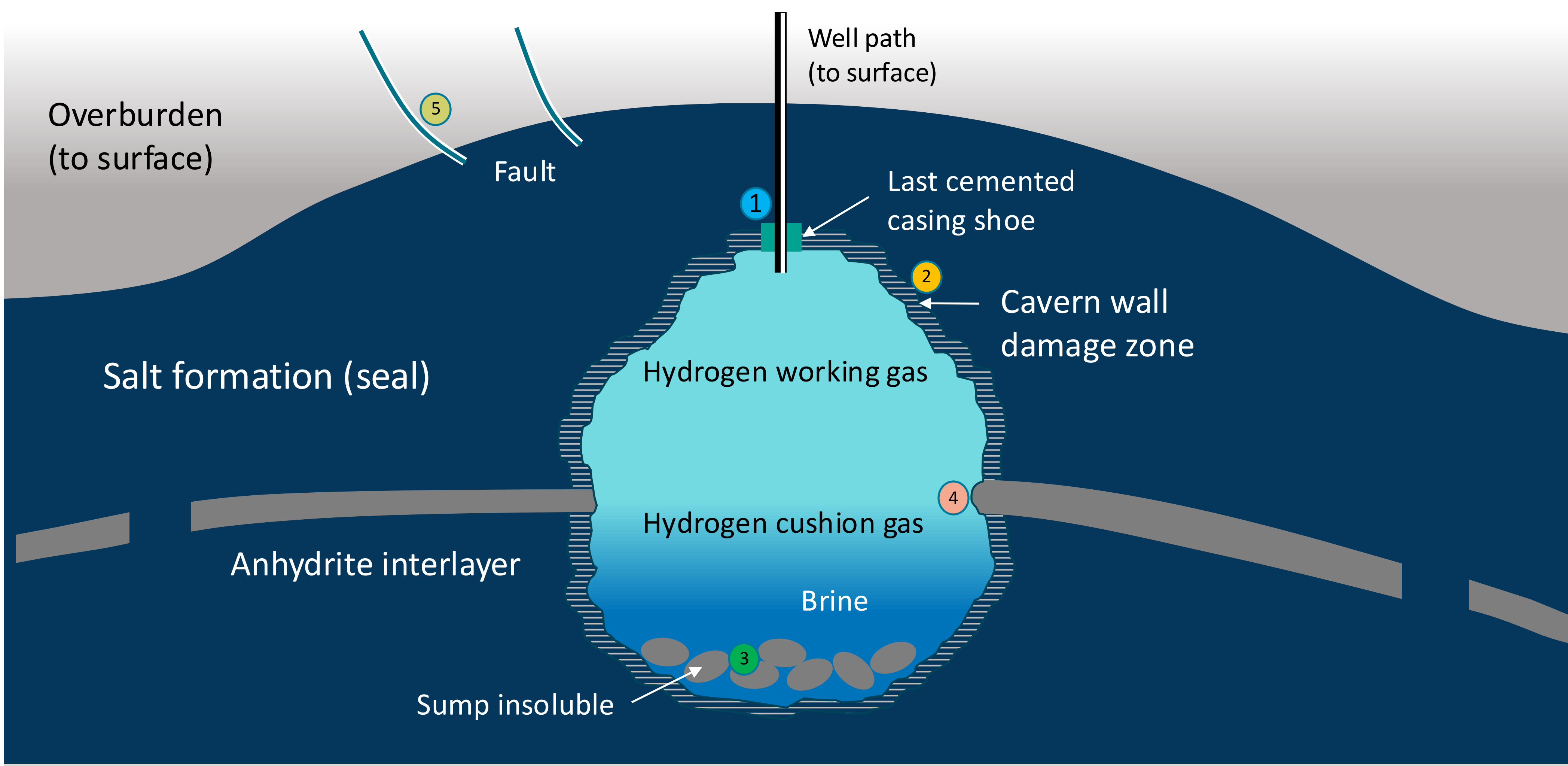


IEA TCP 42 Final Report, 2025.

Salt caverns

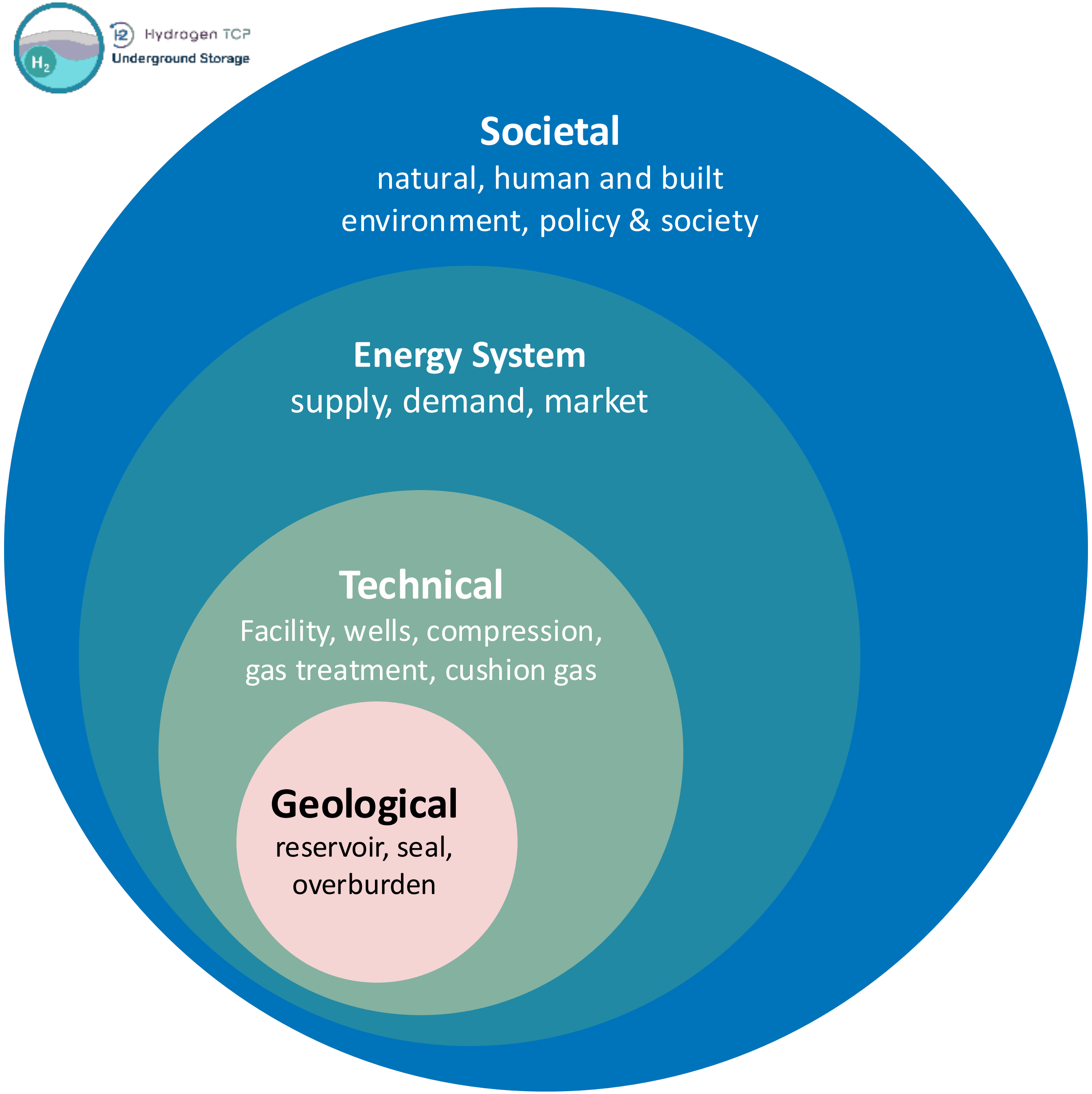


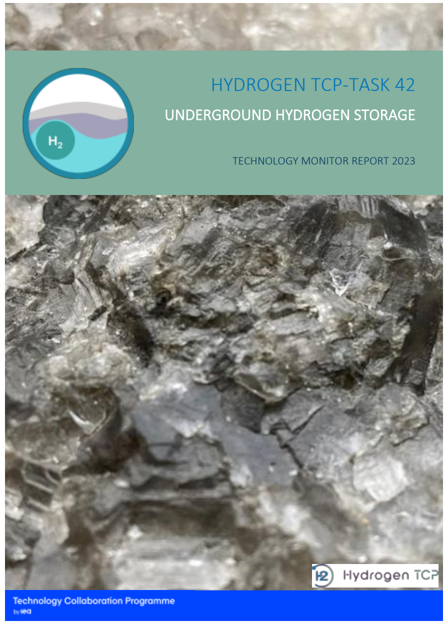
In-depth state of art

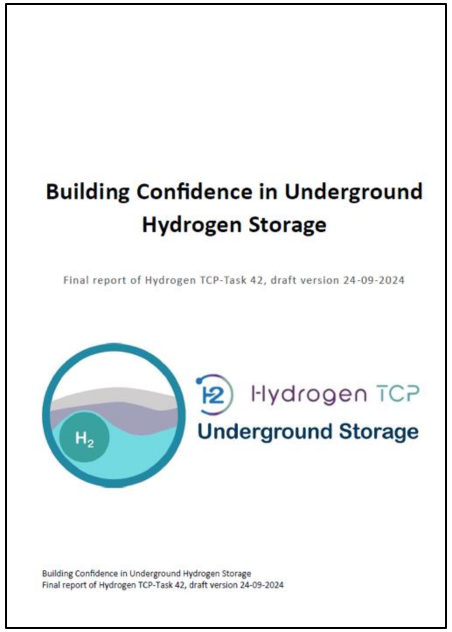


1. H2 leakage via last cemented casing shoe
2. H2 permeation in damage zone
   Microfracturing
   Geomech. failure
3. Microbial reactions induced by brine/sump
   Potential microseismic event due to falling (undissolved) blocks
4. Dissolution of anhydrite
   Permeation/leakage via porous interlayers
   Potential microseismic events due to differences in ductile behaviour intersecting layers
5. Activation of faults due to pressure changes in cavern &/or salt creep

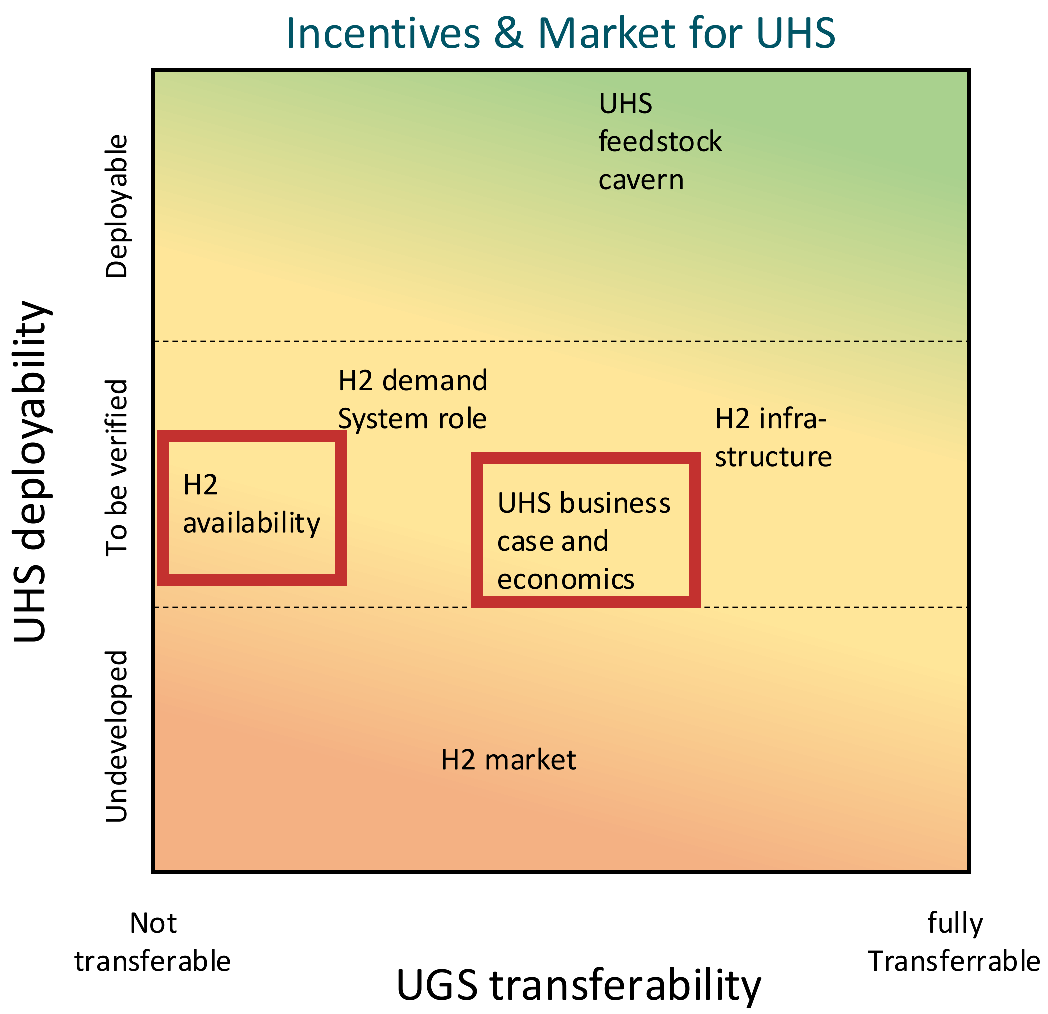
IEA TCP 42 on UHS



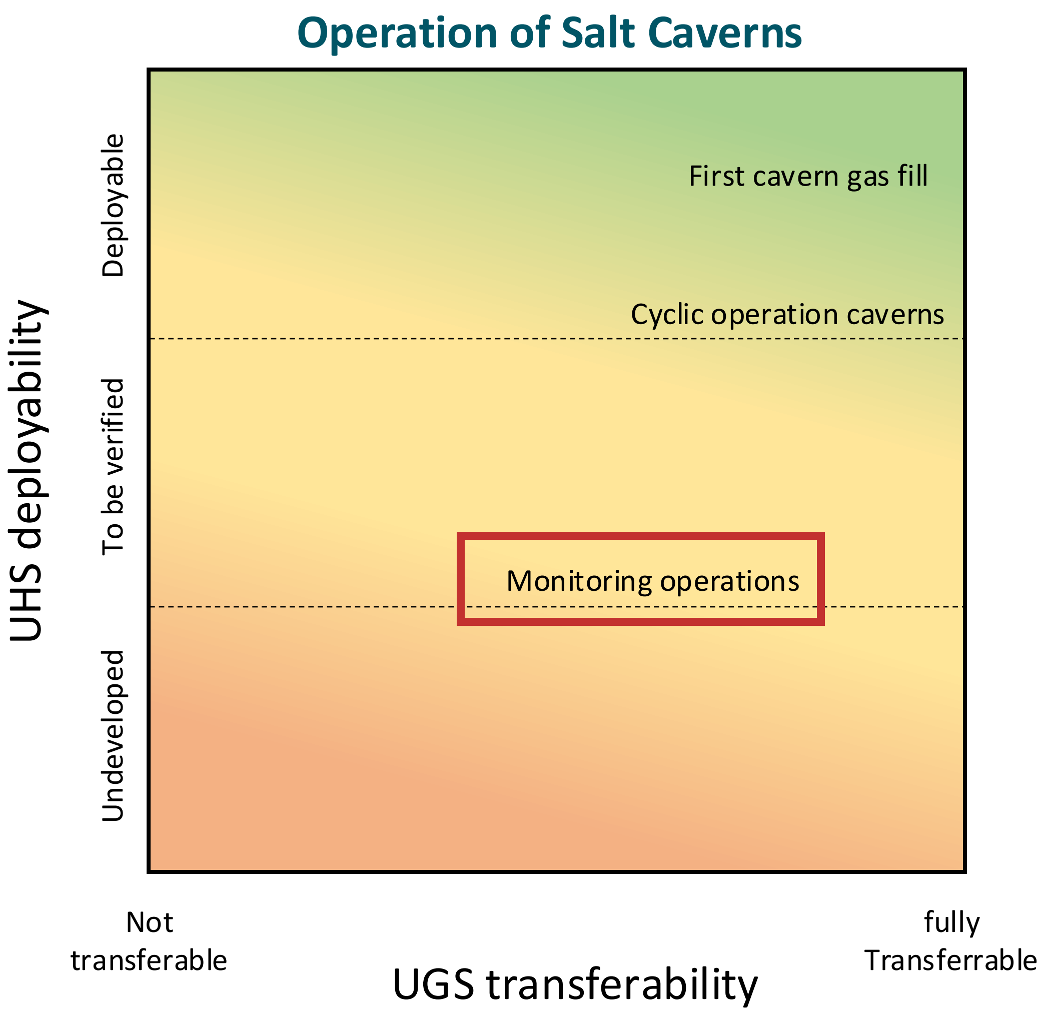


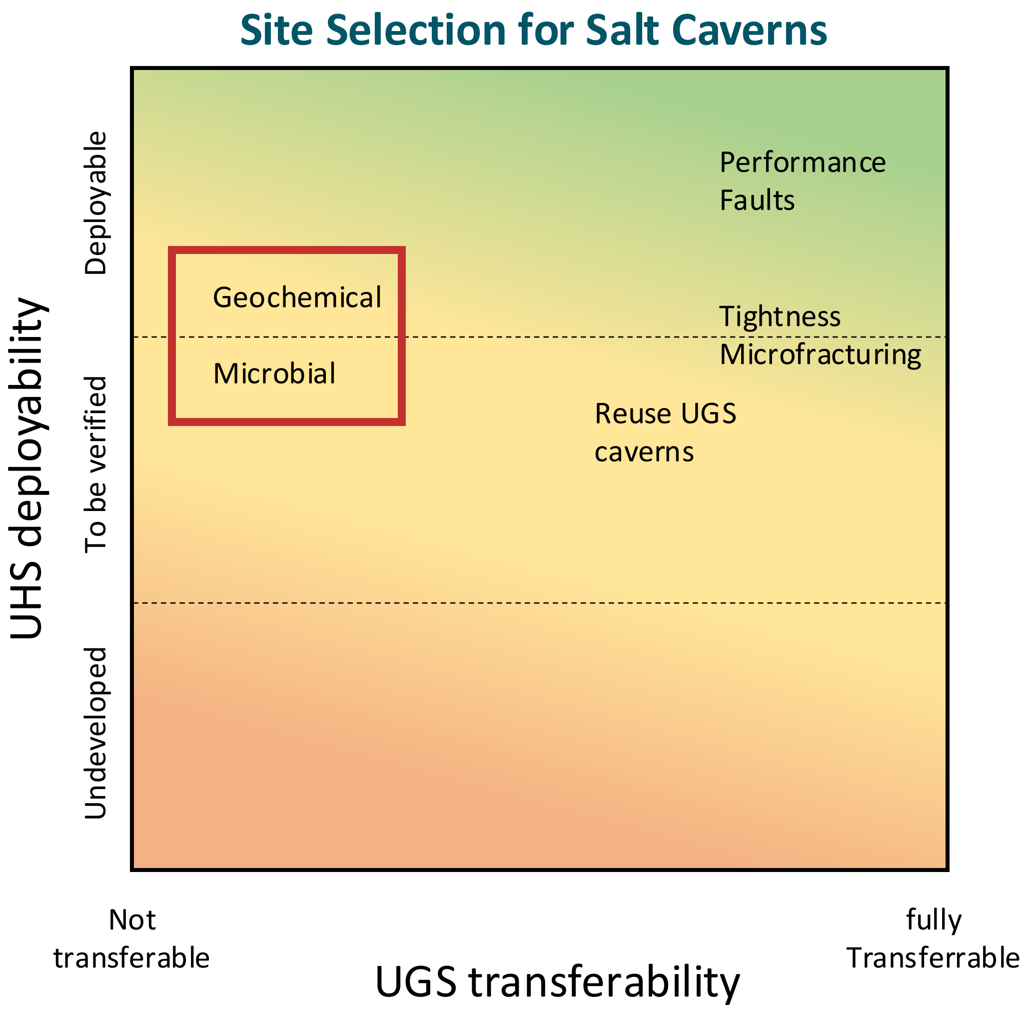


‘Confidence’ in UHS in Caverns >> porous reservoirs



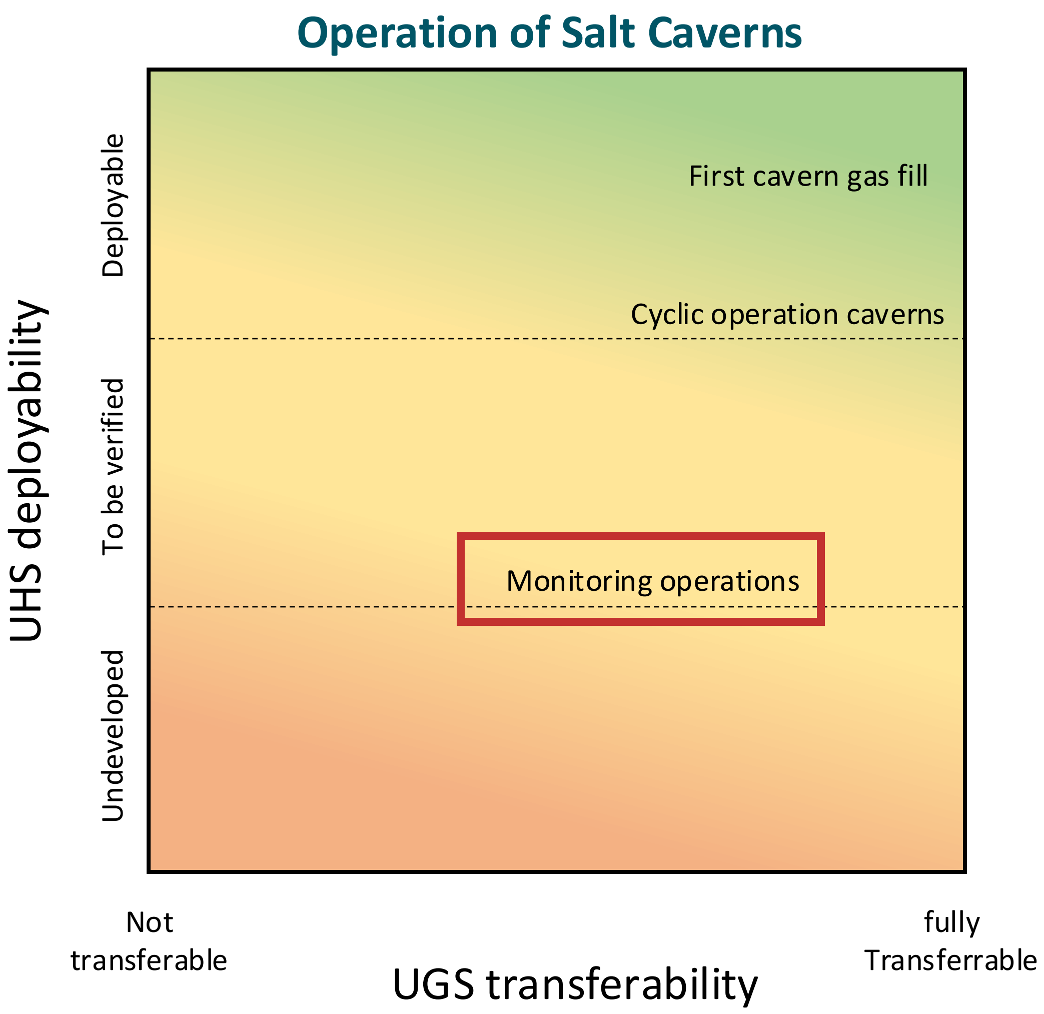
‘Confidence’ in UHS in Caverns >> porous reservoirs

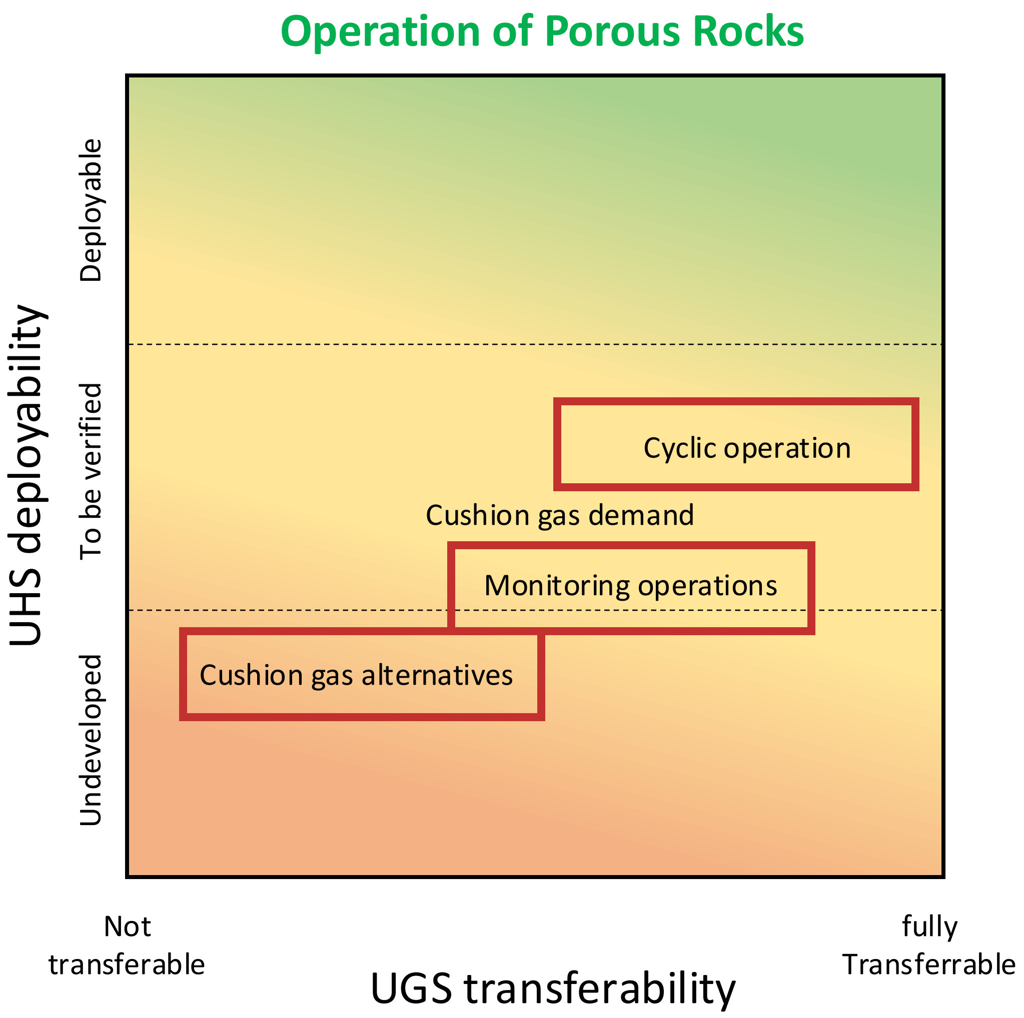




Lesson: mechanics of UGS & UHS are quite similar (except for H2 exposure)

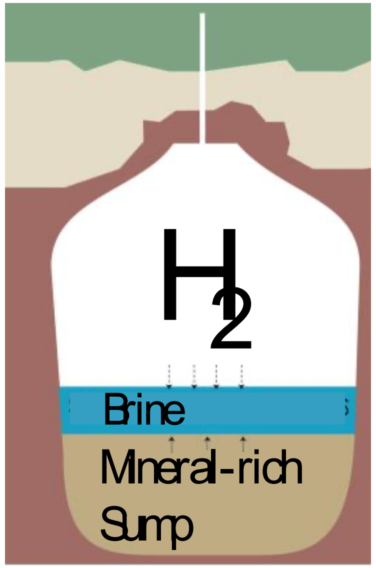
'Confidence' in UHS in Caverns >> porous reservoirs

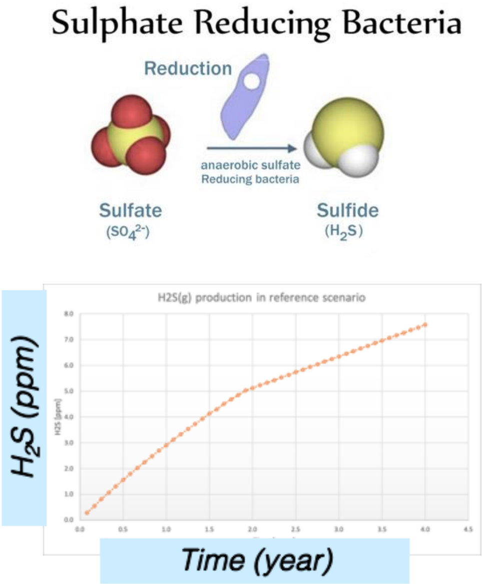




Lesson: mechanics of UGS & UHS are quite similar (except for H2 exposure)

Salt Caverns are great storage tanks: but have challenges too





Maarten Laban MSc thesis, 2020, TU Delft

- Construction time (some years)
- Large volumes of fresh/sea water during construction
- Disposal of large volumes of brine during construction
- Brine stays at the bottom, drying the produced gas needed!
- Mechanics, Mechanics, Mechanics:
  - Minimum pressure to keep it stable
  - Complex mechanics modeling and predictions
  - Deep caverns (+2km) can have higher creep rates
  - Subsidence, sinkhole (structure collapse!)
  - Too rapid cycles can damage walls/roof, cause falls or failure
  - Shear zones at margines (e.g. in US Strategic Pet. Res. Sites)
- Heterogeneities, Insoluble (mineral rich), complex geometries
- Lower static capacity (compared with depleted gas fields)
- Bio-geochemistry & reactions leading to impurities

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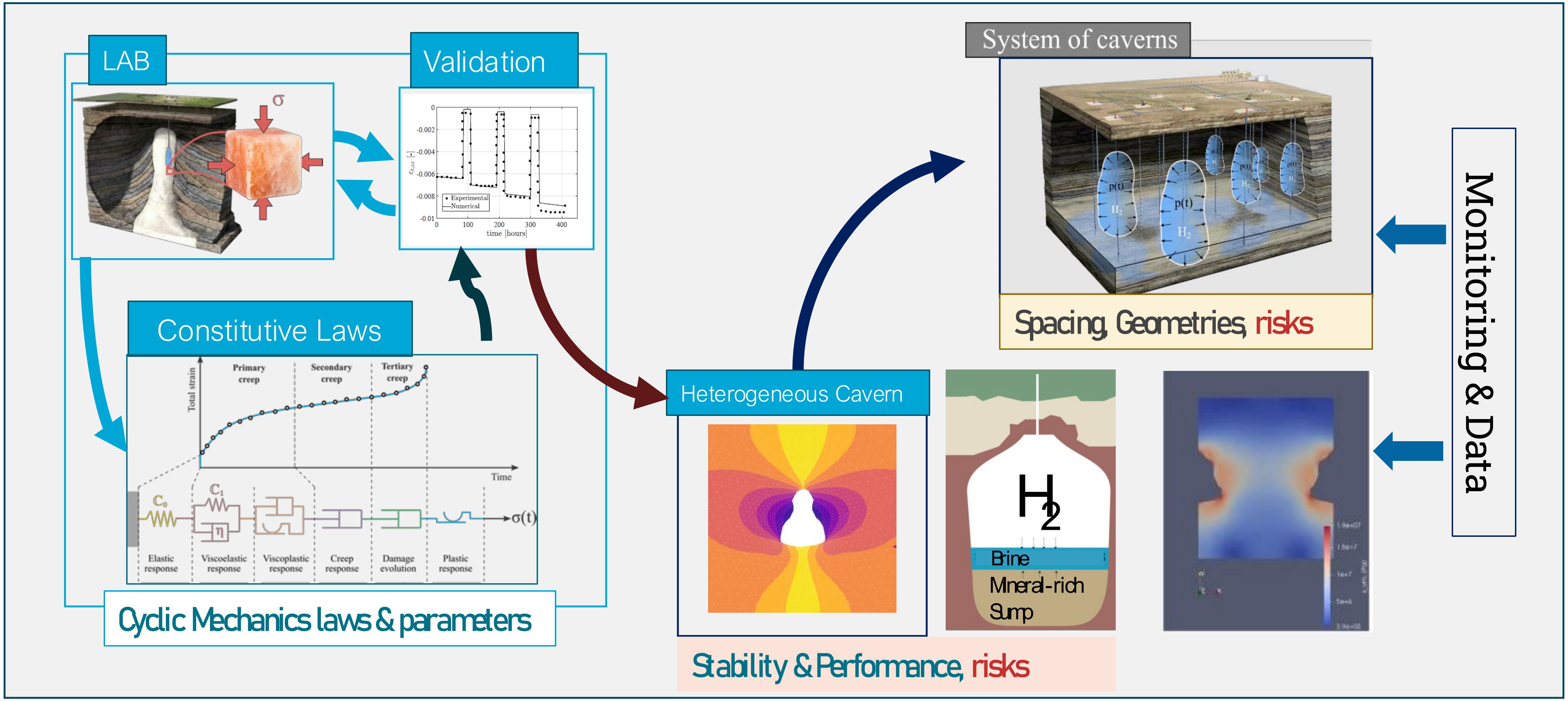
Geology, Geomechanics & Geometry of Caverns



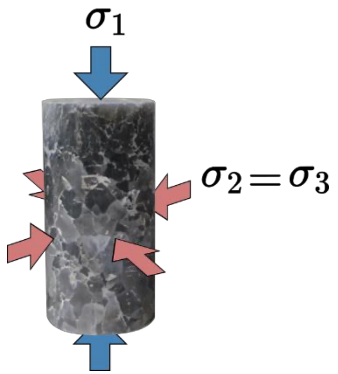
SAFEINCAVE

Open-Source Simulator for forward & inverse modeling:
Calibrate, Simulate, Optimize

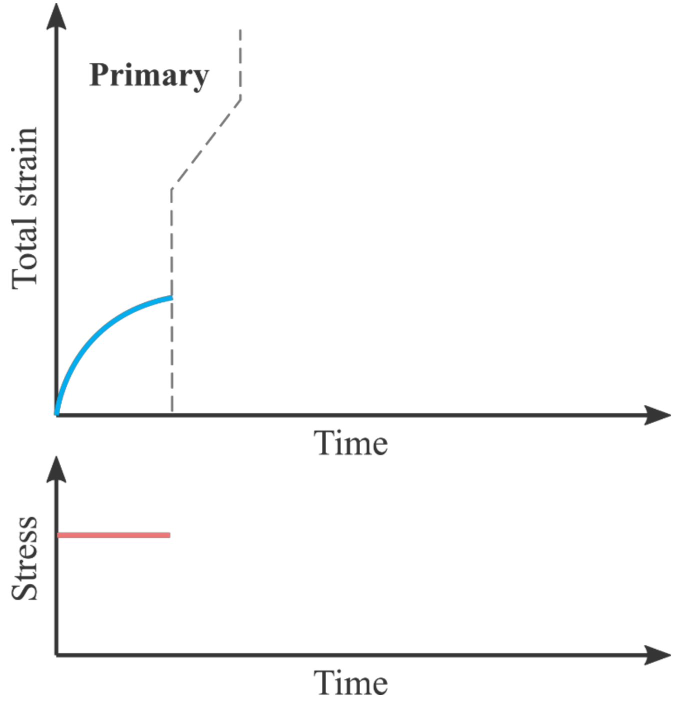
Salt Rock Mechanics

Time-dependent deformation

Creep stages



$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_3 & 0 & 0 \\ 0 & \sigma_3 & 0 \\ 0 & 0 & \sigma_1 \end{bmatrix}$$

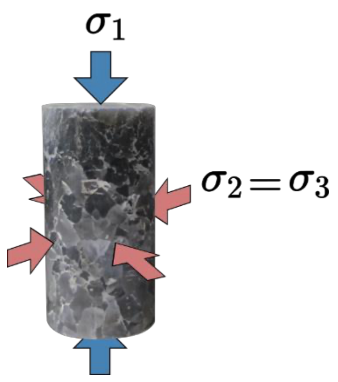


Transient creep:

- Strain rate decreases

Time-dependent deformation

Creep stages



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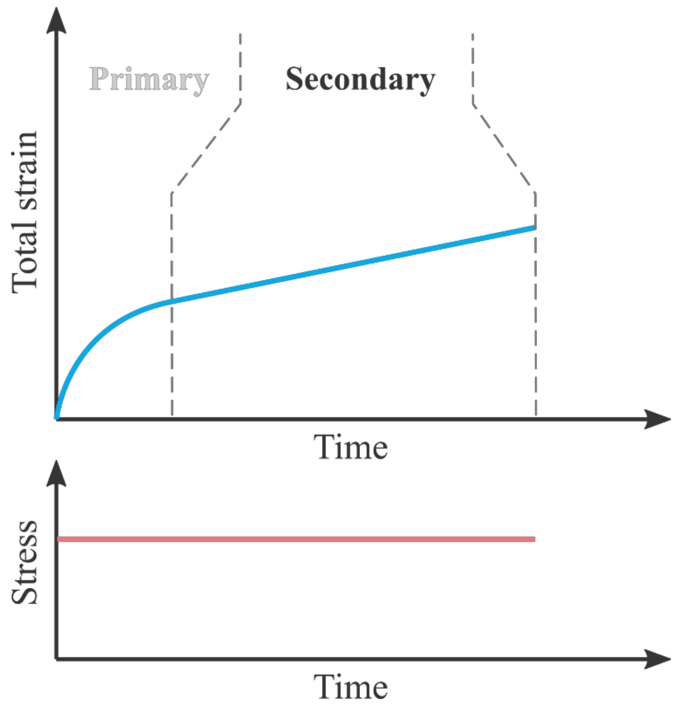
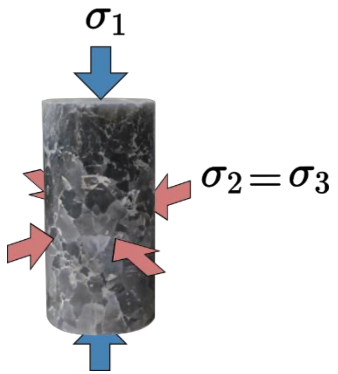


Steady-state creep:

- Strain rate stabilizes

Time-dependent deformation

Creep stages



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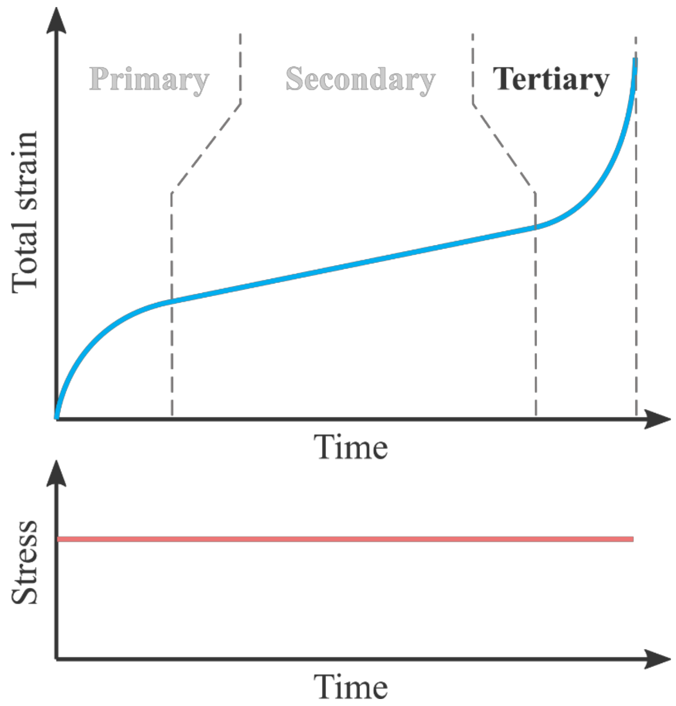

Accelerated creep:

- Strain rate increases
- Micro-crack propagation
- Brittle failure

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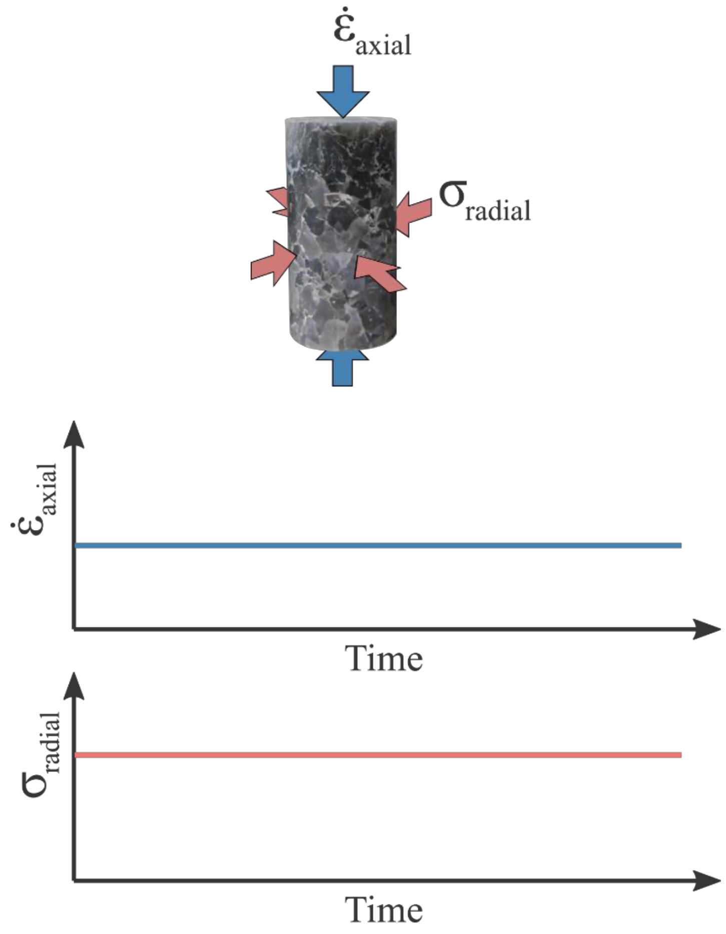
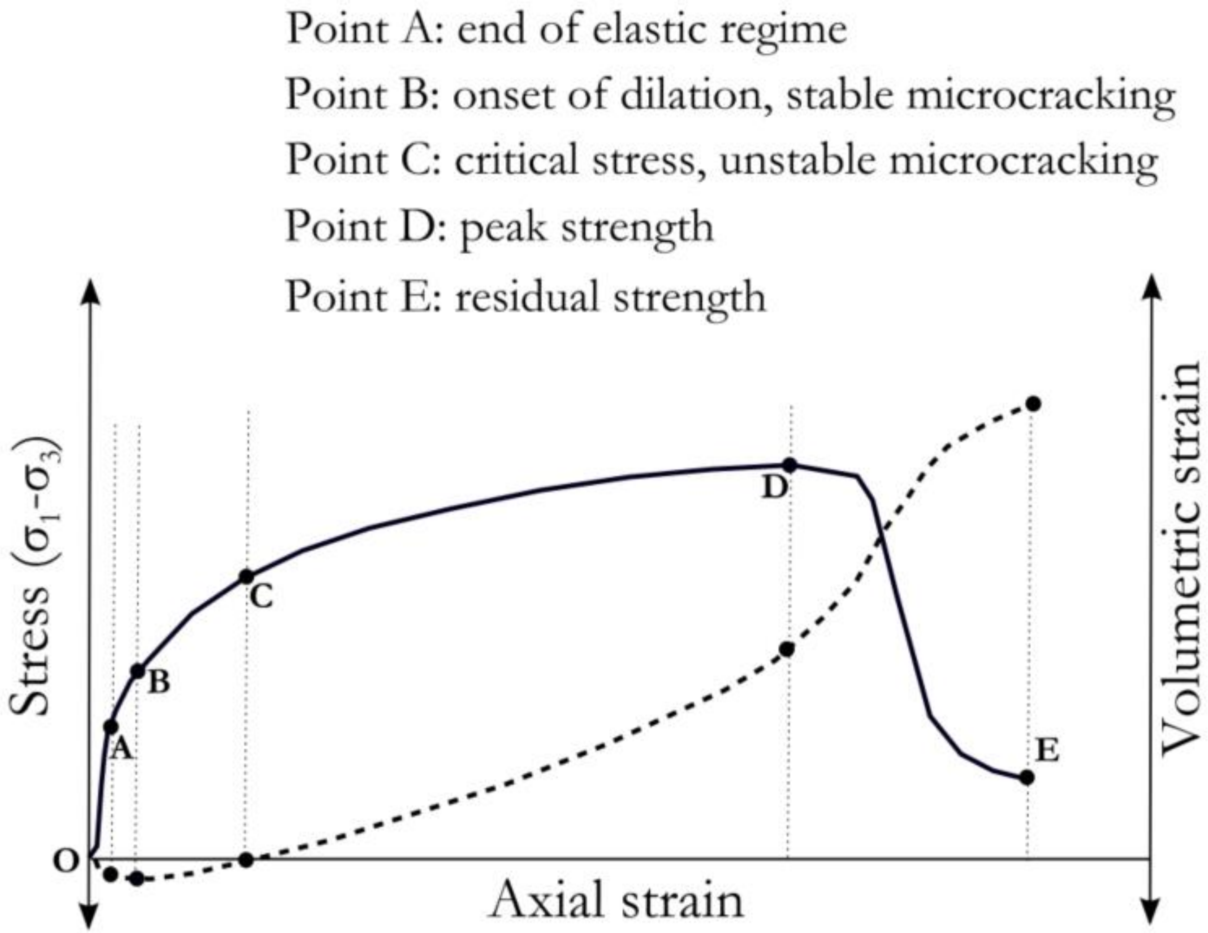
Salt Rock mechanics: a simple lab observation





Kavan Khaledi (2017)

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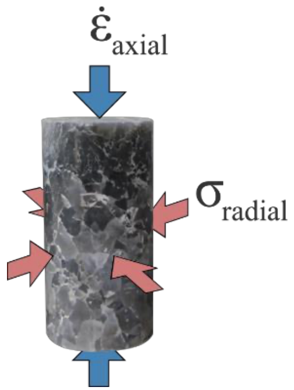
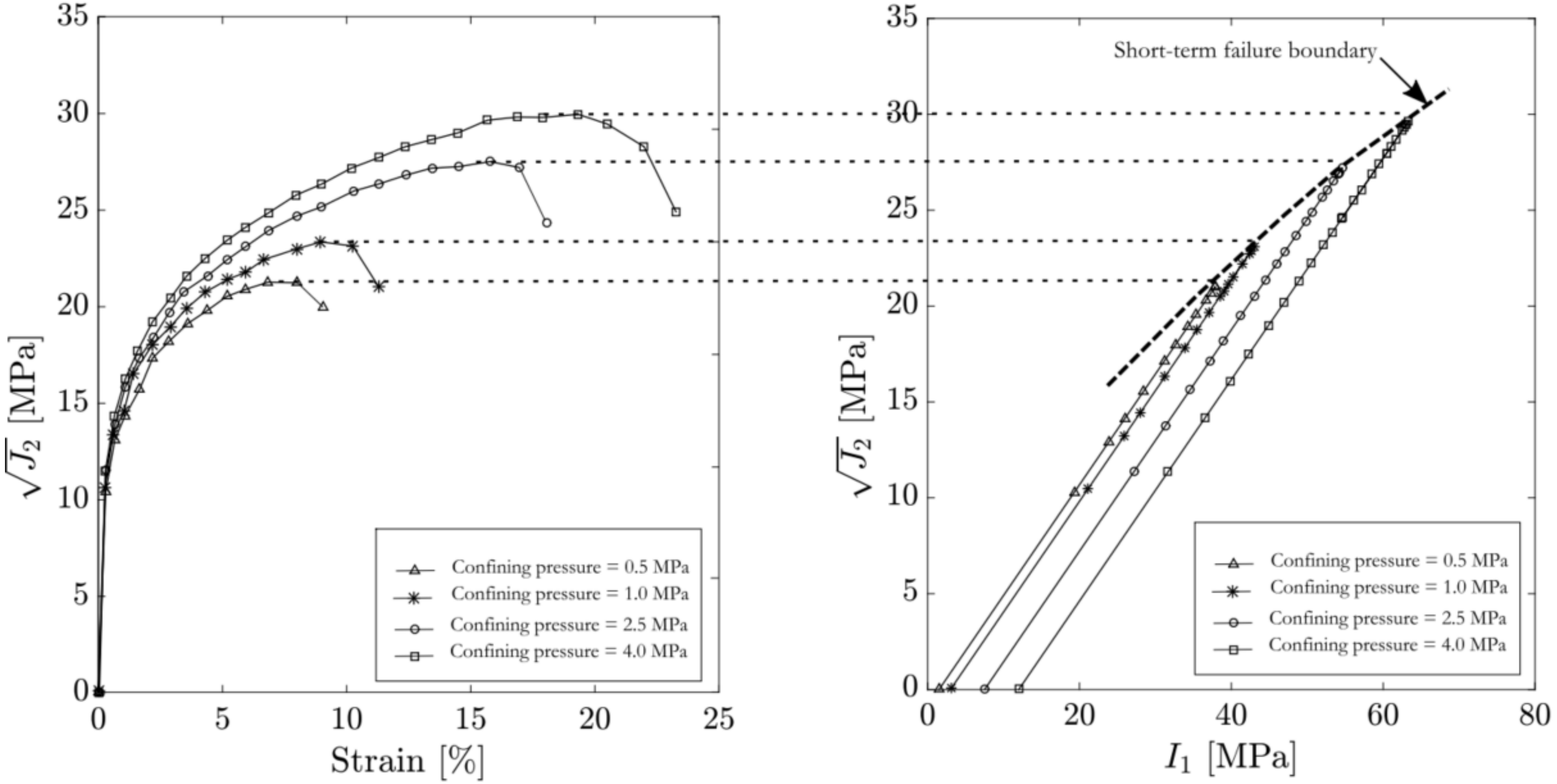
Salt Rock mechanics: a simple lab observation



Günther & Salzer (2007)



Major Challenges to characterize 'the short-term failure' for geologic (uncertain & heterogeneous) rocks:

- Strength of real heterogeneous samples
- Impact of the lab experiment conditions (rates, BC, …) on this curve!

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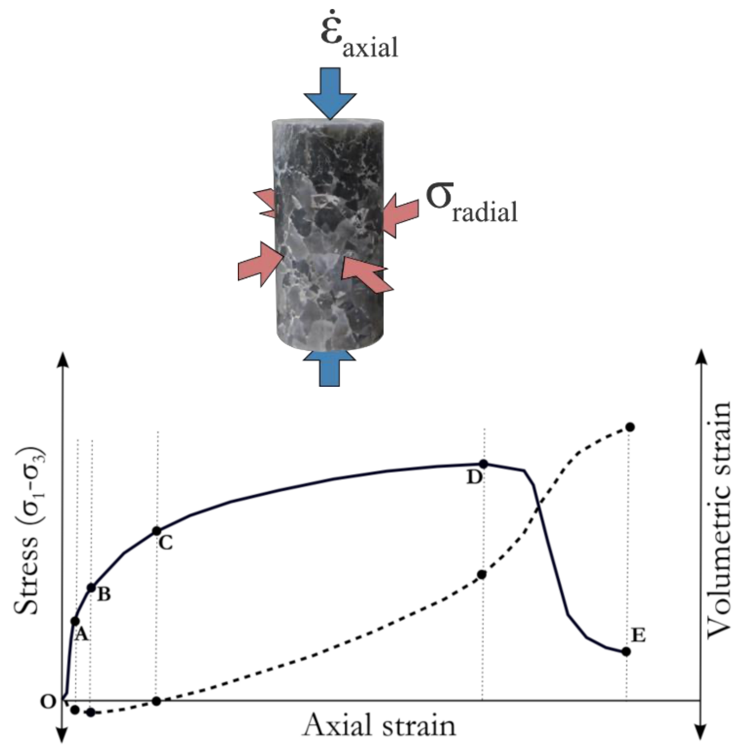
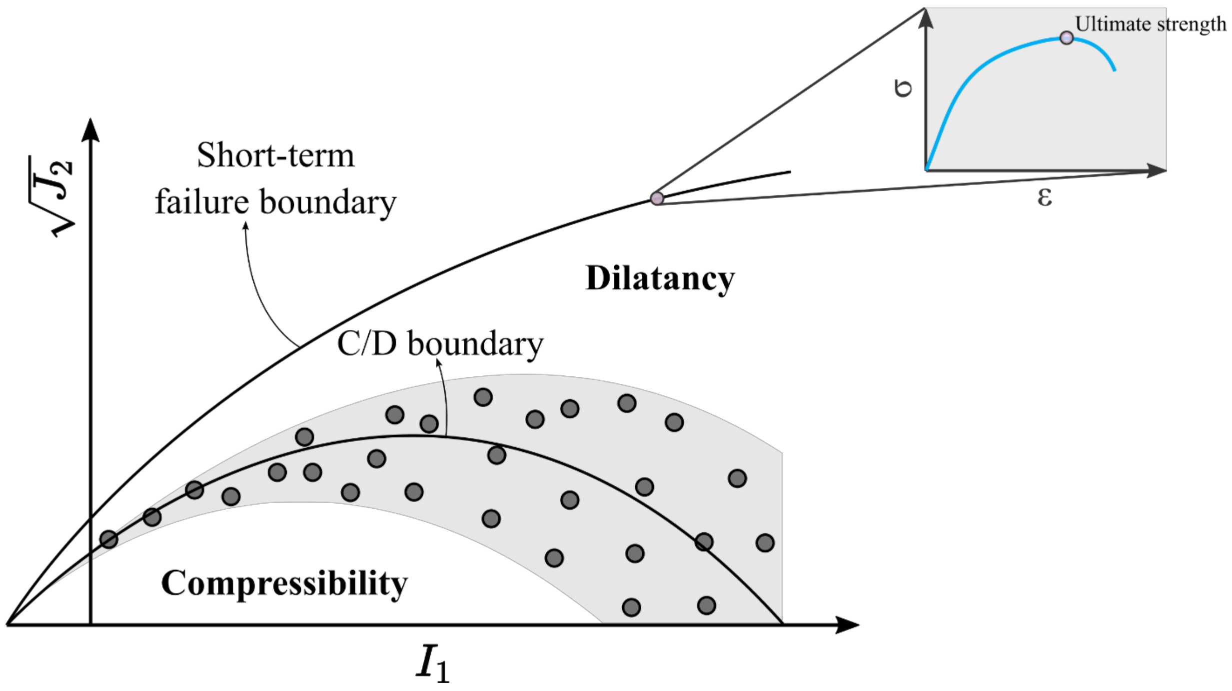
Salt Rock mechanics: short-term & long-term failure

$$I_1 = \sigma_{xx} + \sigma_{yy} + \sigma_{zz}$$

$$I_2 = \sigma_{xx}\sigma_{yy} + \sigma_{xx}\sigma_{zz} + \sigma_{yy}\sigma_{zz} - \sigma_{xy}^2 - \sigma_{xz}^2 - \sigma_{yz}^2$$

$$J_2 = \frac{1}{3} I_1^2 - I_2$$





Cristescu (1993)

Long-term failure zone (C/D) has to be avoided in operations. Operate in compressibility zone!

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Salt Rock mechanics: short-term & long-term failure

$$I_1 = \sigma_{xx} + \sigma_{yy} + \sigma_{zz}$$

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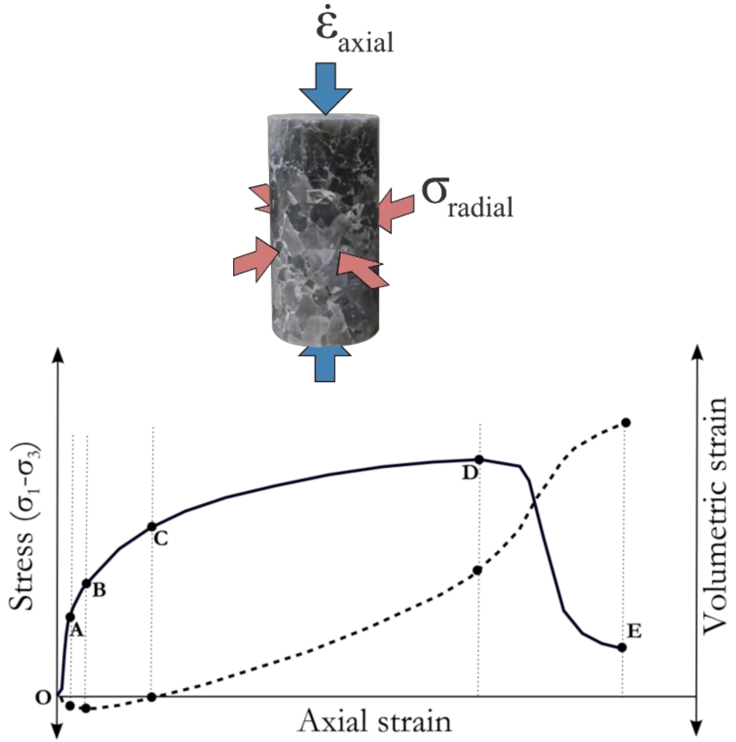

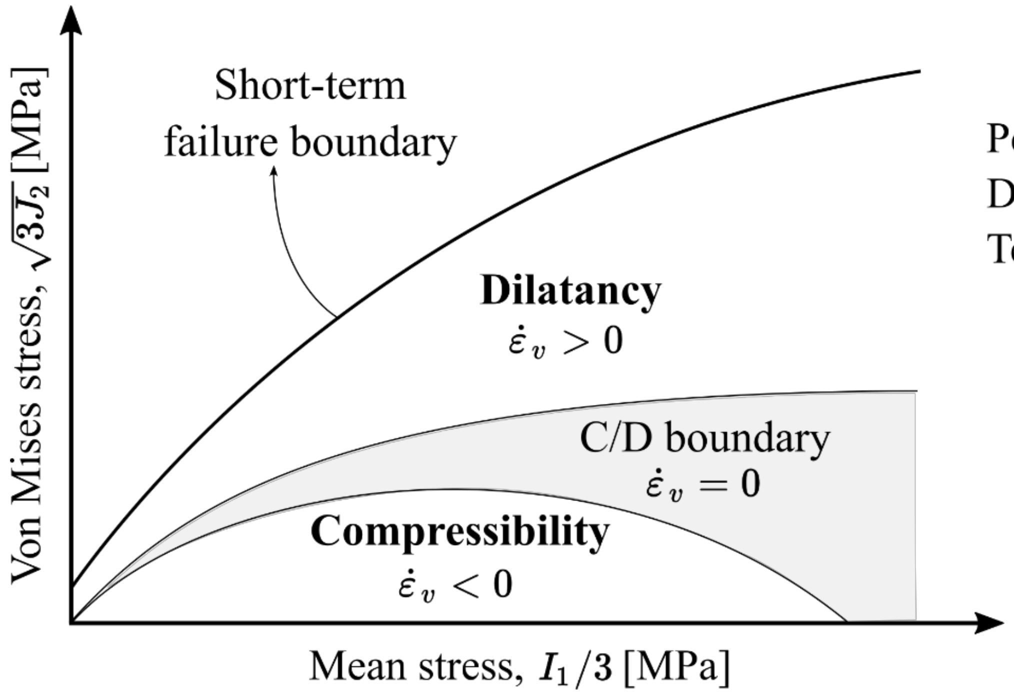

Permeability ↑
Damage ↑
Tertiary creep

Permeability ↓
Damage ↓
No creep failure
Self-healing

Hunsche and Hampel (1999)

Long-term failure zone (C/D) has to be avoided in operations. Operate in compressibility zone!

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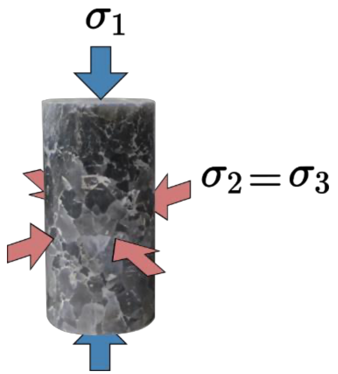
Time-dependent complex behaviour of a rock salt



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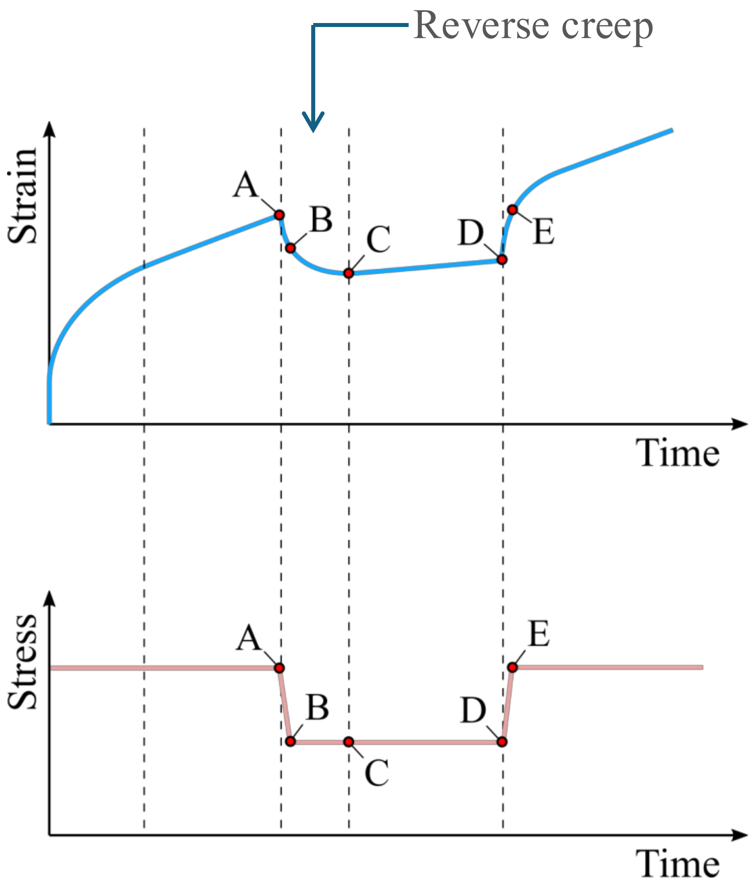
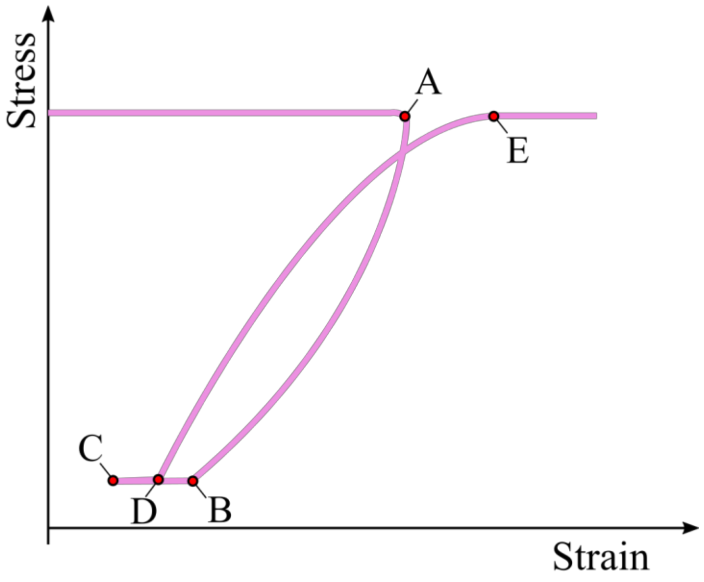
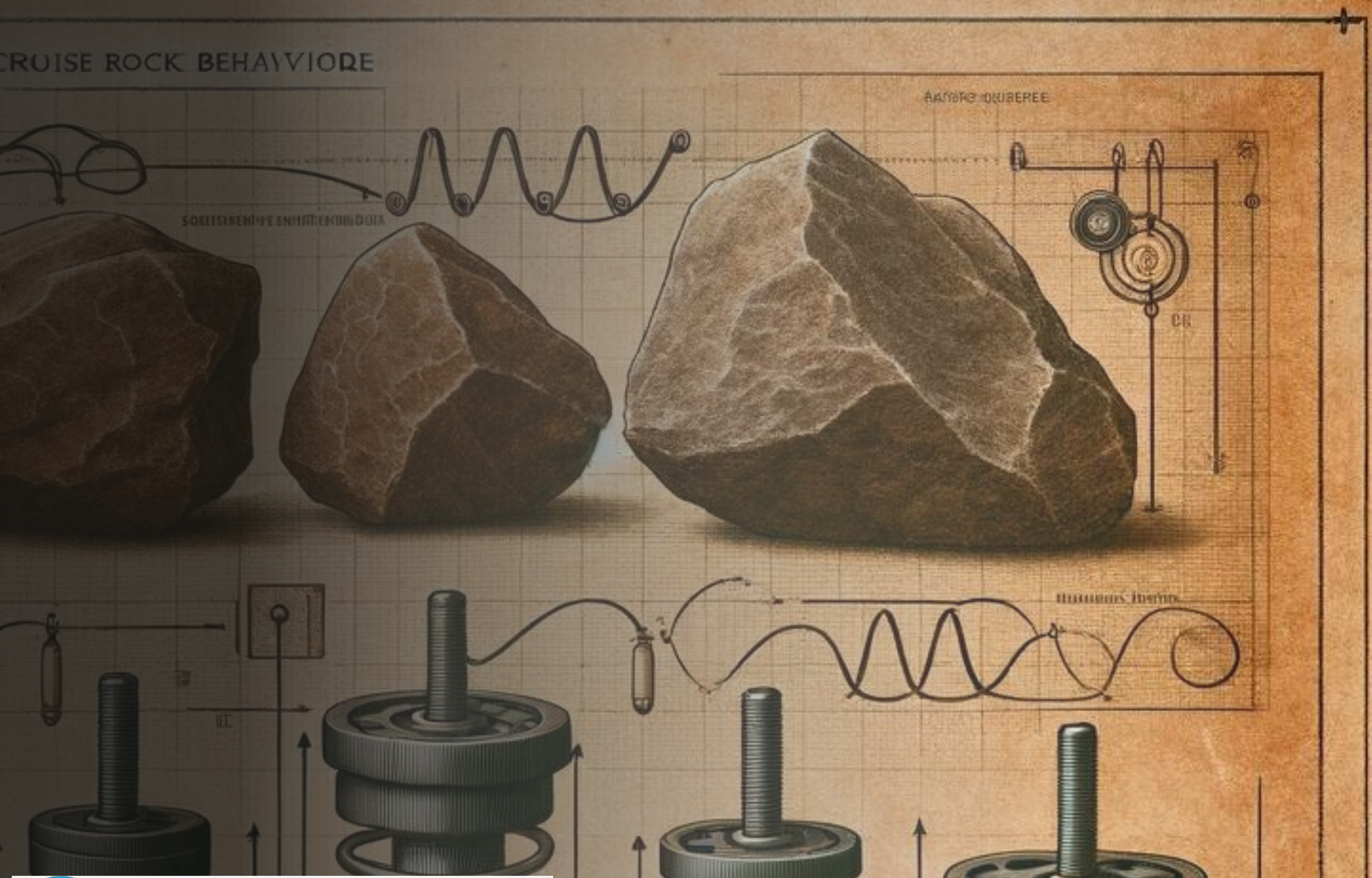




Constitutive Modeling

Basic elements

https://doi.org/10.1016/j.ijrmms.2024.105922



ELSEVIER

International Journal of Rock Mechanics and Mining Sciences

Volume 183, November 2024, 105922

Research paper

A multi-step calibration strategy for reliable parameter determination of salt rock mechanics constitutive models

Hermínio T. Honório [a], Maartje Houben [b], Kevin Bisdom [b], Arjan van der Linden [b], Karin de Borst [b], Lambertus J. Sluys [a], Hadi Hajibeygi [a]

SAFEINCAVE

How to install it? Https://pypi.org/project/safeincave

User Documentation: https://safeincave-docs.streamlit.app/

API Documentation: https://safeincave-api.netlify.app/safeincave.htm

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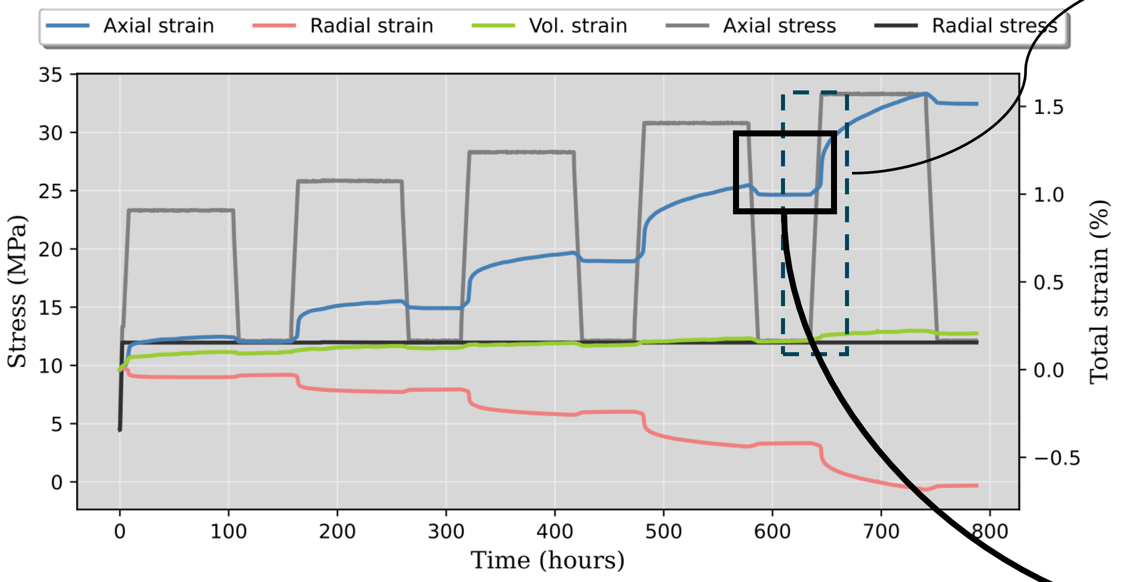
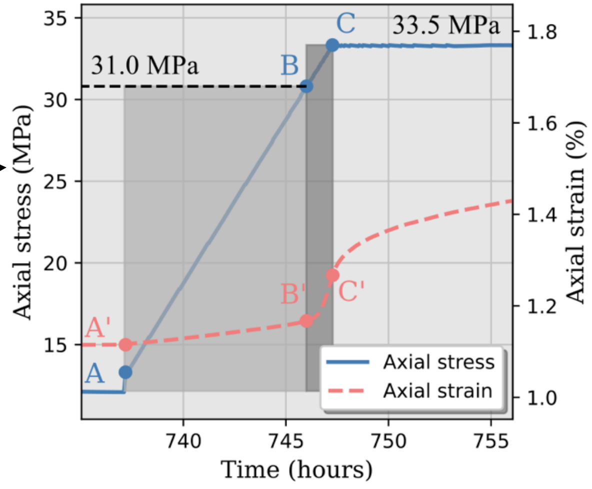
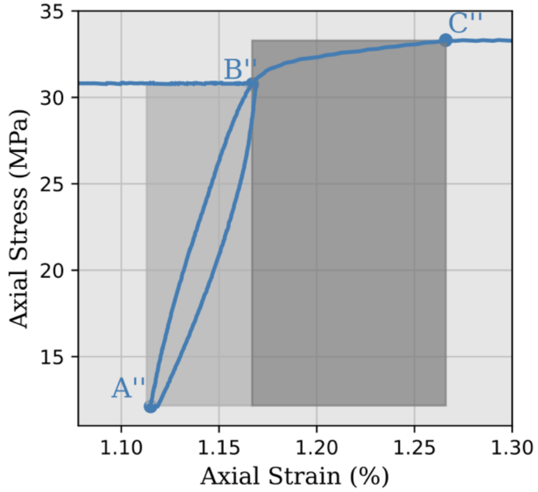
Challenge: Constitutive Laws & Parameters





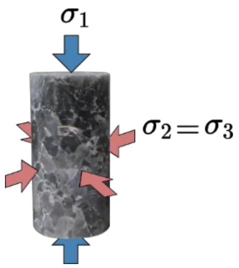
Transient creep

Triggered when stress exceeds a threshold (viscoplastic)



Reverse transient creep

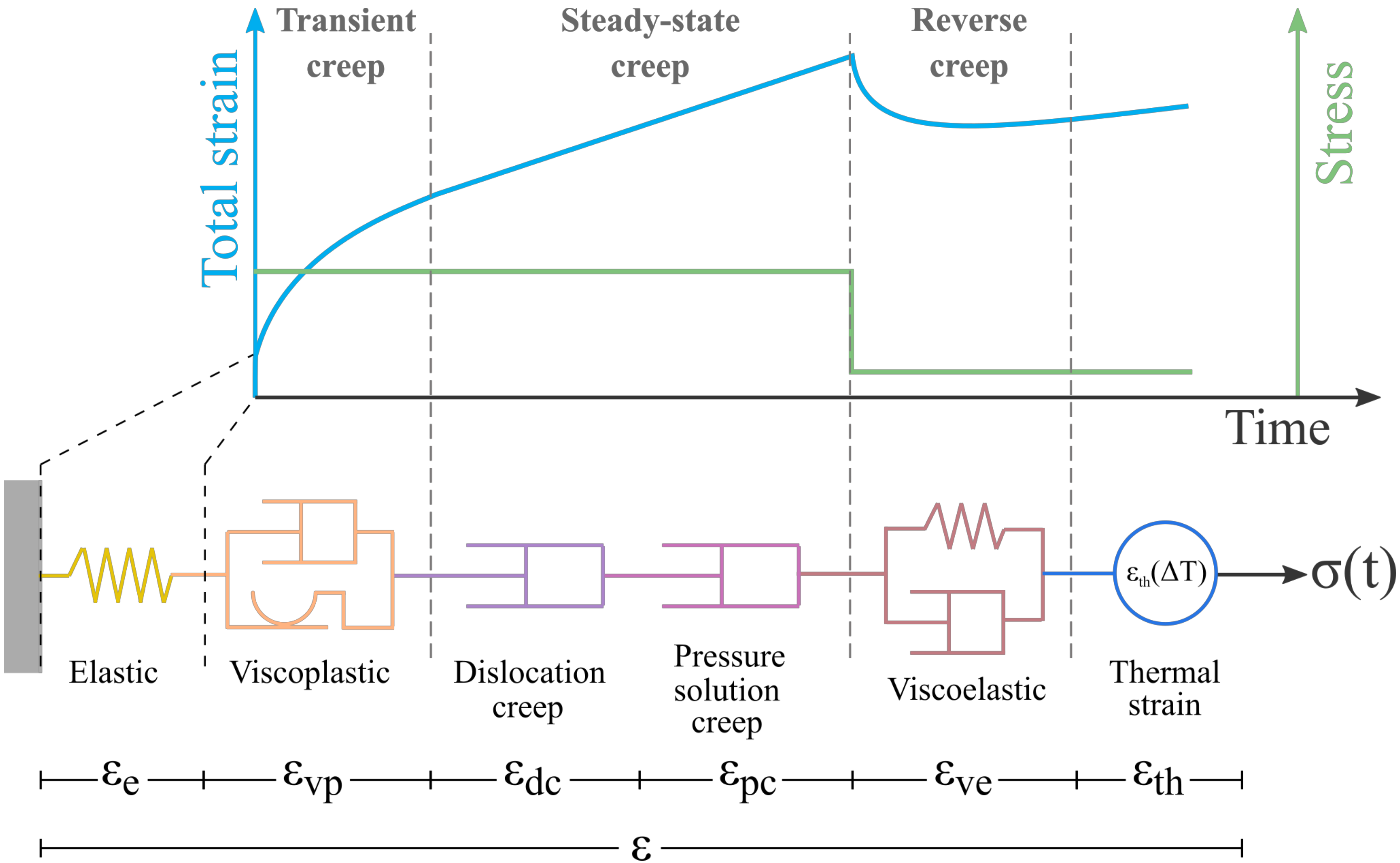
Hysteretic (model viscoelastic)



 Honório& Hajibeygi, Int J Hyd. Energy, 2024

Challenge: Constitutive Laws & Parameters

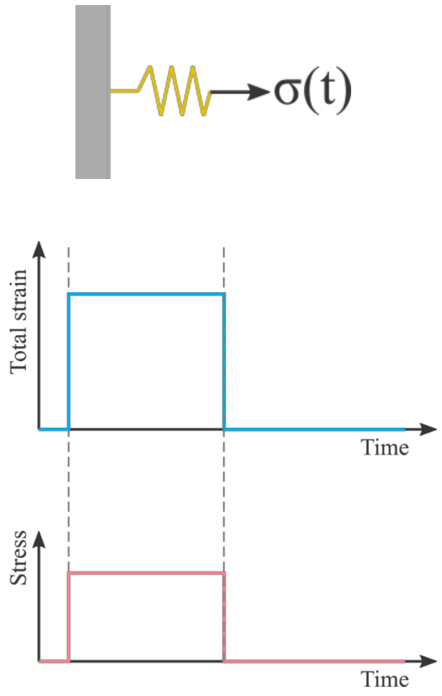
many options & plenty parameters



Honório& Hajibeygi, Int J Hyd. Energy, 2024

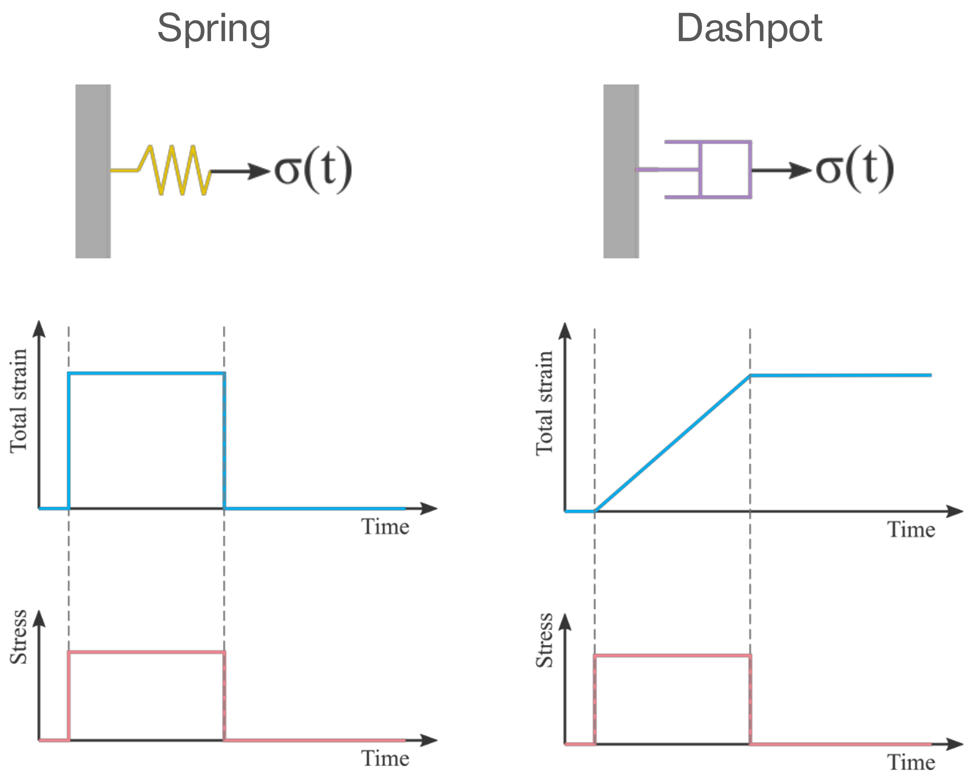
Basic deformation elements: elastic

Spring



$$\boldsymbol{\sigma} = \mathbb{C} : \boldsymbol{\varepsilon}_e \quad \rightarrow \quad \boldsymbol{\varepsilon}_e = \mathbb{C}^{-1} : \boldsymbol{\sigma}$$

Basic deformation elements: steady-state creep



$$\mathbf{s} = \eta(\boldsymbol{\sigma})\dot{\boldsymbol{\varepsilon}}_{ie} \quad \rightarrow \quad \dot{\boldsymbol{\varepsilon}}_{ie} = \frac{1}{\eta(\boldsymbol{\sigma})}\mathbf{s}$$

Dislocation creep:

$$\eta(\boldsymbol{\sigma}) = \frac{1}{A}\exp\left(\frac{Q}{RT}\right) q^{1-n}$$

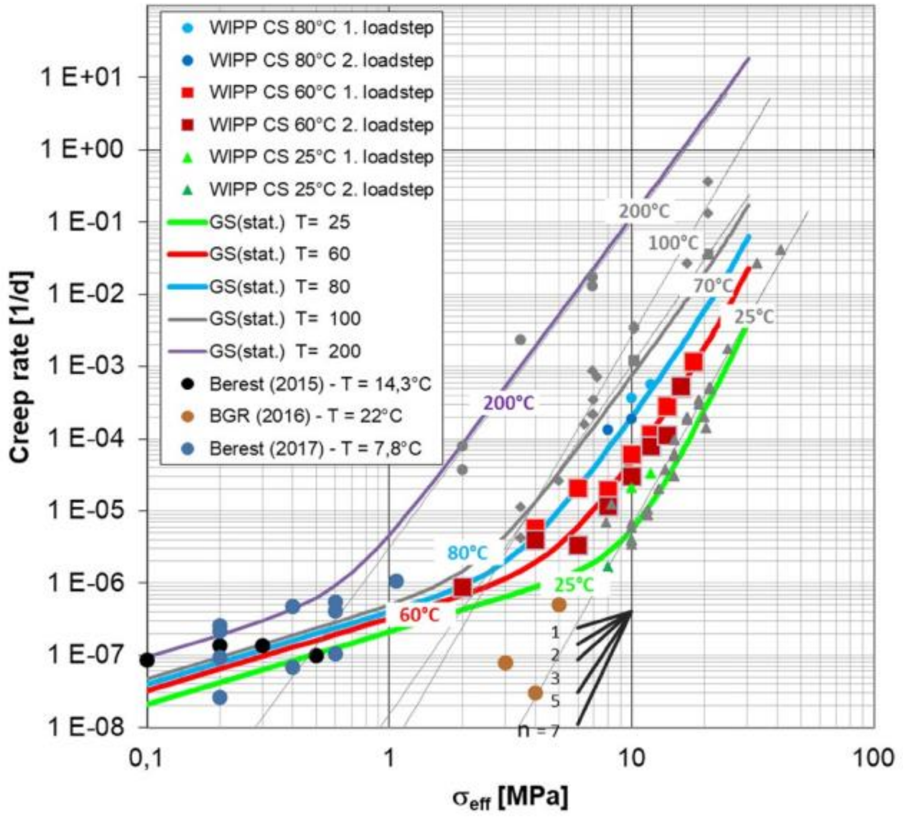
Pressure solution creep:

$$\eta(\boldsymbol{\sigma}) = \eta = \frac{Td^n}{A}\exp\left(\frac{Q}{RT}\right)$$

Note:

$$\boldsymbol{s} = \boldsymbol{\sigma} - \tfrac{1}{3}\,\mathrm{tr}(\boldsymbol{\sigma})\boldsymbol{I}$$

Basic deformation elements: steady-state creep



Bérest *et al* (2019)

$$\mathbf{s} = \eta(\boldsymbol{\sigma})\dot{\boldsymbol{\varepsilon}}_{ie} \quad \rightarrow \quad \dot{\boldsymbol{\varepsilon}}_{ie} = \frac{1}{\eta(\boldsymbol{\sigma})}\mathbf{s}$$

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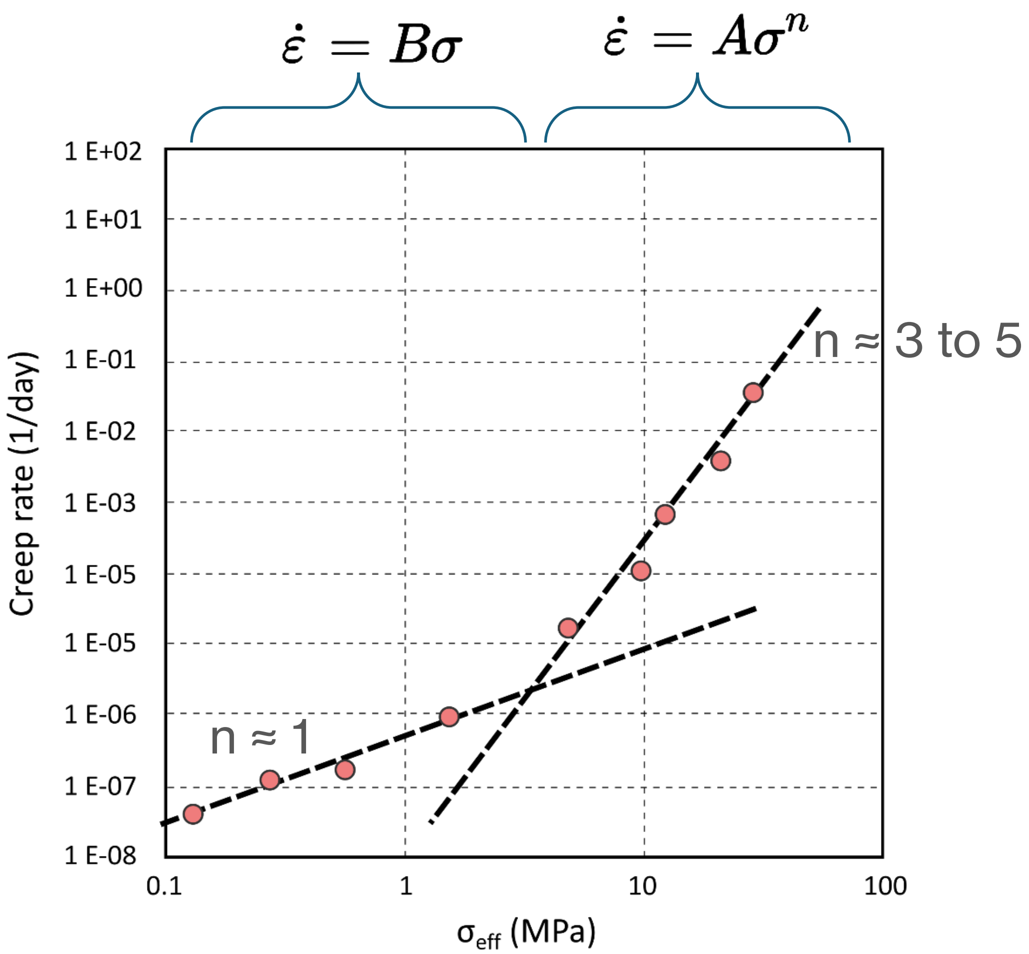
TU Delft

Basic deformation elements: steady-state creep



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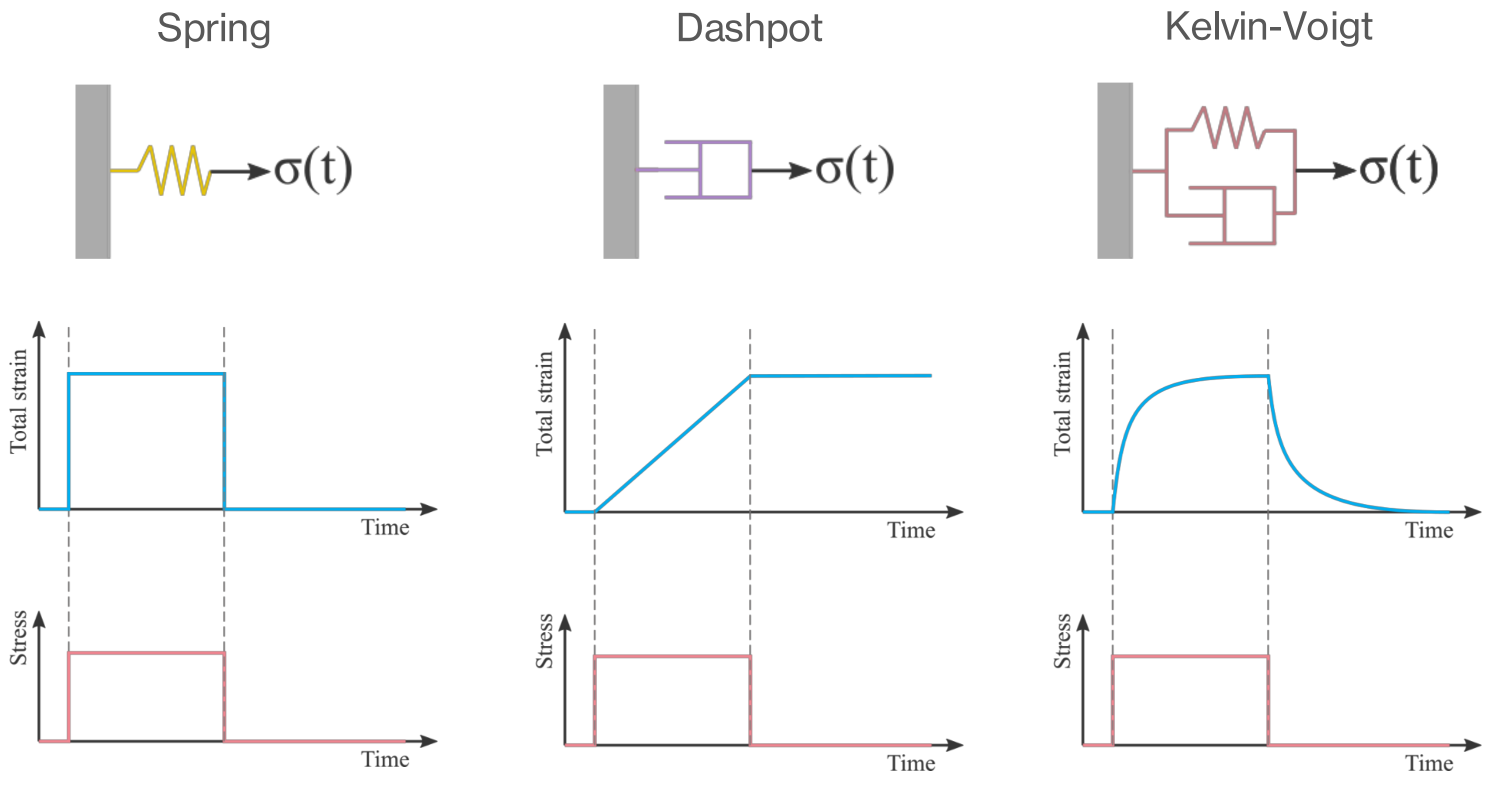
Note:

$$\boldsymbol{s} = \boldsymbol{\sigma} - \tfrac{1}{3}\,\mathrm{tr}(\boldsymbol{\sigma})\boldsymbol{I}$$

Basic deformation elements: viscoelastic



Analytical Solution:

$$\mathbb{C} : \boldsymbol{\varepsilon}_{ve} + \eta \dot{\boldsymbol{\varepsilon}}_{ve} = \boldsymbol{\sigma}$$

$$\rightarrow \quad \dot{\boldsymbol{\varepsilon}}_{ve} = \frac{1}{\eta} \left(\boldsymbol{\sigma} - \mathbb{C} : \boldsymbol{\varepsilon}_{ve} \right)$$

Analytical Solution (const. stress)

$$\boldsymbol{\varepsilon}_{ve}(t_i) = \bar{\mathbb{C}}^{-1}(t_i) : \boldsymbol{\sigma}_0 \cdot$$

$$\bar{\mathbb{C}}(t) = \left(1 - e^{-\frac{E}{\eta} t} \right) \mathbb{C}$$

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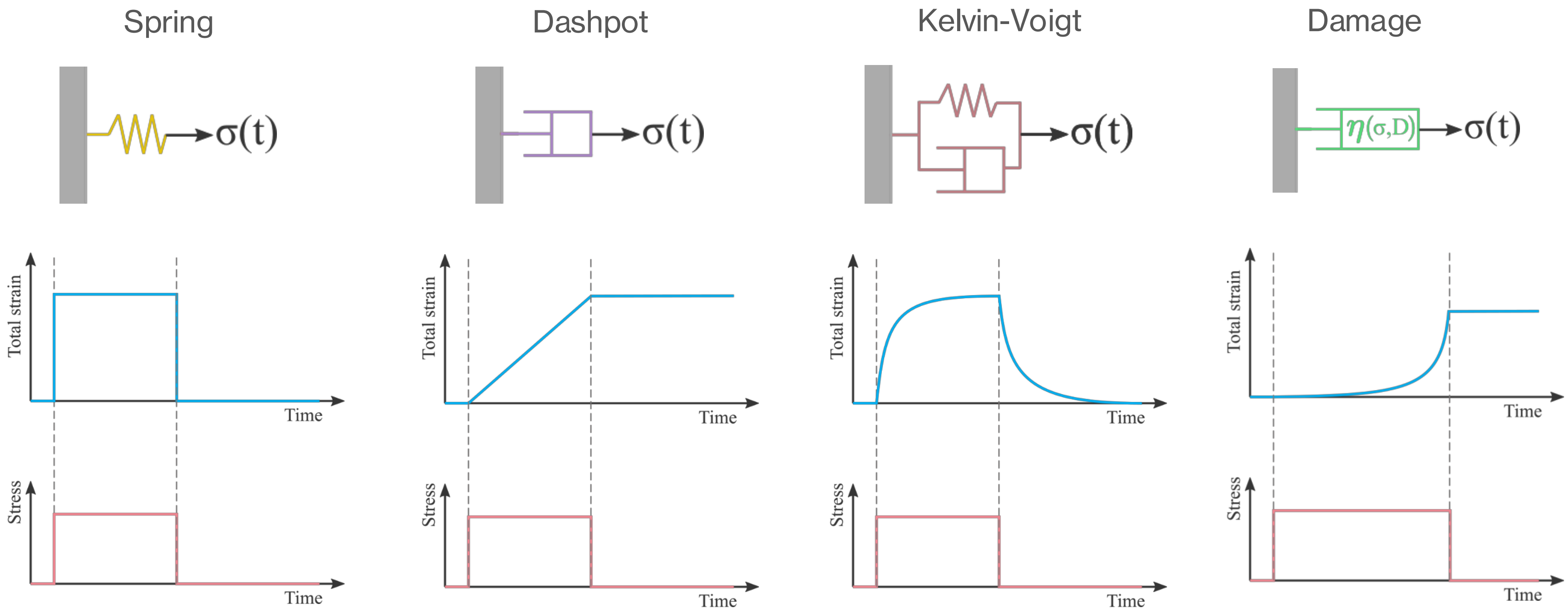
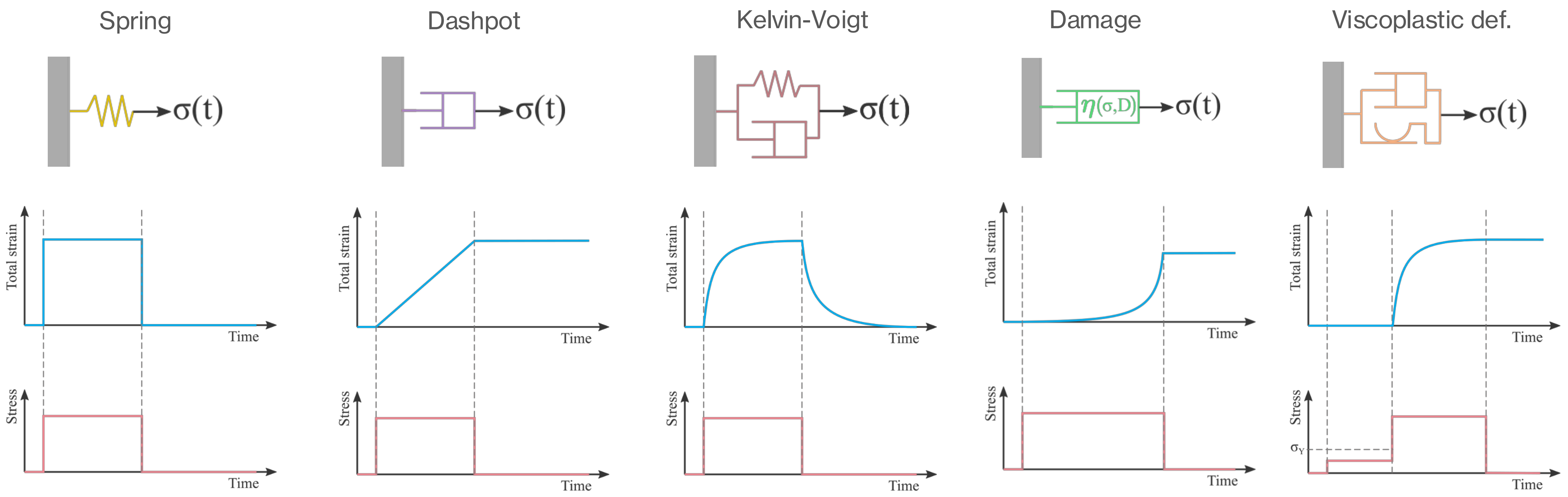
Basic deformation elements: damage



Murakami and Ohno (1980)

$$\dot{\boldsymbol{\varepsilon}}_{ie} = \frac{Aq^{n-1}}{(1-D)^n}\boldsymbol{\sigma}$$

Basic deformation elements: all mechanical deformations



Basic deformation elements: Viscoplastic

$$\dot{\boldsymbol{\varepsilon}}_{ie}(\alpha,\boldsymbol{\sigma}) = \mu_1 \left\langle \frac{F}{F_0} \right\rangle^N \frac{\partial F}{\partial \boldsymbol{\sigma}}$$

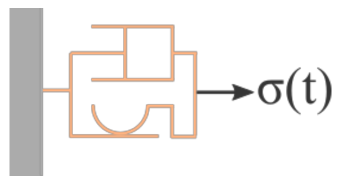
$$F(\alpha,\boldsymbol{\sigma}) = J_2 - (-\alpha \bar{I}_1^{\,n} + \gamma \bar{I}_1^{\,2})\left[\exp(\beta_1 \bar{I}_1) - \beta\cos(3\psi)\right]^m$$

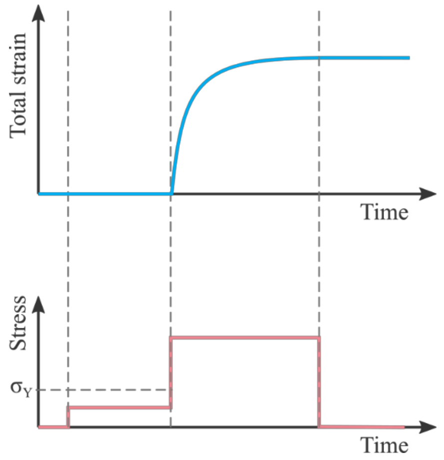
$$\bar{I}_1 = I_1 + \sigma_t$$

$$\alpha = a_1\left[\left(\frac{a_1}{\alpha_0}\right)^{\frac{1}{\eta}} + \xi\right]^{\eta} \qquad \xi(\alpha,\boldsymbol{\sigma}) = \int_{t_0}^{t} \sqrt{\dot{\boldsymbol{\varepsilon}}_{vp} : \dot{\boldsymbol{\varepsilon}}_{vp}}\,\mathrm{d}t$$

Desai and Varadarajan (1986)

Viscoplastic def.





TUDelft

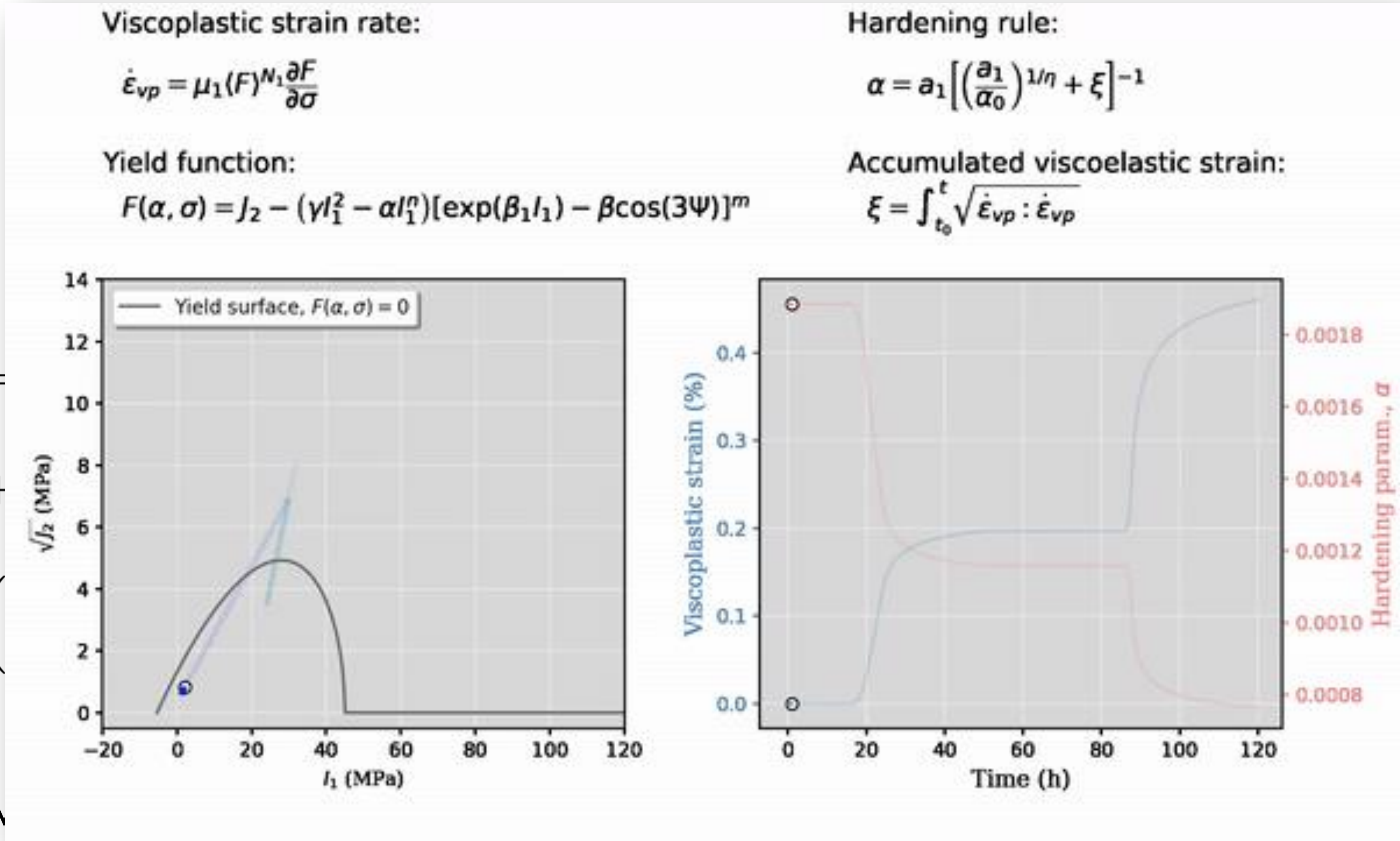
Basic deformation elements: Viscoplastic

$\dot{\boldsymbol{\varepsilon}}_{ie}(\alpha, \boldsymbol{\sigma})$

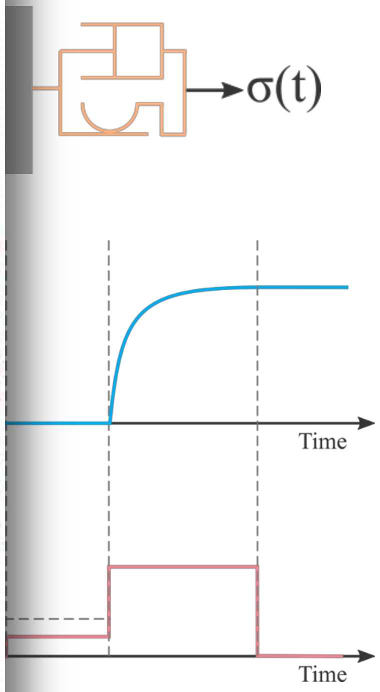
$F(\alpha, \boldsymbol{\sigma}) =$

$\bar{I}_1 = I_1 +$

$\alpha = a_1 \Big[\Big($

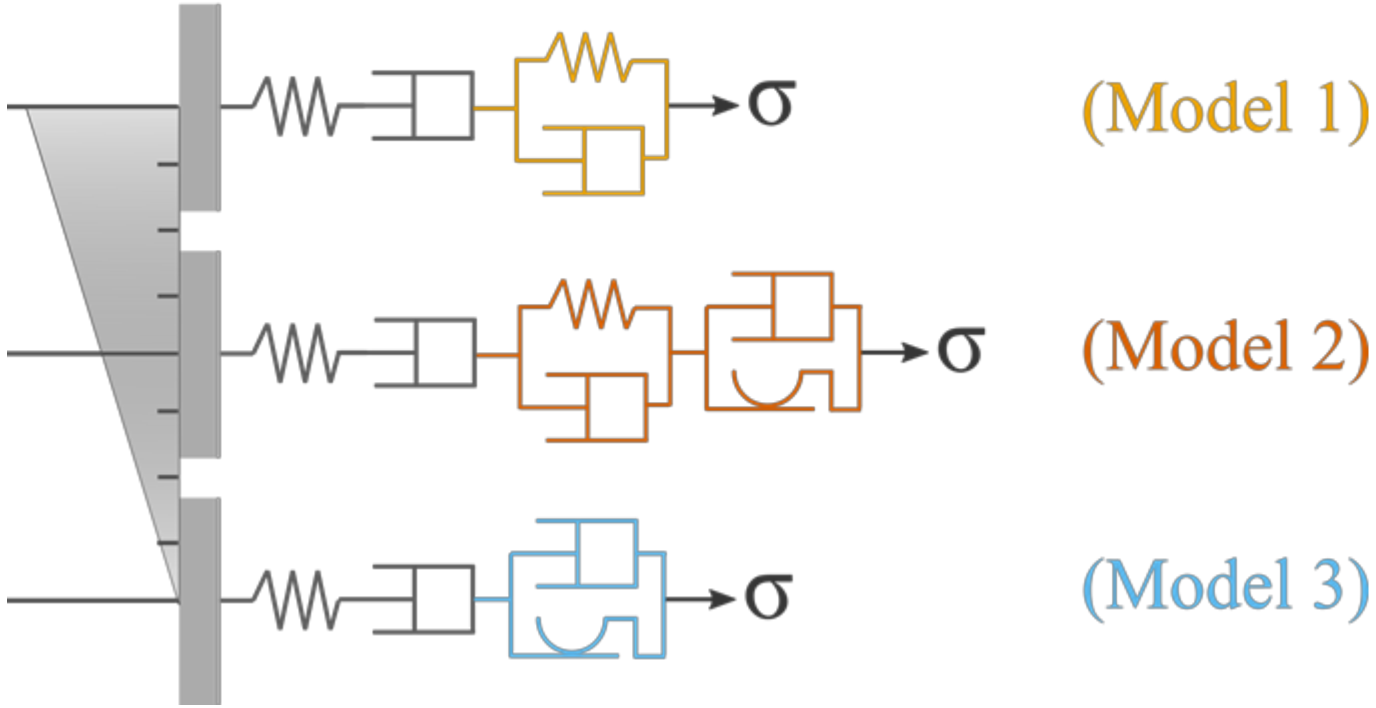


Viscoplastic def.



Desai and V

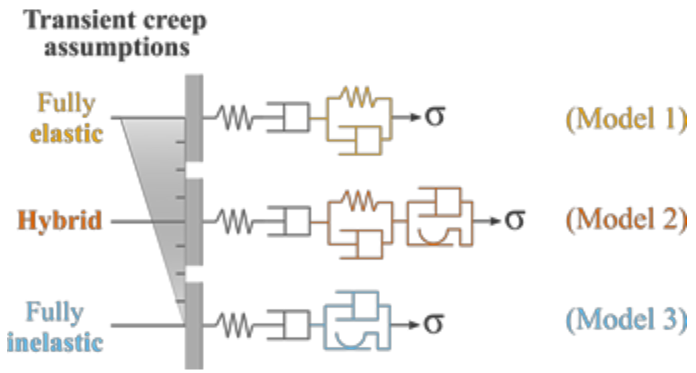
Results

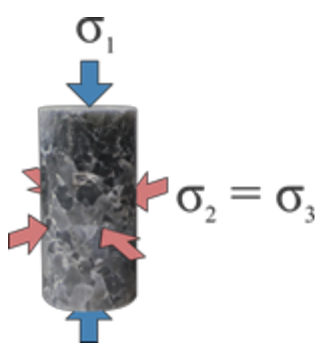


Honório et al. https://doi.org/10.1016/j.ijrmms.2024.105922 (2024)

Results

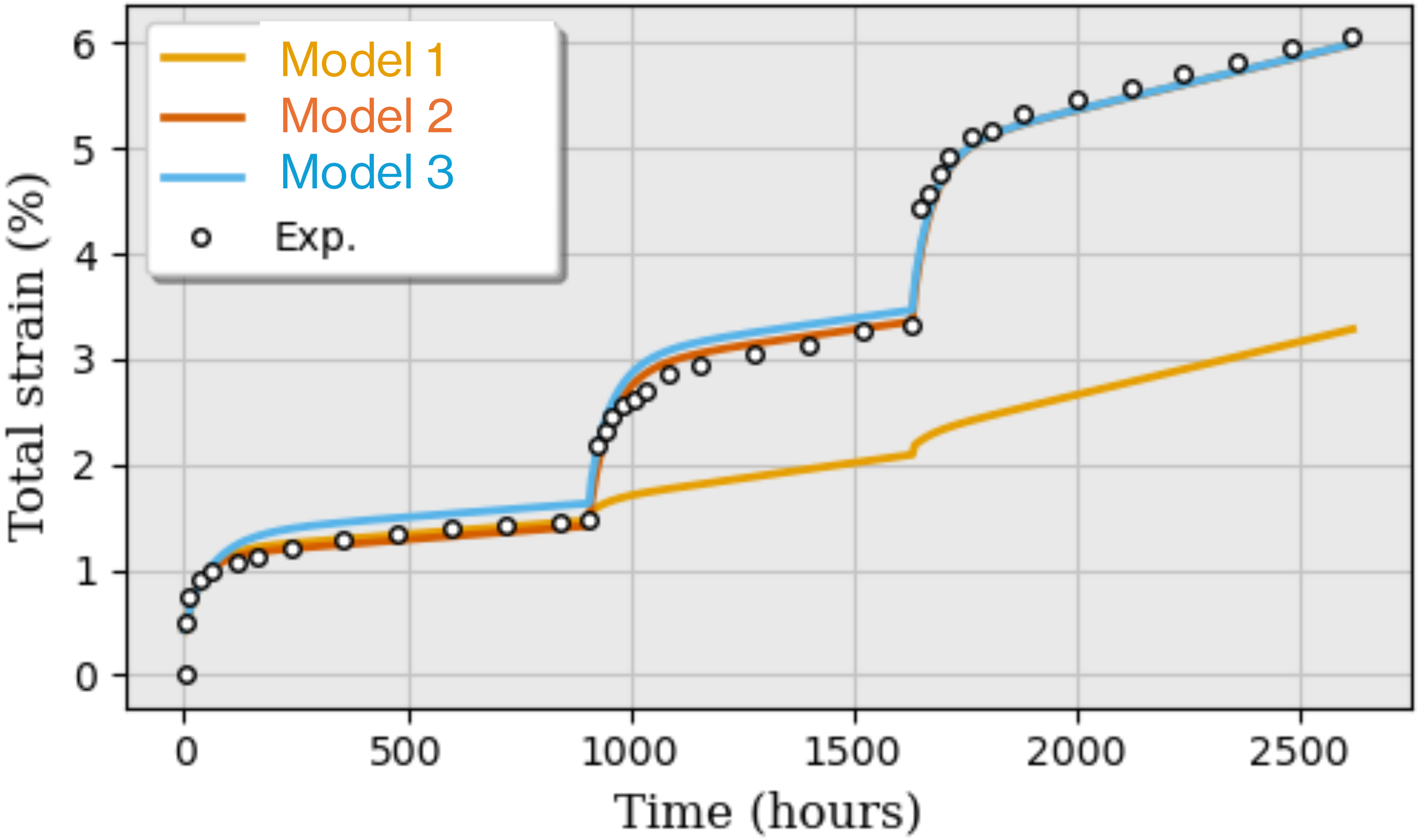
Wang (2004)





σ_1 = 12, 14, 16 MPa

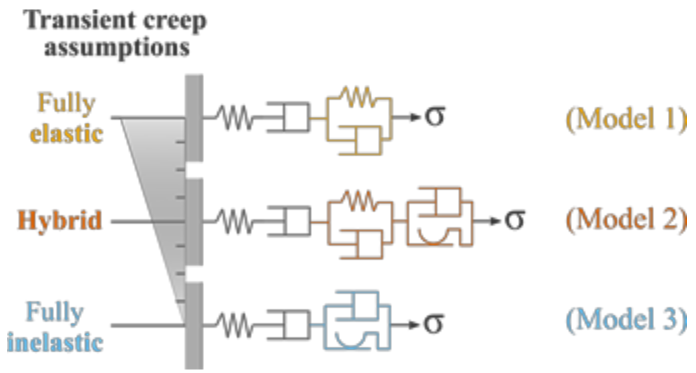
$\sigma_2 = \sigma_3$ = 7.18 MPa

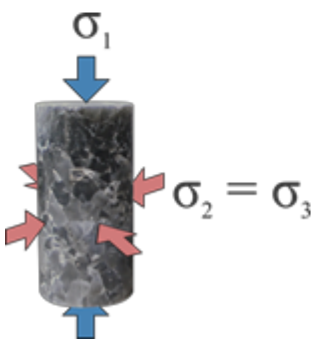


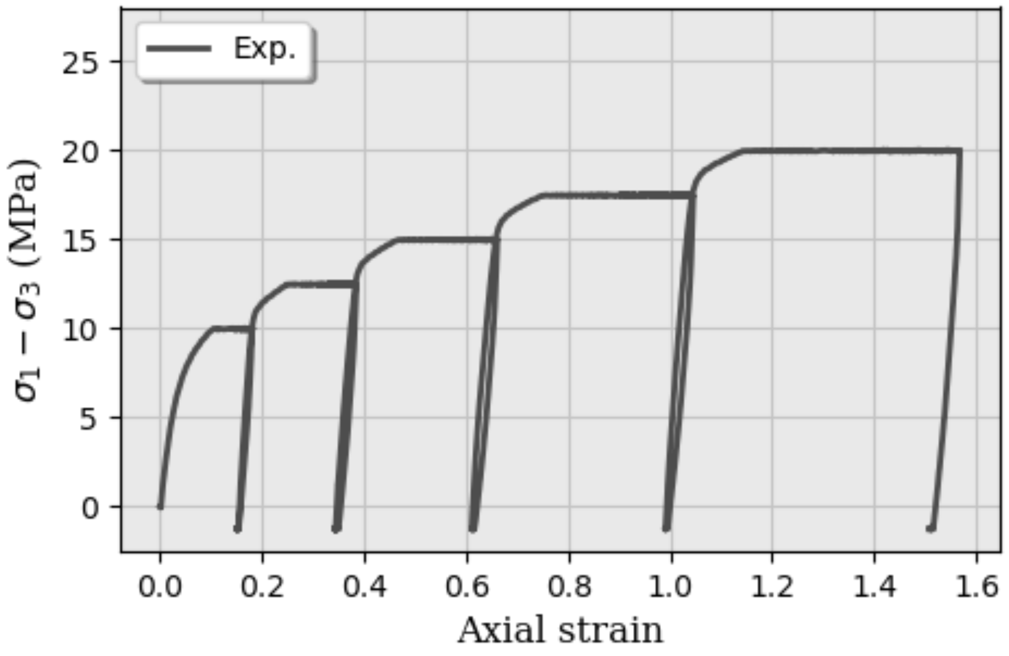
Viscoplasticity (models 2 & 3) is crucial!

Results

Experiment cyclic loading (Shell)







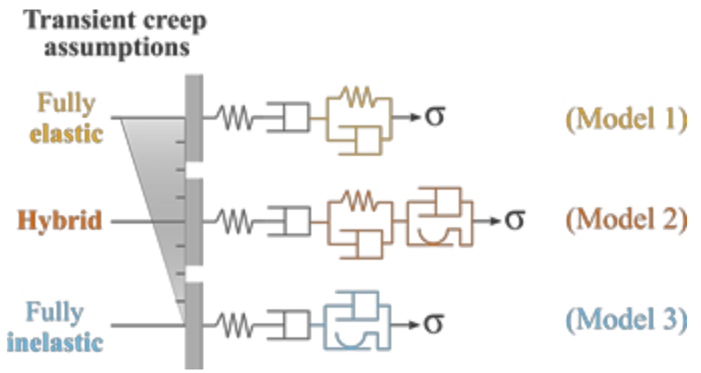
Honório, *et al* (2024)

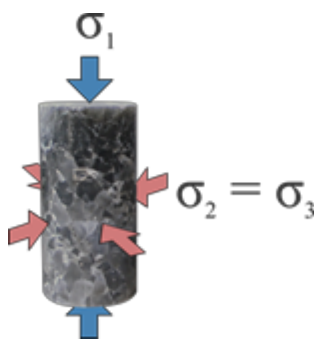
Honório et al. https://doi.org/10.1016/j.ijrmms.2024.105922 (2024)

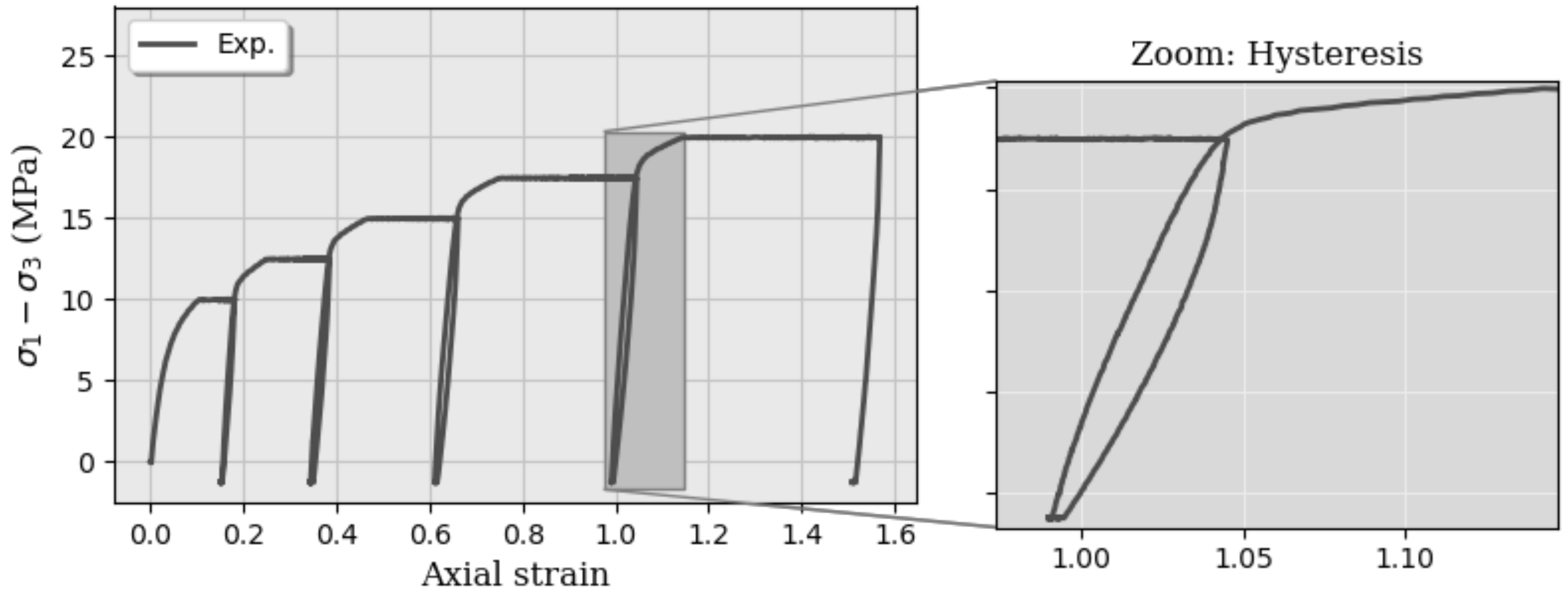
TU Delft

Results

Experiment cyclic loading (Shell)







Honório, *et al* (2024)

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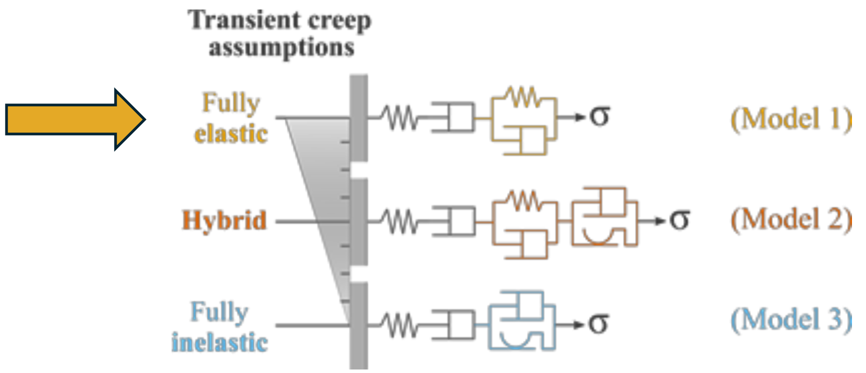

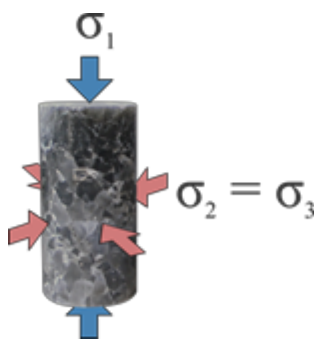

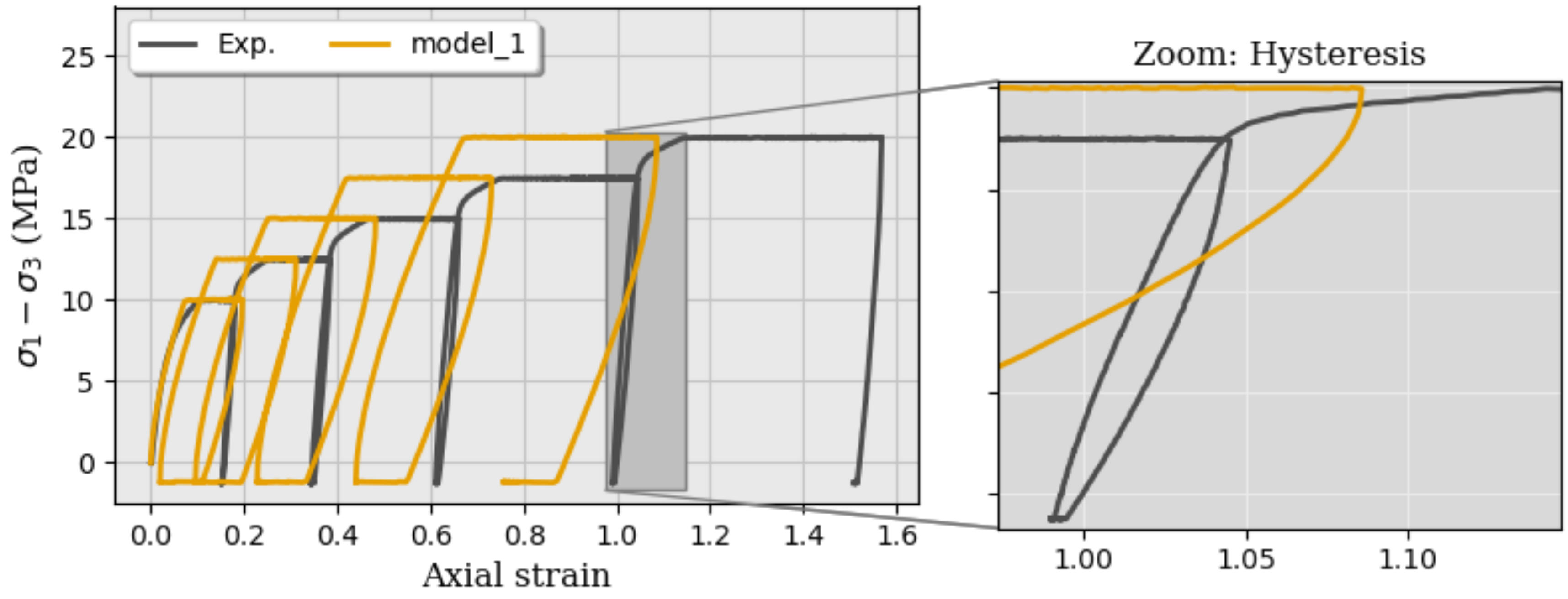

Honório, *et al* (2024)

Honório et al. https://doi.org/10.1016/j.ijrmms.2024.105922 (2024)

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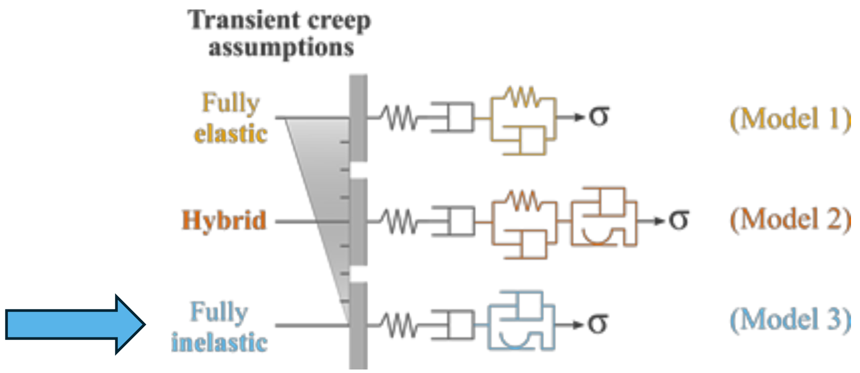

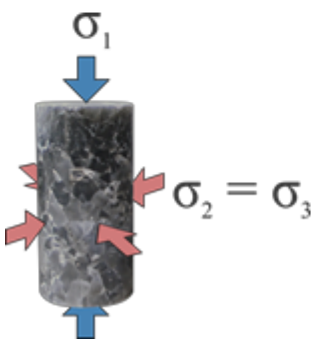

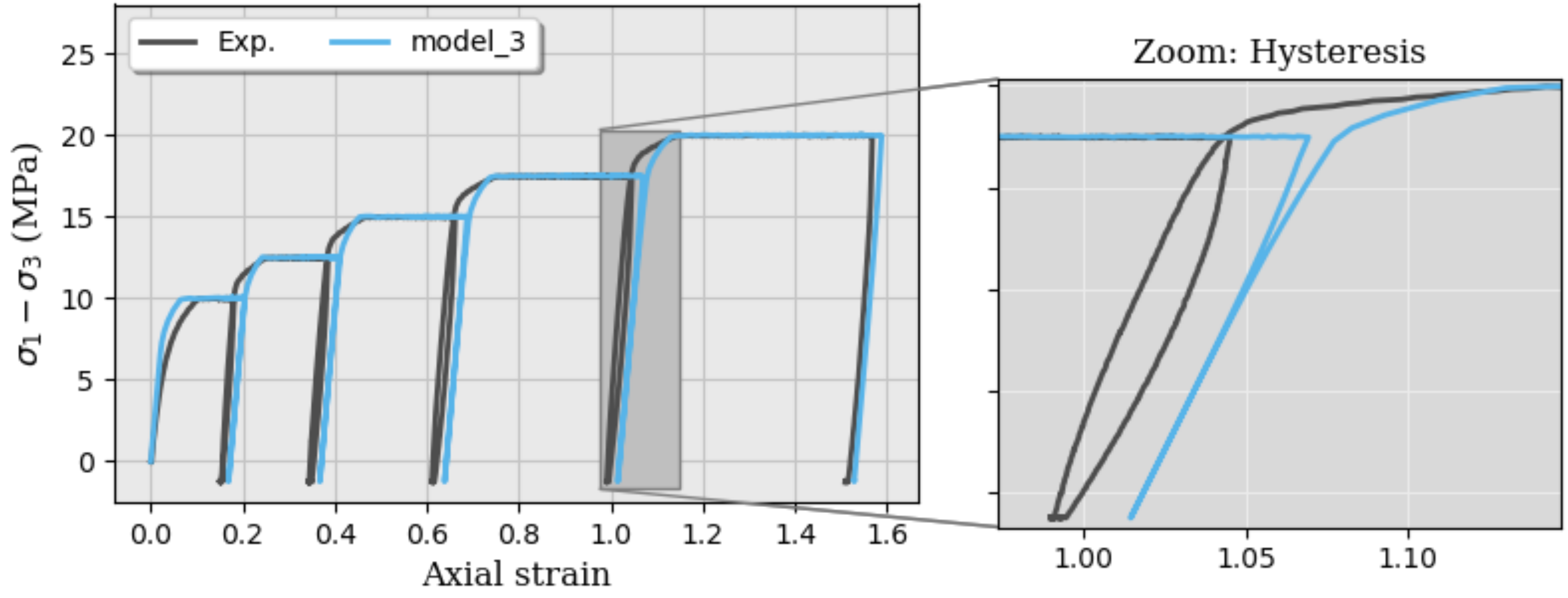

Honório, *et al* (2024)

Honório et al. https://doi.org/10.1016/j.ijrmms.2024.105922 (2024)

TU Delft

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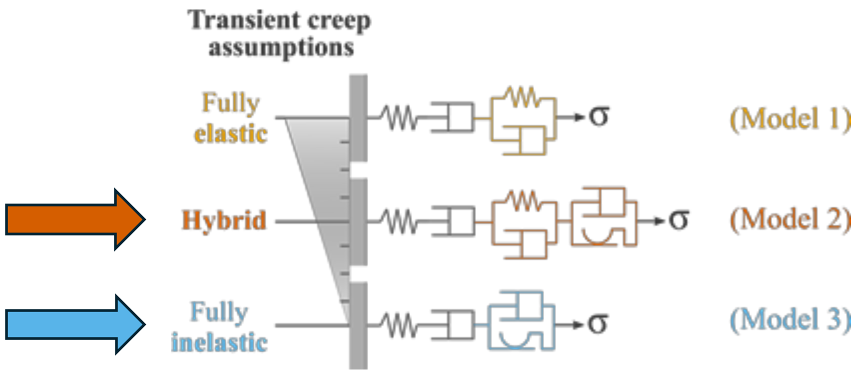
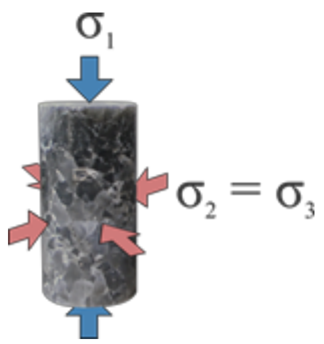
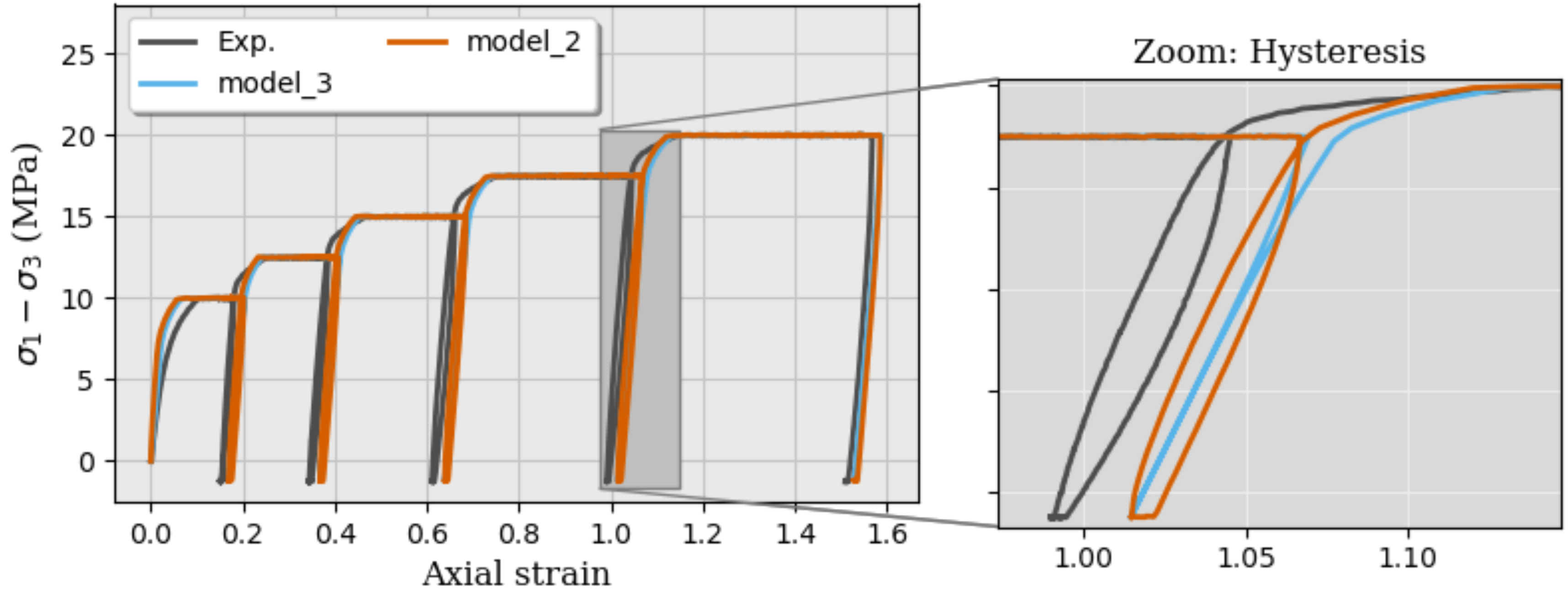






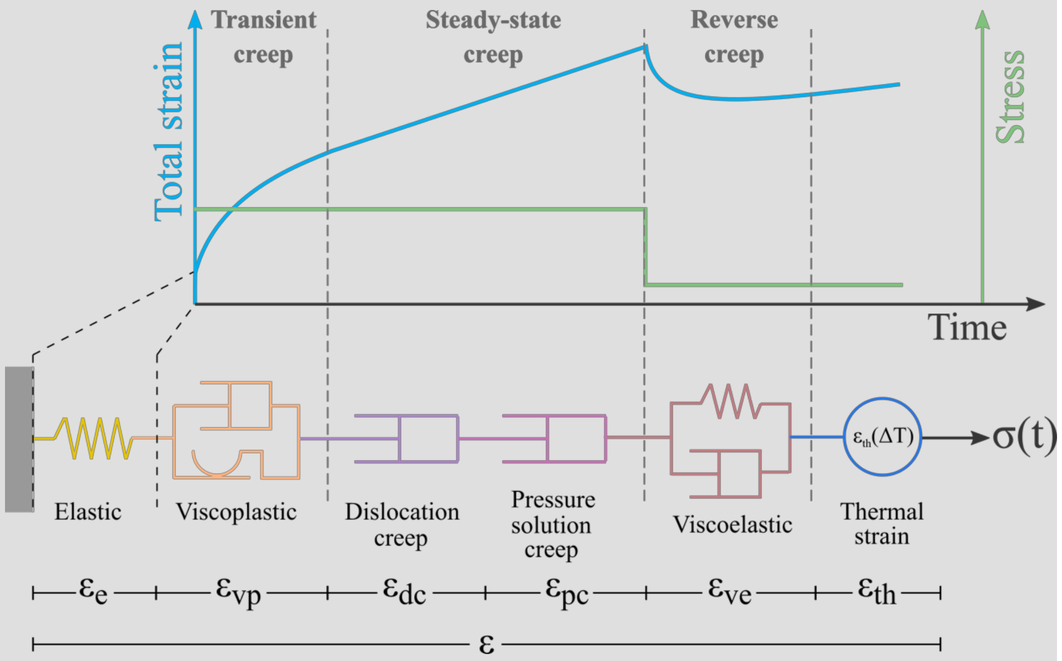
Honório, *et al* (2024)

Visco-elasticity (models 3) is crucial to model hysteretic deformation!

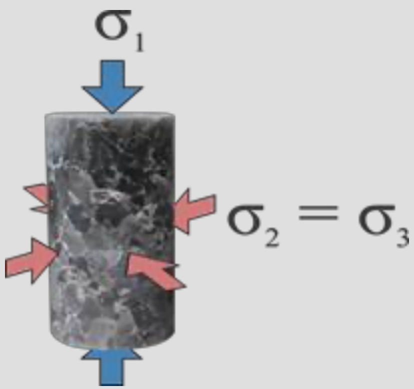
Honório et al. https://doi.org/10.1016/j.ijrmms.2024.105922 (2024)
TU Delft

Model Selection & Parameter Calibration:

Constitutive model



Rock Under Load

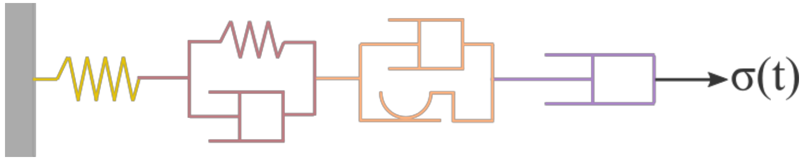


$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{bmatrix}$$

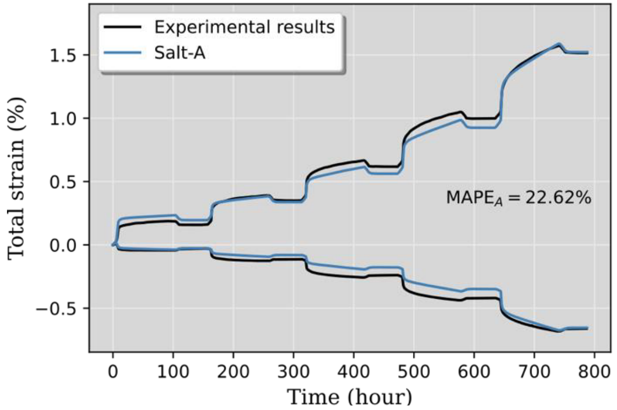
$$\boldsymbol{\varepsilon} = F(\boldsymbol{\sigma}, \mathbf{k})$$

Honório et al. https://doi.org/10.1016/j.ijrmms.2024.105922 (2024)

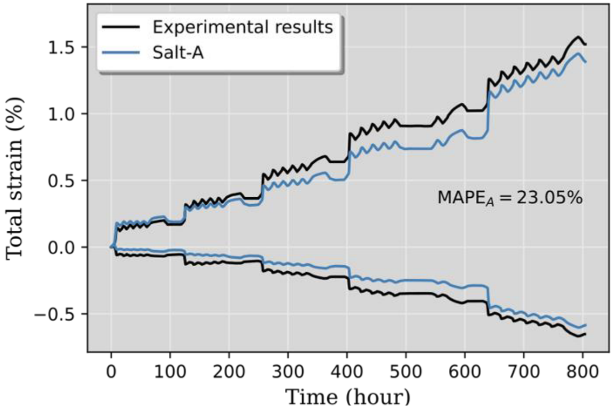
2 Experiments on Similar Samples



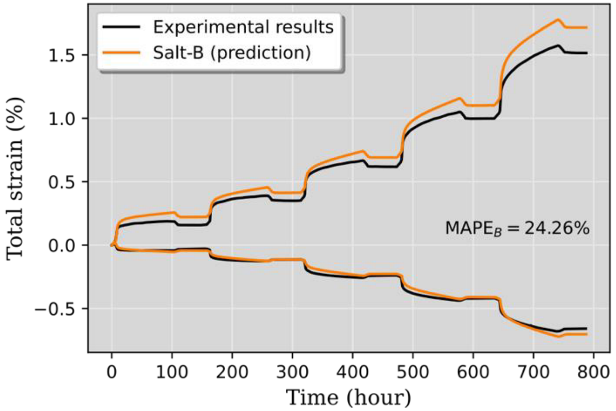
Test1



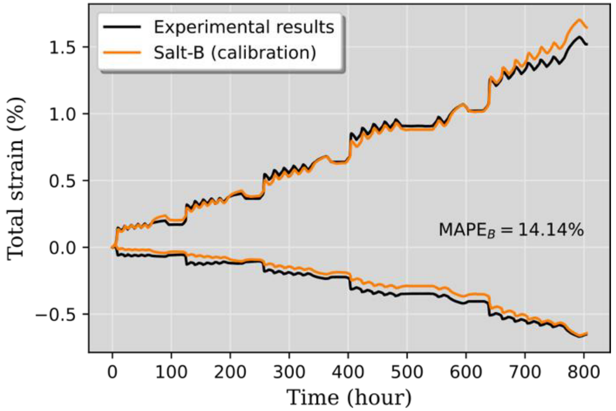
Test2



Test1

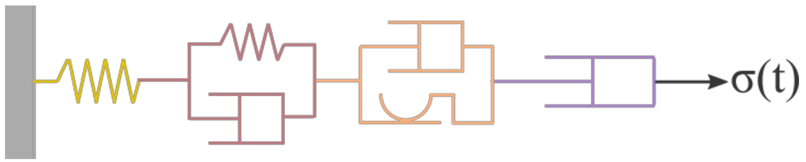


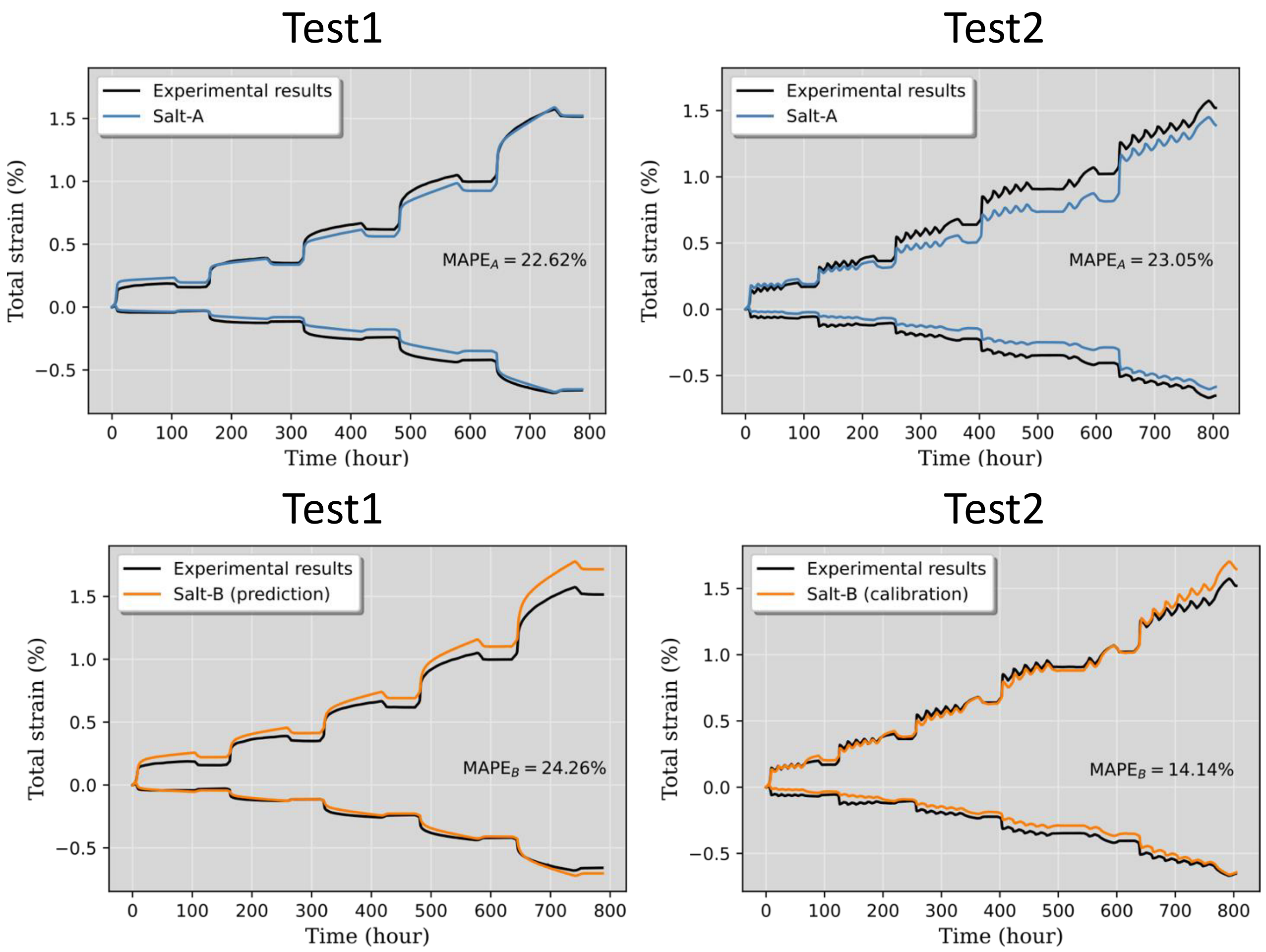
Test2



- Calibrating **k** with Test1 is not predictive for Test 2 & vice versa
- How do we reliably calibrate **k**?

2 Experiments on Similar Samples





- Calibrating **k** with Test1 is not predictive for Test 2 & vice versa
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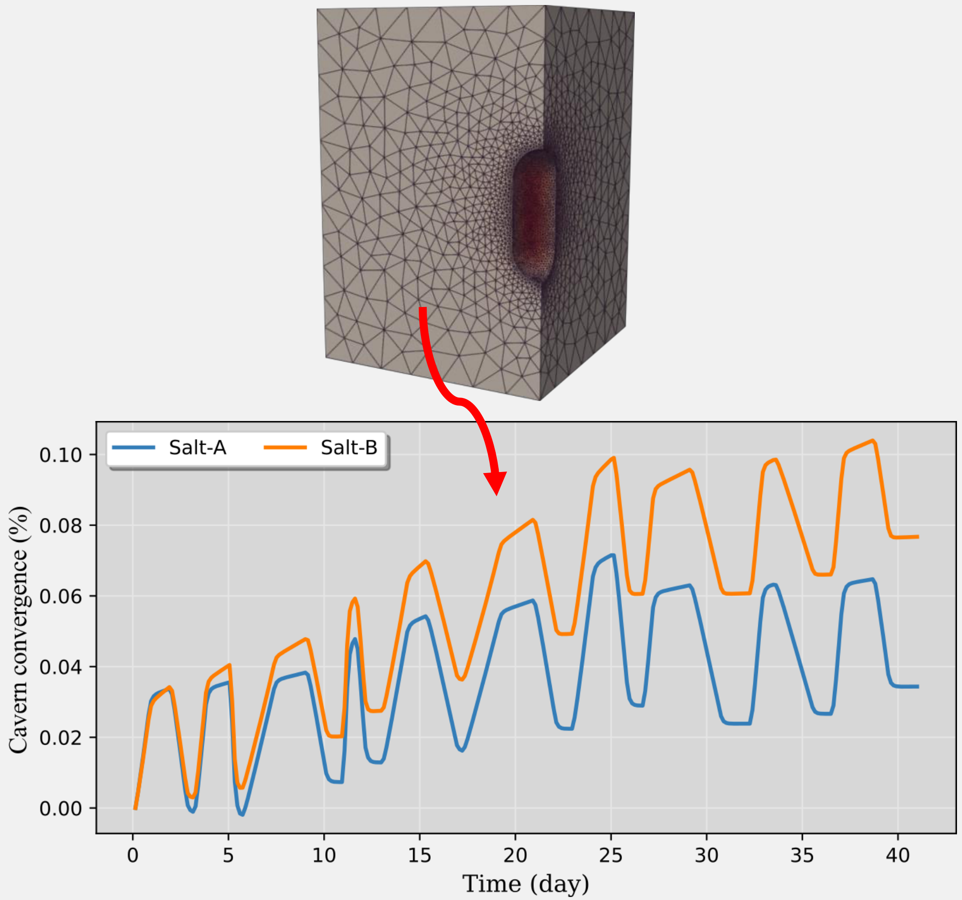
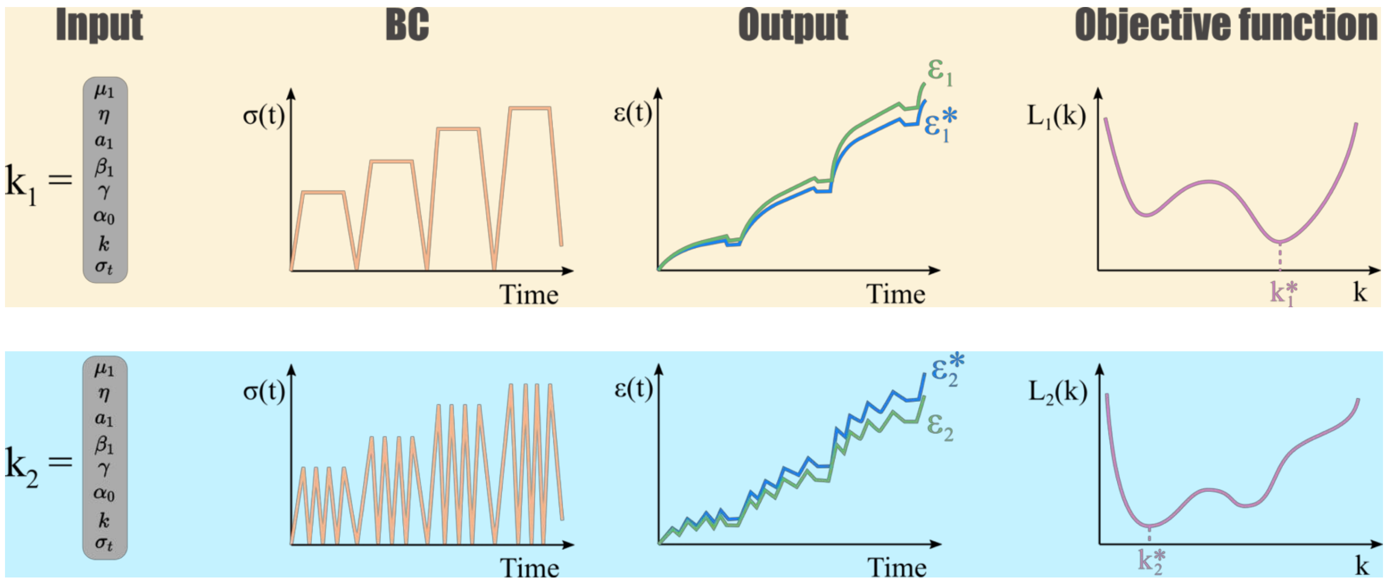


Significantly different results at cavern scale!

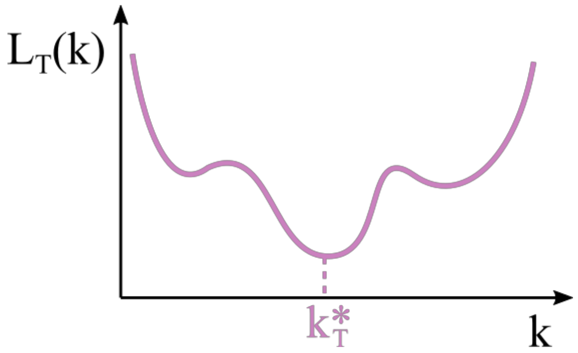
Model Selection & Parameter Calibration
→ Fit on a set **of (independent) experiments!**

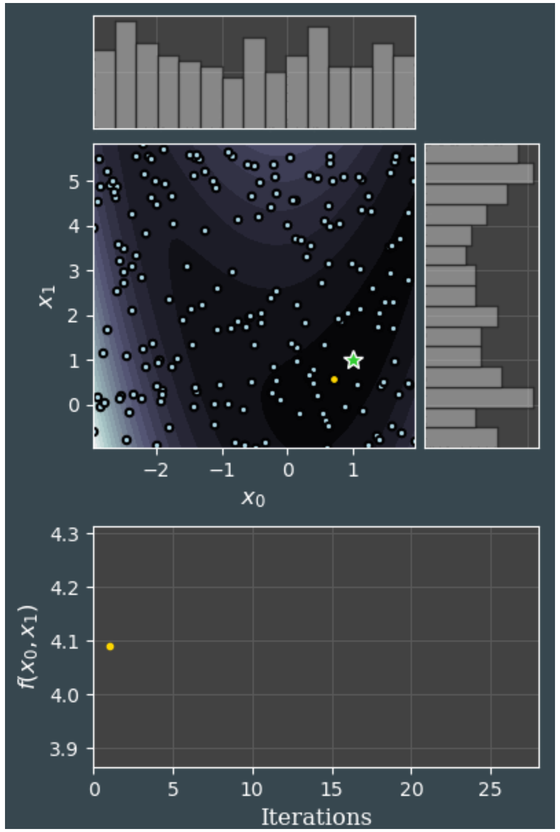
SAFEINCAVE



$$L_T(k) = L_1(k) + L_2(k)$$

$$\text{Find } k^* \text{ such that: } L_T(k^*) = \min_{\forall k \in \mathbb{R}^n} L_T(k)$$

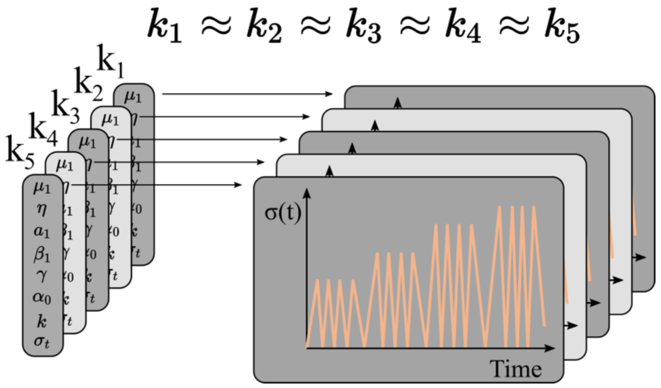




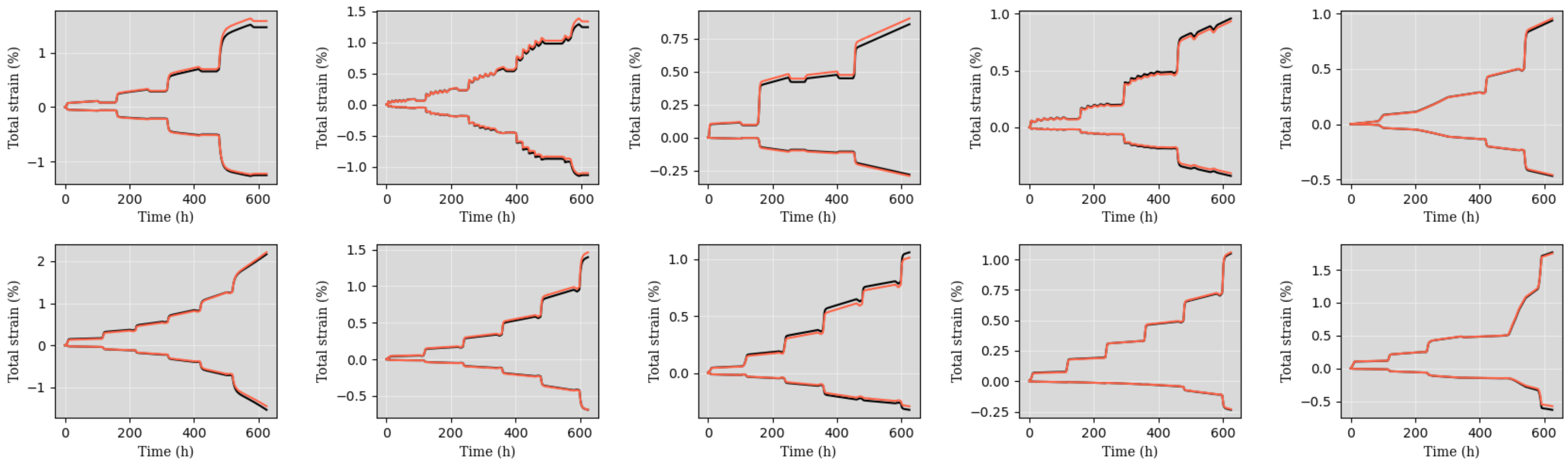
Particle Swarm Optimization
Globally Optimize!

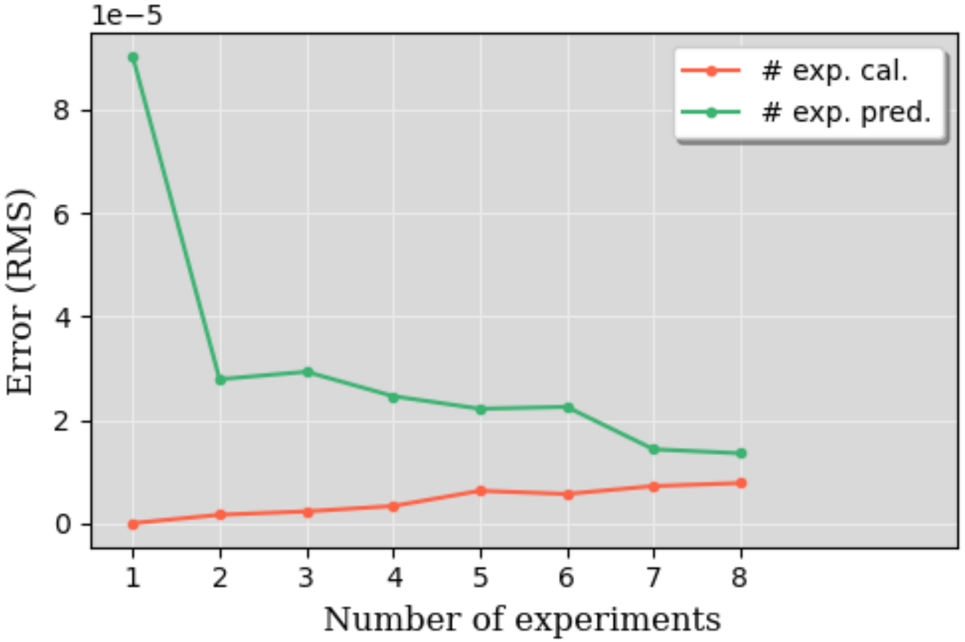
Honório et al. https://doi.org/10.1016/j.ijrmms.2024.105922 (2024)

Test: Model known, parameters uncertain



Model uncertainty: NO
Property uncertainties: YES

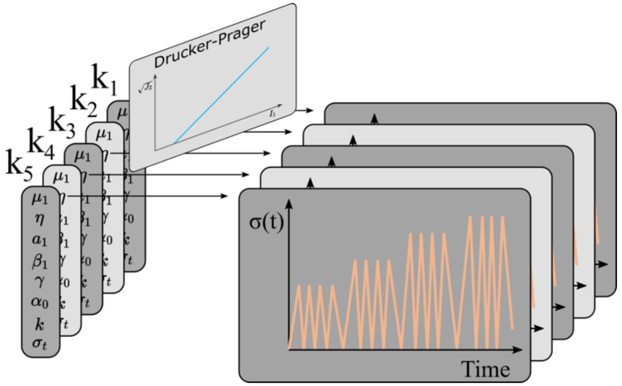


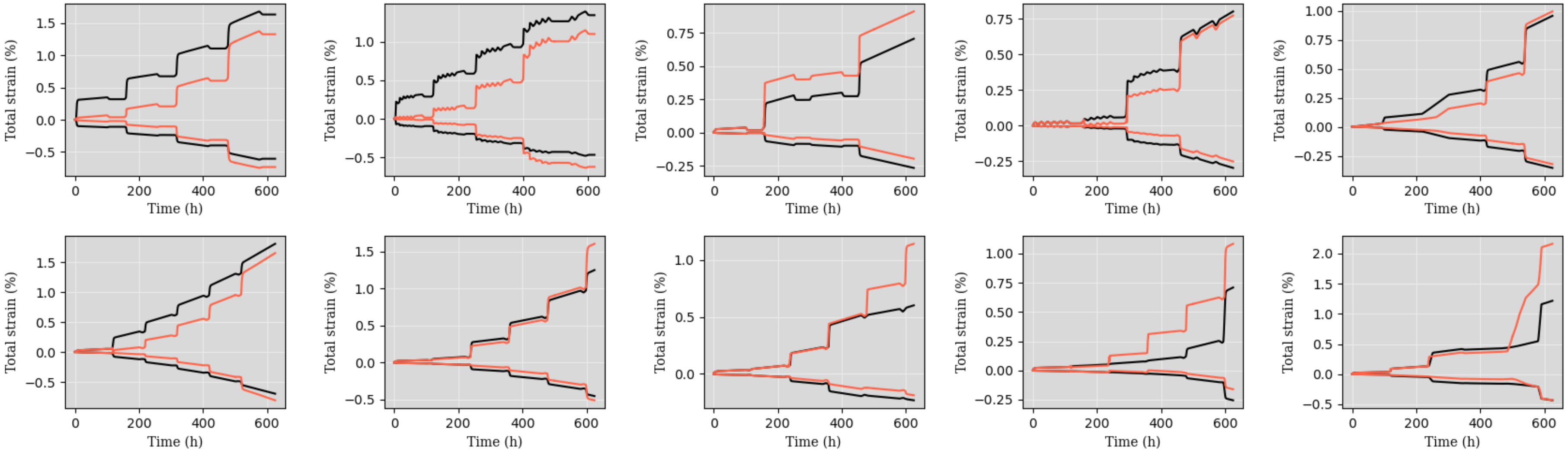


Calibration

Prediction

Test: Model unknown, parameters uncertain





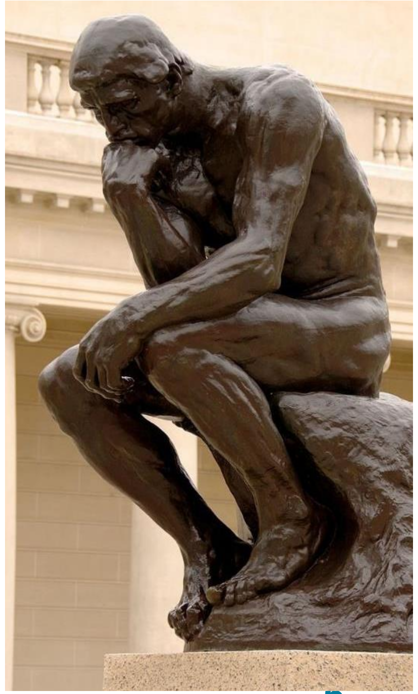
Model uncertainty: YES
Property uncertainties: YES

Calibration

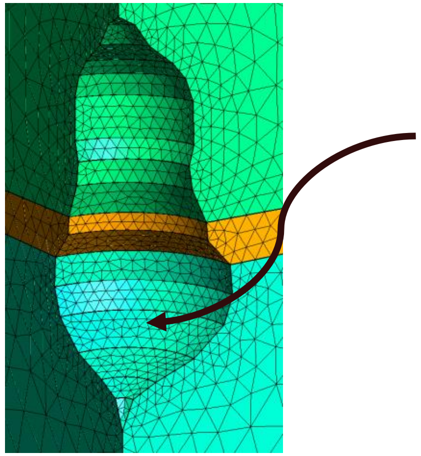
Prediction

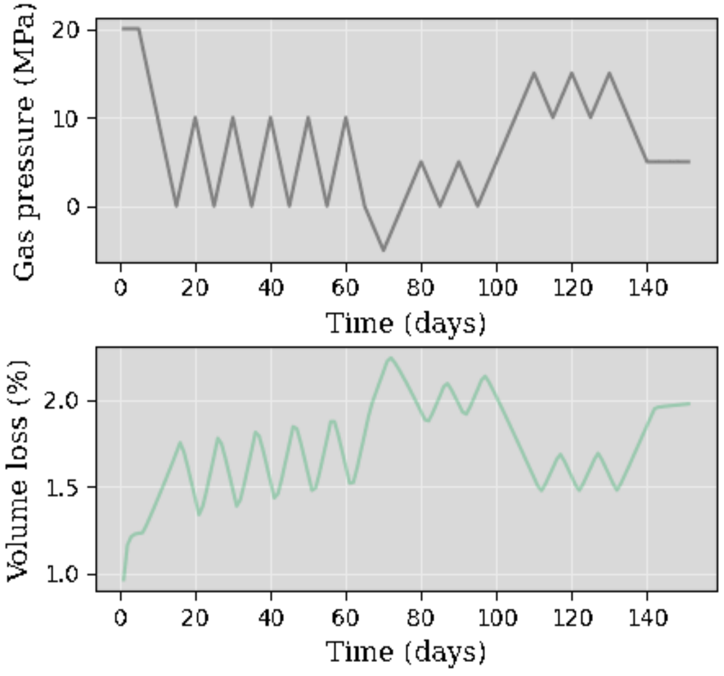
With a wrong model, it is impossible to match many independent experiments/data sets.

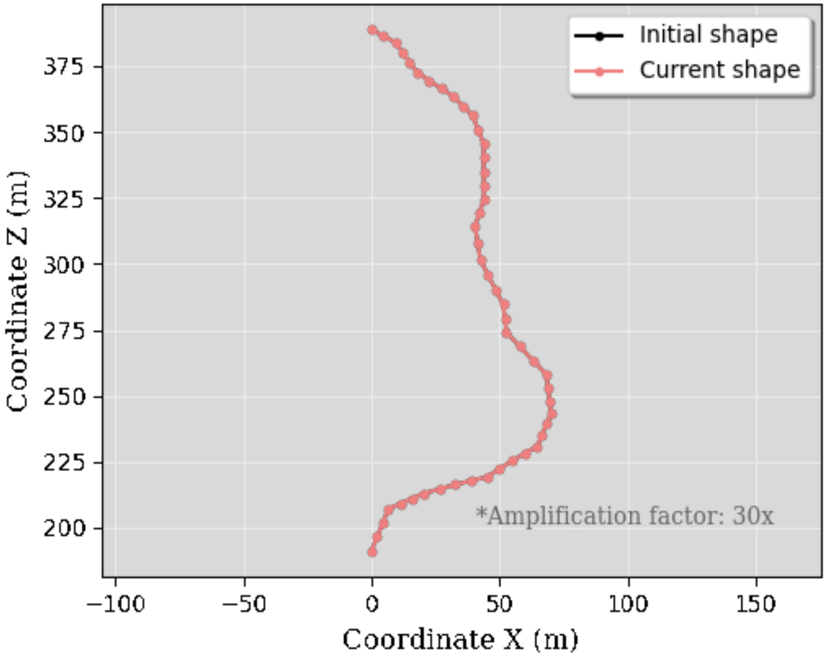
Ask for data! And make sure the model works for many observations!



After calibration, perform 3D complex simulations

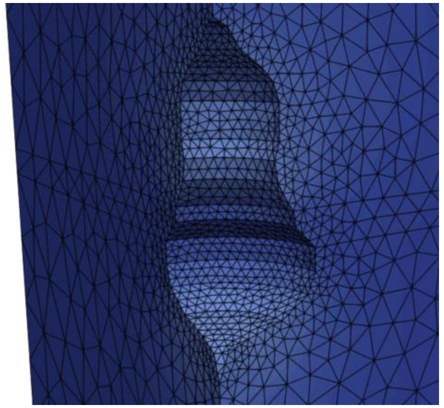






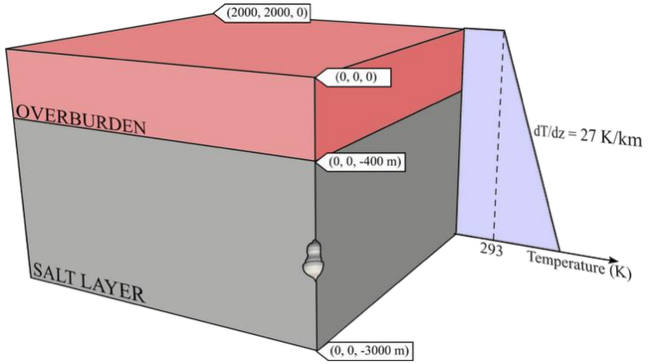
Operation analyses & abandonment with the impact of

- ✓ Geomechanics, Geology and Geometry (heterogeneities, uncertainties, …)
- ✓ Operational conditions (rate, system of cavern, cavern-cavern impact, …)
- ✓ Structure integrity analyses & induced seismicity risks & subsidence with
- ✓ UHS-relevant: pressure solution creep, structural analyses, H2-exposure
- ✓ Abandonment

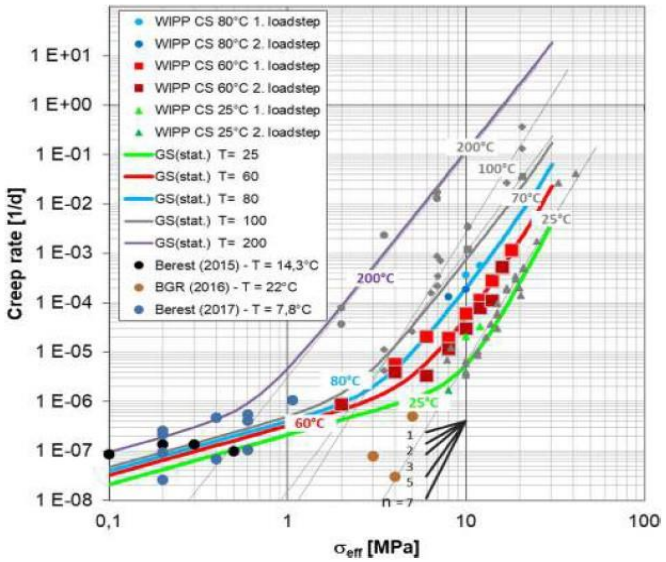


Honório & Hajibeygi, IJHE (2024)

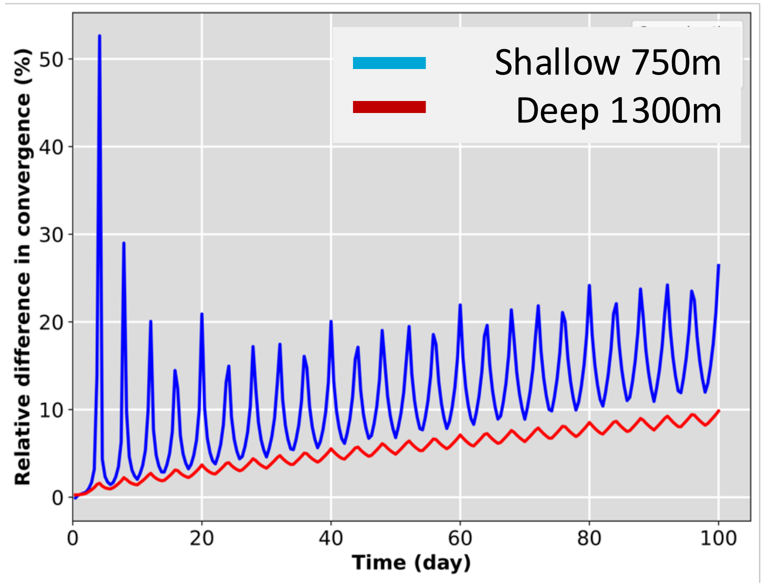
Some UHS-relevant topics:

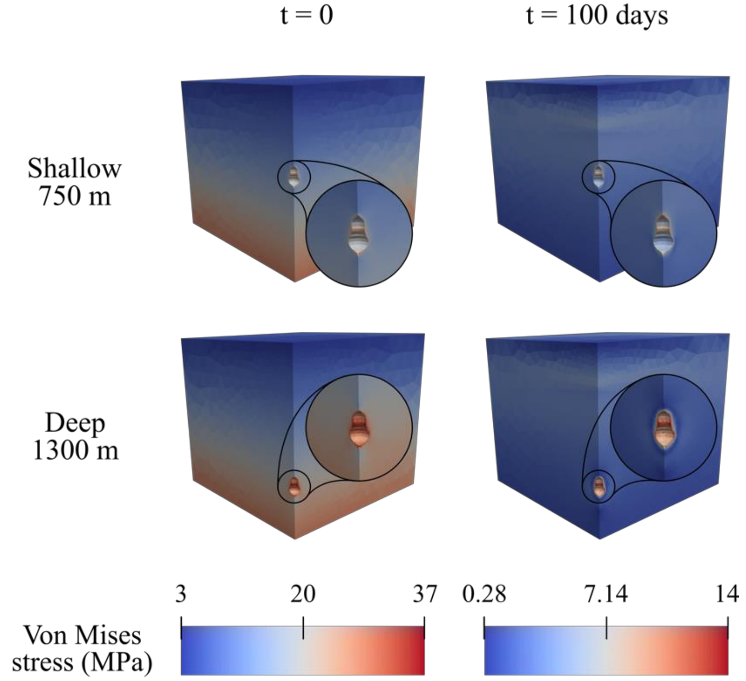


- **Pressure solution creep** (deviatoric stress < 5MPa): important for UHS



Lab tests of Berest 2019

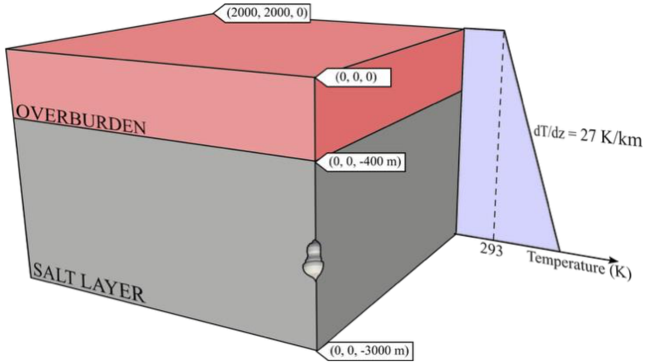




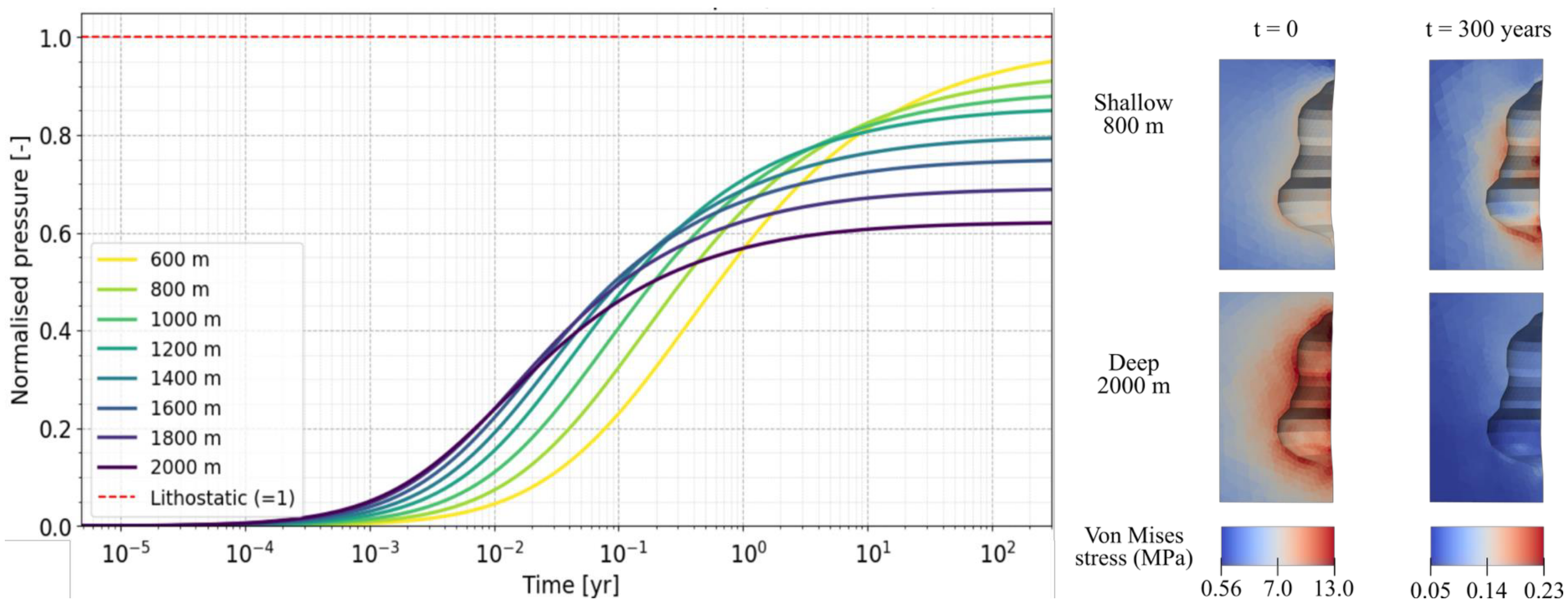
Conclusion: For deeper caverns, shear stresses (von Mises) are higher, thus dislocation creep dominates strain rates.

Amini et al., under review, 2025

Some UHS-relevant topics:



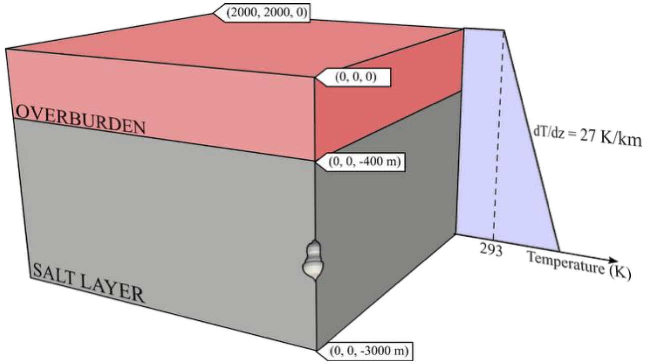
- **Pressure solution creep** (deviatoric stress < 5MPa): important for UHS
- **Abandonment:** over time, pressure build up in shallower caverns > deep ones



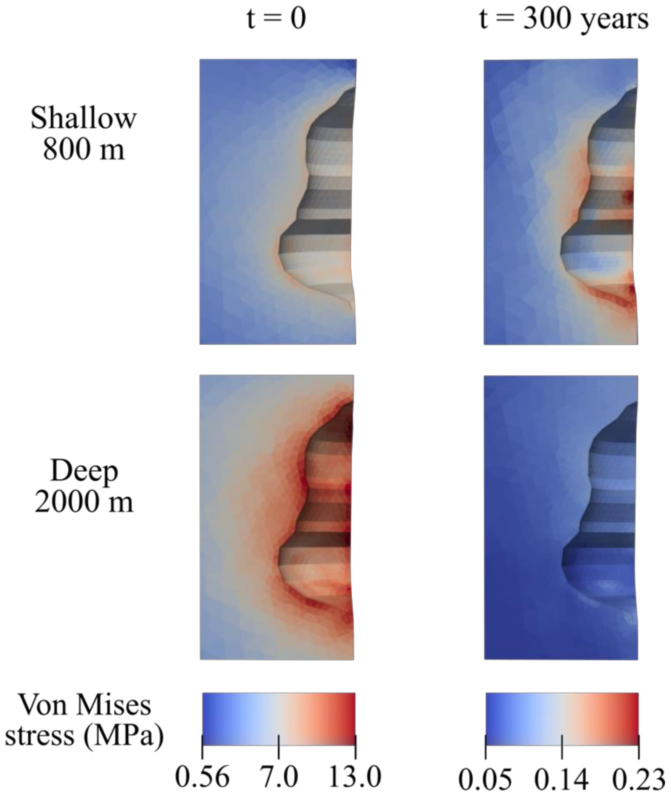
Brine pressure build up over time in deep (blue) vs shallow (yellow) caverns

Amini et al., under review, 2025

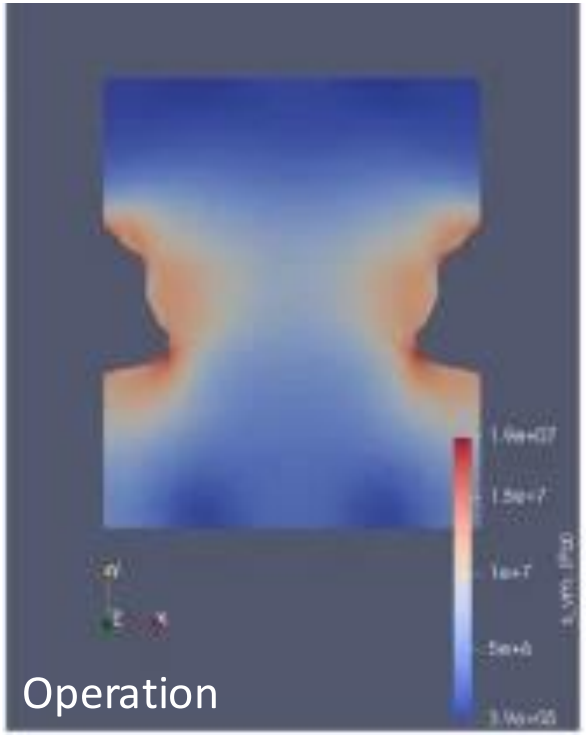
Some UHS-relevant topics:



- **Pressure solution creep** (deviatoric stress < 5MPa): important for UHS
- **Abandonment:** over time, pressure build up in shallower caverns > deep ones
- **Heterogeneity & geometry**: strong impact, very important!
- **Interlayers/non-halite zones:** crucial to be analysed for stability
- **Cavern—Cavern stress impact:** highly important for analyses



Abandoned

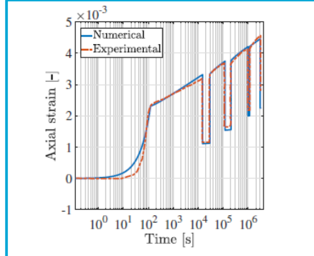


Operation

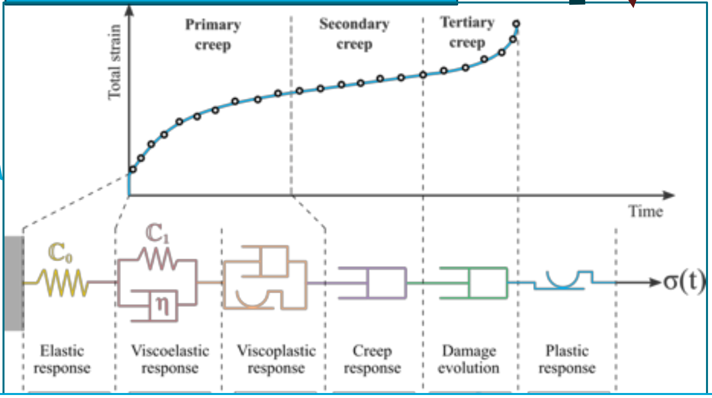
Multiscale Strategy for Mechanics (Porous & Salt Rocks)

LAB

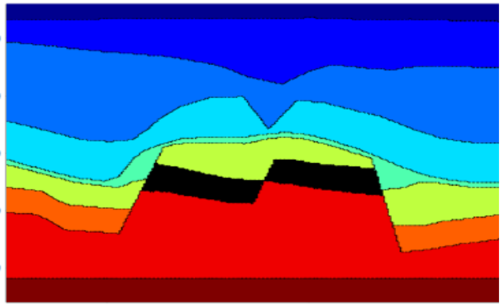
Validation



Constitutive Laws



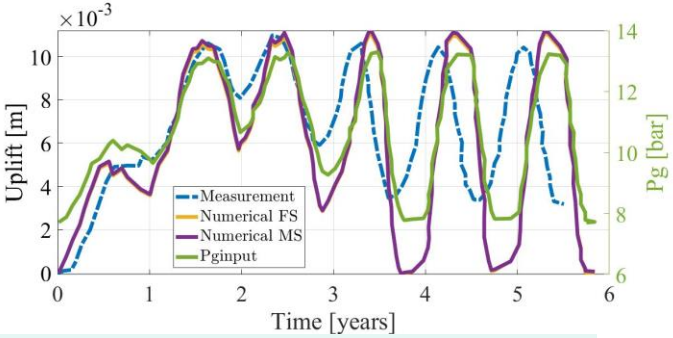
Reliable mechanics laws



Bergemeer Storage Site

Monitoring & Data

- Uplift/subsidence
- Stress Intensities
- Fault stabilities

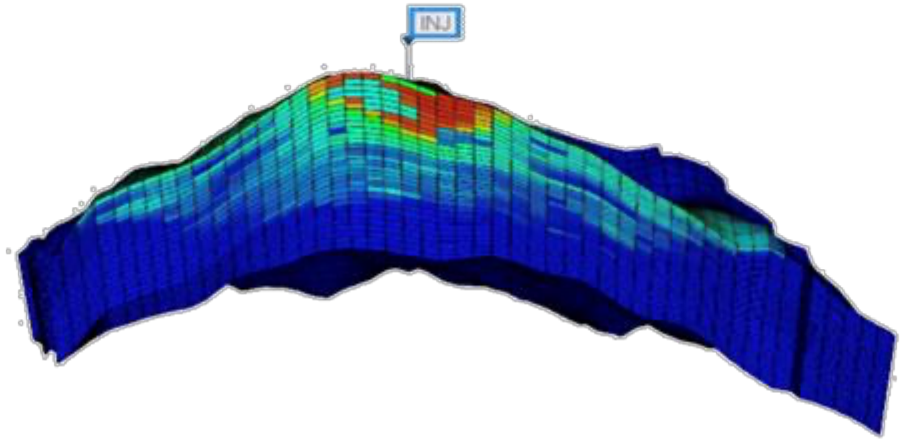


- ✓ Uplift/subsidence
- Stress Intensities
- Fault stabilities
- H2 exposure effects (early results: no effect!)

Kumar et al.,2022, https://doi.org/10.1038/s41598-022-25715-z
Naderloo et al.2023, https://doi.org/10.1016/j.est.2023.107198 …

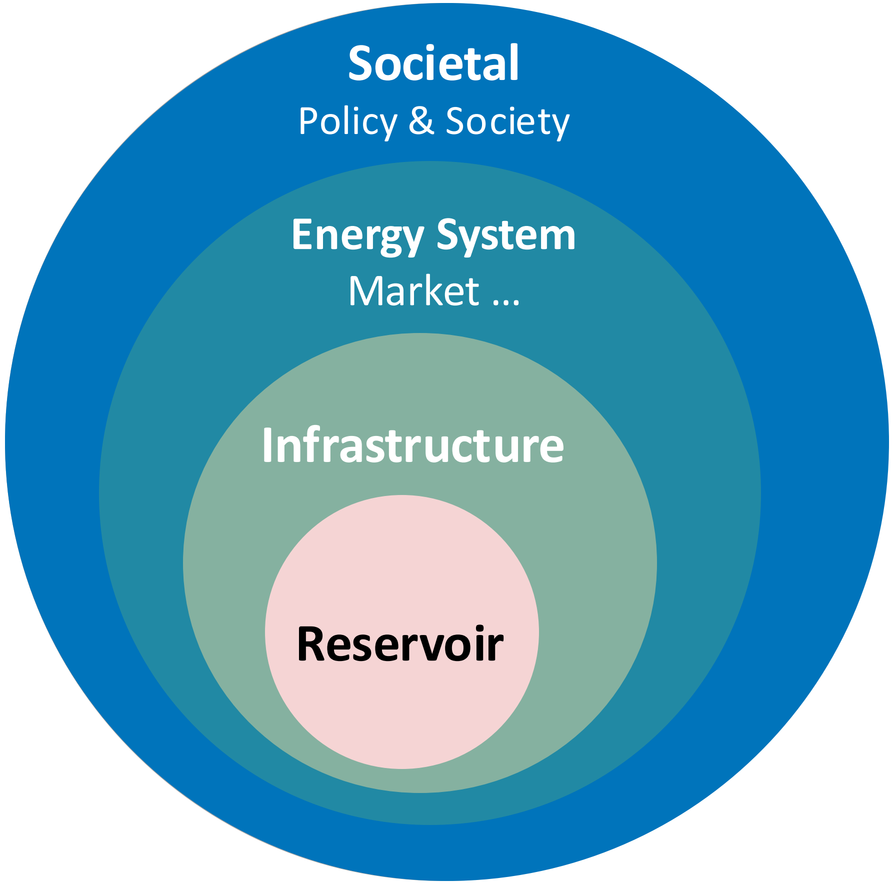
Underground Hydrogen Storage is technically possible.

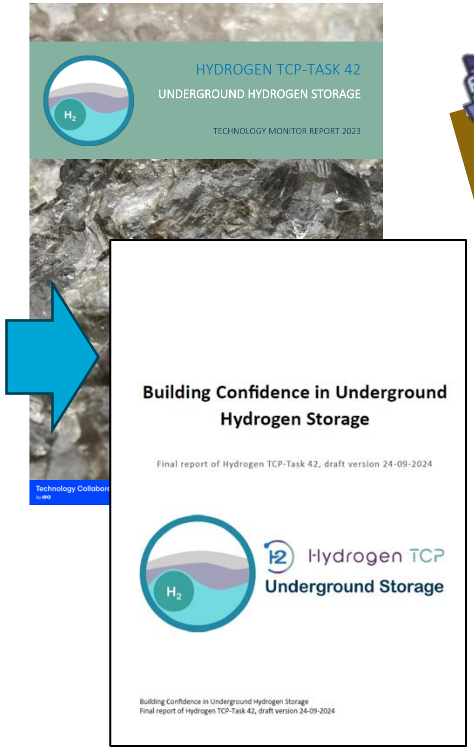
But is it enough to build confidence?



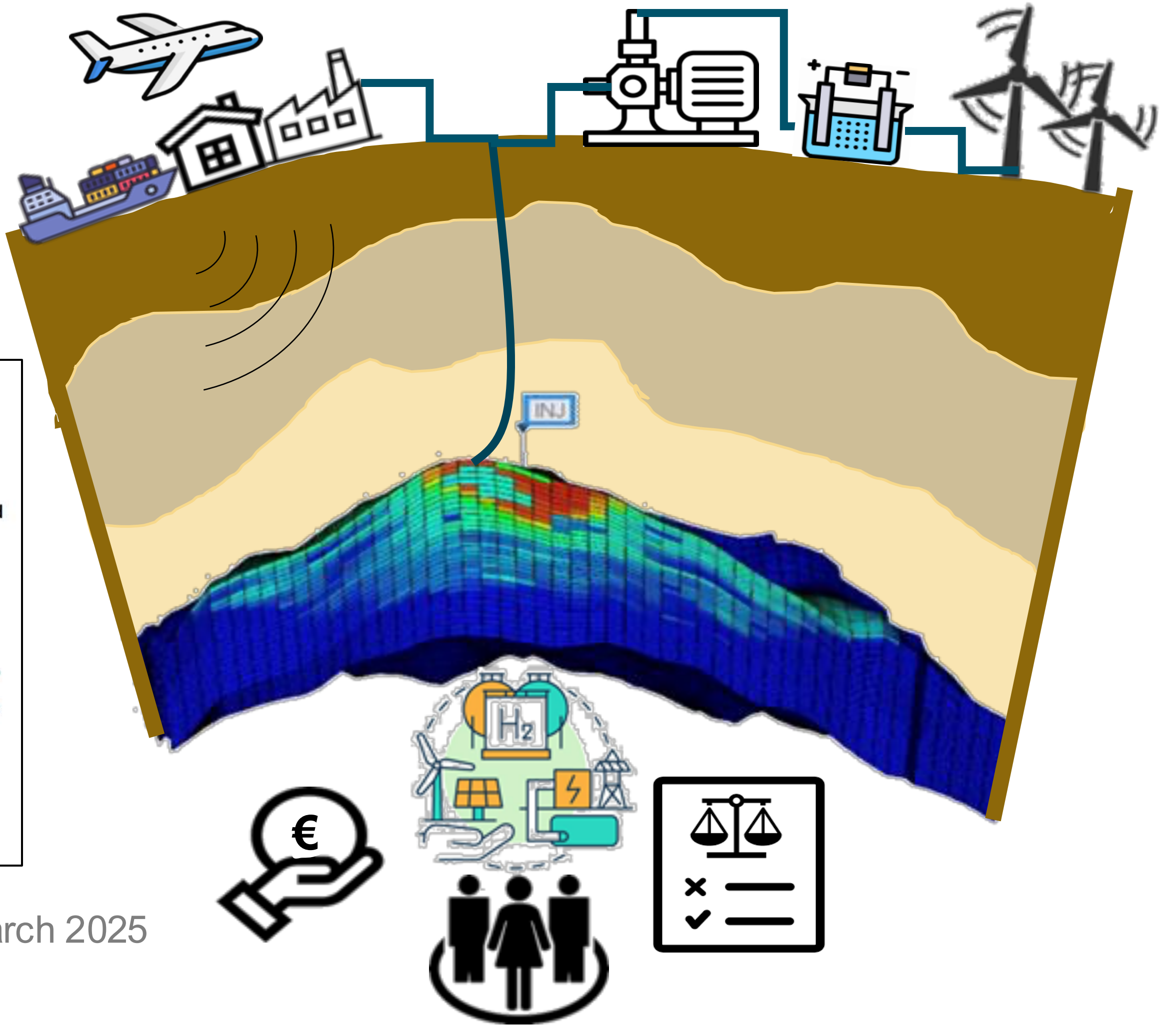
What does it take to build confidence in subsurface storage?

IEA TCP 42 on UHS: global **community** of 57 organizations & +200 experts from university, industry, research & policy





TCP 42 Reports 2023 & March 2025



Many pilots have kicked off (+30 in caverns, +10 in depleted fields)

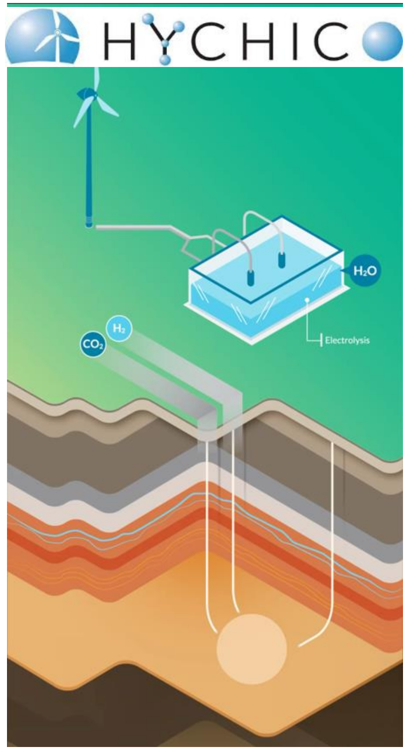
→ Next Phase: Scale Up & Commercial-Scale

NL: UHS in Salt Caverns, Zuidwending

France: UHS in Cavern, Etrez

Austria: UHS in Gas Field, 2023 (RAG)

Germany: UHS in Salt Cavern



Argentina: H_2 & CO_2 → CH_4

groenvermogennl

→ 1st Dutch UHS in Gas Field

~500 potential hosts!

Concluding remarks

- What is ‘the main’ bottleneck of CCS to take place?
  - A. Economic Incentives
  - B. Societal Perception on their risk
  - C. Technical aspects

- What is ‘the main’ bottleneck of H2-based economy for energy?
  - A. Market (costumer) & Economic production of low-carbon H2
  - B. Legal-Regulatory Perspectives
  - C. Technical side of UHS (reservoir)

Concluding remarks

For the mechanics of cycling loading of geological rocks:

- Construct & calibrate the model & parameters, it is essential to:

  A. have a fast numerical and optimisaton method

  B. Use many experiments data

  C. Use field-scale data

For building confidence on your simulation, it is essential to

A. Have a fast and furious simulation strategy

B. Benchmark with lab (at rock-specimen scale) and field (for system operation)

Item B above, needs:

A. Have a fast and furious simulation strategy

B. A robust multiscale modeling & simulation strategty

Concluding remarks

What are the main challenges of mechanics for geologic systems? In what order (A first or B)

A. Size of the problem (km) is huge, compared with the detail resolution (<cm) needed

B. Uncertainty & Heterogeneity of the properties

Although CCS/UHS/UGS are 10-20% of the total value chain for CO_2 management/Energy System, without their development, the value chain won't happen. This is why lots of investments are taking place in them.

Mechanics is an essential element to enable CCS/UHS/UGS technologies!

Thank you all

Our Fascinating Earth

is the biggest battery ever!

And geomechanics is essential to unlock it!

Thanks to all our PhD Students, Postdocs and many colleagues

Willemijn, Mengjie, Sijmen, Filipe, Mathias, Amin, Naomi, Saeed, Zahra, Mahsa, Milad, Herminio, Ryan, Taka
Bert Sluys, Kees Vuik, Martin Lesueur, Anne Pluymakers, Auke Barnhoorn, Denis Voskov, Alexander Heinlein, …

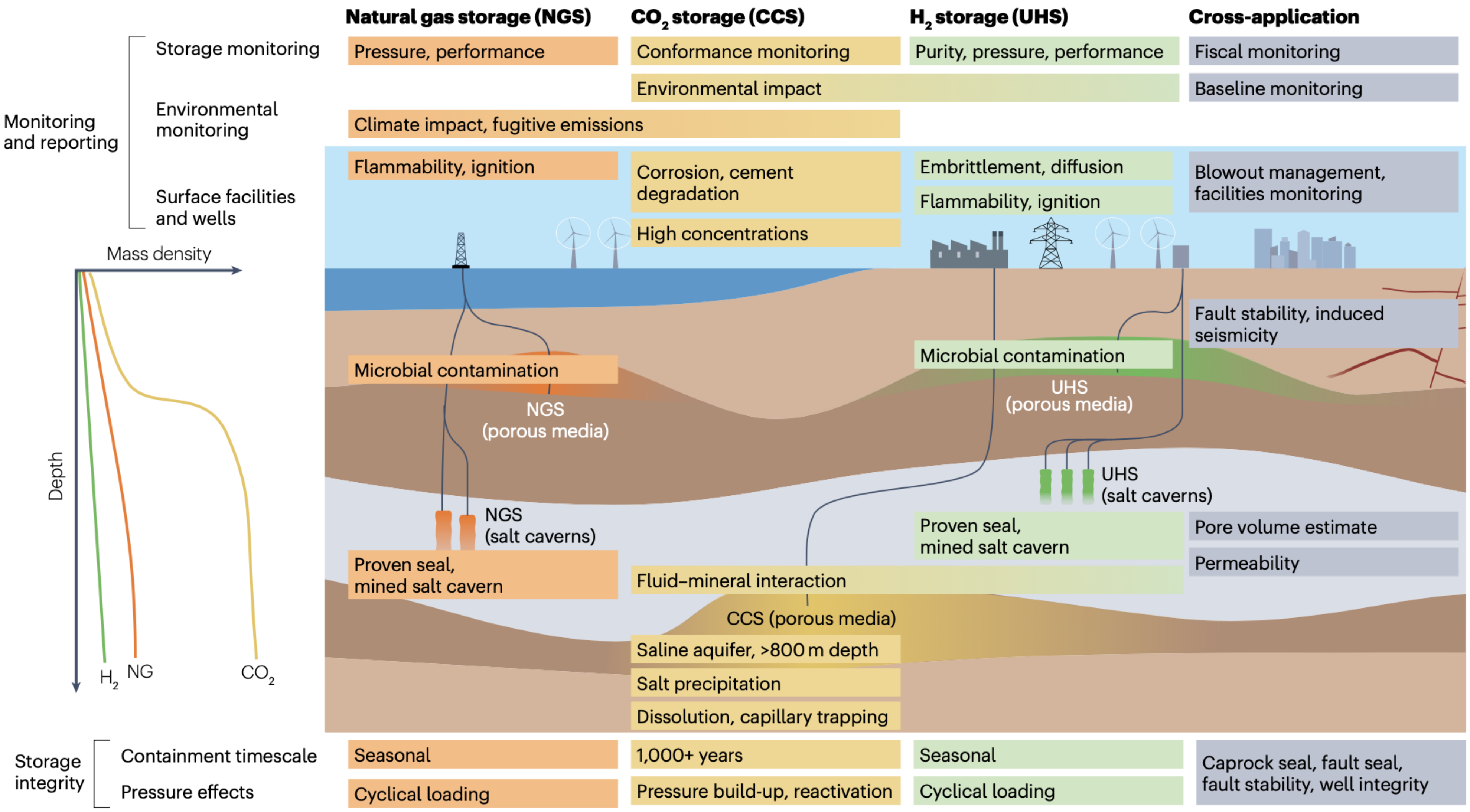
TU Delft

energi SIMULATION

Thank You

Prof.dr. Hadi Hajibeygi
H.Hajibeygi@TUDelft.nl

NGS is much closer to UGS than CCS



Krevor et al., Nature Reviews Earth & Env 2023, doi: 10.1038/s43017-022-00376-8