CO_2-Induced Dissolution and Precipitation Effects on V_P and V_S of Chalk and Sandstone

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Search and Discovery Article #80761 (2026)**
Posted April 30, 2026

*Adapted from extended abstract based on oral presentation given at CCUS (Carbon Capture, Utilization, and Storage Conference), Woodlands, Texas, March 30 - April 1, 2026.
DOI:10.1306/80761Amour2026

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Abstract

Reliable seismic monitoring of CO_2 storage sites requires accurate rock physics models (RPMs) for interpreting 4D seismic anomalies [1]. Current RPMs often assume constant rock frame properties, linking seismic changes solely to fluid substitution and stress variations. However, experimental evidence shows that CO_2 can alter the rock frame through rock-water-CO_2 interactions, affecting acoustic velocities and elastic moduli [2,3], thereby compromising the accuracy of subsurface CO_2 imaging. This study investigates mineralogical, petrophysical, geomechanical, and chemical responses of partially saturated, chalk and sandstone reservoir samples to continuous and intermittent $CO_{2(gas)}$ under both ambient and *in-situ* stress conditions. SEM-EDS, CT scans, and strain and ultrasonic measurements were used to monitor rock behaviors during tests. Dynamic moduli were then back-analyzed using effective elastic media theories to identify key controlling factors, including strain hardening, fluid saturation, and mineral precipitation and dissolution.

Results show limited water saturation (Sw) reduction despite extensive CO_2 volumes injected, suggesting that formation dry out is a slow process, likely due to CO_2 by-passing parts of the pore space. Nevertheless, local halite precipitation occurs mainly towards the inlet. No significant mineral dissolution was observed. Furthermore, CO_2 flooding led to a temporary softening of creep properties and an increased sensitivity of Vp and Vs to stress, whereas a strengthening of the static and dynamic moduli, and pore collapse strength was observed. Notably, Vp and Vs increased during CO_2 injection under creep conditions, despite reduction in Sw. RPM analysis using the Hertz-Mindlin model indicated that the acoustic changes mainly result from salt precipitation with fluid substitution and strain hardening playing a secondary role. The ongoing experiments indicate minimal risk of mechanical instability near the wellbore, especially in chalk formations.

Acknowledgement:

The authors thank the Innovation Fund Denmark for funding this work through the Cerberus project. The authors are also thankful to the

Danish Underground Consortium (Total Energies E&P Denmark, BlueNord and Nordsøfonden) for their constructive discussions and feedback.

Reference:

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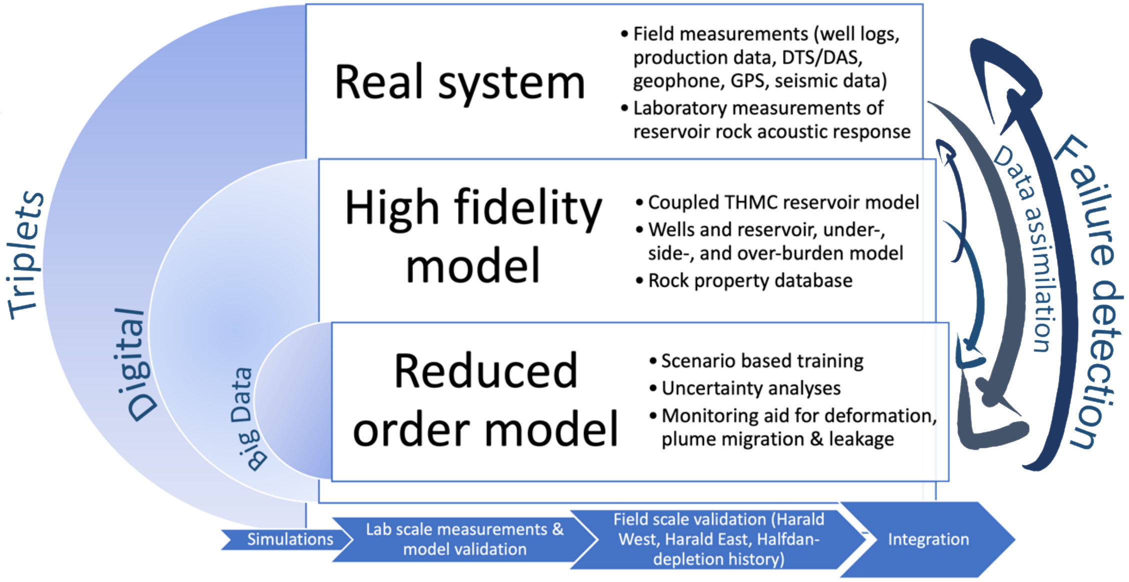
Contextualization

Cerberus

Cerberus

The CO_2 gate-keeper for monitoring of CO_2 storage sites



Real system
- Field measurements (well logs, production data, DTS/DAS, geophone, GPS, seismic data)
- Laboratory measurements of reservoir rock acoustic response

High fidelity model
- Coupled THMC reservoir model
- Wells and reservoir, under-, side-, and over-burden model
- Rock property database

Reduced order model
- Scenario based training
- Uncertainty analyses
- Monitoring aid for deformation, plume migration & leakage

How to detect potential breach of containment early in a cost efficient and reliable manner?

The Cerberus project aims at developing, validating and demonstrating a closed-loop triplet system (simulation tool) for monitoring underground storage.

This study **assesses changes in rock physics properties due to fluid substitution and chemical interactions between solid and fluid phases**

Enhanced **reliability of 4D seismic interpretation** in terms of distribution and amount of CO_2 across a storage complex

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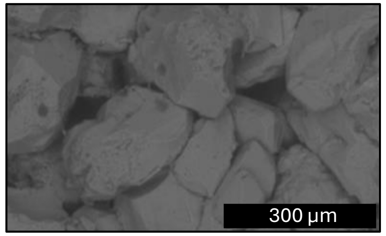
Objectives

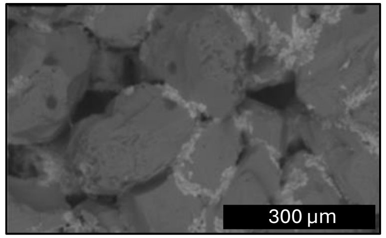
Near-wellbore

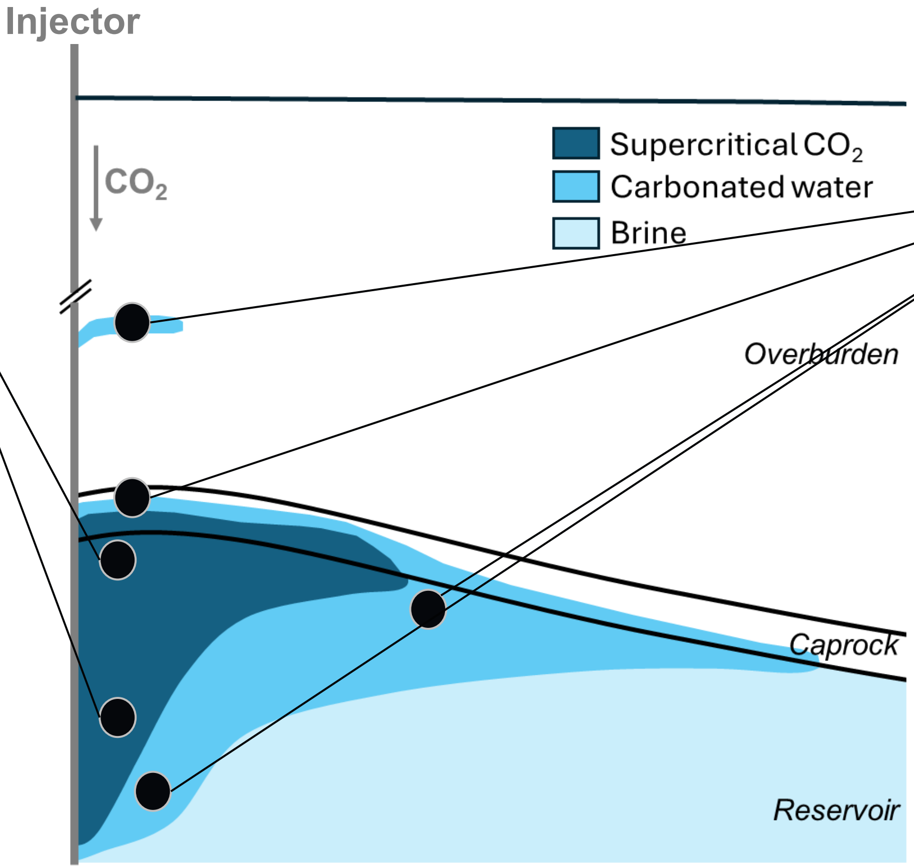
Formation dry-out and salt precipitation

Before



After CO_2 exposure

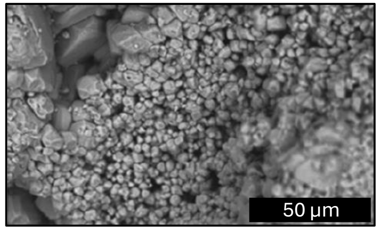




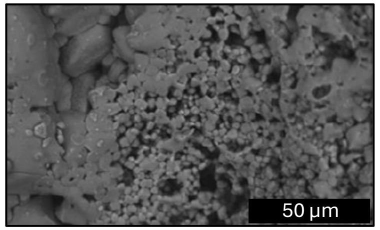
After Vafaie et al., 2023

Reservoir and overburden

Acidification and rock dissolution



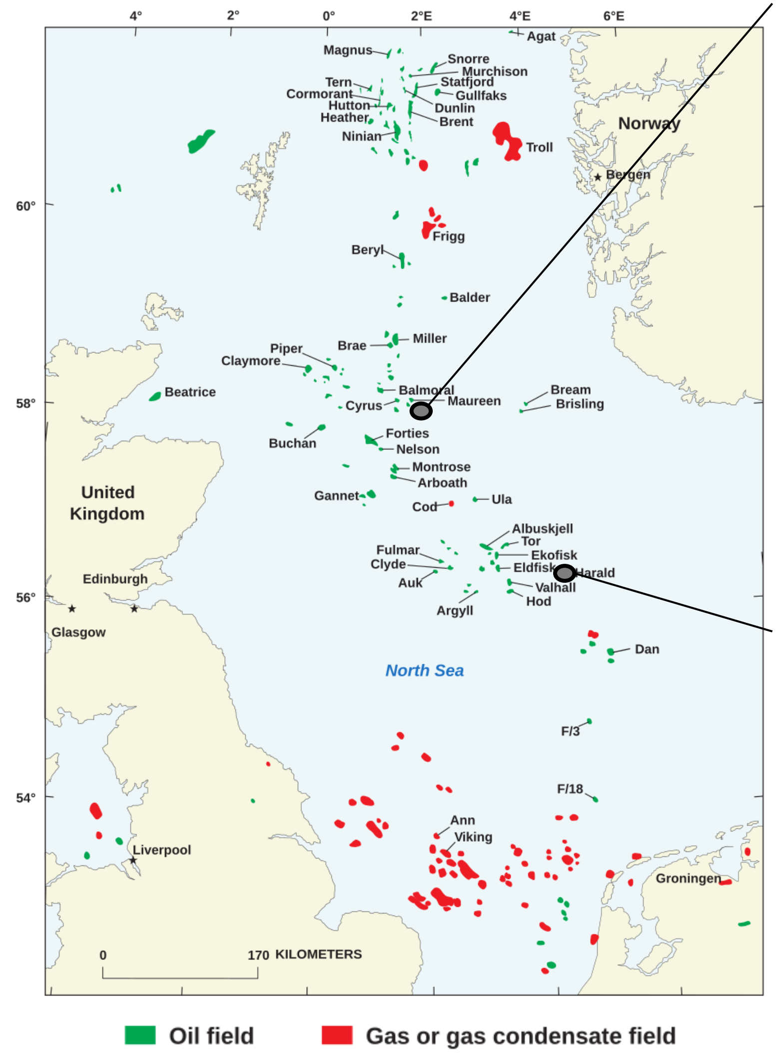
Before



After CO_2 exposure

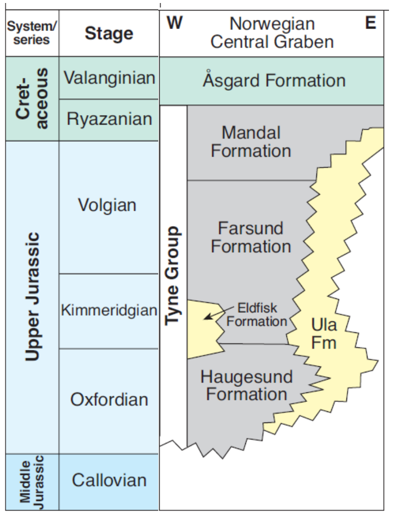
- → Extensive studies on **fluid substitution** and **dissolution effects** on elastic properties
- → Limited studies on **salt precipitation, mainly under aquifer conditions**
- → Need for a comprehensive **rock physics database** to support 4D seismic interpretation across a storage complex

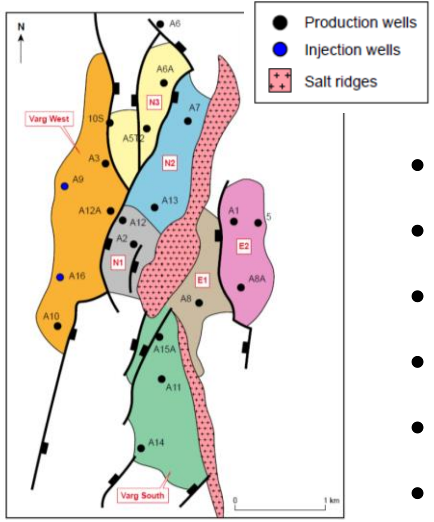
Study Areas



Gautier et al., 2005

Varg field (Sandstone)

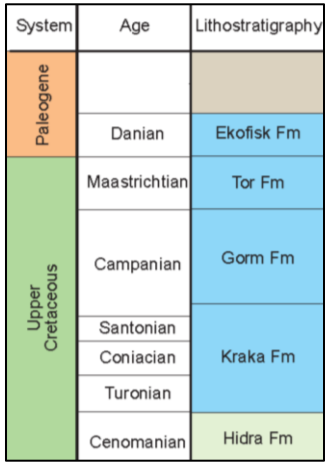


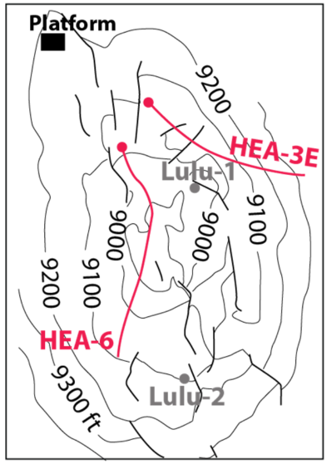


Batié et al., 2005; Remmen et al., 2015

- Oil field
- 4x2 km faulted anticline at a 2.7 km
- Main reservoir: Ula Fm
- Φ_{tot}= 20-25%, K_{air}=100-2000 mD
- Production: 1998-2016
- Gas/water injection

Harald East field (Chalk)

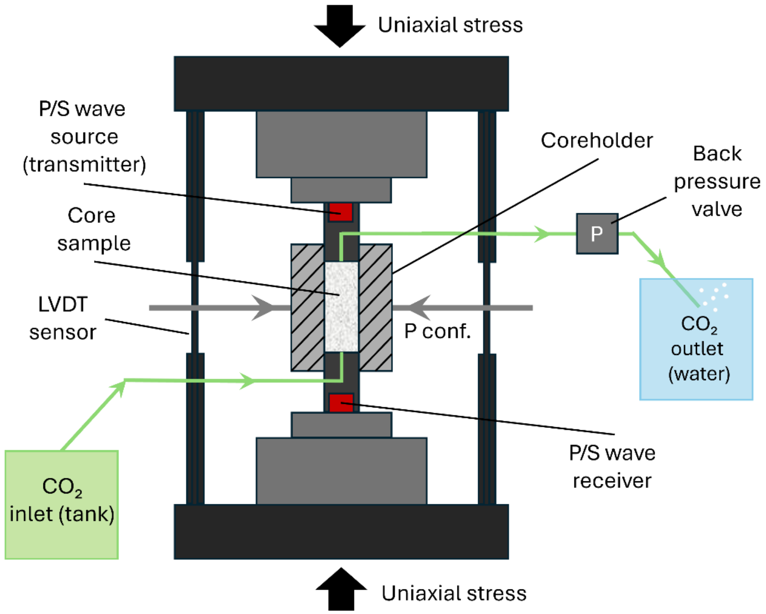




Bergfors et al., 2020; Amour et al., 2025

- Gas field
- 5x3 km anticline at a 2.7 km
- Main reservoir: Ekofisk Fm
- Φ_{tot}= 32.7%, K_{air}=2.2 mD
- Production: 1997-Present
- Gas expansion

Experimental Protocol



Flooding experiments

Initial S_w
- 20 and 40%
- 1.063 g/ml for brine

→

Loading
- Only hydrostatic loading
- Hydrostatic + axial loading (constant σ_r)
- Loading to onset of pore collapse
- σ, ε, $V_{p/s}$ measured

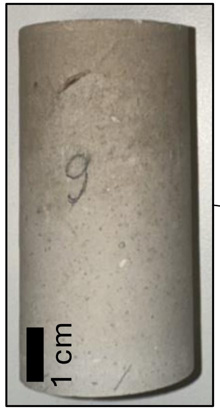
↓

Continuous and intermittent CO_2 gas flooding under constant stress
dP = 25 bar; room temperature
σ, ε, $V_{p/s}$ measured

←

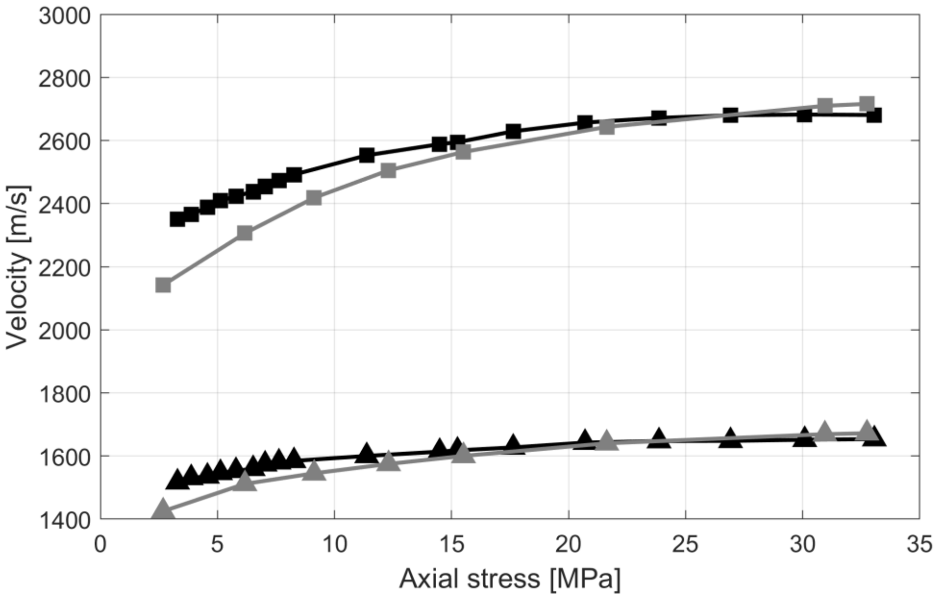
Unloading and reloading
σ, ε, $V_{p/s}$ measured

Six samples studied

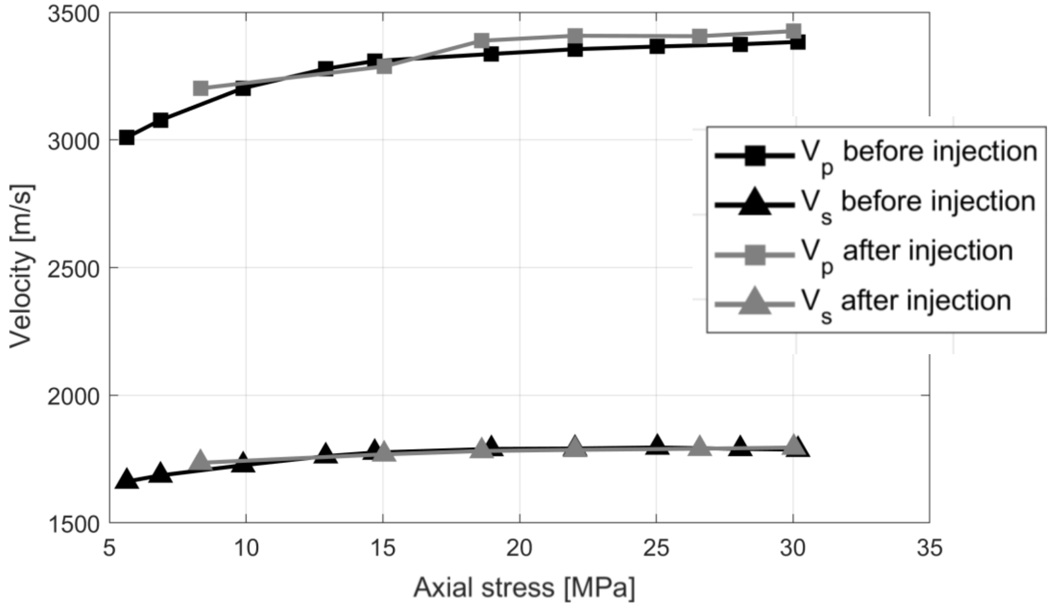


	Type	Por. [%]	Perm. [mD]	Field	PV injected (S_w)
1	Reworked chalk	34.6	1.2	Harald	300 (41 to 23%)
2	Reworked chalk	33.5	1.7	Harald	950 (40 to 30%)
3	Pelagic chalk	30	1.0	Harald	300 (22 to 20%)
4	Pelagic chalk	27.3	0.3	Harald	800 (20 to 19%)
5	Reworked chalk	38.7	3.7	Harald	3800 (21 to 17%)
6	Sandstone	11	1.5	Varg	22000(41 to 28%)

Stress Sensitivity of V_p and V_s



Enhanced stress sensitivity



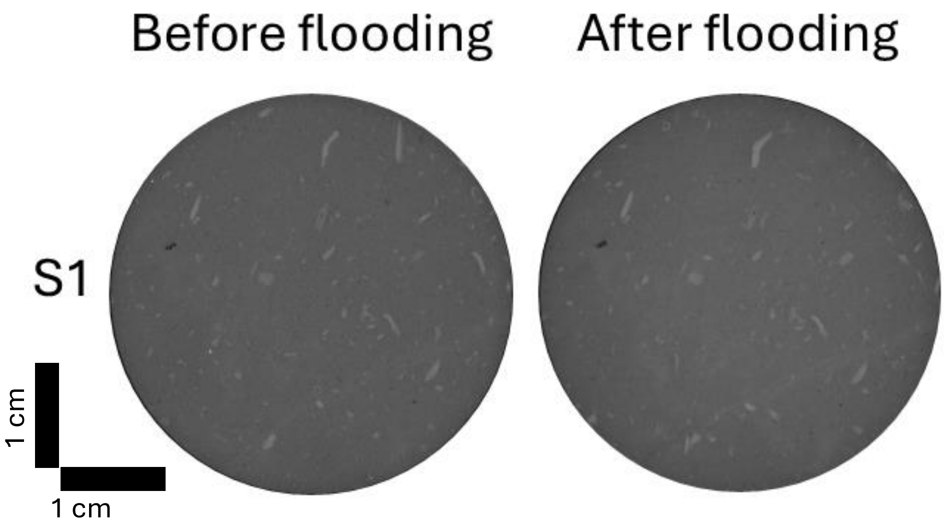
Stress sensitivity unchanged

- Enhanced **stress sensitivity** only observed in samples experiencing **creep rate acceleration**
- Velocity trends deviate from pre-flooding conditions below **15 MPa total axial stress**

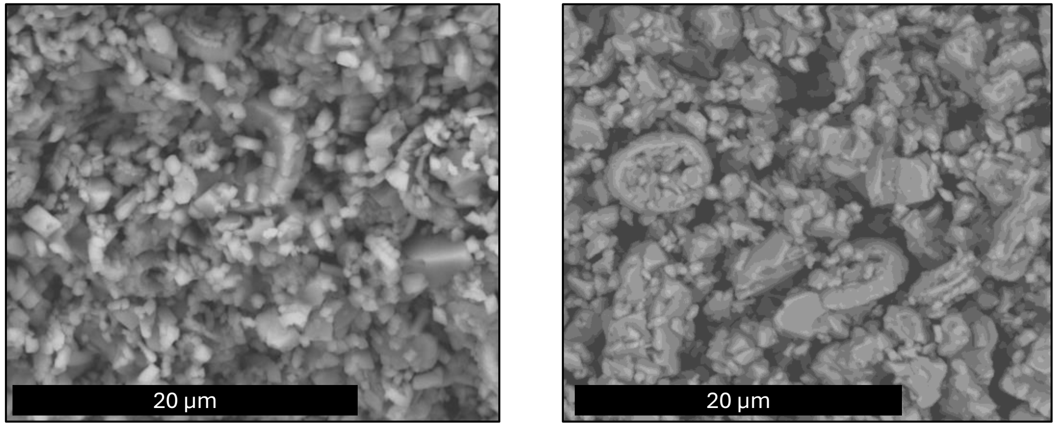
➞ Creep and wave velocities are both influenced by the properties of the grain contacts

Controlling Factors

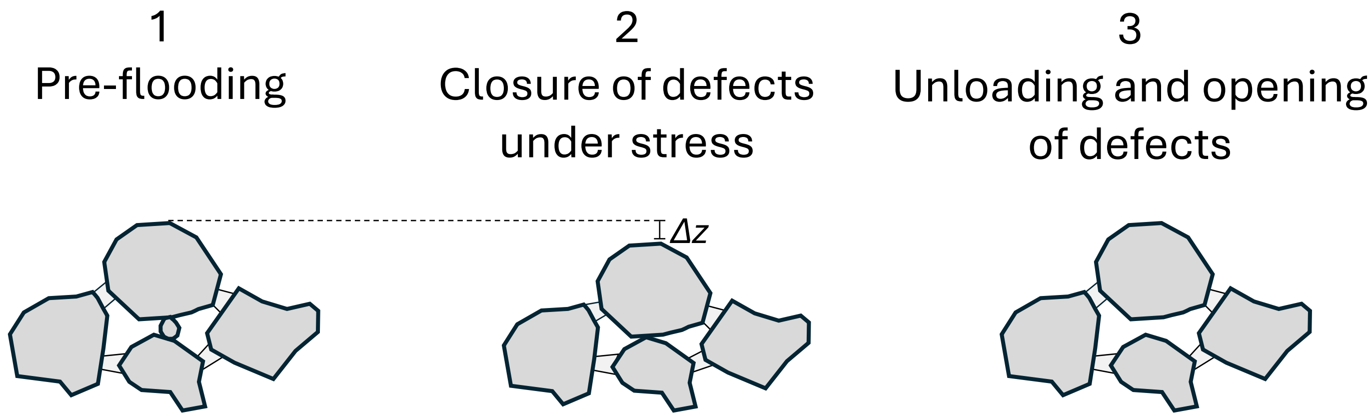
CT scanning



SEM analysis



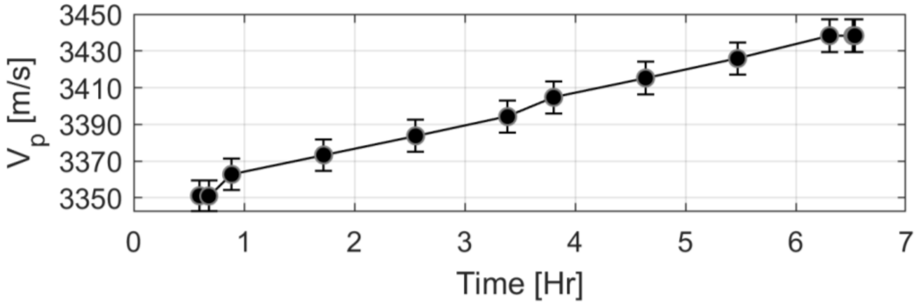
- No evidence of large-scale dissolution
- **Etching** of grains and additional micropores (**defects**)

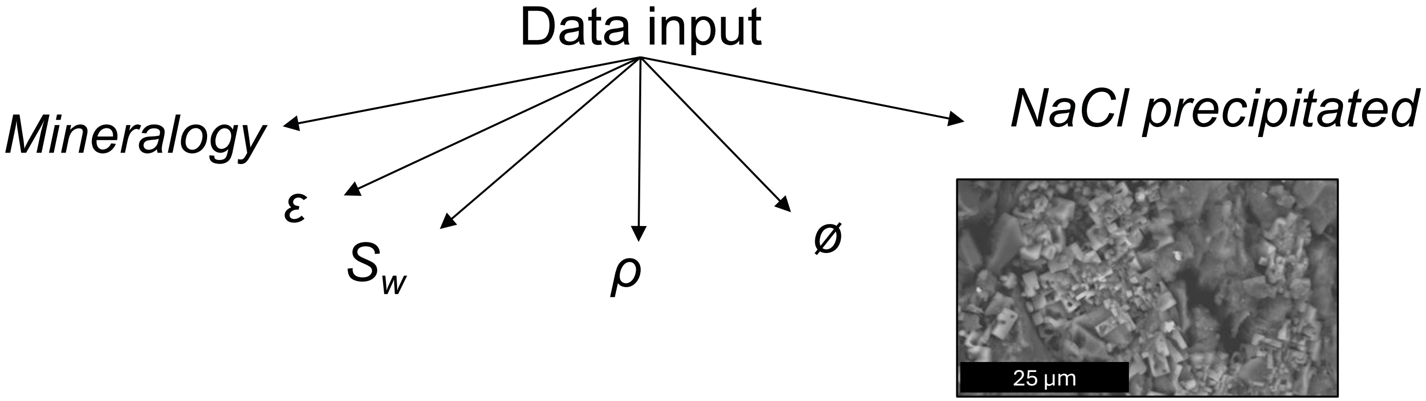


- Defects close as soon as formed due to stress causing **additional axial strain** during creep
- Defects **open upon unloading** and impede wave propagation

Velocity Change during Injection

Rock physics modeling of the experimental data during CO_2 injection




Data input

Mineralogy

ε

S_w

ρ

$\o$

NaCl precipitated

1- Modified Hashin-Shtrikman bounds

$$K_{bulk,t_0} = mK_{mHS-} + (1-m)K_{mHS+}$$

$$G_{bulk,t_0} = nG_{mHS-} + (1-n)G_{mHS+}$$

with m and n adjusted to elastic properties before start of injection

For fluid: $K_{fl.} = \left(\sum_i \frac{f_i}{K_i}\right)^{-1}$

2- Contact cement model applied to salt precipitation

The incremental stiffening of the rock as salt precipitates at the grain contact is estimated as follows (Dvorkin et al., 1994 & 1996):

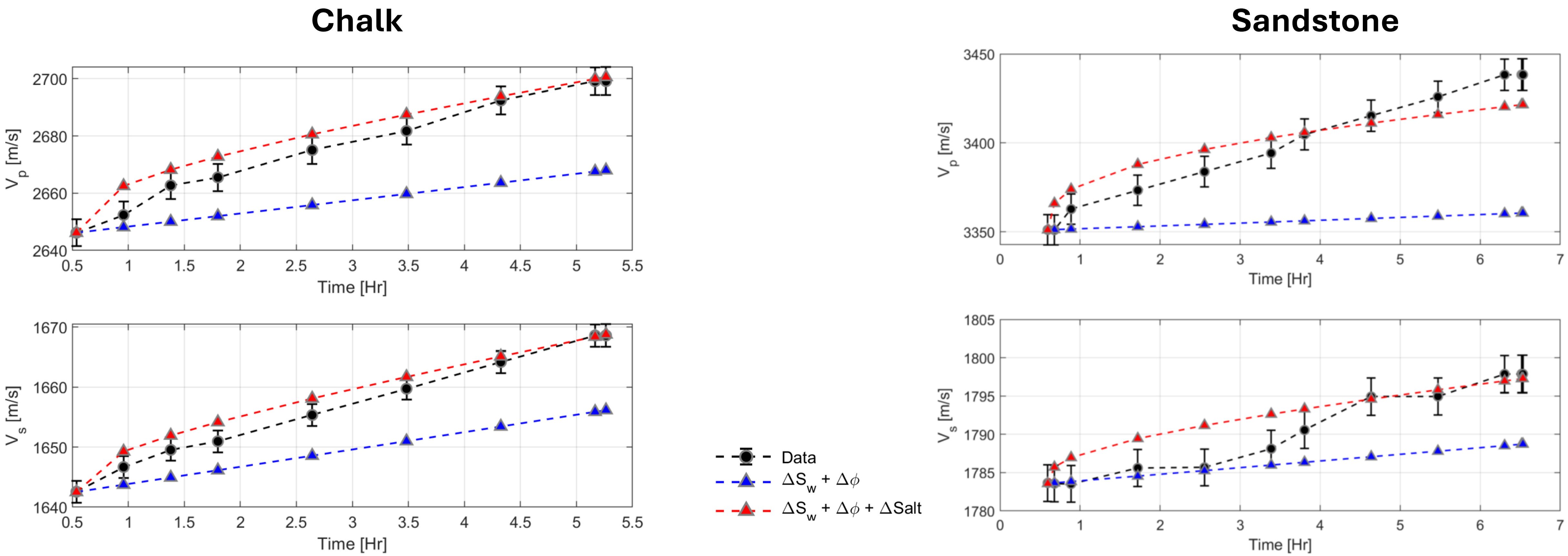
$K_{dry} = K_{dry,t_0} + dK_{dry}$ and $G_{dry} = G_{dry,t_0} + dG_{dry}$

with $dK_{dry} = \frac{C(1-\O)}{12\pi} S_n$ and $dG_{dry} = \frac{C(1-\O)}{20\pi} S_t$

$$S_n = \frac{4aG_0}{1-\nu} \qquad S_t = f\,\frac{8aG_0}{2-\nu}$$

with a the grain contact radius dependent on salt content and an empirical scaling factor α

Rock Physics Modeling



- Systematic **underestimation** of velocity change when i) halite precipitation is not considered and ii) using solely Hashin-Shtrikman bounds
- For chalk, salt precipitation accounts for **>50% change in V_p and V_s (up to 80%)**
- For sandstone, salt precipitation accounts for **90% of V_p change and 62% of V_s change**

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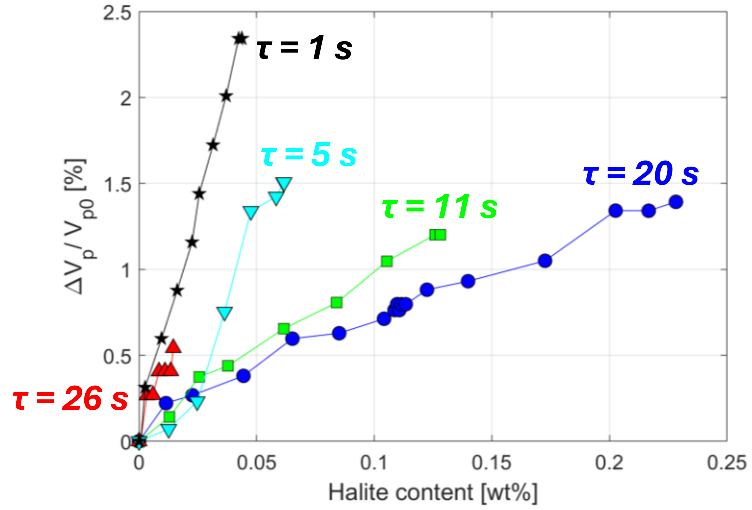
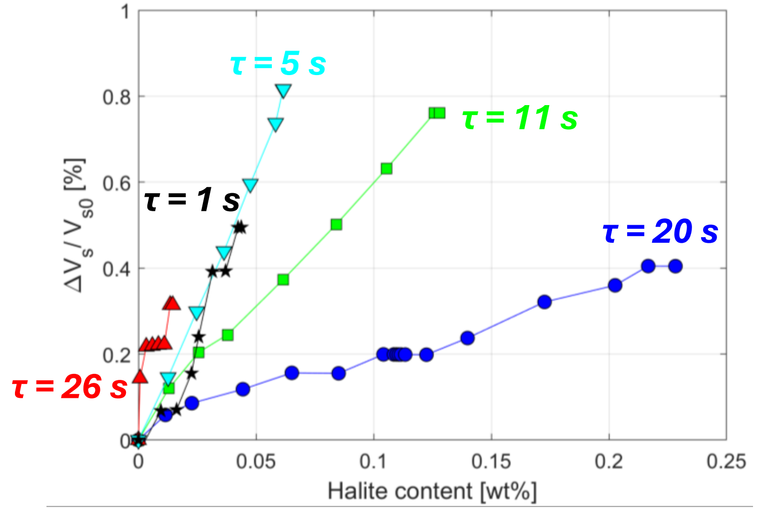
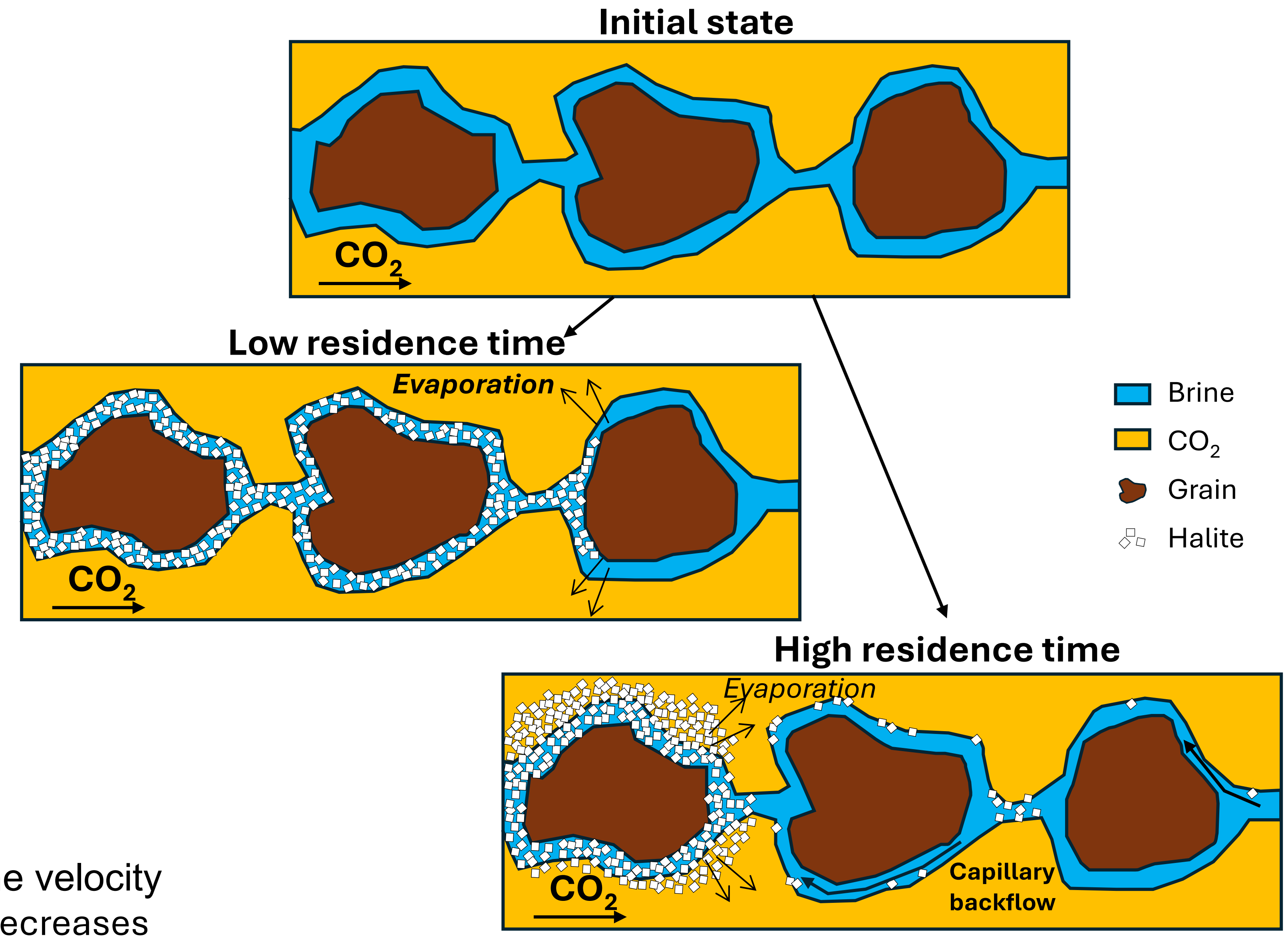
A A P G
S E G

CO_2 Residence Time (τ)





For a given amount of salt precipitation, the velocity change becomes more pronounced as τ decreases



After Miri & Hellevang, 2016 and Chao et al., 2024

Conclusions

- >10% increase in wave velocity due to salt precipitation in near-wellbore area of **aquifers** (S_w= 100%), whereas <5% change is measured in **depleted reservoirs** (S_w< 40%).
- **Salt distribution** influenced by injection rate controls the net change in V_p and V_s of the rock frame.
- **Enhanced stress sensitivity** of V_p and V_s due to uncemented **CO_2-induced defects**, which:
  - close under stress causing additional creep strain.
  - reopen upon unloading impeding wave propagation.
- **Low risk of mechanical instability** in the near-wellbore region upon CO_2 injection in partially saturated chalk.

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