Rock strengths and Earth stresses – assessing safe operation envelope during CO_2 storage in a mature oil and gas field

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Abstract

Having sufficient underground storage capacity available is fundamental for decarbonizing heavy CO_2 emitting regional industrial clusters. We followed the EU storage directive to develop a project, named “CO2 SPICER – CO2 storage pilot in a carbonate reservoir”, to qualify a mature oil and gas-producing field in South-East Czechia for to a CO_2 storage pilot. The project has been funded via Norway Grants and the Kappa program within the Technology Agency of the Czech Republic (TACR).

This poster describes the geomechanical work entailed to ensure geomechanical stability of the 6 formations in the storage complex. This is important to ensure the injected CO_2 remains underground. In all 23 tensile, 8 uniaxial stress and 4 tri-axial, and 21 hydrostatic tests were performed. Each tests was combined with ultrasonic velocity and petrophysical determination. The rock strength was compared to estimates of principal stresses, and a stability evaluation was performed to ensure the safe operational envelope. The geomechanical work is integrated into the other work packages of the project to evaluate risks of leakage, constrain the safe operational envelope, and the potential storage capacity of the field. Moreover, the geochemical implications to strengths have been evaluated.

Integrating geomechanical constraints for reservoir qualification

Geomechanical constraints are relevant for upstream scenario development, dynamic modelling and quantified risk analyses. Here, we develop the safe operational envelope during CO^2 injection as the reservoir pressure is increased and temperature is lowered. When combined with risk acceptance criteria, the injection rate and overall storage capacity can be constrained – important for entire value chain analyses. Rock samples were collected from the formations represented in the storage complex (Tab. 1) from the store repository of the field operator (MND), and a series of tests were performed (Tab. 2) as the base of decision analysis.

Tab. 1: Overview of formations in the storage complex.

Age	Lithostratigraphy	Type	Number of rock samples
Upper Jurassic	Mikulov Fm.	Seal	9
Paleogene	Žarošice Mb.	Seal	9
Upper Jurassic	Vranovice Fm. - nearby field	Reservoir - possible analogue	1
Upper Jurassic	Vranovice Fm. (Nikolčice Fm.)	Reservoir	1
Upper Jurassic	Vranovice Fm.	Reservoir	50
Lower Carboniferous	Myslejovice Fm.	Side seal	8

Tab. 2. Mechanical tests performed for the different formations. Results combined in data base.

Test type	Vran Fm Kurd.	Vran Fm. Res	Zarosice Mb.	Myslejovice Fm.	Mikulov Fm.	Vran fm. / Nikolcice Fm.
Tensile	2	10	4	4	3	0
UCS	1	4	1	1	1	0
Triax	1	2	1	0	0	0
Hydrostatic	2	13	2	1	2	1
Sound vel.	5	41	8	8	8	3
Thermal exp coef	1	2	0	0	1	0

Determining rock strength and Earth stresses

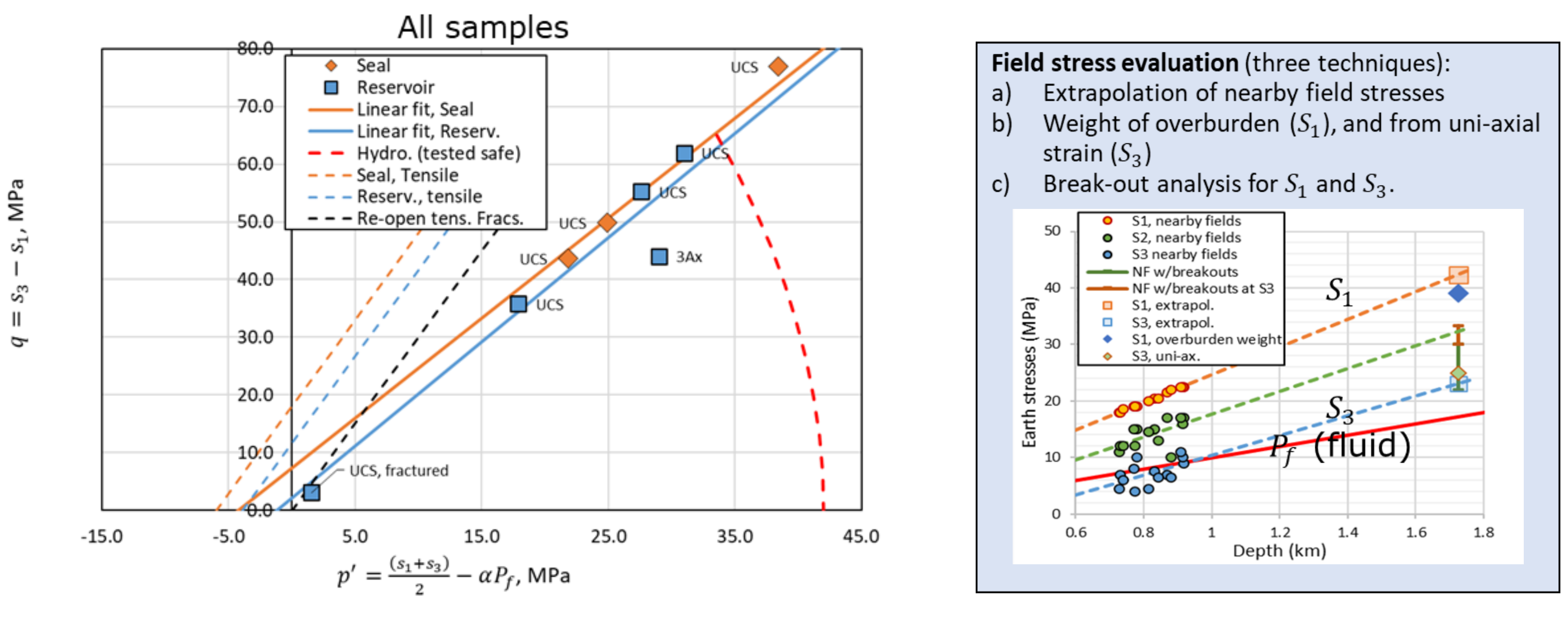
Rock strength of all relevant rock-types in the storage complex (Tab. 1) was measured in Brazilian, UCS and 3ax tests. The critical failure stresses were plotted in the invariant qp-plots of deviatoric and mean effective stress. The reservoir carbonate rocks were weakest (Fig. 1:left).

A 2D stress analysis is suitable, firstly because of lack of in-situ data, and secondly it provides a conservative estimate in the stability analysis. Poly-axial stress tests, with $s_2 > s_3$, display an increase in the s_1 stress at failure.

Deviatoric stress defined as $q = s_1 - s_3$ and mean effective stress $p' = \frac{s_1+s_3}{2} - \alpha P_f$. The principal stresses s_1 and s_2 were estimated in three ways (Fig. 1:right).

Impact of pressure and temperature on effective stresses

- Increasing pore pressure (P_f) reduces p'.
- In weight-controlled systems $s_1 = const$. The uni-axial strain assumption combined with thermoelastic Hooke’s law imply that cooling by ΔT leads to a reduction in s_3 by $\Delta s_3 = \frac{\alpha_T E}{1-\nu} \Delta T$.
- **Cooling reduces s_3 so both p' reduce while q increase**. The thermal expansion (α_T), Youngs modulus (E) and Poisson ratio (ν) were measured on rock samples and used in the estimates.



Field stress evaluation (three techniques):
a) Extrapolation of nearby field stresses
b) Weight of overburden (S_1), and from uni-axial strain (S_3)
c) Break-out analysis for S_1 and S_3.

Fig. 1: (Left) Rock strength tests of sealing formations and the carbonate reservoir rock in qp-space. (Right) Field stresses evaluated using three techniques as no direct measurements were obtained. The extrapolation were from measurements in neighboring field, and the estimate was done via weight of column for s_1 and Poisson ratio for s_3. Break-out analysis were on formation logs were also performed.

Combine strength and uncertain stress – estimate the impact of re-pressurization and cooling

No weak planes were identified. Thus, mechanical stability was performed by evaluating the reservoir rock strength (weakest) in conjunction with in-situ stress changes in qp-plots, where Earth stresses are a dot (rather than circles in $\tau\sigma$ diagrams).

Cold CO_2 injection increases pressure and reduces temperature, thereby changing q and p' via the Biot effective stress relation and the thermal-elastic coupling. The coupling parameters were subject to geologic variation. Monte Carlo simulations were applied to draw parameter sets from PDFs for each realization of pressure and temperature (Figure 2).

The pressure and temperature was varied, and the probability of failure was predicted. The temperature and pressure needed to re-open existing fractures with surface normal parallel to s_3 are shown in Fig. 3:left, while the probability of failure for intact rocks are shown in Fig. 3:right. The pore pressure needed to induce failure is reduced if the reservoir (or near well injection area) is cooled down. The figures below illustrate safe operational envelope for different pressure and temperatures.

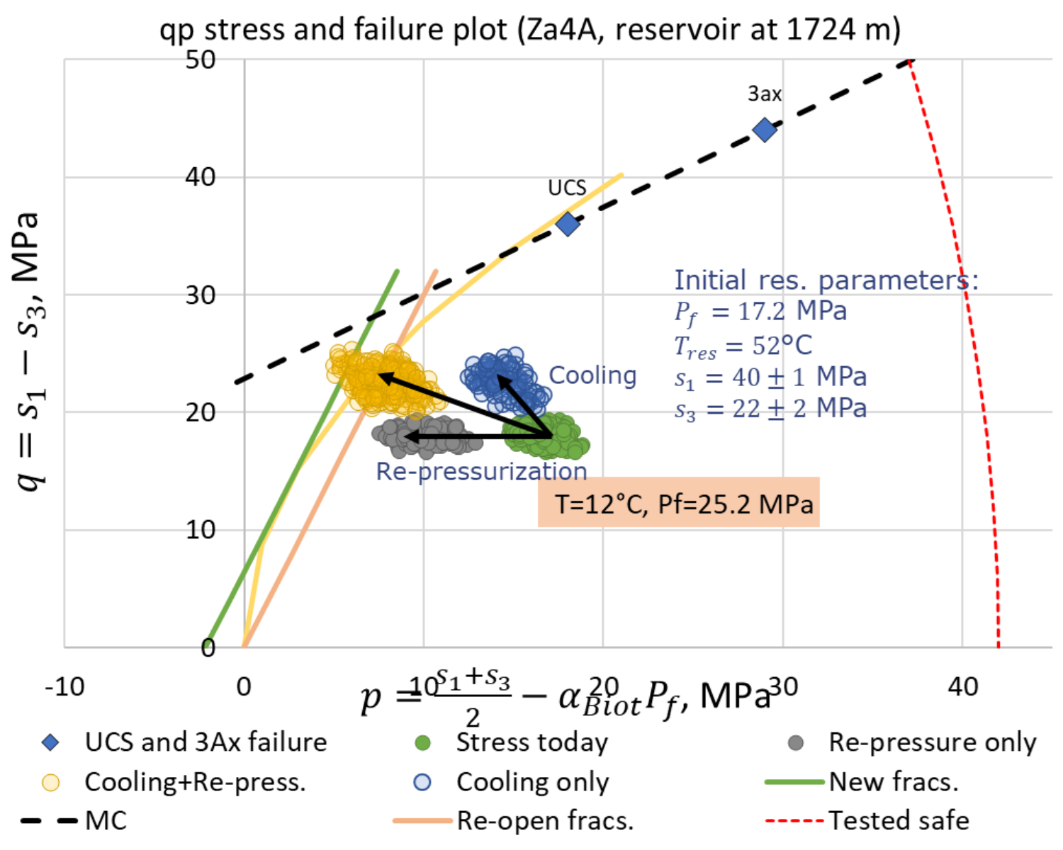


Fig. 2: The probability of failure is determined by counting the number of unstable stress configurations exceeding the failure envelope. New fracs, re-open existing fracture, and shear failure are shown. The Earth effective stresses is perturbed by pore pressure and temperature changes.

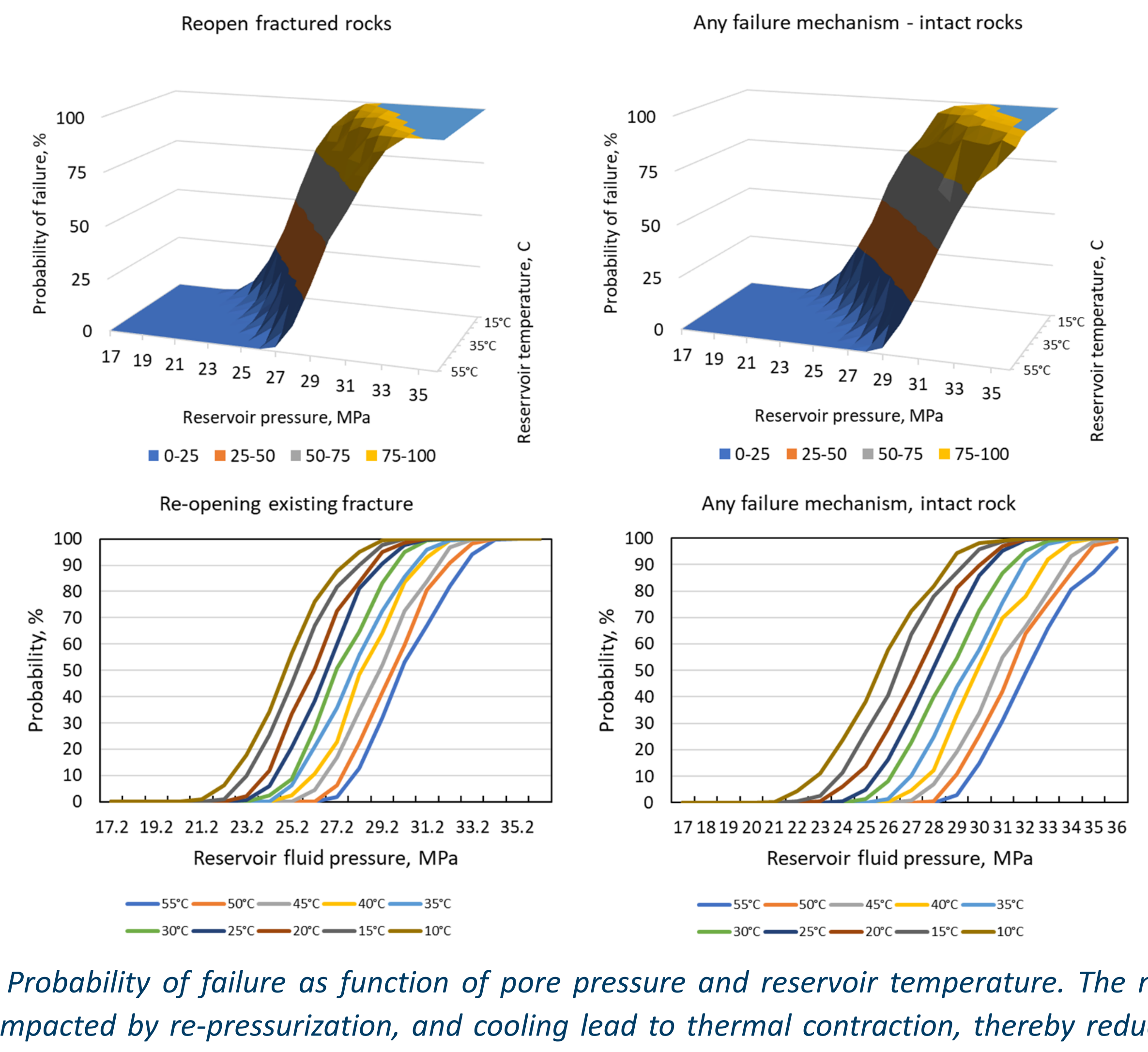


Figure 3: Probability of failure as function of pore pressure and reservoir temperature. The mean effective stress is impacted by re-pressurization, and cooling lead to thermal contraction, thereby reducing the least, horizontal stress. Reopening of existing fractures (left) may increase injectivity, while generating new rock failure may lead to leakage risks if the failure propagate into the overburden formation.

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