Thermal Rock Physics of Shales: Laboratory Experiments under Undrained Conditions

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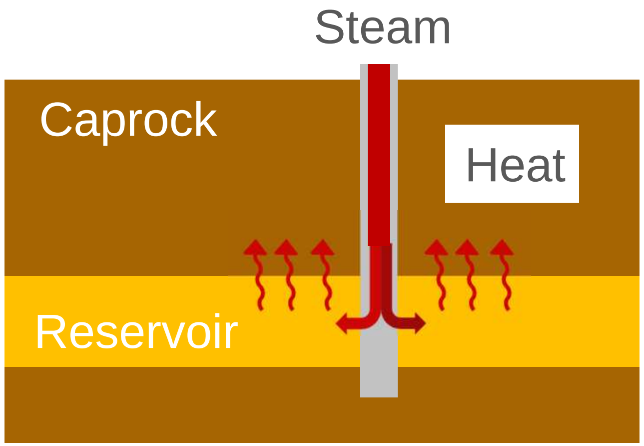
Motivation: Caprock Integrity

Thermal EOR

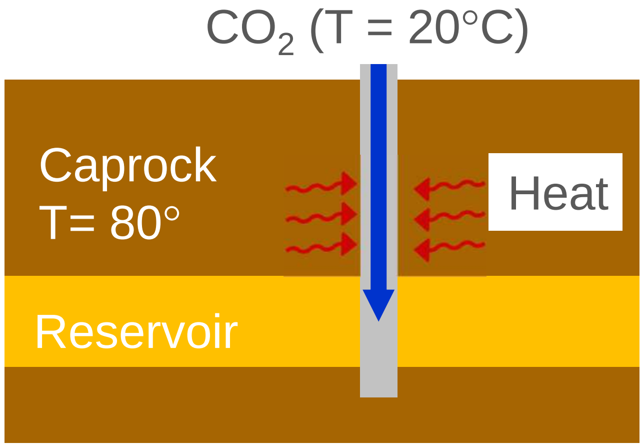


⇨ Heat diffusion into caprock

⇨ Thermally induced pore-pressure and stress changes may result in caprock failure

⇨ Possible risks: fault reactivation, leakage, interface slip

CO_2 sequestration (CCS)



⇨ Temperature difference between injected CO_2 and surrounding formation

⇨ Thermally induced pore-pressure and stress changes around injector wells may result in rock failure and leakage of CO_2

⇨ License-to-operate issue

Drained versus Undrained Rock Properties

Shales have very **low permeabilities** (nD range), which may result in **pore pressure changes** due to depletion-induced stress changes or heating during thermal EOR.

Business impact:

- (Thermally induced) poroelastic effects affect caprock integrity
- Interpretation of 4D seismic

	drained	vs.	undrained
Bulk modulus	low		high
Poisson's ratio	low		≈ 0.5
Pore pressure	constant		varies with stress/temperature

Thermo-hydro-mechanical coupling in shales

Heating of low-permeability shales results in increase of pore pressure

Thermo-poroelasticity (undrained conditions)

$$c' = \frac{dp_p}{dT} = \frac{2GB^2(1+\nu_u)^2(1-\nu)}{9(1-\nu_u)(\nu_u-\nu)}\left[\frac{2\alpha_m(\nu_u-\nu)}{B(1+\nu_u)(1-\nu)} + \phi(\alpha_f-\alpha_m)\right]$$

Chen and Ewy (2005)

c’: coupling coefficient
P_p: pore pressure
T: temperature

Input parameters

G: Shear modulus (drained)
B: Skempton parameter
ϕ: Porosity
ν: drained Poisson’s ratio
ν_u: undrained Poisson’s ratio
α_f: th. expansion coeff. of fluid
α_m: th. expansion coeff. of matrix

Experimental issues:

- G and ν obtained from drained measurements ⇨ superposition of inelastic effects, time consuming test
- What is the effect of bound water on α_f?
- How good is the porosity known?
- Anisotropies are often ignored

Thermo-hydro-mechanical coupling in shales

Experimental determination of c' based on undrained measurements only:

$$c' = \left.\frac{\partial p_p}{\partial T}\right|_{p=const} + \frac{\partial p_p}{\partial p}\cdot\frac{\partial p}{\partial T} = \left.\frac{\partial p_p}{\partial T}\right|_{p=const} + B\cdot\underbrace{\left[\frac{2E_u\alpha_u}{9(1-\nu_u)}\right]}$$

directly measured:
≈ 0.1 MPa/°C

change of mean total stress:
≈ 0.1-0.2 MPa/°C

c': coupling coefficient
P_p: pore pressure
p: mean total stress
T: temperature

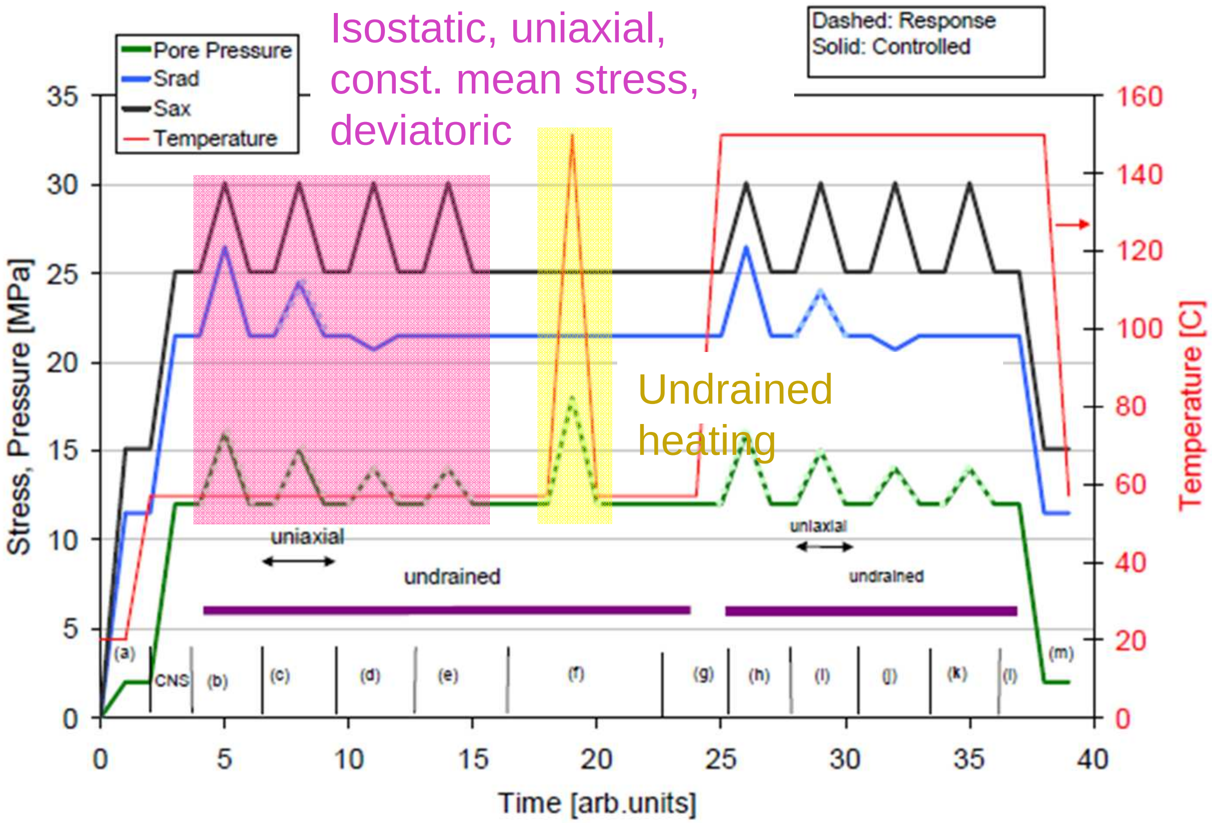
Input parameters:

B: Skempton parameter
E_u: undrained Young's modulus
ν_u: undrained Poisson's ratio
α_u: undrained volumetric thermal expansion coefficient

⇨ Input parameters can readily be obtained from core-plug tests under undrained conditions

⇨ Undrained measurements can be performed quickly (for

Test protocol

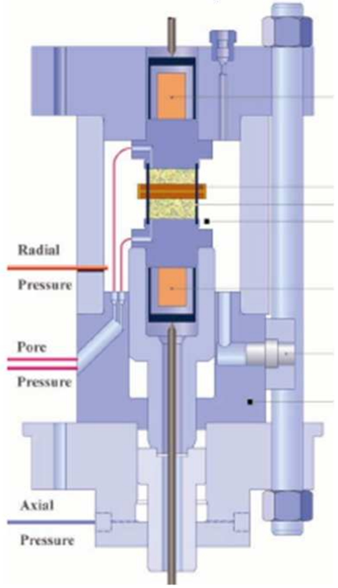


Undrained loading/ unloading cycles: Isostatic, uniaxial, const. mean stress, deviatoric

Undrained heating

Test equipment:

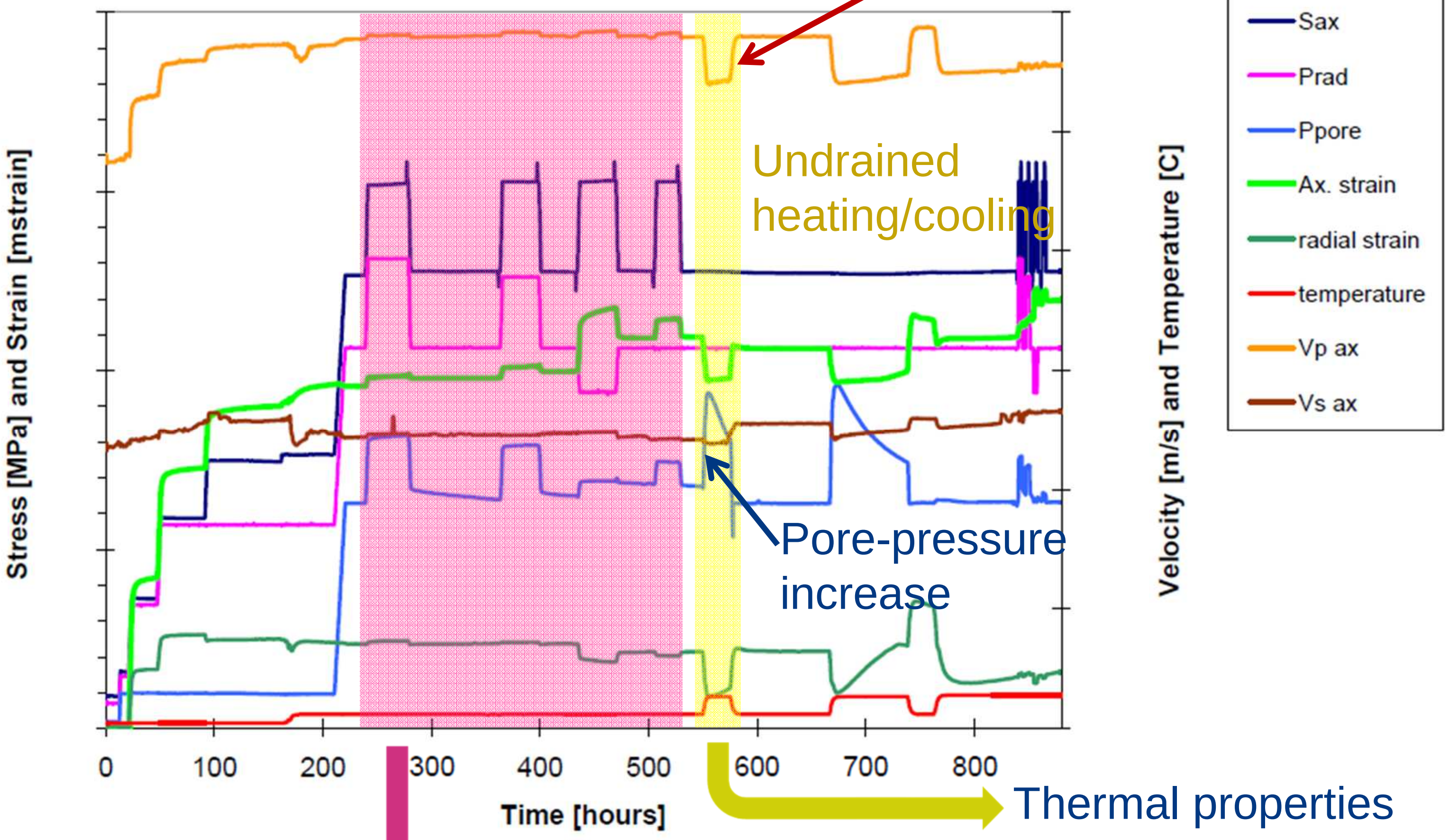
Triaxial compaction cell



Experimental challenges:

- **Small dead volume** (pore pressures and strains have to be corrected for dead volume effects)
- Pore-pressure reduction due to **swelling of sleeve**

Shale #1



Undrained loading/ unloading

Large velocity changes

Undrained heating/cooling

Pore-pressure increase

Thermal properties (α_u, dp_p/dT, $dV_{p,s}/dT$)

Undrained (+ drained) rock properties (E_u, ν_u, B, A, E, ν, $dV_{p,s}/d\sigma$)

Coupling

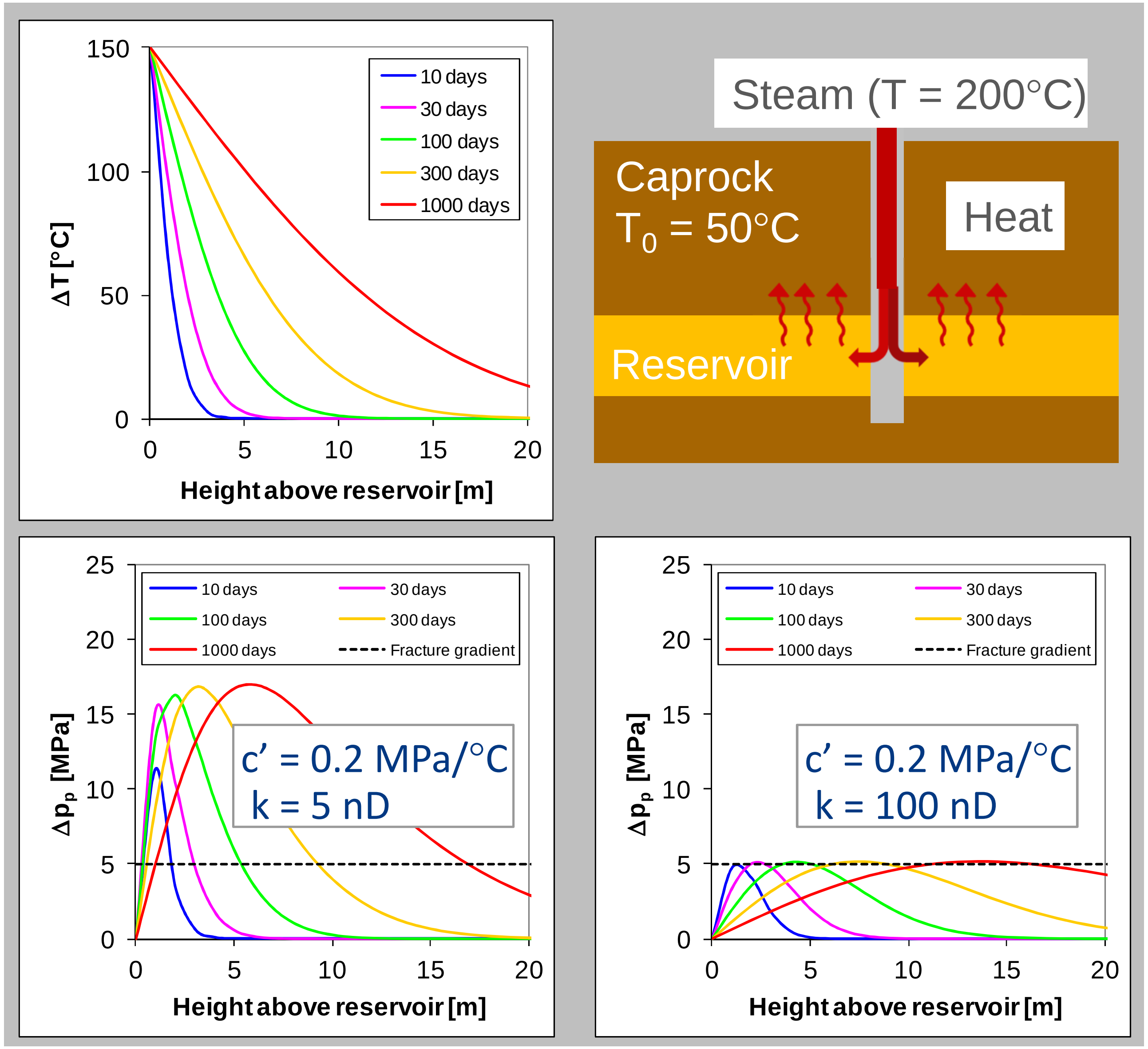
Shale #1

Test results

dp_p/dT @ const p	0.09 MPa/K
Skempton B	0.82
Young's modulus (undr.), E_u	5.5 GPa
Poisson's ratio (undr.), ν_u	0.45
Thermal expansion coeff. (undr.), α_u	$1.0 \cdot 10^{-4}$ K^{-1}
Skempton A	0.43
Young's modulus (drained), E	4.9 GPa
Poisson's ratio (drained), ν_u	0.24
Shear modulus (drained), G	2.0 GPa
Therm. expan. coeff. (drained), α_m	$1.0 \cdot 10^{-4}$ K^{-1}

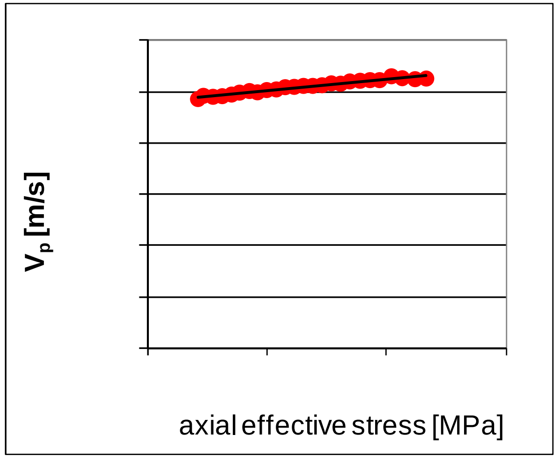
Coupling coefficient

Coupled 1-dimensional simulations



Ultrasonic velocities

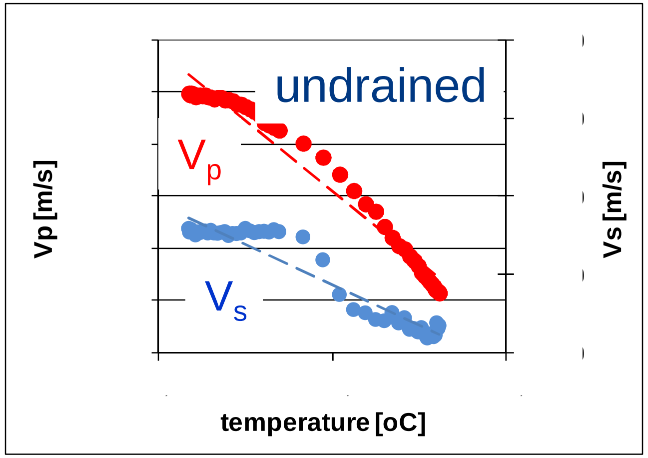
Stress dependence



$$S_p = \frac{\Delta V_p / V_p}{\Delta \sigma'_{ax}} = 2.0 \cdot 10^{-3}\, MPa^{-1}$$

$$S_s = \frac{\Delta V_S / V_S}{\Delta \sigma'_{ax}} \approx 1.5 \cdot 10^{-3}\, MPa^{-1}$$

Temperature dependence



	undrained	drained
$\frac{\Delta V_p / V_p}{\Delta T}$	$-7.9 \cdot 10^{-4}$ K^{-1}	$-6.8 \cdot 10^{-4}$ K^{-1}
$\frac{\Delta V_s / V_s}{\Delta T}$	$-4.8 \cdot 10^{-4}$ K^{-1}	$-3.4 \cdot 10^{-4}$ K^{-1}

⇨ Larger velocity changes for

Ultrasonic velocities: temperature dependence

Expected changes due to thermally induced pore-pressure changes:

$$S_p \cdot \left.\frac{dp_p}{dT}\right|_{p=const} = 2.0 \cdot 10^{-3}\,MPa^{-1} \times 0.09\,MPa \cdot K^{-1} = \boxed{1.8} \cdot 10^{-4}\,K^{-1}$$

$$S_s \cdot \left.\frac{dp_p}{dT}\right|_{p=const} \approx 1.5 \cdot 10^{-3}\,MPa^{-1} \times 0.09\,MPa \cdot K^{-1} = \boxed{1.4} \cdot 10^{-4}\,K^{-1}$$

⇨ Effective-stress dependence of V_p and V_s accounts for measured differences in temperature sensitivities for undrained and

	undrained	drained
$\frac{\Delta V_p / V_p}{\Delta T}$	$-7.9 \cdot 10^{-4}$ K^{-1}	$-6.8 \cdot 10^{-4}$ K^{-1}
$\frac{\Delta V_s / V_s}{\Delta T}$	$-4.8 \cdot 10^{-4}$ K^{-1}	$-3.4 \cdot 10^{-4}$ K^{-1}

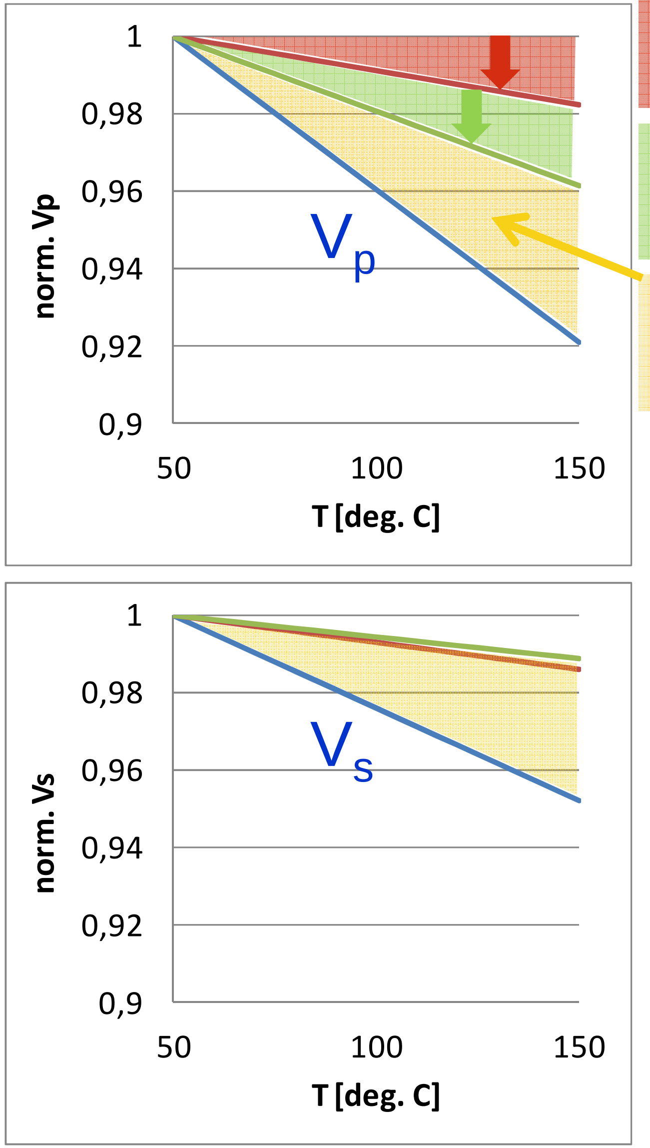
Expected changes due to fluid-compressibility changes:

PVT fluid properties + Gassmann theory (heating from 50°C to 150°C)

↳ $\left.\frac{\Delta V_p / V_p}{\Delta T}\right|_{p_p=const} \approx 1.8 \cdot 10^{-4}\,K^{-1}$ and $\left.\frac{\Delta V_s / V_s}{\Delta T}\right|_{p_p=const} \approx 0$

⇨ Fluid-compressibility changes cannot explain high temperature sensitivity of V_p and

Ultrasonic velocities: temperature dependence



Decrease due to pore-pressure increase

Decrease due to fluid-compressibility changes

Thermally-induced reduction of frame stiffness?

Static stiffness slightly increases with temperature

⇨ Apparent reduction of dynamic stiffness might be the result of velocity dispersion and its temperature dependence

⇨ Temperature sensitivity of V_p and V_s could be significantly smaller at seismic/sonic frequencies

Conclusions

- Thermo-poroelastic properties of shales (coupling coefficient, etc.) can readily be obtained from multi-stage triaxial compaction tests under undrainded conditions.

- Thermally-induced pore-pressure changes in shales may result in rock failure, which has to be taken into account in the assessment of caprock integrity in thermal EOR or CCS.

- The temperature sensitivity of V_p and V_s is attributed to thermally-induced fluid compressibility and pore-pressure changes as well as the temperature dependence of the rock-frame stiffness that is believed to be frequency dependent.

- Better understanding of velocity dispersion in shales is needed for a quantitative interpretation of time-lapse seismic.

Q & A