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

**CO₂ sequestration (CCS)**
- Temperature difference between injected CO₂ and surrounding formation
- Thermally induced pore-pressure and stress changes around injector wells may result in rock failure and leakage of CO₂
- License-to-operate issue
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.

<table>
<thead>
<tr>
<th></th>
<th>drained</th>
<th>vs.</th>
<th>undrained</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk modulus</td>
<td>low</td>
<td></td>
<td>high</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>low</td>
<td></td>
<td>≈ 0.5</td>
</tr>
<tr>
<td>Pore pressure</td>
<td>constant</td>
<td></td>
<td>varies with stress/temperature</td>
</tr>
</tbody>
</table>

Business impact:

- (Thermally induced) poroelastic effects affect caprock integrity
- Interpretation of 4D seismic
Thermo-hydro-mechanical coupling in shales

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

**Thermo-poroelasticity** (undrained conditions)

\[
c' = \frac{dp_p}{dT} = \frac{2GB^2(1+ν_u)^2(1-ν)}{9(1-ν_u)(ν_u-ν)} \left[ \frac{2α_m(ν_u-ν)}{B(1+ν_u)(1-ν)} + φ(α_f-α_m) \right]
\]

\(c':\) 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

Chen and Ewy (2005)
Thermo-hydro-mechanical coupling in shales

Experimental determination of $c'$ based on undrained measurements only:

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

directly measured: $\approx 0.1$ MPa/°C
change of mean total stress: $\approx 0.1$-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
- $\nu_u$: undrained Poisson’s ratio
- $\alpha_u$: 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 homogeneous samples).
Test protocol

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

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

Undrained (+ drained) rock properties

Thermal properties

Coupling
### Test results

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{dp}{dT} @ \text{const } p$</td>
<td>0.09 MPa/K</td>
</tr>
<tr>
<td>Skempton B</td>
<td>0.82</td>
</tr>
<tr>
<td>Young's modulus (undr.), $E_u$</td>
<td>5.5 GPa</td>
</tr>
<tr>
<td>Poisson's ratio (undr.), $\nu_u$</td>
<td>0.45</td>
</tr>
<tr>
<td>Thermal expansion coeff. (undr.), $\alpha_u$</td>
<td>$1.0 \cdot 10^{-4}$ K$^{-1}$</td>
</tr>
<tr>
<td>Skempton A</td>
<td>0.43</td>
</tr>
<tr>
<td>Young's modulus (drained), $E$</td>
<td>4.9 GPa</td>
</tr>
<tr>
<td>Poisson's ratio (drained), $\nu_u$</td>
<td>0.24</td>
</tr>
<tr>
<td>Shear modulus (drained), $G$</td>
<td>2.0 GPa</td>
</tr>
<tr>
<td>Therm. expan. coeff. (drained), $\alpha_m$</td>
<td>$1.0 \cdot 10^{-4}$ K$^{-1}$</td>
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</table>
Coupled 1-dimensional simulations

Steam (T = 200°C)
Caprock
T₀ = 50°C
Heat
Reservoir

ΔT [°C]

Height above reservoir [m]

150
100
50
0
0 5 10 15 20

Δp [MPa]

Height above reservoir [m]

c' = 0.2 MPa/°C
k = 5 nD

c' = 0.2 MPa/°C
k = 100 nD
Ultrasonic velocities

Stress dependence

\[ S_p = \frac{\Delta V_p / V_p}{\Delta \sigma_{ax}} = 2.0 \cdot 10^{-3} \text{MPa}^{-1} \]

\[ S_s = \frac{\Delta V_s / V_s}{\Delta \sigma_{ax}} \approx 1.5 \cdot 10^{-3} \text{MPa}^{-1} \]

Temperature dependence

<table>
<thead>
<tr>
<th>( \frac{\Delta V_p / V_p}{\Delta T} )</th>
<th>undrained</th>
<th>drained</th>
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<tr>
<td>( -7.9 \cdot 10^{-4} \text{K}^{-1} )</td>
<td>( -6.8 \cdot 10^{-4} \text{K}^{-1} )</td>
<td></td>
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</table>

\( \frac{\Delta V_s / V_s}{\Delta T} \)

| \( -4.8 \cdot 10^{-4} \text{K}^{-1} \) | \( -3.4 \cdot 10^{-4} \text{K}^{-1} \) |

\( \Rightarrow \) Larger velocity changes for
Ultrasonic velocities: temperature dependence

Expected changes due to thermally induced pore-pressure changes:

\[ S_p \left( \frac{dp_p}{dT} \right)_{p=\text{const}} = 2.0 \cdot 10^{-3} \text{MPa}^{-1} \times 0.09 \text{MPa} \cdot \text{K}^{-1} = 1.8 \times 10^{-4} \text{K}^{-1} \]

\[ S_s \left( \frac{dp_p}{dT} \right)_{p=\text{const}} \approx 1.5 \cdot 10^{-3} \text{MPa}^{-1} \times 0.09 \text{MPa} \cdot \text{K}^{-1} = 1.4 \times 10^{-4} \text{K}^{-1} \]

- Effective-stress dependence of \( V_p \) and \( V_s \) accounts for measured differences in temperature sensitivities for undrained and drained conditions.

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<tr>
<td>( \frac{\Delta V_p}{V_p} / \Delta T )</td>
<td>-7.9 \times 10^{-4} \text{K}^{-1}</td>
<td>-6.8 \times 10^{-4} \text{K}^{-1}</td>
</tr>
<tr>
<td>( \frac{\Delta V_s}{V_s} / \Delta T )</td>
<td>-4.8 \times 10^{-4} \text{K}^{-1}</td>
<td>-3.4 \times 10^{-4} \text{K}^{-1}</td>
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Expected changes due to fluid-compressibility changes:

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

- Fluid-compressibility changes cannot explain high temperature sensitivity of \( V_p \) and \( V_s \).
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 undrained 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.