Temperature Effects on Wave Velocities and Compaction of Shales

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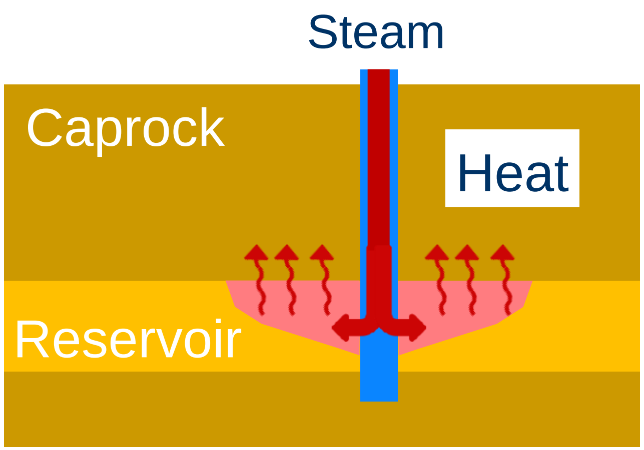
Acknowledgements:
Sponsors of "Rock Physics for Exploration and Reservoir Monitoring" JIP: BP, ConocoPhillips, Det norske, Shell, StatoilHydro, and Total

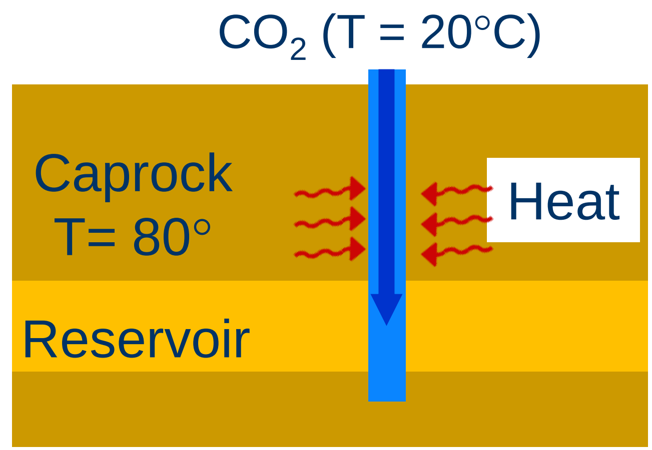
Why are temperature effects important?

Thermal EOR



- ⇨ Heating of reservoir
- ⇨ Heat diffusion into caprock
- ⇨ Thermally induced stress (and pore-pressure) changes
- ⇨ Possible risks: fault reactivation, leakage, interface slip

Fluid injection (e.g. CO_2)



- ⇨ 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

Why are temperature effects important?

Heating induces:

- **Elastic rock expansion and thermal stresses**

  ↳ understood; expansion coefficients should be measured with core material

- **Pore pressure increase in low-permeability rocks**

  ↳ in shales, heat diffusion is faster than pore-pressure diffusion; thermo-poroelasticitiy established but measurement of coupling coefficients recommended (A. Bauer et al., 2012)

- **Irreversible rock compaction** ⇦ This study

  ↳ Not well understood for shales

- **Velocity changes** ⇦ This study

  ↳ Not well understood for shales

  ↳ Understanding important for quantitative interpretation of timelapse seisimic

Temperature dependence of ultrasonic velocities

- For the temperatures range of interest (T < 200°C), the stiffness of rock minerals (quartz) changes only slightly
- If the dry rock does not show any significant temperature dependence the temperature dependence of the saturated-rock stiffness (low-frequency limit) may be described by the Gassmann model:

$$K_{sat} = K_{dry} + \frac{\left(1 - \frac{K_{dry}}{K_{gr}}\right)^2}{\frac{\phi}{K_{fl}(T)} + \frac{(1-\phi)}{K_{gr}} - \frac{K_{dry}}{K_{gr}^2}} \quad ; \quad G_{sat} = G_{dry}$$

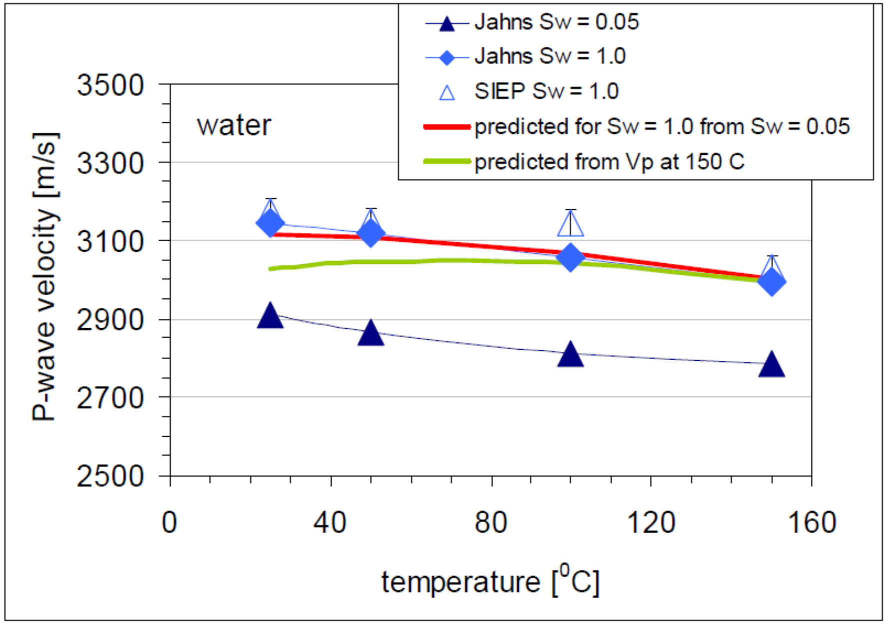
K_{sat}: Bulk modulus of saturated rock
K_{dry}: Bulk modulus of rock frame
K_{gr}: Bulk modulus of grains
K_{fl}: Fluid modulus
G_{sat}: Shear modulus of saturated rock
G_{dry}: Shear modulus of rock frame
ϕ: Porosity
ρ: Density of saturated rock

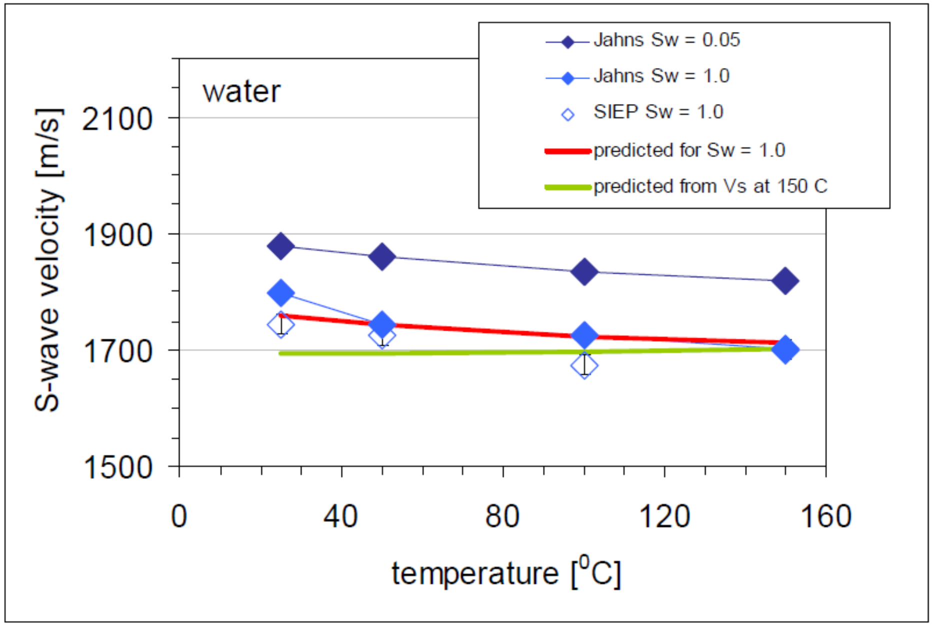
- Velocities are given by:

$$V_p(T) = \sqrt{\frac{K_{sat}(T) + \frac{4}{3}G_{sat}(T)}{\rho(T)}} \; ; \; V_s(T) = \sqrt{\frac{G_{sat}(T)}{\rho(T)}}$$

Temperature dependence of ultrasonic velocities

- For many rocks, deviations from the Gassmann model were observed for both V_p and V_s.
- For water-saturated Castlegate sandstone, it was shown the Gassmann model provides a food description if the temperature dependence of the dynamic rock stiffness for a small but non-vanishing water saturation is taken as "dry-rock" stiffness (drained-rock stiffness)



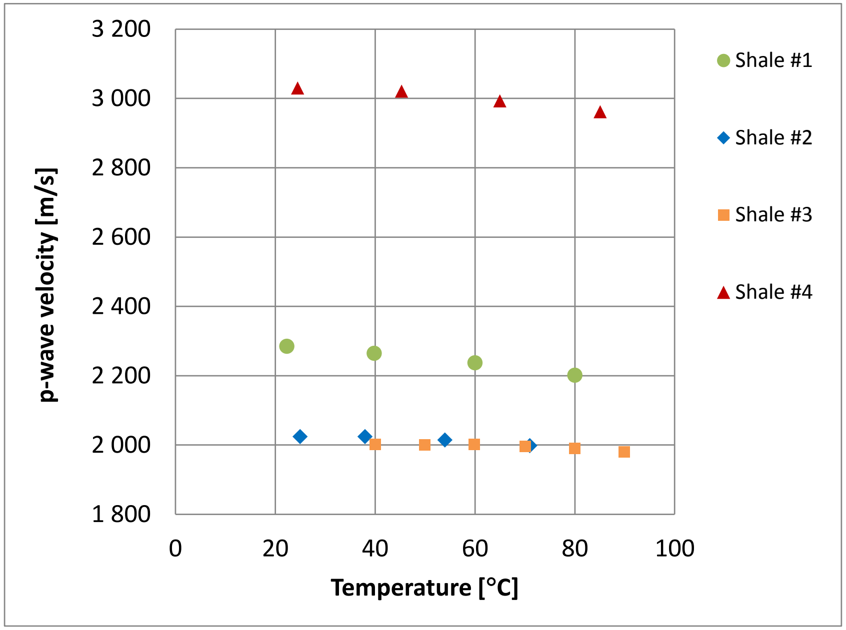


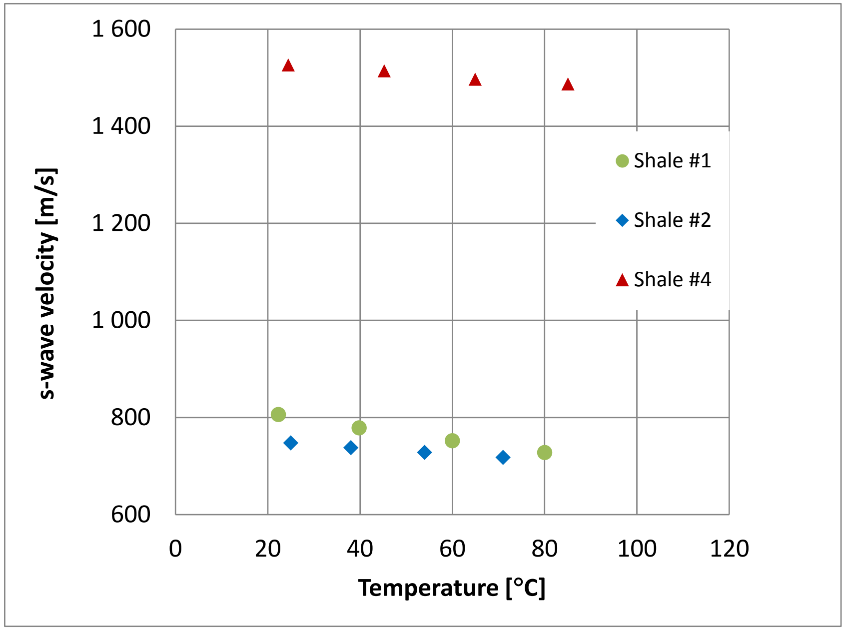
Bauer et al., Euroconference 2011

Temperature dependence of ultrasonic velocities in shales

Core-plug measurements with subsurface shales covering a wide range of depths, porosity, and clay content:

Shale	Age	Depth [mTVD]	Porosity [%]	Clay cont. [wt%]
#1	Paleocene	2620	32	84
#2	Upper Miocene	1730	40	42
#3	Miocene	1750	53	40
#4	Upper Jurrasic	2390	12	73



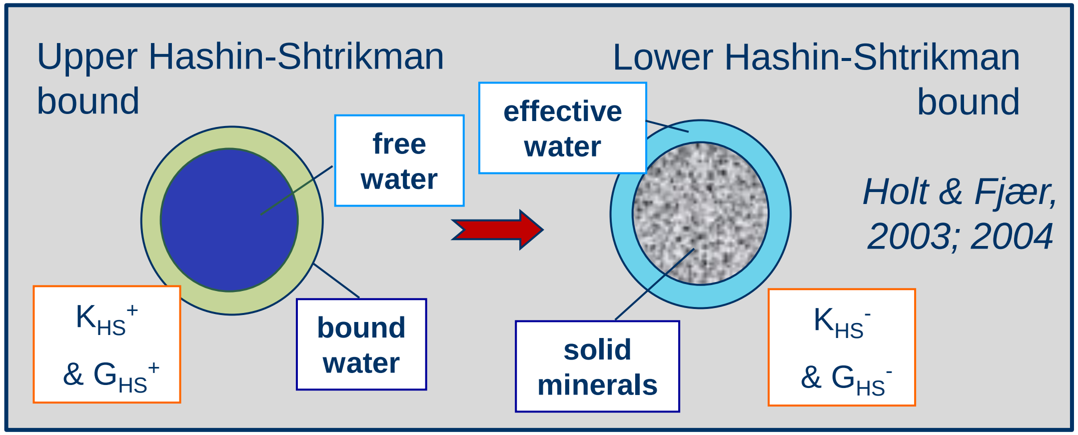


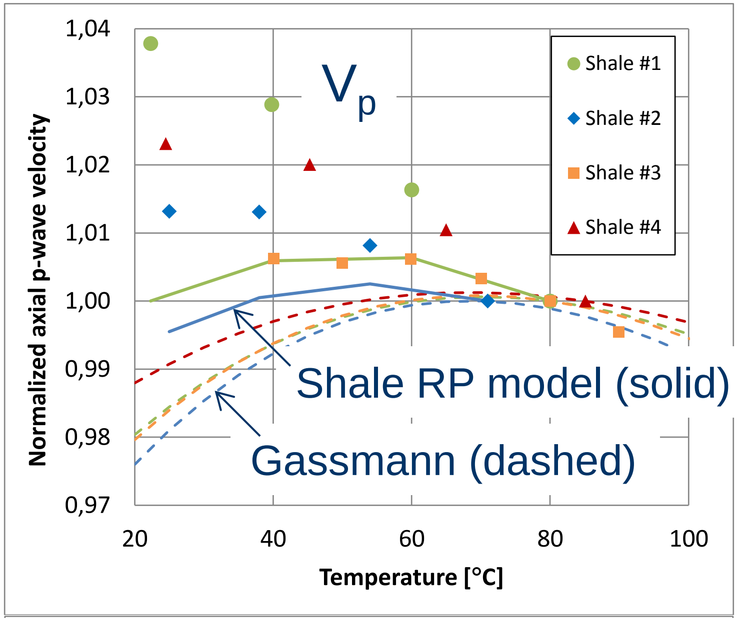
Temperature dependence of ultrasonic velocities in shales

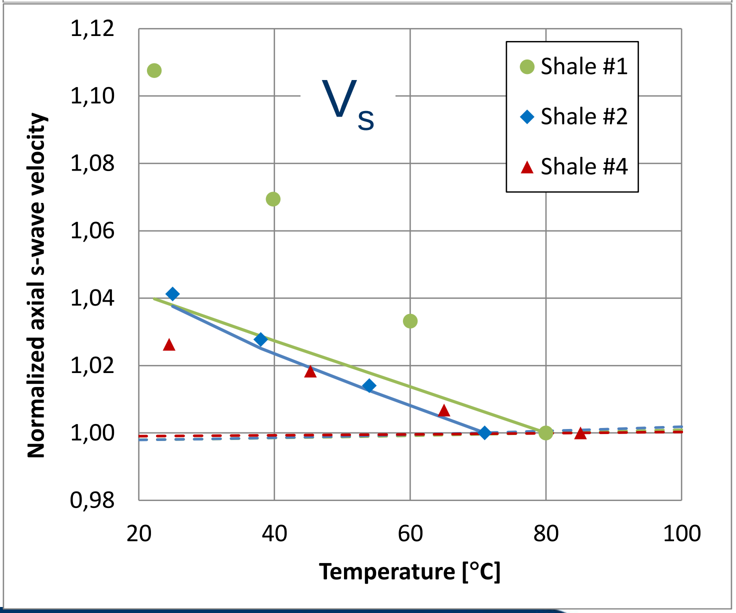
Gassmann model with temperature-independent dry-rock moduli:

- Strong deviation from experimental data
- Gassmann model does not take bound water into account

SINTEF's Shale rock physics (RP) model accounts for bound water. Temperature sensitivity of the bound-water stiffness is not known; assume same sensitivity as that of ice ⇨ trend in the right direction, still strong deviations







Temperature dependence of ultrasonic velocities in shales

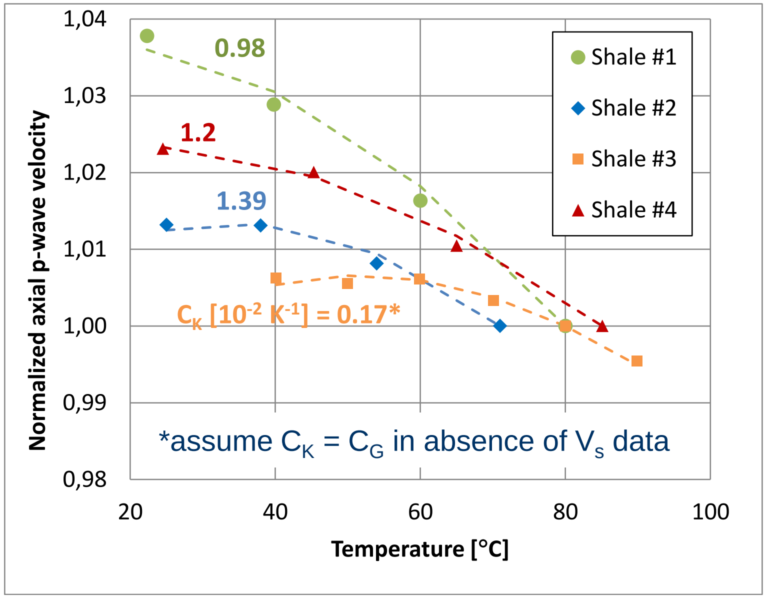
<u>Emperical approach:</u>

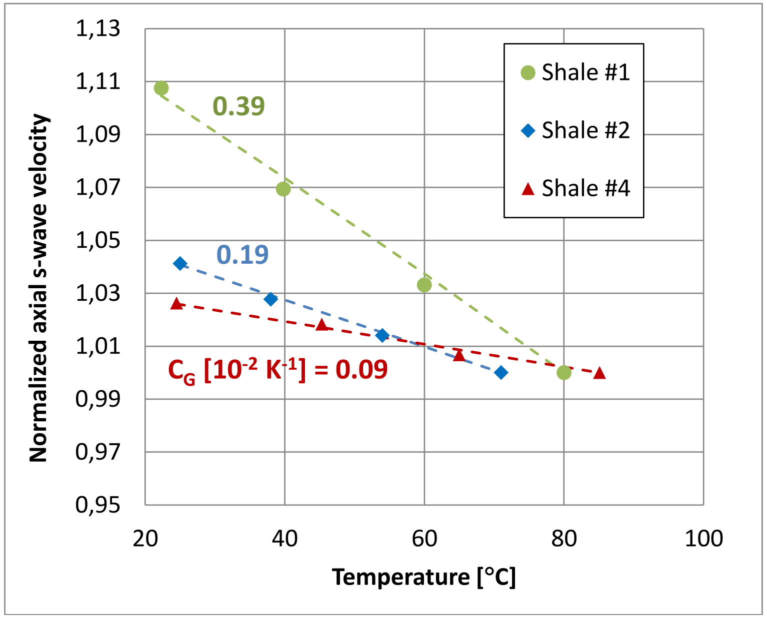
Apply Gassmann model and assume linear temperature dependences of drained-rock moduli:

$$K_{dry} = K_{dry,0}\,(1 - C_K \cdot \Delta T)$$

$$G_{dry} = G_{dry,0}\,(1 - C_G \cdot \Delta T)$$

- Good fit of experimental data for $C_K \approx 1.0 - 1.4 \cdot 10^{-2}\ K^{-1}$, and $C_K \approx 0.1 - 0.4 \cdot 10^{-2}\ K^{-1}$.
- Bound-water effects, fluid-rock interaction, etc. included in drained-rock modulus.

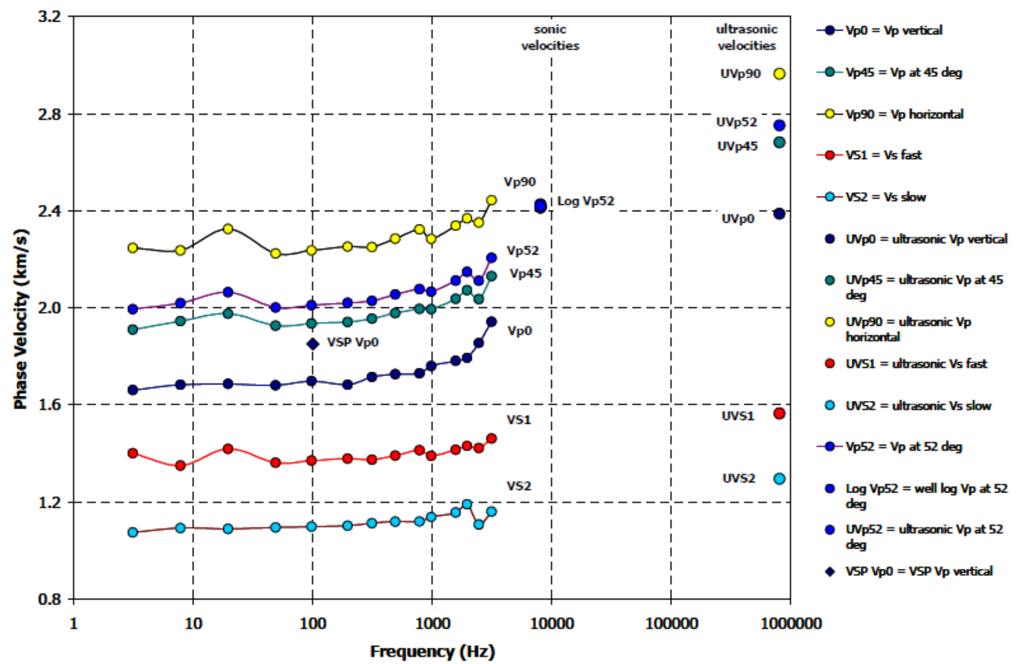




Temperature dependence of shale velocities – Dispersion effects

Is the temperature dependence of ultrasonic velocities the same as that of sonic and seismic velocities?

- There is evidence for <u>relatively large velocity dispersion in shales</u>
- It is likely that velocity dispersion is temperature dependent (previous compaction tests have shown smaller temperature dependence of static stiffness as compared to dynamic drained-rock stiffness)
- **Need for temperature-dependent dispersion measurements**



Duranti, Ewy, Hofmann (2006)

Thermally induced compaction of shales

Project work at NTNU Fall 2012 by Leni Marøen

w/ assistance from Eyvind F Sønstebø, Olav-Magnar Nes, Liang Wang (SINTEF Energy), Andreas Bauer & Rune M Holt

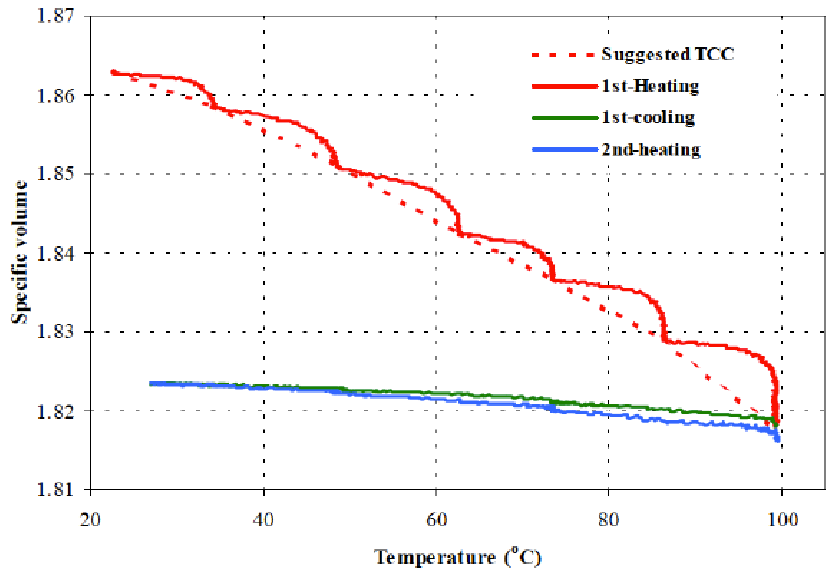
Motivation

- Significant contraction has been observed at elevated temperature (< 100°C) in previous shale experiments at SINTEF – artefact or reality?
- Thermally induced compaction could have significant impact on caprock integrity and wellbore stability

Thermally induced compaction of shales

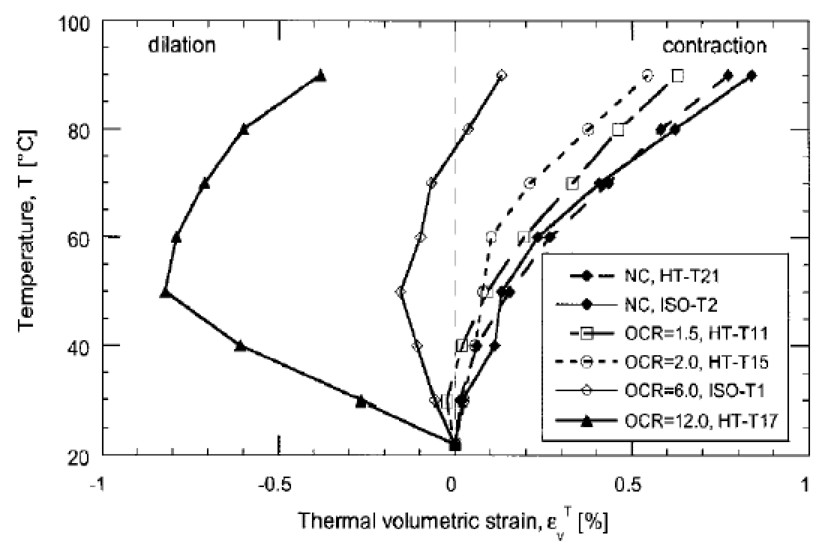
Literature study

Thermal compaction of reconstituted clay (Ghahremannejad, 2003): Largely plastic behaviour during initial heating, elastic behaviour during cooling and reheating



Stress history dependent thermal behaviour of kaolin clay during heating; initial consolidation at 0.6 MPa (Cekerevac et al., 2004)

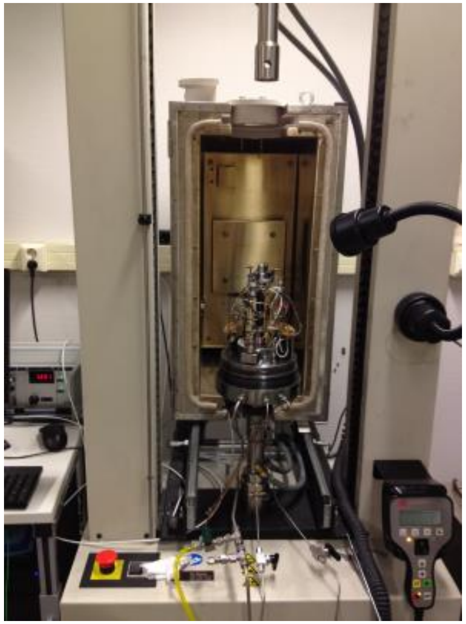
Normally consolidated samples show contraction; heavily overconsolidated samples show dilatancy.

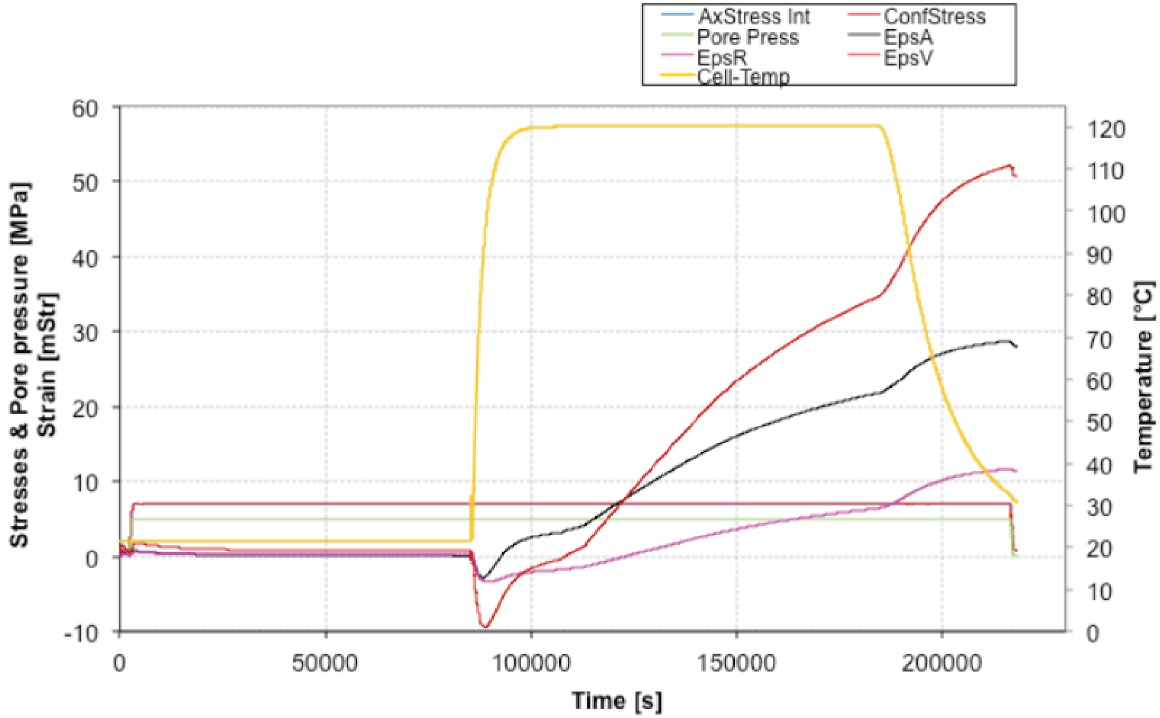


Thermally induced compaction of Pierre shale

Experimental observations

Drained heating of Pierre Shale @ 7 MPa (isotropic) external stress & 5 MPa pore pressure within the SMASH apparatus



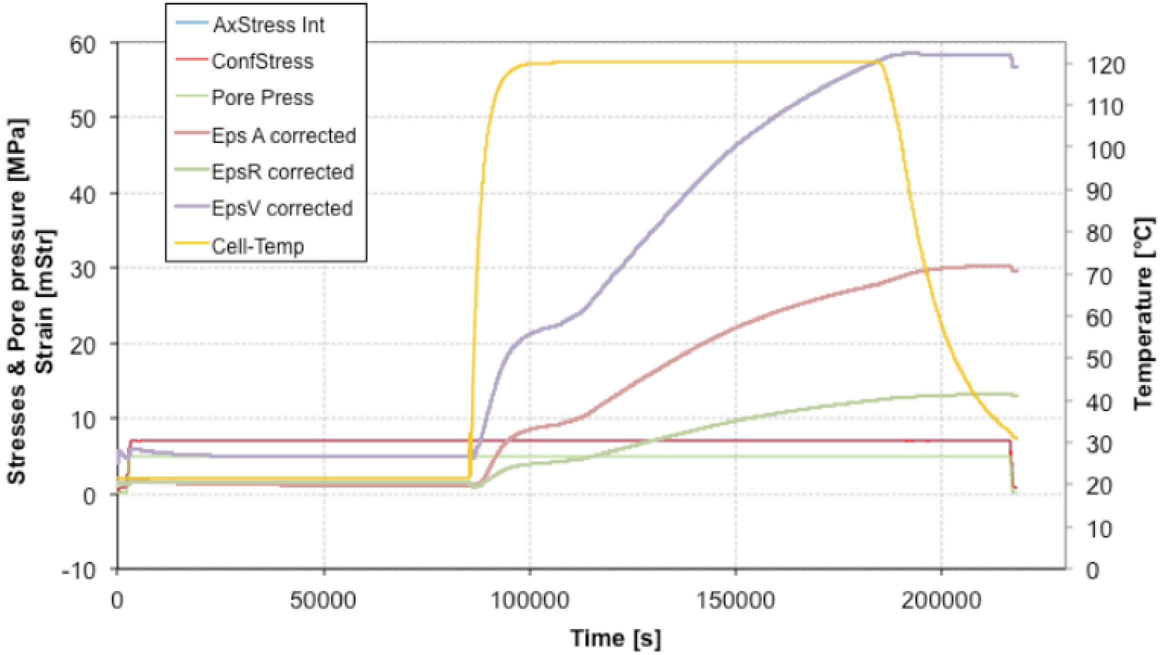


Upon heating, the sample expands, followed by time-dependent irreversible compaction

Thermally induced compaction of Pierre shale

Experimental observations

Strain data corrected with the thermal expansion coefficient, estimated from the cooling stages (when elastic behaviour can be assumed) ($\alpha_{T,vol} = 19 \cdot 10^{-5}$ °C^{-1})



Significant contraction takes place as non-elastic creep.

The volumetric strain corresponds to porosity reduction from 19 to 14 %!

Thermally induced compaction of Pierre shale

P-Wave Velocity

- Strong velocity increase associated with thermally induced compaction
- Velocity drops during initial heating
- Significant velocity decrease at 120 °C indicates loss of "cementation"

SINTEF's Shale Rock Physics model: Choosing K_{bw}=3 & G_{bw} = 2.5 GPa, v_P (at room temperature) is estimated to 2383 m/s (v_S=1024 m/s) for 19 % porosity Pierre Shale
Reducing porosity to 14 % (as at 120 °C), v_P increases to 2708 m/s (without changing K_{bw} & G_{bw})

Conclusions

Thermal Rock Physics of Shales

- Relatively strong reduction of V_p and V_s with temperature (in the absence of thermally-induced compaction)
- Temperature dependence can be described by Gassmann theory by assuming a temperature-dependent drained-rock stiffness accounting for bound-water effects and rock-fluid interaction; better understanding needed
- Not clear if sonic and seismic velocity show same temperature dependence as ultrasonic velocities; need for velocity-dispersion measurements

Thermally-induced compaction of shale

- Significant thermally-induced compaction observed during heating of shale core plugs
- Not clear to what degree thermally-induced compaction would occur in the subsurface; might have significant impact on caprock integrity and wellbore stability; better understanding and more systematic studies needed.