Thermally induced compaction of shales

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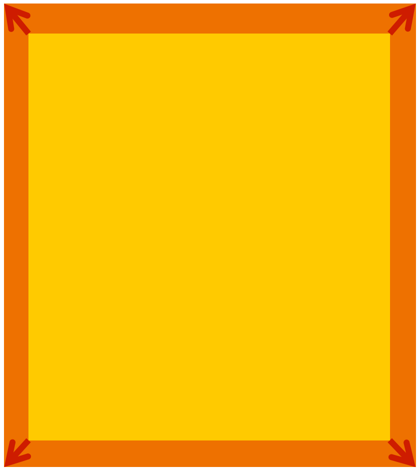
What we learn in physics:
Solids expand upon heating and retract upon cooling

Heat expansion



- Heat expansion and thermal stresses have a large impact on borehole stability and caprock integrity

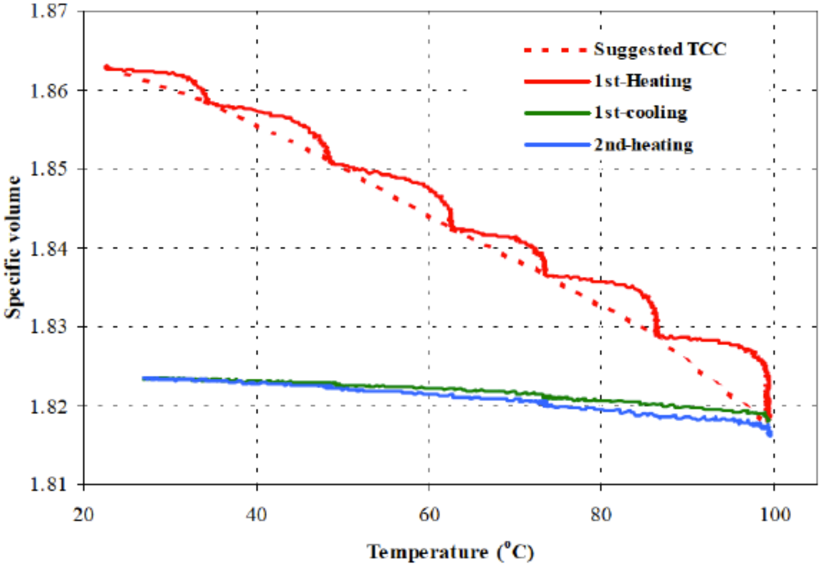
However …

- Heating may result in phase transitions, or non-reversible processes that involve an activation energy (chemical reactions, mechanical processes on the atomic scale)

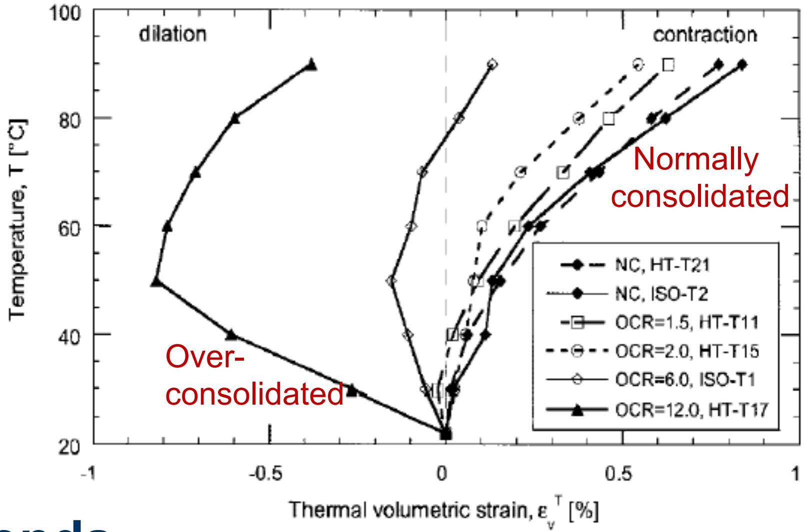
- Rock compaction is visco-plastic (creep behavior), and creep processes may be accelerated at increased temperature

Thermally induced compaction in clay

- ☐ 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 and Laloui, 2004)



Normally consolidated

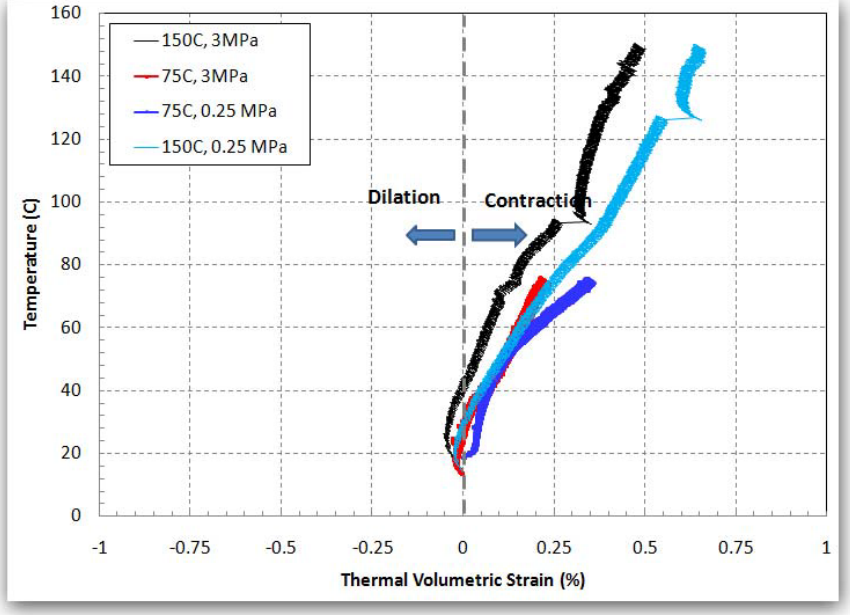
Over-consolidated

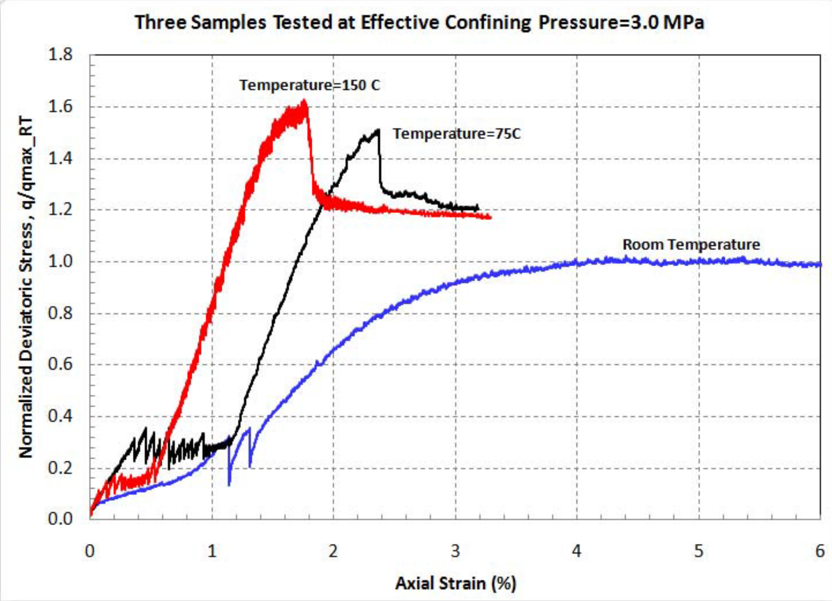
↳ **Degree of compaction depends on overconsolidation ratio**

Thermally induced compaction in caprock shale

B. Xu, Y.G. Yuan, and Z.C. Wang (2011)

- ☐ Thermal contraction of water-saturated Clearwater Shale (10–30% clay content) during drained heating to 75°C and 150°C.
- ☐ Sample stiffness and strength increase (for slow heating rates, allowing for pore pressure equilibration)

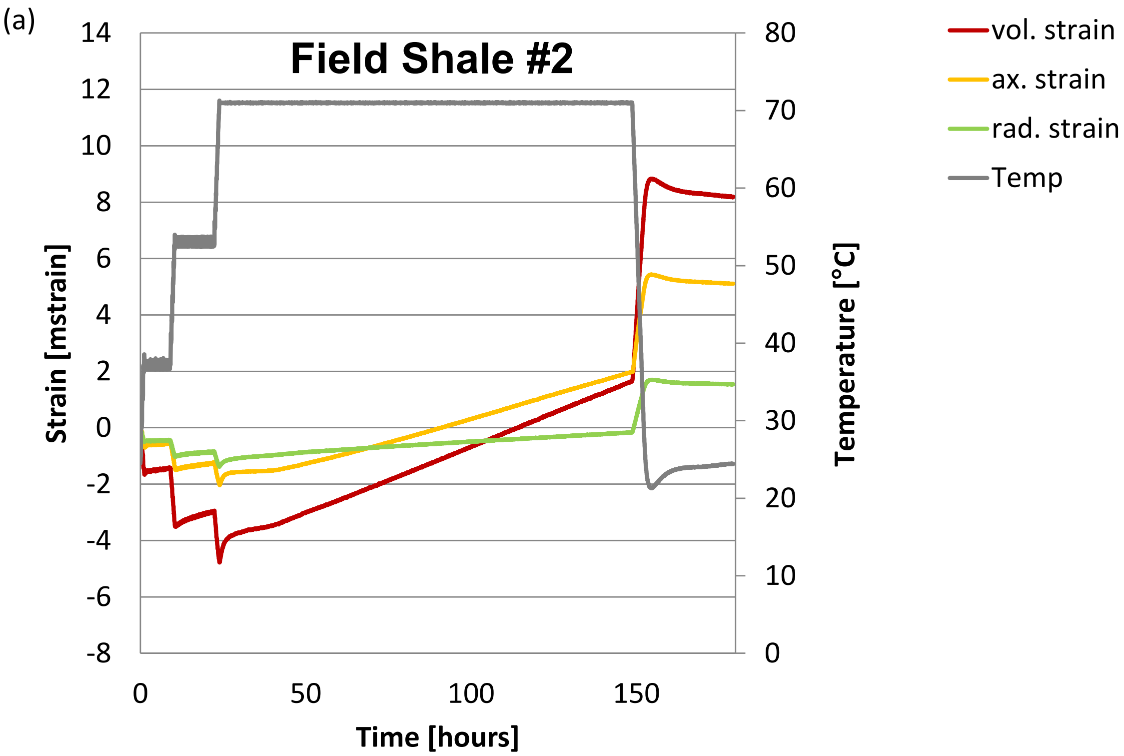


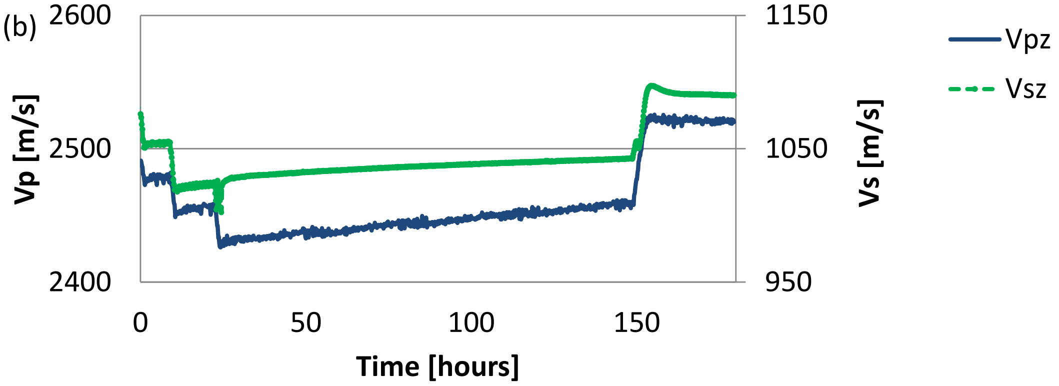


At SINTEF we perform extensive rock-mechanical testing of field shales within the Shale Rock Physics JIP and the Dynamic Borehole Stability JIP

For competent, (over-)consolidated caprock shales, we expected negligible or small thermally-induced compaction for temperatures around in-situ temperature

Test results reveal **large compaction upon heating** at temperature at or below in-situ temperature



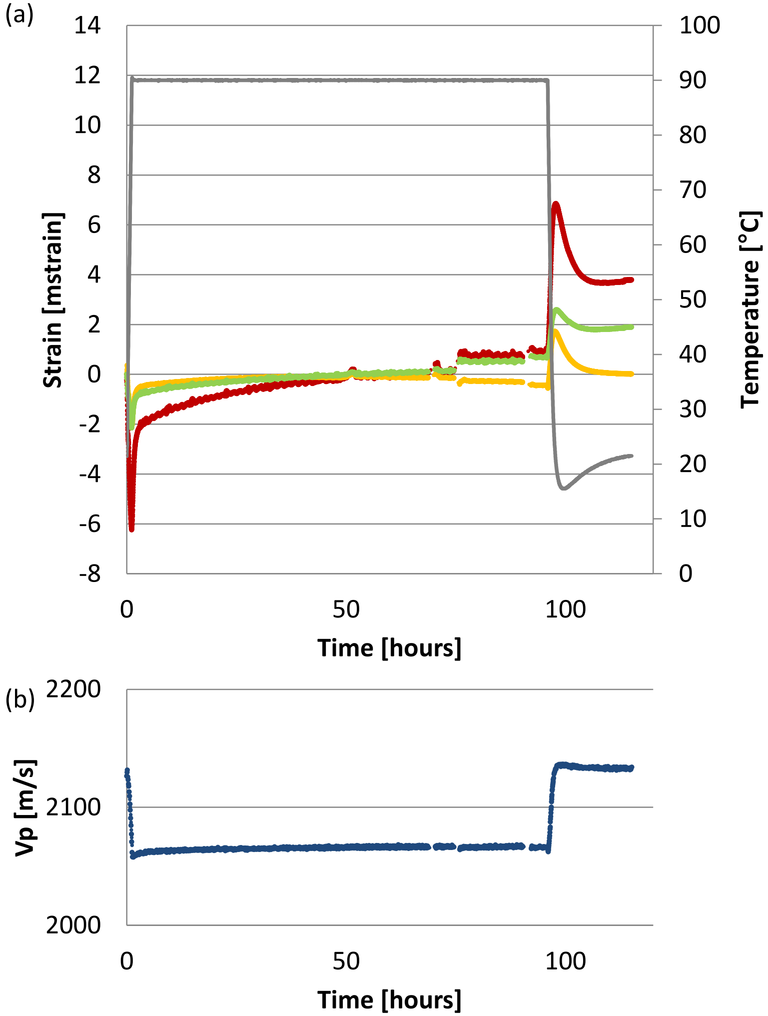


Experimental procedure:

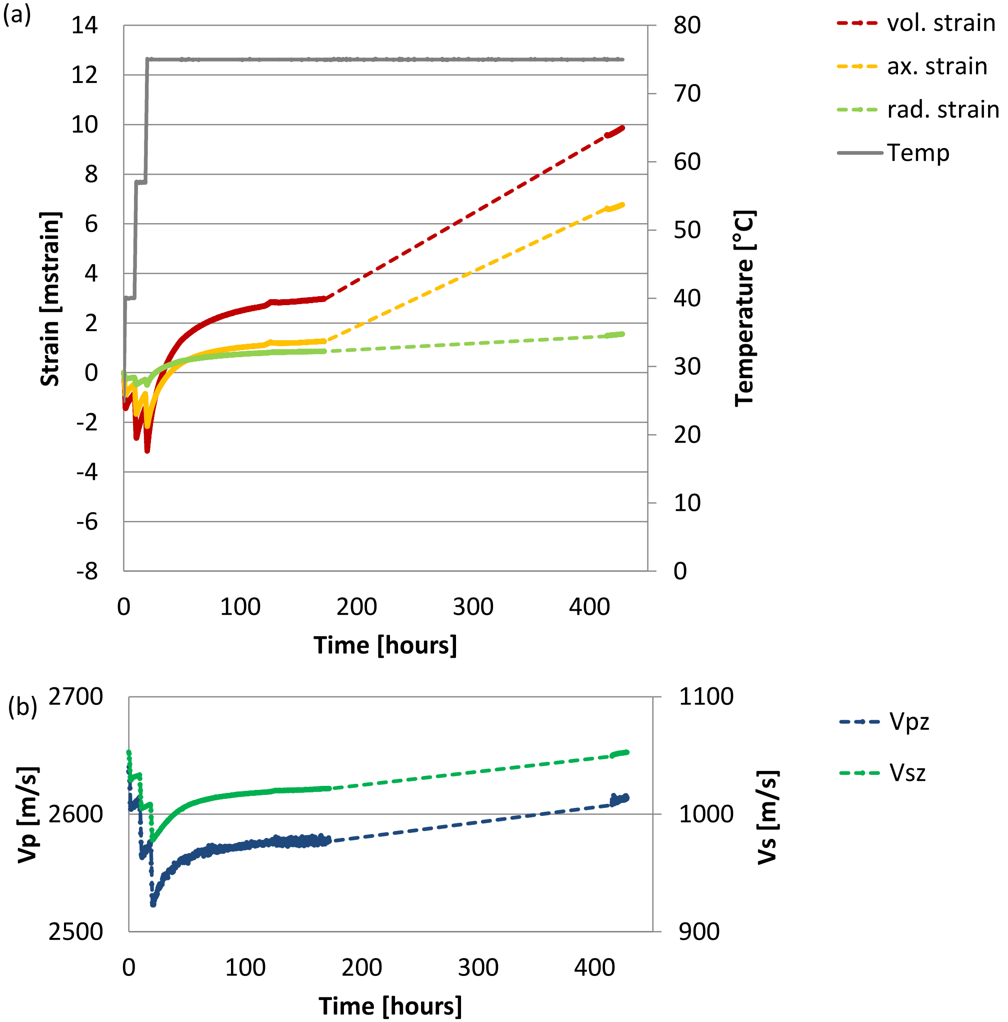
- Shale core plugs fully saturated and brought to in-situ stress condition
- Stepwise heating
- Strains and ultrasonic velocities recorded as a function of time
- Cooling to room temperature

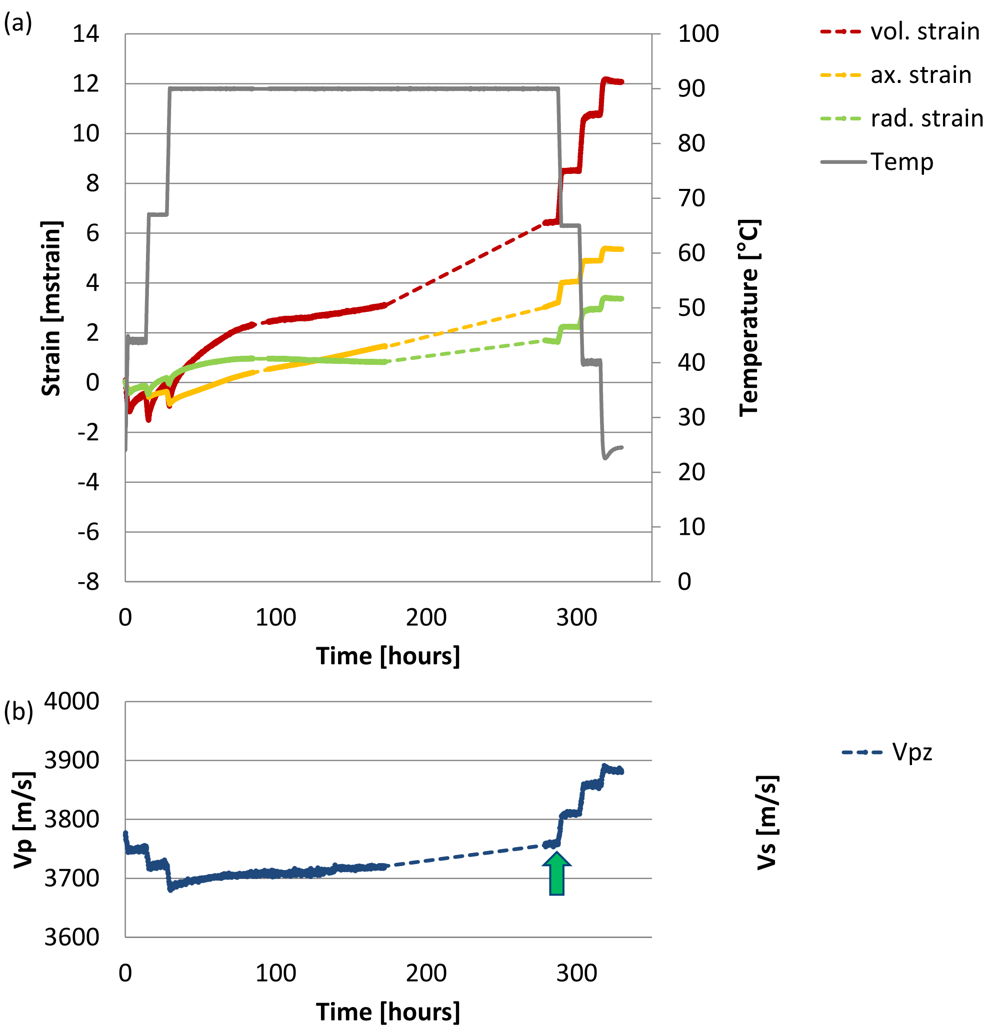
- Heating/cooling cycle results in 0.8% volumetric compaction
- Creep behavior (primary, secondary, and tertiary creep)
- Compaction is also reflected by increase in ultrasonic velocities v_P and v_S

Field Shale #1



Field Shale #3





Field Shale #4

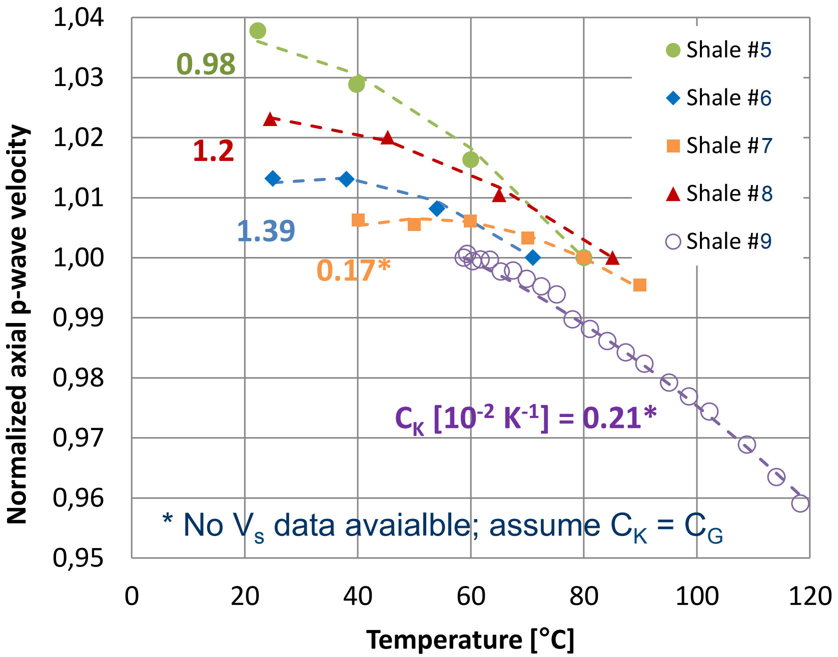
General features are the same for all shales:

- Heat expansion is followed by compaction (primary creep), with the compaction rate increasing with temperature (compaction may partly be explained by drainage effects)
- Reduction of compaction rate until a constant creep rate is established (secondary creep)
- Acceleration of compaction rate after a certain time (tertiary creep)
- Asymmetry between axial and radial strain
- Velocity increase (⬆) upon cooling is reversible; reason for relatively large, reversible velocity changes (both v_p and v_S) is not understood

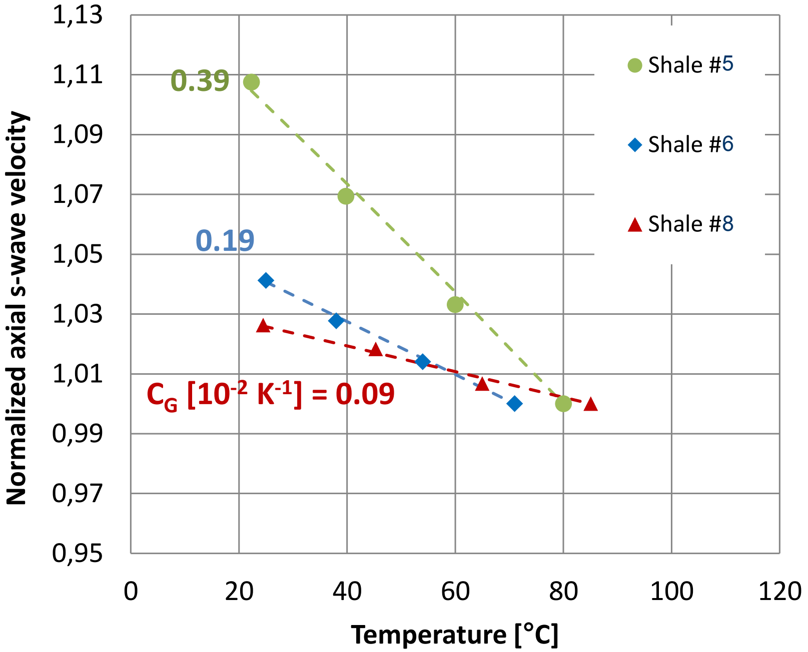
Reversible temperature dependence of ultrasonic velocities of Shales

- Apply Gassmann model
- Assume linear temperature dependence of dry-rock stiffness:

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

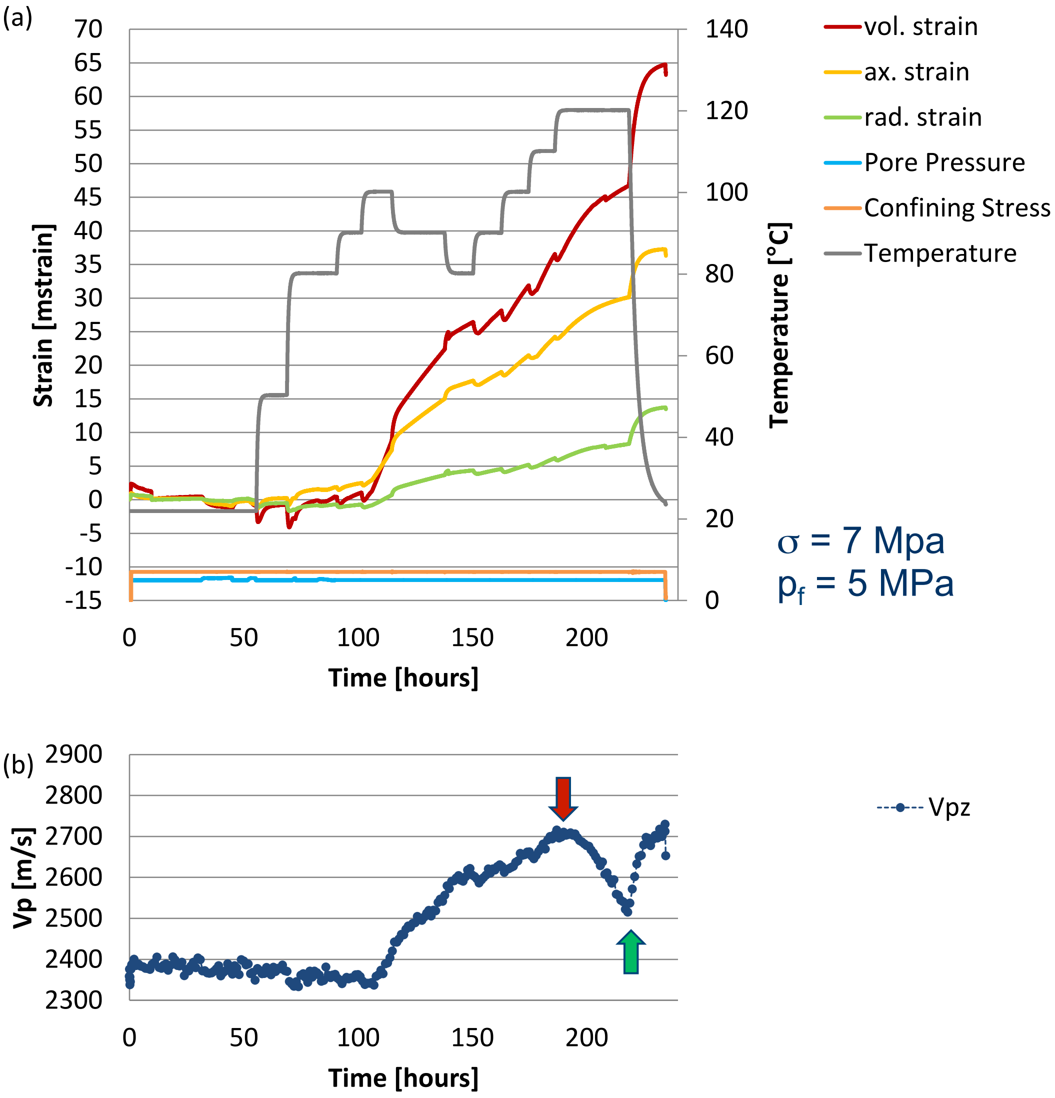


* No V_s data avaialble; assume $C_K = C_G$



Good fit can be obtained by selecting the right temperature-sensitivity coefficients; physics not understood yet

Thermally-induced compaction in Pierre shale (outcrop)

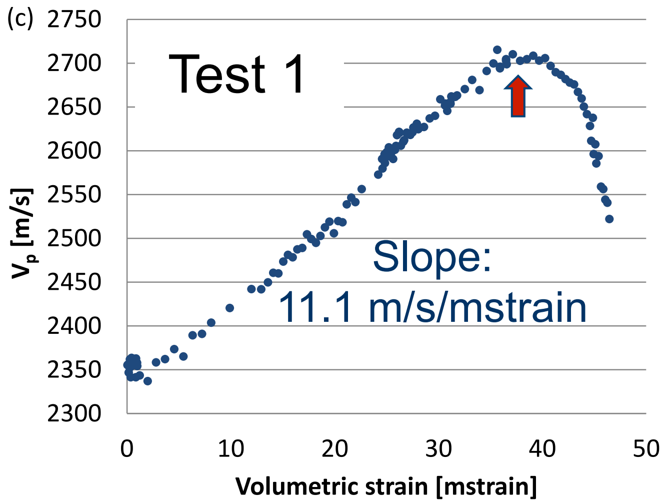


σ = 7 Mpa
p_f = 5 MPa

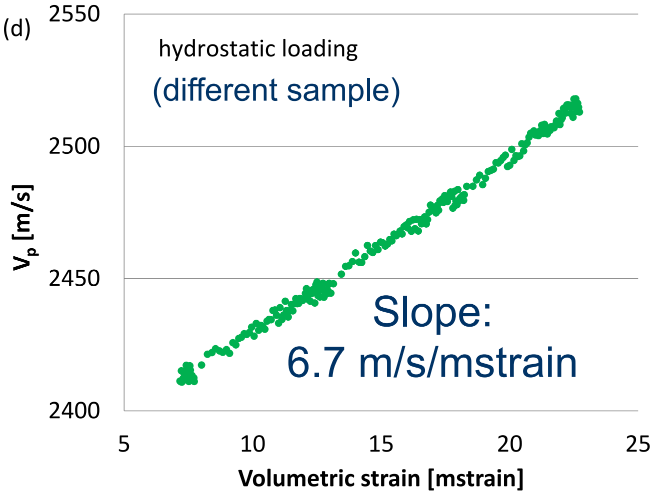
- Volumetric compaction of 6.5% induced by heating to 120°C
- Strong increase in compaction for T ≥ 80°C
- Temperature dependence of creep rates is consistent with Arrhenius law for thermally activated processes ($\propto e^{-E_a/k_B T}$)
- Strong increase in v_P
- velocity decrease (⬇) during consolidation phase at 120°C possibly caused by rock failure at large strains
- Velocity increase (⬆) upon cooling

Thermally-induced compaction in Pierre shale (outcrop)

Heat-induced compaction

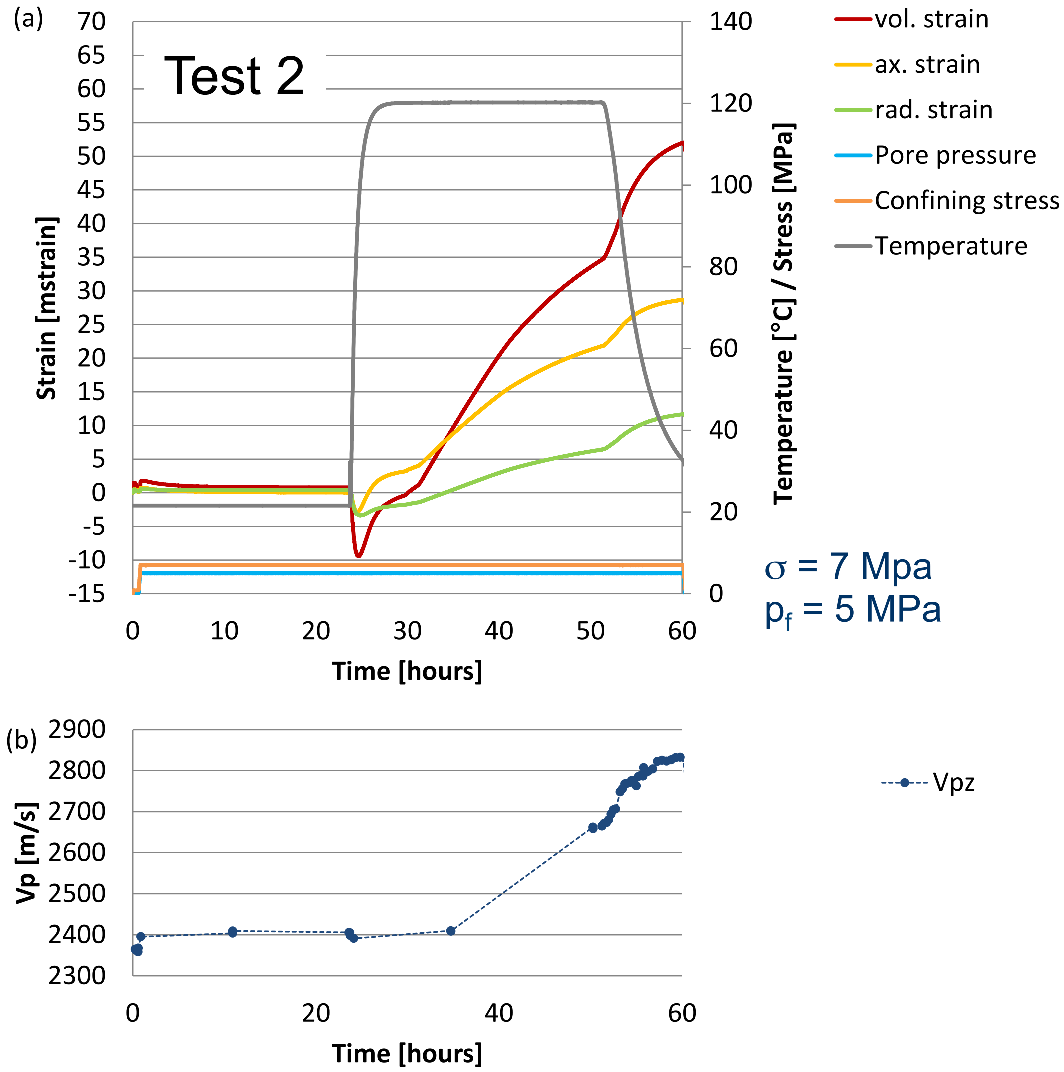


Stress-induced compaction



- Nearly linear dependence of v_P on vol. strain
- Volumetric-strain dependence comparable to that measured during hydrostatic loading, suggesting that velocity changes are mainly controlled by volumetric strain (porosity changes).
- <u>Field shales:</u> volumetric-strain dependence of velocities during heat-induced compaction is by a factor 3 – 9 smaller than during hydrostatic loading, suggesting that heat-induced compaction has a different impact on the microscopic rock structure than stress increments

Thermally-induced compaction of Pierre shale (outcrop)



σ = 7 Mpa
p_f = 5 MPa

- Heating to 120°C in one step
- Observation of characteristic creep behavior at constant stress and temperature
- Irreversible volumetric compaction of 5.1%, which **corresponds to a porosity reduction from 19.2% to 14.1%**
- Irreversible increase of v_P by 423 m/s (17.6%)

Summary of test results

		porosity [%]	Clay [wt%]	Smectite [wt%]	σ'_{conf} [MPa]	T [°C]	$T_{in\text{-}situ}$ [°C]	$\Delta\varepsilon_{vol}$ [%]	ΔV_p [m/s]	ΔV_s [m/s]
Pierre shale (outcrop)	**test 1**	19,2	57,4	31,5	2	120		**5,1**	**423**	**-**
	test 2	19,2	57,4	31,5	2	120		**6,5**	**330**	**-**
Field shales	**#1**	34,2	64	0	4,9	90	74	**0,38**	**6**	**-**
	#2	20	56	29	8,2	71	50	**0,8**	**32**	**10**
	#3	18,6	65	53	10,5	75	75	**≈ 1,34**	**≈ 49**	**≈ 42**
	#4	5	69	0	19,1	90	103	**1,2**	**110**	**-**

- Very large thermally-induced compaction ($\varepsilon_{vol} > 5\%$) for outcrop shale at 120°C
- Large thermally-induced compaction ($\varepsilon_{vol} > 1\%$) for field shales #3 and #4 at temperatures at or below in-situ temperature
- No apparent correlation with initial porosity, smectite content, or applied stress
- Large compaction observed even in a highly compacted, low-porosity shale (shale #4)

Possible reasons for thermally-induced compaction in shale core plugs at or below in-situ temperature

1. **Core damage**: (micro-)cracks formed during core retrieval might not get closed again upon re-establishing the in-situ stress state. Heat may enhance crack healing.

   Relevance for field applications: Damage zone around borehole

2. **Heat-rate effects**: For high heat rates, pore pressure builds up in the rock as a result of fluid expansion and slow drainage, which can result in shear or tensile rock failure. Typical pore-pressure changes: ≈ 0.2 MPa/°C.

   Relevance for field applications: In shales, heat diffusion is generally faster than pore-pressure diffusion; rock failure as a result of pore-pressure increase is a likely to happen for large enough heating

Possible reasons for thermally-induced compaction in shale core plugs at or below in-situ temperature

3. **Brine chemistry**: Samples are exposed to synthetic brine, which might result in rock weakening for not perfectly matched brines

   Relevance for field applications: Drilling fluids may alter visco-plastic properties of surrounding shale formations

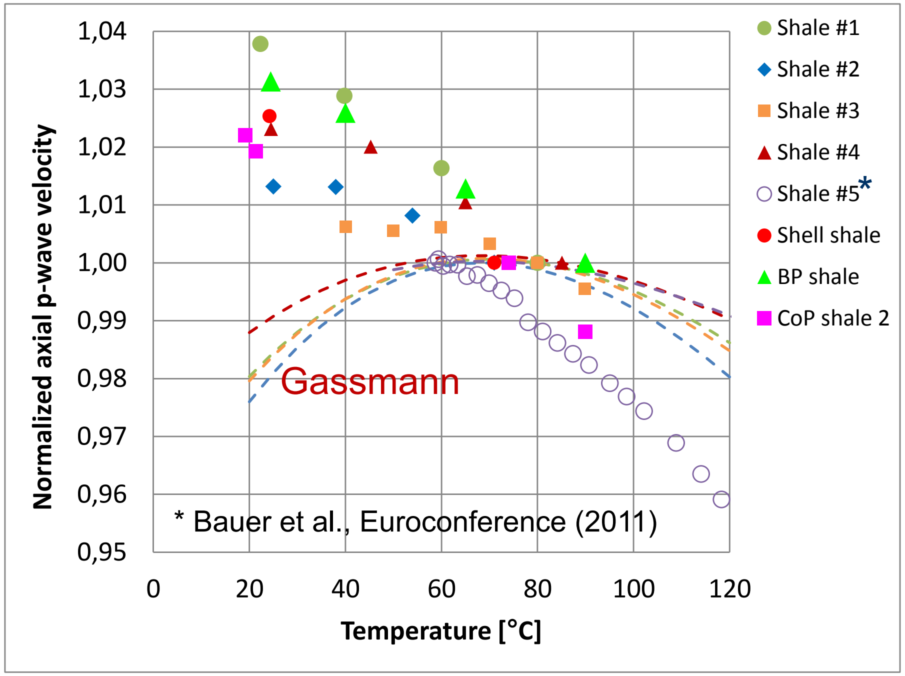
Summary

- ☐ Laboratory tests with core plugs of 5 different shales exhibit sizable compaction (up to > 1% volumetric strain) upon heating accompanied by increases in ultrasonic velocities
- ☐ Temperature are not high enough to cause chemical changes (e.g. smectite-illite transitions)
- ☐ Possible explanations for observed compaction include core damage, heat-rate effects, and brine-chemistry effects
- ☐ Thermally-induced compaction of shales may have strong impact on field applications such as steam injection

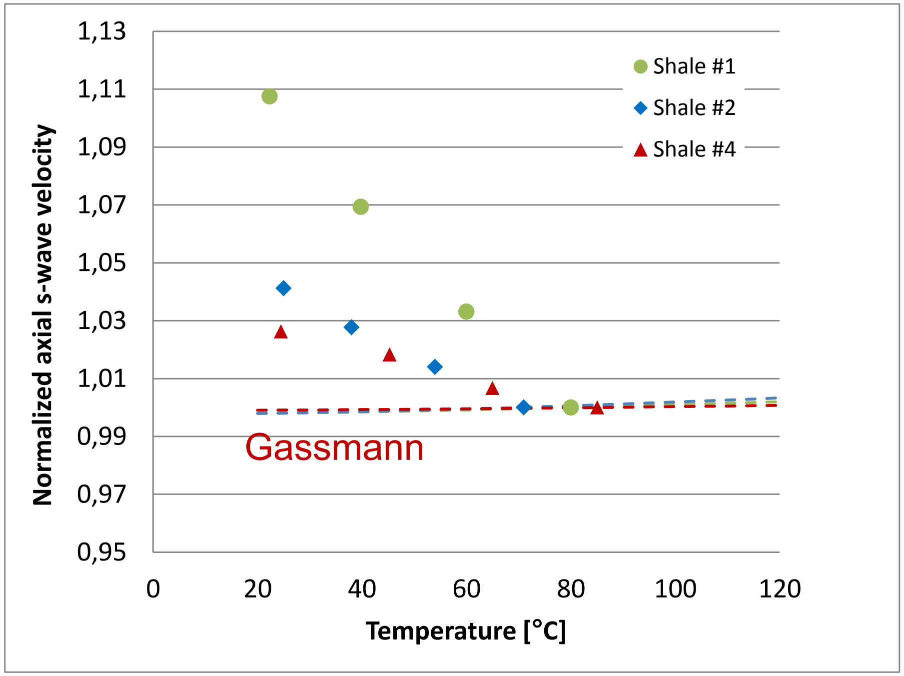
Backup slides

Temperature dependence of ultrasonic velocities of Shales

- Apply Gassmann model
- Assume temperature-independent dry-rock modulus

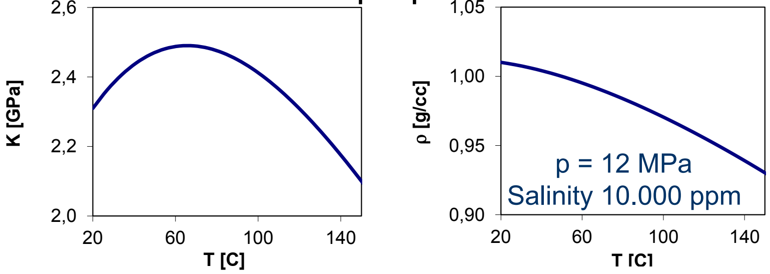


* Bauer et al., Euroconference (2011)



Gassmann model predicts much weaker temperature dependence and wrong trend at low temperatures

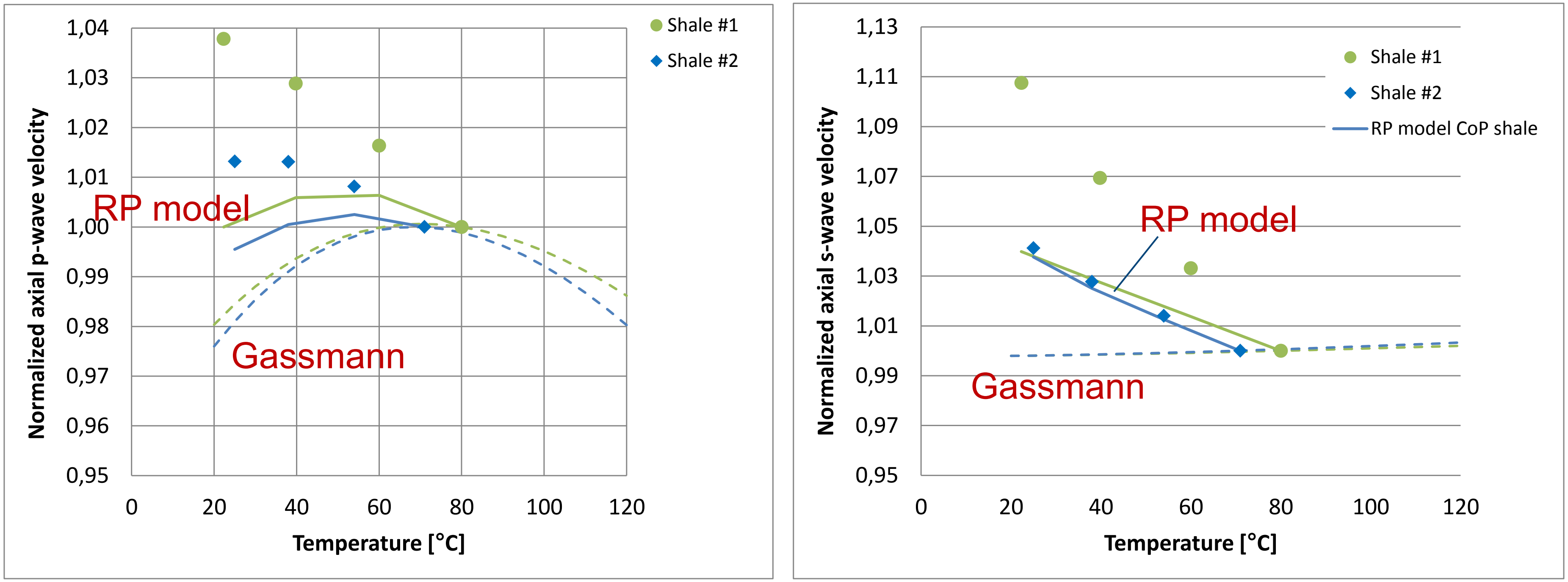
Brine properties



p = 12 MPa
Salinity 10.000 ppm

Temperature dependence of ultrasonic velocities of Shales

- Apply SINTEF's RP model
- Assume that temperature dependence of bulk and shear stiffness of bound water is the same as that of ice



The Shale RP model provides a better description than the Gassmann model (for temperature independent dry-rock stiffnesses) but still underpredicts the temperature dependence of Vp and Vs (except for shale #2 where a good match of the Vs data is obtained).

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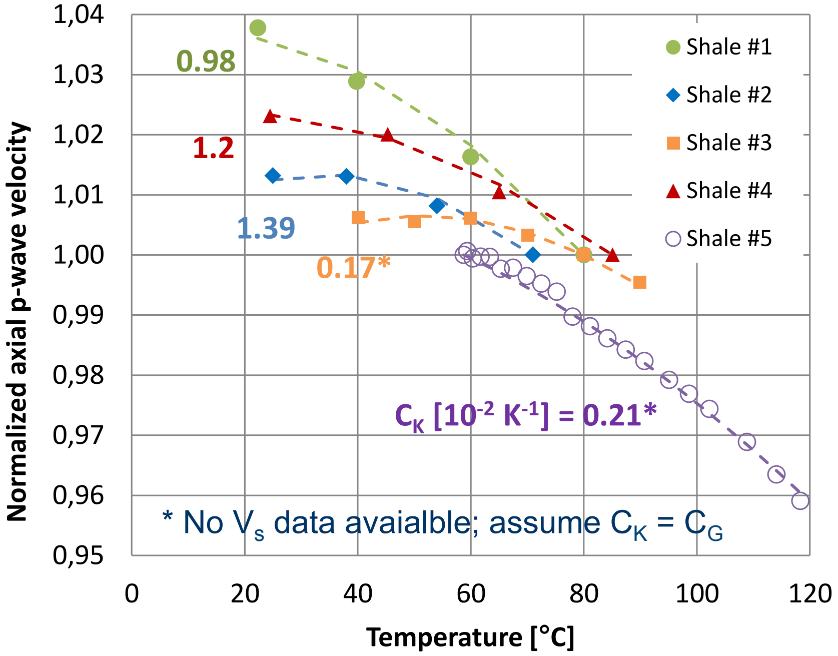

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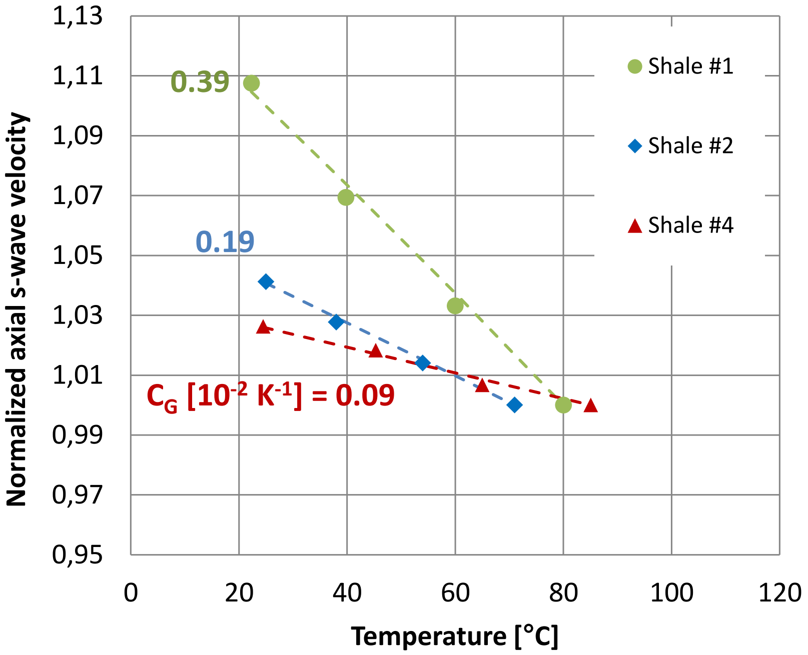

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