Temperature Dependence of Acoustic Velocities in Gas-Saturated Sandstones

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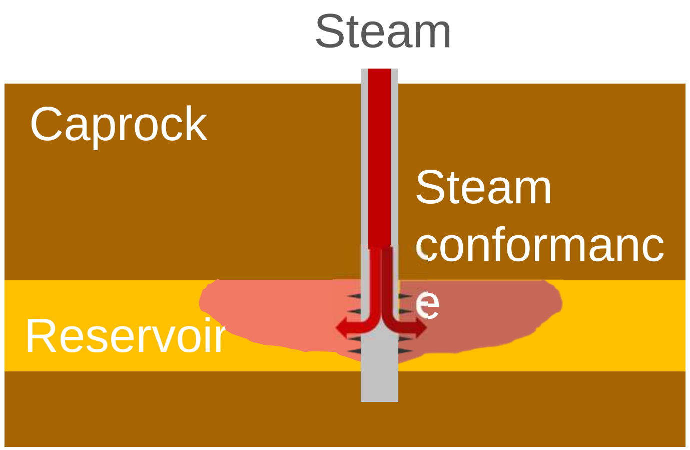
Monitoring of steam conformance

Temperature dependence of seismic velocities enables inversion of time-lapse (cross-well) seismic data for temperature changes in thermal EOR



- What is the temperature dependence of fluid and gas saturated rocks?
- Is the Gassmann model applicable?
- What is the effect of velocity dispersion?

Temperature dependence of ultrasonic velocities

Velocities: $V_p = \sqrt{\dfrac{K_{sat} + \frac{4}{3}\mu_{sat}}{\rho(T)}}$; $V_s = \sqrt{\dfrac{\mu_{sat}}{\rho(T)}}$

Gassmann theory: $$K_{sat} = K_{dry} + \frac{\left(1 - \dfrac{K_{dry}}{K_{gr}}\right)^2}{\dfrac{\phi}{K_{fl}(T)} + \dfrac{(1-\phi)}{K_{gr}} - \dfrac{K_{dry}}{K_{gr}^2}};$$

$$\mu_{sat} = \mu_{dry}$$

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

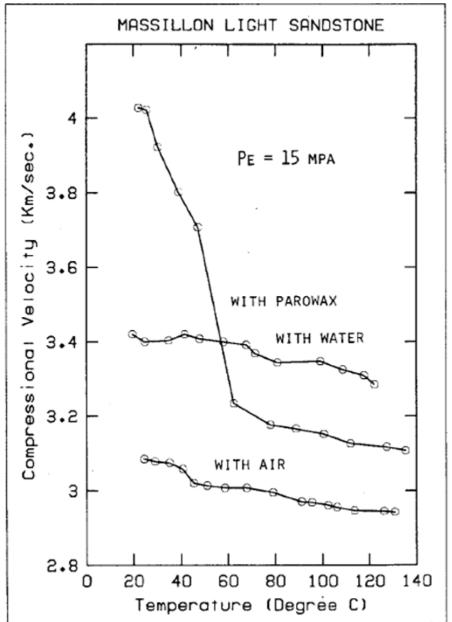


Fig. 3—v_p in Massillon sandstone with air, water, and Parowax.

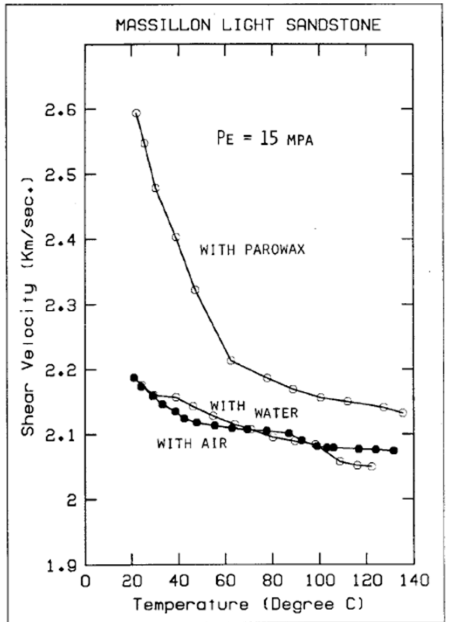


Fig. 4—v_s in Massillon sandstone with air, water, and Parowax.

Wang and Nur, SPE 15646

Measured temperature dependences of V_p and V_s are stronger than expected from Gassmann theory if we assume that the dry-rock stiffness is temperature independent:

- V_s should be nearly temperature. independent (except for some density effects)
- For (partially) gas-saturated rock, K_{fl} is small and little temperature dependence would be expected.

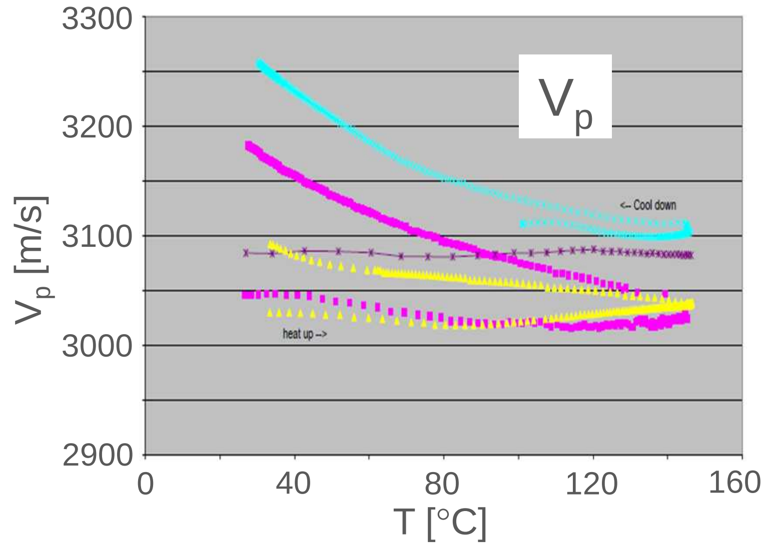
Dry-rock temperature dependence of V_p and V_s

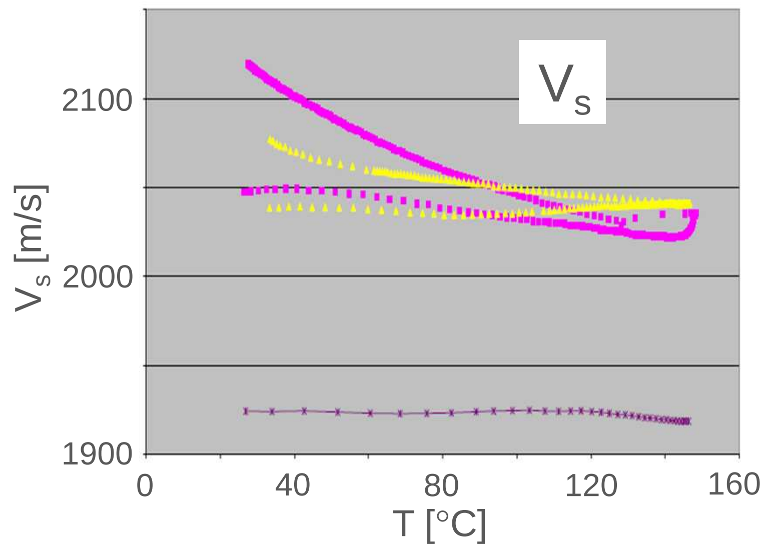
What is “dry”?

Presence of very small amount of water (e.g. condensation during cool down) results in sizable temperature dependence of V_p and V_s.

In the absence of any water (heated under vacuum), V_p and V_s are nearly temperature independent ($\Delta V_p/V_p < 10^{-4}\ K^{-1} \cdot \Delta T$).

Experiments have to be carried out under well-defined conditions to yield reproducible results.





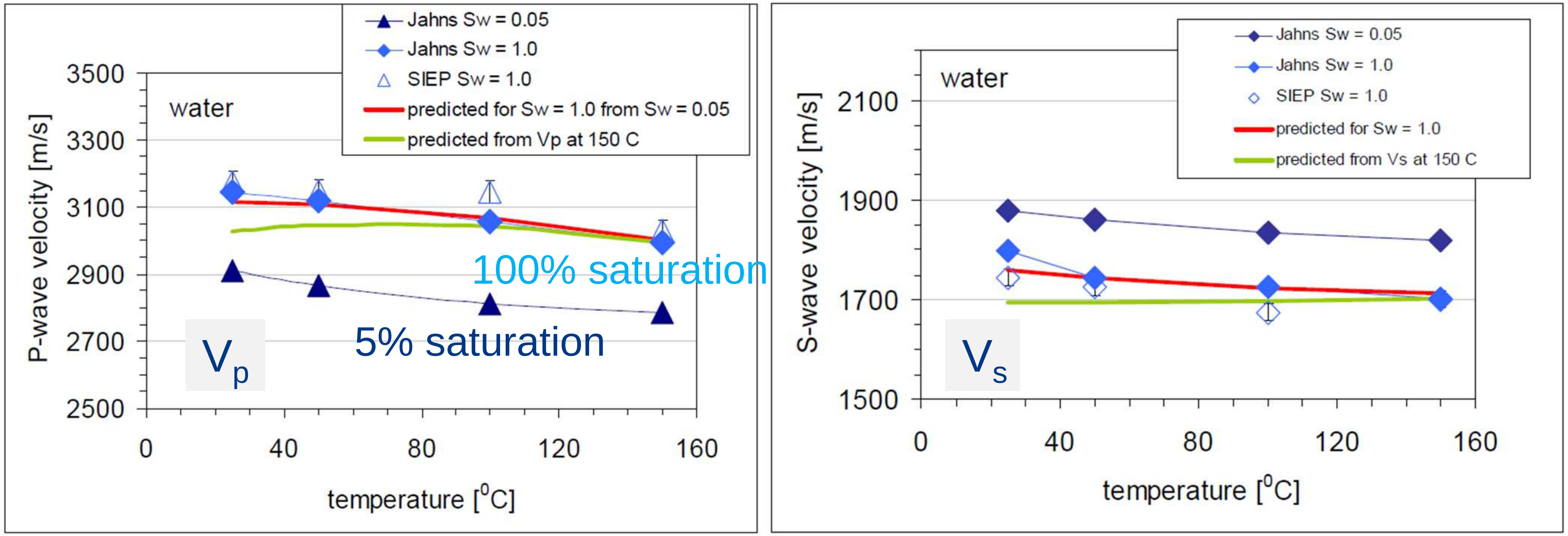
“Dry”-rock temperature dependence of V_p and V_s

Is the Gassmann model applicable if we define “dry rock” as the rock matrix in contact with a small amount of pore fluid (wetting of grain surfaces and grain contacts) ?

Approach:

- Measure temperature dependence of “dry” rock stiffness (with well-defined fluid saturation)
- Apply Gasmann model to predict V_p and V_s of fully saturated rock

V_p and V_s of Castlegate sandstone – Temperature dependence



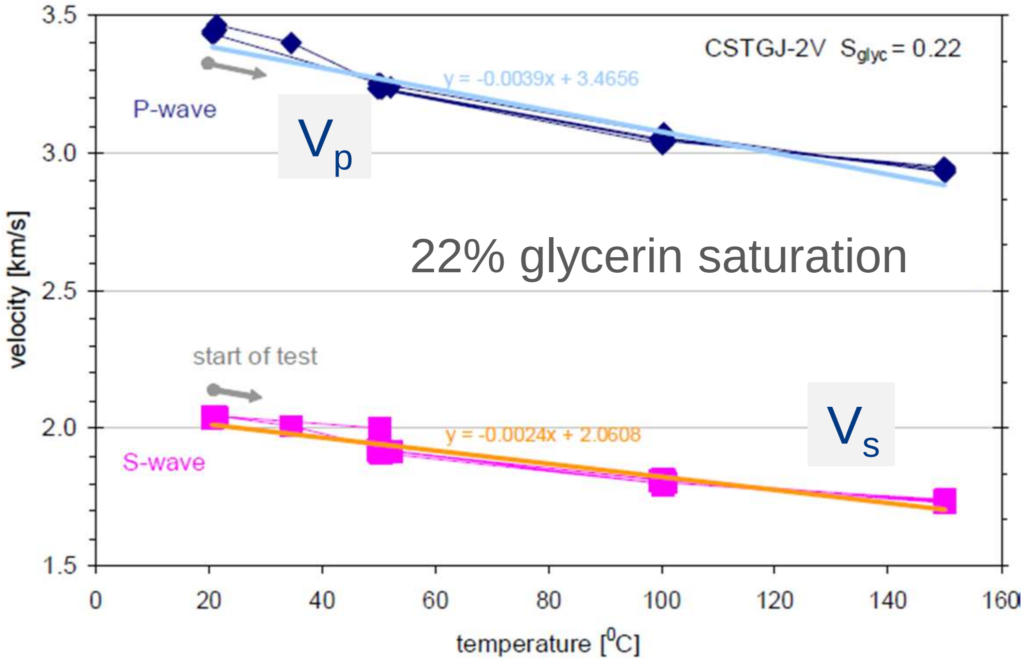
Test done by Gesteinslabor Dr. Jahns, Germany (www.gesteinslabor.de)

Temperature dependence of Vp and Vs can be described by the Gassmann model by taking the temperature dependence of the "dry"-rock stiffness into account

V_p and V_s of Castlegate sandstone – Temperature dependence

"Dry"-rock stiffness depends on pore fluid:

Higher stiffness and enhanced temperature dependence for glycerin as pore fluid



- Compressibility of glycerin is smaller than that of water at RT
- Glycerin has high viscosity at RT
- Viscosity is strongly temperature dependent

Test done by Gesteinslabor Dr. Jahns, Germany

Velocity dispersion

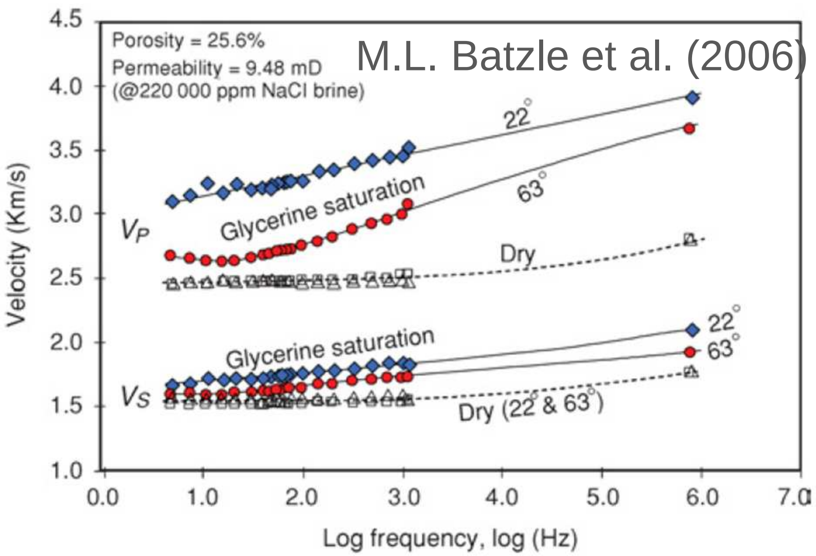
Is the temperature dependence of Vp and Vs at seismic frequencies as high as at seismic frequencies?

Previous studies have shown that the “dry”-rock stiffness is frequency dependent due to time-dependent relaxation processes

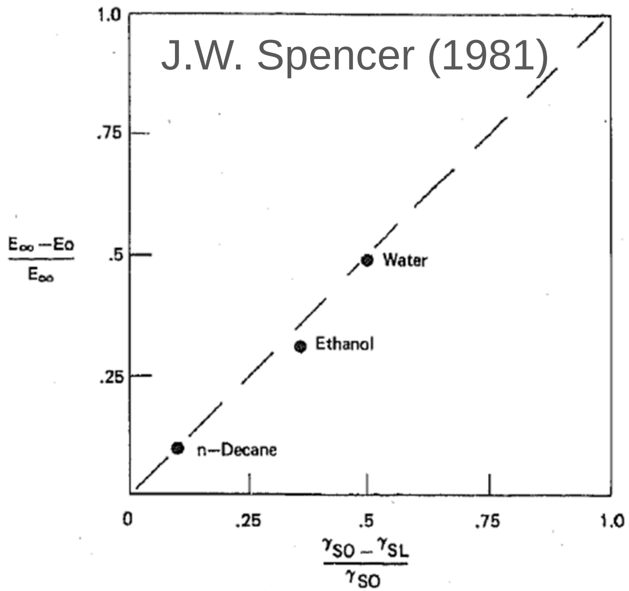
Relaxation times are temperature dependent ⇨ temperature dependence of “dry”-rock stifness

Origin of velocity dispersion:

(A) Local flow (micro cracks, etc.)

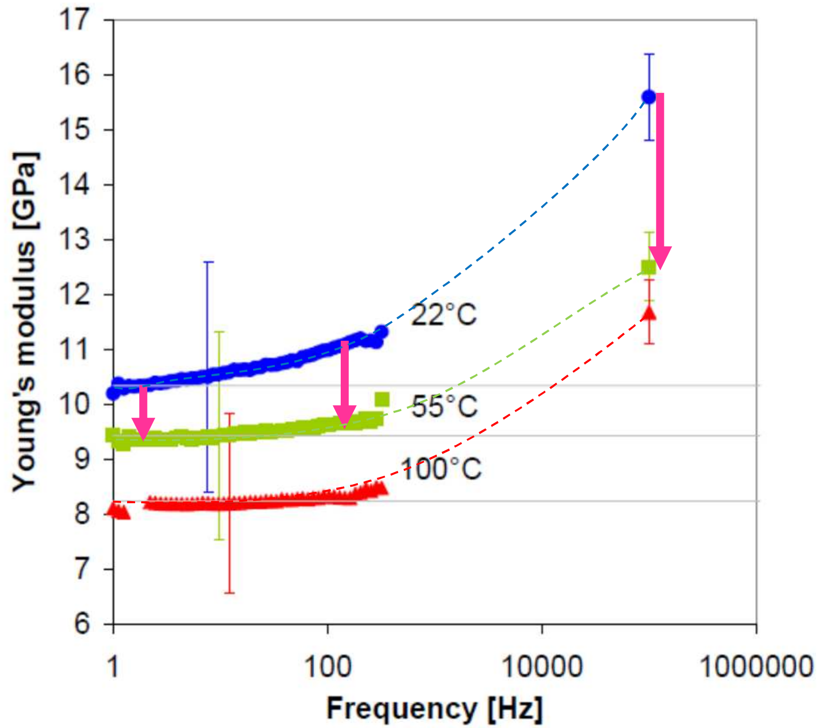


(B) rock-surface energy



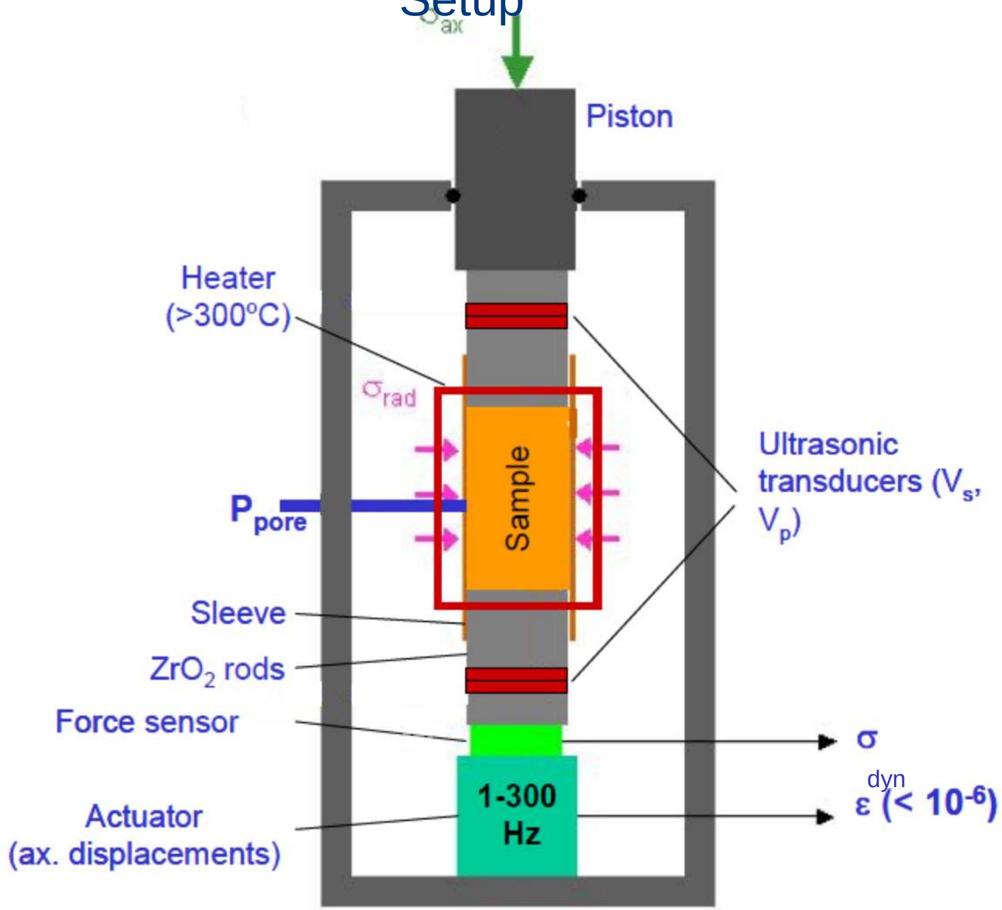
Velocity dispersion in heavy oil sands

Dynamic Young's modulus



- Decrease of dispersion with temperature
- Little dispersion at seismic frequencies ⇨ Gassmann model applicable at seismic frequencies

Experimental Setup



Conclusions

- Gassmann model is applicable for describing the temperature dependence of V_p and V_s of fluid-saturated sandstones if **temperature dependence of “dry”-rock stiffness** is taken into account.

- As “dry”-rock stiffness we define the stiffness of the rock with a small but finite fluid saturation ⇨ **“dry”-rock stiffness depends on pore fluid**.

- **Temperature dependence of V_p and V_s might be significantly smaller at seismic frequencies** than at ultrasonic frequencies due to velocity dispersion effects ⇨ more studies are needed for better understanding

Q & A