Seismic dispersion in shale: The role of saturation

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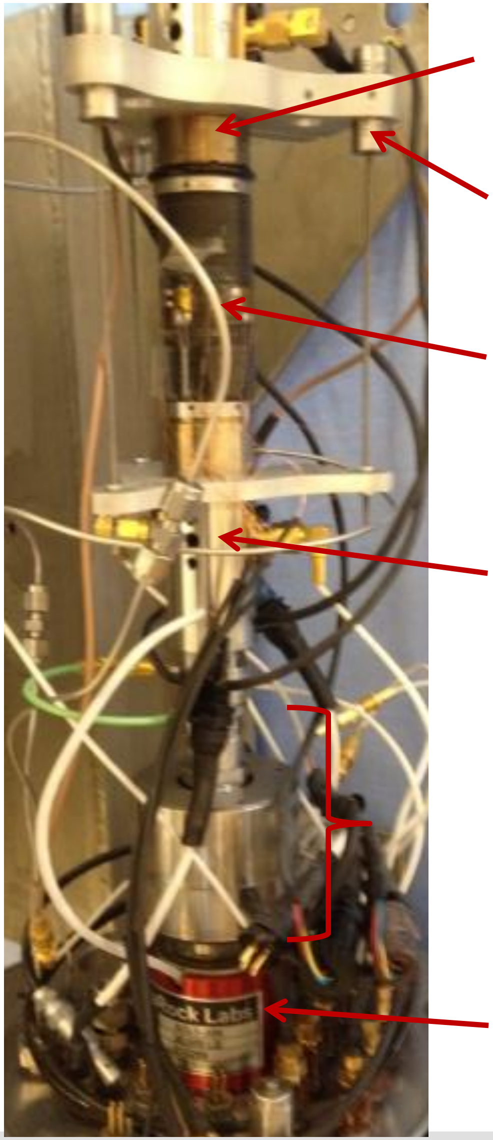
Motivation

- ☐ There are no reliable rock-physics models available that allow for estimating the gas saturation of shales (overburden shales; gas shales) from seismic data. We still don't have a good understanding of the impact of partial gas saturation on rock stiffness and seismic dispersion.

- ☐ In this work, we have measured dynamic stiffness and seismic dispersion of Mancos and Pierre shale with partial water saturation.

New compaction cell for seismic-dispersion measurements

- ☐ **Compaction tests**
- ☐ **Control of confining stress, axial stress, and pore pressure**
- ☐ **Ultrasonic velocities, v_P, v_S**
- ☐ **Dynamic stiffness (Young's modulus, Poissons's ratio) at seismic frequencies (0.1 – 150 Hz)**



Endcap with ultrasonic transducers (Vp, Vs) and pore-fluid line

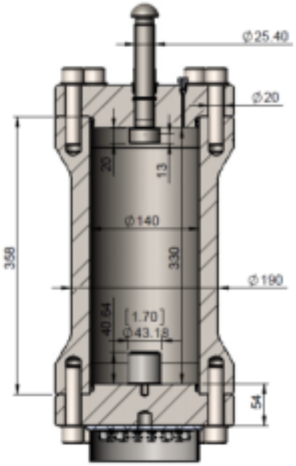
LVDT

Rock sample (1" diameter) with 8 strain gages (4 axial, 4 radial) glued to it (sleeve was removed)

Endcap with ultrasonic transducers (Vp, Vs) and pore-fluid line

Low-frequency unit consisting of piezoelectric actuator and piezoelectric force sensor

Internal load cell

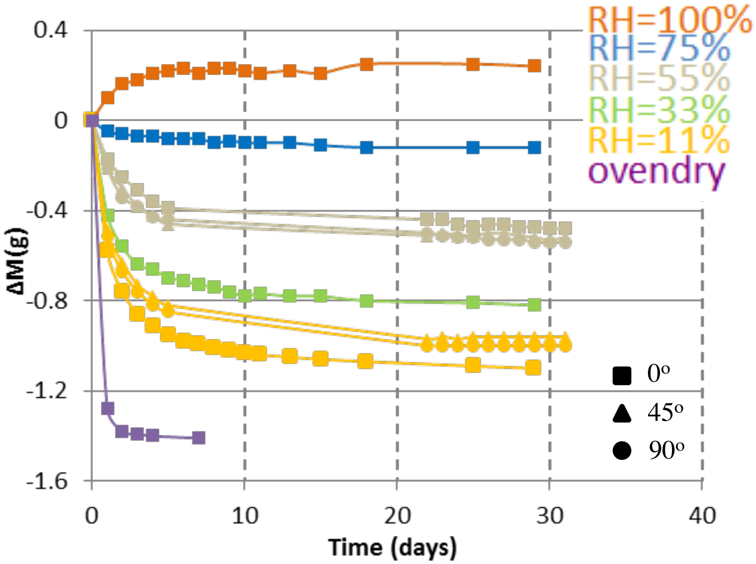


Sample preparation

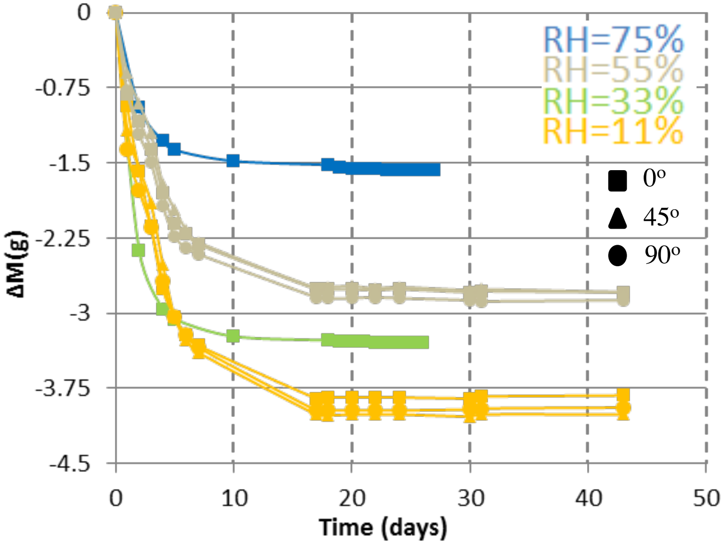
- ❑ Samples were stabilized in desiccators with different relative humidities (RH)

- ❑ Saturations were calculated from weight losses/gains

Mancos shale



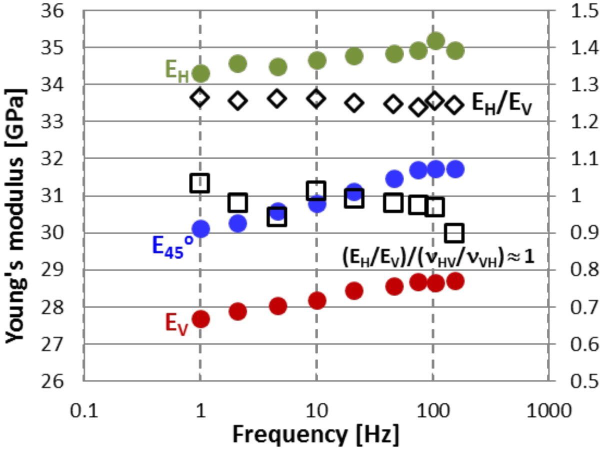
Pierre shale



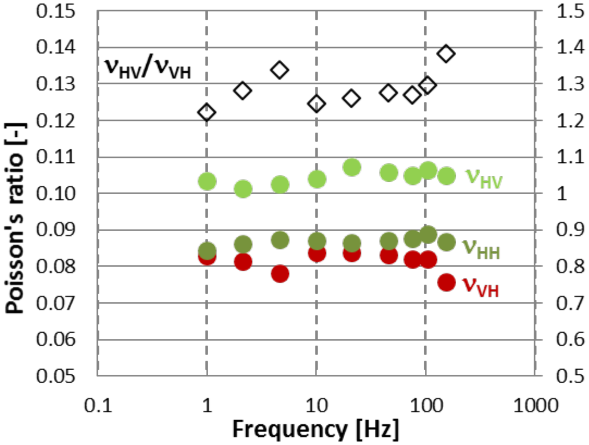
- ❑ For a full characterization of the dynamic-stiffness and velocity anisotropy, measurements were done for three different sample orientations (0°, 45°, 90° with respect to bedding). Measurements for all three orientations were only done for two saturation states (11% and 55% RH). For the other saturation states, the Thomsen anisotropy parameters were extrapolated

Saturation effects: Mancos Shale – seismic-frequency data

RH = 11%

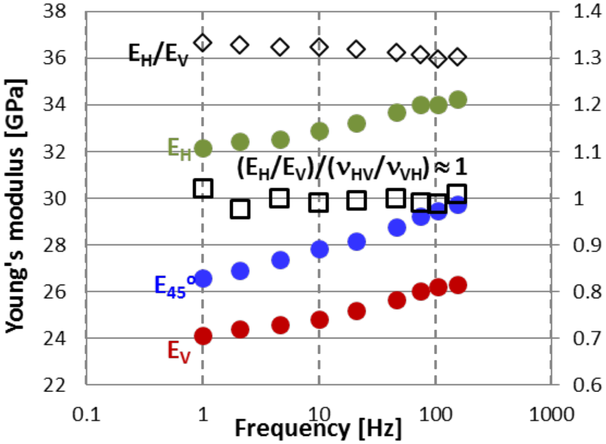


RH = 11%

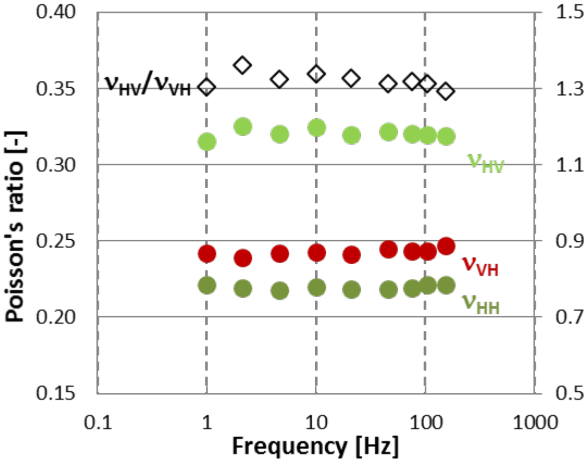


Young's moduli and Poisson's ratios obtained with 0°, 45° and 90° oriented samples are consistent with TI symmetry for both RH = 11% and RH = 86%

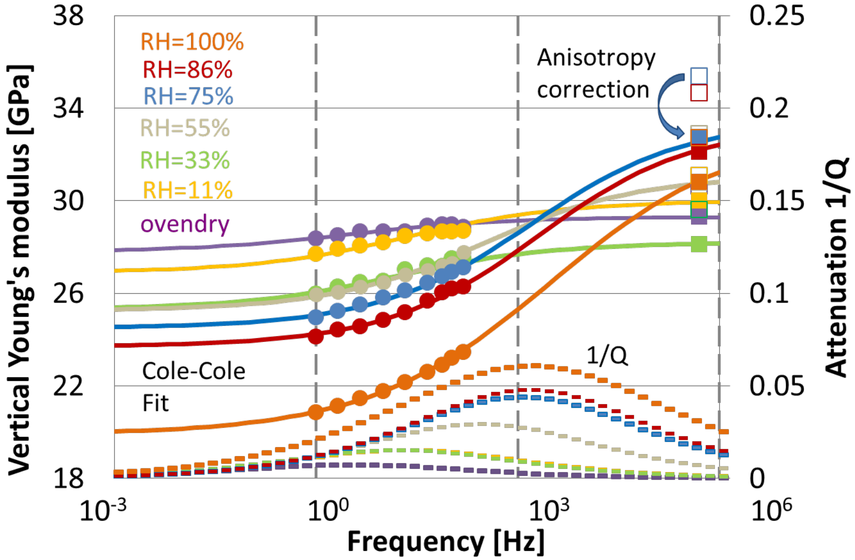
RH = 86%

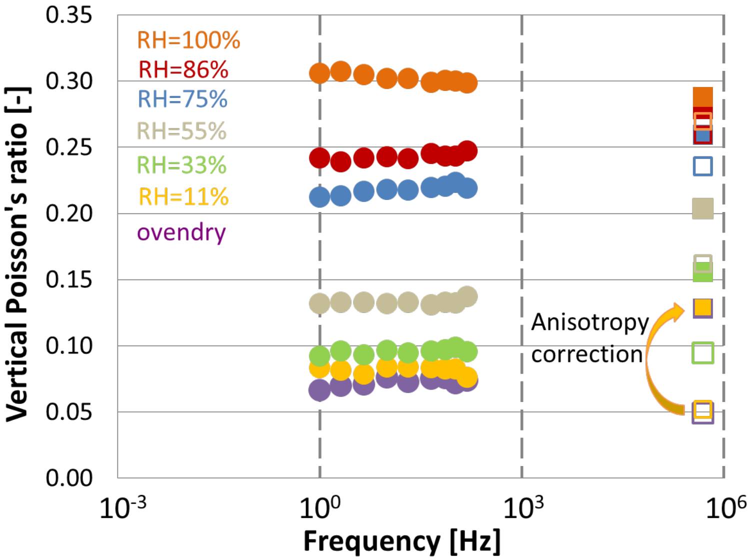


RH = 86%



Saturation effects: Mancos Shale





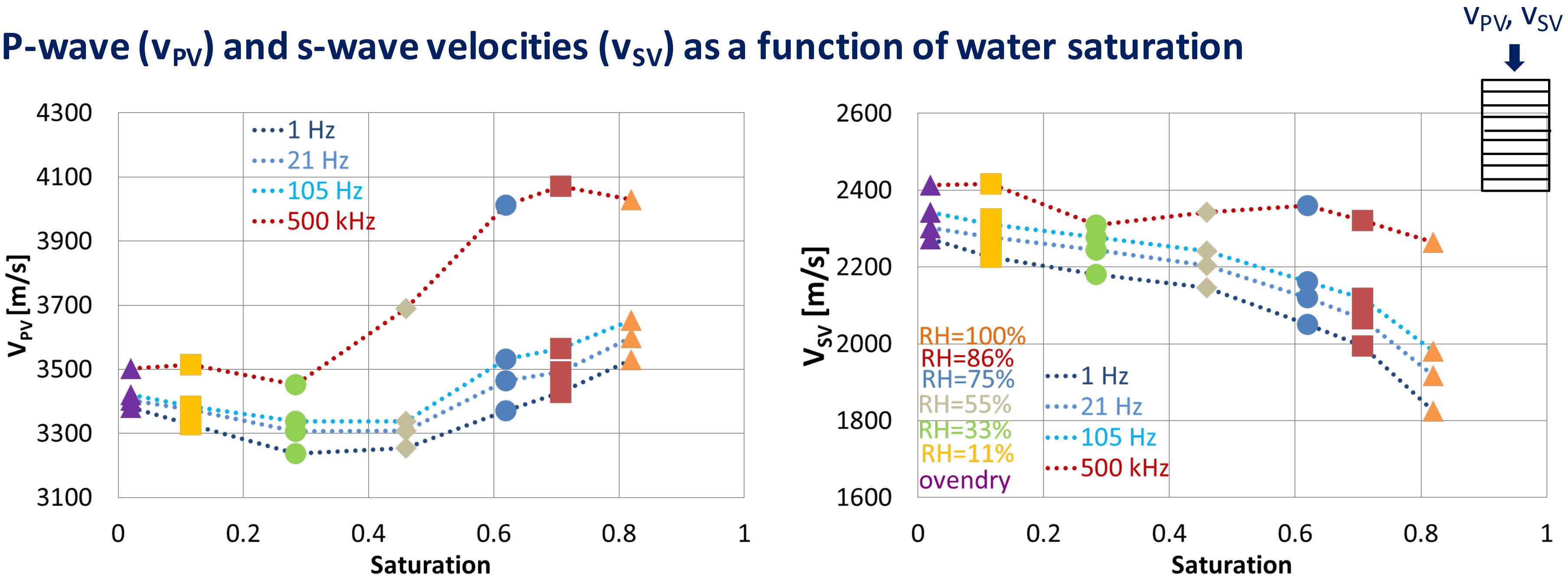
Dynamic Young's modulus and Poisson's ratio

Increase in RH (water saturation) results in:

- Gradual decrease in Young's modulus as seismic frequencies
- Increase of Young's-modulus dispersion
- Gradual increase in Poisson's ratio at both seismic at ultrasonic frequencies (small dispersion)

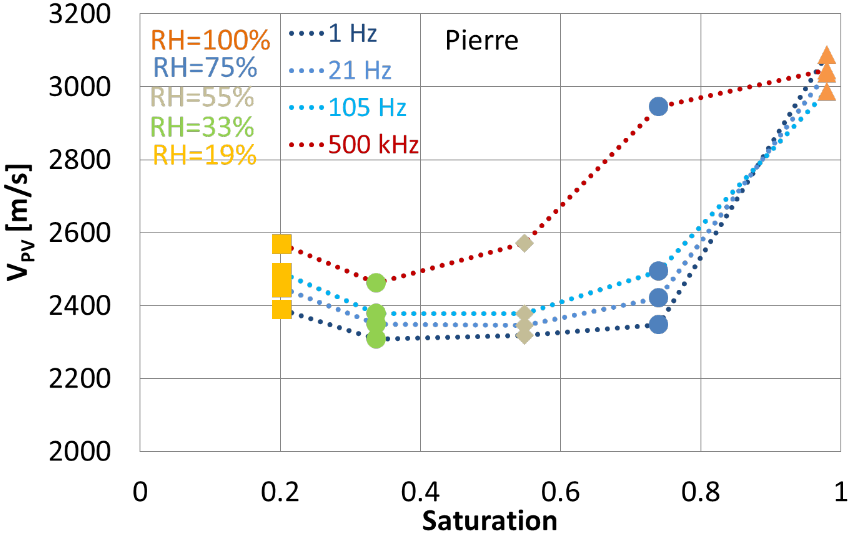
Saturation effects: Mancos Shale

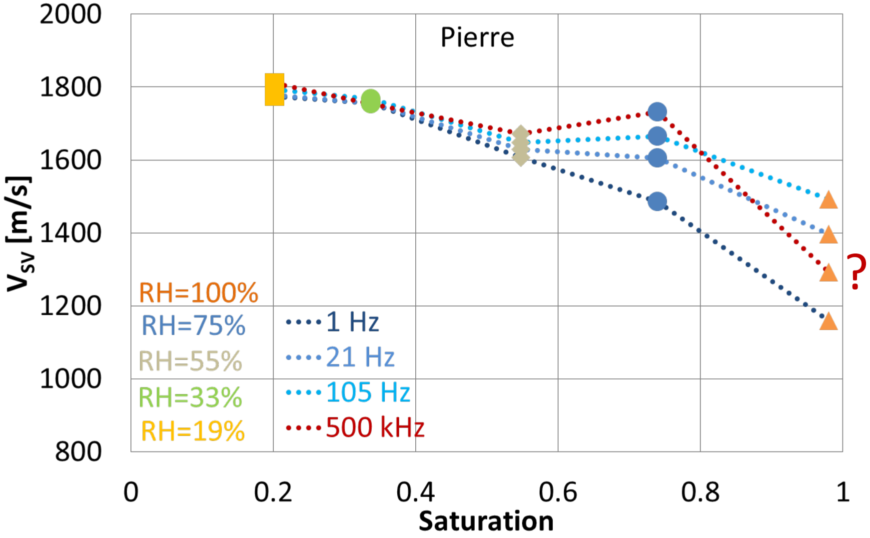
P-wave (v_{PV}) and s-wave velocities (v_{SV}) as a function of water saturation



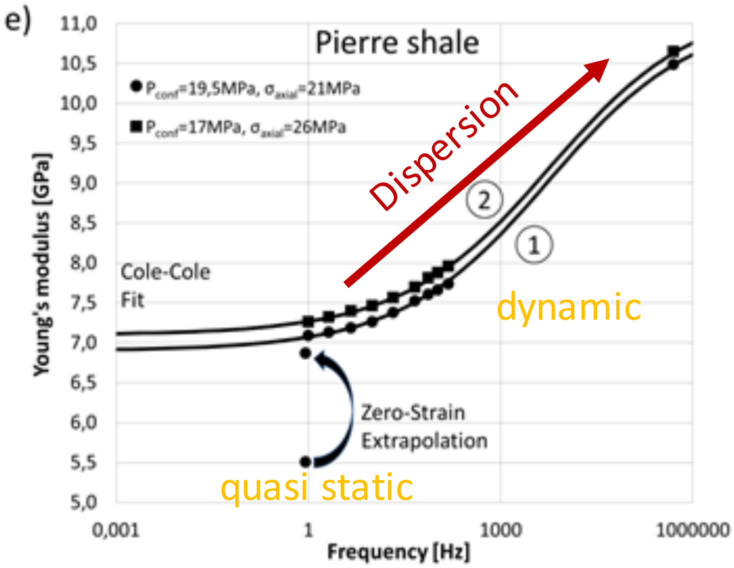
- ☐ v_{PV} decreases slightly up to $S_w \approx 0.3$ for both seismic and ultrasonic velocities. For higher saturations, v_{PV} increases gradually for seismic frequencies, while at ultrasonic frequencies, v_{PV} first increases strongly (velocity dispersion strongly increases between $S_w > 0.3$ and $S_w > 0.6$) and slightly decreases again for $S_w > 0.7$.
- ☐ v_{SV} decreases with increasing saturation. However, as for v_{PV}, velocity dispersion increases between $S_w > 0.3$ and $S_w > 0.6$, resulting in a slight increase of v_{SV} at ultrasonic frequencies in this saturation range.

Saturation effects: Pierre Shale



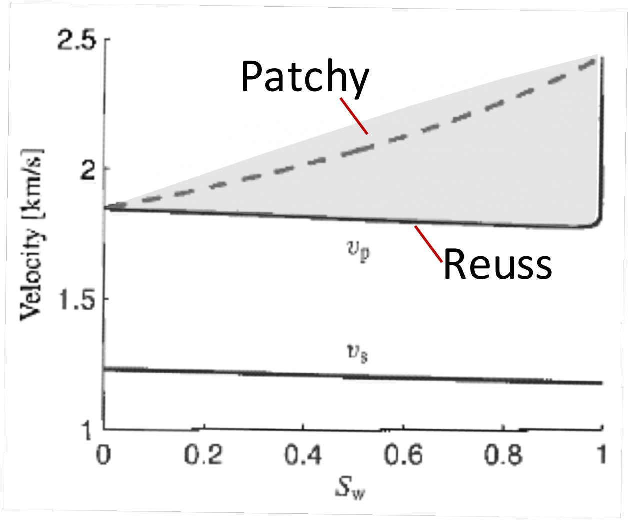


- Saturation effects on stiffness and velocities are qualitatively similar for Pierre shale and Mancos shale (100% water saturation was only measured for Pierre shale)
- v_P data suggests small dispersion for 100% saturation. But: Young's modulus exhibits large dispersion

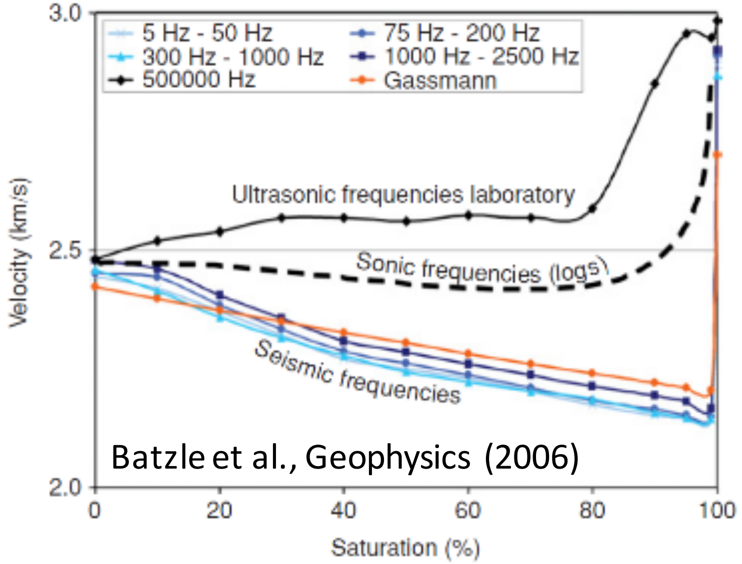


Rock Physics of Partially Saturated Rocks

- ☐ The Gassmann model has successfully been applied. Here, the rock is assumed to be composed of a rock matrix and a fluid phase. The effective stiffness of the fluid phase can be expressed as a function of the stiffnesses of the fluid components:
  - ○ Reuss (isostress) average: $$\frac{1}{K_f} = \sum_i \frac{S_i}{K_i}$$
  - ○ Voigt limit (upper limit): $$K_f = \sum_i S_i K_i$$
  - ○ Brie's equation (empirical): $$K_{f,eff} = (K_w - K_g) S_w^{\,e} + K_g$$



Experimental results for sandstones

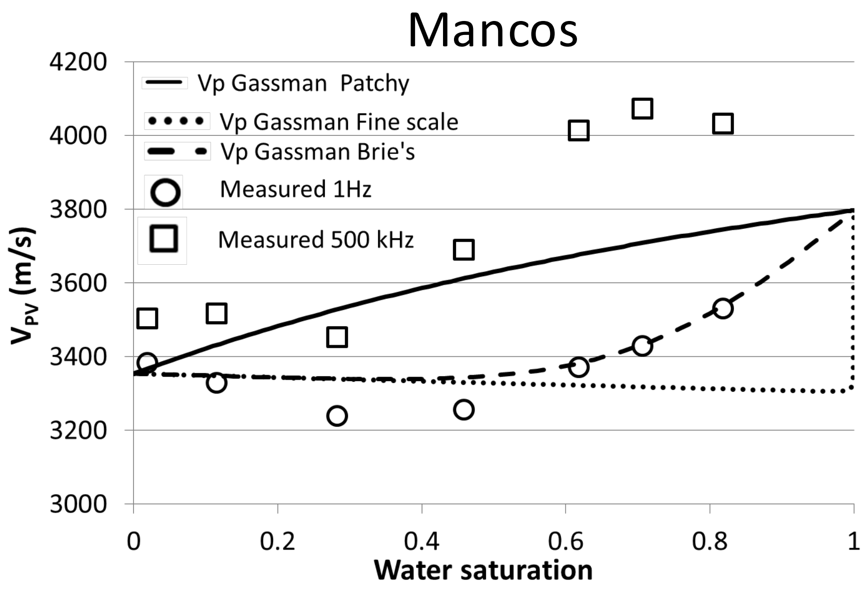


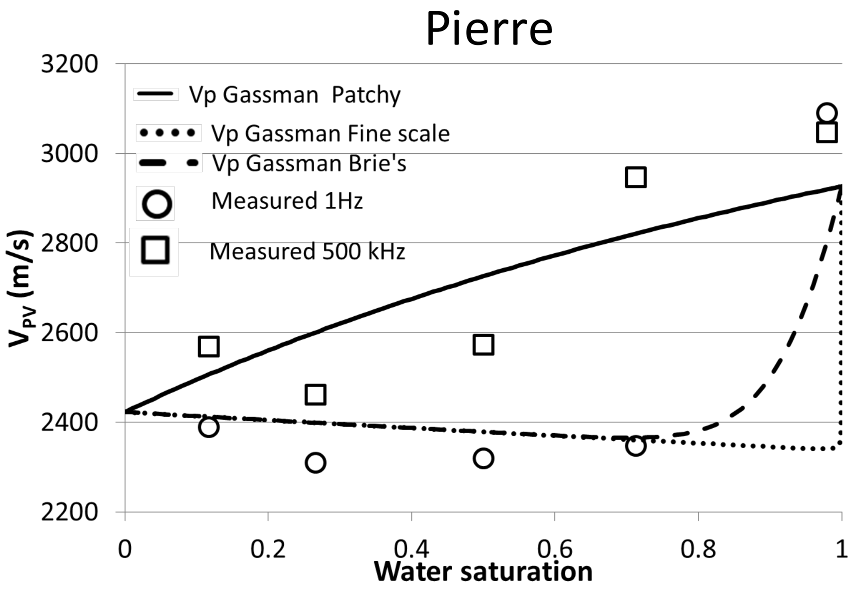
Batzle et al., Geophysics (2006)

Rock Physics of Partially Saturated Shales

Attempt to describe the results obtained with Mancos and Pierre shale by the Gassmann model

Fitting the model to the v_P data seems to look promising:



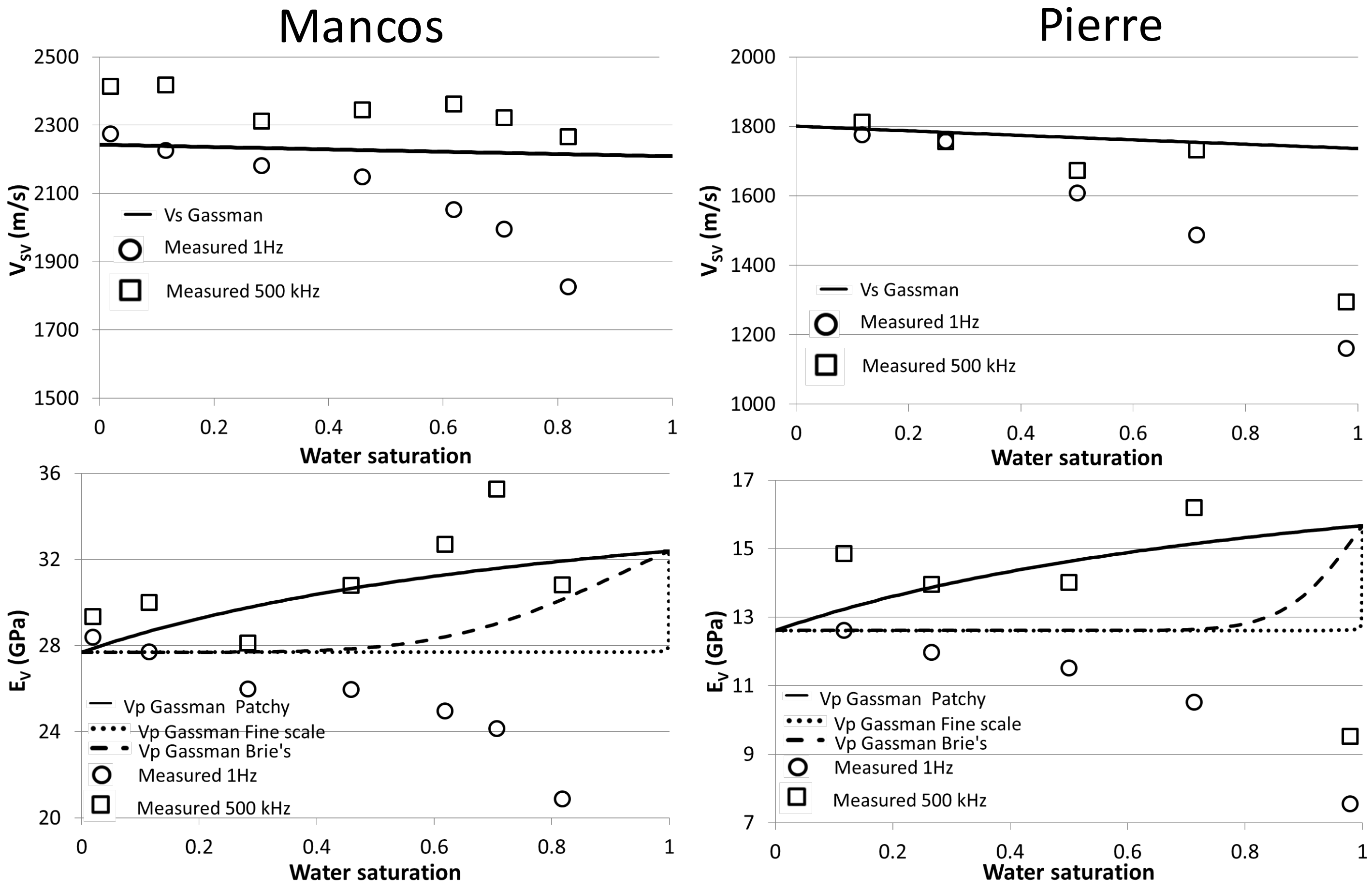


but…

Rock Physics of Partially Saturated Shales

Saturation dependence of v_S, Young's modulus, and Poisson's ratio **cannot be described by the Gassmann model**

Large discrepancies especially for the low-frequency data



What is causing the observed softening and dispersion effects?

Suction effects:

With decreasing relative humidity (RH), the magnitude of the capillary pressure increases (📷 ln RH). At the same time, the water saturation decreases (nearly linear with RH for Mancos and Pierre shale).

Capillary pressure: $p_c = \frac{RT}{V_m} \ln(a_w) = \frac{RT}{V_m} \ln(RH)$

Effective stress (Bishop's law): $\sigma' = \sigma - \gamma(p_{nw} - S_w \cdot p_c)$

Can suction effects explain the observed saturation effects?

- Under certain assumptions, suction effects may explain the observed increase in Young's modulus with decreasing RH
- A suction-induced increase in effective stress should result in micro-crack closure and an increase in Poisson's ratio. However, the opposite is observed

Conclusion: Suction effects have certainly an effect on the stiffness and effective stress acting on the rock matrix; however, they alone cannot explain the experimental results

What is causing the observed softening and dispersion effects?

Lubrication effects:

Water may act as a lubricant; it wets the grain surfaces (reduction of surface energy), and reduces friction between grains

Can lubrication effects explain the observed saturation effects?

- Surface-energy reduction and lubrication may explain both the decrease in Young's modulus and increase in Poisson's ratio with increasing RH
- Dispersion effects may be explained by local flow in and around the water-wetted grain contacts
- The increase in Poisson's ratio with increasing water saturation may be pictured as shear-displacements grain contacts (sliding) with increasing angle with respect to the load direction (reduction of friction angle). Shear displacement does not change the volume and hence does not require local flow, which could explain why Poisson's ration exhibits little dispersion

Conclusion: Lubrication effects in combination with local flow may be the dominant mechanism in rock physics of partially saturated shale

Summary

- ☐ Mancos and Pierre shale exhibit qualitatively similar saturation effects on dynamic stiffness, acoustic velocities, and velocity dispersion
- ☐ An increase in water saturation (relative humidity) results in a decrease of Young's modulus and an increase in Poisson's ratio, as well as an increase in seismic dispersion
- ☐ The experimental results cannot be described by the (anisotropic) Gassmann model or patch-saturation models
- ☐ Lubrication may be the dominant mechanism in the rock physics of partially saturated shales but other effects (suction effects; desiccation-induced porosity changes, etc.) may have an impact as well ⇨ more studies needed

Recent results: Sandstones with partial CO_2 saturation

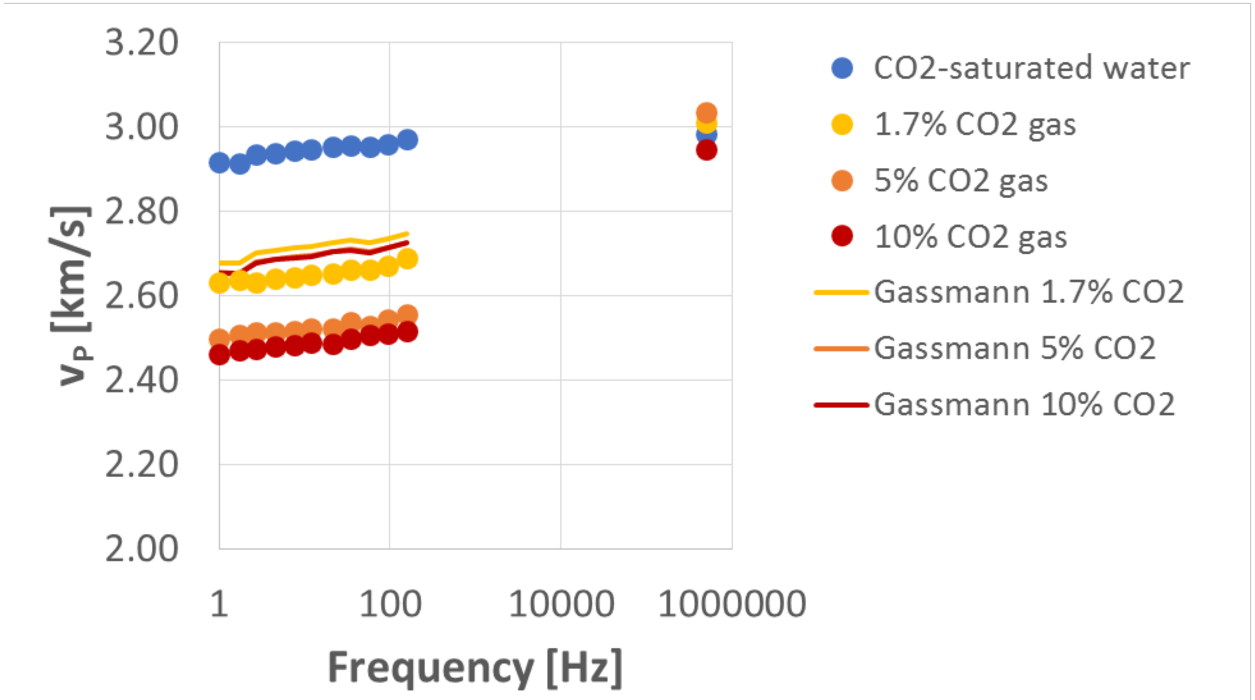
- A (presumably) homogeneous CO_2 saturation in Castlegate sandstone was created by saturating the sample with CO_2-saturated water at a pore pressure of $p_f = 7.5$ MPa and subsequently reducing the pore pressure by holding the effective stress constant ($p_{conf}' = 7$ MPa; $?_{ax}' = 9$ MPa).

- During pressure reduction, CO_2 comes out of solution, and for small gas saturations (< 10%), the CO_2 is immobile and can therefore be assumed homogeneously distributed in the sample

- Studied CO_2-gas saturations:
  - **1.7%** (@ 5.5 MPa)
  - **5%** (@ 5 MPa)
  - **10%** (@ 4.3 MPa)

New CO_2 flow loop

Recent results: Sandstones with partial CO_2 saturation



- ☐ Ultrasonic: Relatively small velocity changes; large increase in attenuation if CO_2 gas is present (to be evaluated)
- ☐ Seismic: relatively small dispersion and attenuation within seismic band; decrease of velocities for 1.7% CO_2 consistent with Gassmann model; velocities at 5% and 10% CO_2 smaller than predicted by Gassmann theory ⇨ partial CO_2 saturation has impact on frame stiffness
- ☐ Dispersion: the Present results suggest that for homogeneously distributed CO_2, dispersion takes place place at ultrasonic frequencies

Outlook

- ☐ Homogeneous CO_2 saturation vs. patchy saturation during drainage/imbibition: Previous low-frequency measurements indicate dispersion within seismic band after CO_2 injection (Spencer and Shine, 2016)

- ☐ Development of improved rock-physics model(s) for partially saturated rocks

- ☐ Higher accuracy of seismic p-wave measurements in anisotropic rocks by direct measurement of p-wave modulus: Radial strain is kept constant by synchronized modulation of confining stress