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The coupled impacts of internal relative humidity on both the linear and nonlinear Young's modulus of siliciclastic sandstones

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It is well known that the water saturation degree (S_w) can strongly affect the linear viscoelastic properties of siliciclastic sandstones, even at low values (a few % points). For example, the impacts on the linear Q was already studied starting from the end of the ´970s, in relation to lunar samples measured in the lab. A decrease in linear moduli with increasing S_w has been repeatedly documented in the literature. Even the effects on mesoscopic nonlinear properties have been reported by multiple groups in the ICNEM community.

The understanding of the physical controls of such effects gain new importance, as more recent geophysical surveying approaches, e.g., based on seismic ambient noise interferometry, try to take advantage of such effects for monitoring changes in the subsurface's hydro-geological states due to, e.g., seasonal or long-term droughts, to floods or to geotechnical operations (for example fluid injections).

We report here about a rock physics, lab-scale experimental campaign, which aimed at improving the physical picture of the pore-scale controls. We focused on changes only due to variations in relative humidity (RH), starting from a "dry"state. Thus, we dealt only with low S_w values (a few % points as well). We measured both the linear, complex-valued Young's modulus and the mesoscopic nonlinear one (only real part thereof) for Berea and Rothbach sandstone specimens conditioned at actual equilibrium states. Here, equilibrium means that the internal and environmental RHs were almost identical, as quantitatively assessed. This is a novelty compared with already published work, especially for nonlinearity results. RH equilibria guarantee the absence of transients due to, e.g., diffusion and/or thin film-flow. They simplify the physical picture of how the moisture is distributed and may interact with the solid skeleton.
We assessed the latter via water vapor sorption and ^{1}H nuclear magnetic resonance (NMR) transverse relaxation spectroscopy measurements on sibling specimens. These two techniques allow inferring the type of water (adsorbed vs capillary-condensed vs freely mobile) and its partitioning within parts of the pore space with different size.

With increasing RH between 0% and 97% RH, corresponding to a S_w increase between 0% and 4%, the linear Young's modulus decreased monotonically of up to 30%. The linear wave amplitude attenuation coefficient (proportional to Q^{-1}) increased of up to 150%, surprisingly not monotonically. A local minimum occurred at about 45% RH. Interestingly, when comparing with older literature for similar siliciclastic sandstones, such local minimum was already observed but completely not addressed.

The nonlinear Young's modulus increased of up to about 300%, confirming what already reported in the literature, i.e., a higher sensitivity of the nonlinear moduli than the linear ones to changes in moisture content, even for such small S_w values. No significant hysteresis was observed upon a full adsorption-desorption cycle.

The key novel observation consists in a correspondence between the RH, at which the local minimum in the wave amplitude attenuation coefficient occurred, and the start of the observation of slow dynamics effects (at the frequency change resolution level we could achieve). Below such RH, a classical cubic nonlinear model more accurately describes the data than a mesoscopic one. The vapor sorption as well as the ^{1}H NMR data suggest that, at such RH, water is predominantly contained in the smallest pores, e.g., within the cementing mineral phases and in the inter-layer space of clayey minerals. It is mainly present in the form of adsorbed thin films, with a few mono-molecular size, contrary to what proposed in recent articles (i.e., order of 1000 mono-molecular size).

We draw two important conclusions from these results:

(1) a (smooth) transition from a predominant classical to a mesoscopic nonlinear behavior seems to be associated with the continuous thickening of adsorbed water films, thus with capillary condensation;

(2) such smooth transition is characterized by a remarkable local maximum in Q (equivalently, a local minimum in wave amplitude attenuation coefficient), whose physical origins is for us not clear and which is worth of in-depth investigation.

These conclusions suggest that the pore-scale controls of the takeover, by mesoscopic nonlinearity, of the macroscopic nonlinear response and of the changes in the linear elastic one are both related with (I) the surface physics and chemistry properties and (II) the pore space properties specific of the investigated sedimentary rock. This is an hypothesis. If validated extensively on other sedimentary rock types, it would mean that a reliable interpretation of the changes in the subsurface's nonlinear elastic response to changes in its saturation state could and should not abstract from the mineralogical, textural and pore-scale properties of the probed geologic formation. Any universal interpretation would not be reliable.

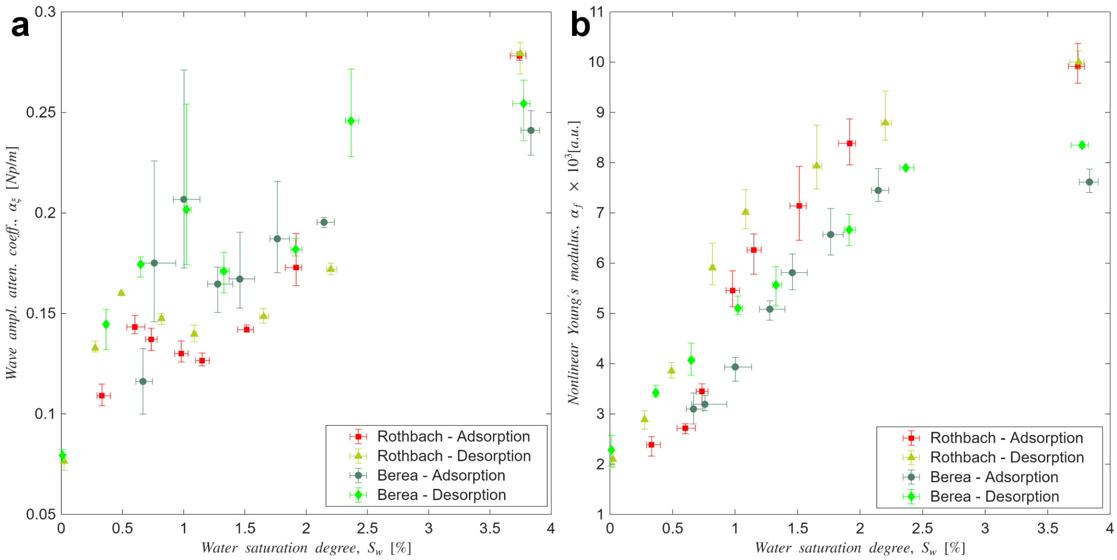

Figure 1: enter image description here

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