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Frequency scaling of seismic attenuation in partially saturated rock samples

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Introduction

Compressibility contrasts in rocks arise from heterogeneities in the matrix and the saturating fluids. When a seismic wave stresses the fluid saturated rock, a pore pressure gradient develops in response to this compressibility contrast. In order to equilibrate the pressure gradient, the saturating fluids flow and part of the wave's elastic energy converts into heat. Wave induced fluid flow (WIFF) is thought to be a major source of intrinsic frequency dependent seismic attenuation (Q^{-1}). How attenuation scales with frequency depends on the geometric distribution of the heterogeneities responsible for WIFF. For a heterogeneous fluid distribution, the high frequency attenuation asymptote scales as $Q^{-1} \propto f^{-\nu}$ with $\nu < 1$ denoting the Hurst exponent, which describes the fluid distribution (e.g. Müller et al. 2008). In the case of squirt flow, WIFF from compliant grain contacts to stiff pores, the high frequency asymptote scales as $Q^{-1} \propto f^{-1}$, assuming a uniform grain contact to pore geometry (Gurevitch et al, 2010). For a uniform distribution of pore scale bubbles throughout the rock, attenuation due to wave induced gas exsolution dissolution (WIGED) (Tisato et al., 2015) has the same frequency scaling as squirt flow (Onuki, 1991). Both, squirt flow and WIGED, behave like a standard linear solid (SLS) with a single relaxation time (Figure 1a) (Zener, 1948). The frequency scaling of the attenuation is a theoretical consideration with which we study how the fluid distribution in a Berea sandstone sample influences the scaling of the high frequency asymptote of the measured attenuation. Partial saturation is achieved by imbibition of water into the sample, resulting in an approximately binary fluid distribution (Figure 1b, WIFF), and by gas exsolution from a water saturated state, forming pore scale bubbles throughout the sample (Figure 1b, WIGED).

Methods

An initial partial saturation of ~99% is achieved by imbibition, pumping water into the pore space via the sample bottom. In a next step, the sample is fully saturated by raising the fluid pressure in the sample to ~11 MPa. To achieve a partial saturation of ~100% by gas exsolution, we lower the confining pressure and then the fluid pressure in the sample. We measure the frequency dependent attenuation and Young's modulus of the partially saturated Berea sandstone sample in the seismic range with the forced oscillation method (O'Connel and Budiansky, 1978) at an effective pressure of ~10 MPa. To analyse the scaling of the high frequency attenuation asymptotes, we fit the data for both fluid distributions with a SLS having a single relaxation time (Zener, 1948).

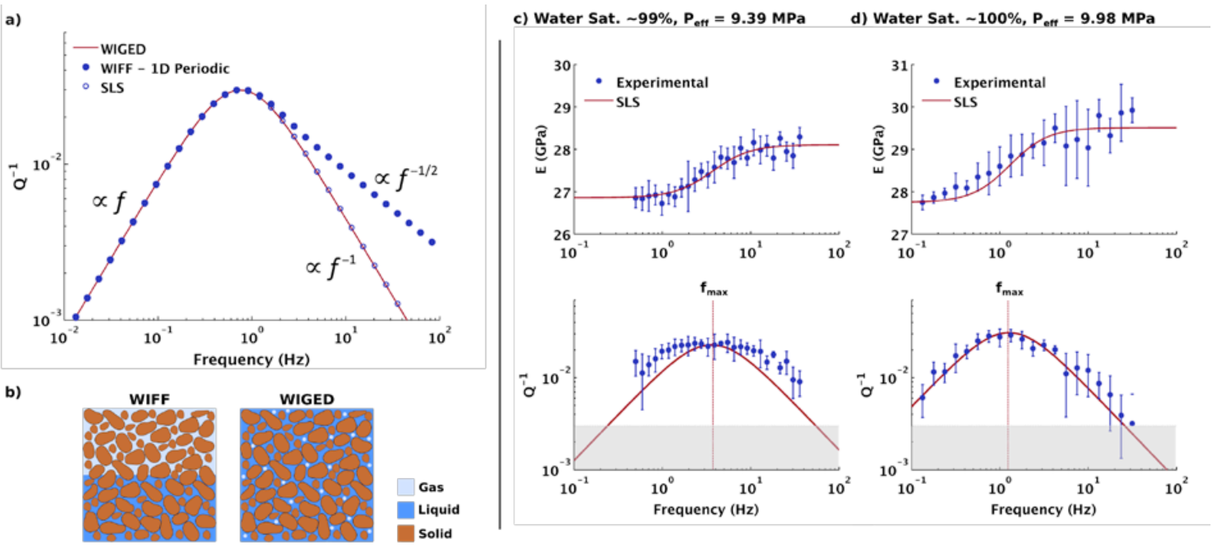

Figure 1: a) Attenuation Q^{-1} from the numerical solution of a simple WIGED model, from the 1-D analytical solution of mesoscopic WIFF for periodically alternating fluid layers (White et al., 1975), and from a SLS model with a single relaxation time. b) A schematic illustration of the fluid distribution for periodically alternating fluid layers and a homogeneous distribution of pore scale gas bubbles. c) and d) Measurements of Q^{-1} and Young's modulus E in a Berea sandstone sample for (c) ~99% water saturation and an effective pressure of 9.39 MPa and (d) ~100% water saturation and an effective pressure of 9.98 MPa.

Discussion and conclusions

The frequency dependent attenuation at ~99% water saturation (Figure 1c) is likely the result of mesoscopic WIFF in response to a heterogeneous water distribution at the sample scale (Chapman et al. 2016). The attenuation at ~100% water saturation (Figure 1d) is likely not caused by mesoscopic WIFF because a homogeneous distribution of pore scale gas bubbles implies that the characteristic length of the water heterogeneities are much smaller than at ~99%. Smaller heterogeneities would cause a shift of the attenuation peak to higher frequencies (White et al. 1975), which we do not observe. We also observe a significant steepening of the high frequency asymptote of the attenuation going from ~99% to ~100% water saturation, as the SLS fit indicates. Squirt flow is eliminated as a mechanism, because it operates at much higher frequencies given the viscosity of water (Gurevitch et al, 2010). This leaves WIGED as a possible mechanism for the attenuation observed at ~100% water saturation.

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