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Numerical modeling of wave-induced fluid flow in 3D patchy saturated media

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Estimating pore fluid properties of saturated porous rocks from seismic data is very important in Exploration Geophysics for finding hydrocarbon reservoirs and in Reservoir Geophysics for monitoring and optimizing their production. Theoretical studies show that pore fluid properties have a major effect on attenuation and velocity dispersion of seismic waves. This effect opens the potential of estimating fluid properties from seismic data. However, despite years of research on this subject, this link is not yet been exploited by the oil industry in exploration and production routines. For that to happen, the effect of fluid properties on seismic attenuation has to be quantified and better understood in laboratory and numerical investigations. A major cause of attenuation and velocity dispersion in the frequency range of interest in exploration (1-100 Hz) is wave-induced flow of pore fluid in the mesoscopic scale. The mesoscopic scale is the scale much larger than the pore size (2-50 nm) and much smaller than the wavelength (hundreds of meters for seismic frequencies). White's model yields frequency-dependent attenuation and velocity dispersion in partially saturated media by the mechanism of wave-induced fluid flow. In this model, a partially saturated rock can be approximated by a medium with mesoscopic-scale heterogeneities fully saturated with one fluid, and the background fully saturated with another fluid. This is frequently referred to as patchy saturation. The passing wave induces different fluid pressure in the regions (the patch and the background) saturated with fluids of different compressibilities. This pressure difference causes flow of the pore viscous fluid between these regions, which then causes loss of energy. White's model can be modeled using Biot's equations for wave propagation in poroelastic media with spatially varying petrophysical parameters. However, solving Biot's equations for wave propagation to calculate seismic attenuation due to wave-induced fluid flow is computationally inefficient because wave propagation and fluid flow occur on very different time scales. A method that is computationally efficient in calculating attenuation related to the fluid flow in the mesoscopic-scale is a quasi-static creep test. Furthermore, for calculating attenuation due to only wave-induced fluid flow at low seismic frequencies, inertial forces are negligible. It is thus enough to solve a simpler mathematical problem, that is, Biot's equations of consolidation (in which inertial forces are excluded). In this work, we numerically calculate attenuation in porous saturated rocks due to wave-induced fluid flow, by solving Biot's equations of consolidation. We use the software COMSOL, which employs the finite element method, to simulate a creep test on a 2D or 3D numerical rock sample with mesoscopic-scale heterogeneities in fluid saturation. The resulting time-dependent stress-strain relations are transformed to the frequency domain, with a fast Fourier transform, and then used to calculate the undrained shear and bulk moduli. With these moduli, we determine the frequency-dependent P- and S-wave attenuation in that sample caused by the mechanism of wave-induced fluid flow.