4th International Workshop on Rock Physics 29 May - 2 June 2017, Trondheim, Norway

Saturation dependence of the elastic modulus in ultrasonic measurements: insights for wave propagation mechanisms.

G. Papageorgiou [a], K. Amalokwu [b, c], M. Chapman [a], A. Best [b]

[a] *University of Edinburgh School of Geosciences Grant Institute, the King's Building West Mains Road Edinburgh, United Kingdom;*
[b] *National Oceanography Center, University of Southampton Waterfront Campus, European Way, Southampton, SO14 3ZH, United Kingdom;*
[c] *currently: University of Texas at Austin, Jackson School of Geosciences, Austin, Texas, USA;*
Contact email: giorgos.papageorgiou@ed.ac.uk

Introduction

Seismic wave velocity and attenuation are properties that are sensitive to fluid content in the pore space. Fluid-saturated rocks exhibit frequency-dependent behaviour due to wave-induced fluid flow (Biot, 1956, Chapman *et al.*, 2002, Murphy, 1982, White, 1975). The dispersion arises from unrelaxed wave-induced fluid pressures occurring between spatially inhomogeneous saturation regimes –patches– and is normally accompanied by seismic attenuation. It has long been recognised and/or suggested that patchy saturation in combination with other mechanisms might be at play and that multiple mechanisms might be required to obtain a better fit between laboratory-scale measurements and theoretical modelling (e.g., Gist, 1994, Wulff and Burkhardt, 1997). In this work, we model the bulk modulus and attenuation as a function of water saturation. We use two modelling approaches to interpret ultrasonic measurements of velocity and attenuation of synthetic rocks under partial saturation conditions. The results show that the interpretation is not unique as different combinations of mechanisms can attain a fit to the experimental data. A major finding of this study is that not all the mechanisms disappear at lower frequencies and this could have important implications for fluid substitution in practice.

Methods

Velocity and attenuation measurements at varying saturation degrees were obtained using the pulse reflection method (see Best *et al.*, 2007) for a cylindrical sample of 30% porosity, 5 cm diameter and approximately 2 cm thickness. The sample was synthetic silica cemented clean sandstone used in Amalokwu et al. (2014) as the "blank" (unfractured) sample with a mineral composition of almost entirely quartz grains (Tillotson *et al.*, 2012). The sample was oven dried to 40^{o} C for about 48 hours and progressively saturated to 40% water saturation by being placed in controlled relative humidity environments and left to reach equilibrium for about two weeks for each distinct saturation measurement. Higher saturations were achieved by using a modified drainage method whereby the samples were progressively drained from 98% saturation down to 50%. For the fully saturated measurement, the sample was placed in distilled, deionised and de-aired water under vacuum and then pressurised to 7 MPa for at least 24 hours until the pressure equilibrated for several hours, ensuring full water saturation.

Theory

A potentially discontinuous rock physics theory that includes patchy saturation effects was implemented using two distinct approaches. In both approaches, the model of White (1975) accounts for the patch effect and the model of Chapman *et al.* (2002) accounts for dispersion due to wave induced flow. In the first approach (which we label: *case 1*), White's model is combined with the squirt flow theory of Papageorgiou and Chapman (2015) and the discontinuity stems from an unevenly high saturation in the crack space of the matrix. In the other approach (labelled *case 2*), the discontinuity is a pressure discontinuity occuring throughout the pore space and it is interpreted as a change in the fluid in contact with the pore wall. In this case, the assumption is that the rock is water wet and the discontinuity stems from the pore space transitioning from a dry to a wetted state. As a result the pressure differentials are not equal but are related by a constant q that we take to be a fitting parameter:

$$\Delta P_{nw} = q \frac{K_{nw}}{K_w} \Delta P_w , \qquad 1 < \mathrm{q} < \frac{K_w}{K_{nw}}$$

The fitting parameters used for the dataset are the crack density, characteristic frequency, patch size and, in case 2, the magnitude of the effect of the discontinuity in what we label as "wet-Gassmann" model.

Grain bulk modulus	Grain shear modulus	Grain Density	Porosity	Permeability
38 GPa	44 Gpa	2590	30.40%	40.7 mD

Table 1: Measured rock physical parameters used as input to the model of Chapman *et al.*, 2002

Squirt model			**White's model** **(patch size)**
Crack density	Case 1	1.35 x 10^{-2}	1.8 mm
	Case 2	1.75 x 10^{-2}	1.4 mm
Crack aspect ratio		1.0 x 10^{-4}	**Wet Gassmann model**
Char. Timescale (sec)	Case 1	5.0 x 10^{-4}	
	Case 2	2.45 x 10^{-7}	Case 2: 4

Table 2: Summary of inverted parameters for each of the two modelling approaches

Results

The results of the measurements are shown in Figures 1, 2 below. The two modelling approaches presented show that different mechanisms can model the same experimental data and both produce similar results. Although the same mechanisms are used in both models (except for the wet-Gassmann model used only in case 2), their interpretations are different. In Case 1, the squirt effect from the cracks comes from the cracks being preferentially saturated and becoming fully saturated at a critical saturation S_0, effectively stiffening the rock frame. This models the jump at low S_w and the dispersion at $S_w = 1$. There is no additional dispersion due to squirt flow beyond S_0 as the cracks are fully saturated. Subsequent dispersion is a result of patchy saturation and it is accounted for by the model of White. In Case 2, the dispersion effect due to squirt flow does not consider the cracks to be fully saturated at S_0, rather the pores and cracks saturate at the same rate and dispersion due to squirt flow is observed at higher values of water saturation. However, the jump in Case 2 is modelled as a discontinuous effective fluid pressure variation which is a static effect as considered here. Apart from patchy saturation, another thing consistent between both approaches is that at full water saturation, the dispersion is due to squirt flow in agreement with previous works on dispersion in liquid saturated rocks (e.g., Chapman *et al.*, 2002, Gurevich *et al.*, 2010, Winkler, 1985).

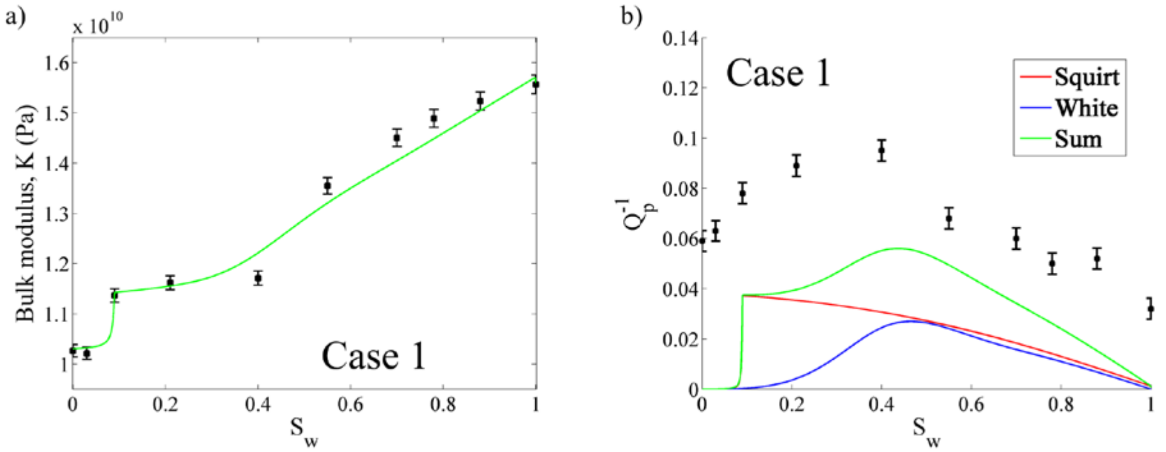

Figure 1: Measured and modelled bulk modulus and attenuation using the case 1 approach

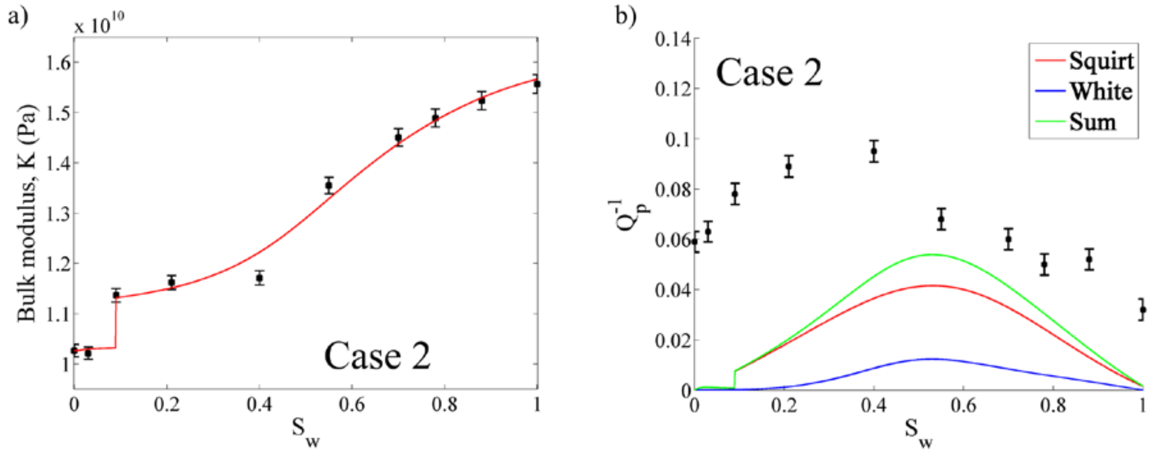

Figure 2: Measured and modelled bulk modulus and attenuation using the case 2 approach

Conclusions

Our study demonstrates that the relationship between bulk modulus and partial saturation is complex and intrinsically involves multiple physical mechanisms. As shown in previous studies, we find that at full saturation there is evidence of rock stiffening which strongly indicates squirt flow effects. All our successful modelling attempts have required the assumption of a patchy saturated medium. Our data show an apparent jump discontinuity in the saturated bulk modulus for low saturations, and we demonstrate that this is consistent with expected behaviour arising from pore-scale capillary effects. The interpretation is not unambiguous, however, since an alternative modelling approach based on multifluid squirt-flow produces similar behaviour. The two approaches both provide compelling fits to the bulk modulus and attenuation data, but their low frequency limits, which are critical for application to field data, are very different. In principle, this ambiguity could be resolved by performing the experiments over a wider frequency range.

Acknowledgements

GP's contribution to this work was carried out within the DiSECCS (EP/K035878/1) project https://www.bgs.ac.uk/diseccs. DISECCS is funded by the Engineering and Physical Sciences Research Council (EPSRC) UK.

References

Amalokwu, K., Best, A.I., Sothcott, J., Chapman, M., Minshull, T. & Li, X.-Y., 2014. Water saturation effects on elastic wave attenuation in porous rocks with aligned fractures, *Geophysical Journal International*.

Best, A.I., Sothcott, J. & McCann, C., 2007. A laboratory study of seismic velocity and attenuation anisotropy in near-surface sedimentary rocks, *Geophysical Prospecting,* 55**,** 609-625.

Biot, M.A., 1956. Theory of propagation of elastic waves in fluid-saturated porous solid, I. Low frequency range, II. Higher frequency range, *J. of the Acous. Soc. of America,* 28**,** 168-191.

Chapman, M., Zatsepin, S.V. & Crampin, S., 2002. Derivation of a microstructural poroelastic model, *Geophysical Journal International,* 151**,** 427-451.

Gist, G.A., 1994. Interpreting laboratory velocity measurements in partially gas-saturated rocks, *Geophysics,* 59**,** 1100-1109.

Gurevich, B., Makarynska, D., de Paula, O.B. & Pervukhina, M., 2010. A simple model for squirt-flow dispersion and attenuation in fluid-saturated granular rocks, *Geophysics,* 75**,** N109-N120.

Murphy, W.F., 1982. Effects of partial water saturation on attenuation in Massillon sandstone and Vycor porous glass, *J. Acoust Soc. Am.,* 71**,** 1458–1468.

Papageorgiou, G. & Chapman, M., 2015. Multifluid squirt flow and hysteresis effects on the bulk modulus–water saturation relationship, *Geophysical Journal International,* 203**,** 814-817.

Tillotson, P., Sothcott, J., Best, A.I., Chapman, M. & Li, X.-Y., 2012. Experimental verification of the fracture density and shear-wave splitting relationship using synthetic silica cemented sandstones with a controlled fracture geometry, *Geophysical Prospecting,* 60**,** 516-525.

White, J.E., 1975. Computed seismic speeds and attenuation in rocks with partial gas saturation, *Geophysics,* 40**,** 224-232.

Winkler, K., 1985. Dispersion analysis of velocity and attenuation in Bera Sandstone, *Journal of Geophysical Research,* 90**,** 6793-6800.

Wulff, A.M. & Burkhardt, H., 1997. Mechanisms affecting ultrasonic wave propagation in fluid-containing sandstones under high hydrostatic pressure, *Journal of Geophysical Research: Solid Earth,* 102**,** 3043-3050.