Laboratory measurement of seismic velocity dispersion in cracked quartzite

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SUMMARY

Reversible fluid flow within low aspect ratio cracks is expected to cause seismic velocities in hard rock to be strongly frequency dependent. Experimental measurements are necessary to constrain theoretical velocity dispersion models in order to allow comparisons between laboratory measurements at megahertz frequencies, sonic logging at kilohertz frequencies and in-situ exploration seismic at typically 10-300 Hz frequencies, but are rare due to the complexity of low frequency measurements on core samples. Quartzite samples from Cape Sorell, Australia and Alberta, Canada are thermally cracked to induce ~2% crack porosity with aspect ratio <0.01. The shear and Young's moduli of the samples are measured at frequencies of 0.01-1 Hz and 1 MHz while the samples are dry, saturated with argon and saturated with water over effective pressures of 10-150 MPa. As anticipated, no dispersion is exhibited while the samples are dry. Similarly, no dispersion is observed while the samples are argon saturated as a result of the low viscosity and high compressibility of argon. Water saturation, however, causes significant dispersion in both the shear and Young's moduli of the samples between the low and high frequency measurements.

Key words: seismic, velocity dispersion, cracks.

INTRODUCTION

Pore fluids affect seismic wave speeds by increasing the effective stiffness of the pore, and thus the overall stiffness of the rock, when compressed by passing seismic waves. The stiffness of the rock can be related to seismic wave speeds by the Christoffel equations. The amount of additional stiffness induced by the pore fluid when compressed by a seismic wave depends strongly on the frequency of the seismic wave and the viscosity of the fluid. Maximum stiffness is achieved when the frequency is high enough that the pore fluid does not have sufficient time to flow. For this reason, measurements conducted in the laboratory with ultrasonic transducers (MHz) can be expected to measure higher stiffnesses and seismic velocities than measurements made using sonic logging (kHz), active source in-situ seismic (Hz) and passive source seismic (≤ Hz). Measurements can also be expected to be sensitive to the pore pressure; as the effective pressure changes (confining pressure minus pore pressure) the crack apertures and distribution of fluid within the fracture network will change, causing changes in the rock stiffness and seismic velocities.

Numerous theoretical models exist which predict the frequency dependence of the seismic velocity based on factors such as pore fluid viscosity, fluid density, rock porosity, permeability, crack aspect ratio and tortuosity of fractures. Despite this extensive theoretical investigation of frequency dependence, the effect of fluid saturation on wave speeds through liquid saturated cracked rock remains largely untested experimentally. As interest in time-lapse seismic monitoring of petroleum production, geothermal energy, geological CO_2 sequestration, repositories for nuclear waste, etc. grows, the ability to accurately characterize fracture networks, pore pressure and fluid flow within low porosity crystalline rock becomes increasingly important. Although numerous high frequency (ultrasonic) measurements exist, very few measurements have been made at the lower frequencies of the seismic band in the controlled laboratory environment.

Here, velocity dispersion measurements of two cracked quartzites (one from Cape Sorell, Australia, one from Alberta, Canada) over frequencies 0.01-1 Hz and at 1 MHz are presented. The shear and Young's moduli of the quartzites was measured with the samples dry, argon saturated and water saturated over a range of effective pressures from 10-150 MPa.

METHOD

The Cape Sorell and Canadian quartzites were selected for their homogeneity and near mono-minerallic nature. They were thermally cracked by heating them to 1100ºC and quenching them in liquid nitrogen and water, respectively, inducing porosities of 2.3% and 2.4% in each. Thin sections and SEM images show that the low aspect ratio cracks are relatively isotropically distributed (Figure 1) and mercury porosimetry confirms there is very little variation in size, with a distribution of pore throat sizes centred around 0.4 □m and 0.7 □m, respectively, for each quartzite (Figure 2).

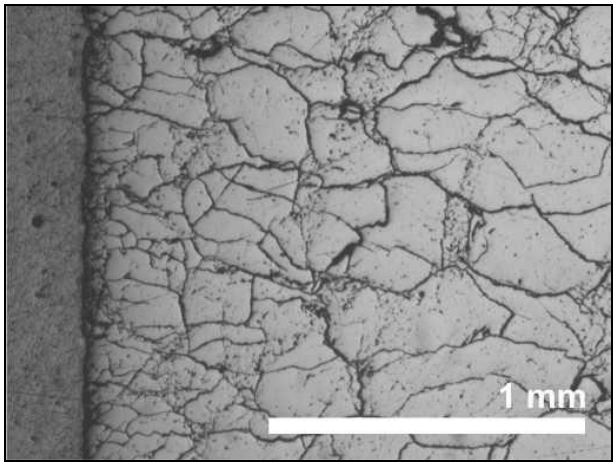

Figure 1: Thin section image of the Canadian quartzite after thermal cracking, showing the relatively isotropic distribution of cracks from the edge of the sample.

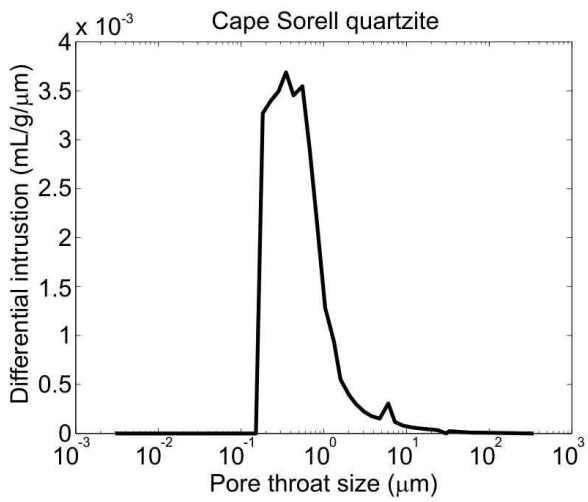

Figure 2: Mercury porosimetry of the Cape Sorell quartzite showing pore size vs. differential intrusion volume.

After characterization of the cracks, low frequency measurements were made using torsional and flexural forced oscillation. The experimental assembly (Figure 3) was a cylindrical beam comprised of steel, polycrystalline alumina, and the fractured specimen encased within a copper jacket. The top of the beam was held fixed while the bottom was driven using time-varying electromagnetic drivers, with the polarization of the applied force depending on whether the apparatus was operating in flexural or torsional mode. The resulting flexure or torsion was measured at two locations within the beam using parallel plate capacitors.

The displacement, d, at each of the tranducers caused by the flexure of the beam at x_i can be related to Young's modulus, E, by:

$$d(t) = -D\int_0^{x_i} \frac{M(x,t)}{E(x)I(x)}dx$$

where D is the radial distance from the centre of the beam to the point of measurement, M is the local value of the time-varying bending moment and I is the polar moment of inertia of the beam. The displacement measured by the transducers in torsion can similarly be related to the applied torque, the moment of inertia of the beam, and, in this case, the shear modulus.

Low frequency measurements were made on the samples over frequencies 0.01-1 Hz and at effective pressures of 10-150 MPa with the samples dry, argon saturated and water saturated. As the experimental assembly involves an upper and lower pore fluid reservoir, permeability measurements were undertaken as well by adjusting the pore pressure in a single reservoir and monitoring the decay or growth of pore pressure in the other.

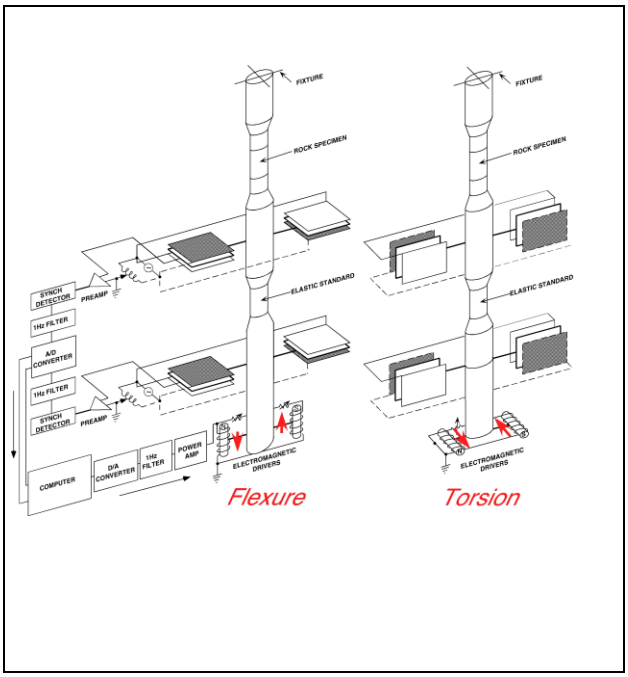

Figure 3: Experimental arrangement for forced-oscillation studies in torsion and flexure with alternative driver/displacement transducer polarizations.

High frequency measurements (1 MHz) were made using piezoelectric P- and S-wave transducers glued onto aluminum buffers which sandwiched the samples. Traveltime smeasured through the buffers alone were subtracted from traveltimes through the whole assembly, and P- and S-wave velocities were used in conjunction with the bulk densities of the samples to calculate high frequency shear and Young's moduli for the samples. Measurements were made under similar saturation and pressure conditions to those undertaken at low frequency.

RESULTS

Measurements of the moduli of both quartzites show both the shear and Young's moduli increasing with effective pressure as the cracks in the samples undergo progressive closure. This effect was quite strong, with the shear modulus of the dry Canadian quartzite increasing from 11.9 GPa to 34.9 GPa over confining pressures 10-150 MPa at high frequency; an increase of 193%. Similarly, Young's modulus increased from 25.3 GPa to 77.4 GPa. The shear modulus of the Cape

Sorell quartzite increased from 10.9 GPa to 36.0 GPa from 10-130 MPa confining pressure and the Young's modulus from 20.2 to 78.5 GPa. The cracks are estimated to close around ~100 MPa (Figures 4, 5).

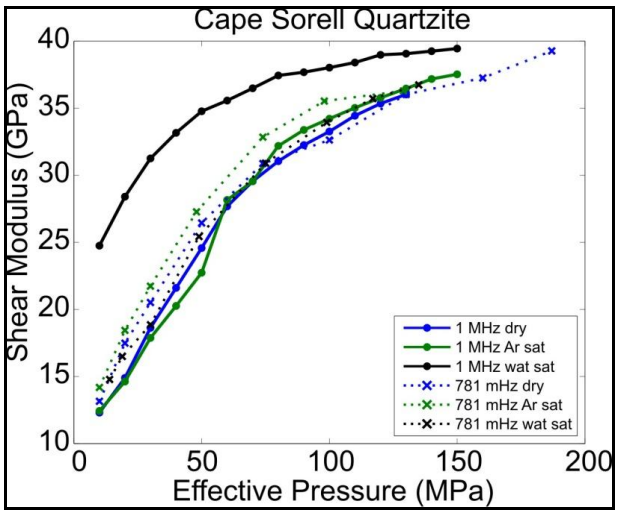

Figure 4: Shear modulus measurements at 781 mHz and 1 MHz for the Cape Sorell quartzite, measured dry, argon saturated and water saturated showing significant dispersion when the sample is water saturated.

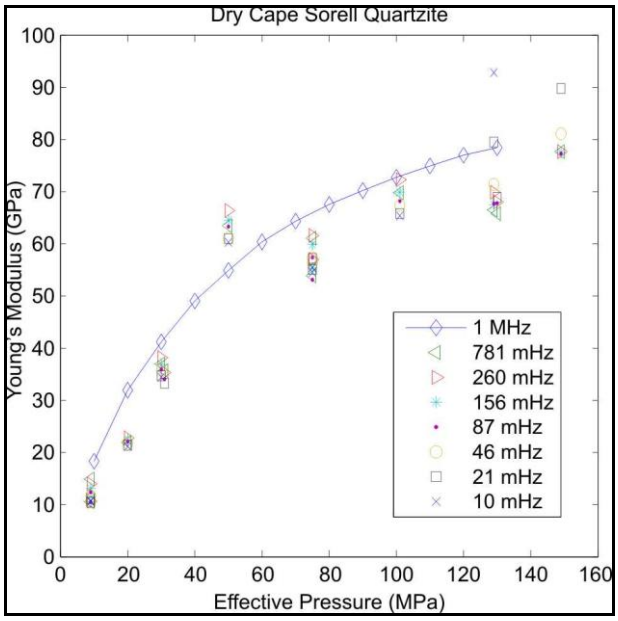

Figure 5: Young's modulus measurements the dry Cape Sorell quartzite showing the as expected lack of dispersion between the high and low frequency measurements, as well as the progressive crack closure as Young's moduli values increase dramatically until ~100 MPa of confining pressure.

Preliminary results show that no dispersion occurs across the measured frequencies when the samples are dry or argon saturated (Figure 5). Significant velocity dispersion does, however, exist for both the shear and Young's moduli between the low frequency and high frequency measurements when the samples are water saturated. (Figure 4). The water saturated samples do not show any dispersion between 0.01-1 Hz, but between 1 Hz and 1 MHz significant dispersion occurs. This effect is most pronounced at pressures less than ~100 MPa when the cracks remain open. These experimental results will provide important measurements with which to constrain theoretical models.

CONCLUSIONS

Thermal cracking induced a relatively isotropic distribution of low-aspect ratio fractures into both quartzite samples. Porosities on the order of ~3% were measured, and progressive crack closure was observed until ~100 MPa, causing significant stiffening of both the shear and Young's moduli of the samples.

Successful forced oscillation measurements on the quartzite samples demonstrate the capability of the newly developed flexural measurement capacity of the Australian National University laboratory. In conjunction with the torsional measurements, the apparatus allows the calculation of both the Young's and shear low frequency moduli.

No frequency dispersion was observed in the dry and argon saturated samples, however a significant effect was observed when the samples were saturated with water. As expected, this dispersion was greater at lower pressures when the cracks within the samples were open. The velocity dispersion measurements provide important experimental data with which to test theoretical models of frequency dependent pore fluid behavior in cracked rocks.

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