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Experimental results on the combined effects of frequency and pressure on the dispersion of elastic waves in porous rocks

Jérôme Fortin, L. Pimienta, Y. Guéguen, and A. Schubnel, Laboratoire de Géologie, École Normale Supérieure, Paris
E. C. David, Australian National University, Canberra
M. Adelinet, IFP Energies nouvelles, Rueil Malmaison

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Abstract

Experimental results are presented on the dispersive nature of elastic waves in porous rocks. These results show the combined effects of frequency, pressure, and fluid viscosity on the bulk modulus in fluid-saturated sandstone and basalt. At low frequency (0.1 Hz), samples behave as though fully drained: The bulk modulus remains unchanged under argon-, glycerin-, and water-saturated conditions. However, the high-frequency (or unrelaxed) bulk modulus, deduced from ultrasonic velocities, is clearly modified by the nature of the fluid. In addition, the bulk dispersion between low and high frequencies is significant at low confining pressure when cracks are open and decreases as cracks are closed. Although cracks represent a small fraction of total porosity, they produce a dispersion caused by squirt-flow processes. A simple quantitative model can be used to predict the frequency effect and explain the experimental results well.

Introduction

In recent years, experimental progress has been made in understanding the mechanisms responsible for the dissipation of elastic wave energy in rocks. The main question that motivates such investigation is how to compare elastic wave velocities measured in laboratory conditions to elastic wave velocities recorded in the field (seismology, seismic reservoir characterization). To answer this question, two effects should be taken into account: heterogeneity of rocks and a frequency effect. Only the frequency effect will be discussed in this article.

When cracks and pores are connected within a rock, stress can induce fluid flow from one inclusion to another. Because cracks are more compliant than equant pores, a stress wave builds a higher fluid pressure within a crack than within a pore, and consequently, fluid flows from crack to pore at a local scale (O'Connell and Budiansky, 1977).

In theory, three main frequency regimes can be defined, depending on the ability of the fluid to move at the passing of a wave. The first regime appears at low frequency and is the drained regime. In this regime, the pore pressure defined at the scale of a representative elementary volume (REV) is constant and is unaffected by a seismic wave.

At intermediate frequency, pore pressure remains locally uniform but changes when the wave passes through. This is the undrained regime. Note that these two regimes are defined within the framework of the poroelasticity theory, and the undrained moduli can be predicted from the drained moduli using the Biot-Gassmann equations. Such situations (drained or undrained regime) are expected in field measurements.

In laboratory conditions, most elastic wave data are obtained in the megahertz (MHz) range. At such high frequency, there is usually no time for fluid-pressure equilibrium to occur (even at the REV scale) (Guéguen et al., 2011). The stiffest elastic behavior of the rock behaves as if the pores or cracks were totally isolated. This is the high-frequency regime (or unrelaxed regime). This last regime is not accounted for by poroelasticity,

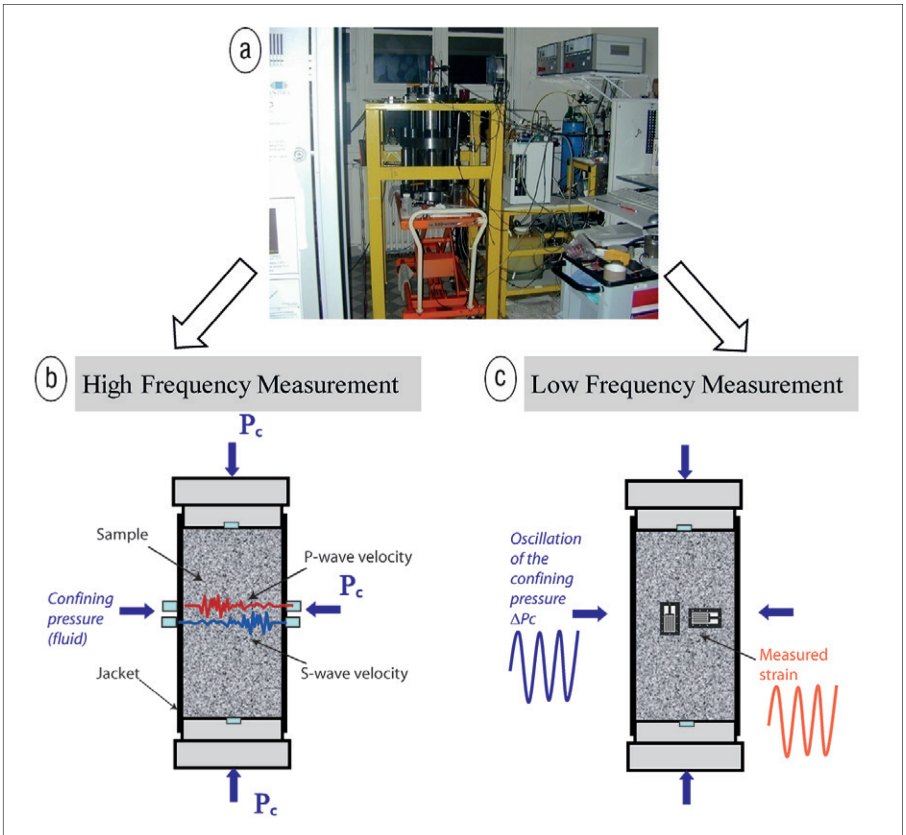

Figure 1. Experimental setup. (a) Photo of the cell installed at ENS Paris. (b) PZT transducers are glued onto the samples. From the ultrasonic velocities, the high-frequency (1-MHz) bulk modulus is deduced. (c) The low-frequency bulk modulus is obtained by oscillating the confining pressure and measuring the resulting volumetric strain.

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but the elastic moduli (or the P- and S-velocities) can be calculated from effective-medium theory. In general, if a rock is dry, no dispersion of elastic waves is expected.

To investigate the frequency effect on the elastic properties of saturated rocks, we measured in the laboratory the bulk modulus at high frequency (1 MHz) and at low frequency (0.1 Hz) under pressure and with different nature of pore fluids.

Experimental setup

Measurements in the laboratory of elastic wave velocity at frequency used in the field are difficult to obtain. Batzle et al. (2006) gives a review of the available laboratory techniques. At ENS Paris, we developed a new technique based on the strain-stress method to measure the bulk modulus at low frequency (Figure 1). A rock sample 4 cm in diameter and 8 cm in length is submitted to hydrostatic pressure in the range of zero to 100 MPa (Fortin et al., 2007). Pore pressure can be applied using independent volumetric servopumps. Axial and radial strains are measured by strain gauges glued directly onto the sample.

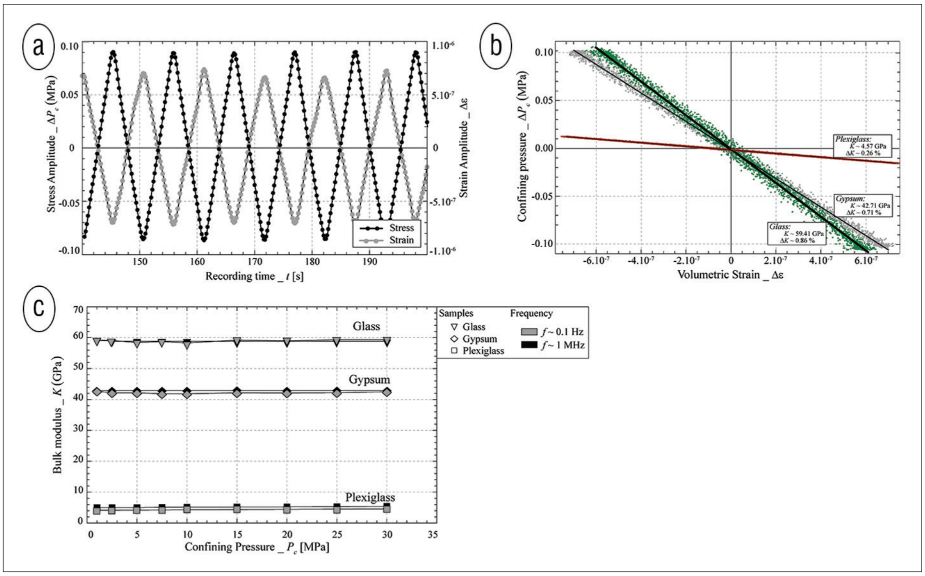

Figure 2. (a) Stress (black curve) and volumetric-strain (gray) oscillations versus time. In this experiment, oscillations were applied on a gypsum sample, and the mean confining pressure was 1 MPa. The stress-oscillation amplitude was 0.2 MPa, and the induced strain-oscillation amplitude was ~10^{-6}. (b) Example of linear regression for three standard samples (Plexiglas, gypsum, and glass). For these three measurements, the frequency was 0.1 Hz, and the mean confining pressure was 1 MPa. (c) Evolution of the high-frequency bulk modulus (black) and low-frequency bulk modulus (gray) for the three standard samples. As expected, no dispersion of the bulk modulus is observed. After Pimienta, personal communication, 2014. Used by permission.

Ultrasonic velocities are obtained from measurement of the time of flight of a pulse transmitted through the sample, using P- and S-transducers (PZT). From the ultrasonic velocities, the high-frequency (1-MHz) bulk modulus is obtained. The low-frequency bulk modulus is obtained by oscillating the confining pressure around a mean value (at a frequency in the range of 0.001 to 0.1 Hz) and measuring the resulting volumetric strain (Figure 2a). The amplitude of the stress oscillation and the amplitude of the resulting volumetric-strain oscillation should be small enough to obtain a perfect linear elastic behavior of the sample (strain amplitude < 10^{-6}). Then the low-frequency bulk modulus is obtained from the slope of the confining pressure versus volumetric strain (Figure 2b).

To test this experimental setup, experiments were performed on three standard samples in dry conditions: Plexiglas, gypsum, and glass (Pimienta et al., 2013). For these samples, Figure 2c gives the evolution of the high-frequency (HF) bulk modulus (1 MHz) and the low-frequency (LF) bulk modulus (0.1 Hz) versus confining pressure (zero to 35 MPa). Figure 2c shows an excellent match between the HF and LF moduli and shows that the moduli remain constant as confining pressure increases. These results are expected because these three standard samples have no porosity.

Dispersion of elastic moduli in sandstone and in basalt

We investigated the dispersive nature of elastic waves in two rocks: a porous basalt and a porous sandstone. Fontainebleau Sandstone is an Oligocene arenite found in the region of Île-de-France near Paris, formed by pure quartz grains that are well sorted and have an almost constant grain size of about 250 μm. The connected porosity is 13%, and the permeability is 190 10^{-15} m^2 (David et al., 2013). The second rock is an alkali-fresh and young basalt (less than 10,000 years old) with a connected porosity of about 8%. Pore distribution is bimodal: Crack porosity is 1%, and equant-pore porosity is 7%. The initial permeability of this basalt is 1 10^{-15} m^2 (Adelinet et al., 2010; Guéguen et al., 2011).

Results on Fontainebleau Sandstone. A series of three hydrostatic cycles (saturated with argon, glycerin, and then water) was carried out on Fontainebleau Sandstone (David et al., 2013) at a fixed pore pressure of 5 MPa. The first hydrostatic cycle, in which the sample is saturated with argon gas, is equivalent to a dry cycle. Glycerin was selected because the pore-fluid effect on elastic properties is strongly dependent on fluid viscosity (the viscosity of glycerin is three orders of magnitude higher than that of water).

Figure 3a summarizes the evolution of P- and S-wave ultrasonic velocities with pressure. Velocities increase with pressure as cracks are closed gradually. As expected, a clear effect of the fluid is observed, and both V_P and V_S are sensitive to changes in pore-fluid bulk modulus and density.

Figure 3b shows the estimated high-frequency bulk modulus for different saturating fluids. Increasing the bulk modulus and density of the saturating fluid results in an increase of the saturated-rock bulk modulus and velocity. Moreover, a stiffer fluid limits the effect of confining pressure on velocity, which is seen as less pressure dependence of velocity and modulus in Figure 3. In contrast, larger pore-fluid bulk modulus causes V_S to take on higher values only at low pressures.

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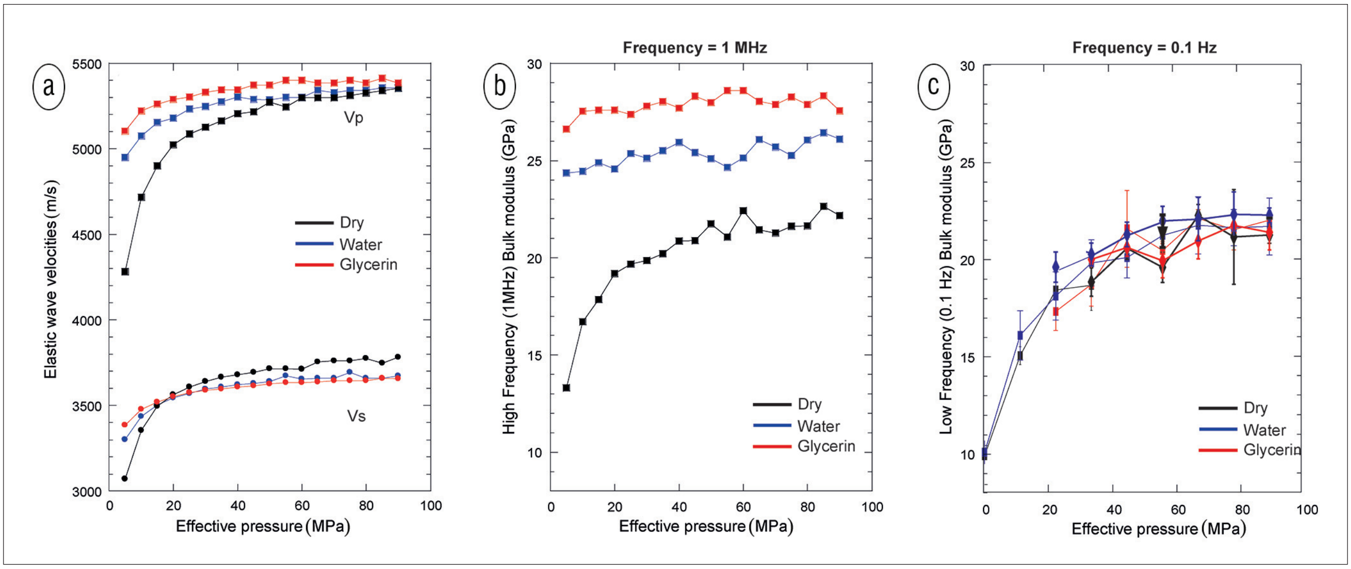

Figure 3. Data obtained on 13% porosity Fontainebleau Sandstone. (a) Ultrasonic velocity measurements (P- and S- wave velocities) for dry, glycerin-saturated, and water-saturated Fontainebleau Sandstone samples, as a function of effective pressure. (b) High-frequency bulk modulus from elastic wave velocities for the dry, glycerin-saturated, and water-saturated cycle. (c) Bulk-modulus measurements at low frequency (0.1 Hz), using oscillations of confining pressure (dry, glycerin saturated, and water saturated). At this frequency, bulk moduli are not affected by pore fluid, and saturated samples behave as though fully drained. Note also the good match between the (c) low-frequency and (part b, black curve) dry high-frequency bulk modulus over the complete pressure range. After David et al., 2013, Figures 5 and 6.

Figure 3c summarizes experimental measurements of low-frequency (0.1-Hz) bulk moduli. For all confining pressures, the glycerin- and water-saturated low-frequency bulk moduli are equal to the rock dry bulk modulus. In other words, at this low frequency, bulk modulus is not sensitive to fluids, meaning that the measured saturated samples behave as though fully drained. This is confirmed by the good match between low-frequency bulk modulus and dry high-frequency bulk modulus over the complete pressure range (Figure 3c and black curve in Figure 3b).

Figure 4 summarizes the results obtained with glycerin as pore fluid. In addition to the low-frequency (or drained) bulk modulus and the high-frequency bulk modulus, the prediction of the undrained modulus (obtained from the Biot-Gassmann equation) is plotted (dashed line). This figure shows that there is a significant difference between the undrained bulk modulus and the high-frequency saturated bulk modulus. In addition, the difference between the two moduli decreases when pressure increases. We therefore interpret that the dispersion effect is caused by the existence of cracks or compliant pores. As pressure increases, cracks close (Guéguen et al., 2011).

How do we explain that at 0.1 Hz, the saturated samples behave as though fully drained? In low-frequency conditions, fluid pressure has time to reach local equilibrium so that any representative elementary volume is isobaric. Then poroelastic theory applies. Elastic moduli are "relaxed" ones. Following Cleary (1978), three relaxation times τ can be considered when a fluid phase is saturating small-scale sites: (1) τ_1 at the site scale, (2) τ_2 between sites at the REV scale (local), and (3) τ_3 between REV at the global scale l.

The third one allows separation of drained and undrained regimes. The frequency cutoff, f_u, between drained and

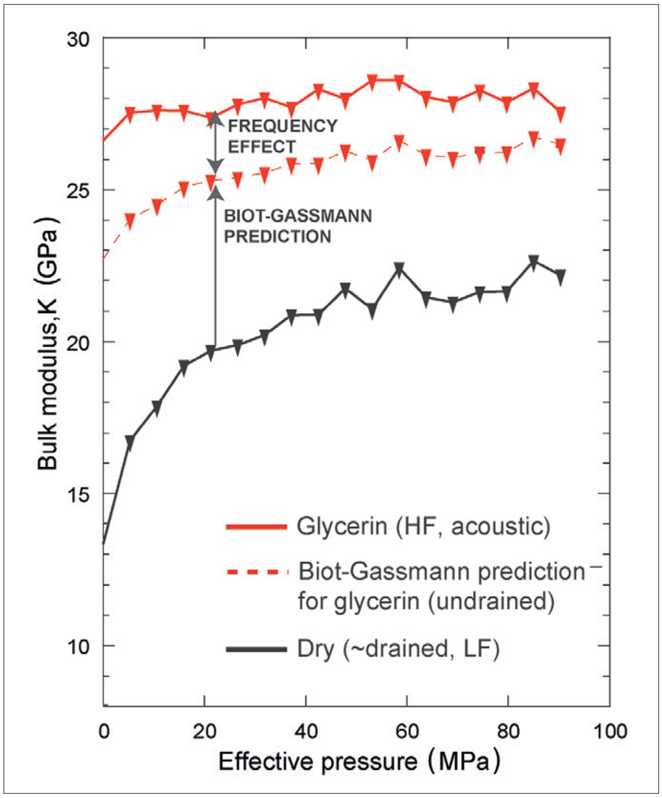

Figure 4. Data obtained during the hydrostatic cycle with glycerin as pore fluid. The evolution of the drained modulus (experimentally equal to the dry modulus) is plotted in black. The undrained modulus is obtained from the drained modulus by using the Biot-Gassmann equation and is plotted as the dashed red line. The high-frequency saturated modulus is plotted as the red line. The frequency effect is clearly demonstrated. Note that such effect is more pronounced at low pressure.

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undrained regimes, deduced from τ_3, can be written as (Cleary, 1978)

$$f_u = \frac{k}{\phi \eta C_f l^2},$$

where k is permeability, η is fluid viscosity, Φ is porosity, and C_f is fluid compressibility.

Taking the characteristic length to be the rock-sample length, it is found that the critical frequency below which drained behavior occurs is f_u = 4 Hz (for glycerin) and f_u = 2 kHz (for water). This confirms that at 0.1 Hz, the measured low-frequency bulk modulus is indeed for a drained condition. Under glycerin saturation, our low-frequency measurements might be close to the limit of drained behavior, which might be exceeded with a lower-permeability rock.

Results on basalt. The basalt investigated in Adelinet et al. (2010) is characterized by a perfect bimodal porosity, i.e., cracks and equant pores. Equant pores are produced during degassing of the lava flow and are trapped during the cooling of lava. Cracks are caused by thermal cracking. Thus, this rock is characterized by an "ideal" microstructure. Two hydrostatic cycles (saturated by argon and then water) were carried out on these samples at a fixed pore pressure of 10 MPa (Adelinet et al., 2010; Adelinet et al., 2011).

As for the Fontainebleau Sandstone, we observed experimentally that at a frequency of 0.1 Hz, the moduli are drained moduli (the cutoff frequency for this rock is estimated for water to be f_u = 25 Hz). Thus, the undrained moduli can be predicted using the Biot-Gassmann equation.

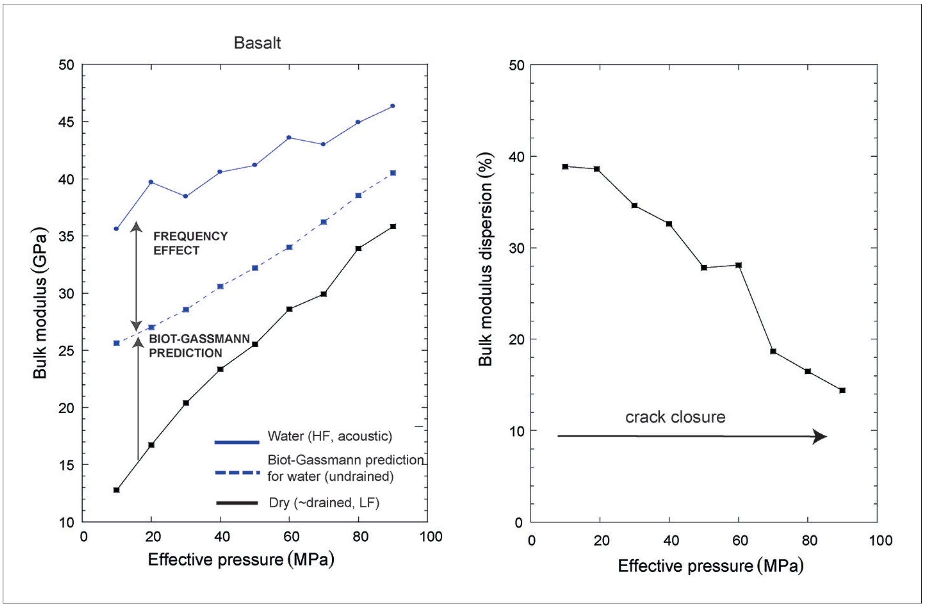

Figure 5. (a) Data obtained on basalt during the hydrostatic cycle with water as pore fluid. The evolution of the drained modulus is plotted in black. The undrained modulus is obtained from the drained modulus and the Biot-Gassmann equation and is plotted as the dashed blue line. The high-frequency saturated modulus is plotted as the blue line. (b) Evolution of the bulk dispersion with pressure. The frequency effect on the measured moduli diminishes as pressure increases as a result of crack closure. Obtained from data published in Adelinet et al., 2010.

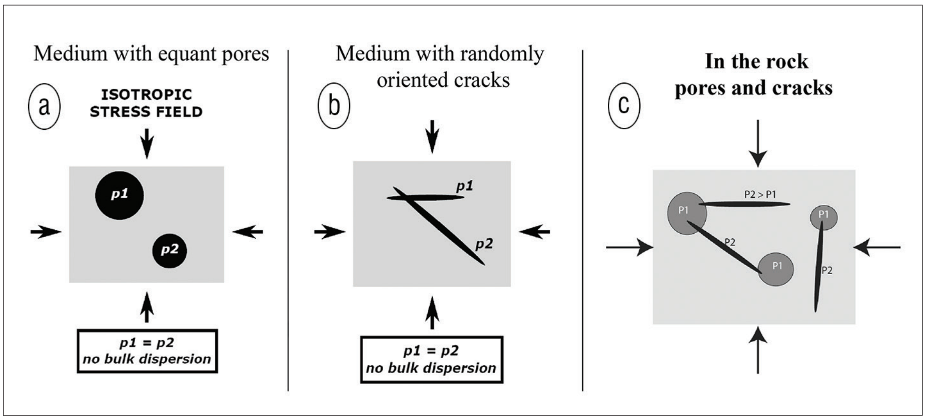

Figure 6. Sketch of the elastic behavior of fluid-saturated equant pores and cracks submitted to hydrostatic pressure. (a) If a medium contains only equant pores, the pore pressure induced by the changes of the stress field is the same in the different pores, and no frequency effect is expected. (b) If the rock contains randomly oriented cracks, as for the first case, no frequency effect is expected. However, (c) if the medium contains pores and cracks, a frequency effect should be observed, resulting from a squirt flow from cracks to pores because cracks are more compliant than pores.

Figure 5 summarizes the results. Again for this rock, there is a significant difference between the undrained bulk modulus and the high-frequency saturated bulk modulus. We can define the modulus K (saturated) dispersion as the quantity

$$D = \frac{K^{HF} - K^{LFU}}{K^{LFU}},$$

where K^{HF} is the saturated high-frequency modulus and K^{LFU} is the undrained low-frequency modulus. Thus, parameter D quantifies the frequency effect (Adelinet et al., 2011).

In basalt, the dispersion is about 40% at a confining pressure of 10 MPa, and it decreases rapidly with pressure. At a confining pressure of 90 MPa, the dispersion is about 10%. From mechanical data, during this loading, the porosity reduction is about 0.7%, meaning that a large part of the preexisting cracks are closed at 90 MPa. Again, as for Fontainebleau Sandstone, the overall conclusion is that crack closure reduces the dispersion effect.

A simple model to predict the frequency effect

How should we interpret the experimental results obtained on basalt and sandstone? Several types of macroscopic fluid-flow mechanisms can be considered (Sarout, 2012). Here, the samples are fully saturated. Thus, the frequency

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effect might be attributed to a squirt-flow mechanism proposed initially by Mavko and Nur (1975) and later treated quantitatively by O'Connell and Budiansky (1977). When a wave passes through a rock containing cracks, a pore-pressure gradient is induced, depending on crack distribution. As a consequence, the Biot-Gassmann equations underestimate the rock elastic properties in the high-frequency range.

In the case of randomly oriented cracks, because all cracks are submitted to the same boundary conditions and experience the same pore pressure, no bulk dispersion is expected (Figure 6a). If the rock contains perfectly equant pores, pores are again isobaric, and theoretically, no pressure gradient is expected (Figure 6b). However, if the rock contains pores and cracks, then a pressure gradient is induced from cracks to pores (Figure 6c). This mechanism is in agreement with the experimental results: The dispersion effect decreases as the pressure increases, i.e., when cracks are closed.

The experimental results lead to a simple quantitative model to predict the frequency effect (Adelinet et al., 2011). Let us assume that a rock contains a bimodal porosity of cracks and equant pores (Figure 7). Effective-medium theory provides a way to calculate the high-frequency moduli for dry and saturated rocks. In the framework of the noninteraction approximation, exact relations are known to express effective moduli, as a function of the equant porosity, crack density, and mean crack-aspect ratio $\zeta = w/c$ (where w and c are crack aperture and crack length, respectively).

From the dry modulus, the undrained modulus can be estimated with the Biot-Gassmann equation. Then, dispersion D can be predicted as a function of the crack-aspect ratio and crack fraction R. The crack fraction is defined as

$$R = \frac{\phi_{\text{crack}}}{\phi_{\text{T}}},$$

where Φ_{crack} is crack porosity and Φ_{T} is total porosity (Adelinet et al., 2011; Guéguen et al., 2011).

Figure 8 shows the evolution of the bulk dispersion as a function of crack fraction R for different crack-aspect ratio values. No dispersion is expected when the medium contains only pores ($R = 0$) or only randomly oriented cracks ($R = 1$). Dispersion depends on aspect ratio and can reach a value of 50% for a crack-aspect ratio of 0.005. The maximum D is calculated to occur for $R \sim 0.2$.

We check the bulk dispersion data against theoretical predictions. There is only one free parameter, which is the crack-aspect ratio. Figure 8b shows how theoretical predictions and experimental data can be compared and which aspect ratio range is compatible with the data. This comparison is done with the results obtained on the basalt sample. The comparison between experimental data and theoretical prediction is that the aspect ratio should be close to 0.01. This agrees nicely with independent results derived from elastic wave velocity data (Adelinet et al., 2010; Guéguen et al., 2011).

Conclusion

New measurements of the bulk modulus at low frequency (0.001 to 0.1 Hz) have been obtained in the laboratory on Fontainebleau Sandstone and basalt samples under confining pressure and in conjunction with ultrasonic velocity measurements using different pore fluids. This experimental setup allows estimation of the frequency effect on elastic wave velocities. At low frequency, samples behave as though fully drained under glycerin and water saturations. Velocity dispersion between low and high frequencies is significant at low confining pressure when cracks are open, and it decreases as cracks are closed. Although cracks represent a small fraction of total porosity, they produce a dispersion because of squirt-flow processes. A simple

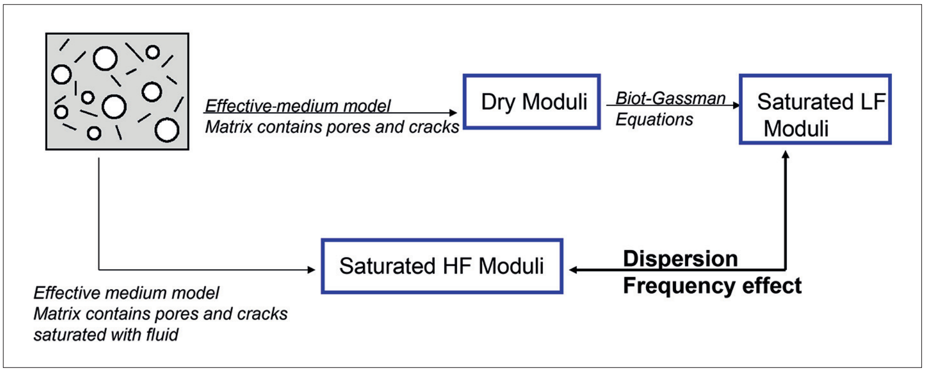

Figure 7. Sketch of a simple model to predict the frequency effect.

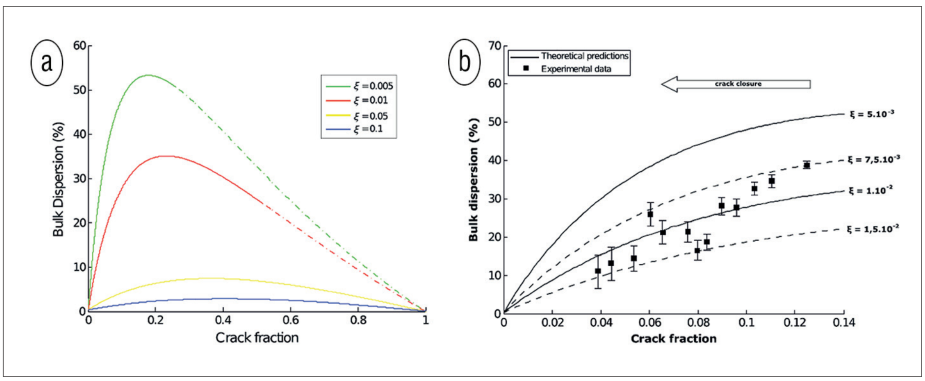

Figure 8. (a) Theoretical prediction of bulk dispersion (D) as a function of crack fraction for different values of crack-aspect ratio. There is no bulk dispersion when R = 0 or R = 1 (medium with only pores and only cracks, respectively). Dispersion increases with smaller aspect ratio values. (b) Comparison between experimental data obtained on basalt (Figure 5) and theoretical predictions (Figure 8a). We assume that equant porosity does not change with pressure. Then porosity evolution with confining pressure corresponds to crack-porosity evolution, which can be deduced from mechanical data. There is a good match between the data and prediction for a crack-aspect ratio of $\sim 10^{-2}$. After Gueguen et al., 2011, Figures 3 and 4.

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quantitative model can be used to predict the frequency effect, and it explains the experimental results well.

Such measurements of elastic properties over large frequency ranges are crucial to clearly separate the very low-frequency drained regime, the low- to intermediate-frequency Gassmann regime, and the isolated high-frequency regime. Using lower-permeability rocks or higher-viscosity pore fluids, it might be possible to see the transition frequencies in the laboratory. Such measurements are done at ENS Paris. In addition, to reproduce elastic wave velocities at low frequency, the measurement of two elastic moduli is necessary. Thus, the experimental setup is modified to measure at low frequency the bulk modulus and the Young's modulus. TLE

References

Adelinet, M., J. Fortin, Y. Guéguen, A. Schubnel, and L. Geoffroy, 2010, Frequency and fluid effects on elastic properties of basalt: Experimental investigations: Geophysical Research Letters, **37**, no. 2, paper L02303, http://dx.doi.org/10.1029/2009gl041660.

Adelinet, M., J. Fortin, and Y. Guéguen, 2011, Dispersion of elastic moduli in a porous-cracked rock: Theoretical predictions for squirt-flow: Tectonophysics, **503**, nos. 1–2, 173–181, http://dx.doi.org/10.1016/j.tecto.2010.10.012.

Batzle, M. L., D.-H. Han, and R. Hofmann, 2006, Fluid mobility and frequency-dependent seismic velocity — Direct measurements: Geophysics, **71**, no. 1, N1–N9, http://dx.doi.org/10.1190/1.2159053.

Cleary, M. P., 1978, Elastic and dynamic response regimes of fluid-impregnated solids with diverse microstructures: International Journal of Solids and Structures, **14**, no. 10, 795–819, http://dx.doi.org/10.1016/0020-7683(78)90072-0.

David, E., J. Fortin, A. Schubnel, Y. Guéguen, and R. Zimmerman, 2013, Laboratory measurements of low- and high-frequency elastic moduli in Fontainebleau Sandstone: Geophysics, **78**, no. 5, D369–D379, http://dx.doi.org/10.1190/geo2013-0070.1.

Fortin, J., Y. Guéguen, and A. Schubnel, 2007, Effect of pore collapse and grain crushing on ultrasonic velocities and V_p/V_S: Journal of Geophysical Research: Solid Earth, **112**, B8, B08207, http://dx.doi.org/10.1029/2005JB004005.

Guéguen, Y., M. Adelinet, A. Ougler-Simonin, J. Fortin, and A. Schubnel, 2011, How cracks modify permeability and introduce velocity dispersion: Examples of glass and basalt: The Leading Edge, **30**, no. 12, 1392–1398, http://dx.doi.org/10.1190/1.3672484.

Mavko, G., and A. Nur, 1975, Melt squirt in asthenosphere: Journal of Geophysical Research, **80**, no. 11, 1444–1448, http://dx.doi.org/10.1029/JB080i011p01444.

O'Connell, R., and B. Budiansky, 1977, Viscoelastic properties of fluid-saturated cracked solids: Journal of Geophysical Research, **82**, no. 36, 5719–5735, http://dx.doi.org/10.1029/JB082i036p05719.

Pimienta, L., J. Fortin, and Y. Guéguen, 2013, A new apparatus for measurement of frequency effects on rocks' elastic properties: Presented at the Second International Workshop on Rock Physics.

Sarout, J., 2012, Impact of pore space topology on permeability, cut-off frequencies and validity of wave propagation theories: Geophysical Journal International, **189**, no. 1, 481–492, http://dx.doi.org/10.1111/j.1365-246X.2011.05329.x.

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Corresponding author: Jerome.fortin@ens.fr