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RESEARCH ARTICLE

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Key Points:

- Local and global flows can be sensed by strain gauge-scale dispersion measurements
- The length center located strain-gauge position mainly affects the attenuation related to squirt flow, but not that related to global flow
- Ultrasonic results are averaged properties and may not be used to predict in details the local dispersion measured by strain gauges

Supporting Information:

- Supporting Information S1

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Dispersion and Attenuation of Elastic Wave Velocities: Impact of Microstructure Heterogeneity and Local Measurements

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Abstract The variation of the seismic properties with frequency of a brine-saturated sandstone sample with a porosity of 22% was measured using a forced oscillation apparatus. Two pairs of orthogonal biaxial strain gauges were pasted at different locations at the length center of the sample. In the frequency range of 1–300 Hz, using these two pairs of strain gauges, we observed experimentally the same global flow but different local flows (squirt flow). Therefore, the observation of the local flow is influenced by the position of the strain gauges in contrast to the global flow. Indeed, local flow is strongly influenced by the microstructure (structure of the grain contacts and microcracks). In particular, we show that although the sample is homogeneous in terms of porosity and crack density, it is not the case in terms of crack aspect ratio, which may slightly vary along the sample. A 3D diffusion model coupled with a simple squirt model was built to further interpret the data. These results show that the wave-induced fluid flows occur at different scales and controls the dispersion and attenuation of saturated rocks.

1. Introduction

Wave-induced fluid flows (WIFFs), such as Biot model (Müller et al., 2010; Pride et al., 2004), patchy saturation model (Dutta & Odé, 1979; White et al., 1975), and squirt-flow model (G. Mavko & Mukerji, 1998; G. Mavko & Nur, 1979), are physical mechanisms to interpret the dispersion and attenuation caused by seismic waves in fluid-saturated rocks. The analytical or numerical solutions of these models have been widely used to interpret the measurement results of dispersion and attenuation of elastic waves. The models can be subdivided into two categories: macroscopic (global flow) and microscopic (local flow). On one hand, global flow occurs as the pressure gradient is under the wavelength scale, equalizing pressure throughout all the connected representative element volumes (REVs). Therefore, macroscopic models do not require any description of the geometry at the pore scale. On the other hand, microscopic models—typically as squirt flow—differ from the global flow theory. Local flow occurs at the scale of pore size; in this case, the pore pressure does not have the time to equilibrate at the REV scale when the wave passes through. In fact, the local pore pressure gradient is the result of contrasting compressibility between connected compliant cracks and stiff pores. Such local fluid flow may also occur between cracks distributed along different directions. Experimentally, the squirt flow mechanism is generally observed at low effective pressure (Adelinet et al., 2010), since cracks are closed at high effective pressures. Squirt flow is closely associated with the crack's geometry, and O'Connell and Budiansky (1977) built a first model to describe the influence of the crack geometry. More recently, Gurevich et al. (2010) presented a squirt model that is an approach corrected from Murphy III et al. (1986), allowing (i) the low-frequency limit consistent with the Gassmann (1951) prediction and (ii) the high-frequency limit consistent with that predicted by Mavko and Jizba (1991). The squirt flow can also be regarded as an additional acoustic energy loss mechanism. Bourbié et al. (1987) verified this by comparing different loss mechanisms in porous media with experimental observations. A more elaborate model, that is the dual-scale model or the BISQ theory (Dvorkin & Nur, 1993; Dvorkin, 1994), is to combine dynamic Biot theory and squirt-flow mechanism.

Direct observations of dispersion and attenuation of elastic modulus in the seismic frequency range are of great importance because these experimental results are essential to understand the physical mechanisms, related to fluid flows, and how they could affect seismic surveys. Subramaniyan et al. (2015) investigated

Figure 1. Scheme of the prepared sample with four biaxial strain gauges (A, B, C, and D) and Wheatstone diagonal half bridge pairing A with B, and C with D. V_i and V_o are the input and output voltage, respectively. V1 and V2 are two dead volumes caused by the pressure detector and pump. The outlet pressure can be controlled by the pressure regulator. R_1 and R_2 are the strain gauges, and R_3 and R_4 are the constant resistant.

a Fontainebleau sandstone and provided evidence of squirt flow. Yin et al. (2017) observed velocity dispersion and attenuation of a sandstone and interpreted it as a result of local squirt flow. Pimienta et al. (2015) observed two peaks of attenuation on broadband measurements on a saturated Fontainebleau sandstone and interpreted them as being related to a combination of squirt flow and drained/undrained transition. Furthermore, they pointed out that the drained/undrained transition is related to a global flow. To further interpret their observations, they built a model to describe the global attenuation and proposed a concept of “dead volume” (Pimienta et al., 2016). In addition, Borgomano et al. (2017) provided evidence of the effect of dead volumes while investigating the dispersion of a saturated limestone. Their experiments and analytical solutions provided a nice idea that one can use the “dead volume” to observe the global-drainage flow. All these experiments were conducted and interpreted under two assumptions: (i) the sample is macroscopically homogenous, and (ii) there is a REV which represents the basic pore-crack structure pattern of the sample, and the size of the REV is smaller than the size of the strain gauge. Most samples meet the first assumption since the macroscopically homogeneity can be conveniently examined using the CT method for instance. However, the second assumption is difficult to validate, and heterogeneities at microscale-like microcracks may become controlling factors of dispersion and attenuation in fluid-saturated sedimentary rocks. Few experimental studies investigate the effect of local heterogeneity, and most of the time, dispersion and attenuation are obtained from averaging measurements obtained by strain gauges and or even using only one strain gauge; this is enough to prove the existence of squirt flow for instance. In this study, we intend to investigate further by examining the results obtained by different sets of

strain gauges before averaging, which will allow us to investigate the influence of heterogeneities in the pore-crack structure on both global and local flows.

To do that, we conducted forced-oscillation experiments on a sandstone sample. It is a sandstone coming from an oil/gas reservoir in production, characterized by a more complex microstructure compared with Berea and Fontainebleau sandstone. We measured the variation of elastic moduli and their attenuation with frequency under air-, brine-, and oil-saturated conditions using two pairs of orthogonal biaxial strain gauges. In addition, CT scanning was conducted on this sandstone to observe directly the pore structure underneath the strain gauges. The results obtained locally with 6-mm-long strain gauges revealed—as expected—two distinct transitions of attenuation and dispersion of elastic moduli, one related to the global drainage flow and the other related to the local squirt flow. However, if the strain gauges show the same attenuation and dispersion due to global flow, it is not the case for local flow, highlighting the effects of local heterogeneity at microscale. Finally, a 3D diffusion model coupled with a simple squirt model was developed to interpret the experimental data, and the use of ultrasonic measurements to predict the dispersion and attenuation associated with global and local flows is discussed.

2. Experiments and Measurements

We conducted experiments of forced oscillations on a porous reservoir sandstone, first in dry condition, then saturated with brine, and finally with oil, with a characterized dead volume as a boundary condition. The dead volume allows global fluid flow to occur. Two pairs of biaxial strain gauges, in a diagonal half-bridge configuration, were pasted on the lateral surface of the cylindrical core, at the same vertical position, i.e., midlength of the sample, and at orthogonal positions (Figure 1). Indeed, as described by Pimienta et al. (2016), the vertical position of the strain gauge (distance to the boundary conditions) may influence the dispersion/attenuation results related to global flow.

2.1. Stress-Strain Apparatus

All the measurements were conducted by the stress-strain apparatus installed in a rock physics laboratory in Beijing. Here, we briefly present some information of the apparatus used in our experiments. More details can be found in the papers of Yin et al. (2017) and Sun et al. (2018). An oscillating stress is applied axially at a given frequency to the column consisting of the rock sample and two end-caps (i.e., reference aluminum, Figure 1). Two pairs (Figure 1, A and B and C and D) of 1,000 ohms of foil gauges from BCM (SB-1500-5-P-2) were bonded on the surface of the sample to measure the strain induced by the axial stress. The sample was placed inside a vessel, which can provide confining pressure loaded by nitrogen gas. A dead volume for the pore fluid was induced and named as V1 (shown in Figure 1). On the other end of the sample, there is also a dead volume (V2 shown in Figure 1) caused by the pump, which can be removed by closing a valve. The influence of the dead volume was previously investigated by Pimienta et al. (2016) and Sun et al. (2019).

In the apparatus, the stress distribution in the rock-aluminum column is uniform. The Young's modulus (E), Poisson's ratio (ν), extensional attenuation (inverse quality factor, Q_E^{-1}), and tangent of Poisson's phases difference (Q_v^{-1}) can be calculated using the following:

$$E = E_{al} \times \frac{\varepsilon_{al}}{\varepsilon_{ax}}, \quad (1)$$

$$\nu = \frac{\varepsilon_{ra}}{\varepsilon_{ax}}, \quad (2)$$

$$Q_E^{-1} = \tan(\varphi_{al} - \varphi_{ax}), \quad (3)$$

$$Q_v^{-1} = \tan(\varphi_{ra} - \varphi_{al}), \quad (4)$$

where the E_{al} is the Young's modulus of the bottom aluminum end-cap used as a stress reference, ε_{al} is the axial strain measured on that end-cap, ε_{ax} is the axial strain measured on the sample, ε_{ra} is the radial strain measured on the sample, φ_{al} and φ_{ax} are the axial strain phases of the aluminum and the sample, and φ_{ra} is the radial strain phase of the sample.

The strains are measured through a Wheatstone diagonal half-bridge (Figure 1). In this configuration, all the resistances (R_2 and R_4) and strain gauges (R_1 and R_3) are preset to 1,000 ohms. Strain (ε_{al} , ε_{ra} , and ε_{ax}) can be deduced using the formula:

$$\varepsilon = \frac{2V_o/V_i}{F \left(1 - \frac{V_o}{V_i} 10^{-6} \right) A}, \quad (5)$$

where V_i is the supplying voltage of 12 V, and V_o is the output voltage (usually at the magnitude of 100 mV) of the Wheatstone bridge. The gauge factor F is $150 \pm 5\%$. The amplifier coefficient A is 1,000, which is used to amplify the output voltage V_o . Therefore, the magnitude of the strain amplitude is in the order of 10^{-7} to 10^{-8} , guaranteeing that the rock is deformed purely elastically (Mavko et al., 2003). The signals are averaged over several cycles and the numbers of cycles depend on the applied stress frequency, such as 1 Hz corresponds to 50–60 cycles and 100 Hz corresponds to 100–120 cycles. In theory, the uncertainty of the Young's modulus and the Poisson's ratio is 10.85% (the calculation is shown in the Support Information S1), given the uncertainty of the gauge factor ($150 \pm 5\%$) and the resistance of the strain gauge ($1,000 \pm 10\%$). However, using a standard sample, i.e., aluminum, we found that the uncertainty of the Young's modulus and the Poisson's ratio is much lower than 10.85%. For the aluminum sample with the nominal value ($E = 72$ GPa, $\nu = 0.33$), the measurement is 71 GPa for Young's modulus, 0.333 for Poisson's ratio. This leads for standard sample, to an uncertainty of 1.4% for the Young's modulus and 1% for the Poisson's ratio. The smaller uncertainty may be due to several aspects: (i) the uncertainty of the gauge factor F is lower than the nominal value of 5%, and (ii) the resistance of strain gauges has an error of 1% most of the time instead of the nominal value of 10% simply because the system compensated for the error related to the strain gauge resistance. After several measurements done on several standard samples, we found the errors (uncertainties) for the Young's modulus to be 4% ($\pm 2\%$) and 3% ($\pm 1.5\%$) for the Poisson's ratio. In addition to the strain gauge uncertainty (4% for E , 3% for ν), the measurements

Figure 2. Micro-CT images (a), (b), (c), and (d) are the slices under the positions of the strain gauges A, B, C, and D. The length and width of the box are 6.4 and 6 mm, respectively, which are close to the length of the strain gauge (5–6 mm). The four images look homogenous and they are quite similar each other. Pictures obtained by a polarizing microscope at (e) polarized light and (f) orthogonal light. In (e) and (f), the symbols Q, D, P, F, and C correspond to the quartz, dolomite, pores, feldspar, and clay, respectively. The pores correspond to the dark areas, and their sizes span from 10 to 300 μm and are therefore much smaller than the strain gauges (6 mm).

conducted on different locations of the sample can cause an additional uncertainty due to slight misorientation of the strain gauge. This additional uncertainty is estimated using signals from three locations at the midheight of an aluminum sample. They are 0.6% for the Young's modulus and 0.6% for the Poisson's ratio. Finally, we expect that the overall uncertainty in the Young's modulus is $4.0\% + 0.6\% = 4.6\%$, and in the Poisson's ratio is $3\% + 0.6\% = 3.6\%$. That corresponds to an error of $\pm 2.3\%$ for the Young's modulus and $\pm 1.8\%$ for the Poisson's ratio. We propagate the uncertainties to the bulk modulus K and the shear modulus G . This gives an error of $\pm 4.1\%$ for K and $\pm 4.1\%$ for G .

On the other hand, the error of the Young's modulus attenuation is ± 0.005 , which is also estimated by the standard aluminum, a zero-attenuation medium. In addition, the maximum error related to the locations is estimated to be ± 0.003 (the calculation is shown in the Support Information S1). Then, the error of the Young's modulus attenuation equals ± 0.008 . Propagating these uncertainties in the calculation gives an error of ± 0.012 for the bulk modulus attenuation and ± 0.012 for the shear modulus attenuation.

2.2. Rock Sample and Fluids Properties

A plug of porous sandstone was cored with a length of 72 mm and a diameter of 38 mm within a core coming from a depth interval of 2527.62–2528.25 in an oil-bearing reservoir from Eastern China. The reservoir rock is from Shahejie Formation, which was formed in the age of Paleogene. The XDR and polarizing microscope analysis give us the following mineral compositions: quartz (40%), feldspar (30%), dolomite (25%), and clay (5%). Different colors represent different minerals or pores (Figures 2e and 2f). Quartz and feldspar correspond to white and gray colors, respectively. The cements such as clay appear as yellow areas between the two minerals (quartz and feldspar). The pores correspond to the dark areas and their sizes span from 10 to 300 μm , and are therefore much smaller than the strain gauges (6 mm). Note that the homogeneity of the pore structure will be discussed in section 4.1. The porosity, of 22.0%, was measured by the triple-weight method. The permeability, of 200 mD, was measured using nitrogen gas and Darcy's law at 5 MPa effective pressure. The petro-physical properties of the sample are shown in Table 1. All properties

Table 1

Q11 Petro-Physical Properties of the Sandstone

Sample no.	Sandstone (S1)
Solid grain density, ρ_0 (kg/m ³)	2070
Diameter, D (mm)	38
Length, L (mm)	72
Bulk modulus of solid grains, K_0 (GPa)	45
Porosity, Φ (%)	22%
Permeability, κ (mD)	200
Dry bulk modulus at 15 MPa, K_d (GPa)	10.8
Dry shear modulus at 15 MPa, G_d (GPa)	7.7
Lower dead volume, V_1 (ml)	40
Upper dead volume, V_2 (ml)	20
Length of the strain gauge, l (mm)	6
Confining oscillation pressure, ΔP_0 (MPa)	0.2

Note. All the parameters are measured except for K_0 that is calculated by the Voigt-Reuss-Hill average of all the mineral components.

were measured, except for the skeleton bulk modulus that was obtained by Voigt-Reuss-Hill average (Man & Huang, 2011).

A brine and a mineral oil were used sequentially as saturating fluids, and their physical properties are listed in Table 2. The oil has a higher viscosity than the brine. The salinity of the brine is 10% (100,000 ppm), which can prevent the expansion of clays inside the sample that may decrease the permeability (Batzle et al., 2006). The dynamic viscosities of the oil and brine were measured with a Brookfield viscometer at 23°C and were estimated around 68 and 1.08 cP, respectively.

2.3. Sample Saturation

We first dried the sample in an oven at 60°C for 48 hr, and then let it naturally moisturize for 24 hr at ambient conditions to reduce the influence of moisture in the dry experiments (Murphy et al., 1991; Thierry, 1993). The oscillatory stress-strain measurement was first conducted on the room dry sample at the confining pressure of

15 MPa (depth of ~1,500 m). Then, the sample was gradually saturated with brine which was injected from the bottom of the sample (Figure 1) using a syringe pump (model 100DM, Teledyne Isco, Lincoln, USA, the accuracy of 0.01 ml). During the injection of brine, a vacuum pump was linked to the outlet of the top fluid line until the brine flows out of the sample. Then, a constant pore pressure gradient of 1.5 MPa was applied to flush the sample with at least three pore volumes of brine at the confining pressure of 16.5 MPa. The differential pressure is equivalent to the dry condition (15 MPa). This procedure ensures a full saturation of the sample. The valves at both ends of the sample were then closed for the oscillation measurements. That is, the dead volume V_2 was removed, but the V_1 is still there. After the measurements, the brine was substituted by oil, a more viscous fluid (~68 cP at 23°C). The volume of the oil injected was estimated in two ways: (i) the oil volume injected by the syringe pump and (ii) the volume of brine collected in the graduated cylinder at the outlet. As with the brine, we flushed the sample with oil at a fluid pressure of 1.5 MPa. No more water was observed at the outlet of the fluid. The dispersion measurements were also done at a differential pressure of 15 MPa, with a pore pressure at 1.5 MPa and a confining pressure at 16.5 MPa. It should be noted that we do not completely exclude that the saturation method may result in some patchy saturation (with oil and residual brine) inside the sample. However, from the retrieved brine in the graduated cylinder, the maximum residual amount of brine in the sample was estimated below than 30% of the pore volume. The related attenuation from the patchy saturation model (based on corrected White's model; Dutta & Odé, 1979) was found to be negligible as shown by the prediction shown in the Support Information S1.

3. Results and Analysis

3.1. Dry Measurements

The frequency-dependence of Young's modulus (E , Figure 3a), extensional attenuation (Q_E^{-1} , Figure 3b), Poisson's ratio (ν , Figure 3c), and corresponding tangent of phase difference (Q_ν^{-1} , Figure 3d) of the sample were measured at dry condition. The bulk modulus (K , Figure 3e), bulk attenuation (Q_K^{-1} , Figure 3f), shear modulus (G , Figure 3g), and shear attenuation (Q_G^{-1} , Figure 3h) were derived from E , Q_E^{-1} , ν , and Q_ν^{-1} based on the formula provided by Borgomano et al. (2017), assuming isotropic conditions. The circles and crosses in Figure 3 correspond to the measurements of two pairs of orthogonal strain gauges. The gray error bar means an error of $\pm 2.3\%$ for the Young's modulus, $\pm 4.1\%$ for the bulk modulus and $\pm 4.1\%$ for the shear modulus. The error is ± 0.008 of the Young's modulus attenuation and the Poisson's phase difference and ± 0.012 for the bulk modulus attenuation and the shear modulus attenuation.

For Pair #1 (the circles in Figure 3), as the frequency increases from 1 to 100 Hz, the dispersion of all the moduli is below 1%, and attenuation is lower than 0.010, which is considered negligible for the low-frequency measurements and might be due to a system response (Chapman et al., 2016; Lebedev & Gurevich, 2014; Mikhaltsevitch et al., 2014; Spencer, 1981; Subramaniyan et al., 2015). For Pair #2 (crosses in Figure 3), the results show the same elastic dispersion and attenuation. The consistency of the elastic

Table 2

The fluid properties in our experiment at the pressure of 0.1 MPa and 23 °C. K_f is the fluid bulk modulus

Fluid	Viscosity (cP)	Density (kg/cm ³)	K_f (GPa)	Compressibility $1/K_f$ (GPa ⁻¹)
Brine	1.08	1,100	2.5	0.4
oil	68	890	1.8	0.56

moduli with frequency and with pressure ensures the homogeneity of the sample so that strain gauges stick in different positions give the same results. In addition, the consistency suggests that the crack densities under the strain gauges are similar. Indeed, it is well known from effective medium theory that the elastic moduli and its evolution with confining pressure, in dry condition, are mainly sensitive to crack density and not to crack aspect ratio (Kachanov, 1993).

3.2. Brine-Saturated Sample

The frequency-dependence of Young's modulus (E , Figure 4a), extensional attenuation (Q_E^{-1} , Figure 4b), Poisson's ratio (ν , Figure 4c), and corresponding tangent of phase difference (Q_ν^{-1} , Figure 4d) of the sample were measured at full brine-saturations and differential pressures of 15 MPa. We used the Kramers-Kronig (K-K) relationship (Mikhailov et al., 2016) to verify whether the Young's moduli and attenuation measured by the two pairs of strain gauges are consistent with each other and reliable. The result obtained from the K-K relations (red and blue lines are shown in Figure 4a) shows a perfect match with the measured Young's moduli in the range of 1–300 Hz. This ensures us that our experimental data are due to viscoelastic dissipation and has physical meanings.

Figure 3. (a and b) Dry Young's moduli and (c and d) Poisson's moduli of two pairs at confining pressure of 15 MPa. (e), (f), (g), and (h) are the bulk modulus, bulk attenuation, shear modulus, and shear attenuation deduced using (a)–(d). The error of (a) is ± 0.41 GPa, (c) is ± 0.004 , (e) is ± 0.45 GPa, and (g) is ± 0.3 GPa. (b) and (d) have an error of ± 0.008 . (f) and (h) have an error of ± 0.012 .

Figure 4. (a and b) Young's moduli and (c and d) Poisson's moduli of brine saturated sample at a differential pressure of 15 MPa. (e), (f), (g), and (h) are the bulk and shear moduli and attenuation deduced using (a)–(d). Cross dots are obtained from Pair #2, whereas circle dots are deduced from Pair #1. Red (Pair #1) and blue lines (Pair #2) in (a) are the predictions of Kramers-Kronig relationship deduced from attenuation. The error of (a) is ± 0.5 GPa, (c) is ± 0.006 , (e) is ± 0.82 GPa, and (g) is ± 0.4 GPa. (b) and (d) have an error of ± 0.008 . (f) and (h) have an error of ± 0.012 .

The bulk modulus (K , Figure 4e), bulk attenuation (Q_K^{-1} , Figure 4f), shear modulus (G , Figure 4g), and shear attenuation (Q_G^{-1} , Figure 4h) were derived using E , Q_E^{-1} , ν , and Q_ν^{-1} as in section 3.1. For the results from Pair #1, as the frequency increases from 1 to 300 Hz, the Young's modulus increases from 19.5 to 21.8 GPa (Figure 4a), Poisson's ratio from 0.27 to 0.31 (Figure 4c), the bulk modulus from 14.2 to 19.1 GPa (Figure 4e), and the shear modulus from 7.8 to 8.4 GPa. The frequency dependence of the corresponding attenuation and phase difference show one obvious peak at 3 Hz and negligible attenuation at 10–100 Hz. When the frequency is in the range of 100–300 Hz, the attenuation seems to increase again. For the measurement from Pair #2 (crosses in Figure 4), when the frequency increases from 1 to 300 Hz, the Young's modulus increases from ~ 20.2 to ~ 23.0 GPa (Figure 4a), the Poisson's ratio from ~ 0.25 to ~ 0.31 (Figure 4c), the bulk modulus from ~ 13.8 to ~ 20.0 GPa (Figure 4e), and the shear modulus from 8.0 to 8.8 GPa (Figure 4g). Young's attenuation (Figure 4b) exits at the band of 1–300 Hz with a nonnegligible level, and two peaks appeared with the magnitude of 0.05 at 2 Hz and 0.04 around 100 Hz. The tangent of Poisson's phases (crosses, Figure 4d) seems to have the same trend with the Young's attenuation. In addition, the bulk attenuation (Figure 4f) shows two peaks with a magnitude of 0.12 at 3 Hz and 0.1 around 100 Hz. Compared with the measurements of Pair #1, Pair #2 measured a similar bulk attenuation peak at ~ 3 Hz but presents a different peak at ~ 100 Hz. The first attenuation peak at 3 Hz is caused by the dead volume V1 (Pimienta et al., 2016), which is verified by connecting the second dead volume (V2, Figure 1). Using the dead volume V2, the bulk modulus (Figures 5a and 5c) of both pairs reduce by ~ 1 GPa at the frequency of 1–30 Hz. The F5

Figure 5. Bulk modulus and attenuation in the brine-saturated sample measured by two different pairs of strain gauge. In this experiment, two different dead volumes are used. (a) and (b) are the results from Pair #1. (c) and (d) are the results from Pair #2. Black and red correspond to the dead volume V1 and V1 + V2, respectively. Theoretically, the dead volume should only affect the global flow, as it is observed in this experiment.

attenuation (Figures 5b and 5d) within 1–30 Hz for both pairs increases immediately and the characteristic frequency (3 Hz) moves slightly to 4 Hz. This convinces us that the attenuation peak at 3 Hz is caused by the dead volume, which, in other words, is related to global-drainage flow. In addition, in the frequency range of 30–100 Hz, the bulk modulus is higher than the Gassmann prediction (red dash lines in Figure 5). The shear modulus is constant for frequencies lower than 10 Hz and increases slightly in the frequency range 10–300 Hz. There is nonnegligible shear modulus attenuation above 10 Hz for both pairs of strain gauges, considering the error bar of the shear modulus attenuation (Figure 4h). Shear modulus attenuation is not expected for global flow but is predicted in the case of squirt flow (local flow). Thus, in the frequency of 10–300 Hz, dispersion and attenuation are therefore probably caused by a local flow, for instance, the squirt-flow mechanism. Given that the viscosity of the fluid can influence the critical frequency, we supplemented an experiment in section 3.3 using the oil instead of brine, to demonstrate that the second transition is actually related to the squirt mechanism.

3.3. Oil-Saturated Sample

In squirt-flow theory, the characteristic frequency of the dispersion and attenuation is inversely proportional to fluid viscosity (Dvorkin et al., 1995). Higher pore fluid viscosity can decrease the characteristic frequency for squirt flow. We therefore supplemented the data by injecting oil with a higher viscosity (68 cP), and the measurements are shown in Figure 6. The frequency dependence of Young's modulus (E , Figure 6a), extensional attenuation (Q_E^{-1} , Figure 6b), Poisson's ratio (ν , Figure 6c), and corresponding tangent of phase difference (Q_v^{-1} , Figure 6d) were measured at a differential pressure of 15 MPa. K-K relationship (Mikhaltsevich et al., 2016) was used again to verify whether the Young's moduli and attenuation measured by two pairs of strain gauges are correlated on a viscoelastic point of view. The predictions of the K-K relationship (red and blue lines are shown in Figure 6a) show a perfect match with the measured Young's moduli (Figure 6a). This proves that our dispersion and attenuation data of oil-saturated sample are consistent and indeed have physical meaning, like those obtained on the brine saturated sample. The bulk modulus (K , Figure 6e), bulk attenuation (Q_K^{-1} , Figure 6f), shear modulus (G , Figure 6g), and shear attenuation (Q_G^{-1} , Figure 6h) were derived using E , Q_E^{-1} , ν , and Q_v^{-1} as shown in section 3.1. For the results of Pair #1, as the frequency increases from 1 to 100 Hz, the Young's modulus increases from ~21.4 to ~22.9 GPa (Figure 6a), Poisson's ratio from

Figure 6. (a and b) Young's moduli and (c and d) Poisson's moduli of the oil-saturated sample at a differential confining pressure of 15 MPa. (e and f) and (f and h) are the bulk and shear moduli and attenuations deduced by (a)–(d). Cross dots are obtained from Pair #2, whereas circle dots are deduced from Pair #1. Red (Pair #1) and blue lines (Pair #2) in (a) are the predictions of Kramers-Kronig relationship. The error of (a) is ± 0.55 GPa, (c) is ± 0.006 , (e) is ± 0.86 GPa, and (g) is ± 0.4 GPa. (b) and (d) have an error of ± 0.008 . (f) and (h) have an error of ± 0.012 .

0.28 to 0.32 (Figure 6c), the bulk modulus from ~ 16.6 to ~ 21.2 GPa (Figure 6e), and the shear modulus from 8.4 to 8.9 GPa. The frequency dependence of the Young's attenuation shows a blur peak with a magnitude of 0.04 at 2–4 Hz. Poisson's phase shows a clear peak at ~ 8 Hz. The bulk attenuation shows a peak at 8 Hz with the magnitude of 0.12. For the results measured by Pair #2 (crosses, Figure 6), as the frequency increases from 1 to 100 Hz, the Young's modulus increases from 23.7 to 25.1 GPa (Figure 6a), the Poisson's ratio from 0.265 to 0.30 (Figure 6c), bulk modulus from 16.8 to 21.2 GPa (Figure 6e), and shear modulus from 9.1 to 9.2. For the Young's attenuation (Figure 6b), one blur peak appears below 3 Hz, and negligible attenuation is observed at 30–100 Hz. For the Poisson's phase (Figure 6d), the peak appears at 2 Hz. In addition, the bulk attenuation (Figure 6f) shows a peak with a magnitude of 0.12 at 2 Hz. Compared with the measurements of Pair #1, Pair #2 gives a smaller peak and critical frequency of bulk attenuation. Note however that the bulk modulus over the frequency band of 1–100 Hz is higher than the Gassmann prediction (15.2 GPa for oil-saturated sample) which proves that the dispersion and attenuation are caused by the squirt flow again.

3.4. Comparison of Brine- and Oil-Saturated Sample

The bulk moduli and attenuation of brine saturated and oil saturated sample are put together using the apparent frequency $f^* = f * \eta_{\text{fluid}} / \eta_{\text{brine}}$, where the η_{fluid} and η_{brine} are the fluid and brine viscosities, respectively (Borgomano et al., 2019; Pimienta et al., 2015). The bulk modulus and shear modulus versus the

Figure 7. (a) Bulk modulus, (b) bulk attenuation, (e) shear modulus, and (f) shear attenuation from Pair #1. (c) Bulk modulus, (d) bulk attenuation, (g) shear modulus, and (h) shear attenuation from Pair #2. All these moduli are measured at a differential pressure of 15 MPa. The apparent frequency $f^* = f \cdot \eta_{\text{fluid}} / \eta_{\text{brine}}$ normalizes the influence of the fluid viscosity. η_{fluid} is the viscosity of brine or oil (Table 2). The empty square dots are the measurements from the brine-saturated sample, while the solid square dots come from the oil-saturated sample. The relative error of (a) and (c) and (e) and (g) is $\pm 4.1\%$, that is, ± 0.45 GPa for K and ± 0.3 GPa for G , and (b) and (d) and (f) and (h) have an error of ± 0.012 . Blue curves in (a) and (b) and (c) and (d) are the predictions of the 3D diffusional model incorporated with a squirt model. The gray curves are the predictions using the simple squirt model of Gurevich et al. (2010).

apparent frequencies are shown in Figure 7. For the measurements of Pair #1 and Pair #2, when the sample is saturated with oil, the bulk moduli (solid squares, Figure 7a) dropped slightly compared to that of the brine saturated sample (empty square, Figure 7a), around 1 GPa at the differential pressure of 15 MPa. This is attributed to the slightly higher compressibility of the oil. Moreover, the trends of bulk dispersion (empty squares, Figures 7a and 7c) of the brine-saturated and oil-saturated sample (solid squares, Figures 7a and 7c) are consistent over frequencies. For frequency < 30 Hz, results obtained from Pair #1 (Figure 7a) and Pair #2 (Figure 7b) are consistent and are related to global flow (see sections 3.2 and 3.3). However, at the bandwidth of 30–20 kHz, the bulk dispersion measured by Pair #1 (Figure 7a) shows a sharp increase, while the dispersion measured by Pair #2 (Figure 7b) shows a smoother increase. Given the error bar, the bulk modulus obtained from the ultrasonic measurements in oil saturation conditions

Figure 8. Porosity analysis of the four slices of Figures 2a, 2b, 2c, and 2d. The black and white areas correspond to pore and grains, respectively. The corresponding porosities of (a), (b), (c), and (d) are $\varphi_A = 22.1\%$, $\varphi_B = 20.9\%$, $\varphi_C = 21.9\%$, and $\varphi_D = 21.0\%$.

(red star shown in Figures 7a and b) is overall consistent with the low frequency measurements and is around 3 GPa higher than the Gassmann prediction (red dash lines, Figure 5). For apparent frequencies higher than 30 Hz, the dispersion and attenuation are related to local flow (squirt flow). For the bulk modulus attenuations (Figures 7b and 7d), when the apparent frequency is higher than 30 Hz, the measurements of Pair #1 shows an attenuation peak of 0.12 at ~700 Hz, while the attenuation peak measured by Pair #2 is 0.10 at ~150 Hz. Therefore, attenuation caused by the squirt mechanism ($f^* > 30$ Hz) depends on the strain gauge position; it is also the case for the elastic modulus dispersion (Figure 7a) but in a much lesser extent. In addition, the shear modulus (Figures 7e and 7g) and associated attenuation (Figures 7f and 7h) from the two pairs have the same trend. Given the error bar, the shear modulus has nonnegligible dispersion and attenuation at the frequencies 10–1,000 Hz for Pair #1 and 10–200 Hz for Pair #2. The increase in shear modulus for frequencies >30 Hz associated with nonnegligible attenuation is consistent with the measurements on the bulk modulus and is consistent with a squirt-flow mechanism.

4. Discussion

4.1. Pore Heterogeneity

In section 3, the strain gauges of Pairs #1 and #2 show the same global flow but different squirt-flow response (microscopic flow). To further investigate the cause of the difference, the areas under the four strain gauges (A, B, C, and D shown in Figure 1) were scanned by a μm CT and the four slices are shown in Figures 2a, 2b, 2c, and 2d. We get the porosity distribution shown in Figure 8 by setting the pore as 0 and the grains as 1. The porosities were then calculated using the formula $P = 1 - M$, where P is the porosity and M is the mean value of the slice. The estimation results are 22.1%, 20.9%, 21.9%, and 21.0% at A, B, C, and D, respectively. These values are consistent with the porosity (Table 1), measured by triple weight method. To find the size of the

Figure 9. The estimation of REV's length. (a), (b), (c), and (d) are the porosity dependence on the scale of the rectangle on which porosity is estimated. For length >4 mm, the porosities span of the random rectangle keep constant; therefore, 4 mm is the length of REV.

REV, the porosities of blocks of various sizes and randomly located within the slices were calculated (Figures 8a, 8b, 8c, and 8d). Figures 9a, 9b, 9c, and 9d show that the size of the REV's (i.e., when porosity becomes insensitive to block size) is around 4 mm, which is smaller than the length of the strain gauge of 6 mm. The sample is therefore homogenous in porosity compared to the strain gauge scale. This porosity homogeneity can also be inferred from the measurements in Figure 5, where at a frequency of ~20 Hz, the measured bulk modulus is in good agreement with Gassmann's prediction. Hence, the differences of the attenuation caused by squirt mechanism for apparent frequency >30 Hz between the measurements of Pairs #1 and #2 are supposed to be related to change in crack properties, which cannot be seen on Figure 8 as the crack porosity is much lower than the total porosity. The two main parameters regarding the crack properties are (i) the crack density and (ii) crack aspect ratio. In our measurements obtained in dry condition, the evolution of the bulk modulus with frequency is similar for Pairs #1 and #2, implying that the crack density below the two pairs is the same. Therefore, the difference between the crack properties below Pairs #1 and #2 can only be related to the other parameter, i.e., the crack aspect ratio.

4.2. Crack Aspect Ratio

We adopted the method introduced by David (2012) to calculate the aspect ratio using the evolution of bulk and shear modulus with confining pressure obtained from ultrasonic measurements (Figure 10a). The method is summarized as follows: $\alpha(p)$ is the aspect ratio for any open cracks at the confining pressure p . We define the initial crack aspect ratio as α^i at ambient pressure, i.e., $\alpha^i = \alpha(p = 0)$. Then, the general form of the evolution of the aspect ratio (α) with confining pressure p is expressed as follows:

$$\alpha(p) = \alpha^i - \int_0^p \frac{4(1-\nu^2)}{3K\pi(1-2\nu)} dp, \quad (6)$$

where the K and ν are the crack-free bulk modulus and Poisson's ratio (David & Zimmerman, 2012), respectively. Furthermore, David et al. (2012) assumed that the evolution of cumulative crack density $\Gamma(p)$ versus the confining pressure p follows the expression:

Figure 10. (a) Evolution of the bulk modulus and shear modulus deduced from ultrasonic measurements with confining pressure. (b) Inferred crack density (dash lines) versus confining pressure and the fitting curve (red line) using Formula 7. (c) and (d) are the dependence of cumulative crack density and crack porosity versus the aspect ratio.

$$\Gamma(p) = \Gamma_0 e^{-p/\hat{p}}, \quad (7)$$

where the Γ_0 is the cumulative crack density at ambient pressure $\Gamma(p = 0)$ and $\hat{p}$ is a constant. Results are given in Figures 10b where the red curve is the fitting results using Equation 7. In addition, a crack porosity distribution function against the aspect ratio is expressed as

$$\phi_c(\alpha) = \frac{4}{3} \pi \alpha \gamma(\alpha), \quad (8)$$

where the $\gamma(\alpha) = d\Gamma(\alpha)/d\alpha$ is the crack density at the aspect ratio α . $\Gamma(\alpha)$ is the cumulative crack density against the aspect ratio α (Figure 10c). The crack porosity versus the aspect ratio is shown in Figure 10d. We define the main aspect ratio $\alpha_{\text{main}} = 4.5 \times 10^{-4}$, which is the aspect ratio corresponding to the peak of the curve $\phi_c(\alpha)$ (Figure 10d). The critical frequency for squirt flow is given by Jones (1986):

$$F_c = \frac{\alpha^3 B}{\eta}, \quad (9)$$

where the expression of B is given in Gurevich et al. (2010) and $B = \frac{4\pi G_h(3K_h + G_h)}{3(3K_h + 4G_h)} \left[\frac{K_h}{K_{\text{dry}}} \right]^{1/2}$. In

Figure 10a, the bulk modulus K_h measured at high pressure is around 16.5 GPa, and G_h is around 8.7 GPa. K_{dry} is around 10.8 GPa shown in Figure 3. Then, B is around 9.97 GPa. The corresponding critical frequency is therefore 823 Hz using Formula 9 with an aspect ratio of 4.5×10^{-4} . This is consistent with the critical frequency obtained by Pair #1 (Figures 7a and 7b). However, for Pair #2, instead of using 4.5×10^{-4} , a different aspect ratio $\alpha = 2.5 \times 10^{-4}$ can predict much better the critical frequency (Figures 7c and 7d), and the critical frequency for Pair #2 is 141 Hz. This value (2.5×10^{-4}) is close to 4.5×10^{-4} , and according to Figure 10d, it is also a reasonable value. Note that a change of a factor 2 in the crack aspect ratio leads to a change in crack porosity less than 0.1% and cannot be seen on CT scan from Figure 8.

In a second step, we use the squirt model of Gurevich et al. (2010) that allows us to predict the variation of the elastic moduli with frequency. In the model, we use as an input a crack aspect ratio of 4.5×10^{-4} for Pair #1

and $\alpha = 2.5 \times 10^{-4}$ for Pair #2. Figure 7 shows a good consistency between the theoretical predictions (gray curves in Figures 7a, 7b, 7c, and 7d) and the experimental values (empty and solid square dots in Figure 7) for the bulk modulus and its attenuation. The prediction of the squirt model of Gurevich et al. (2010) was also tested for the shear modulus. In terms of amplitude, the shear attenuation predicted is in good agreement with the measurements (gray curves on Figures 7f and 7h). As expected from theoretical prediction (Adelinet et al., 2011; Gurevich et al., 2010), dispersion and attenuation are smaller for the shear modulus than for the bulk modulus. Note that for the shear modulus, dispersion and attenuation curves are close to the error bar of ± 0.3 GPa ($\pm 4.1\%$) for the elastic modulus and ± 0.012 for the attenuation. Therefore, it could be the reason that the prediction of the simple squirt model cannot match with the measurement very well.

4.3. Dual-Scale Model: Global and Local Flows

The squirt model of Gurevich et al. (2010) is used to describe the local flow. However, our experimental results show two transitions, which are related to global and local flows. To further understand these results, we built a dual-scale model to describe the dispersion and attenuation in a full range of frequency 10^{-1} to 10^6 , as illustrated in Figure 7. A 3D model that describes the influence of the global flow induced by the dead volumes has been previously developed by Sun et al. (2019). The theory of the 3D model is based on the poroelastic theory (e.g., Gueguen & Bouteca, 2004; Zimmerman, 2000). The model describes the variations of the pore fluid pressure in a homogenous porous medium induced by the oscillation of a confining pressure. The equation in the frequency domain is (Sun et al., 2019):

$$i\omega P_f(z, r, \omega) - \frac{\kappa B K_m}{\eta \alpha} \nabla^2 P_f(z, r, \omega) = i\omega B P_c(\omega), \quad (10)$$

$$\mu_m = \mu_{\text{dry}}, \quad (11)$$

where $P_f(z, r, \omega)$ is the pore fluid pressure at a position (z, r) in polar coordinate. ω is the angle frequency. κ and K_m stand for the permeability of the rock and drained bulk modulus, respectively. The amplitude of oscillated confining pressure $P_c(\omega)$ is typically in the range of 0.2 MPa. μ_{dry} is the shear modulus of dry sample, which equals the undrained shear modulus μ_m . The Skempton's coefficient is

$$B = (1/K_m - 1/K_u)/(1/K_m - 1/K_s), \quad (12)$$

and Biot's coefficient is

$$\alpha = 1 - \frac{K_m}{K_s}, \quad (13)$$

where K_u and K_s are the undrained bulk modulus and skeleton bulk modulus (Kümpel, 1991), respectively.

Then, we follow exactly the same idea as Gurevich et al. (2010) and Mavko and Nolen-Hoeksema (1994), using the assumption that rock matrix is composed of grains, empty stiff pores, and fluid saturated compliant microcracks. Cracks are assumed to be connected to the stiff pores. When the frequency is sufficiently low, the fluid-filled compliant pores are in a relaxed state, allowing the modified frame to have the same values as the rock's dry, or drained moduli. For the frequencies sufficiently high, the fluid in the crack has no time to relax, resulting in the crack behaving as the "stiff" component in the background matrix. For the intermediate frequencies, the fluid in the crack is partially relaxed, and the modified moduli ($K_{mf}(P, \omega)$ and $\mu_{mf}(P, \omega)$) for the fluid case are given as follows:

$$\frac{1}{K_{mf}(P, \omega)} = \frac{1}{K_h} + \left(\frac{1}{\frac{1}{K_{\text{dry}}(P)} - \frac{1}{K_h}} + \frac{3i\omega\eta}{8\phi_c(P)\xi^2} \right)^{-1}, \quad (14)$$

$$\frac{1}{\mu_{mf}(P, \omega)} = \frac{1}{\mu_{\text{dry}}(P)} - \frac{4}{15} \left[\frac{1}{K_{\text{dry}}(P)} - \frac{1}{K_{mf}(P, \omega)} \right], \quad (15)$$

where the η , ξ , and $\phi_c(P)$ are the fluid viscosity, the crack aspect ratio, and the crack porosity at the confining pressure P , respectively.

Incorporating the $(K_{mf}(P, \omega)$ and $\mu_{mf}(P, \omega))$ into Gassmann's equation by replacing the drained/dry moduli $(K_{dry}(P, \omega)$ and $\mu_{dry}(P, \omega))$, Gurevich et al. (2010) obtained a simple but useful squirt model. In our paper, we replaced the $(K_{dry}(P, \omega)$ and $\mu_{dry}(P, \omega))$ in the 3D diffusion model of Sun et al. (2019) by $(K_{mf}(P, \omega)$ and $\mu_{mf}(P, \omega))$. By doing so, the simple squirt model is incorporated into the 3D diffusion model.

By using the parameters shown in Table 1 and Table 2, the predictions of the dual model were shown in Figure 7. The blue lines are the predictions using the aspect ratio $(\alpha = 4.5 \times 10^{-4})$, Figures 7a and 7b) and the aspect ratio $(\alpha = 2.5 \times 10^{-4})$, Figures 7c and 7d). Using $\alpha = 4.5 \times 10^{-4}$ (blue lines in Figures 7a and 7b), the bulk modulus dispersion trend matches well with the measurements obtained by Pair #1; the attenuation in terms of critical frequency and magnitude fit well over all the frequencies. Using $\alpha_{\text{Pair \# 2}} = 2.5 \times 10^{-4}$, the predictions are in better agreement with bulk measurements of Pair #2. For both the aspect ratios, the misfit between the modeling and measurement may be due to the simplification of the squirt-flow model, which is limited to one crack aspect ratio. But they have the same unrelaxed moduli. This is expected using the Crack Pore Effective Medium (CPEM) theory (see Fig. 6 from Adelinet et al., 2011; Fortin et al., 2007): the variation of the moduli with crack aspect ratio is negligible as long as the crack aspect ratio is lower than 10^{-3} , but it will not be the case for a variation in the aspect ratio from 10^{-3} to 10^{-2} . Therefore, the predictions convince us that a slight change in the aspect ratio give different patterns of dispersion and attenuation and can explain our measurement results.

4.4. The Heterogeneities In Terms of Crack Aspect Ratio

These predictions and results suggest that the REV of 4^3 mm^3 (Figure 9) is adequate for porosity and crack density and that the sample is homogeneous in terms of these two properties. However, our results suggest that the sample is heterogeneous in terms of crack aspect ratio; i.e., the aspect ratio varies in space. And the crack aspect ratio is important to predict correctly the transition between relaxed and unrelaxed regimes. The heterogeneity in crack aspect ratio cannot be revealed using tomographic (micro-CT) images (Madonna et al., 2012) due to the resolution of the scan in comparison to the crack aperture. Regarding the relaxed regime, the REV estimated from dry conditions can apply to the saturated undrained media based on poroelasticity, which is well illustrated by the bulk modulus at 20 Hz in Figures 7a and 7c. Indeed, in this case, the main properties which are needed for the prediction of the saturated undrained moduli are the dry moduli and the porosity. For the unrelaxed regime, with respect to effective medium theory, the REV defined from dry sample can apply to the saturated media using the same crack density but a crack aspect ratio that varies in space, which corresponds to the measurement at 10,000 Hz in Figure 7a. Furthermore, these analyses can lead to a conclusion that ultrasonic measurements are generally in the unrelaxed regime and are nonlocal measurements as the wave propagation is controlled by all the elementary volumes on the wave's path and therefore cannot be used to predict strictly the local dispersion curves measured by strain gauges.

To overcome the heterogeneities related to the variation in the aspect ratio, more strain gauges should be used to get a mean property. Another option is to use larger strain gauge or global strain sensor like DCDT, but in most cases, caution should be taken when modeling squirt flow from ultrasonic measurements and compare this prediction to squirt flow measured by strain gauges.

On the other hand, the heterogeneity due to small change in crack aspect ratio does not influence the global flow at the strain gauge scale, and no differences in the elastic moduli dispersion with frequency can be observed. This final point is surely one reason that Gassmann's equation is well predictive in most experiments. In addition, this final point seems to be a direct method to identify the squirt flow from global flow. However, more experiments should be conducted to improve our understanding of how the difference of the pore-crack structure affect the squirt-flow measurements in forced-oscillation experiments, tampering with our capability to correctly model it for upscaling purposes.

5. Conclusion

The frequency-dependent elastic moduli and attenuation of reservoir sandstone were measured by two pairs of strain gauge. These experimental results reveal that the wave-induced fluid flows occur at different scales. The controls of dispersion and attenuation are from both microscopic and macroscopic pore structure properties of rocks.

In our study, we show that the attenuation related to global flow is unaffected by the position of the strain gauges glued at the middle height of the sample, while the attenuation related to the squirt flow is sensitive to the strain-gauge position. The CT results and the stress-strain measurements obtained at dry condition exclude the possibility of a change in crack density in the sample. A slight change in the crack aspect ratio underneath the strain gauges is therefore responsible for the difference in the attenuation due to squirt flow. Therefore, although it was possible to define the REV for porosity and crack density and to show that the sample is homogeneous in terms of these two properties, we find that the sample is heterogeneous in terms of crack aspect ratio. Heterogeneity in the local squirt-flow dispersion due to varying crack aspect ratio may affect the attenuation and dispersion of elastic moduli at intermediate and high frequencies. From an experimental point of view, averaging strain gauges may affect the squirt-flow observation. We therefore recommend analyzing local strain one by one before averaging them. By doing so, one can check the microstructure heterogeneity of the sample. In turn, the comparison of the different strain gauges may help to identify the local flow from the global flow in the lab, in combination with ultrasonic results.

As a consequence, for heterogeneous rocks in term of crack aspect ratio, the ultrasonic measurements, which are nonlocal measurements obtained generally in the unrelaxed regime, may not be used to predict strictly the local dispersion and attenuation curves measured by strain gauges, especially for the case in which there is only one pair of strain gauges. Nonetheless, the complete relaxed regimes, is not affected by the crack aspect ratio, and the REV defined for dry conditions apply for the saturated undrained regime, and was consistently observed in our measurements.

Finally, elastic and anelastic properties of sedimentary formations are vital knowledge for exploration and production of oil and gas among other resources; the newly dual-scale model, that predicts reasonably our experimental data, can be a powerful tool for understanding the dispersion and attenuation of elastic waves in such media.

Data Availability Statement

Data sets are available online (<https://doi.org/10.5281/zenodo.4001697>).

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