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A study on the relationship between rock microstructure and wave dispersion in carbonates and sandstones

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ABSTRACT

The dependence of the wave properties of common rocks on their microstructure is not fully understood. Porosity, fluid type and rock texture significantly affect acoustic wave propagation. The P-wave velocities in water-saturated rocks are predicted from measurements in gas-saturated rocks, using the Gassmann theory. The dispersion is estimated from the difference between this predicted velocity and the measured one, where the latter corresponds to the unrelaxed state. In this work, ultrasonic compressional and shear wave velocities are measured in full-water and full-gas saturated tight carbonates and sandstones. By adding experimental data from the literature, we evaluate the compressional wave velocity dispersion as a function of porosity for all these lithologies (240 samples). It shows that dispersion increases with porosity in the low porosity range, but decreases in the high porosity range. For each lithology, the dispersion peak occurs at a porosity of approximately 15 %. The new findings here reflect the intrinsic natures of shallow earth rocks, which will contribute to better understandings on earth rocks for researchers of rock physics and exploration geophysics areas.

Keywords: Compressional wave velocity dispersion, Porosity, Ultrasonic measurement

1. INTRODUCTION

Rock anelasticity is affected by texture, porosity and pore fluids. Studies on attenuation and dispersion are essential in estimating the properties of rocks and guiding seismic inversion. Jeong and Hsu (1995) showed that ultrasonic attenuation increases with void content in carbon composites. Klimentos et al. (1990) established a correlation between attenuation, porosity and clay content in sandstones based on measurements. Since it has been considered that if the dispersion is completely characterized for all frequencies then attenuation is known for all frequencies and vice versa (Carcione et al., 2018; Mavko et al., 2009). Dispersion is closely related to porosity and reflects the intrinsic properties of rocks.

The two different lithologies are considered in this work. Carbonates cover a range of depositional facies, with complex porous media and considerable textural variability, showing a diversity of pore types, a wide range of pore sizes and fluid distribution heterogeneity (Lopes et al., 2014). Some deep sandstone reservoirs contain high porosity values, however, the tight sandstones have geological characteristics of low permeability, low porosity and developments of micro-cracks (Guo et al., 2018).

Laboratory measurements of ultrasonic waves in rocks have been frequently used to investigate the relations between the rock properties and wave properties. Moreover, Gassmann equation can be used to predict the compressional wave velocity of a water-saturated rock based on the properties of the dry-rock skeleton and fluid (Gassmann, 1951). However, it is only valid at the low frequency limit, where the wave-induced pore fluid pressures are equilibrated throughout the pore space (King

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and Marsden, 2002). At ultrasonic frequencies, the wave-induced fluid pressure gradient between stiff and soft pores does not equilibrate. This results in a stiffening effect, and the compressional wave velocity will be underestimated by the Gassmann equation. The velocity dispersion can be estimated by calculating the difference between the measurements and Gassmann prediction at full liquid saturation (Regnet et al., 2015).

In this work, we measure ultrasonic compressional and shear wave velocities in 18 carbonates and 17 sandstones at full-gas saturation states and full-water saturation. Together with the experimental data of the two lithologies in literature (Regnet et al., 2015; Han et al., 1986; Wang, 2016a; Wang, 2016b; Guo et al., 2018; King et al., 2000), dispersion is estimated by using Gassmann theory and the two measured velocities at full water and full-gas saturations. The relation between dispersion and porosity is analyzed.

2. EXPERIMENTAL DATA

2.1 Rock Specimens

The experimental set-up of Guo et al. (2009) is used for the ultrasonic-wave measurements on 18 carbonates (5 limestones and 13 dolomites) and 17 sandstones. The carbonates are collected from Ordovician and Cambrian formations (> 4.0 km depth), West China, with low-moderate porosity, dissolved pores and rare clay. The sandstones, collected from the Paleogene formation, in the Dongying sag, East China (around 4.0 km depth), are composed of feldspar, quartz, and rare clay.

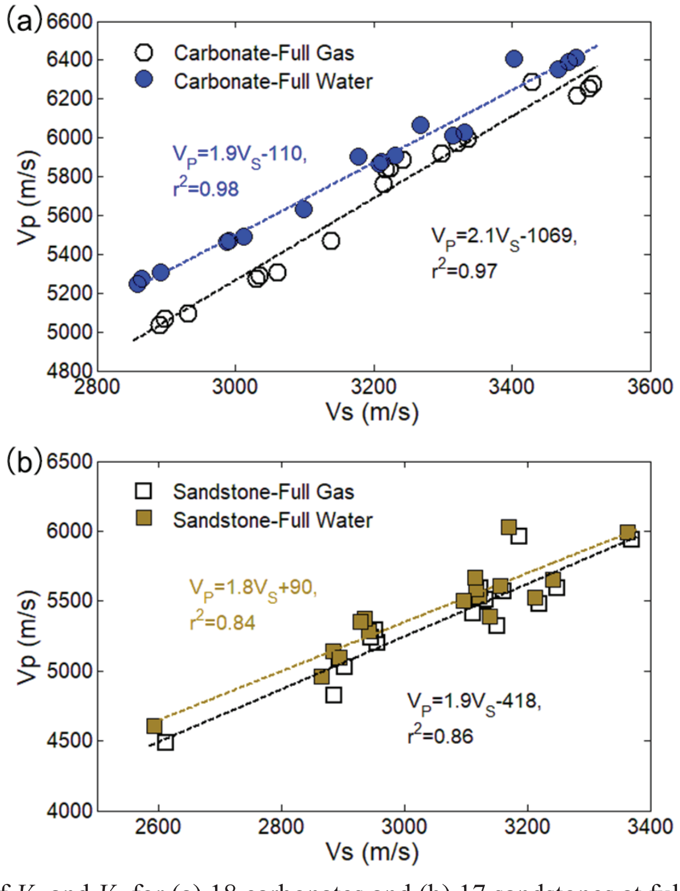

Figure 1. Crossplots of V_P and V_S for (a) 18 carbonates and (b) 17 sandstones at full gas and full water saturations. Linear fits are shown.

Ultrasonic P- and S-wave velocity (V_P and V_S) were measured for each sample at full water and full gas (nitrogen) saturations, respectively. Measurement frequency is 1 MHz. Figure 1 shows crossplots of V_P and V_S for 18 carbonates and 17 sandstones at full gas and full water saturations. The correlation of a linear fitting between V_P and V_S in carbonates is better than sandstones. The slope of V_P versus V_S is 1.9 in carbonates, higher than those in sandstones. For each lithology, the slope of V_P versus V_S at full water saturation is lower than that at full gas saturation. In addition to our measurements on the two lithologies, experimental data by Regnet et al. (2015), Han et al. (1986), Wang (2016a), Wang (2016b), Guo et al. (2018) and King et al. (2000) are analyzed.

2.2 Determination of The Bulk Modulus of The Mineral (K_0)

If the mineral contents, components and geometrical parameters are known, we can use the effective medium theories to estimate the bulk modulus of the solid (Ba et al., 2016). However, for most rocks, these properties can hardly be obtained. In another method the rocks are classified into the same lithology and sub-phase, and by analyzing the set of sorted specimens with similar lithological characteristics and minerals, a linear fitting of the velocity-porosity relations in low porosity range can give an estimation of the effective solid modulus for the whole set (Yan et al., 2011). In this work, we taken the porosity less than 8 %. For each of the two sets, V_P and V_S at zero porosity are computed, and thus, K_0 is obtained.

Modulus K_0 is obtained from the limestones, sandstones (our data), and from the results by Han et al. (1986), Wang (2016a), Guo et al. (2018). K_0 is 89.2 GPa for the carbonate set of Wang (2016b) and 40.0 GPa for the sandstone set of King and Marsden (2002). For our dolomites and the limestones of Regnet et al. (2015), K_0 is taken from Mavko et al. (2009), since the lack of data in the low porosity range.

3. RESULTS AND DISCUSSION

3.1 Gassmann Fluid Substitution

The Gassmann theory (Gassmann, 1951) theory is used to estimate the bulk modulus of water-saturated rock ($K_{(\mathrm{sat})}$) based on the velocity measurements of gas-saturated/dry rocks. Gas is light and assumed to cause no stiffening effect at ultrasonic frequencies, therefore the gas-saturated ultrasonic measurements reflect a relaxed state and give the dry-rock bulk modulus, K_b. The Gassmann theory is based on the assumption that wave-induced fluid pressures are equilibrated throughout pore space in rock, i. e., the low-frequency (LF) limit. The Gassmann equation is

$$\frac{K_{(\mathrm{sat})}^{(\mathrm{LF})}}{K_0 - K_{(\mathrm{sat})}^{(\mathrm{LF})}} = \frac{K_b}{K_0 - K_b} + \frac{K_f}{\phi(K_0 - K_f)} \tag{1}$$

where K_f and K_0 are the bulk moduli of fluid and mineral mixture, respectively, ϕ is the rock porosity, and K_b is the bulk modulus of the rock skeleton without pore fluids (e.g., Mavko et al., 2009; Carcione, 2014). $K_{(\mathrm{sat})}^{(\mathrm{LF})}$ is computed from equation (1) for each specimen, where the fluid properties are obtained at the measurement conditions according to Batzle and Wang (1992).

The P-wave velocity dispersion is then estimated as the difference between the measured P-wave velocity at ultrasonic frequencies (high-frequency, HF), $V_{\mathrm{P(sat)}}^{(\mathrm{HF})}$, and the velocity obtained from the Gassmann equation, $V_{\mathrm{P(sat)}}^{(\mathrm{LF})}$, as follows

$$\text{Dispersion}=\frac{V_{\mathrm{P(sat)}}^{(\mathrm{HF})} - V_{\mathrm{P(sat)}}^{(\mathrm{LF})}}{V_{\mathrm{P(sat)}}^{(\mathrm{LF})}} \tag{2}$$

3.2 Dispersion Versus Porosity in Tight Rocks

The dispersion is estimated by using equation (2) in the two sets of tight rocks (carbonate and sandstone) with three sub-phases, limestone, dolomite, sandstone, as is shown in Figure 2. The dispersion is generally positive in the tight rocks, indicating the predicted velocity by Gassmann theory is lower than the measured ultrasonic P-wave velocity. Similar phenomena were reported by King et al. (2002), and attributed to the presence of compliant pores or open microcracks, and the related squirt-flow mechanism. However, in these tight specimens, the dispersion is mostly less than 5 %, and apparently increases with porosity. It is also shown the sub-phases of dolomite and limestone in carbonates share the same trend of linear fitting, each phase cannot be distinct from the others by dispersion. However, by the dispersion in these tight rocks, the two lithologies can be distinguished, with sandstone having the higher dispersion and fitted slope (0.21), and carbonates having the lower slope (0.14).

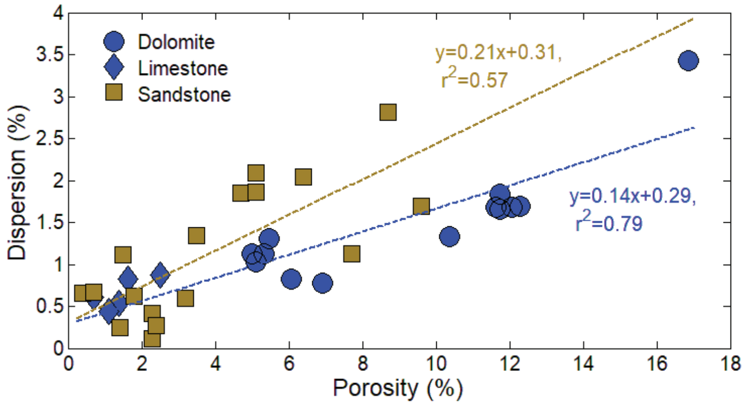

Figure 2. Crossplot of P-wave velocity dispersion and porosity for the tight carbonates (including dolomites and limestones) and sandstones in our measurements. The dashed linear represent the regressions.

3.3 Relation Between Porosity and Dispersion

Porosities of specimens in the tests of this study are mostly less than 12 % (tight rocks). The measured conditions of these data reflect the actual in-situ conditions of typical shallow geological formations. Figure 3 presents the crossplots of porosity and dispersion for the two lithologies. The most interesting point is that although rocks exhibit a trend of dispersion increasing with porosity in low porosity range (<15 %), but decreases for moderate to high porosities (> 15 %). A Gaussian fitting on the different lithologies shows that the dispersion peaks at a porosity approximately 15% (the porosities in carbonate and sandstone are 15.7 % and 14.9 %, respectively).

In addition, some negative values of dispersion in Figure 3a and 3b indicate that the fitted/given K_0 in each rock set may be not appropriate for each specimen, however there is no effective approach to precisely determine K_0 for each sample, in lack of the detailed lithology and mineral information. The analysis here provides the general statistical trend for the considered rocks.

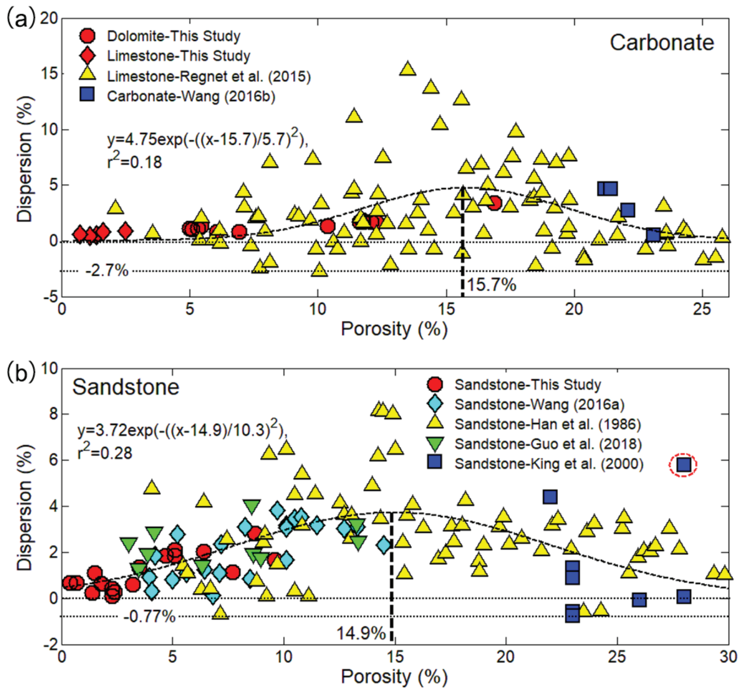

Figure 3. Crossplots of P-wave dispersion and porosity for the whole datasets of (a) carbonates and (b) sandstones. Gaussian fits are shown.

4. CONCLUSIONS

Ultrasonic measurements are performed on the two sets of tight rocks, including 18 carbonates and 17 sandstones, at the full-water and full-gas saturation states. By assuming the rock matrix is relaxed at full-gas saturation, the Gassmann theory is used to predict the P-wave velocity at full water saturation at the low frequency limit. Wave dispersion is then estimated by the difference between the Gassmann prediction and ultrasonic measurements. In the tight rock specimens of this study, the dispersion increases with porosity, and the different lithologies can be distinguished with the different linear fitting slopes. However, regarding each lithology, the sub-phases (e. g., dolomite and limestone in carbonates) cannot be distinct from each other. By incorporating the experimental data in literature, a statistical analysis on the 9 data sets with 240 specimens shows the P-wave dispersion peaks at a moderate porosity around 15 % (carbonate 15.7 %; sandstone 14.9 %) for different lithologies, which indicates the dispersion decreases with porosity in the high porosity range, instead of increases. The characteristics of other lithologies or rock types remain to be investigated. The combination research of geology and geophysics on this topic will help highlighting people's understanding on shallow earth rocks.

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REFERENCES

1. Ba J, Zhao JG, Carcione JM, Huang XX. Compressional wave dispersion due to rock matrix stiffening by clay squirt flow. Geophys. Res. Lett.. 2016;43:6186–6195.
2. Batzle M, Wang Z. Seismic properties of pore fluids. Geophysics. 1992;57(11):1396–1408.
3. Carcione JM. Wave Fields in Real Media. Theory and numerical simulation of wave propagation in anisotropic, anelastic, porous and electromagnetic media, Elsevier., Third edition, extended and revised. 2014.
4. Carcione JM, Cavallini F, Ba J, Cheng W, Qadrouh A. On the Kramers-Kronig relations. Acta Rheologica. 2018; https://link.springer.com/article/10.1007%2Fs00397–018-1119–3
5. Gassmann F. Elastic waves through a parking of spheres. Geophysics. 1951;16:673–685.
6. Guo M, Fu L, Ba J. Comparison of stress-associated coda attenuation and intrinsic attenuation from ultrasonic measurements, Geophysical Journal International, 2009;178:447-456.
7. Guo MQ, Ba J, Ma RP, Chen TS, Zhang L, Pang MQ, Xie JY. P-wave velocity dispersion and attenuation in fluid-saturated tight sandstones: Characteristics analysis based on a double double-porosity structure model description. Chinese Journal of Geophysics. 2018;61(3):1053–1068.
8. Han DH, Nur A, Morqan D. Effects of porosity and clay content on wave velocities in sandstones. Geophysics. 1986;51(11):2093–2107.
9. Jeong H, Hsu DK. Experimental analysis of porosity-induced ultrasonic attenuation and velocity change in carbon composites. Ultrasonics. 1995;33(3):195-203.
10. King MS, Marsden JR. Velocity dispersion between ultrasonic and seismic frequencies in brine-saturated reservoir sandstones. Geophysics. 2002;67(1):254–258.
11. King MS, Marsden JR, Dennis JW. Biot dispersion for P-and S-wave velocities in partially and fully saturated sandstones. Geophysical Prospecting. 2000;48(6):1075–1089.
12. Klimentos T, McCann C. Relationships among compressional wave attenuation, porosity, clay content, and permeability in sandstones. Geophysics. 1990;55(8):P998–1014.
13. Lopes S, Lebedev M, Müller TM, Clennell MB, Gurevich B. Forced imbibition into a limestone: measuring P-wave velocity and water saturation dependence on injection rate. Geophysical Prospecting. 2014;62(5):1126-1142.
14. Mao ZG, Zhu RK, Luo JL, Wang JH, Du ZH, Su L, Zhang SM. Reservoir characteristics, formation mechanisms and petroleum exploration potential of volcanic rocks in China. Petroleum Science. 2015;12(1):54–66.
15. Mavko G, Mukerji T, Dvorkin J. The Rock Physics Handbook: Tools for Seismic Analysis of Porous Media, New York, Cambridge University Press. 2009.
16. Regnet JB, Robion P, David C, Fortin J, Brigaud B, Yven B. Acoustic and reservoir properties of microporous carbonate rocks: Implication of micrite particle size and morphology. Journal of Geophysical Research:Solid Earth banner. 2015;120(2):790–811.

17. Wang DX. Study of the rock physics model of gas reservoirs in tight sandstone. Chinese Journal of Geophysics. 2016a;59(12):4603–4622.
18. Wang ZZ. Research on the Effects of Pore Structure on the Elastic Wave Properties in Carbonate Rocks,, Doctoral dissertation. 2016b. Retrieved from CNKI., http://kns.cnki.net/kns/brief/default_result.aspx. Qingdao: China University of Petroleum, (East China)
19. Yan XF, Yao FC, Cao H, Ba J, Hu LL, Yang ZF. Analyzing the mid-low porosity sandstone dry frame in central Sichuan based on effective medium theory. Applied Geophysics. 2011;8(3):163–170.