A laboratory study of $Q_s/Q_p$ and $V_p/V_s$ ratios for water saturation estimate in fractured and non-fractured sandstones.

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The ratio of compressional to shear velocity ($V_p/V_s$) is indicative of lithology and saturation for reservoir rocks. The ratio of compressional to shear attenuation ($Q_s/Q_p$) has been shown to be a more sensitive gas indicator. Using synthetic, silica-cemented, sandstones with aligned penny-shaped voids (fracture density of $0.0298 \pm 0.0077$) to simulate the effect of fractures in the Earth according to theoretical models, we conducted laboratory ultrasonic experiments to investigate the effects of aligned fractures would have on these relationships. Our results for the non-fractured rock agree with published results, but the fractured rock exhibits different behaviour which could have potential implications for fluid saturation estimation from remote seismic measurements in fractured rocks.
Introduction

Partial gas saturation and aligned fractures are common in the subsurface, both having effects on elastic wave properties (e.g., velocity dispersion and attenuation), the latter causing seismic anisotropy (velocity and Q-variation with direction and shear wave splitting). P- to S-wave velocity ratio ($V_p/V_s$) is widely used in reflection seismology and formation evaluation as a diagnostic tool for lithology and water/gas saturation. However, P- to S-wave attenuation ratio ($Q_s/Q_p$) has been shown to be sensitive to the degree of saturation over a wider range of saturation than velocity. Winkler and Nur (1982) showed that, by combining both $Q_s/Q_p$ and $V_p/V_s$, a more precise estimate of the degree of saturation may be possible. Studies combining both attenuation and velocity data for saturation estimation are limited and, furthermore, are constrained to approximately isotropic rocks. In particular, the effect of aligned fractures on these relationships is unknown even though aligned fractures are commonly encountered in the Earth.

In this study, we present novel laboratory ultrasonic measurements on two synthetic analogues of natural sandstones, one containing aligned fractures and the other left blank, as a function of water saturation ($S_w$). The aim was to investigate the effect of aligned fractures in porous rocks on elastic wave properties when under different liquid/gas saturation states, to inform the development of a suitable theoretical rock physics model for fractured reservoir characterization.

Methods

The samples used in this study are the same as those used by Tillotson et al. (2012), who give full details of sample manufacturing and characterization. Samples were made from a mixture of sand, kaolinite, and aqueous sodium silicate gel using a similar approach to Rathore et al. (1995), by arranging a predetermined number of 2 mm diameter aluminium discs of 0.2 mm thickness on successive 4 mm layers of sand mixture. The rock is baked and the aluminium is leached out with acid to leave penny-shaped voids in a silica-cemented sandstone. Image analysis of X-ray CT scans was used to obtain the fracture density, $\epsilon_f = 0.0298 \pm 0.0077$ and an average fracture aspect ratio of $0.088 \pm 0.001$ (see Tillotson et al. 2012). The porosity and permeability of both samples are 30.43% and 40.7 mD for the blank sample, and 31.68% and 18.1 mD for the fractured sample, respectively. Ultrasonic wave velocity and attenuation measurements were taken at different water saturation ($S_w$) states using the ultrasonic pulse-reflection method to accuracies of ±0.3% and ±0.2 dB/cm respectively using the ultrasonic pulse-reflection method (see Tillotson et al. 2012).

Partial water saturation was achieved by placing the samples in an atmosphere of known and controlled relative humidity (RH) (figure 1) for about two weeks, until they had reached equilibrium (e.g., King et al. 2000). Controlled relative humidity (RH) was achieved using aqueous saturated salt solutions given by Greenspan (1977). The aqueous salt solution was placed at the base of a vacuum desiccator, over which a wire gauze held the rocks in suspension. A hygrometer was also placed in the desiccator to monitor relative humidity after which the desiccator was sealed. The maximum $S_w$ achieved using this method was ~ 0.4 for both rocks. The rocks were fully saturated using a method described by McCann and Sothcott (1992). To achieve intermediate $S_w$ values, we used a modified air/water drainage technique. Although steps were taken to minimize heterogeneous saturation, it should be pointed out that the objective was to observe differences between the fractured rock and the blank rock response as a function of saturation using identical saturation and measurement methods. The drainage method gave pre-determined saturations of approximately $S_w = 0.90, 0.80, 0.70$ and 0.55.

Results

We present all results at an effective pressure of 39.9 MPa (confining pressure 40 MPa, pore fluid pressure equal to atmospheric pressure of 0.1 MPa) and a single frequency of 650 kHz obtained from Fourier analysis of broadband signals. In the fractured rock, wave propagation is parallel to fracture alignment (i.e., 90° to the fracture normal).
The dry $V_p/V_s$ ratio of the blank synthetic rock sample (~ 1.58) is in good agreement with values reported for dry (or gas saturated) clean natural sandstones (e.g., Brie et al. 1995, Castagna et al. 1985, Murphy et al. 1993). The results for the blank rock (figure 1a) shows the higher saturation values plot towards the right because of higher $V_p/V_s$ ratios. Also, there is a clear separation by the reference value of $Q_s/Q_p = 1$, as observed by Winkler and Nur (1982). $Q_s/Q_p > 1$ indicates partial saturation, while $Q_s/Q_p < 1$ indicates full water saturation (Winkler and Nur 1982, Klimentos 1995). Frequency dispersion is evident from the continuous increase from dry to water saturation compared to the data from Murphy (1982) and Winkler and Nur (1982) measured at lower frequencies of about 560 Hz and 1kHZ respectively (figure 1b). In the data of Murphy (1982), the $V_p/V_s$ ratios form a cluster around similar values for dry and partially saturated states as predicted by Gassmann’s equations. In practice, it has been shown that this is not consistent with sonic well log observations which also show evidence for dispersion (e.g., Caspari et al. 2011, Brie et al. 1995), which should be considered (e.g., Koesoemadinata and McMechan 2001).

Consequently, the distribution of the $V_p/V_s$ versus $S_w$ relationship depends on wave frequency, heterogeneities in pore and crack compressibility, saturation distribution, porosity and permeability. Using the White-Dutta and Ode model of poro-visco-elastic wave attenuation, we can begin to see how dispersion can control the $V_p/V_s$ versus $S_w$ distribution and also the attenuation distribution (figures 2a and 2b respectively). The attenuation ratio on the other hand, although also controlled by these factors, has been shown to almost always plot above the reference line of $Q_s/Q_p = 1$ for partially saturated rocks and below it for fully saturated rocks (Winkler and Nur 1982).

![Figure 1. a) Ultrasonic (650 kHz) $Q_s/Q_p$ versus $V_p/V_s$ ratios for the blank rock sample at different saturation values ($S_w$ ratios from 0 - 1) written in text next to the corresponding data point. b)Massilon sandstone data from Murphy 1982 (black diamonds, 560 Hz) and Winkler and Nur 1982 (red circles, 1 kHz).](image-url)

The fractured rock (Figure 3a) shows a similar behaviour to the blank rock in terms of the $V_p/V_s$ ratios where the higher saturations plot towards higher values of $V_p/V_s$ ratios. However, the attenuation ratios are not separated by the reference value of $Q_s/Q_p = 1$ as partial saturation values fall below the reference line, with the $Q_s/Q_{p2}$ ratios falling even lower still. As pointed out by Amalokwu et al. (2014), this could lead to interpretation errors when using $Q_s/Q_p$ as a diagnostic tool for fluid saturation. Also, depending on the wave polarization, the $V_p/V_s$ ratio in the fractured rock would be different as would be expected for an anisotropic medium. The $V_p/V_s$ ratio is not as sensitive as the $Q_s/Q_p$ ratio to the presence of fractures (e.g., figure 3b) and could be useful for saturation diagnostics when using both ratios (e.g., monitoring artificial fracturing of gas, CO$_2$ or geothermal steam reservoirs). Amalokwu et al. (2014) present evidence that our observations in the fractured rock sample are dominated by viscous losses and not scattering.
Figure 2. a) Model predictions of $V_p/V_s$ ratio versus $S_w$ at different frequencies assuming a gas patch size of 8 mm. $V_p$ predictions are from the White and Dutta-Ode model, while the $V_s$ is obtained from Gassmann’s equations. b) White and Dutta-Ode model predictions of $Q^{-1}_p$ versus $S_w$ at different frequencies assuming a gas patch size of 8 mm.

Figure 3. a) Ultrasonic $Q_s/Q_p$ versus $V_p/V_s$ ratios for the fractured rock sample at different saturation values ($S_w$ ratios from 0 - 1) written in text next to the corresponding data point. b) combination of the $Q_s/Q_p$ versus $V_p/V_s$ ratios for both the blank and fractured rock sample. Note that the subscript $S1$ = fast shear wave and $S2$ = slow shear wave in the fractured rock.

Conclusions

We present novel laboratory experimental data that provides evidence for frequency dependent saturation effects on elastic wave velocity and attenuation. We have also shown that fractures aligned in the direction of wave propagation can change the $Q_s/Q_p$ versus $V_p/V_s$ relationships which have been shown to be good saturation indicators in blank rocks. Although the observed different behaviour between non-fractured rocks and rocks with aligned fractures could lead to errors in saturation interpretation from remote seismic measurements, it could also be useful for exploration, especially for monitoring of fractured gas saturated reservoirs. The data also help to inform the development of partial saturation models for fractured rocks needed for interpreting multi-component seismic datasets.
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References


