

Changes of shear moduli in carbonate rocks: Implications for Gassmann applicability

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Summary

Understanding the effects of saturation on the acoustic properties of porous media is paramount for using amplitude versus offset (AVO) technique and 4-D seismic. Most laboratory research on saturation effects has been carried out in sandstones, despite the fact that about half of the world's oil and gas reserves are in carbonates. We conducted saturation experiments in carbonates with the intention to fill this gap. These experimental data are used to test theoretical assumptions in AVO and seismic analysis in general. Earlier studies have shown that the complex pore structures of carbonates produce poorly defined porosity-velocity trends. Although porosity is the most important factor to control sonic velocity, our data document that pore type, pore fluid compressibility and variations in shear modulus due to saturation are also important factors for velocities in carbonate rocks. Complete saturation of the pore space separated our samples into two groups: one group showed decreases in shear bulk modulus of the rock by up to 2 GPa, the other group showed increase by up to 3 GPa. This change in shear modulus questions Gassmann's assumption of constant shear modulus in dry and saturated rocks. It also explains our observation that velocities predicted with by the Gassmann equation under- and overestimates the measured velocities of saturated carbonate samples. In addition, the V_p/V_s ratio shows an overall increase with saturation. In particular, rocks displaying shear weakening have distinct higher V_p/V_s ratios.

Introduction

Laboratory experiments have shown that sonic velocity of carbonates is mainly controlled by porosity and pore types (e.g., Anselmetti and Eberli, 1993, 1999; Wang, 1997). The effect of saturation on velocity in carbonate rocks, however, has been evaluated in few studies. Ravavich et al. (1984) measured 94 Mission Canyon Formation carbonate plugs and concluded that porosity is the major factor influencing velocity, whereas petrographic fabric and pore-fluid type have no statistically relevant influence. Japsen et al. (2002) and Assefa et al. (2003) measured effects of water saturation on shear velocity on low porosity chalk (34 samples) and oolitic grainstone and packstone rocks (39 samples), respectively. Their data display consistent lower shear modulus for wet samples. On average, the shear strength is reduced by 0.5 GPa in chalk (Japsen et al., 2002) and 2 GPa in oolitic grainstone and packstone (Assefa et al., 2003). Their data are the first indications that the assumption of constant shear modulus in the Gassmann theory might not always be valid. Consequently, estimating saturated velocities using the Gassman equation might be

inaccurate. Indeed, Wang et al. (2000) show that Gassmann-calculated compressional velocities in samples from carbonate reservoirs in Alberta, Canada, statistically underestimate the measured water-saturated velocity by around 5%. His data also show that the difference between Gassmann-calculated and measured oil-saturated velocities statistically increases in measurements carried out at low effective pressures.

The aim of this study is to further investigate the effect of saturation on carbonate samples on a wider range of porosities and pore types. We selected 30 limestone samples from Cretaceous and Miocene reservoirs with porosities from 5% to over 30%. The rocks consist of wackestones, packstones and grainstones, and their pore types range from microporosity over interparticle and moldic to intraframe.

Experimental setup

Measuring the velocity under dry and saturated conditions on a single sample under variable confining pressure is challenging, because the sample might be altered during pressurization. To overcome this experimental dilemma we adopted the following procedure. We selected macroscopically homogeneous samples and cut them in half. Samples with nearly identical porosities (less the 2% variation) in both halves were used for this experiment. One half of each sample was measured first under dry conditions using variable hydrostatic confining pressure in a series of small steps from 2 MPa up to a maximum of 80 MPa and back down to 2 MPa. The pore pressure was kept constant at 1 atmosphere. If, upon completion of the pressure cycle, no hysteresis effect was detected, the sample was judged to be unaltered and measured under saturated conditions. Otherwise, the 2nd half of the sample was used for the measurements under saturated conditions. The samples were saturated with degassed, distilled water for at least 12 hrs under vacuum conditions (~ 2.5 MPa) to assure complete saturation. During the measurement the pore fluid pressure was kept constant at 2 MPa. The same effective pressure steps as used in the dry sequence were measured.

Ultrasonic velocities were measured at center frequency of 1 MHz, using a pulse transmission technique (Birch, 1960). A single compressional wave and two independently orthogonally polarized shear waves are simultaneously measured using Geoverde[®] transducer arrangements.

Effect of porosity and pore type on velocity

Despite the almost mono-mineralic composition of the carbonates in our sample set, the compressional velocity

ranges from 3000 to 6000 m/s (Fig 1). This range is mainly caused by variations in the amount of porosity and pore type. In general, velocities show a inverse correlation with porosity, but the scatter of samples with the same porosity can be as high as 1500 m/s. The observed scattering in the velocity-porosity cross-plot cannot be related to compositional variations. The scattering in the velocity is an effect of carbonate specific pore types (Anselmetti and Eberli, 1999). If a dominant pore type is assigned to each sample, it can be seen that all these characteristic pore-types form clusters in the velocity-porosity diagram (Anselmetti and Eberli, 1999). The elastic properties of these different pore types explain why rocks with the same porosity can have completely different velocities. For example rocks with a dominant moldic porosity have velocities which are over 1500 m/s faster than a rock with mainly interparticle pore type and similar porosity. This is explained by the usually strong frame and low compressibility of moldic rocks. In contrast, rocks with interparticle, intercrystalline, or microporosity have relatively low velocities (Anselmetti and Eberli, 1999).

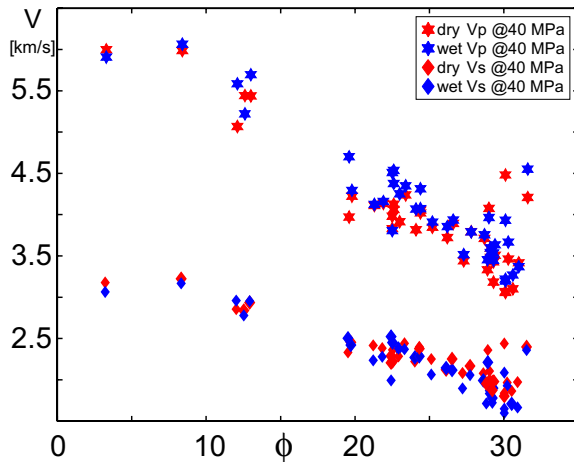


Figure 1: Plot of saturated and unsaturated p- and s-wave velocities versus porosity display the variations of sonic velocities at a given porosity.

Effect of saturation on Vp/Vs ratio

Most of the compressional velocities of the water-saturated samples are higher than the dry samples, and most of shear wave velocities are decreasing in the saturated samples (Fig. 1). The Vp/Vs ratio exhibits a wide range of values from 1.65 to 1.9 under dry conditions and 1.75 to 2.05 for the wet conditions, respectively (Fig. 2). The Vp/Vs ratio of the saturated samples tends to increase with saturation in all samples. The bulk of the dry Vp/Vs ratios show small deviation (± 0.05) from the average value of 1.72. In contrast, the saturated Vp/Vs ratios show larger deviations from the average value of 1.86. The Vp/Vs ratio shows an inverse correlation with the porosity in the dry samples, but the wet samples display an increasing scatter in Vp/Vs with increasing porosities (Fig. 2).

The observed higher compressional velocity and lower shear wave velocity of saturated samples is in agreement with the Gassmann theory. Table 1 summarizes the effects

of gas water substitution on the bulk and shear moduli, the velocities, the Vp/Vs ratio and the ratio between measured and Gassmann-predicted velocity. Gas-water substitution causes an increase in bulk modulus and an increase in compressional velocity. If the bulk modulus remains constant, the increased bulk density due to water-filled pores slightly reduces both Vs and Vp. This effect does not change the Vp/Vs ratio.

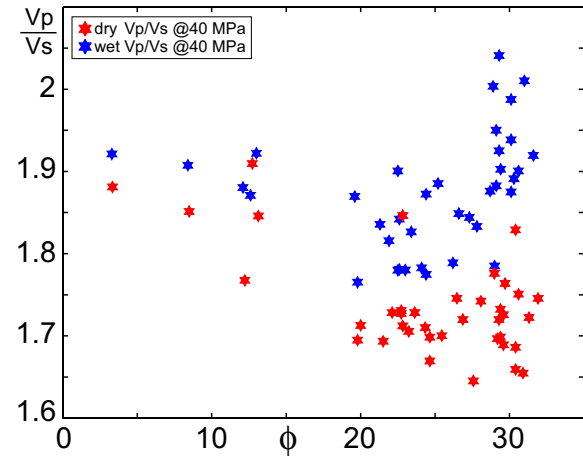


Figure 2: Plot of Vp/Vs ratio versus porosity show an increase of the ratio with saturation and larger scattering of the saturated samples at porosities above 25%.

Effects of gas to water substitution	Modulus	V _p	V _s	V _p /V _s	V _p /V _{Gas}
Compressibility decrease	K↑	↑	-	↑	-
Bulk density increase	-	↓	↓	-	-
Shear strengthening	μ↑, K↑	↑	↑	↑?	↑
Shear weakening	μ↓, K↑	↓	↓	↑	↓

Table 1: Effects of saturation on Vp, Vs and caused by four different mechanisms in carbonates (K = bulk modulus, μ = shear modulus).

Anselmetti et al. (1997) noticed that the Vp/Vs ratio increases with porosity and explained the larger scatter at higher porosities with the higher sensitivity of the shear wave to fabric weakening. Our data shows that this higher sensitivity in the shear wave is more pronounced in the saturated state.

The scatter in Vp/Vs ratios in the saturated samples has the potential of being a good indicator for the influence of distinct pore types. Preliminary results show that higher ratios occur in carbonates with interparticle porosities. This finding is in concert with Tsuneyama et al. (2003), who also observed higher Vp/Vs ratios in grainstone facies with interparticle porosity. Consequently, Vp/Vs might have the potential of separating rocks with microporosity from rocks with interparticle/intercrystalline porosity.

Shear strengthening and weakening due to saturation

In our data set the μ_w/μ_d varies from ~0.8 to 1.35, documenting that the wet shear modulus changes with saturation (Fig. 3). This variation indicates that both, shear strengthening and shear weakening, occur in carbonates due to saturation. Saturated samples, which show shear weakening, display distinct higher Vp/Vs ratios than their dry counterparts (Fig. 3). These samples with shear weakening and high Vp/Vs ratio consist mostly of rocks with interparticle/intercrystalline porosity. In contrast, carbonate rocks with dominant microporosity and moldic pore types tend to show less effects of fluid saturation on velocity.

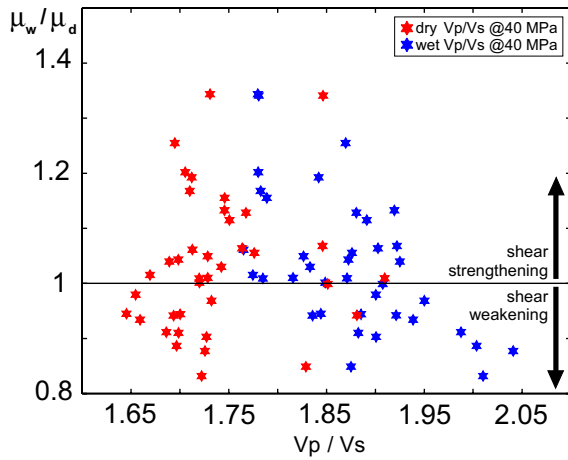


Figure 3: Ratio of wet to dry shear bulk modulus versus the Vp/Vs ratio of both the wet and dry samples. Note that each μ_w/μ_d value has a pair of Vp/Vs values.

Gassmann theory

The Gassmann theory (1951) is based on the fact that rocks in which pore space is filled with a fluid that is less compressible than gas become more resistant to compression. This bulk modulus change has been calculated using the following equation (Gassmann, 1951):

$$K_{Gass} = K_d + \frac{(1 - K_d/K_g)^2}{\frac{\phi}{K_f} + \frac{1-\phi}{K_g} - \frac{K_d}{K_g^2}} \quad (1)$$

where,

K_{Gass} is the Gassmann bulk modulus of the rock saturated with a fluid of bulk modulus K_f , a matrix modulus of K_g , a dry bulk modulus of K_d and porosity ϕ .

One important assumption of Gassmann equation is that the rock frame properties are not altered by the fluid, with the exception from the additional stiffening of the rock frame by the fluid. Under this assumption the shear bulk modulus μ should not change during saturation:

$$\mu_{dry} = \mu_{wet} \quad (2)$$

A Gassmann-predicted velocity $V_{p_{Gass}}$ can be calculated with the following equation:

$$V_{p_{Gass}} = \sqrt{\frac{K_{Gass} + (4/3)\mu}{\delta_b + \phi\delta_f}} \quad (3)$$

If the assumption of equation 2 is violated, the calculated Gassmann velocity will either over- or underestimate the measured saturated velocity. Our experiments with ultrasonic frequencies indicate that the shear modulus indeed changes with saturation and consequently the Gassmann-predicted velocities might also be inaccurate under low frequency conditions.

Effect of shear modulus variation on Vp

Figure 4 shows the change in shear modulus versus difference between Gassmann predicted and measured saturated velocity. Two groups can be identified. One group of samples in the lower left quadrant of the plot shows a decrease in shear modulus and Gassmann over-prediction of velocity. The other group in the upper right quadrant shows an increase in shear modulus and Gassmann under-prediction of velocities. Gassmann derived velocities both over and underestimate saturated velocities in carbonates by as much 400 and 600 m/s, respectively. The saturation of the pore space reduces the shear modulus by up to 2 GPa. Other samples show an increase in shear modulus of up to 3 GPa. Initial results show that samples of interparticle and intercrystalline porosity show extreme high shear variations. Samples with high microporosity and well-sorted grain-size distribution show low deviation from the dry shear modulus. An intraframe coral sample shows no change in shear modulus at all.

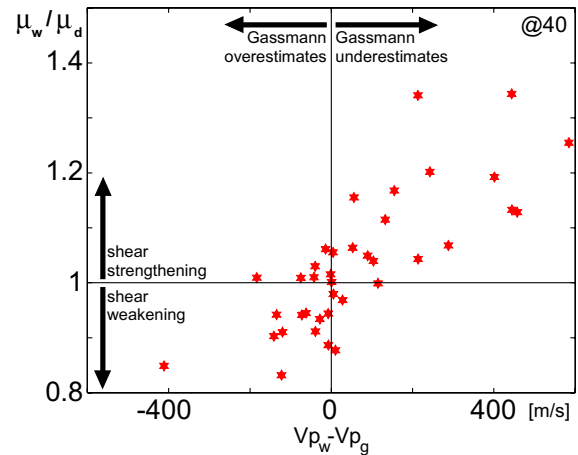


Figure 4: Plot of changes in shear modulus versus the difference between measured and Gassmann-predicted velocity. Gassmann underestimates the velocities in samples with shear strengthening and overestimates the velocities in samples with shear weakening.

In sandstones, shear modulus changes have been attributed to several mechanisms including viscous coupling,

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reduction in free surface energy and dispersion due to local flow (Khazanehdari and Sothcott, 2003). We speculate that similar mechanisms cause the observed changes in shear modulus in our carbonate samples. Local flow is assumed to strengthen the shear modulus in saturated samples, whereas water-rock interaction at grain contacts is assumed to weaken the rock frame properties.

Conclusion and implication for Gassmann applicability

The assumption of constant shear modulus in Gassmann's theory seems not to be valid for our samples and probably most carbonate rocks. Gassmann's theory assumes two mechanisms caused by saturation: fluid compressibility and fluid density effects (Table 1). We observed shear weakening and shear strengthening, which affect indirectly the velocity of the compressional wave. Further, it has been observed that saturated samples show distinctive higher V_p/V_s ratio's than unsaturated samples. The highest V_p/V_s ratio's of these saturated samples are observed in samples which show shear weakening.

Rock-fluid interactions are assumed to cause the shear modulus change in the saturated rock by alteration of the rock frame properties. The change in shear modulus is the main cause for the difference between measured velocities and Gassmann-predicted velocities. The factors which are causing the change of the shear modulus are not well understood yet, but preliminary results suggest connection to the pore types. These findings put emphasize on the importance of pore type for velocity prediction. It is well established that pore type variations cause compressibility variations at any given porosity. Our findings indicate that it might also have a control on shear modulus variation. In any rate the observed shear modulus variation reduces the applicability of the Gassmann theory for velocity prediction in carbonates.

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