In laboratory experiments we measured the saturation effects on the acoustic properties in carbonates and the results question some theoretical assumptions. In particular, these laboratory experiments under dry and wet conditions show that shear moduli do not remain constant during saturation. This change in shear modulus puts Gassmann’s assumption of a constant shear modulus into question and also explains why velocities predicted with the Gassmann equation can be lower or higher than measured velocities.

Background and experimental setup. Porosity is the most important factor controlling sonic velocity but 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. Most laboratory research on saturation effects has been carried out in sandstone, despite the fact that about half of the world’s oil and gas reserves are in carbonates. Only a few studies had investigated the effect of saturation on velocity in carbonate rocks. Rafavich et al. (1984) conclude that porosity is the major factor influencing velocity and that pore-fluid type has no statistically relevant influence. In contrast, Japsen et al. (2002) and Assefa et al. (2003) measured consistently lower shear modulus for wet samples of low porosity chalk and oolitic grain-packstone, respectively. Their data indicated for the first time that the assumption of constant shear modulus in Gassmann theory might not always be valid in carbonates. A consequence of variable shear modulus is that estimation of saturated P-wave velocity using the Gassmann equation might be inaccurate. Such an underestimation was indeed reported by Wang (2000) in samples from carbonate reservoirs in Alberta, Canada.

The aim of the study described in this article was to further investigate the effect of saturation on different carbonates. We selected 30 limestone samples from Cretaceous and Miocene reservoirs with porosities from 3% to over 30%, and having different texture and pore types.

Measuring sonic velocity under dry and saturated conditions on a single sample under variable confining pressure is an experimental challenge, because the sample might be altered during pressurization. To overcome this experimental dilemma we selected macroscopically homogeneous samples and cut them in half. Samples with nearly identical porosities (less than 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 steps from 2 MPa up to a maximum of 80 MPa and back down to 2 MPa. If, upon completion of the pressure cycle, no hysteresis effect was detected, the sample was considered unaltered and measured under saturated conditions. Otherwise, the second half of the sample was used for measurements under saturated conditions. The samples were saturated with degassed, distilled water for at least 12 hours under vacuum conditions 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. A single compressional wave and two orthogonally polarized shear waves were simultaneously measured at center frequency of 1 MHz.

Effect of saturation on $V_P$, $V_S$, and $V_P/V_S$ ratio. Gas-water substitution causes an increase in bulk modulus and in compressional-wave velocity ($V_P$). In we exclude the bulk moduli stiffening effect, then the increased bulk density due to water-filled pores slightly reduces both the shear-wave velocity ($V_S$) and $V_P$. This density effect solely does not change the $V_P/V_S$ ratio (Table 1).

<table>
<thead>
<tr>
<th>Effects of gas-to-water substitution</th>
<th>Compressibility decrease</th>
<th>Bulk density increase</th>
<th>Shear strengthening</th>
<th>Shear weakening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus</td>
<td>$K$</td>
<td>$\downarrow$</td>
<td>$\uparrow$</td>
<td>$\downarrow$</td>
</tr>
<tr>
<td>$V_P$, $V_S$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\uparrow$</td>
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$K$=bulk modulus, $\mu$=shear modulus

Many compressional velocities of our water-saturated samples are higher than the dry samples, and most shear-wave velocities decrease in the saturated samples (Figure 1). The observed higher compressional velocity and lower shear-wave velocity in our saturated samples agrees with Gassmann theory. However, several samples display almost...
no effect of saturation on $V_P$. For example, a peloidal- and echinoidal-dominated grainstone to packstone with interparticle porosity and considerable microporosity shows no stiffening effect of saturation on $V_P$ over the entire pressure range from 2 to 40 MPa (Figure 2a). In contrast, a recrystallized grainstone with intercrystalline and vuggy-moldic porosity is an example for strong effects of saturation on $V_P$. There is a distinct higher velocity in the low-pressure regime and a convergence at higher pressures (Figure 2b). This latter behavior can be expected from the theory because the induction of incompressible fluid into the pore space will stiffen the rock and increase $V_P$. $V_S$ decreases in most samples with eight samples showing an increase of $V_S$ (Figure 3). However, the magnitude of decrease (up to 15%) in $V_S$ with saturation is often more than can be explained solely by the density effect.

Figure 4 shows the general trend of decreased shear-wave velocities and increased P-wave velocities with saturation. This trend helps discriminate between dry and saturated rocks.

A plot of all data gives evidence that in carbonates discriminating fluid saturation based on P- and S-wave velocities is still possible, despite a small overlap. The $V_P/V_S$ ratio exhibits a wide range of values—1.65-1.9 under dry conditions and 1.75-2.05 for wet conditions (Figure 5). The $V_P/V_S$ ratio of the saturated samples tends to increase with saturation in all samples. The bulk of the dry $V_P/V_S$ ratios show small deviation (± 0.05) from the average value of 1.72. In contrast, the saturated $V_P/V_S$ ratios show larger deviations from the average value of 1.86. In the dry samples, $V_P/V_S$ shows an inverse correlation with the porosity, but the wet samples display an increasing scatter in $V_P/V_S$ with increasing porosities. Anselmetti and Eberli (1997) explained the larger scatter at higher porosities with the higher sensitivity of the shear wave to fabric weakening.

A plot of shear modulus under dry conditions ($\mu_d$) versus the shear modulus under saturated conditions ($\mu_w$) documents that the shear modulus changes with saturation (Figure 6). The saturation of the pore space reduces the shear modulus by up to 3.8 GPa. The shear modulus decreases up to 20% and increases up to 35% in our data set with saturation, documenting that the wet shear modulus changes with saturation (Figure 7a). 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 $V_P/V_S$ than their dry counterparts (Figure 5).

Gassmann theory. This 1951 theory 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:

$$K_{Gass} = K_t + \frac{(1-K_f/K_m)^2}{\frac{1}{K_f} + \frac{\phi}{K_m} - \frac{1}{K_t} - \frac{\phi}{K_m} - \frac{1}{K_t}}$$

(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 $K_m$, a dry bulk modulus of $K_t$, and porosity $\phi$. One important assumption of the Gassmann equation is that the fluid does not alter the rock frame properties, with the exception of the additional stiffening of the rock frame by the fluid. Under this assumption the shear bulk modulus $\mu$ should not change during saturation:

$$\mu_{dry} = \mu_{sat}$$

(2)

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

$$V_{PGass} = \sqrt{K_{Gass} + (4/3)\mu}$$

(3)

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

Effect of shear modulus variation on $V_P$ calculated with Gassmann theory. Gassmann’s theory was established for
low frequencies, and thus it is not necessarily valid for ultrasonic measurements. It is assumed that velocity dispersion occurs, caused by squirt dispersion due to microcracks and grain-to-grain contacts, which will be superimposed on the predicted Gassmann velocities. Therefore, the difference between calculated Gassmann velocities and measured ultrasonic velocities are often used as an estimate of the difference between high- and low-frequency velocity values.

Figure 7 shows the change in shear modulus versus difference between Gassmann-predicted and measured saturated velocity. Gassmann-derived velocities both over- and underestimate saturated velocities in carbonates by as much 200 and 600 m/s, respectively. Two groups can be identified. One group (lower left quadrant of the plot) shows a decrease in shear modulus and Gassmann overprediction of velocity. The other group (upper right quadrant) shows an increase in shear modulus and Gassmann underprediction of velocities. Initial results show that samples of interparticle and intercrystalline porosity show extreme high shear variations. Grainstones with a lot of microporosity display shear weakening in our data set. Recrystallized limestones with large grain-to-grain contact areas show shear strengthening. An intraframe coral sample shows no change in shear modulus.

In sandstones, shear modulus changes have been attributed to several mechanisms including viscous coupling, 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 implications for Gassmann applicability.
The assumption of constant shear modulus in Gassmann’s theory seems not to be valid for our samples and probably many carbonate rocks. 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 $V_P/V_S$ ratios than unsaturated samples. The highest $V_P/V_S$ ratios 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, but preliminary results suggest connection to the pore types. These findings emphasize 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 Gassmann theory for velocity prediction in carbonates.


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Figure 7. Display of changing shear moduli and its effect on velocity prediction of saturated rocks using Gassmann’s equation. Gassmann underestimates the velocity in samples which display shear strengthening (light yellow field) and overestimates the velocity in samples with shear weakening.