

Testing Gassmann fluid substitution in carbonates: sonic log versus ultrasonic core measurements

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Summary

The technique of fluid substitution is widely used to model elastic properties of rocks saturated with different fluids. The applicability of this technique to in-situ seismic and sonic measurements is a matter of frequent debate. Most of the analysis is based on laboratory measurements, with little or no constraints from field environments. In addition, until recently, most of the data were from sand reservoirs. Applicability of Gassmann fluid substitution to carbonates is even more uncertain. To analyze this problem, we compare elastic moduli obtained using fluid substitution against the moduli obtained from sonic and density logs. The dry moduli for fluid substitution are obtained from ultrasonic measurements on 50 core samples from a cretaceous reservoir buried at 5000 meters depth in Santos Basin, offshore Brazil. The good agreement between the saturated moduli obtained from cores and logs is obtained. This shows that the Gassmann equations can be applied not only in siliciclastic reservoirs, but also deep and complex carbonates reservoirs.

Introduction

The technique of fluid substitution is widely used to model elastic properties of rocks saturated with different fluids (Smith et al., 2003; Mavko et al., 1998). This technique is based on the Gassmann (1951) equations which are exact under certain assumptions. However, Gassmann fluid substitution requires a number of parameters which are usually obtained from laboratory measurements. It is not entirely clear how applicable are these parameters, and the technique itself, to field measurements made at different conditions and different frequencies. This is especially questionable for carbonate rocks, where some of the assumptions of the Gassmann equations may be violated (Adam et al, 2006, Vanorio et al, 2007) . Therefore it is desirable to perform a comparison of the results of fluid substitution with measured field data. This can be done, in particular, if we have both detailed laboratory measurements and good sonic log data from the same well. Grochau and Gurevich (2008) recently proposed such an approach and applied it to a sandstone reservoir in Campos Basin.

Here we apply a similar method to a carbonate reservoir in Santos Basin, offshore Brazil. It corresponds to a continuously sampled interval of 36 meters at a depth over

5000 meters. Compressional and shear velocities, density and porosity were measured on 50 samples covering the entire reservoir interval.

Methodology

To analyze how fluid substitution technique is effective we have to compare the modeling results with the elastic constants derived from the sonic logs of the well. A rigorous quality control of all parameters is fundamental in this procedure.

First of all, the 50 carbonate samples were dried under dry room conditions to extract the ultrasonic measurements. Two pairs of piezoelectric transducers were positioned at the sample sides (top and base) to acquire shear and compressional velocities. A sinusoidal pulse of 500kHz was propagated through the sample and the time of flight was registered. To determine the stress dependence of elastic properties, the sample was immersed in a pressure chamber with hydraulic oil. The confining pressure varied from 1000 to 6000 psi. The porosity of the samples was measured in the laboratory using a porosimeter with nitrogen injection.

Secondly, a good estimation of the reservoir effective pressure is necessary to compare with laboratory data. The reservoir effective pressure P_{Effec} is estimated from the relation

$$P_{Effec} = A h_w + B (h_r - h_w) - \eta P_{por} , \quad (1)$$

where A and B are ocean water and lithostatic pressure gradients, h_r and h_w are reservoir and water depths, η is the effective stress coefficient and P_{por} is the pore pressure obtained from the Repeated Formation Test (RFT) of the well.

The next step is to use the dry laboratory measurements at the effective stress (P_{Effec}) determined using equation (1) and estimate the saturated bulk modulus using Gassmann equation

$$\frac{1}{K_{sat}} = \frac{1}{K_g} + \frac{\phi \left(\frac{1}{K_f} - \frac{1}{K_g} \right)}{1 + \phi \left(\frac{1}{K_f} - \frac{1}{K_g} \right) / \left(\frac{1}{K_d} - \frac{1}{K_g} \right)} , \quad (2)$$

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where K_{sat} , K_d and K_g are respectively saturated, dry and grain bulk moduli, and ϕ is total porosity. The grain bulk modulus is mostly that of calcite, but the exact value is not clear. In order to get effective bulk modulus, a range of K_g can be used to find the best fit between modeled and measured elastic moduli.

It is also important to use correct value for the fluid bulk modulus. In the case of brine, we use the relation given by Mackenzie (1981) to obtain compressional velocity of brine (V_f) as a function of salinity, temperature and depth. The brine density (ρ_f) can be obtained from salinity and temperature at reservoir conditions. Finally, we calculate the fluid bulk modulus (K_f) from the relation $K_f = \rho_f V_f^2$.

The last consideration in this methodology is that if the shear sonic log is not available, we cannot derive bulk or shear modulus of the logs. Instead, we can compare P-wave moduli derived from lab and well log measurements $M_{sat} = K_{sat} + 4\mu/3$ and $M_{log} = \rho V_p^2$. Here ρ and μ are the sample density and shear modulus obtained from laboratory measurements, and V_p is P velocity from the sonic log.

Results

The continuous 20 meters of carbonate core analyzed here represents an interval of a Cretaceous reservoir buried at 5000m depth in Santos Basin. The core for laboratory measurements was sampled with an average 30cm interval. The measured porosity of the samples and those derived from the well density log (Figure 1) shows a very good agreement: a deviation of 0.016 (RMS) was obtained between these two datasets. The range of porosities is from almost zero to a maximum of 23%. The porosity

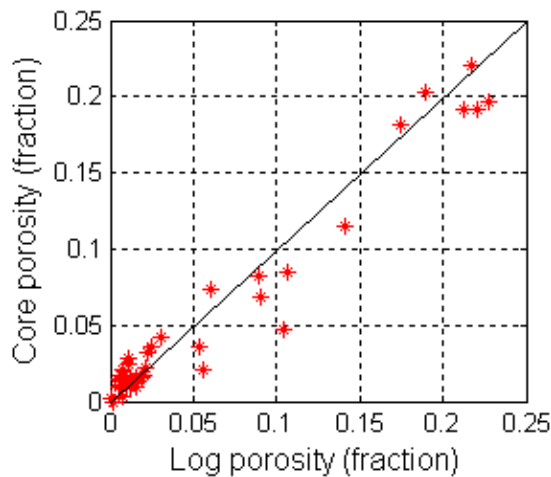


Figure 1: Correlation between porosities derived from the density well log and the porosities measured in the laboratory.

distribution along the interval (Figure 2a) shows very low porosity at the bottom, representing massive carbonates, with increasing porosity into the top, indicating higher energy of the depositional system.

To perform fluid substitution, we estimate fluid bulk modulus (K_f) to be 4GPa. To achieve this value we first

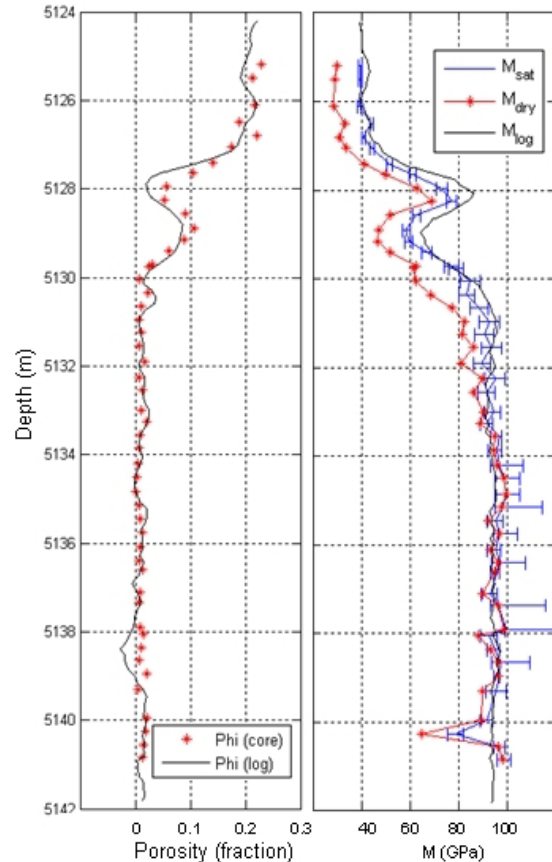


Figure 2a: Porosity measured in 50 carbonate samples (red) showing good agreement with the porosity derived from density log (black). (2b) P-wave elastic moduli from lab measurements in red (dry) and from well log (black) and in blue the results of fluid substitution using Gassmann. The blue bars represent grain bulk modulus bounds with limits

estimate water compressional velocity of 1815m/s using water salinity of 250.000 ppm, and average depth of 5130m and temperature of 65°C (Mackenzie,1981). The brine density of 1170kg/m³ was also obtained using the pressure, salinity and temperature conditions at that depth.

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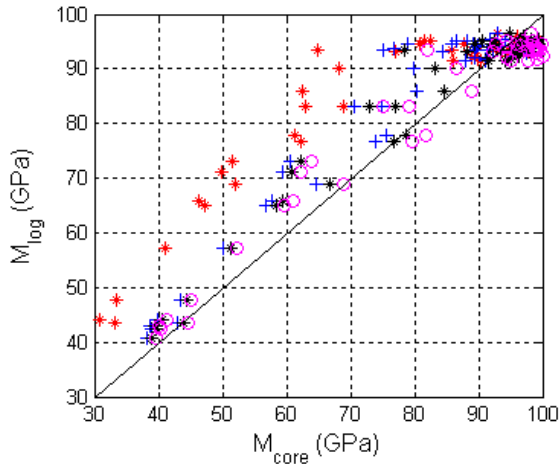


Figure 3: Correlation between P-wave elastic modulus derived from the sonic well log and the dry (red stars) and saturated using Gassmann with K_{grain} of 55GPa (blue crosses), 60GPa (black stars) and 65GPa (magenta circles).

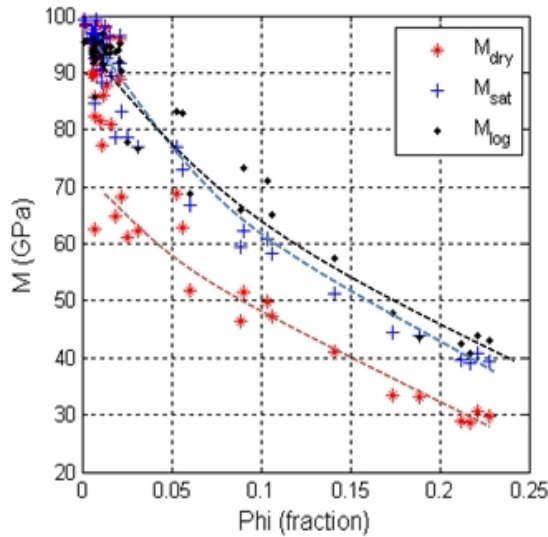


Figure 4: P-wave elastic moduli of dry rock (red), saturated using Gassmann (blue) and derived from well logs (in black). The dashed lines are the main trends showing the moduli dependence with the porosity. Notice the close approximation of the elastic moduli saturated by Gassmann and the elastic moduli derived from well log

The results of fluid substitution are shown in Figure 2b: the compressional-wave elastic modulus of the dry sample (M_{dry}) is plotted in red, saturated modulus obtained from fluid substitution (M_{sat}) in blue, and the modulus derived from the well log (M_{log}) in black. The blue bars represent bounds of M_{sat} obtained using the range of grain bulk moduli between 55 and 65GPa. We take 60GPa as an average bulk modulus for calcite. This value was calculated from dry measurements on samples with nearly zero porosity (depth 5134.7m).

Analysis and Discussion

As can be seen in Figure 2b, the saturated moduli obtained from lab and log measurements show a reasonable agreement, except at depths around 5128m. The discrepancy in this interval can probably be explained by the differences between porosities derived from core and the well log. The porosity discrepancy could be caused by inadequate core sampling or core damage. In any case, lower porosity of the sample can cause higher moduli, and this can be the cause of the discrepancy between M_{log} and M_{sat} .

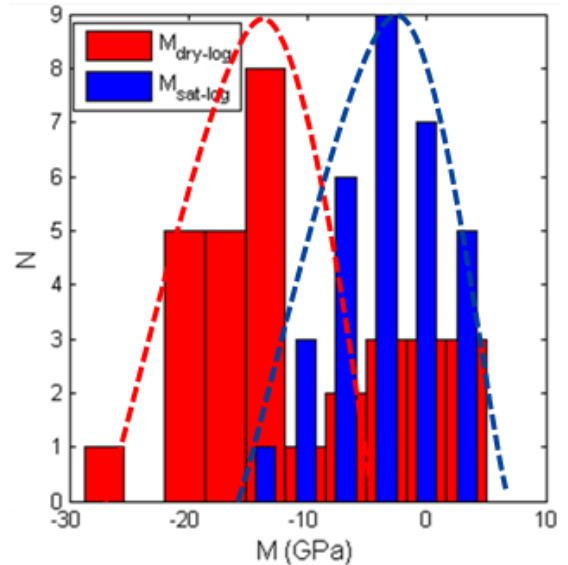


Figure 5: Histogram showing that the differences between dry and log derived P-wave elastic moduli are much higher (15GPa) than after Gassmann substitution (red). This histogram is restricted to samples with porosity higher than 1% and they fully saturated with brine.

Figure 3 shows the cross-plot of M_{log} with M_{dry} and M_{sat} . We see that M_{sat} (black stars) are much closer to the black straight line (100% fit) than the M_{dry} (red stars); the RMS deviation of the differences are 4GPa and 12GPa,

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respectively. The discrepancy is the largest for a few points corresponding to the depth around 5128m as discussed above.

It is well known that the P-wave elastic modulus strongly depends on porosity. Figure 4 shows this dependence, where the dry P-wave elastic modulus (in red) decreases from 80GPa to less than 30GPa as the porosity increases from almost zero to 23%. Almost parallel trends are observed for the saturated P-wave elastic modulus (in blue) and the P-wave elastic modulus derived from the logs (in black). Note that we observe a consistent shift of about 15 GPa between the trends of saturated and dry moduli (for porosities over 3%).

The histograms of differences $M_{dry} - M_{log}$ and $M_{sat} - M_{log}$ are shown in Figure 5. We restricted the histogram to samples with porosities higher than 1%. The average difference between sonic log and dry lab moduli is about 15 GPa, but it almost vanishes after fluid substitution.

Conclusions

Our results demonstrate that Gassmann fluid substitution in carbonates using ultrasonic measurements on dry samples yields elastic moduli that are in a good agreement with the P-wave moduli derived from well sonic and density logs. This good agreement demonstrates that the Gassmann equations can be applied not only in siliciclastic reservoirs, but also in the complex reservoirs made of carbonates, even at large depths. The workflow tested here can be useful for quantitative seismic interpretation and time lapses studies.

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EDITED REFERENCES

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REFERENCES

- Adam, L., M. Batzle, and I. Brevik, 2006, Gassmann fluid substitution and shear modulus variability in carbonates at laboratory seismic and ultrasonic frequencies: *Geophysics*, **71**, no. 6, F173–F183, [doi:10.1190/1.2358494](https://doi.org/10.1190/1.2358494).
- Gassmann, F., 1951, Über die Elastizität poroser Medien (Elasticity of porous media): *Vierteljahrsschrift der Naturforschenden Gessellschaft in Zurich*, **96**, 1–23.
- Grochau, M., and B. Gurevich, 2009, Testing Gassmann fluid substitution: sonic logs versus ultrasonic core measurements: *Geophysical Prospecting*, **57**, no. 1, 75–79, [doi:10.1111/j.1365-2478.2008.00726.x](https://doi.org/10.1111/j.1365-2478.2008.00726.x).
- Mackenzie, K. V., 1981, Nine-term equation for the sound speed in the oceans: *The Journal of the Acoustical Society of America*, **70**, no. 3, 807–812, [doi:10.1121/1.386920](https://doi.org/10.1121/1.386920).
- Mavko, G., T. Mukerji, and J. Dvorkin, 1998, *The Rock Physics Handbook*: Cambridge University Press.
- Smith, T. M., C. H. Sondergeld, and C. S. Rai, 2003, Gassmann fluid substitutions: A tutorial: *Geophysics*, **68**, 430–440, [doi:10.1190/1.1567211](https://doi.org/10.1190/1.1567211).
- Vanorio, T., C. Scotellaro, and G. Mavko, 2007, To fluid-substitute or not to fluid substitute: How pore shape and chemical processes affect Gassmann predictability: SEG Expanded Abstracts.