Petrophysical Characterization of Carbonates

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Abstract

Brazilian carbonate fields have been developed based on seismic data interpretation, and static and dynamic reservoir models. An appropriate inversion seismic data depends on the knowledge of the relationship between depositional geometries, facies, rock fabric and the seismic and petrophysical properties. Based on the premise that the seismic properties are functions of saturation and differential pressure (confining pressure minus pore pressure), we conducted analysis of laboratory velocity measurements (compressional-Vp and shear-wave-Vs) dry and brine-saturated of approximately 35 rock samples of carbonates, and correlated them to porosity for a better understanding of seismic signatures.

The rock samples, covering a wide range of depositional environments, were analyzed qualitatively and quantitatively. A crucial step was the establishment of a relationship between measured compressional (V_P) and shear-wave (V_S) velocities dry and brine-saturated with bulk porosities. Saturation of the pore space caused an increase and decrease in compressional and shear-wave velocities as well as changes in the bulk and shear modulus. The Vp/Vs ratio also shows changes in brine-saturated samples. An increase in the Vp/Vs ratio was verified in most of samples but in a few no changes was observed.

This data analysis was applied to establish, in the future work, the rock – seismic signature relationship to develop an up scaling tool to improve seismic inversion data in order to reduce uncertainty in the seismic interpretation in Brazilian carbonates fields.

Introduction

The rock velocities are strongly dependent on the rock porosities and this relationship is linear in siliciclastic rocks. Otherwise, in carbonate rocks, a non-linear relationship and also a large scatter in the correlation is observed. In addition to porosity, the pore type, depositional facies and diagenesis, overprint control the petrophysical properties of carbonate rocks. Saturation effects on the acoustic properties due pore fluid compressibility and variations in shear modulus were observed and disagree with theoretical assumptions.

Few studies have been done in acoustic properties of carbonate rocks. Bastos et al, 1998 and Vasquez et al 2009, studied Brazilian carbonates, where they measured ultrasonic compressional and shear wave velocities. Bastos et al (1998) also measured static and dynamic elastic constants. Anselmetti and Eberli, 1999; Eberli et al, 2003; Kumar and Han, 2005; Weger et al, 2007 have been analyzed the relationship between velocities and carbonate pore types. Anselmelti & Eberli (1999) and Eberli et al (2003) presented a systematical measured plugs velocities in carbonate rocks showing a wide range of scattering when compared with porosity and/or permeability. The authors showed that the carbonate textures, specially the pore types, are the most important factor in the large scatter correlation between porosities and velocities. Based on Lucia (1985) porosity classification, they observed that coarse moldic or intraframe rocks and interparticle porosity or high microporosity rocks presented the most prominent velocity contrast, V_P up to 5000 m/s and lower than 2500 m/s, respectively. Considering the saturation effects on the acoustic properties in carbonates, some laboratories experiments under dry and wet conditions show that shear modulus change during saturation (Wang 2000; Baechle et all, 2009). These results question theoretical Gassmann assumption that shear modulus remain constant during saturation.

Taking in consideration the high interest in hydrocarbon production from carbonate reservoirs, we conducted a study of acoustic and petrophysical parameters in order to quantify the effect of saturation on different carbonates in Brazilian fields.

Method

Approximately 35 carbonate Brazilian rock samples from 1000 to over 2500 m depths were selected and the acoustic measurements (compressional and shear wave velocities) on dry and brine-saturated samples were realized at *in situ* overburden pressure, and pore pressure. The samples were measured under dry conditions using variable hydrostatic confining pressures in steps from 5 MPa up to 50 MPa. The samples were brine-saturated to simulate the *in situ* formation water (65000 ppm of NaCl) under vacuum conditions. During the wet measurements, the pore fluid pressure was kept constant at 5 MPa and the differential pressure (confining pressure minus pore pressure) was the same in both measurements.

The grain bulk density of all samples was measured in the helium pycnometer and the sample porosity was determined by the difference between the grain bulk density and the dry bulk density divided for grain bulk density.

The thin sections, impregnated with blue epoxy were described in order to qualitatively determine the pore types, depositional facies and diagenetic alterations. These petrographic interpretations were performed based on Dunham classification (1962, in Memoir 77).

Results

Effect of Porosity and Pore Structure and Velocity

In the studied samples, the compressional velocities Vp ranges from 2600 to 5400 m/s (Figure 1) and the shear-wave velocities ranges from 1300 to 2800 m/s (Figure 1). The Figure 1 shows the linear inverse correlation between velocities and porosity, but some scatter values were observed. For example, at porosity of 30 % the scatter in Vp is 1100 m/s and in Vs is 600 m/s at porosity of 28 % (Figure 1). These values out of the trend represent mostly variations in pore type. In this example, the rock samples with high velocities present predominantly vugular and intragranular porosity (Figure 2a). Otherwise, the samples with low velocity, intergranular porosity to microporosity were observed.

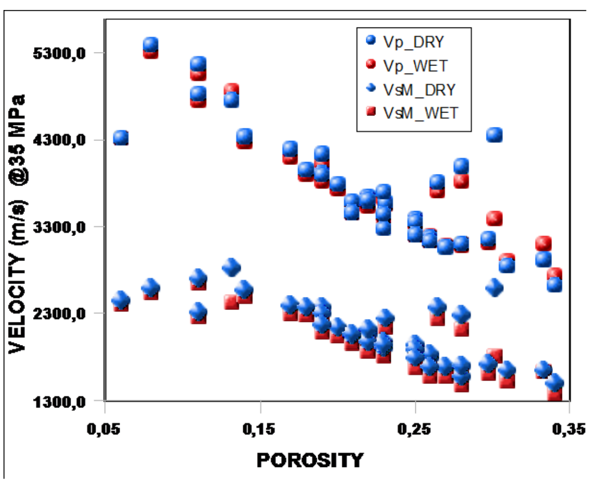
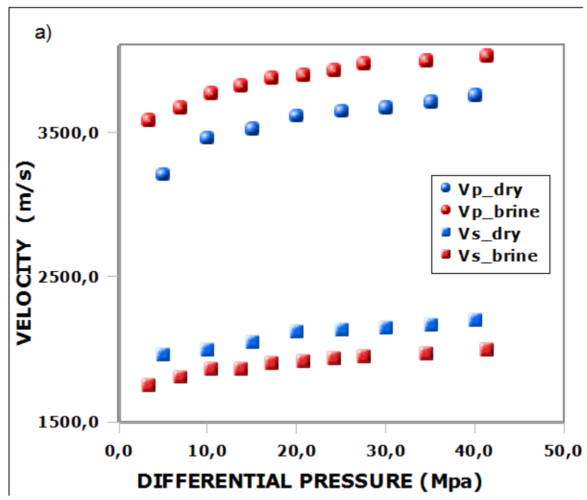


Figure 1 - Vp and Vs versus porosity for dry (blue) and brine-saturated samples (red). Some samples show an increase of Vp and a decrease of Vs with saturation as expected from Gassmann theory.

Effect of Water Saturation on Velocity

Fluid substitution cause an increase in bulk density due fluid-filled pores and changes in both compressional velocity (Vp) and shear-wave velocity (Vs). If the pore-space compressibility decreases with increase of the bulk modulus, the compressional velocity should increase, without changes in shear-wave velocities. In some brine-saturated samples, shear strengthening or weakening are observed and shear modulus will increase if shear strengthening is observed and will decrease in case of shear weakening.

In the analyzed data set, the compressional velocities of almost half of the saturated samples are higher than the dry samples (Figure 2a). In the other half, the compressional velocities of saturated samples decrease up to 400 m/s. All of the shear-wave velocities decrease in saturated samples up to 200 m/s. The Figure 2a shows the compressional and shear-wave velocities (dry and brine-saturated) at different pressures from a rhodolitic limestone sample. The 16% increase and reduction in Vp and Vs, respectively, could not be solely explained because density increase with saturation (Figure 2a). In this case shear weakening was also observed.



b)

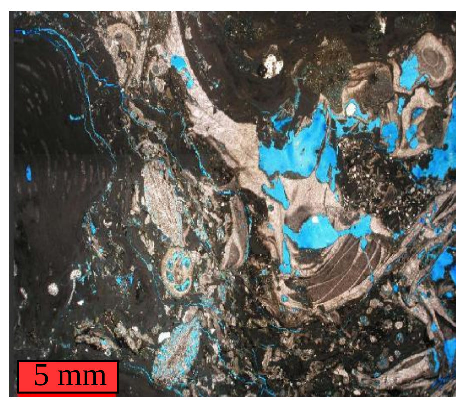


Figure 2 - a) Effects of saturation on compressional and shear-wave velocities. An increase of Vp and decrease of Vs due saturation is observed; b) Optical microscopy photo of the biolitite to red algae with vugular porosity.

Figure 3 show the trend of the correlation between compressional velocities and shear-wave velocities, dry and brine-saturated. In general, the shear-wave decreased and compressional velocity increased with saturation. This plot put in evidence that it is possible, in some cases, to discriminate dry and saturated rocks, despite the observed velocities overlap. The Vp/Vs ratio shows a range of values between 1.58 and 2.10 under dry conditions and 1.65 to 2.10 for wet samples (Figure 4). The Vp/Vs ratio of the samples increased with saturation in all samples but, in both cases, dry and saturated, the deviation from the average value was about 0.17. The wet samples exhibited an increasing scatter in Vp/Vs at high porosities (20 - 30%) and the discrimination between dry and wet samples was possible. Anselmeti and Eberli (1999) explained the scatter at high porosities with the high sensitivity of the shear wave to fabric weakening.

A plot of shear modulus under dry conditions versus the shear modulus under saturated conditions confirmed that the shear modulus changes with saturation (Figure 5). The saturation of the pore space reduced the shear modulus up to 5.3 GPa. In the analyzed data set the shear modulus decreased up to 50 % and increased up to 10 % with saturation. This variation indicated that both shear strengthening and shear weakening are observed in carbonates due to saturation. Saturated samples, which showed shear weakening, displayed higher Vp/Vs than the dry counterpart (Figures 4 & 5).

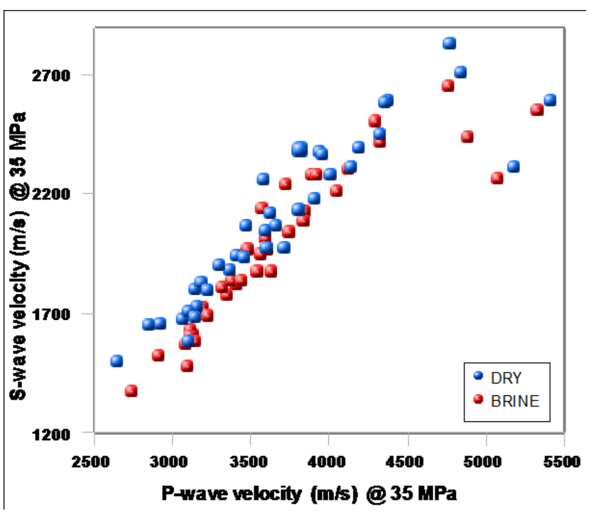


Figure 3 – Vp versus Vs for dry and saturated samples. With saturation a trend of decreased Vs and increased Vp in some samples may permit to discriminate between wet and dry carbonates, but a overlap was observed.

Gassmann Theory

The Gassmann theory (1951) is based on the fact that rocks which the pore space is filled with water or oil are more resistant to compression than rocks filled with gas. One important statement of the Gassmann equation is that the fluid does not modify the rock properties, with one exception of the stiffening of the rock by the fluid. Under this statement the shear bulk modulus μ should not change with saturation. If this statement is violated, the calculated Gassmann velocities will either over or under predict the measured saturated velocity. The presented data set showed that the shear modulus indeed changed with saturation and, consequently, the Gassmann calculated velocity could be inaccurate.

Figure 6 shows the compressional velocities dry, brine-saturated and Gassmann-predicted at different pressures from a rhodolitic limestone sample (Figure 2a). In this sample, associated with a decrease in shear modulus, the Gassmann-predicted velocity underestimated the brine-saturated velocity up to 100 m/s. Regardless of the shear weakening, the under-predicted Gassmann velocity maybe associated to vugular and intragranular porosity.

Baechle et al (2009), speculated that the same mechanisms observed in sandstones like viscous coupling, reduction in free surface energy, and dispersion

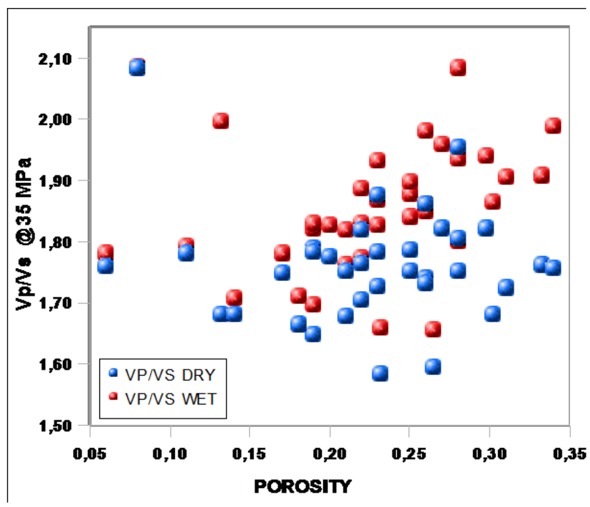


Figure 4 - Plot of Vp/Vs ratio versus porosity shows a increase of the Vp/Vs ratio with saturation and a larger scattering of the saturated samples of porosity above 28%.

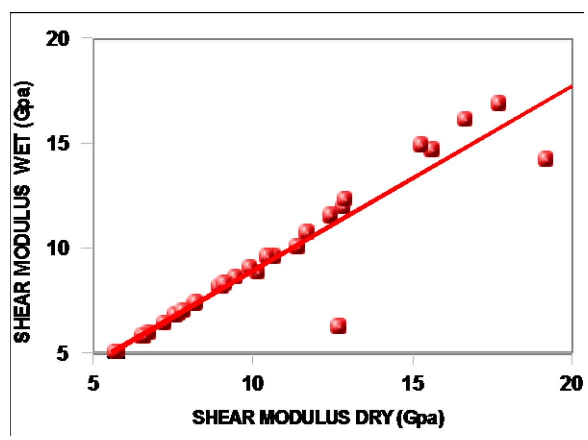


Figure 5 – Cross-plot of changes in shear modulus with saturation. This graphic disagree with Gassmann theory which assumes no change in shear modulus in saturated rocks.

due to local flow, may explain the changes in carbonates shear modulus.

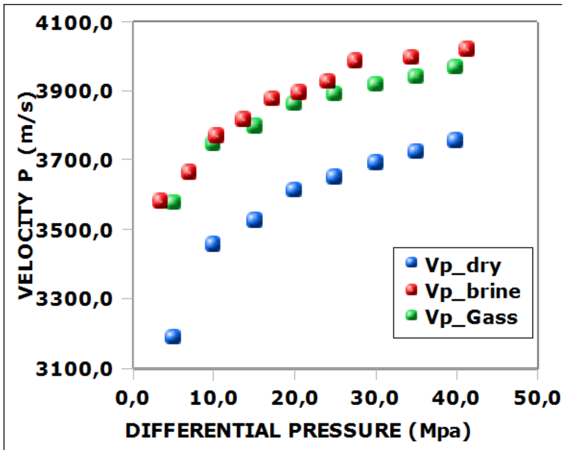


Figure 6 - Compressional velocities-Vp at different pressures for dry (blue) and, brine-saturated samples (red) and Gassmann-predicted (green). The Gassmann-predicted velocities were under-predicted in this sample.

Conclusions

The analysis of limestone samples with different pore types under dry and brine saturated conditions showed the effect of changes in pore fluids on petrophysical properties of carbonates. The brine-saturated samples exhibited higher Vp/Vs ratios than dry samples where high shear weakening was also observed (up to 10 %). In some samples where the shear weakening was less than 2%, the Vp/Vs ratio was almost the same.

The Gassmann theory assumes that shear modulus is constant and disagrees with our study. We observed shear weakening and shear strengthening, which affected the velocity of analyzed carbonate rocks. It is well established that pore type variations cause changes in compressibility at given porosity, but shear modulus variations are not already understood. Some authors assumed to be related to rock-fluid interactions, where the pore types and grain-to-grain contact geometry affect the shear modulus. These observations reduce the applicability of Gassmann theory to predict velocity in carbonates at high frequencies and introduces uncertainty In AVO analysis and seismic inversion data

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References

Anselmetti, F. S. and Eberli, G. P., 1999, The velocity-deviation log: A tool to predict pore type and permeability trends in carbonate drill holes from sonic and porosity or density logs: American Association of Petroleum Geologists Bulletin, v. 83, p. 450-466.

Baechle, G. T., Eberli, G.P., Weger, R. J., Massaferro J. L., 2009, Change in dynamic shear moduli of carbonate rocks with fluid substitution. Geophysics v. 74, p. 135-147.

Bastos, A. C., Dilon, L. D., Vasquez, G. F., and Soares, J. A., 1998, Core-derived acoustic, porosity & permeability corelations for computation pseud0-logs, Geological Society, London, Spetial publications, V. 136, p, 141-146

Eberli, G.P., Baechle G.T., Anselmetti, F.S. and Incze, M.L. - 2003 - Factors controlling elastic properties in carbonate sediments and rocks. The Leading Edge, p. 654 – 660

Kumar, M., and Han, D.-H., 2005, Pore shape effect on elastic properties of carbonate rocks: SEG Technical Program Expanded Abstracts, p. 1477-1480.

Lucia, F. J., 1995, Rock-fabric/petrophysical classification of carbonate pore space for reservoir Characterization: American Association of Petroleum Geologists Bulletin, v. 79, p. 1275-1300.

Scholle, P. A. and Scholle, U., 2003, Carbonate Classification – Rock and Sediments, Association of Petroleum Geologists, Memoir 77, chapter 20, p 284-292.

Vasquez, G.F., Junior, E. A. V., Ribeiro, C, J, B., Leão, M. andJusten, J. C., 2009, Experimental determination of the effective pressure coeficients for brazilian limestones and sandstones, Revista Brasileira de Geofísica, 27, p. 49-53.

Wang, Z., 2000, The Gassmann equation revisited: Comparing laboratory data with Gasmann's prediction, in Z. Wang and A. Nur, eds., Seismic and acoustic velocities in reservoir rocks, vol. 3 – Recent developments: SEG, 8-23.

Wyllie, M. R. J., Gregory, A. R. and Gardner, L. W., 1956, Elastic wave velocities in heterogeneous and porous media: Geophysics, v. 21, p. 41-70.

Weger, R. J., Baechle, G. T, Eberli,G. P., Massaferro, J. L. and Sun, Y-F, 2007, Quantification of pore structure and its effect on sonic velocity and permeability in carbonates, Association of Petroleum Geologists Bulletin, p2-25