



Petrophysics and Rockphysics of Carbonates from Brazil and Portugal

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Abstract

Here are showed results of physical laboratory analysis of carbonates from several sedimentary basins of Brazil and Portugal. Due to large oil discoveries done on carbonatic reservoirs of the Brazilian pre-salt, the study about carbonates from the Atlantic passive margins became mandatory. In this work hundreds of rock samples are analyzed for porosity, grain and bulk density, permeability and elastic velocities. Results cover rocks with a large range of porosity and permeability values over seven orders of magnitude. Grain density proves to be a good matrix type indicator and bulk density holds a very reliable linear correlation with porosity. The relationship between air permeability and porosity presents a high dispersion, indicating the occurrence of several types of porosity and grain sizes. Elastic wave velocities show a high dispersion anticorrelation with porosity. This is mainly controlled by the dominant porosity type and mineral matrix. These results allow estimation for any saturation condition, what would be very useful to support any exploration and reservoir studies in carbonates.

Introduction

This paper presents results for petrophysics and rock physics laboratory experiments done over some hundreds of carbonate rock samples extracted from outcrops of several sedimentary basins of Northeastern Brazil and Western Portugal.

The lithotypes investigated are basically limestones, dolomites and carbonatic tufas. The rock samples were picked up from Araripe, Potiguar, Sergipe-Alagoas and São Francisco basins, in Brazil, and Lusitanian Basin, in Portugal. Figure 1 shows a schematic map of localization for the Brazilian basins and Figure 2 shows the same for the Portuguese basin.

Rocks from Araripe basin are laminated limestones and dolomites of the Crato Formation (Aptian-Albian ages). The Crato Formation is composed by six cycles of laminated limestones intercalated with marl and shale levels (Neumann, 1999).

Carbonatic tufas, limestones and dolomites from Potiguar basin belong to the Jandaíra Formation, a carbonatic platform formed during the South Atlantic open in the period Campanian-Santonian (Reyes-Perez *et al*, 2003).

Rock samples from São Francisco basin are limestones and dolomites extracted from Salitre Formation, a neoproterozoic carbonatic unit deposited in a shallow epicontinental marine system (Medeiros and Pereira, 1994). Limestone samples are from outcrops, while dolomites were extracted from two caverns (Toca da Barriguda and Toca da Boa Vista).



Figure 1 – Map of localization of the Brazilian basins (highlighted in pink) whose rock samples are investigated in this paper. Adapted from www.phoenix.org.br.

Limestones and dolomites representative of Cotinguiba (Cenomanian-Coniacian) and Riachuelo (Albian) Formations of Sergipe-Alagoas basin are also analyzed.

The rock physical properties measured in this work are grain density, total density, porosity, permeability and elastic properties (P and S wave velocities). Furthermore, dynamic elastic moduli are also calculated from elastic wave velocities and total density.

All results were found for rocks in dry condition and at room temperature. Density, porosity and permeability values were measured at ambient pressure, while elastic velocities (and associated elastic moduli) were determined under 40 MPa of confining pressure.

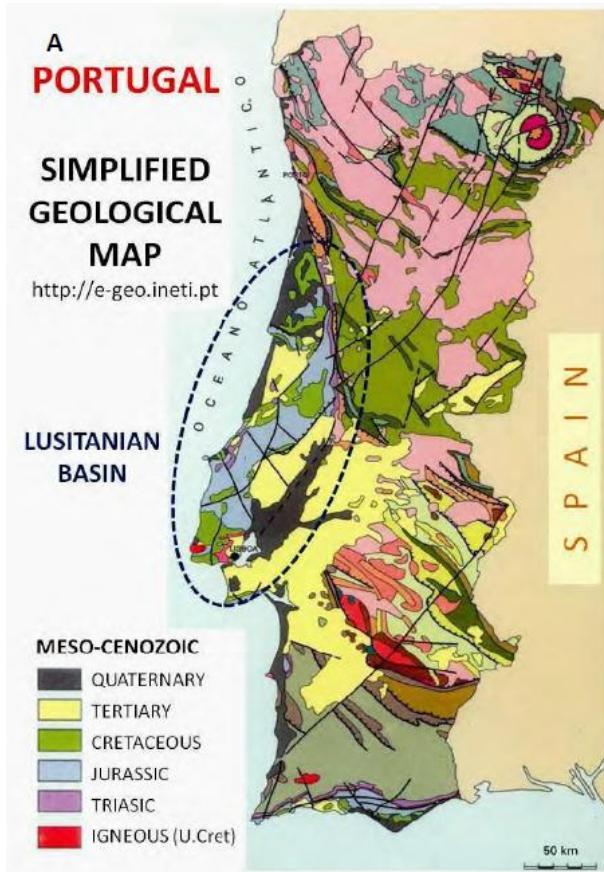


Figure 2 – Map of localization of the Lusitanian Basin, Portugal. Extracted from <http://metododirecto.pt/CM2010>.

Method

All rock samples used in this work were extracted from outcrops, through hand sample plug preparation or via *in situ* core extraction, which uses a portable core extractor (Figure 3). For plug preparation from hand samples some equipments were used, as a rock slabbing saw (Figure 4a), a drill press diamond tool (Figure 4b) and an endface precision grinder (Figure 4c). In case of cores extracted *in situ*, when in laboratory, they are only cut in the saw and have their endfaces flat parallel into the grinder. The final step of plug preparation is to dry the plugs under 80°C of temperature during 24 hours and to measure their weight, length and diameter, for total volume and density calculations.

Grain density and porosity were measured using a gas porosimeter linked to a matrix cup. These properties were measured under ambient pressure and the gas used was analytical quality nitrogen. Indeed what is measured in this method is the grain volume, which allows for grain density calculation, since the dry rock weight is equal to the grain mass. In addition, pore volume is calculated as the difference between the plug total volume and the grain density, allowing the calculation of porosity.

Air permeability was measured using a gas permeameter connected to a high pressure coreholder. For the

permeability tests of this work it was used a confining pressure of 2000 psi and a nitrogen input pressure of 70 psig. In this method, for a non-turbulent flow, the difference between gas input and output pressures is related to flow rate through the Darcy’s Law, giving the value of air permeability.



Figure 3 – Portable core extractor used to obtain *in situ* rock plugs on outcrops.

P and S wave velocities were measured using a high pressure chamber available at the Laboratory of Petrophysics of the Federal University of Campina Grande. Measurements were done at room temperature and with pore pressure system open to atmosphere (dry samples). The velocities showed here were obtained under 40 MPa of confining pressure, although velocities have been recorded from 5 to 40 MPa of confining pressure. In this system three waves propagating in the plug axis direction are recorded: one P and two mutually orthogonal shear waves (S_1 and S_2). The elastic moduli presented here were calculated using the isotropic linear elastic equations showed in Sheriff (1991).

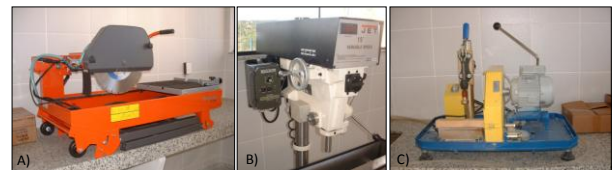


Figure 4 – Equipments used in this work to obtain rock plugs in laboratory from hand samples extracted on outcrops: a) rock slabbing saw; b) drill press diamond tool; c) endface precision grinder.

Results

Figure 5 shows grain density against porosity values for 450 analyzed carbonate plugs. In this and in the following figures symbol shape is indicative of lithology while

symbol color indicates basin of provenance. Solid circles indicate limestones, open diamonds are associated to dolomites and open squares represent carbonatic tufas. Black symbols represent plugs acquired on Araripe Basin, green ones on Potiguar Basin, dark blue on Sergipe-Alagoas (SE/AL) Basin, light blue on São Francisco Basin and red ones on Lusitanian Basin (Portugal).

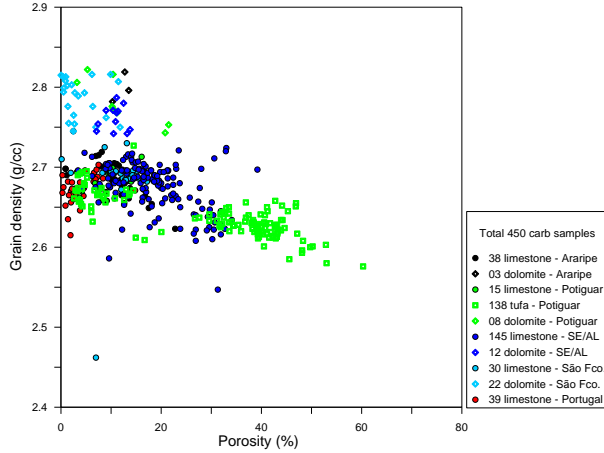


Figure 5 – Grain density versus porosity for 450 carbonate samples (limestone, dolomite and tufa) from Brazilian and Portuguese sedimentary basins.

From Figure 5 it is possible to see that there is a large range in porosity, from almost 0% up to 60%. Limestones from Portugal and dolomites from Sergipe-Alagoas, São Francisco and Araripe basins present maximum porosity around 15%. Limestones from Potiguar and São Francisco basins are limited to a maximum of 20% in porosity. Limited to a maximum of 25% of porosity are dolomites from the Potiguar basin and limestones of the Araripe basin. Limestones from Sergipe-Alagoas basin show porosity values up to 40%. Finally, carbonatic tufas from Potiguar basin have porosity maximum of 60%. May be worth see that the maximum porosity of dolomites is lower than the maximum porosity of limestones, at least for the Sergipe-Alagoas, São Francisco and Araripe basins.

Grain density reflects rock mineral composition. In this sense, dolomite samples show grain density up to 2.82 g/cc, which is the density for a pure dolomite sample. Values lower than 2.82 g/cc indicate non-pure dolomites. On the other hand, limestone and tufa samples show grain densities limited to 2.72 g/cc, indicating that the tufa samples have a limestone matrix. In the same way, grain densities lower than this value suggest non-pure limestones.

Figure 6 shows the relationship between bulk density and porosity. Except for some few samples, reliable linear regression fits may be defined for limestones and dolomite matrix cases. This feature may be very useful to estimate porosity based only in the knowledge of bulk density (and vice-versa).

Figure 7 presents air permeability versus porosity in a lognormal scale. For comparison purposes, black curves

indicate the three regions of grain size described by Lucia (1995) for carbonates with intergranular porosity. As can be seen, the most of our rock samples stay in a region of the graph which would be proper for very fine grain carbonates or, alternatively, with predominant vugular porosity. Furthermore, may be Lucia's model need to be adapted to our carbonatic rocks. Note permeability ranges over seven decades of logarithm values.

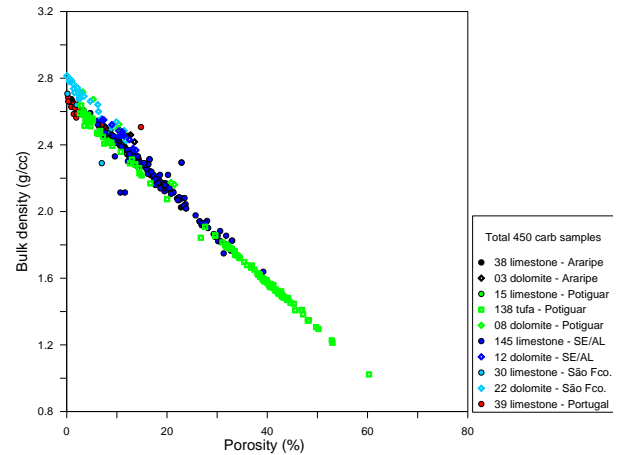


Figure 6 – Bulk density versus porosity for 450 carbonate samples from Brazilian and Portuguese basins.

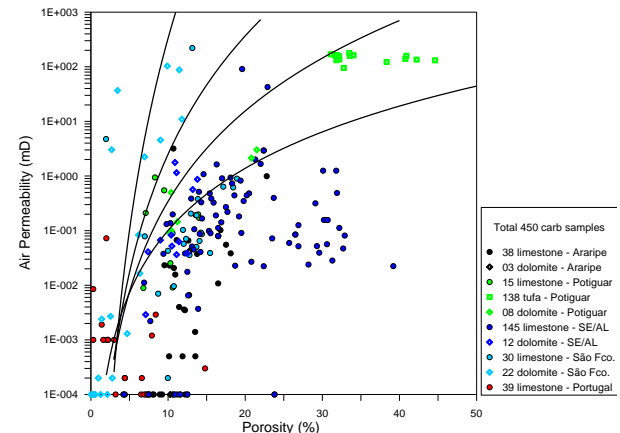


Figure 7 – Air Permeability versus porosity for carbonate samples from Brazilian and Portuguese basins.

Figure 8 show P wave velocity versus porosity measured on 301 dry carbonate samples under room temperature and 40 MPa of confining pressure. The main features of this graph are the high dispersion degree and the fact that especially high porosity tufas present P wave velocity value higher than expected for a given value of porosity, in comparison with others lithofacies. This behavior is due to the type of predominant porosity. As discussed by Baechle et al. (2004), microporosity tends to decrease elastic velocities, while vugular and moldic ones tend to be associated with high elastic velocity values. Nevertheless, linear functions may be fitted to predict one variable as a function of the other. This result points out that the quantification of porosity type may improve fit.

Figure 9 presents the relationship between S_1 wave velocity and porosity. A similar behavior to Figure 4 is observed and the causes for this behavior are the same, once these results are for dry samples.

Elastic anisotropy can be seen in Figure 10 which shows the VS_1/VS_2 ratio against porosity. Ninety percent of these samples presents anisotropy lower than 5%, what allows to classify them as of low degree elastic anisotropy. Maximum anisotropy was found for some carbonatic tufa samples.

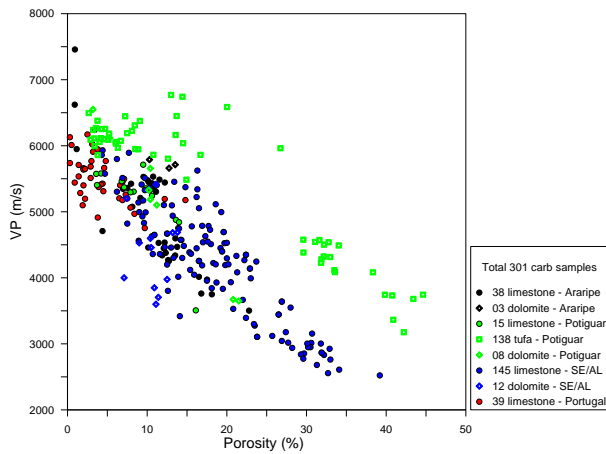


Figure 8 – VP versus porosity for 301 dry carbonate samples under 40 MPa of confining pressure.

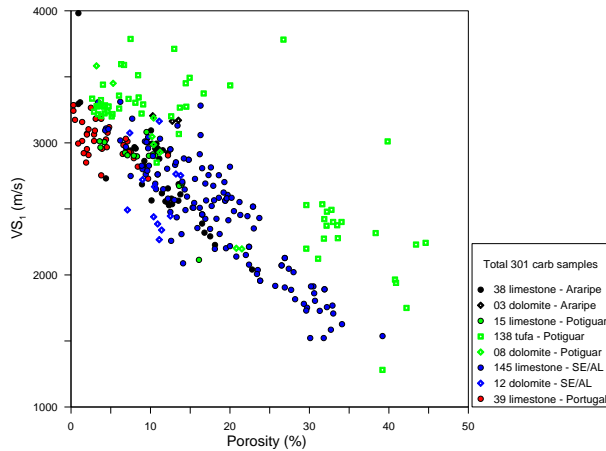


Figure 9 – VS_1 versus porosity for 301 dry carbonate samples under 40 MPa of confining pressure.

Figures 11 to 14 show elastic dynamic moduli versus porosity. The relationships between the elastic moduli (Young's, Bulk and Shear moduli) and porosity are nonlinear, although they are dependent on elastic velocities and bulk density, which are linearly correlated to porosity. This occurs because elastic moduli depend on the square of P and S wave velocities. Poisson's ratio, in turn, depends on the square of VP and VS ratio, which reduces the nonlinearity effect caused by the quadratic term.

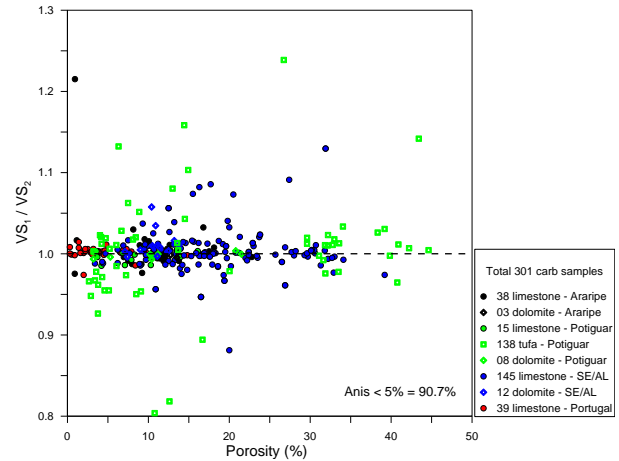


Figure 10 – VS_1/VS_2 versus porosity for 301 dry carbonate samples under 40 MPa of confining pressure.

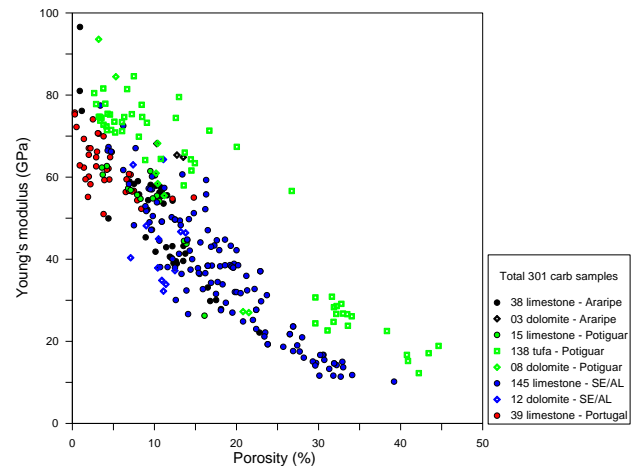


Figure 11 – Young's modulus versus porosity for 301 dry carbonate samples under 40 MPa of confining pressure.

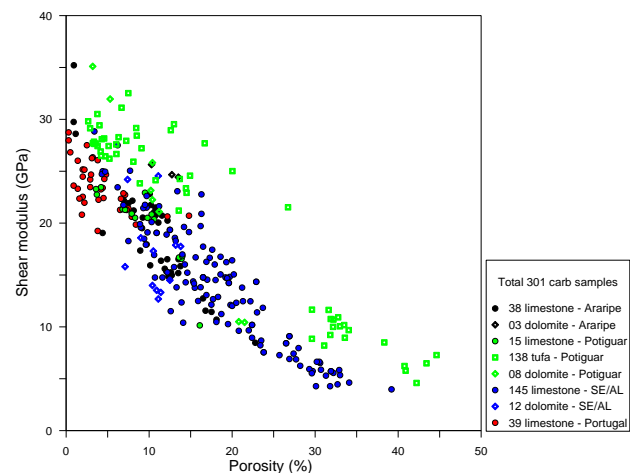


Figure 12 – Shear modulus versus porosity for 301 dry carbonate samples under 40 MPa of confining pressure.

In general, these figures show a somewhat lower dispersion than the figures about velocities and porosity, giving, thus, relationships more robust than those. However, the level of observed dispersion indicates the dependence of elastic moduli on the type of porosity. Even though the high dispersion, Poisson's ratio shows a fairly linear decreasing with the increasing of porosity.

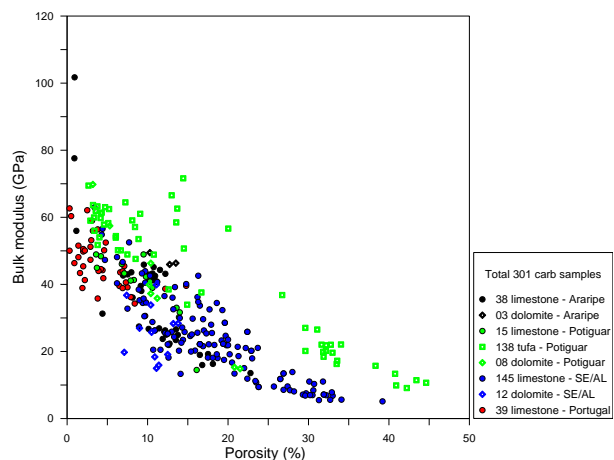


Figure 13 – Bulk modulus versus porosity for 301 dry carbonate samples under 40 MPa of confining pressure.

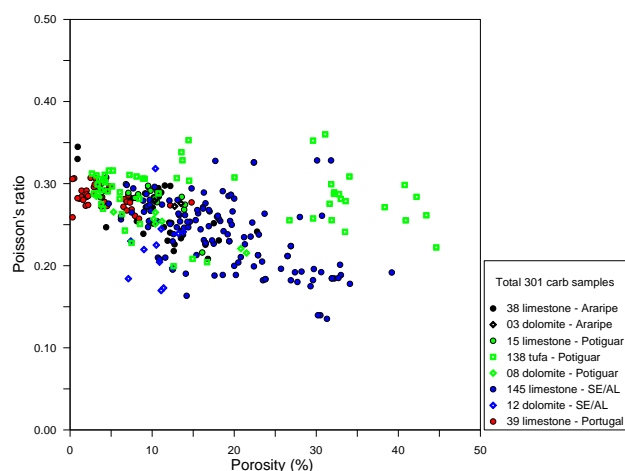


Figure 14 – Poisson's ratio versus porosity for 301 dry carbonate samples under 40 MPa of confining pressure.

Conclusions

A representative number of carbonatic rock samples were characterized through laboratory experiments to give their basic petrophysics and rockphysics properties. They are distributed in a large range of porosity (0% up to 60%) and permeability values are over seven orders of magnitude. Grain density is a good mineral matrix indicator, allowing the separation of dolomites from limestones.

Bulk density and porosity hold on a very reliable linear anticorrelation, which allows the estimation of one property based on the knowledge of the other. The

specific linear fit depends on the mineral matrix type. The relationship between air permeability and porosity presents a high dispersion, indicating the occurrence of several types of porosity and grain sizes.

Elastic wave velocities show a high dispersion anticorrelation with porosity. This is mainly controlled by the dominant porosity type and mineral matrix. In general microporosity reduces elastic velocities, while vugular and moldic porosities tend to maintain the high elastic velocities proper for carbonates. As a consequence, dynamic elastic moduli also show the same dependence on porosity type and on mineral matrix composition. Elastic anisotropy tends to be small. Ninety percent of the samples exhibits anisotropy lower than 5%.

Poisson's Ratio for these carbonatic rocks presents a small decreasing with porosity increasing. Even though the high dispersion, the majority of samples has Poisson's Ratio between 0.2 and 0.3. Under high confining pressure the rock compressibility depends on porosity type while rock permeability depends on pore size and connectivity.

These results allow estimation for any saturation condition, what would be very useful to support any exploration and reservoir studies.

Future studies should focus on quantifying the effect of the type of porosity on the dispersion of the relations between the elastic properties and the porosity of these carbonatic rocks.

Acknowledgments

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