

EXPERIMENTAL DETERMINATION OF THE EFFECTIVE PRESSURE COEFFICIENTS FOR BRAZILIAN LIMESTONES AND SANDSTONES

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ABSTRACT. There are numerous efforts to obtain information about saturation and pressure changes due to reservoir production from time-lapse seismic data. In spite of some good examples existing on the literature, there are a lot of approximations behind those studies. Generally, it is assumed that the seismic properties are functions of saturation and differential pressure P_d (overburden minus fluid pressure). Actually, the stress that governs the seismic behavior is the effective stress P_{ef} , which is not exactly equal to P_d . In fact it is equal to the overburden stress minus n times the fluid pressure. Such coefficient (n) is known as the effective stress coefficient. Sometimes, depending on the circumstances, it might be identified as the Biot-Willis coefficient taking into consideration the bulk modulus of the porous media. In this paper, laboratory results in a tentative to quantify the n values for Brazilian limestones and tight sands will be presented. It is important to point out, that is the first effort to perform this sort of measurements on Brazilian rocks. The results have shown that the mentioned approximations can introduce errors on pressure estimations from time-lapse data even for high porosity rocks.

Keywords: effective pressure, porepressure, seismic velocities, Biot-Willis coefficient, 4D seismic.

RESUMO. Há vários esforços no sentido de obter informações sobre mudanças de saturação e pressão, devidas à produção dos reservatórios, a partir de dados sísmicos com lapso de tempo. Apesar de alguns bons exemplos existentes na literatura especializada, várias aproximações são feitas para a realização destes estudos. Geralmente, é assumido que as propriedades sísmicas são funções da saturação e da pressão diferencial P_d (pressão de soterramento menos pressão de fluido). Na verdade, a tensão que determina o comportamento sísmico é a tensão efetiva P_{ef} , que não é exatamente igual a P_d . De fato, esta é igual à tensão de soterramento menos n vezes a pressão de fluido. Tal coeficiente n é conhecido como coeficiente de tensão efetiva. Eventualmente, a depender das circunstâncias, este pode ser identificado com o coeficiente de Biot-Willis considerando o módulo de compressão volumétrica do meio poroso. Neste trabalho serão apresentados resultados de medidas em laboratório procurando quantificar os valores de n para calcários e arenitos fechados brasileiros. É importante salientar que este é o primeiro esforço de realização deste tipo de medidas em rochas brasileiras. Os resultados mostram que as aproximações mencionadas podem introduzir erros nas estimativas de pressão a partir de dados de monitoramento sísmico mesmo para rochas muito porosas.

Palavras-chave: pressão efetiva, poro-pressão, velocidades sísmicas, coeficiente de Biot-Willis, sísmica 4D.

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INTRODUCTION

It is well known that the stress state influences the mechanical and petrophysical properties of rocks. Porosity, permeability and seismic velocities may be strongly dependent on the stress magnitude and orientation. It was considered in the study only the simple case of hydrostatic stress, herein referred as pressure. Saturation state is other great factor acting on mechanical properties variation. In time-lapse studies, both states can change in different ways and combinations, leading to a kind of puzzle for the geoscientists to distinguish what effect are governing the different seismic response between two surveys.

To our knowledge, every trial to obtain porepressure variation from time-lapse seismic has been done considering the assumption of an effective pressure P_{ef} equal to the differential pressure P_d , that is:

$$P_{ef} = P_d \approx P_c - P_p \quad (1)$$

This assumption agrees with the effective stress concept introduced by Terzaghi in 1923 as being the excess of the total stress over the neutral stress (porepressure) that acts exclusively in the solid phase of soils (Skempton, 1960), and "all the measurable effects of a change in stress, such as compression, distortion, and a change in shearing resistance, are due exclusively to changes in the effective stress" (Terzaghi et al., 1996).

This concept had been modified to include any linear combination of confining and porepressure that allows the reduction of independent variables (Lade & de Boer, 1997). If we consider some physical property of a porous media that depends on the total stress (here confining pressure), it will be also dependent on porepressure, that acts hydrostatically over all the grain free surfaces,

$$Q = Q(P_c, P_p) \quad (2)$$

The effective pressure would be a linear combination

$$P_{ef} = P_c - nP_p \quad (3)$$

such that

$$Q = Q(P_c, P_p) = Q(P_{ef}) \quad (4)$$

The coefficient n is the so-called porepressure coefficient or effective pressure coefficient (Biot, 1955; Christensen & Wang, 1985).

Nur & Byerlee (1971) had shown that, for the volumetric bulk compression of a porous media, the coefficient n is equal to the Biot-Willis coefficient (Biot & Willis, 1957),

$$n = 1 - \frac{K_{dry}}{K_{sol}} \quad (5)$$

where K_{dry} and K_{sol} are the bulk moduli of the dry rock and the solid fraction, respectively (the inverse of the compressibility). Todd & Simmons (1972), studying the pressure-dependence of seismic velocities of rocks, concluded that, for the compressional-wave velocity, this porepressure coefficient can be written as

$$n = 1 - \frac{(\partial V_p / \partial P_p)_{P_d}}{(\partial V_p / \partial P_d)_{P_p}} \quad (6)$$

where $(\partial V_p / \partial P_p)_{P_d}$ and $(\partial V_p / \partial P_d)_{P_p}$ are the partial derivatives of the velocity with respect to the porepressure for constant differential pressure and to the differential pressure for constant porepressure, respectively. These derivatives may be obtained from special velocity measurement experiments on the lab, and this n might be interpreted as an empirical porepressure coefficient. This empirical n can be extended to any physical property Q as

$$n = 1 - \frac{(\partial Q / \partial P_p)_{P_d}}{(\partial Q / \partial P_d)_{P_p}} \quad (7)$$

A coefficient $n = 1$ means that the porepressure compensates the effect of confining pressure, while $n < 1$ means that the effect of confining pressure is greater than that of porepressure and $n > 1$ means that the porepressure surpasses the confining pressure effect. There are some reported results on the determination of n , however they are far from being conclusive. For instance, King (1966) found n values greater than unity for the compressional and shear-wave velocities on Boise, Bandera, Berea and Torpedo sandstones. Whereas Christensen & Wang (1985) found n values less than unit for compressional-wave velocity and bulk modulus, but greater than unity for shear-wave velocity and Poisson's ratio of Berea sandstone. Prasad & Manghnanani (1997) as well as Xu et al. (2006) found effective pressure coefficients $n < 1$ for Berea, Michigan and Lyons sandstones. Such a variety of results indicates that the behavior of n with pressure and petrophysical properties needs further investigation.

Gurevich (2004) discussed the validity of the effective stress concept and concluded that, for a rock with homogeneous and linearly elastic solid phase the coefficient n for the seismic velocities must be equal to 1. He claims that the violation of the homogeneity and linear elastic behavior of the grains may be the reason of the different experimental results. Berryman (1992, 1993) derived effective stress coefficients for various properties of rocks composed of different mineral constituents, showing that each physical quantity may be governed by a particular effective stress associated with a given effective stress coefficient.

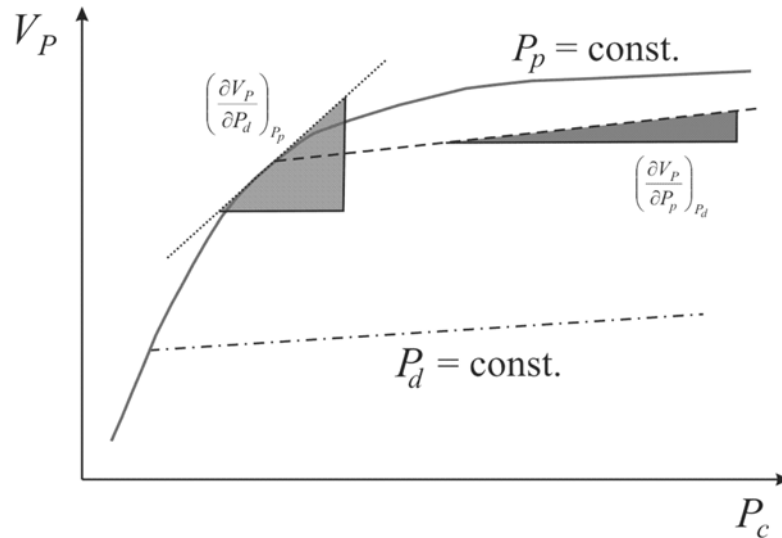


Figure 1 – Schematic diagram illustrating how to compute the derivatives on the numerator and denominator in the experimental equation for the effective-stress coefficient (Eq. (6)). The numerator is calculated from the slope of the $V_P - P_c$ curve at constant P_d , and the denominator is calculated from the slope of the tangent of $V_P - P_c$ at constant P_p . Note that V_P could be replaced with any rock property.

Besides time-lapse seismic, geopressure prediction on petroleum exploration also assumes that the effective stress is equal to the differential pressure. This is a very important issue, since “subsurface geopressures are often the dominant decision variable in the selection of drilling fluids and wellbore casings, which are two of the largest costs in most drilling programs. Under-designing the drilling fluid or casing program can result in unplanned expenses, nonproductive time due to fluid influx, fluid loss or wellbore instability, inability to reach total depth, and even catastrophic environmental damage, blow-outs, or rig fires” (Standifird et al., 2004).

METHOD

It were measured the elastic velocities at ultrasonic frequencies on the laboratory by the pulse transmission technique (Vasquez et al., 2000) on a set of limestone and sandstone samples. The samples were saturated with brine to simulate the *in situ* formation water (65000 ppm of NaCl for the limestone and 240000 ppm for the tight sand).

The velocities were measured varying the confining pressure from atmospheric up to 6000 psi. The porepressure was increased until 4000 psi in 500 psi steps. On the other hand in some samples it was used 8000 psi for the final confining pressure.

From the experimental data, it was derived empirical porepressure coefficients for compressional-wave and shear-wave velocities and also for the bulk and shear moduli. The empirical

coefficients were derived using Equation (5), through the scheme illustrated on Figure 1. Note that a constant differential pressure curve with positive slope corresponds to n less than unity, while those with negative slope correspond to n greater than 1. The case in which $n = 1$ corresponds to a perfect horizontal “ $P_d = \text{constant}$ ” curves (Vasquez et al., 2007).

In order to obtain the derivatives of velocities and moduli related to a confining pressure, it had been fitted the data points with functions generally used to describe the velocity-pressure behavior of rocks, especially the Mavko (2004) and Eberhart-Phillips et al. (1989):

$$V(P) = a_M - b_M \exp\left(-\frac{P}{c_M}\right) \tag{8}$$

and

$$V(P) = a_H + b_H - P - c_H \exp(-d_H P) \tag{9}$$

respectively. Similar pressure laws were used for the bulk and shear moduli. The results obtained with these different pressure laws were very consistent (both fitted functions are shown in figures illustrating velocities and moduli as a function of confining pressure as large and small dashed lines, and they are almost always coincident, as can be seen on those pictures).

It is important to notice that the bulk modulus of the pore fluid varies with the porepressure. In order to remove this effect from the data, it was also derived a normalized bulk modulus and its

corresponding effective-pressure coefficient. The effect of fluid changes was removed using Gassmann's equation (Gassmann, 1951):

$$\frac{K_N}{K_{sol} - K_N} = \frac{K_{sat}}{K_{sol} - K_{sat}} - \frac{1}{\phi} \left[\frac{K_{fl}}{K_{sol} - K_{fl}} - \frac{K_{flN}}{K_{sol} - K_{flN}} \right] \quad (10)$$

where K_N is the desired normalized bulk modulus, K_{sat} is the measured bulk modulus with rock saturated with fluid which bulk modulus is K_{fl} , and K_{flN} is the fluid bulk modulus used as the reference for normalization. It was used the lowest porepressure as the reference saturation state. The fluid properties were obtained from the relations published by Batzle & Wang (1992). This approach does not take into account frequency related effects on seismic velocities.

SAMPLE SET

The samples selected for this study comprises unconsolidated to medium consolidated limestones and a set of tight sandstones.

The limestones are calcirudite to rhodolite with a matrix that varies from micritic to calcarenitic. Some samples have also siliclastic grains (mainly quartz). The occurrence of macro-foraminifera is common as well. Since these limestones were not very well consolidated, the samples were covered with metal jackets with pervious screens at the ends to avoid sample degradation during cleaning as well as petrophysical and acoustic measurements. Although this jacketing process had been proved not to change the velocities measurements, in some cases the quality of waveform signal is very poor, especially for the shear wave in saturated samples. Due to these difficulties, it was not possible to pick a complete set of measurements unless on three samples (5005, 5062 and 5070). On the other hand, compressional-wave data collection was possible on six samples. The petrophysical properties of the samples are listed in Table 1. Figure 2 illustrates photos from thin sections representing two of the limestone samples and a scanning electron microscopy (SEM) showing the existence of complex micro porosity on these rocks.

Table 1 – Petrophysical properties of the limestone samples.

Sample	ρ_{ma} (g/cc)	ϕ (%)	κ (md)
5001	2.71	23.15	2.25
5005	2.75	29.74	7.63
5057	2.70	33.52	1097.9
5062	2.72	30.78	1237.05
5070	2.67	26.24	34.11
5088	2.71	26.46	225.17

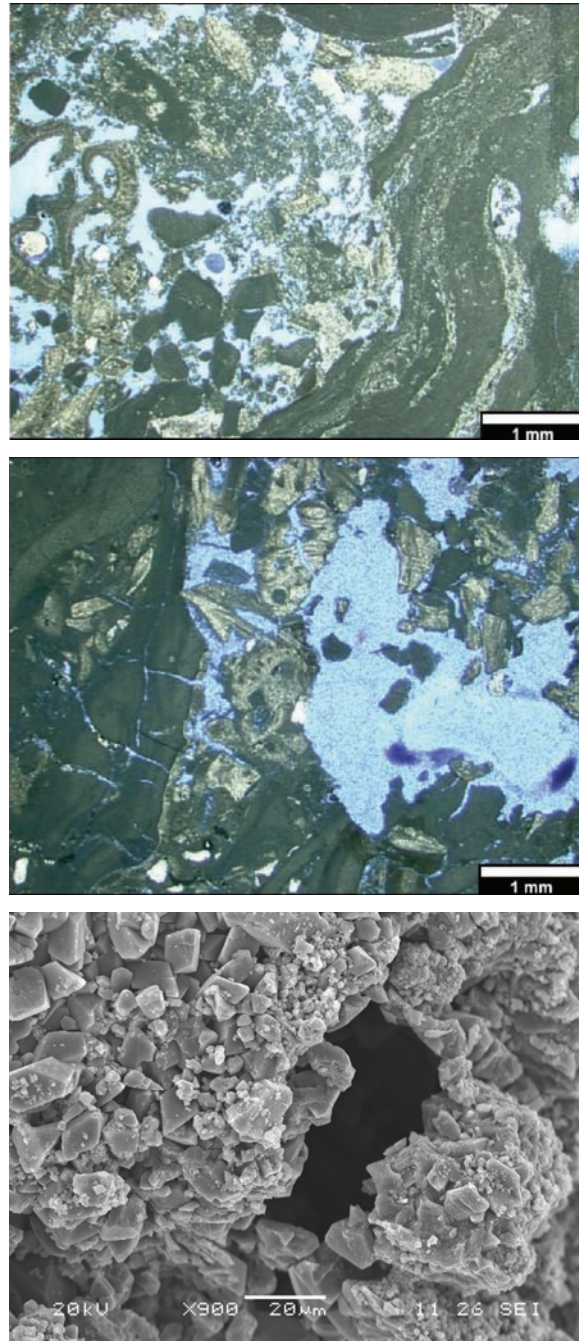


Figure 2 – (a) Optical microscopy photo of the limestone sample 5005. This is a calcirudite with calcarenitic matrix, with intergranular porosity. (b) Thin section from sample 5062, biolite to red algae with vugular porosity. (c) SEM image of sample 5062.

The sandstones samples are well consolidated arkosic sandstones, with more than 50% Feldspar on average, fine to medium grained, poorly to moderately sorted, and relatively rich in chlorite, especially as fringes around the grains. As usual on consolidated samples, the signal quality was very good even for the sa-

turated samples. The petrophysical properties of the sandstones are listed on Table 2. Note that the porosity of these sandstones is large mainly due to the micro porosity associated to the presence of chlorite. In this sense, it may be considered tight sandstone. Figure 3 shows thin sections images of the sandstone facies, with detail of the fringes as well as a SEM image illustrating the grain boundaries.

Table 2 – Petrophysical properties of the sandstone samples.

Sample	ρ_{ma} (g/cc)	ϕ (%)	κ (md)
5965	2.66	18.50	0.90
5976	2.65	15.20	8.66
6047	2.65	13.20	11.17
6090	2.65	19.40	14.46
6125	2.65	18.00	16.04
6492	2.66	16.50	0.31

RESULTS

Carbonates

In Figure 4 it can be observed an example of compressional-wave velocity *versus* confining pressure curves for the sample 5005, with the zero porepressure curves (dots) along with the velocity data for distinct differential pressure values. Actually, zero porepressure means atmospheric pressure (14.7 psi or 0.1 MPa). The data for low differential pressure (1000 psi or 6.89 MPa) shows some dispersion around the fitted line. It was also noticed that data for high differential pressure suggests n values higher than unity. In principle the velocity curves for different porepressure values would be “parallel” to each other if the porepressure coefficient was equal to unit. From Figure 5, which shows the velocity *versus* confining pressure for different porepressure values for sample 5005, it becomes evident that n is not equal to 1.

The measurements were repeated successively with different stress paths and in some limestone samples the repeatability was not as good as expected. These “bad results” were associated with sample destruction, maybe due to pressure cycling and calcite dissolution. Since calcite is more soluble in brine than in fresh water we could try to avoid this problem using a tampering solution. In some samples there were strong evidences that the dissolution was followed by migration of thin particles and subsequent obliteration of the pore space and permeability reduction. From an initial selection of ten samples, four were destroyed by these procedures. Of course, these “bad results” were abandoned through our study, since the samples lost the integrity during the experiment.

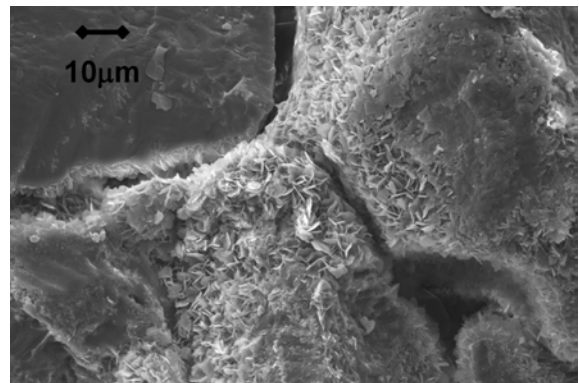
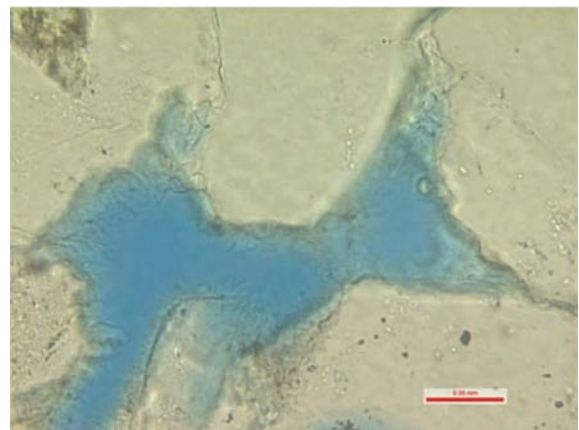
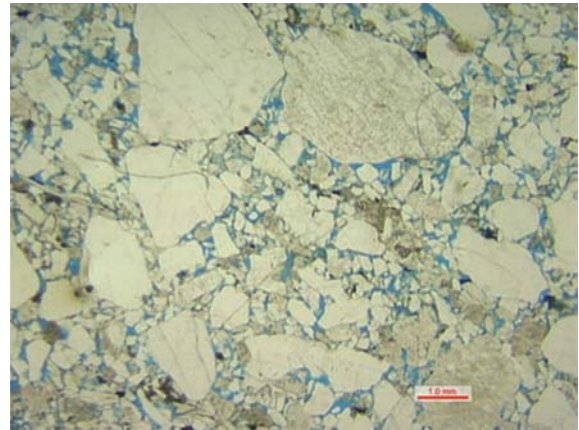


Figure 3 – (a) Typical thin section image of the sandstone samples. This is a fine to medium grained sandstones, poorly sorted with dispersed large grains. (b) Detail of the grain boundaries with chlorite fringes. (c) SEM image of sample 5965.

The rock bulk modulus as a function of confining pressure for the same sample 5005, along with the constant differential pressure curves is shown on Figure 6. In Figure 7 the curves obtained for the bulk modulus after the normalization process represented by Equation (10) are presented. The dots represent the normalized bulk modulus as a function of confining pressure for zero porepressure, and the other curves are the constant differential

pressure curves. It is worth to point out that the normalization of the bulk modulus leads to effective pressure coefficients close to one for moderate and low differential pressure values. This effect was present on the other samples as well: the n values corresponding to the normalized bulk modulus is equal or very close to unity. In general, for higher differential pressures (and confining pressure) n tends to be greater than unit.

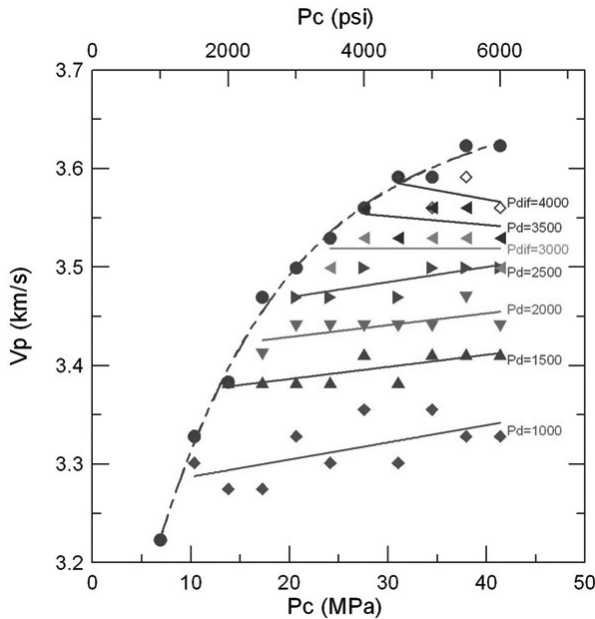


Figure 4 – Velocity curves for sample 5005 as a function of confining pressure for zero porepressure (dots) along with constant differential pressure curves.

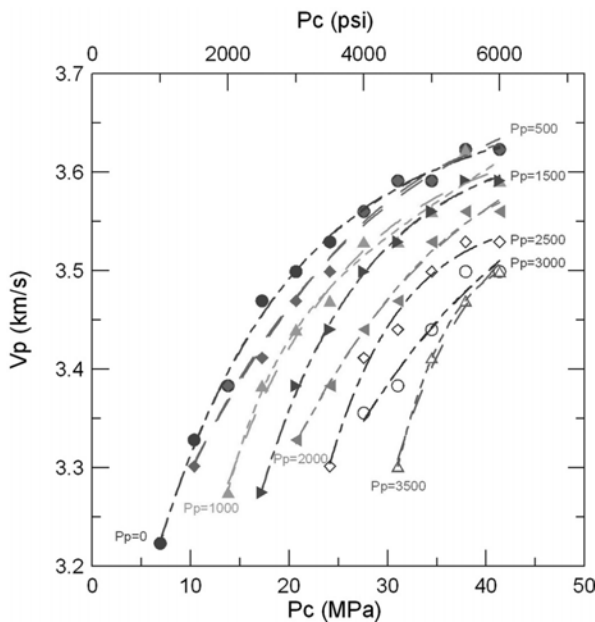


Figure 5 – Velocity curves for sample 5005 as a function of confining pressure for different porepressure values.

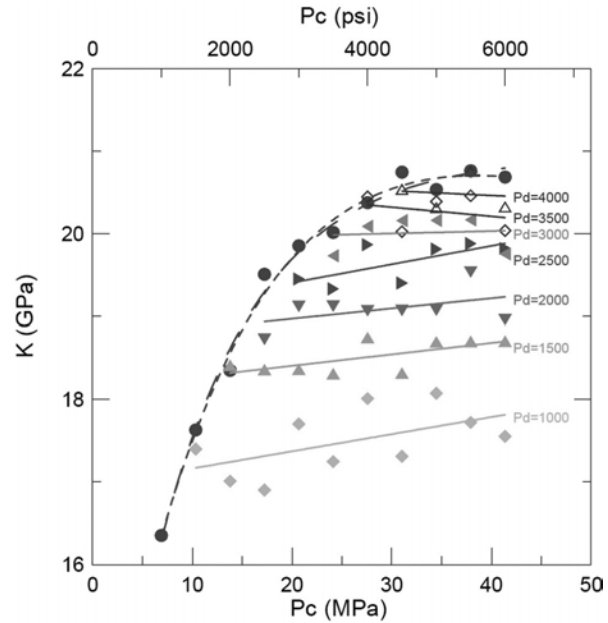


Figure 6 – Bulk modulus curves for sample 5005 as a function of confining pressure for zero porepressure (dots) along with constant differential pressure curves.

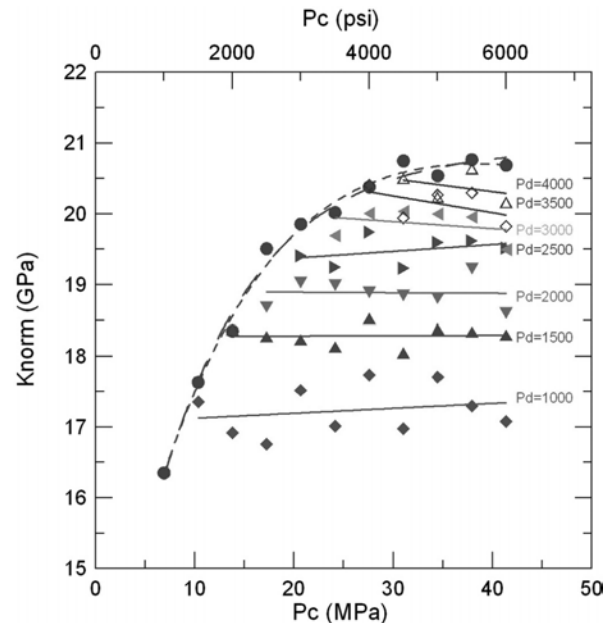


Figure 7 – Normalized bulk modulus curves for sample 5005 as a function of confining pressure for atmospheric porepressure (dots) along with constant differential pressure curves.

Figure 8 illustrates the effective pressure coefficients for the bulk modulus of sample 5005 before and after the normalization process among with the classical Biot-Willis coefficient for bulk compression of porous materials, given by Equation (5). We note that the empirical n is greater than the Biot-Willis coefficient and that the n values obtained after normalization of the bulk modulus

are closer to one. Besides, there is a sharp variation on n values at 2500 psi and 3000 psi (17.24 and 20.68 MPa, respectively) that needs a better understanding. We suspect that this may be associated with pore space alteration due to brine-calcite interaction and pressure cycling or with the presence of bi-modal porosity distribution. Pore compressibility experiments on neighbor samples, not shown in this article, also exhibits anomalous behavior around these pressures.

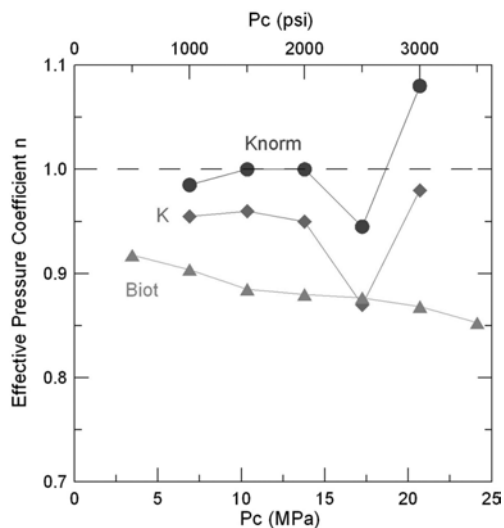


Figure 8 – Effective pressure coefficients for the bulk modulus of sample 5005 before (diamonds) and after (dots) the normalization process, along with the classical Biot-Willis coefficient for bulk compression of porous material, for atmospheric porepressure.

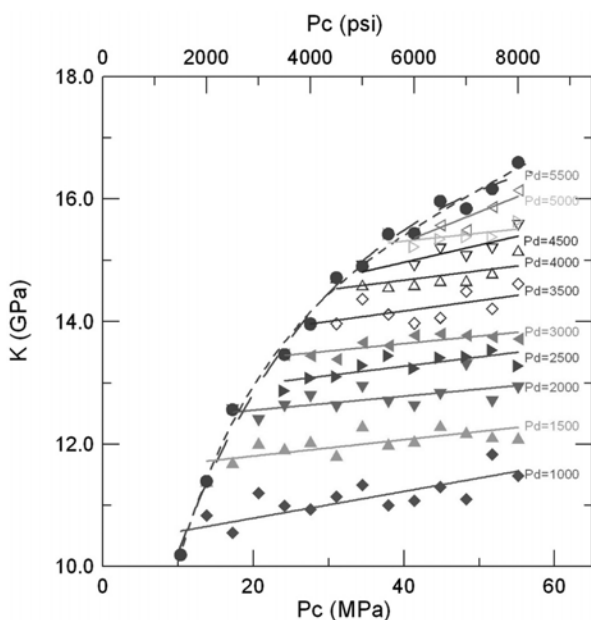


Figure 9 – Bulk modulus curves for sample 5062 as a function of confining pressure for porepressure vented to the atmosphere (dots) along with constant differential pressure curves.

Figures 9 and 10 show the behavior of the bulk and shear moduli for another limestone sample (5062) for various differential pressures along with the data for the pore system vented to the atmosphere (dots). The data are quite consistent.

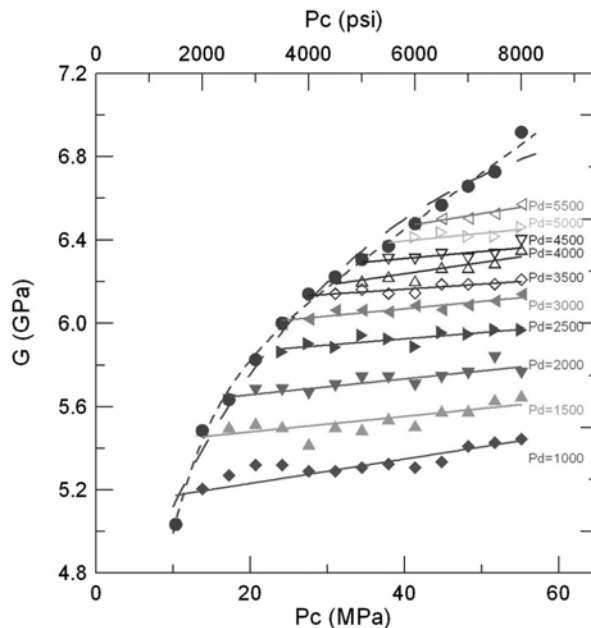


Figure 10 – Shear modulus curves for sample 5005 as a function of confining pressure for porepressure vented to the atmosphere (dots) along with constant differential pressure curves.

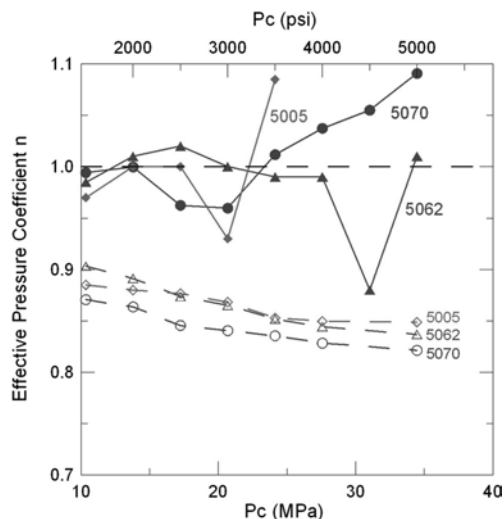


Figure 11 – Effective pressure coefficient for the normalized bulk modulus for three limestone samples at 500 psi (3.45 MPa) porepressure. Dashed lines correspond to the Biot-Willis coefficient.

The results for the empirical porepressure coefficients referring to the normalized bulk modulus for the three samples that there is a complete set of measurements (compressional and shear-waves) was represented as a function of confining pressure in Figure 11. Note that the sample 5062 seems to have a wrong

data at 4500 psi (31.03 MPa). These data points are listed in Table 3. Figure 12 summarizes the results of effective pressure coefficients for the P-wave velocity for all the limestone samples, for a constant porepressure of 500 psi (3.45 MPa). There are some evidences that n depends on differential pressure.

Table 3 – Empirical effective pressure coefficients for the normalized bulk modulus of three limestone samples at 500 psi (3.45 MPa) porepressure.

Pp=500 Pc (psi)	Effective pressure coefficient n		
	5070	5062	5005
1500	0.99	0.99	0.97
2000	1.00	1.01	1.00
2500	0.96	1.02	1.00
3000	0.96	1.00	0.93
3500	1.01	0.99	1.09
4000	1.04	0.99	
4500	1.05	0.88	
5000	1.09	1.01	

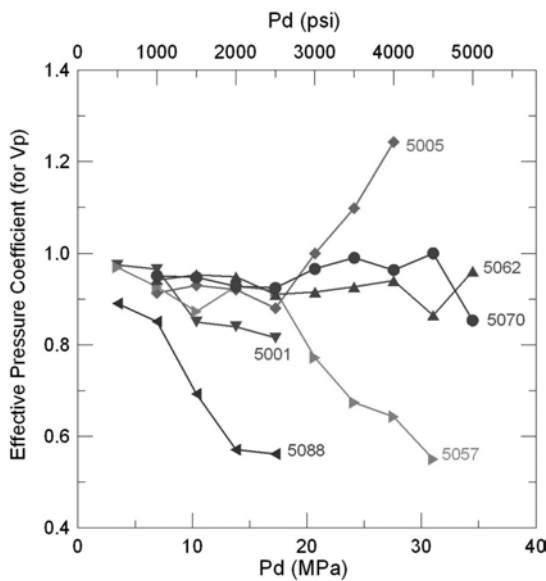


Figure 12 – Effective pressure coefficients for the compressional-wave velocity of the limestone samples for a constant porepressure of 500 psi (3.45 MPa).

Sandstones

Due to the low permeability of the sandstone samples and the clorithe-brine interaction, that causes obliteration of pore-throats, it was difficult to obtain full water saturation by the imbibition method for all samples. The saturation was then estimated by weighting the sample before and after the saturation process and the fluid bulk modulus used for the calculations were estimated by the Wood's formula (compressibility equals to the weighted average of brine and air compressibilities).

The compressional and shear-wave velocity data for the sandstone 5976 ($S_w = 89\%$) are illustrated on Figures 13 and 14, along with the curves for constant porepressures, atmospheric and 500 psi (open dots and open diamonds). The compressional-wave velocity and bulk modulus for sample 5965 at various differential pressures are illustrated on Figures 15 and 16, along with the curve for 500 psi (3.45 MPa) constant porepressure (open dots). The brine saturation for this sample was estimated to be 57%.

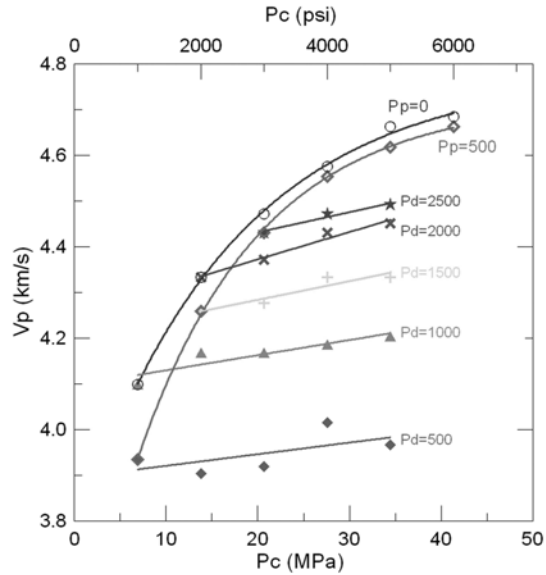


Figure 13 – Compressional-wave velocity as a function of confining pressure for sandstone sample 5976 for atmospheric and 500 psi porepressure (open dots and open diamonds) along with constant effective pressure curves.

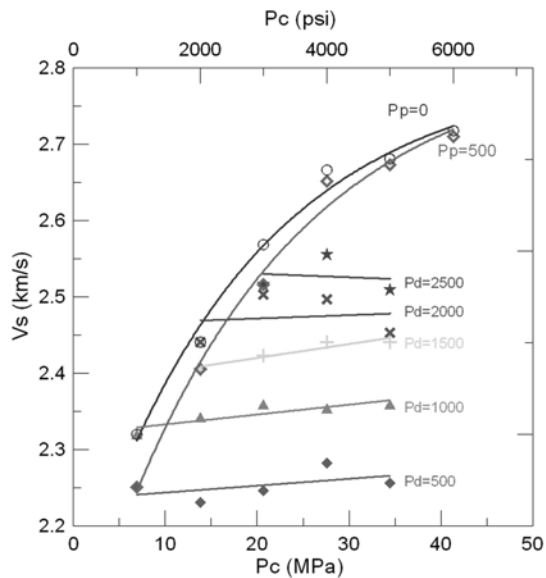


Figure 14 – Shear-wave velocity as a function of confining pressure for sandstone sample 5976 for atmospheric and 500 psi porepressure (open dots and open diamonds) along with constant effective pressure curves.

The effective pressure coefficients for compressional-wave velocity for all the sandstones samples are shown on Figure 17 as a function of porepressure for a constant confining pressure 2500 psi (17.24 MPa). As can be noted, it seems that the n values depend on porepressure itself. This is another issue on time-lapse studies.

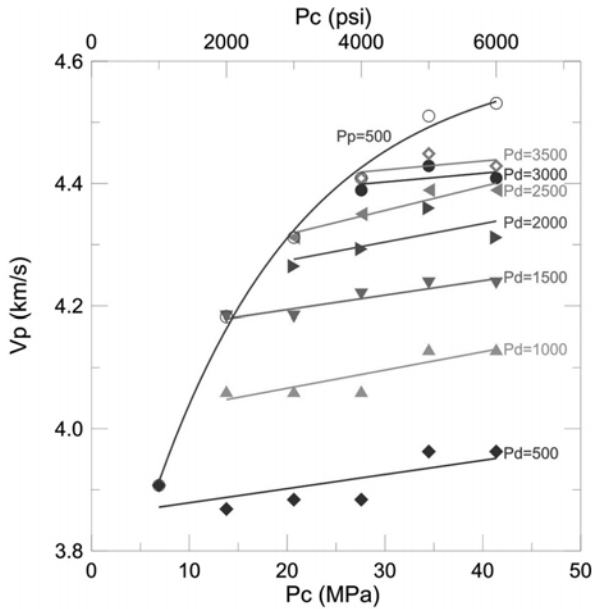


Figure 15 – Compressional-wave velocity for sample 5965 at various differential pressures along with the curve for 500 psi (3.45 MPa) constant porepressure (open dots).

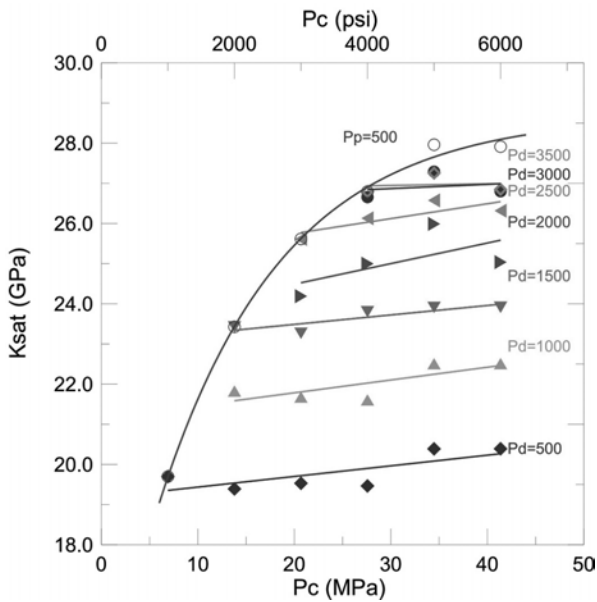


Figure 16 – Bulk modulus for sample 5965 at various differential pressures along with the curve for 500 psi (3.45 MPa) constant porepressure (open dots).

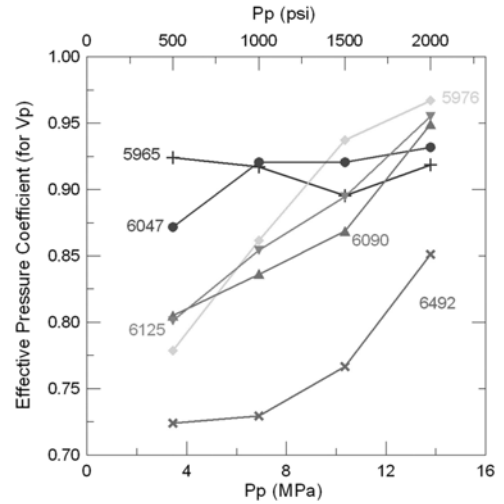


Figure 17 – Effective pressure coefficients for the compressional-wave velocity for all the sandstones samples as a function of porepressure for a constant confining pressure 2500 psi (17.24 MPa).

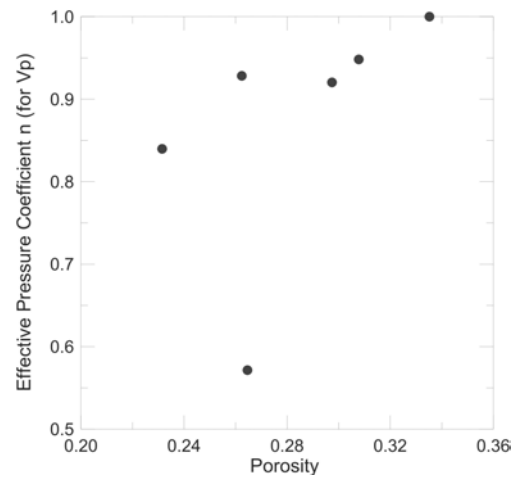
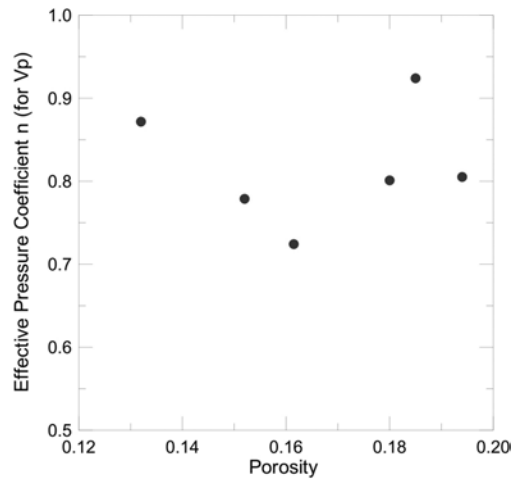


Figure 18 – Effective pressure coefficient as a function of porosity for the (a) sandstone and (b) limestone samples (porepressure 500 psi, confining pressure 2500 psi).

It is interesting to compare the n coefficients for the sandstone and limestone samples. Figure 18 (a) and (b) summarizes the n values obtained for the compressional-wave velocity of the sandstones and limestones, respectively, as a function of porosity, for a porepressure of 500 psi (3.45 MPa) and confining pressure of 2500 psi (17.24 MPa). The data points are listed on Table 4. In spite of the data scattering, there is a trend of increasing n with porosity even considering the different kinds of rock composition and texture.

Table 4 – Effective pressure coefficients n for the compressional-wave velocity of the sandstone and limestone samples at 2500 psi (17.24 MPa) confining pressure and 500 psi (3.45 MPa) porepressure with the porosity ϕ (decimal units).

Rock type	Sample	n	ϕ
Sandstone	6047	0.87	0.1320
	5976	0.78	0.1520
	6492	0.72	0.1615
	6125	0.8	0.1800
	5965	0.92	0.1850
	6090	0.81	0.1940
Limestone	5001	0.84	0.2315
	5070	0.93	0.2624
	5088	0.57	0.2646
	5005	0.92	0.2974
	5062	0.95	0.3078
	5058	1.00	0.3352

DISCUSSION

It was found effective pressure coefficients n different than unity, even for the high porosity limestone samples.

The values reported here for the effective pressure coefficient are relatively close to unity when compared to those reported by Xu et al. (2006), that obtained n values as low as 0.3 for Lyons sandstone, that is a clean tight sandstone. It must be remembered that our limestone samples are very porous, unconsolidated and that the pore space is well communicated. On the other hand, our sandstone samples are very well consolidated and have relatively low permeability, with much of the porosity contained on shales.

This deviation of the effective pressure coefficient from unit can lead to erroneous porepressure interpretation from time-lapse data and even on the feasibility study phase or on geopressure prediction. The error due to the n value comes from the fact that, for some porepressure variation ΔP_p , assuming a constant confining pressure, the effective pressure variation is $\Delta P_{ef} = -n\Delta P_p$, while the differential pressure variation is $\Delta P_d = -\Delta P_p$. As an example, for $n = 0.8$ the variation of differential pressure is 25% greater than the variation on the ef-

fective pressure. So, for an observed change in the porepressure, we would have an overestimation of changes in bulk modulus. On the other hand, an observed change in seismic velocity or impedance would lead to underestimates of the porepressure variation. The error does not depend only on the n values, but also on the velocity-pressure sensitivity for the particular reservoir.

Although the n values for the unconsolidated limestone are not so far from unity, it has a stronger pressure sensitivity of velocities and elastic moduli when compared to consolidated rocks, so that any pressure variation should correspond to a large variation on the elastic property.

Another important issue is that the effective pressure coefficient seems to depend on the porepressure, so that for each time-step on a 4D study, a different n value must be considered.

CONCLUSIONS

We measured the effective pressure coefficients for the seismic velocities and elastic moduli of Brazilian limestones and sandstones. The results show that, even for unconsolidated rocks, there is a deviation of the effective pressure coefficient from unity that can lead to errors on porepressure prediction from seismic data and also on time-lapse studies. These striking results are the first obtained for Brazilian rocks. Nevertheless, more experimental investigations with different rock and fluid types are needed in order to obtain a better understanding of the effective pressure coefficients and its influences on pressure estimation from seismic data.

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