Applying the Pride model for estimating consolidation parameter of carbonate rocks

Soares T., Ceia, M., Missagia, R., and Lima Neto, UENF/CCT/LENEP, Macaé – RJ, Brazil

This paper was prepared for presentation during the 16th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 19-22 August 2019.

Abstract

The estimation of dry bulk modulus is determinant for the success of the application of Biot-Gassmann theory to forecast fluid changes within a reservoir. The Pride model is one of the various models described in literature for predicting the dry elastic moduli of rocks. However, that model depends on the consolidation parameter and its appropriate choice implies in the accuracy of that model. In this paper, Pride model is used for estimating the consolidation in carbonate rock with different textures.

Introduction

The formation of carbonate sedimentary rocks is influenced by physical processes dominated by complex biological and diagenetic processes that do not occur in siliciclastic rocks. The generation of siliciclastic sediments is related to the intensity and type of physical energy, such as winds, waves, direction and intensity of currents, which affect sediment texture on the depositional site. On the other The formation of carbonate sedimentary rocks is influenced by physical processes dominated by complex biological and diagenetic processes that do not occur in siliciclastic rocks.

The success of the Biot-Gassmann theory depends on the accurate characterization of the dry rock bulk modulus. There are several theories described in the literature that aim to evaluate the dry rock bulk (Kdry) and shear moduli (Gdry) from mineralogy and porosity info, as Geertsma (1961), Krief et al. (1990) and Nur et al. (1995). Pride (2003) presented a model that related the dry bulk and shear moduli as a function of porosity and the consolidation parameter, which depends on differential pressure and the degree of consolidation between the grains. Lee (2005) derived a generalization of Pride's and applied that theory to consolidated and unconsolidated sandstones. Zhang *et al*. (2009) studied the accuracy of Pride model compared to Krief and Nur models and found that it provides the best results once such consolidation parameter could vary with different rocks while Krief model has no adjustable parameter and in Nur model, the critical porosity is usually constant for the same type of rocks.

Ceia et al. (2015) used part of the database reported by Fournier & Borgomano (2009), which consists of measurements of the physical properties of microporous mixed carbonate-siliciclastic rocks obtained at two wells located within the South Provence Basin, in France.An empirical model was obtained from Ceia et al. (2015) through estimating a best fit surface that could describe the consolidation parameter as a function of those two properties for each pressure. A polynomial result that combines second order dependence to aspect ratio and third-order dependence to porosity.

In this work, Pride model is applied to carbonate to estimate consolidation parameter.

Data set

Chalk Group

Part of the database was used from *Rogen et al.* (2005) was used which consists of 56 chalk samples from the Tor Formation of the Chalk Group from the Dan Field (25 oil zone samples),the South Arne Field (29 oil-zone samples) and the Gorm Field (two water-zone samples) in the Danish North Sea (The Tor Formation is of Maastrichtian age and is the main oil-producing formation in these fields. According to information from field operators, present effective stress on reservoir rocks is nearly equal for the three fields, because the present difference in burial depths of about 900 m is counteracted by differences in overpressure. The depositional texture from Rogen *et al*. (2005) according to Dunhan(1962) is mudstone and wackestone.

Urgonian limestone, Barremian–Aptian, SE France

The database of Fournier *et al.*(2014) is used partially. The data set consists of 214 limestone samples from Lower Cretaceous platform carbonates collected in various localities in Southeast France, displaying porosity values ranging from 0.1% to 23.1%. Additionally, the present work integrates the 85 microporous samples published. The Lower Cretaceous deposits from Provence consist of platform carbonates, with ages ranging from Valanginian to Early Aptian.
The depositional texture from from Fournier et al.(2014) is grainstones and packstones.

Formation of southern England

Assefa *et al.* (2003) to explore the relationship between the seismic, petrophysical and geological properties, ultrasonic compressional- and shear-wave velocity measurements were made under a simulated in situ condition of pressure (50 MPa hydrostatic effective pressure) at frequencies of approximately 0.85 MHz and 0.7 MHz, respectively, using a pulse-echo method. The measurements were made both in vacuum-dry and fully saturated conditions in oolitic limestones of the Great Oolite Formation of southern.

Theory

Pride model relates the dry rock moduli to porosity as described in Equation 1.

$$K_{dry} = \frac{K_{ma}(1-\phi)}{(1+c\phi)} \quad (1)$$

Where:

Kma = Mineral bulk modulus;
ϕ = Porosity;
c = Consolidation Parameter.

According to Pride (2003), the consolidation parameter indicates the degree of consolidation of a rock and usually ranges from 2 to 20 in sandstones (Figure 1). Lee (2005) defined that in practic applications, such parameter can be viewed as a free parameter to fit the observation data if porosity, P- and S-wave velocities are known. In practice a broad range of values can be used to estimate Kdry within the Voigt and Reuss bounds.

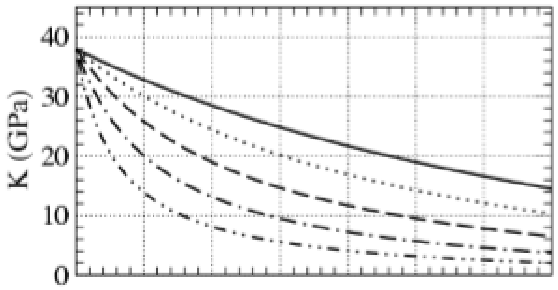

Figure 1: The frame formuli equation (1) and consolidation factors c and various porosities. The solid was taken to be quartz (Kma= 38 Gpa) (Pride, 2003)

Method

Estimation of Kma and Gma

The mineral bulk and shear modulus were estimated using Hill's average of the Voigt and Reuss bounds of the mineral content provided by XRD results. according to Eqs. 2, 3 and 4.

$$M_{ma_V} = \sum_{i=1}^{n} M_{ma_i} f_{ma_i} \quad (2)$$

$$\frac{1}{M_{ma_R}} = \sum_{i=1}^{n} \frac{f_{ma_i}}{M_{ma_i}} \quad (3)$$

$$M_{ma_H} = \left(\frac{M_{ma_V}+M_{ma_R}}{2}\right) \quad (4)$$

Where:

Mma=Mineral modulus (bulk or shear);

fma=Fraction of each mineral phase (i);

n=number of mineral phases;

V=subscript to refer to Voigt bound;

R=subscript to refer to Reuss bound;

H=subscript to refer to Hill average

Results

Table 1: Range of consolidation parameter used in this study.

Database	Texture	Range of Consolidation Parameter
Assefa *et al*. (2003)	The Great Oolite is composed mainly of oolitic, skeletal and oncolitic grainstones and packstones.	14.5 to 27.3.
Fournier *et al*. 2014	Grainstone, packstone, rudstone and wackestone/floastone.	3.3 to 48
Rogen *et al*. (2005)	Mudstone and wackestone	9 to 42

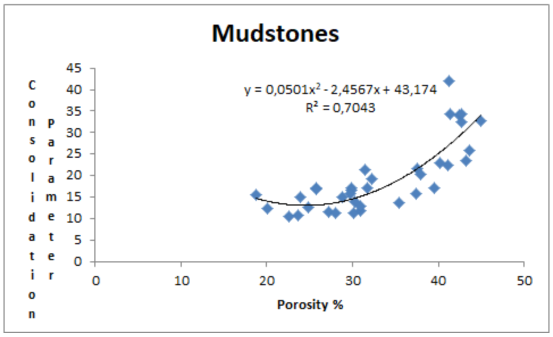

Figure 2: Consolidation parameter X porosity for the mudstone from data Rogen *et al*. (2005).

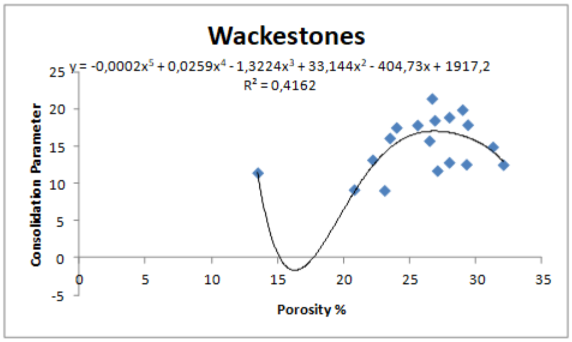

Figure 3: Consolidation parameter X porosity for the wackestones from data Rogen *et al*.2005 (2005).

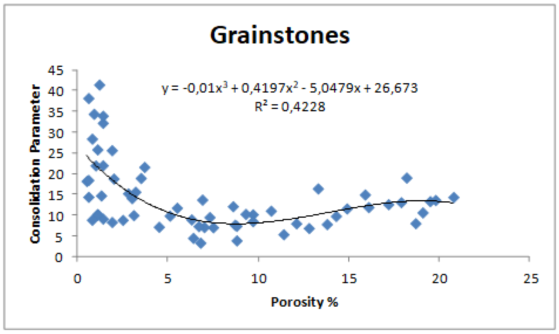

Figure 4: Consolidation parameter X porosity for the grainstones from data Fournier *et al*. 2014

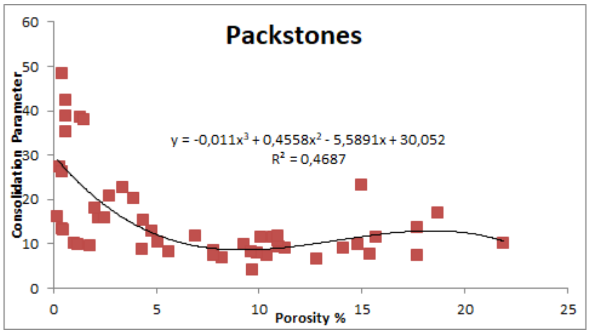

Figure 5: Consolidation parameter X porosity for the packstones from data Fournier *et al*. 2014

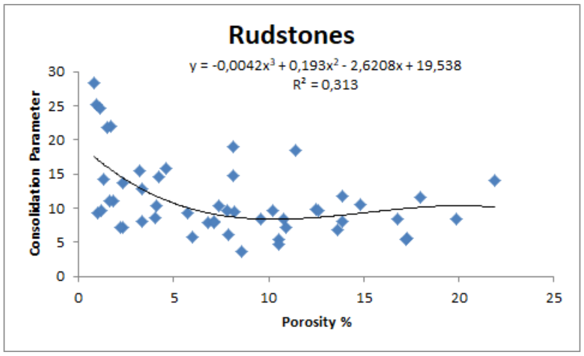

Figure 6: Consolidation parameter X porosity for the rudstone from data Fournier *et al*. 2014.

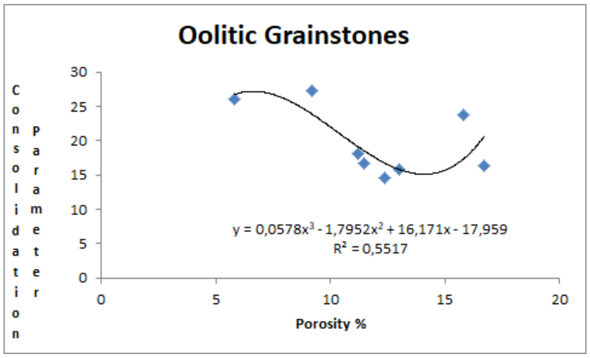

Figure 7: Consolidation parameter X porosity for the oolitic grainstone from data Assefa *et al*.

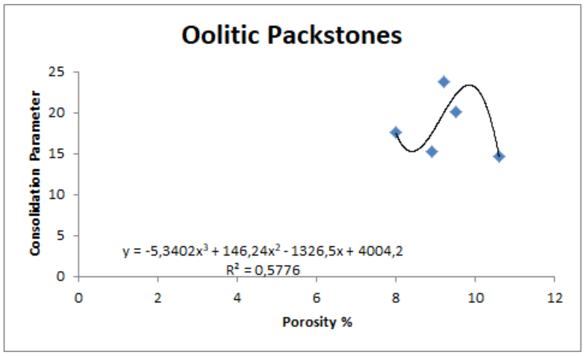

Figure 8: Consolidation parameter X porosity for the oolitic packestones from data Assefa *et al*. (2003).

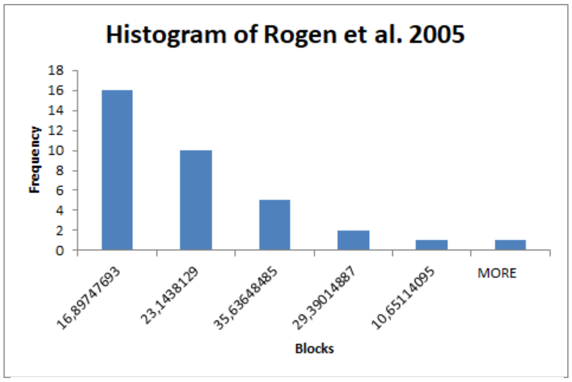

Figure 9 : Histogram of frequency of the values of consolidation parameter of Fournier et al. 2014.

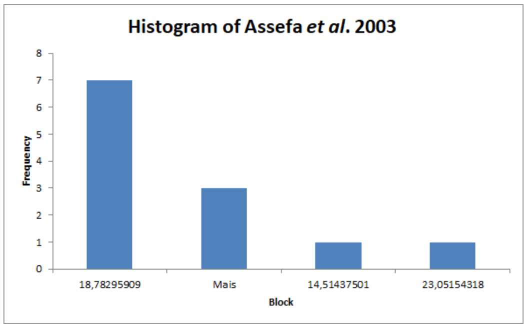

Figure 10: Histogram of frequency of the

values of consolidation parameter of Assefa

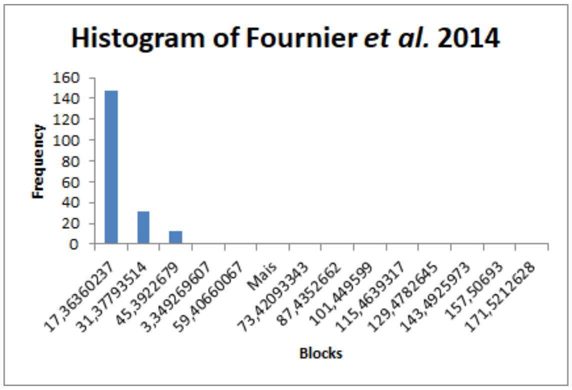

Figure 11:Histogram of frequency of the values of consolidation parameter of Fournier et al. 2014.

Discuss

The analysis of the graphs and their distribution of points shows that grainstones, packstones and rudstones (grain-dominated textures show a better polynomial fit as such was also observed in the work of Ceia et al. (2015). The values of the consolidation parameter in carbonates according to with the set of data studied is above that described in the literature by Lee (2005) that ranges from 2 to 20. By the statistical analysis of the parameter of consolidation in carbonates we have a value varying from 3.3 to 48 as can be seen in the histograms in the Figures as can be seen in Figures 2, 3, 4, 5, 6, 7 and 8.
The adjustment with the highest R^2 is the polynomial adjustments of the consolidation parameter in relation to the porosity by varying the degree of the polynomials from 2 to 5 for all datasets studied.

Conclusions

Carbonate rocks present a great textural variation which leads to a complex relationship between texture and other parameters, we conclude that grain dominated rocks present a better polynomial fit of third degree. I interval of the value of the consolidation parameter in carbonate rocks is higher than in siliciclastic rocks due to their texture characteristics.

Acknowledgment

Thanks CAPES. CNPq/INCT- Geofísica for financial support and CNPq for Research Grant of Productivity in Technological Development and Innovation.

References

Assefa, S., Mc Cann, C., & Sothcott, J. (2003). Velocities of compressional and shear waves inlimestones. *Geophysical prospecting*, *51*(1), 1-13.

Ceia, Marco AR et al. Relationship between the consolidation parameter, porosity and aspect ratio in microporous carbonate rocks. Journal of Applied Geophysics, v. 122, p. 111-121, 2015.

Ceia, M., Missagia, R., Lima Neto, I. and Archilha N. 2013. Estimation of the Consolidation Parameter on microporos carbonate rocks. 83rd Annual International Meeting, SEG, Expanded Abstracts. doi: 10.1190/segam **2013-0752.1.**

Churcher, P. L., French, P. R., Shaw, J. C., & Schramm, L. L. (1991, January). Rock properties of Berea sandstone, Baker dolomite, and Indiana limestone. In SPE International Symposium on Oilfield Chemistry. Society of Petroleum Engineers.

De Paula, O., M. Pervukhina, and B. Gurevich, 2010. Testing Gassmann fluid substitution in carbonates: sonic log versus ultrasonic core measurements: 80th Annual International Meeting, SEG, Expanded Abstracts

De Oliveira, G. L., De Ceia, M. A., & Misságia, R. M. (2013, August). Experimental measurements of pore volume compressibility of sandstones and carbonates. In 13th International Congress of the Brazilian Geophysical Society & EXPOGEF, Rio de Janeiro, Brazil, 26–29 August 2013 (pp. 1089-1094). Society of Exploration Geophysicists and Brazilian Geophysical Society.

Dunham, R. J. (1962). Classification of carbonate rocks according to depositional textures.

Fournier, F., Léonide, P., Kleipool, L., Toullec, R., Reijmer, J. J., Borgomano, J., ... & Van Der Molen, J. (2014). Pore space evolution and elastic properties of platform carbonates (Urgonian limestone, Barremian–Aptian, SE France). Sedimentary Geology, 308, 1-17.

Geertsma, J., 1961, Velocity-log interpretation: the effect of rock bulk compressibility: SPE Journal, 1, no. 4, 235–248,

Krief, M., J. Garat, J. Stellingwerff, and J. Ventre, 1990, A petrophysical interpretation using the velocities of P- and S-waves (full-waveform sonic): The Log Analyst, 31, 355–369.

Lee, M. W., 2005. Proposed moduli of dry rock and their applications to predicting elastic velocities of sandstones: U. S. Geological Survey, Scientific Investigations Report 2005–5119.

Neto, Irineu A. Lima et al. Carbonate pore system evaluation using the velocity–porosity–pressure relationship, digital image analysis, and differential effective medium theory. Journal of Applied Geophysics, v. 110, p. 23-33, 2014.

Pride, S. R., 2003. Relationships between seismic and hydrological properties: Kluwer.

Rasolofosaon, P., N. Lucet, and B. Zinszner, 2008, Petroacoustics of carbonate reservoir rocks: The Leading Edge, 27, 1034–1039

Røgen, B., Fabricius, I. L., Japsen, P., Høier, C., Mavko, G., & Pedersen, J. M. 2005, Ultrasonic velocities of North Sea chalk samples: Influence of porosity, fluid content and texture. Geophysical Prospecting, 53(4), 481-496.

Zhang, J., H. Li, H. Liu, and X. Cui, 2009. Accuracy of Krief, Nur, and Pride models in the study of rock physics: 79th Annual International Meeting, SEG, Expanded Abstracts