Synthetic modeling of density logs, the related uncertainties, and limitations for geohazard characterization of a post-salt portion in the Búzios Field

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Abstract

More than half of the post-salt interval of the Búzios' Field, an ultradeep water reservoir located in Santos Basin, does not have density logs in the available wells for this study, causing increased uncertainty in petrophysical evaluations, seismic processing velocity modeling, geomechanical modeling, and characterization of shallow section geohazards. Therefore, the present work proposes alternative ways of modeling synthetic density logs using distinct calibration methods of an already established equation available in the literature. From the obtained results, it was possible to define the best fitting methodologies for the lithologies present in the interval of interest, to understand the limitations of the empirical relationship for rocks with low burial depth (<1500 m) and low density (<2.2 g/cm³), including the proposition of a minimization error equation. The proposed methodology for generating and calibrating the density curves can be applied to the characterization of any other basins or fields, regardless of the geological context, due to the robust hypothesis adopted in this research.

Introduction

Rock density is one of the most used petrophysical properties when performing activities in the oil and gas industry, namely: seismic inversion, seismic-well ties, seismic modeling, estimative of porosity, elastic properties, and overburden stresses, geomechanical modeling, and for a better limitation of well drilling operational window (Avseth *et al.*, 2005; Zoback, 2010). Rock density values can be directly measured in the laboratory using rock samples or through geophysical logs (Ellis and Singer, 2008). However, for economic and operational reasons, coring and density logs are rarely obtained in shallow intervals (post-salt and salt sections) of the Santos Basin pre-salt fields as these sections are not the production targets (Rocha and Azevedo, 2009). This information limitation causes an increase in petrophysical evaluation uncertainty, as well as in the seismic processing workflows (construction of velocity models for seismic migration), in the geomechanical modeling, and in the geohazards characterization, even resulting in overtime during well drilling. The most practical and economical way to obtain density values estimative in poorly or unsampled intervals is by using empirical rock physics properties relationships. Gardner *et al.* (1974) proposed a global equation ($\rho = \alpha Vp^{\beta}$) based on laboratory compressional velocity (Vp) and density (ρ) measurements on rock samples from different sedimentary basins, ages, and depths, illustrating a relationship between these two physical properties. This study, despite providing unique values for the parameters α and β (α =0.31 and β=0.25 for ρ in g/cm³ and Vp in m/s), already indicates the necessity of these constants calibration for each lithology and distinct geological contexts.

Búzios' Field post-salt interval, the focus of this study, is inserted in the Drifte Supersequence, corresponding to a phase of thermal subsidence and frank expansion of the southern Atlantic Ocean (Moreira *et al.*, 2007). According to Pereira *et al.* (1990), in the interval equivalent to this Supersequence, between the Albian and Cenomanian, occurred the phases of sea level rising and generation of retrogradation sequences, with deposition of carbonates, shales, and marls of the Guarujá and Itanhaém formations. Still according to these authors, later, between the Upper Cretaceous and the Eocene, with the sea level reduction and the expansion of the sedimentary contribution, the progradant sequences were formed marked by shales, siltstones, besides sandstones and diamictites resulting from turbiditic flows of the Itajaí-Açu and Marambaia formations.

From the understanding that the shallow section of the Búzios Field presents a geological context inherent to the Brazilian southeastern margin, the main objective of this work is to purpose a methodology for performing synthetic modeling of density logs using different methods for calibrating the potential equation proposed in the work of Gardner *et al.* (1974) and to evaluate the uncertainties and limitations of these indirect estimative. The α and β parameters of the equation were fitted using physical properties Vp and ρ cross plot for the main lithologies present in the geological formations with post-Aptian depositional age. Since few wells from the target field have post-salt density logs available for the research, an alternative methodology was proposed and tested to increase the spatial sampling. It consisted of the incorporation of well logs from another field, located near Búzios and presenting similar geological context in the post-salt section. Blind tests performed in three of the wells helped in the definition of the best methodology to adjust the parameters of the original equation for the study area, as well as in the understanding of the limitation of the method for low burial depth intervals. This limitation was circumvented with an error minimization equation recommended in this work.

Motivations

The Gardner *et al.* (1974) empirical relationship for density values prediction is one of the most applied and established methodologies in the oil and gas industry. However, since it is a general trend between the physical properties Vp and ρ of rocks from different sedimentary basins, depositional ages, and depth, function calibration is essential to represent the distinct lithologies and geological contexts.

In literature, some studies have already demonstrated the importance and gains of this empirical relationship calibration. Castagna and Backus (1993), based on the adjustment of this empirical equation, found specific values of α and β for different lithologies. Gutierrez (2001) concluded that regrouping the physical properties of siliciclastic rocks from the La Cira-Infantis Field (Colombia) into depositional cycles of larger stratigraphic orders, resulted in larger correlation coefficient values. It is worth noting that in the latter work, the correlated properties were Vp and porosity coming from ρ, and that the thicknesses of the depositional cycles ranged from 850 m (basin scale) to 5 m (high-resolution stratigraphy). Nwozor *et al.* (2017), from adjustments of the same function (Gardner *et al.*,1974) and using data from Niger Delta sandstones and shales, concluded that adjusting the α and β coefficients provided an increase in assertiveness on the order of 60% in density values when compared to the curve generated with the original Gardner parameters. Ghawar *et al.* (2021) tested the applicability of the same equation and a derived equation for anhydrite from the Sirte Basin, Libya, concluding that the mean difference between the measured and calculated density curves was smaller when using the derived and adjusted equation.

During the literature survey, it was noted the absence of similar studies for shallow intervals of the main producing fields in Santos Basin, despite the relevance of the topic for petrophysical evaluations, geomechanical modeling, and geohazards characterization. To fill this gap, the study here presented aims to perform synthetic modeling of density logs in the post-salt section of the Búzios Field addressing different methods for calibrating the potential equation of Gardner *et al.* (1974).

Dataset

For this research, six wells with compressional sonic and density logs in a portion of the post-salt interval of the Búzios Field were used. Among the six wells, five primarily aimed at the pre-salt reservoirs of the Santos Basin, and only one aimed at investigating the post-salt interval. To increase the spatial sampling, ten wells from an adjacent field, with a similar geological context in the post-salt interval, were used. Figure 1 indicates the location of both fields.

It was also necessary to use geological markers from the 16 wells. The markers represent the top of the four main post-Aptian formations present in the post-salt interval (Guarujá, Itanhaém, Itajaí-Açu, and Marambaia).

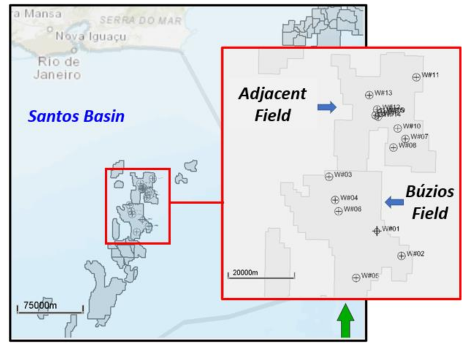

Figure 1- Location map of the study area with the wells used (note the location of the adjacent field, which provides more wells to the study).

Method

The methodology developed in this work consists of ten main steps, as illustrated in Figure 2: (i) identification of Búzios Field, namely: sandstone, shale, argillite, siltstone, diamictite, marl and limestone; (ii) creation of four zones from formations tops geological markers (Guarujá, Itanhaém, Itajaí-Açu and Marambaia); (iii) density and compressional sonic logs upload from wells located in both the area of study and the selected adjacent field; (iv) conversion of the compressional wave transit time (μs/feet) into compressional velocity (m/s) through the equation Vp=304800/Δt; (v) quality control of the geophysical logs by spurious values elimination; (vi) global fitting of the α and β parameters of the Gardner *et al.* (1974) potential equation for each lithology from the physical properties Vp and ρ cross plot; (vii) lithologies regrouping by geological formation and application of local adjustment of the parameters α and β; (viii) generation of the density curves for each lithology from the global adjustments and the formation adjustments; (ix) results validation from blind tests based on three wells previously separated, comparing the calculated curves to the original ones; (x) application of a methodology to minimize the siliciclastic rocks density curve errors.

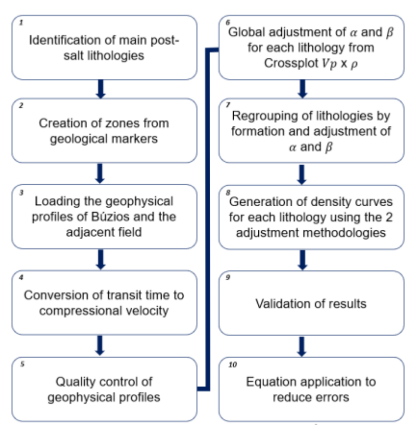

Figure 2 - Proposed workflow for density log modeling

Results and Discussions

The percentage analysis between the post-salt thickness with density logs compared to the total post-salt thickness in the six wells used from the Búzios Field, indicates that more than half of the interval (52%) has no density logs run, causing some lithologies low sampling, such as argillite and limestone, and absence of information for the diamictite lithology. The percentage of density logs available in Búzios post-salt gets even lower (37%) if we disregard the unique investigative well present in this study (W#06), acquired for the post-salt evaluation. On the other hand, the addition of the density logs in the post-salt of the adjacent field provided satisfactory gains for this study: an increase in the percentage of logged post-salt interval from 37% to 54%, disregarding well W#06 (Table 1); a five times increase in the number of points available to perform the Vp x ρ cross plot, and an increase in the correlation coefficient from 0.7367 to 0.9068 from the cross plot of all points (Figure 1).

Table 1 - Increase in the percentage of post-salt sampled with density data after the incorporation of the adjacent field wells.

Búzios Field	Total thickness of post-salt (m)	Thickness of post-salt with density (m)	Percentage of post-salt with density (%)
W#01	2203,57	1049	48%
W#02	1004,4	345	34%
W#03	2153	853	40%
W#04	1551,46	584	38%
W#05	1270,55	335	26%
5	8182,98	3166	37%
Búzios and Adjacent Field	**Total thickness of post-salt (m)**	**Thickness of post-salt with density (m)**	**Percentage of post-salt with density (%)**
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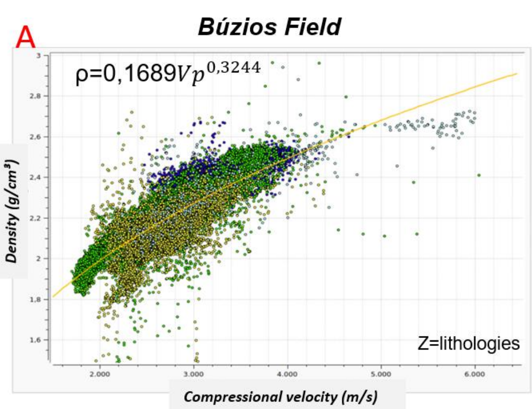
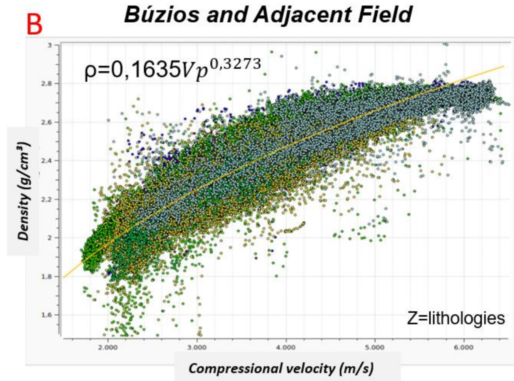
W#03	2153	853	40%
W#04	1551,46	584	38%
W#05	1270,55	335	26%
W#07	2936,94	2129	72%
W#08	3372,38	2055	61%
W#09	3009,66	2221	74%
W#10	3764,97	2640	70%
W#11	3945,98	2950	75%
W#12	2169,64	1195	55%
W#13	1155,93	485	42%
W#14	4368,27	3423	78%
W#15	2076,18	950	46%
W#16	4379,96	2395	55%
15	39362,89	23609	54%



Crossplot	Nº of points	R
Vp x ρ	28.096	0,7376



Crossplot	Nº of points	R
Vp x ρ	160.342	0,9068

Figure 1 - (A) Cross plot Vp x ρ of the Búzios Field points; (B) Cross plot Vp x ρ of the Búzios Field points plus the adjacent field. Note the increase in the number of points and R due to data increment.

The quality control performed on the original ρ and Vp logs, starting with the elimination of spurious values, was also an important step in the increase of the correlation coefficients obtained in the cross plots. The increases were from: 0.7367 to 0.8347 for the Búzios Field data and from 0.9068 to 0.9222 for the Búzios Field plus the adjacent field. The Búzios Field was more sensitive to the elimination of spurious points, with a 10% increase in the correlation coefficient. This greater sensitivity is because the field has a smaller number of initial points and, consequently, has less representativeness of the post-salt.

The calibration of the parameters α and β of Gardner equation from the correlation of the properties Vp x ρ for each lithology, using the methodology of global adjustment of Búzios Field points plus the adjacent field points, resulted in correlation coefficients equal to or greater than 0.8869 in all seven lithologies studied. On the other hand, the calibration using the same adjustment methodology, considering only the points of the Búzios Field, provided correlation coefficients lower than those found with the sum of the points of the two fields. Table 2 illustrates the percentage increase in correlation coefficients with the additional data from the adjacent field. In the same table, it is also possible to note that the values of the estimated coefficients are different from those proposed in the work of Gardner *et al.* (1974), reinforcing the need for an adjustment of this equation for the study area, as well as for any other field or basin. This result is in line with the work of Castagna and Backus (1993) and Nwozor *et al.* (2017), who state that from adjustments of the empirical relationship of Gardner *et al.* (1974), they found specific values of α and β for different lithologies.

Meanwhile, the calibration of the parameters α and β of the original potential equation from the Vp x ρ correlation for each lithology, now considering the methodology of adjustment by formation of the Búzios Field points and the Búzios Field points plus the adjacent field points, resulted in the correlation coefficients values reduction, compared to the global adjustments (Table 2). Therefore, the global adjustment of the constants using the Búzios Field points plus the adjacent field points provided the best fit. This result is different from the one presented by Gutierrez (2001), who concluded that regrouping the rocks' physical properties (compressional velocity and porosity from density) into higher-order depositional cycles (basin scale to metric scale), resulted in higher correlation coefficients. This divergence does not invalidate any of the methodologies cited and may be associated to the difference in scales used in the work of Gutierrez, 2001 (cycles from 850 to 5 meters thickness) and the associated uncertainties in defining the geological markers of the study area.

Table 2- Correlation coefficients obtained from the global and local fits of parameters α and β.

Global and local adjustment of Gardner Equation parameters								
		Búzios			Búzios and adjacent Field			
Formation	Lithologies	α	β	R	α	β	R	Increase of R adding data from adjacent field
Global	Sandstone	0,28	0,25	0,5844	0,19	0,30	0,9187	33%
Marambaia	Sandstone	0,15	0,32	0,5352	0,20	0,29	0,8031	27%
Itajaí-Açu	Sandstone	0,60	0,16	0,4645	0,29	0,24	0,8045	34%
Global	Shale	0,18	0,31	0,8651	0,16	0,33	0,9405	8%
Marambaia	Shale	0,25	0,27	0,8179	0,23	0,28	0,8066	-1%
Itajaí-Açu	Shale	0,30	0,24	0,6443	0,21	0,29	0,7710	13%
Global	Claystone	0,85	0,10	0,3859	0,09	0,39	0,9114	53%
Marambaia	Claystone	0,85	0,10	0,3859	0,09	0,39	0,9114	53%
Global	Siltstone	0,11	0,36	0,8370	0,21	0,29	0,9417	10%
Marambaia	Siltstone	0,08	0,41	0,6357	0,14	0,34	0,7713	14%
Itajaí-Açu	Siltstone	0,36	0,22	0,8603	0,22	0,28	0,8484	-1%
Global	Diamictite				0,12	0,35	0,8970	90%
Marambaia	Diamictite				0,13	0,34	0,9131	91%
Itajaí-Açu	Diamictite				0,17	0,32	0,8595	86%
Global	Marl	0,58	0,17	0,6778	0,28	0,26	0,9056	23%
Itanhaém	Marl	0,66	0,15	0,7220	0,43	0,21	0,8621	14%
Guarujá	Marl	1,80	0.03	0,1330	0,63	0,16	0,8375	70%
Global	Limestone	0,32	0,24	0,8423	0,30	0,25	0,8869	4%
Itanhaém	Limestone	0,11	0,37	0,7913	0,65	0,16	0,6776	-11%
Guarujá	Limestone	0,95	0,11	0,6527	0,34	0,23	0,7813	13%
	Average							31%

The blind test performed on the siliciclastic rocks (sandstones and shales) in well-type W#04 (Figure 2; Figure 3; Figure 4; and Figure *5*), shows that the difference average between between the density curves generated using the global fit (D2) and the formation fit (D3) were: 0,23% for the Marambaia Formation sandstones, 0,26% for the ItajaíAçu Formation sandstones, 2,19% for the Marambaia Formation shales, and 0,44% for the Itajaí-Açu Formation shales. This shows that the two methodologies provide curves with very similar density values. The mean percentage errors calculated between the synthetic density curves (D2 and D3) and the original density curve (D1) also provided similar values, whether using the curves generated with global or formation adjustment. For the curves generated by global adjustment, the mean percentange errors were: 7,27% in Marambaia Formation sandstones, 4,53% in Itajaí-Açu Formation sandstones, 4,09% in Marambaia Formation shales, and 4,16% in Itajaí-Açu Formation shales. For the curves generated with adjustment by formation, the mean percentage errors were: 7,50% in Marambaia Formation sandstones, 4,27% in Itajaí-Açu Formation sandstones, 1,90% in Marambaia Formation shales, and 4,60% in Itajaí-Açu Formation shales. Therefore, the largest mean percentange error presented a difference of 7,5% of the original values and occurred in the low density (<2.2 g/cm³) and low burial depth (<1500 m) sandstones present in the Marambaia Formation.

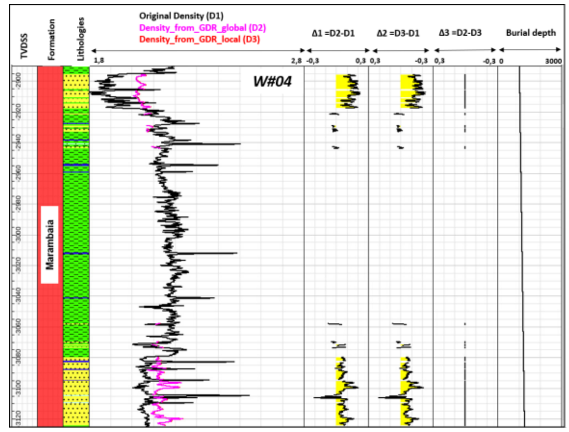


*Figure 2- Blind test performed on Marambaia Formation sandstones from well W#04. Δ1 represents the difference between density curve generated using the global fit (D2) and the original density (D1). Δ2 represents the difference between density curve generated using the formation fit (D3) and the original density (D1). Δ3 represents the difference between density curve generated using the global fit (D2) and the density curve generated using the formation fit (D3)***.***

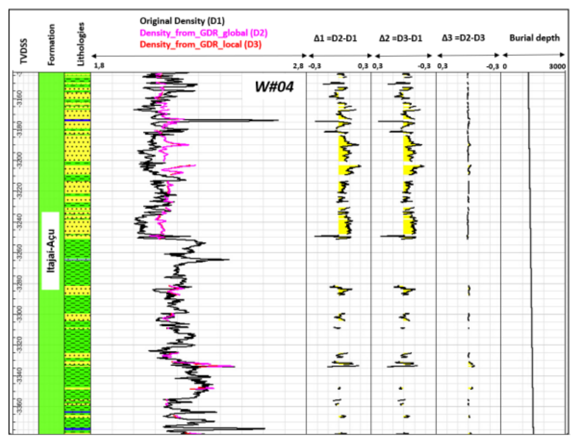


Figure 3- Blind test performed on the Itajaí-Açu Formation sandstones from well W#04.

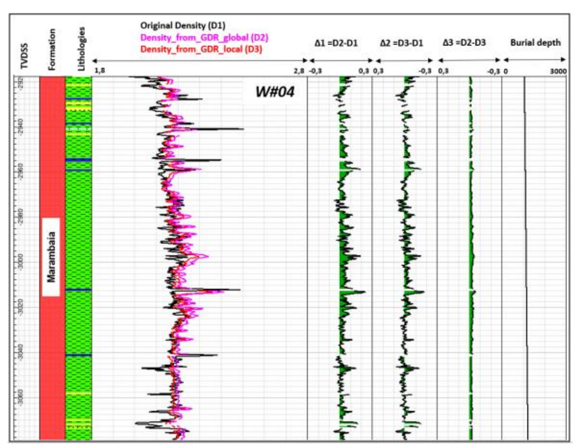


Figure 4- Blind test performed on the Marambaia Formation shales from well W#04.

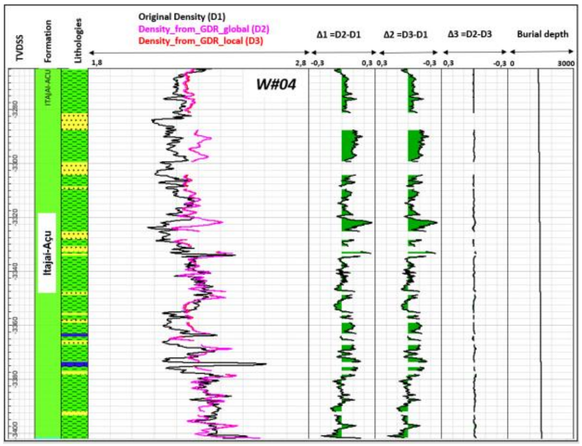
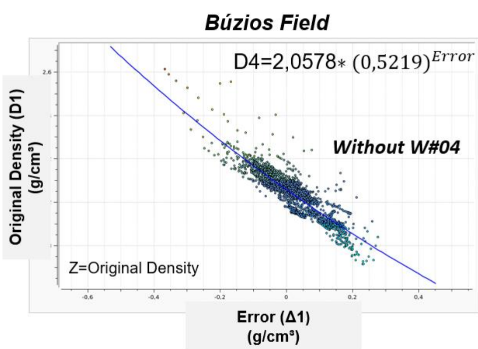


Figure 5- Blind test performed on the Itajaí-Açu Formation shales from well W#04.

The error calculations (Δ1 and Δ2) between the synthetic (D2 and D3) and the original (D1) density curves also indicate that both fitting methodologies used tended to overestimate the values of low-density siliciclastic rocks present in Búzios Field post-salt. The cross plot between the original density (D1) x Error (Δ1) in Marambaia Formation sandstones and shales for well W#04 shows that there is a good relationship between increasing error with decreasing original density values (Figure 8). In other words, in siliciclastic rocks with low burial depth and low density, the Gardner *et al.* (1974) density model shows higher uncertainties.



Lithology	Formation	Crossplot	R
Sandstone	Marambaia	D1 x Δ1	0,8856

Figura 8- Cross plot between the original density (D1) x Error (Δ1) in Marambaia Formation sandstones. D4 is the density curve error minimization.

The exponential equation (ρ=m*nΔ1), proposed in this research, resulted in a better fit of the points of the original density (D1) x Error (Δ1) cross plot for the Marambaia Formation sandstones and shales in Búzios Field and was capable to minimize the errors of the density estimations in the blind test performed in well W#04. In figure 9 is possible to clearly observe that the density curve error minimization (D4) is closer to the original density curve (D1). As presented in

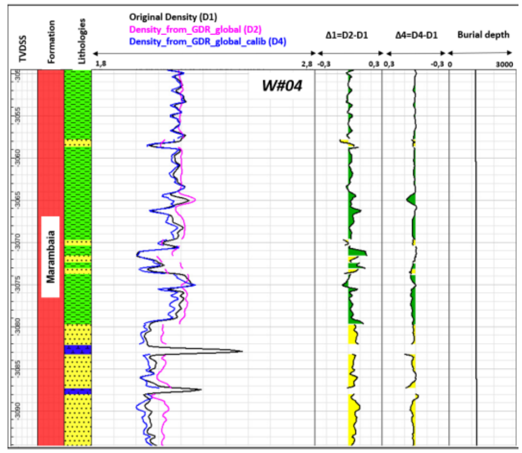


Figure 9- Error minimization blind-test performed on Marambaia Formation sandstones and shales of well W#04. Note that the density curve generated after the adjustment with the exponential equation (D4) is much closer to the original density curve (D1), validating the proposed methodology.

Table 3, the average error reduced from 7.27% to 0.52% for sandstones, and from 4.09% to 0.77% for shales.

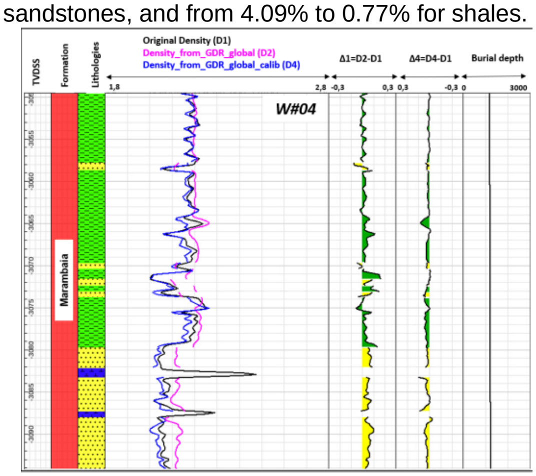


Figure 9- Error minimization blind-test performed on Marambaia Formation sandstones and shales of well W#04. Note that the density curve generated after the adjustment with the exponential equation (D4) is much closer to the original density curve (D1), validating the proposed methodology.

Table 3- Mean density error reduction in Marambaia Formation siliciclastic rocks after using the exponential equation proposed in this work.

Error minimization using exponential equation							
	Imput	Calibration methodology	Formation	Lithologies	Well	Results (g/cm³)	Results (%)
Average error	Δ1=D2-D1	Global	Marambaia	Sandstone	W#04	0,0727	7,27%
Average error (Exp.Equation)	Δ4=D4-D1	Global	Marambaia	Sandstone	W#04	0,0052	0,52%
Average error	Δ1=D2-D1	Global	Marambaia	Shale	W#04	0,0409	4,09%
Average error (Exp.Equation)	Δ4=D4-D1	Global	Marambaia	Shale	W#04	0,0077	0,77%

The blind tests performed for the carbonate rocks (marls and limestones) in wells W#01, W#04, and W#16 shows that the difference average between the density curves generated from the global (D2) and formation (D3) fit were: 2,07% for the Itanhaém Formation marls and 2,28% for the Guarujá Formation limestones. For the curves generated by global adjustment, The mean percentage errors calculated between the synthetic (D2 and D3) and the original (D1) density curves were: 0,46% in the Itanhaém Formation marls and 0,71% in Guarujá Formation limestones. For the curves generated with formation adjustment, the mean percentage errors were: 2,53% in the Itanhaém Formation marl and 2,98% in the Guarujá Formation limestones. Therefore, the largest average error did not exceed a 3% difference from the original values.

The cross plot between original density (D1) x Error (Δ1) for the carbonate rocks did not show a clear relationship between the increase of the mean error with the decrease of the original density values. Thus, the error minimization methodology applied in sandstones and shales, could not be used in the marls and limestones. However, as shown in

Table ***4***, in general, the mean errors found for the carbonate rocks were lower than those found for the siliciclastic rocks.

Table 4- Blind test results for W#01, W#04, W#16 wells. Note the calculated mean error values between the synthetic (D2 and D3) and original (D1) density curves and the mean difference between the global (D2) and formation (D3) fit density curves.

Results validation using Blind-tests							
	Imput	Calibration methodology	Formation	Lithologies	Well	Results (g/cm³)	Results (%)
Average error	Δ1=D2-D1	Global	Marambaia	Sandstone	W#04	0,0727	7,27%
Average error	Δ2=D3-D1	Local	Marambaia	Sandstone	W#04	0,0750	7,50%
Aver.difference	Δ3=D2-D3		Marambaia	Sandstone	W#04	0,0023	0,23%
Average error	Δ1=D2-D1	Global	Itajaí-Açu	Sandstone	W#04	0,0453	4,53%
Average error	Δ2=D3-D1	Local	Itajaí-Açu	Sandstone	W#04	0,0427	4,27%
Aver.difference	Δ3=D2-D3		Itajaí-Açu	Sandstone	W#04	0,0026	0,26%
Average error	Δ1=D2-D1	Global	Marambaia	Shale	W#04	0,0409	4,09%
Average error	Δ2=D3-D1	Local	Marambaia	Shale	W#04	0,0190	1,90%
Aver.difference	Δ3=D2-D3		Marambaia	Shale	W#04	0,0219	2,19%
Average error	Δ1=D2-D1	Global	Itajaí-Açu	Shale	W#04	0,0416	4,16%
Average error	Δ2=D3-D1	Local	Itajaí-Açu	Shale	W#04	0,0460	4,60%
Aver.difference	Δ3=D2-D3		Itajaí-Açu	Shale	W#04	0,0044	0,44%
Average error	Δ1=D2-D1	Global	Itanhaém	Marl	W#01	0,0046	0,46%
Average error	Δ2=D3-D1	Local	Itanhaém	Marl	W#01	0,0253	2,53%
Aver.difference	Δ3=D2-D3		Itanhaém	Marl	W#01	0,0207	2,07%
Average error	Δ1=D2-D1	Global	Guarujá	Limestone	W#04, W#16	0,0071	0,71%
Average error	Δ2=D3-D1	Local	Guarujá	Limestone	W#04, W#16	0,0298	2,98%
Aver.difference	Δ3=D2-D3		Guarujá	Limestone	W#04, W#16	0,0228	2,28%

Conclusions

The results presented in this work indicate that the usage of data from a nearby field with a geological context analog to Búzios post-salt is a wise strategy since it allowed the density modeling of lithologies that had been poorly and/or unsampled in the study area. Added to this, the inclusion of these data also provided an increase in correlation coefficient values cross plots between the physical properties ρ and Vp for all seven lithologies studied. That is, by increasing the sampling, a better fit was obtained.

The α and β parameters adjustment from the lithologies regrouping by geological formation, contrary to what was initially thought, caused a reduction in correlation coefficients from the Vp x ρ cross plots when compared to the R values obtained from the global adjustment. The worse fit, even at a smaller scale level, may have occurred for two reasons: i) lithologies of the same formation may have distinct permo-porous characteristics and diagenetic nature; ii) uncertainties inherent to the definition of the geological markers and subsequent creation of the stratigraphic zones internal to the post-salt.

The modeling validation results obtained from blind tests in Búzios Field wells allowed us to conclude that both the global and formation adjustment methodologies provided synthetic density curves with minimal differences between them and, consequently, with close average errors. This result, associated with the uncertainties of the post-salt zoning and the lower R values found in the formation adjustments, suggests that the calibration methodology of the original potential equation (Gardner et al., 1974) by global adjustment, using Búzios Field plus the adjacent field data, is the most appropriate for density modeling in the study area. It is important to notice that the area lacks stratigraphic refinement on a smaller scale, which may bring similar results to those found by Gutierrez (2001).
It is worth observing that there is a clear limitation of the empirical relationship between the original potential equation for estimating the density of the siliciclastic rocks with low burial depth and density. Regardless of the calibration methodology used, the calculated densities tended to overestimate the actual density values in sandstones and shales. Thus, the identification of a correlation pattern between the errors of the estimates and the original density values is fundamental to proposing an exponential equation proven to minimize the errors, as presented in this paper.

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References

ANP. 2023. Agência Nacional do Petróleo, Gás Natural e Biocombustíveis.
AVSETH, P., MUKERJI, T., MAVKO, G. 2005. Quantitative seismic interpretation: Applying rock physics tools to reduce interpretation risk. Cambridge Univ Pr.
CASTAGNA, J.P., BACKUS, M.M., 1993. Offset-Dependent Reflectivity—Theory and Practice of Avo Analysis. Society of Exploration Geophysicists.
ELLIS, D.V. AND SINGER, J.M. 2008. Well Logging for Earth Scientists. 2nd Edition, Springer, Berlin,
GARDNER, G., GARDNER, L., GREGORY, A. 1974. Formation velocity and density—the diagnostic basics for stratigraphic traps. Geophysics 39, 770–780.

GHAWAR, BAHIA AND ZAIRI, MONCEF AND BOUAZIZ, SAMIR. 2021. Using artificial intelligence methods for shear travel time prediction: A case study of Facha member, Sirte basin, Libya. Kuwait Journal of Science

GUTIERREZ, M.A. 2001.Rock physics and 3-D seismic characterization of reservoir heterogeneities to improve recovery efficiency. Doctoral dissertation, Stanford University,

MOREIRA, J. L. P., MADEIRA, C. V., GIL, J. A., MACHADO, M. A. P. 2007. Bacia de Santos. Boletim de Geociências da Petrobras, Rio de Janeiro, v. 15, n. 2.

NWOZOR, K., ONUORAH, L.O., ONYEKURU, S., EGBUACHOR, C. 2017.Calibration of Gardner coefficient for density velocity relationships of tertiary sediments in Niger Delta Basin. J. Petrol. Exp. Prod. Technol. 7 (3), 627–635.

PEREIRA, M.J., MACEDO, J.M. 1990.Santos Basin: the outlook for a new petroleum province on the Southeastern Brazilian continental shelf. Boletim Geocienc. Petrobras 4.

ROCHA, L. A. S., AZEVEDO, C. T. 2009. Projetos de Poços de Petróleo. 2ª Ed. Rio de Janeiro: Interciência.

ZOBACK, M.D. 2010. Reservoir Geomechanics. Cambridge University Press.