Effect of grain contact and pore size on elastic velocities of carbonate rocks

José Agnelo Soares[1], Rayssa Lima Costa Coura[1], [1] Federal University of Campina Grande

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Abstract

This paper analyzes the integrated effect of grain contacts and of macro and micro pores on elastic velocities of carbonate rocks from Araripe Basin, northeastern Brazil. In this paper grain contact quality and macro and micro porosities were estimated from microCT digital images, while elastic wave velocities were measured in a pressure vessel under confining pressure of 40 MPa in dry samples. An index for grain contact quality is proposed here based on the volume reduction of 3D models for grain contacts with the increasing of the smoothing applied during model generation. Multivariate nonlinear regression functions were obtained in order to get relations between elastic velocities, macro and micro digital porosities, besides the quality index for grain contacts. These functions allowed estimation of VP and VS with the highest possible accuracy, i.e., with a coefficient of determination $R^2=1$. These relationships have potential to be used for mapping grain contact quality and microporosity in carbonate reservoirs. Grain contact quality is an important variable for geomechanics, while microporosity affects rock permeability. These two later variables are of much more difficult estimation than macroporosity and elastic wave velocities, which can be estimated from well logging and seismic data.

Introduction

As discussed by Soares et al. (2014), the relationship between elastic velocities and porosity of carbonate rocks presents a substantial dispersion, which can be caused by variations in the composition of the samples, porosity type and variation in grain contact quality. However, there is not known in literature a study of the integrated effect of these variables on the relationship dispersion between elastic velocities and porosity of such rocks. The evaluation of the grain contact quality offers the potential to be used in mapping the spatial distribution of geomechanical rock properties, which is especially important in the case of reservoirs of low homogeneity, as occurs in the Brazilian pre-salt carbonate reservoirs.

Baechle et al. (2004) analyzing thin sections of carbonate rocks concluded that microporosity in combination with macroporosity parameters reduce uncertainties in both velocity and permeability trends. The correlation between microporosity to velocity is much higher and better than the correlation of total porosity to velocity.

Weger et al. (2004), through digital image analysis of thin sections of carbonate rocks, characterized the pore system in carbonates to quantify the influence of poretypes on velocity. They concluded that perimeter over area of pores is the most dominant factor controlling velocity at a given porosity with the dominant pore size being the second, while pore roundness alone is the least important factor of the three. Combining all three parameters and porosity in a multivariate linear regression increases correlation to velocity from R^2 of 0.49 (porosity alone) to R^2 of 0.78.

Baechle et al. (2007) applied a dual porosity differential effective medium (DEM) model to model the velocity of carbonates with macro and micro porosity derived from digital image analysis of thin sections. The model predicts that the compliant micropores have a strong influence on the sonic velocity of porous carbonates because increasing concentrations of micropores reduce the rock stiffness. These velocity predictions with the dual porosity DEM model show significant better velocity prediction than empirical models, e.g. the Wyllie time average equation.

Murphy III et al. (1986) showed that the acoustic behavior of sandstones is strongly controlled by contacts between the mineral grains. These contacts are made up of narrow gaps, which persist even in highly cemented sandstones, suggesting that a similar effect can occur even in carbonate rocks.

Soares et al. (2014) quantified the effect of grain contact quality on the relationship between the elastic velocity and the porosity of dried samples of carbonate tufa. The analysis was based on laboratory measurements of porosity, grain density and velocities. X-ray microCT images were used for determination of the density of unknown mineral phases. Finally, correcting measured velocities, in order to exclude the effect of grain contacts, dispersions in the relationship between elastic velocities and porosity were drastically reduced.

This paper analyzes the integrated effect of grain contact quality and pore size on elastic velocities of eight samples of carbonate rocks extracted from outcrops of the Araripe basin, located in the Northeast region of Brazil.

Method

In this paper the variables controlling the elastic velocities are all estimated from analysis of digital images of microCT. For such purpose the software Avizo Fire was used. The variables analyzed are the macroporosity, microporosity and the quality of the grain contacts.

The macroporosity of samples was quantified by setting a threshold on grayscale for further image segmentation. This step defines which pixels correspond to macropores and which ones correspond to the mineral phases. After segmentation, the macroporosity is estimated by the ratio of the number of pixels that represent the macropores and the total number of pixels in the image. Figure 1 shows the Avizo workflow used for calculating the macroporosity.

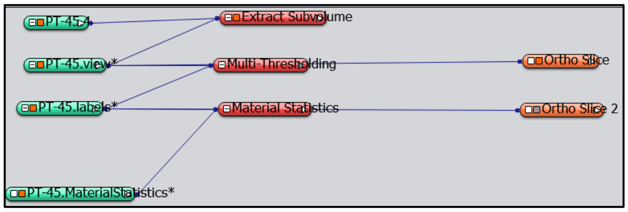

Figure 1 – Workflow for macroporosity estimation.

To calculate the microporosity initially it was defined a sample volume to facilitate computer processing. The image is converted to 64 bits, required format for the arithmetic calculation which will be submitted later. Then, the image is segmented with the goal of separating the intermediate phase, which contains the microporosity. The intermediate phase covers a certain range of gray scale values, from the threshold of pores (Lp) up to the threshold of solids (Ls). With the thresholds defined, equation (1) is applied for the calculation of an index of microporosity of each pixel (I_{mi}), according Al Ratrout et al. (2013).

$$I_{mi} = b \times \left(1 - \frac{(a - Lp)}{(Ls - Lp)}\right) \qquad (1)$$

Eqaution (1) contains in ***a*** the original converted image and in ***b*** the corresponding converted image of the intermediate phase. It was calculated a mean value ***m*** of the indexes of microporosity of all pixels of the region corresponding to the intermediate phase of the images. Finally, one can obtain the value of microporosity according to equation (2).

$$\Phi_{micro} = \frac{Vfi}{Vt} \times m \qquad (2)$$

where ***Vfi*** corresponds to the volume of the intermediate phase and ***Vt*** is the total volume of the sample. Figure 2 shows the Avizo workflow used for calculating the microporosity.

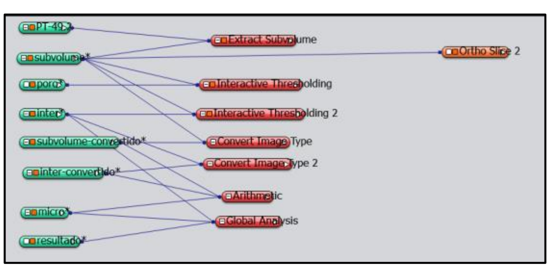

Figure 2 – Workflow for microporosity calculation.

Figure 3 shows the workflow adopted to evaluate the grain contact quality.

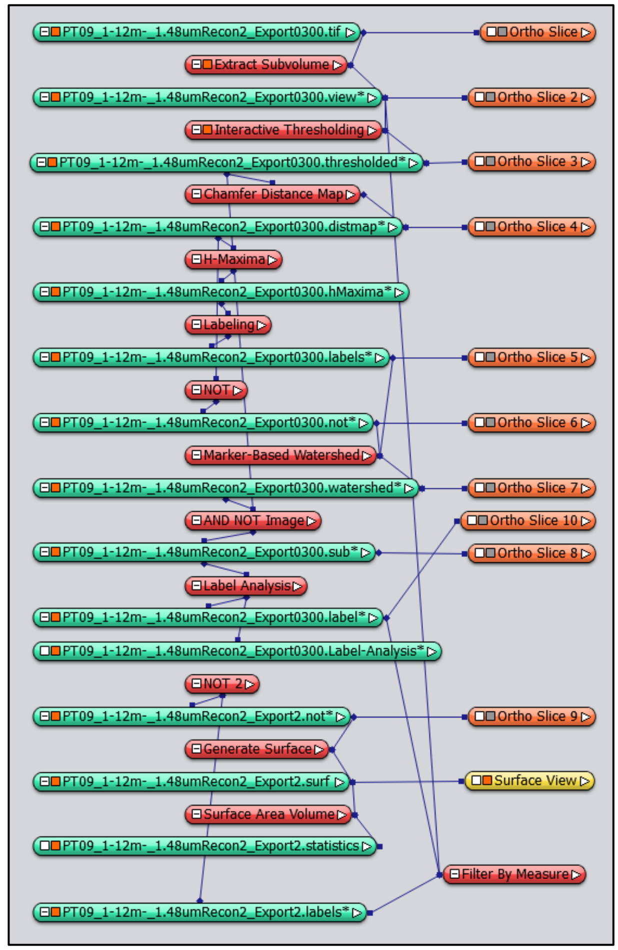

Figure 3 – Workflow for grain contact quality evaluation.

The analysis of grain contact quality, as proposed here, is based on how the volume of contacts is reduced with the increase of smoothing of the 3D grain contact digital model. We propose an index of quality for grain contacts which expresses the volume reduction suffered by contacts with the increase in digital model smoothing. Planar contacts, approximately two-dimensional, are associated with best quality indexes of contacts between grains. On the other hand, point-shaped contacts, nearly 3D, show lower quality indexes.

The procedure for analysing the quality of contacts between the mineral grains, shown in Figure 3, consists of, after the image has been segmented, generate a map of the lines of separation between the grains. This is achieved by generating a map of distances between the grains, identification and individualization of the regions of maximum distance, and obtaining the final image for the difference between the original binary image and the map of lines of separation among grains.

The image that contains the mineral grains and their respective lines of separation among grains is inverted in order to activate only the lines of separation between the grains. Then, three-dimensional models of these lines of separation between grains (contacts) are generated with different levels of smoothing. Finally, it is achieved the volume of surface area for every level of model smoothing.

The percentage of volume of contacts for each level of smoothing is calculated and the quality index of the contacts is given by the difference between the percentage of volume with minimum and maximum smoothing, respectively.

Results

Figure 4 shows the volume of grain contacts depending on the level of smoothing in the generation of 3D models of grain contacts. The reduction in the volume of contacts with the increase in the level of smoothing is a feature of each sample. There are samples whose volume is greatly reduced, as in the case of the sample 41_B, and others whose volume suffers less reduction, as in the case of the sample 9F_H4, indicating the type and quality of grain contacts.

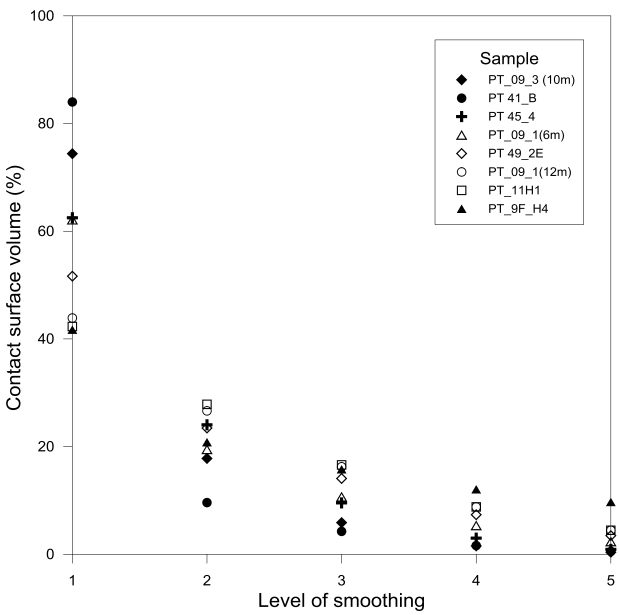

Figure 4 – Reduction of contact volumes with the increasing of the level of smoothing.

Table 1 presents the velocities of P and S waves, measured in plugs under 40 MPa of confining pressure, the macro and the micro porosities, and the quality index of grain contacts (QI_{GC}) for all analyzed rock samples.

Table 1 – Petrophysical parameters calculated for the set of analyzed samples.

Sample	VP (m/s)	VS (m/s)	ϕ_{macro} (%)	ϕ_{micro} (%)	QI_{GC} (%)
41_B	6835	3687	1.1	0.4	83.5
45_4	4547	2632	17.6	7.7	61.6
49_2E	5423	3023	9.1	1.9	48.2
09_3(10m)	5172	2863	9.1	3.8	74.0
11_H1	5661	3164	12.7	11.5	37.8
09_1(12m)	4708	2731	4.3	18.6	39.4
09_1(6m)	4254	2536	12.6	11.5	59.8
9F_H4	5413	2956	10.6	6.8	32.0

Figures 5 and 6 present the 3D models of grain contacts to the 9F_H4 and 41_B samples, with increasing levels of smoothing. It is seen that for the sample 9F_H4, which presents the lowest quality index of grain contacts, the reduction in the contacts volume with increased smoothing is smaller than the observed in the sample 41_B, which presents the highest quality index of grain contacts.

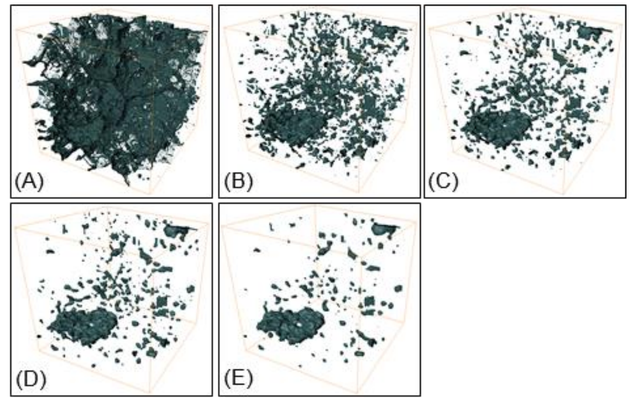

Figure 5 – 3D models of grain contacts to the 9F_H4 sample with smoothing levels ranging from 1 to 5 for (A) to (E).

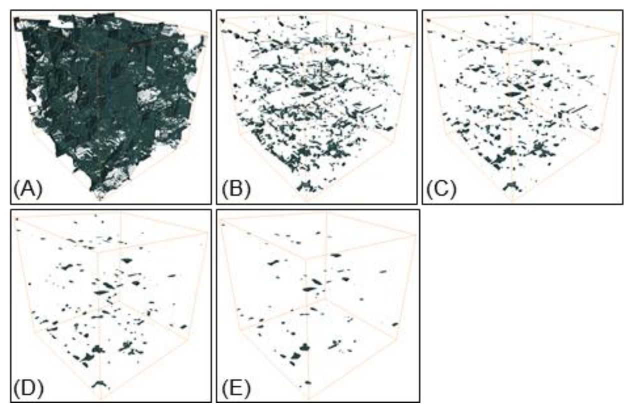

Figure 6 - 3D models of grain contacts to the 41_B sample with smoothing levels ranging from 1 to 5 for (A) to (E).

Figures 7 and 8 show, respectively, relationships between P-wave and S-wave velocities with porosity as conventionally measured in the laboratory. Velocities were measured in dry samples and under confining pressure of 40 MPa, while porosity was measured under atmospheric pressure. Although a reduction of velocities with increasing of porosity is seen, there is a high dispersion in these relationships, which can be seen by the coefficient of determination R^2.

Figure 9 shows the relationship between total porosity as conventionally measured in a gas porosimeter and macroporosity as calculated from microCT digital images. There is an excellent correlation between porosity measured by both methods, demonstrating that the porosity measured conventionally in these samples does not include the microporosity and that digital macroporosity can be used to obtain reliable relationships between rock porosity and elastic wave velocities.

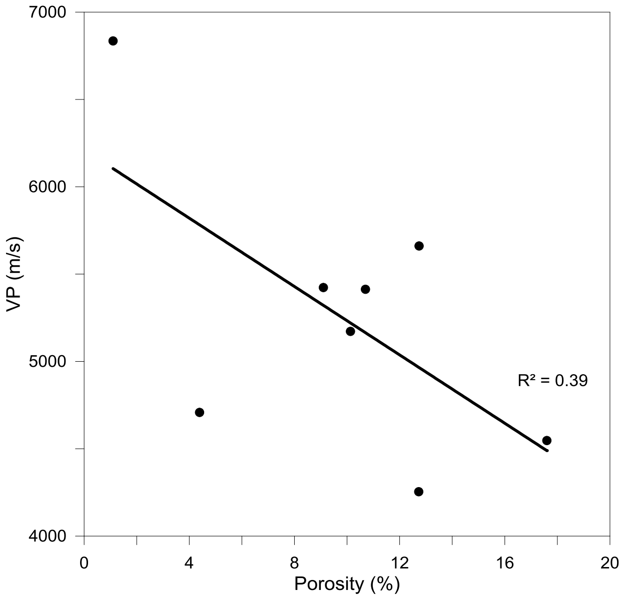

Figure 7 – Relationship between P wave velocity and porosity, both measured conventionally.

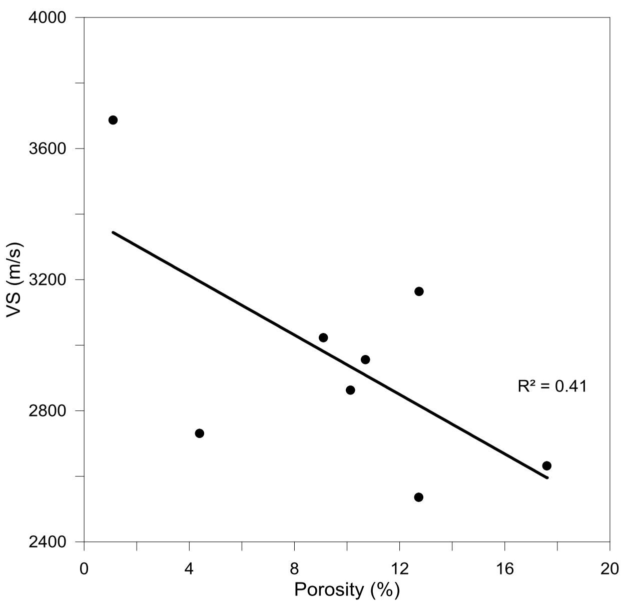

Figure 8 – Relationship between S wave velocity and porosity, both measured conventionally.

In order to investigate the effect of porosity and quality of grain contacts on the elastic velocities of carbonate rocks, multivariate nonlinear regression functions of the type piecewise linear breakpoint were obtained. Functions linking elastic velocities with macro and micro digital porosities as well with quality index of grain contacts were achieved.

The equations 3 and 4 present the multivariate function obtained for P wave velocity in dry rocks under confining pressure of 40 MPa. These expressions feature coefficient of determination $R^2 = 1$, allowing the estimation of the VP with the highest possible accuracy.

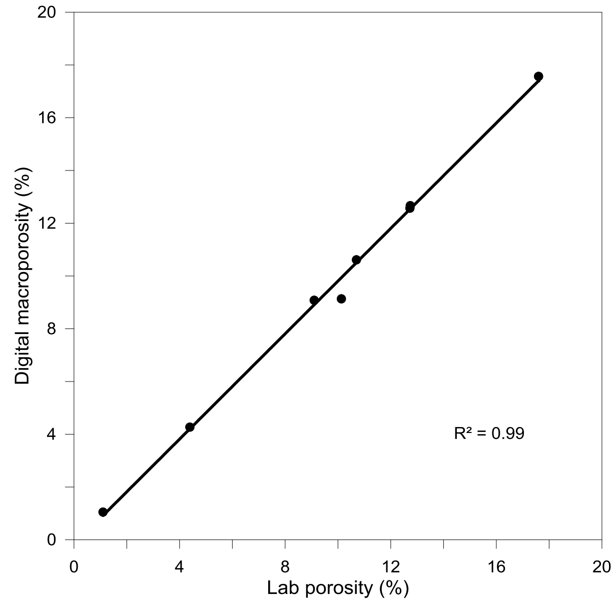

Figure 9 – Relationship between lab measured porosity and digital microCT macroporosity.

Similarly, the equations 4 and 5 feature the functions for the S-wave velocity, also with coefficient of determination $R^2 = 1$.

For VP ≤ 5251.6 m/s the expression (3) can be applied.

$$\mathrm{VP} = 11330 - 73.7828\emptyset_{macro} - 203.73\emptyset_{micro} - 287.848\mathrm{QI}_{GC} \qquad (3)$$

And for VP > 5251.6 m/s the expression (4) applies.

$$\mathrm{VP} = 5640 - 124.223\emptyset_{macro} + 87.2933\emptyset_{micro} + 15.5092\mathrm{QI}_{GC} \qquad (4)$$

In the case of S-wave velocity, for VS ≤ 2949 m/s the equation (5) applies,

$$\mathrm{VS} = 5167.85 - 28.449\emptyset_{macro} - 73.777\emptyset_{micro} - 23.882\mathrm{QI}_{GC} \qquad (5)$$

And for VS > 2949 m/s,

$$\mathrm{VS} = 2569 - 30.569\emptyset_{macro} + 40.4868\emptyset_{micro} + 13.6057\mathrm{QI}_{GC} \qquad (6)$$

Figure 10 presents the relationship between the estimated P wave velocity and VP as conventionally measured, considering VP only as a function of the macroporosity. In this case there is a considerable dispersion between the measured and estimated VP, with a coefficient of determination $R^2 = 0.86$.

Adding the microporosity in regression function, we obtain a relationship between estimated and measured VP with a coefficient of determination $R^2 = 0.97$, which represents a considerable improvement in the ability to estimate VP. This result is shown in Figure 11.

Finally, using the equations 3 and 4, which include the quality index of grain contacts, the estimation of VP was the best possible, showing a coefficient of determination $R^2 = 1$. The relationship between the estimated VP from equations 3 and 4 and the measured VP is presented in Figure 12.

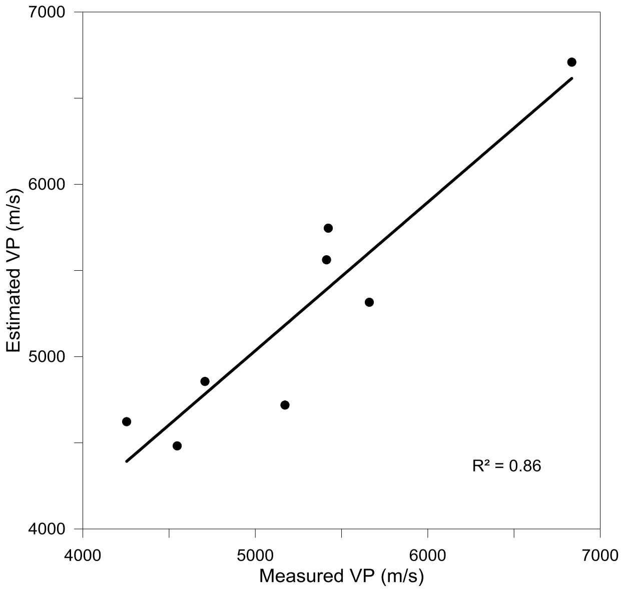

Figure 10 - Relationship between estimated VP as a function of only the macroporosity and the measured VP.

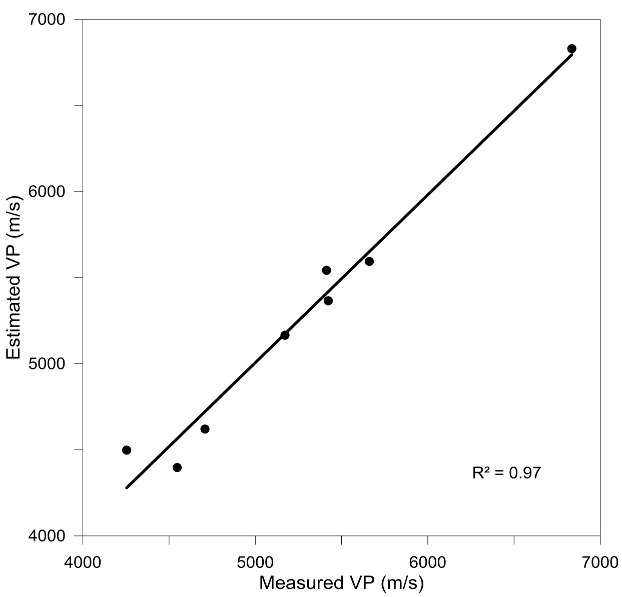

Figure 11 – Relationship between the estimated VP as a function of macro and micro porosities and the measured VP.

Similarly, S-wave velocities under 40 MPa of confining pressure were estimated, considering VS just as a function of macroporosity (Figure 13), as a function of the macro and the micro porosities (Figure 14) and, finally, using the equations 5 and 6, which consider the joint influence of the two types of porosity and the quality index of grain contacts (Figure 15).

As observed for the case of VP, there was a significant reduction of the determination coefficient for the estimative of VS, whereas was considered the influence of microporosity and of quality index of grain contacts.

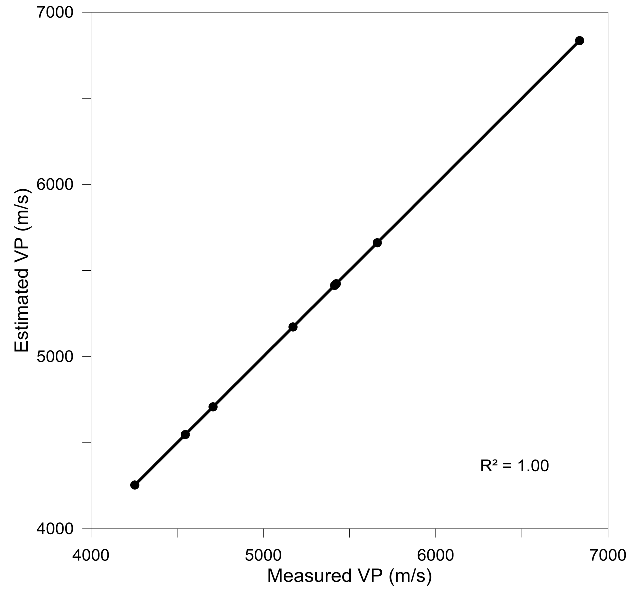

Figure 12 – Relationship between the estimated VP as a function of the macroporosity, microporosity and the quality index of contacts between grains.

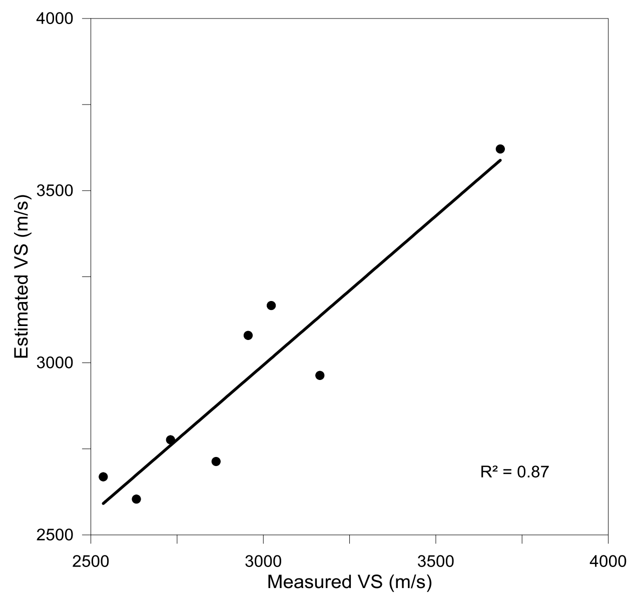

Figure 13 - Relationship between estimated VS as a function of only the macroporosity and the measured VS.

Equations 3 to 6 have two variables of relatively easy determination (elastic velocities and macroporosity) and two others of difficult determination (microporosity and quality index of grain contacts). These equations allow, for seismic or well logging data, the adoption of an inversion algorithm to estimate the microporosity and the quality index of grain contacts.

Grain contact quality is an important variable for geomechanical characterization of reservoirs and microporosity can control properties of storage and flux of fluids, especially in tight carbonate reservoirs.

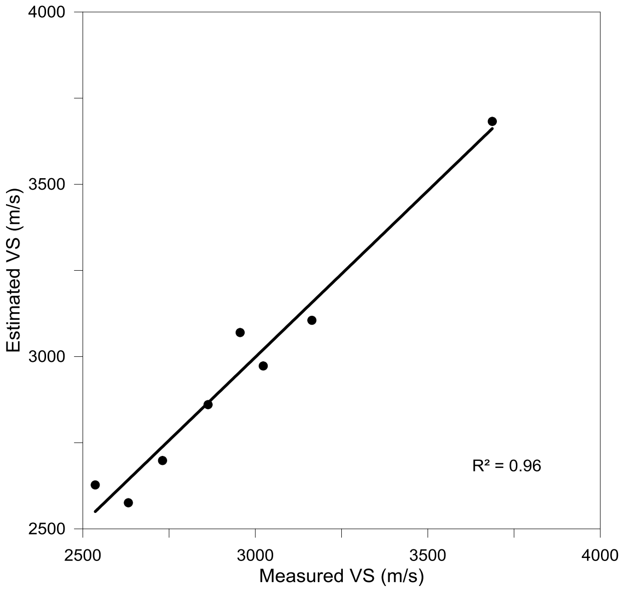

Figure 14 - Relationship between the estimated VS as a function of macro and micro porosities and the measured VS.

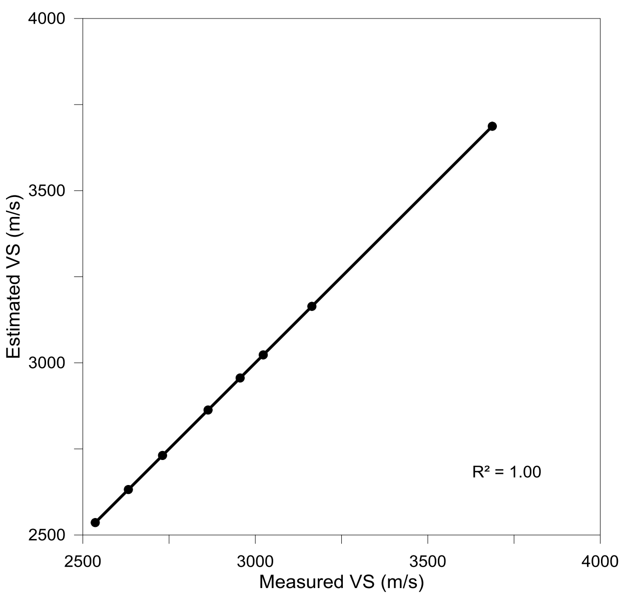

Figure 15 – Relationship between the estimated VS as a function of the macroporosity, microporosity and the quality index of contacts between grains.

Conclusions

In this paper was proposed a new method to analyze the integrated effect of grain contact quality and pore size on the dispersion observed on the relationship between the elastic velocities and porosity for samples of carbonate rocks.

The analysis of grain contact quality, as proposed here, is based on how the volume of contacts is reduced with the increase of smoothing on 3D digital model.

In order to investigate the effect of porosity and quality of grain contacts on the elastic velocities, multivariate regression functions were obtained, to get functions linking the elastic velocities with porosity size and quality index of grain contacts. These expressions allow the estimation of the VP and VS with the highest precision possible.

These results have the potential to increase the precision of porosities maps obtained from seismic data inversion, once reduce the dispersion of the relationship between elastic velocities and porosity.

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