A MODEL FOR PERMEABILITY OF CARBONATE ROCKS BASED ON PORE CONNECTIVITY AND PORE SIZE

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Abstract

This work analyzed sixteen samples of carbonate rocks, with very different compositional and textural characteristics, from microCT images, developing 3D models to evaluate their petrophysical properties. A cubic subvolume of 150^3 voxels from the microCT images for each rock sample was analyzed. In this research pore connectivity is evaluated and is investigated its relationship with the lab-measured rock permeability. The Euler number was estimated for macro pores and for micro pores, in order to analyze pore connectivity. Procedures have been developed to analyze porosity, permeability and macro and micro pores connectivity. The results show the Euler number as a good indicator of pore connectivity in carbonate rocks, both for macro pores and for micro pores. Data statistical analysis indicates that the main microCT-derived properties controlling carbonate rock permeability are macro pores connectivity, micro pores permeability and microporosity. This result suggests that well-connected micro pores are an alternative path for the fluid flow where macro pores are badly connected. A piecewise nonlinear model is proposed here to estimate permeability of a wide range of carbonate rocks. This model is based on microCT rock properties analysis and it achieves an explained variance of 99.6%.

Introduction

Kalam et al (2011) conducted a study of the technique of digital physics applied to rocks using microCT analysis and digital processing of three-dimensional images. That study analyzed carbonate reservoirs with the aim of determining petrophysical parameters such as permeability and porosity, which allow the evaluation of reservoirs in different aspects.

Carbonate porosity is extremely variable in terms of magnitude, showing values between 1% and 35%, and pore size that can vary from hundreds of micrometers to a few nanometers (Lucia, 2007). The primary porosity in carbonate rocks is predominantly intergranular. The recognition of this type of porosity depends on the size and shape of the grains in the rock matrix. In rocks formed by coarse grains, intergranular pores can be easily identified, but for carbonate rocks with fine grains, intergranular pores are more difficult to be identified. Vugular porosity can be connected by intergranular pore channels or by fractures (Oliveira, 2012). Absolute permeability of sixteen rock samples used in this work was lab-measured using a gas permosimeter.

Kozeny-Carman equation (Tiab & Donaldson, 2004) allows estimate the absolute permeability of a rock through a correlation with porosity, specific surface and the tortuosity of pore system. Kozeny-Carman equation is shown on equation (1).

$$k_{koz} = \left(\frac{1}{2\tau {S_0}^2}\right)\frac{\emptyset^3}{(1-\emptyset)^2} \qquad (1)$$

Where K_{koz} is the absolute permeability of Kozeny-Carman, τ is the tortuosity, S_0 is the specific pore surface and ϕ is the rock porosity.

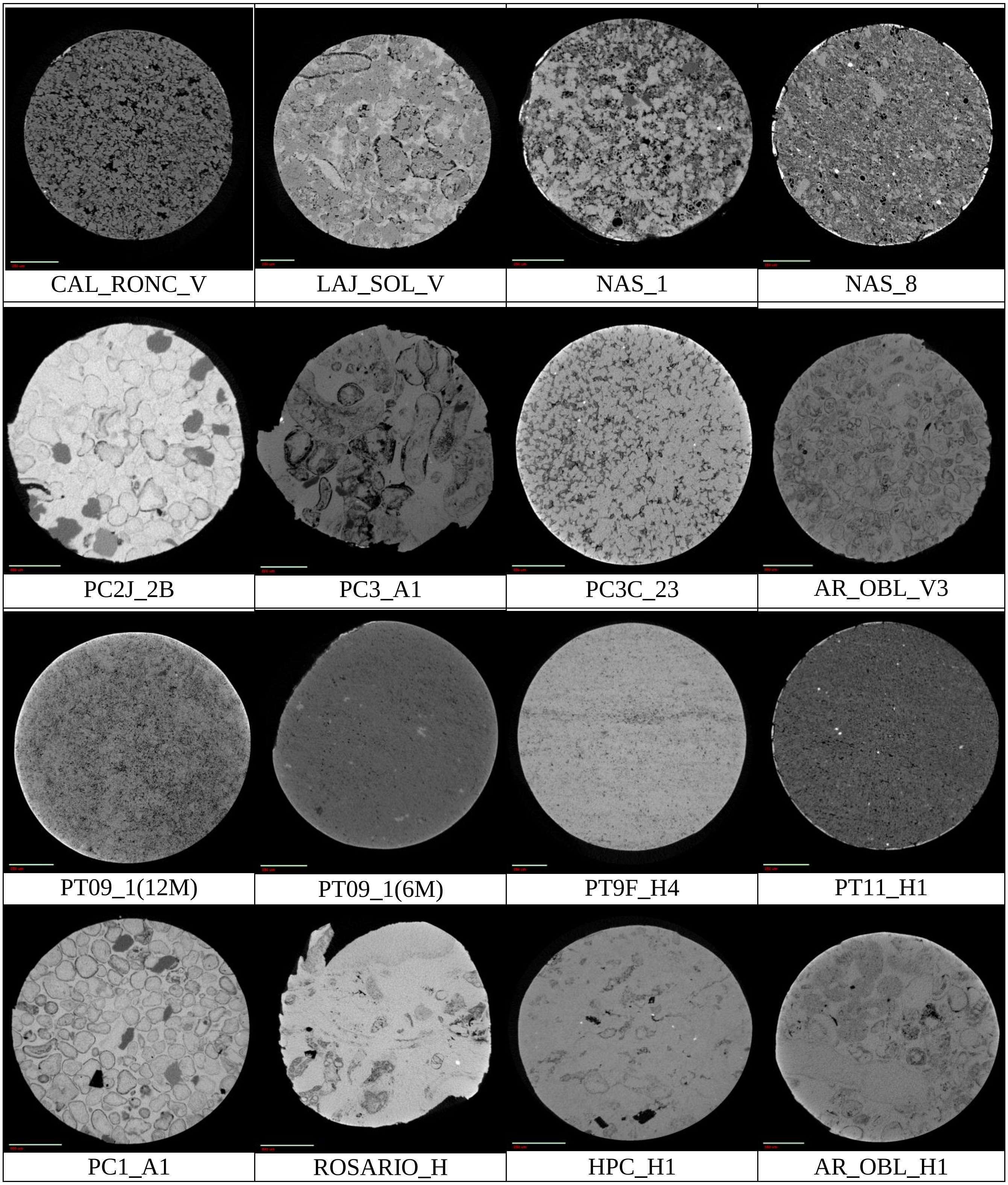
Connectivity is a property that provides information about the structure of a porous medium. It is obtained by means of the Euler-Poincaré characteristic number (CEP), which refers to an integral geometric measure which can offer an estimate of the connectivity of the porous space (Roque *et al*., 2009). For a three-dimensional structure, the CEP is defined by the number of isolated parts less connectivity (Arcaro, 2009).

The objective of this research is to evaluate pore connectivity of a set of carbonate rocks and investigate their relationship with the permeability measured in these rocks. Digital measurements of the Euler number for both macro and micro pores, besides digital porosity and permeability, were done.

Method

For this work 16 samples of carbonate rocks were selected with different geological characteristics, in order to investigate the effectiveness of the Euler number as a robust indicator of pore connectivity in carbonatic rocks. Figure 1 presents a panel with microCT images of the 16 chosen rock samples.

In this group there are seven samples composed of grain-supported bioclastic grainstones (LAJ_SOL_V, ROSARIO_H, AR_OBL_H1, AR_OBL_V3, PC3_A1, PC2J_2B and PC1_A1), four samples composed of matrix-supported microporous grainstones (PT09_1 (12 m), PT09_1 (6 m), PT45_4 (10 m) and PT11_H1), two samples of wackstones (NAS_1 and NAS_8) one sample of grain-supported dolostone (PC3C_23V), one sample of caliche (CAL_RONC) and one sample of calcareous hardpan (HPC_H1). Therefore, this group of samples consists of diversified carbonatic facies, in order to obtain robust analysis for application in a wide range of carbonate rocks.



CAL_RONC_V LAJ_SOL_V NAS_1 NAS_8

PC2J_2B PC3_A1 PC3C_23 AR_OBL_V3

PT09_1(12M) PT09_1(6M) PT9F_H4 PT11_H1

PC1_A1 ROSARIO_H HPC_H1 AR_OBL_H1

Figure 1 – Panel showing microCT images of the sixteen carbonate rock samples used in this work. The length of the white bar in left down side of each image corresponds to 500 μm for the samples PC2J_2B, PC3_A1, PC3C_23, AR_OBL_V3, PC1_A1 e ROSARIO_H. For other samples, the length of the scale bar is 250 μm.

This work investigates, through the analysis of microCT images, the petrophysical properties in the scales of macro and micro pores. The properties investigated are: porosity, permeability and pore connectivity. It is understood here macro pores as those easily identifiable in microCT images, while micro pores are identified in the images as dark regions of few defined contours.

The macroporosity of samples was determined as discussed in Porto (2015). The microporosity values were determined in accordance with the procedure adopted by Al Ratrout et al. (2013).

Figure 2 shows the workflow for calculating permeability of macro pores. For the calculation of permeability were adopted default values suggested by the software, namely: input pressure of 130 KPa, output pressure of 100 KPa and fluid viscosity equal to 0.001 Pa.s (typical value for water).

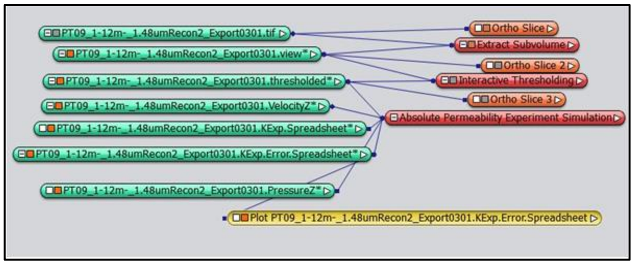


Figure 2 - Workflow to calculate the permeability of macro pores.

Figure 3 shows the workflow to calculate the Euler number representing the connectivity of macro pores. This workflow also contains the elements for the generation of the 3D model of the macro pores.

Figure 4 shows the workflow used for calculation of permeability, the Euler number and for the generation of 3D models of micro pores. For the calculation of permeability the same default parameters suggested by the software were adopted.

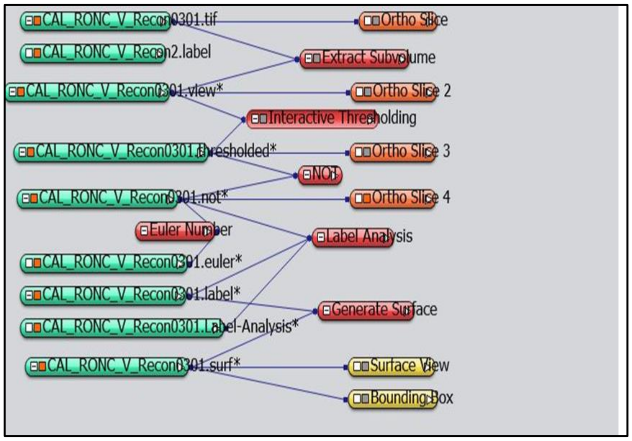


Figure 3 - Workflow for calculating the Euler number that represents the connectivity of macro pores.

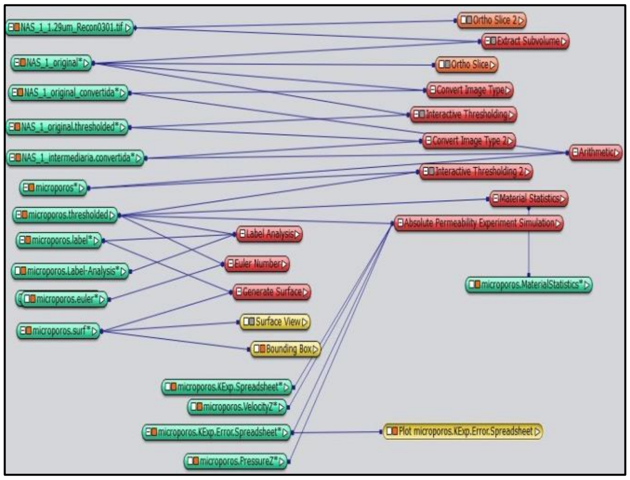


Figure 4 - Workflow used for calculation of permeability, the Euler number and for generation of 3D models of micro pores.

Results

Table 1 shows measured values of permeability of samples and those estimated by microCT for macroporosity and microporosity, permeability of macro and micro pores and pore connectivity through the logarithm of the Euler number [Log (NE)] for macro and micro pores. The Euler number is based on the principle of Euler-Poincaré and it is estimated by the Euler Number command of the Avizo Fire software.

The Euler number calculated assumes positive values, indicating low pore connectivity, or negative ones (for high connectivity of pores) within a large range of values. In order to facilitate the observation of small variations within a broad range of values, it is adopted, as pore connectivity indicator, the logarithm of the Euler number. When the Euler number is negative, a negative sign is applied to the logarithm of the absolute value of the Euler number.

Table 1 – Lab-measured permeability and properties measured by microCT.

Sample	K_{LAB} (mD)	ϕ_{macro} (%)	ϕ_{micro} (%)	K_{macro} (mD)	K_{micro} (mD)	Log (EN_{macro})	Log (EN_{micro})
CAL_RONC_V	2.026	19.1	14.6	65.2	53.0	-3.371	-4.539
PC3C_23_V	0.199	8.1	11.2	99.2	183.2	-3.391	-3.755
NAS_1	1.348	8.1	17.1	19.7	107.8	+2.780	-3.323
PC3A_1	0.009	24.7	14.4	530.5	355.5	-3.057	-3.033
AR_OBL_V3	0.296	16.5	12.3	110.8	175.2	-3.020	-3.257
ROSARIO_H	0.477	5.6	6.0	64.6	105.3	-2.676	+3.126
LAJ_SOL_V	0.109	9.9	5.5	37.3	40.5	-2.507	-4.137
PC2J_2B	0.149	4.5	2.2	77.2	58.0	+2.338	+2.464
HPC_H1	0.013	6.6	3.7	40.1	20.6	+2.505	+2.546
PC1A_1_1	0.153	10.4	14.4	81.1	120.3	+2.573	+1.968
AR_OBL_H1	0.008	11.6	6.6	33.0	31.8	+3.119	-3.015
PT9F_H4	1.813	2.6	6.8	27.2	43.4	+3.357	-4.154
NAS_8	0.023	11.7	21.6	19.5	157.3	+3.356	-4.477
PT09_1(12M)	0.001	6.2	18.6	15.2	80.9	+3.723	-4.545
PT09_1(6M)	0.007	4.4	11.5	13.0	30.3	+3.832	-4.134
PT11_H1	0.041	4.8	11.5	13.3	35.4	+3.862	-4.295

Can be seen from Table 1 that almost all rock samples show micro pores well connected, i.e., $\log(EN_{micro}) < 0$. However, the majority of samples present badly connected macro pores. Sometimes high permeability values are controlled by well-connected macro pores, but other times the rock permeability is driven by well-connected micro pores.

As example, Figure 5, 6 and 7 show 3D model for the macro pores of the samples PC3C_23_V, ROSARIO_H and NAS_8, respectively. They are examples of rock samples with well, median and badly connected macro pores. In these figures clouds of connected pores are shown in the same color.

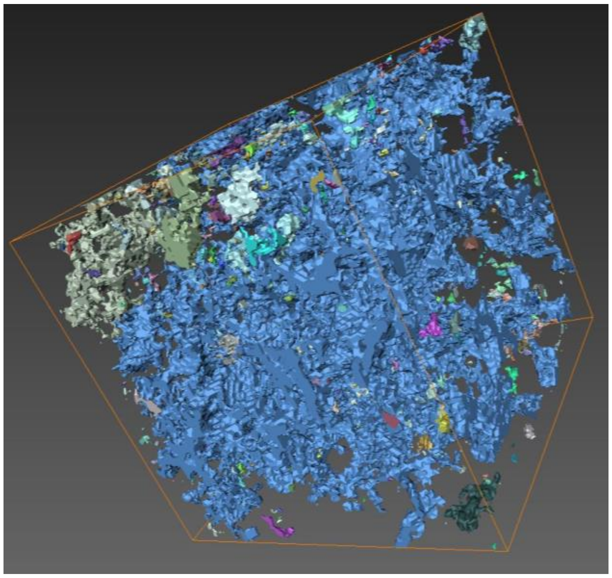


Figure 5 – 3D model of the well-connected macro pores dolostone sample PC3C_23_V. $\mathrm{Log}(EN_{macro}) = -3.391$.

In order to evaluate the influence of the digital-determined properties on the lab-measured permeability, a ranking of variables was constructed based on the parameter F of the univariate linear multiple regression, which is shown in the Table 2. Properties with higher F have more power to predict rock lab-measured permeability.

Table 2 – Ranking of influence for digital-evaluated properties on lab-measured permeability, based on univariate linear multiple regression.

Property	F parameter
$\mathrm{Log}(EN_{macro})$	1.108
K_{micro}	0.950
ϕ_{micro}	0.549
K_{macro}	0.208
$\mathrm{Log}(EN_{micro})$	0.046
ϕ_{macro}	0.044

This statistical analysis show that the three most digital influencing properties are, in this order, macro pores connectivity and micro pores permeability and porosity. Note that the porosity given by the macro pores has the minor influence on the lab-measured values of permeability.

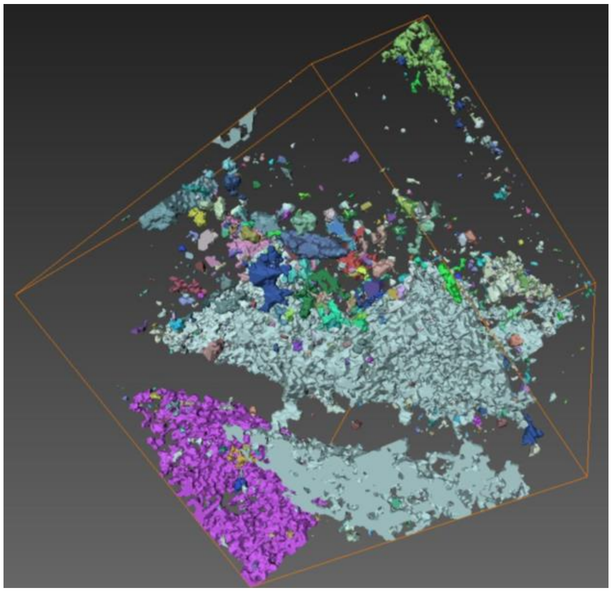


Figure 6 – 3D model of the median-connected macro pores for the sample of bioclastic grainstone ROSARIO_H. $\mathrm{Log}(EN_{macro}) = -2.676$.

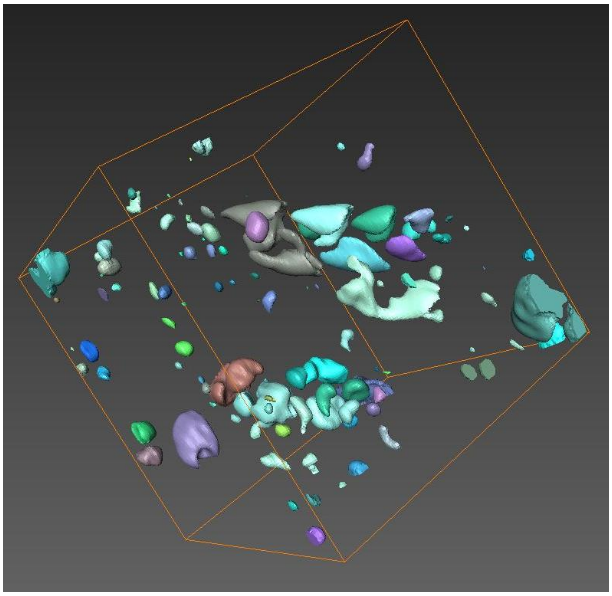


Figure 7 – 3D model of the badly-connected macro pores for the sample of microporous wackstone NAS_8. $\mathrm{Log}(EN_{macro}) = +3.356$.

Applying a piecewise nonlinear multivariate regression to the digital properties listed in Table 2 as predictors of the lab measured rock permeability it was found an explained variance of 99.1% ($R^2=0.991$) for only the three first properties of Table 2. If the first four variables are put as predictors, a $R^2=0.995$ is found. Finally, if all the six variables are considered an explained variance of 99.6% is achieved.

Equations (2) and (3) correspond to the best model achieved to predict lab-measured gas permeability of the 16 carbonate rock samples analyzed in this work. Equation (2) is valid for lab permeability equal or less than the breakpoint of 0.417 mD. Equation (3) is valid for lab permeability higher than this breakpoint.

$$K_{LAB}\ (\mathrm{mD}) = 0.144895 - 0.022618\ \log(EN_{MACRO}) + 0.001008\ K_{MICRO} - 0.003402\ \phi_{MICRO} - 0.000881\ K_{MACRO} + 0.012953\ \log(EN_{MICRO}) + 0.000229\ \phi_{MACRO} \qquad (2)$$

for $K_{LAB} \leq 0.417$ mD, and

$$K_{LAB}\ (\mathrm{mD}) = 0.297013 + 0.274073\ \log(EN_{MACRO}) - 0.092001\ K_{MICRO} + 0.787456\ \phi_{MICRO} + 0.098193\ K_{MACRO} + 0.569993\ \log(EN_{MICRO}) - 0.407271\ \phi_{MACRO} \qquad (3)$$

for $K_{LAB} > 0.417$ mD.

Applying the model given by equations (2) and (3) to predict lab-measured permeability the values of predict permeability can be crossploted against the really measured lab permeability, as can be seen in Figure 5.

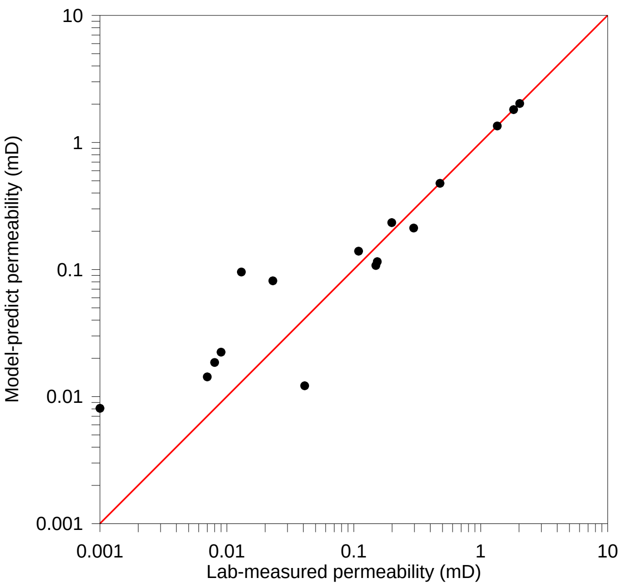


Figure 5 – Crossplot of predict rock permeability against lab-measured rock permeability.

Someone can see from Figure 5 that model-predict permeability values are very well fitted for lab permeability values higher than 0.1 mD. However, for lab permeability lower than 0.1 mD the precision of prediction is limited to one order of magnitude, what yet may be considered as a good predictor in comparison to alternative methods.

This proposed model can predict lab permeability for carbonate rocks into the range of permeability analyzed, based only on digital microCT analysis.

Conclusions

This work presents a new model for the estimation of permeability of carbonate rocks. The model has as input porosity, pore connectivity and permeability digitally estimated by microCT image analysis. These properties are analyzed separately in relation to macro and micro pores. The Euler number proved to be an efficient indicator for pore connectivity of carbonate rocks.

The set of samples used for the generation of the model is composed of a wide range of carbonate rocks, so that the proposed model is robust. The proposed model has two multilinear functions, one valid for permeabilities lower than or equal to 0.417 mD, and the other valid for permeabilities greater than this value.

Within the range of permeability measured in the samples investigated the performance of the model was quite satisfactory, achieving a coefficient of determination $R^2 = 0.996$.

The model presented here indicates that the most important variables in the control of permeability of carbonate rocks are macro pores connectivity, permeability of the micro pores system and microporosity.

Acknowledgments

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