Study of Fractal-scaling Porosity Using High-resolution X-ray Tomography in Volcanic Rocks: Preliminary Results

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ABSTRACT

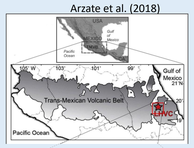
Characterization of rocks from geothermal reservoirs is crucial to better understand their behavior. Los Humeros geothermal field contains one of the most important reservoirs in Mexico. This reservoir contains volcanic rocks product of various cooling processes. In the present study, we use four different samples, three distinct andesites and one highly altered volcanic rock from Los Humeros reservoir. We acquired 3D images using X-rays microtomography to visualize and estimate porosity in these rocks. In the three andesites, we used the maximum possible resolution of 0.5 micros/voxel. In the altered sample, we used four different resolutions of 0.5, 3, 14 and 53 microns/voxel and took physical and digital subsamples at various locations in the original core plug to compare and identify its heterogeneity. From the 3D images, image porosity after segmentation and fractal-scaling porosity were estimated. From the core plug, the experimental porosity was obtained by a collaborative lab (IPICYT). The fractal-scaling porosity approximates the fractal porosity under the assumption that all pores have the same size approximately equal to the box size, used in the box counting method. The calculations were done in all images at all resolutions.

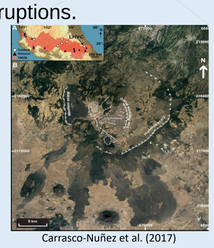
We found that the image porosity at the highest resolution is generally closer to the experimental porosity. However, the altered sample, even at this resolution, presents some variations. The image porosity of this sample at the other resolutions shows values far from the experimental porosity, as the pore space could not be fully capture. As a matter of fact, the fractal dimension increases from the lower resolution to the higher resolution as a mainly magnification effect, as well as the porosity. The fractal-scaling porosity, which uses the fractal dimension, the average spherical equivalent diameter, and the size of the image gives estimates of porosity very close to the image porosity. This demonstrates the fractal character of all these samples, implying that the pore structure in these rocks can be better evaluated using Fractal geometry. The different results obtained in the altered sample corroborates its diverse processes. To complete this study, we are working on finding potential correlations between these porous structures and permeability, and adding more samples.

MOTIVATION

Los Humeros Geothermal Field

- ✓ One of the oldest producing fields in México (Arzate et al., 2018)
- ✓ Third producing geothermal energy (~70MW) in México (Peiffer et al., 2018)
- ✓ It´s a multiple caldera of large dimensions (~21x15 km) with a complex evolution of various major eruptions.




Carrasco-Nuñez et al. (2017)

Fractal Porosity

- ✓ Fractal behavior in rocks has been found in many (e.g. Krohn, 1988; Lafond et al., 2012)
- ✓ The fractal scaling porosity equation deduced by Vega & Jouini (2015)

$$\phi_{scaling} = \frac{Be^{-Do}\times V_p}{V_T} \cong e'^{(2-Do)} \qquad \text{(Eq. 1)}$$

where B: constant of dimensionality; Do: *fractal dimension;* e: pore size; V_p: pore volume; V_T: total volume; $e' = \frac{e}{L}$ with L: size of the sample; estimates porosities at the plug scale using images in some carbonate rocks.

=> Due to the importance to estimate rock properties at different scales, we have tested this equation for the case of volcanic rocks here.

METHODOLOGY

We used 5 samples from 4 different levels, 4 of them are andesites (N4, N6a, N6b & N7) and 1 is an altered volcanic (N3).

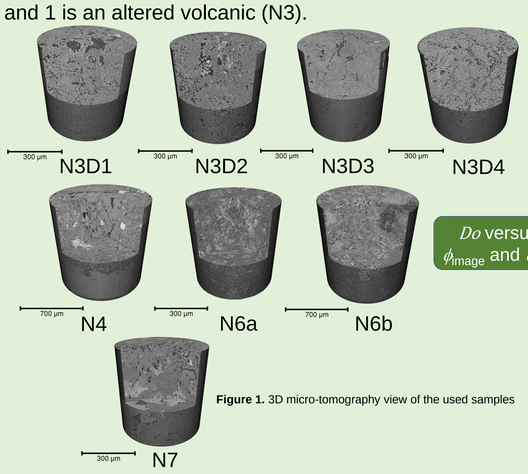


Figure 1. 3D micro-tomography view of the used samples

Flow Diagram Procedure

(Ia) Samples N4, N6a, N6b & N7 3D image acquisition at high and low resolution (10 & 0.5 microns/voxel)

(Ib) Sample N3 3D image acquisition at various resolutions (53, 14, 3, 0.5 microns/voxel)

(II) Image processing (segmentation & filtering)

@ 0.5 microns/voxel 4 samples: N3 D1, N3 D2, N3 D3, N3 D4

(III) Image porosity (ϕ_{image}), pore size distribution and fractal dimension analysis

Do versus ϕ_{image} and ϕ_{exp}

(IV) Study on $\phi_{scaling}$ equation application in these volcanic rocks

Study trends of e versus L

Comparison of $\phi_{scaling}$ with ϕ_{image} & ϕ_{exp} (experimental porosity)

MAIN RESULTS

Fractal scaling porosity & Image porosity

- In general, $\phi_{scaling}$ using mean pore size at the image scale estimates well ϕ_{image}

Sample name	Rock type	$\phi_{scaling}$	ϕ_{image}	$\Phi_{scaling}/\phi_{image}$	
N4	Andesite	0.059	0.063	0.94	
N6a	Andesite	0.042	0.032	1.31	
N6b	Andesite	0.078	0.085	0.92	
N7	Andesite	0.018	0.013	1.38	
N3 (D1)	Altered volcanic	0.064	0.143	0.45	Heterogeneity
N3 (D2)		0.060	0.126	0.48	
N3 (D3)		0.041	0.062	0.66	
N3 (D4)		0.052	0.079	0.66	

- *Do* versus ϕ_{image}

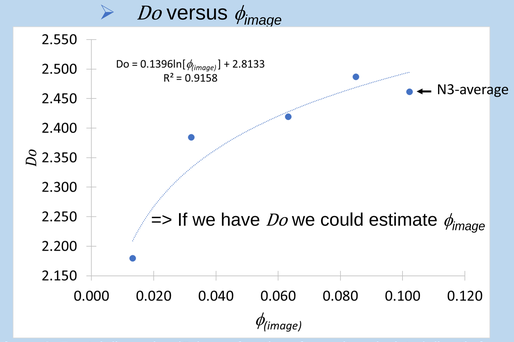


Figure 2. Fractal dimension (*Do*) as a function of porosity calculated directly from the images (ϕ_{image}) at the highest resolution (0.5 microns/voxel)

Scaling from image-scale to core-plug porosity

- Best estimates are found using the maximum pore size at the scale to study, as in Vega & Jouini (2015) in carbonate rocks.
- Maximum pore size e at each measured image-scale L in sample N3

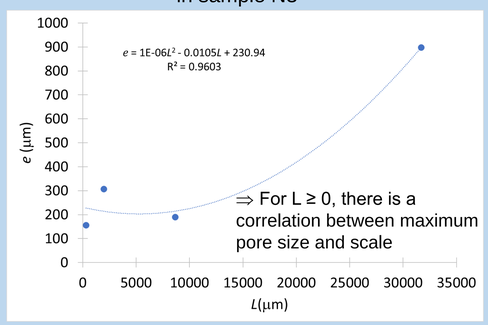


Figure 3. Trend of the maximum pore size (e) with scale (L) for sample N3

- *Do* versus ϕ_{exp}

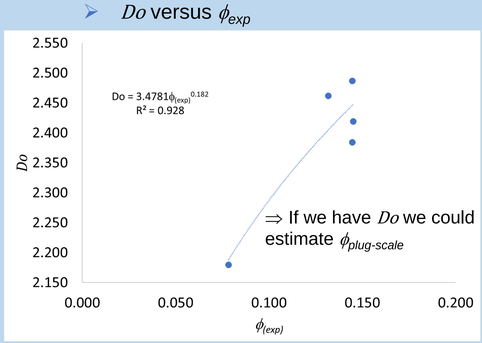


Figure 4. Trend of the fractal dimension (Do) and the measured porosity (ϕ_{exp})

- Estimates of $\phi_{(plug\text{-}scale)}$ from the results of this study

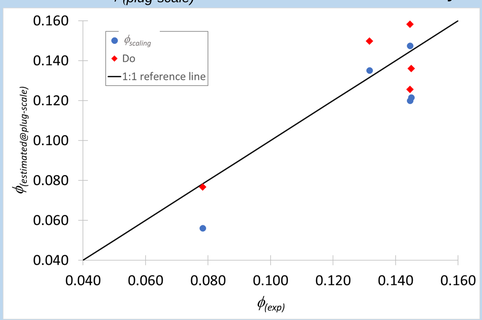


Figure 5. Estimated porosity at the plug scale ($\phi_{estimated@plug\text{-}scale}$) using two different methods: $\phi_{scaling}$ from equation 1 and approximated pore sizes calculated from Fig 3, and by using the correlation between Do and the measured porosity in the plugs (Fig. 4).

To evaluate approximated values of the maximum pore size of N4, N6a, N6b and N7, we used the trend found for N3 (Fig. 3) at the plug scale (~25400 µm) plus the absolute value of the shift between each sample and N3 at zero L. This was possible by interpolating the points at 0.5 and 10 microns/voxel in each of these samples.

Sample name	Rock type	Estimated		$\phi_{(exp)}$	$\Phi_{scaling}/\phi_{exp}$	ϕ_{Do}/ϕ_{exp}
		$\phi_{scaling}$	ϕ_{Do}			
N4	Andesite	0.122	0.136	0.145	0.84	0.94
N6a	Andesite	0.120	0.126	0.145	0.83	0.87
N6b	Andesite	0.148	0.158	0.145	1.02	1.09
N7	Andesite	0.056	0.077	0.078	0.72	0.99
N3 (average)	Altered volcanic	0.135	0.150	0.132	1.02	1.14

Both estimates from *Do* and from the fractal scaling equation predict the porosity at the plug-scale better than 28%.

CONCLUSIONS

We show here that the fractal scaling porosity ($\phi_{scaling}$) using the average pore size, estimates well the porosity resolved in the images for the andesites samples. This indicates that the porous fractal structure is captured enough to reproduce the resolved pore space.

For the highly altered volcanic rock sample, the fractal scaling porosity ($\phi_{scaling}$) does a lesser job on predicting the image porosity (ϕ_{image}). In spite of this, the average values fit well the relation between fractal dimension (Do) and image porosity. These findings demonstrate the fractal character of all these samples, and that it is possible to obtain or predict the image porosity from the fractal dimension, as far there is a determined correlation.

We also found that the best estimates of the porosity at the plug scale ($\phi_{estimated@pug\text{-}scale}$) are given by the maximum pore size when using the fractal scaling porosity equation, which agrees with previous work in carbonate rocks.

It is observed that a correlation between the maximum pore size and scale (L) could help to assess the scaling porosity with relative low error (less than 28%). However, a more accurate method needs to be develop to obtain precise maximum pore sizes.

The relationship between fractal dimension and measured porosity gives better estimations of porosity than the fractal scaling porosity. However, that relation only can be used for the plug scale calculations and needs to have the experimental measured values, which sometimes are not available. On the other hand, the fractal scaling porosity only requires an analysis of the sample images at different scales to eventually estimate the porosity at any scale of interest.

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