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Improved method for effective rock microporosity estimation using X-ray microtomography

H.E. Cid[a,b,*], G. Carrasco-Núñez[a], V.C. Manea[a,c,d]

[a] X-ray Microtomography Laboratory (LUMIR), Centro de Geociencias, Universidad Nacional Autonoma de Mexico, Campus Juriquilla, Queretaro, 76230, Mexico
[b] Energy Futures Lab, Imperial College London, London, SW7 2AZ, UK
[c] National Institute of Earth Physics, Magurele, Ilfov 077825, Romania
[d] Computational Geodynamics Laboratory, Centro de Geociencias, Universidad Nacional Autonoma de Mexico, Campus Juriquilla, Querétaro, 76230, Mexico

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ABSTRACT

Petrophysical analysis using X-ray microtomography provides key textural and compositional information, useful to investigate porous media characteristics of hydrocarbon and geothermal reservoirs. Several approaches, used for rock porosity estimation from tomography data, rely mainly on visual or mathematical segmentation algorithms that attempt to obtain thresholding values to segment a phase solved by pixel analysis resolution. Therefore, porosity is evaluated using only pores above pixel resolution (macroporosity), and dismiss pores sized less than the pixel resolution (microporosity) that can be essential to characterize permeability conditions of geothermal reservoirs. Here we propose an improved method to calculate the total effective porosity and simulate the absolute permeability of rock samples. This method combines the analysis of X-ray computed microtomography (μCT) with the interpretation of data using a powerful thresholding method that is based on the greyscale interclass variance. The 3D volume is segmented into three domains: solid, pores above resolution and, an intermediate region where each pore below resolution is linearly combined with solid matrix resulting in a grey scaled pixel equal to this combination. For the intermediate region, the microporosity was calculated employing a Matlab code that provides a new thresholding value containing pores, both above and below resolution (total porosity). Finally, by using this new calculated thresholding value the total effective porosity was obtained and an absolute permeability simulation was implemented only to the connected pores. Our results show that micropores contribute for nearly 50 percent of the total porosity and that microporosity plays a key role in estimating effective porosity, and assessing the geothermal potential of a rock reservoir.

1. Introduction

Macro and microporosity are important parameters for geologic reservoirs, especially in those where natural gas and water vapor represent main economic resources, including coal seams, gas shales and vapor-dominated geothermal systems. Macroporosity volume fraction is usually small in low permeability geologic systems compared to standard oil and water-dominated reservoirs, and may not play a significant role on the permeability of these systems (Ehrenberg et al., 2006). In contrast, microporosity can be a determinant factor related to extraction efficiency as it accounts for most of the pore connectivity, which in turn has an strong influence in gas diffusion processes (Armatas, 2006). Usually, uniformly low permeability can be found in the following systems: geothermal reservoirs (Raharjo et al., 2016; White et al., 1971), coal seams and gas shales (Cui et al., 2009). While considering flow through a porous medium, only interconnected pores are of interest, as the pores not connected to the main void space do not contribute to the flow. For low porosity materials a large part of the total void space may be nonconducting, consequently, the effective porosity of a porous medium is defined as the ratio of the volume of the conducting pores to the total volume (Koponen et al., 1997). For such media, the microporosity responsible for pore connectivity may therefore have a great impact on the overall permeability system. Consequently, it is of crucial importance to obtain a realistic estimate the total rock porosity, considering the microporosity.

Currently, there are two main experimental methods for determining permeability of very low permeability rocks. One method

* Corresponding author at: X-ray Microtomography Laboratory (LUMIR), Centro de Geociencias, Universidad Nacional Autonoma de Mexico, Campus Juriquilla, Queretaro, 76230, Mexico.
E-mail address: hectorcid@geociencias.unam.mx (H.E. Cid).

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uses gas for core sample analysis and the other uses mercury (Hg) intrusion curves (from Hg porosimetry) (Cui et al., 2009). However, the need of a fast, accurate, and routine determination of permeability makes these steady-flow permeability measurements (API, 1998) unpractical because of the related time scales and the instrumentation requirements for measuring extremely small pressure drops of flow rates. Furthermore, these methods are invasive and destructive. In consequence, new microscopic based analysis has been used to make qualitative and quantitative studies of microporosity conductivity. However, microscope analysis such as scanning electron microscopy (Katz and Thompson, 1985; Zhao et al., 1993), confocal microscopy (Fredrich, 1999) and transmission electron microscopy (Chalmers et al., 2012; Pittman, 1971) are in most of the cases limited to 2D representations of porous matrix and, only in exceptional cases, after long and expensive methodologies 3D representations of small volumes can be obtained having limited representativeness of the analyzed reservoir.

X-ray computed microtomography is an advanced technique originally introduced for clinical purposes in the 1970s by the English engineer GN Hounsfield (Hounsfield, 1973). Since then, it has been applied to study material microstructures (Salvo et al., 2003; Stock, 1999), biological soft tissues (Momose et al., 1996; Wyss et al., 2002), geological samples (Ketcham and Carlson, 2001; Mees et al., 2003), among other applications. Due to their high energy, X-rays have a great penetration power on matter, which allows them to interact with electrons close to the nucleus, and offering precise information on rock physical arrangement and chemical composition of their mineral phases (Gualda and Rivers, 2006). More recently, μCT has been applied to quantify the petrography of rocks (Van Geet et al., 2000), providing additional advantages over other methods because of its non-invasive and non-destructive nature, and at the same time allowing a 3D assessment of samples preserving their integrity. μCT image acquisition is based on the attenuation coefficient phenomenon, which is directly related to the sample density and atomic number, providing a deep access to rock chemical composition (Attix, 2004). These characteristics offer the possibility to produce 3D gray-level computer volumes, useful in the determination of several key rock properties such as porosity, permeability, density differences and degree of fracturing.

In this paper we introduce an improved method for the estimation of total effective porosity and absolute permeability of porous materials, based on the previous work (Bauer et al., 2011). Here we describe the parameters used to acquire a high-resolution X-ray microtomography and the algorithm implemented to denoise the reconstructed volume. Furthermore, we employed an advanced segmentation methodology using the observed differences between simple and complex segmentation methodologies. Additionally, in order to accurately address the microporosity estimation and to obtain thresholding values, we implemented the intermediate zone theory (Ji et al., 2015), which is based on the fundamental physical principles of the μCT technique. The purpose of this procedure is to avoid relying on visual criteria but rather employing mathematical procedures developed by Otsu (1979). Based on segmentation results we offer a Matlab code to easily calculate the total porosity of the sample, which includes both macro and microporosity.

2. Materials and techniques

The samples selected for this study were porphyritic andesite rocks obtained from a geothermal well located at Los Humeros geothermal field Mexico (Fig. 1), at a depth of about ~1700 m, which is located within Los Humeros Caldera. The rock consists in a dense gray-color porphyritic andesite lava flow including phenocrysts of plagioclase (1–4 mm) and smaller pyroxenes and oxides, within a glassy to microcrystalline (plagioclase) matrix with alteration (about 15%) of silica, carbonates, epidote, chalcedony, sericite. Plagioclase crystals are usually euhedral, but sometimes they exhibit sieve and fractured features and some show a glomeroporphyritic or pseudotrachylitic texture.

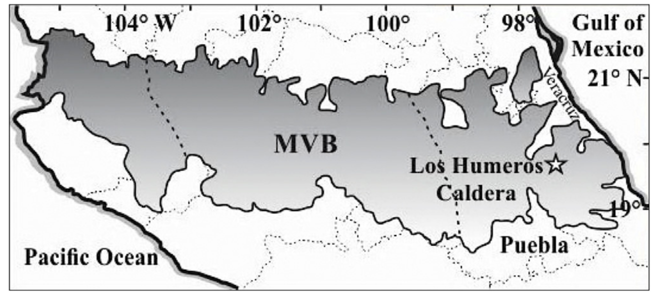

Fig. 1. Location of Los Humeros geothermal field within the eastern Mexican Volcanic Belt (MVB).

To perform a high resolution microtomography, a 5.67 mm height 3 mm-diameter cylindrical subsample was extracted using a Delta Type 1 DP400 drill. The sample was imaged using a Carl Zeiss Xradia Versa-510 X-ray μCT, equipped with an X-ray tube with a tungsten anode. The operating voltage was set to 50 kV and the current of the X-ray source to 83 μA, providing a maximum power of 3W. No filters were used for the analyzes. The detection was performed by an Andor CCD camera with a maximum resolution of 2MP. Source and detector were positioned at a distance from the sample of about 6 mm and 10 mm, respectively, in order to achieve a voxel size of 0.50 μm using a 20× objective, which is the highest resolution the μCT can reach. The actual scanned volume was a 500 μm-diameter 500 μm-height cylinder with a spatial resolution determined by some parameters such as pixel size, distance from the source to the sample and distance from the sample to the CCD camera. Average intensity was set to a value of >3000 counts, therefore, the exposure time per radiograph was fixed to 15s, maintaining a transmission percentage around 15–20%. We clearly observed that increasing the number of projections reduces drastically noise and enhances the image contrast for a given filter without any counterpart except for a longer acquisition time. Following these observations, we used a number of 4000 projections obtaining an angular step of 0.09°, taking only one image per angular step.

Scout-and-Scan Control System and Reconstructor Software (Zeiss) were used for image acquisition and reconstruction. Reconstruction procedure includes the implementation of a soft smooth filter as a standard for all the analyzed samples. The two main artifacts in the images are beam hardening and ring artifacts. Beam hardening occurs due to the absorption of low energy X-rays at the edge of the sample. Thus, the software interprets this region as an area of high attenuation, leaving it whiter than the center of the sample. Ring artifacts appear due to a problem in the detection of a pixel in CCD camera. As the sample is rotated, concentric rings appear in the images. This artifact can be reduced by the implementation of a secondary reference in which the detection problem is eliminated averaging several projections with no sample in place but with the same intensity. For each scan, a volume of 1000^3 voxels was reconstructed and converted in a 16-bit gray-level image. After a preliminary sample analysis (Fig. 2) we distinguished three different zones: 1) a well-defined macroporosity (pore size >0.5 μm, in black color), 2) a microporous phase or the glassy to microcrystalline (plagioclase) matrix (pore size <0.5 μm, intermediate gray level), and 3) a solid phase compound of pyroxenes and plagioclase phenocrysts (bright zones).