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Pore structure characterization and classification using multifractal theory—An application in Santanghu basin of western China

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ABSTRACT

It is difficult to extract quantitative information of pore space from thin section. A novel method to characterize the pore space using multifractal analyses is presented, with the help of mercury injection capillary pressure (MICP) and nuclear magnetic resonance (NMR) transversal relaxation time (T_2) data. Thin sections were processed via multi-threshold segmentation using particle swarm optimization (PSO) algorithm to obtain binary images containing pore space and mineral matrix. After multifractal analyses of binary images, the interrelationship between multifractal parameters and pore structure is investigated in detail. A crossplot for pore structure classification is put forward with types predefined by MICP and NMR experiments. The result shows that different pore types demonstrate their unique multifractal characteristics. Multifractal dimensions are positively correlated with the median capillary pressure, whereas negatively correlated with average pore radius and the T_2 geometric value. D_{min} and D_0 can be served as good indicators of pore structure types in the case study. This study provides an effective way of pore structure characterization and classification based on thin section, especially for regions without MICP and NMR experiments.

1. Introduction

The geometry and topology of the pore space plays an important role in reservoir characterization since the transport property and reservoir storage capacity is controlled by pore volume, pore connectivity and the coordination with neighboring throats (Li et al., 2010). Methods used petrophysical experiments, geophysical well logging data or their integration were often utilized to characterize the pore structure in petroleum engineering (Batyrshin et al., 2005; Schoenfelder et al., 2008; Li et al., 2010; Aliakbardoust and Rahimpour-Bonab, 2013; Schmitt et al., 2013; Hinai et al., 2014). Conventionally, petrophysical data was used as the calibrator of downhole geophysical well logging curves, aiming for quantitative information of pore structure in reservoir conditions. Therefore, pore structure evaluation by petrophysical experiments becomes the main task for formation evaluation. There are mainly two approaches to investigate the pore structure, one is the direct observation on pore space and its interrelationship with the rock matrix using petrophysical data such as NMR T_2 (Frosch et al., 2000), scanning electron microscope (SEM) (Lock et al., 2002), thin section (Verwer et al., 2011), MICP (Aliakbardoust and Rahimpour-Bonab, 2013), X-ray computerized tomography (X-CT) (Tiwari et al., 2013) and isothermal adsorption (Guo, 2013). The second approach is statistical methods of these petrophysical data including Euclidean geometry description (Talukdar et al., 2002) and fractal geometry analysis (Li, 2010; Giri et al., 2012).

It is known that the Euclidean geometry works with objects which exist in integer dimensions (zero-dimensional points, one-dimensional lines and curves, two-dimensional surfaces like planes, and three-dimensional solid objects such as balls and blocks. However, many things in nature are better described as having a dimension which is not a whole number, because of a property called self-similarity. The part is identical to the whole object on a smaller scale if we magnify some part of the object. Fractal is a new branch of mathematics, based on the idea of self-similar forms proposed by Mandelbrot (1982). It can be used to describe irregular geometrical shapes with non-integral dimensions. The fractal property can be characterized by fractal dimension using box counting method

$$D = \lim_{\delta \to 0} -\frac{\log N(\delta)}{\log \delta} \tag{1}$$

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where D is the fractal dimension, δ is the magnification factor or scale and $N(\delta)$ is the number of self-similar parts under the fixed magnification factor.

Porous rocks are found to have fractal characteristics and many researchers used the fractal statistics to predict properties of pores, rocks and their interaction with fluids. Katz and Thompson (1985) measured fractal parameters on rock fracture surfaces using SEM and revealed that the electrical conductivity is strongly correlated with the fractal dimension. Abdassah et al. (1996) investigated the effect of rock wettability on saturation exponent by fractal concepts of pores and revealed that fractal dimension is positively correlated with porosity. Lipiec et al. (1998) showed that the fractal analysis provides a relevant quantification of the changes of pore and root structure in relation to soil compaction. Crampin (1999) found that the criticality of the distributions of stressed fluid-saturated crack, microcrack and low aspect ratio pores in reservoir rock is resulted from the pervasive self-similarity. Larraz (2002) characterized different samples of Claus reaction alumina catalyst by the fractal dimension parameter employing nitrogen absorption porosimetry. Li (2010) demonstrated that the pore size distribution size is coupled with the fractal dimension and increases with the decrease in fractal dimension. Peng et al. (2011) calculated the fractal dimension of rock pores based on gray CT images and found a positive relationship between the fractal dimension and the rock pore ratio. Turcio et al. (2013) presented a new model for effective permeability prediction by introducing microstructure parameters such as radius distribution, turtosity fractal dimension and pore volume fractal dimension. Xu et al. (2013) developed a physical conceptual model for two-phase geometrical structure of nature porous media according to the fractal characteristics of pore-scale geometrical structure of nature porous media and indicated that the fractal dimension for pore size distribution and turtosity fractal dimension have significant effect on the multiphase flow through unsaturated porous media. Liu et al. (2014) quantified the relationship between the microstructure of rocks and transport properties by the combined microtomographic and fractal analyses.

Contrary to the classical geometry, the fractal geometry has unique advantages in pore structure characterization since it unveils the unification of the ordered and disordered, determination and randomness.

However, fractal geometry has its drawback since it cannot depict the heterogeneity and local scale properties of the object (Essex and Nerenberg, 1990; Hargis et al., 1998; Tang et al., 2003; Brewer and Girolamo, 2006). Recent studies indicate that multiple fractal dimensions were needed to describe statistical scaling behavior in many fields such as geosciences, soil and material sciences (Bittelli et al., 1999; Posadas et al., 2001; Vázquez et al., 2008; Ferreiro and Vázquez, 2010; Martínez et al., 2010; Kwasny and Mikuła, 2012). Analysis based on multiple scaling exponents can be regarded as the multifractal approach. Multifractal is a non-uniform fractal that unlike a uniform fractal exhibits local density fluctuations (Ferreiro and Vázquez, 2010). Multifractal is characterized by the singularity strength and multifractal dimensions by decomposing self-similar measures into intertwined fractal sets. The multifractal approach is superior to fractal since the local scale properties can be well studied.

Thin section is the cheapest and easiest way to explore the two dimensional topological property of pores and throats and their coordination, despite the lower resolution and magnitude compared with SEM and CT. MICP and NMR can investigate the pore spaces and their distributions by quantitative parameters, however they require regular samples, consume longer times and cannot be carried out massively. Thus, it is vital to extract quantitative information from thin section for pore structure evaluation. Multifractal approach provides important information of the pore space as compared to Euclidean geometry, which was applied in this study.

The main objectives of this work are twofold. The first component is to investigate the multifractal property of pore space and screen featured multifractal parameters which are sensitive to pore structure. The second component is to develop an approach for pore structure classification based on these featured multifractal parameters, with a maximal effort of using these thin sections.

The rest of the paper is organized as follows. In Section 2 we introduced the basic concept and algorithm of multifractal approach. In Section 3 we presented the material used for multifractal analyses and investigated intrinsic multifractal characteristics of rocks with different pore types. We drew our conclusion and discussion in Section 4.

2. Multifractal theory and the algorithm

The details of multifractal theory have been discussed in earlier works by authors (Posadas et al., 2001; Gutierrez and Jose, 2006; Vázquez et al., 2008; Ferreiro and Vázquez, 2010; Chakraborty et al., 2014). A brief description of the multifractal approach by box counting algorithm is given in this paper.

Assuming that the size of a two dimension binary object (here the pore-rock matrix binary photo extracted from thin section, 255 represents the pore space and 0 represents the rock matrix) is $N \times N$(where $N = 2^m$, m is a positive integer). The object is cut into $N(\varepsilon)$ boxes if we use a box with the size of $\varepsilon \times \varepsilon(\varepsilon = 2^0, 2^{1,}, \cdots, 2^m$, ε is the box size) to cover the object. If the pores counted in the ith box of size ε can be stated as $M_i(\varepsilon)$, the mass probability in the ith box can be expressed as

$$P_i(\varepsilon) = \frac{M_i(\varepsilon)}{\sum_{i=1}^{N(\varepsilon)} M_i(\varepsilon)} \quad (2)$$

where M_i is the counted number of pore spaces in the ith box of scale ε and $N(\varepsilon)$ is the total number of boxes covered with size ε.

For pores with multifractal property, the mass probability $P_i(\varepsilon)$ scales with the size ε

$$P_i(\varepsilon) \propto \varepsilon^{a_i} \quad (3)$$

where a_i is the Lipschitz–Hölder exponent or singularity strength, characterizing the density in the ith box.

Different boxes can have the same singularity strength a_i, as seen in Eq. (3). If $N_a(\varepsilon)$ is used to count the box number when singularity strength ranges from a to $a + da$, then

$$N_a(\varepsilon) \propto \varepsilon^{-f(a)} \quad (4)$$

where a is the singularity strength and $f(a)$ is the multifractal spectrum.

$f(a)$ is a monotonic function and reaches the maximum value when

$$\frac{df(a(q))}{da(q)} = 0 \quad (5)$$

where q is the moment order of the distribution with the range of .

The partition function of the moment order q for ε can be expressed as

$$X(q,\varepsilon) = \sum_{i=1}^{N(\varepsilon)} P_i^q(\varepsilon) \propto \varepsilon^{-(q-1)D_q} \quad (6)$$

where D_q is the fractal dimension of the moment order q.

With Eq. (6), the expression of multifractal dimensions can be expressed as

$$D_q = \frac{1}{q-1} \lim_{\varepsilon \to 0} \frac{\log \sum_{i=1}^{N(\varepsilon)} P_i^q(\varepsilon)}{\log \ \varepsilon} \quad (7)$$