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Fractal dimensions of shale

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ABSTRACT

High-resolution images provide detailed information about pores whose characteristic sizes are usually on the order of few nanometers to micrometers in shales, but it remains challenging to relate the acquired information to the transport properties of a sample whose size is usually on the order of centimeters. It is not yet possible to determine the effective connectivity of the pore space at the core scale (~1 cm) from high-resolution images. With this in mind, we analyze drainage experiments conducted on cores to interpret the topology of the connected path of the pore space at the core scale. Our study for different shales shows that the distance traveled inside the pore space—the length of the pore space—by the nonwetting phase at each capillary pressure is a fractal, unlike the pore volume, which is not necessarily a fractal. We determine the fractal dimensions for different shales and present two fractal models. This study can have major implications for understanding hydrocarbon transport in shales.

1. Introduction

Pore-scale modeling (Bryant and Blunt, 1992; Celia et al., 1995; Bakke and Oren, 1997; Blunt, 2001; Thompson, 2002; Knackstedt et al., 2001; Hassanizadeh et al., 2002) is based on the notion that we can model fluid flow by accounting for the interactions among the pores. Pore-scale images (Oren and Bakke, 2003; Piri and Zuleima, 2007; Zuleima and Piri, 2007; Wildenschild and Sheppard, 2013) have helped this field of study significantly by shedding light on the topology of the pores and their connections. Pore-scale images constitute an indispensable part of our today's understanding for shales (Loucks et al., 2009, 2012; Curtis et al., 2012a,b). They have allowed us to visually observe the pores and even classify them based on their topology (Dewers et al., 2012; Milliken et al., 2013).

High-resolution images shed light on the complexity of the pore space (Blunt et al., 2013), but it is a non-trivial task to relate our pore-scale understanding of the pore space to core-scale measurements such as permeability (Mostaghimi et al., 2013; Shabro et al., 2014), drainage, and imbibition. Relating our understanding of the small scale to that of the large scale requires us to define a representative elementary volume (REV) of the pore space. REV is the smallest volume of the pore space that is representative of the pore space at the core scale (Norris and Lewis, 1991; Bear, 2013). The REV has not yet been defined for shales; even for more permeable formations such as Bureau sandstones, this is still matter of active research (Ovaysi et al., 2014).

Determination of the effective connectivity of the pore space based on high-resolution images at scales relevant to the size of the core (~1 cm) has not been done. Such a determination will require building a backbone model (Lindquist and Venkatarangan, 1999; Prodanovic et al., 2006, 2007) that is representative of the connectivity of the pore space at the core scale. This task becomes more challenging with decreasing the characteristic size of the pores, which is relevant to tight formations such as shales, because our large-scale model has to embrace smaller pores.

The difficulty of obtaining the effective connectivity of the pore space based on high-resolution images has led to interpretations of core-scale measurements being used as alternatives. Core-scale measurements embrace the effective connectivity but they entail further analyses because the effective connectivity is not the main derivative of such measurements. To determine the effective connectivity based on core-scale measurements, we hypothesize a pattern for the pore space and test whether the pattern is consistent with lab measurements such as permeability. To account for the effective connectivity, researchers have proposed five theoretical models (Washburn, 1921; Fatt, 1956; Mason and Mellor, 1995; Sakhaee-Pour and Bryant, 2014, 2015), which are relevant to different formations. The scarcity of the developed models points to the difficulty of developing a pore model which is representative at the core scale.

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Recently, Sakhaee-Pour and Bryant (2015) developed a theoretical pore model that allowed them to capture drainage experiments for shale samples. They indicated that spatial distribution of the pore space can be captured using acyclic pore models. The developed models are acyclic in a graph theoretic sense. The Bethe lattice (1935) is the classic example of an acyclic graph; trees are the most familiar natural example.

We analyze the fractality of the pore space of shales in the present study. Fractals possess self-similar patterns repeated at different scales and spatially (Mandelbrot, 1983; Feder, 2013). Many applications have been found for fractals, not only because of their beauty, which has itself received attention (Peitgen and Richter, 2013), but also because their governing rules simplify complex features in nature. The length and volume of a fractal are related to its characteristic size as follows:

$$L(\delta) = a\delta^{1-D_l} \tag{1}$$

$$V(\delta) = b\delta^{3-D_l'} \tag{2}$$

where L is the fractal length, a is a fitting parameter, δ is the characteristic size used for measurement, D_l is the fractal dimension that relates the characteristic size to the fractal length, V is the fractal volume, b is a fitting parameter, and D_l' is the fractal dimension that relates the characteristic size to the fractal volume.

Researchers have used fractals to model transport properties of porous media (Hammecker et al., 2004; Cai et al., 2010; Cai and Yu, 2011). There has been a growing interest in using fractals for understanding the transport properties of tight formations. Researchers have employed fractals to capture heterogeneity of stimulated volume (Zhang et al., 2015a), complex geometries of fractures (Wang et al., 2015), and change in apparent and relative permeabilities (Mo et al., 2015; Zhang et al., 2015b).

Fractals have found applications in analyzing the topology of the pore space. Katz and Thompson (1985) first used the basic notion of fractals for pore space characterization when they realized the number of objects observed in two-dimensional images was a function of the characteristic size. They stated that the fractal dimensions relevant to the length and volume are the same ($D_l = D_l'$) (Katz and Thompson, 1986), although that was disputed by Roberts (1986).

More recently, researchers have used fractals to characterize the pore volume of different shales. Liang et al. (2015) showed that the fractal dimension of Wufeng shale that controls the pore volume is between 2.49 and 2.63. Liu et al. (2015) investigated the pore volume of Yanchang shale using nitrogen adsorption/desorption and concluded that its pore volume follows the general fractal rule. Researchers have also used fractal models for characterizing the pore volumes of other shales based on nitrogen adsorption/desorption (Bu et al., 2015) and mercury intrusion (Lai and Wang, 2015; Tang et al., 2015).

Shale formations (Kethireddy et al., 2014; Eshkalak et al., 2014; Saneifar et al., 2014) are the main interest in the present study due to the complexities of their pore structures and because their transport properties are not fully understood (Dastidar et al., 2007; Sakhaee-Pour and Bryant, 2012). The pore structure can have a significant effect on the spatial distributions of the wetting and nonwetting phases (Sakhaee-Pour and Bryant, 2014).

2. Pore-scale images of shales

Pore-scale images of shales indicate that they host pores with self-similar shapes (Sondergeld et al., 2010). Researchers even classified the shales into different groups based on the similarity of the pores (Desbois et al., 2009). The observed self-similarity of the pores suggests that the pore space of a shale can be fractal. There are two challenges, however, for determining the fractal dimensions of shales based on those images.

First, the characteristic size of a pore is usually on the order 10 nm (Ambrose et al., 2012), which is much smaller than that of a highly permeable formation (Katz and Thompson, 1985). As a result, high-resolution images are required, and such images are usually limited to an extremely small volume of the pore space. Thus, it is difficult to determine whether the pores captured in high-resolution images are even part of connected pores at a larger scale relevant to the size of the cores (~1 cm).

Second, the high-resolution images are obtained without confining stress. Pores studied under such conditions can be different from those under in-situ conditions. We may be able to classify pores into existing and non-existing based on high-resolution images, but we do not yet fully understand how they deform under loading at the small scale (pore scale). The presence of cement on the pore wall suggests that the pore is not fully closed (Laubach, 2003; Olson et al., 2009), which is important especially for micro fractures.

3. Drainage results

We analyze the drainage data of shales acquired under confined boundary conditions because they are more representative of in-situ conditions. The interpretation of the drainage experiment helps us better understand the effective connectivity of the pore space at the core scale. We use mercury intrusion capillary pressure measurements (Fig. 1) available in the literature (Heath et al., 2011; Dewers et al., 2012). Mercury is the nonwetting phase for rocks, and the ratio of the pore volume occupied by the mercury determines the wetting phase saturation as follows:

$$S_w = 1 - S_{nw} = 1 - \frac{V_{Hg}}{V_p} \tag{3}$$

where S_w is the wetting phase saturation, S_{nw} is the nonwetting phase saturation, V_{Hg} is the volume of the mercury injected into the sample, and V_p is the total pore volume of the rock.

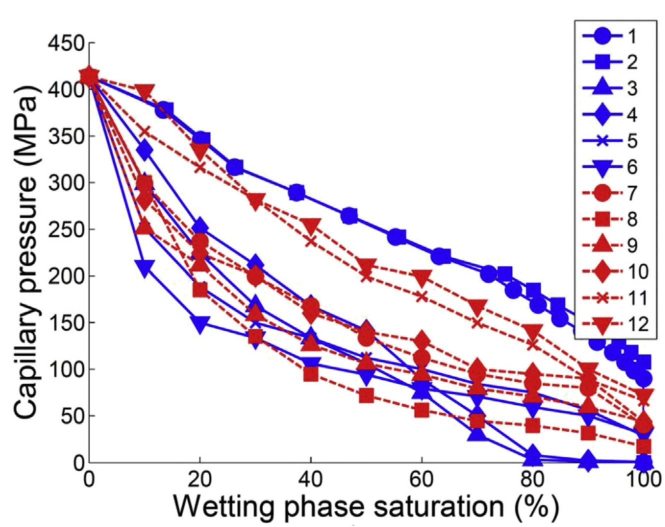

Fig. 1. Capillary pressure measurements of different shales (Heath et al., 2011; Dewers et al., 2012) whose properties are listed in Table 1. The lack of plateau-like trends in the variation of capillary pressure with wetting phase saturation reveals that the acyclic pore models can capture the pore space (Sakhaee-Pour and Bryant, 2015).