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Stochastic shale permeability matching: Three-dimensional characterization and modeling

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ABSTRACT

The recently-discovered promise of shale-gas reservoirs necessitates their characterization. As a first step, two-dimensional (2D) scanning electron microscope (SEM) imaging can provide excellent view of the complexity associated with such reservoirs, and has been used in recent years to study organic materials, clays, minerals, and the pores in shales. Other important information, such as the connectivity of the pores in 3D and such macroscopic properties as the permeability are difficult to infer from 2D SEM images. Newer techniques, such as focused ion-beam SEM (FIB-SEM) have been utilized to overcome the shortcomings. The extremely small sample size and the costs associated with the FIB-SEM technique limit, however, wide use of the FIB-SEM in characterization of shale samples. An alternative approach is to use the recently developed advanced algorithms for 3D reconstruction that use one or a few 2D samples. Such methods may not, however, be able to fully reproduce the shale permeability. To accurately reproduce the permeability, we propose a new method based on a combination of the Metropolis-Hastings and the genetic algorithms. The new method learns from its own previously generated realizations of the shale and produces models that match the existing permeability data. The method is validated with the measured permeability for an actual 3D shale sample. It generates an ensemble of stochastic realizations that honor the permeability data, which may then be used for more accurate characterization of shale gas reservoir and analysis of their pore network.

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1. Introduction

Due to their special intrinsic physical characteristics, such as multimodal nano-scale structures and complex features, shale formations are of much interest in various studies in earth science, including geology, water resources, oil/gas reservoirs, CO_2 sequestration, and many other related subsurface systems and phenomena. Owing to their immense hydrocarbon content as unconventional reservoirs, shales have recently become even more important. The size of the pores in shales is a distinct aspect of such formations that gives rise to complex morphology and connected flow paths. Such multiscale pore structures have considerable influence on the methodology and tools for studying shale reservoirs in terms of fluid flow, imaging, pore network modeling, and interpretation of the data (Javadpour, 2009; Sahimi, 2011).

Permeability is perhaps the most critical property for evaluating shale gas reservoirs. A precise evaluation of the permeability helps one to understand how the pore networks and important petrophysical parameters in unconventional reservoirs differ from those in the conventional ones. Unlike conventional reservoirs, gas flow in shale gas reservoirs is determined by various properties, including the multiscale structure of the reservoirs, their nano-porosity, and special flow mechanisms. Therefore, a considerable number of samples are needed to understand the variability and complexity of the features that determine the permeability.

Accurate 2D and 3D imaging is a prominent tool for better understanding of the complexities of shale gas reservoirs (Javadpour et al., 2012; Loucks et al., 2012). Such images provide excellent inside look into the depositional environment, mineralogy, maturation, thermal condition, total organic carbon (TOC), strain/stress properties, porosity, permeability, and the pore network of the formation. Thus, deeper studies of such reservoirs inevitably require a large number of samples using two- or three-dimensional (3D) images. Due to its use of various signals, high-resolution focused ion-beam scanning electron microscope (FIB-SEM) method (Lemmens et al., 2011) offers images that contain very useful information about the morphology and composition of shale samples (Loucks et al., 2012). Such images also provide a means for accurate evaluation of the complex connectivity in the pore network of shale reservoirs. Such key parameters as the TOC, mineralogy, porosity, permeability, and other petrophysical properties are best evaluated through the use of such images. The necessity of using several 3D samples to represent the heterogeneity and complexities in shale gas reservoirs was investigated by Kelly et al. (2015), who concluded that a vast number of samples are needed to improve the likelihood of a reliable assessment of the various petrophysical parameters. Obtaining such a large number of 3D images is, however, neither feasible nor practical.

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Nomenclature

AUX	Auxiliary data
C_D	Covariance of experimental data
C_m	Covariance of shale samples parameters
CCF	Cross-correlation function
CCSIM	Cross-correlation based simulation
d_{exp}	Experimental data
$D_T(u)$	Data event as position u
d_{JS}	Distance between two models using the JS method
DI	Digital image
E	Euclidean distance
G	Simulation grid
GA	Genetic algorithm
JS	Jensen-Shannon
M	Porous media model
$\mathbf{m}_{cand}$	Candidate model
$\mathbf{m}_{prior}$	Prior model
MCMC	Markov Chain Monte Carlo
MH	Metropolis-Hastings
mutStep	Flag for mutation
OL	Overlap region
P	Size in x direction
Q	Size in y direction
R	Size in z direction
S	Least-squares misfit function
SD	Soft data
SEM	Scanning electron microscope
T	Template
TOC	Total organic carbon
μ	Mean or expectation of the distribution
ρ	Acceptance probability
σ	Standard deviation
ω	Weight

On the other hand, 2D images can be provided with ease and at a low cost. Because of the obstacles involved with obtaining 3D images, Tahmasebi et al. (2012, 2015a) proposed a new approach based on taking one or more 2D images and building a 3D model stochastically. The models generated by their approach exhibit petrophysical and flow properties similar to those directly observed and measured in actual samples. Their method produces an ensemble of 3D realizations that provide acceptable approximation of the same properties in the 2D image(s). We should point out that, in addition to our method, there are several other important techniques that can reproduce the connectivities at small sales (see, for example, Adler et al., 1990; Roberts and Teubner, 1995; Yeong and Torquato, 1998a, 1998b; Jiao et al., 2009; Mehmani et al., 2013; Gerke and Karsanina, 2015; Gao et al., 2015). But, they have never been tested for reconstructing models of shale reservoirs.

Aside from recent progress in producing various equi-probable 3D realizations of shales (Tahmasebi et al., 2015a), reproduction of accurate permeability for complex structures remains an essentially open problem (Veselý et al., 2015; Gao et al., 2015). Indeed, it is perhaps excessive expectation of reproducing the existing experimental data using the current 3D stochastic models, when they are generated from one or very few 2D images. Intuitively, we know that 2D images can hardly convey, for example, a flow property that depends on the spatial pore connectivity in 3D. Furthermore, since one cannot study all the core data and samples due to the limitations of cost and time-consuming nature of the task, stochastic modeling can generate many samples, quantify the uncertainties, and put forward a range of variability. Clearly, the initial data - here the input 2D images - should represent the variability in the structures, in which case the stochastic methods produce various possible realizations in a matter of a few CPU seconds.

Building a 3D model of porous media based on limited data has been investigated extensively. Such models may be divided into three groups. In one group, called *object-based techniques*, the pore and grain structures are treated as a set of objects that are defined based on the prior knowledge of the pore space (Pyrcz and Deutsch, 2014). Clearly, such techniques are not applicable to random structures. Instead, the second group, called *pixel-based methodologies*, can be used effectively to produce the shapes that are hard to fit to a specific regular object (Strebelle, 2002; Okabe and Blunt, 2004). Unlike the object-based methods, however, these techniques are unable to produce very realistic pore structures. Thus, one must resort to the third class of such techniques, called *process-based models* (Bryant and Blunt, 1992; Coelho et al., 1997; Biswal et al., 1999, 2007; Øren and Bakke, 2002) that produce very realistic models by mimicking the real processes that form the porous media. They are not, however, general enough as they are designed for specific sedimentary conditions appropriate for a given reservoir and, thus, need to be defined separately for every new type of reservoir. Furthermore, they also require highly intensive computations.

As a very effective alternative, a combination of the object- and pixel-based methods can produce more realistic morphology for porous media (Tahmasebi et al., 2012). In other words, the strength of pixel-based method for producing complex pore space and object-based methods for realistic models are integrated. For this aim, one of the recent techniques in this class of methods (Tahmasebi et al., 2015a) is implemented in the present study.

None of the previously described methodologies is capable of reproducing accurately the experimental data for the permeability and electrical conductivity. They are able to produce the spatial structure of the pore space of porous media, but reproducing the data for the flow and transport properties is not guaranteed. This is the reason why the stochastic methods produce an ensemble of realizations and, consequently, the petrophysical properties that are used for uncertainty quantification. They produce a range of, for example, permeability, instead of one single value. In this paper, a new iterative stochastic method for reproducing the permeability from 2D SEM images is proposed. Using concepts from the genetic algorithm (GA) and data mining, the new method uses various 2D images from different parts of a shale gas reservoir in order to iteratively improve the estimation of the permeability. To this end, the accepted realizations are pooled together to make a set of soft data (SD) on which the subsequent models are conditioned. The pool of the realizations and the SD are updated progressively, building upon the previously-accepted realizations. As with the optimization problems, the initial guesses (i.e. models) may produce results very different from the existing experimental data. At the later steps, however, as the pool of the realizations and the SD are updated, the calculated attributes draw closer to the actual measured experimental data. Thus, this paper presents a framework by which the experimental properties can be reproduced more or less exactly.

The rest of this paper is organized as follows. In the next section we discuss the methodology that we propose in this paper, including an algorithm that was recently suggested and utilized in the present paper, and how it is integrated with the GA. The method is then validated by two examples, a 2D synthetic model of shales and a 3D example based on an actual shale sample.

2. Methodology

Major obstacles to the development of shale reservoirs are their costly analysis and studies that point to the need for the development of more efficient technologies. As mentioned earlier, a basic and common type of study is conducting extensive analysis of various aspects of a large number of samples, including their mineralogy and some essential petrophysical and laboratory properties. Permeability is a key property that is evaluated for

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