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Multiscale study for stochastic characterization of shale samples

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ABSTRACT

Characterization of shale reservoirs, which are typically of low permeability, is very difficult because of the presence of multiscale structures. While three-dimensional (3D) imaging can be an ultimate solution for revealing important complexities of such reservoirs, acquiring such images is costly and time consuming. On the other hand, high-quality 2D images, which are widely available, also reveal useful information about shales' pore connectivity and size. Most of the current modeling methods that are based on 2D images use limited and insufficient extracted information. One remedy to the shortcoming is direct use of *qualitative* images, a concept that we introduce in this paper. We demonstrate that higher-order statistics (as opposed to the traditional two-point statistics, such as variograms) are necessary for developing an accurate model of shales, and describe an efficient method for using 2D images that is capable of utilizing qualitative and physical information within an image and generating stochastic realizations of shales. We then further refine the model by describing and utilizing several techniques, including an iterative framework, for removing some possible artifacts and better pattern reproduction. Next, we introduce a new histogram-matching algorithm that accounts for concealed nanostructures in shale samples. We also present two new multiresolution and multiscale approaches for dealing with distinct pore structures that are common in shale reservoirs. In the multiresolution method, the original high-quality image is upscaled in a pyramid-like manner in order to achieve more accurate global and long-range structures. The multiscale approach integrates two images, each containing diverse pore networks – the nano- and microscale pores – using a high-resolution image representing small-scale pores and, at the same time, reconstructing large pores using a low-quality image. Eventually, the results are integrated to generate a 3D model. The methods are tested on two shale samples for which full 3D samples are available. The quantitative accuracy of the models is demonstrated by computing their morphological and flow properties and comparing them with those of the actual 3D images. The success of the method hinges upon the use of very different low- and high-resolution images.

1. Introduction

Characterization of oil and gas reservoirs, whether conventional or unconventional, enhances the understanding of their lifetime performance and management. Developing a comprehensive reservoir model is an outstanding challenge that requires various tools for data gathering, data integration, and rapid updating of the model. Because they store a substantial amount of hydrocarbons, shale reservoirs are considered one of the main energy resources of both today and the future. Hydrocarbons may be present within kerogen pores and adsorbed on clays. They can be in the form of gas and oil in the pores and fractures. Because most of such processes occur in the same area, and due to the low permeability of shales, the fluids do not migrate significantly.

Although several methodologies are available for conventional reservoirs [34], ranging from pore-scale modeling to flow simulation at large scales, characterization of unconventional reservoirs is not yet a mature research field. One limitation is that, due to some of the fundamental morphological variations across shale reservoirs, many methods for modeling of conventional reservoirs cannot be used for shales. For example, in conventional reservoirs, accurate modeling of large-scale structures (e.g., channels) is the aim, whereas in shale reservoirs, small-scale features or pores play the more vital role in fluid flow, as they connect the main paths for fluids and their transport. Such a prominent difference in the methods forces analysis of a huge number of shale samples, which is vital for their direct characterization. Analysis of a

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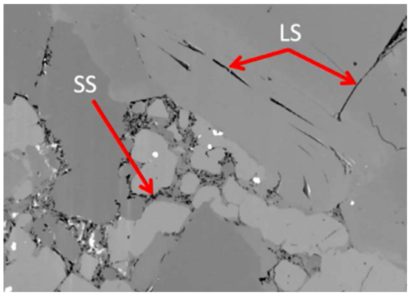

Fig. 1. A 2D shale sample ($20 \times 16\,\mu m^2$) representing small-scale (SS) and large-scale (LS) pores. The multimodal and multiscale distribution of pore spots is clear.

very large number of shale samples is necessary mainly because of the aforementioned significant variability in the intrinsic properties of shales. Because the large number of samples from various locations of a shale reservoir can also increase understanding of its depositional environment, mineralogy, maturation, thermal condition, total organic carbon (TOC), strain/stress properties, porosity, and permeability, having access to a significant number of samples — including two- or three-dimensional (2D/3D) images — and developing accurate methods of analysis are essential for the characterization.

Two-dimensional imaging studies are becoming more popular in shale reservoir characterization [27], with high-resolution focus ion-beam scanning electron microscopy (FIB-SEM) being an increasingly essential part of acquiring 2D and 3D images of shales [25]. Such images reveal important details about the pore network and pore connectivity and provide a more reliable platform for shale reservoir modeling. One can also extract from the images some of the aforementioned key petrophysical parameters such as the TOC, mineralogy, porosity, and permeability [27,37]. One of such images is provided in Fig. 1 in which the co-occurrence of the small-scale (SS) and large-scale (LS) features is illustrated. Obtaining ultra-high-resolution 3D images is, however, costly and time consuming. Two additional shortcomings are the very small edge size of 3D images (typically 10 μm) and the loss of pores and grains during layer milling [25]. Therefore, generating high-quality 3D images is an outstanding challenge. On the other hand, 2D images can be obtained with ease at a larger scale (hundreds of μm) and at a lower cost and much higher efficiency.

Given their availability, using 2D images to reconstruct a representative 3D digital sample will be very beneficial to the modeling of shale reservoirs. If the reconstruction is accurate and efficient, there is no need to fully scan a sample in 3D when a few, or even a single, 2D image can convey the same heterogeneity and morphological information. To this end, several available statistical methods can extract the important statistics and then stochastically reconstruct a large number of realizations of 3D models [1,18,31,32]. These methods are typically based on an optimization technique, such as simulated annealing, by which one tries to minimize the difference between the inferred statistical properties of the 2D images and those of the simulated model. The statistics extracted using such methods are not very rich, however, and may not be able to model key morphological information in shales. Such methods are also mostly based on two-point statistical descriptors that cannot reproduce the complex structures abundant in shale reservoirs, and cannot directly use *qualitative* or *soft* information, and all the necessary physical rules and morphological information that must be transformed into numerical data.

Process-based methods [5,6,8,9,50] try to develop 3D models by mimicking the physical processes that form the porous medium. Though realistic, such methods are, however, computationally expensive and require considerable calibrations. Moreover, they are not general enough, because each of them is developed for a specific type of rock, as each type is the outcome of some specific physical processes.

Some of such issues can be addressed by adding higher-order statistical measures to the “tool box” of modeling, provided that such measures can be extracted with relative ease and efficiency. This paper proposes the use of higher-order statistics together with 2D images to reconstruct a corresponding 3D model of a shale reservoir, which is a realization of the reservoir that stochastically exhibits petrophysical properties similar to the bulk sample. The emphasis of this study is on the practical problem of reconstructing multiscale features in shale reservoirs, motivated by the fact that most of the current economically feasible shale resources concurrently exhibit both nano- and large-scale pores.

The rest of this paper is organized as follows. Section 2 discusses the idea behind using higher-order statistical methods. Section 3 presents a methodology of reconstruction with an iterative technique that improves the initial model, and introduces a histogram-matching method for more accurate reproduction of bimodal porosity distribution in shale samples. Section 4 presents the results of several sets of simulations, including computation of petrophysical properties and some key parameters of shale reservoirs, and their comparison with the bulk experimental data. Section 5 is a summary.

2. The critical role of higher-order statistics

Broadly speaking, reservoir reconstruction may be viewed as an inverse problem for which the aim is to build a model based on a limited amount of data. This can be done using two distinct techniques: deterministic and stochastic. Deterministic methods [21] are no longer very popular because they provide only a single realization of a reservoir and cannot be used for reliable uncertainty assessment. Generally speaking, one is interested in having an ensemble of the plausible models or realizations of a reservoir.

Because they can provide a range of possible variations, stochastic methods have become popular in reservoir modeling. Tahmasebi et al. [40,43,44,46,47] provide a comprehensive comparison of various higher-order statistical methods, which may be classified based on two main techniques: object-based and pixel-based methods. Object-based simulations try to represent a porous medium as a collection of stochastic objects whose properties are defined by such statistical information as proportion, shapes, interactions, and other morphological data. Despite providing more-realistic models, object-based methods are not applicable when a large number of constraints need to be honored by the model. They are also computationally intensive. Pixel-based methods, on the other hand, use a single cell, rather than an object, and perform conditioning of the constraints with ease. But, aside from their flexibility for conditioning, pixel-based methods cannot provide physically realistic models because they use lower-order statistical properties. Extensive research has demonstrated that models generated based on such methods more often than not fail, when used in flow and transport simulations (see, for example, [38,39]).

A critical shortcoming of the current methods of modeling porous media is their inability for using rich qualitative (soft) information. For example, pixel-based methods [16,26,17] rely only on limited quantitative information, namely, the covariance functions, and cannot translate qualitative (soft) information into practical use. Likewise, object-based methods [12,29] can reproduce some limited quantitative features, such as data on the morphological properties, but not any qualitative features. In fact, most, if not all, of the current reconstruction methods are not able to fully reproduce the physical properties of a porous medium such as their effective permeability's, leading to inaccurate models. There are, of course, several approaches to modeling of porous media and