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Spatial Analysis of Fabric Elements in the Berea Sandstone through Petrographic Image Analysis

Summary

A sample set of Berea sandstone core plugs were selected to investigate fabric elements in sandstones with very low intersample variability in bulk porosity and permeability. Thin sections from the ends of the plugs were analyzed via Petrographic Image Analysis (PIA). PIA is a process where digital binary images of porosity are analyzed with a pattern recognition algorithm. The result is the derivation of "pore types", based on size and shape of the porosity elements, and their relative abundance in each sample. The pore typing procedure indicates that the Berea samples are not homogeneous, but possess zones of both closely packed and loosely packed grains, recognized by Gratton and Fraser (1935). Spatial order of the pore types is quantified through Fourier analysis of the binary images from each thin section. The spatial analysis of these pore types indicates that fabric elements are not random, but preferentially located.

Introduction

Petrophysical properties of natural porous media are controlled by the volume, geometry, and interconnectivity of the three dimensional network of pores. Ambiguous results are often produced from traditional petrographic methods, when attempting to relate petrography to petrophysics. Therefore, an objective method of classifying and quantifying the porous microstructure will enable a link between petrophysical characteristics and fluid flow in porous media.

Recent literature has described a methodology for objectively capturing and quantifying pores in thin section. This methodology, referred to as Petrographic Image Analysis (PIA), classifies subpopulations of pores into types according to size and shape, and numbers these "pore types" in ascending order according to size. Moreover, it has been shown that two dimensional image data strongly relates to three dimensional petrophysical properties in reservoir rocks (Ehrlich et al., 1984, Ehrlich et al., 1991a, McCreesh et al., 1991, Ehrlich et al., 1991b, Bowers et al., 1994, and Murray et al., 1994,). Commonly, a strong relationship exists between pore size and throat size (Ehrlich et al., 1991b). This relationship ensures that pore size information will be relevant in understanding the variation of petrophysical properties associated with fluid flow in porous media.

Flow paths, or permeable flow circuits, are believed to be caused by the imperfection inherent in the packing of any dynamically packed aggregate. Graton and Fraser (1935) fast described such features as “packing flaws” in sandstones. These packing flaws can be subdivided into “closely” and “loosely” packed domains. Prince and Ehrlich (1990) and Prince et al. (1995), showed that these packing flaws can be resolved via the application of a Double Fourier Transform upon the binary porosity image.

Petrographic Image Analysis

The procedure originally set forth by Ehrlich et al. (1991a), was used to derive pore types in the Berea samples. The fast step in the PIA procedure is image acquisition, resulting in an image where porosity is stored as black and rock matrix is stored as white. Thus, a binary image of the optically resolvable porosity is stored for the next step in the procedure.

The binary image is then subjected to erosion-dilation processing. This procedure is designed to characterize precisely porosity elements (porels) of varied and potentially complex geometries. This also provides optimal input into a pat tern recognition/classification algorithm for deriving pore types from the porel size and shape distributions (Ehrlich et al., 1984). The result is a frequency distribution of the “smooth” and “rough” area crass intervals.

The smooth/rough area spectra are then used to derive pore types. The spectra of all porels in a given sample is summed through all views (up to a million individual porels), thus providing the needed precision to decompose the complex nature of porels in the plane of section. In accordance with normal petrographic insight, a reservoir commonly possesses less than ten pore types.

A Polytopic Vector Analysis (PVA) procedure is employed to objectively derive pore types from the image data. SAWVEC A is a principal components algorithm (PCA) used to determine the number of pore types (or end members). Following SAWVEC A and the determination of the number of end members (pore types), the data is submitted to the SAWVEC B algorithm. The SAWVEC B algorithm then produces two types of information: the smooth/rough spectrum (a measure of size and shape) of each pore type and the relative proportion of each pore type in each sample (Ehrlich et al., 1991a). Moreover, the average size of each pore type can also be derived. The data derived here is now sufficient to characterize the microgeometry of a given sample suite. This information can be used in conjunction with physical measurements to characterize the microstructure of any given reservoir. Moreover, another procedure may be employed to quantify the porous microstructure via the use of “mosaic images”.

The “mosaic” procedure utilizes the basic image capturing method described above. However, in the mosaic procedure, juxtaposed images are assembled to make one large “mosaic” image. This is achieved through the overlapping of adjacent views in both the x and y directions. The goal is an image on the scale of the thin section, that will be square. Generally, these mosaic images are large enough to analyze the fundamental structure present in the sample.

The microstructure of pores in sandstones consist of fundamental elements made up of closely packed domains and loosely packed domains (Graton and Fraser, 1935, Prince et al., 1995, and Anguy et al., 1995). The closely packed domains are areas where sand grain boundaries are tightly associated, resulting in regions that exhibit locally low porosity values. Furthermore, loosely packed domains are areas where sand grains are not tightly associated, thus resulting in regions of locally expanded porosity. These loosely packed domains tend to propagate in three dimensions (Prince and Ehrlich, 1990, Prince et al., 1995, and Anguy et al., 1995). Thus, the portion of the microstructure associated with these loosely packed domains would likely control the movement of fluids through the medium. The mosaic images are analyzed via a double-Fourier transform algorithm to discern the fundamental microstructure present in any given sample.

The use of both mercury porosimetry and permeability modeling has implied the existence of preferential “circuits”, or flow paths, through sedimentary fabrics. It is believed that these flow paths are caused by the imperfect packing of sand grains during deposition. During deposition, many localized closely packed domains develop simultaneously. However, these closely packed domains are not necessarily mutually oriented. Thus, where these closely packed zones, with slightly different orientations, interact, a zone of flawed packing arises. These packing flaws can be quantified via a 2-D Fourier analysis of the binary images derived from thin sections as described by Prince and Ehrlich (1990) and Prince et al. (1995).

The 2-D Fourier transform utilizes both rows and columns of binary data. Therefore, the image represented by the function f(x,y) is transformed into a series of spatial frequencies ($F(\omega_x,\omega_y)$), each with a discrete amplitude and phase angle (Prince and Ehrlich, 1990). This is given in Equation 1:

$$\frac{1}{N^2}\sum_{x=0}^{N-1}\sum_{y=0}^{N-1} f(x,y)e^{\frac{-2\pi i(x\omega_x+y\omega_y)}{N}} = F(\omega_x,\omega_y)$$

Where: ω_x,ω_y is spatial wave number.

The 2-D Fourier transform function is reversible. Thus, the original image may be recovered through the use of the inverse transform. This is given as Equation 2:

$$\sum_{\omega_x=-\frac{N}{2}}^{\frac{N}{2}-1}\sum_{\omega_y=-\frac{N}{2}}^{\frac{N}{2}-1} F(\omega_x,\omega_y)e^{\frac{2\pi i(x\omega_x+y\omega_y)}{N}} = f(x,y)$$

Equation 2 is a complex function consisting of a real and imaginary portion, as well as component information related to the harmonic power and phase angle in the 2-D Fourier transform for f(x,y). The spatial wave numbers represent the number of times a feature repeats in the processed image. The harmonic power represents the contribution of any given frequency to the entire image, and the phase angle relates to the position of any given feature with respect to the edge. In application, the harmonic (or radial) power spectrum is utilized to quantify the amount of porosity associated with any given wavelength (see Prince and Ehrlich, 1990 for a complete description).

The Fourier transform is applied to the mosaic of binary images for each sample. The principle form of output used in this study is the radial power spectrum. The radial power spectrum is similar to an X-ray diffractometer trace, yielding information about the size of repeating elements in the binary image. thus, this form of output could be used to discern the size of packing domains.

Analysis of the resolved features from the radial power spectrum suggest spatial relationships of pores, that is closely versus widely spaced pores. Moreover, this information can be extrapolated to spatial relationships of grain packing domains. Therefore, the radial power spectrum can be used to filter for features associated with microstructure of any given sample. Thus, the porosity associated with the packing domains may be quantified. This data can then be related to porosity types derived from the PIA/SAWVEC procedure, and in turn directly to petrophysical properties.

Berea Sandstone

PIA Results. The Berea sandstone is a deltaic marine sandstone of Early Mississippian age, found in the eastern Michigan Basin (Gunn, 1986). The Berea sandstone is a well sorted quartzose sandstone, and contains small amounts of associated minerals including plagioclase as well as trace amounts of biotite, muscovite, and rock fragments. The grains are well rounded and average in size between 250 and 300 micrometers. Quartz is the primary cementing agent, although small amounts of carbonate cement (patchy in nature and generally occluding porosity) is present. The feldspars and rock fragments are in various stages of dissolution throughout the Berea. This dissolution as left some moldic porosity, and resulted in some pore filling clay minerals.

Here, the Berea samples were chosen specifically due to their lack of apparent variation. The traditional thought is that because there is small itersample variation of porosity and permeability, the microstructure is completely homogeneous. However, the PIA procedure indicates that three discrete pore types are present in the Berea sandstone, and exist in varying abundance.

Pore type 1 (PT 1) denotes relatively small intergranular pores, with and average pore radius of 12 micrometers. From the SAWVEC output it is possible to make an inference on connectivity of any given pore type. For example, high percentages of "rough" area suggest a complex pore geometry and a greater likelihood of connectivity to other pores. Following that speculation, the SAWVEC output indicates that these pores are not well connected. The lack of connectivity is likely due to occlusion by quartz cement.

Type 2 pores (PT 2) are also intergranular pores. PT 2 pores possess an average radius of 17 micrometers The SAWVEC output reveals that pores of this type are much more rough than pores of type 1. This complex geometry suggests a higher degree of connectivity between pores of type 2, versus those of type 1.

Pores of type 3 (PT 3) are dominant in the Berea samples, with an average pore radius of 20 micrometers. Type 3 pores are intergranular pores, as well as moldic pores from the dissolution of unstable grains (i.e., feldspars). Type 3 pores also posses a complex pore geometry indicating a high degree of connectivity. PT 3 is only slightly larger than PT 2, and only slightly less complex in shape.

Fourier Analysis Results. The Fourier transform is used to quantify the spatial order of porosity. Each "mosaic" image from each sample was subjected to the Fourier procedure. The radial power spectrum of each sample is examined to determine the maximum grain size. The samples displayed a variation in maximum grain size from 280 to 380 micrometers. The radial power spectra are also used to quantify porosity associated with the "loosely packed domains" or expanded porosity regions. The expanded porosity features for the Berea samples ranged in size 400 to 490 micrometers. The binary porosity images were filtered for the length scale associated with these peaks as described above, resulting in proportion of porosity from each sample associated with the loosely packed domains.

Spatial Order of Berea Pores. T he Fourier variables are used to relate pore types to packing domains In the Berea samples, PT 2 and PT 3 are the largest and the most interconnected pore types. That degree of interconnection implies that the majority of pores associated with PT2 and PT3 lie in the loose-packed domains. A strong relationship between the loose packed domains and pore types 2 and 3 exists in the Berea samples. Therefore, certain pore types are shown to preferentially lie with in certain packing domains

Discussion and Conclusions

The Berea samples originally chosen for their apparent homogeneity prove not to have a completely homogeneous microstructure. Homogeneity is first disproven prove by the PIA pore typing procedure, which yielded a stable three end member solution (3 pore types). The existence of discrete pore types in Berea, indicates that the traditional thought regarding porosity variability does not translate into the microstructure of all natural porous media. Therefore, objective classification and quantification of the pore network via the PIA procedure is necessary Furthermore, spatial order of the packing domains, and thus the sedimentary fabric within the porous microstructure, can be quantified by the Fourier procedure.

The strong relationship that commonly exists between pore size and throat size, ensures that microstructure information will be relevant to understanding the variation of petrophysical properties in reservoir rocks (Ehrlich et al., 1991b). It is thought that the sedimentary packing flaws create flow paths or circuits. Here, a technique was applied that utilizes petrographic images to resolve these flow paths, subdivided into "closely" and "loosely" packed domains. The quantification of porosity (and porosity types) and their spatial arrangement is essential in the understanding of fluid flow in natural porous media.

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