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Analysis and Visualization of 2D and 3D Grain and Pore Size of Fontainebleau Sandstone Using Digital Rock Physics

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Abstract. Fontainebleau sandstone is sandstone found in one of the cities in France. This sandstone has unique characteristics, which is a clean-fine sandstone, composed of 99% quartz, virtually devoid of clay, with the grain size of about 200 µm. Fontainebleau sandstone is widely used as a reference in the study of rock microstructure analysis and modelling. In this work analysis regarding the grain and pore size of Fontainebleau is presented. Calculation of 2D pore size and grain size distribution were done on the 299 slice of digital image of the Fontainebleau sandstone using Feret's diameters, equivalent diameters ($d = 4A/P$), and by means of local thickness/separation using plate model. For the 3D grain and pore size distribution, calculation of local thickness and local separation of the structure were used. Two dimensional analysis by means of Feret's diameter and equivalent diameter reveal that both grain and pore size distributions are in the form of reverse-J shaped (right skewed) while the local thickness/separation approach produces almost similar to symmetric Gaussian distribution. Three dimensional analysis produces fairly symmetric Gaussian distribution for both the grain and pore size. Further image processing were conducted and were succeed in producing three dimensional visual of the colour coded structure thickness (grain related) and structure separation (pore related).

1. Introduction

Digital rock physics (DRP) is an approach to analyze the characteristics of rock by utilizing digital data in the form of digital images, by means of computational methods. In DRP, there are two keys component i.e., the digital representative of the rock or might also referred as the digital sample, and the method of characterizing the digital sample. In obtaining a digital sample one could use a reconstruction method by means of various instruments such as X-ray micro CT and neutron tomography which will produce 3D data, or SEM and optical digital microscope for 2D image output. The advantage of this approach is that the digital data of the sample is highly representative. The other approach is to generate the digital sample using computer model by using various modeling scheme. This approach provide the easiness to manipulate the model's parameters, and the digital samples can be generated far more easily compared to the instruments based reconstruction. The second component is the characterization method which is highly related to the properties of the rock that will be calculated. The advantage of performing digital characterization is that the approach is non-destructive: the sample will be intact after the characterization is being performed. Other than that, the process of characterizing the sample is repeatable, various characterizations are also widely, and by the advancement of computing technology, the process are becoming more and more faster.

Digital characterization is also considered important in terms of generating representative digital sample through computer modeling scheme. The generated models are considered representative when the characteristics match the real samples. Several characteristics have been used as the basis of benchmarking the result from the computer modeling. For example, two point correlation function has been used to describe the similarity of computer models with the real sample [1, 2]. Other physical parameters such as permeability, specific surface area, have also been used to describe the similarity. Statistical properties have also been proved to be quite significant in terms of analysis of the similarity of the microstructure between the computer model and the real sample [3].

This paper presents the application of digital approach to explore the advantage and the possibilities of the digital image processing and analysis (DIPA) as the basic tool in Digital Rock Physics (DRP). Specifically, we aimed to analyze the characteristics of the digital sample of Fontainebleau sandstone by calculating the grain and pore size by means of several methods. The performed analysis was focused mainly on determining the most representative approach in estimating the grain and pore size as well as the distribution. This paper also presents the ability of DRP in visualizing the pore and grain structure of Fontainebleau sandstone.

2. Sample and methods

2.1. Fontainebleau sandstone

Fontainebleau sandstone is a unique sandstone found in France which has characteristics of being clean with 99% quartz of Oligocene age, and contains almost no clay. It is well recognized as a well-sorted, medium-grained, which has connected porosity ranging from 3% to 15%. For a given porosity, the pore geometry can vary significantly. The unique characteristics of Fontainebleau sandstone has made it suitable as a calibration experiments, and a good reference in the study of rock and microstructure modeling. The digital data of Fontainebleau sandstone was produced by means of a μ-CT imaging technique from a 2.25mm × 2.25mm × 2.25mm section of Fontainebleau sandstone which is spatially discretized at a resolution of 7.5 μm/pixel.

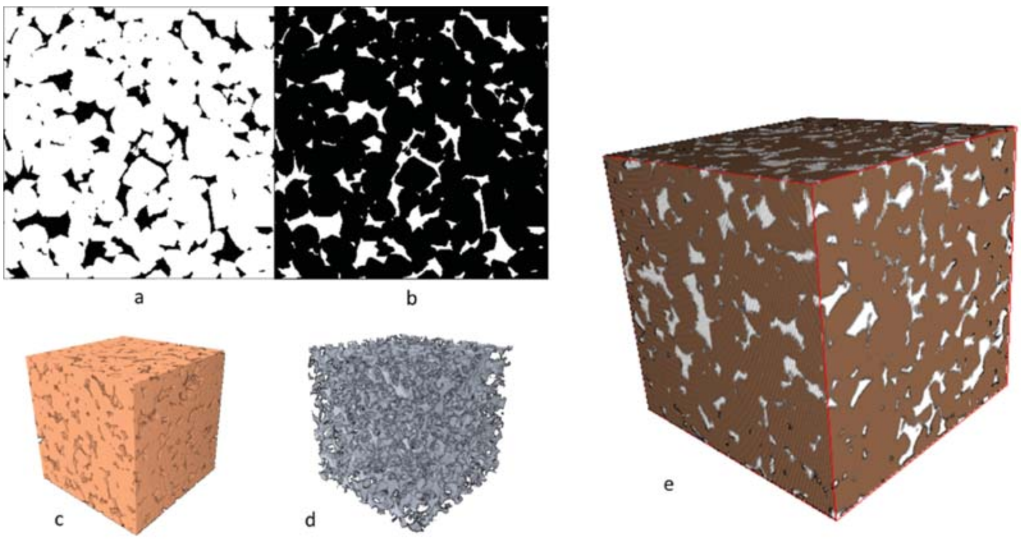

Figure 1. a. 2D slice of the grain structure (white areas are the grains), b. 2D slice of the pore structure (white areas are the pores), c. 3D visual of the grain, d. 3D visual of the pore, and e. 3D visual of the combination of grain and pore simultaneously.

2.2. Grain size and pore size calculation

Grain size and pore size are usually measured by experimental-based methods. Pore size of a porous rock is commonly estimated by mercury injection porosimetry (MIP). This method is basically measures the pressure required to force mercury into the voids of a porous rock and also measures the intruded Hg volume at each pressure at the same time. The pressure is a function of the contact angle (θ), size, and geometry of pores and surface tension (γ). The pores are usually assumed to be cylindrical and the relation between pressure, P (expressed in Pa), and equivalent pore diameter, d (expressed in mm), is given by the Young-Laplace equation [4]:

$$P = -\frac{4\gamma \cos\theta}{d} \tag{1}$$

Grain size is often measured by sieve analysis. In this method, the sample is crushed and the grains are passed through a sieve with certain size. The volume of grains which do not pass each sieve denote the fraction of the rock related to the grain size.

In this study we analyze both grain and pore size of the digital Fontainebleau sample using 2D and 3D approach. The 2D approaches are calculation of Feret's Diameter (FD), Equivalent Diameter (ED). Feret's diameter is defined as the longest distance between any two points along the selection boundary, also known as maximum caliper [5]. Equivalent diameter is calculated as d = 4A/P where A is the area of the object and P is the perimeter. FD and ED can be applied on both grain and pore by interchanging the phase in the processed images. For calculation of grain diameter, the object is the solid part (defined as white which has binary value of 1), as for calculation of the pore diameter, the image is inverted thus the pore is defined as white.

We also used the diameter estimated by Local Thickness (LT) approach. The diameter estimated by Local Thickness is also known as structure thickness that gives an estimation of the grain size which it measures the estimation of the thickness of the object. The local thickness which is the diameter of the largest sphere (for 3D measurement, and circle for 2D measurement) is estimated by fulfilling two conditions defined by Hildebrand and Ruegesegger [6] . The property often referred as estimated grain size. The estimated pore size can be obtained also by inverting the image thus creating a set of images where the white (with binary value of 1) is the pore space. For the 2D pore & grain size calculation, the LT approach uses the 2D slices as the plate model for input of the calculation.

3. Result and discussions

The calculations were performed on the Fontainebleau sandstone to obtain the distribution of the grain size and pore size in 2D and 3D. Subsequently, the average, minimum and maximum grain and pore size can also be calculated.

3.1. Pore size and grain size distribution

The result from calculation of the mean, minimum, and maximum of grain size are presented in Table 1 while the result from calculation of the mean, minimum, and maximum of pore size are presented in Table 2. Based on experiment by Song and Renner [7], the grain size is in the range of 180 - 270 μm while the pore size is in the range of 20 - 50 μm. The grain size distribution is in the form of a fairly symmetric Gaussian distribution. On the other hand, the pore size distribution display pattern of long tails in the direction of pore sizes comparable to the largest grain size.

Based on the result presented in Table 1, Feret diameter and Equivalent diameter produce underestimated value of the minimum grain and pore size, and also yield overestimated value of the maximum of both grain and pore size. Among them, the Feret diameter gives much larger mean diameter. The 2D local thickness measurement of grain size produced better result compared to other measurements. For pore size, the 3D local thickness measurement returned a better result compared to the other ones, even though all the measurement produced overestimated value of maximum pore size.

TABLE 1. Result of mean, minimum and maximum value of the grain size obtained using Feret diameter, Equivalent diameter, and local thickness (2D and 3D). All values are measured in µm.

	Feret 2D	Eqiv 2D	Local 2D	Local 3D
Mean	643	245	176	189
Min	11	10	153	23
Max	3182	1652	207	368

TABLE 2. Result of mean, minimum and maximum value of the pore size obtained using Feret diameter, Equivalent diameter, and local thickness (2D and 3D). All values are measured in µm.

	Feret 2D	Eqiv 2D	Local 2D	Local 3D
Mean	118	39	27	54
Min	11	10	23	23
Max	1260	200	207	173

Figure 2 shows the distribution of the calculated diameters. figure 2 a,b,c shows the distribution of the grain size obtained by applying the (a) Feret's diameter, (b) Equivalent diameter, (c) Local thickness measurement on 2D slices of the Fontainebleau sandstone image set in the z (trans-axial) direction. figure 2 d,e,f shows the distribution of the pore size obtained by applying the (a) Feret's diameter, (b) Equivalent diameter, (c) Local thickness measurement on 2D slices of the Fontainebleau sandstone image set in the z (trans-axial) direction. Figure 3 shows the grain and pore size distribution obtained using 3D local thickness measurement.

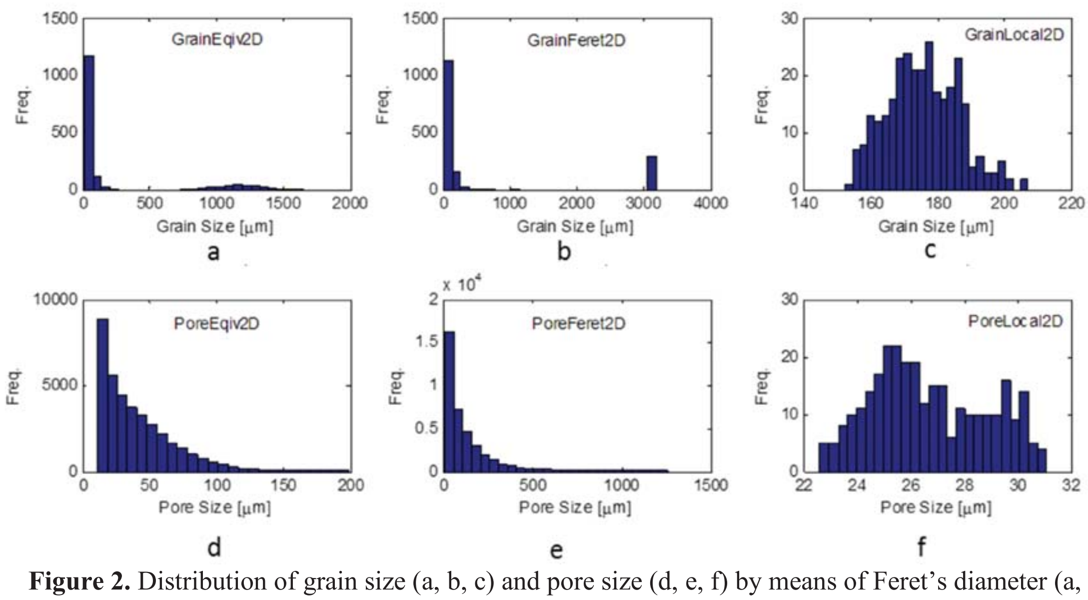

Figure 2. Distribution of grain size (a, b, c) and pore size (d, e, f) by means of Feret's diameter (a, d), Equivalent diameter (b, e), and the Local Thickness (c, f) measurement on 2D slices of the sample.

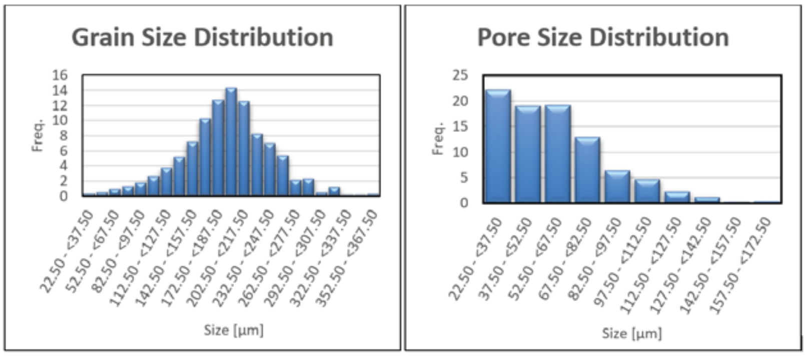

Figure 3. Left: grain size distribution obtained from 3D local thickness measurement. Right: pore size distribution obtained from 3D local thickness measurement.

As seen in figure 2, the Feret diameter and Equivalent diameter approach produced quite similar results of both the grain size and pore size diameter, i.e., the right skewed distribution. The grain size distribution obtained from these two methods might be interpreted that the medium is poorly sorted, on the contrary to physical observation that the Fontainebleau sandstone is well-sorted. However, the pore size distribution matches the description from [7], i.e., exhibit long trail in the direction of the grain size. On the other hand, the 2D local thickness measurement produced fairly symmetrical Gaussian distribution for both grain and pore size distribution which is match the ones from [7] for the grain size, but not the pore size distribution. In figure 3 we observe the pattern that matches the one described in [7]: fairly symmetrical Gaussian distribution of the grain size, and a right-skewed distribution of the pore size distribution.

These pattern describes several feature of the sample. The similarity of the pore size distribution from the Feret diameter, Equivalent diameter and the 3D local thickness measurement with the reference [7] describe that the 2D pore structure of Fontainebleau sandstone exhibit similar characteristics to the 3D structure, thus the 2D approach produces suitable result. However, the difference of the pore size distribution obtained from the 2D local thickness method might be caused by the sliced particles on the boundary of the sample, thus gives underestimated value of minimum pore size as well as the shifted distribution, from right-skewed to Gaussian.

The difference between the grain size distribution from the Feret diameter and the Equivalent diameter with the 2D and 3D local thickness measurement as well as the reference [7] describe that the 2D grain structure of Fontainebleau is unrelated to the 3D grain structure. This can be interpreted that the description of the grain structure might be dependent to the slice direction, although this still needs to be confirmed by performing 2D analysis on other slice direction (x, and y). The right-skewed pattern could also be caused by the existence of isolated grains in 2D slices. On the other case, the similarity between the result from 2D and 3D local thickness for the grain size distribution describe that the method predicts the circularity pattern of the grains (from 2D analysis) having a similarity to the sphericity pattern of the grains (from 3D analysis), thus can be described that the grains are generally do not have certain direction of elongation. The distribution of the pore and grain can be visualized as described in the next subchapter.

3.2. Pore Size and Grain Size Visualization

The method of obtaining the pore and size distribution by means of 3D local thickness is based on the calculation of local separation for a point in pore as defined by Hildebrand and Ruegsegger [6] as the diameter of the largest sphere which fulfils the conditions as follows: the sphere encloses the point (but the point is not necessarily the center of the sphere) and the sphere is entirely bounded within the pore surfaces. The local separation itself is based on the distance transform methods [8] . The method starts with a “skeletonization” to obtain the medial axes of all structures and the “sphere-fitting” local separation measurement is then made for all the voxels lying along this axis. The grain and pore size distribution can be measured the same way by inverting the solid-void phase of the structure, depending on the one that we would like to measure (the white part of the image is the phase that will be subjected to the distance transform measurement).

The distance transform method produces a set of images consisting the number which represent the calculated distance from the medial axes. The generated value of the calculated distance is small, only in the leftmost range of the grayscale value. Thus if we want to visualize the result, it would only generate dark image. Through simple image processing, a suitable color coded image can be generated. The steps of obtaining such image is described as follows (the steps can be applied to any dataset which already in binary or black and white images):

1. Using the binary image of the digital sample (IM0), calculate the local separation based on the distance transform implemented in CTAn (CT Analyser, Bruker MicroCT) producing a set of image which contains value of the calculated distance transform. The new dataset (IM1) can be visualized in CTVox or any other software such as Fiji/ImageJ, however, the grayscale images will all appear as uniform black images.
2. IM1 can be visually enhanced by using custom color palette available in software such as CTAn and Fiji/ImageJ. However, the applied custom palette does not actually modify the image. There are two procedure that can be applied to produce the real color coded:
   - Using Fiji/ImageJ: adjust the window level by applying auto-level which will stretch the grayscale value. Subsequently, a suitable color palette can be chosen arbitrarily from the *Lookup Tables* to produce a set of color coded image based on the grain/pore size (IM2).
   - Using CTAn: expand the histogram of IM1 by performing arithmetic multiplication of IM1 with a multiplication factor depending on the original IM1 gray level range. Subsequent to this step, which only produced grayscale image with expanded histogram, DataViewer software (Bruker MicroCT) can be used to apply custom color palette and to further convert the grayscale image to color coded image (IM2).
3. The produced color coded image (IM2) can be visualized as shown in figure 4 and figure 5.

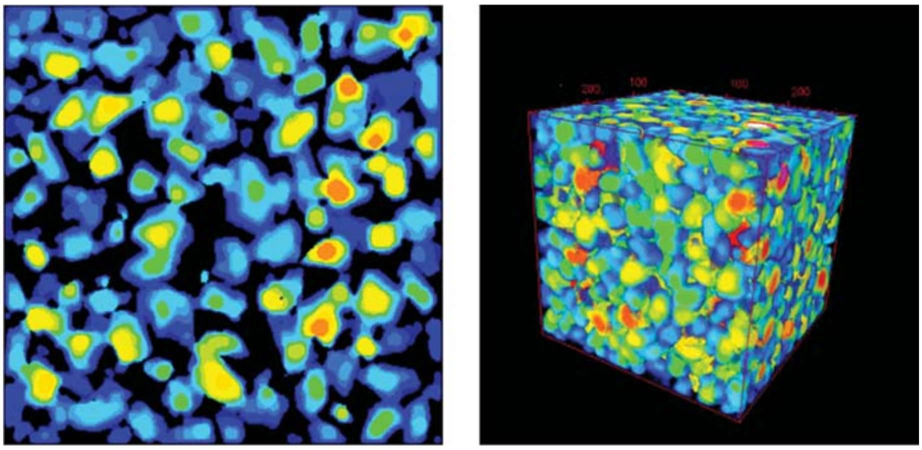

Figure 4. Left: grain size distribution obtained from 3D local thickness measurement. Right: pore size distribution obtained from 3D local thickness measurement (visualized using Fiji/ImageJ with Lookup Tables 16 colors).

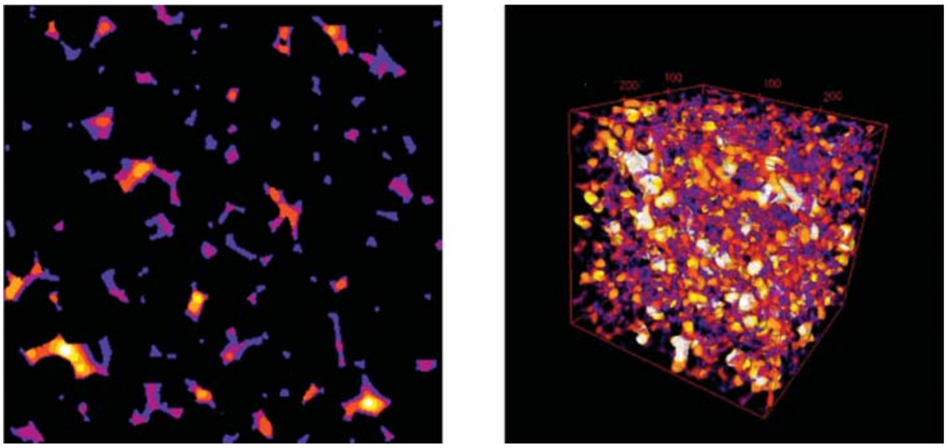

Figure 5. Left: grain size distribution obtained from 3D local thickness measurement. Right: pore size distribution obtained from 3D local thickness measurement (visualized using Fiji/ImageJ with Lookup Tables Fire)

The produced color-coded images for both grain and pore size distribution can be visualized in 2D, Orthoslice as well as in 3D using various software. The advantage of having these images is that we can visually observe and qualitatively analyze both the grain and pore structure of the sample. By analyzing figure 4 (the 2D slices), we can identify the rough pattern of the grain distribution, i.e., the sample shows the dominance of large grain. On the other case, by analyzing figure 5 (the 2D datasets) we can also identify the rough pattern of the pore distribution, i.e., the sample contains large number of small pores. These qualitative analysis are consistent with the produced size distribution.

4. Conclusion

The applied digital image processing and analysis has been proved to be suitable in providing information regarding the grain and pore size distribution as well as the mean, minimum and the maximum range of the size. The DRP approach provides easier way to produce such information, compared to experimental based one. Two dimensional analysis by means of Feret's diameter and equivalent diameter reveal that both grain and pore size distributions are in the form of reverse-J shaped (right skewed). The 2D local thickness/separation approach produces almost similar to symmetric Gaussian distribution. Three dimensional local thickness analysis produces fairly symmetric Gaussian distribution for grain and size and reverse-J shaped distribution. By comparison to previous researches, the 3D local thickness approach produces best result for grain size distribution, and the 2D local thickness approach produces best result for pore size distribution. For future works, the validation of various microstructure modeling scheme can be enhanced using comparison of the grain and pore size distribution by means of the local thickness measurement. Visualization of the size distribution can be easily performed by applying a simple digital image processing which later provide a qualitative way of analyzing the microstructure characteristics of the digitized sample.

Acknowledgments

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