# INFLUENCE OF GRAIN SORTING AND GRAIN SHAPE/ELONGATION ON THE INTERGRANULAR POROSITY OF CUBIC PACKING FOR SEDIMENTARY ROCKS

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**Abstract.** Porosity, being the main storage parameter in porous reservoir rocks, relates to the microscopic void spaces in rocks where oil and gas are accumulated. Diagenetic processes may damage porosity since they affect the systematic arrangements of grain particles and causes grain rearrangements. The extent to which the grain rearrangements may occur depends on the original packing of the grains and how extensively the packing has now been modified. The present study deals with the geometry of cubic packing of grains for a sandstone and carbonate rock core samples obtained from different parts of India which are known for undertaking hydrocarbon activities. Cubic packing is studied including the theoretical model along with the obtained model from the digitally analyzed image through Field Emission Scanning Electron Microscopy (FESEM) with the help of MATLAB coding. A set of particles (idealized as spheres of varying radii) was added to the ideal cubic assemblage of eight spherical particles and thus, the effect of grain sorting on intergranular porosity was observed. The same model was taken into account to estimate the effect of degree of elongation. But the only difference was a set of particles (idealized as spheres of varying radii) was added to the ideal cubic assemblage of eight elongated particles. Thus, it is concluded that the nature of pore systems at micrometer to millimeter scale gets affected by the grain sorting. Digital images acquired from FESEM-Back Scattered Electron imaging gives promising inputs for grain size distribution which in turn discloses the frequency of available grain sizes corresponding to different size ranges. Porosity obtained from cubic assemblage influences the shape and degree of elongation of the grains responsible for the formation of interstitial pore spaces which may affect the storage capacity of porous reservoir rocks.

**Keywords:** Porosity, Cubic Packing, Grain Size Distribution, Degree of Elongation

# 1 Introduction

The quantification and characterization of reservoir rock properties is most valuable in numerous fields, e.g., geology, geophysics, geochemistry, hydrology, hydraulic fracturing, reservoir engineering, petroleum exploration, mining, and civil engineering [20]. In each of these research areas, certain rock parameters are more important, depending on the particular area. Apart from other physical properties, porosity and permeability are the fundamental properties of sedimentary rocks to have a significant effect on the hydrocarbon storage and production [10]. For modeling flow through porous reservoir rocks, realistic numerical data of porosity is needful to characterize the nature of pore systems at various scales, prominently at minute scales. Primary syn-depositional porosity of sedimentary parameters may get varied due to differences in grain size, shape, roundness, sorting and packing, or due to the filling of finer reflux between larger grains. Also, porosity differences may result from post-depositional diagenetic processes such as grain rearrangement, pore filling with crystalline material or modification of the original grains by physical and chemical processes [16, 21]. Thus, depositional processes are most damaging to porosity during early burial because of packing changes and ductile grain deformation [2].

Grain rearrangements during these processes can be quantified indirectly by modeling different packing arrangements theoretically to calculate porosity. This effective utilization of space by mutual arrangement of the constituent grains of an aggregate is called packing [20]. Depending on the mode of deposition, all natural sediment particles existing in their natural form may or may not be packed in their tightest possible manner and their packing can range from loose random packing to dense random packing. The extent to which the grain rearrangements may occur depends on the original packing of the grains and how extensively the packing has now been modified [21]. This modification in grain rearrangements will have an effect on the physical properties of the material. The present study focusses on the influence of packing of grain particles on the physical property called porosity.

Ideal assemblages of systematic packings composed of uniform size of grains have no influence of grain sizes on their porosity. It has also been shown that along with a grain size of uni-modal well-rounded spheres, the grain size of the uni-modal prolate grains also have no effect on the intergranular porosity of different types of ideal packings [16]. But it is very difficult to represent actual conditions with uniform size of grains available in it as this type of condition rarely occurs in nature. The presence of non-uniform sizes affects the porosity of rocks because they have a direct impact on the arrangement of grains and pore throat size which is the main influential parameter in the porosity estimation [18]. The more non-uniformly graded the material is, smaller the pores between the grains, hence smaller the porosity values. At the same time sorting also play an influential role in porosity value as the comparatively smaller size of grains fills the space available between the larger grains resulting in lower porosity compared to the previous one. Spherical sized grains have less porosity compared to non-spherical grains as spherical grain settle in denser arrangement than that of non-spherical grains creating wider space which contributes to higher porosity. Packing of two or more shapes tends to block and cancel the effects of radical shape while in only single-shape packs it causes a wide grain volume range and much wider space for porosity [24].

It is advantageous to consider the simple type of packing like cubic and then to examine the deviations that become more and more complex and chaotic [9]. Graton and Fraser (1935) have established that in assemblages of uniformly sized spheres, the porosity ranges from a maximum of 47.6 percent if the spheres are cubically packed. Various experiments have been conducted to find out random packing density of spheres. The maximum packing density (volume fraction of spheres) is approximately 0.64 in the random close-packed (RCP) limit for hard spheres [4, 8, 23, 24, 27]. But the influential factors for packing density are particle shape and method of packing: regular or irregular(random), where the latter furthermore gets affected by the densification [3]. Packing density higher than 0.64 can be achieved by using a collection of particles with a variety of sizes that is grain size distribution. Desmod and Weeks (2014) have numerically generated number of sphere packings with different particle radii distributions like binary, linear, Gaussian and lognormal, varying polydispersity and skewness independently of one another. But, they truncate certain distributions with the particle size to generate packings within a reasonable time frame. Dexter and Tanner (1972) have specified that granular materials have a grain size distribution which is well defined by a log-normal distribution function, that is, the weights of the particle sizes present are distributed normally with respect to the logarithms of the respective particle diameters. They have proved that as the standard deviation increases, packing density increases.

The present study deals with the cubic assemblage of discrete grain particles of different shapes that include equi-sized spherical as well as equi-sized elongated grains. Cubic assemblage is formed when a square layer, in which two sets of rows intersect at $90^{\circ}$, overlie upon the second square layer. Two hemispheres and one cylinder having a diameter equal to those hemispheres, together form each elongated grain. In the present study, an attempt is made to compose a model which has a framework of eight spherical grains, to which further a set of grains was added to observe the effect of sorting. The same model was repeated with eight elongated grains as a framework and then intergranular porosity was calculated.

## 2 Methodology

### 2.1 Sample Description

For the analysis, one carbonate and one sandstone core plug sample of approximately 2.5 cm diameter from different parts of India (Sandstones from upper Assam Arakan basin and carbonate from Bombay offshore) were collected for porosity analysis. Bombay Offshore basin is located on the western continental shelf of India between Saurashtra basin and Kerala Konkan in the south covering an area of 120000 square km from the coast. The basin is in the late Cretaceous to Holocene age [15]. While upper Assam basin being a part of Assam-Arakan basin is mostly of Tertiary and Quaternary age [17].

## 2.2 Field Emission Scanning Electron Microscopy (FESEM)

A scanning electron microscope uses secondary electrons and backscattered electrons for imaging samples which gives enough data at sufficient resolution by which the pore space distribution can be realistically described. FESEM uses the field emission gun firing electrons to scan the area concerned. The ideal resolution of this microscope is 0.5 nm which can typically reach up to 5 nm with 30 kV with conducting material whereas it can be reached up to 50 nm with non-conducting material such as rock [12]. Secondary electrons show morphology and topography on samples, while backscattered electrons illustrate contrasts in composition in multiphase samples [1].

The significance of FESEM study is its fixed magnification ratio for observing the pore structure on a given location of a sample and also the appropriate number of FESEM images need to be taken for the description of the sample as it is difficult to identify the features like smallest pore structure including matrix pores and organic matter nanopores of sample if the magnification is not appropriate enough [5].

Sample preparation for this instrument is very important as the smooth flat surface is required for clear imaging. Before analyzing it in the microscope the sample surface should be dried to avoid absorption of X-ray and coated with gold to avoid charging [13]. This method is faster and less expensive than other conventional methods. Image collected by FESEM is a rich source of information for variability in porosity, mineral distribution [18]. Backscattered electron image is collected and image processing is applied to make the image more informative by filtering it and extract the pore information quantitatively. Fig. 1. Shows a digital image of carbonate sample acquired from FESEM (Make-Ziess and Model- Sigma) Back Scattered Electron imaging.

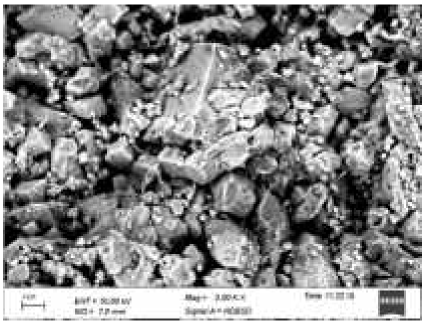

**Fig. 1.** FESEM-BSE image of a carbonate rock sample collected from Bombay offshore basin.

## 2.3 Analysis of FESEM Images

The analysis of the images obtained through FESEM can be done using various platforms such as ImageJ, MATLAB, etc. [19]. ImageJ enable to estimate porosity based on thresholding which includes connected and isolated pore spaces. In such case, grain size distribution plotting becomes tedious as one has to measure all grain sizes manually which may incorporate manual errors. Here the whole study has been done using MATLAB software, to provide for an alternative for the much used ImageJ. The development of MATLAB code focus on plotting the grain size distribution instead of pore size distribution, because a set of grain sizes is needed to observe the effect of grain sorting on the intergranular porosity. Fig. 2. shows the flowchart of the workflow to obtain porosity of available samples.

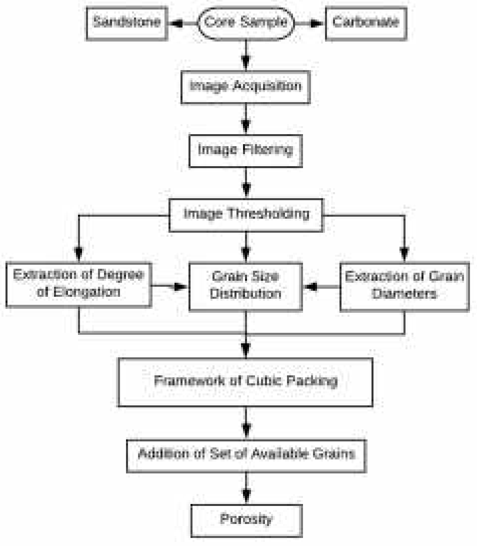

**Fig. 2.** Flowchart of the workflow to obtain porosity of available samples.

**Filtering.** Before performing calculations of porosity of the rock, it is important to apply noise removal filters which remove the arbitrariness in the images to a great extent. Processing of the image was started by applying Gaussian filter to enhance the image properties to remove noise as well as to remove small details from image prior to large object extraction and bridging of all small gaps in lines and curves. The new value of the pixel is assigned as the weighted average of the neighborhood pixels. Fig. 3. shows the original and filtered image for carbonate sample.

**Thresholding.** The FESEM images obtained are 2D -raster images of the sample. A threshold value was used to differentiate pores from the rock grains which was obtained from Otsu’s threshold method. After thresholding, the processed images were obtained and was compared with the original FESEM obtained image manually to ascertain whether the threshold value actually represents the sample. Otsu thresholding was used to convert a grayscale image into a binary image. Iteration of all the possible threshold values to calculate a measure of spread for the pixel levels each side of the threshold is done by Otsu’s thresholding method. The aim is to find the threshold value where the sum of foreground and background spreads is at its minimum.

**Fig. 3.** Carbonate Sample a) Original Image b) Filtered Image.

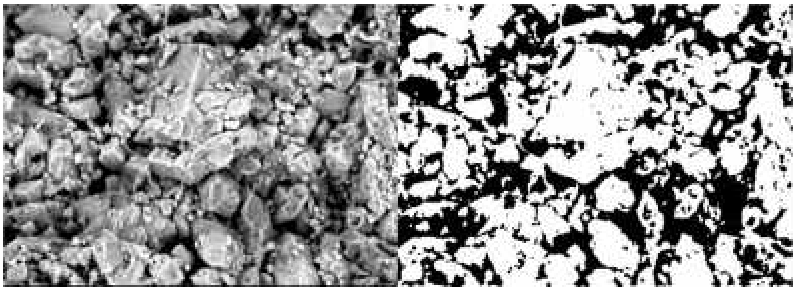

**Fig. 4.** Carbonate Sample a) Original Image b) Image after thresholding.

**Grain size distribution.** The grain diameters, as well as the maximum length between the farthest pixels of the grains, were measured. The shape anisotropy expressed by grain elongation E was calculated using the equation given by Nabawy (2014):

Degree of Elongation (E) = the length of the grain / the diameter of the grain

Different classes consisting of different range of particles were segregated so as to identify the diversity of the grain sizes present in the sample that was obtained through FESEM analyzed an image in turn to get a histogram of frequency versus grain sizes. Maximum likelihood Technique was used to find out the distribution that fits best to the available data. SPC for excel tool by BPI Consulting LLC was used for statistical analysis of the data [23]. The goal of maximum likelihood is to find the parameter values that give the distribution that maximize the probability of observing the data. In some cases, as the range of data is less, probability plots are plotted to find the goodness of fit of the distribution. If the probability plot is close to a straight line, then the specified distribution fits the data.

This grain size distribution was used to add another set of spheres within the available pore spaces of cubic packing. The limiting packing density to add another set of spheres was taken according to the equation given by Dexter and Tanner which takes into account the standard deviation of the available set of particles.

The equation to represent packing density as a function of standard deviation is given as

$$D = D_f - (D_f - D_0)\exp(-M\pm) \tag{1}$$

Where D is the packing density, $D_0$ = 0.6366 $D_f$ =1, is the final limiting packing density as $\pm \rightarrow 0$, $M$ = 0.19, ± is the standard deviation of a given set of grain sizes. The given equation is valid for $0 < \pm < 0.7$.

## 3 Results and Discussions

The estimated grain sizes from FESEM analyzed image were plotted against the frequency of their occurrence to get a grain size distribution as shown in Fig. 5. Similar histogram analysis was done for carbonate sample. The statistical analysis of grain size distribution for both samples show that samples follow a lognormal three-parameter distribution with a P-value of 0.46 for a carbonate sample and that of 0.86 for sandstone sample. The standard deviation of the grain size distribution is presented in figure 7. The standard deviation of the carbonate and sandstone samples corresponds to 0.002 and 0.003, respectively. Such a less value indicates that addition of a set of grains to the remaining pore spaces can follow the equation (1) given by Dexter and Tanner (1972) to estimate packing density which in turn gives porosity of the packing. Histogram presented in Fig. 5. shows that fine sized grains have more frequency of occurrence in the focused part of the sample as compared to the coarse sized grains. Thus, the sample has a higher chance of getting filled by finer reflux within pore space.

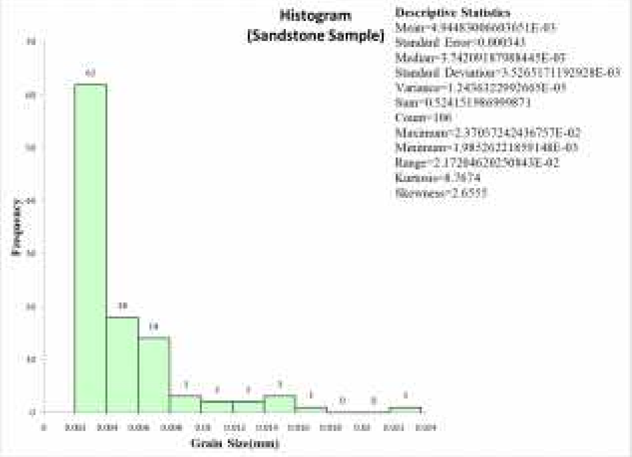

**Fig. 5.** Grain Size Distribution of Sandstone Sample

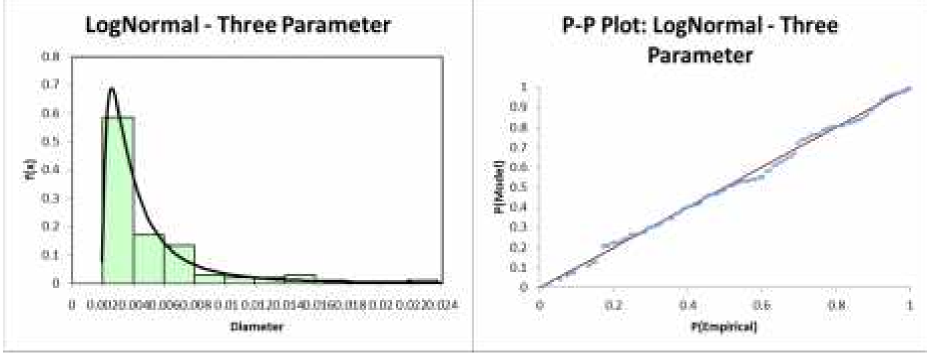

**Fig. 6.** Statistical Analysis of Grain Size Distribution of Sandstone Sample

Porosity values based on cubic packing assemblage in figure 7 Show a different range of values of porosity. From the studied samples, the uniform size of grains irrespective of their shape does not influence on the porosity of packing. But the addition of a set of grains within the available void spaces affects the packing porosity. Addition of another set of grains occupies the remaining pores and causes porosity reduction from 47.60% to 20.26% and 17.44% for carbonate sample and sandstone sample respectively.

The anisotropy of grains was observed by measuring the degree of elongation of both the samples. The maximum measured value of the degree of elongation (E) within all grain sizes was 2.07 for carbonate while 2.25 for sandstone sample. When sorting of grains is considered to add a group of grains within the available pores of cubic packing of elongated grains, the value of porosity gets considerably reduced as compared to spherical grains. Thus, observed results show a direct effect on the intergranular porosity of cubic assemblage. It was observed that the uniform grain size irrespective of shape does not influence on the intergranular porosity. But on the addition of a set of grains from available grain size distribution, mixing of different sizes of particles utilize the pore space available thus reduce the porosity of resulting assemblage.

## 4 Conclusion

In this study, different grain sizes of carbonates and sandstones were measured from the obtained FESEM analyzed images. As an alternative for conventional ImageJ software, a MATLAB code was developed to serve as a substitute for measuring quantitative data from digital images. The code was successful in extracting grain sizes, which includes, grain diameters and the degree of elongation of grains. The developed code is applicable to FESEM –BSE image of polished rock surface. These measured grain size values were then used to plot the grain size distribution. The statistical analysis of grain size distribution implied that both the distributions are lognormal-three parameters. These parameters were then used to form cubic assemblage. A new methodology was developed in terms of packing density and grain sorting to introduce a set of grains to the existing assemblage, which made possible to mix different sizes of grains in a single model. Mixing of different sizes of discrete spherical particles to ideal cubic assemblage causes significant reduction in porosity. Anisotropy factor of grains was included in the model in terms of their elongation. It was observed that the extent of porosity reduction upon adding of different sizes of spherical grains to a cubic assemblage of elongated grains, was more than the extent to which porosity reduction occurred in case of the cubic assemblage of spherical grains. Thus, it is concluded that the nature of pore systems at micrometer to millimeter scale gets affected by the grain sorting. Grain anisotropy has a significant influence on porosity as the value gets reduced considerably as compared to isotropic grains. Digital image analysis technique focusses small area of the sample to derive grain size distribution. Hence to estimate reservoir porosity, analysis on repetitive small samples is required to get an overall description. The study shows the effect of grain shape in terms of degree of elongation and grain size distribution in terms of degree of sorting on porosity.

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