PETROPHYSICS, IMAGE ANALYSIS, AND SAMPLE SIZE

Christopher M. Prince
VP Imaging Technology, PTS Laboratories, Inc., Houston, TX

This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Calgary, Canada, 10-12 September, 2007

ABSTRACT

The relationship between the characteristics of the pore network and petrophysical properties such as permeability is a stochastic one. This means that in order to quantify, or even investigate petrophysical relationships using image analysis a large sample is required. There are exceptions, but as a rule a sample size of a few millimeters and an image containing a few dozen pore bodies is not adequate to the task and any mathematical models relating petrology to petrophysics based upon such imagery are doomed to failure.

Sample size is the key. For example, clastic sediments are relatively simple in that the pore fabric in clastics is relatively consistent and a sample the size of a 1 to 2-inch core plug is generally enough to quantify the pore fabric in fine- and very fine-grained sands. At deposition all particulate solids self-assemble into clusters of well-packed grains separated by packing flaws. The packing flaws constitute zones of expanded porosity that are responsible for virtually all of the fluid flow through the pore network. The flaw network persists during dewatering and cementation and the diameter of the flaws can be used to measure permeability with a high degree of accuracy.

This important relationship has been built upon hundreds of thin sections imaged over the past 15 years at resolutions of 2 microns or higher, producing imagery that contains tens of thousands of pore bodies, not just a few dozen. Such images have been used for many years to calculate permeabilities, NMR characteristics, and other petrophysical properties with a high degree of accuracy.

INTRODUCTION

Sample size is not often discussed in the literature, but it remains one of the most important underpinnings of the analytical procedure (Size, 1987). Samples must be representative of the lithology from which they are taken and large enough to be fully descriptive. Both petrologists and petrophysicists in the petroleum industry are somewhat limited in that their samples are generally samples of opportunity, 1 to 2-inch core plugs taken at either a regular or irregular spacing. From these samples we have to measure a wide variety of properties ranging from the grain size distribution to irreducible water saturation. The goal of this paper is not to debate the efficacy of core plug samples. On a practical level we are limited to 1 to 2-inch core plugs. They form the basis of decades of research. The goal of this paper is to discuss sample size as applied to image analysis at the macro scale, that of a standard core plug.

Some of the first efforts at image analysis of porosity were simply designed to be able to quantify the shapes and sizes of porosity and unambiguously image porosity in thin section (Fabbri, 1984, Crabtree, et al, 1984), but when applied to petrophysics these efforts broke down for a variety of reasons, but principally among them was sample size. Analysis was limited to 30+ individual binary images of porosity, each containing 10-30 ‘pores’ (pore bodies exposed in thin section). This produced a sample containing at most a few hundred individuals to create a size/roughness spectrum (Ehrlich, et al, 1991). The relationship between petrology and petrophysics is a stochastic one and requires samples based upon thousands of individuals, not hundreds.

Normally, when we discuss sample size, we are trying to determine a sample size that will minimize the inter-sample variance between adjacent samples. In image analysis we have another important consideration, the yardstick we are using. The fundamental unit in image analysis is the pixel or voxel. It is a discrete unit, and given a discrete measurement system it is not possible to measure at a precision greater than the pixel size. For example, if we are trying to measure the size of any object in an image, no matter if it is truly a discrete object like a mineral grain, or it is one that has been discretized by selection. If the length of that object is 10 pixels, the best that we can do is measure within 5% of its ‘true’ size; 7% if we are measuring on a slant relative to the orientation of the image. The net result is that, given a fixed image space we are in a constant trade-off between precision and sample size (Figure 1).

If our objective in image analysis is to relate the characteristics of the pore network to some petrophysical property, a fixed image space of 512^2, 1024^2, or 2048^2 may not be adequate to the task. For example, a simple experiment was conducted to measure one of the most basic petrophysical parameters: porosity. It should be stated that the ‘porosity’ we are measuring is ‘optical porosity’ which does not include any pore surface features finer than approximately 1.5 times the pixel size; nor does it include individual pore bodies smaller than approximately one half the thickness of the thin section. Experience has shown that it is more akin to ‘effective’ porosity (Prince, 1999).

Three samples were selected for their homogeneity and their relative lack of diagenesis. Sample 1 and Sample 2 (shown in Figure 1) are unlithified sands from the Gulf of Mexico and were imaged at 1.9µm resolution. The images cover an area of ~1.6cm x 1.6cm, which is approximately the size of the largest square area within a standard core plug. Sample 3 is a well-sorted quartz arenite from the Fontainebleau sandstone. It was imaged at 4.4µm resolution and covers approximately the same area. Total Optical Porosity (TOP) for each sample is listed in Table 1 along with the mean and modal grain size.

Each image was iteratively sampled for porosity in a grid pattern starting with a sample rectangle measuring 50 pixels on a side. Sampling the entire image, the porosity was calculated for each sample rectangle. From these, a mean and standard deviation were derived. At that point the sample size was increased by 50 pixels and the process repeated, calculating the mean and standard deviation for sample sizes ranging up to one half the image height.

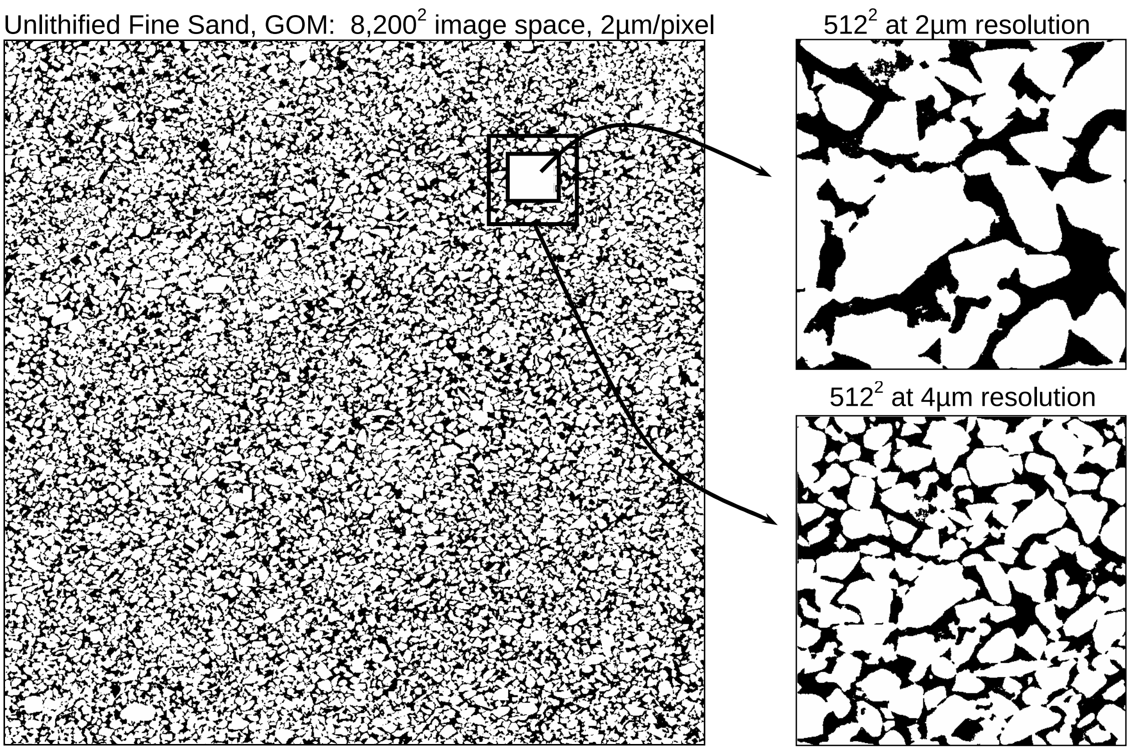

Figure 1 – An illustration of sample size in relation to image analysis. Ideally, our sample size should be large enough to minimize the intra-sample variance. From a sedimentological standpoint, we would like the sample to be large enough to capture some of the spatial information, associated with packing and fabric. If our image space is limited to 512 x 512 pixels, in order to achieve 2µm resolution we must use a sample size containing at most two dozen grains/pore bodies, or we can opt for lower precision and capture a sample containing a few dozen grains/pore bodies. Neither of these samples capture macro-scale spatial information.

The results, shown in Figure 2 show several relationships between sample size and porosity. Note that when the sample size is less than the grain size the standard deviation is very high. Given a sample size less than or equal to grain size, a large proportion of the subsampled areas are completely filled with 'grain' or 'pore'. The graph also suggests that at 1.9µm resolution with a grain size of approximately 200 µm an image space of 1024^2 or 2048^2 may not adequate to obtain a reliable measurement of porosity. The standard deviation does fall below 1 PU until sample size reaches 3-5mm. With its lower resolution, the standard deviation obtained from Sample 3 never falls below 1.5PU. Finally, if grain size were the limiting factor we would expect the standard deviation to fall much more rapidly than it does. The curve does not begin to flatten until the sample size reaches 1 mm, approximately 5 times the modal grain size, and there is significant variation extending out to 5mm. This suggests that there is some larger multi-grain fabric element that must be accounted for in any sample, and these samples were chosen for their homogeneity and relative lack of diagenetic modification. Both of these processes tend to increase macro-scale heterogeneity.

	TOP (%)	Mean (μm)	Mode(μm)
Sample 1	27.0	225	181
Sample 2	30.8	215	192
Sample 3	26.7	225	210

Table 1 – Total Optical Porosity, mean grain size, and modal grain size.

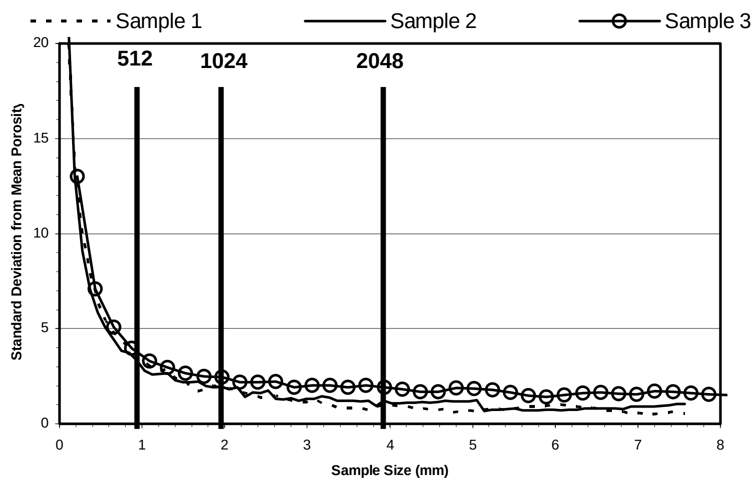

Figure 2 – Standard Deviation in porosity versus sample size. The vertical lines denote a sample size of 512^2, 1024^2, and 2048^2 pixels at 1.9μm resolution.

Small-Scale Fabric

At deposition, sedimentary particles spontaneously aggregate into well-packed clusters of grains (Prince, *et al*., 1995). No long-range process exists to align the internal fabric of these domains. Therefore, as sedimentation proceeds and these clusters grow, they ultimately impinge upon one another, creating a compromise zone or 'packing flaw'. Packing flaws propagate throughout the matrix forming an interconnected network of large, well-connected pores, the 'permeability circuits' of Graton and Fraser (1935).

Given that this fabric element exists, the porosity in the image can be segregated into two fundamental classes (i) 'expanded porosity' comprising large, well-connected porosity associated with packing flaws, and (ii) 'well-packed' porosity comprising small, poorly-connected pores associated with the grain clusters. Figure 3 contains the Fontainebleau Sandstone image filtered to expose the packing flaws (gray overlay). Note the size and distribution of the well-packed clusters. They tend to be approximately 5 grains (~1mm) in maximum dimension.

Analysis of the distribution and size of these two classes of porosity has shown that the proportions of well-packed and expanded porosity vary systematically with diagenesis. All of the example thin sections are somewhat unusual in that they have never undergone compaction and dewatering. As mechanical diagenesis proceeds, the clusters grow and consolidate (Prince and Ehrlich, 2000), increasing the need for a larger sample to capture and describe them. Further analysis has shown that the modal flaw size can be used to very precisely predict permeability from thin section imagery (Prince, 1999). Once again we are confronted with trying to correctly assess the nuances of porosity, which demands high resolution, while still managing to have an image matrix that is large enough to encompass a representative sample.

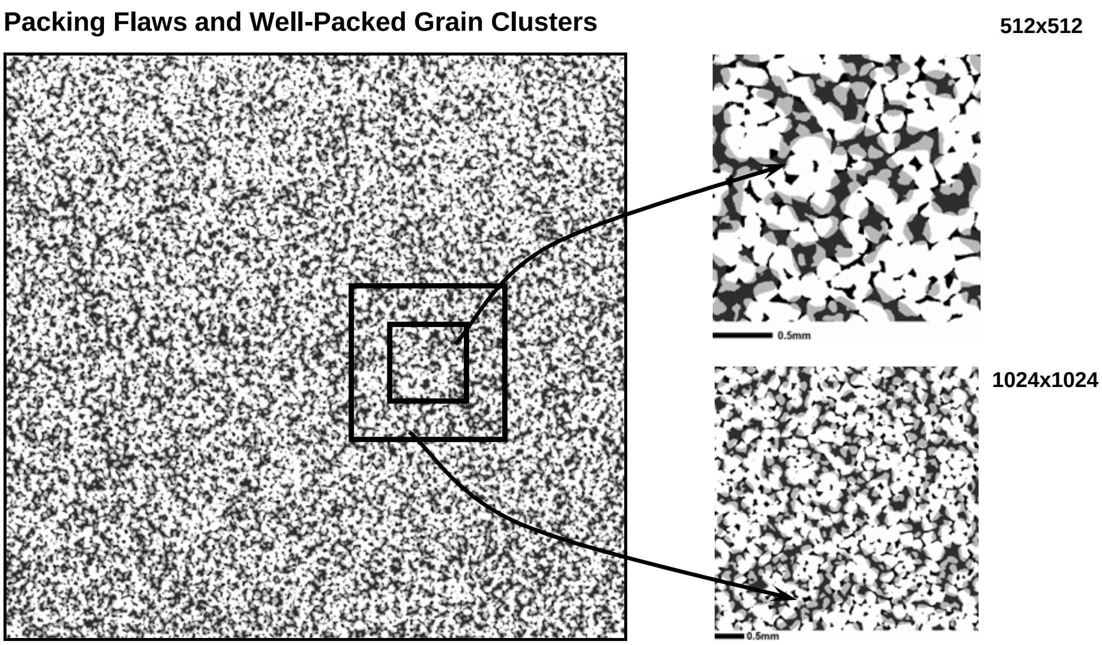

Figure 3 – Sample 3 filtered to expose the packing flaws and well-packed clusters. Porosity is black, grains are white, and packing flaws are overlain by gray. Note that the well-packed clusters of grains are separated by zones of enlarged porosity.

The porosity experiment was repeated on Sample 3 using images containing the expanded and well-packed components of the pore network. The results, shown in Figure 4, indicate that the scale of variability in the network of packing flaws extends out to at least 6mm, and that is from a sample selected for its homogeneity. Similar experiments with more common samples with heterogeneous diagenesis and grain size indicate that the 6mm figure may represent a minimum.

SUMMARY

Sample size is critical. In any analytical procedure samples must be large enough to describe the thing we are trying to assess. Image analysis of porosity requires a sample size large enough to be representative, but it also requires that the image be captured at a resolution fine enough to describe the nuances of pore size and shape. Several early attempts to investigate the relationship between porosity to petrophysics using image analysis failed, principally due to the small sample size. Once the technology was developed to increase the size of the image matrix to encompass the entire sample at high resolution, the precision of the analysis increased to the point that image analysis could be used to produce robust estimates of petrophysical parameters routinely.

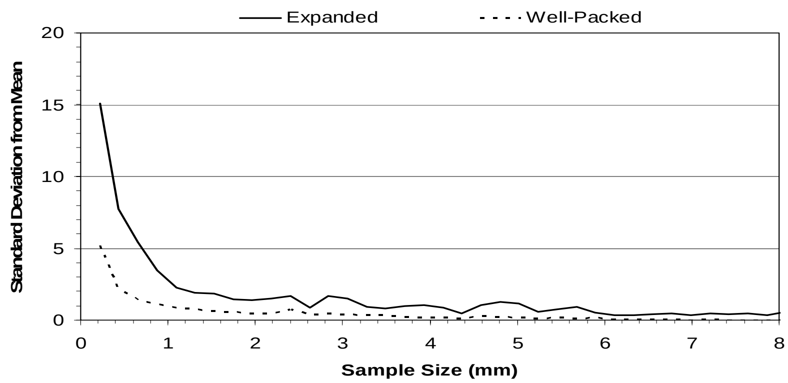

Figure 4 – Standard Deviation in porosity versus sample size for Expanded and Well-Packed porosity, Sample 3. The vertical lines denote a sample size of 512^2, 1024^2, and 2048^2 pixels at 4.4µm resolution.

REFERENCES

Crabtree, S.J., R. Ehrlich, and C.M. Prince, 1984, Evaluation of strategies for segmentation of blue-dyed pores in thin sections of reservoir rocks: Comp. Vision, Graphics, and Image Processing, v.28, p. 1-18.

Ehrlich, R., S.J. Crabtree, K.O. Horkowitz, and J.P. Horkowitz, 1991, Petrography and reservoir physics I: Objective classification of reservoir porosity: AAPG Bulletin, v.75, p. 1547-1562

Fabbri, A.G, 1984, Image Processing of Geologic Data, Van Nostrand, Reinhold, New York, 244p.

Graton, L.C. and H.J. Fraser, 1935, Systematic packing of spheres with particular relation to porosity and permeability: Jour. Geology, v.43(8), p.785-909.

Prince, C.M., R. Ehrlich, and Y. Anguy, 1995, Analysis of Spatial Order in Sandstones II: Grain Clusters, Packing Flaws, and the Small-Scale Structure of Sandstones: Jour. of Sedimentary Research, v. A65 (1), p. 13-28.

Prince, C.M., 1999, Textural and diagenetic controls on sandstone permeability: Gulf Coast Assoc. of Geological Societies Transactions, v.49, p. 42-53.

Prince, C.M. and R. Ehrlich, 2000, A test of hypotheses regarding quartz cementation in sandstones: A quantitative image analysis approach *in* R.H. Worden and S. Morad, eds., Quartz cementation in sandstones: International Association of Sedimentologists Special Publication no. 29.

Prince, C.M., R. Ehrlich, and M.B. Carr, 2000, The effect of sandstone microfabric upon relative permeability end points: Jour. Petroleum Science and Engineering, v.24, p169-178.

Size, W.B, 1987, Use of representative samples and sampling plans in describing Geologic variability and trends, in Size, W.B ed., Use and Abuse of Statistical Methods in the Earth Sciences. IAMG Studies in Mathematical Geology No. 1, p. 3-19