

PREDICTING ROCK PROPERTIES FROM DIGITAL CORE IMAGES

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ABSTRACT

Digitally archived core images cannot take the place of a slabbed core, but a digital archive of core accessed from the internet or the corporate intranet enhances the ability to view, manipulate, and analyze the core, while remaining immune from the effects of desiccation. Currently, most of the available imagery is either in the form of 1:2 scale photographs, or low resolution digital images, digitized at 100 dots per inch (dpi). Such images are useful for viewing, and qualitative assessments of bedforms and facies. High-resolution imagery digitized at resolutions greater than 1000 dpi can be obtained with the most recent digital cameras and automatically processed using spatial analysis to generate grain size logs of the pay intervals. The grain size log can then be used to generate continuous downcore estimates of permeability.

The spatial analysis technique was originally developed in an attempt to rapidly acquire an unbiased grain size distribution from thin section. During the past year it has been applied to digital imagery of quartz grain packs and slabbed core. The grain size distributions obtained from spatial analysis of quartz grain packs have been verified by direct measurement of sand grains and by laser particle size analysis (LPSA). Grain size distributions obtained from spatial analysis of digital images of slabbed core have been verified by direct measurement of sand grains, and LPSA. At present, the spatial analysis technique is applicable for unconsolidated sands and semi-lithified rock. However, the technique requires high-resolution imagery. The resolution of an image digitized at 1000 dpi is approximately 40 μm per pixel and is adequate to estimate grain size down to the fine sand range ($\sim 150 \mu\text{m}$). A developing technology allows us to digitize slabbed core at resolutions of about 5000 dpi and increase the resolution down to the coarse silt range ($\sim 40 \mu\text{m}$).

With recent advances in digital cameras, image compression techniques, and high-density data storage technology (DVD), the acquisition of imagery from slabbed core should not stop at only providing an archivalable digital core image. Image data can be used to acquire useful petrophysical information including synthetic logs of grain size, permeability, and capillary pressure in a cost effective manner.

INTRODUCTION

It has long been standard practice to photograph slabbed core as a means of archiving the core. The photos commonly range from 1:2 to 1:4 scale and are images covering a 1-foot section of core. They are used for a variety of purposes ranging from bedform examination to

sample site selection. Recent advances in digital cameras and image processing technology have begun to have an effect in that much of the imagery is now available in a digital format. A digital format has several advantages, not the least of which is its low cost and accessibility to the end user. It also has a distinct advantage in that it can be analyzed for a wide variety of geological and petrophysical information ranging from net pay to grain size and permeability.

The ability to extract useful information from an image is limited by the resolution of the image and the size of the field of view. Most of the available imagery is in the form of photographs, each covering a 1-foot field of view, but even photographs can be digitized at 400 dpi using a flatbed scanner. The images are then indexed to one another to re-assemble them into the original 3-foot sections. The images are enhanced and segmented into 'masks' – binary images of fractures and pay (Figure 1). The relative percent of pay is calculated directly from the 'pay' mask at virtually any subsampling interval and used to create a pay log. The fracture masks are used to insure that any pixels overlying fractures are not tallied in the net pay calculations. The pay mask can also be used to generate bed thickness spectra and can be filtered, removing pay layers that are below a given thickness. The filtered masks are then used to recalculate net pay and used to quantify the uncertainty of pay estimates (Prince and Shafer, 2002; Griffin and Shafer, 2001).

Further experiments have also shown that this type of imagery can also be used to measure grain size, but the resolution is limited by the resolution of the image. A new class of imagery, high-resolution (up to 7000 dpi) images covering a small (1-2cm²) field of view, is becoming available (details provided in the Appendix). This type of imagery does not contain any 'macro' information, but they can be used for grain size analysis and permeability estimation. Between the two types of imagery, it may be possible to automate the analysis of slabbed core, generating not only pay logs, but grain size and permeability logs as well. The primary objective of this paper is to demonstrate the viability of image analysis for grain size determination and permeability estimation.

Grain Size Analysis

Grain size measurement has been hotly debated among petrologists for decades (e.g. Southard, 1989). If sediment grains were spherical, it would be a relatively simple task, but they are not. They have mutually orthogonal long (*a*), intermediate (*b*), and short (*c*) axes, and there are many different methods for measurement. Each method has implicit assumptions regarding the axis being measured, and each has specific limitations. For example, the bias produced by thin sectioning insures that grain size measured from thin section will be finer than that measured by sieve. In addition, both sieve and LPSA measurements are 'whole sample' measurements that include fine silts and clays, while thin section methods tend to measure the 'framework' grains to the exclusion of fine silts and clays.

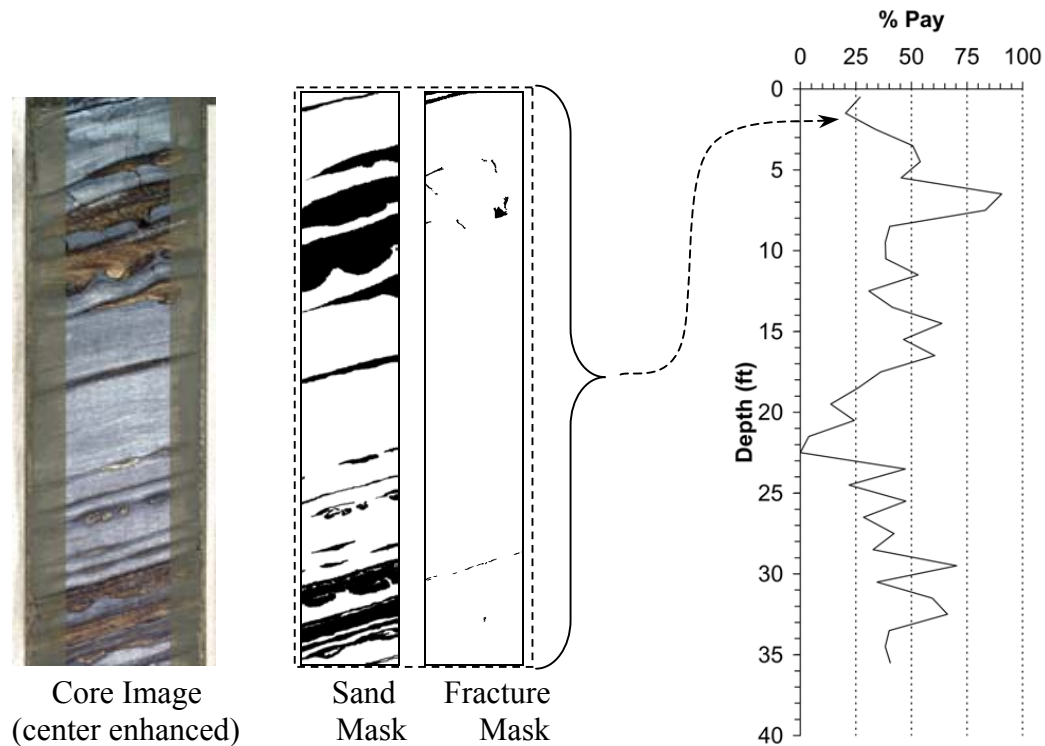


Figure 1 – Digital core images are enhanced and segregated into pay and fracture masks. The masks are then used to calculate net pay.

The use of any one grain size analysis technique is generally a function of its utility for a specific application. Figure 2 contains a comparison of Laser Particle Size Analysis (LPSA), sieve analysis, and two optical techniques. The first of the optical techniques is analogous to a point count grain size analysis, where the longest “apparent” grain dimension is measured on 100+ grains. Unlike the “apparent” grain size observed in thin section the measured grains are on the surface of the core and are completely visible. This “direct measurement” technique does not suffer from the bias associated with thin section analysis. The second optical technique also uses direct measurement to measure the *a*- and *b*-axes of over 1500 loose grains (API, 1998).

The results in figure 2 serve to illustrate the differences in grain size measurements when used to analyze a sample of loose sand. The optical analysis of long and intermediate axes indicated that the modal length of the *a*-axis was approximately 500 μm , while that of the *b*-axis was 330 μm . The modal size obtained from sieve was 330 μm , the same size as the *b*-axis, while the modal size from direct measurement was 500 μm , the same as the *a*-axis. The mean grain size obtained from LPSA is about 410 microns, an average of the *a*- and *b*-axes.

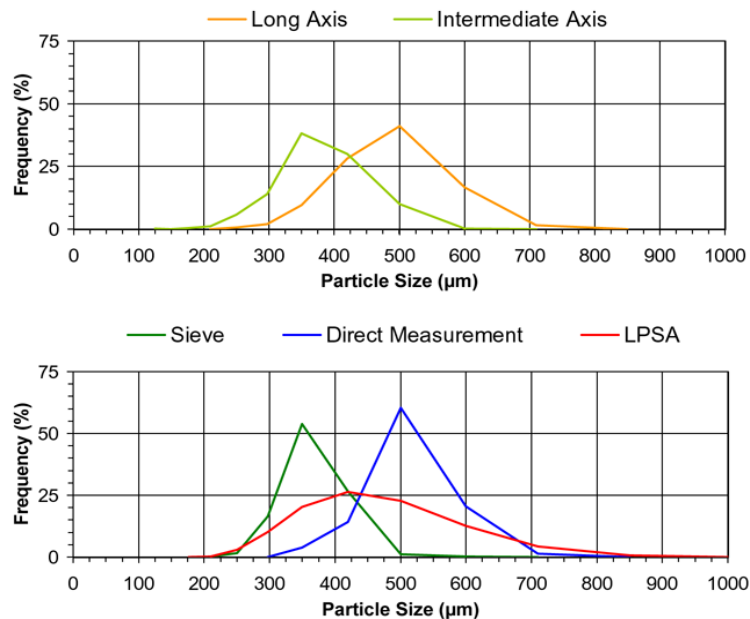


Figure 2: A comparison of grain size distribution data for different techniques.

Spatial Analysis

Spatial analysis is a third image analysis technique that can be used to measure the grain size distribution. It uses the spatial characteristics of the image to quantify grain size and was first developed as a means of obtaining an unbiased grain size from thin section (Prince and Ehrlich, 1990; Prince et al, 1995). A 2-D Fourier transform is used to decompose an image into its constituent spatial frequencies (harmonics). The output of the transform is in the form of a radial power spectrum, representing the squares of the harmonic amplitudes. When applied to a binary image of porosity digitized from thin section, the resulting radial power spectrum provides a measure of spatial density, the center-to-center distance between image features (grains/pores). Grain size defines the minimum center-to-center distance at which grains can pack together. As a result, the image features tend to vary at frequency characteristic of the grain size distribution.

The example in Figure 3 was taken from a thin section of an artificial sand created by sintering 177-210 μm glass beads. The radial power spectrum shows a prominent grain size peak ranging from 160-220 μm, while the apparent grain size shows a strong bias toward the fine end of the distribution, a bias typical of thin sections (Figure 3A). The power spectrum is normalized for area (Prince, 1991), and used to estimate the cumulative size-frequency distribution (Figure 3B). The result is an 'area-frequency' distribution, the 2-D equivalent of a volume frequency. It should be noted that the technique is only sensitive to the grains forming the framework of the sediment. Given a medium-grained (250 μm) sand, the finest particles, very fine silts and clays that would normally be part of the 'pan' in sieve analysis are generally not part of the grain framework. In addition, while much of the fine 'tail' of the apparent grain size

distribution can be attributed to the bias associated with thin sectioning, practical experience has shown that the technique is relatively insensitive to the tails of the distribution.

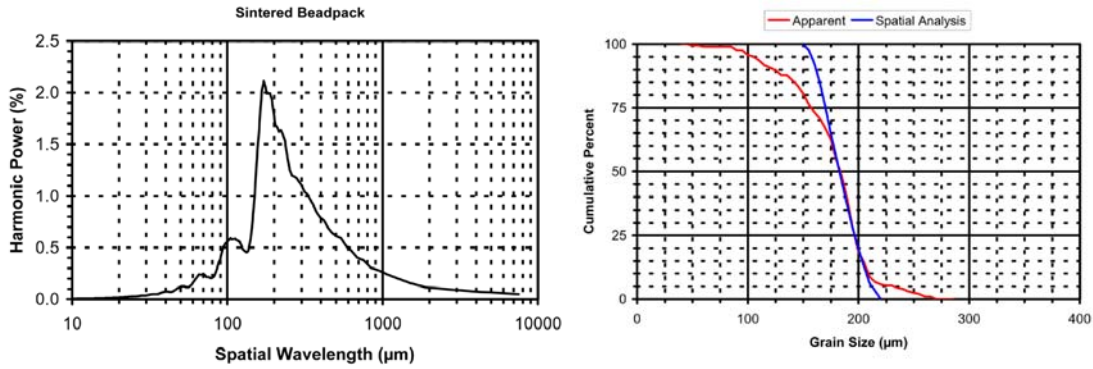


Figure 3 – **A)** A radial power spectrum of a binary image collected from thin section. The spectrum shows a well-defined peak at 170-200 microns. **B)** A comparison of cumulative frequency curves generated from spatial analysis and that derived from measuring the longest apparent dimension of 300 grains.

A high-resolution image of sand taken under reflected light shares many features with a binary image digitized from thin section. The variation in light intensity along the surface of a single grain produces an increase in brightness associated with each grain. The result is an image that is mottled and the spatial density of the mottling is a function of the grain size distribution. When the image is decomposed into its constituent harmonics, this mottling produces a spike on the radial power spectrum that is characteristic of the grain size distribution (Figure 4). The result compares favorably both with LPSA spectra and the apparent grain size distribution measured directly from the image.

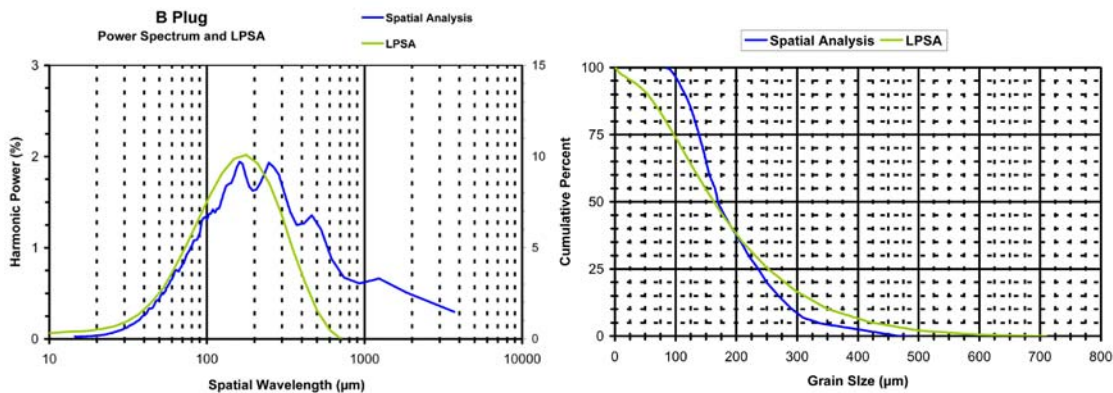


Figure 4 –The radial power spectrum of a high-resolution core image shows good agreement with the incremental size results from LPSA and direct measurement and the cumulative frequency curves also show good agreement.

As a means of comparing image analysis with LPSA, a series of high-resolution images were taken from four different intervals of unlithified core (Figure 5). Additional images were digitized from the ends of three core plugs, one of which was lithified. The slab core and the ends of core plugs were imaged with a Nikon D1X digital camera with interchangeable lens capability. After imaging, each sample was processed using LPSA, and each image was optically analyzed using two methods: spatial analysis, and the direct measurement of 100-150 grains per image. Both incremental and cumulative grain size curves were generated from all three measurements and compared.

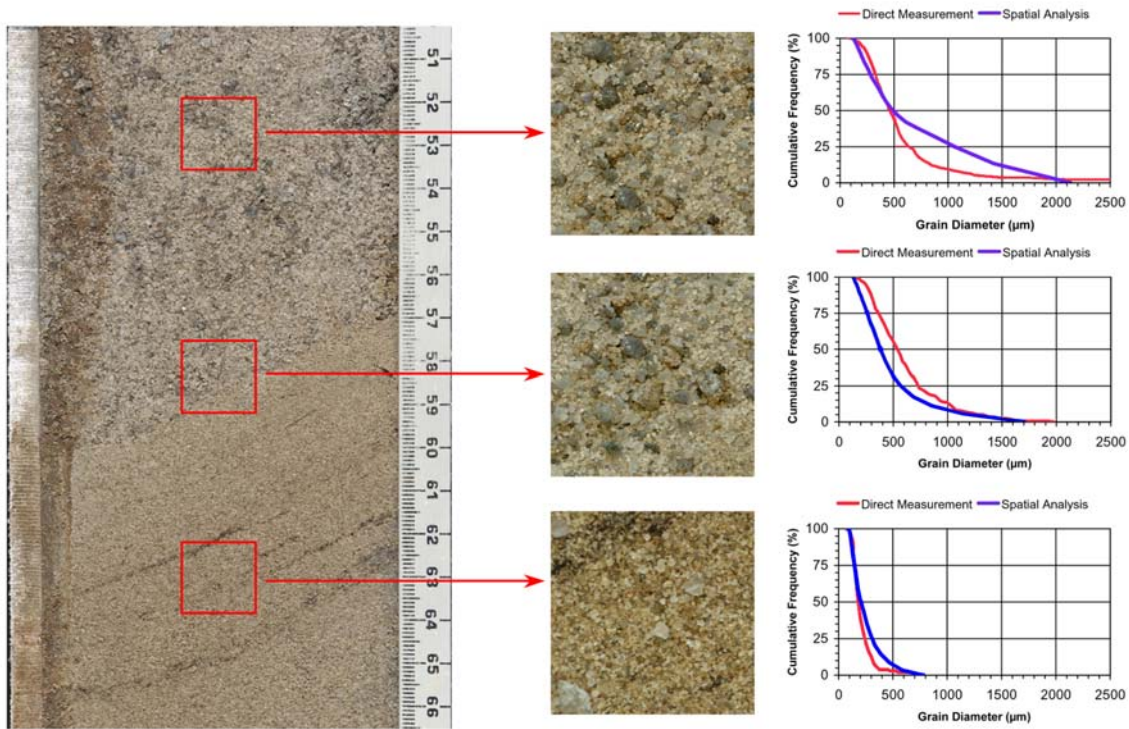


Figure 5 – Three high-resolution images were digitized from each of four core intervals and the images were processed using both spatial analysis and direct measurement.

RESULTS AND DISCUSSION

Grain Size Estimates

The results show that in terms of average (median or mean) grain size, there is very little difference between the results (Figure 6). A comparison of cumulative frequency curves also shows relatively good agreement. A comparison of the grain sorting obtained from each technique revealed differences between spatial analysis and LPSA. However, given that spatial analysis and direct measurement are grain framework methods, while LPSA is a whole sample test, and given that spatial analysis is relatively insensitive to the tails of the distribution, there is no reason to expect any agreement between sorting measurements or any of the higher-order moments of the grain size distribution.

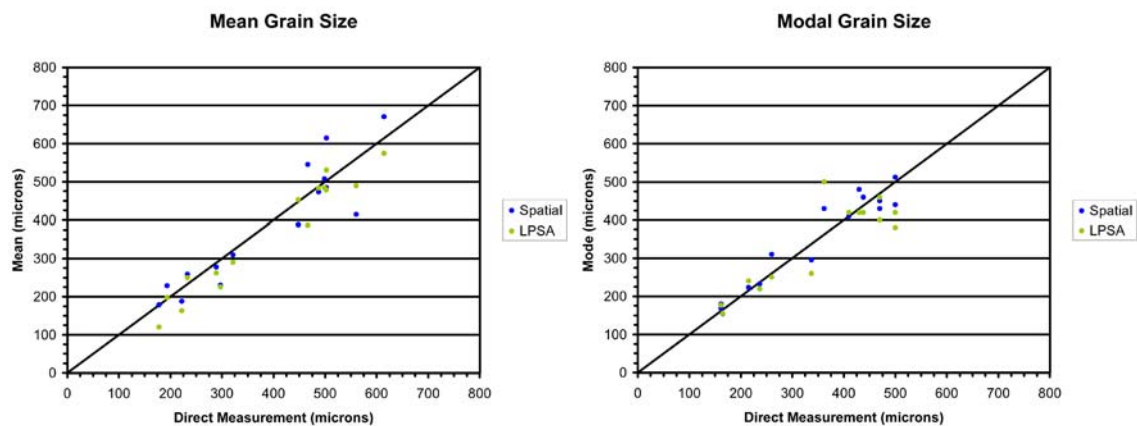


Figure 6 – Cross-plots of the mean and modal grain size using direct measurement as the standard.

Permeability Estimation

In unconsolidated sands, permeability can usually be estimated from the average grain size (Graton and Fraser, 1935; Beard and Weyl, 1973; Pryor, 1973; Shepherd, 1989). Grain size defines the fundamental spatial framework of the sediment and the average size of the voids within that framework. Such estimates are based upon the notion of an intrinsic permeability: $K = c d^{-2}$, where permeability (K) varies exponentially with the average grain diameter (d). The constant (c) can vary widely depending upon the units (Darcies or gpd/ft^2), but the exponent commonly ranges between 1.6 and 2.1 (Krumbein and Monk, 1943; Shepherd, 1989).

Spatial analysis has proven to be a reliable means to estimate permeability from thin section. When using a binary image from thin section, permeability can be estimated both from the modal pore diameter and the modal grain size (Prince, 1999). Permeability estimates were generated for each sample using simple linear regression between $\log(K)$ and the modal grain size. The results, shown in Figure 7, show a relatively good agreement between the estimated and measured permeabilities. Permeability was also

estimated from the LPSA results based on a texture coefficient that is an appropriate combination of mean grain size, V_{shale} , and other characteristics of the GSD.

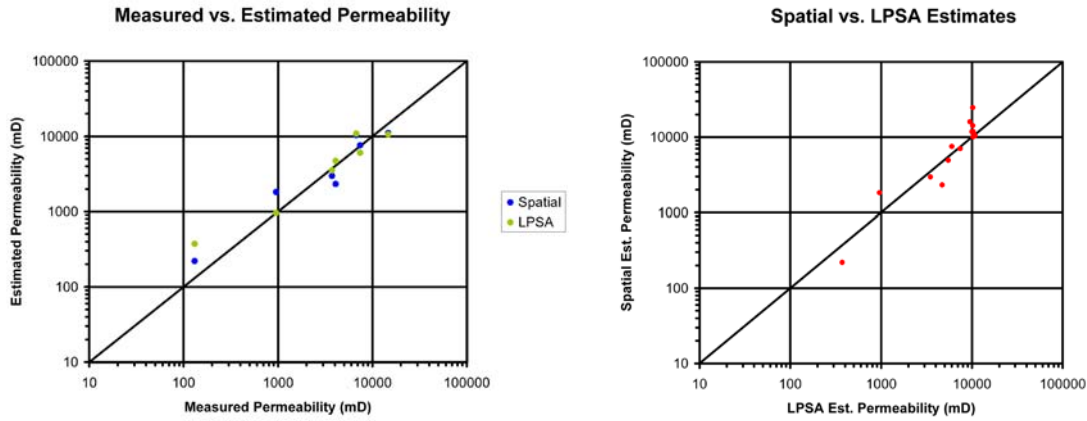


Figure 7 – Permeability estimates from grain size data.

SUMMARY AND CONCLUSIONS

Digital image analysis of core imagery has the potential to increase the amount of information that can be extracted from core. Unlike core plugs sampled at discrete intervals, the information in a core image is continuous, and can be used to create synthetic logs from slabbed core. Most of the available imagery is in the form of photographs or low-resolution digital images. Digital image analysis has been used to quantify macro properties such as net pay, and has been used to quantify bed thickness and the uncertainty of pay estimates, but they do not have the resolution for grain size assessment or permeability estimates.

The advent of new, relatively inexpensive large matrix cameras and an intelligent tiling algorithm has increased our ability to rapidly acquire high-resolution digital core imagery. While not widespread, this technology has the potential to automate macro assessments, like net pay, but the results of this paper show that it is also possible to use high-resolution imagery for grain size assessment and permeability estimation. Using a series of high-resolution images of slabbed core, grain size analysis was performed using spatial analysis as well as the direct measurement of grains. The corresponding core intervals were then subsampled for LPSA. A comparison of the results shows that all three techniques produce very similar estimates of the average grain size in spite of the fact that LPSA is a ‘whole sample’ assessment, while both spatial analysis and direct measurement are grain framework. However, given the difference between the techniques it was not possible to compare the higher moments of the grain size distribution like sorting, skewness, or kurtosis.

The average grain size data was used to estimate permeability. LPSA estimates were based upon the mean grain size and other GSD variables, while estimates using spatial analysis were based upon the modal grain size. Again, the permeabilities estimated from each technique showed a very high degree of correspondence.

While they are subject to verification in a larger study, these preliminary results suggest that digital image analysis of slabbed core has the potential to be used for grain size assessment and permeability estimation. Given that this is the case, it may be possible to automate the process to the extent that net pay, bed thickness, horizontal and vertical variograms, grain size and permeability logs, as well as a variety of other properties are generated in the background as the core is being imaged. The digital archiving of core is a means of retaining a 'virtual' core that is immune to the effects of dessication, plugging, or rough handling, but digital image analysis of slabbed core has the potential to substantially increase the amount and type of information available from what is an increasingly expensive sample.

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Appendix - Core Imaging Technology

In the past two years the primary author has used these techniques for a number of different projects, and this experience has led to three fundamental observations: First, it is generally better to use a white light image for segmentation. If we neglect the effects of diffusion and seepage along fractures that can lead to overestimation of net pay, images taken under UV light fluorescence over a limited color range and the ability to segregate the image is dependant upon one image characteristic: intensity (brightness). The features in the white-light image can be distinguished using hue (color), saturation (color richness), as well as intensity. Third, if the image is digitized at higher resolution (600-1200 dpi), pay zones can also be distinguished and segmented using image texture, greatly enhancing our ability to automate the process of image segmentation.

The advances in camera technology in the past 5 years have lead to the advent of relatively inexpensive color cameras capable of producing large images (1-3,000 x 2-4,000 pixels), but the number of pixels is still relatively small, and the resolution of the image is controlled by the size of the field of view, Table 1A. At present, the only practical means of digitizing large fields of view at high resolution is to use a ‘tiling’ procedure in which several images are digitized and indexed to one another to produce a composite image covering the entire 3-foot section of core. Indexing a series of images manually is extremely time consuming, but the recent development of an intelligent tiling algorithm has reduced the time required to generate an image to a few minutes. The principal advantages of this type of imagery lie in the uniform illumination throughout the field of view and the increase in resolution. The uniform illumination insures that color response is uniform throughout the image (and the core), which enhances the ability to segment the image using color. The increase in resolution to 600-1200 dpi enables the use of textural filters for segmentation of pay zones. Together, the uniform illumination and the higher resolution mean that it is now possible to automate the identification and segmentation of pay intervals within the core.

The same system can be used to digitize high-resolution images, but there are practical limitations with scanning time, image size, storage, and the ability of any downstream software to handle large images. At 600 dots per inch resolution, an image of a 4 x 36 – inch section of slabbed core measures 2,400 x 21,600 (~52 Mpixels) and occupies approximately 160 Mbytes of disk space. If we double the resolution to 1200 dpi, we quadruple the area in pixels, and the storage required. There are commercially available wavelet compression software packages that can provide 95% compression while preserving resolution and color fidelity. With compression, a 3-foot section of core digitized at 1,200 dpi occupies approximately 32 Mbytes of storage.

In spite of these advances, an image digitized at 5000 dpi is still impractical. Such an image would measure 20,000 x 175,000 pixels (3,500 Mpixels), even with wavelet compression the file size would be approximately 600 Mbytes, and the image would be unreadable by virtually all of the commercially available image display software. For these reasons, we now perform a two-stage digitization process. An image is digitized at medium resolution (600-1200 dpi) for macro analysis, followed by a lens change to

digitize a series of high-resolution images down the center of the core for subsequent grain size analysis. The procedure is not ideal, in that we still do not have a high-resolution image of the entire core, but given the constraints of image size and storage, it is a means of extracting both macro and micro information from the core.

TABLE 1A: A Comparison of Grain Size Classification, Grain Size, Required Image Resolution And Camera Matrix

Grain size Classification	Grain Size less than (microns)	Image* Resolution required (dpi)	Window Size Camera Mega Pixels			
			6" by 6"	1" by 1"	0.5" by 0.5"	
Sand	<u>VCRS</u>	2000	50	0.1	0.003	0.001
	<u>CRS</u>	1000	101	0.4	0.010	0.003
	<u>MED</u>	500	202	1.5	0.041	0.010
	<u>FINE</u>	250	403	5.9	0.163	0.041
	<u>VFIN</u>	125	806	23.4	0.650	0.163
SILT	<u>CRS</u>	62	1,626	95	2.6	0.7
	<u>MED</u>	31	3,252	381	10.6	2.6
	<u>FINE</u>	16	6,300	1,429	39.7	9.9
	<u>VFIN</u>	8	12,600	5,715	158.8	39.7
CLAY	4	25,200	22,861	635	159	

Note* = Assumes four pixel required to define grain