THE USE OF HIGH-RESOLUTION CORE IMAGERY IN RESERVOIR CHARACTERIZATION: AN EXAMPLE FROM UNLITHIFIED MIOCENE TURBIDITES.

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ABSTRACT

High-Resolution core imagery has a wide range of uses in reservoir characterization. These uses range from real-time imagery for plug selection, to the analysis of macro properties such as net reservoir or sedimentary fabric, and the analysis of micro properties such as grain size and permeability. Core is routinely photographed. High-resolution digital imagery affords the opportunity to do work with the imagery.

There are many other advantages in that images digitized at 1200 dpi can be projected down to 100dpi, assembled in near real-time and sent via internet to a reservoir characterization team at the home office. Where they can then be used to select the location of Special Core Analysis (SCAL) plugs before the core is wrapped or sealed in wax. These near real-time thumbnails allow all of the groups involved in the project to 'read from the same page' regardless of their location.

The most far-reaching benefit of high-resolution digital core imagery is in the analysis of the core. At 1200 dpi the resolution is equivalent to that of a 10x hand lens employed in the core layout room. This means that most of the routine core description tasks that require the core to be shipped to the core analyst or the core analyst to travel to the core can be performed from the images in the home office. At 1200dpi the images can be used to quantify a number of macro properties such as net reservoir and net pay, fracture density and orientation, bed thickness spectra, as well as uncertainty.

For the core discussed in this paper, the 1200 dpi images were supplemented by very-high resolution (~5000 dpi) images of the core as well as thin section imagery (~13,500 dpi). Together they were used to generate a grain size log with a sample spacing of 3 inches. Once complete, the grain size data was paired with porosity data from both core plugs and thin sections to create a permeability log of the entire sequence. The resulting logs compared favorably with all of the other log-derived data and, given the unlithified state of the core, proved to be a reliable source of permeability data in a heterogeneous reservoir, complementing the plug-derived measurements obtained from the lab.

INTRODUCTION

Imagery of slabbed core is an integral part of any reservoir geologist's office, ranging from ¼ scale photos taped together and pinned on the wall, to bound photo catalogues, and now digital databases. It provides an important visual reference to assess a variety of macro-scale characteristics ranging from the assessment core recovery and damage, planning for SCAL plugs, measurement of net sand, stratigraphic thicknesses, and a variety of other tasks.

The advent of digital imagery has generated new opportunities for the acquisition of large- and small-scale petrophysical information. One approach has been to create discrete bitmaps highlighting different petrologic and petrophysical classes and then use them to generate synthetic sand logs, bed thickness spectra, and quantify other macro-scale properties such as variation and uncertainty (1). When mated with digital UV imagery, pay logs can be generated at any scale. High-resolution imagery contains the same macro-scale information, but it also contains micro-scale information that can be used to measure grain size (2), or quantify secondary porosity (3).

The present example is a sequence of unlithified Miocene turbidites from offshore West Africa. The core was slabbed, stored for two months, and the significant pay intervals were scanned on site, producing continuous 1200dpi imagery of approximately 110 feet of the core. In addition, discrete very high-resolution (~5300dpi) fields of view sampled every 3" throughout the pay intervals (Figure 1). The 1200 dpi images were designed to provide a permanent archive of the core at a magnification approximately equal to that of a 10x hand lens. They can also be used for grain size analysis, but at 1200dpi the pixel size is approximately 21 microns. While the technique can assess the presence of particles down to approximately 40 microns, adequate description of grain size requires 8-10 pixels. Below a median size of 175 μm very high-resolution imagery is used for grain size measurement. Thin sections and laboratory measurements from sixty-six core plugs supplemented the core imagery from this well.

IMAGE ANALYSIS

Image Subsampling and Pre-Treatment

The 1200 dpi images were sub sampled at depths coincident with the listed thin section depths. Along with the very high resolution images, each image subsample was enhanced using a contrast stretch and an edge enhancing filter (Figure 1).

Grain Size Analysis

Grain size measurements were conducted using two different methods: Direct Measurement, measuring the long axis of 100-300 grains per image, and Spatial Analysis, an image analysis technique used to quantify the texture of an image.

Direct Measurement

This procedure is commonly employed in thin section, but it is known to produce biased results associated with the 2D nature of the sample (4). This may or may not be true for direct measurement of core imagery. The surface of the core represents a 2D slice, but at the scale of a sand grain the surface has relief and given unlithified sands entire grains are visible on the surface, eliminating the bias associated with slicing.

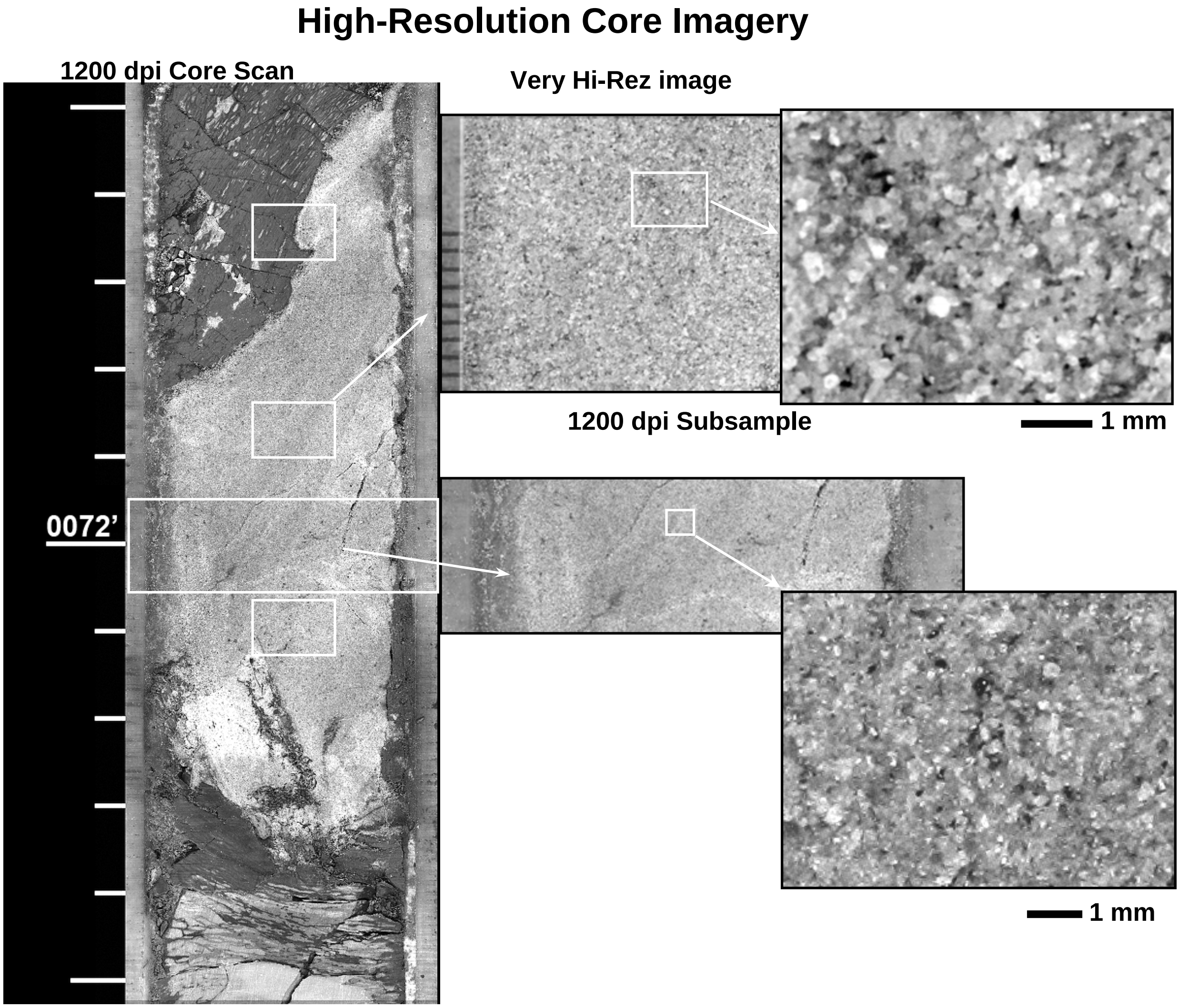

Figure 1 – Core imagery included 1200 dpi core scans and individual high-resolution frames samples on a 3-inch spacing. The 1200 dpi core images were sub sampled at depths equivalent to those of the thin sections. The insets illustrate the true resolution.

Spatial Analysis

A 2-D Fourier transform is used to decompose an image into its constituent spatial frequencies. The output of the transform is in the form of a radial power spectrum normalized for area. The result is an area-frequency distribution, the 2D equivalent of a volume-frequency distribution (5,6). 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. Spatial analysis is used to quantify this texture in a manner that is comparable with other methods of measuring grain size (2).

Results

Grain size spectra were compiled for over 298 samples, including 234 core images and 64 thin sections and Trask grain size statistics were calculated for each. The first task was to compare the results reported from core plugs (thin section and Laser Particle Size Analysis - LPSA) with those obtained from core image analysis. Sample 54, illustrated in figure 2, was typical of most samples in that there was very little disagreement between the results obtained from each method. All of the individual spectra seemed to arise from the same sample, but the cumulative frequency curves obtained from LPSA tend to be coarser. The only extreme differences were found two samples where the core plug measurements did not bear much similarity to those obtained from core. Illustrated by sample 64.90 in figure 2, the grain size spectra seemed to arise from two different populations and are attributed to sampling differences.

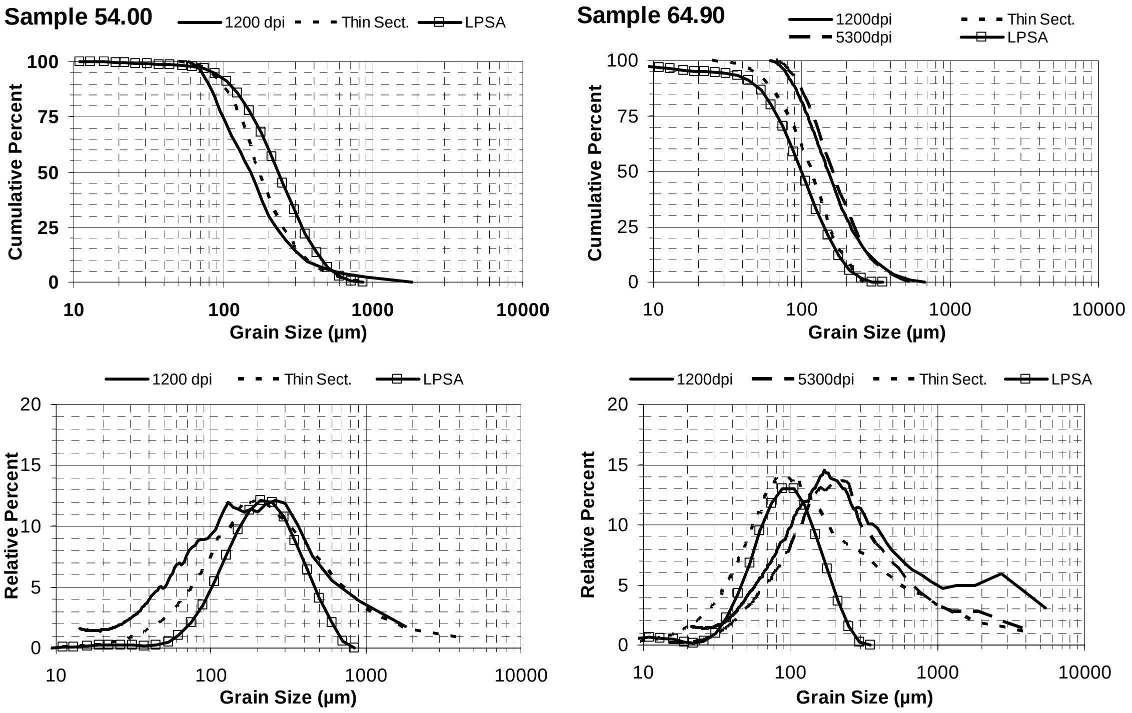

Figure 2 – A comparison suggested that much of the variability in the results was associated with sampling. Sample 54.00 illustrates a sample from a relatively homogeneous interval where the grain size results show good correspondence, but there were others like sample 64.90 taken from a laminated interval, where the results suggested that the core plug was not from the interval observed in the core.

The grain size statistics were assembled into several grain size logs, a section of which is illustrated in figure 3A. To clearly demark the pay intervals on the log, shale intervals were assigned average grain sizes of 1µm.

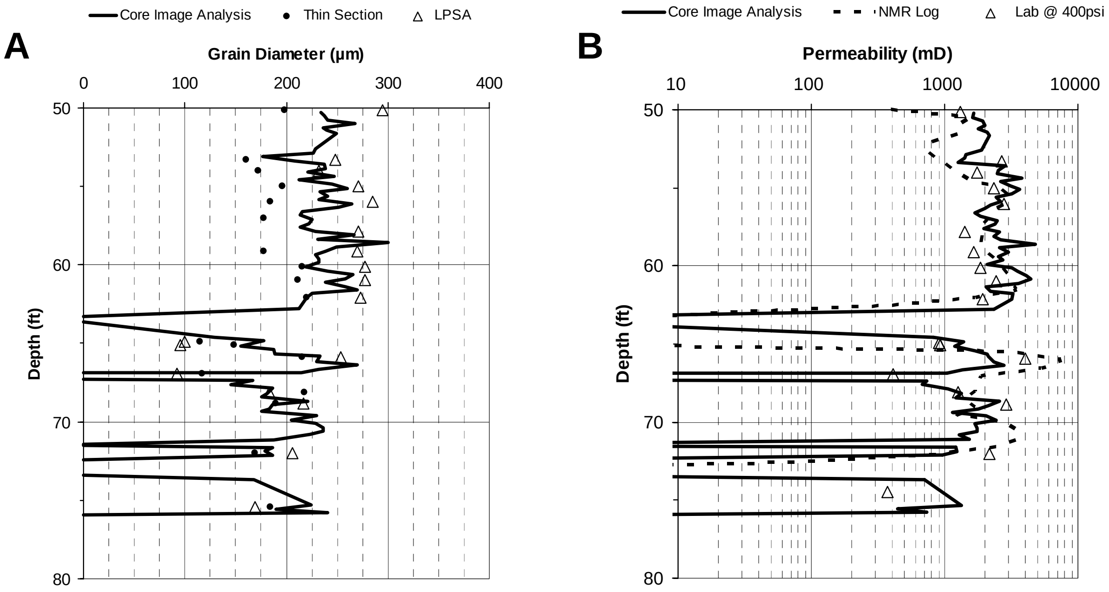

Figure 3 – A section of the grain size and permeability logs. (A) The median grain size log was supplemented by thin section and LPSA measurements from 64 core plugs. (B) The estimated permeability log compared favorably with both laboratory measurements and NMR log estimates. Note that coverage is incomplete. Only the principal pay sections were digitized for analysis.

PERMEABILITY ESTIMATES

Permeability was estimated using Equation 1, relating permeability to modal grain size ('Mode' eq. 1) and porosity ('Por' eq. 1) (7). Generation of a permeability log was a multi-stage process. Modal grain size was determined from each grain size spectrum. Effective porosity was estimated for each sample depth using three sources, laboratory measurements taken from core plugs at 400psi confining pressure, thin section analysis, and log data. These values were then used to estimate effective porosity throughout the core. The final step was to use the most robust permeability measurements from the core plugs (both thin section and laboratory measurements) to calibrate the estimation equation:

$$\mathrm{Log}(K) = \alpha{*}\mathrm{Mode} + \beta{*}\ \mathrm{Por} + \gamma \qquad (1)$$

The 'seed' values were taken from relatively undisturbed sections of the core and samples where there was close agreement between thin section, lab and NMR log. These values were then used to derive the coefficients (α, β, γ) in equation 1 through the use of multiple regression.

The results, shown in figure 3B, compare favorably with those obtained from the NMR log. Within the medium and fine sand intervals there was also a relatively close agreement with laboratory measurements, but within one interval containing very fine-grained sand this agreement broke down and the laboratory results were much greater than those reported from core.

CONCLUSIONS

High-Resolution core imagery has a greater information content than standard photographic or digital core imagery. This type of core imagery contains all of the macro-scale information preserved in standard core imagery, but can be used to assess a variety of micro-scale properties such as grain size.

The core discussed in this paper was digitized on-site and the 1200dpi imagery was supplemented both by very-high resolution imagery, core plug measurements and thin section analyses. A comparison showed that there was very little difference between core image analysis results and those obtained from either thin section or LPSA. When supplemented by porosity information, the resulting grain size logs were used to generate a permeability log covering 110 feet of core with a 3-inch sample spacing. The resulting permeability values are comparable to those obtained from the NMR log and from core plugs at 400psi confining pressure. While the unlithified core discussed herein is not typical of all reservoir sands, the results of this work indicate that the techniques used to measure grain size and estimate permeability are viable and may be applicable to lithified core as well.

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