HETEROGENOUS CARBONATES – INTEGRATING PLUG AND WHOLE CORE DATA USING ROCK TYPES

Mark Skalinski, Rafael Salazar, Gerry LaTorraca, Zheng Yang, and John Urbach – Chevron ETC

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ABSTRACT

The biggest challenge in carbonate reservoir characterization is the multiscale heterogeneity in the pore geometry and the rock texture. The standard laboratory characterization of the rock properties using plugs (1”-1.5” diameter) raises the question about how representative a plug is of this intrinsic multiscale heterogeneity found in carbonates. Whole core samples sometimes are used to try to cover the scale of heterogeneity.

This paper is part of an ongoing study, where we aim to integrate three scales of data: whole core, plug, and mini-plug (5mm diameter) using tomography (CT) images and measured petrophysical properties. Petrophysical rock types (PRTs) and digital rock simulations are the tools used to connect these different scales. In this paper we explore the relation between laboratory measurements performed on plug scale and whole core scale, by using PRTs.

We also present an example of integration of these two scales for permeability using a Darcy flow solver for upscaling. Upscaled values for permeability are within 10% of the full Lattice-Boltzmann pore scale solution.

INTRODUCTION

In figure 1, we show three scales of CT images: Whole core 4” diameter at 158 um/pixel, plug 1” diameter at 22 um/pixel, and mini-plug 1cm diameter at 6.6 um/pixel. This collection of images shows an example of the heterogeneity at multiple scales that can be found in carbonates, and represents one of the big challenges in characterization of carbonate reservoirs. Proper upscaling from core to log scale and beyond becomes a critical element of the modeling and interpretation process and directly affects the quality of the 3D reservoir models. The effect of carbonate heterogeneity on core sample size has been investigated by several authors: Ehrenberg [1], Worthington [2], Tweheyo [3], MacDonald [4]. A general consensus is that the permeability of heterogeneous carbonates is scale dependent and bigger size core samples are preferable since they tend to satisfy better the requirement of being a Representative Elementary Volume (REV). There is some previous work on the integration of multiscale rock models using digital rock

technology tools, Prince [5], Grader [6], Zhang [7], Creusen [8]. While some authors use rock typing based on petrophysical measurements, they use statistical 3D models for the rock heterogeneity. In other cases CT images are used for rock typing, but no petrophysical measurements were included. In this study we use both: multiscale CT images and petrophysical measurements to define the PRTs. We use the PRTs for plug and mini-plug location and for the upscaling of pore scale modeling results.
The core material comes from the 2nd Eocene carbonate reservoir in the Middle East carbonate Wafra field, in Partitioned Zone.The five 1-2 ft whole core samples used come from the dolomitized subtidal carbonate ramp section having high porosity and permeability. Diagenetic modification includes anhydrite nodules, dissolution molds and vugs. In section 1, we describe the whole core characterization program, including CT imaging, Full diameter (FD) core sample selection, PKS measurements, slabbing and grid mapping of mini-permeability, resistivity and CT derived porosity. In section 2, we describe how we obtain the PRTs from the slab data. In section 3, we explain how we select the plug locations, and compare the standard porosity and permeability plug values to the FD sample values. In section 4, we explore a possible upscaling procedure for permeability, starting from pore scale derived values to a whole core grid scale, which will use the same PRTs grids.

1. WHOLE CORE SCALE

The selection of the five core intervals was guided from heterogeneity indicators from several well logs, including FMI images. The selected five 1-2 ft whole core pieces were subjected to CT imaging at 158 um/pixel resolution. The whole core CT images of uncleaned cores were used to select 9 FD 3” long pieces of core for further study. Figure 2 shows whole core CT scans sections and the location of the selected FD core samples.

Standard porosity (Boyle) and air permeability (two horizontal and one vertical) measurements were performed on the 9 FD cores after cold cleaning. These measurements, together with CT scan data will be treated as a reference for the whole core scale. The FD cores were then reassembled with the remaining core, slabbed, photographed and subjected to 1cm^2 grid mini-permeability measurements using a Tiny-permII handheld device, which uses pulse decay air injection calibrated to air permeability. Although mini-permeability measurements might not be accurate in absolute terms, they are very useful for capturing permeability variations. Mini-permeability measurements indicate high heterogeneity for most of the samples. For instance, sample 6 revealed 2 orders of magnitude permeability change over 1cm distance. The 9 FD core pieces were than saturated with 50K salinity brine and subjected to the same 1cm^2 grid resistivity measurements using a specially designed four electrode system. In general, permeability trends show an inverse relationship with resistivity. In figure 3, we show the slab surface of the FD core pictures with the 1cm grid marked (column 1), averaged CT values over 1cm layer (column 2), mini-permeability values in log-scale transferred to color map (column 3), and resistivity in log-scale transferred to color map (column 4).

2. ROCK TYPING USING CT AND PETROPHYSICAL DATA

The use of only CT values for rock typing can be misleading: Given the coarse resolution of whole core CT images (150-300 um/pixel) and their poor signal to noise ratio, it is possible to have two pixels with the same CT value corresponding to different pore sizes and permeabilities. We decided to complement the CT values with actual measured petrophysical properties. We use the mini-permeability and resistivity measurements done on the 1cm grid over the slab surface of the FD core samples described in the previous section. We estimate porosity values for each 1cm grid location in this way: (1) we locate the CT range minimum and maximum values that correspond to pore and solid values, (2) We adjust the range such that we calibrate the estimated total porosity $\emptyset = (CT_{max} - CT)/(CT_{max} - CT_{min})$ of the FD image to the laboratory measured FD porosity, (3) we averaged, on the same 1cmx1cm grid and 1cm depth, the porosity calibrated values to produce an estimated 1cm^3 porosity map on the same grid as the mini-permeability and resistivity. We assume that the 1cm depth corresponds to the investigation volume of mini-permeability and resistivity measures.

We use the grid values for porosity, permeability and resistivity to do the petrophysical clusters analysis. The PRT clustering was performed using the K-Means method after normalizing all variables by Z-scores. The data set was best partitioned by a five cluster solution, which captured the right level of sample heterogeneity. In figure 4 we show the position of the five PRTs clusters in a 3D plot with porosity, permeability and resistivity as coordinates. Table 2 contains a list of the cluster centers for the three variables.

Table 2 Petrophysical Cluster Centers

	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 4**	**Cluster 5**
Number of volumes	111	49	96	127	155
Permeability(mD)	52.626	2543.259	1041.333	318.564	309.911
Porosity (frac)	0.137	0.374	0.3212	0.403	0.280
Resistivity (ohm-m)	14.618	5.909	3.741	3.168	4.159

Labels (colors) for the five petrophysical clusters were assigned back to the grid of the slab FD core samples as shown on figure 5. The color scheme used is in correspondence with the colors scheme used in figure 4. As we expected grid locations with same PRTs are clustered in neighboring regions.

3. PLUG SCALE

The five petrophysical rock types extracted from the surface maps were used for selecting the location of 26 plugs from the 9 FD core samples. The plug locations were defined to obtain a good representation of all petrophysical clusters. This selection was sometimes compromised by the geometry of the FD sample and ability to drill a competent plug. The circles on figure 5 indicate the position of horizontal plugs while cylinders indicate the position of the vertical plugs. The plugs were CT imaged at 22 um/pixel resolution. Figure 6 shows the plug CT images.

After CT imaging, standard PKS measurements were done on the plugs. Figure 7 shows the Porosity-Permeability cross-plot for the FD core samples (red) and plugs (blue). A clear scale effect can be observed with FD samples about half order of magnitude higher. This effect can be interpreted as having an REV for permeability larger than 1".

4. MULTISCALE PREDICTION MODELS

Pore scale 3D models can be obtained from x-ray microCT tomograms by using an adequate image resolution to get a percolating pore body. These models are used to simulate from first principles petrophysical properties of the rock such as permeability by numerically solving the Stokes equations on 3D pore grid using a Lattice Boltzmann (LB) solver. The current capabilities on imaging and computation limit this approach to samples up to ~1000^3 pixels. Heterogeneity in rocks such as carbonates could require a larger core scale. In this section we show one example of the integration of these two scales. We apply a LB solver to extract the permeabilities of consecutive cubes of size 216^3 pixels arranged in a coarse grid of 6x6x4 dimensions and we use them as input for a Darcy flow solver on the coarse grid scale to obtain an upscaled effective permeability. We compare this result with a full LB simulation in the total volume of 1296x1296x864 pixels. The model volume is extracted from a microCT image of the sample *s11c* at $\Delta X = 6.6$ micron/pixel resolution.

The **Lattice Boltzmann** solver [9] implements the single relaxation time BGK approximation on a D3Q19 cartesian grid, with a body force term in the direction of flow, and a relaxation parameter value $\propto = 1.5$ (determined by calibration with laboratory measured permeabilities on a set of test rock samples).

We solve the **steady state Darcy flow** equation $\nabla \cdot [\boldsymbol{k}(\vec{r})\, \nabla \mathrm{p}(\vec{r}) = 0]$, for the pressure field $\mathrm{p}(\vec{r})$, given a permability field $\boldsymbol{k}(\vec{r})$ with Dirichlet boundary conditions. Using finite differences in the 3D cartesian coordinate system we obtain [10]:

$$\frac{1}{\Delta X^2} \sum_{l=i,j,k} \left[K_{l+\frac{1}{2}}(P_{l+1} - P_l) - K_{l-\frac{1}{2}}(P_l - P_{l-1}) \right] = 0$$

where the indices i, j, k, correspond to the grid direction x, y, z, for the discrete values of pressure and the transmissibility coefficients are calculated from the grid permeabilities by $K_{l\pm 1/2} = 2/(1/K_l + 1/K_{l\pm 1})$ in each direction $l = i, j, k$. We solve for the pressure values as a function of the neighbors pressure values:

$$P = \sum_{l=i,j,k} \left(K_{i-\frac{1}{2}} P_{i-1} + K_{i+\frac{1}{2}} P_{i+1} \right) \Big/ \sum_{l=i,j,k} \left(K_{l-\frac{1}{2}} + K_{l+\frac{1}{2}} \right)$$

and we iterate until convergence, starting from an initial linear pressure distribution between the two pressure values $P_1 = 1, P_2 = 0$ on opposite faces (boundaries) of the volume in the direction of the simulated flow, while in the transversal direction to the flow, we use impermeable boundary conditions. We finally compute the upscaled effective permeabilities k_x^*, k_y^*, k_z^* in the outlet (or inlet) face, for instance:

$$k_x^* = \frac{L_x}{L_y L_z (P_2 - P_1)} \sum_{j,k} K_{L_x - \frac{1}{2}} \left(P_{L_x} - P_{L_x - 1}\right)$$

where the sum runs over the sites on the outlet (or inlet) face.

In figure 8 we show the volume used for both simulations: (1) The full volume LB simulation as a reference, and (2) The Darcy upscaling simulation from partial volumes LB results. In figure 9 we show the results for k_z on each of the 6x6x4 sub-volumes of size 216^3. We compare in figure 9 the upscaled value of 171mD (red) to the full scale value 193mD (green) and to the plug measured value of 223mD (dashed line). The upscaled value is within 10% of the full scale value, showing that our upscale solution is reasonable. Depending on the heterogeneity of the rock texture respect to the sub-volume sizes, we may need to include off-diagonal terms of the permeability tensor in the Darcy upscaling solution. For comparison, standard averaging formulas would yield the following k_z averages: 288 mD (arithmetic), 124 mD (harmonic) and 203 mD (geometric).

CONCLUSIONS

- Multiscale heterogeneity in carbonates is captured by 3D CT imaging at several scales. In order to integrate these images at different scales we can use PRTs from physical measurements on the slab core surface: 2D petrophysical maps can be used for plug selection, and PRTs could be extended to the whole core volume by correlating with CT properties.
- We also test in this paper a possible upscaling procedure for permeability once all PRTs are sampled at pore scale level. Starting with a large simulation volume, we estimate permeability in two ways: direct full LB simulation, and Darcy upscaling from smaller sub-volumes permeabilities (also from LB simulations). Both results coincide are within 10%, showing the potential of this method for populating pore-scale derived properties to plug and core scale.

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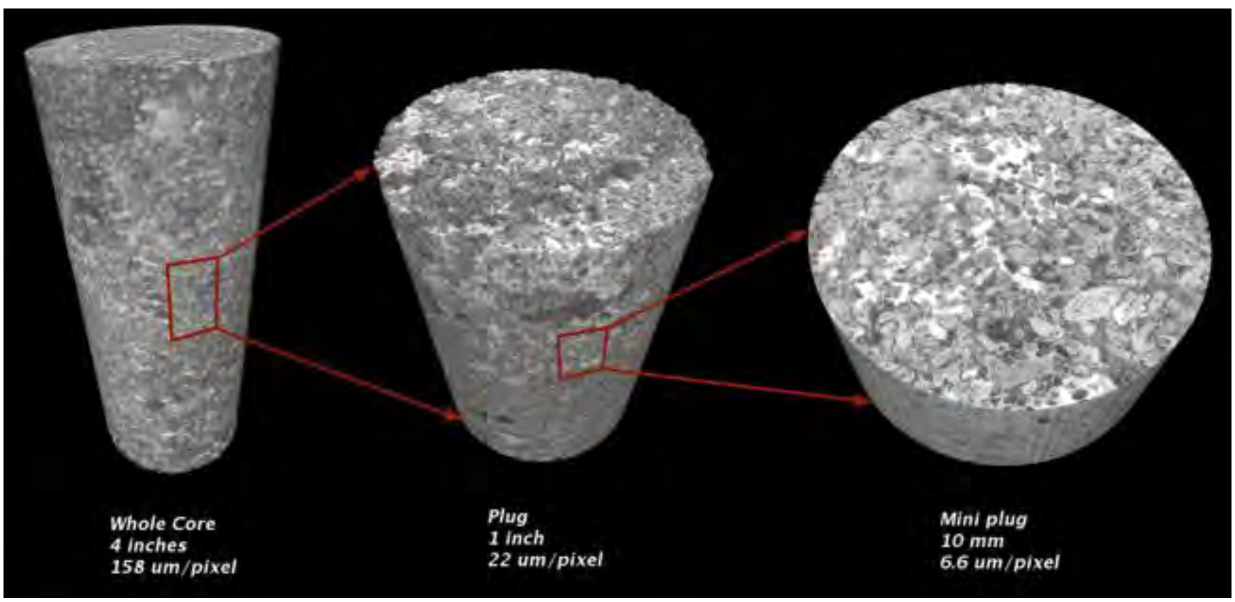

***Figure 1**. 3D rendering of the tomogram for core plug S11C (middle), the corresponding whole core section tomogram (left), and an internal region tomogram (right), showing the rock texture heterogeneity at three scales.*

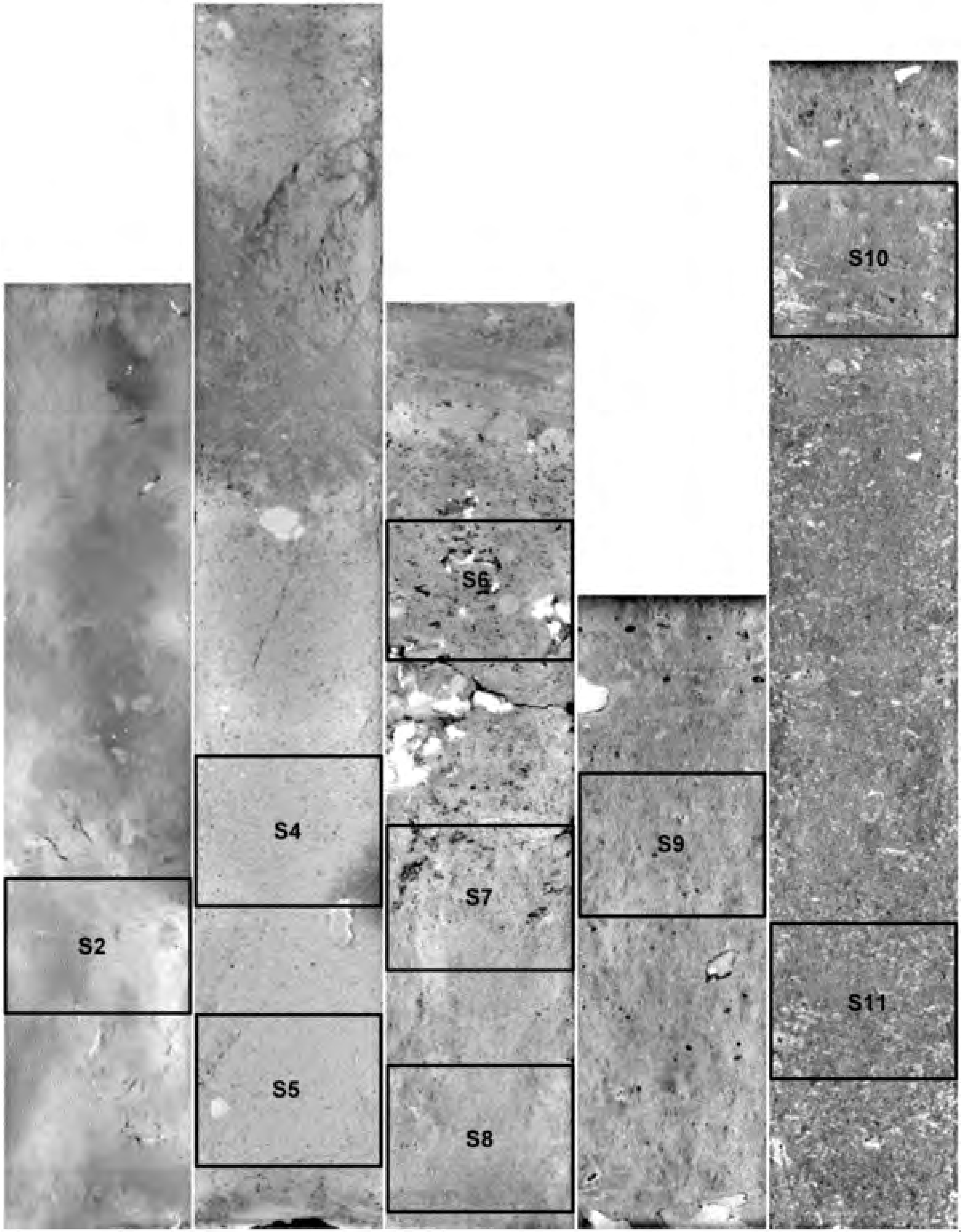

Figure 2. *Virtual slab surface extracted from the whole core tomograms, showing the different rock textures and the location of the FD core samples.*

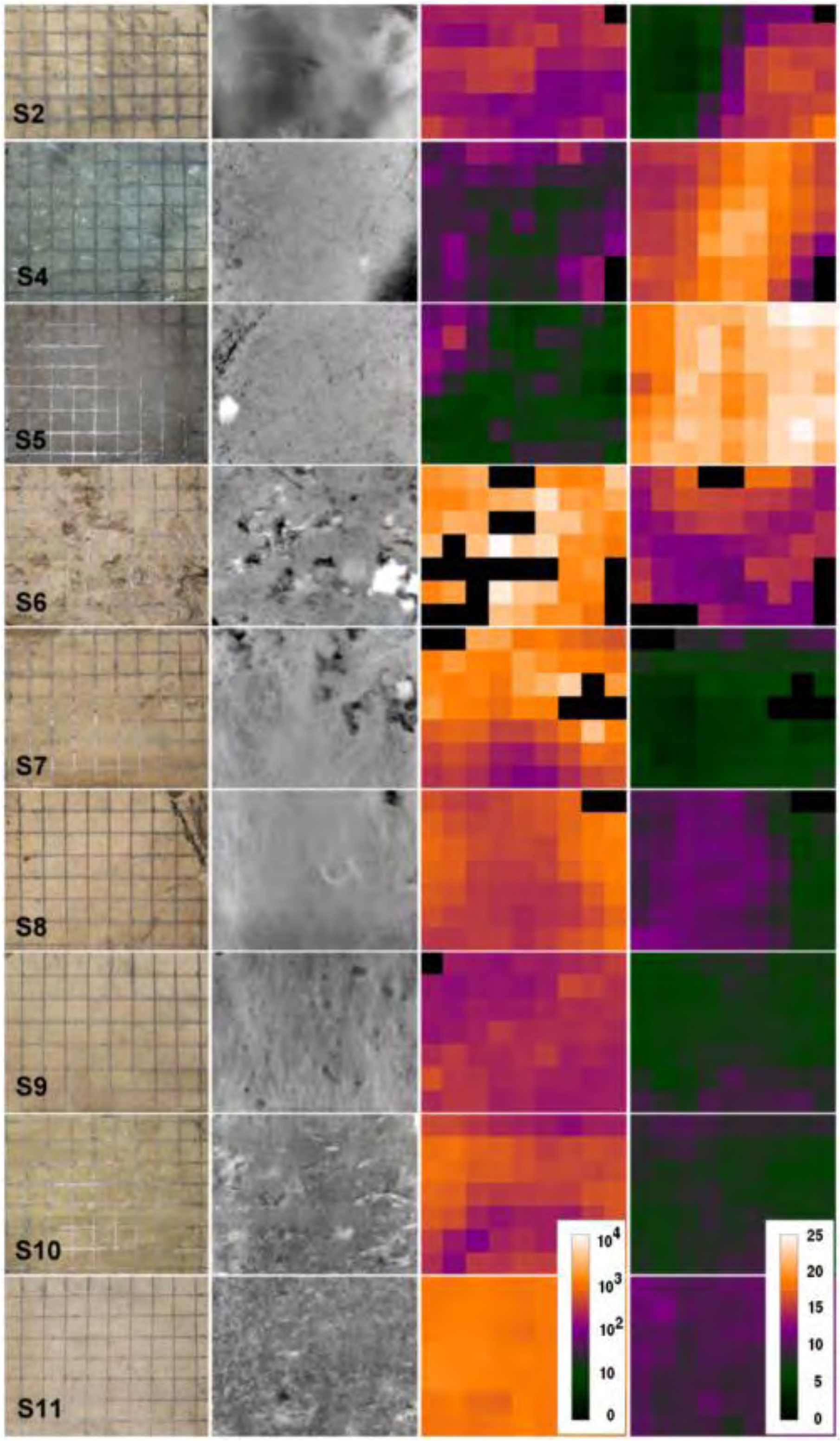

Figure 3. *Slab surface of each FD cores (top to bottom) shown as (from left to right): picture, CT image averaged on 1cm thick, mini-permeability (mD), and resistivity (ohm-m), both measured in a grid of 1cm spacing, and scaled to a color map in log scale as shown.*

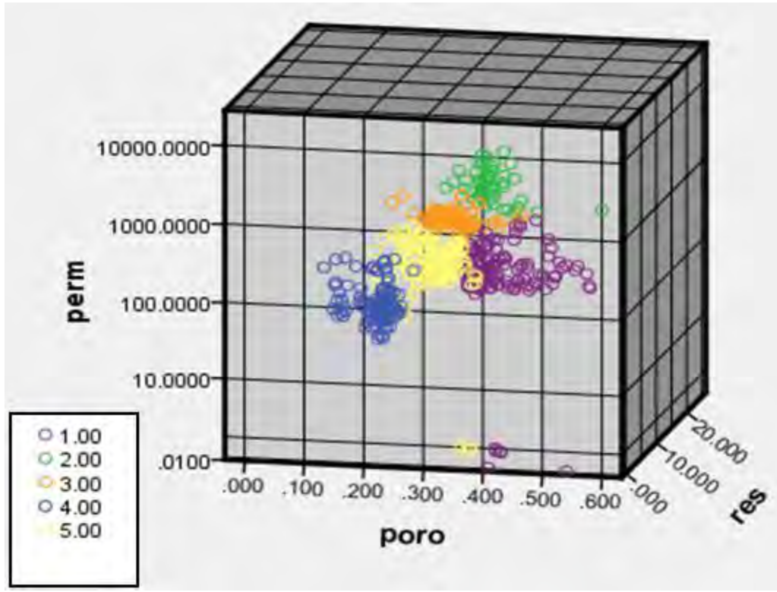

Figure 4. *Five petrophysical rock types identified as cluster by using the K-means technique.*

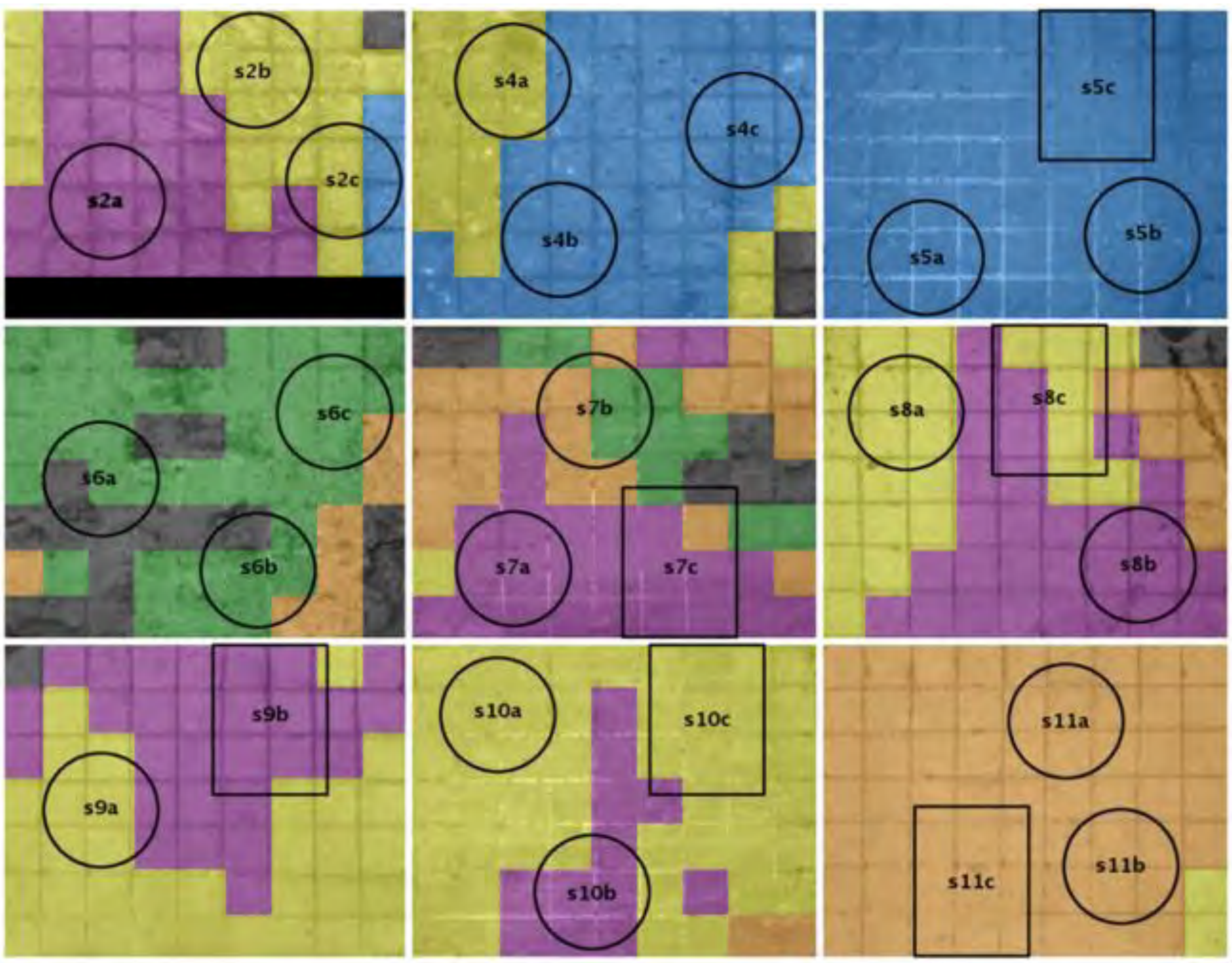

Figure 5. *Plug positions vs. petrophysical clusters on the FD core surface.*

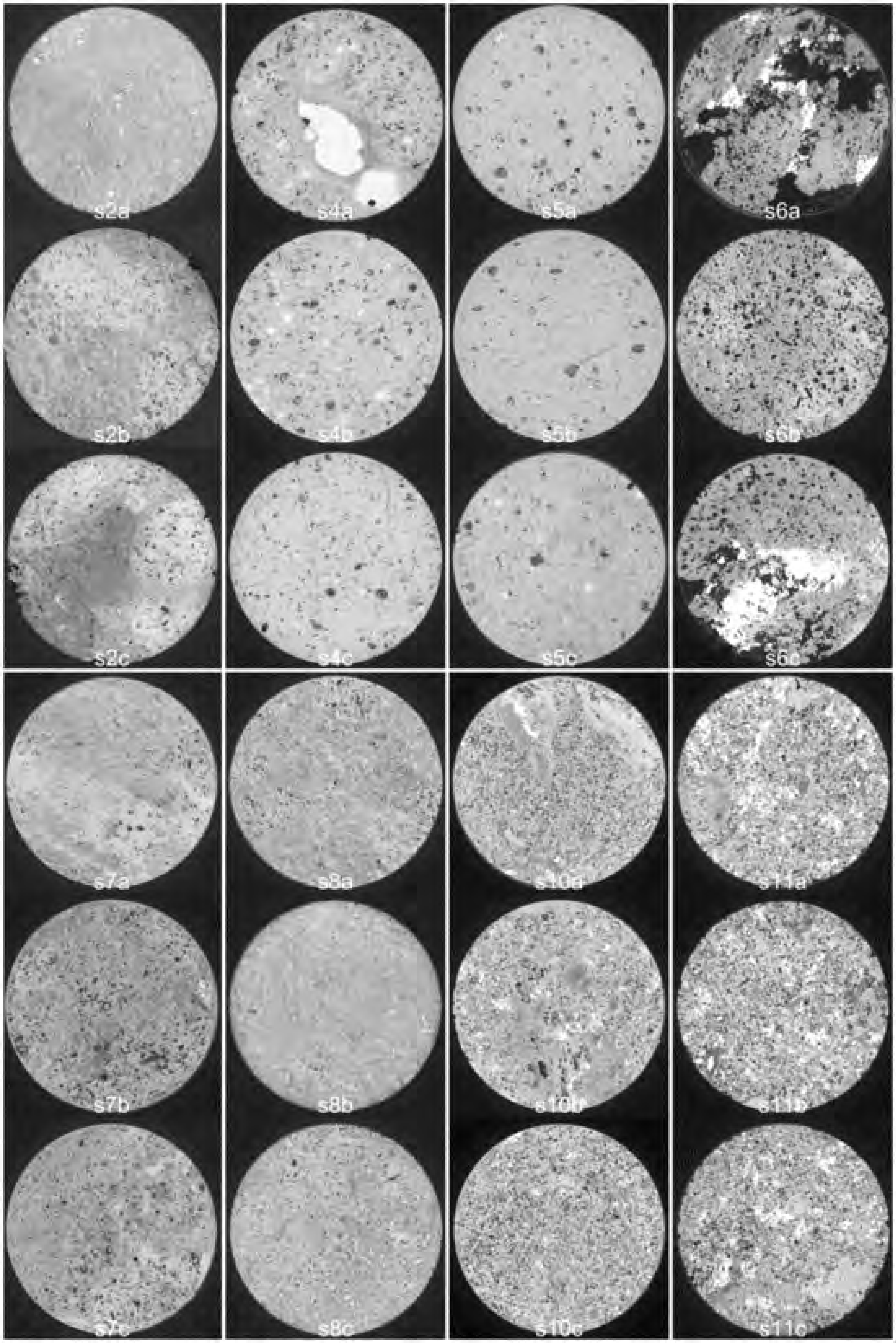

Figure 6. *CT scans of the 1" diameter plug samples.*

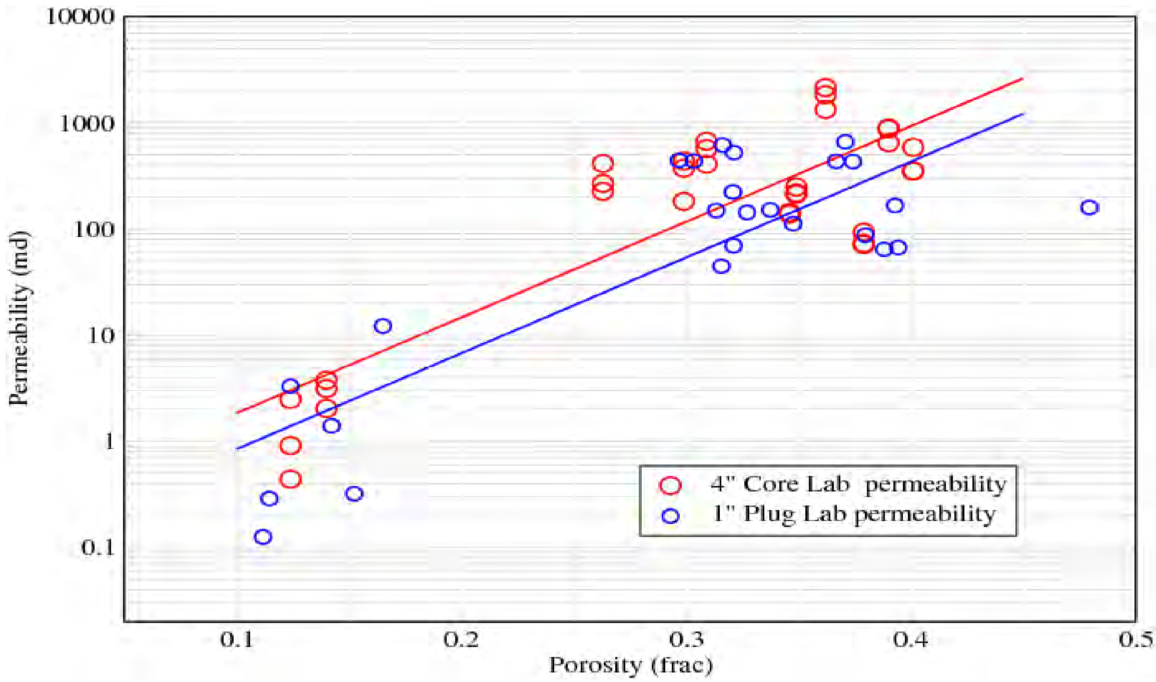

Figure 7. *Porosity versus permeability for the laboratory measured values on FD core and plug samples. Since plugs were drilled both horizontally and vertically, FD core data includes horizontal and vertical permeability measurements.*

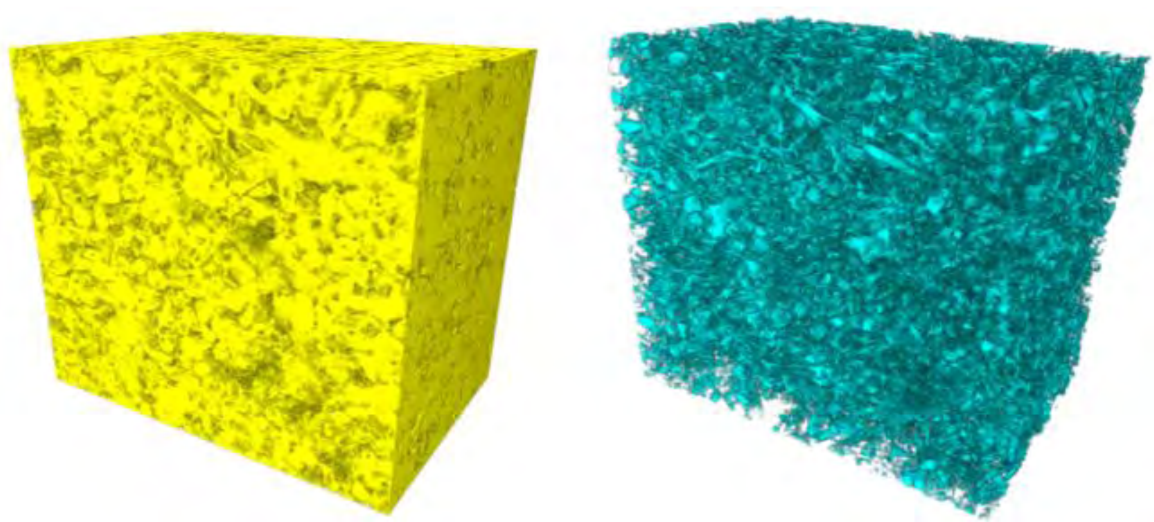

Figure 8. Rendering of the volume (about 0.5cm3) used on the simulation. The segmented solid phase (left) and pore phase (right) are shown. Porosity segmented at this resolution is about 17%, while the total porosity measured in the plug is 32%. The unaccounted porosity is below the image resolution and is assumed impermeable.

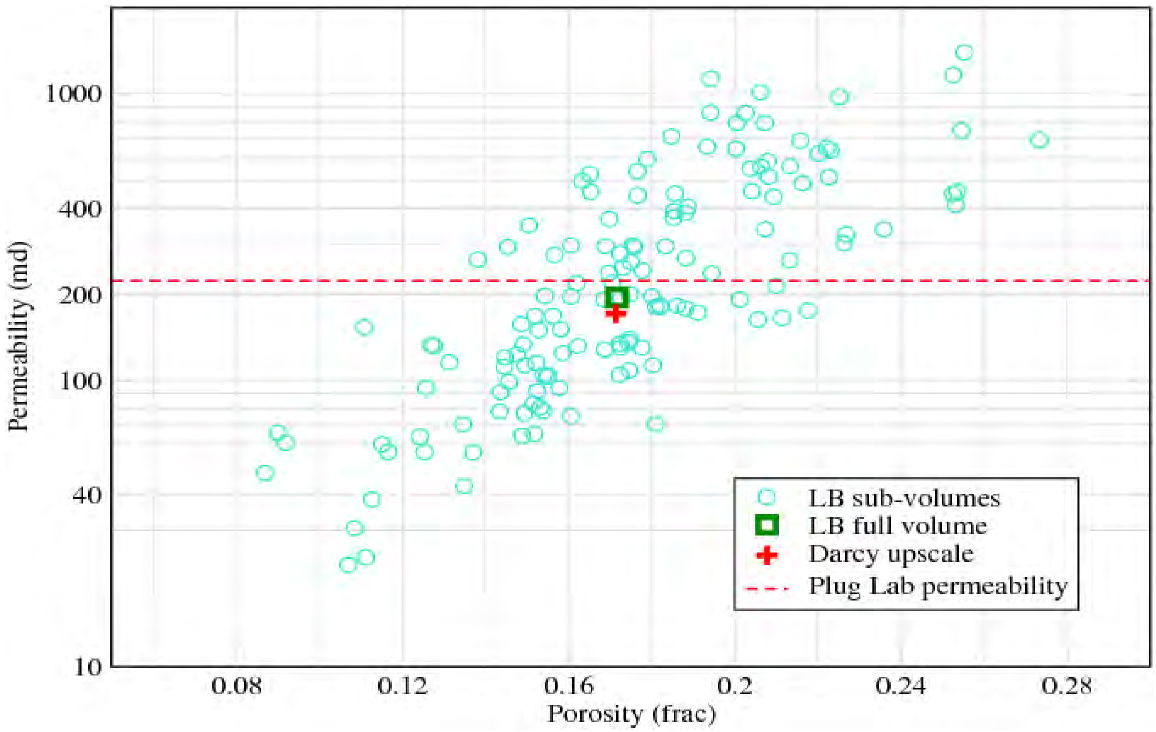

Figure 9. *Porosity versus permeability. Comparison of k_z values simulated using LB on the full size model 193mD and the Darcy upscaled permeability 171mD from a set of sub-volumes values computed from LB. The plug measured permeability is 223mD.*