Integrating multiple image scales and digital image analysis to characterize qualitatively and quantitatively carbonate rock

Irineu A. Lima Neto, Marco A. R. Ceia, Roseane M. Misságia, Grazielle L. P. Oliveira, Victor H. Santos, Ronaldo P. R. Paranhos, Universidade Estadual do Norte Fluminense (UENF/LENEP)

Summary

This study introduces approaches for digital image analyses from multiple image resolutions and techniques, blue resin-impregnated tin sections, Computed Tomography (CT) data from medical to micro resolution, and scanning electron microscopy (SEM) images using a variety of magnifications. The methodology is proposed for each type of image considering its resolution for threshold analysis and binary result, highlighting the pore system for qualitative and quantitative analysis of a limestone sample. The results showed that the high-resolution images are suitable to quantify the pore system properties (thin section and IMX-LNLS µCT data), although the medical CT exhibited low resolution and uncertainty that limited analysis, and SEM was employed to image texture and pore occurrences for a better qualitative analysis. All results were discussed to characterize the limestone sample, treating important insights about DIA and a wide set of images in the discussion.

Introduction

Heterogenous rocks as carbonates have been widely characterized by digital image analysis (DIA) aiming to characterize textural complexities, mineralogy, pore types, etc (e.g., Weger, 2006; Weger et al., 2009). Pore geometry has been verified to impact the acoustic velocity in carbonates (Anselmetti et al., 1998), and recent studies have correlated the pore aspect ratio as a useful parameter that represents the stiffness or softness effect of the rock compressibility by the grain-to-grain contact, increasing or decreasing elastic parameters and P- and S-wave velocities (Assefa et al., 2003; Kumar and Han, 2005; Keys and Xu, 2002; Xu and Payne, 2009).

This study aims to characterize qualitatively and quantitatively a carbonate rock (clean limestone) using multiple image types and scales, including blue resin-impregnated thin sections, Computed Tomography (CT) data from medical to micro resolution, and scanning electron microscopy (SEM) images using a variety of magnifications. The methodology is proposed according to type of image, discussion and results are presented in this study.

Data set

The data set comprises a unique outcrop sample called A1/1-(3.3)K (Figure 1), from many that were collected in the Sultanate of Oman, a Cretaceous limestone from the central portion of Huqf-Haushi uplift (see complete data set in Lima Neto et al., 2018). It is a packstone limestone core sample that exhibits interparticle and intercrystalline main pore type. The texture is grain-dominated, based on skeletal and non-skeletal ooids, bivalve bioclasts, fossil fragments, and Halimeda (green algae). The matrix is supported by calcite microcrystal fabric and quartz is an accessory (very low occurrence). Porosity is partially connected, resulting in low permeability. Helium gas porosity is 21.94%, grain density 2.68 g/cm³. The X-ray diffraction analysis (XRD) shows a mineral weight of 98.5% calcite, 0.9% quartz, and 0.6% halite. Helium gas permeability is ~6.74 mD (at 600 psi).

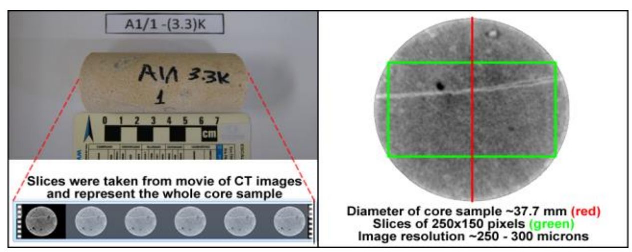

Figure 1 – Schematic summary of workflow applied to medical X-ray CT: 7 slices were taken from CT movie (core sample A1/1-(3.3)K).

Methodology

This study employed images of the packstone limestone A1/1-(3.3)K using multiple scales: 1) thin sections (pixel resolution 1.942 µm), 2) CT scans (multiple resolutions – see Figure 2), and 3) Scanning electron microscopy (SEM) (magnifications ranging from 200 to 5000X). The pore system was evaluated qualitatively by overall images, and quantitatively using suitable resolutions to characterize, in special, macro-mesopores, supposing limitations to identify micropores.

The blue resin-impregnated tin section images were processed using Fiji-ImageJ and JPOR toolset (free and open source software), recognizing the marked pores and generating binary images. In total, a set of 6 images per sampled thin section at the same resolution were analyzed to supply sufficient detail about the pore system (Figure 3). The threshold was performed by JPOR toolset that has an artificial intelligence trained to recognize pores marked in blue (Groove and Jerram, 2011).

The CT images were employed firstly using medical equipment (lower resolution – see Figures 2 and 5), and after others with a best resolution (the best resolution from IMX-LNLS µCT – see Figures 2 and 4). Although the differences in resolution from CT, each grayscale image was analyzed to calibrate a threshold during the segmentation phase, generating binary image (2D or 3D) highlighting the pore system. Figure 1-right shows the resulted image from medical CT, and Figure 4 summarizes the methodology to treat 3D volumes. In general, the method can be summarized in steps below, aiming to:

1) Capture representative 2D images from CT sections (or 3D volume, depending on the CT equipment);

2) Convert 2D/3D images to grayscale and estimate pore resolution;

3) Differentiate pores and mineral matrix by threshold calibration;

4) Analyze the detected pore system under resolution limitations.

The Fiji-ImageJ was applied to perform threshold calibration and estimate image porosity for 2D analysis, and the licensed GeoDict software for 3D analysis. Grayscale of CT image represents the texture of samples, ranging from white (mineral matrix composites) to black (open-pore structures at dry-room conditions). Therefore, our objective was to calibrate the black background threshold for image porosity identification to approximately equal to the measured helium gas porosity (laboratory reference of porosity) for medical CT (due to the poor resolution) and Otsu's method for IMX-LNLS data (higher resolution allows automatic threshold under an interpreter supervision).

The SEM images were employed to qualify the pore type and occurrences, supporting discussions in addition to other DIA methods, due to the very high resolution able to show specific pore details, including micropores that may be unrecognizable from other employed methods in this study, as shown in Figure 5. Thus, some images were selected to try quantifying structures of interest in DIA, performing a threshold analysis of 2D grayscale images similarly to CT by Fiji-ImageJ software.

Results and discussion

The thin section images and IMX-LNLS µCT data volume were applied to quantify pores due to the best resolution (Figure 2). The resulted binary images were analyzed to compute pore properties as:

- Perimeter over Area (PoA) - defined by the ratio between the total pore space area and the total perimeter that encloses the pore space. Small PoA value indicates a simple pore system.

- Dominant pore size (DomSize) - indicates a complex structure, defined as the upper boundary of the cumulative pore sizes that compose 50% of pore volume (Figure 6 - D).

- Pore aspect ratio - defined as the ratio between the major and minor semi-axes of an ellipse that encloses each pore, characterizing the pore geometry. Normally ranges from 0 to 1 as an oblate pore approximation due to lack of orientation. A representative mean or median value is commonly computed to characterize the pore system.

- Gamma – describes the roundness of a pore as the perimeter over the area of an individual pore normalized to a circle, defined by Anselmetti et al. (1998). Thus, it expresses the pore roundness, resulting in a perfect spherical pore the gamma = 1.

The pore properties are displayed in Figure 6. Image porosity was computed and compared with laboratory helium gas porosity, in which µCT results are closer than thin sections by the best resolution as expected. Low differences between 2D (slices from data volume) and 3D (entire data volume) µCT results between Fiji-ImageJ and GeoDict are due to the statistically way employed in each method of the same data. Pore aspect ratio is a 2D property, exhibiting approximate results for images computed in 2D (OM thin sections and µCT slices processed by Fiji-ImageJ); however, 3D µCT volume processed by GeoDict was considered the ratio between higher and lower semi-axes of ellipsoid adapted at each pore, causing higher results in comparison. Similarly, the same is observed for gamma, PoA, and DOMSize, showing that limitations may occur to compute 2D properties from 3D pores (µCT processed by GeoDict). This kind of study suggests that 2D pore properties may be better estimated directly by 2D DIA approaches.

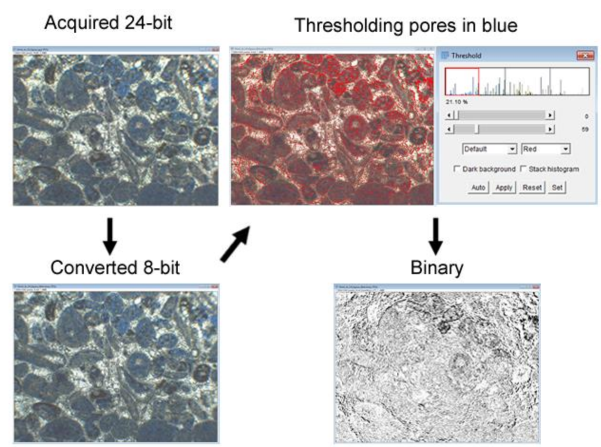

Figure 3 – Flowchart for digital image analysis (DIA) of blue resin-impregnated thin sections using Fiji-ImageJ and JPOR toolset – sample A1/1-(3.3)K. The binary image in result displays the pore system in black (Lima Neto et al., 2018).

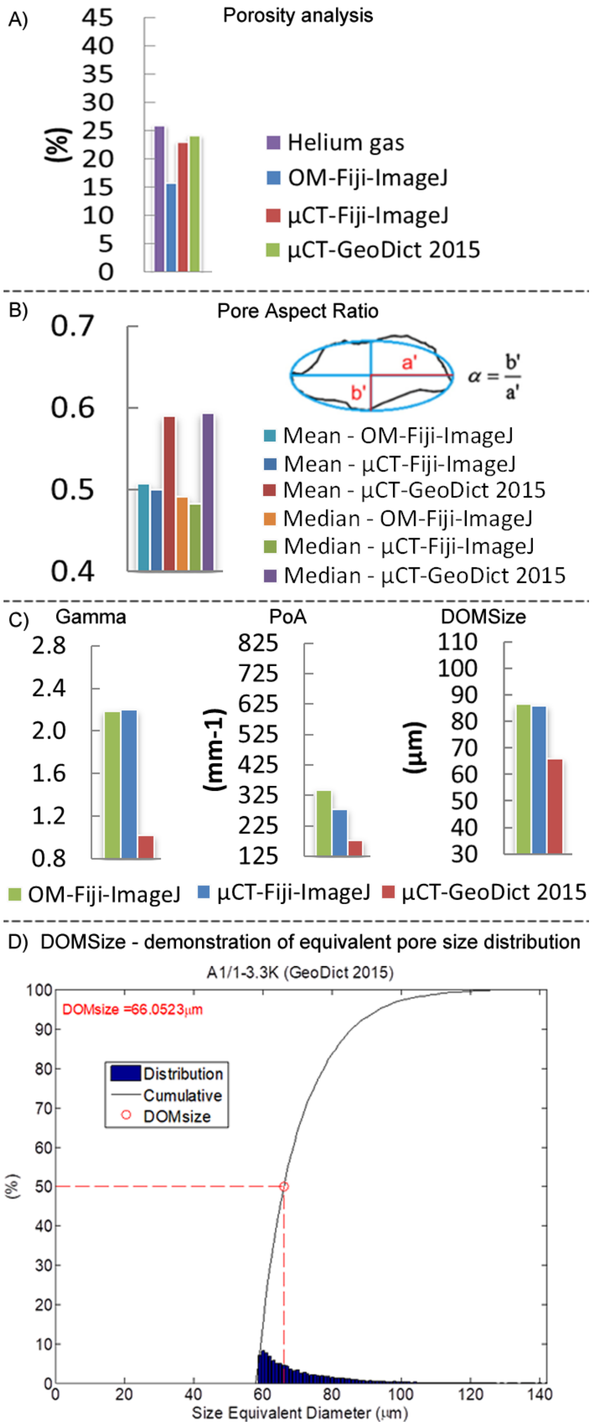

Figure 6 – Quantitative results from DIA analysis (thin sections from optical microscopy – OM, and µCT IMX-LNLS data processed as 2D-Fiji-ImageJ and 3D-GeoDict): A) porosity, B) pore aspect ratio, C) Gamma, PoA and DOMSize, and D) an example of DOMSize estimation. Adapted from Lima Neto et al. (2018).

Qualitative analyses were performed using all images and resolutions. Unfortunately, images such as medical CT with low resolution resulted in difficulties and uncertainties to perform accurate pore system recognition. Figure 5 shows the result, estimate the threshold for correct image porosity is difficult, aiming to separate the porosity voids from the rest of the objects in the image. Thus, poor data quality resolution can arise from the introduction of noise that makes difficult the thresholding process. Additionally, automatic thresholding techniques may not work well for low-resolution images, causing porosity overestimation, as observed during this work. For example, there is carbonate intraparticle porosity occurrence in structures as oolites (slice #5 – A1/1-(3.3)K in Figure 5) that were not recognized in this study by resolution limitation, and automatic thresholding to recognize this particular pore type overestimates the image porosity to ~50% (higher than the helium porosity of 21.94%, that can access microporosity not observed by image analysis resolution in this study). The manual porosity thresholding performed in these images was able to recognize only very large pores of all core samples under the limits of resolution. Pore structures as geometry and connectivity were not calculated properly. The results suggested employing higher resolution as IMX-LNLS µCT to characterize pore system properties, especially for carbonate core samples that have heterogeneous pore system and probably a high occurrence of microporosity. Figure 5 shows the resulted null threshold of slice #7 that was discarded by image porosity overestimation. Thus, the threshold ranges from 26 to 96, and image porosity 20.59 – 21.65% (mean value of 21.35%).

The qualitative analyses from SEM images allowed us to 1) compose different image scales of interest and identify the micro-texture of the occurrences; 2) differentiate pores and mineral matrix of grayscale 8-bit images by threshold calibration; 3) analyze the detected pore system in a specific situation (in this case, a quantitative image analysis could be employed to characterize some pore structures). Figure 6 shows the results from image analysis of 4 groups of different magnification sequences (left to right), allowing the detailing of the texture properties. Thus, mineral matrix and pore structures are highlighted according to the interest, in this case, vuggy macropores from dissolution, mineral structures as halite occurrence, presence of microporosity and microfractures.

Conclusions

An extensive digital image analysis (DIA) was performed for an example of the packstone limestone (A1/1-(3.3)K) using multiple image scales and resolutions, including thin sections from optical microscopy, computed tomography (CT) scans (multiple resolutions, from medical to micro scale), and scanning electron microscopy (SEM) with a wide range of magnifications (from 200 to 5000X). Each kind of image needs a methodology for 2D and 3D imaging and pore system recognition as presented, showing multiple methods applied in this work, aiming quantitative and/or qualitative discussion of results. In fact, quantitative analysis was possible by employing the best resolution images from 2D blue-resin thin sections and IMX-LNLS µCT data volume, which was processed by 2D and 3D approaches to quantify pore properties as image porosity, pore aspect ratio, PoA, gamma and DOMSize. This study showed important insights and discussions about thresholding during DIA, although the limitations from medical CT data and uncertainties about the pore system due to low resolution. The results from SEM images were fundamental to qualify the pore system and pore occurrence, allowing to image micropore and structures that were not possible to define using other available image methods and resolutions, highlighting vuggy macropores, microporosity, microfractures and mineral structures of interest.

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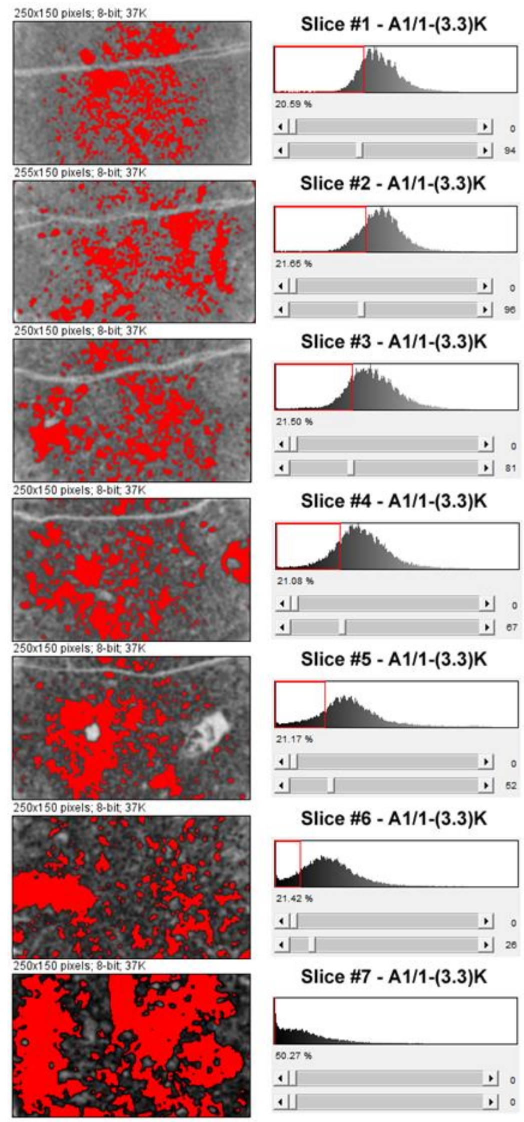

Figure 5 – Pore recognition and visual threshold calibration of 7 representative image slices of core sample A1/1-(3.3)K – medical CT. Difficulties in recognize the pore system due to the low resolution.

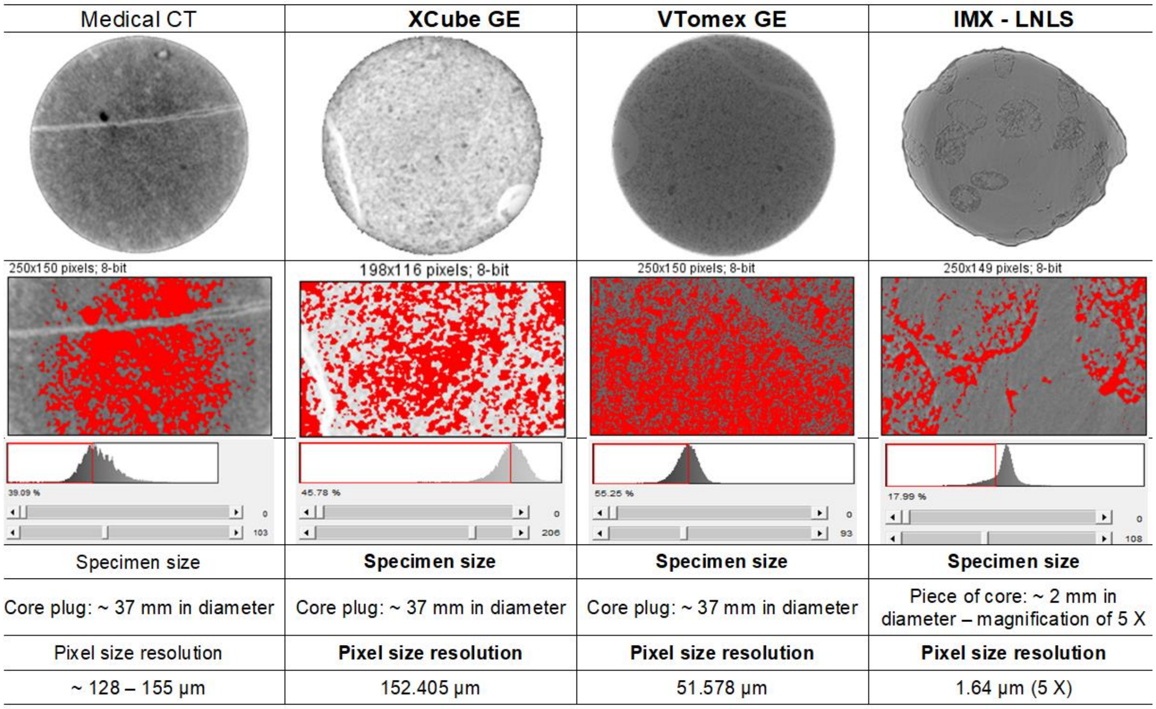

Figure 2 – Comparison between different scales of X-ray tomography (CT) tests and images using the core sample A1/1-(3.3)K. Pores are highlighted in red. Uncertainties are mitigated with the resolution increase.

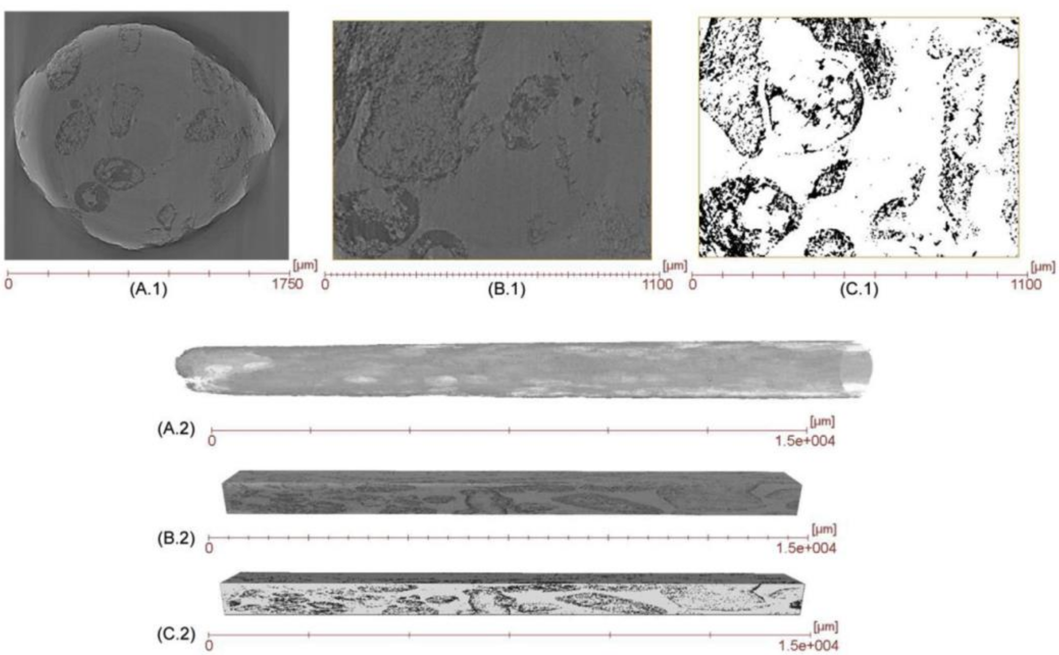

Figure 4 – Summary of IMX-LNLS CT. Pairs of images represent a slice (0.1) of 3D volume (0.2) (e.g., sample A1/1-3.3 K): (A) grayscale data taken from measurement and reconstruction procedures to obtain a data volume of 2048 × 2048 x 2048 voxels; (B) selected volume of interest for analysis and segmentation avoiding rings originating from border scattering; and (C) respective binary data volume highlighting pores in black for properties accounted for and estimated by DIA (Lima Neto et al., 2018).

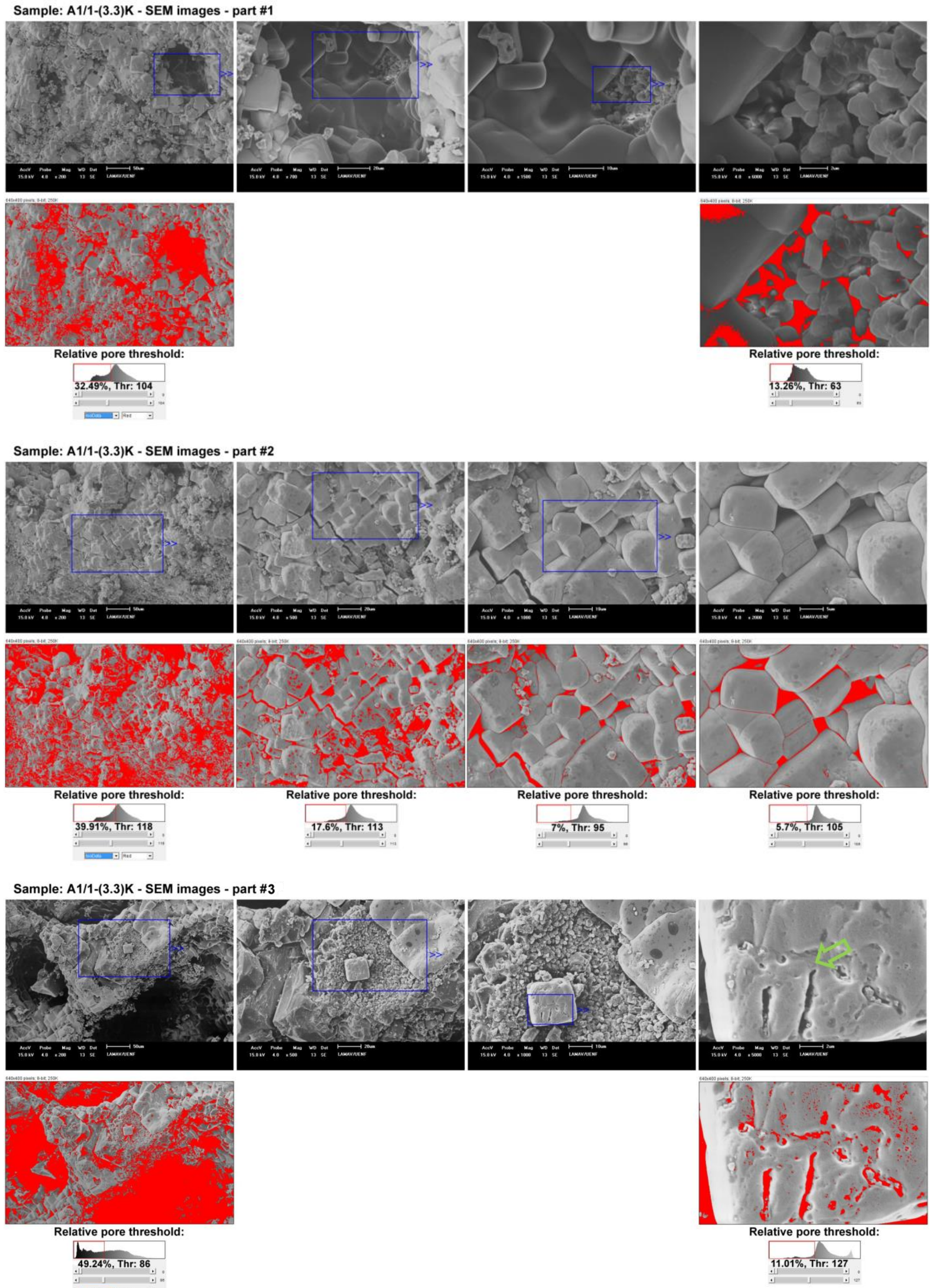

Figure 6 – SEM grayscale 8-bit images of core sample A1/1-(3.3)K magnifications of 200, 500, 1000, and 5000X, left to right, respectively. Details highlighted in: part #1- vuggy macropore and halite crystals occurrence, part #2 – microfracture presence and microporosity in a micritic matrix, and part #3 - dissolution effects that may cause vuggy macropores and presence of intracrystalline porosity (green arrow).