Mapping Residual Phase Saturations in Carbonate Core Material at Multiple Scales*

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Abstract

The prediction of multiphase flow properties of carbonate core material requires understanding the heterogeneity and wettability of pore systems comprising scales from centimeters down to tens of nanometers. In this article we describe multiscale experimental studies of flooding in carbonate samples at scales from plug scales down to tens of nanometers. Imaging allows one to determine the amount of residual phase and knowledge of its microscopic distribution within the rock pore space allows a better understanding of recovery mechanisms. This in turn informs the design and implementation of improved or enhanced recovery processes. While the importance of the pore scale structure, mineralogy and wettability in dictating the residual phase distribution is widely acknowledged, little quantitative information on these properties and dependencies has been directly available. This study bridging the core, plug and pore scales using x-ray (micro)-tomographic imaging, petrographical (SEM and SEM-EDS) imaging and wettability mapping leads to a better understanding of pore scale mechanisms and recovery processes. The experimental techniques used are reviewed, emphasizing the registration technology which enables spatial alignment and integration of 2D SEM-based information with 3D micro-CT images. Application of these techniques to visualization of pore scale oil and brine populations is presented, with a particular focus on characterizing native state carbonate plug material.

Method

A set of native state reservoir carbonate plugs (1 inch diameter) were imaged using the micro-CT facility from which a 3D tomographic image was obtained. To improve oil differentiation in CT, the residual oil was then exposed to a reactive species which attenuates the hydrocarbon, improving overall x-ray attenuation of this phase alone. The plug was then re-imaged, and image registration was subsequently performed to directly visualize the attenuation difference in these two conditions. For higher resolution imaging, smaller subplugs (diameter 3-6 mm) were taken from the native state plug and subjected to the same preparation and imaging protocol mentioned above. Following this, the residual oil phase was removed by soxhlet extraction followed by treatment in methanol, after which the subplug was dried in air. The cleaned subplug was reimaged and the resulting 3D tomographic image was registered to the attenuated condition, and a difference map was

produced from the density variations in the samples; this gives an accurate mapping of the oil saturation in situ. For even higher resolution, a polished section was prepared from within the CT scanned volume of the cleaned subplugs, and imaged with field emission SEM. The 2D images were registered to their corresponding slice in the subplug tomogram.

Results

Figure 1 compares identical slices from the 3D tomogram of one plug, with the right hand image corresponding to the native state and the left hand image giving the difference in registered tomograms between the condition with stained oil and the cleaned state. The difference map thus serves to highlight the hydrocarbon phase; the brightest regions in the upper half of this left hand slice indicate increased presence of residual hydrocarbon. For the native state, the darker regions in the lower half of this right hand slice are of higher porosity and associated with larger pores and more intergranular porosity. Accordingly, the regions rich in hydrocarbon phase appear to correlate to the microporous regions of the plug.

The images at this scale in are limited to voxel resolutions of 12 microns, which are larger than most individual pores. Higher resolution is attainable when the field of view is smaller. We image 4 mm subplugs which facilitates investigation of the rock and its residual phase at closer to pore scale. For one such subplug, Figure 2 displays a pair of registered tomographic slices. It is apparent that the regions with little hydrocarbon are associated with either solid grains or larger pores, thus locally higher residual saturations are more correctly identified as belonging to meso/microporous regions.

Tomography at the plug and subplug scales shown in Figure 1 and Figure 2 are both of too low resolution for direct identification of all pore sizes associated with the distribution of the residual oil, as pores vary from 50 nm to 100 microns in these carbonate samples. FESEM imaging of polished sections from subplugs allows one to resolve most pores, and registration to the corresponding micro-CT slice facilitates direct comparison to residual oil prevalence. Figure 3 shows the FESEM image of a small field of view along with regions identified in the tomogram as being oil rich. The registered image pair supports the conclusion from Figure 2 that the residual oil is primarily concentrated in the carbonate mesopores of intermediate size.

Conclusions

Advances in our ability to visualize multiple fluid phases in reservoir rocks at the pore scale, and integrate this information with the core scale behavior it dictates have been presented. In ongoing work we are focused on incorporating upscaling methods for flow properties from pore to plug to core scales, including simulations based on the use of steady and unsteady state upscaling techniques under different flow regimes. The aim is to replicate special core analysis (SCAL) type measurements via calibrated imaging and modeling studies.

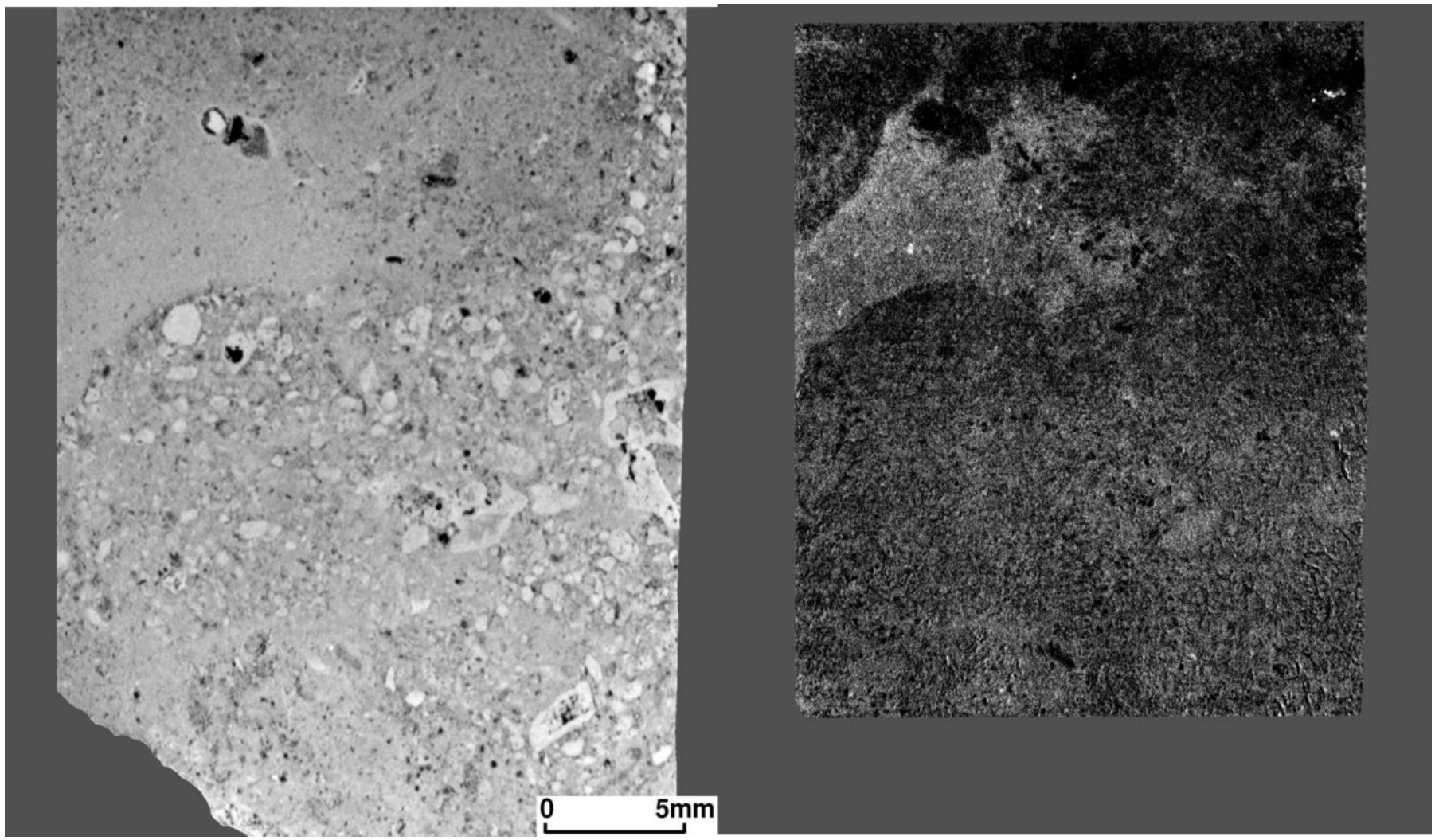

Figure 1. The same tomographic slice of a native state carbonate plug, showing (at left) the difference map between the oil-contrasted condition, and the native state (at right).

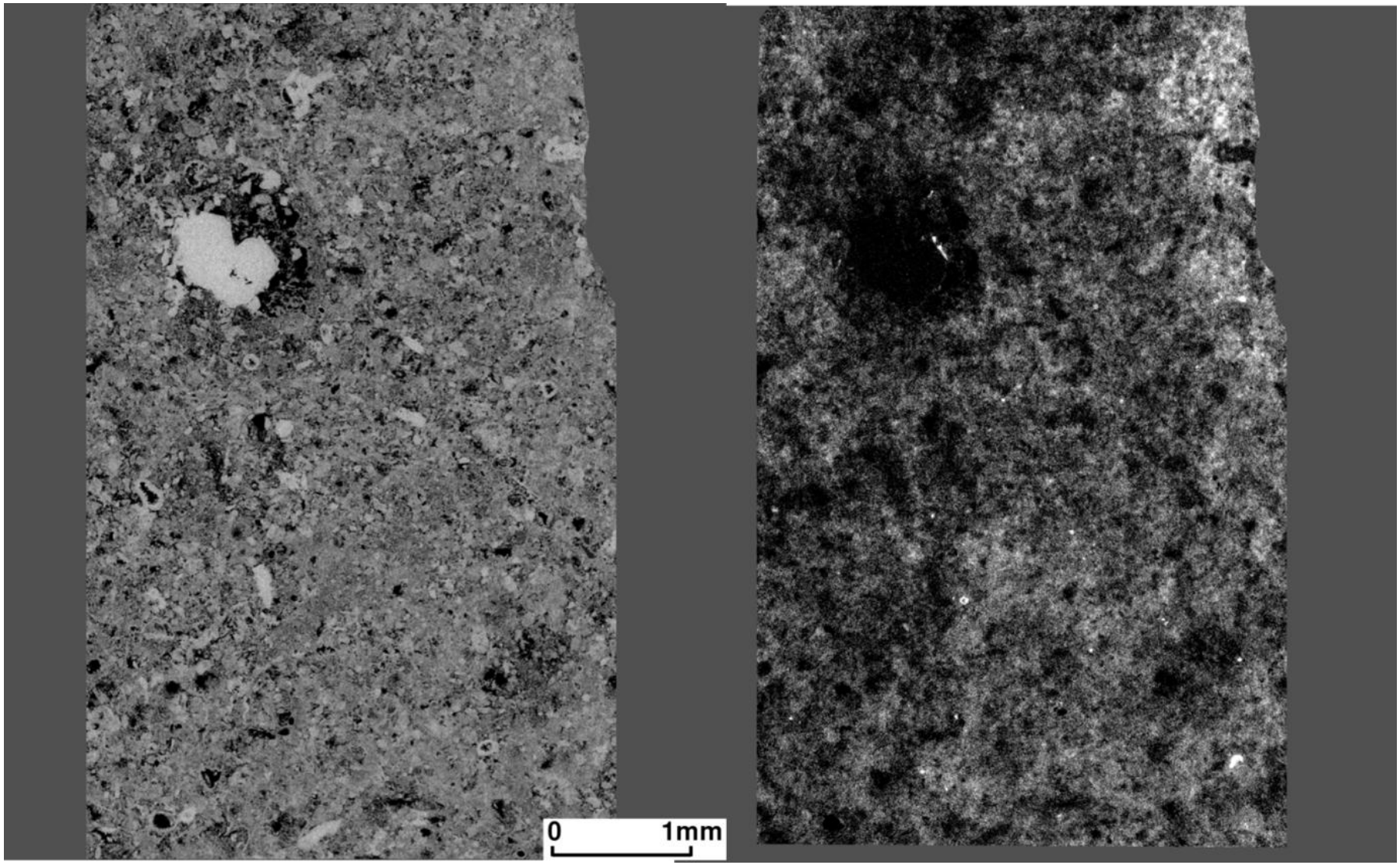

Figure 2. The same tomographic slice of a subplug of 4 mm diameter from the native state carbonate plug, showing (at left) the difference map between the oil-contrasted condition, and the cleaned, empty condition (at right).

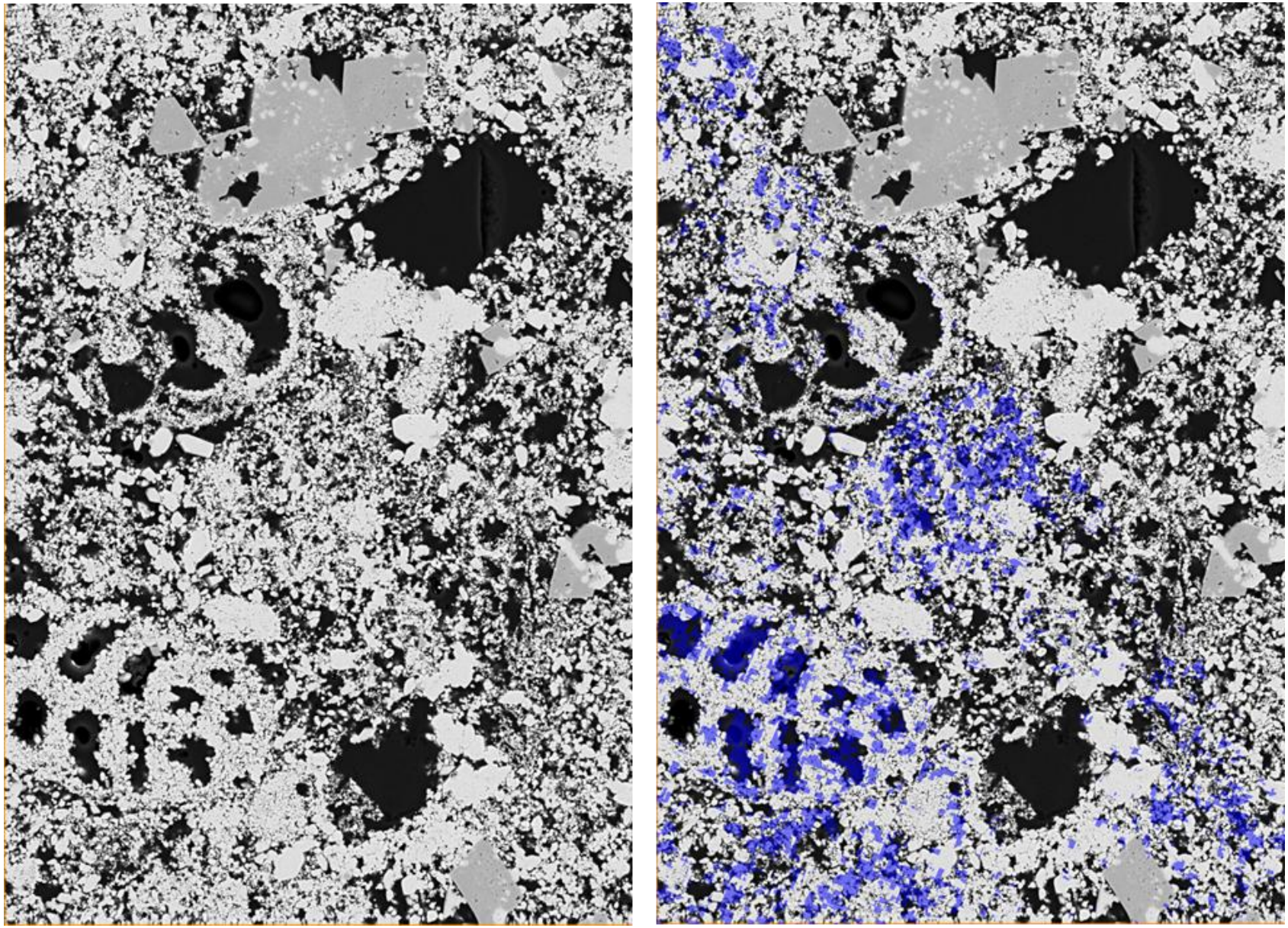

Figure 3. FESEM image (600 micron field of view) from the polished section of a native state carbonate subplug after cleaning (at left), and registered to 3D tomographic data (at right) in which blue regions correspond to oil saturation.