Non-Destructive Local X-Ray Tomography for Multi-Length Scale Analysis of Reservoir Rocks: Validations and Observations

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ABSTRACT

Digital core analysis (DCA) is a fast and cost-effective solution for analyzing the porosity and fluid transport dynamics in rock samples. Despite the myriad new advancements made in the analysis technique, DCA is ultimately dependent on the quality of the input data, which must be carefully collected in order to deliver reliable results. X-ray microscopy (XRM) is now a popular approach to this data collection, owing to the high quality of data that is provided by modern laboratory scanners. Furthermore, the non-destructive nature of x-rays enables multiple examinations of the same sample at many different length scales, enabling capture of representative elementary volumes at each feature size. This is especially important for carbonaceous samples, due to the presence of pores down to the single- and sub-micron length scales.

In order to fully utilize the multi-length scale imaging approach, it is important to preserve the internal structure of the sample, minimizing disruptions from sample preparation procedures. While traditional x-ray microtomography setups categorically restrict high-resolution analyses to small sample sizes, novel approaches to XRM have now enabled single- and sub-micron resolution on samples up to tens of millimeters in size. This approach utilizes so-called local tomography where interior volumes may be selected with low resolution and then optically enlarged for higher-resolution microstructure investigations.

While the local tomography technique has previously been believed to introduce many imaging artifacts, we demonstrate here that the artifacts are relatively minimal with an x-ray imaging geometry that permits local tomography by utilizing high feature contrast. We demonstrate the precision obtained with the sample-size-to-field-of-view ratio as high as 8:1 using digitally-acquired petrophysical parameters as the measurement comparison criteria.

INTRODUCTION

X-ray microscopy, in recent years, has become a staple of modern digital core analysis laboratories. These systems non-destructively produce 3D data corresponding to the 3D structure of the sample, which may range from the meso- to the nano-scale. Results from this measurement technique may be subsequently processed and analyzed to compute a flow model, measuring parameters ranging from porosity and absolute permeability to relative permeability, formation factor, and residual water & oil saturations, to name a few [1-2].

METHOD

Instrumentation

Modern digital core analysis laboratories often contain micro computed tomography instrumentation (micro-CT), which provides sufficient resolution to see the meso- and micro-structure of sandstones and carbonates [1-2]. Traditional flat panel architecture systems generally achieve high spatial resolution – down to 1 µm or slightly below – when samples may be placed very close to the X-ray source. This is due to the reliance of these systems on high geometric magnification in order to achieve a small effective pixel size, which mandates a small source-to-sample distance to also minimize geometric penumbra [3]. While this may be sufficient for high-resolution analysis of small cores samples (e.g., <1 mm Feret diameter), it is not possible to examine the fine pore networks when the sample size is large using this geometry. This reduces the flexibility of such instruments, since regions of interest (ROIs) must carefully be physically extracted from bulk samples, which is challenging to achieve in practice.

By pairing a high-resolution detector with a high-brightness microfocus X-ray source, resolutions down to sub-micron levels within large samples may now be achieved using commercially available X-ray instrumentation [3]. In the experiments that follow here, an Xradia MicroXCT-200 laboratory x-ray microscope is used, which follows this novel approach to allow resolutions down to 1 µm on samples up to 10s of mm in size. This affords the operator flexibility to do large-volume survey scans using coarser resolution and then optically zoom in on specific regions of interest with higher resolution. Fig. 1 shows a schematic diagram of the system described. For the fine structure of the pore networks within carbonates and examination of shale, commercially available X-ray instrumentation is now able to achieve spatial resolutions down to 50 nm in the laboratory. This technique is, however, beyond the scope of this paper and the details are described elsewhere. [1-4]

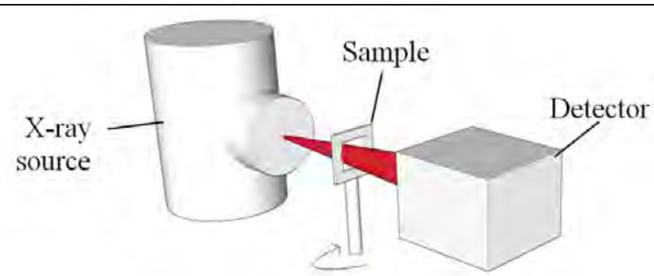


Figure 1. Schematic diagram of a laboratory micro-CT setup. The system used here employs a high-resolution detection system, allowing large samples to be imaged while maintaining high spatial resolution.

Imaging Procedure

The virtual sub-sampling technique described relies on the technique of *local tomography*, where more information is visible in the individual radiographs than is intended for the reconstructed 3D volume, and where this extra information exists only in a portion of the total radiograph series [5]. While the extra information adds artifacts and noise to the reconstruction, practical application of the local tomography technique has demonstrated the viability of this approach. [6-7]

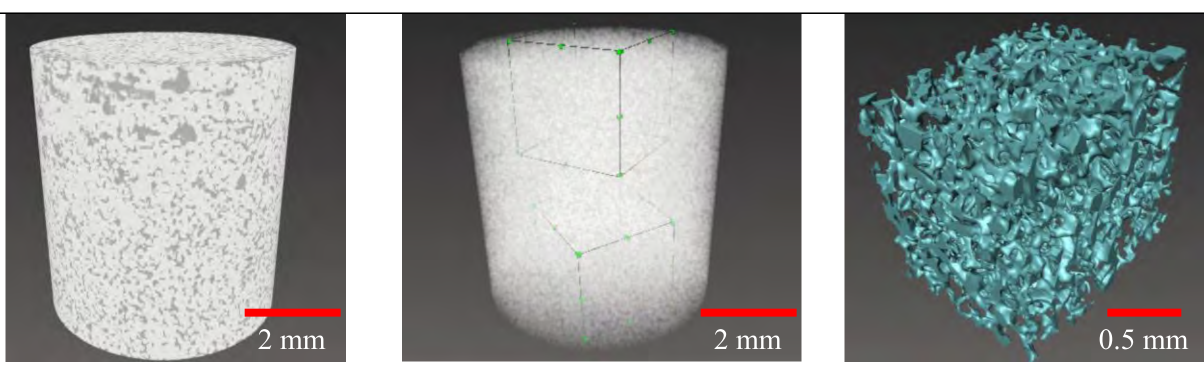
In the experiments presented here, a rigorous validation of interior tomography using the MicroXCT-200 instrument was carried out, in order to investigate the true accuracy of the result. This study encompasses two parts: simulation and application, described next.

Simulation

A reef carbonate sample was first drilled out as a ~4 mm core using a bench-top drilling machine [8], then imaged with pixel resolution ~2 μm using the X-ray microscope described above, utilizing the full 2048 pixels available in the detector. In this scan, the entire sample was captured in all of the radiographs, producing a full tomography (i.e., not local), and was then reconstructed as usual to produce a 3D volume of clear virtual slices. Next, a central region, 255 pixels wide and 255 pixels high, was cropped from the radiographs to produce a simulated interior tomography data set, which was then independently reconstructed using the same routine as for the full tomography scan. The 3D volume from the full tomography was then cropped to match the 3D volume from the simulated interior tomography, so that the same regions in each sample could be compared. Both results were smoothed with a non-local means denoising filter and segmented using the 2DHistogramSegmentation module in the analysis software [9] and compared on the basis of porosity.

Application

A castlegate sandstone sample was first cored to ~5 mm, then imaged in 3D with ~5.6 μm pixel size ("full, coarse tomography"). After imaging and subsequent reconstruction, an interior region was selected and non-destructively imaged with higher resolution, ~2.2 μm pixel size, using local tomography. Next, an attempt was made to physically drill out the region of the local tomography from the full sample, which was imaged with the same resolution as in the local tomography. While a best-effort was made to physically extract the same region as examined with local tomography, the region could not be perfectly isolated using traditional coring tools (Fig. 2b). Once all the scans had been collected, the interior and drilled-out regions were virtually matched to their origins within the coarse scan using an automated analysis routine so that all results could be compared to those achieved in the initial full (coarse) tomography. These matched regions were smoothed with a non-local means de-noising filter and segmented using thresholds (in the interest of time savings and due to the high clarity of all results). Fig. 2 shows a 3D rendering of the full sample, local tomography & drilled-out regions, and the rendered pore network.



(a) (b) (c)

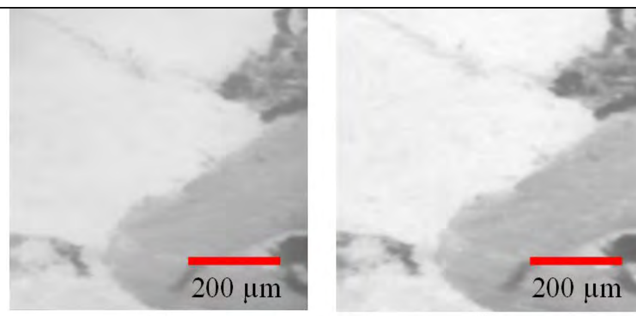
Figure 2. Schematic diagram of the applied local tomography experiment. (a) shows a 3D rendering of the full (coarse) tomography, from which a region was selected for higher-

resolution analysis using local tomography. This region would then be subsequently drilled out for imaging with full tomography, employing the same high resolution as the local scan. (b) shows the regions of the local tomography (top box) and drilled-out sample (bottom box). Practical limitations of the drilling tool prevented the extraction of the exact desired region. (c) shows a high resolution 3D rendering of the pore network.

RESULTS

Simulation Results

The first experiment, comparing a local tomography result to a full (coarse) scan, showed minimal variation in porosity, possibly within the statistical variations of segmentation [10]. This demonstrated that local tomography provides results consistent with full (coarse) tomography, serving as a validation of the local tomography technique. The results are illustrated by the example slices shown in Fig. 3.



(a) (b)

Figure 3. Example 2D virtual slice of the (a) local and (b) full (coarse) tomography. The porosity of the local tomography was measured to be 13.0%, while that of the full tomography was 14.3%.

Application Results

The results compared included: a) full (coarse) tomography, b) drilled-out simulation using the full (coarse) tomography results, c) local tomography simulation using the full (coarse) tomography results, d) actual drilled-out tomography results, and e) actual local tomography results. This set of 3D volumes was compared on the basis of several reservoir parameters, including porosity, network (absolute) permeability, network formation factor, residual water saturation, residual oil saturation, and water relative permeability at residual oil saturation. The flow simulations on all extracted pore networks were performed using the two-phase code developed by [11]. Table 1 summarizes these results, from which minimal changes are observed between the different scans. Fig. 4 shows the two-point correlation function for the coarse scan suggesting a representative elementary volume (REV) of ~1 mm (10x decay length). Because this value is smaller than the imaging volume in all scans, an REV may thus be considered to have been achieved for all results [4]. Fig. 5 shows the capillary pressure and Fig.

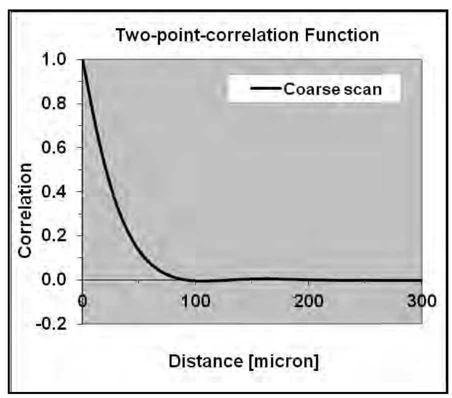
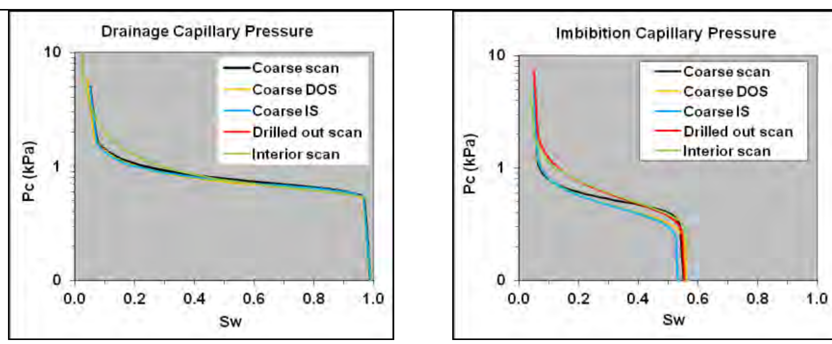


Figure 4: Two-point correlation function for the coarse scan, suggesting REV of ~1 mm.

6 the relative permeability curves, which show minimal measureable difference between the scans. This further supports the validity of the local tomography results, demonstrating that, from the standpoint of reservoir engineering, local tomography and full tomography produce consistent results. The similarity of petrophysical properties between all scans additionally suggests that, even for the lower-resolved coarse scan, the resolution is sufficient for this rock type.

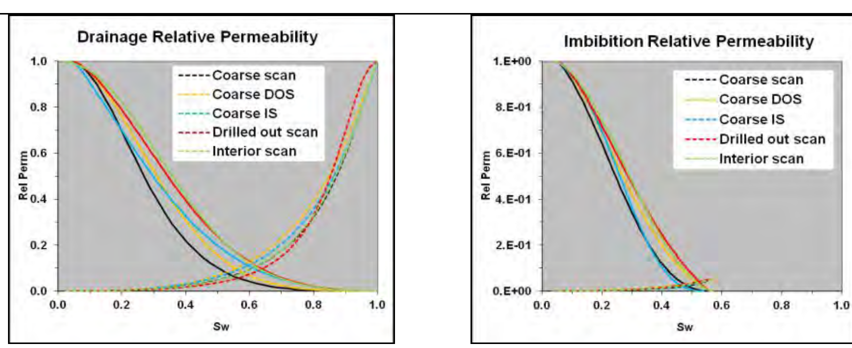
Table 1. Summary of results from the application experiments.

	Coarse, full (a)	Coarse, drilled simulation (b)	Coarse, local simulation (c)	Fine, drilled full (d)	Fine, local (e)
Shorthand Label	*Coarse scan*	*Coarse DOS*	*Coarse IS*	*Drilled out scan*	*Interior scan*
Physical size [μm]	2775	1276.5	1276.5	1226.5	1226.5
Pixel size [μm]	5.55	5.55	5.55	2.23	2.23
Porosity	0.215	0.232	0.219	0.229	0.225
Network Perm (mD)	630	676	597	621	721
Formation factor	37	36	40	31	28
Residual water saturation	0.050	0.05	0.049	0.05	0.040
Residual oil saturation	0.45	0.43	0.461	0.443	0.434
Water rel. perm. at residual oil saturation	0.05	0.052	0.042	0.051	0.051



(a) (b)

Figure 5. (a) Drainage and (b) imbibition capillary pressure curves.



(a) (b)

Figure 6. (a) Drainage and (b) imbibition relative permeability curves.

SUMMARY

In the results presented here, local tomography has been validated against full tomography using both simulation and physical extraction results. The difficulties encountered with physically extracting the volume of interest using a coring tool simply support the need for local tomography in practical digital core analysis laboratories. Using this approach, analysts can use large-volume 3D scans to locate interesting regions within their samples, then quickly and precisely enlarge those regions using non-destructive local tomography with reliable quantification of several reservoir parameters.

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