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Virtual Petrophysical Laboratory – Part 3 Erosion Simulation in Porous Media

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Summary

This paper presents an erosion simulation in a computer based petrophysical laboratory of porous media done directly in 3D space. It is the first step in modeling simultaneous erosion and deposition in synthetic rock samples. The foundation of the system was presented in the first two papers[1,2] during Geoconvention 2020 and 2021. These two previous papers presented modeling and visualization of rock samples followed by estimating the total porosity, effective porosity, tortuosity, and resistivity. Erosion is simulated in our virtual laboratory by dynamic modification of the solid parts of the model along established flow paths that connect two opposite model faces. The dynamic model changes refer to post-processing of a model that has been already created and more or less extensively tested. This is opposite to adding structural model features during its creation (e.g. creating correlated pore network with specific properties in a predefined direction).

This study and experiments were done using a model equivalent to 134 million equal size cells but compacted into less than 0.6 million cells of variable size. The process and algorithms were tested by comparing changes in estimates and model images with color mapping of results in 2D and 3D space. In addition, capillary pressure curves shape changes versus changes in the model structures helped in the final evaluations of the new process.

Dynamic Sample Modifications – Erosion Test

Dynamic sample changes are done after the model is already built to make structural pore/grain network modifications that correspond to natural processes observed in petroleum reservoirs, soils, catalysts, etc. Here is a list of steps in the process after model is created and evaluated:

- Finding effective porosity and continuous paths that connect two opposite faces of the tested sample.
- Marking all solid cells (cubes) along the path that outline the pore surface. Specifically, a surface solid cell has to have at least one empty neighbor of any size.
- These cells form the original pore surface and in the next step there are subdivided to desired resolution.
- New smaller cells from these subdivided larger cells are redefined into new pore and grain cells. These form a new, more refined, pore surface (see Figure 1 – presenting a pore cast image).

At the final stage some of these new subdivided rock cubes will change into empty cubes representing pore space (grey cells in Figure 1) while the remaining smaller cubes will retain ‘grain’ definition (not visualized in the pore-cast mode). The whole process is more complicated and requires many traverses of the octree that represents the model. Finding and marking neighbor cells of different properties in specific direction is part of these steps.

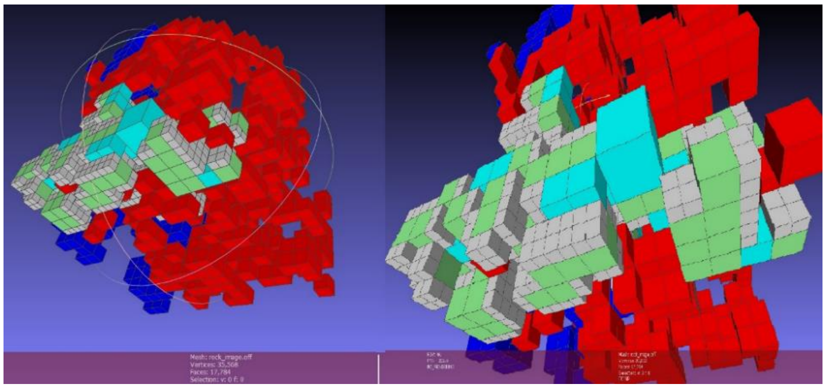

Figure1. Two views of a pore cast visualizing erosion: Red – unconnected porosity; Green/Blue shades – connected porosity; Grey – new pore cells added by the erosion process – they used to be part of solid cells that not shown here.

The eroding process can only happen in the active pore network, which must have connectivity between two opposite model faces as shown in Figure 1. The new pore space cells (grey) represent a layer of the most outer rock cells prior to the process. In other words these new pore cells are neighbors of the new smaller rock cells (left out in the pore cast).
These dynamic changes to the rock/pore structures are based on stepwise subdivision of variable size octree cells (cubes) representing the sample model as presented in our two pervious papers during Geoconvention 2020 and 2021.
The erosion process starts after a sample model is built and initial estimates of the petrophysical variables are done and connectivity is verified. It is a separate process and can be done prior or after other simulated processes (e.g. capillary pressure curves test).

Research Novelty

A typical implementation of a multiscale pore network where pore space varies from large (macro) to micro pores is based on different elements interconnected in specific ways. The elements may include balls and tubes organized into a lattice representing the pores and pore throats. Additional elements and/or lattices may represent micro porosity, grains, particles, etc.

In our virtual laboratory we have only one element a cube of different size that is used to re-create a rock without any intermediate representations. Thus, all parts of the pore network, grains, and anything else are built using the same elements (cubes of different size but with different properties: grain, pore, fluid type, conductivity, etc.). In addition, grains and other 'solid' materials are not ignored but participate in modeling and estimating. This is important when implementing erosion or deposition processes.

Erosion Visualization

Several rock samples have been built and tested to verify the workings of the new procedures and algorithms. Here we present visualization and testing of a sample using an octree with nine levels of subdivision and corresponding to a model with 134,217,728 cells of equal size. The original model was represented by an octree with the total nodes equal to 664,633 and the total-leaf-nodes equal to 581,554. This shows how the adaptive data structure of variable size cubes can help in compressing homogeneous spaces into larger units.

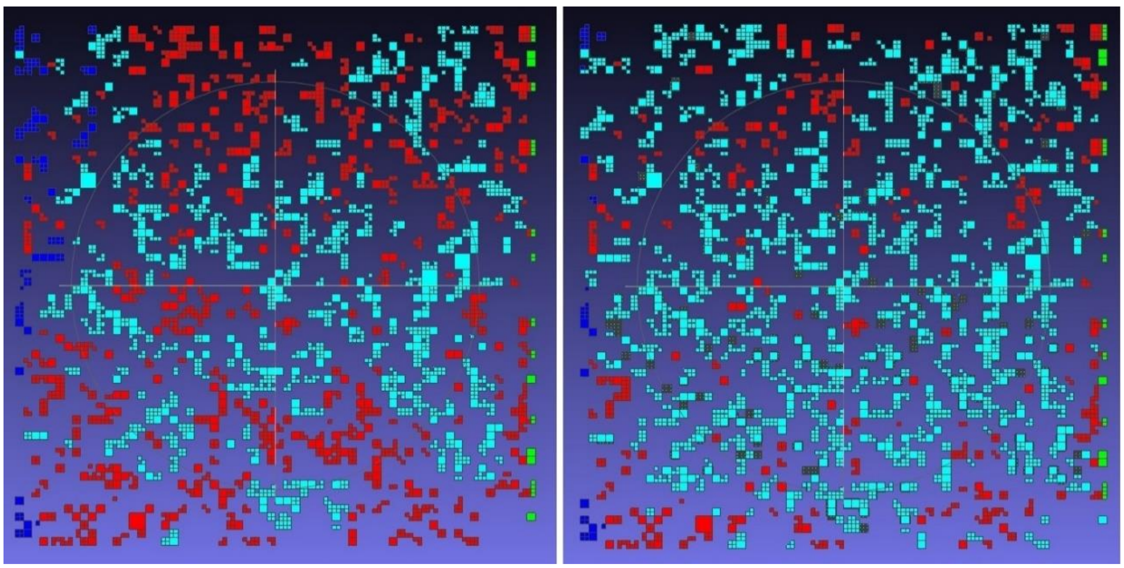

Figure 2. Original 2D cross-section of a model (Left) compared to the same model after erosion simulation (Right). Color cell mapping is: Green/Blue connected pore network; Red: unconnected porosity; Grey: rock matrix.

This homogeneous sample had porosity of 25.4% and effective porosity (interconnected) of 11.7%.
The corresponding numbers after the erosion were: total-nodes of 15,491,865; total-leaf-nodes of 7,068,468; total porosity of 26.7%; and total effective porosity of 19.4%.

As we can see the erosion process doubled number of nodes and cells. It increased slightly the total porosity by 1.3%. However, the effective (interconnected porosity) increased by 7.7%. This was enough to produce a large change in flow properties estimated by electrical resistivity (shown in Table 1). This table shows several estimates using traditional statistical formulas (arithmetic, geometric, and harmonic means) and estimates from well published chain and bundle upscaling algorithms. Two additional columns present estimates obtained applying our 'mesh' algorithm based on the octree data structure, and advanced electrical circuit transformations and calculations[3].The non-statistical estimates were estimated in horizontal and vertical direction.

Table 1. Resistivity [Ohm*m] comparison between
'Before' and 'After' erosion process.

Electrical Resistivity Estimate Type	Before Erosion Ohm*m	After Erosion Ohm*m
Arithmetric	53,162,865	43,385,849
Geometric	11,466,241	1,498,298
Harmonic	559	258
Horizontal Chain	294,188	81
Horizontal Bundle	24	4
Horizontal Mesh	188,886	54
Vertical Chain	193,878	68
Vertical Bundle	23	4
Vertical Mesh	143,364	46

The 1st three estimates do not differ in horizontal and vertical directions, while the chain/bundle/mesh estimates are different in horizontal and vertical directions if a sample is not exactly homogeneous. In this case the vertical estimates are even smaller for chain/bundle/mesh evaluations but close enough to confirm the model homogeneity.

All estimates show that our sample changed from slightly conductive to well conductive sample, which can be contributed by interconnecting micro-porosity as shown in Figure 2, where red unconnected cells on the left image were shown to be connected in green (part of the effective network) on the right-side image.
Figure 3 shows the same two samples (before and after erosion) with and without cell grid for better visualization of porous cells after the erosion (right image). The grid lines enhance differences between images as shown in red circle areas in lower parts of both images. The differences in these two images without grid lines are difficult to distinguish because the overall porosity has not changed much. The differences are represented by very thin layers of cells along the effective network, which do not change much the sample image.

Figure 4 presents 3D views of samples at the beginning of the drainage simulation where non-wetting phase (NWP) is advancing from the left side forming a blue finger. The shape of the advancing finger did not change after the erosion simulation. However, we can see fewer red unconnected porosity cells and additional new fingers in blue confirming effectiveness of the process.

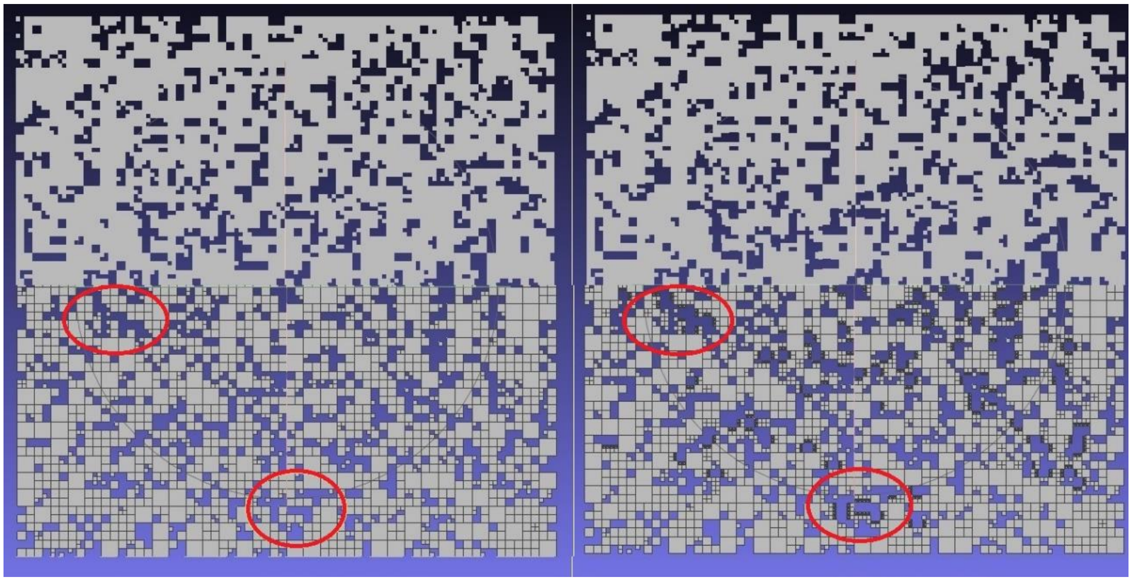

Figure 3. A cross-section images before and after erosion in two modes where upper part does not have the grid lines shown in lower parts of images. Blue color shows the pore space while grey rock matrix.

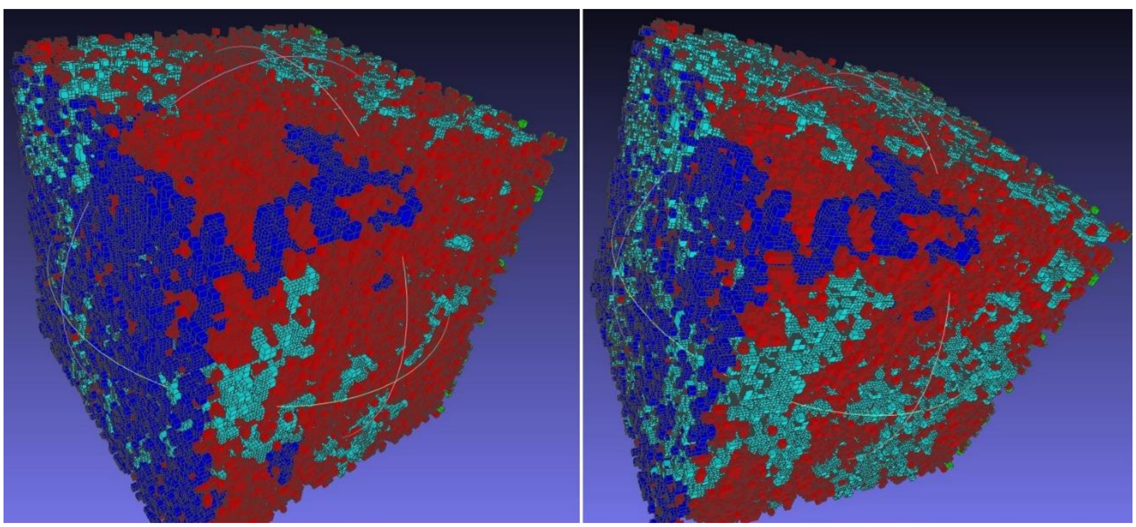

Figure 4. A 3D view of both samples (before and after erosion) shows a NWP advance in blue at the beginning of the Drainage Simulation. Color Mapping is; Blue: NWP; Green: WP; Red: unconnected porosity.

Capillary Pressure Curves for Erosion Verification

The saturations of the wetting and non-wetting fluids are recorded for each pressure. At each step of the drainage and imbibition process, nine values of electrical resistivity are estimated. Presented results and visualization show how erosion affects flow properties, fluid saturations, electric resistivity, the capillary curve hysteresis, and 3D shapes of the non-wetting fluid paths at break-through events.

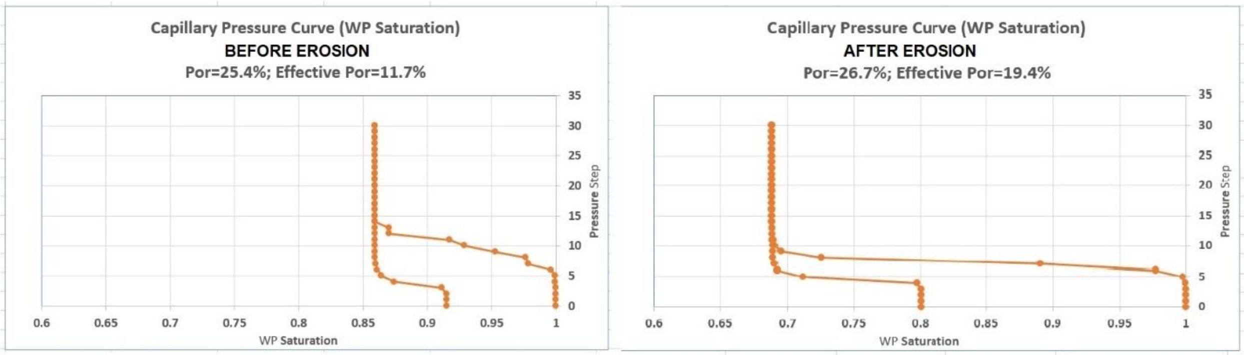

Figure 5. Wetting phase saturation (relative to the effective porosity) versus pressure before and after erosion.

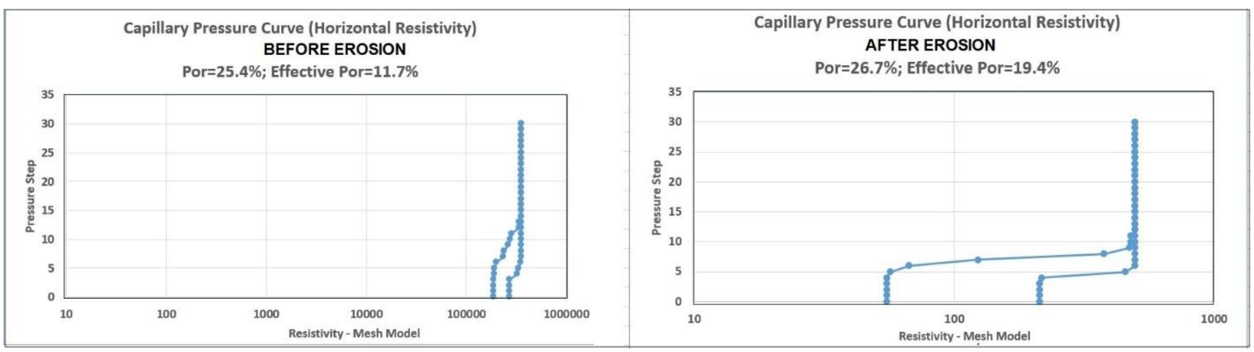

Figure 6. Resistivity hysteresis before and after erosion.

Both Figure 5 and Figure 6 show significant changes in flow properties due to the erosion process in the tested sample. Erosion caused large changes in the saturations and large changes in resistivity estimates. Furthermore, the after shape became smoother indicating that the interconnectivity increased and eliminated some of the most limiting pore throats in the original sample.

Summary

Here we present a software prototype, which simulates erosion processes significant for the petroleum and other industries. It enables testing scientific hypotheses and helps in the understanding "cause and effect" related to erosion in porous media.

The designed software and processes create and test large pore network structures directly in 3D space without intermediate representations or using different elements to model porosity and micro-porosity. This paper shows that the same adaptive octree data structure suits well to build large models and simulate advanced processes in virtual samples of porous media that correspond to processes observed in natural environments.

The described software is based on connectivity algorithms in octrees and computer procedures that model natural events in porous media. Dynamic structure changes are implemented as a set

of post-processing procedures. Furthermore, all elements of a virtual rock sample are built and processed the same way avoiding implementing different intermediate objects as it is done in similar studies. Presented here results were derived by simulating and testing a very large model corresponding to 134 million of cubic cells of equal size on a standard personal computer.
Simulating deposition processes is going to be a natural extension of the current work when improving and enhancing our Virtual Petrophysical Laboratory.

References

1. Leon Fedenczuk, Kristina Hoffmann, Virtual Petrophysical Laboratory – Part 1: Modeling and Visualization, Geoconvention 2020, Calgary, June 2019.
2. Leon Fedenczuk, Kristina Hoffmann, Virtual Petrophysical Laboratory – Part 2: Testing and Simulation, Geoconvention 2021, Calgary September 2020.
3. Leon Fedenczuk, Kristina Hoffmann, and Tom Fedenczuk, New Pore and Reservoir Scale Upscaling Solution for Large Models, submitted to Global Petroleum Show, Calgary, June 2022.