

SYSTEMATIC PARAMETER STUDY FOR FORMATION FACTOR MODELING AT THE PORE SCALE

Matthias Halisch ⁽¹⁾, Sven Linden ⁽²⁾, Jens-Oliver Schwarz ⁽²⁾, Sarah Hupfer ⁽¹⁾, Andreas Wiegmann ⁽²⁾

⁽¹⁾ Leibniz Institute for Applied Geophysics (LIAG), Stilleweg 2, D-30655 Hannover, Germany

⁽²⁾ Math2Market GmbH, Stiftsplatz 5, D-67655 Kaiserslautern, Germany

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ABSTRACT

Digital Rock Physics (DRP), in combination with state of the art 3D imaging techniques, such as high resolution micro CT (μ -CT) or Synchrotron CT (Sr-CT), has progressed to a well established methodical instrument for petrophysical process modeling and simulations at the pore scale, respectively. Besides hydraulic and acoustic (elastic) rock properties, which probably form the largest field of interest for DRP, electric conductivity / resistivity is also of great interest since it is essentially used to determine (e.g.) water saturation, formation producibility, and at least the volume of oil- and/or gas in place of the formation. For this, formation resistivity factor (F) is measured by default during classic core analysis in the laboratory, in order to evaluate the parameters as mentioned above and to characterize the pore system of the rock in more detail. Nevertheless, to provide reliable statistics, experimental time increases significantly, same as the amount of cores that need to be investigated. This is where DRP and non-destructive 3D imaging become relevant. Though the experiment as well as the analytical calculation of F is straight forward, numerical modeling of this parameter by using CT obtained geometries is significantly affected by different boundary conditions, such as:

- a) The 3D scan resolution (voxel resolution);
- b) The image processing / phase segmentation;
- c) The ratio of mineral to water resistivity;
- d) The overall computational domain size;
- e) The micro-scale sample (formation) heterogeneity.

The amount of pores that can be detected is directly linked to the resolution of the imaging, since F is mostly dominated by the porosity. False or inaccurate segmentation of phases can increase this effect in addition. The parametric setup of the model greatly increases computational power and time. Finally, the domain needs to be representative, which is especially challenging for heterogeneous (e.g. layered) samples. In this systematic parameter study, the authors showcase a selection of these effects by using data from three different rock samples (i. young sandstone; ii. reservoir sandstone; iii. porous carbonate). The results are compared to experimental, i.e. laboratory obtained data, and discussed critically in order to evaluate and develop better and optimized numerical tools and workflows for this specific modeling purpose.

INTRODUCTION

The classical and empirical relationship between rocks and the saturation fluids is essential for the interpretation of electrical borehole measurements since the early 1940's [1, 2]. The

fundamental proportionality between the resistivity of a water saturated rock (ρ_0) and the resistivity of the pore fluid (ρ_w) led to the infamous and so called Archie's law:

$$\rho_0 = F \cdot \rho_w \quad (\text{E1})$$

The introduced parameter F , the formation resistivity factor, is a measure of the increase in resistivity of a pore fluid by presence of a non-conductive rock matrix. Formation factor is dependent on the geometrical (spatial) distribution of the electrolyte within the rock, related to the internal structure of the rock, of the pore space and of the wettability conditions therein [3]. Hence, F mostly – but not exclusively – is assigned to the (effective) porosity of the investigated rock. This finding led to the first Archie equation [2]:

$$F = \frac{1}{\Phi^m}, \quad (\text{E2})$$

where m denotes the so called cementation exponent. Since porosity can be easily assessed by modern 3D digital imaging techniques and evaluation software tools, reliable modeling results are still challenging to derive, and strongly depend upon the boundary conditions as mentioned in the introducing abstract. The toolbox GeoDict (developed and distributed by Math2Market GmbH) is a generic approach for computer aided material engineering, and has been used for the formation factor modeling. It contains geometric models for virtual material synthesis and provides numerical tools for the prediction of material properties on the micro-scale. The basic concept is the simulation of physical processes on digital objects that are derived from either μ -CT images, or from synthesized images and models. This toolbox is able to predict a broad range of mechanic, electric and hydraulic rock properties, including parameters of routine and special core analysis [5, 6].

Explicit Jump Immersed Interface Method for Electrical Conduction

The Explicit-Jump immersed interface method is a very fast finite difference method to solve partial differential equations [7, 8]. Here it is applied to solve the stationary electrical conduction, heat conduction and diffusion equation in reservoir rocks:

$$\nabla \cdot (\sigma \nabla U) = f, \quad (\text{E3})$$

where U denotes the electric potential and $\sigma > 0$ the piecewise constant electric conductivity. The equation is composed of Ohm's and Kirchhoff's law. The stationary electrical conduction equation is directly solved on segmented μ -CT images, where each individual phase is assigned an individual electrical conductivity value. Harmonic averaging is used to derive conductivities between material interfaces. The potential is discretized in a regular grid even in solid phases. Additional jump variables across material interfaces are introduced, where the continuity of the electrical flux yields the need for extra equations. A so called Schur complement formulation for these new variables is derived such, that fast Fourier transforms (FFT) and BiCGStab methods can be used to solve the linear system. If the values of the jump variables are known, the FFT solves the electrical conduction equation directly. This means that instead of solving a 3D problem in order to find the electrical potential, a 2D problem is solved derive the jump variables. Hence, computational time is reduced significantly. In addition, this method has a very good convergence rate even in geometries with high contrast in conductivity, such as it is mandatory

for natural rocks. The convergence rate solely depends on the number of jumps, i.e. the surface area of the material interfaces.

SAMPLE MATERIAL, μ -CT IMAGING & MODEL SETUP

For this study, three different rocks have been used (Fig.1, left to right): a highly porous carbonate, a young tertiary sandstone, and a cretaceous reservoir sandstone. The carbonate (denoted as EBK) is characterized by high porosity (up to 48 %) composed of inter- and intra-granular void space, and by a high degree of mineralogical pureness (> 99 % CaCO_3). The tertiary sandstone (denoted as IG) features large and sharp edged quartz grains that are covered by cristobalite needles, an overall low clay mineral content (< 2 %) and few but large muscovite crystals. The porosity can reach 37 % and is dominated by intergranular voids only. The reservoir sandstone (denoted as BE) features a porosity of up to 25 %, which is composed of inter-granular voids of the quartz grain matrix as well as of micro-pores, which are related to the clay agglomerations (up to 9 vol.-%) within.

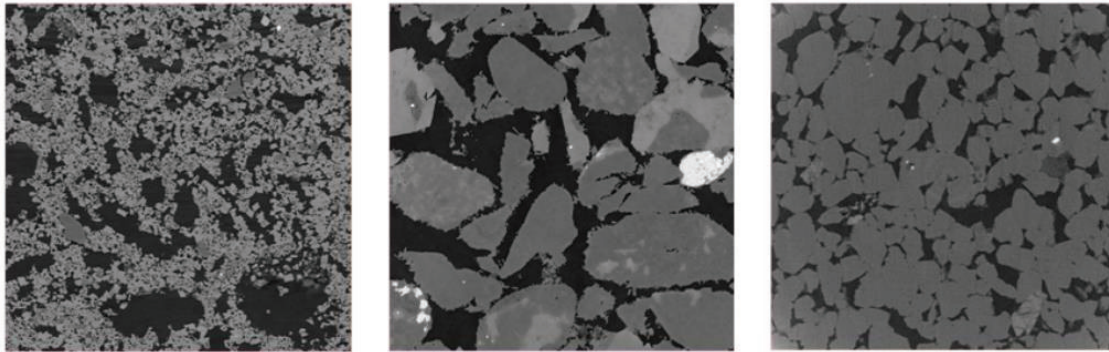


Figure 1: μ -CT cross sections of the three investigated samples at a scanning resolution of 2 microns each (from left to right hand side): carbonate, young (tertiary) sandstone, reservoir (cretaceous) sandstone.

From all materials, a small plug (4 mm diameter, 8 mm length) has been prepared for the μ -CT imaging. The samples have been entirely scanned with a GE phoenix nanotom S tomograph, with three different voxel resolutions: 2 μm , 5 μm and 10 μm . Within the 2 μm scan, a region of interest of 1000^3 has been cropped and registered to the 5 μm scan, which then has been cropped at the same relative domain size and registered to the 10 μm scan, which has been cropped in the same way. Hence, for all samples, the exact same region of interest, i.e. 2 mm edge length (= 1000^3 @ 2 μm , 400^3 @ 5 μm and 200^3 @ 10 μm) has been extracted for three different scan resolutions. The 3D data sets have been processed individually, which means that they have been filtered (non local mean) and registered with scanning electron data for a best fit segmentation solution by using Otsu [9] and watershed algorithms [10]. For the formation factor modeling, the following conductivities have been used [3, 11]: $\sigma_w = 5 \text{ S/m}$, $\sigma_{\text{matrix_EBK}} = 1\text{e-}10 \text{ S/m}$; $\sigma_{\text{matrix_IG}} = 1\text{e-}12 \text{ S/m}$; $\sigma_{\text{matrix_BE}} = 1\text{e-}12 \text{ S/m}$. Boundary conditions have been set to periodic, stopping criteria was a model (σ_0) accuracy equal or better than 0.001 S/m and a maximum of 10,000 iterations or 240 h maximum run time, respectively.

RESULTS

First of all, results of segmentation errors are showcased (Fig.2), since the segmentation threshold directly influences the amount of porosity of the 3D data set, and hence of the modeled F-value. The “best fit threshold” has been used as starting (center) point to vary the threshold stepwise for selected percentages to this value. It is clearly visible, that the segmentation threshold, as a function of scan resolution, has a tremendous influence upon the measurable porosity of the 3D data sets, even for very small segmentation misfits. The resolution effect is especially for the carbonate detectable, due to the clearly visible spreading of the error curves, caused by the loss of intra-granular voids with increasing voxel resolution. $\pm 2\%$ threshold error may cause already $\pm 2.5\%$ to 6% of porosity change. For the IG sample, this effect is below $\pm 2.5\%$ change in porosity, due to the absence of micro porous structures.

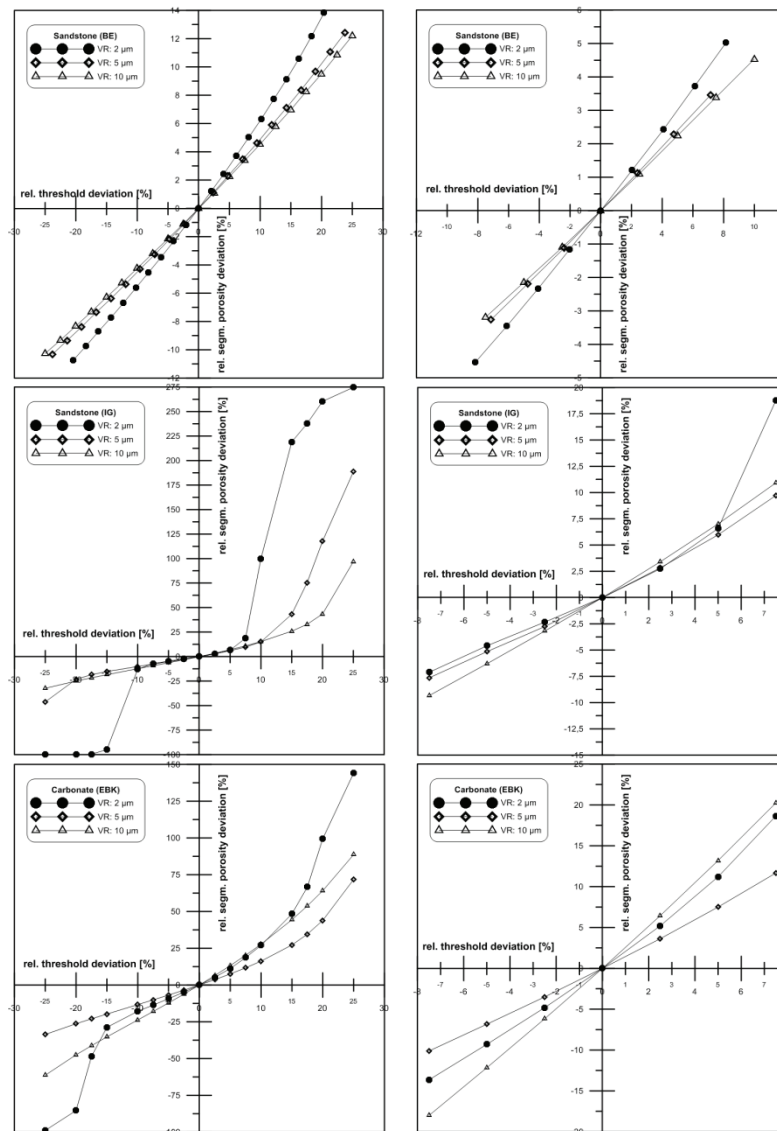


Figure 2: Results of the segmentation error (x-axis = rel. threshold deviation related to the best fit threshold) on the segmented data set porosity (y-axis: rel. porosity deviation related to the best fit threshold) for the carbonate (top), tertiary (middle) and cretaceous sandstone (bottom). The right column is zoomed in ($\pm 7.5\%$ on x-axis) for a better view on deviations at small changes for each sample. Hence, the left hand column showcases the full investigated deviation range ($\pm 25\%$ on x-axis).

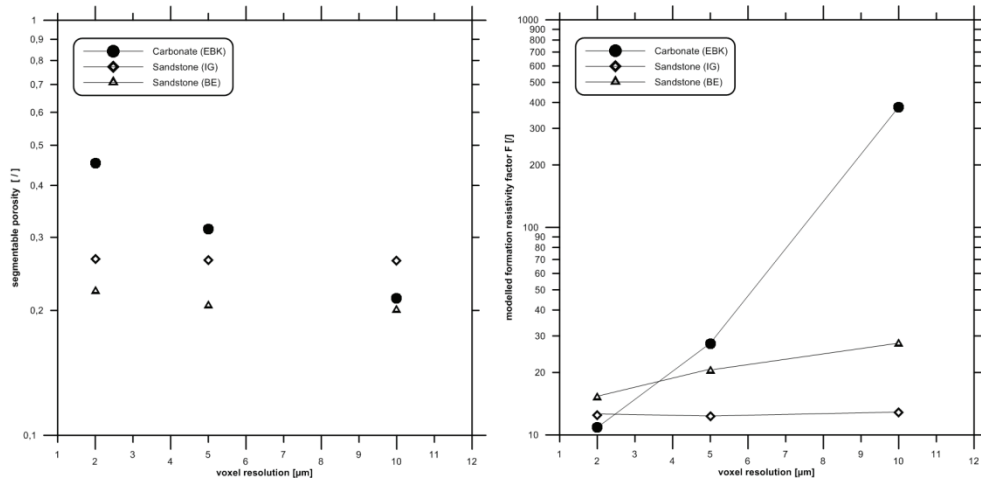


Figure 3: Relationship between scan resolution and segmented porosity (left hand side) and modeled F (right hand side), respectively, for each of the three samples.

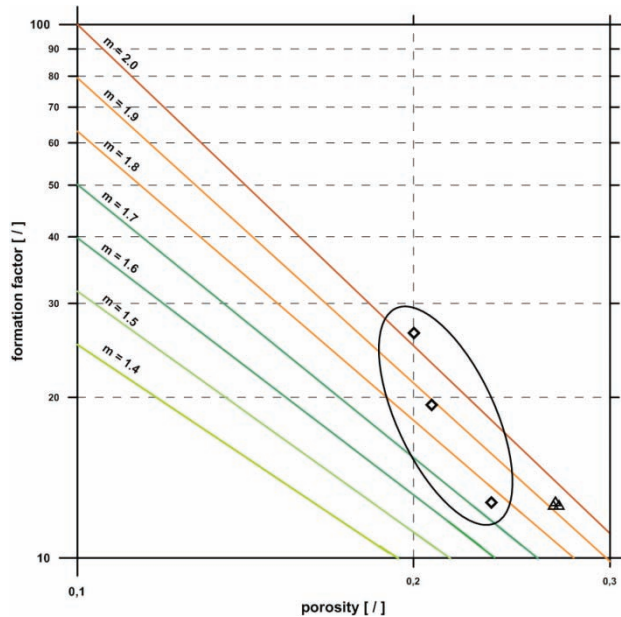


Figure 4: Scan dependent formation factor values versus porosity, including cementation exponent ranges related to (E2), for the two different investigated sandstones. Diamonds = BE; triangles = IG.

CONCLUSIONS & OUTLOOK

This study has shown that formation factor modeling is very case sensitive towards the 3D scan resolution, the segmentation threshold, and hence the segmented porosity. As a result, additional information of the sample material (e.g. scanning electron microscopy images for a highly reliable segmentation procedure; mineralogical information to estimate the amount and expected types of pore structures) in close combination with high 3D image resolution is highly recommended. Though modeling time may be drastically decreased (factor 50 for the EBK, 130 for the IG and for the BE) by using coarse image resolution, i.e. smaller model domains, results may lead to significantly different interpretation of the reservoir characteristics.

This data base is being constantly increased for a broader range of rocks in order to transfer this knowledge to get reliable interpretation results. For this, ongoing studies on representativeness of the 3D data sets, on impact of the pore fluid (conductivity) and on heterogeneous (anisotropic) rock types are performed and hopefully published in the near future.

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