THE REV CHALLENGE – ESTIMATING REPRESENTATIVE ELEMENTARY VOLUMES AND POROUS ROCK INHOMOGENEITY FROM HIGH RESOLUTION MICRO-CT DATA SETS

Dr. Matthias Halisch
Leibniz Institute for Applied Geophysics (LIAG), Stilleweg 2, D-30655 Hannover, Germany

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ABSTRACT

Micro Computed Tomography (µ-CT) imaging forms a great method to investigate internal rock structures – e.g. the void space, fluid distribution, etc. – fast, in three dimensions and non-destructively. Since the last decade, µ-CT has progressed to faster imaging as well as to faster reconstruction times, and especially to high quality image resolution and sharpness (in the micron or even sub-micron range). With this, access is granted to the investigation of small pore space features (e.g. clay induced porosities or porous networks, formed by dissolved mineral phases) as well as to representative, i.e. predictive fluid flow modeling. Although modeling of fluid flow through small sample networks may increase the knowledge of fluid dynamics on a microscopic scale, representative modeling of physics remains the most important task. For this, porosity has proven to be the parameter of choice to characterize a porous media by terms of fluid dynamics and to determine a representative elementary volume (REV) for it. The REV is reached, when the average porosity in the probing volume becomes independent of the size of the volume. Nevertheless, this approach does not consider sample inhomogeneities or directional porosity variations, e.g. caused by layering effects. Hence, the author would like to present an advanced method to estimate representative elementary volumes derived by high resolution µ-CT imaging. This Method is based upon a variance analysis of directional micro-porosity logs, which have been calculated from 3D image quantification analysis. Additionally, a new method to estimate the sample inhomogeneity – as a quality control feature for the REV estimation – is introduced. With this analysis, it is furthermore possible to investigate scale, i.e. REV edge size, dependent structural effects and transitions.

INTRODUCTION

The fundamental theory of the challenging REV estimation has been introduced by [1]. This approach has been developed and consequently enhanced over the past years. The probably best publication related to this topic was written by [2]. Since the extensive theory can be reviewed there, only the basic idea will be introduced. Porosity, as a geometrical, or structural porous medium property, it is a good parameter to determine a REV, since for consolidated (porous) rocks a distinct correlation between porosity and other, CFD related properties, as permeability, does exist [3]. This relationship between porosity and permeability can be utilized to determine a REV quite easily. For unconsolidated rocks, a specific REV for each of them (e.g. permeability) needs to be considered separately [1]. Figure 1 reflects the main idea of this approach.

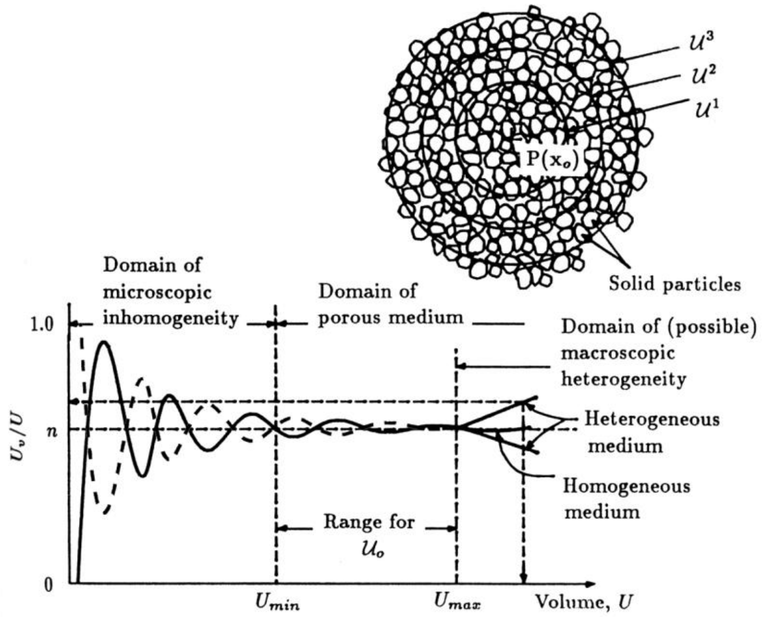

Figure 1: The basic REV principle, shown by the variation of porosity (n) within the neighborhood of a point $P(x_0)$ as a function of the averaging volume (U). Modified after [2].

Figure 1 shows that if an infinitesimal small and cubic elementary volume is considered, which may be randomly distributed within the porous medium domain, porosity may vary between zero and one, because the volume is either related to rock matrix (grain material) or to pore space. If the volume is increased step by step, porosity alternates between a maximum and minimum value until they converge to each other. At a distinct point, the domain of (microscopic) inhomogeneity is discontinued (figure 1, left hand side) and the porous media domain is entered (figure 1, middle section). In this range, property variations are minimal and almost converge to the in-situ porosity value. Hence, the material may be described as a homogeneous medium. In fact, it is possible that heterogeneity may increase again, related to 'macroscopic' volume features (e.g. fractures) so that the function diverges again (figure 1, right hand side). It should be mentioned that the minimum volume size U_{min} for a representative elementary volume strictly depends on the specified domain accuracy [2].

PROCEDURE

For this research, different types of sandstones have been used. For this abstract, the results of only one of them will be presented in detail. It is a so called “Bentheimer sandstone” (upper cretaceous), which is similar and comparable to the well known Berea or Fontainebleau type sandstones. It is characterized by good porosity and permeability, respectively. A detailed petrophysical and mineralogical characterization can be found within [4]. Practically, the classical REV estimation for this sandstone has been applied as follows:

- The high resolution 3D data set of each CT mini-plug has been used to derive a maximized cubic sample volume. In case of this specimen, it has been possible to achieve a maximum edge length of 1750 voxel (= 3.0625 mm).
- Next, randomly distributed non-overlapping cubic subvolumes have been extracted and analyzed for their effective porosity. The edge length of these subvolumes has been stepwise increased, starting from 50 voxel and ending up at the maximum edge size of 1750 voxel. Quantitative investigations have been performed with AVIZO Fire, a special software distributed by the Visualization Science Group (VSG, www.vsg3D.com).
- Afterwards, the so derived porosity values are plotted against their corresponding subvolume edge length, as shown within figure 1.

This procedure has been applied and repeated on each of the different types of sandstone. The edge length ‘cut-off’ value for the REV determination has been set individually for each sample volume. As reference, the effective laboratory scale porosity value, derived by helium pycnometry, has been used (fig.1, green line).

REV ANALYSIS

The results of this classical approach are shown in figure 2. With ongoing enlargement of the REV, porosity scattering decreases continuously as predicted by [2]. Though, standard deviation for the porosity also decreases markedly. Remarkably, mean and median values of porosity, starting at a REV edge length of 500 voxel (850 microns), remain almost constant. This effect can be directly related to the homogeneity of the Bentheimer sandstone. At edge lengths larger than 1000 voxel (1.75 mm), changes become minimal. Therefore it seems legitimate to characterize this zone as the predicted porous media domain for this rock type (REV), depending on the specified accuracy (voxel resolution) of this type of analysis. Furthermore, it can be seen that porosity generally tends to be underestimated, although scanning resolution is high. This is a side effect of the image, i.e. gray value based phase segmentation, and should be taken into account, when results of (e.g.) transport modeling are discussed. Based upon these results, the cut off value for this REV has been set to 1250 voxel with an image resolution of 1.75 microns. The results of the classical REV estimation are shown in figure 2. Nevertheless, this approach does not take small scale local / spatial porosity variations, e.g. caused by clayey agglomerations, and inhomogeneities directly into account! Therefore it seems reasonable to take a closer look on the spatial porosity distributions.

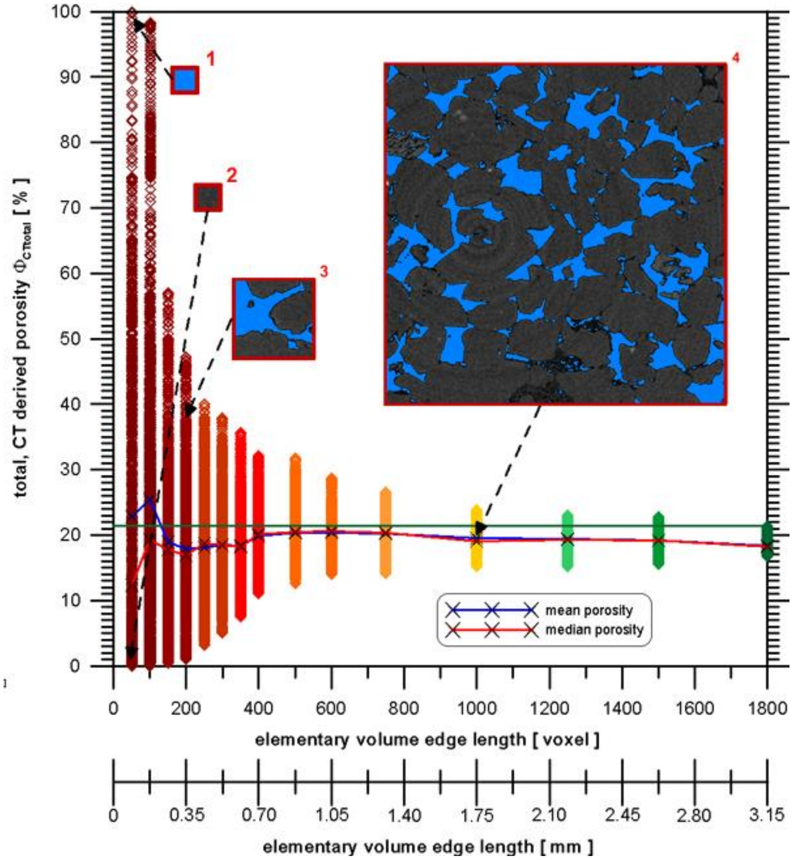

Figure 2: Estimation of the REV of the Bentheimer sandstone sample [4] by using the classical approach of [1]. The green line indicates the lab derived porosity for the sample, the blue and red one the mean and median porosity derived by CT analysis, respectively. The color coding from red (left hand side) to green (right hand side) indicates the transition into the REV domain.

For this, porosity has been calculated ‘slice by slice’ (slice thickness = 1 voxel = 1.75 µm) for a variety of REV edge lengths in x-, y- and z-direction. By doing this, it is possible to investigate porosity variations on a small scale and - furthermore - to detect the REV size at which these variations become minimal. In case of an ideal, i.e. isotropic rock, variations in each direction and despite of the sample volume should be constant. Although specific rock types indicate isotropic behavior on a lab scale, it seems obvious that this should not be mandatory assumed on a microscopic scale. In theory, inhomogeneity of these variations should become smaller and smaller with increasing REV size, but with greater sensitivity to small scale sample features. After collecting the “slice porosity”, a special statistical procedure is applied, the so called variogram analysis [5]. This type of analysis characterizes a spatial data set as a function, which describes the degree of spatial dependence of a spatial random field or statistic process. It is defined as the variance of the difference between field values at two locations across realizations of the investigated field. In practice, porosity as a function of REV size should indicate a saturation curve behavior, if representativeness in each direction is reached.

Figure 3 (top) shows the derived axis dependent porosity “logs” and below, the resulting variograms are shown. As a result it can be pointed out, that for the x-direction the saturation behavior has not been reached yet, which means, that the edge length in this direction needs to be increased in order to reach representativeness. For the y- and z-direction, this condition has been achieved as seen within figure 3 (bottom).

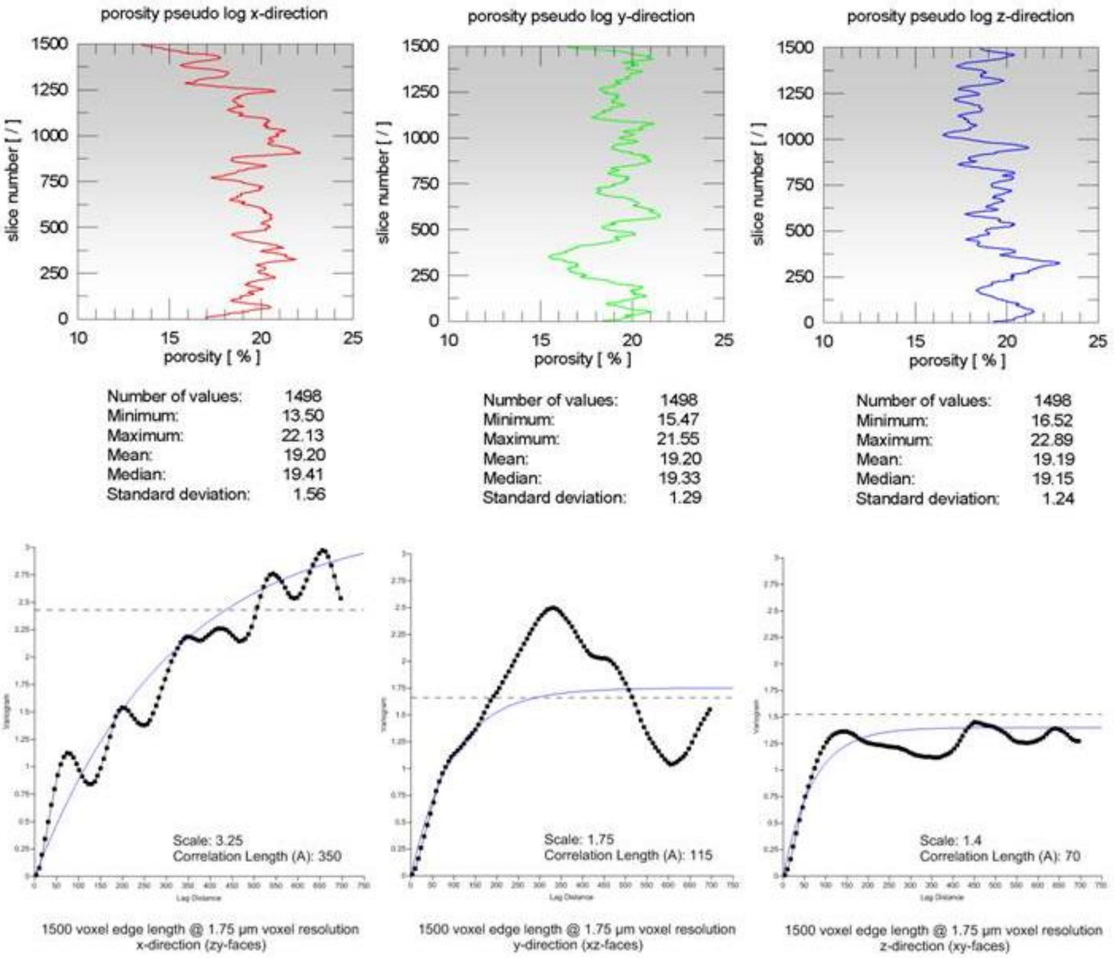

Figure 3: Directional porosity pseudo logs and variogram analysis for the porosity distribution of the sandstone sample [4].

INHOMOGENEITY ANALYSIS

Due to a sensitivity analysis, standard deviation of porosity seems to be the numerical value to investigate scale, i.e. REV edge size, dependent structural effects and transitions. For this, porosity standard deviation (S_{Phi}) has been calculated for a large set of edge lengths (250 to 1500 voxel) for the CT specimen and for each spatial direction (x-, y- and z-axis). Theoretically, S_{Phi} should greatly decrease with increasing sample volume, until the lower (constant) data limit, which solely depends on the scanning resolution, is reached. The gap between each directional deviation value can be used to quantify the degree of inhomogeneity and anisotropy of the pore network structure. For a better quantification of the inhomogeneity, it seems reasonable to introduce a new statistical parameter: the so called inhomogeneity factor I_{Phi} [5]. It is defined as the ratio between the difference of maximum to minimum and the minimum deviation value. For similar directional deviation values S_{Phi}, ΔS_{Phi} and therefore I_{Phi} tend to zero, indicating a homogeneous porous medium. The larger ΔS_{Phi} the larger the structural and directional inhomogeneity of the sample. In theory, each time the pore network is ‘disturbed’, either by a natural or an induced structural feature, I_{Phi} should increase first, and then decrease again until the next sample volume dependent feature is added. Figure 4 shows the results for the investigated sandstone specimen. For the Bentheimer sandstone sample, three distinct minima of inhomogeneity could be found: at 300 voxel, 750 voxel and 1325 voxel edge size, respectively. Due to classical mineralogical investigations (SEM, thin sectioning) and due to qualitative investigation of the CT data sets, it is possible to link these minima to three sample “features”. The first feature correlates with the dominating matrix grain size (formed by the quartz grains). The second one approximates the average distance between dissolved feldspar minerals, which form small and locally distributed pore networks within the large pore network of the sample. Coherently, the third minimum correlates with the mean distance between arbitrary clay agglomerations, which – similar to the dissolved feldspar – form local and very complex pore networks, so that the inhomogeneity increases substantially, after this sample feature is added within the investigated REV.

CONCLUSIONS

The classical REV estimation technique works properly for homogeneous sandstones. In addition with the advanced variance analysis, based upon directional micro porosity logs, it is possible to take small scale sample anisotropy (e.g. caused by layering effects) into account. Furthermore, in combination with the inhomogeneity analysis, it is possible to characterize the complexity of the porous sample network, and which kind of pore network feature may influence the (e.g.) fluid flow transport mechanisms to some extent. With the combination of these three methods and with this knowledge, predictive fluid flow modeling does receive a higher accuracy and quality of evidence [4] as far as the mentioned types of sandstones are considered. In a next evaluation step, strongly anisotropic sandstones as well as carbonates will be investigated.

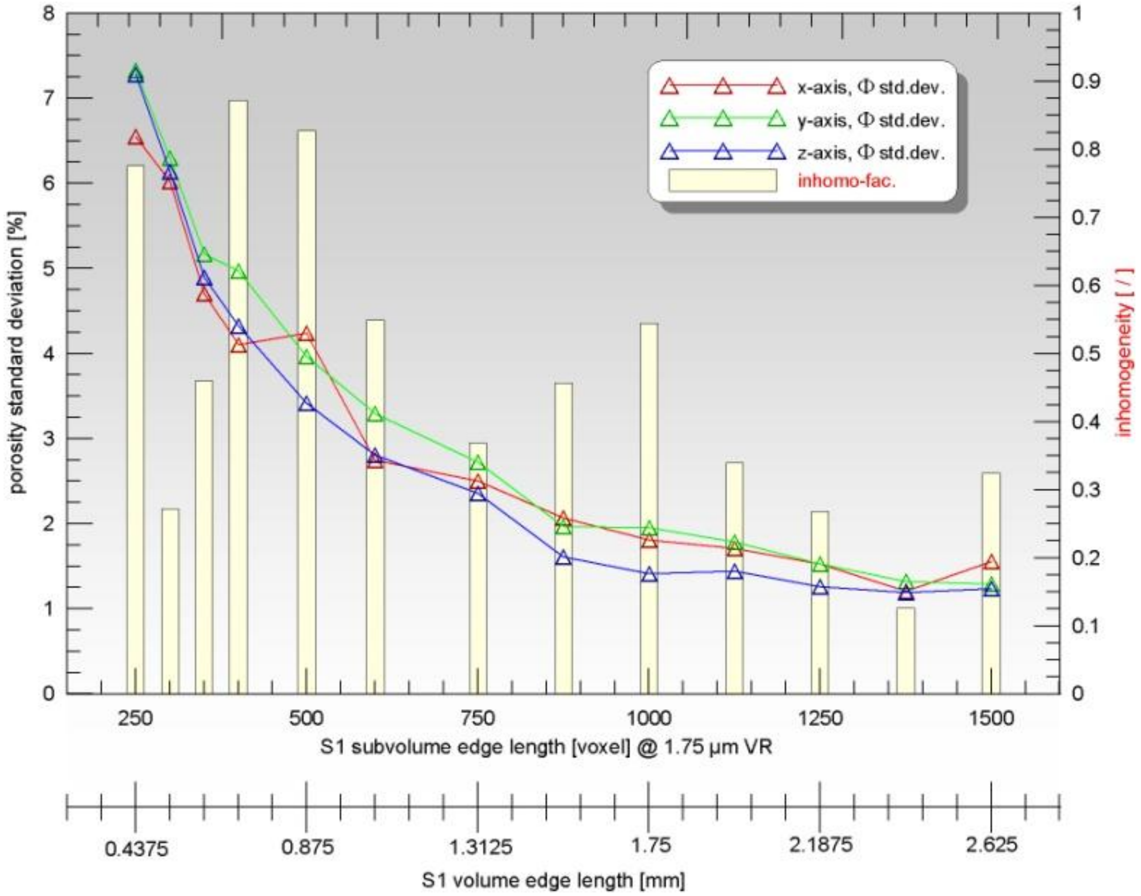

Figure 4: Directional S_{Phi} and resulting I_{Phi} for a variety of subvolume edge sizes of the investigated sandstone specimen [4].

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