A Multi-scale Approach to Determine the REV in Complex Carbonate Rocks

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Keywords: CT, porosity, Representative Elementary Volume (REV) and travertine

ABSTRACT

Complex porous carbonates display heterogeneity at different scales, influencing their reservoir properties (e.g. porosity) especially since different porosity types may exist on different spatial scales. This requires a quantitative geometric description of the complex (micro)structure of the rocks. Modern computer tomography techniques permit acquiring detailed information concerning the porosity network at different scales. These datasets allow evolvement to a more objective pore classification based on mathematical parameters. However computational limitations in complex reservoir models do not allow incorporating heterogeneities on small scales (e.g. sub-meter scale) in full-field reservoir simulations [*Nordahl and Ringrose*, 2008]. The suggested workflow allows characterizing different porosity networks in travertine rocks as well as establishing confidence intervals regarding the Representative Elementary Volume (REV) of these samples. The results of this study prove that one has to be very critical when determining the REV of heterogeneous complex carbonate rocks, since they are influenced by both resolution and size of the dataset.

1. INTRODUCTION

Heterogeneity is a general characteristic of carbonate reservoir rocks, and relates to their geological history: sedimentary origin, burial history and diagenesis processes. All previous mentioned processes have an influence on the complexity of the porosity network. In order to address this problem the concept of the Representative Elementary Volume (i.e. the smallest value that can be taken as a representation for the entire sample area/volume that does not respond to small changes in volume or location) was first introduced by *Bear* [1972].

These complex porosity systems require 3 dimensional (3D) information in order to obtain reliable estimations of petrophysical parameters (i.e. permeability, pore connectivity). In this respect there is an urgent need to update existing pore classification systems defined in 2D based on petrography [*Choquette and Pray*, 1970; *Lønøy*, 2006; *Lucia*, 1995], to a more objective classification in 3D.

2. MATERIALS AND METHODS

2.1. Samples

This study will particularly focus on monomineralic travertines as case study since these lithologies cover a wide range of porosity types, i.e. micro- till macro(vug) and micro-karst porosities. They can be considered as the most complex porosity systems in carbonate rocks. Furthermore they form important potential reservoir rocks and building stones. Consequently with regard to the latter large quarries exist where they are excavated. Samples originate from travertine deposits in the south-western part of Turkey, near the city of Denizli.

2.2. Workflow

In order to study the macro-pore systems present in travertine rocks a workflow, shown in Figure 1, using different imaging techniques has been developed. Due to progress in X-ray Computed Tomography (CT), rapid, non-destructive, high-resolution 2D and 3D examination and analysis of

almost any kind of material, including earth and soil materials is currently available in practice.
Cores are primarily scanned with a medical CT scanner, the Siemens Somatom (Figure 1, step1). In this study the cores have a diameter of 10cm and are between 10 and 30 cm long. The main disadvantage is that the resolution of these scans is limited to 0.5 mm in 3 dimensions.
In a next step plugs (2 cm diameter and 4 cm long) are drilled out of the larger cores. These samples are scanned using microfocus CT. Samples are scanned at a resolution of $(27\ \mu m)^3$ using a SkyScan 1172 system.
In a final step micro-plugs can be drilled out of the plugs. These micro-plugs have a diameter of 7 mm and are 1.5 cm long. Since they are this small they can be scanned using a General Electric nanotom at resolutions of $(3\ \mu m)^3$.
As a result, in this workflow parts of the original sample are scanned at 3 different resolutions. This allows investigating pores with pore sizes from approximately 10 µm up to several cm. Moreover the more detailed information concerning the porosity network of the scans in step 2 and 3 can be used as a training image in multiple point geostatistcs. This technique allows to statistically improve the images of scans with a lower resolution.

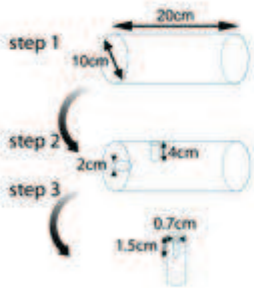

Figure 1: *Workflow using different CT systems for different sample sizes.*

2.3. Image analysis

The purpose of image segmentation is the separation of materials (monomineralic rock and air). Quantitative analysis of the porosity requires a voxel by voxel determination of void and rock phases. For segmentation an in-house dual-thresholding algorithm is used, based on the principle first described by *Canny* [1986] for an edge detecting algorithm.
Resulting segmented slices are imported into Morpho+ [*Brabant et al.*, 2011] and Avizo Fire. Morpho+ also allows splitting complex pore structures at pore throats based on a watershed algorithm. These results are used to calculate several shape parameters such as form ratio (based on L, I and S - L is assigned to the longest dimension, I is the longest dimension perpendicular to L, and S is perpendicular to both L and I), sphericity and roundness. Based on the results of this analysis and on particle classification systems [*Blott and Pye*, 2008], a pore classification is proposed. Figure 2 presents an overview based on the form ratio's I/L and S/I. In this diagram 5 shape classes are defined: rod, blade, cuboid, plate and cubic shapes.

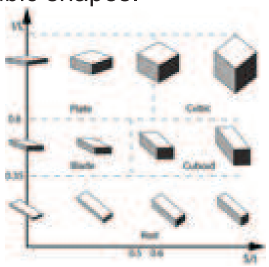

Figure 2: *Diagram of the theoretical pore shapes based on I/L and S/I form ratio's*

2.4. The Representative Elementary Volume (REV)

The REV is originally defined by the following concept by *Bear* [1972]. P is a mathematical point in a porous medium. ΔU_i represents a volume for which P is the centroid. This volume is much larger than a single pore or crystal. For this volume it is possible to define the ratio n_i by formula (Eqn.1).

$$n_i = \frac{(\Delta U_v)_i}{\Delta U_i} \quad (1)$$

with: $(\Delta U_v)_i$: the volume of void space within ΔU_i

By repeating the same procedure for different i, a series of shrinking volumes can be obtained. Figure 3 represents the evolution of n_i in function of the volume. This figure indicates that below a certain value ΔU_0 large fluctuations in the ratio n_i occur.

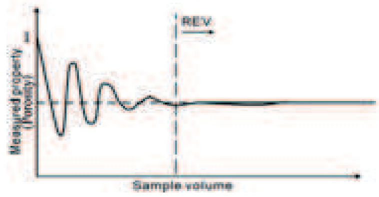

Figure 3: *Schematic graph of how a measured property varies with sample volume with definition of the domain of the representative elementary volume (REV) (modified from Bear [1972])*

However using this graphical method to determine the REV remains subjective. It is necessary to define the size of the REV based on objective mathematical parameters. The chi-square criterion is proposed as a measure of the fluctuation of the porosity inside a selected sample volume. This procedure is based on the fact that the smaller the value of χ^2 becomes, the closer the selected volume corresponds to the volume of the REV. This combination of a numerical – statistical approach was already suggested by *Gitman et al.* [2007]; *Zhang et al.* [2010]. In the sample volume, 5 centroids of test volumes are randomly chosen. In each test volume the ratio n_i is calculated (Eqn. 1.). The deviation of one result compared to the mean value of the ratio n_i is tested by the χ^2 criterion. In this case a desired accuracy of 95% is chosen for the χ^2 parameter. The statistical degree of freedom is equal to 2, because five samples are compared for each volume and the size of the REV follows a lognormal distribution. Hence the number of degrees of freedom equals the number of realizations – the number of distribution parameters (2)-1.
For each sample, the size of the REV is calculated 20 times using the procedure described above. In order to fit a statistical distribution to these results QQ-plots and Lilliefors-test can be used [*Lilliefors*, 1969]. If a log normal distribution can be fitted a 95% confidence interval for the size of the REV can be calculated.

3. RESULTS

3.1. Pore shapes

This approach allows to separate different types of pore shapes as well as to assess the anisotropy of the porosity in the sample by using the orientation of the longest dimension. The pore space inside a travertine rock can hence be classified based on the pore shapes. Moreover the rod-like shaped pores are divided into vertical and horizontal rod shaped pores.
Quantification of the different recognized classes allow to identify different types of depositional environments e.g. in “reed dominated facies” the quantity of rod-like shaped pores (25%) will be dominant while in a “flatpool facies” the cubic shaped pore (30%) will dominate.

3.2. REV

Three principal travertine facies types have been analysed: the flatpool, reed and cascade dominated facies. Table 1 & 2 show an overview of the results for the large core samples and the microplugs. On the CT scans of both the core and the micro-plug, the flatpool facies has the smallest REV, while the cascade facies always has the largest REV. However for the microplugs the size difference of the REV becomes much smaller and the confidence intervals are all in the same order of magnitude.

Table 1: *Overview of the size of the 95% confidence bounds of the REV’s in different travertine facies based on medical CT scans of 10 cm Ø cores*

Facies type	Lower boundary [mm^3]	Upper boundary [mm^3]
Flatpool	880	1513
Reed	6110	15883
Cascade	46916	138975

Table 2: *Overview of the size of the 95% confidence bounds of the REV's in different travertine facies based on micro-CT scans of 0.7 cm Ø micro-plugs*

Facies type	Lower boundary [mm^3]	Upper boundary [mm^3]
Flatpool	0.12	0.29
Reed	0.16	0.38
Cascade	0.21	0.49

4. CONCLUSION

The proposed workflow allows to study the porosity network of different travertine lithologies. Based on 3D CT data sets different facies types can be automatically and hence objectively recognized. This study also illustrates that the size of the REV on a mm to dm scale is dependent on the lithology of the analyzed rocks and hence on the dominant pore shapes. Also the resolution and sample size has an important influence on the size of the REV. However pervious studies also suggested the influence of the parameter under investigation such as particle size distribution in sands [*Al-Raoush and Papadopoulos*, 2010].

5. ACKNOWLEDGEMENTS

This research is carried out in the framework of a project supported by the FWO.

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