Pore Shapes and Pore Geometry of Reservoir Rocks from μ-CT Imaging and Digital Image Analysis

Matthias Halisch[1], Mayka Schmitt[1,2], Celso Peres Fernandes[2]

[1] Leibniz Institute for Applied Geophysics (LIAG), Dept. 5 Petrophysics & Borehole Geophysics, Stilleweg 2, D-30655 Hannover, Germany
[2] Federal University of Santa Catarina, Porous Media and Thermophysical Properties Laboratory (LMPT), Mechanical Engineering Department, 88040-900 Florianópolis, SC, Brazil

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ABSTRACT
Recent years have seen a growing interest in the characterization of the pore morphologies of reservoir rocks and how the spatial organization of pore geometry affects the macroscopic behaviour of rock-fluid systems. With the availability of high-resolution 3D imaging, such as X-ray micro-computed tomography (μ-CT), the detailed quantification of particle shapes has been facilitated by progress in computer science. Here, we show how the shapes of irregular rock structures (pores) can be classified and quantified based on binary 3D images. The methodology requires the measurement of basic 3D particle descriptors (length, width and thickness) and a shape classification that involves the similarity of artificial objects, which is based on main pore network detachment and 3D sample size. A watershed algorithm was applied to preserve the pore morphology after separating the main pore networks, which is essential for the pore shape characterization. The results were validated for a variety of sandstones, either from distinct reservoirs or used as reference material for laboratory research. Furthermore, this study generalizes a practical way to correlate specific particle shapes, such as rods, blades, cuboids, plates and cubes, to characterize asymmetric particles of any material type with 3D image analysis. In this manuscript we would like to showcase results for a small variety of reservoir sandstones from the North German Basin area.

INTRODUCTION
Natural and artificial materials are often characterized by their pore/grain shape or size distributions as determined by distinct analytical instruments. Several investigations have been conducted to classify pore types/shapes, and most of them are associated with 2D quantification. However, a 3D pore with irregular shapes cannot be appropriately characterized from 2D image sections in pore-typing procedures, nor can the number of pores (Buller et al., 1990). Knowledge of pore morphology is essential and is one of the main parameter that controls fluid flow at the pore scale.

Petrophysical properties such as permeability, electrical conductivity and drainage capillary pressure are strongly influenced by throat sizes, which are constrictions of minimal cross-sectional area between pores. Moreover, to the best of our knowledge, the systematic 3D pore shape quantification of sedimentary rocks based on sample size, pore network detachment and distinct geometrical descriptor measurements has not been comprehensively reported in the literature.

Though 3D imaging has become a reliable method for qualitative and quantitative pore scale characterization, many investigations that analyse irregular particle shapes are still performed with 2D approaches (Petrak et al., 2015; Zhang et al., 2016). So far, μ-CT studies of 3D features have mostly been related to the characterization of volcanic rocks (Eiríksson et al., 1994; Riley et al., 2003) or spheroid objects (Robin & Charles, 2015), and these features are usually described by means of equivalent size or shape parameters, such as roundness or aspect ratio (Little et al., 2015). All of these authors concluded that these measurements cannot adequately describe the diverse forms of irregularly shaped particles. Available high-resolution techniques might provide qualitative and quantitative pore structure information. However, many materials, including sedimentary rocks, lack information regarding the deep comprehension of irregular particle (pore or grain) shape analysis and a systematic way of classifying it, e.g., describing it to be similar to artificial object forms. A detailed pore shape characterization is necessary for many applications and can be used to infer the dominant mechanisms that act in a heterogeneous rock in response to its macro properties.

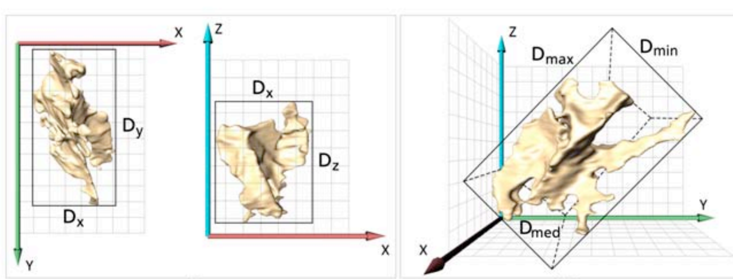
SAMPLES & METHODOLOGY

In this study, the pore shapes of three sandstone rocks from distinct fields in Germany were analysed and classified based on X-Ray μ-CT and digital image analysis. The sandstone samples (Bentheimer, Obernkirchen and Flechtingen sandstone) have been used and characterized in previous studies in detail (Halisch et al., 2013, 2015). The 3D images of the analysed rocks were acquired at similar scanning resolutions (1.5 μm voxel size). A watershed algorithm was applied to separate the main pore networks into individual pores and to preserve the essential pore morphology. Next, the most suitable marker extent parameter was defined. Three subsamples with volumes of 1000^3, 500^3 and 250^3 voxels were extracted from each rock to investigate the effect of sample sizes (representativeness) on the pore shape classification. The advantage of using the proposed approach is that shape parameters can be calculated directly from the preserved pore textures with no need for an equivalent volume (sphere or resistor) conversion, which creates absolutely mismatched results for the shape classification. Additionally, the image visualization and analysis are completely automated and performed with the Avizo Fire (Ver. 9.01) software suite for a large number of particles, which are geometrically described to facilitate the quantification analysis.

To describe and quantify a particle form (in this case: pores) in three-dimensions, morphological parameters such as length, width and thickness are required. These 3D parameters must be perpendicular (orthogonal) to each other but do not need to intersect at a common point (Blott & Pye, 2008). To perform the pore shape classification approach that is proposed and described in this work, we conventionally assigned the following practice for the geometrical descriptor of individual particles: *(L)* is the longest pore dimension, *(l)* is the longest pore dimension that is perpendicular to *L*, and *(S)* is the smaller pore dimension and perpendicular to both *L* and *l*. In practice, two methods were applied to measure *L*, *l* and *S* from the 3D irregular shaped objects, such as the pores that were found in the analysed sedimentary rocks: (i) the bounding-box (BB) and (ii) the Feret caliper (FC) geometries. With this geometrical information, it is possible to perform pore shape classification for equancy based upon the different aspect ratios as described by Schmitt et al. (2016). Another common dimensional feature that is used to characterize the "thickness" of 3D particles is the equivalent diameter (EqD), also known as the maximum inscribed sphere method (Dong, 2007), which gives the analysed object a corresponding spherical diameter size with equal voxel volumes.

RESULTS

Figure 1 shows the differences in the geometrical parameters *L*, *l* and *M* for bounding-box (a) and Feret caliper (b) methods, which are drawn in a three-dimensional pore particle. The showcased pore was detached from the main pore network of the Bentheimer sample after applying the watershed algorithm and choosing the third highest 3D lengths from the 25 highest 3D volume particles. The attached table depicts the values of the grid-cell axes and 3D geometrical parameters of the analysed pore particle. For BB methods, a box is assigned to each pore, with the box orientated parallel to the coordinate system of the 3D data set. FC methods assign an individual surrounding box to each separated pore, directly related to the true main elongation of the structure. The classical BB and EqD methods under estimate the pore geometry and the pore volume significantly in comparison to the FC methods. This result has been observed for any of the investigated reservoir rocks, since the true pore / particle orientation is only taken into account for the advanced FC methods.



(a) (b)

Pore particle of rock sample BE02b, 250 cubic volume pixels			
3D geometrical parameters	*(μm)*		
Grid-cell Axes	X = 200	Y = 300	Z = 250
Bounding-box	D_x *(S)* = 170	D_y *(L)* = 295	D_z *(l)* = 212
Feret caliper/diameter	D_{max} *(L)* = 326	D_{min} *(S)* = 169	D_{med} *(l)* = 318
Equivalent diameter	D_{eq} *(l)* = 117		

Figure 1: Comparison of different results of the geometrical pore extent estimation for the classical bounding box methods (upper left, a) and Feret caliper methods (upper right, b) for a single pore of a Bentheimer sandstone.

Accordingly, the pore shape classification is also severely affected by using different pore geometry descriptors. Results of the pore shape classification of the five largest pores within a 250³ voxel volume of the Obernkirchen sandstone sample are shown in figure 2. The right column of figure 2 shows the results of the equancy plots, determined by BB (upper plot) and FC (lower plot) methods. Whereas BB methods lead to mostly slightly non-equant and moderately non-equant shapes (upper right and right corner of the plot), FC methods shift towards moderately non-equant and very non-equant shapes (right corner and middle of the plot). More importantly, the aspect ratios change significantly.

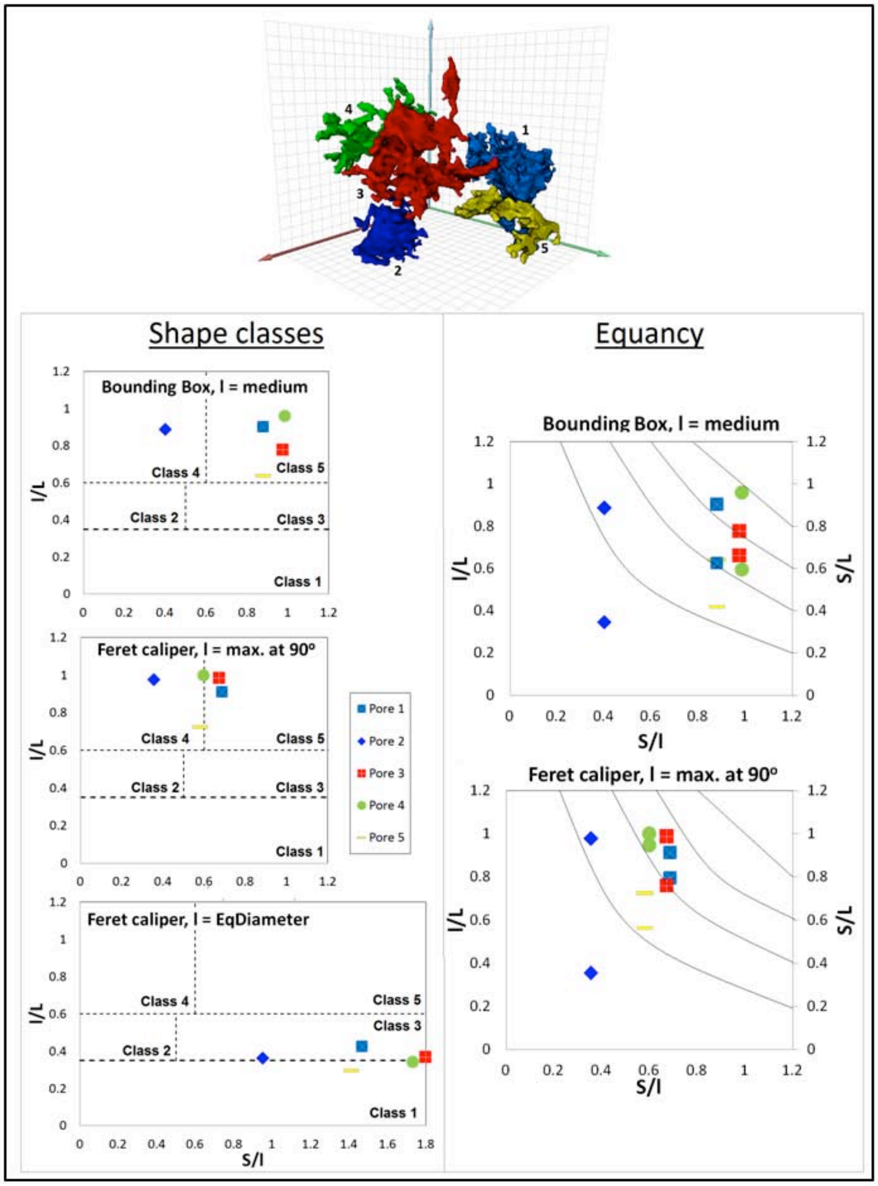


Figure 2: Pore shape results of equancy (right column) and shape classes (left column) based on different descriptors for five selected pores in a 250³ voxel volume of Obernkirchen sandstone.

Furthermore, the left column of figure 2 shows the results for the shapes classes, determined by BB, FC and EqD methods. BB descriptors lead to mostly cubic/spherical-like pore shapes (upper right corner of the shape plot), FC descriptors shift towards more plate-like shapes which estimate the true pore shapes much better, related to the 3D pore scale image on top of figure 2. EqD descriptors completely mismatch the true shape and lead to cuboid/ellipsoid/rod-like pores (lower right corner of the shape plot).

Very similar results have been observed for all of the investigated sandstone samples within this study. The classical BB and EqD descriptors always tend to underestimate the pore geometry. The study has shown that the mismatch for “well defined pore networks”, i.e. Bentheimer or Berea type rocks, is about 10 % - 18 % off the true axial geometry. The more “complex”, i.e. the more irregular shaped the individual pore gets, which is mostly the case for (e.g.) more compacted or layered rocks, the higher the geometrical mismatch will be for these methods. In case of the Flechtingen sandstone, a mismatch of up to 200 % has been measured. The FC methods still have a slightly mismatch against the true geometry, but within this study, it never exceeded ± 20 %. Accordingly, the resulting aspect ratios and shape classes are influenced in the same way for most of the investigated 3D volumes as described in the section above, which might lead to significantly falsified geometrical pore network characterizations.

SUMMARY & CONCLUSIONS

Within this study we have investigated different methods to determine pore geometrical descriptors from binarized 3D pore scale imaging data sets. Additionally, we have created a pattern of shape classes that might be used for the enhanced classification of pore shapes. We have showcased the differences for the existing methods, as well as the significant impact upon the results. It can be concluded that BB and EqD methods are not the appropriate choice to characterize both, pore shape and geometry reliably. Accordingly, Feret caliper methods have shown the smallest deviation against the “true” pore characteristic of the investigated sandstones.

OUTLOOK

As part of an ongoing research project, more and more types of sandstones from conventional and unconventional reservoirs are investigated. Consequently, other rock types like carbonates and claystones are included within the near future. The two main goals of this project are to “connect” topological pore features, such as surface area or fractal dimension, to corresponding pore classes. In a second step, these relationships will be used to calculate and characterize pore class dependent petrophysical properties, e.g. like pore class dependent T_2-diffusion mapping. First results are already promising.

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REFERENCES

1. Buller, A.T., Berg, E., Hjelmeland, O., Kleppe, L., Torsaeter, O., and Aasen, J.O. (1990): *North sea oil & gas reservoirs – II*. Graham and Trotman Publishing, London, 234-237, 1990.
2. Blott, S.J., and Pye, K. (2008): *Particle shape: a review and new methods of characterization and classification.* Sedimentology, 55, 31-63
3. Dong, Hu (2007): *Micro-CT Imaging and Pore Network Extraction*. PhD Thesis, Imperial College London, 2007.
4. Eiríksson, J., Sigurgeirsson, M., and Hoelstad, T. (1994): *Image analysis and morphometry of hydromagmatic and magmatic tephra grains, Reykjanes volcanic system, Iceland*. Jökull, 44, 41-65.
5. Halisch, M., Vogt, E., Müller, C., Cano-Odena, A., Pattyn, D., Hellebaut, P., and van der Kamp, K. (2013): *Capillary Flow Porometry - Assessment of an alternative method for the determination of flow relevant parameter of porous rocks*. Proceedings, Annual Meeting of the Society of Core Analysts 2013, Napa Valley, USA, SCA2013-007.
6. Halisch, M., Linden, S., Schwarz, J.O., Hupfer, S., and Wiegmann, A. (2015): *Systematic parameter study for formation factor modeling at the pore scale.* Proceedings, Annual Meeting of the Society of Core Analysts 2015, St. John's, Canada, SCA2015-A018.
7. Little, L., Becker, M., Wiese, J., and Mainza, A.N. (2015): *Auto-SEM particle shape characterization: Investigating fine grinding of UG2 ore*. Miner. Eng, http://dx.doi.org/10.1016/j.mineng.2015.03.02
8. Petrak, D., Dietrich, S., Eckardt, G., and Köhler, M. (2015): *Two-dimensional particle shape analysis from chord measurements to increase accuracy of particle shape determination*. Power Technology, 284, 25-31.
9. Riley, C.M., Rose, W.I., and Bluth, G.J.S. (2003): *Quantitative shape measurements of distal volcanic ash*. J. Geophys. Res. 108, 2504 ff.
10. Robin, P.Y.F., and Charles, C.R.J. (2015): *Quantifying the three-dimensional shapes of spheroidal objects in rocks imaged by tomography*. Journal of Structural Geology, 77, 1-10.
11. Schmitt, M., Halisch, M., Müller, C., and Fernandes, C.P. (2016): *Classification and quantification of pore shapes in sandstone reservoir rocks with 3D X-ray micro-computed tomography*. Solid Earth, 7, 285-300, 2016, doi:10.5194/se-7-285-2016
12. Zhang, Y., Liu, J.J., Zhang, L., De Anda, J.C., and Wang, X.Z. (2015). *Particle shape characterization and classification using automated microscopy and shape descriptors in batch manufacture of particules solids*. Particuology, http://dx.doi.org/10.1016/j.partic.2014.12.012