PS Measuring Pore Throat Geometry and Angularity Through Mathematical Morphology*

Aurelien G. Meyer[1], Lars Stemmerik[1], Peter Frykman[2] and Meysam Nourani[2]

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[1]University of Copenhagen, Copenhagen, Denmark (aurgab@snm.ku.dk)
[2]Geological Survey of Denmark and Greenland, Copenhagen, Denmark

Abstract

The geometry of pore space affects the storage and fluid flow capacity of a rock. Pore networks are typically composed of multiple pores of complex shapes connected by minuscule tubes typically showing converging-diverging geometries. Due to computer and software limitations, fluid flow models have commonly been based on simplified pore models. The classical pore-network or capillary tube models consist of spherical pores connected by tubes of constant circular or triangular section.

However, the effect of tube geometry on fluid flow is a well-known problem in hydrology and engineering. Fluid flow in converging-diverging pipes may be complex and turbulent. Turbulences often occur in the vicinity of a constriction, where zones of stagnant or reverse flow contrast with zones of rapid flow. The geometry of the constriction appears to control the flow characteristics in its vicinity. Moreover, throat morphology also controls the likeliness of fluid snap-off, an intra-pore trapping phenomenon which affects hydrocarbon production.

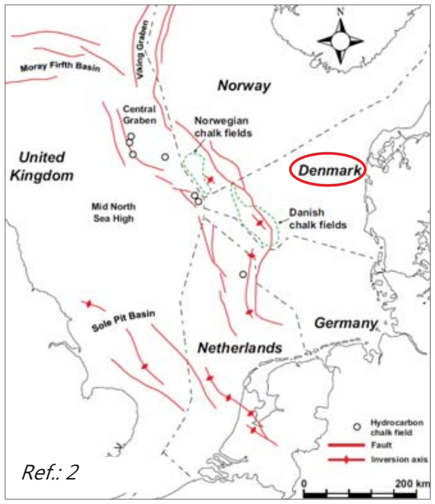
However, current 2D and 3D techniques such as mercury injection, computed tomography scanning and image analysis are unable to measure this geometry in rock samples. An image analysis technique called mathematical morphology has been applied to characterize porosity in laterally continuous pore networks, e.g. in sandstones. Morphology consists in studying the modification of objects such as pores through successive erosion-dilation cycles, using an expanding structuring element. This method allows the extraction of petrophysical parameters such as pore and throat diameters in 2D. This study shows that the pore throat geometry strongly affects the behaviour of the structuring element as its size increases. As a result, the diameter of an elongated, acute pore throat is more correctly measured through morphology than that of a less acute throat. Based on this behaviour, the geometry of the pore throat can in turn be calculated.

This study introduces a pore shape descriptor called angularity to represent the angle of opening of pore walls from the throat towards the body. This study provides the first quantification of this parameter using 2D thin section images. The novel methodology is tested on rock samples

from the upper Maastrichtian Tor Formation, the most prolific chalk reservoir of the North Sea. Once adapted to 3D, it is envisioned that the technique could improve fluid flow modeling at the pore-scale in hydrocarbon reservoirs.

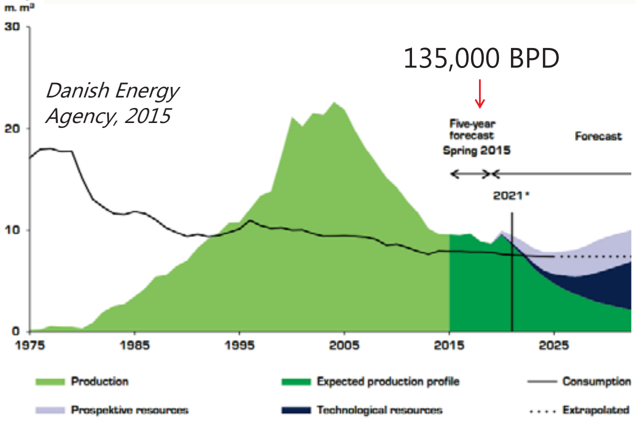
1. Motivations

- Chalk is a lithified pelagic carbonate ooze deposited on continental shelves. In the North Sea region (N. Europe), up to > 2 km (7,000 ft.) of chalk represent the Upper Cretaceous-Lower Tertiary and host significant oil and gas reserves.
- Chalk porosity consists almost exclusively of primary matrix interparticle micro-porosity. Even at burial depths of 2-3 km, North Sea chalk often shows high porosity (> 30 %) but low permeability (< 5 md).
- The spatial architecture of microporosity plays a critical role in controlling the spatial distribution and flow behaviour of fluid phases[1].
- The image analysis technique presented herein aims to provide 2D pore network descriptors. It is tested on chalk from outcrop and subsurface localities of the North Sea region.



Ref.: 2

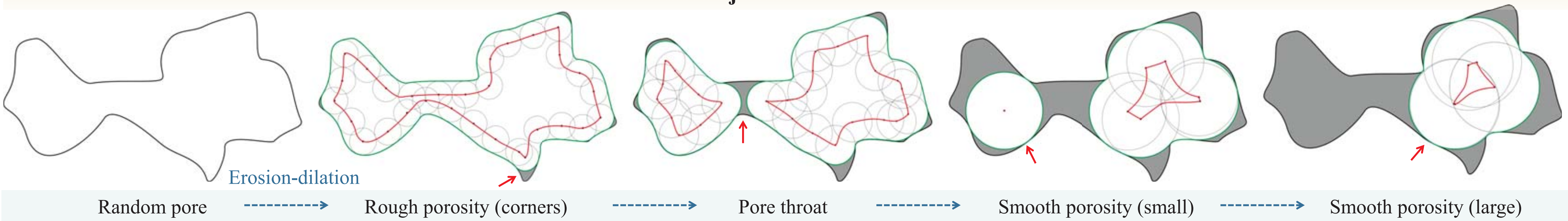
The chalk play, a key asset of Denmark



Danish Energy Agency, 2015

2. Method – Mathematical morphology and porosity analysis

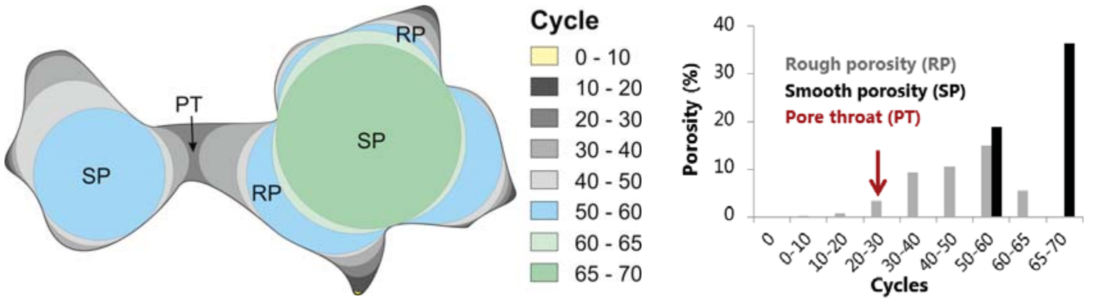
Object extraction



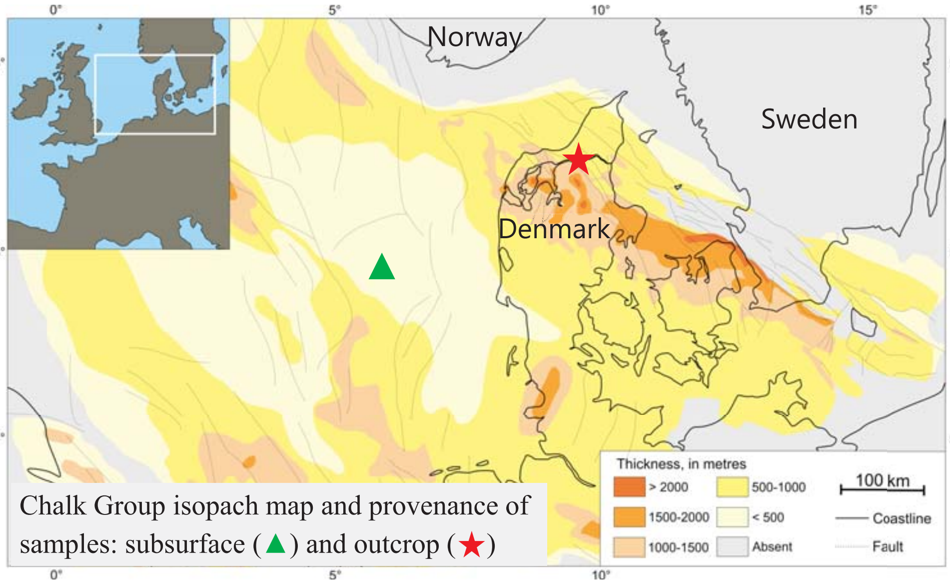
Random pore ---------→ Rough porosity (corners) ---------→ Pore throat ---------→ Smooth porosity (small) ---------→ Smooth porosity (large)

- Mathematical morphology is the analysis of an object using a structuring element (SE), e.g. a disc.
- Cyclic operations known as erosion-dilation modify the shape and size of porosity components.
- By repeating these operations over multiple cycles, porosity is simplified until complete removal.
- Porosity changes can be converted to 2D pore geometry, in particular 2D pore and throat diameters[8,9] as well as body/throat volume ratio.

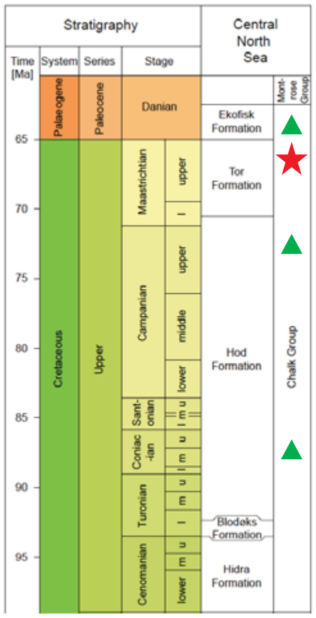
Architecture of a pore

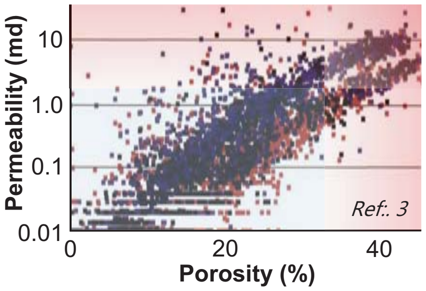


3. Geological setting

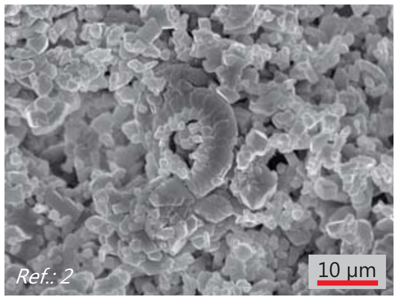


Chalk Group isopach map and provenance of samples: subsurface (▲) and outcrop (★)





Chalk is economic as oil reservoir rock only if porosity > 35 %, clay and silica content < 3 %, and if fractured.



Chalk (SEM) consists of a mixture of bioclasts (e.g. coccoliths, foraminifers, sponges, bryozoans), clays and diagenetic cements (e.g. silica, calcite).

Centre for Oil and Gas - DTU
The Danish Hydrocarbon Research and Technology Centre

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4.1. Results – Image binarization

Threshold definition

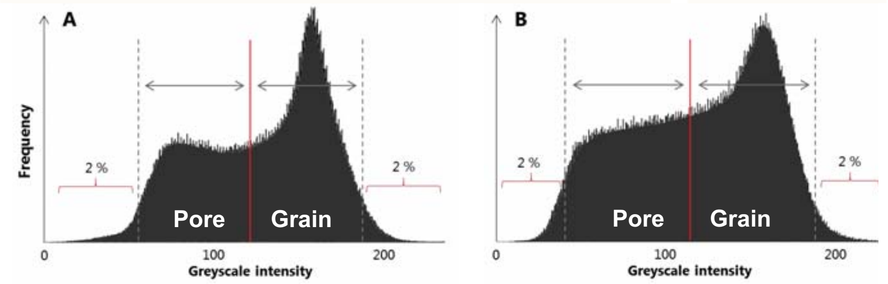
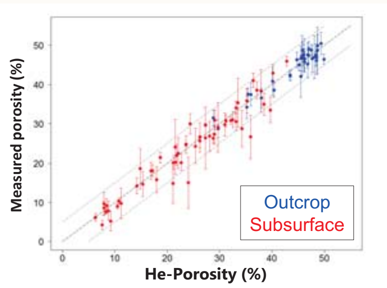
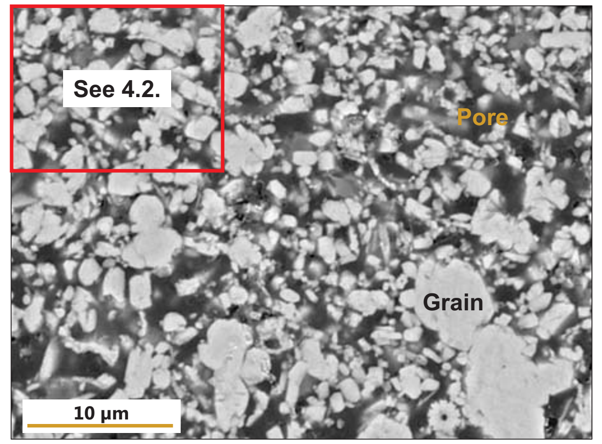


Image vs. Plug porosity

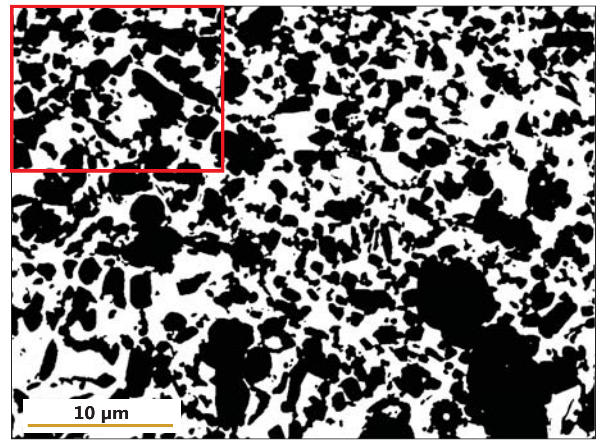


Binarization

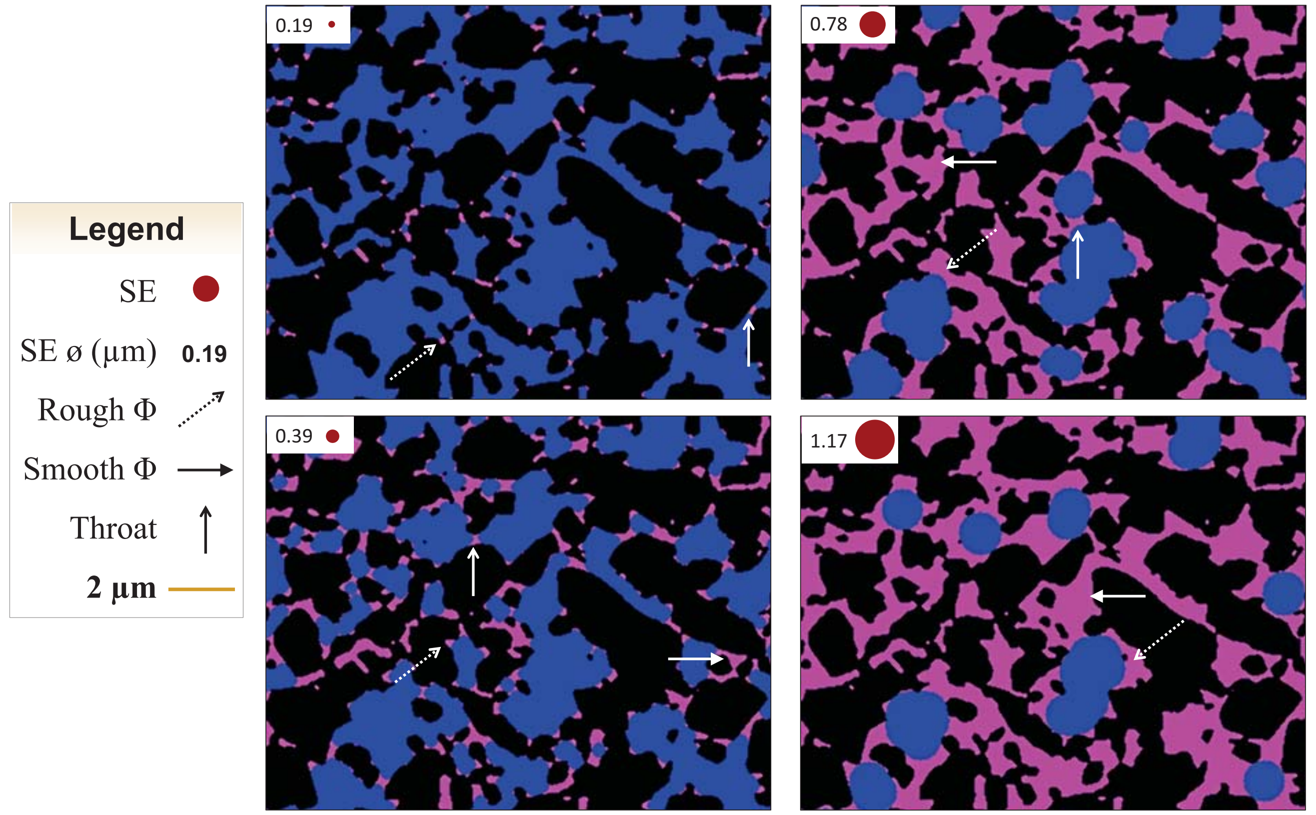
Original SEM image



Segmented image

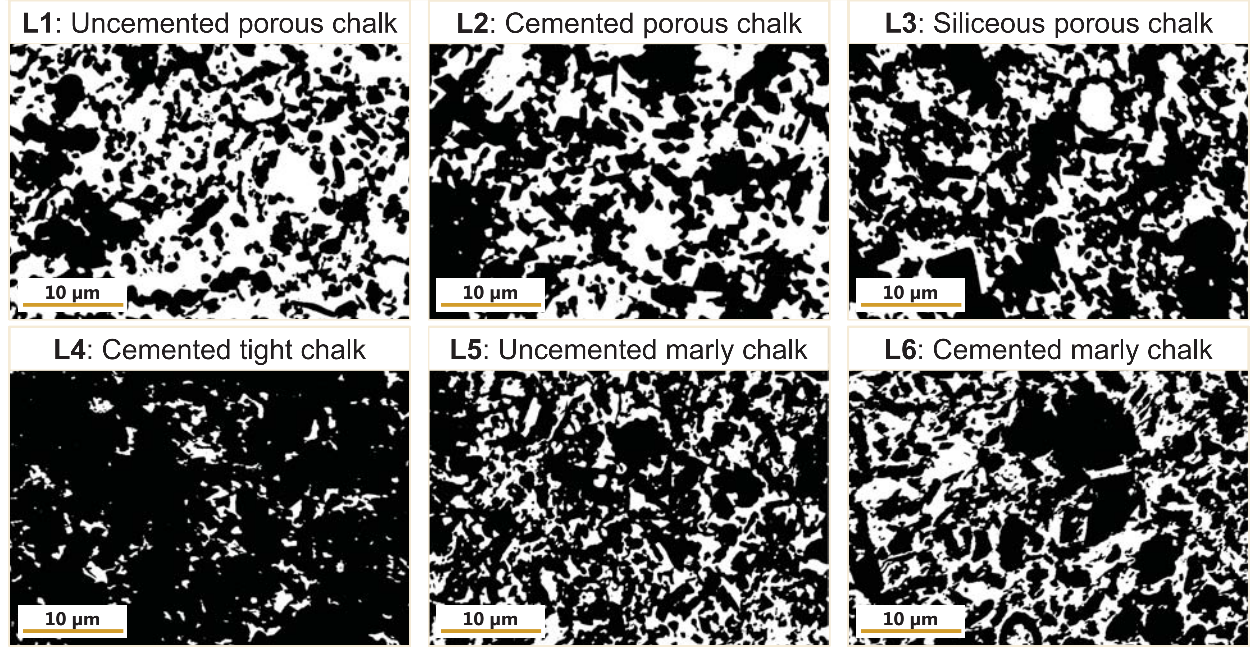


4.2. Results – Mathematical morphology

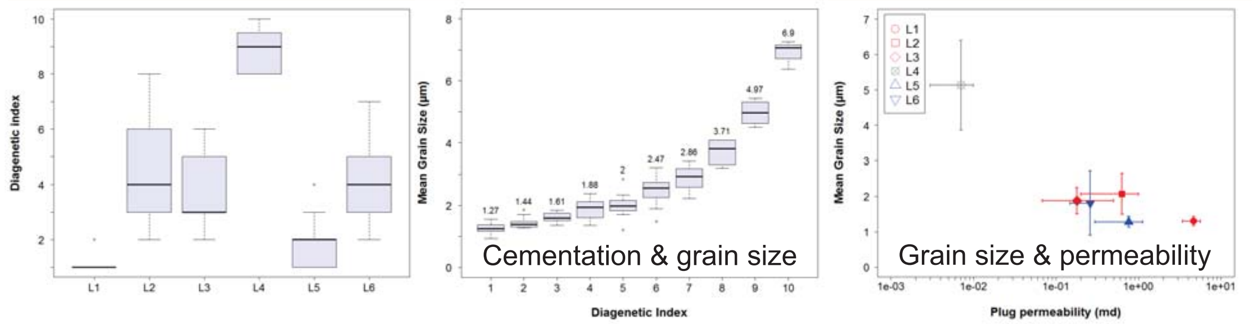


4.3. Results – Porosity characterization

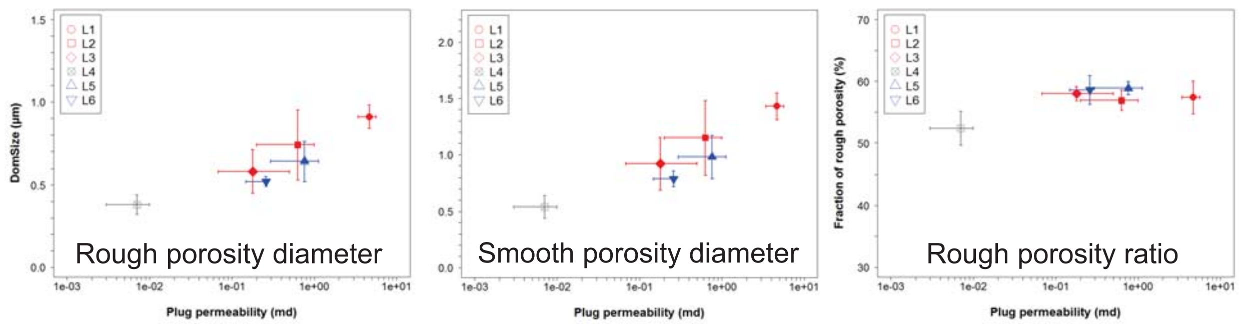
Lithotypes


L1: Uncemented porous chalk
L2: Cemented porous chalk
L3: Siliceous porous chalk
L4: Cemented tight chalk
L5: Uncemented marly chalk
L6: Cemented marly chalk

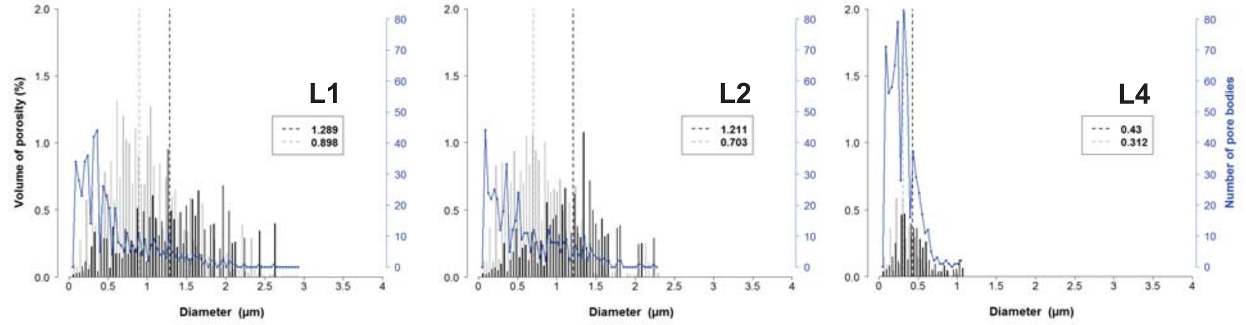
Lithotypes characterization



Porosity characterization

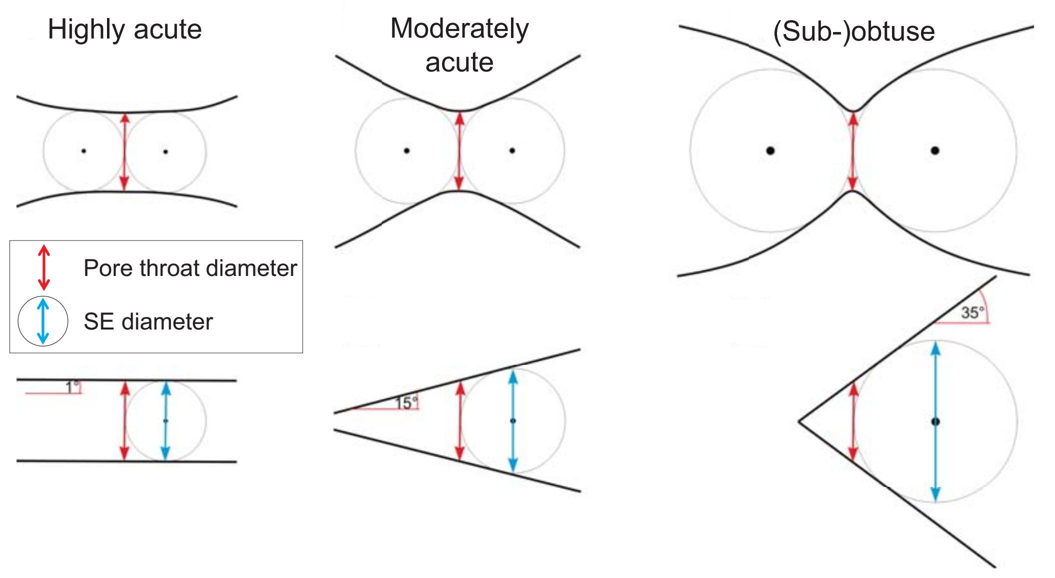


Smooth and Rough pore diameter distributions



4.4. Results – Pore throat diameter and angularity

Effect of pore throat geometry on erosion-dilation

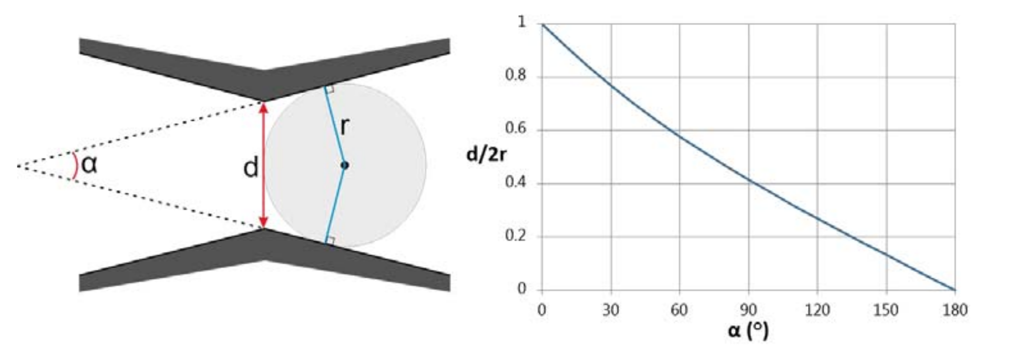


A pore throat diameter corresponds to the diameter of the structuring element (SE) when a pore breaks up at its throat to result in two smaller pores.
However, the throat geometry plays a role. The diameter of a throat with an acute geometry (e.g. channel) is more accurately measured than that of a more obtuse throat.
This study therefore attempts to measure the throat opening angle *α* using the SE radius *r* and the decrease in porosity *ΔP* as *r* increases by one increment, e.g. r_1 to r_2:

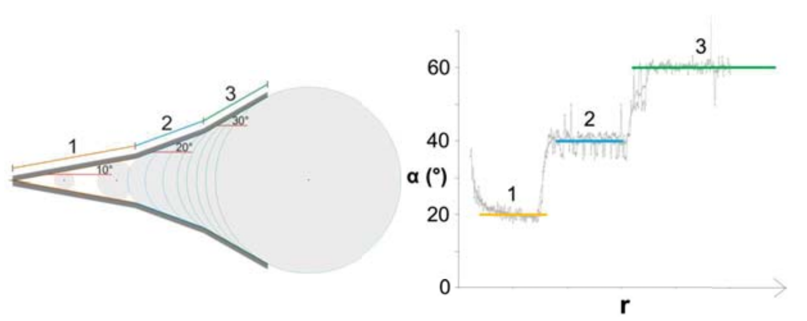
$$\frac{\Delta P}{{r_2}^2 - r^2} - \frac{1}{\tan(\alpha/2)} + \pi/2 - \alpha/2 = 0$$

Angularity is introduced as an average *α* for each rock sample and could be an additional pore shape descriptor.

Pore throat angularity and apparent diameter

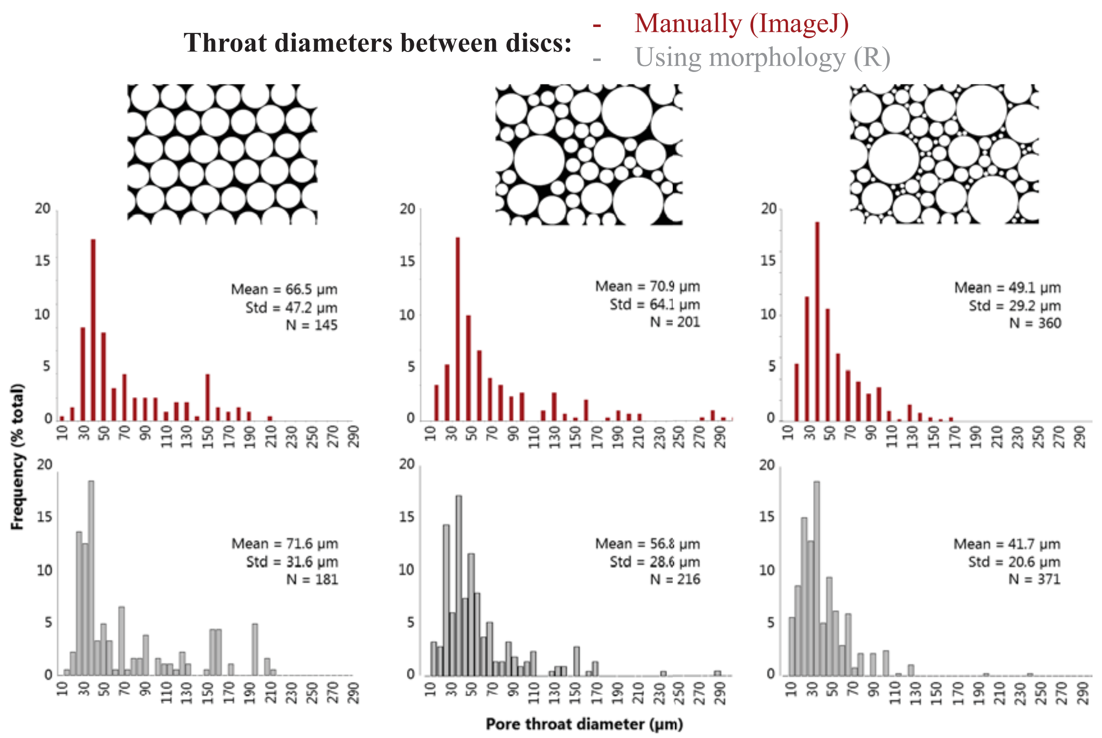


Throat angularity measured through morphology

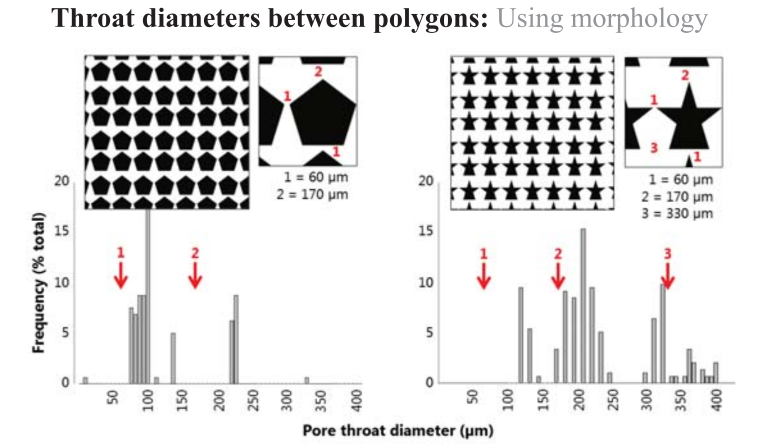


Effect of throat angularity on image-induced throat diameter distributions

Throat diameters between discs: - Manually (ImageJ) - Using morphology (R)



Throat diameters between polygons: Using morphology



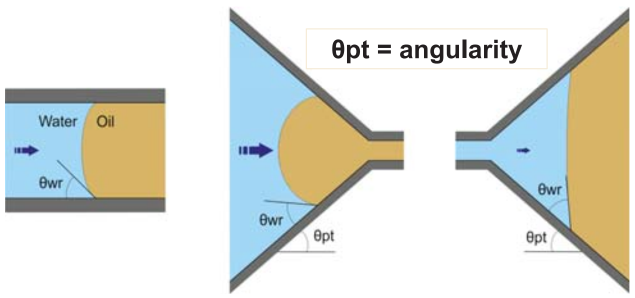
Pore throat diameters are inaccurately measured where different throat angles occur on the image.
Higher angularity results in overestimated diameters.

- ➢ Throat diameter measurements using morphology are at best relative and should be used with caution.

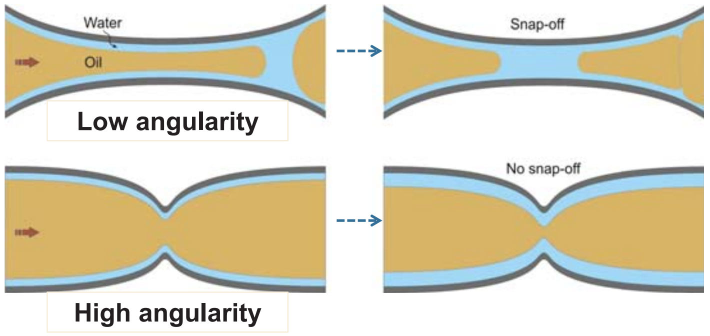
5.1. Discussion - Pore throat angularity and fluid flow

- Pore throat angularity is known to affect fluid circulation in single- or multi-phase systems by modifying the capillary drive or causing turbulences or fluid snap-off [4].
- Standard techniques, e.g. MICP, NMR, CT-scanning, do not provide information on throat morphology.
- This study documents the first attempt to estimate pore throat angularity from 2D images and could improve fluid flow models at the pore scale.

Capillary drive

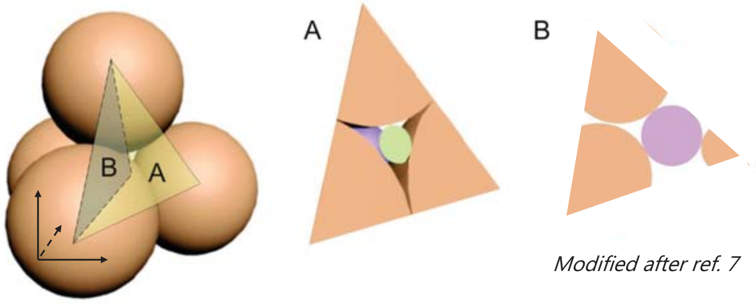


Snap-off and oil trapping



5.2 Discussion – 2D images to characterize 3D pore space

Cross-sectioning of 3D pore space



Modified after ref. 7

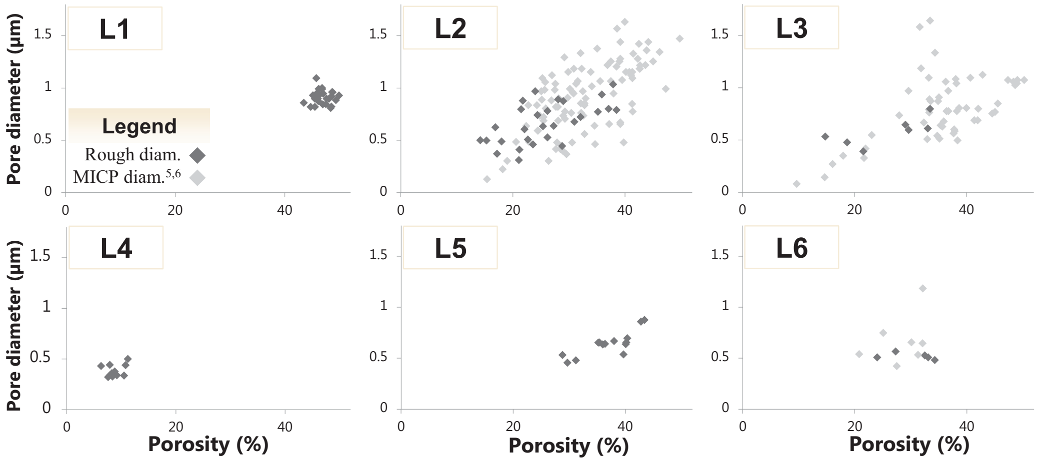
Tetrahedral sphere packing: 1 pore body, 4 throats.

Section A: the 3D throat becomes a “pore body” (green) and 3 “throats”.

Section B: the 3D pore body becomes a “pore body” (purple) and 3 “throats”.

- By crosscutting pore elements randomly, a thin section image may change their identity depending on its orientation.
- The actual diameter of the throat which would be invaded by mercury can simply not be calculated from images.

Mercury entry capillary diameter vs. Dominant rough pore diameter



6. Conclusions

- This study provides the first application of mathematical morphology on SEM images to characterize microporosity (chalk).
- A preliminary image segmentation is necessary to separate porosity and grains. In chalk, the mid-point of the greyscale histogram gives image porosity values similar to He-porosity.
- A characterization of the 2D structure of the pore space can then be obtained rapidly (~ 4 minutes per image), including the apparent 2D pore body and throat diameter distributions, and the body/throat volume ratio.
- The characterization of the pore system geometry, in particular the size and shape of pores and throats constitutes the basis for flow modelling.
- Classical pore models commonly assume simplified pore and throat properties obtained stochastically or through petrophysical techniques, e.g. MICP, NMR, although pore geometry affects the flow capacity of porosity.
- Image analysis can easily provide essential pore shape descriptors.
- The main disadvantage of image analysis is to provide 2D shape descriptors which needs to be translated into 3D.
- Based on a comparison of image and MICP data, it appears that dominant rough porosity diameter is equivalent to entry capillary diameter.
- This technique offers an alternative to costly and time-consuming techniques.
- Further work is needed to adapt to the technique to 3D data, e.g. FIB-SEM.

7. References

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8. Acknowledgements

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