Investigating rock micro-structure of sandstones by pattern recognition on their X-ray images

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SUMMARY

Analysing rock micro-structure from micro-computed tomographic images of porous media is vital to understand fluid-flow and estimating petrophysical properties like permeability. The two main approaches of analysing rock micro-structure are (1) through experiments, a time-consuming process and (2) using numerical simulations which are a part of the standard digital rock physics (DRP) workflow. The standard DRP workflow requires the micro-computed tomographic (micro-CT) images to be segmented into distinct phases (pores and minerals). Segmentation is a user-biased and manual process. It relies heavily on the user to choose a threshold(s) that distinguishes unique phases present in the rock micro-structure. Thus, introducing uncertainty in these petrophysical properties. Our approach to resolving this subjectivity and uncertainty in analysing rock micro-structure is to directly apply techniques on the micro-CT images or the greyscale images, rather than using segmented images. For this purpose, we use a pattern recognition technique namely the Grey-Level Co-occurrence Matrix (GLCM). The GLCM technique is used to calculate spatial maps that describe features present in the rock micro-structure. Calculating these spatial maps at varying length-scales by using different displacement vectors aid in analysing the grain-sizes, grain-pore interface and pore-sizes. Unlike the histograms which only preserve the frequency of intensity values that represent different features in micro-CT images, GLCM is a second-order pattern recognition technique that additionally preserves the spatial variation and occurrence of grey-level intensity values. This method of studying the rock micro-structure using greyscale images and pattern-recognition techniques provides an advantage over the conventional segmentation techniques because full-information regarding the rock micro-structure captured during micro-computed tomography is preserved and a threshold-less workflow leads to lesser user subjectivity. Lastly, the GLCM based analysis also provides a pathway for automated investigation of rock-microstructure.

Key words: GLCM, Pattern recognition, micro-CT, porous media, petrophysical properties

INTRODUCTION

The advent of state-of-art imaging techniques such as high-resolution micro-computed tomographic (micro-CT) images provide insights into the rock micro-structure (Blunt *et al.*, 2013). Micro-CT images capture different phases of the porous rocks by the variation in the greyscale intensity which is a function of the density of the phases. Standard DRP techniques which are used to derive rock properties cannot be applied directly to the micro-CT images. The micro-CT images or greyscale images need to be segmented to identify phases of a porous rock such as pores, quartz and clays. However, segmentation is a user-biased, manual and time-consuming process. While several segmentation algorithms have been developed such as global thresholding, locally-adaptive thresholding and region-growing methods, the manual choice of threshold poses a significant challenge (Iassonov *et al.*, 2009) . There is no growth truth for comparison and hence, one must rely on computationally expensive numerical simulation or laborious lab experiments.

Unlike the standard DRP workflow, Pattern-recognition techniques, on the hand, provide us an opportunity to explore and extract scientific information directly from micro-CT images of the porous rocks. In particular, GLCM is a second order statistical and pattern recognition technique developed by (Haralick & Shanmugam, 1973; Haralick et al., 1973). The GLCM Maps or spatial maps capture the information regarding relative occurrence of different phases in any porous rock and their frequency of occurrence. Thus, proving to be more informative than the first-order histogram which only incorporates information regarding frequency of occurrence.

The results from the paper show GLCM of a Bentheimer sandstone. The GLCM Maps illustrate how different features (pores and minerals) can be identified based on the relative occurrence of the greyscale information from micro-CT images (Singh *et al.*, 2019). Additionally, the four quadrants in a GLCM can be used to differentiate the presence of pores, grains (or minerals) and the interfaces between pore-grain phases. Lastly, calculating these GLCM maps with different displacement vectors provide us an indication of the length-scales or the size-distribution of both pore and minerals (or grains).

METHOD AND RESULTS

GLCM Maps (or GLCM) are a square matrix (as defined in mathematics) describing the relative occurrence of greyscale intensity values and whose size is dependent on the quantization of the image. In order to calculate GLCM maps for porous rocks, three main parameters are required: 1) orientation, (2) displacement vector and (3) grey-level quantization of the micro-CT image (Haralick, Shanmugam and Dinstein, 1973). Orientation refers to the angle of investigation for the GLCM. Displacement vector describes the distance between two-pixels in the image for which GLCM should be calculated. For example, a displacement vector of '1', would take into consideration pixels right adjacent to each other in the micro-CT image. Lastly, quantization of the micro-CT image governs the size of the GLCM Map. Thus, a 16-bit micro-CT image will have a GLCM of size 65536 × 65536.

The overall workflow involves (1) obtaining 16-bit micro-CT images sandstones, e.g. Bentheimer Sandstone, (2) Image Preparation which includes re-quantization of the micro-CT image to lower quantization so that we avoid a sparse GLCM which is not the true representation of the rock structure. (3) Calculate the GLCM Maps, and (4) Identify different rock phases (pores and minerals) from the GLCM Maps (Singh *et al.*, 2019) and investigate the rock micro-structure.

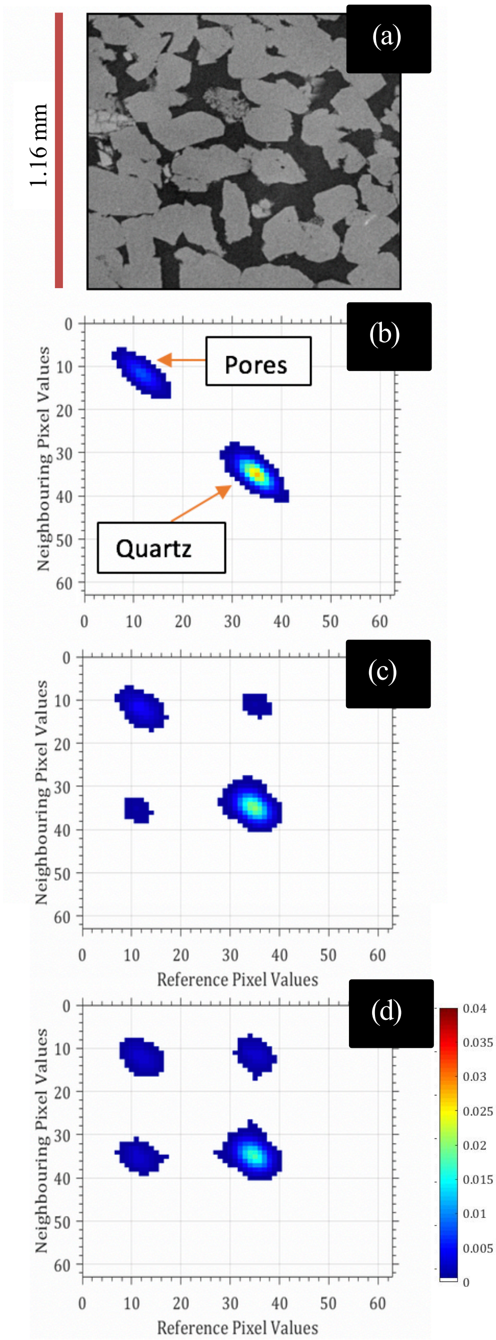

Figure 1. GLCM map for the Bentheimer sandstone. (a) A 400 × 400 2-D Slice of a Bentheimer sandstone with a resolution of 2.92 µm. This image is re-quantized to a 6-bit image, (b) GLCM map of Bentheimer sandstone in (a) using an orientation of 0º with displacement vector of 1, (c) GLCM map using a displacement vector of 7, and (d) GLCM map using a displacement vector of 15.

The GLCM map of Bentheimer sandstone (Figure 1b) shows the probability of relative occurrence different phases such as pores and quartz. Feature identification is best done when considering complete greyscale information regarding the different phases, hence a displacement vector of 1 was chosen. The top left high-density region in the GLCM (Figure 1b) indicates the pores and the rest of the regions indicate quartz grains. By clustering the pores together in comparison to the other mineral (or quartz) features, we can infer the porosity of the Bentheimer sandstone. Additionally, by varying the displacement vector to 7 (Figure 1c) and 15 (Figure 1d), there is a drastic change in the GLCM maps. When the displacement vector is increased, the length-scale at which we identify features changes. The GLCM maps with displacement vector of 7 has lower probability representing pore and the interfaces at the grain-pore boundary start to become visible. Similarly, for the displacement vector of 15, we notice that the interfaces at the grain-pore boundary become more prominent than at lower displacement vectors. Thus, the GLCM Maps calculated for different displacement vectors give a strong indication of the pore and grain size distributions in Bentheimer sandstone. Overall, the rock-microstructure and the features at various length scales can be investigated using the GLCM and varying the parameters such as the displacement vector.

CONCLUSIONS

Pattern recognition techniques such as GLCM allow the direct-use of grey scale micro-CT images instead of the conventional segmented images that are user-based and largely a manual process. Not only this, GLCM allows us to carry out feature identification with an additional information regarding their spatial arrangement. Identifying features such as pores and minerals and can give an indication of the porosity of the porous rock (granular). GLCM maps derived for varying displacement vector or length-scales aid in inferring both the pore and grain-size distributions. Overall, application of pattern recognition techniques to pore-scale imaging open new avenues to alleviate subjectivity and provide an automated method for investigating the rock micro-structure.

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