Estimate elastic moduli of arenites from micro-tomographic images with digital rock physics

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SUMMARY

Numerical computation from high resolution 3D micro-tomographic (micro-CT) images of rocks (known as digital rock physics) has the potential to predict elastic properties more accurately. However, successful examples are limited to samples with simple structure and mineralogy. Here, we propose a practical digital rock physics workflow for somewhat more complex and ubiquitous rocks, namely, sandstones that contain mostly quartz and a small fraction of dispersed clay (known as arenites). We build a segmentation workflow that effectively detects feldspar and clay minerals from micro-CT images, despite their greyscale similarity to quartz. We apply a suite of post-computation corrections to compensate for the effects of sample size and resolution of the micro-CT images on the computed moduli. To compare the computation results against laboratory ultrasonic measurements, we divide the digital samples into subsamples to reconstruct the porosity-moduli trends and compare this trend against laboratory measurements. Computed bulk moduli agree well with the ultrasonic measurements on the dry samples at 40MPa. Computed shear moduli remain overestimated, which is likely caused by poor knowledge of the mineral stiffness. We compensate for this effect using a heuristic correction to the matrix moduli. The final version of the workflow provides accurate elastic moduli trends with porosity and clay content based on only two samples of Bentheimer sandstone.

Key words: elastic moduli; digital rock physics; micro-CT image segmentation.

INTRODUCTION

Quantitative interpretation of reflection seismic measurements is often used to map the spatial distribution of reservoir properties in the subsurface. The relationships between reservoir characteristics and observed seismic properties are referred to as rock physics (Mavko et al., 2009). Analytical models of rock physics rely on idealized microstructures and simplify the physics of rock deformation. For example, rocks are often modelled as solid particles with isolated ellipsoidal inclusions (Eshelby, 1957; Zimmerman, 1990). Digital rock physics (DRP) aims to overcome this limitation (Ahmed et al., 2017; Ahmed et al., 2019; Andrä et al., 2013a, b; Arns et al., 2002; Dvorkin et al., 2011; Makarynska et al., 2008). In DRP, 3D geometry of the mineral and pore phases of a rock is imaged to digitize the sample into a dataset. Micro-tomographic (micro-CT) is the most popular method to acquire such pore-scale information, which is attained from the local x-ray absorption difference (Andrä et al., 2013a). Then, various physical processes can be simulated on this digital rock sample to quantify the corresponding effective rock properties (Andrä et al., 2013b). With the recent development of high-resolution 3D imaging technique and ever-growing computational resources, DRP has the potential to provide a comprehensive analysis of rock properties and to simulate various conditions and processes that would be time and cost demanding if they were to be performed in the laboratory.

Successful examples of DRP for estimating elastic moduli are limited to samples with simple structure and mineralogy. In this study, we propose a practical DRP workflow for estimating elastic moduli of somewhat more complex and ubiquitous rocks, namely, sandstones that contain mostly quartz and a small fraction of dispersed clay (known as arenites). Based on micro-CT images of Bentheimer sandstone, we segment clay and feldspar as separate phases instead of treating all the solid material as one ‘mineral phase’. A suite of post-computation corrections is applied to compensate for the effects of sample size and resolution of the micro-CT images on the computed moduli. To compare the computation results against laboratory measurements, we divide the digital samples into subsamples to reconstruct the porosity-moduli trends and compare this trend against laboratory measurements (Dvorkin et al., 2011). We find that the computed moduli are consistent with the laboratory measurements at higher pressure.

METHOD AND RESULTS

Bentheimer is an outcrop sandstone, with mainly quartz (>90% of the matrix), as well as accessory feldspar, kaolinite and other minor rock fragments, which is a typical kind of arenite. Cylindrical (38.5 mm in diameter, 70.0 mm length) samples for laboratory ultrasonic measurements are visually indistinguishable from one another, and have been extracted from the same sandstone block right next to each other to guarantee similar porosity and texture. Samples were frequently sprinkled with water while being cored for cooling. Then, samples were put into a drying chamber at 50℃ for 24h. Velocities were measured at ultrasonic frequencies (1MHz) inside a pressure cell (Figure 1).

Cylindrical (5 mm diameter, 20 mm length) samples for micro-CT imaging are extracted from the same sandstone block as for ultrasonic measurements. For this study, two sets of micro-CT images of Bentheimer sandstone were studied with the Versa XRM-500 (XRadia-Zeiss) X-ray microscope (Figure 2). Although feldspar and clay particles can be identified visually, their automatic segmentation is challenging. Here, we apply a more advanced segmentation workflow (Liang et al., 2020) taking advantage of both pixel intensity and morphology of different minerals (Figure 3). This workflow is implemented in a commercial software named AVIZO.

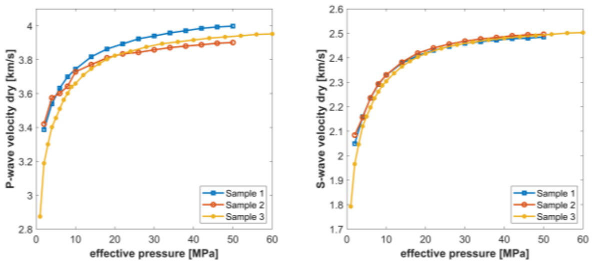

Figure 1. Pressure dependent ultrasonic velocities of three Bentheimer sandstone samples at dry conditions. Samples are dried in a vacuum at 50℃ for 24h. The effective pressure is varied by changing confining pressure.

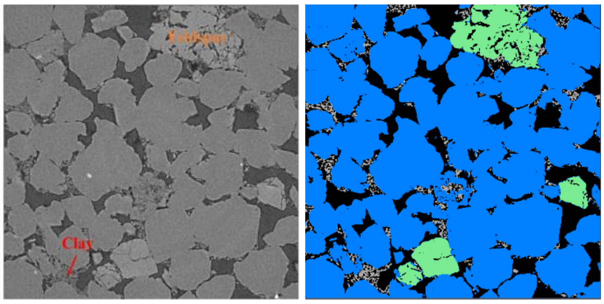

Figure 2. Micro-CT image of Bentheimer sandstone in greyscale and the corresponding segmented labels.

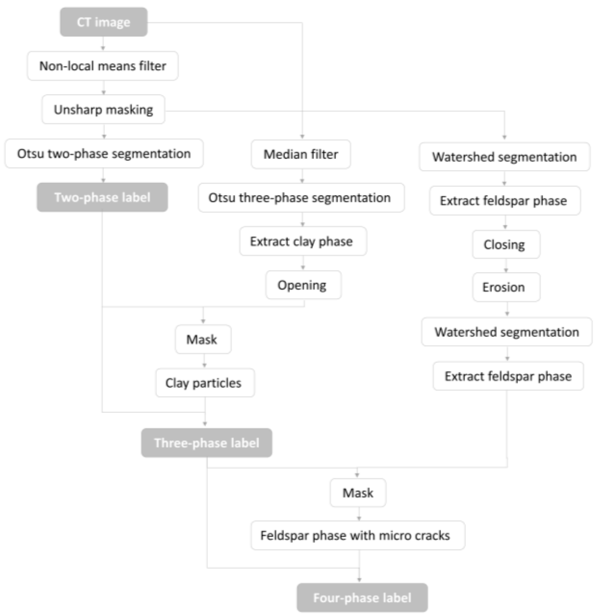

Figure 3. Optimised segmentation workflow for Bentheimer sandstone.

According to the previous study (Liang et al., 2020), there is an exponential relationship between computed moduli and image edge length due to the boundary effect. Also, there is a linear relationship between the computed moduli and voxel size. We apply the corresponding corrections to the computed moduli for the edge length and voxel size effect. A sharp drop of solid phase shear modulus with a small amount of clay has also been reported by Vernik, (1997) and Goldberg and Gurevich, (1998). We apply an empirically determined matrix moduli to provide a much better agreement of the computed shear moduli (Liang et al., 2020). To compare the computation results against laboratory measurements, we divide the digital samples into subsamples to reconstruct the porosity-moduli trends and compare this trend against laboratory measurements (Dvorkin et al., 2011). We assess the accuracy of the predicted moduli by comparison with the moduli-porosity trends from the laboratory measurements on Bentheimer sandstones and from literature data (Han et al., 1986). We only analyse the measurements in the range of relatively high confining pressure or effective pressure (40MPa), which increases the stiffness of intergranular contacts by closing the voids between the contacting grains (Glubokovskikh et al., 2015) and suppressing the sorption-induced deformations (Yurikov et al., 2018). The results are shown in Figure 4.

The computed moduli agree well with the measurements on Bentheimer samples as well as Han et al., (1986) data. The observed agreement means that the proposed workflow may provide a rock physics template for velocity-porosity-clay relationships using only two sets of micro-CT images. Derivation of this template from the laboratory data would require ultrasonic measurements on dozens of samples and thin section/XRD for determination of the clay content.

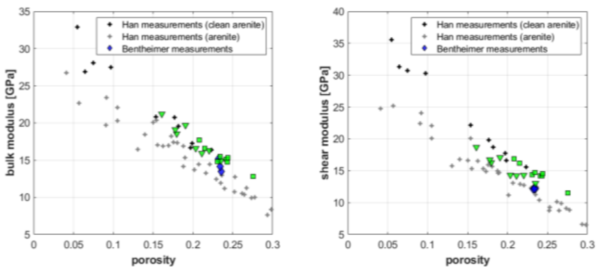

Figure 4. Computed moduli versus measurements. Green square and triangle marks stand for computed moduli from subsamples of two samples. The moduli deduced from our ultrasonic measurements on Bentheimer sandstones are shown in blue diamonds. Also, we show similar measurements on clean arenites (<2% clay) with black cross and arenites (2-14% clay) with grey cross from published laboratory data set of Han et al., (1986).

CONCLUSIONS

This paper develops an optimised digital rock physics workflow for predicting elastic moduli of sandstones with low clay content. We apply a multi-stage four-phase segmentation workflow that targets feldspar and clay minerals. In order to do so, we use a combination of mathematical morphology filters, Otsu and watershed segmentation algorithms. We compensate for scanning parameters which may reduce significantly the discrepancy between the measurements and computed moduli. We correct for the shear moduli overestimating effect using a heuristic correction to the matrix moduli. Eventually, the computed moduli for multi-mineral matrix agrees well with the ultrasonic measurements at

40MPa, where the effect of unresolved compliant pores is small. Our workflow provides accurate moduli trends with porosity and clay content based on two samples of Bentheimer sandstone. Traditionally, such a relationship for quantitative interpretation would require ultrasonic measurements on dozens of samples and thin sections/XRD.

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