Rock elastic property upscaling through multi-resolution Micro-CT/FEB-SEM imaging and refined moduli input through Nanoindentation

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Linear isotropic elastic properties using FEM (SAKHR)

Elastic property predictions of rocks using numerical simulations are typically overestimated when compared to laboratory results regardless of the algorithms used. This overestimation is prevalent amongst sandstones as well as carbonate rock types but the degree of overestimation is much higher for carbonates due to the complex pore structures and heterogeneity in pore scales. One key reason attributed towards the systematic overestimation is the Micro-CTs inability to resolve pores below the limiting scanning resolution at representative volumes. In this paper we used a standard Silurian dolomite (SD) rock to establish a multi-scale imaging and "upscaling" framework for improved numerical prediction of linear elastic properties using a Digital Rock Physics (DRP) approach. We defined upscaling as the process of integrating information from high resolution images to obtain improved estimates using the lower resolution images. A combination of multi-resolution X-ray-CT and FIB/SEM images for the dolomite rock were used. Simulations results were compared to in-house laboratory acoustic velocity test results for same sample material and a reduction of overestimation from 8.9% to 4.5% for predicted P-wave velocity and from 11.9% to 7.8 % for predicted S-wave velocity were found (**Fig. 1**). The red dashed line connecting the percentage differences is a guide for eye only and not a trend line. Details of this work can be found in the PhD dissertation Chapter 4 (Faisal 2017). SS denotes single scale simulations and MS denotes simulations that integrated the multiscale correlation approach.

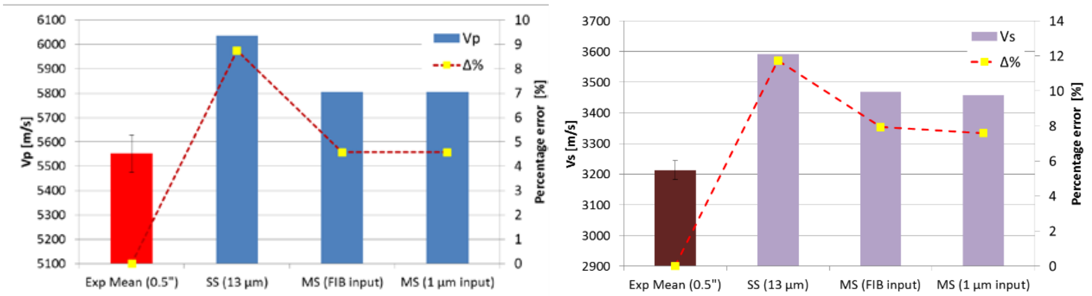

Fig. 1: Effect of multiscale DRP workflow on numerical linear elastic property prediction compared to experimental Vp (top) and Vs (bottom). SS denotes single scale simulations and MS denotes simulations that integrated the multiscale correlation approach

Just like with the standard SD sample, one of the first things we did with the Umshaif carbonate reservoir plug images was to simulate concentrically increasing cube sizes at a given location to see if a representative volume element (RVE) could be identified. For linear elastic simulations a FEM Garboczi algorithm (Garboczi 1995) embedded in the in-house platform SAKHR was used. Unlike the SD, a conclusive RVE size for effective linear elastic bulk and shear moduli properties could not be identified for this sample as the reservoir Umshaif sample was not as homogeneous as SD.

Multi-scale imaging across four (41 µm, 13 µm, 5 µm and 1 µm) imaging scales were accomplished for the Umshaif sample. Segmentation performance of semi-automated Otsu algorithm (successful for SD sample) was compared against manual segmentation which was found to be more appropriate for the heterogeneous Umshaif sample.

Improved mineral moduli estimate through nanoindentation

Mineralogy for Umshaif sample was confirmed to be 100% calcite through EDS characterization. In addition to using standard calcite mineral moduli reported in literature as input for numerical simulations, one of the key additions we have made in our study is the use of nanoindentation technology to make local elastic moduli measurements of the constituent minerals. With nano-indentation we locally probed the polished surface of the material to identify a range for the local Young's modulus and hardness values. Recently (Saenger 2016) highlighted nanoindentation's possible role in elastic property prediction improvement. They did not incorporate the moduli into their finite difference simulations but suggested the implementation of nanoindentation findings in future simulations. Details of nanoindentation experimental and analysis technique can be found in (Faisal 2017). The indenter was calibrated using a fused silica sample for which ideal hardness = 9.35 GPa and ideal Young's modulus = 71.3 GPa are known. We performed several (3x3 to 10x10) maps distributed across the rock macro-wafer. After necessary processing and filtering of data we generated stiffness histogram. Normal distribution fit was assumed for our data and the corresponding distribution parameters: mean and first standard deviation were computed using maximum likelihood estimation technique. We checked the Kolomogorov-Smirnov goodness of fit test for the Gaussian distribution with our data in Matlab. P value of $p = 0.6022$ was found showing that the data can be fit by normal distribution at a significance level of 5%. Table 1 below shows the respective values for K and G computed using Equations 1 and 2:

$$K=E/3(1-2\vartheta) \quad (1)$$

$$G=E/2(1+\vartheta) \quad (2)$$

Table 1: Mean bulk and shear moduli of the carbonate sample obtained by microindentation

	TC
Mean Young's modulus ± standard deviation	62.32 ± 5.92
Mean Bulk [GPa]	52.34
Mean Shear [GPa]	24.16

Before comparing the effect of changing input moduli on FEM simulations, we compared the mean moduli values obtained from nanoindentation against calcite reported values from Rock Physics Handbook (RPH). Results showed that the nanoindentation mean bulk and shear moduli were lower than all reported calcite values. Simulations using RPH calcite moduli (K= 63.7 GPa, G=31.7 GPa) were performed on the largest sub-volumes extracted from 0.5 inch ROIs and 1.5 inch plugs during the RVE analysis. For the Umshaif sample we noted a decrease of 20% in simulated effective bulk modulus, 26% in effective shear modulus (and 12.3 % in Vp) by using nanoindentation measured moduli in our FEM simulations instead of literature calcite values. Simulations using RPH calcite moduli (K= 63.7 GPa, G=31.7 GPa) were performed on the largest sub-volumes extracted from 0.5 inch regions of interest (ROIs) and 1.5 inch plugs during the RVE analysis. For the Umshaif sample we can see (Table 2) a decrease of 20% in simulated effective bulk modulus, 26% in effective shear modulus (and 12.3 % in Vp) by using nanoindentation measured moduli in our FEM simulations instead of literature calcite values.

Table 2: Comparison of FEM simulation effective bulk and shear moduli results for given sub-volumes of Umshaif sample using RPH calcite input vs. nanoindentation measured mean moduli

	Ø	K_RPH	K_nano	% Δ K	G_RPH	G_nano	% Δ G
ROI1_650	0.14	37.15	29.88	21.70	20.39	15.56	26.86
ROI2_630	0.13	37.60	30.77	19.98	20.71	15.81	26.84
1.5" plug _650	0.09	47.61	38.64	20.82	25.47	19.44	26.86

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