Multiscale Characteristics of Anisotropic, Heterogeneous Pore Structures and Compositions and Its Impact on Mechanical Properties of Shale

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ABSTRACT

The performance of unconventional resources reservoir is a function of the hydro, mechanical, and chemical properties of shale. Multiscale characteristics of anisotropic, heterogeneous pore structure and compositional (e.g., clay, cement, organics, etc) distribution profoundly influence the hydro, mechanical, and chemical response of shale materials during stimulation and production. In this work the impact of these lithologic heterogeneities on physical, chemical, and mechanical properties is investigated over a micron to core scale of shale samples for Cretaceous Mancos Shale. In particular, mechanical properties (yield and failure strength, nonlinear elasticity, anisotropy, etc.) are controlled by a variety of geologic variables, including detrital and authigenic mineralogy including cements, organic content, and the spatial distribution of these characteristics.

Principal macroscopic lithofacies at a deci-meter scale over a host sample (-40cm diameter and 15 em thick) are petrographically examined. Mudstone core samples are first subdivided into principal macroscopic lithofacies. Thin sections impregnated with fluorochromes are examined using laser scanning confocal microscopy and optical microscopy with different filters to characterize micro-facies (e.g., abundance, size, and spatial distribution of porosity, organics, and mineralogy). Micro-computed tomography (micro-CT) is also employed to characterize 3D pore structures and feature distribution over 1" core samples. In particular, the mineralogical spatial distribution is measured using electron microprobe and QEMSCAN at the thin section scale. Advanced multiscale image analysis for texture classification is used to identify key features of samples which are further analyzed using dual focused ion beam-scanning electron microscopy (FIB-SEM), multibeam-SEM, transmission electron microscopy (TEM) and energy dispersive X-ray spectrometry (EDS) for nano-pore and organic-pore structures and mineralogies at nano scale and micro-pillar testing. These unprecedented multi-scale characterization effort will be combined with small and ultra-small angle neutron scattering (SANS and USANS) studies to augment pore-size distribution of thick thin sections from a nano-meter to-centi-meter scale (over 7 orders of magnitude).

A suite of mechanical testing is conducted on the core samples using uniaxial compression strength and triaxial compression tests to determine mechanical properties of samples (e.g., parallel and perpendicular to bedding) with various lithofacies under a range of confining conditions. In addition, Brazilian disk testing is performed to evaluate the impact of local heterogeneity on failure characteristics. For a limited set of testing a micro-CT system is used to measure the deformation of core samples during triaxial experiment. In addition, a micropillar compression technique is applied to investigate size-scale and anisotropy effects on mechanical response (e.g., elasto-plastic deformation) of micro-pillar (10 micron diameter and 20 micron height). Pillar machining is done with focused Ga ion milling and SEM imaging is applied at 20-SOnm

resolution. Micropillar compression is performed with a nanoindenter and flat diamond indenter. Micro-pillar experimental results include displacement responses over CSM contact stiffness and load and the uniaxial compressive strength and Young's Modulus.

Multiscale 3-D image stacks will be segmented to rigorously test the scale of a representative elementary volume based on multiple measures from multiscale image analysis and pore-scale numerical simulations including lattice Boltzmann simulations and computational fluid dynamics. A micro-mechanical testing will be also performed to match mechanical testing results. With primary features of lithofacies honored, 3-D digital rocks will be reconstructed using feature extraction techniques and multipoint stochastic approach for constructing multiscale response surfaces. A combination of SANS and USANS data and multiscale imaging data delineating pore structures and mineralogical and geochemical composition will be used to estimate two-point and three-point correlations of pore systems from the nanometer to the centimeter scale. This combined approach will highlight the significance of proposed methodology to understand fluid/rock interactions across scales crucial to emerging subsurface issues such as unconventional gas and oil resources, enhanced oil recovery, and geologic storage of CO_2.

Comparison of multiscale characterization and mechanical experiments is useful to mechanistically evaluate the relationship between mechanical response and micro-lithofacial features across scales. Coupled with pore structure characterization, this work will reveal the scale of representative element volume for mechanical properties. SEM images of micro-pillar testing will reveal how a microscale heterogeneity governs mechanical response. Comparison of micro-pillar and core-scale mechanical testing will reveal the significance of microscale properties in the mechanical response on the core samples. This will allow us to provide a science-based approach for engineering solutions and make more accurate prediction of reservoir pe1formance by developing a multi-scale understanding of mudstone response to reservoir stimulation effm1s.

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