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# Multiscale pore networks and their effect on deformation and transport property alteration associated with hydraulic fracturing

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## Abstract

We performed a series of laboratory and image analysis on organic shale samples before and confined compressive strength tests. Following failure, we often observe an increase in pore volume in the sub-micron range, which appears to be related to the formation of microcracks that in some cases cross or terminate in organic matter, intersecting the organic-hosted pores. Samples with higher clay content tended not to display this behavior. The microcrack networks allow the hydrocarbons to migrate to the main induced tensile fractures. The disconnected nature of the microcracks causes only a slight increase in permeability, consistent with other observations.

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*Keywords:* shale; hydraulic fracturing; microstructure; transport properties

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## 1. Introduction

The ability to produce hydrocarbons from shales at economically viable rates depends on the success of hydraulic fracture stimulation, which creates a system of interconnected, induced fractures around the wellbore [1]. These fractures allow transmission of fluids through the otherwise extremely low-permeability shale matrix [2]. However,

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with typical fracture spacings in the induced fracture network of meters to tens of meters [1], movement of hydrocarbons from their initial residence place in the organic matter and/or intergranular pore space is nontrivial. For example, in the Barnett shale (porosity of 5% and permeability of $10^{-19}$ $m^2$ [2]) the diffusion time into fractures with half-spacing of 75 m for methane at 24 MPa and 65°C is about 75 years. Recent work has suggested that hydraulic fracture stimulation is associated with some permeability enhancement in the unfractured matrix as well, perhaps by 10-100 times the original value [3-5]. Applying this case to the calculation above, the diffusion time would be reduced to approximately 9 months. Having some means of enhancing the unfractured matrix permeability seems a necessary component of economic production from shales. We show how the pore system, microscale deformation style, and mineralogy of shales combine to allow this permeability enhancement.

The pore system in shales consists of disconnected networks of cracks and voids at multiple scales [6] (Figure 1). A significant fraction of the porosity is present in the organic matter, which itself ranges in morphology from discrete, micron-size macerals to a migrated form that can fill preexisting fractures or intergranular volume. Since much of the hydrocarbons are present in the pore space of this organic matter, this pore space must be connected to the induced fracture system to allow production. During hydraulic fracture stimulation, a large volume around the wellbore experiences shear failure, as evidenced by microseismic monitoring results [7]. This shear failure may involve slip on or opening of preexisting fractures, or creation of new fractures [8,9]. A recent study [10] has suggested that this shear failure causes pervasive microfracture (apertures <100 nm) development, including microfractures that propagate through or terminate within organic matter. While these fractures tend to be discontinuous, rather than throughgoing, they presumably connect enough of the organic-hosted porosity with the main, induced fracture system to allow observed production rates. This is due to the disconnected nature of the shale pore system: the organic-hosted porosity may be effectively tapped to allow discharge of hydrocarbons.

Here we present an analysis of previously obtained experimental results to illustrate the ways in which shale microstructure controls fracturing behavior at the microscale. Our analysis indicates that strain partitioning occurs between the organic matter and clay within the shale, with the organic matter being more prone to brittle failure (deformation on discrete planes accompanied by volume increase) while the clay tends to experience a mixture of ductile (distributed deformation accompanied by volume decrease) and brittle failure. This phenomenon is likely due to the different morphologies of the clay and organic matter, although it may also be related to zonations in mechanical strength within the organic matter as well as highly localized zones of high fluid pressure sustained by the disconnected pore network. Our results highlight the role that microstructure plays in bulk deformation of heterogeneous media like shales.

## 2. Experimental summary

Daigle et al. [10] performed experiments on preserved samples of Eagle Ford shale (Karnes County, Texas, USA) and a siliceous shale from the northern Rocky Mountains, USA (hereinafter referred to as "siliceous"). Cores were received preserved in wax and sampled using a specialized mineral oil-lubricated coring barrel. All samples and carcasses were stored in mineral oil after subsampling. Subsequent nuclear magnetic resonance (NMR) measurements did not show any indications of mineral oil imbibing into the shale matrix. 1" diameter samples were taken orthogonal to the borehole axis (horizontal samples) and, where possible, also parallel to the borehole axis (vertical samples). Material from each sample was set aside for gas adsorption and scanning electron microscope (SEM) imaging. Samples were then failed in confined compressive strength tests with a confining pressure of 5 MPa. The failed samples were then subsectioned, where possible, for SEM imaging, and material was reserved for gas adsorption measurements.

A second set of horizontal samples was used for NMR measurements at different differential stresses. In these tests, the samples were placed in a pressure vessel designed to fit inside the NMR instrument. The confining and axial stresses were then increased, up to a maximum of 31 MPa. Transverse relaxation time ($T_2$) distributions were recorded at each pressure step to investigate the pore system response. When the spin axes of protons in the rock sample are aligned in the presence of an external, inhomogeneous field, $T_2$ is the characteristic decay time for the component of the magnetic field produced by the aligned protons transverse to the applied field. In most rocks, $T_2$ is proportional to pore size, and a distribution of $T_2$ values may be mapped to a distribution of pore sizes [11]. Due to