

## Fracture-Matrix Interaction and Gas Recovery in the Barnett Shale

Qinhong Hu<sup>a</sup>, Xianguo Liu<sup>b</sup>, Stefan Dultz<sup>c</sup>, Robert P. Ewing<sup>d</sup>, and Harold D. Rowe<sup>a</sup>

<sup>a</sup>*Department of Earth and Environmental Sciences, University of Texas at Arlington, Arlington, TX, USA*

<sup>b</sup>*School of Environmental Studies, China University of Geosciences, 430074 Wuhan, P. R. China*

<sup>c</sup>*Institute of Soil Science, Leibniz University of Hannover, Hannover, Germany*

<sup>d</sup>*Department of Agronomy, Iowa State University, Ames, IA, USA*

Located in the Fort Worth Basin in north-central Texas, the Barnett Shale is a Mississippian-age marine shelf deposit which ranges in thickness from 200 ft in the southwest to 1,000 ft to the northeast. The formation is a black, organic-rich (4.5% total organic carbon, TOC) shale composed of fine-grained, non-siliciclastic rocks with extremely low permeabilities (0.07-5  $\mu\text{d}$ ) (Grieser et al., 2007). Hydrogeological data on the Barnett Shale are limited and display a wide range, especially for the permeability (Table 1). As indicated in Sigal and Bin (2008), most rock property measurements on shale gas reservoir rocks are proprietary, as are many of the details on how the measurements are performed.

Table 1: Compilation of pertinent hydrological and geochemical information on the Barnett Shale

	Curtis (2002)	Bowker (2007)	Gale et al. (2007)	Grieser et al (2006)	Hill et al. (2007)	Sigal and Qin (2008)	Zhao et al. (2007)
Porosity (%)	4.4	6	5.52 $\pm$ 0.28		6	4-8	3.8-6.0
Permeability ( $\mu\text{d}$ )				0.07-5	20	0.01-0.6	0.15-2.5
TOC by weight (%)	4.5			4.5			3.5-4.5
Free gas (%)					55		
Sorbed gas (%)					45		
Water saturation (%)	43	25	28.9 $\pm$ 7.2				

While the term “Barnett Shale” is widely used, most of the Barnett Formation is mudstone rather than shale (Gale et al., 2007). Mudstone is a relatively non-fissile clastic rock containing dominantly non-calcareous, clay-sized particles, while shale is characteristically fissile because of its higher clay mineral content (Gale et al., 2007). The Barnett Formation is primarily composed of clay-size quartz and feldspar, with subsidiary dolomite, clay minerals, organic material, pyrite, and microfossils and fossil fragments. But in keeping with common usage, we use the term “shale” to indicate the gas-producing mudstone in the Barnett Formation.

The Barnett Shale is a profitable gas field, but the current gas recovery rate is only 10-15% of the estimated gas in place (Curtis, 2002). Recovery in this extremely tight formation is limited by diffusive gas transport from the matrix storage to the stimulated fracture network. But despite the importance of diffusion to gas production, there is no systematic study examining permeability and diffusivity of the Barnett Shale (Bowker, 2007). Here we describe a new study of pore structure (pore connectivity, pore-size distribution) and gas desorption from both shale cores and crushed shale particles, and the subsequent gas transport into the hydraulic fractures. The low gas diffusivity is likely due to low pore connectivity, which also has not been systematically studied in the Barnett Shale. Chemical diffusion in sparsely-connected pore spaces is not well described by classical Fickian

behavior; anomalous behavior is suggested by percolation theory, and confirmed by results of our preliminary imbibition tests.

The imbibition test is a relatively easy screening technique for determining whether a rock sample has low connectivity (Hu et al., 2006). Where applicable, imbibition can also be a more detailed test for estimating the crossover length  $\chi$  (depth to constant accessible porosity). Because of the mathematical analogy between diffusion and imbibition, water imbibition (being easier to conduct because of its shorter experimental duration) constitutes a powerful and economical way to probe the pore connectivity of the shale. Imbibition tests involve exposing one face of a dry rock sample to water, and monitoring the water uptake rate over time (Hu et al., 2001). If gravity effects are negligible, imbibition into a porous medium normally leads to mass uptake proportional to time<sup>0.5</sup>. This square-root-of-time scaling is generally accepted as a mathematical fact, but we have observed that an exponent of 0.5 applies only to rocks with well-connected pore spaces. At low connectivities an exponent of 0.26 is obtained, while at intermediate connectivities we see the 0.26 exponent, followed by a transition to the classical 0.5 exponent. In other words, just above the percolation threshold, solute diffusion (analogous to water imbibition) is anomalous at short times and distances, but later assumes “classical” (Fickian) long-term behavior. The distance to the wetting front at this transition is the correlation length  $\chi$  of percolation theory. Our preliminary imbibition work on the shale sample from Texas (Figure 1) indicates low pore connectivity.

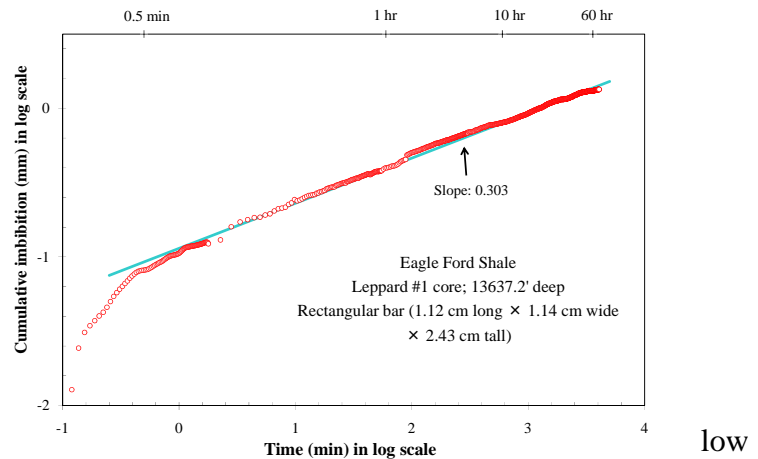


Figure 1. Low pore connectivity, indicated from an imbibition test, for a shale sample from South Texas.

In addition to the imbibition approach, a suite of complementary and innovative experimental and modeling approaches will be utilized to evaluate the implications of low porespace connectivity, particularly in the fracture-matrix interaction, on low gas recovery in fractured shale:

**1. Edge-only accessible porosity distribution:** In a rock with sparsely-connected pores, the accessible porosity decreases with distance from an edge (e.g., a fracture). We will measure the decrease in accessible porosity with distance from an exposed face in order to assess pore connectivity in the shale samples. Samples will be dried, subjected to vacuum, and wetted with a solution containing both nonsorbing (bromide and perrhenate) and sorbing (strontium and cesium) tracers; these tracers will occupy the evacuated connected pore spaces. Using micro-scale LA-ICP-MS mapping techniques (Hu and Möri, 2008), laser energy will vaporize a hole into the rock sample in sub-micron increments, allowing the resident tracer concentrations to be measured. In this way, tracer concentration profiles – related to accessible porosity – can be measured directly, rapidly, and with high sensitivity.

**2. Pore connectivity imaging using Wood’s metal intrusion:** Dultz et al. (2006) applied a new approach of injecting the molten alloy Wood’s metal (50% Bi, 25% Pb, 12.5% Zn, and 12.5% Cd) into feldspars to determine porosity and pore connectivity. Because this alloy is solid below 78 °C, pore structures filled by the metal can be readily imaged on polished sections. We will use a mercury porosimetry apparatus to inject molten Wood’s metal (120 to 150 °C) into shale samples under high pressure (60,000 psi, which will invade pores down to 3 nm diameter). Pore spaces containing

solidified alloy will be imaged with a scanning electron microscopy to study pore connectivity in Barnett Shale.

**3. Sorption and transport in crushed shale:** We will perform laboratory column experiments, under steady-state flow conditions, using crushed shale samples to remove diffusion-limited transport process encountered in intact shale. First, gas-phase transport will be conducted to evaluate methane retention in shale, with the breakthrough curve measured by an in-line methane analyzer. Second, a suite of transport experiments with both non-sorbing ( $\text{Br}^-$  and  $\text{ReO}_4^-$ ; as diffusivity tracers with different aqueous diffusion coefficients) and sorbing ( $\text{Sr}^{2+}$  and  $\text{Cs}^+$ ) liquid tracers will be conducted, to evaluate their diffusion and sorption in shale. The effluent samples are analyzed by ICP-MS to obtain breakthrough curves for data interpretation. The above two tests provide a “base case” to be compared to the more complex subsequent tests in fractured shale.

**4. Fracture-matrix interaction in fractured shale:** We will study the interaction of gaseous methane sorption and diffusive fracture-matrix exchange in the shale. Cores will be tested at two different water saturation levels: one dry, and one corresponding to field saturation. Partially saturated shale cores will be obtained by equilibrating initially saturated cores to various relative humidities by holding them in closed chambers with different oversaturated brines. We will prepare a saw-cut fracture core (length 10 cm, diameter 4 cm, and fracture aperture 100  $\mu\text{m}$ ). The diffusivity of methane is controlled by its kinetic molecular diameter, and by the pore size and connectivity of the shale samples; the micropores of the Barnett Shale may result in methane diffusion in the Knudsen range. After flow tests are complete, the flow reactor will be opened and the distribution of liquid tracers within the fractured core characterized by LA-ICP-MS. The results will provide direct assessment of diffusion confounded by pore connectivity of the fractured shale.

**5. Pore-scale network modeling:** All experiments will be simulated using a pore-scale network modeling approach. Our experience is that doing parallel “experiments” in the laboratory and the computer results in greater understanding than either alone. The random walk methods used can be quite CPU-intensive and time-consuming, and the variability of a medium increases near the percolation threshold. Our Monte Carlo methods are therefore impractical for applications other than research, and ways should be found to either speed them up, or to obtain results in some other fashion.

Overall, the outcomes of this work will fill significant knowledge gaps regarding the effects of pore connectivity on diffusive gas transport and gas recovery in fractured shale system, and should lead to approaches to improving gas recovery.

#### References:

- Bowker, K.A. 2007. Barnett Shale gas production, Fort Worth Basin: Issues and discussion. *AAPG Bull.*, 91(4): 523-533.
- Curtis, J.B. 2002. Fractured shale-gas systems. *AAPG Bull.*, 86(11): 1921-1938.
- Dultz, S., H. Behrens, A. Simonyan, G. Kahr, and T. Rath. 2006. Determination of porosity and pore connectivity in feldspars from soils of granite and sapolite. *Soil Sci.*, 171(9): 675-694.
- Ewing, R.P., and R. Horton. 2002. Diffusion in sparsely connected pore spaces: Temporal and spatial scaling. *Water Resour. Res.* 38: 1285, doi:10.1029/2002WR001412.
- Gale, J.F.W., R.M. Reed, and J. Holder. 2007. Natural fractures in the Barnett Shale and their importance for hydraulic fracture treatments. *AAPG Bull.*, 91(4): 603-622.

- Grieser, B., B. Shelley, B.J. Johnson, E.O. Fielder, J.R. Heinze, and J.R. Werline. 2006. Data analysis of Barnett shale completions. *SPE J.*, SPE 100674.
- Hill, R.J., E. Zhang, B.J. Katz, and Y.C. Tang. 2007. Modeling of gas generation from the Barnett Shale, Fort Worth Basin, Texas. *AAPG Bull.*, 91(4): 501-521.
- Hu, Q., and A. Möri. 2008. Radionuclide transport in fracture-granite interface zones. *Phys. Chem. Earth*, 33(14-16): 1042–1049.
- Hu, Q., P. Persoff, and J.S.Y. Wang. 2001. Laboratory measurement of water imbibition into low-permeability welded tuff. *J. Hydrol.*, 242(1-2): 64-78.
- Hu, Q., R.P. Ewing, L. Tomutsa, and M.J. Singleton. 2006. Pore connectivity, episodic flow, and unsaturated diffusion in fractured tuff. Proceedings of the 11th International High- Level Radioactive Waste Management Conference (IHLRWM), pp. 70–76, April 30 - May 4, 2006, Las Vegas, NV. <http://www.ocrwm.doe.gov/science/pdf/abstracts/46985.pdf>
- Sigal, R.F., and B. Qin. 2008. Examination of the importance of self diffusion in the transportation of gas in shale gas reservoirs. *Petrophysics*, 49(3): 301-305.
- Zhao, H., N.B. Givens, and B. Curtis. 2007. Thermal maturity of the Barnett Shale determined from well-log analysis. *AAPG Bull.*, 91(4): 535-549.