Water Interactions with Shales, and Impacts on Gas Mobilization

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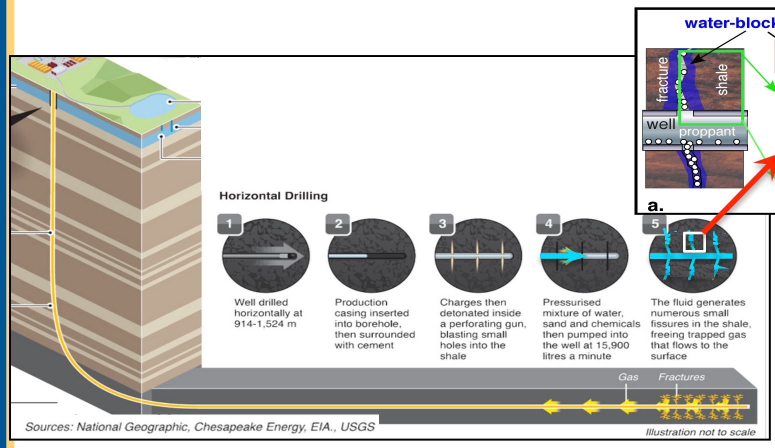
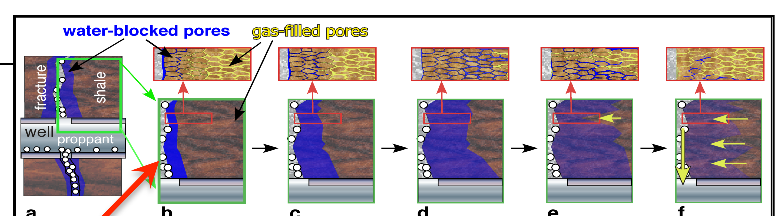
ABSTRACT

The use of water-based hydraulic fracturing fluids in stimulation of unconventional reservoirs is problematic because of formation damage from water blocking, and because of costs associated with use of large volumes of water are required treatment of flowback water. This research is designed to improve understanding of how water interferes with the desired counter-flow of gas from shale into fractures, through a combination of laboratory and modeling investigations of matrix-fracture interactions. Most of our experiments have been conducted on Woodford shales, which were found to exhibit significant and strongly hysteretic water adsorption/desorption isotherms. Most samples, with the exception of one calcite-rich shale, showed very high capillary retention (water blocking). A new pore scale model, based on many particle dissipative particle dynamics (MDPD), was developed to investigate multiphase transport processes in nanoporous media. This model naturally takes into account dynamic contact angle, Knudsen diffusion and adsorption processes in pore-space. The developed pore-scale model is used to assess the influence of pore-level mechanisms at the macroscopic scale, with the objective of developing more appropriate macroscopic modeling approaches for multiphase flow through shale matrix.





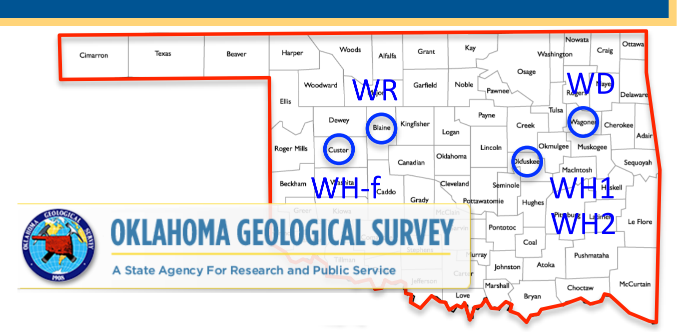
Water-based hydraulic fracturing fluids occupy shale pores along newly generated fractures, block flow of gas to wells.

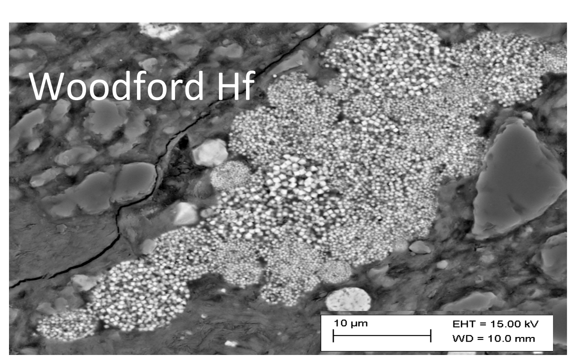
OBJECTIVES

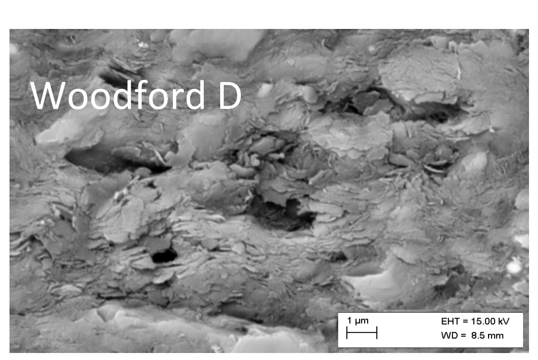
- Understand water-based fracturing fluid imbibition rate dependence on shale and fluid properties.
- Understand threshold capillary pressures needed for gas breakthrough after water imbibition.

SHALE SAMPLES

Most of our first stage of laboratory measurements on gas shales have been obtained on samples from wells in the Devonian Woodford Shale play (Oklahoma Geological Survey).







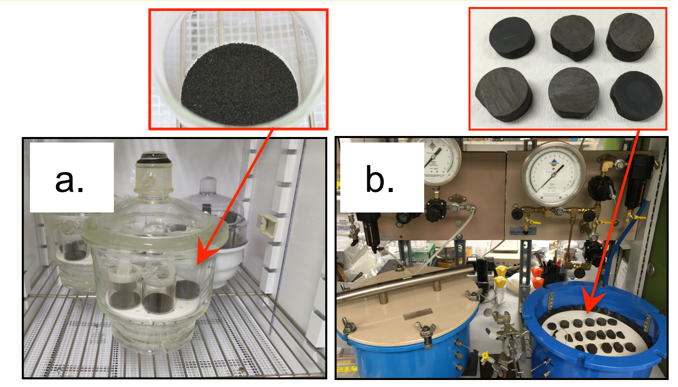
LBNL label	Operator	Well	Sample depth	county	Total Carbon	Inorganic Carbon	Organic Carbon	bulk density	grain density	porosity
			m		mass %	mass %	mass %	g/cm3	g/cm3	
WHf	GHK	Hoffman	4346.3 - 4347.2	Custer, OK	4.29	0.40	3.89	2.58	2.76	0.065
WR	Pan American	Roetzal	2569.0 - 2569.9	Blaine, OK	7.11	0.00	7.11	2.41	2.62	0.081
WD	Res Dev Tech	Dunkin	282.3 - 283.1	Wagoner, OK	6.07	0.46	5.61	2.41	2.59	0.070
WH1	Star Resources	Holt	1126.7 - 1127.6	Okfuskee, OK	6.29	3.61	2.68	2.42	2.69	0.100
WH2	Star Resources	Holt	1128.5 - 1129.4	Okfuskee, OK	5.54	0.00	5.54	2.50	2.68	0.067

STRONG CAPILLARY RETENTION OF WATER IN SHALE

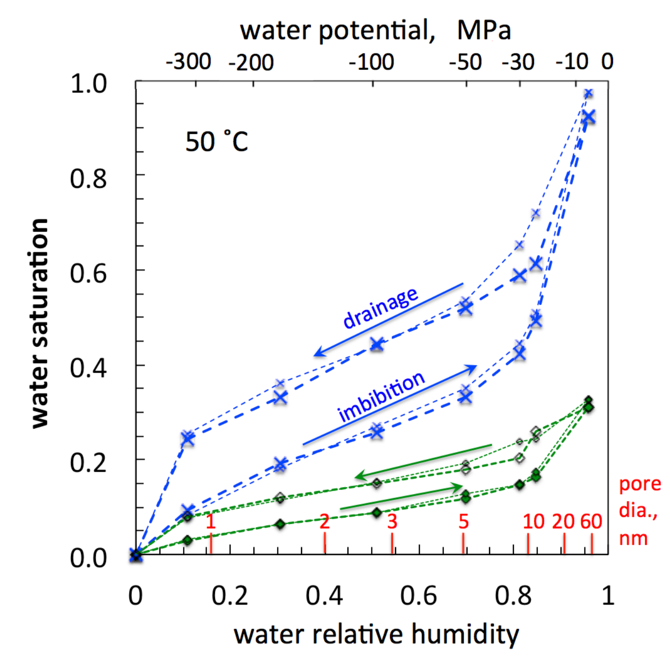
The relation between water activity (relative humidity, capillary pressure) and water saturation needs to be understood in order to predict water distribution in shales and threshold pressure differences needed to allow gas flow through a water-blocked zone.

We have measured shale water saturation during water vapor adsorption (imbibition) and desorption (drainage) over a wide range of water activities (relative humidities).

- B.E.T. measurements using N_2 and Kr underestimate specific surface areas of these shales.
- Pore-sizes largely < 50 nm
- Large capillary hysteresis of water retention.
- Strong capillary retention of water in most of our samples indicate that redistribution of imbibed water is important for gas counter-flow from matrix pores.



Measuring wetting and draining water isotherms (a.) equilibration in fixed relative humidity environments, (b.) pressure plate outflow/inflow.



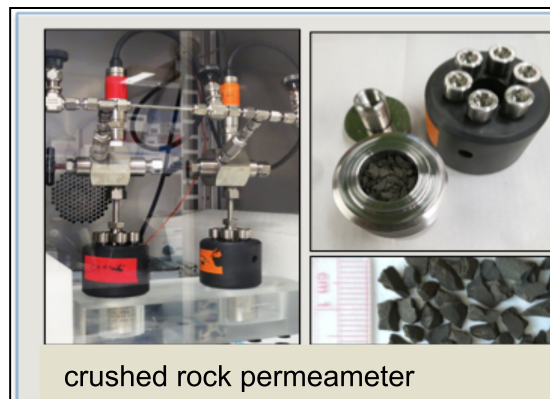
Wetting and draining water isotherms (50 °C) obtained by equilibration in fixed relative humidity environments.

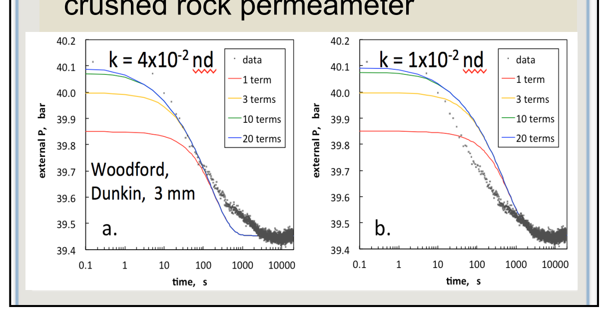
MULTISCALE NATURE OF SHALE PERMEABILITY

We have used a variety of methods to characterize shale permeability at different scales. At the smallest scale, the crushed rock method (Luffel, 1993) is applied. Lowest permeabilities are obtained at this scale (mm scale fragments), with fine-scale deviations from model assumptions reflecting influences of irregular shape and variable permeability (Hannon, 2016).

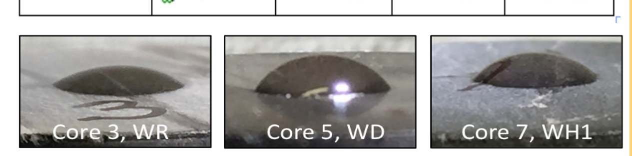
Other permeability measurements applied on the Woodford shale include gas probe methods (Goggins et al, 1988) and calculations based on transient water imbibition rates (Tokunaga & Wan, 2001).

- Effectively impermeable internal domains (sub nano-Darcy)
- Microfracture networks within shale matrix enhance permeability
- Importance of wettability in limiting water imbibition rates.





Method	Shale sample	#3, WR	#5, WD	#7, WH1
Pycnometer	Porosity	0.081	0.070	0.100
Water imbibition	S, m/(sqrt(s))	1.5E-06	4.5E-06	1.4E-06
	k(estimated), m^2	4E-22	5E-20	1E-22
gas probe	P, Pa	1.7E+05	1.0E+05	1.3E+05
	k(apparent), m^2	3.0E-17	6.0E-16	1.5E-16
	k_∞, m^2	4E-18	2E-16	4E-17
	b, Pa	1.1E+06	2.2E+05	4.3E+05



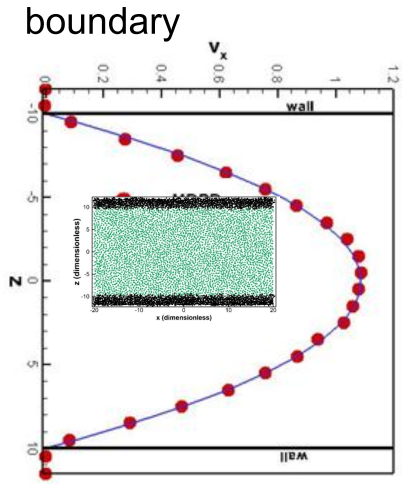
Water droplets on Woodford shale yield contact angles ranging from 15° to 70°.

PORE-SCALE MODEL DEVELOPMENT

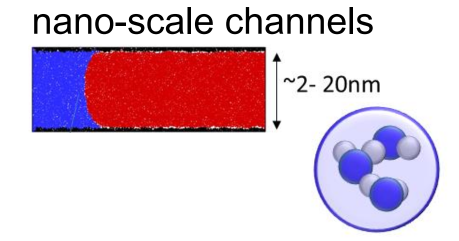
Pore-scale model based on many-body dissipative particle dynamics (MDPD) method

- System is represented by a set of interacting particles and each particle represents a small cluster of atoms or molecules. Evolution of particles in space and time is governed by Newton's equation of motion.
- Can naturally represent slip flow, wettability, dynamic contact angle changes and adsorption/desorption processes.
- The model will be used to improve understanding of pore-scale physics and develop and test macroscopic models relevant for shale matrix and matrix-fracture multiphase flow exchange.

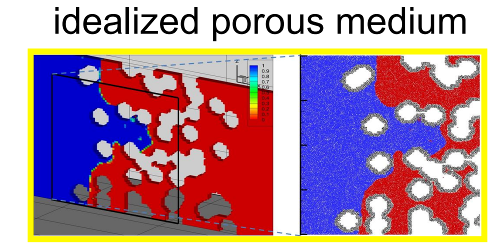
Single-phase flow: Verification against the Navier-Stokes-model results with no slip boundary



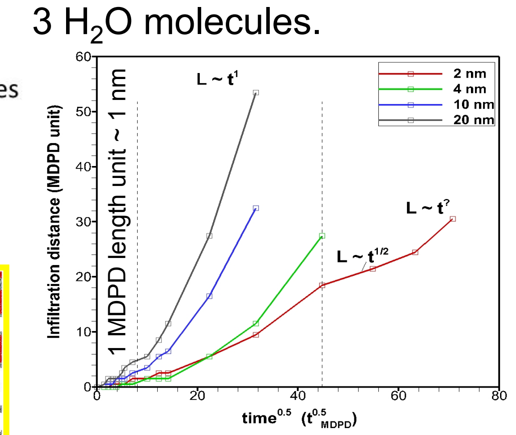
Two-phase flow in nano-scale channels



Forced imbibition into an idealized porous medium



MDPD simulation for the interface movement as functions of time and nano-channel size in 2-phase flow. 1 MDPD particle represents 3 H_2O molecules.



6400 MDPD time unit ~ 1 µs

SUMMARY

- Large hysteresis in adsorption-desorption isotherms show that high capillary pressures are needed to percolate through water-blocked shale matrix.
- Wettability strongly influences water imbibition rates.
- Predicting water imbibition rates in nanoporous shales based on traditional hydraulic scaling models appears unreliable.

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