Saturation-Dependent Relative Permeability in Shales Based on Adsorption-Desorption Isotherm*

Shiv P. Ojha[2] and Siddharth Misra[1]

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Abstract

Relative permeability in shales is an important petrophysical parameter for purposes of accurate estimation of production rate and recovery factor, efficient secondary recovery, and effective water management. We present a method to estimate saturation-dependent relative permeability in shales based on the interpretation of the low-pressure nitrogen adsorption-desorption isotherm measurements. Relative permeability were determined for 30 samples from the gas- and oil-window of Eagle Ford and Wolfcamp shale formations. These sample have low-pressure helium porosity (LPHP) in the range of 0.04 to 0.09 and total organic content (TOC) in the range of 0.02 to 0.06. The samples were ashed to study the effects of removal of organic matter on the pore size distribution, pore connectivity, and relative permeability. The estimated irreducible water saturation and residual hydrocarbon saturation are directly proportional to the TOC and LPHP, and exhibit 15% variation over the entire range. Pore connectivity, in terms of average coordination number, decreases by 33% with the increase in TOC from 0.02 to 0.06. The estimated fractal dimension is close to 2.7 for all the samples. The estimated relative permeability of aqueous phase and that of hydrocarbon phase at a given saturation is inversely proportional to the TOC. Relative permeability curves of the hydrocarbon phase for geological samples from various depths in a 100-feet interval indicate that the hydrocarbon production rate will vary drastically over the entire interval and these variations will increase as the hydrocarbon saturations reduce in the formation. In contrast, relative permeability curves of the aqueous phase suggest limited variation in water production rate over the entire interval. Further, based on the relative permeability curves, the hydrocarbon production is predicted to be negligible for hydrocarbon saturations below 50% and the water production is expected to be negligible for water saturations below than 80%. Efforts are ongoing to use the laboratory-based estimates to predict field-scale production and recovery rates.

Reference Cited

Coasne, B., K.E. Gubbins, and R.J.-M. Pellenq, 2005, Temperature Effect on Adsorption/Desorption Isotherms for a Simple Fluid
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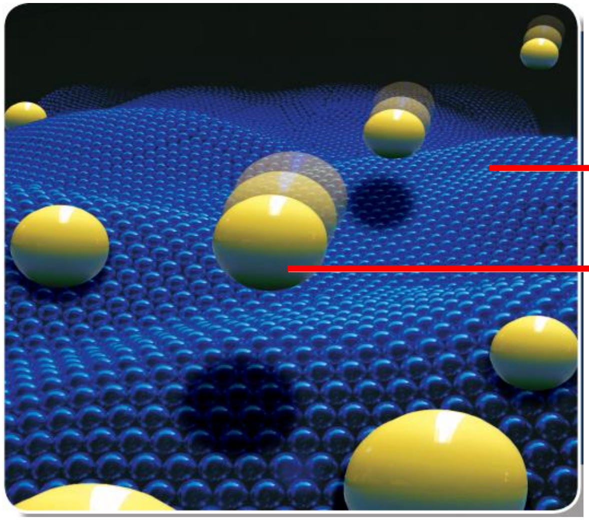
Shiv Ojha and Siddharth Misra
University of Oklahoma

Presenter: Siddharth Misra

Outline

- Introduction
- Adsorption-Desorption Measurements
- Interpretation Methodology
- Results
- Conclusions

Introduction



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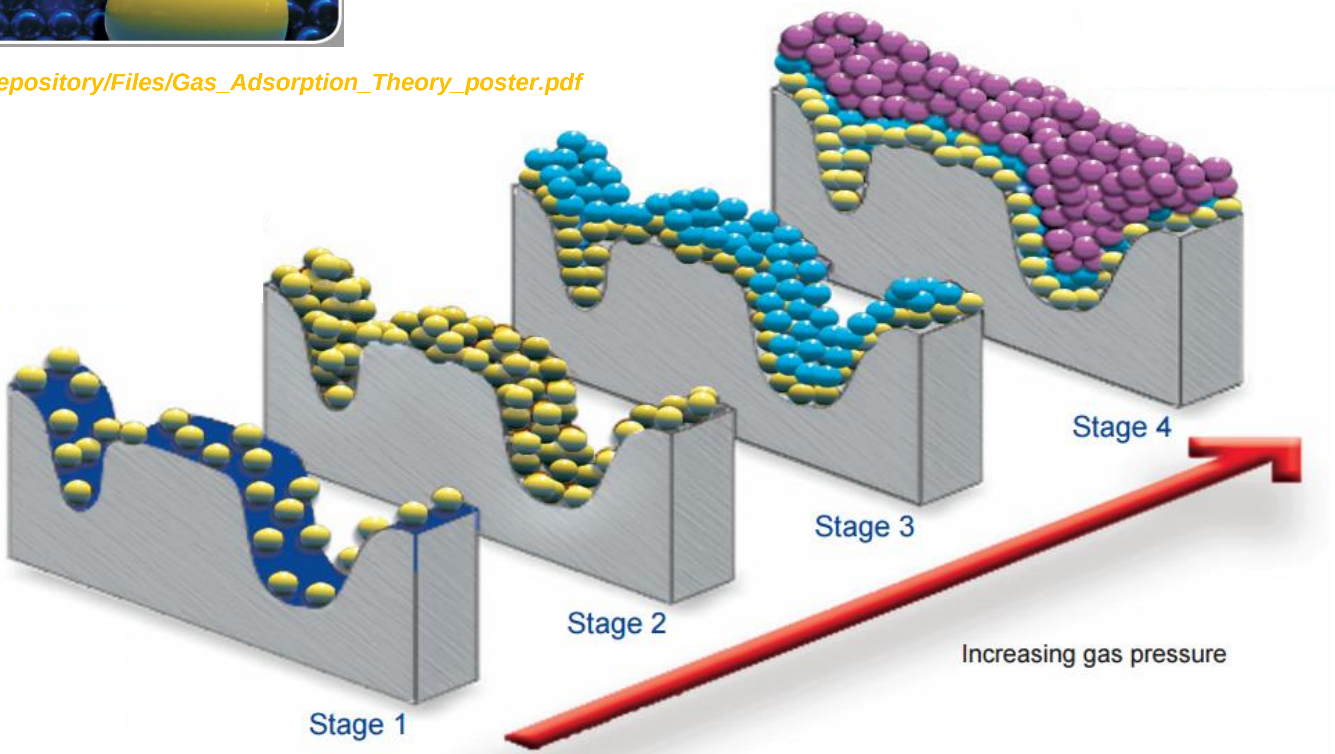
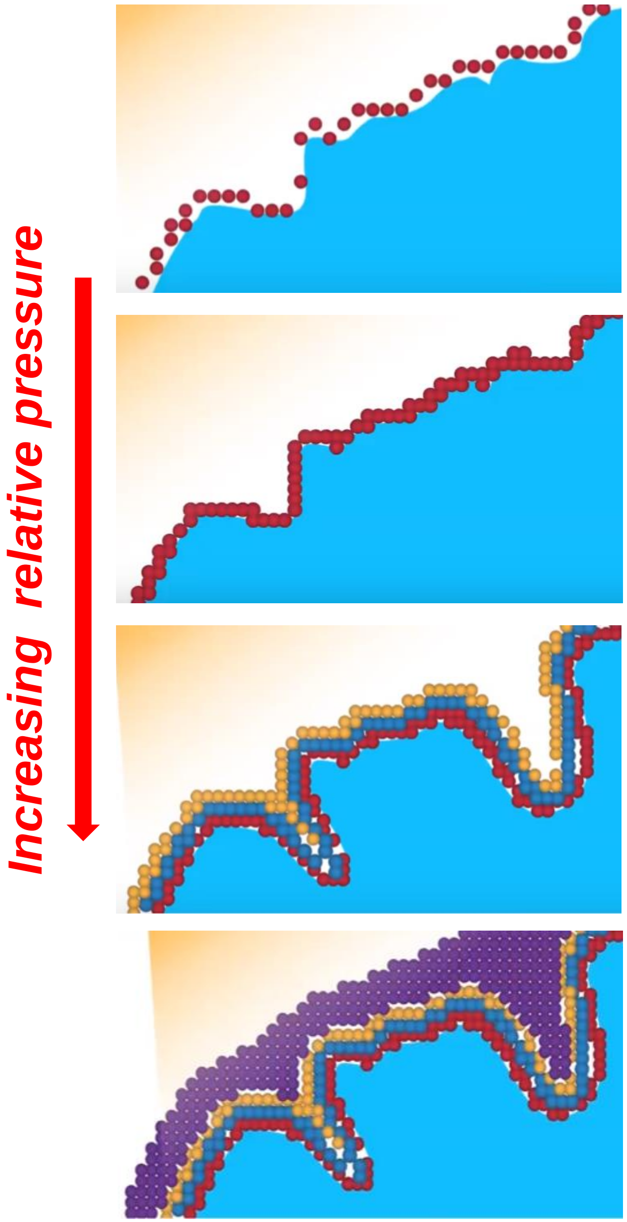
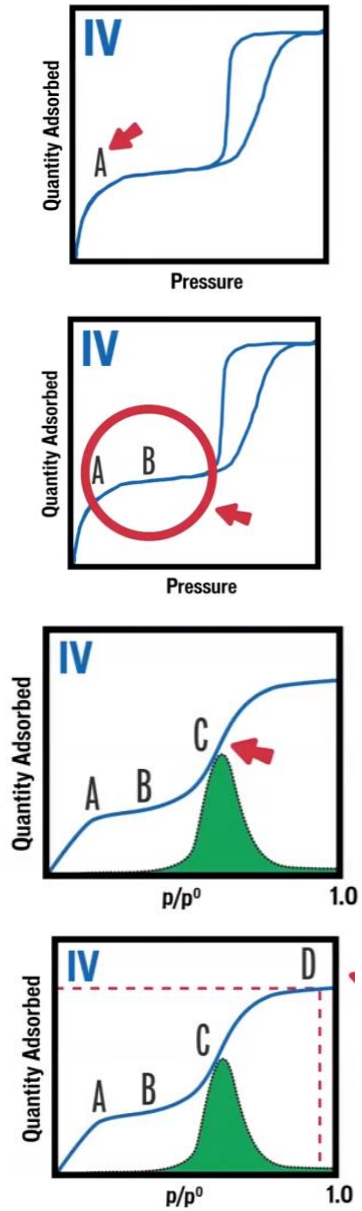


Introduction



AAPG-ES 2016



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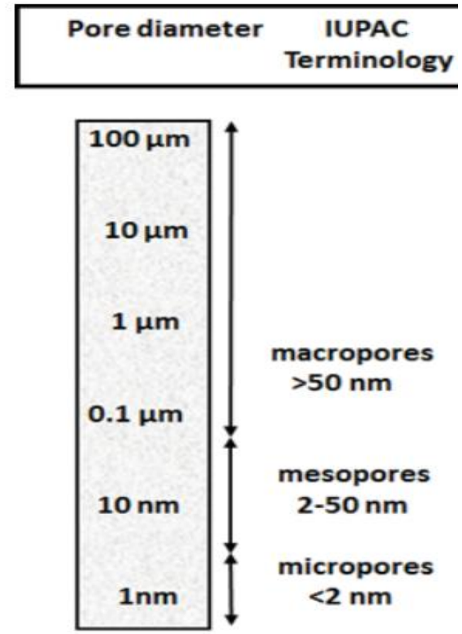

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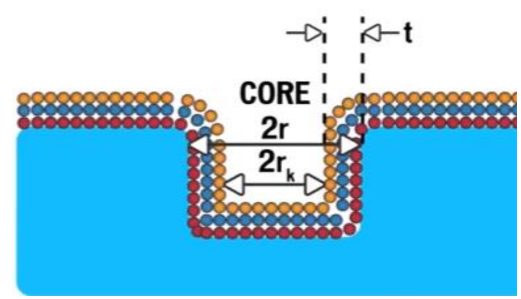
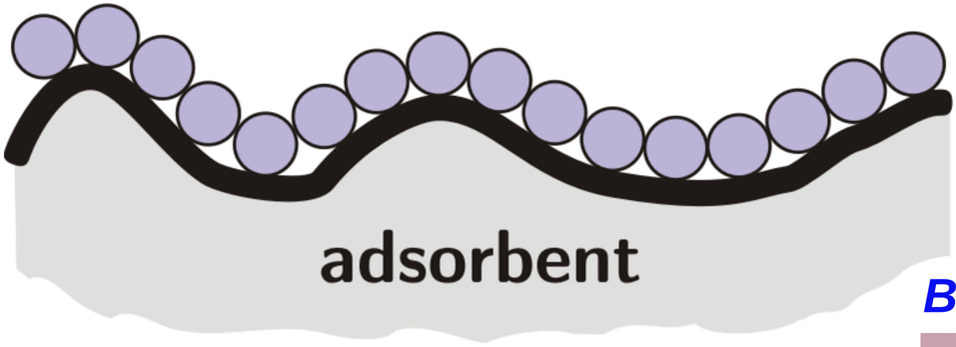


Misra

Introduction: Mono- vs Multi-Layer Adsorption

Langmuir Equation : Monolayer adsorption



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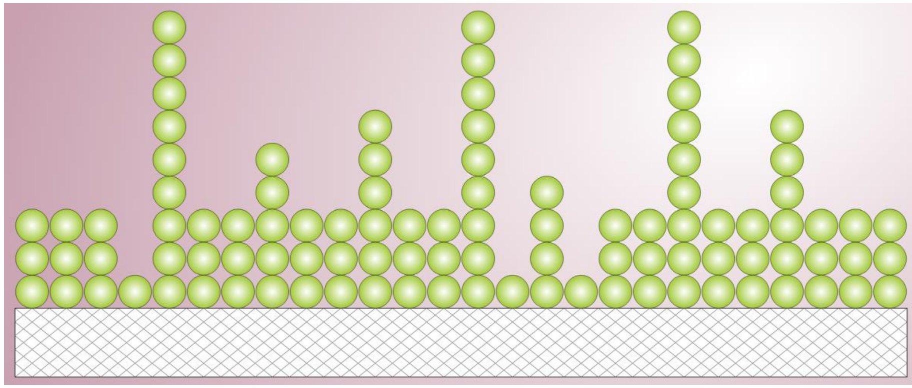
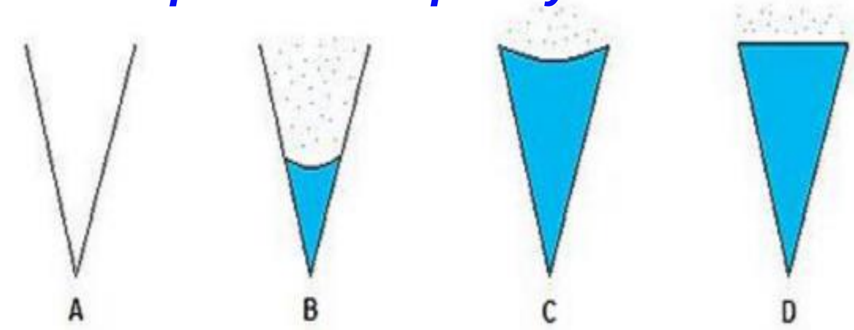
BET Equation : Multi-Layer Adsorption



https://en.wikipedia.org/wiki/BET_theory#/media/File:BET_Multilayer_Adsorption.svg

Kelvin Equation : Capillary Condensation

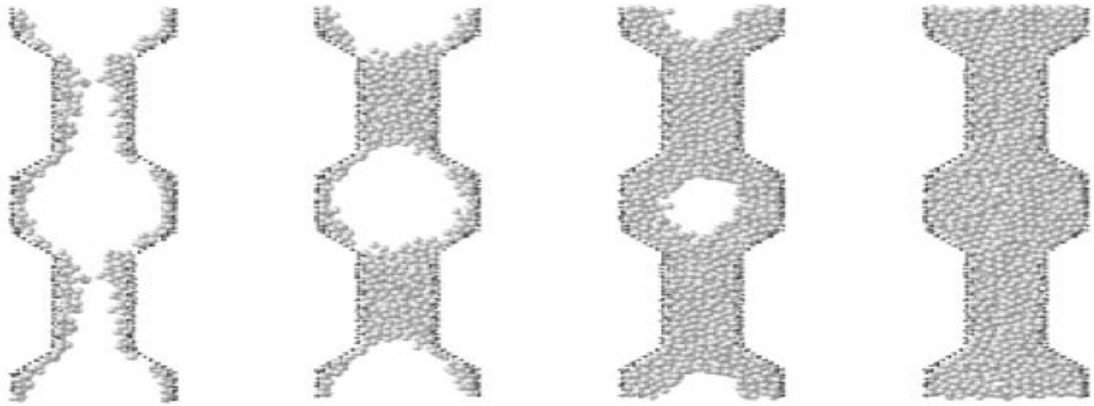


https://en.wikipedia.org/wiki/Capillary_condensation

Introduction: Adsorption vs Desorption

Adsorption of Argon atoms in 5 nm silica pore with 2.5 nm constriction

Coasne et al., 2005

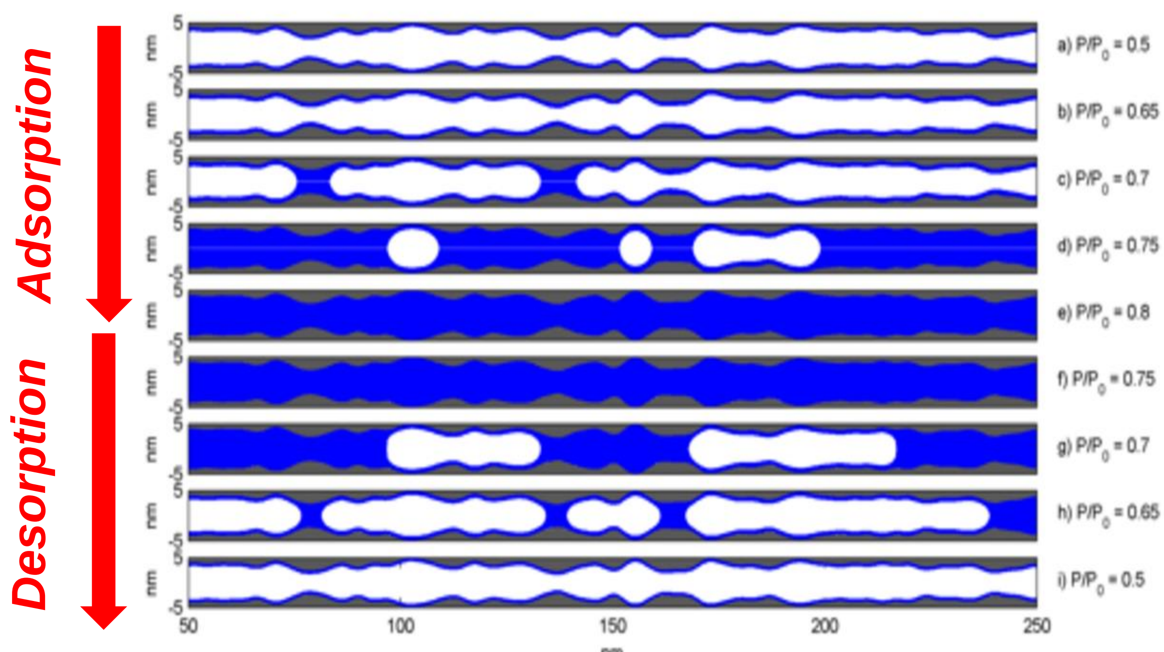


$P = 0.04P_0$ $P = 0.08P_0$ $P = 0.25P_0$ $P = 0.26P_0$

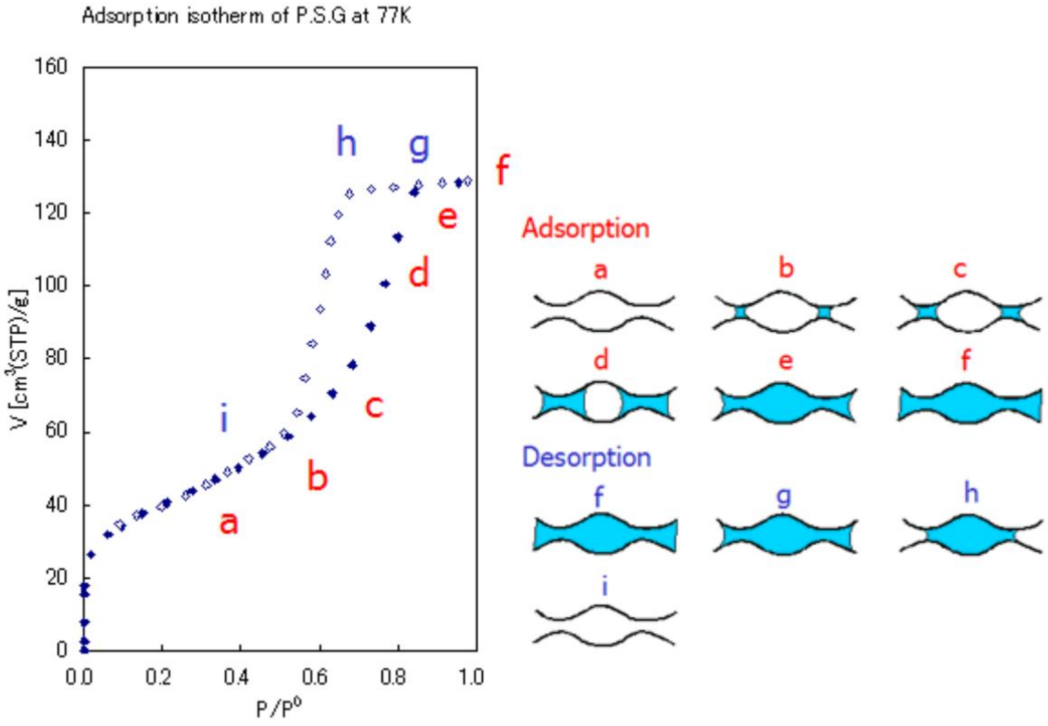
Increasing relative pressure

Configuration of adsorbate in a corrugated mesopore during adsorption and desorption

http://www.nce.ulg.ac.be/gommes/research.php



Introduction: Adsorption vs Desorption



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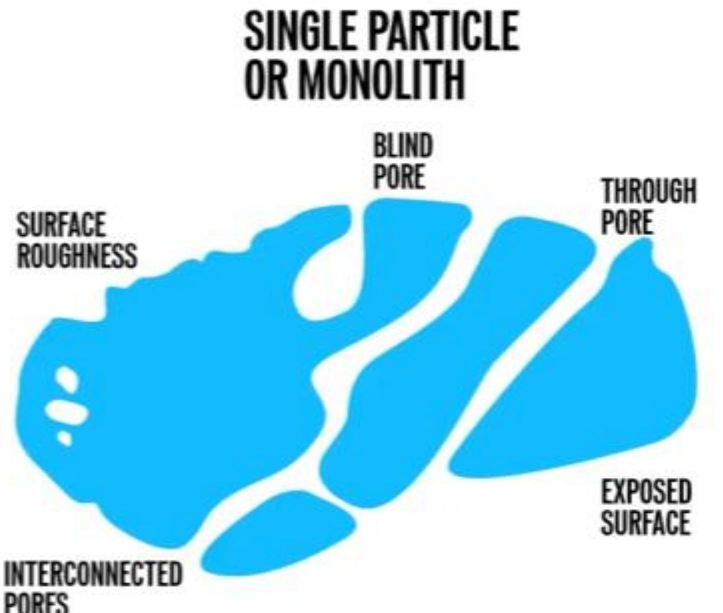

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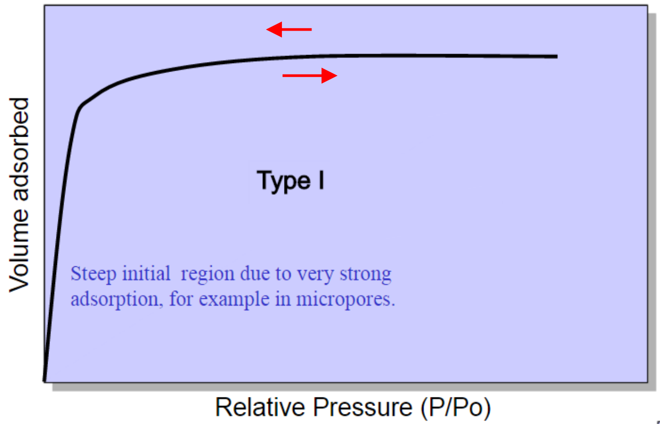
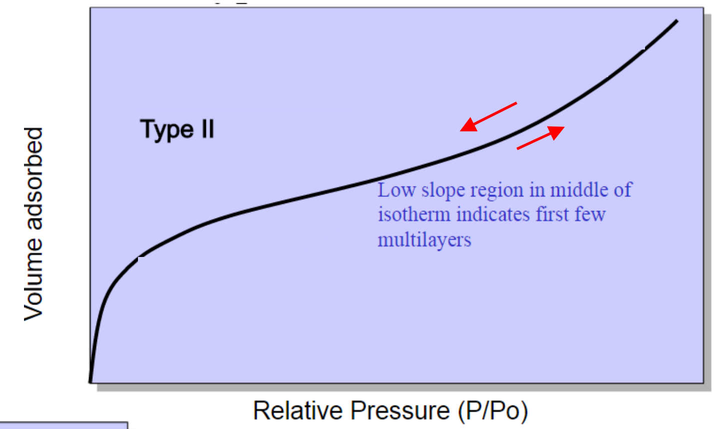
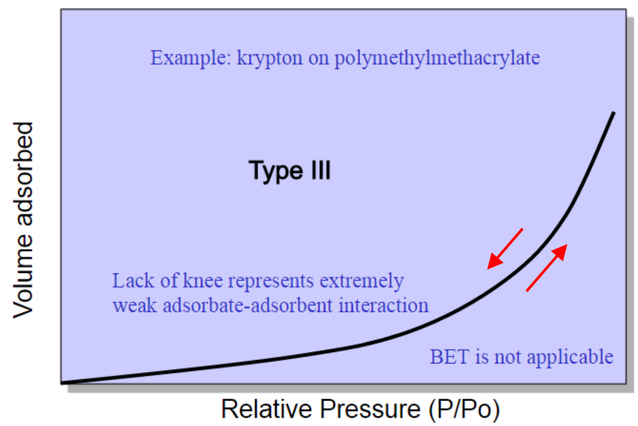
Introduction: Isotherm Types







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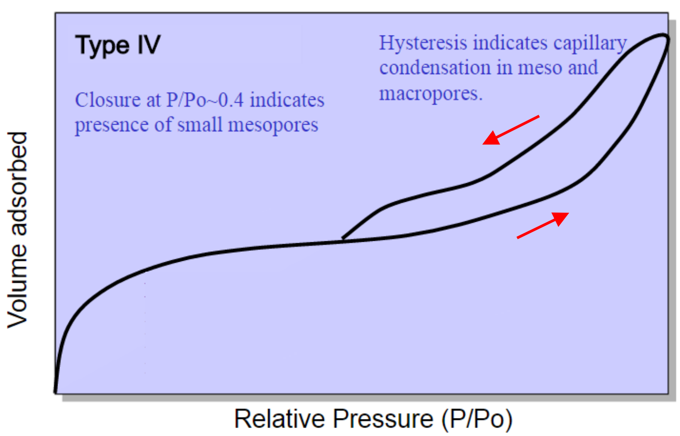
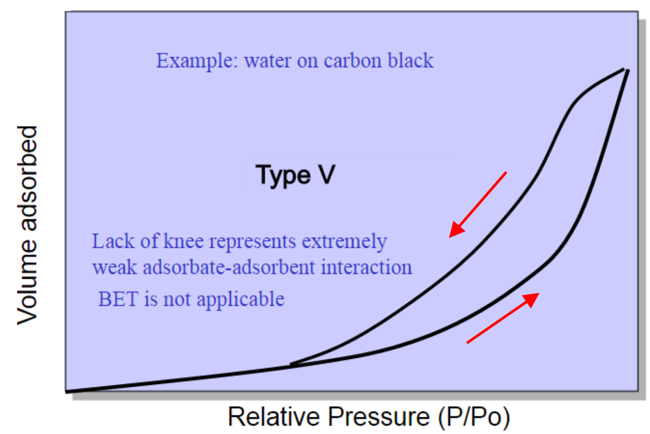
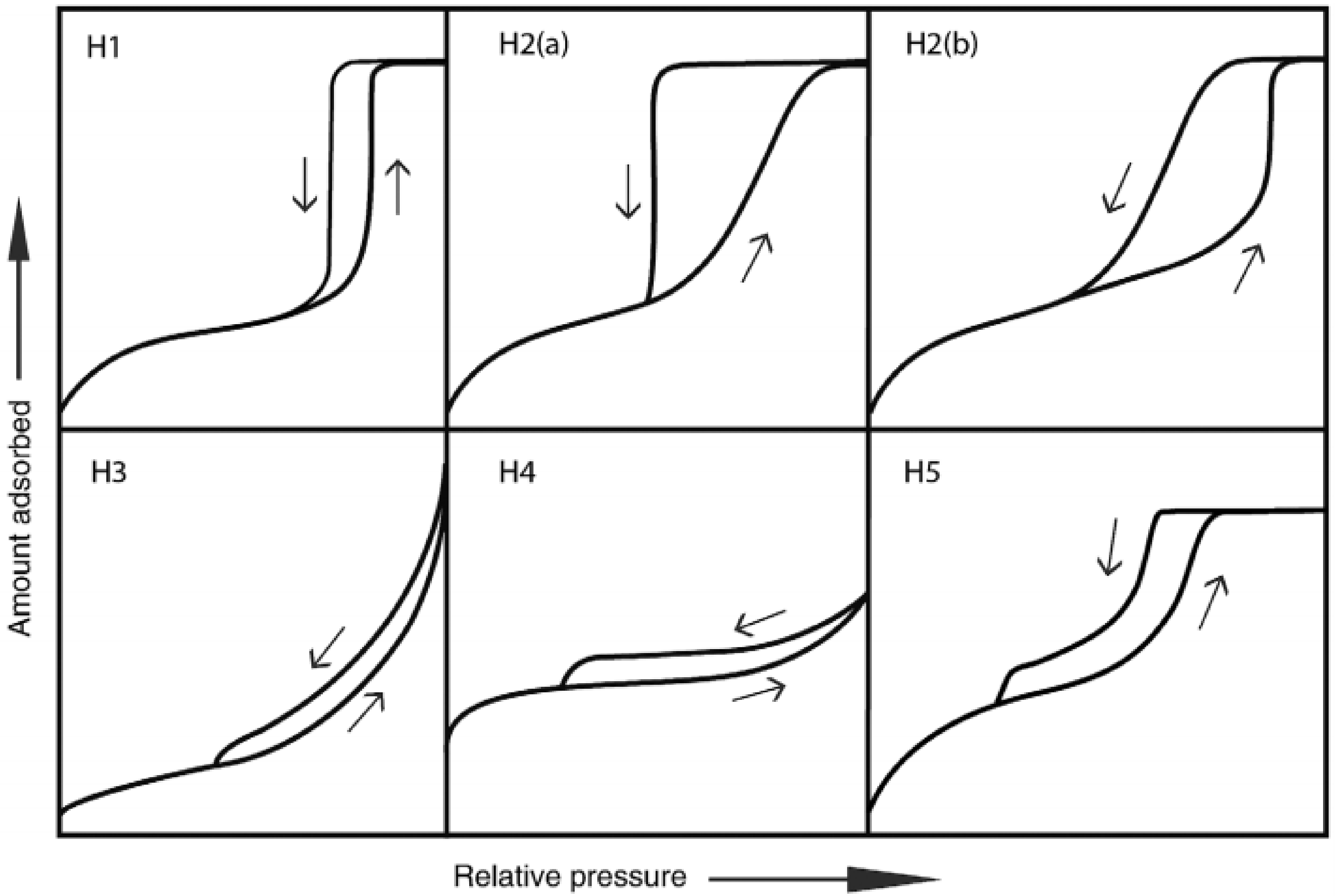




Introduction: Hysteresis Types

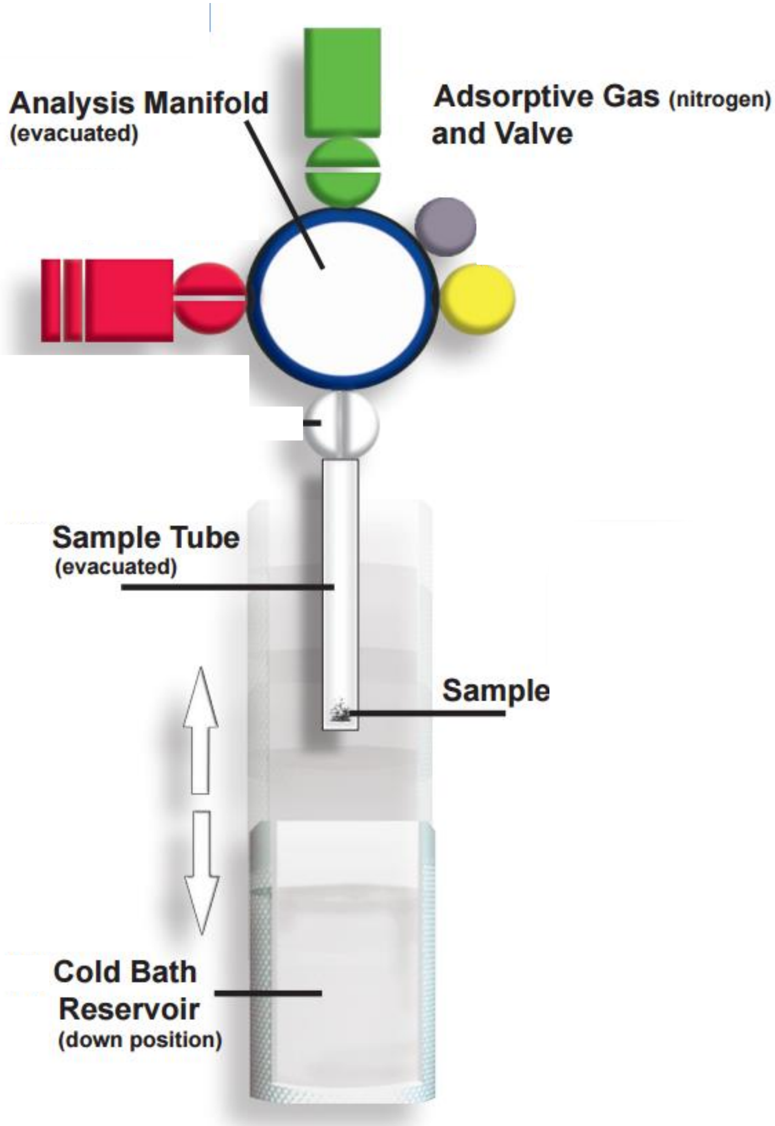


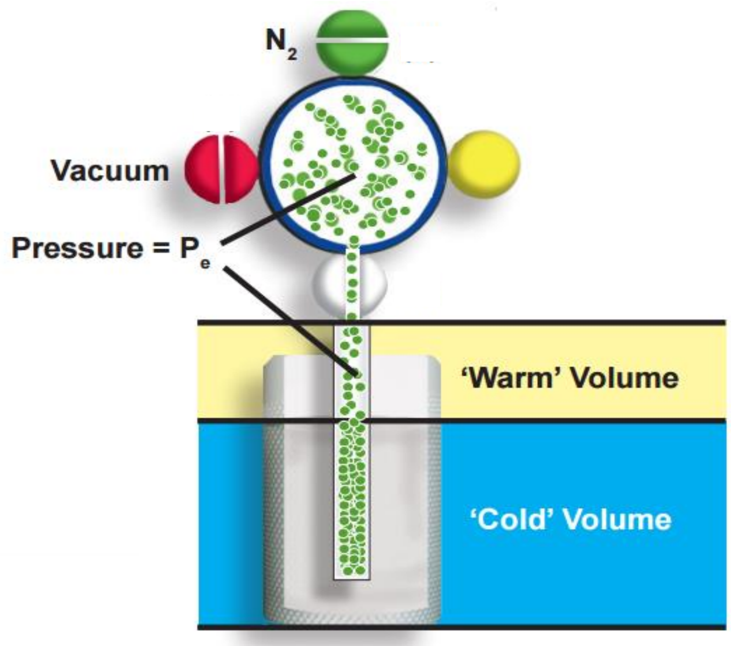
Motivation

- Identify permeability jail, decline in hydrocarbon production rate, and water production in low-permeability reservoirs
- Currently, there are limited direct/indirect laboratory-based techniques to measure or estimate relative permeability of shales
- Use laboratory adsorption-desorption measurement on shale samples to estimate pore-size distribution, pore connectivity, and relative permeability for pore size in the range of 7 nm to 200 nm
- Compare these estimates across oil , condensate, and gas windows of Eagle Ford shale and Wolfcamp shale
- Investigate the effects of organic matter on these estimates

Adsorption-Desorption Isotherm Measurements

Micromeritics ADI Apparatus





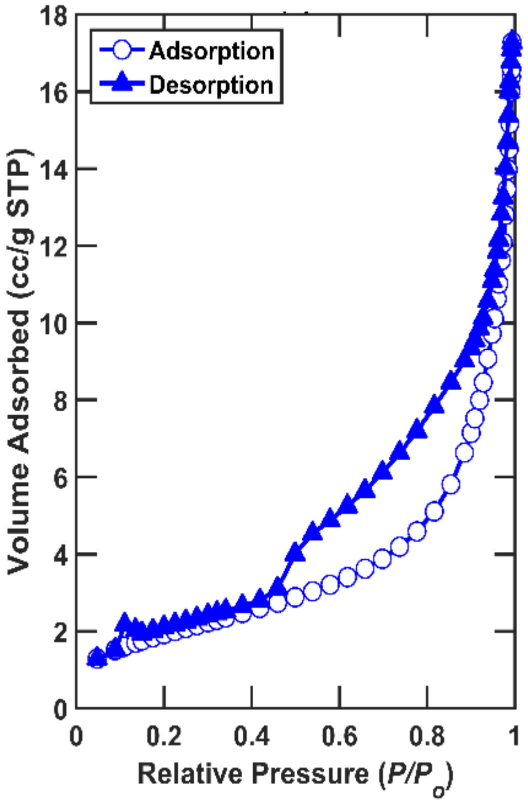
Adsorption-Desorption Isotherm Measurements

Rock Samples

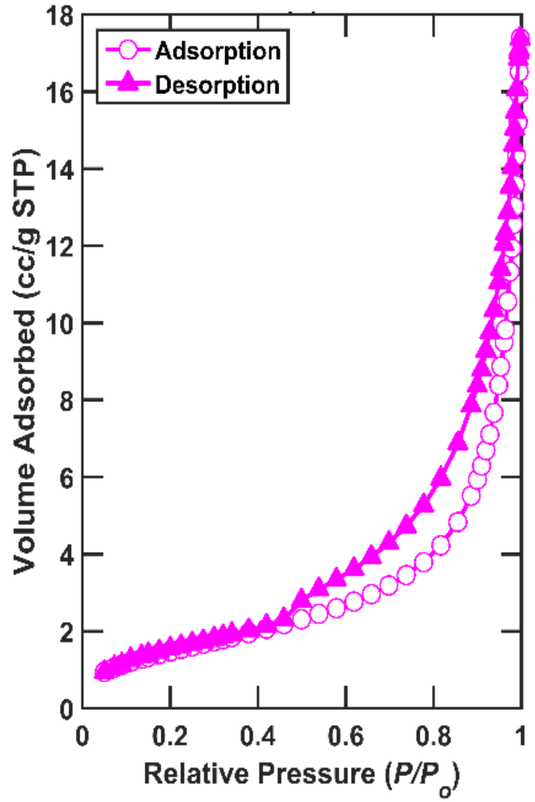
Formation	Maturity	Number of samples	TOC, wt%	Porosity, %	Clay, wt%	Non-clay, wt%
Wolfcamp	Condensate	8	0.2 – 15.5	4.49 – 11.52	44 – 70	10 – 30
Eagle Ford	Gas	9	0.4 – 3.3	4.27 – 8.33	10 – 20	60 – 80
	Oil	6	1.5 – 4.9	7.65 – 10.22		

Adsorption-Desorption Isotherm Measurements

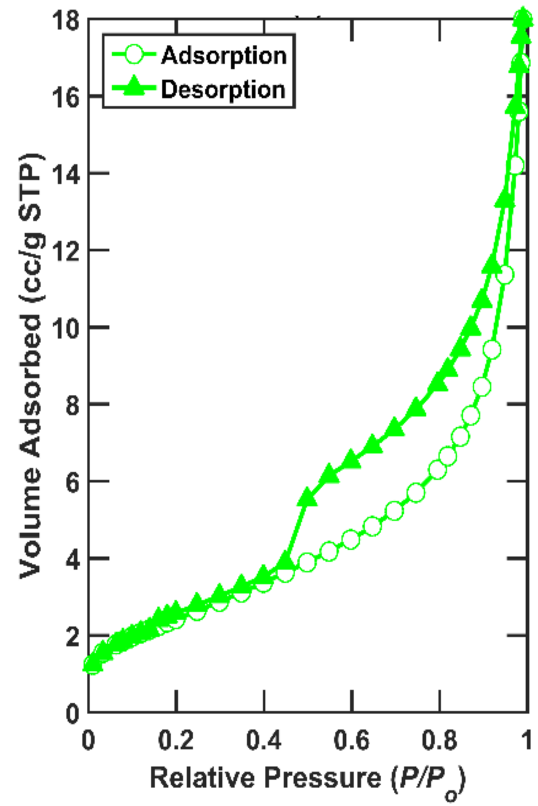
Comparison across various windows



Eagle Ford Gas-Window Sample



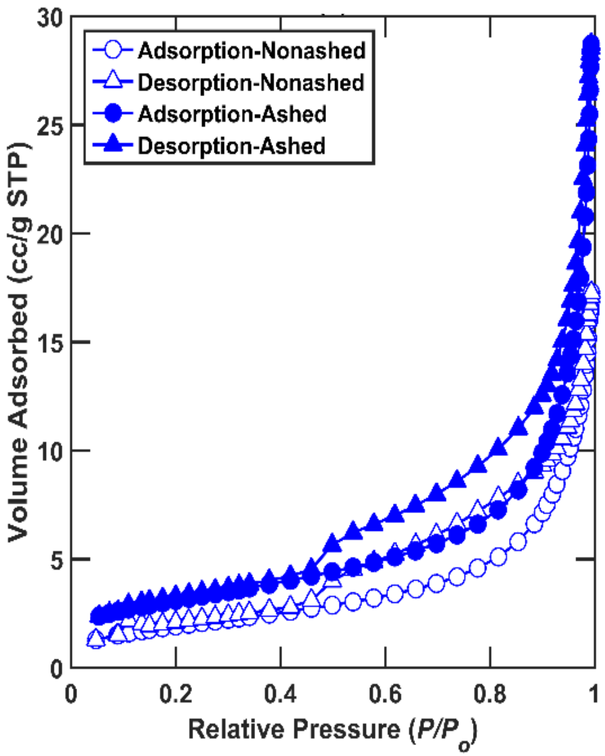
Eagle Ford Oil-Window Sample



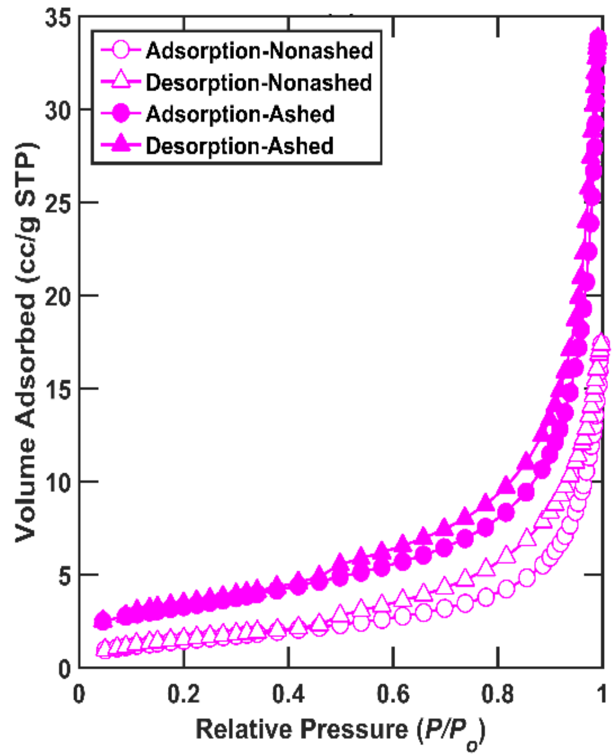
Wolfcamp Condensate-Window Sample

Adsorption-Desorption Isotherm Measurements

Effect of removal of organic matter

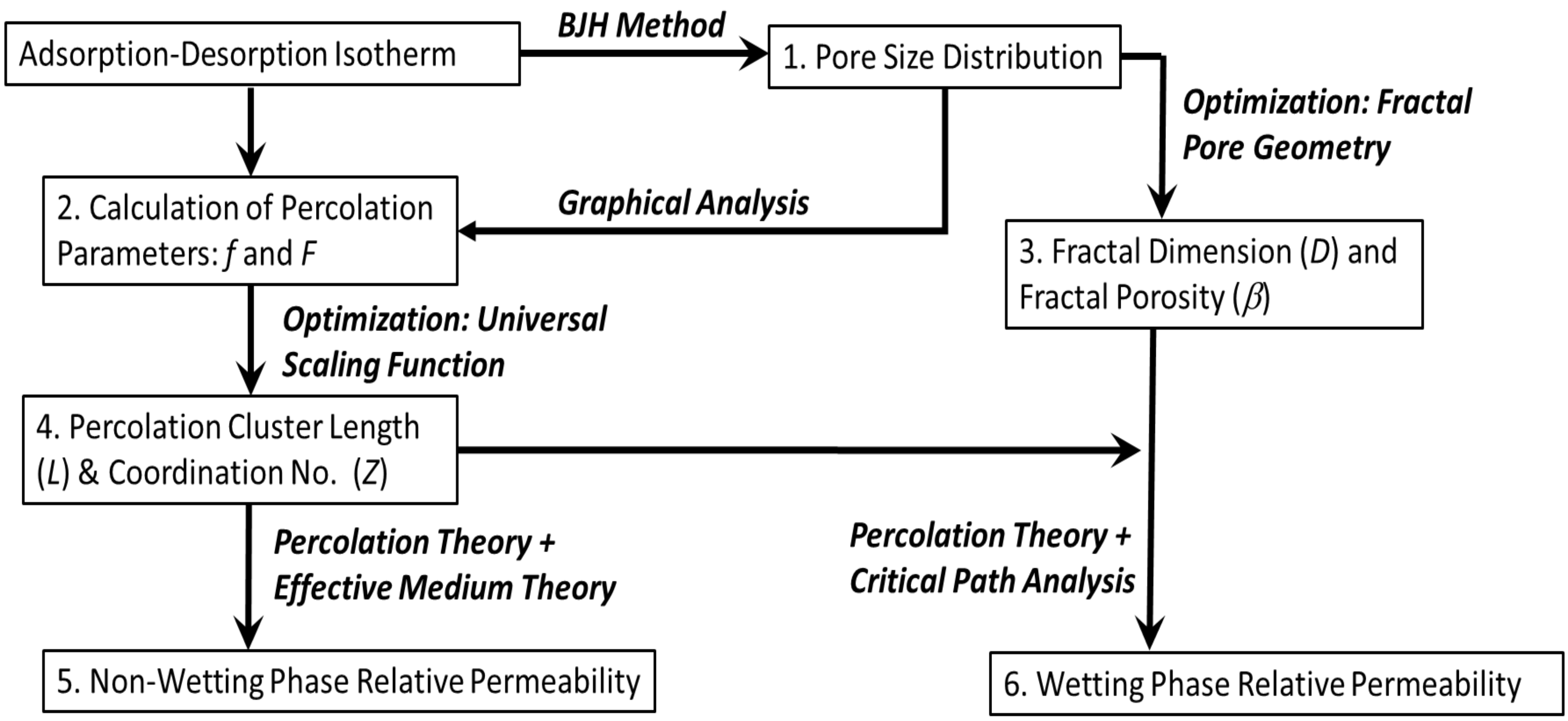


Eagle Ford
Gas-Window Sample



Eagle Ford
Oil-Window Sample

Interpretation Methodology



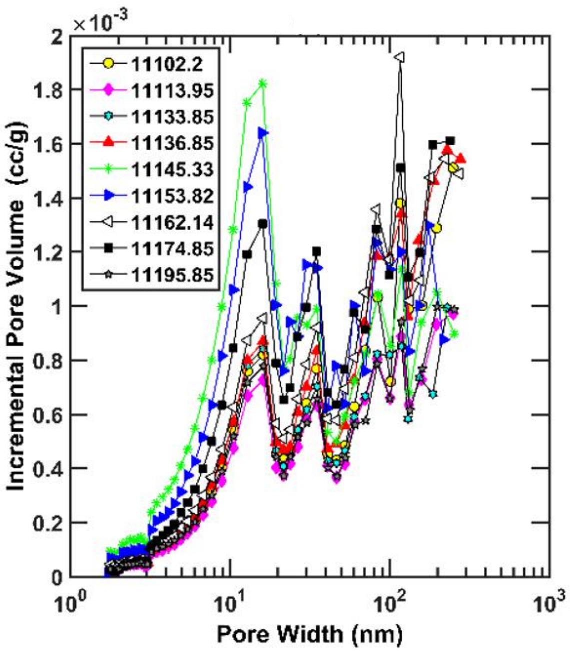
Results: Pore Size Distribution

Thickness of adsorbed layer

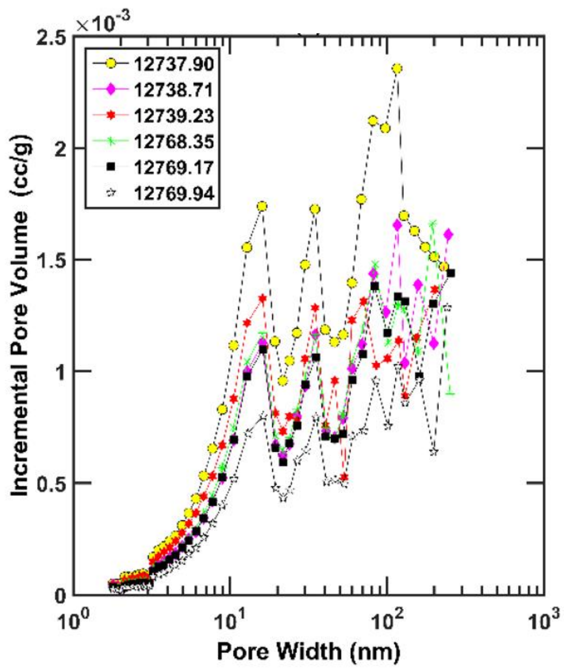
$$t = 0.1\left(\frac{60.65}{0.03071 - \log\left(\frac{P}{P_o}\right)}\right)^{0.3968}$$

Pore radius in which condensation occurs

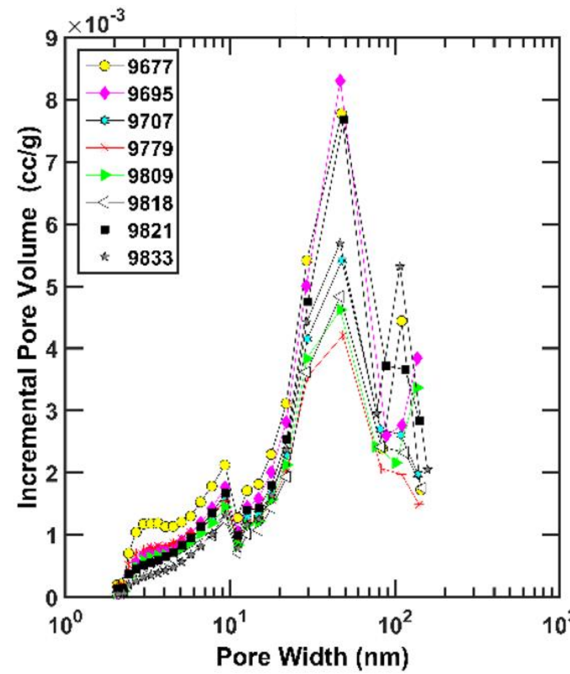
$$r = \left(\frac{2\gamma V_L}{RT\ln\left(\frac{P}{P_o}\right)}\right) + t + 0.3$$



Eagle Ford Gas-Window Sample



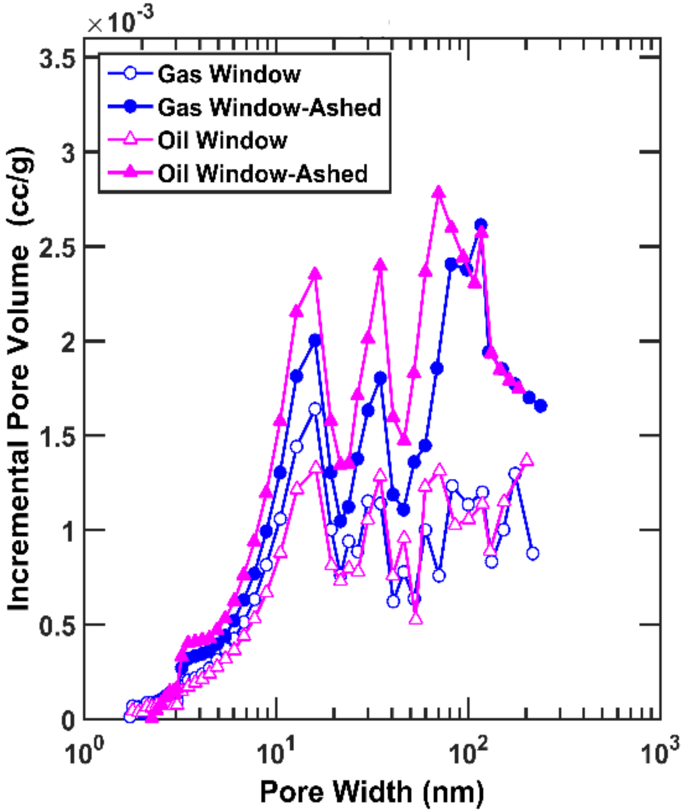
Eagle Ford Oil-Window Sample

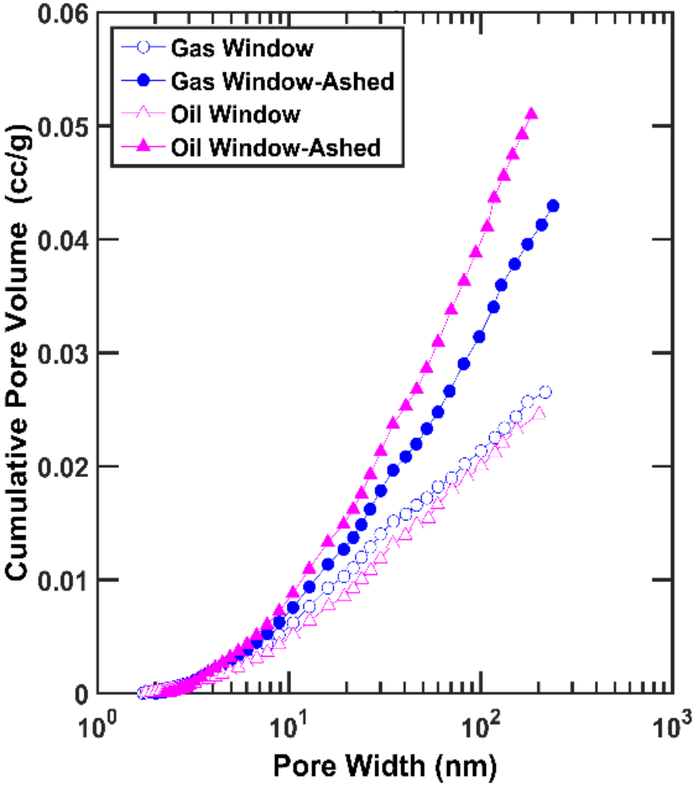


Wolfcamp Condensate-Window Sample

Results: Pore Size Distribution

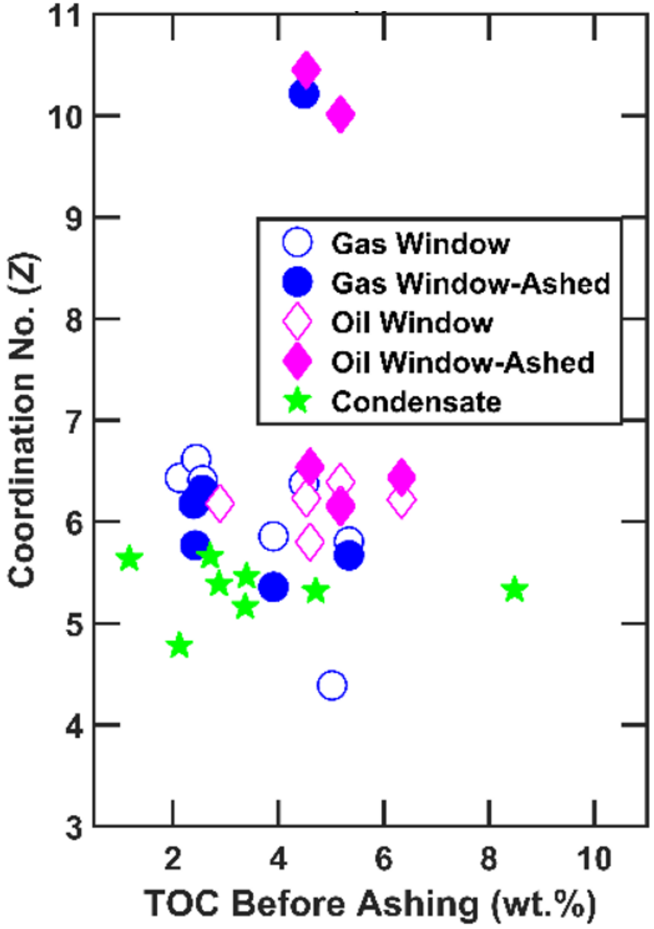
Effect of removal of organic matter



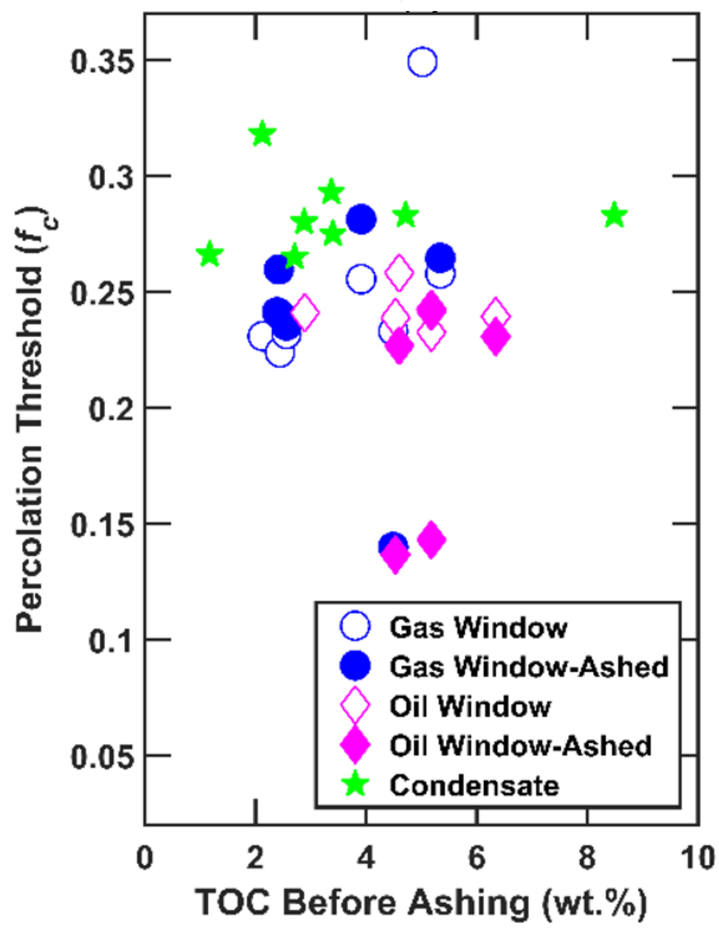


Eagle Ford Samples

Results: Pore Connectivity

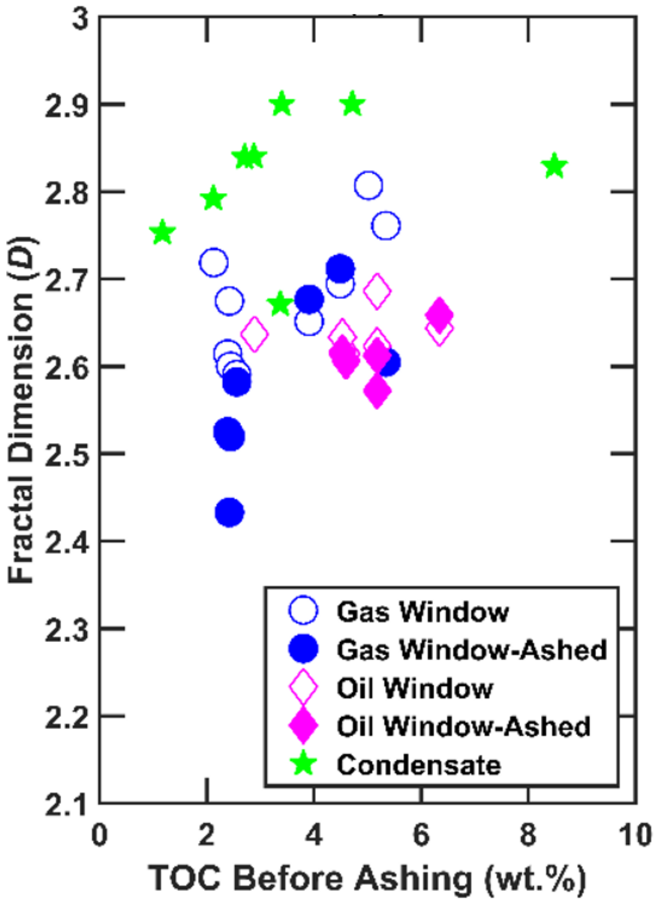


Short-Range Pore Connectivity

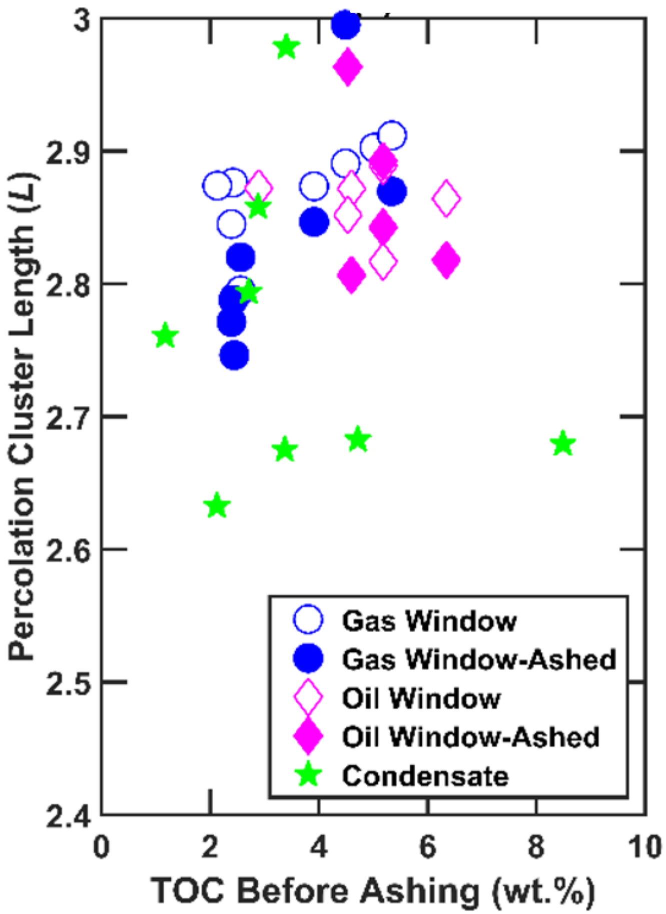


Long-Range Pore Connectivity

Results: Pore Complexity

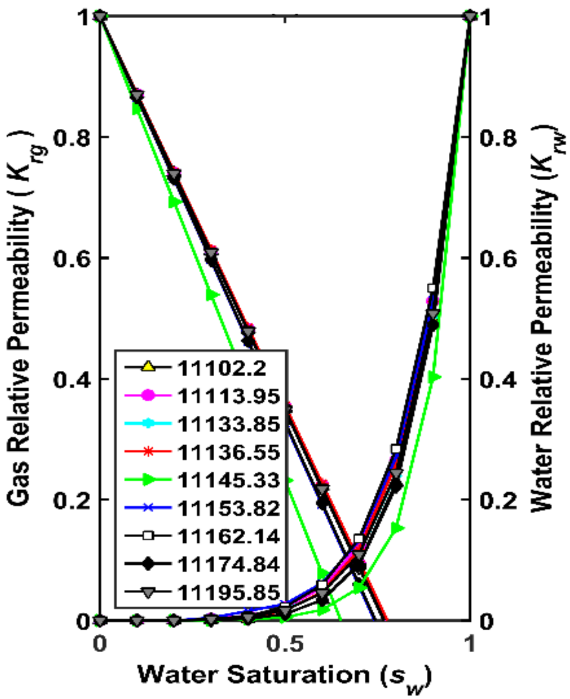


Pore Complexity

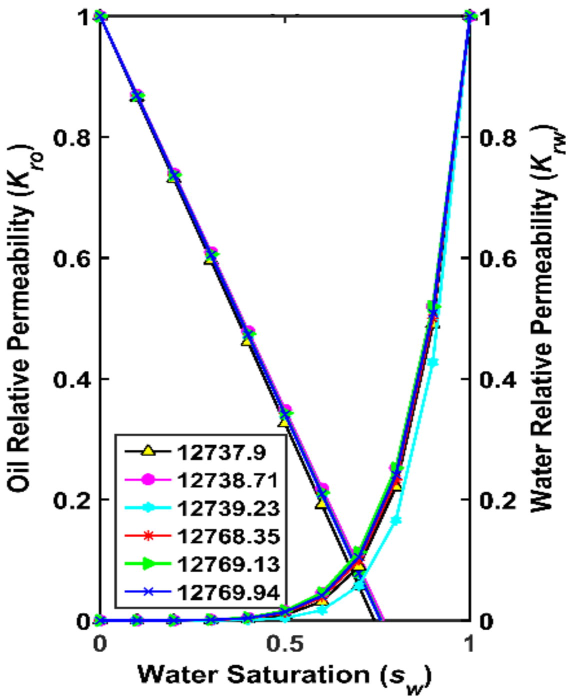


Dead end vs connected pores

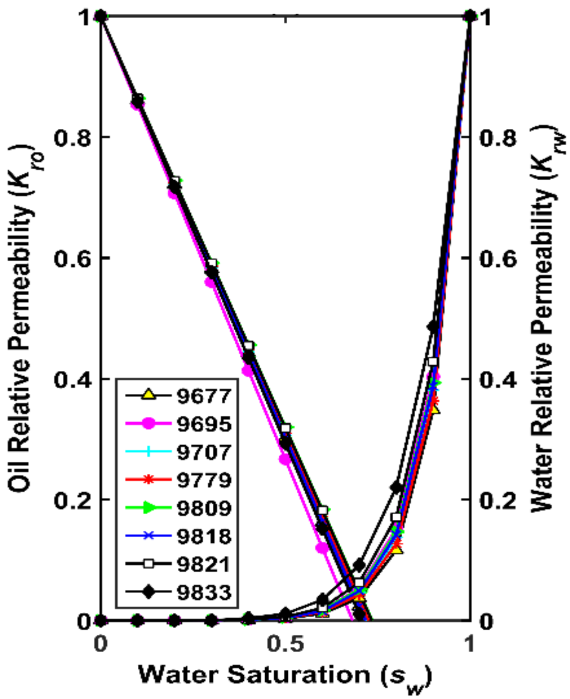
Results: Relative Permeability



Eagle Ford
Gas-Window Sample

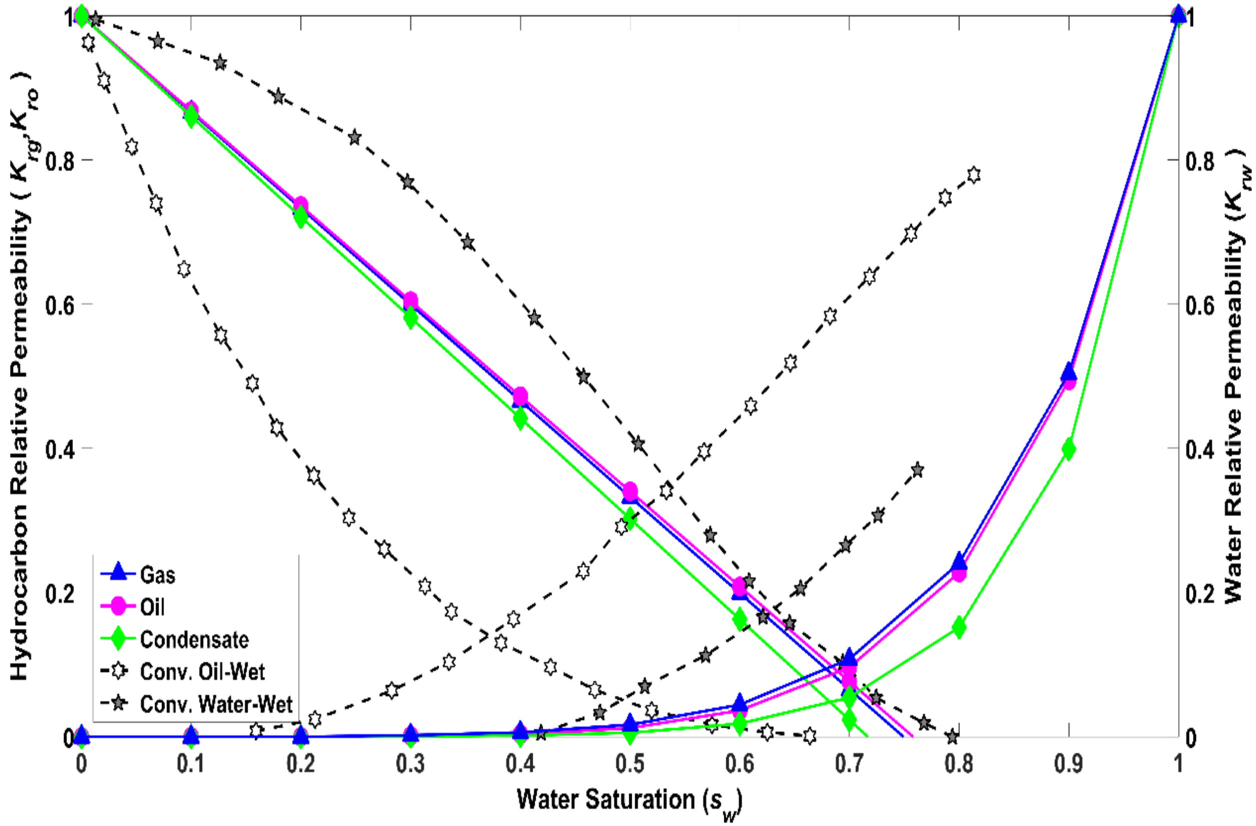


Eagle Ford
Oil-Window Sample



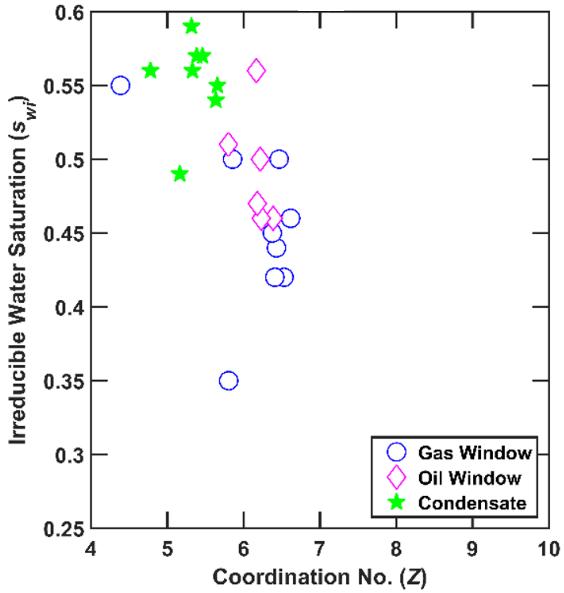
Wolfcamp Condensate-
Window Sample

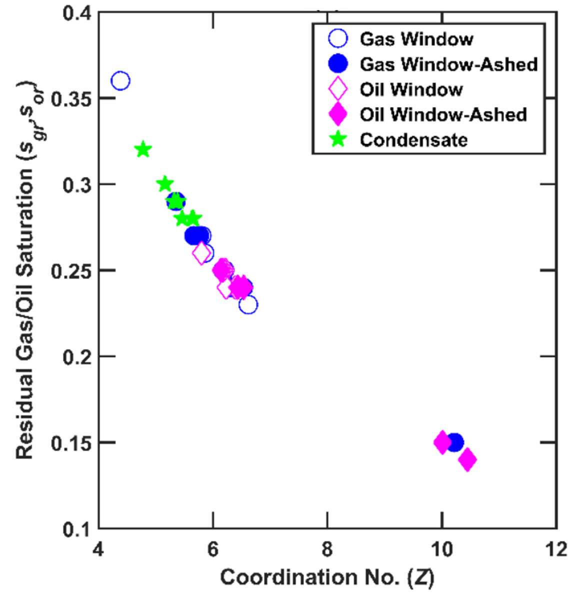
Results: Relative Permeability

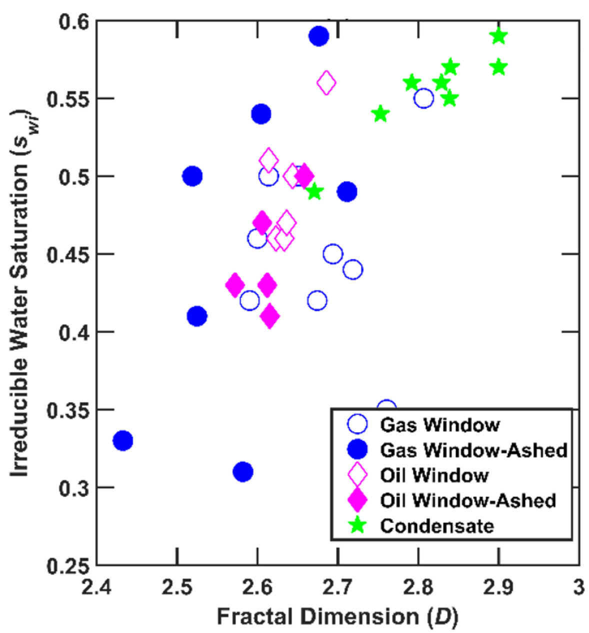


	Non-Ashed			Ashed	
	Eagle Ford Gas	Eagle Ford Oil	Wolfcamp Condensate	Eagle Ford Gas	Eagle Ford Oil
s_{gr} / s_{or}	0.23-0.36	0.24-0.26	0.28-0.32	0.15-0.29	0.14-0.26
s_{wi}	0.35-0.55	0.46-0.56	0.49-0.59	0.31-0.59	0.41-0.5

Results: Residual Saturations







Conclusions

- Relative permeability curves exhibit minimal variation with depth
- Samples exhibit large variations in kerogen content, pore connectivity, range of connected pore network, pore complexity, and saturations
- Relative permeability estimates support the low water-cut during hydrocarbon production, absence of correlation between hydrocarbon production decline and increase in water production, and existence of permeability jail in shale formations
- Our interpretation methodology indicates that Eagle Ford samples will have better flow capacity compared to Wolfcamp samples

Thank You