Evaluating Production Performance of Permian Basin Wells to Improve Hydrocarbon Recovery

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COLORADO SCHOOL OF MINES MUDTOC

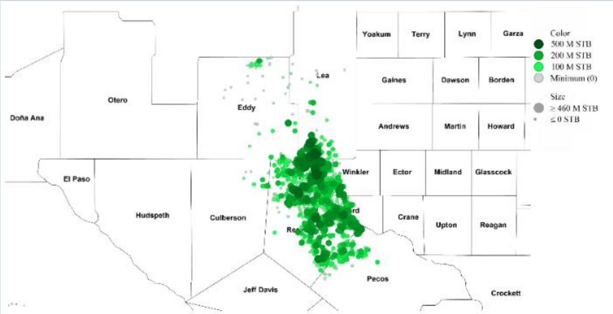
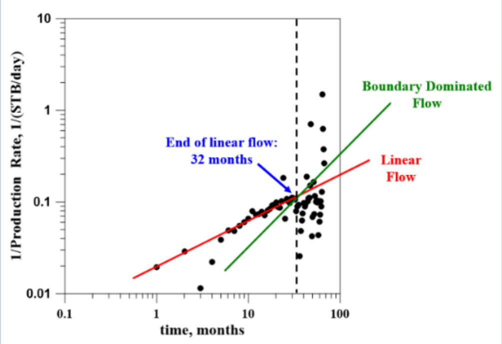
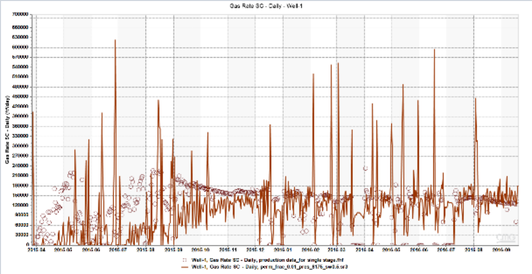
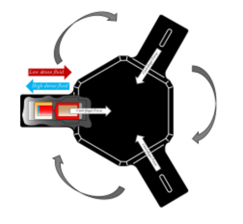
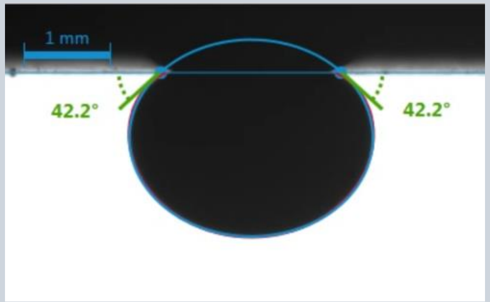
Drivers and Motivation

- **Permian Basin** is the most prolific oil and gas producing geologic basins in the United Sates—spanning West Texas and Southeastern New Mexico. It has produced more than 33.4 Bbbl of oil and 118 Tcf of natural gas during a 100-year period (EIA 2018).

- The ever-increasing water production and usage in the Permian Basin is a major issue and continues to require attention.

- Classical waterflooding in unconventional reservoirs is not plausible because of the small pore size and low permeability of the mudstone matrix. A practical alternative is cyclic gas injection.

Project Plan

Phase 1:	Phase 2:	Phase 3:
• Determine production characteristics of Delaware Basin wells • Plan for several innovative EOR experiments  	• Build an appropriate numerical model to forecast future performance • Prepare for the EOR experiments   	• Conduct EOR experiments • Characterize field performance using numerical model (history match production data) • Automated interpreation  

Reservoir Properties

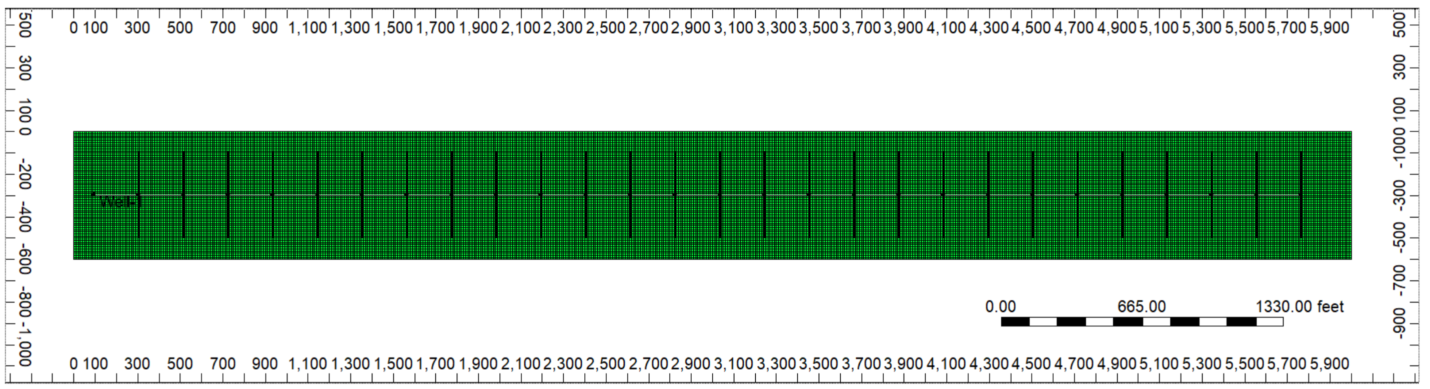
• Gross thickness:	600 ft
• Initial res pressure:	8175 psia
• Reservoir temp:	181.5 °F
• Porosity:	0.06
• Matrix permeability:	0.0003 mD
• Matrix pore compressibility:	1×10^{-5} psia^{-1}

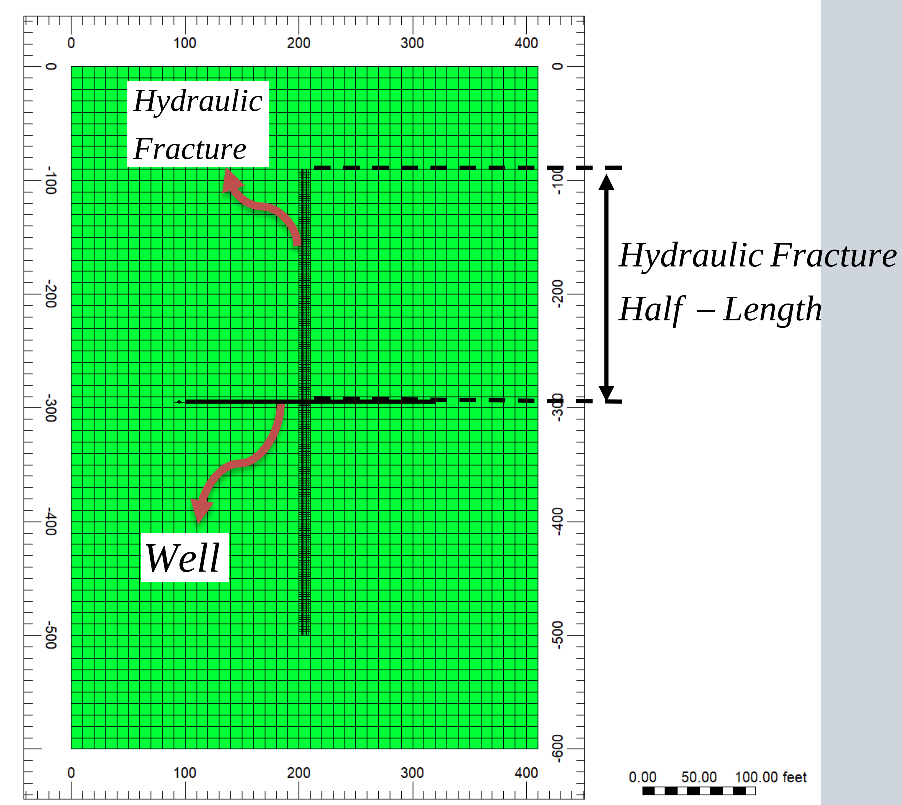
Numerical Model Grid Structure

- IMAX : 600
- JMAX : 60
- KMAX : 60

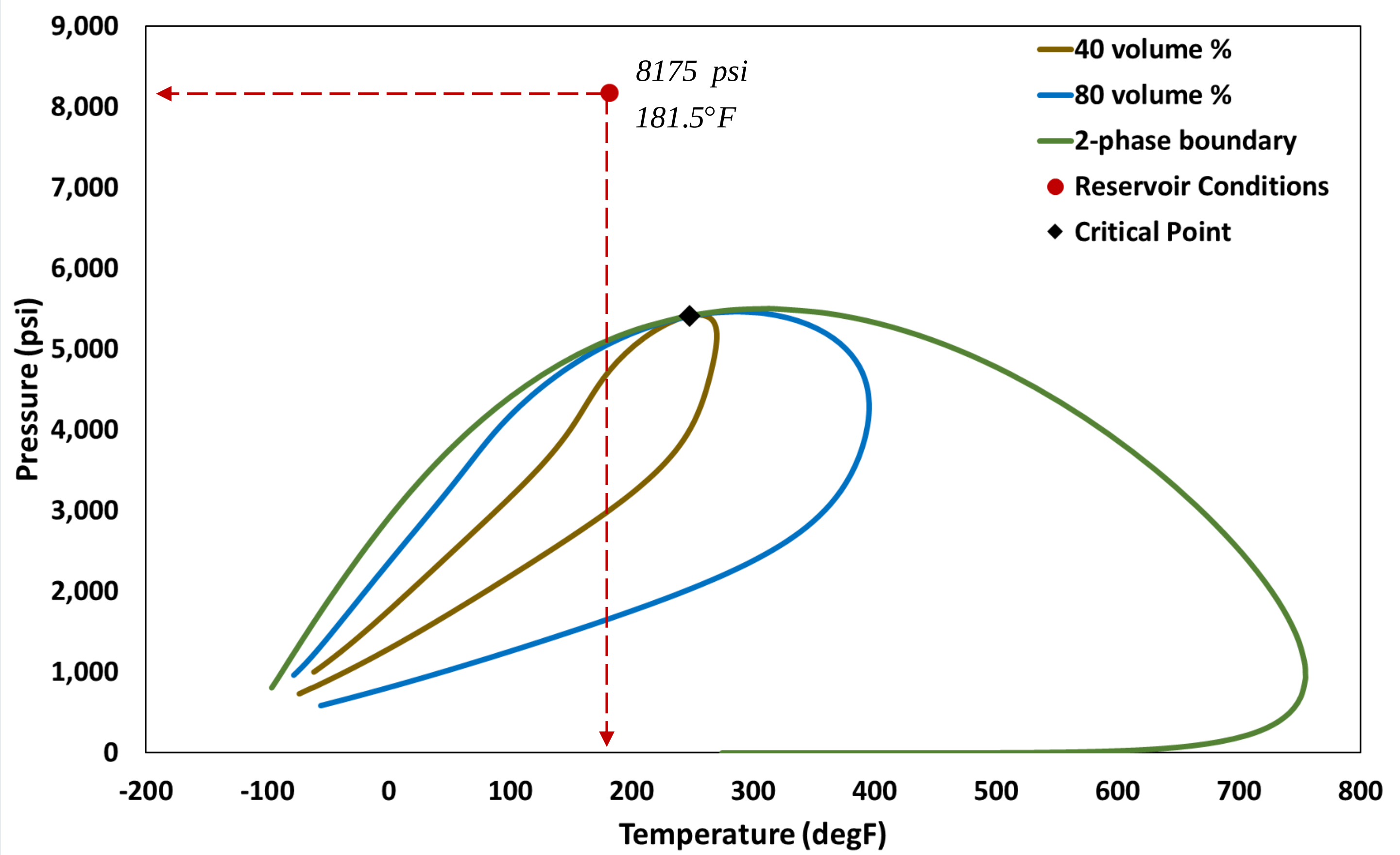
Δx : 10 ft
Δy : 10 ft
Δz : 10 ft

27 HF stages





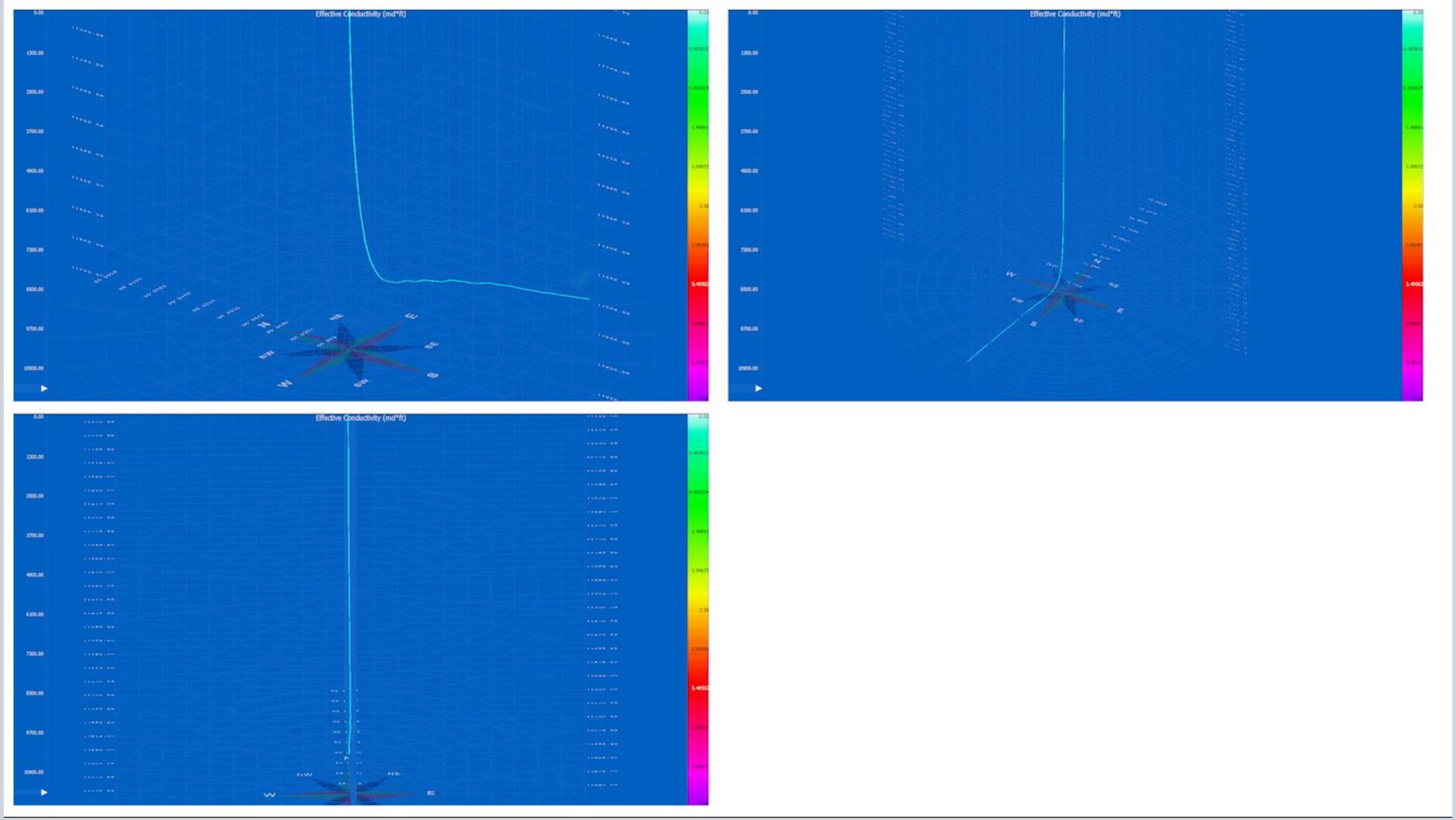
Hydrocarbon Fluid Model



Component	Mole Percent
N_2 to CO_2	0.9
CH_4	67.59
C_2H_6	9.24
C_3H_8	5.51
IC_4 - NC_4	2.79
IC_5 - FC_6	2.31
FC_7 - FC_{10}	5.62
FC_{11} - C_{15}	2.98
FC_{16} - C_{22}	1.69
FC_{23} - C_{30+}	1.35

GOHFER Hydraulic Fracture Model

COLORADO SCHOOL OF MINES MUDTOC

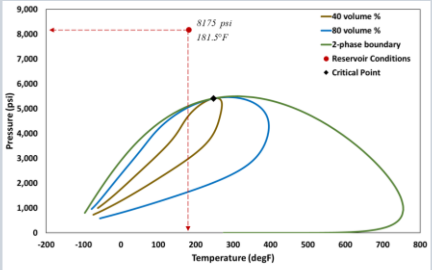


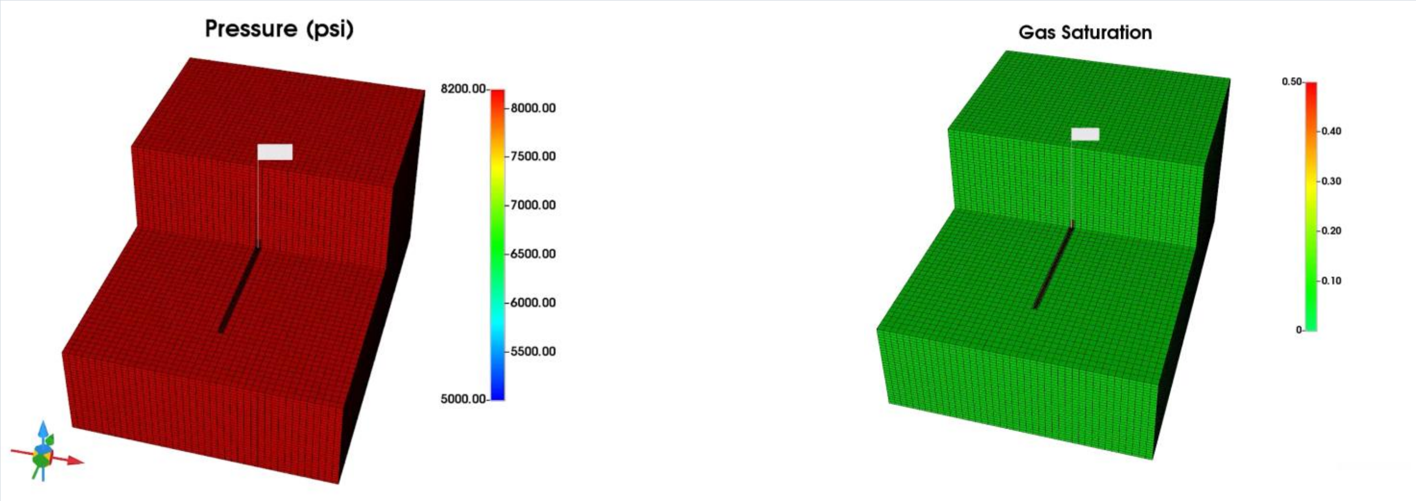
GOHFER Hydraulic Fracture Model Results

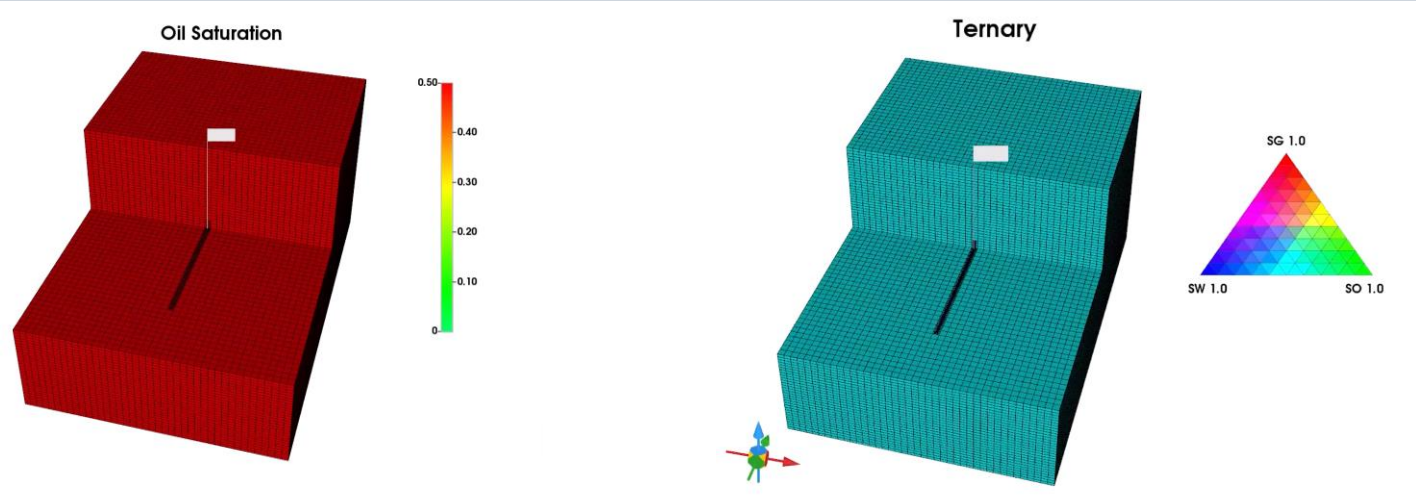
COLORADO SCHOOL OF MINES MUDTOC

INPUT PARAMETERS	Number of Stages	27
	Cluster per stage	4
	Stage Length (ft)	212
	Cluster Spacing (ft)	52
	Total Perforation shot per stage	24
	Perforation Diameter (in)	0.54/0.46
OUTPUT PARAMETERS	Average Proppant Concentration (lb/ft^2)	0.24
	Average Fracture Width (in)	0.32
	Proppant Cutoff Length (ft)	350.34
	Estimated Flowing Fracture Length (ft)	27.34
	Fracture Height (ft)	48.41
	Average Effective Conductivity (mD.ft)	0.78

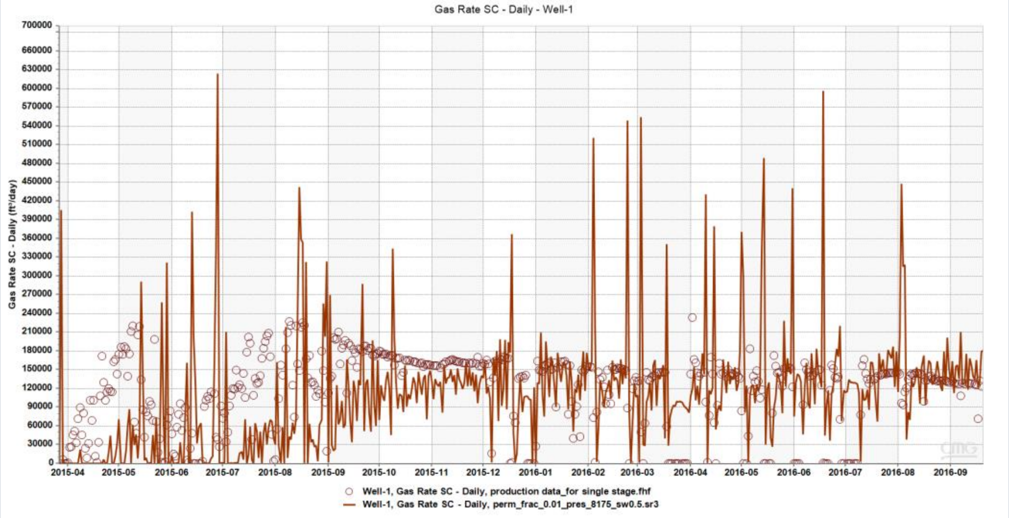
CMG Model (GEM) History Match Results

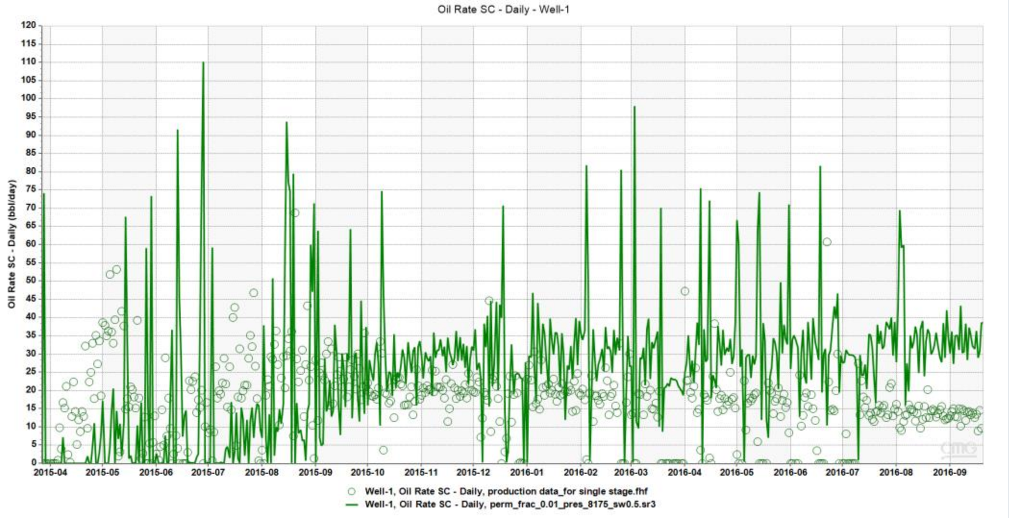


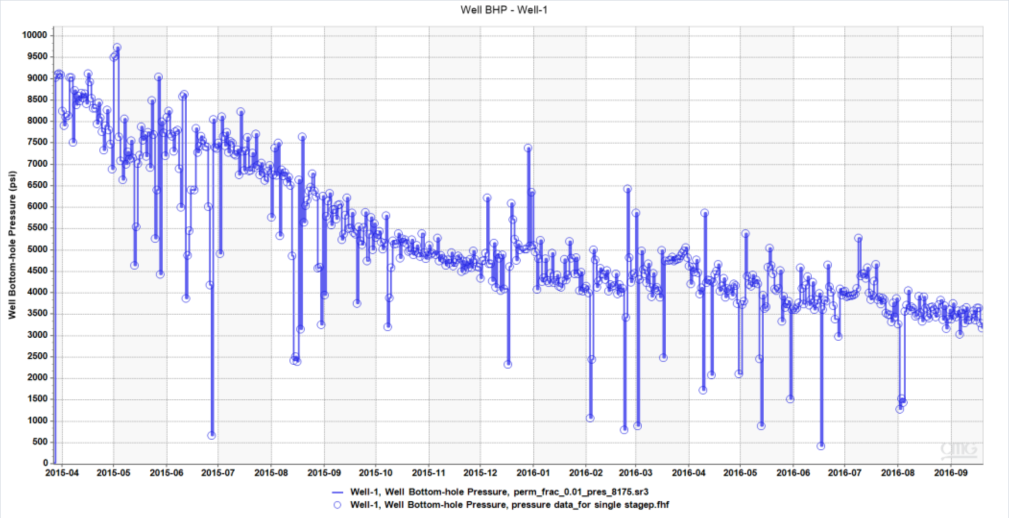




CMG Model History Match Results





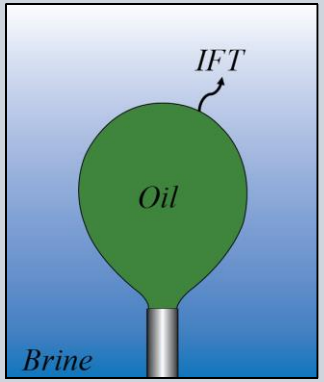


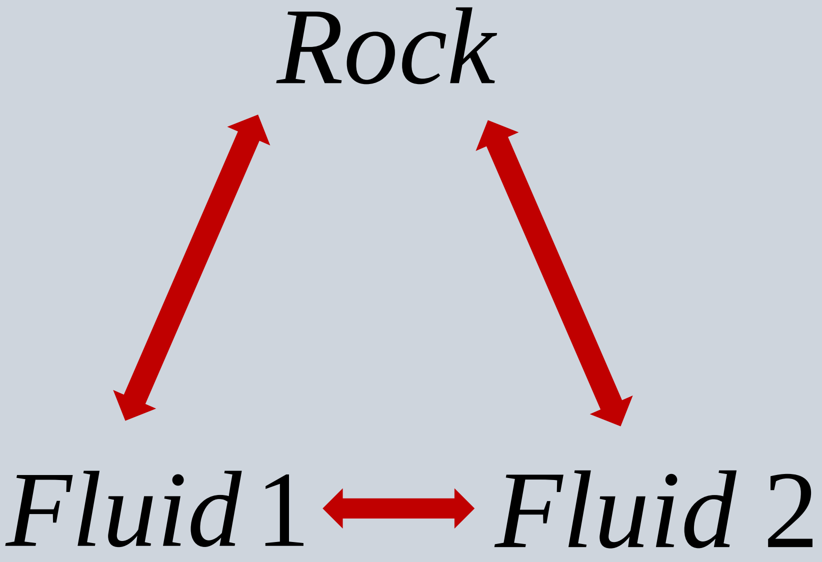
Experimental data is required to tune the history matching

Fluid- Rock Interactions

Fluid-Fluid Interactions

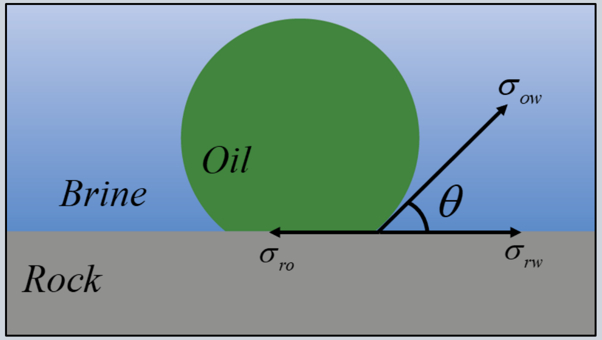
IFT: **The force of attraction between the molecules at the interface of two fluids.**





Fluid-Rock Interactions

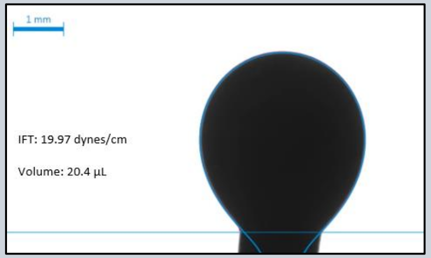
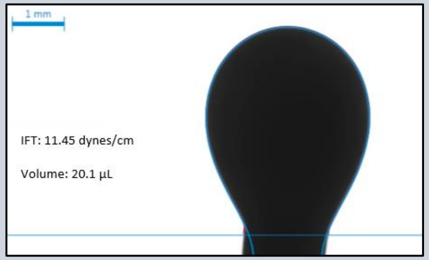
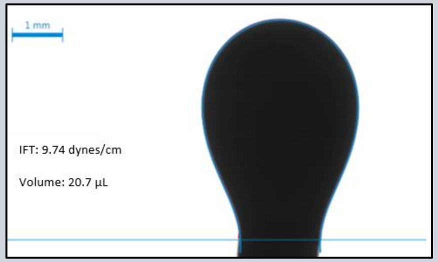
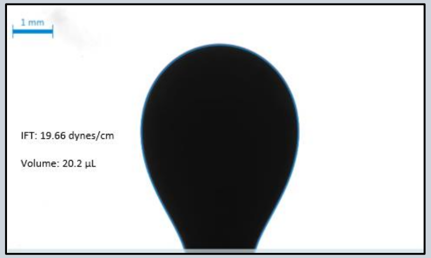
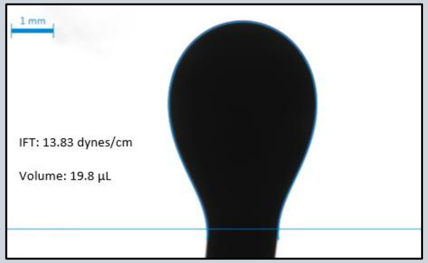
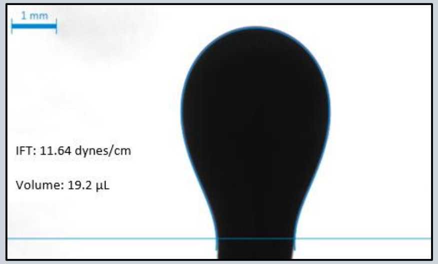
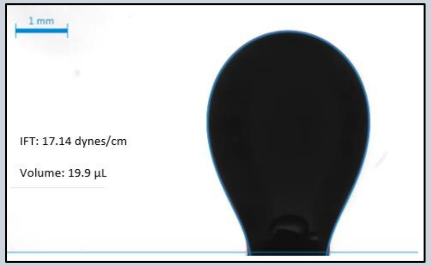
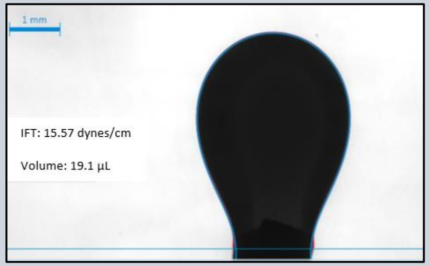
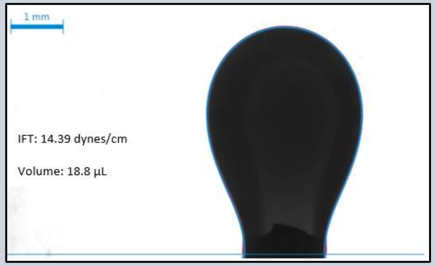
Wettability: **Tendency of a fluid to spread on (or adhere to) a solid surface in the presence of another immiscible fluid.**



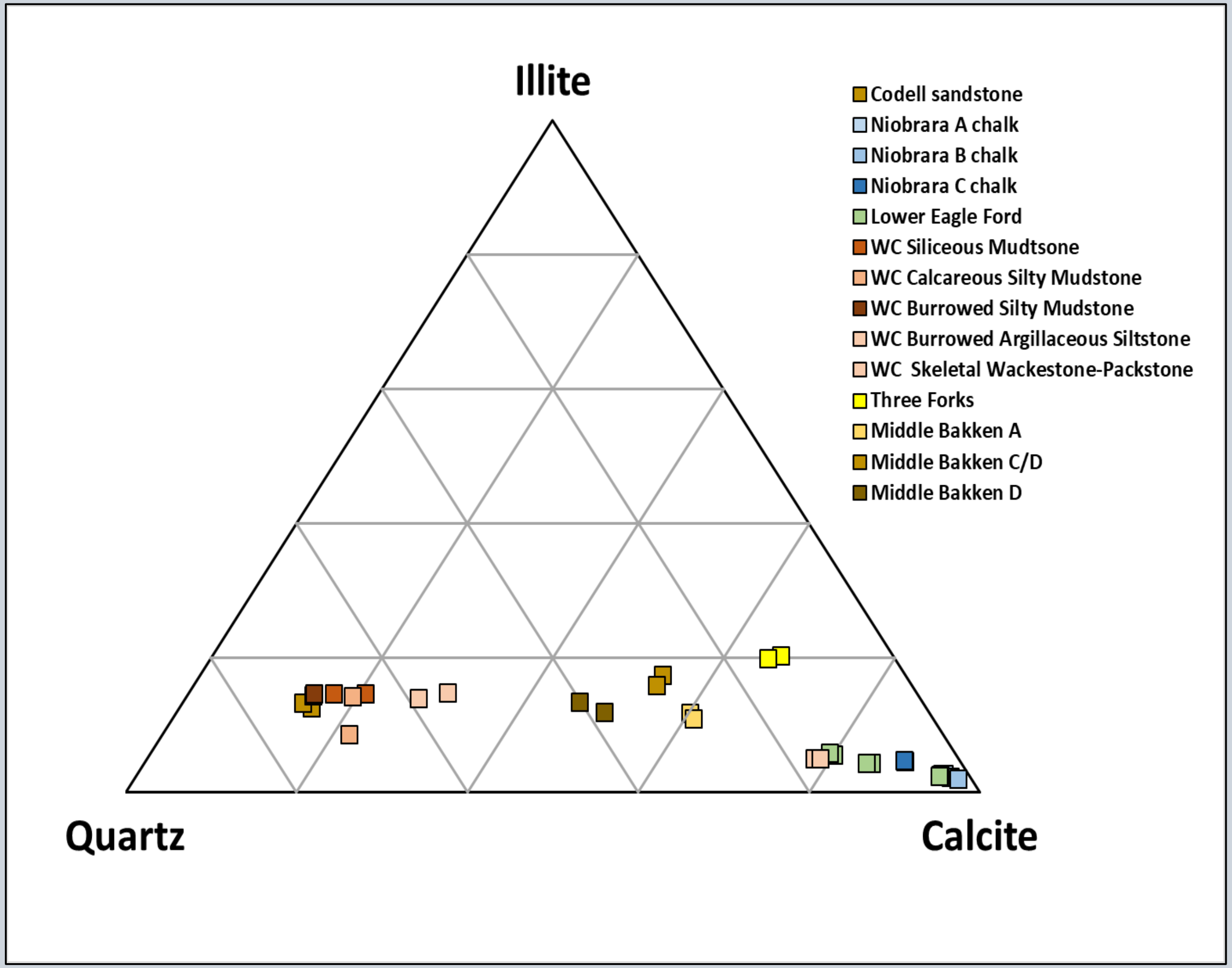
Interfacial tension → *Wettability* → *Capillary pressure* → *Relative permeability*

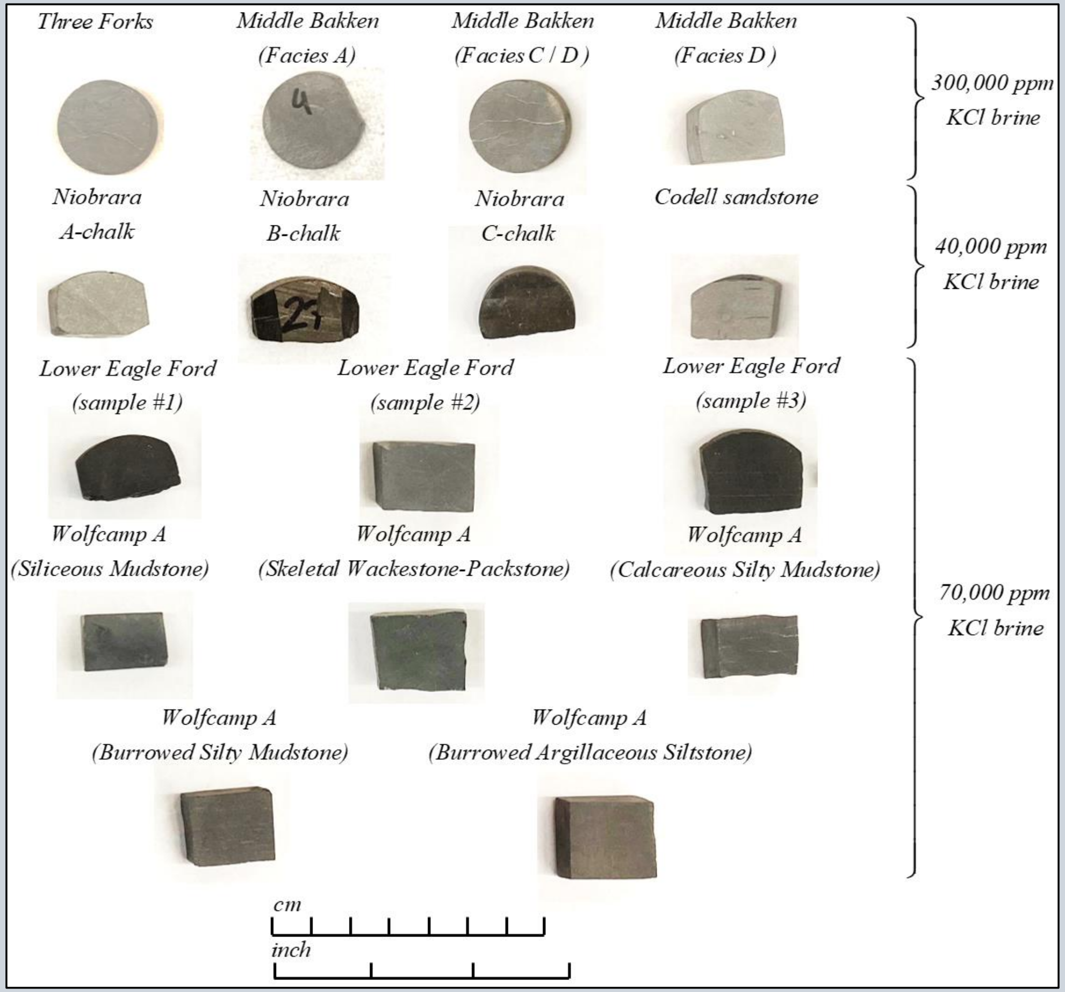
Typical IFT Measurements for Four Basins

COLORADO SCHOOL OF MINES
MUDTOC

	Ambient Conditions	Reservoir Conditions	Reservoir Conditions with CO_2
DJ Basin	 IFT=19.97 dynes/cm	 IFT=11.45 dynes/cm	 IFT=9.74 dynes/cm
Eagle Ford and Wolfcamp	 IFT=19.66 dynes/cm	 IFT=13.83 dynes/cm	 IFT=11.64 dynes/cm
Williston Basin	 IFT=17.14 dynes/cm	 IFT=15.57 dynes/cm	 IFT=14.39 dynes/cm

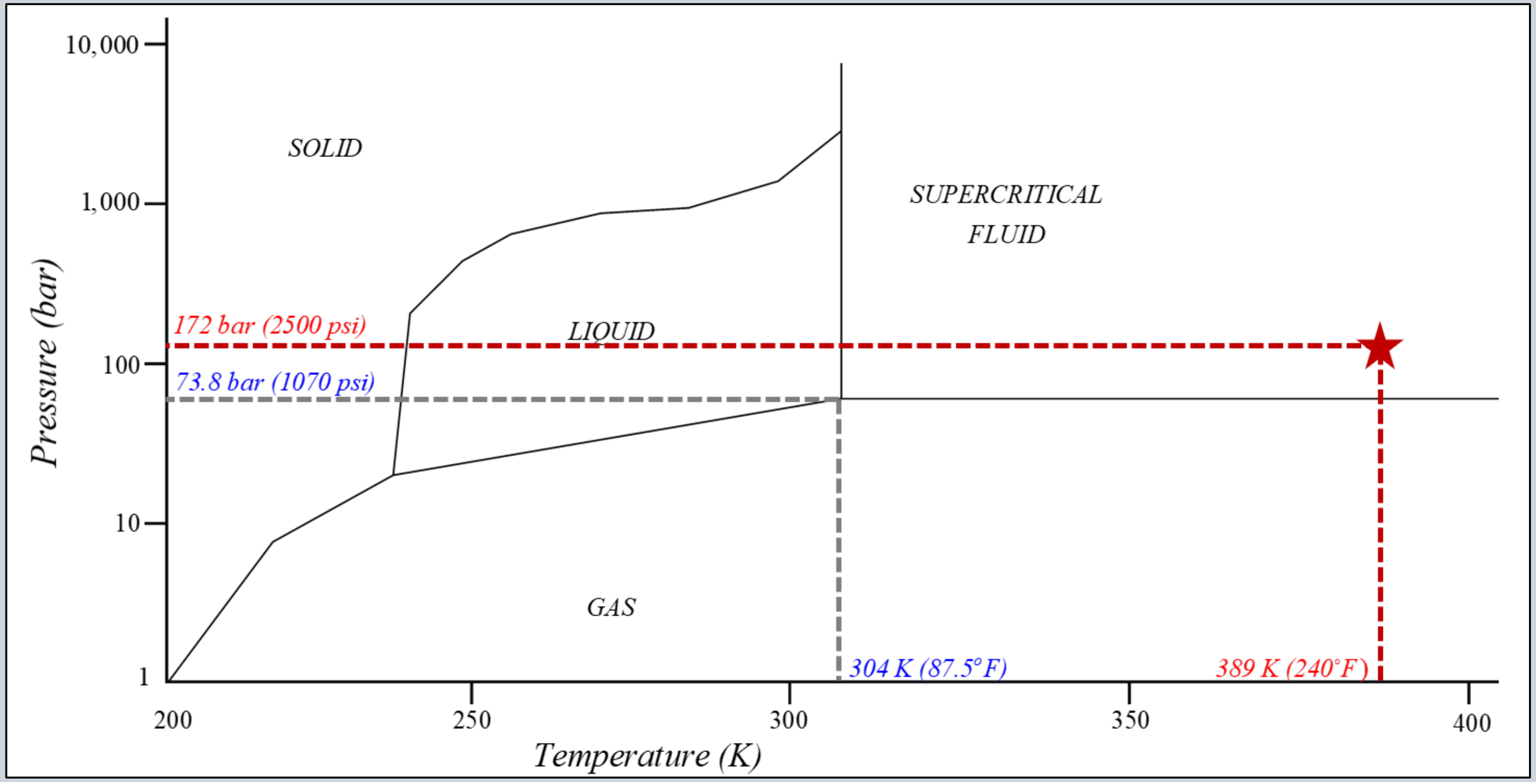
Rock Samples Used in Contact Angle Measurements





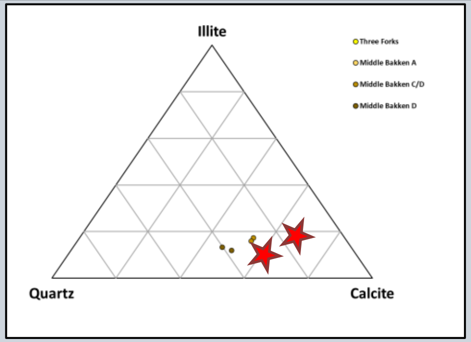
Experimental Procedure for Contact Angle Measurements

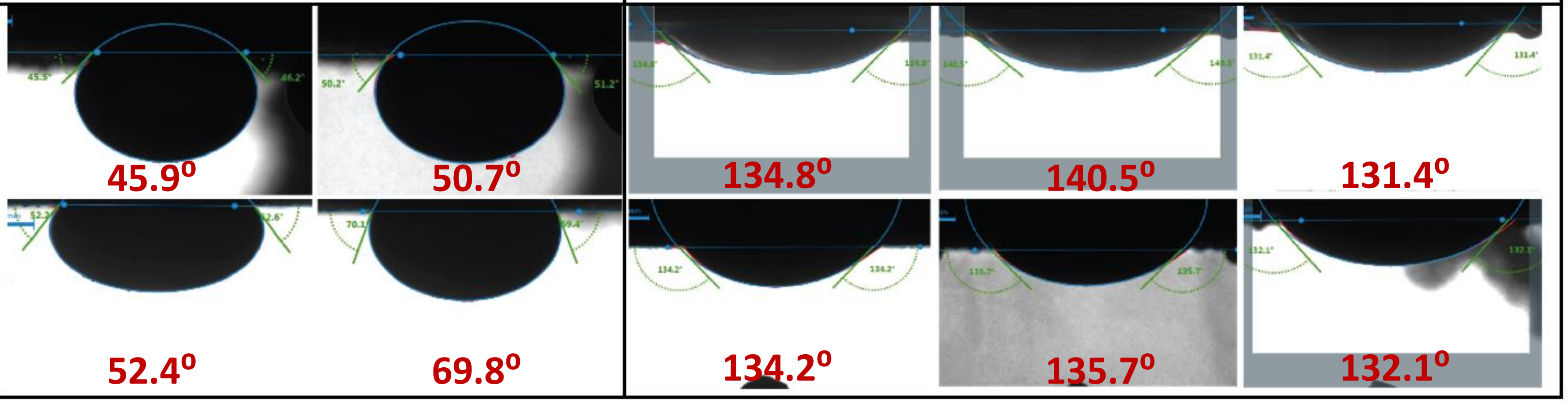
1) Measuring contact angle of unaged samples in ambient conditions and reservoir conditions (240°F & 2500 psi).
2) Measuring contact angle of aged samples in ambient conditions and reservoir conditions (240°F & 2500 psi).
3) Injecting CO2 to the cell above supercritical conditions.



(Modified from Budisa and Schulze-Makuch 2014)

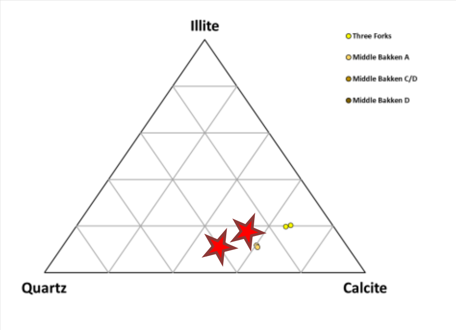
Contact Angle Measurements

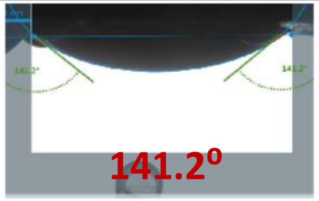
Williston Basin	Parameters		Location
	Formation Brine Salinity (ppm)	300,000	
	Formation Brine Density (g/cc)	1.1743	
	Oil Density (g/cc)	0.8812	



	Unaged		*Aged*		
	Ambient Conditions	*Reservoir Conditions*	*Ambient Conditions*	*Reservoir Conditions*	*Reservoir Conditions with CO_2*
Three Forks Formation	45.9^o	50.7^o	134.8^o	140.5^o	131.4^o
Middle Bakken Formation (Facies A)	52.4^o	69.8^o	134.2^o	135.7^o	132.1^o

Contact Angle Measurements

Williston Basin	Parameters		Location
	Formation Brine Salinity (ppm)	300,000	
	Formation Brine Density (g/cc)	1.1743	
	Oil Density (g/cc)	0.8812	

	Unaged *Ambient Conditions*	*Unaged* *Reservoir Conditions*	*Aged* *Ambient Conditions*	*Aged* *Reservoir Conditions*	*Aged* *Reservoir Conditions with CO_2*
Middle Bakken Formation (Facies C/D)	 52.7^o	 68.5^o	 146.8^o	 147.9^o	 141.2^o
Middle Bakken Formation (Facies D)	 56.1^o	 62.0^o	 139.8^o	 140.1^o	 137.4^o

Contact Angle Measurements

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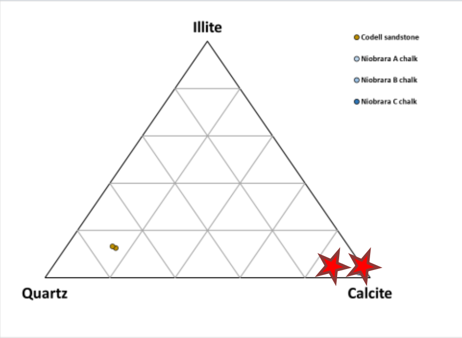
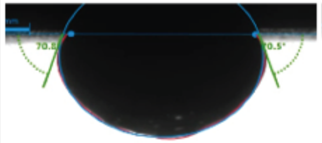
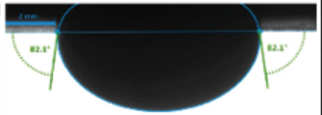
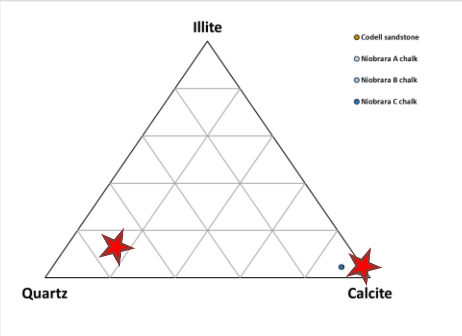
DJ Basin	Parameters		Location
	Formation Brine Salinity (ppm)	40,000	
	Formation Brine Density (g/cc)	1.0406	
	Oil Density (g/cc)	0.8634	

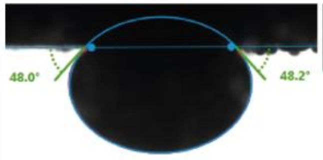
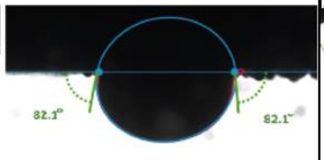
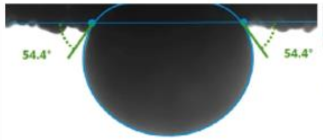
	Unaged		*Aged*		
	Ambient Conditions	*Reservoir Conditions*	*Ambient Conditions*	*Reservoir Conditions*	*Reservoir Conditions with CO_2*
Niobrara Formation (Chalk A)	 70.7°	 86.8°	 95.2°	 110.3°	 107.3°
Niobrara Formation (Chalk B)	 49.8°	 82.1°	 124.1°	 137.2°	 134.6°

Contact Angle Measurements

COLORADO SCHOOL OF MINES MUDTOC

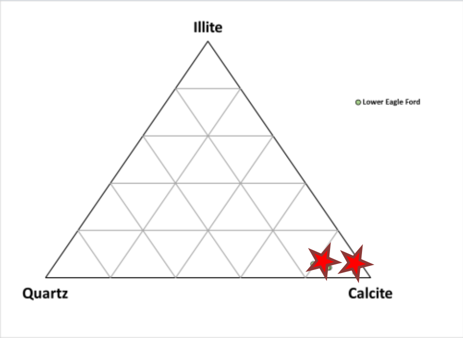
DJ Basin	Parameters		Location
	Formation Brine Salinity (ppm)	40,000	
	Formation Brine Density (g/cc)	1.0406	
	Oil Density (g/cc)	0.8634	

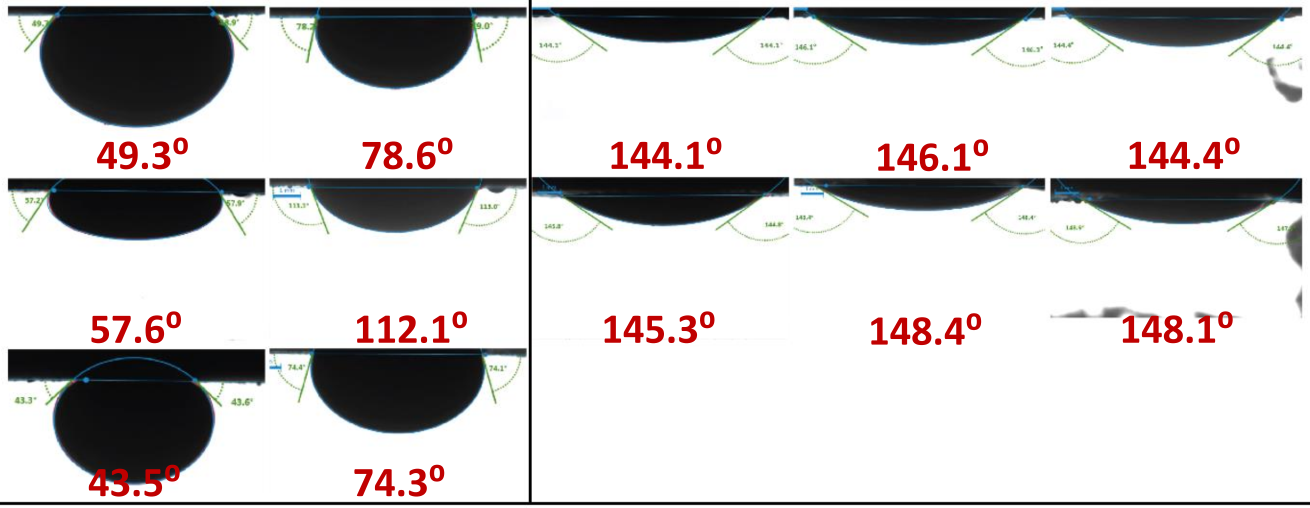


	Unaged		*Aged*		
	Ambient Conditions	*Reservoir Conditions*	*Ambient Conditions*	*Reservoir Conditions*	*Reservoir Conditions with CO_2*
Niobrara Formation (Chalk C)	 48.1°	 82.1°	 103.6°	 107.7°	 102.8°
Codell sandstone	 54.4°	 82.2°	 114.2°	 114.8°	 111.8°

Contact Angle Measurements

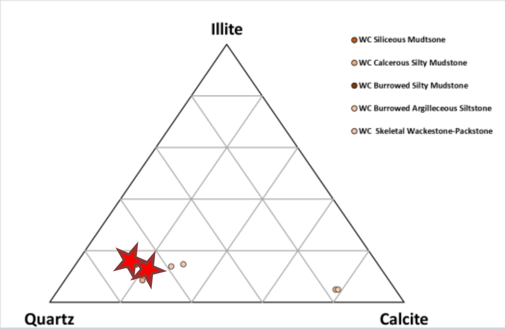
COLORADO SCHOOL OF MINES
MUDTOC

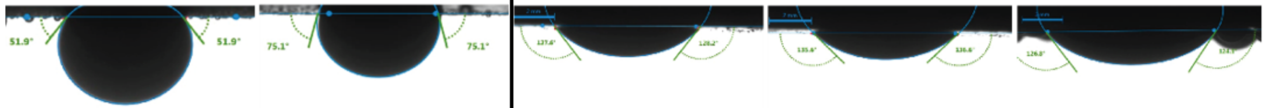
Eagle Ford	Parameters		Location
	Formation Brine Salinity (ppm)	70,000	
	Formation Brine Density (g/cc)	1.0566	
	Oil Density (g/cc)	0.8634	



	Unaged		*Aged*		
	Ambient Conditions	*Reservoir Conditions*	*Ambient Conditions*	*Reservoir Conditions*	*Reservoir Conditions with CO_2*
Lower Eagle Ford	49.3°	78.6°	144.1°	146.1°	144.4°
	57.6°	112.1°	145.3°	148.4°	148.1°
	43.5°	74.3°			

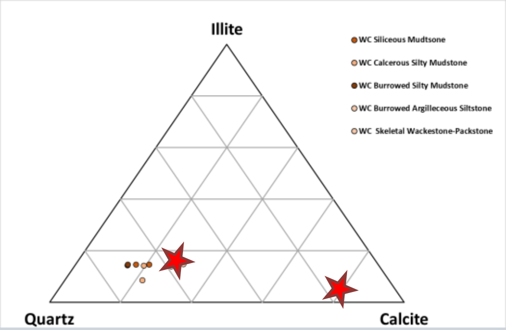
Contact Angle Measurements

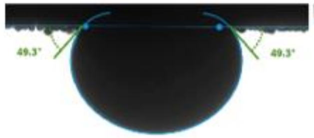
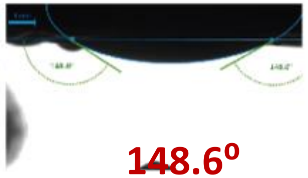
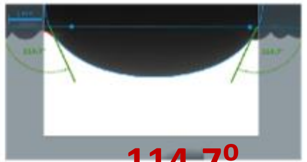
Permian Basin	Parameters		Location
	Formation Brine Salinity (ppm)	70,000	
	Formation Brine Density (g/cc)	1.0566	
	Oil Density (g/cc)	0.8634	



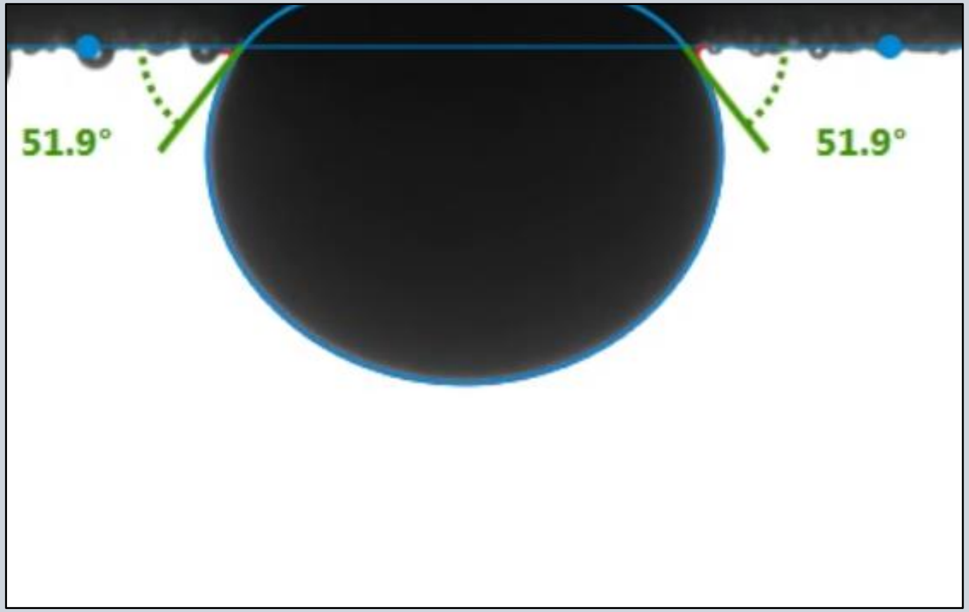
	Unaged		*Aged*		
	Ambient Conditions	*Reservoir Conditions*	*Ambient Conditions*	*Reservoir Conditions*	*Reservoir Conditions with CO_2*
Wolfcamp A (Siliceous Mudstone)	**51.9°**	**75.1°**	**127.9°**	**129.5°**	**125.5°**
Wolfcamp A (Calcareous Silty Mudstone)	**45.8°**	**63.7°**	**112.8°**	**120.9°**	**117.7°**
Wolfcamp A (Burrowed Silty Mudstone)	**48.5°**	**61.5°**	**100.8°**	**108.5°**	**106.4°**

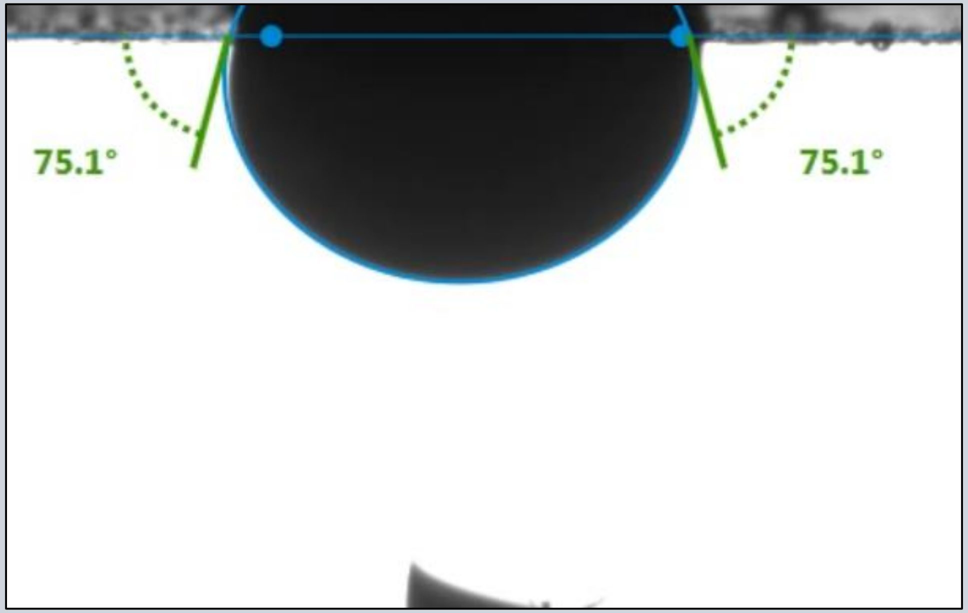
Contact Angle Measurements

Permian Basin	Parameters		Location
	Formation Brine Salinity (ppm)	70,000	
	Formation Brine Density (g/cc)	1.0566	
	Oil Density (g/cc)	0.8634	

	Unaged		*Aged*		
	Ambient Conditions	*Reservoir Conditions*	*Ambient Conditions*	*Reservoir Conditions*	*Reservoir Conditions with CO_2*
Wolfcamp A (Burrowed Argillaceous Siltstone)	 **49.3°**	 **72.3°**	 **146.4°**	 **152.2°**	 **148.6°**
Wolfcamp A (Skeletal Wackestone-Packstone)	 **69.2°**	 **91.4°**	 **103.8°**	 **116.7°**	 **114.7°**

Effect of Temperature

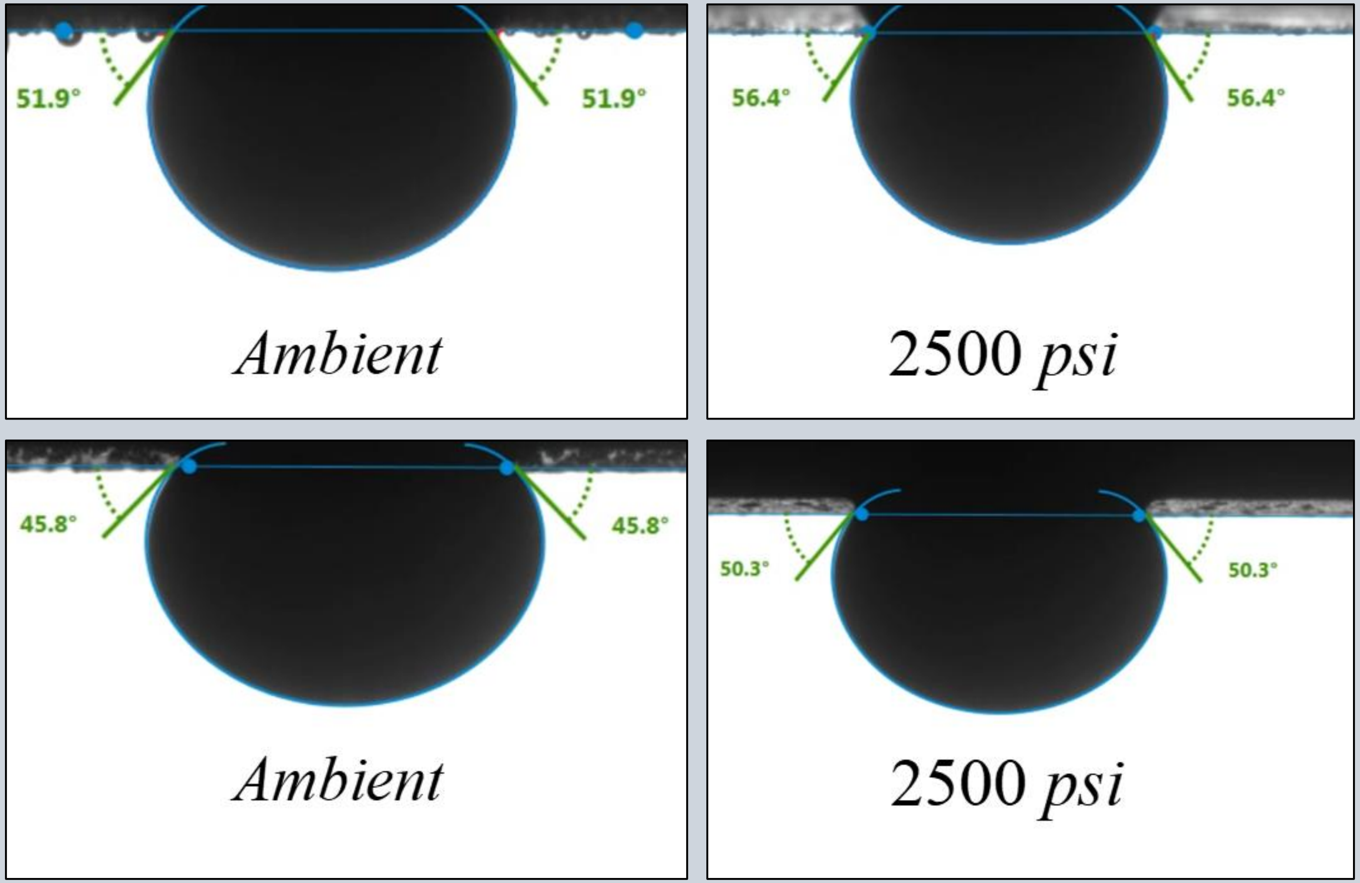




- Rapid increase (<3 hrs)
- Permanent
- Change varies

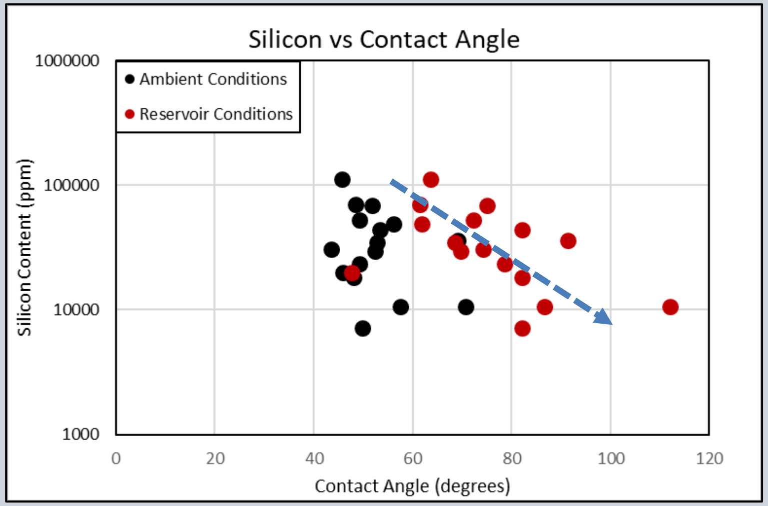
Sample Basin/Formation	Change (in degrees)
Williston Basin	5-7
DJ Basin	16-34
Eagle Ford	29-54
Wolfcamp	13-23

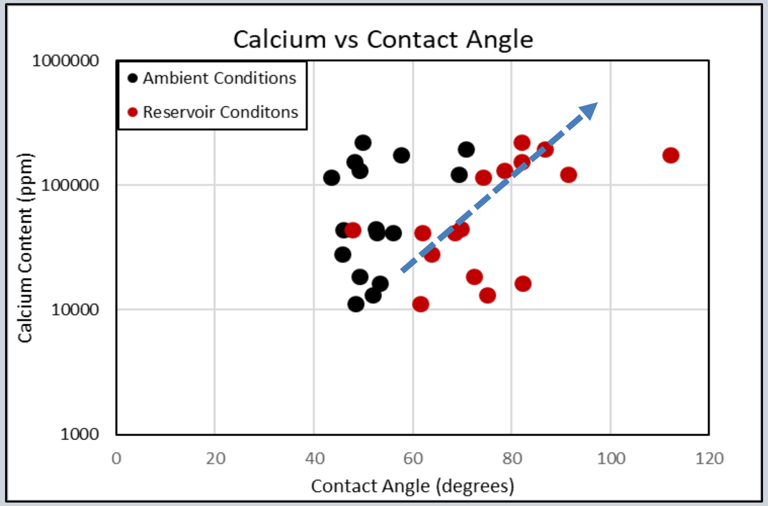
Effect of Pressure

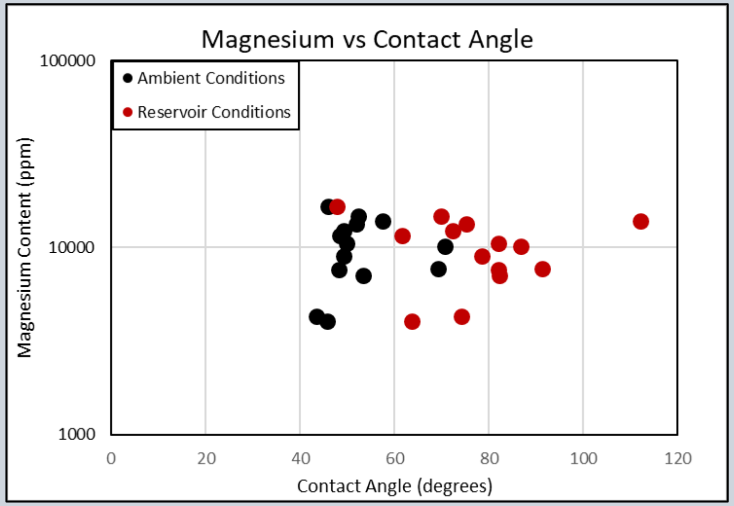


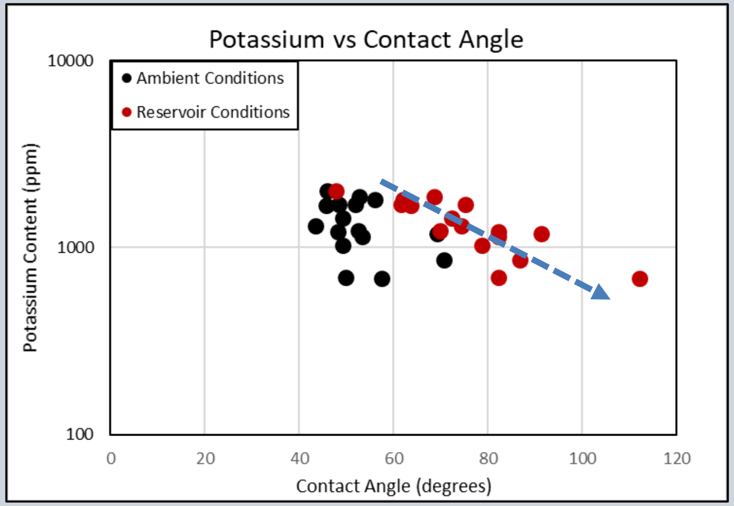
- Immediate increase
- Temporary
- Change is same on all samples (~4.5º)

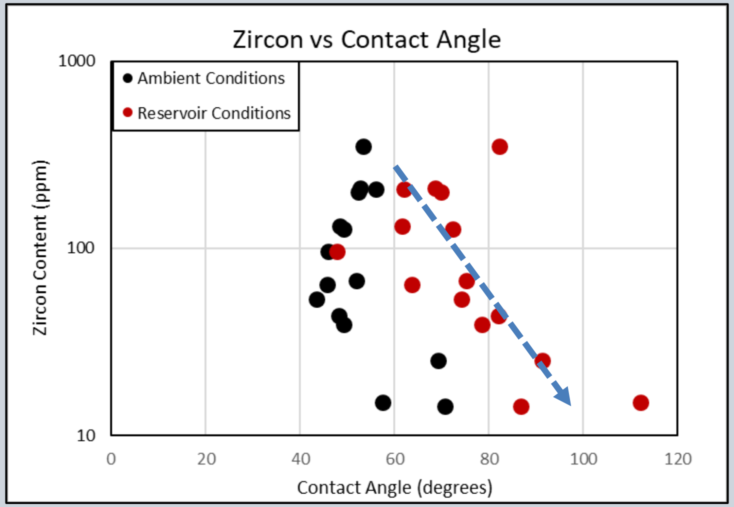
Effect of Mineralogy on Contact Angle Changes (Unaged Cores)



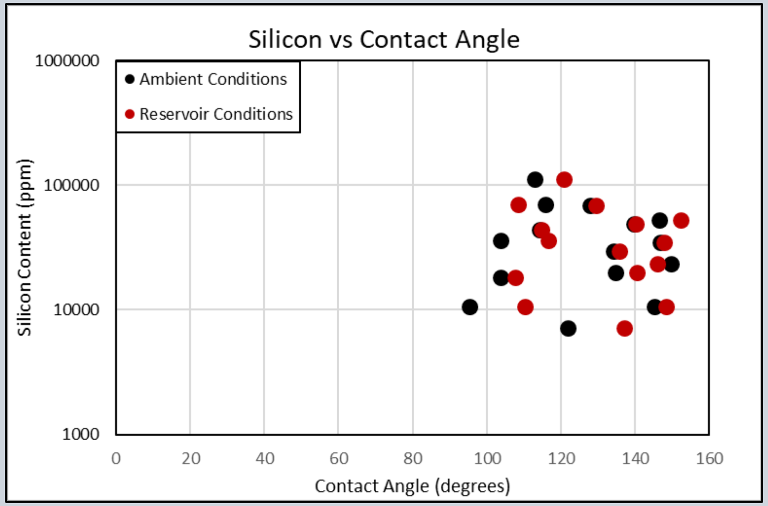


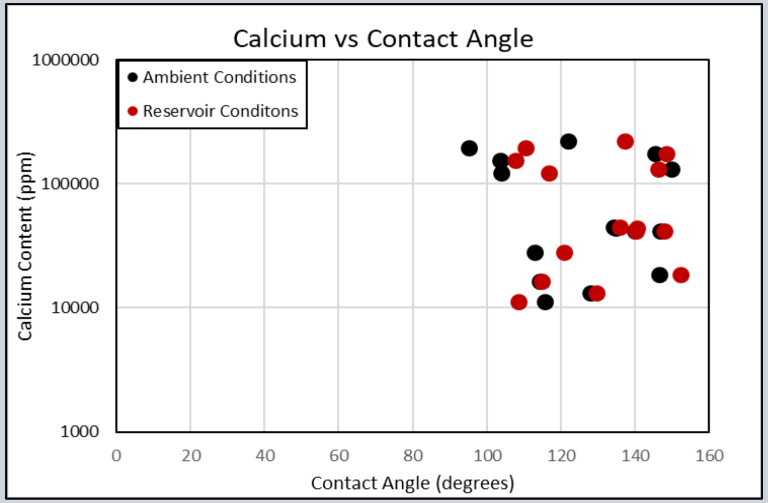


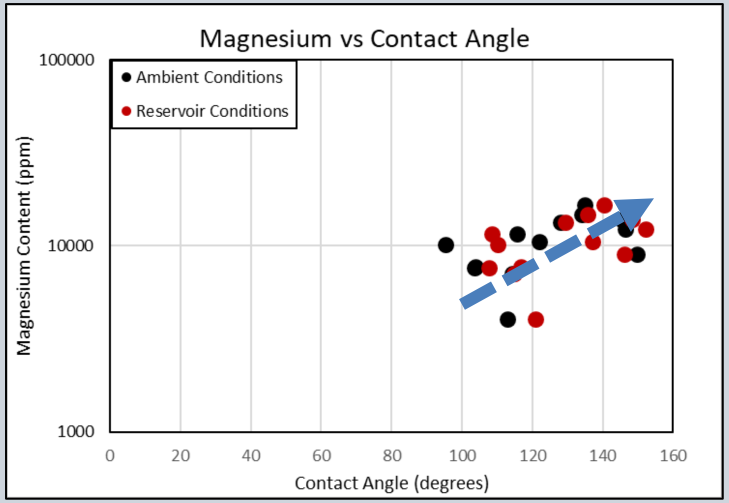


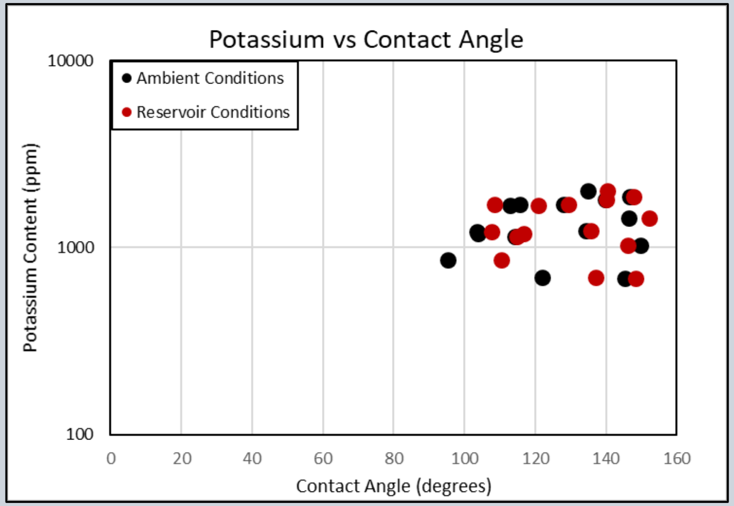


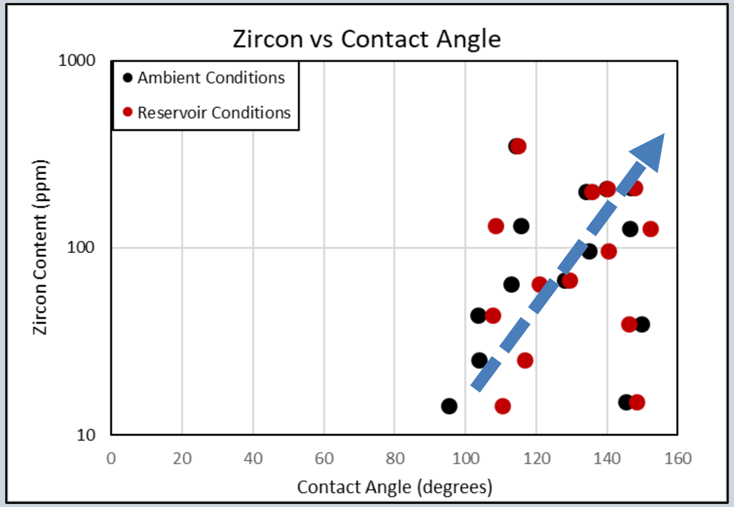
Effect of Mineralogy on Contact Angle Changes (Aged Cores)











Effect of Mineralogy on Contact Angle Changes (Aged Cores with CO2)

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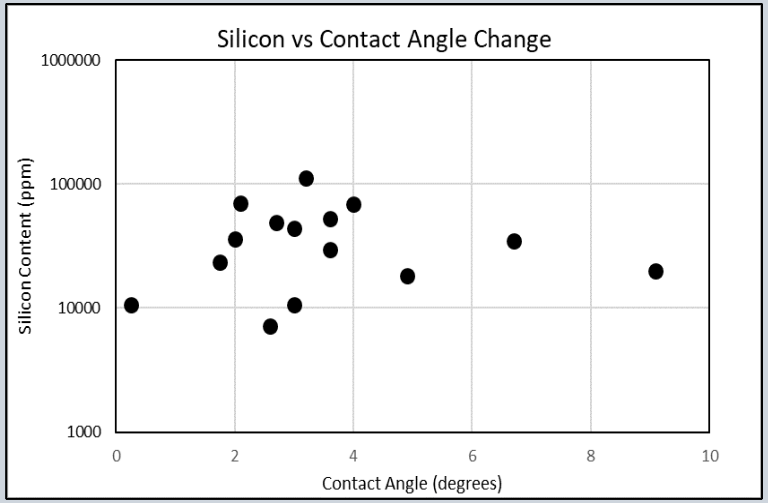

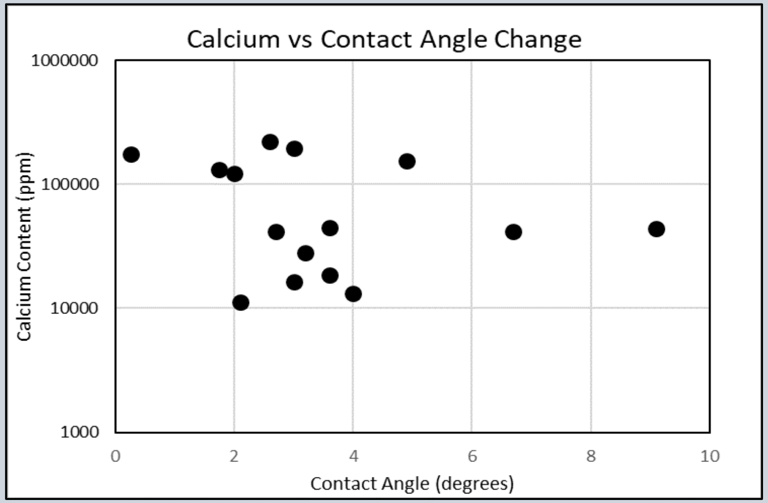

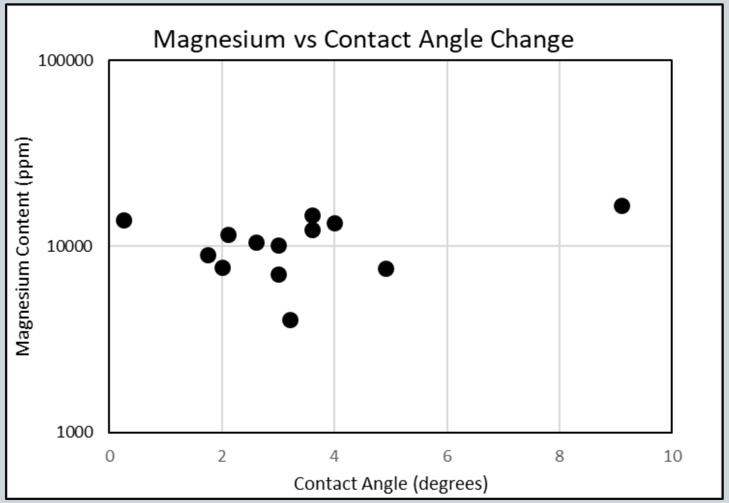

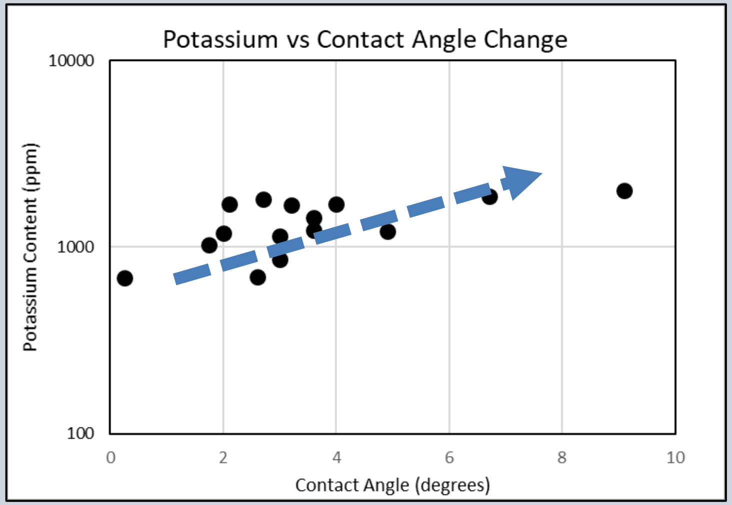

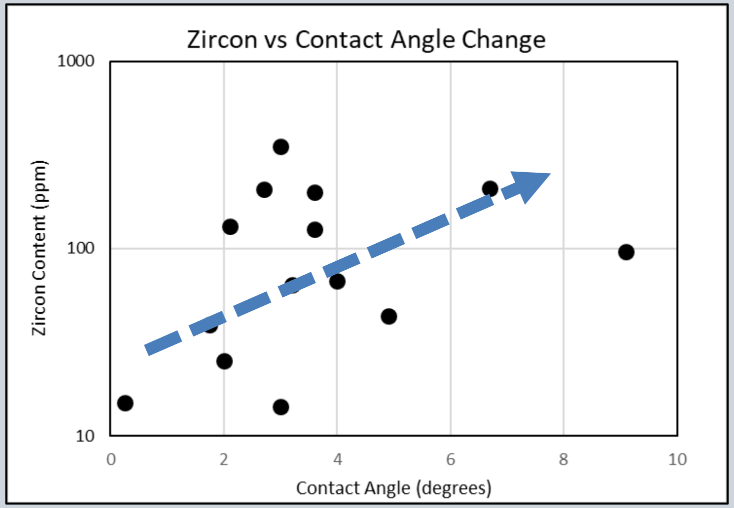

Comparison of Results

Sample	Unaged		Aged		Aged+CO2	Change by CO2
	Ambient	Reservoir P & T	Ambient	Reservoir P & T	Reservoir P & T	
Middle Bakken (Facies A)	52.4	69.75	134.2	135.7	132.1	3.6
Middle Bakken (Facies C/D)	52.7	68.5	146.8	147.9	141.2	6.7
Middle Bakken (Facies D)	56.05	61.95	139.8	140.1	137.4	2.7
Three Forks	45.85	47.75	134.8	140.5	131.4	9.1
Niobrara A-Chalk	70.65	86.75	95.2	110.3	107.3	3
Niobrara B-Chalk	49.8	82.1	121.9	137.15	134.55	2.6
Niobrara C-Chalk	48.1	82.1	103.6	107.7	102.8	4.9
Codell sandstone	53.4	82.15	114.2	114.8	111.8	3
Lower Eagle Ford	49.3	78.6	144.2	146.1	144.35	1.75
Lower Eagle Ford	57.55	112.05	145.3	148.35	148.1	0.25
Lower Eagle Ford	43.45	74.25	N/A	N/A	N/A	N/A
Wolfcamp A (Siliceous Mudstone)	51.9	75.1	127.9	129.45	125.45	4
Wolfcamp A (Calcareous Silty Mudstone)	45.8	63.7	112.8	120.9	117.7	3.2
Wolfcamp A (Burrowed Silty Mudstone)	48.45	61.5	100.8	108.5	106.4	2.1
Wolfcamp A (Burrowed Argillaceous Siltstone)	49.3	72.3	146.4	152.2	148.6	3.6
Wolfcamp A (Skeletal Wackestone-Packstone)	69.2	91.35	103.8	116.7	114.7	2

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