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EVALUATING PRODUCTION PERFORMANCE OF PERMIAN BASIN WELLS TO IMPROVE HYDROCARBON RECOVERY

COLORADO SCHOOL OF MINES MUDTOC

Drivers and Motivation

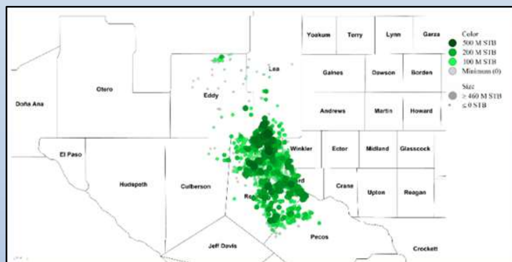
COLORADO SCHOOL OF MINES MUDTOC

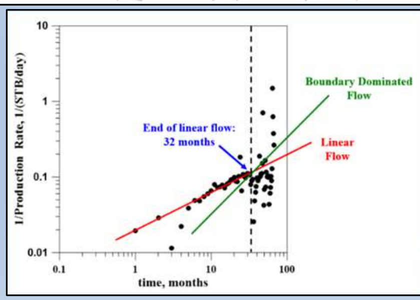
- **Permian Basin** is the most prolific oil and gas producing geologic basins in the United Sates—spanning West Texas and Southeastern New Mexico. It has produced more than 33.4 Bbbl of oil and 118 Tcf of natural gas during a 100-year period (EIA 2018).
- The ever-increasing water production and usage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

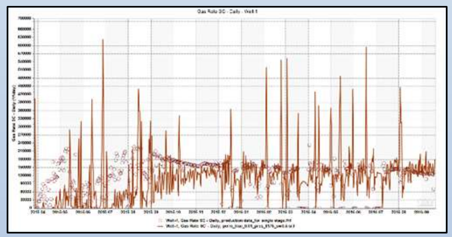
- Determine production characteristics of Delaware Basin wells
- Plan for several innovative EOR experiments

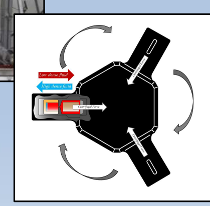




Phase 2:

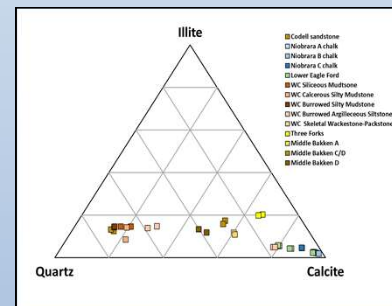
- Build an appropriate numerical model to forecast future performance
- Prepare for the EOR experiments

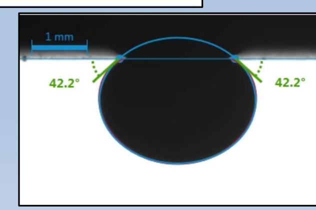




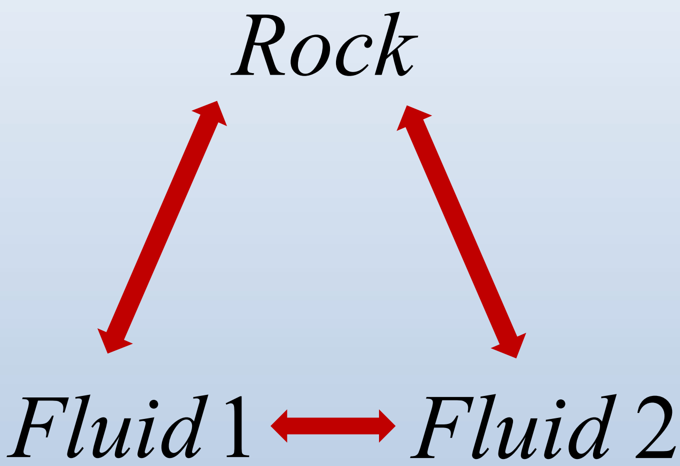
Phase 3:

- Conduct EOR experiments
- Characterize field performance using numerical model (history match production data)
- Automated interpreation



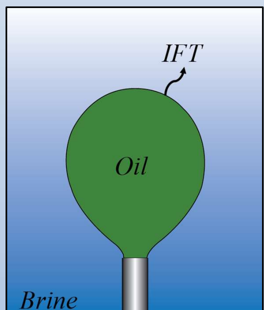


Fluid-Rock Interactions



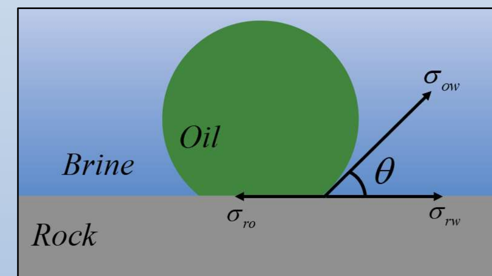
Fluid-Fluid Interactions

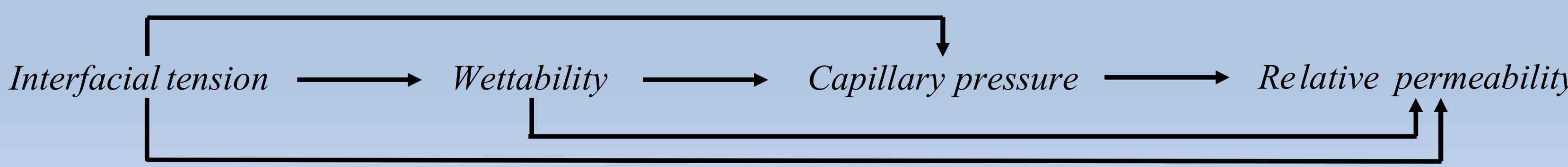
IFT: The force of attraction between the molecules at the interface of two fluids.



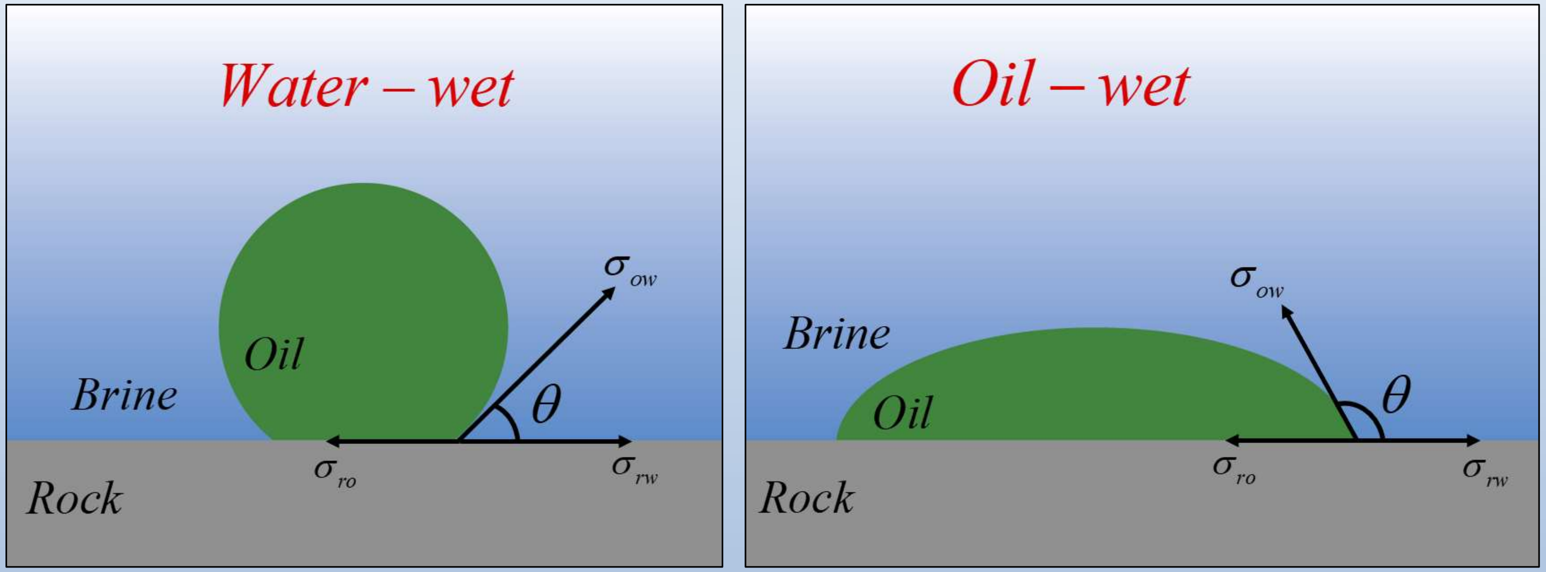
Fluid-Rock Interactions

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





Wettability Concept



$\sigma_{ro} = IFT\ between$ rock and oil (dynes / cm)

$\sigma_{rw} = IFT\ between$ rock and brine (dynes / cm)

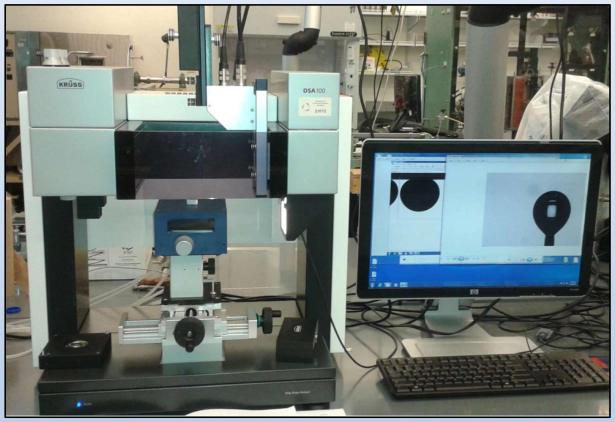
$\sigma_{ow} = IFT\ between$ oil and brine (dynes / cm)

$$\theta > 90 \Rightarrow Oil-wet$$

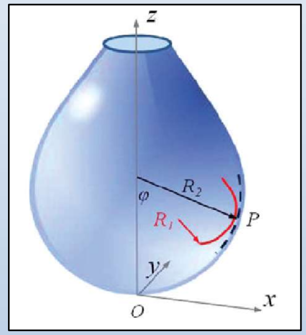
$$\theta < 90 \Rightarrow Water-wet$$

$$\theta = 90 \Rightarrow Intermediate-wet$$

Drop Shape Analyzer (DSA-100)



Pendant drop method (IFT)



(Yakshi-Tafti et al. 2011)

$$\sigma\left(\frac{1}{R_1}+\frac{1}{R_2}\right)=\Delta p=\Delta\rho g z+C$$

$$\frac{1}{R_1}+\frac{\sin\varphi}{x}=\frac{\Delta\rho g z}{\sigma}+\frac{2}{b}$$

where;

$\sigma = IFT\ (N/m)$

$R_1\ \&\ R_2 =$ *principal radii of curvaturelar to* R_1

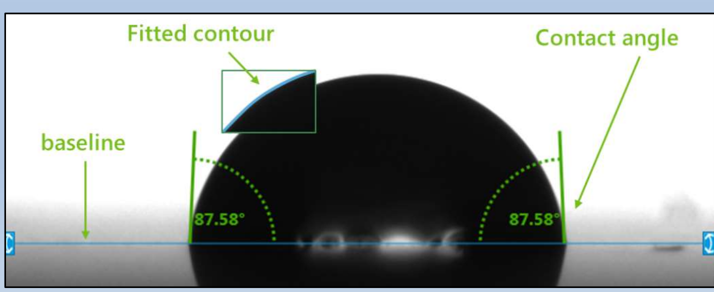
$\Delta p =$ *differential pressure* (N/m^2)

$\rho =$ *density* (kg/m^3)

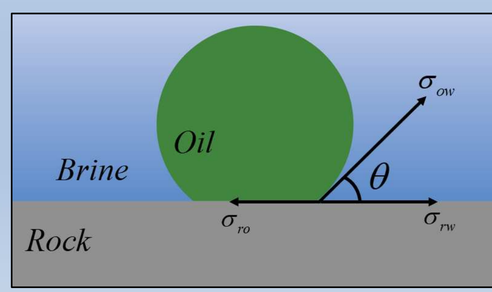
$g =$ *graviatational acceleration* $(9.8\,m^2/\text{sec})$

$\varphi =$ *angle between* R_1 *and* $z-axis$

Captive droplet method (Wettability)



(KRÜSS 2016)



$$\sigma_{ro}=\sigma_{rw}+\sigma_{ow}\cos\theta$$

where;

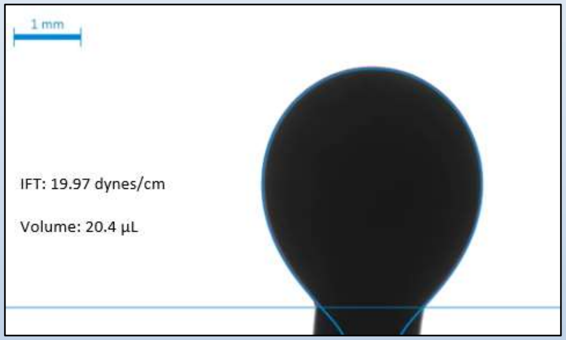
$\sigma_{ro} =$ *IFT between rock and oil* $(dynes/cm)$

$\sigma_{rw} =$ *IFT between rock and brine* $(dynes/cm)$

$\sigma_{ow} =$ *IFT between oil and brine* $(dynes/cm)$

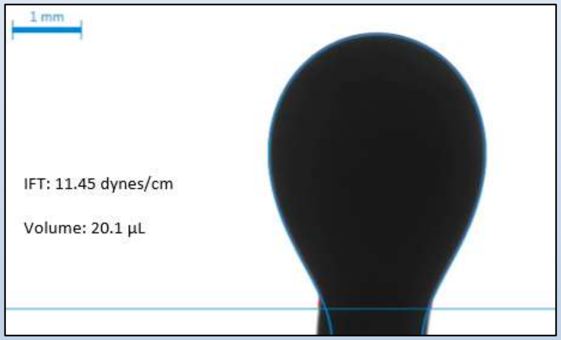
IFT Measurements - Niobrara

Ambient Conditions



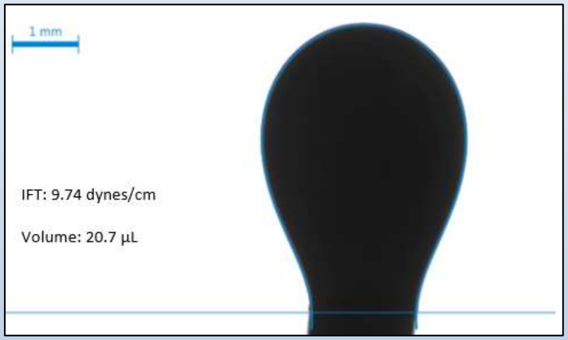
IFT=19.97 dynes/cm

Reservoir Conditions



IFT=11.45 dynes/cm

Reservoir Conditions with CO_2



IFT=9.74 dynes/cm

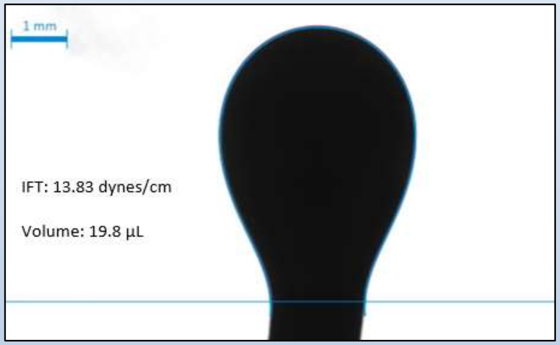
Parameters	
Formation Brine Salinity (ppm)	40,000
Formation Brine Density (g/cc)	1.04
Oil Density (g/cc)	0.84
Oil Viscosity (cP at 20^{o}C)	8.13
pH (brine)	6.4
pH (brine+CO2)	4.75

IFT Measurements – Eagle Ford and Wolfcamp

Ambient Conditions

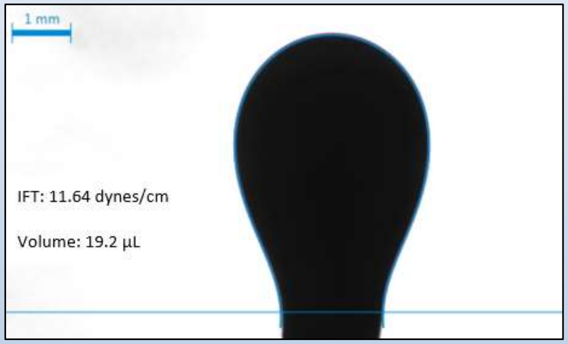
IFT=19.66 dynes/cm

Reservoir Conditions



IFT=13.83 dynes/cm

Reservoir Conditions with CO_2



IFT=11.64 dynes/cm

Parameters	
Formation Brine Salinity (ppm)	70,000
Formation Brine Density (g/cc)	1.06
Oil Density (g/cc)	0.84
Oil Viscosity (cP at 20^{o}C)	8.13
pH (brine)	6.29
pH (brine+CO2)	4.72

IFT Measurements – Bakken and Three Forks

Ambient Conditions

IFT=17.14 dynes/cm

Reservoir Conditions

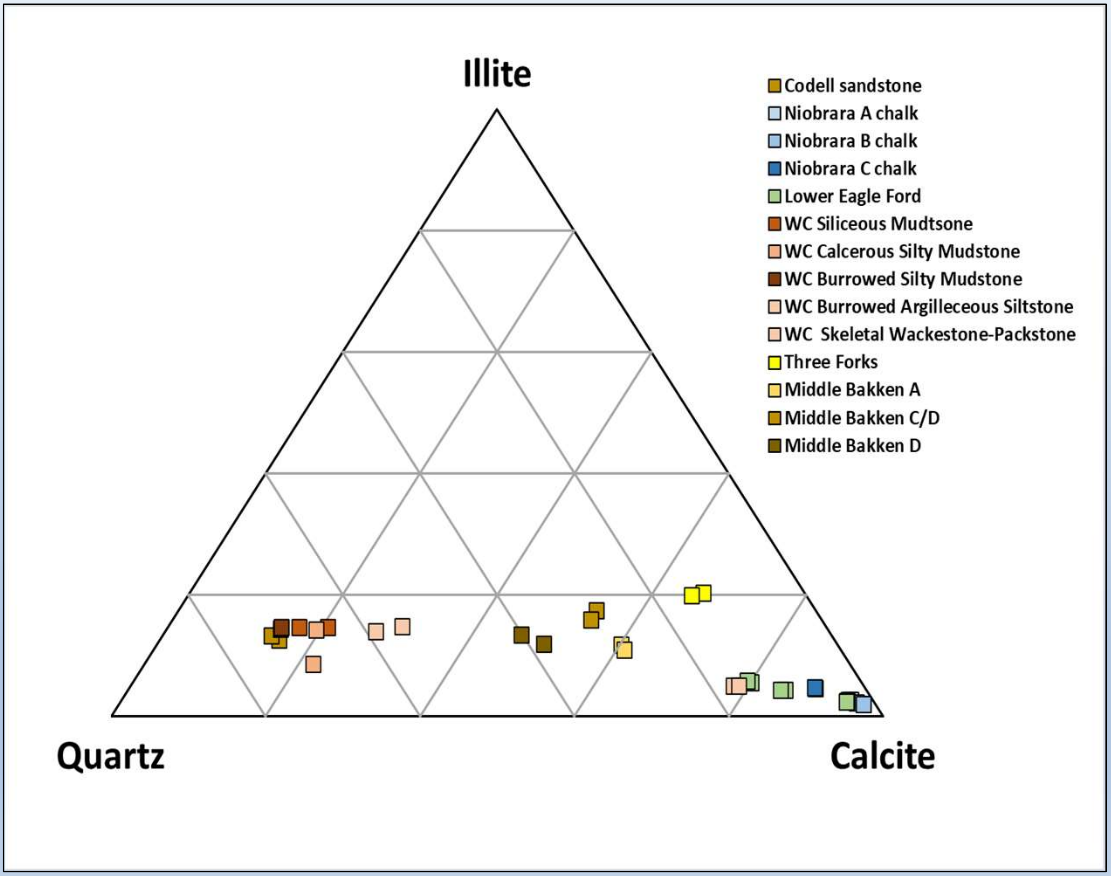
IFT=15.57 dynes/cm

Reservoir Conditions with CO_2

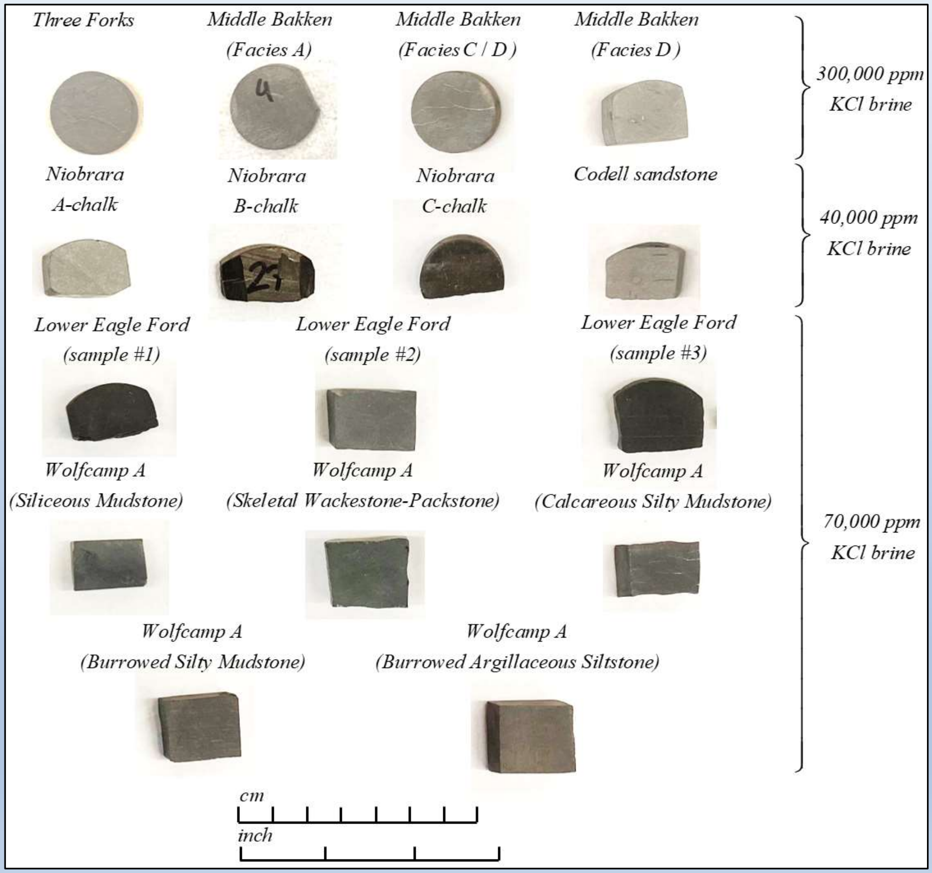
IFT=14.39 dynes/cm

Parameters	
Formation Brine Salinity (ppm)	300,000
Formation Brine Density (g/cc)	1.17
Oil Density (g/cc)	0.88
pH (brine)	6.04
pH (brine+CO2)	4.65

Samples



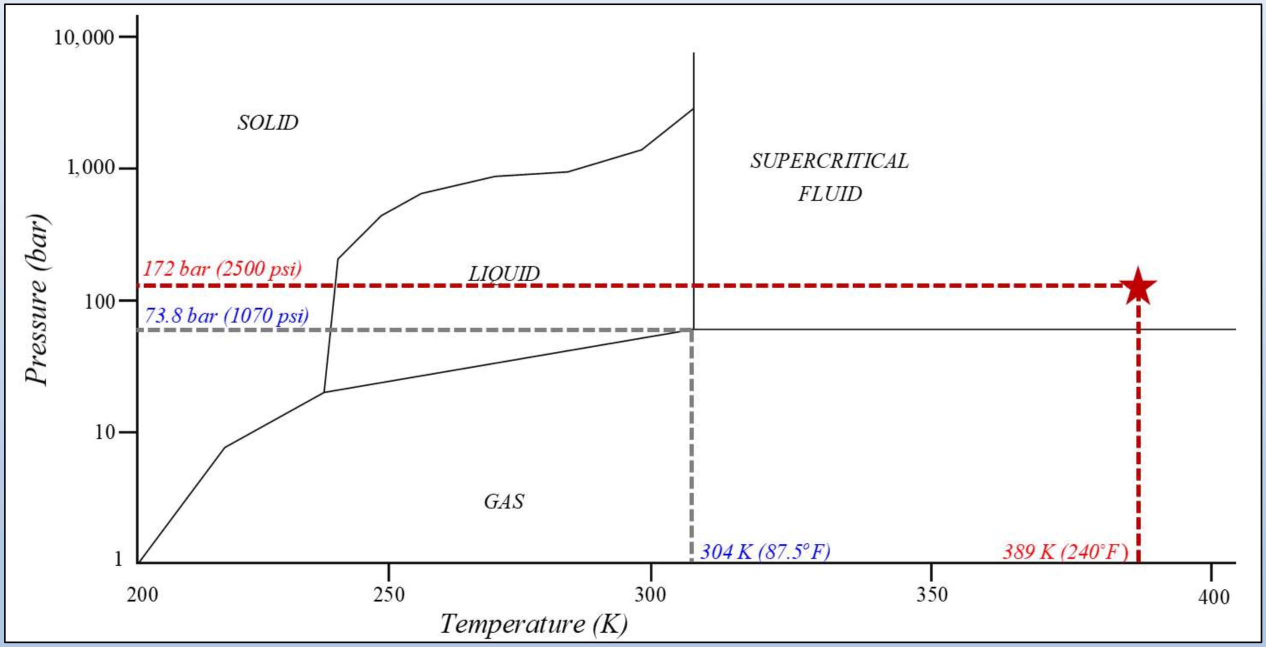
Illite
Quartz
Calcite
Codell sandstone
Niobrara A chalk
Niobrara B chalk
Niobrara C chalk
Lower Eagle Ford
WC Siliceous Mudtsone
WC Calcerous Silty Mudstone
WC Burrowed Silty Mudstone
WC Burrowed Argilleceous Siltstone
WC Skeletal Wackestone-Packstone
Three Forks
Middle Bakken A
Middle Bakken C/D
Middle Bakken D



Three Forks
Middle Bakken (Facies A)
Middle Bakken (Facies C / D)
Middle Bakken (Facies D)
300,000 ppm KCl brine
Niobrara A-chalk
Niobrara B-chalk
Niobrara C-chalk
Codell sandstone
40,000 ppm KCl brine
Lower Eagle Ford (sample #1)
Lower Eagle Ford (sample #2)
Lower Eagle Ford (sample #3)
Wolfcamp A (Siliceous Mudstone)
Wolfcamp A (Skeletal Wackestone-Packstone)
Wolfcamp A (Calcareous Silty Mudstone)
Wolfcamp A (Burrowed Silty Mudstone)
Wolfcamp A (Burrowed Argillaceous Siltstone)
70,000 ppm KCl brine
cm
inch

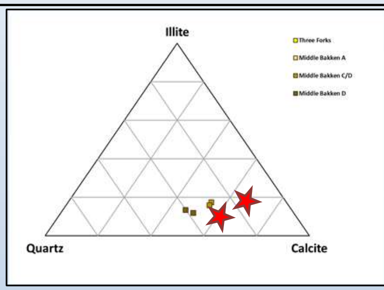
Experimental Procedure

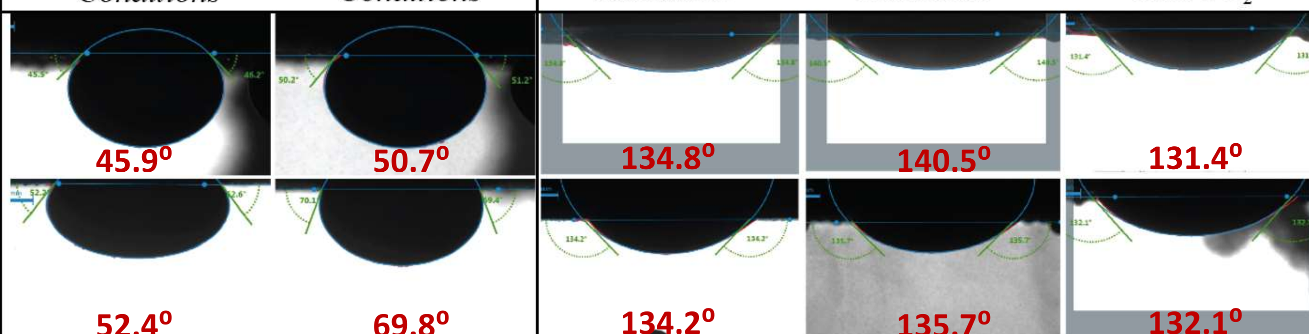
1) Measuring contact angle of **unaged** samples in ambient conditions and reservoir conditions (240ºF & 2500 psi).
2) Measuring contact angle of **aged** samples in ambient conditions and reservoir conditions (240ºF & 2500 psi).
3) Injecting **CO2** to the cell above supercritical conditions.



(Modified from Budisa and Schulze-Makuch 2014)

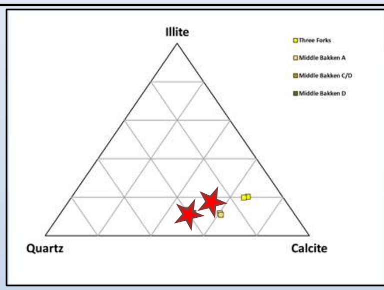
Contact Angle Measurements

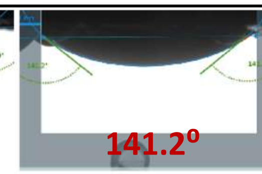
Williston Basin	Parameters		Location
	Formation Brine Salinity (ppm)	300,000	
	Formation Brine Density (g/cc)	1.17	
	Oil Density (g/cc)	0.88	



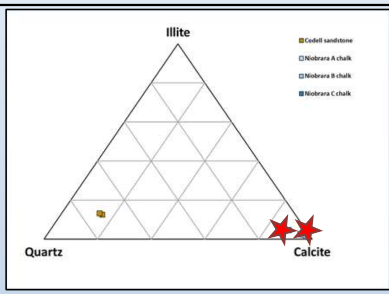
	Unaged		*Aged*		
	Ambient Conditions	*Reservoir Conditions*	*Ambient Conditions*	*Reservoir Conditions*	*Reservoir Conditions with CO_2*
Three Forks Formation	45.9°	50.7°	134.8°	140.5°	131.4°
Middle Bakken Formation (Facies A)	52.4°	69.8°	134.2°	135.7°	132.1°

Contact Angle Measurements

Williston Basin	Parameters		Location
	Formation Brine Salinity (ppm)	300,000	
	Formation Brine Density (g/cc)	1.17	
	Oil Density (g/cc)	0.88	

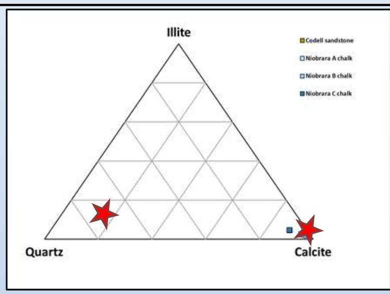
	Unaged		*Aged*		
	Ambient Conditions	*Reservoir Conditions*	*Ambient Conditions*	*Reservoir Conditions*	*Reservoir Conditions with CO_2*
Middle Bakken Formation (Facies C/D)	 52.7^o	 68.5^o	 146.8^o	 147.9^o	 141.2^o
Middle Bakken Formation (Facies D)	 56.1^o	 62.0^o	 139.8^o	 140.1^o	 137.4^o

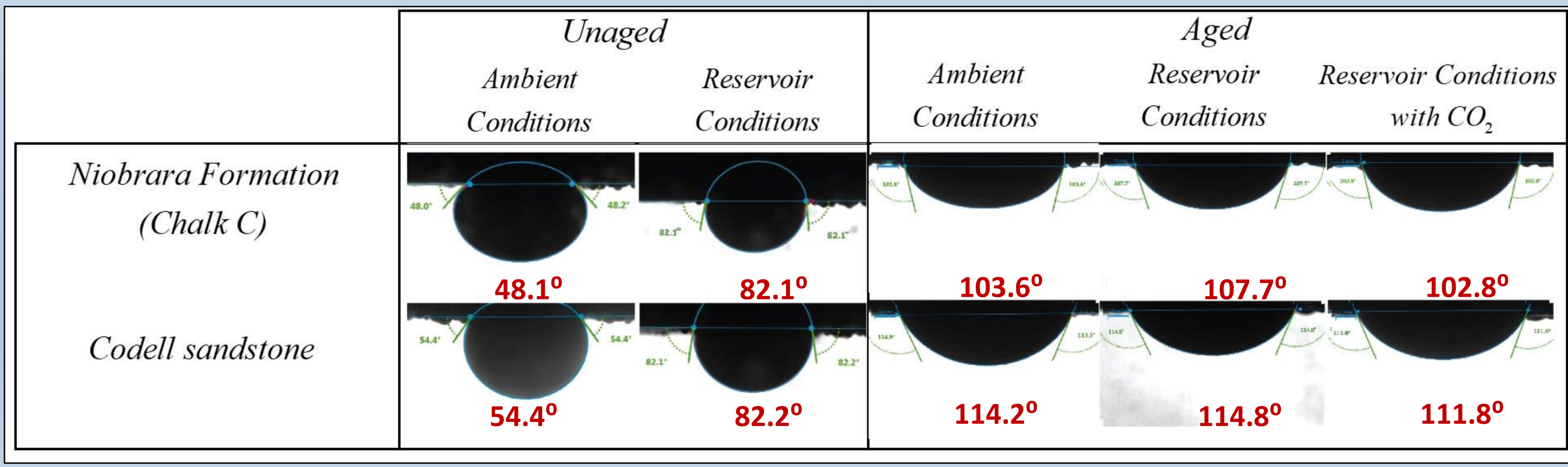
Contact Angle Measurements

DJ Basin	Parameters		Location
	Formation Brine Salinity (ppm)	40,000	
	Formation Brine Density (g/cc)	1.04	
	Oil Density (g/cc)	0.86	

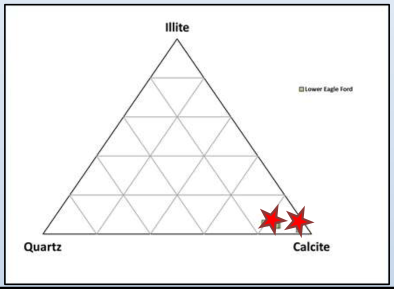
	Unaged		*Aged*		
	Ambient Conditions	*Reservoir Conditions*	*Ambient Conditions*	*Reservoir Conditions*	*Reservoir Conditions with CO_2*
Niobrara Formation (Chalk A)	 **70.7°**	 **86.8°**	 **95.2°**	 **110.3°**	 **107.3°**
Niobrara Formation (Chalk B)	 **49.8°**	 **82.1°**	 **124.1°**	 **137.2°**	 **134.6°**

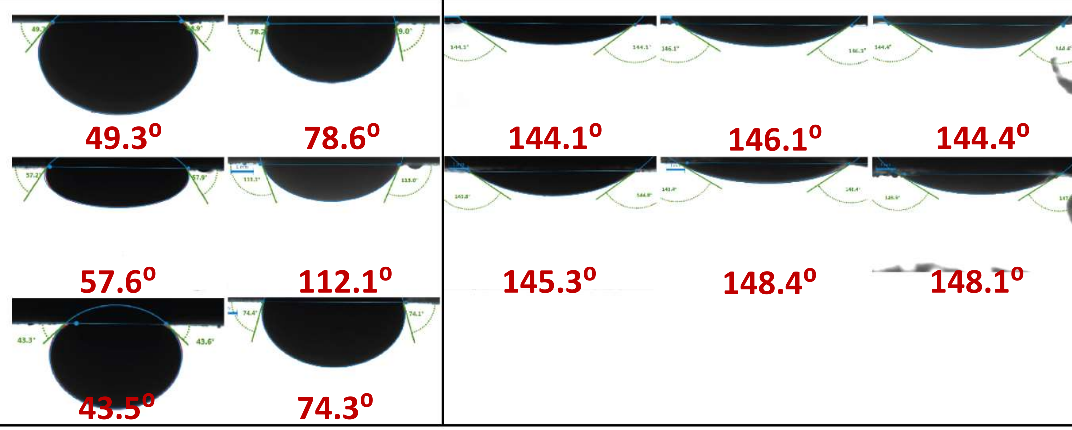
Contact Angle Measurements

DJ Basin	Parameters		Location
	Formation Brine Salinity (ppm)	40,000	
	Formation Brine Density (g/cc)	1.04	
	Oil Density (g/cc)	0.86	



Contact Angle Measurements

Eagle Ford	Parameters		Location
	Formation Brine Salinity (ppm)	70,000	
	Formation Brine Density (g/cc)	1.06	
	Oil Density (g/cc)	0.86	

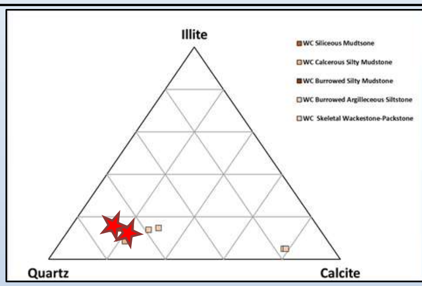


	Unaged		*Aged*		
	Ambient Conditions	*Reservoir Conditions*	*Ambient Conditions*	*Reservoir Conditions*	*Reservoir Conditions with CO_2*
Lower Eagle Ford	49.3°	78.6°	144.1°	146.1°	144.4°
	57.6°	112.1°	145.3°	148.4°	148.1°
	43.5°	74.3°			

Contact Angle Measurements

MINES MUDTOC

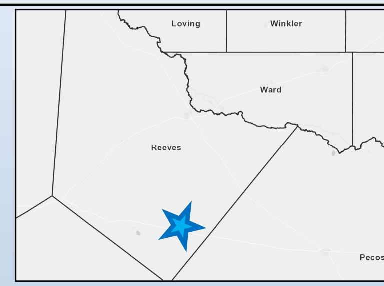
Permian Basin

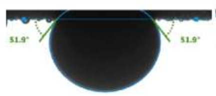


Parameters

Parameters	
Formation Brine Salinity (ppm)	70,000
Formation Brine Density (g/cc)	1.06
Oil Density (g/cc)	0.86

Location



	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°

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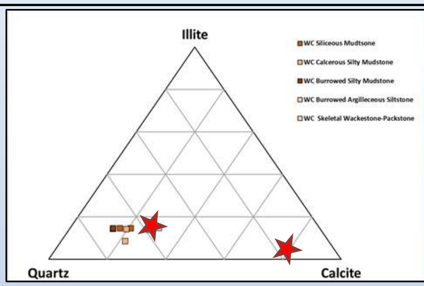
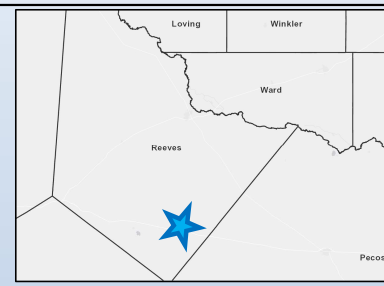
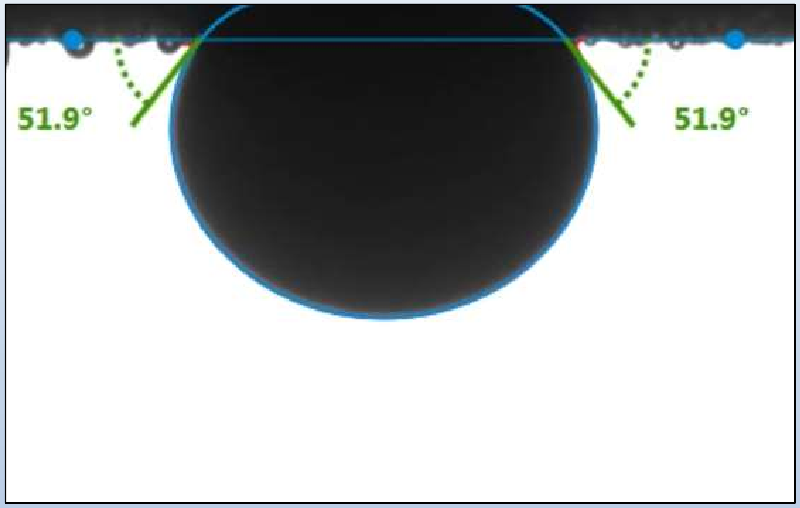
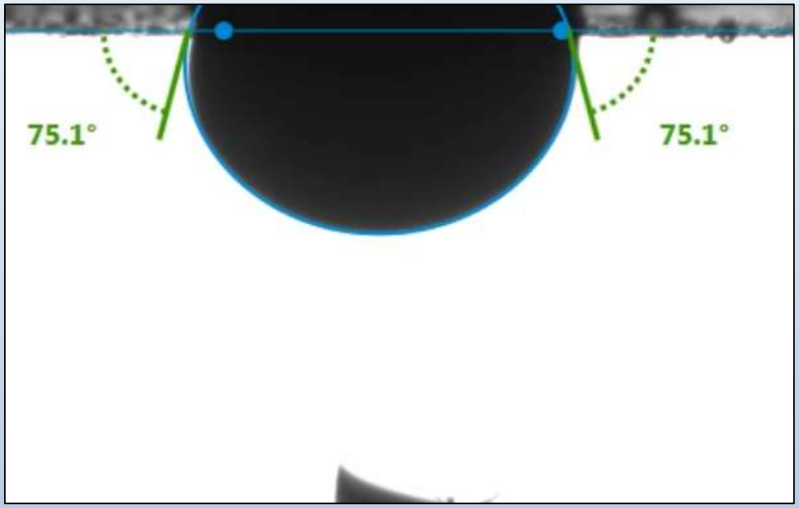
Contact Angle Measurements

Permian Basin	Parameters		Location
	Formation Brine Salinity (ppm)	70,000	
	Formation Brine Density (g/cc)	1.06	
	Oil Density (g/cc)	0.86	

	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

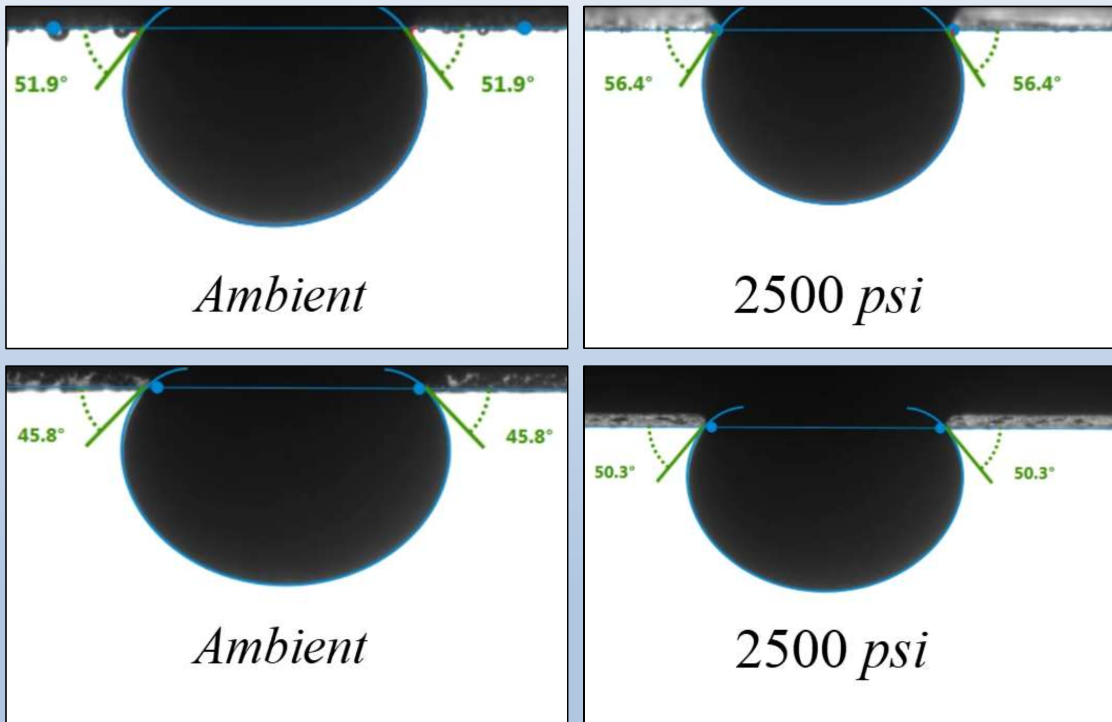




- Rapid increase (<3 hrs)
- Permanent
- Change varies

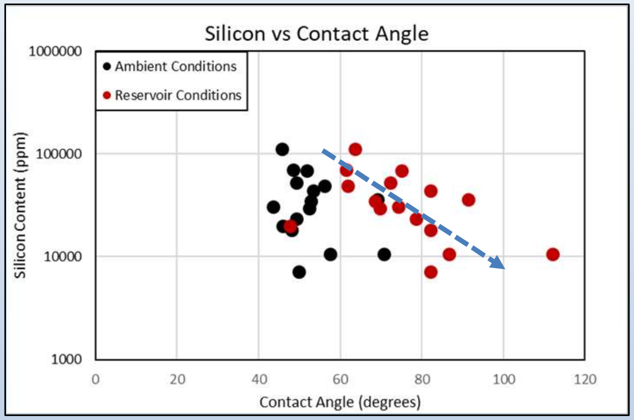
Sample Basin/Formation	Change (in degrees)
Williston Basin	5-7
DJ Basin	16-34
Eagle Ford	29-54
Wolfcamp	13-23

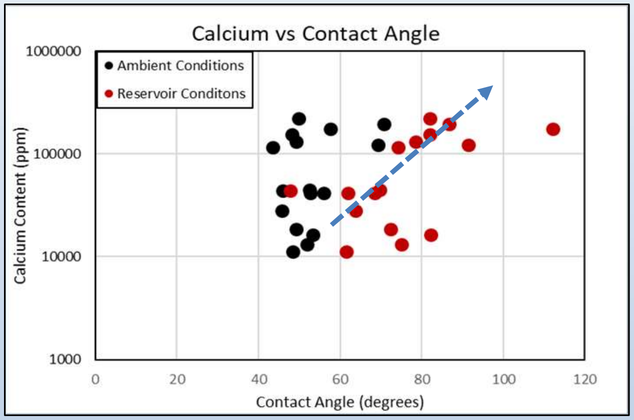
Effect of Pressure

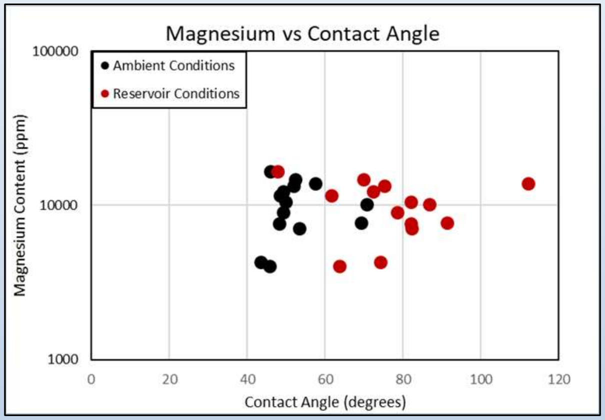


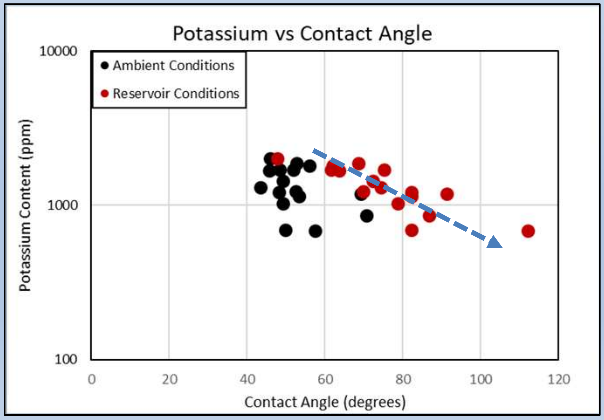
- Immediate increase
- Temporary
- Change is same on all samples (~4.5°)

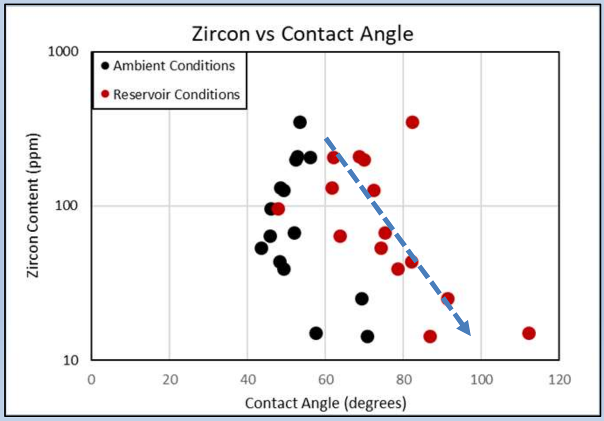
Effect of Mineralogy on Contact Angle Changes (Unaged Cores)











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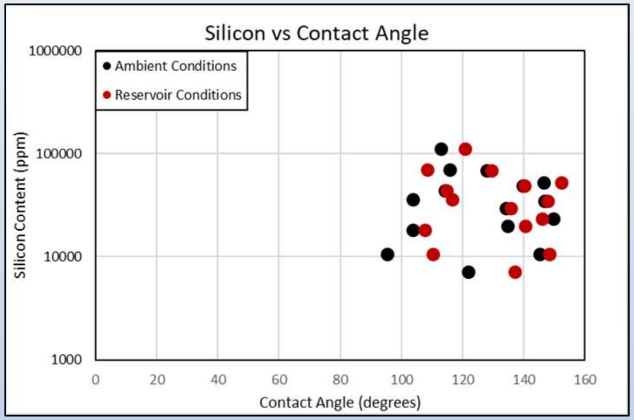
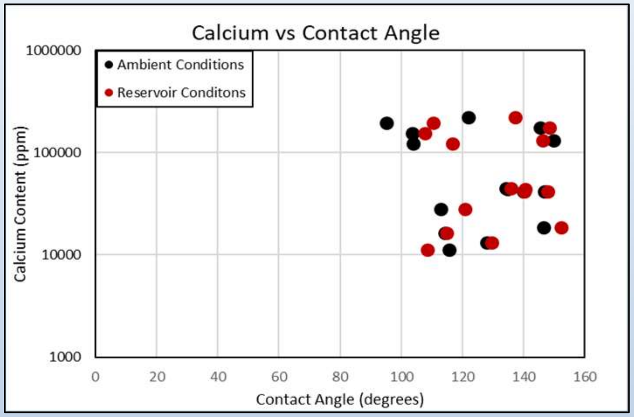
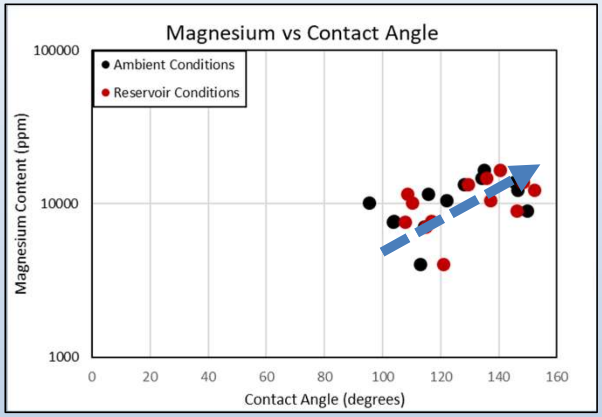
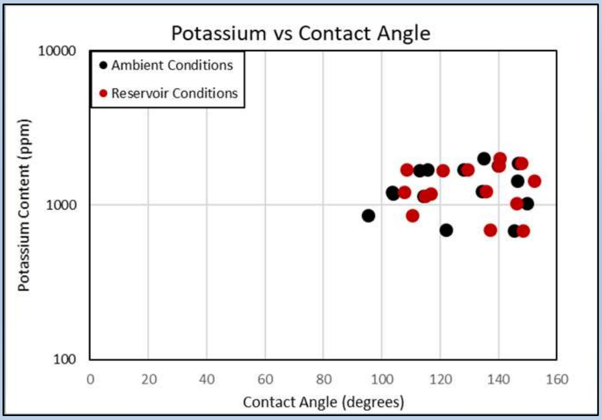
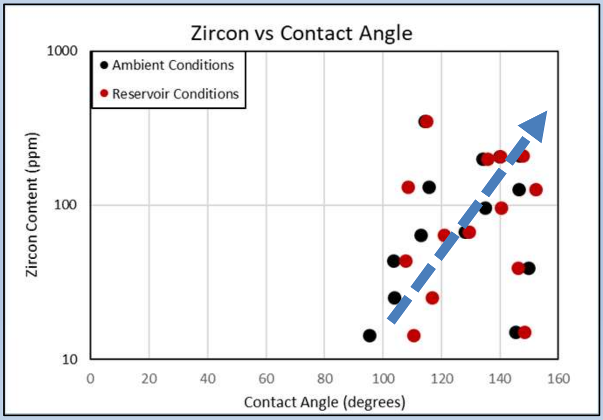
Effect of Mineralogy on Contact Angle Changes (Aged Cores)



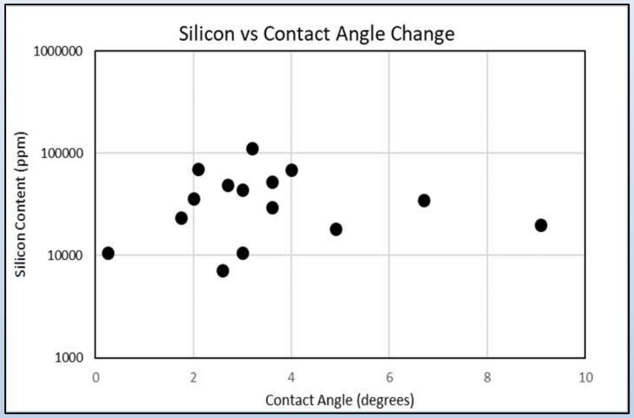


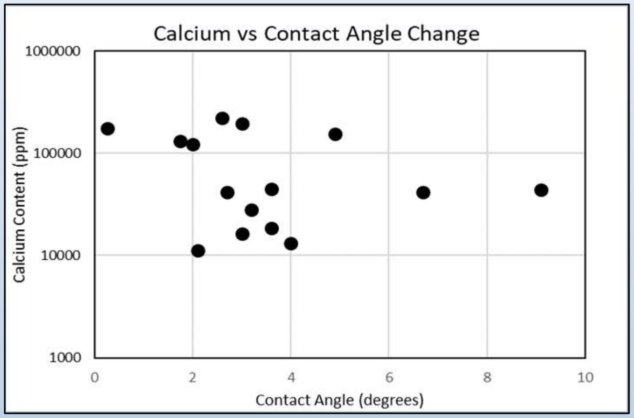


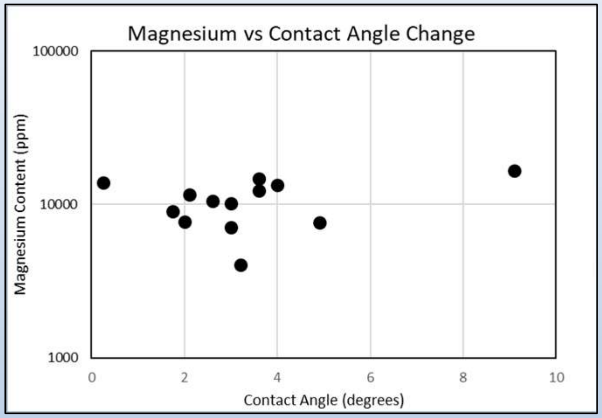


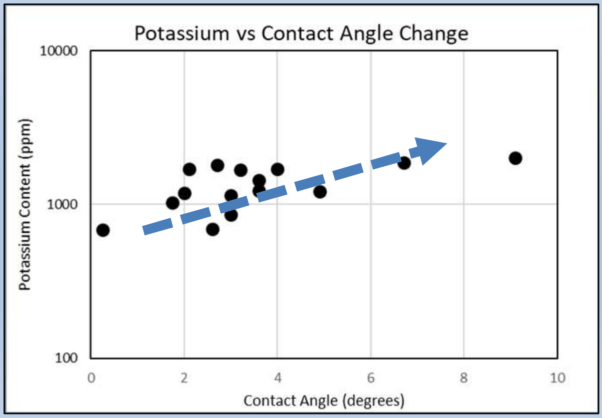


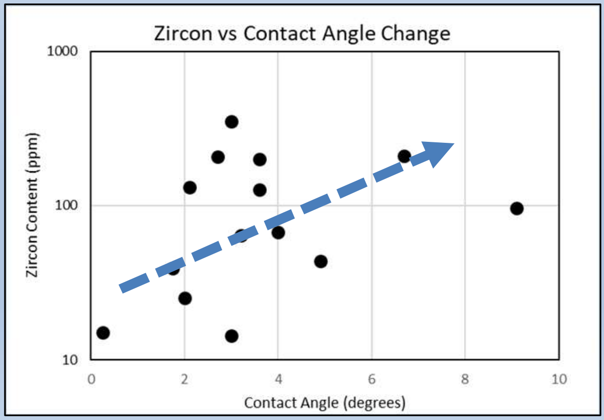
Effect of Mineralogy on Contact Angle Changes (Aged Cores with CO_2)











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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