Wettability Alteration in Reservoirs: How It Happens and How It Boosts Production*

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Abstract

Current economic conditions have challenged producers to find methods to lower costs and improve production. The current 50% reduction in oil prices means we need significant changes to stay competitive. Reservoir wettability can have a pronounced effect on hydrocarbon recovery and offers a method to substantially improve well performance and increase reserves for little investment. We know that each reservoir has a wettability state that leads to maximum recovery, but the initial wettability of a reservoir is usually not optimal. Traditionally, we have used surfactants and chemical agents to try and optimize reservoir wettability and recovery, but this process is expensive and does not always produce the desired results. This talk will outline recent advances in the science of reservoir wettability, as well as a practical methodology to realize the goal of increasing well recovery in unconventional and conventional reservoirs.

First, laboratory and field examples of successes and failures are considered. Using this basis, a theory is developed that directly links water chemistry and reservoir wettability. The theory also illuminates the key characteristics of the reservoir that control wettability. The approach can explain the successes and failures of low salinity waterflooding and provide the basis for designing the correct fluid chemistry while minimizing negative effects such as reservoir damage. This provides the ability to optimize reservoir wettability with simple systematic changes to the water chemistry of well fluids in both unconventional and conventional reservoirs.

The successful approach to reservoir wettability alteration requires several key steps: screening the formation to evaluate the applicability of the technique, simple laboratory tests to determine the optimal water chemistry and quantify the increased recovery, economic evaluations to estimate costs and benefits, and finally, comprehensive geochemical models to design the wettability modifying fluids. The technique has several advantages compared to current methodologies for wettability alteration including substantially lower costs, no environmental impacts, and ease of application.

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Wettability alteration in reservoirs: How it happens and how it boosts production.

Geoffrey Thyne

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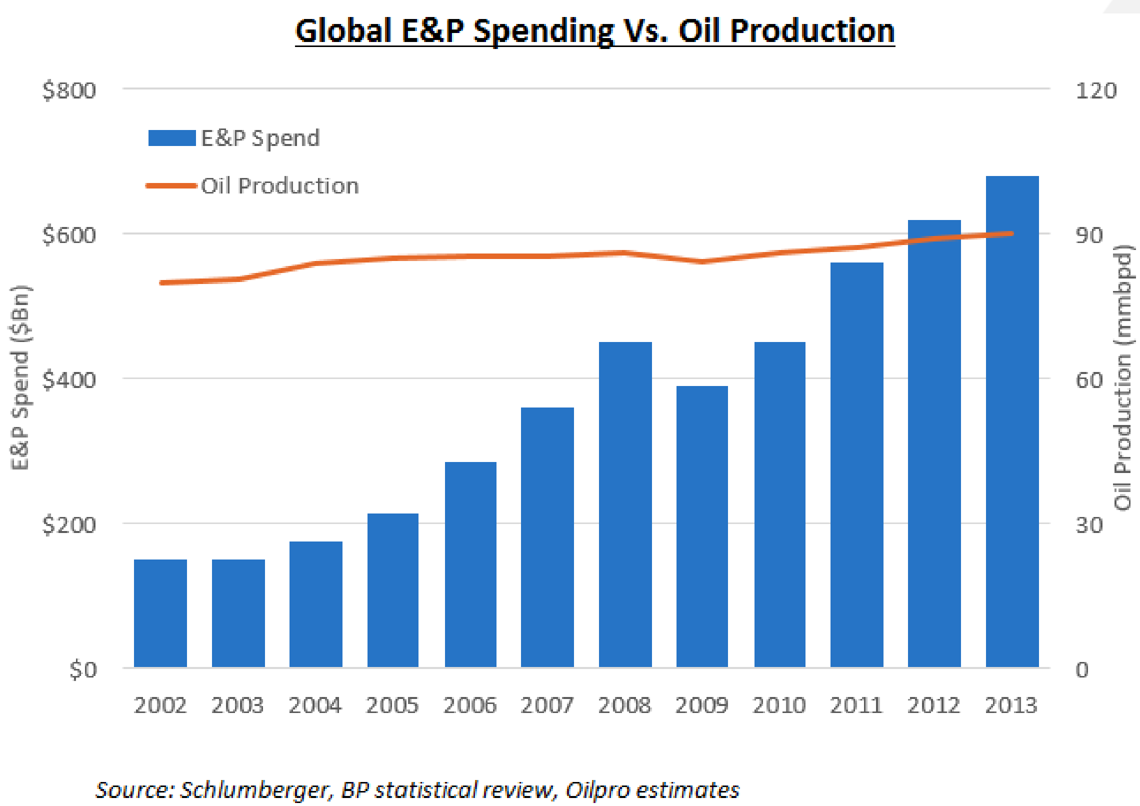
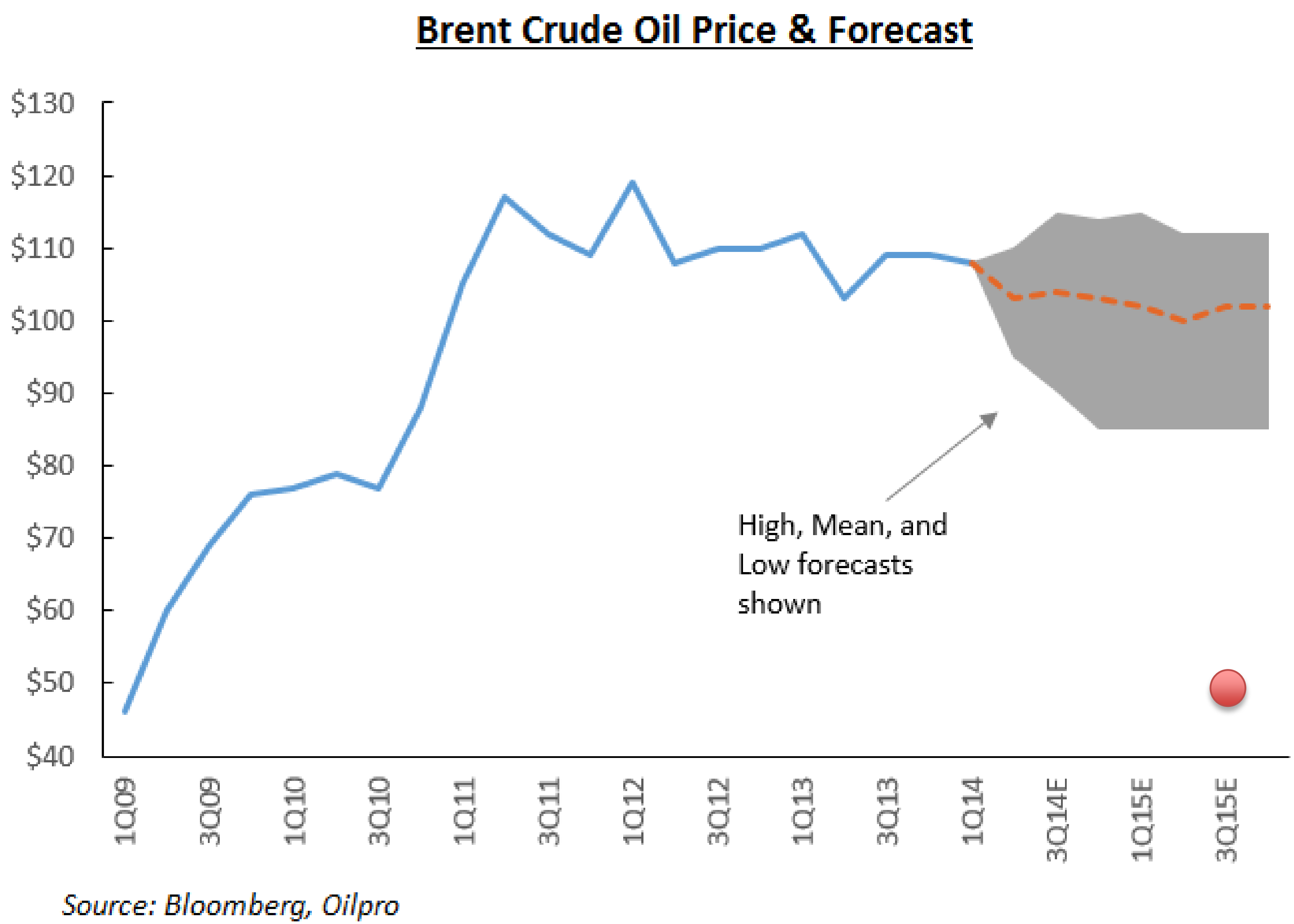
Engineered Salinity

Global Industry Investment

Exploration is not returning value



ESal Engineered Salinity


Brent Crude Oil Price & Forecast
$130
$120
$110
$100
$90
$80
$70
$60
$50
$40
1Q09
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1Q10
3Q10
1Q11
3Q11
1Q12
3Q12
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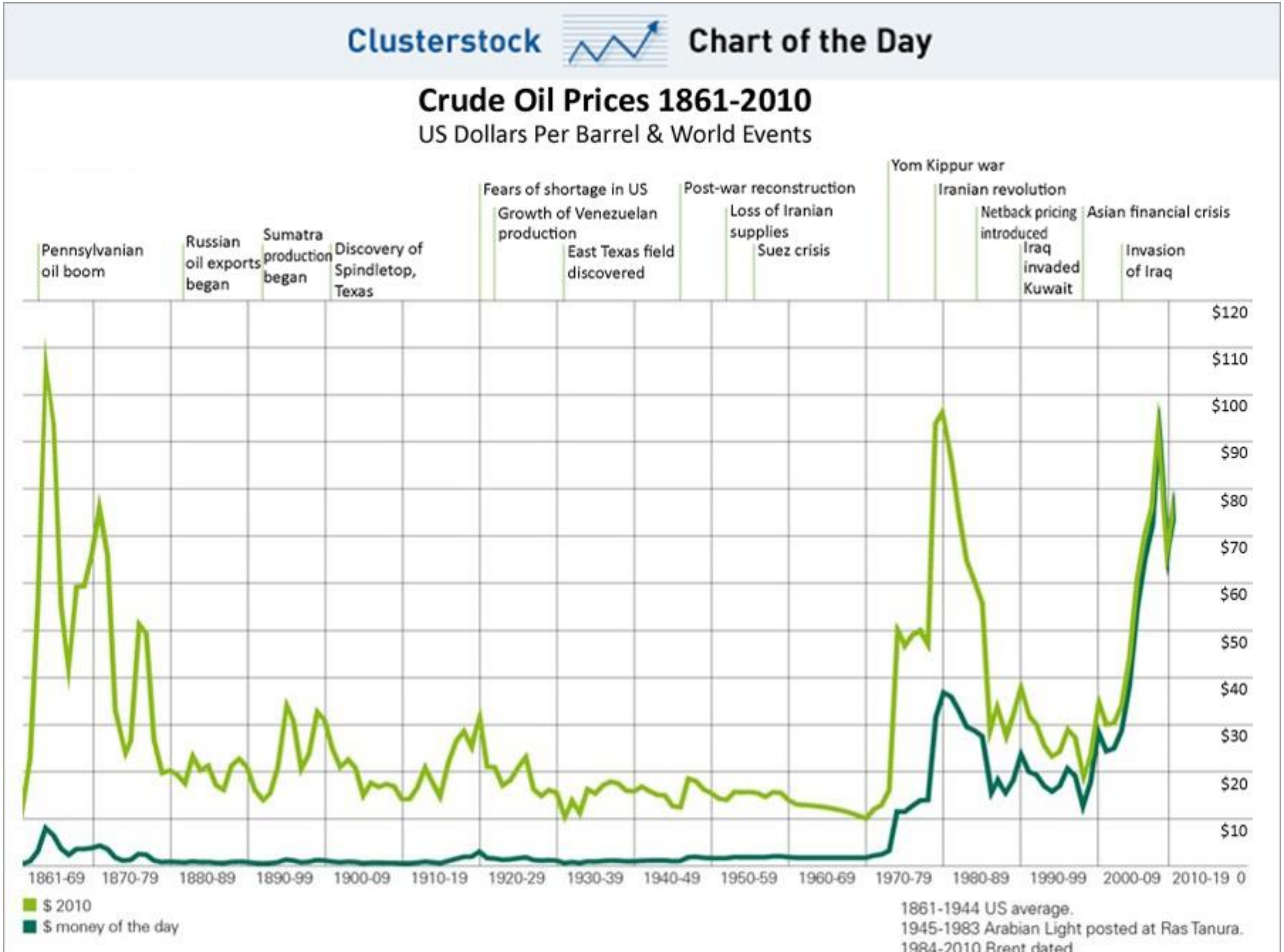
1Q15E
3Q15E
High, Mean, and
Low forecasts
shown
Source: Bloomberg, Oilpro


Clusterstock
Chart of the Day
Crude Oil Prices 1861-2010
US Dollars Per Barrel & World Events
Pennsylvanian oil boom
Russian oil exports began
Sumatra production began
Discovery of Spindletop, Texas
Fears of shortage in US
Growth of Venezuelan production
East Texas field discovered
Post-war reconstruction
Loss of Iranian supplies
Suez crisis
Yom Kippur war
Iranian revolution
Netback pricing introduced
Iraq invaded Kuwait
Asian financial crisis
Invasion of Iraq
$120
$110
$100
$90
$80
$70
$60
$50
$40
$30
$20
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0
1861-69
1870-79
1880-89
1890-99
1900-09
1910-19
1920-29
1930-39
1940-49
1950-59
1960-69
1970-79
1980-89
1990-99
2000-09
2010-19
$ 2010
$ money of the day
1861-1944 US average.
1945-1983 Arabian Light posted at Ras Tanura.
1984-2010 Brent dated.

What I learned so far this year

- It is time to figure out how to make a living on $40.00 oil or lower. *Gillespie -2015*.
- A key issue is recognizing value.

Will you recognize value?

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Outline

- Take Home.
- Why use this technique?
- What is this technique?
- Science and Engineering.
- Practical Aspects.

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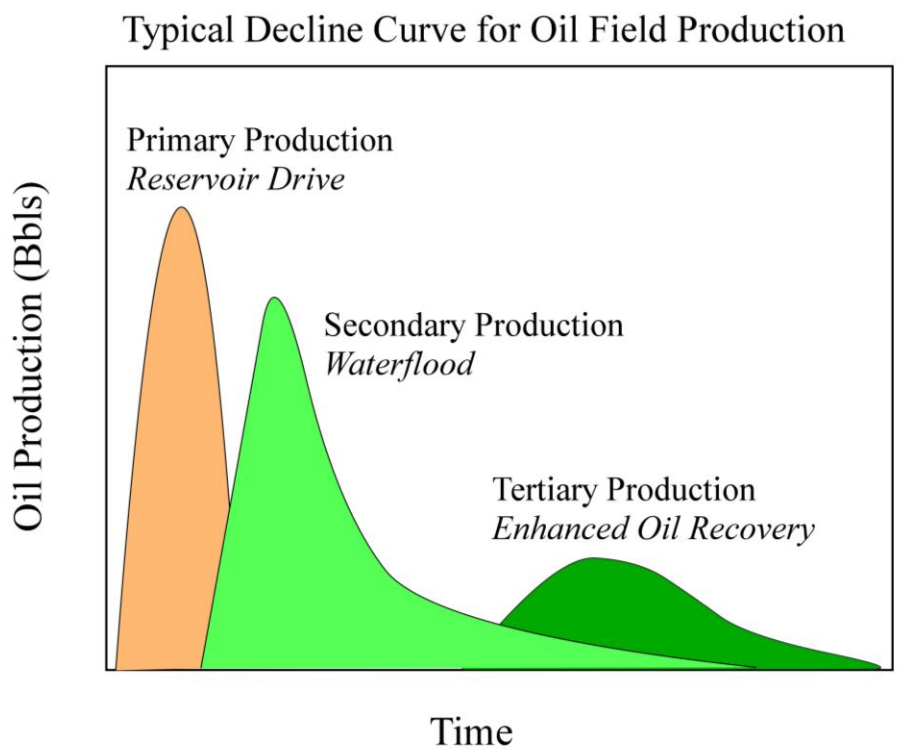
Take Home Message

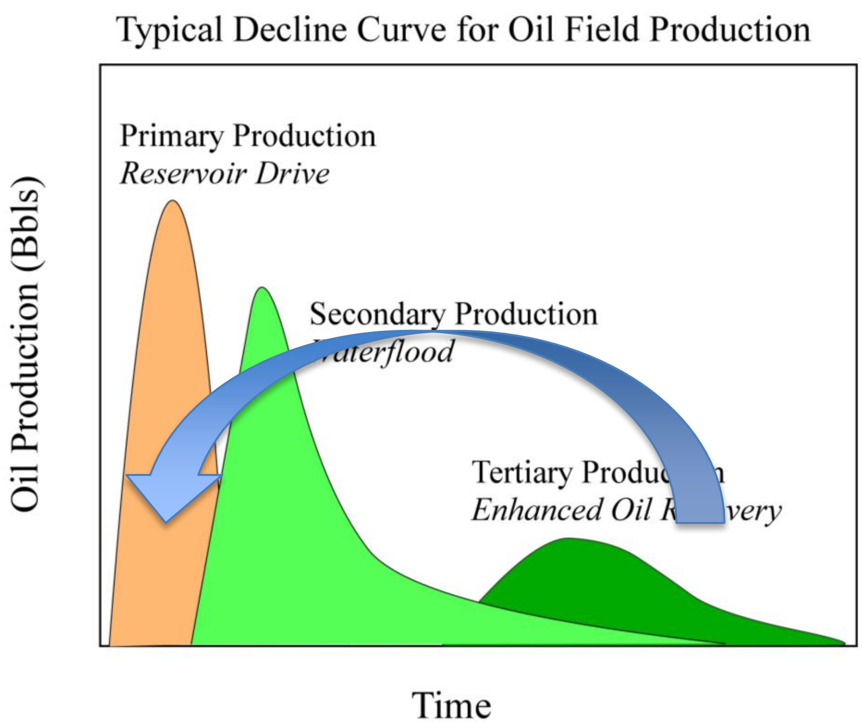
- Typical Oilfield Production



ESal Engineered Salinity

Take Home Message

- Wettability Alteration can be employed at any stage.
- Can be deployed during D&C (unconventional).



What I learned so far about wettability

- Wettability is the ability of an immiscible fluid to adhere to or spread on a rock surface in the presence of another immiscible fluid (e.g. oil and water).
- The concept of wettability is useful in petroleum reservoirs, but functional reservoir wettability is not traditional wettability, rather it is the adhesion (sorption) of oil to rocks.

Wettability Modification

- Recent Papers:
  - Mahani et al. 2015 (Shell) – carbonate mechanism, field results.
  - Ayirala and Yousef 2014 (Aramco)– review of performance and guidelines for projects.
  - Brady et al. 2013 (Sandia) – mechanisms and modeling.
  - Mwangi et al. 2013 (LSU)– methods and experiments.
  - Dang et al. 2013 (SPE 166447) – modeling low sal.

Why Alter Wettability by Salinity?

- No Change in Normal Operations.
- Increase in Recovery is High (5-25% OOIP).
- Increase Reserves for minimal investment.
- Low additional production cost ($0.50 to $5 per bbl).
- Works in Clastics and Carbonates.
- Response is Rapid (3-9 months).
- No Surfactants ($$).
- Minimal Environmental Impact.

Reserve Growth

Reservoir	Reserves	Worth	%OOIP	bbls Gained	Worth
OOIP (MMbbl)	bbls in field	$100/bbl	$50/bbl	(15% OOIP)	(gained)
2	700,000	$70,000,000	$35,000,000	300,000	$15,000,000
4	1,400,000	$140,000,000	$70,000,000	600,000	$30,000,000
8	2,800,000	$280,000,000	$140,000,000	1,200,000	$60,000,000
10	3,500,000	$350,000,000	$175,000,000	1,500,000	$75,000,000
15	5,250,000	$525,000,000	$262,500,000	2,250,000	$112,500,000
25	8,750,000	$875,000,000	$437,500,000	3,750,000	$187,500,000
50	17,500,000	$1,750,000,000	$875,000,000	7,500,000	$375,000,000
75	26,250,000	$2,625,000,000	$1,312,500,000	11,250,000	$562,500,000
100	35,000,000	$3,500,000,000	$1,750,000,000	15,000,000	$750,000,000

Application to Conventional Reservoirs

- Evidence from clastic and carbonate reservoirs show 10-30% OOIP additional recovery.
- Increase value in new reservoirs.
- Increase value in existing reservoirs.
- Discover hidden value in stripper/depleted fields.
- Increase production at low cost.
- Increase reserves with single pilot.

Application to Unconventional Reservoirs

- Evidence from Bakken, Milk River and Wolfcamp that current fluids do not optimize wettability.
- Instead of fresh water formulations, brackish water formulations may improve production.
  - Water source costs are lower
  - Reuse of flowback
- May be able to use geophysical logs (FMI) to determine in-situ wettability.

Success and Failure in the Field

Successes

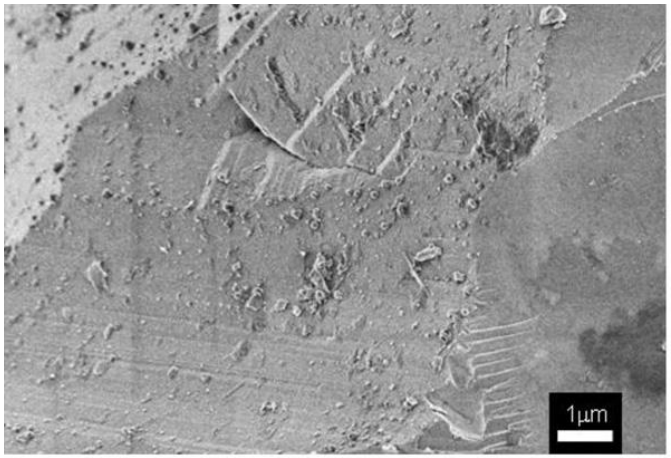
- BP - North Slope – waterflooding SS field (10-15% OOIP).
- Conoco-Phillips - North Sea – waterflooding deep chalk field (30% OOIP).
- Shell - Syria –waterflooded SS field - (10-15% OOIP).
- Pioneer - Spraberry SS (lab) – 10% OOIP.
- ExxonMobil – lab experiments and patents.

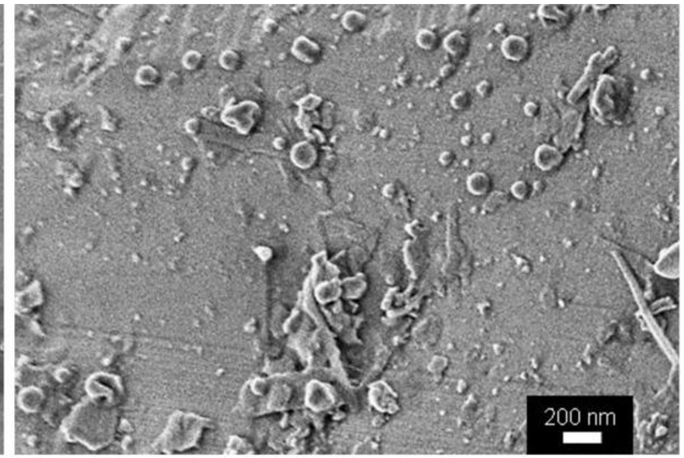
Failures

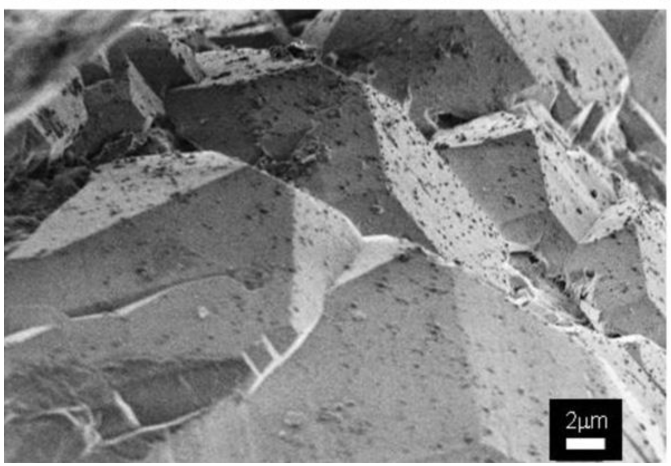
- Wyoming – low salinity Minnelusa SS
  - no increase in recovery.
- North Sea – low salinity into Stratfjord with minimal response (<2% OOIP)

Observations of Reservoir Wettability

FESEM images - Sandstone surface coated with oil, at pH of 4 in 0.01 M NaCl







Lebedeva and Fogden 2011

What scale are we talking about?

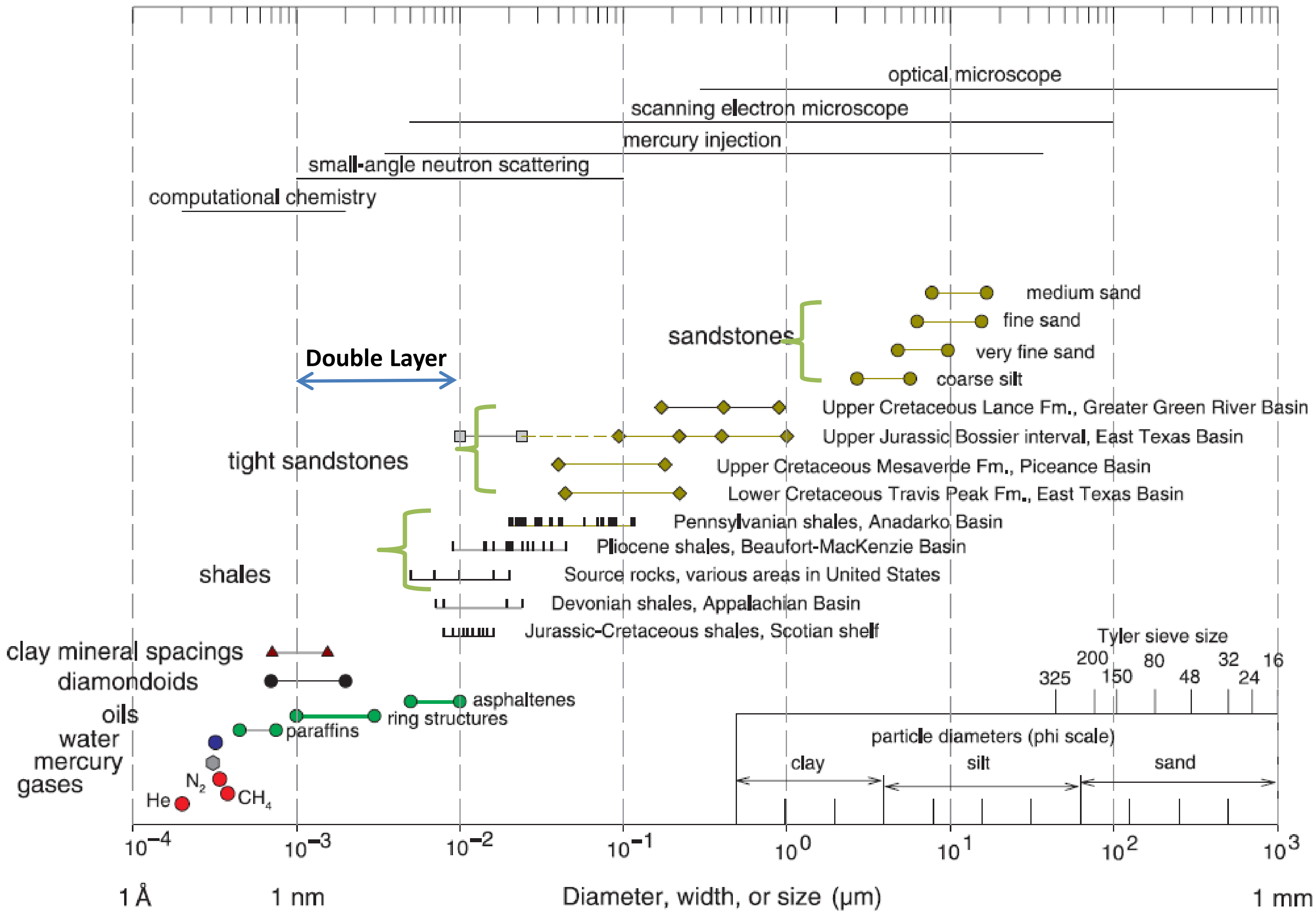
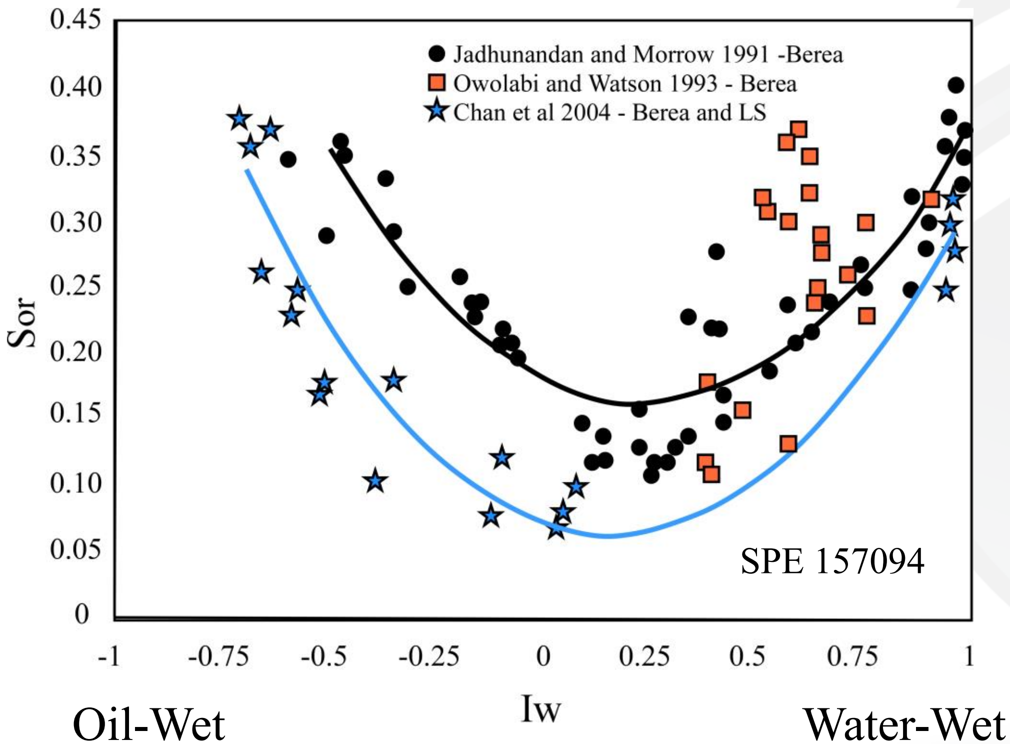


Figure 2. Sizes of molecules and pore throats in siliciclastic rocks on a logarithmic scale covering seven orders of magnitude. Measurement methods are shown at the top of the graph, and scales used for solid particles are shown at the lower right. The symbols show pore-throat sizes for four sandstones, four tight sandstones, and five shales. Ranges of clay mineral spacings, diamondoids, and three oils, and molecular diameters of water, mercury, and three gases are also shown. The sources of data and measurement methods for each sample set are discussed in the text.

Nelson 2009

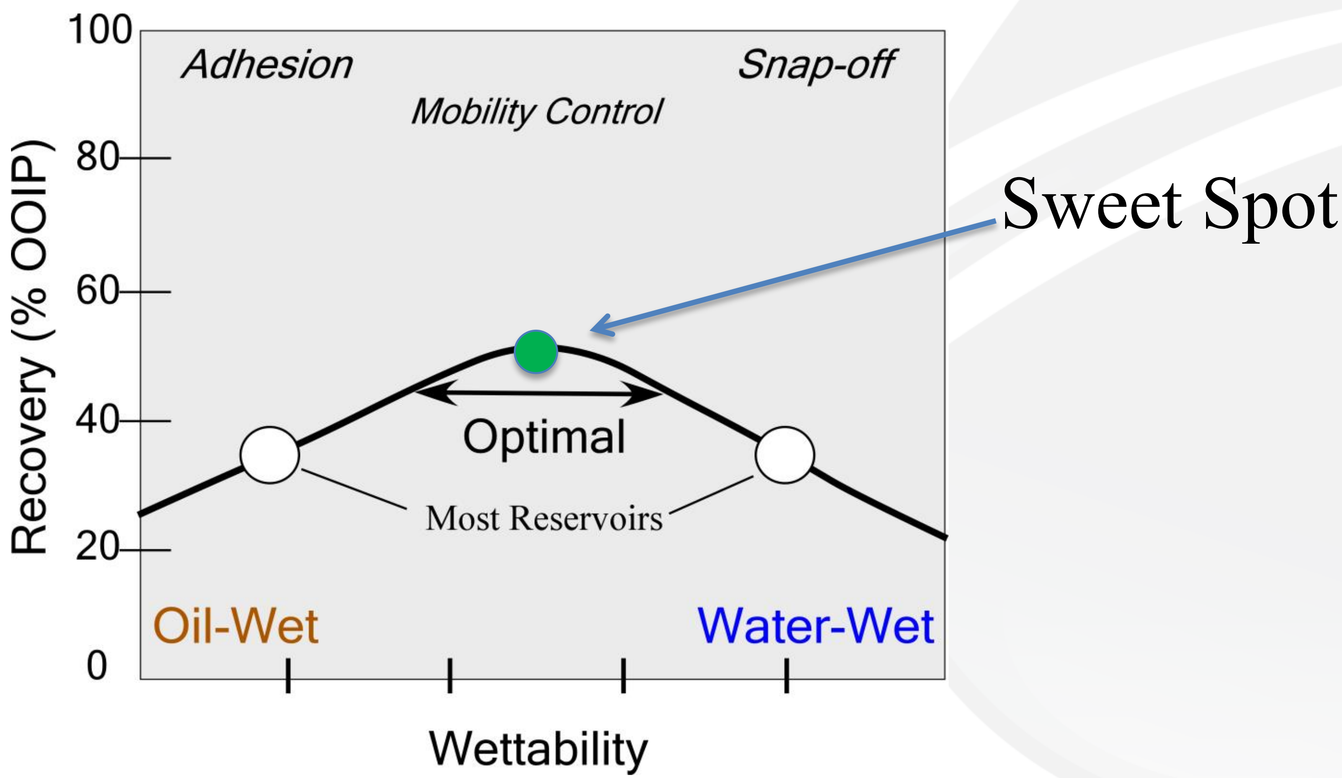
Functional Reservoir Wettability

- Reservoir wettability is the equilibrium between water, rock and oil.
- Wettability is major control on recovery.
- *"Hydrocarbon-wet systems retard hydrocarbon mobility".*
- *"Water-wet systems promote hydrocarbon mobility".*



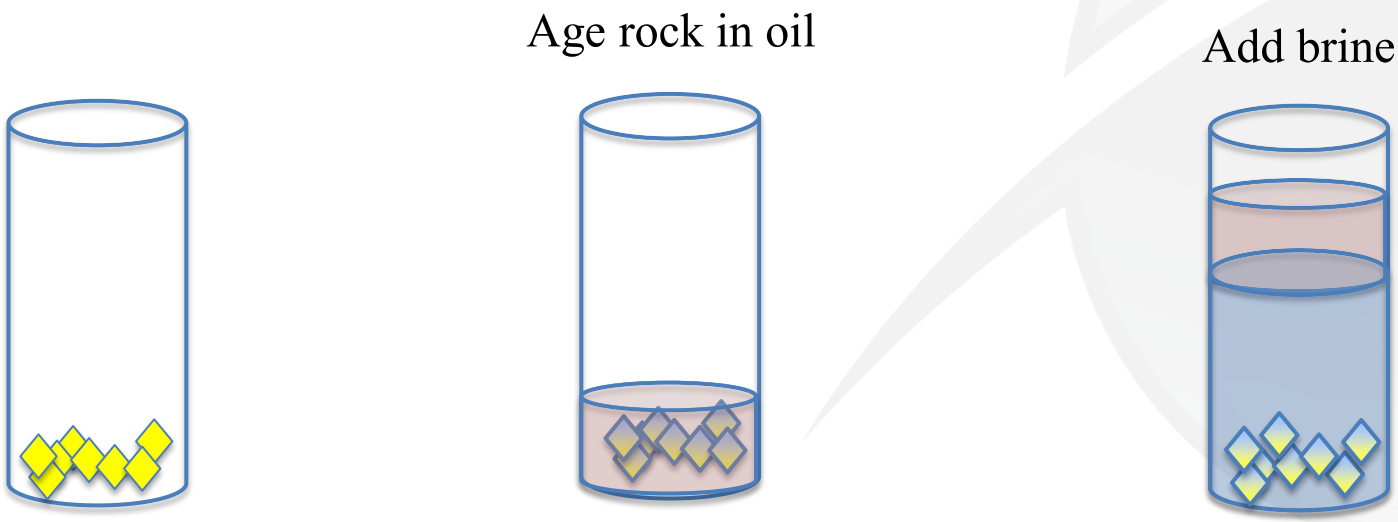
Functional Reservoir Wettability

Recovery = Oil Release + Oil Mobility



Water Films?

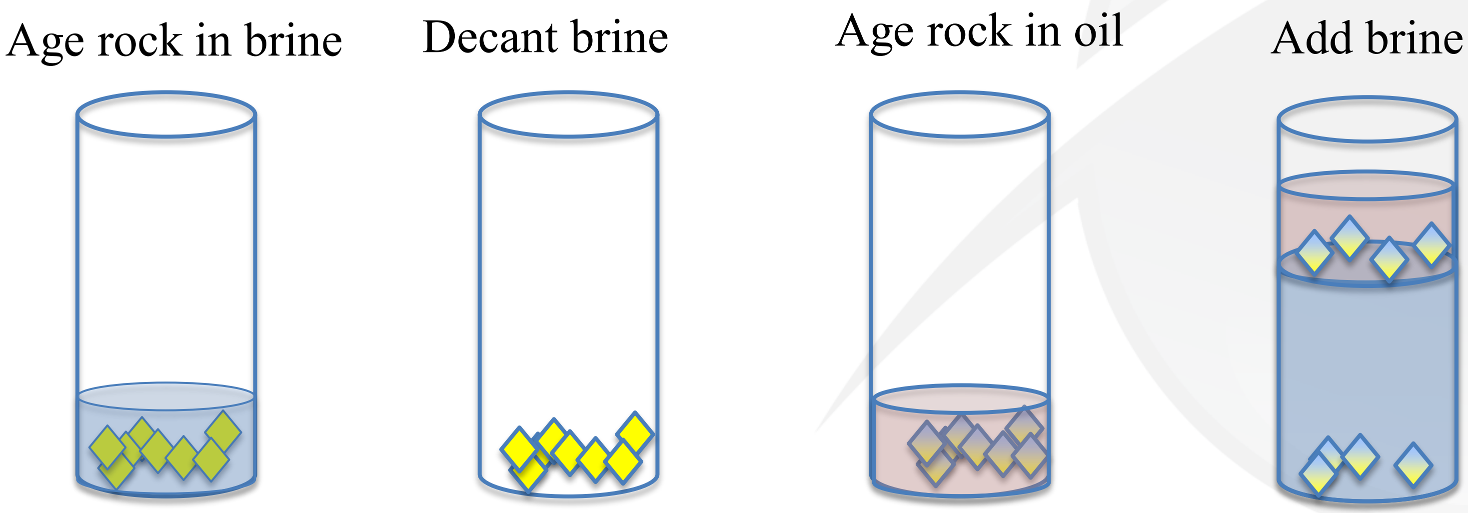
- Modified Flotation Test shows importance of water films in functional reservoir wettability
  - Age rock in 3ml of oil (decane) for 48 hours, stir every 12 hours.
  - Add brine to oil-rock mixture.
  - Stir and allow 24 hours.
  - Decant, dry, and weight fractions.



From Mwangi and others, 2013

Water Films?

- Modified Flotation Test
- Allows rapid investigations in wide range of rock types
  - Age 0.2 grams of rock in brine for 48 hours.
  - Decant brine.
  - Age rock in 3ml of oil (decane) for 48 hours, stir every 12 hours.
  - Add brine to oil-rock mixture.
  - Stir and allow 24 hours.
  - Decant, dry, and weight fractions.



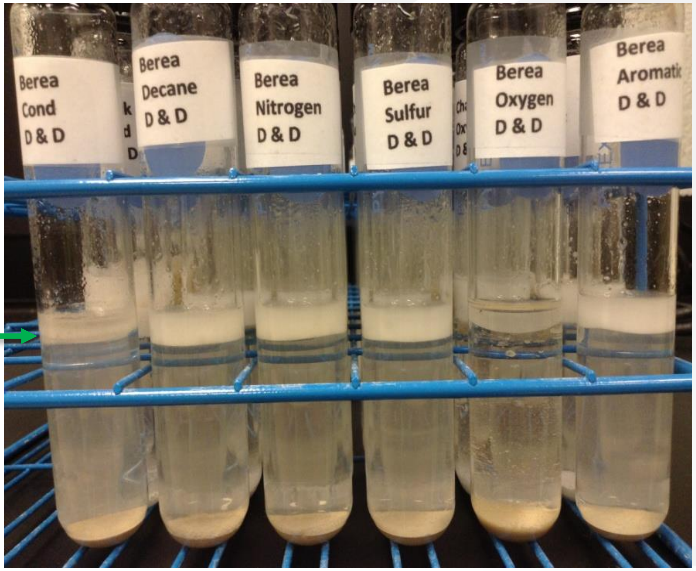
From Mwangi et al. 2013

Lab Tests - Modified Floatation

Rock powder floats in oleic phase

Initial separation

Rock particles settle to interface



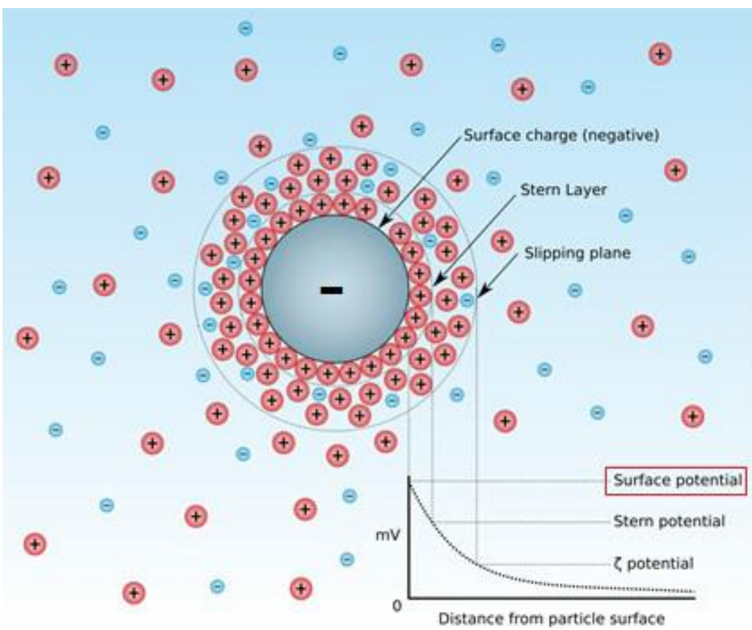
After 24 hours

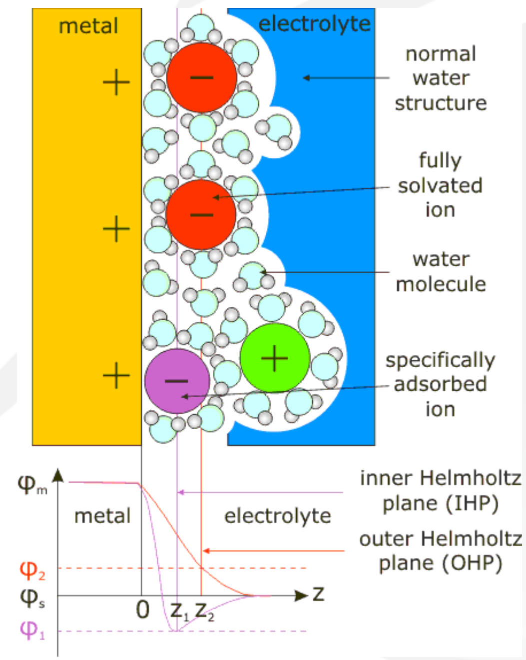
How do we link wettability to salinity?

- Functional Reservoir Wettability is the equilibrium between water, rock and oil.
- FRW is dependent on the balance of forces between the oil-water and water-rock interfaces.
- Force (pressure) between surface with a water film and oil in the reservoir is composed of:
  - 1 – electrostatic (attractive or repulsive),
  - 2 – van der Waals (attractive),
  - 3 – structural or hydration (repulsive below 3-4 nm).
- Change in water chemistry changes the balance.

Functional Reservoir Wettability Models

- Model of aqueous, oil and surface reactions.
- Double layer models assume surfaces are coated with water and electrostatic forces are dominant.





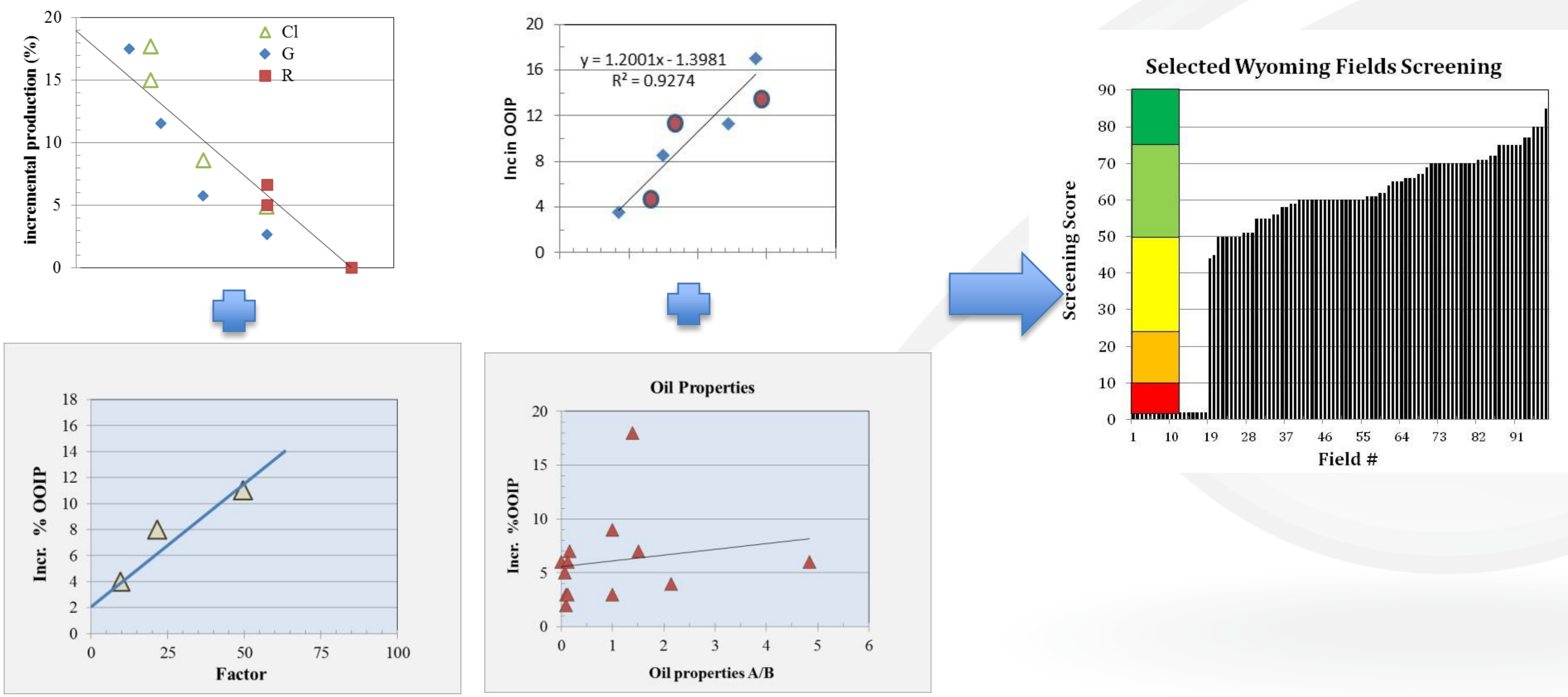
ESal™ Work Flow

- Evaluation (is my field a good candidate?)
  - Screening – Generate Field Score
    - empirical model generates quantitative score based on field, oil, water and rock properties
    - preliminary water source assessment
  - Scoping – Economic Assessment of Projects
    - expense/profit modeling (modified Kinder-Morgan)
    - multiple economic evaluations and scenarios
- Experiments and Models
  - Wettability Measurements
    - rapid scan to find optimum chemistry
  - Modeling to assess other fluid-fluid-rock interactions
  - Design injection fluid chemistry for optimum wettability
- Deployment
  - Select water source
  - Generate water treatment specifications
  - Install equipment

Screening for good candidates

Use lab and field to determine empirical relationships.

Input rock, water, oil and field properties to algorithm and calculate aggregate weighted score.

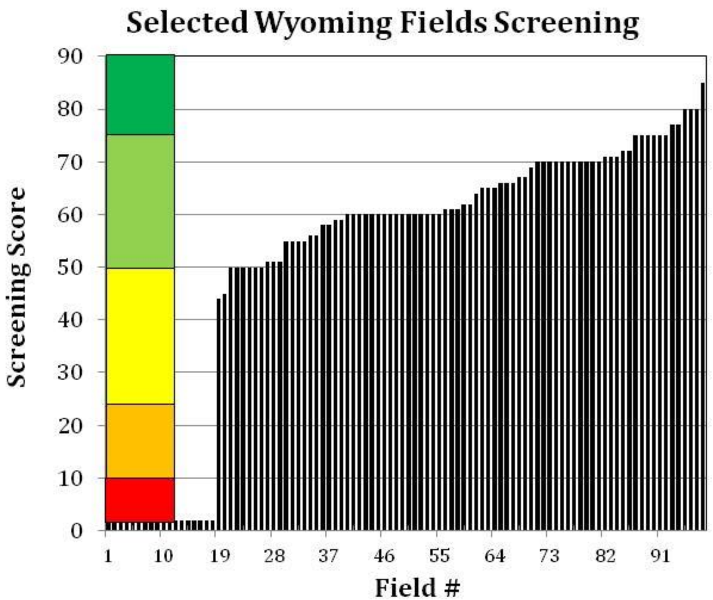


Example Wyoming Screen

Use Esal™ Screening Tool

Evaluate 100 fields with public data

- Sandstones - Almond, Chugwater, Fox Hills, Frontier, Lakota, Lance, Mesaverde, Minnelusa, Muddy, Nugget, Shannon, Sussex, Tensleep, and Wasatch.
- Carbonates - Madison, Phosphoria and Embar.



Scoping Tool

ESal Engineered Salinity

Default/Calculated Cell	Option/Data Entry Cell

Developed Area Resource Details	Value
*Original Oil In Place (OOIP,bbls)	9,617,523
Cumulative Oil Production (bbls)	2,885,257
*Last Monthly Oil Production (bbls)	6,204
*Last Water Production (bbls/well-month)	20,000
*Percent(%) Produced Water Reinjected	70%
*Treated Water Initial TDS	40,000
*Monthly Production Decline Rate (%/mo)	1.50%
*Average Depth (feet)	7,145
*Initial Formation Volume Factor (rb/stb)	1.05
*Current Formation Volume Factor (rb/stb)	1.05
Average Net Pay Thickness (feet)	40
Oil Gravity (API)	37
Initial Oil Saturation (Soi)	90%
Porosity (md)	0.20
Permeability (md)	235.00
Planned Active Wells	**Value**
*Active Producing Wells	7
*Active Injection Wells	3
***Total Active Wells**	10
Mineral Lease Shares	**Lease Share**
*Federal Lease	80.00%
*Tribal Lease	0.00%
*State Lease	10.00%
*Private Lease	10.00%
*Private Override Share	80.00%
Royalty & Tax Rates	**Rate**
*Federal Lease	12.50%
*Private Override	5.25%
*Tribal Lease	18.75%
*State Lease	16.70%
*Private Lease	18.75%
*Property Tax	6.95%
*State Severance Tax	6.00%
*Tribal Severance Tax	8.50%

Please Choose an Analog from the Dimensionless Curve Library

Code	Dimensionless Curve	HCPVs	Inc. Oil
1	ESal Low Incremental	2.2521	5.01%
2	Esal Mid Incremental	2.2521	9.92%
3	ESal High Incremental	2.2521	15.03%
4	ESal Custom Analog (13.9%)	2.9800	13.91%
***Enter Code of Analysis Curve**		2	2

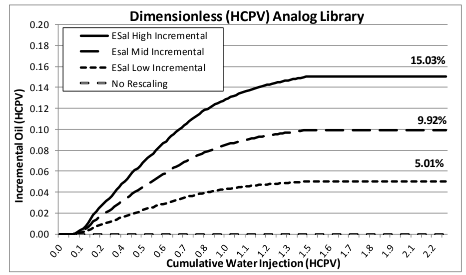
Analog & Injection Rate Assumptions	Analysis Value	Default/Calc Override
Dimensionless Curve	Esal Mid Incremental	
Analog's Max HCPV Inj & Incremental Oil	2.25 HCPVs	9.92% Incr Oil
Rescale Max Incremental Oil (%HCPV)	9.92%	
Rescale Injection Rate (%HCPV/Year)	11.65%	
*Hydrocarbon Pore Volume (HCPV,rb)	10,098,399	
Oil Pricing Assumptions	**Analysis Value**	**Default/Calc Override**
*1=Constant, 2=Time Trend, 3=Random	1	
*Constant or Starting Oil Price ($/Bbl)	$50	$50.00
*Oil Price in 25 Years (Time Trend)	N/A	
Acquistion & Well Development Costs	**Analysis Value**	**Default/Calc Override**
Oil Property Acquistion Cost ($)	$0	
Additional Well Work CAPEX ($)	$0	
Water Treatment CAPEX	**Analysis Value**	**Default/Calc Override**
* Treatment Technology (1=RO, 2=EDR)	1	
*Treatment CAPEX ($/water-bpd)	$363	
*Processed Water-Barrels/Day (bpd)	3,220	
*Total Est. Treatment CAPEX	$1,167,146	

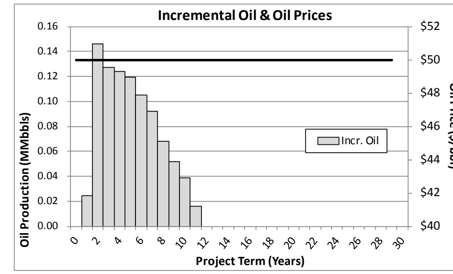
Total Upfront CAPEX & Design Fees	$1,242,146	

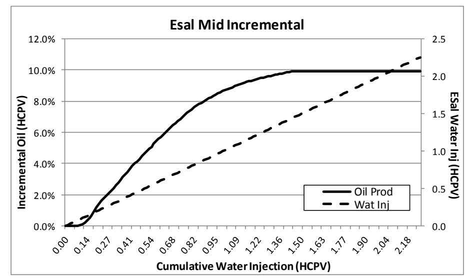
Operating Costs	Analysis Value	Default/Calc Override
* Water Treatment OPEX/wbbl	$0.40	
*Desal Maintenance Cost (%CAPEX/year)	1%	
*Electricity Price	$0.070	
*Utilities in Lift Costs ($/bbl-liquid)	$0.40	
*Other Lift Costs ($/well-year)	$32,839	

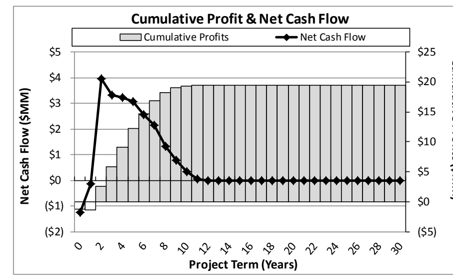
ESal Company Fees/Royalties	Analysis Value	Default/Calc Override
*Project Consulting & Design	$75,000	
*ESal Incr. Oil Royalty Override	4.0%	

Scoping Project Notes:

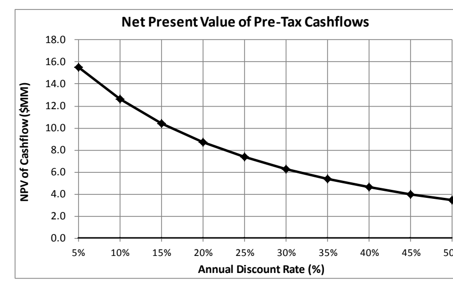








Summary ESal Scoping Results	
Water Injection Rate (HCPV/Year)	11.65%
Duration of E-Sal Flood (Years)	10.50
Cum. Incremental Oil Produced (MMbbls)	0.91
Post-ESal Recovery Factor	39%
Treatment Costs per Bbl Oil (OPEX+CAPEX)	$5.54/bo + $1.36/bo
Calculated Pre-Tax IRR (%)	**145.22%**
Incremental Nominal Oil Revenues ($MM)	**$45.64**
Capital Investment ($MM)	**($1.17)**
Royalties, Severance, Ad Valorem ($MM)	($12.96)
Incremental Operating Costs ($MM)	($10.48)
ESal Design/Consult Fee	**($0.08)**
ESal Royalty Overrides	**($1.59)**
Cumulative Pre-Tax Profits ($MM)	**$19.37**



Scoping - Economic Benefits
Most expensive cost scenario and $50/BBL

<u>Inputs</u>
Capex and Opex
Royalty & Taxes
Pricing

Analog Method (KinderMorgan)

<u>Outputs</u>
Incremental Recovery, IRR, Revenues, NPV's Cum PreTax, etc.

Reservoir Formation	OOIP BBLS in field	wells	%OOIP recovery	Project Life Years	CumPreTax ($) millions
Nugget 3	127,744,810	19	5	9	64.27
	127,744,810		10	11	257.64
	127,744,810		15	12.75	476.06
Nugget 2	46,115,627	18	5	7.5	14.39
	46,115,627		10	10	81.50
	46,115,627		15	10.5	154.61
Almond	40,486,587	125	5	10.25	20.61
	40,486,587		10	8.5	79.89
	40,486,587		15	9.75	148.94
Mesaverde 2	16,025,030	59	5	8.5	7.36
	16,025,030		10	11	32.24
	16,025,030		15	10.5	58.28
Nugget 1	9,617,523	10	5	10	4.76
	9,617,523		10	10	19.37
	9,617,523		15	10	35.05

Questions?