Advanced Petrophysics:
Interfacial Phenomena and Wettability

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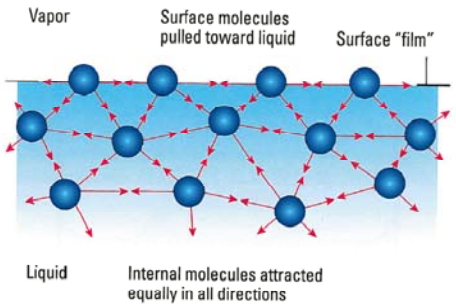
PGE381L Outline

- Introduction to petrophysics, geology, and formation data
- Porosity
- Fluid saturations
- Permeability
- Quantification of heterogeneity, spatial data analysis, and geostatistics
- **Interfacial phenomena and wettability**
- Capillary pressure
- Relative permeability
- Dispersion in porous media
- Introduction to petrophysics of unconventional reservoirs

What do we learn in this lecture?

- What are surface and interfacial tensions?
- Parameters affecting surface tension
- How to quantify surface and interfacial tensions?
- What is wettability?
- Parameters affecting wettability
- How to quantify wettability?
- Reliability of laboratory measurements for assessment of wettability
- Impacts of wettability on reservoir properties and well logs

Interfacial and Surface Tensions



Source: Fundamentals of Formation Testing by Schlumberger

Surface Tension: The contractile force per unit length that exists at the interface of a liquid and its vapor, dynes/cm or ergs/cm2

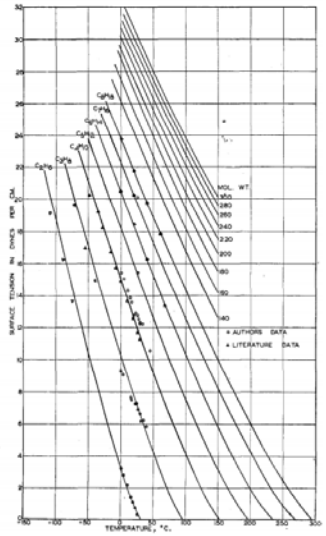
Interfacial Tension: The contractile force per unit length that exists at the interface between two immiscible liquids, a liquid and a gas, or a fluid and a solid, dynes/cm or ergs/cm2

Parameters Affecting Surface Tension

- **Pressure**
- **Temperature**

surface entropy $S^s = -\left(\frac{\partial \sigma}{\partial T}\right)_P$

- **Solute concentration**
- **…**



Source: Katz and Saltman, 1939

How to Quantify Surface and Interfacial Tensions?

- **Parachors for Computing Surface and Interfacial Tensions**
- **Capillary Rise Experiment**
- **Sessile Drop Method (Drop Weight Method)**
- **Pendant Drop Method**
- **Ring Method**
- **Wilhelmy Plate**
- **Spinning Drop Method**

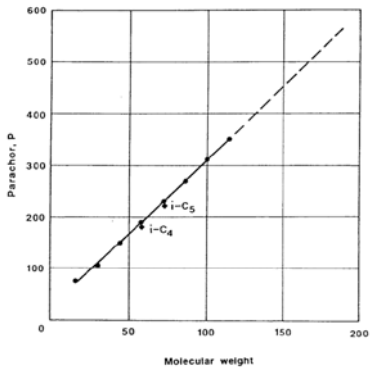
Parachors for Computing Surface and Interfacial Tensions

The parachor for a pure substance:

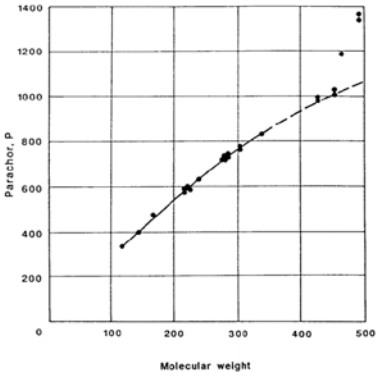
$$\Lambda = \frac{M\sigma^{\frac{1}{4}}}{\rho_L - \rho_g} \rightarrow \sigma = \left[\Lambda\left(\frac{\rho_L - \rho_g}{M}\right)\right]^4$$

The interfacial tension between reservoir oil and gas:

$$\sigma = \left[\sum_{i=1}^{i=N} \Lambda_i \left(x_i \frac{\rho_L}{M_L} - y_i \frac{\rho_g}{M_g} \right)\right]^4$$

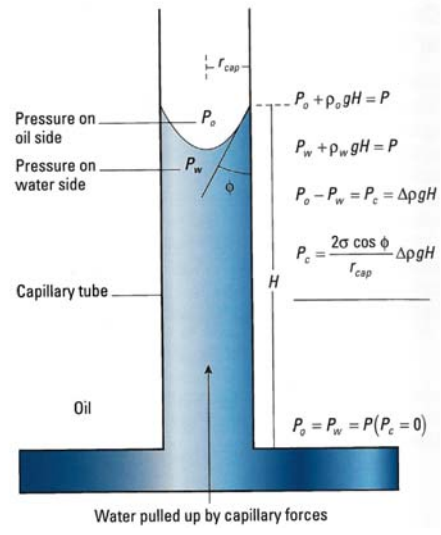


Source: Katz et al., 1959



Source: Firoozabadi et al., 1988

Capillary Rise Experiment



Source: Fundamentals of Formation Testing by Schlumberger

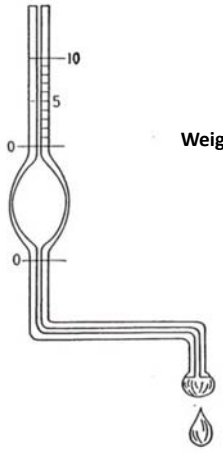
$$\sigma = \frac{rh\left(\rho_w - \rho_{mw}\right)g}{2\cos\theta}$$

Characteristic capillary length: $\kappa^{-1} = \sqrt{\frac{\sigma}{\rho_w g}} = \sqrt{\frac{rh}{2}}$

How to correct for the volume of the liquid in the spherical meniscus?

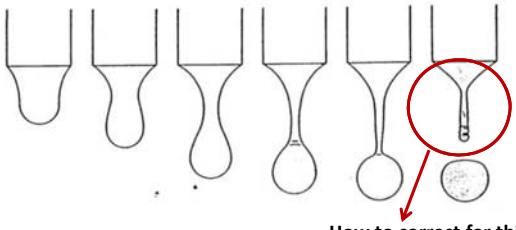
Sessile Drop Method (Drop Weight Method)

Assumption: The size of the liquid drop is proportional to surface tension of the liquid.



$$W_{ideal} = 2\pi r\sigma$$

Weight of drop — Radius of tube



$$W_{actual} = W_{ideal} f = 2\pi r\sigma f$$

How to correct for this residual liquid?

Correction factor

$$f = f\left(\frac{r}{V^{1/3}}\right)$$

Volume of drop

Count the number of droplets! → Estimate surface tension!

Sessile Drop Method (Drop Weight Method)

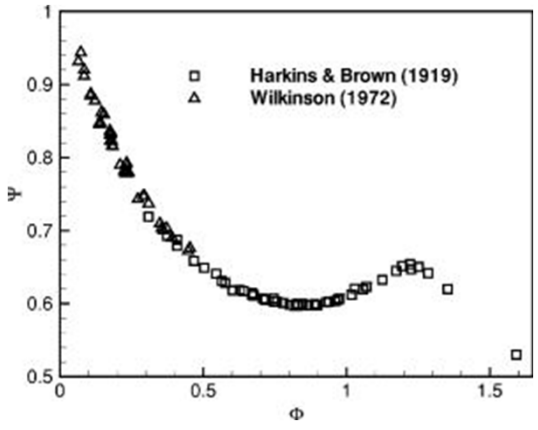
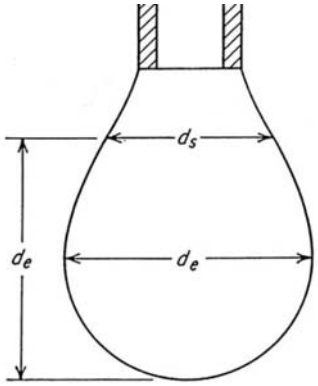


Image source: Yildirim, O. E., et al., 2005, Physics of Fluids.

Pendant Drop Method



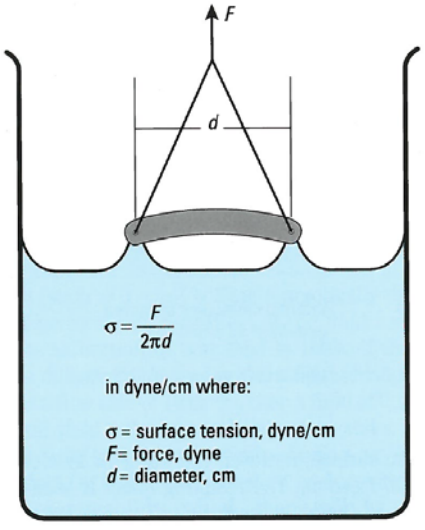
$$\sigma = \frac{g d_e^2 \left(\rho_L - \rho_g\right)}{H}$$

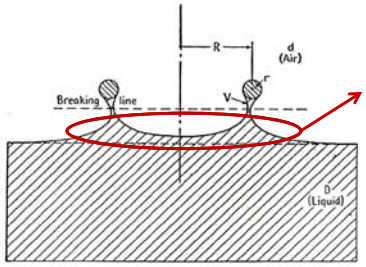
$$H = f\left(\frac{d_e}{d_s}\right)$$

$$H = 2\left[\left(\frac{1}{r_1} + \frac{1}{r_2}\right) - \frac{1}{r_0}\right]$$

r_1 and r_2 are the radii of curvature of the drop and r_0 is the radius of curvature at the apex.

Du Noüy Ring Method

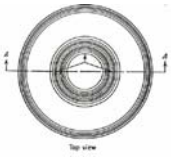


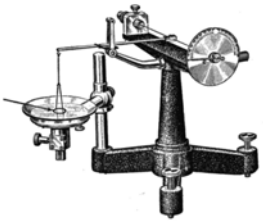


Corrections are needed to account for the mass of this lifted liquid

$$F = w_{ring} + 2\pi d\sigma f$$

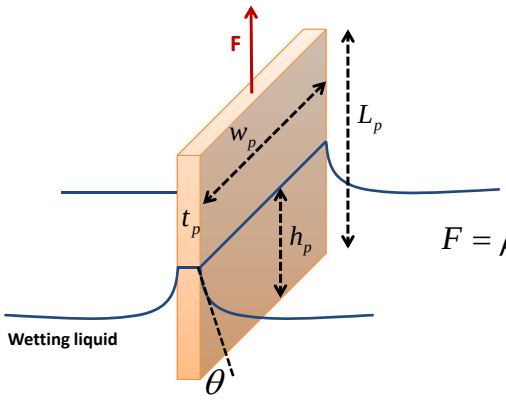
correction factor





Source: Holmes, H.N., 1922, Laboratory Manual of Colloid Chemistry

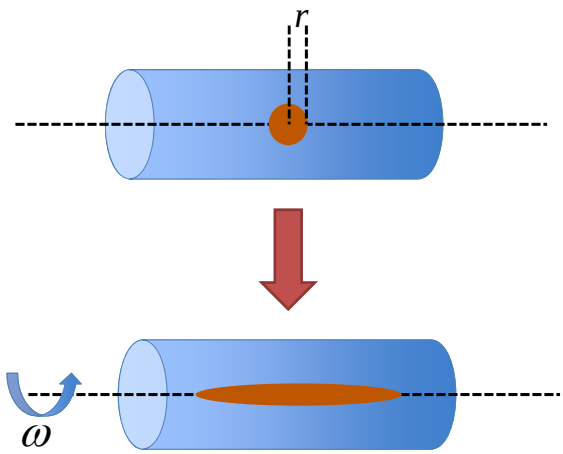
Wilhelmy Plate



$$F = \rho_p g\left(L_p w_p t_p\right) + 2\sigma\left(w_p + t_p\right)\cos\left(\theta\right) - \rho_L g\left(h_p w_p t_p\right)$$

$$\sigma = \frac{F}{2\left(w_p + t_p\right)\cos\left(\theta\right)}$$

Spinning Drop Method



$$\sigma = \frac{1}{4}\Delta\rho\omega^2 r^3$$

Wettability

Wettability is a tendency for one fluid to spread on or adhere to a solid surface in the presence of other immiscible fluids


Image source: Wikipedia

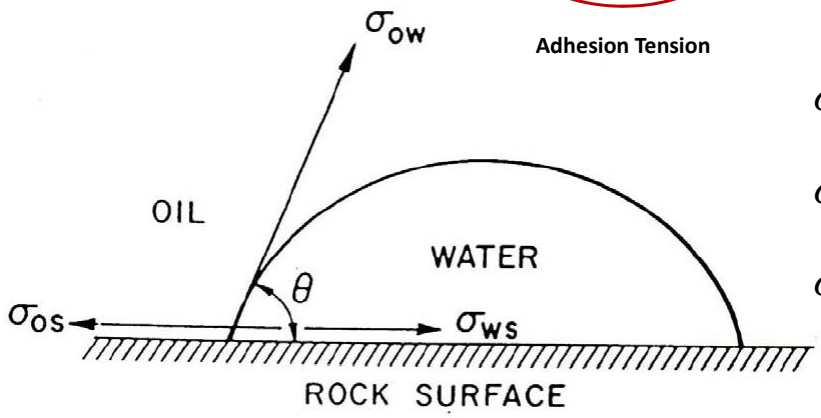

Image source: Wikipedia

Image source: Zinszner, B. and Pellerin, F. M., 2007, A geoscientist's guide to petrophysics: IFP Publications.

Young-Dupre Equation

$$\sigma_{os} - \sigma_{ws} = \sigma_{ow} \cos(\theta)$$

Adhesion Tension

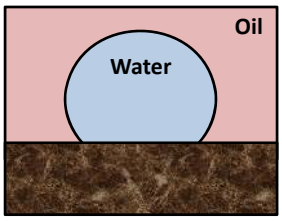


$\sigma_{os} = \sigma_{ws}$ ➡ ?

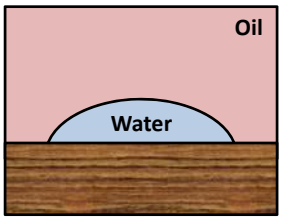
$\sigma_{os} < \sigma_{ws}$ ➡ ?

$\sigma_{os} > \sigma_{ws}$ ➡ ?

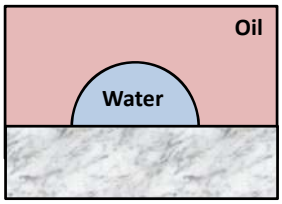
Wettability



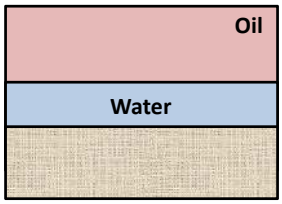
Surface is oil wet



Surface is water wet

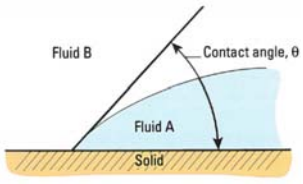


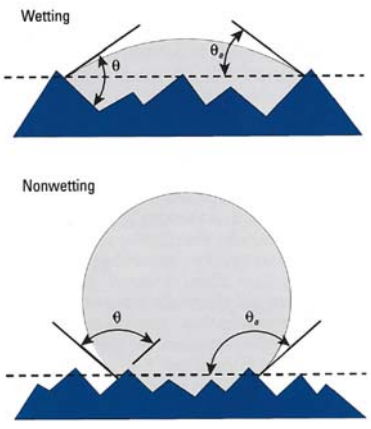
Surface of neutral wettability



Surface is totally water wet

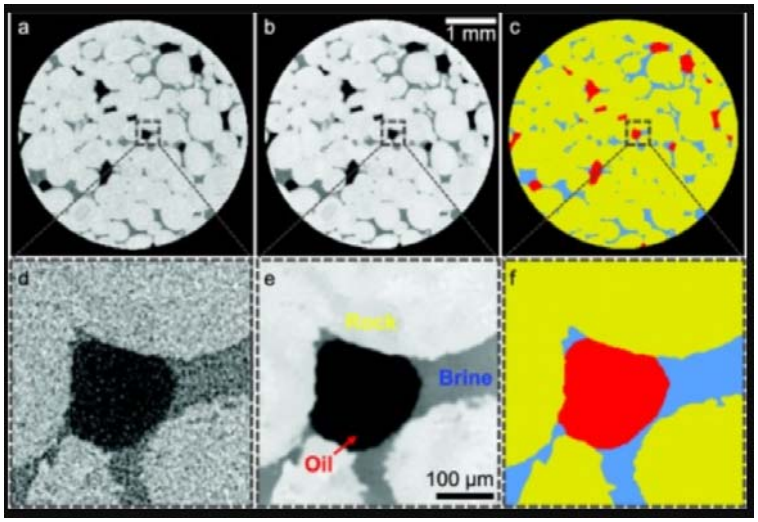
Wettability





Source: Fundamentals of Formation Testing by Schlumberger

Wettability of Porous Media



Source: AlRatrout et al., 2017, https://doi.org/10.1016/j.advwatres.2017.07.018

Parameters Affecting Wettability

- Surface roughness
- Fluids properties
- Solid surface properties
- Pressure
- Temperature
- …

How to Estimate Wettability?

- **How to Estimate Wettability?**
  - **Laboratory-based wettability assessment**
    - **Contact Angle Method**
    - **Amott Wettability Test**
    - **United States Bureau of Mines (USBM) Wettability Index**
    - **Direct observation in the pore-scale domain**
  - **In-situ wettability assessment**
    - **Interpretation of well logs such as NMR, resistivity and dielectric measurements**

Experimental Wettability Assessment

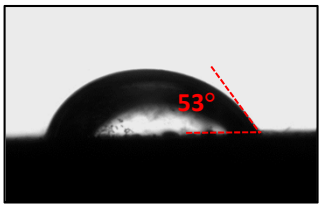
Amott Cell

- **Measures fluid saturation due to spontaneous imbibition**
- **Quantitative wettability index**
- **Measurement takes days to weeks**

USBM

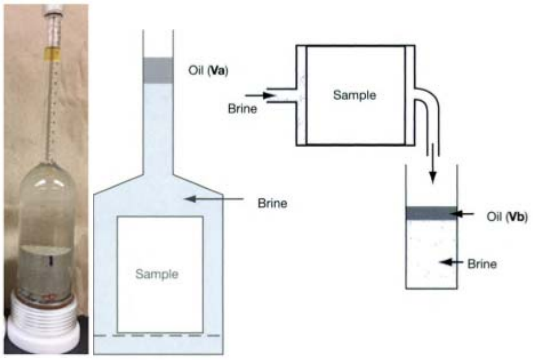
- **Measures fluid saturation due to forced imbibition**
- **Quantitative wettability index**
- **Measurement takes hours to days**

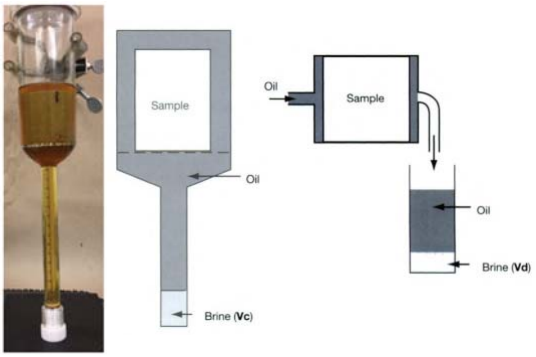
Contact Angle



- **Measures the contact angle between brine and rock surface**
- **Qualitative assessment**
- **Often measured only at the rock surface**

Amott Wettability Test





$$WI_w = \frac{V_a}{V_a + V_b}$$

$$WI_o = \frac{V_c}{V_c + V_d}$$

Image source: Zinszner, B. and Pellerin, F. M., 2007, A Geoscientist's Guide to Petrophysics.
Image source: Newgord et al., 2018, SPWLA (Heidari's research group)

Amott Wettability Test

Spontaneous Imbibition:

$$WI_w = \frac{Volume\ of\ oil\ displaced\ by\ brine\ imbibition}{Volume\ of\ oil\ displaced\ by\ brine\ imbibition + forced\ displacement}$$

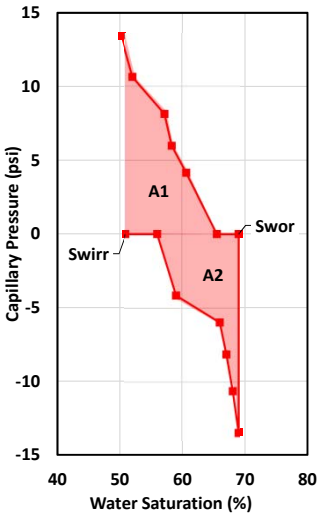
$$WI_o = \frac{Volume\ of\ brine\ displaced\ by\ oil\ imbibition}{Volume\ of\ brine\ displaced\ by\ oil\ imbibition + forced\ displacement}$$

$$Amott\ Index = WI_w - WI_o = \frac{S_{wirr} - S_{spw}}{S_{wirr} - S_{wor}} - \frac{S_{wor} - S_{spo}}{S_{wor} - S_{wirr}}$$

Strongly oil-wet $-1 < Amott\ Index < +1$ Strongly water-wet

Imbibition Cell

United States Bureau of Mines (USBM) Wettability Index



Forced Imbibition:

$$USBM = \log \frac{A_1}{A_2}$$

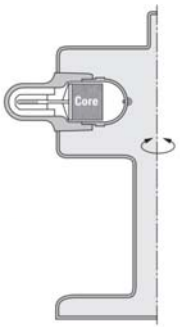


Image source: Schlumberger Oilfield Review, Fundamentals of Wettability.

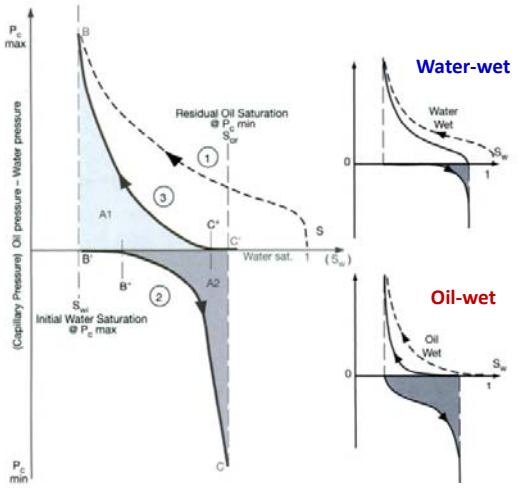
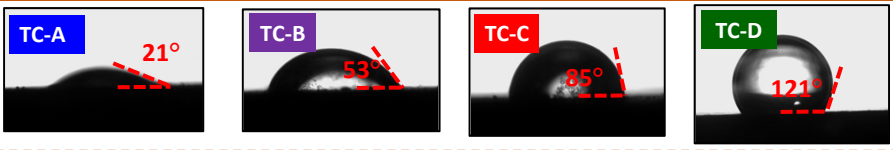


Image source: Zinszner, B. and Pellerin, F. M., 2007, A Geoscientist's Guide to Petrophysics.

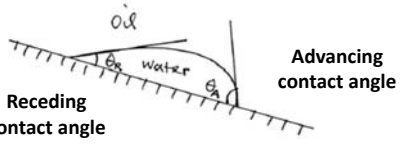
Contact Angle Method

Sessile Drop Test

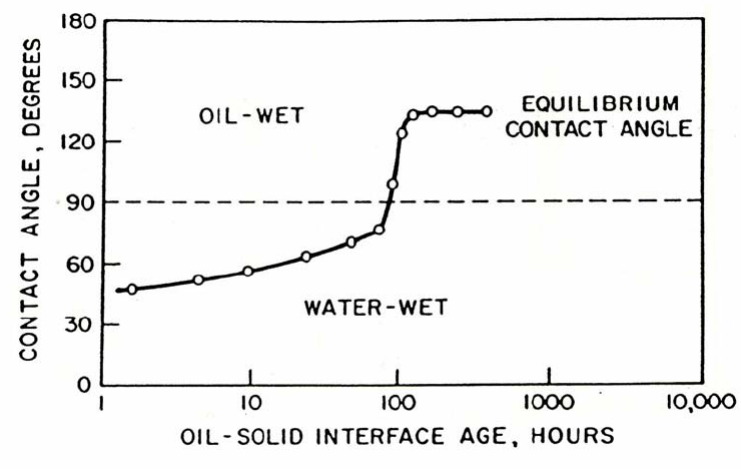


Sample	Contact Angles	USBM	Amott	Summary
TC-A	21° – 36°	0.45	0.4	water-wet
TC-B	48° – 101°	-0.18	0.2	mixed-wet
TC-C	72° – 97°	0.16	0.1	mixed/slightly hydrocarbon-wet
TC-D	120° – 137°	-0.16	-0.6	hydrocarbon-wet

Source: Newgord et al., 2018, SPWLA (Heidari's research group)



Contact Angle Method



You might need to wait for a long time!

Source: Craig, 1971

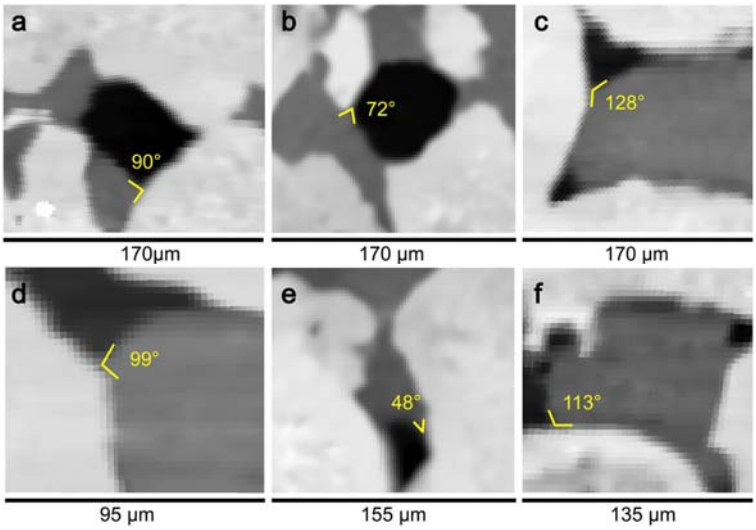
Example

Kerogen sample
Low thermal maturity

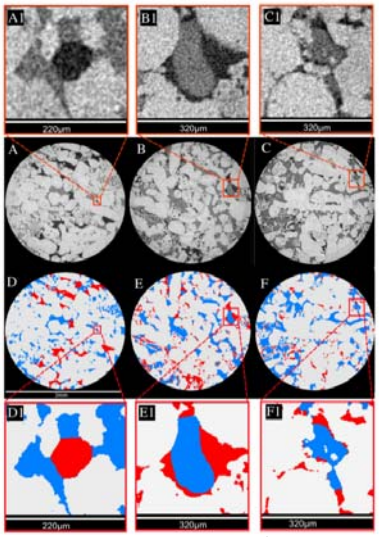
Kerogen sample
High thermal maturity

Source: Jagadisan and Heidari, 2019

Direct Observation in the Pore-scale Domain

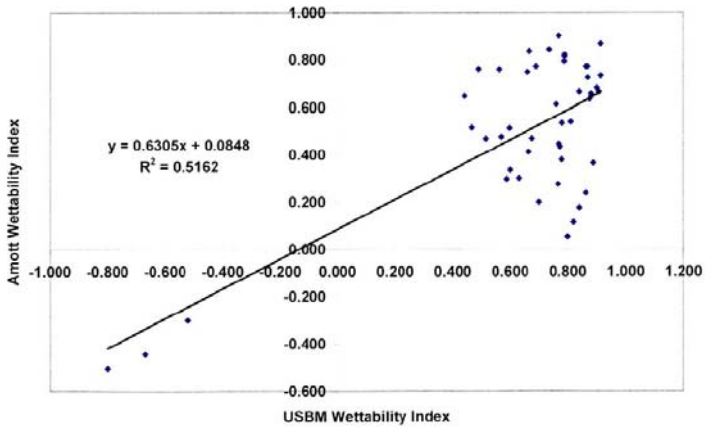


Source: Alhammadi et al., 2017, Scientific Reports



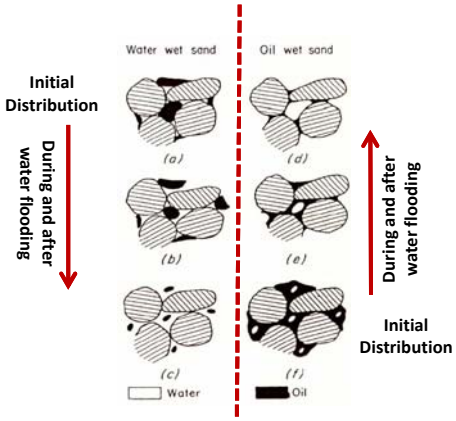
Source: AlRatrout et al., 2018, DOI: 10.1029/2017WR022124

How Do Different Wettability Indices Correlate?

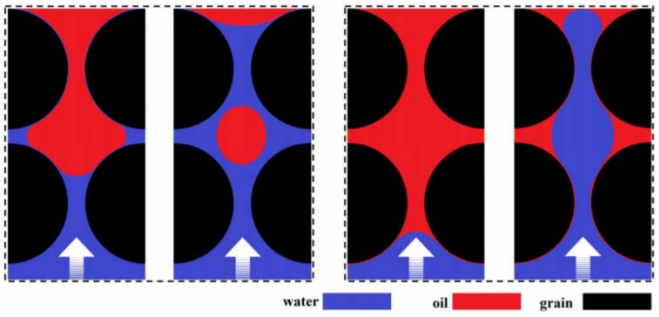


Source: Donaldson et al., 1969

Impact of Wettability on Spatial Distribution of Fluids

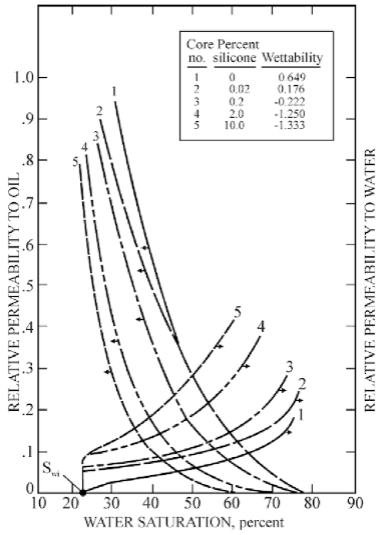


Source: Peters, E. J., 2012, Advanced Petrophysics; Raza et al., 1968



Source: Mohammadmoradi and Kantzas, 2016, SPE-181309

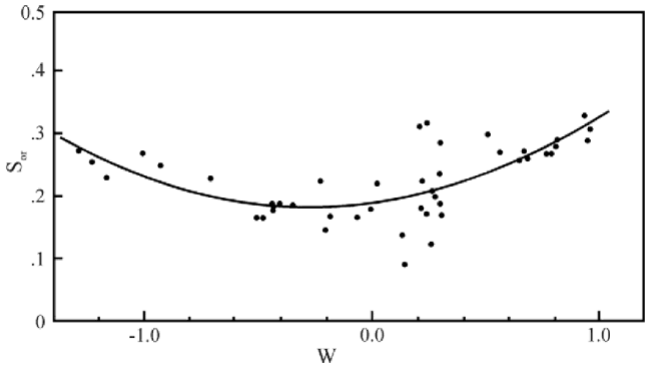
Effect of Wettability on Irreducible Water Saturation and K_r



Source: Erle C. Donaldson and Waqi Alam, 2008, Wettability

Impact of Wettability on Ultimate Recovery

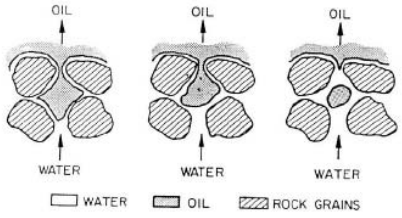
Residual oil saturation as a function of wettability



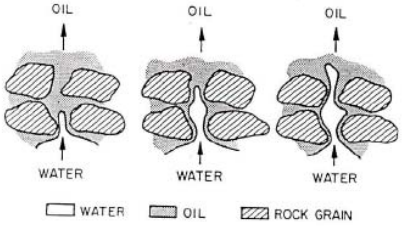
Where do you expect to find maximum oil recovery?

Source: Erle C. Donaldson and Waqi Alam, 2008, Wettability

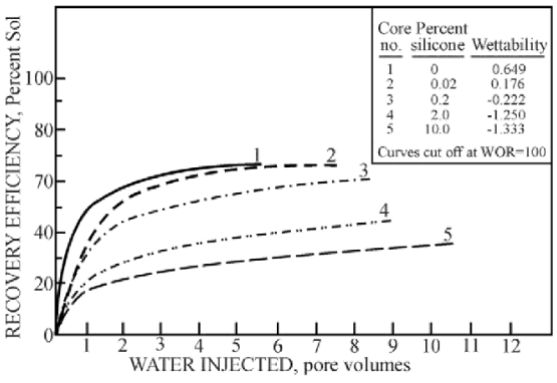
Impact of Wettability on Recovery Efficiency



strongly water-wet medium



strongly oil-wet medium

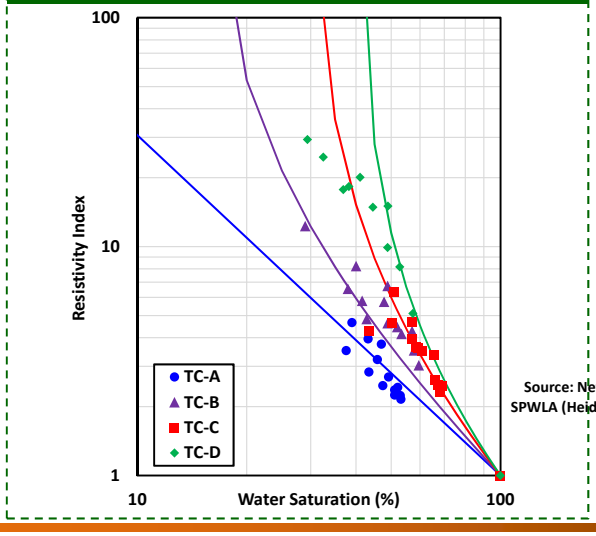


Source: Erle C. Donaldson and Waqi Alam, 2008, Wettability

Source: Peters, E. J., 2012, Advanced Petrophysics; Raza et al., 1968

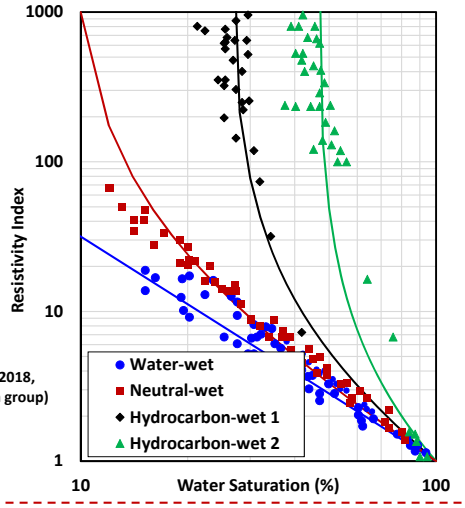
Impact of Wettability on Resistivity Measurements

Experimental Data from Heidari's Research Group



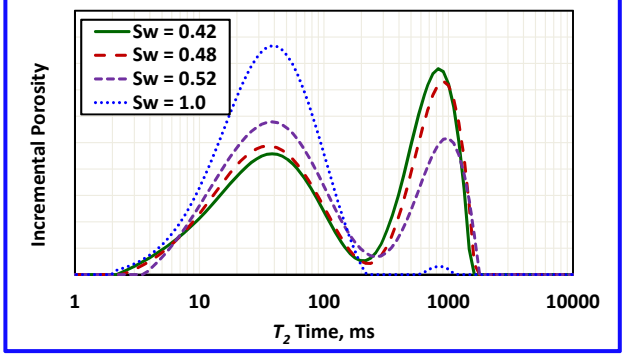
Source: Newgord et al., 2018, SPWLA (Heidari's research group)

Field Data from Sweeney & Jennings (1960)

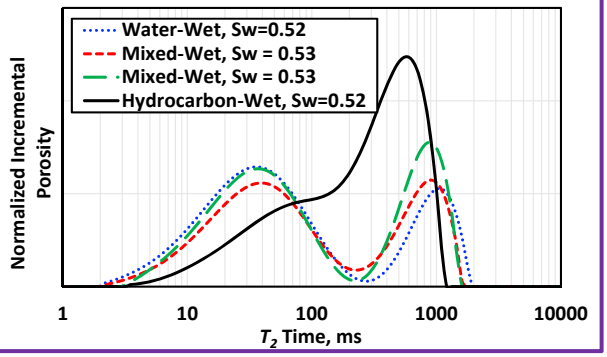


Impact of Wettability on NMR Measurements

Water-wet Texas Cream at different water saturation levels



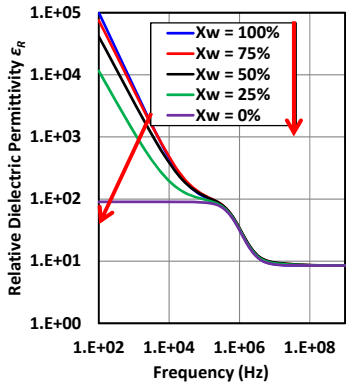
Water-, Mixed-, and Oil-wet Texas Cream at 52% water saturation



Source: Newgord et al., 2018, ATCE (Heidari's research group)

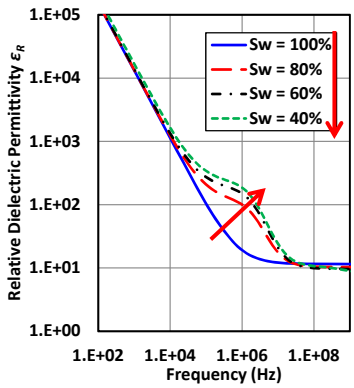
Impact of Wettability on Dielectric Measurements

Wettability



X_w = volume fraction of water-wet grains

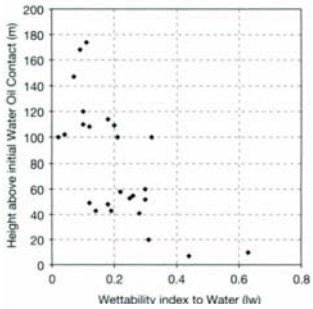
Water Saturation



Source: Garcia and Heidari, 2018, SPWLA

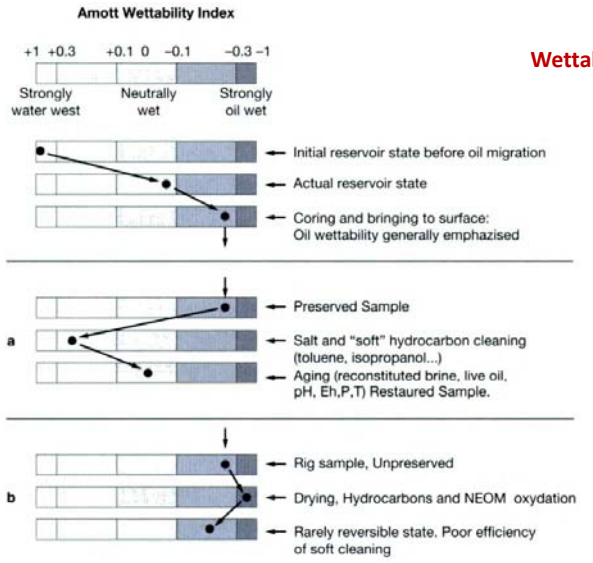
Reasons Behind Alteration of Wettability in the Reservoir

- **Properties of porous media**
  - **Mineralogy**
    - ➔ **Speeding or slowing down the adsorption of polar molecules**
  - **Roughness of pore walls**
- **Geological history**
  - **The distance from the free water level**
  - **Oil type**
  - **Active tectonic processes**



Source: Zinszner, B. and Pellerin, F. M., 2007, A Geoscientist's Guide to Petrophysics; Hamon, 2000

Are Laboratory Measurements Representative of in-situ Condition?



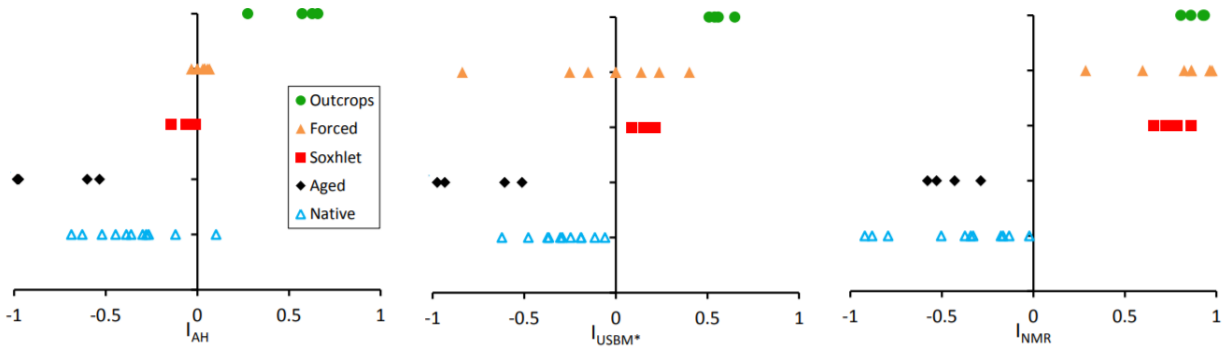
Wettability state can be highly unsteady!

Wettability evolution over the course of geologic time

Wettability alteration depends on sampling and processing condition

Image source: Zinszner, B. and Pellerin, F. M., 2007, A Geoscientist's Guide to Petrophysics.

Impact of Sample Preparation on Wettability Estimates



Source: Al-Muthana et al., 2012, SCA

Are Laboratory Measurements Representative of in-situ Condition?

- How the rock wettability might be altered?
  - Flushing by drilling mud
  - Deposition of organic molecules precipitated during depressurization
  - Temperature and pressure changes can lead to fluid composition changes, possibly causing asphaltenes and waxes to precipitate and coat pore surfaces
  - Exposure to oxygen
  - Drying and alteration during storage and transport

What are the Options for in-situ Assessment of Wettability?

- What in-situ measurements are sensitive to wettability?
- What are the existing methods for analyzing this data for wettability assessment?
- What are the uncertainties associated with these methods?
- The way forward …

Complementary References

- Peters, E. J., 2012, Advanced Petrophysics. Live Oak Book Company. Chapter 6
- Zinszner, B. and Pellerin, F. M., 2007, A Geoscientist's Guide to Petrophysics. Editions Technip.

Advanced Petrophysics:
Interfacial Phenomena and Wettability

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