Petrophysics

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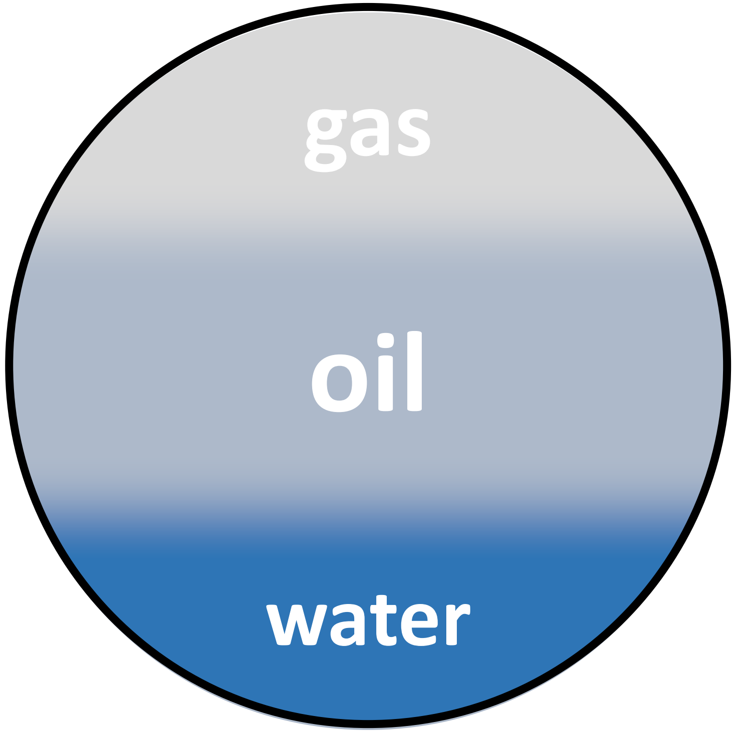
Multiphase Flow

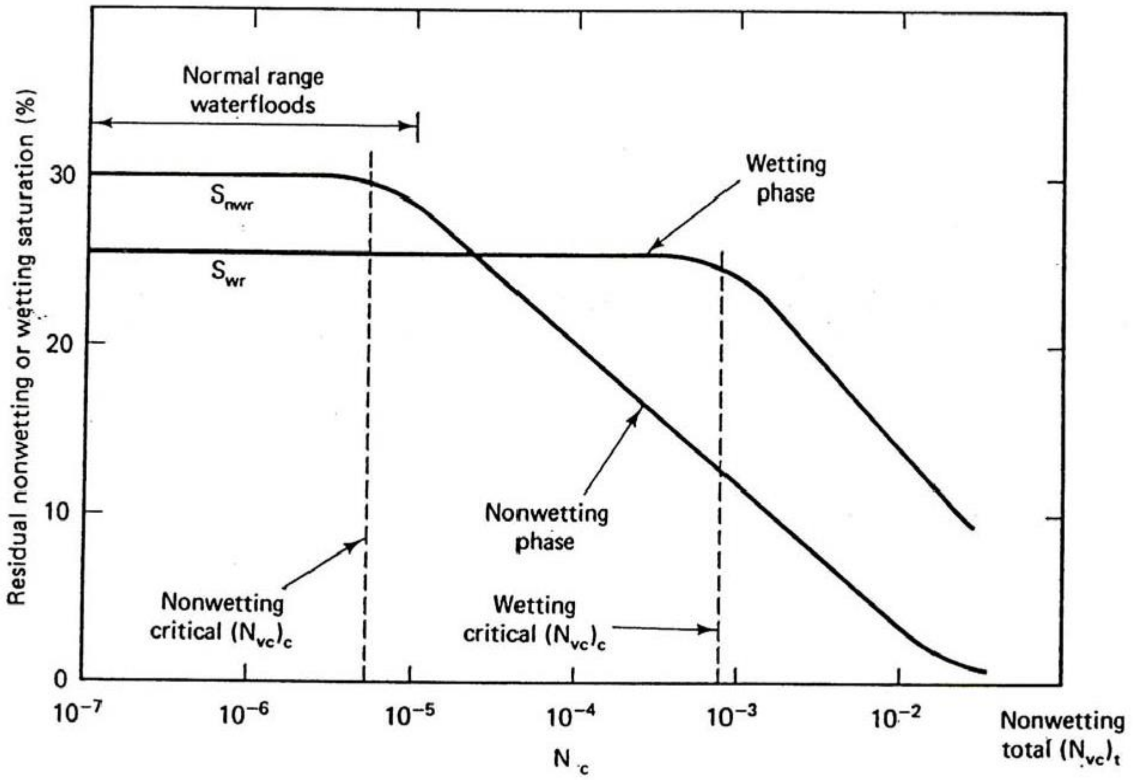
- When more than one fluid occupies the pore space of a porous medium:
  - Fluid saturations must be tracked.
  - Interfacial forces between the immiscible fluids and between the fluids and rock surface come into play.
  - The rock surface can show a marked affinity for one of the fluids.
  - Because of small pore throat, capillarity plays a role, and there is a difference in the fluid pressure between the phases.
  - There is a difference in the flow capacity of the rock and fluids.



Capillary Number

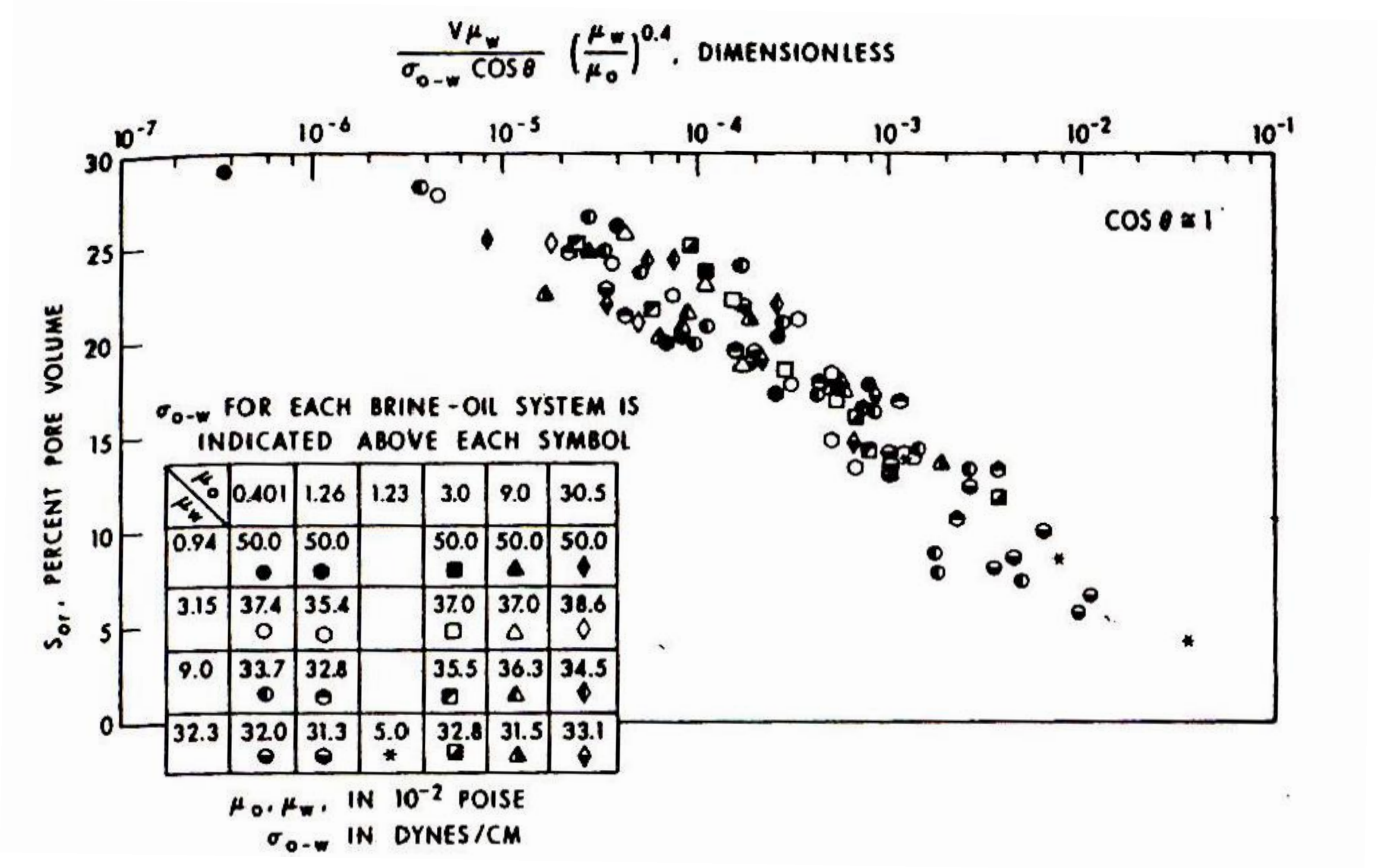
- Interfacial tension is the contractile that exist at the interface of two immiscible fluids such as oil and water, and it is zero for the two miscible fluids, where the system forms a single-phase.
- There is no simple relationship between the surface tensions of liquids and their interfacial tensions.
- Capillary number represents the relative effect of viscous drag forces versus interfacial tension forces acting across an interface between two immiscible fluids.
- The residual oil saturation for an immiscible displacement in a porous medium is a function of the capillary number, or in other words, the interfacial tension between the fluids, the wettability, the fluid viscosities and the displacement rate.
- Figure to the right shows typical correlations for a wetting fluid displacing a non-wetting fluid and for a non-wetting fluid displacing wetting fluid.

$$S_{\mathrm{or}} = f_1(\sigma\cos\theta, \mu_{\mathrm{nw}}, \mu_{\mathrm{w}}, \nu) = f_2\left(\frac{\mu_{\mathrm{nw}}}{\mu_{\mathrm{w}}}, N_{\mathrm{c}} = \frac{\mu_{\mathrm{w}}\nu}{\sigma\cos\theta}\right)$$



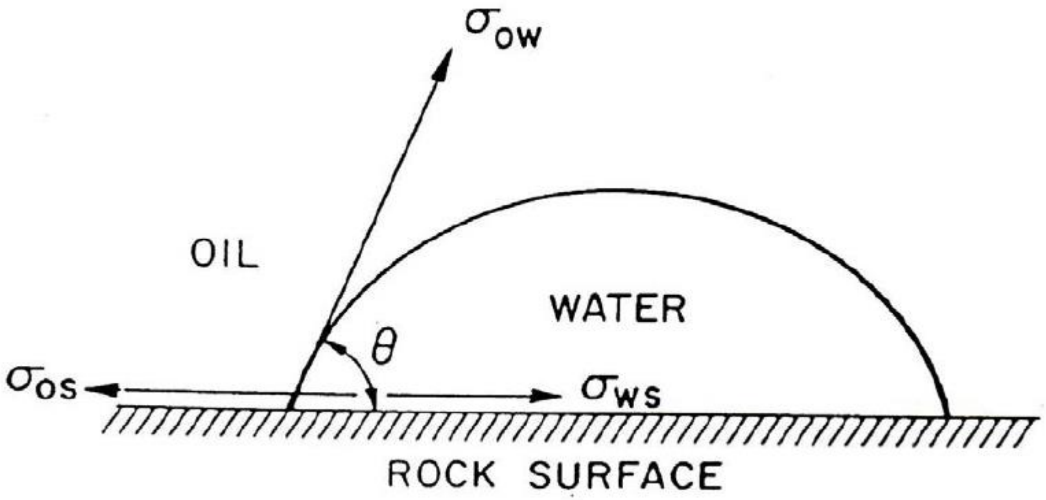
Capillary Number

- Figure to the right shows capillary desaturation experimental data from Abrams (1975) obtained on the same core sample but at different viscosity ratios. Clearly, the decrease in residual oil saturation with increasing capillary number is evident. Note that capillary number is modified, includes viscosity ration to improve correlation.

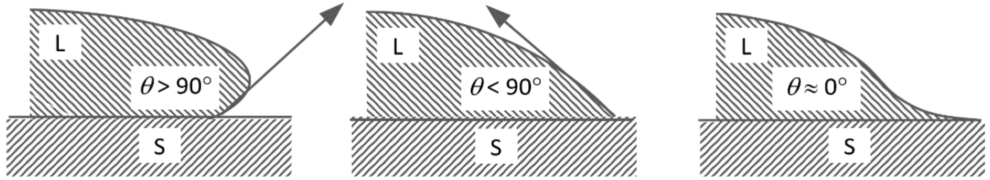


Wettability

- Wettability is a tendency for one fluid to spread on or adhere to a solid surface in the presence of other immiscible fluids.
- The fluid that spreads or adheres to the surface is known as the wetting fluid.
- In a petroleum rock system, the solid surface is the reservoir rock which may be sandstone, limestone or dolomite, together with cementing material. The fluids are water, oil and gas.
- Either water or oil is the wetting phase, gas is always non-wetting phase.



- There are three interfacial tensions.
- The contact angle is measured through the more dense fluid.
- This contact angle shows the wettability of the fluid.
- Complete spreading of crude oil or water on a surface has never been observed with reservoir fluids.



Determination of Wettability

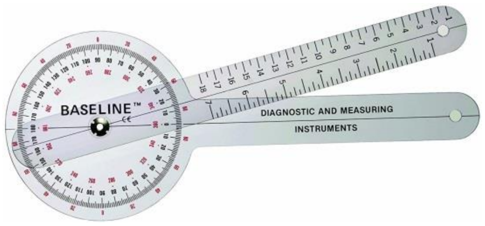
- Motivation for the determination; wettability affects:
  - The microscopic fluid distribution at the pore scale
  - The magnitude of irreducible water saturation
  - The efficiency of immiscible displacement
  - The residual oil saturation
  - The capillary pressure curve
  - The relative permeability curve
  - The electrical properties of the porous medium
- Reservoir wettability is usually determined either by contact angle measurement using reservoir fluids and a pure mineral surface or by an imbibition test on a reservoir core sample using refined oil and synthetic brine.
- No wettability determination method involves the simultaneous use of reservoir fluids and reservoir rock.

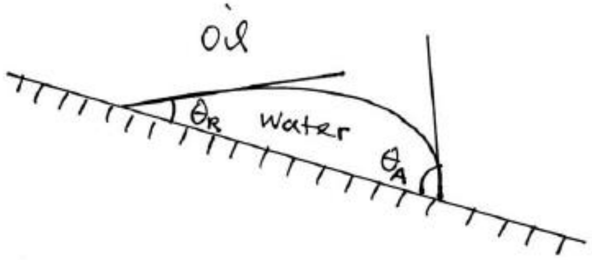
for water-wet reservoirs, the irreducible water saturation is usually greater than 20-25% whereas for oil-wet reservoirs it is generally less than 15% and frequently less than 10% of pore volume

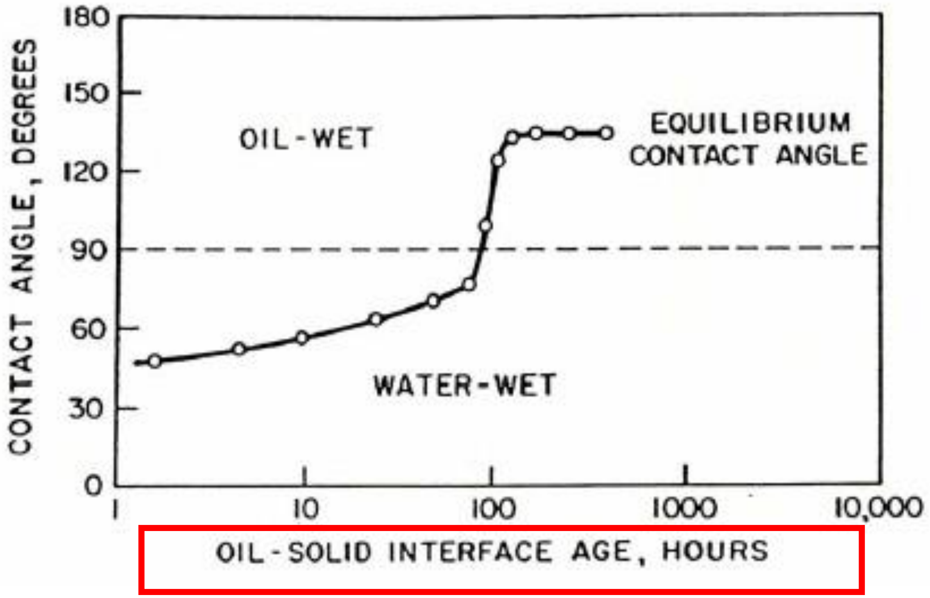
Contact Angle Method
Sessile Drop Method
Modified Sessile Drop Method
Amott Wettability Test
USBM Wettability Index

Contact Angle Method

- The contact angle measurement essentially seeks to establish whether or not the reservoir oil contains surface active agents that could make an originally preferentially water wet mineral surface become preferentially oil wet over time.
- The contact angle measurement is performed with a contact angle cell using an instrument know as a goniometer, and two contact angles are normally measured.
- Advancing contact angle: Angle observed on surface that has never been in contact with second phase. Usually, we report the advancing contact angle.
- Receding contact angle: Angle observed on surface previously in contact with second phase.
- Graph to the right shows the importance of aging to establish adsorption equilibrium and to avoid reporting wrong (premature) results.
- From the experiments, there is evidence that the contact angle is affected by which fluid was first in contact with the solid.

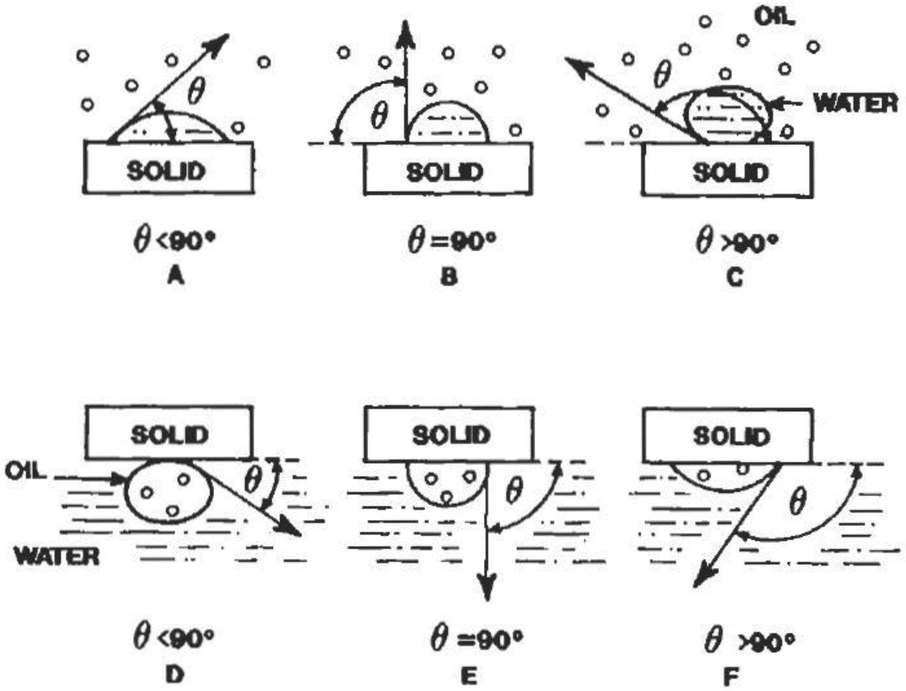




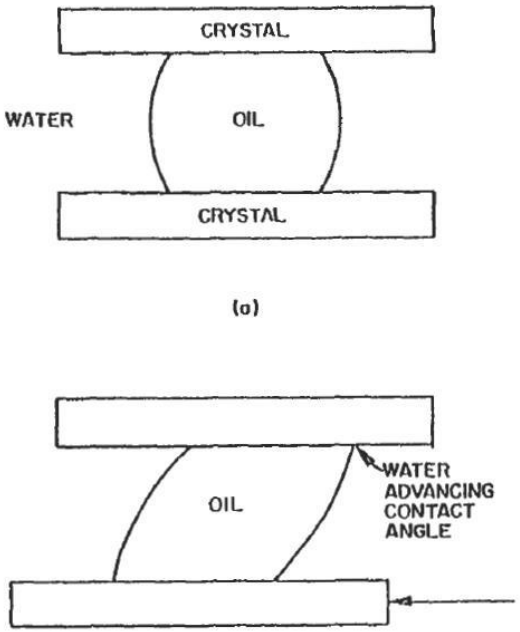


Contact Angle Method

Sessile Drop Method



Modified Sessile Drop Method



Amott Wettability Test

- After the reservoir core sample has been flushed with brine to residual oil saturation and evacuated to remove gas, it is then subjected to the following tests:

1) The core is immersed in oil and the volume of brine displaced by the imbibition of oil is measured after 20 hours.
2) The core is centrifuged under kerosene and the additional brine displaced by centrifuging is measured.
3) After centrifuging in the oil, the core is immersed in brine and the volume of oil displaced by the imbibition of brine is measured after 20 hours.
4) The core is centrifuged under brine and the additional oil displaced by centrifuging is measured.

$$WI_{\mathrm{w}} = \frac{\text{Volume of oil displaced by brine imbibition}}{\text{Volume of oil displaced by brine imbibition} + \text{forced displacement}}$$

$$WI_{\mathrm{o}} = \frac{\text{Volume of brine displaced by oil imbibition}}{\text{Volume of brine displaced by oil imbibition} + \text{forced displacement}}$$

The difference $(WI_{\mathrm{w}} - WI_{\mathrm{o}})$ is used as the wettability measure:

- It ranges between -1 and 1.
- An index -1 indicates a strongly oil-wet rock
- An index +1 indicates a strongly water-wet rock

Class Exercise:

- An experiment was performed on a preserved core to determine its wettability. The core was flushed with brine until residual oil was achieved. Then spontaneous and forced imbibition tests were performed with the following results:
  - Volume of brine displaced spontaneously from the core when immersed in kerosene for 20 hours = 0.2 cm^3
  - Additional volume of brine expelled from the core when centrifuged under kerosene = 1.95 cm^3
  - Volume of oil displaced spontaneously from the core when immersed in brine for 20 hours = 1.0 cm^3
  - Additional volume of oil expelled from the core when centrifuged under brine = 1.8 cm^3
- Characterize the wettability of the core as either water wet, oil wet or intermediate wet by computing an appropriate numerical wettability measure from the given data.

$$WI_{\mathrm{w}} = \frac{\text{Volume of oil displaced by brine imbibition}}{\text{Volume of oil displaced by brine imbibition} + \text{forced displacement}}$$

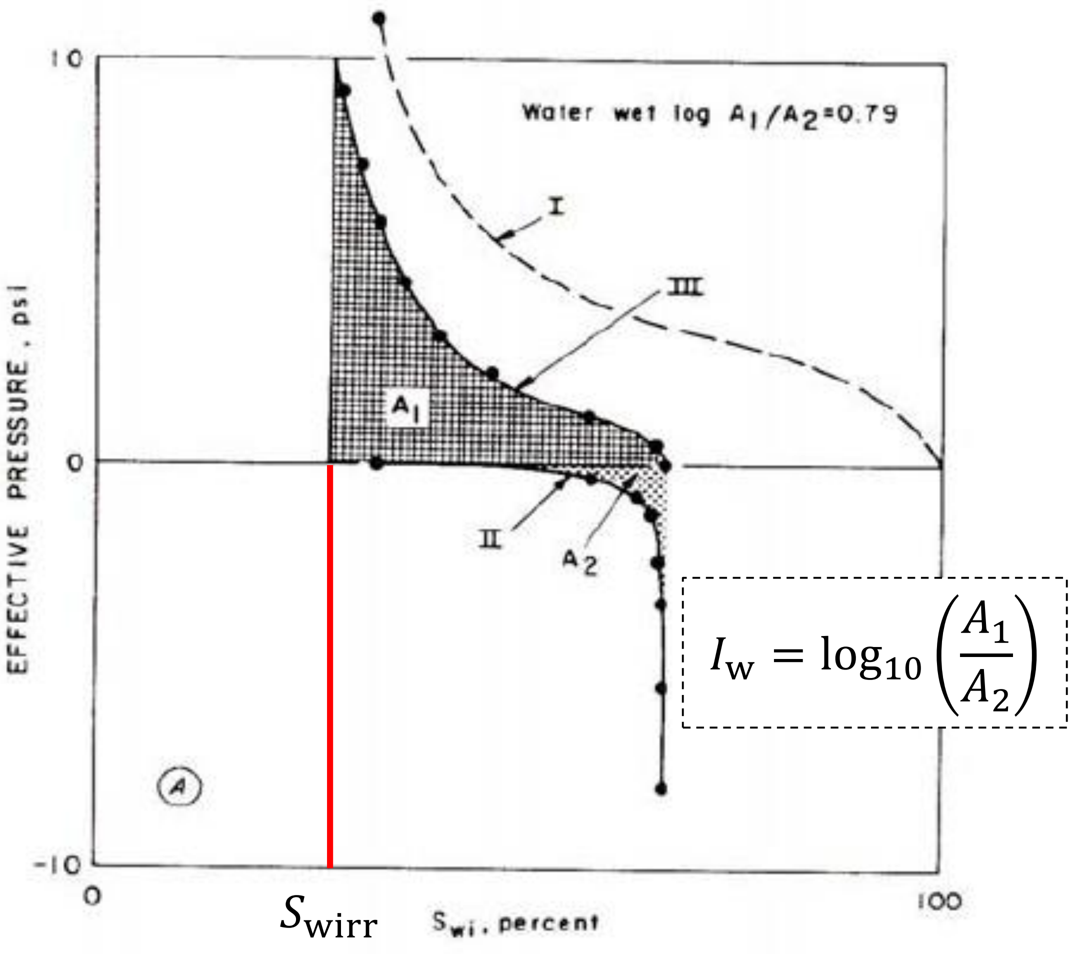
$$WI_{\mathrm{o}} = \frac{\text{Volume of brine displaced by oil imbibition}}{\text{Volume of brine displaced by oil imbibition} + \text{forced displacement}}$$

The difference $(WI_{\mathrm{w}} - WI_{\mathrm{o}})$ is used as the wettability measure:

- It ranges between -1 and 1.
- An index -1 indicates a strongly oil-wet rock
- An index +1 indicates a strongly water-wet rock

USBM Wettability Index

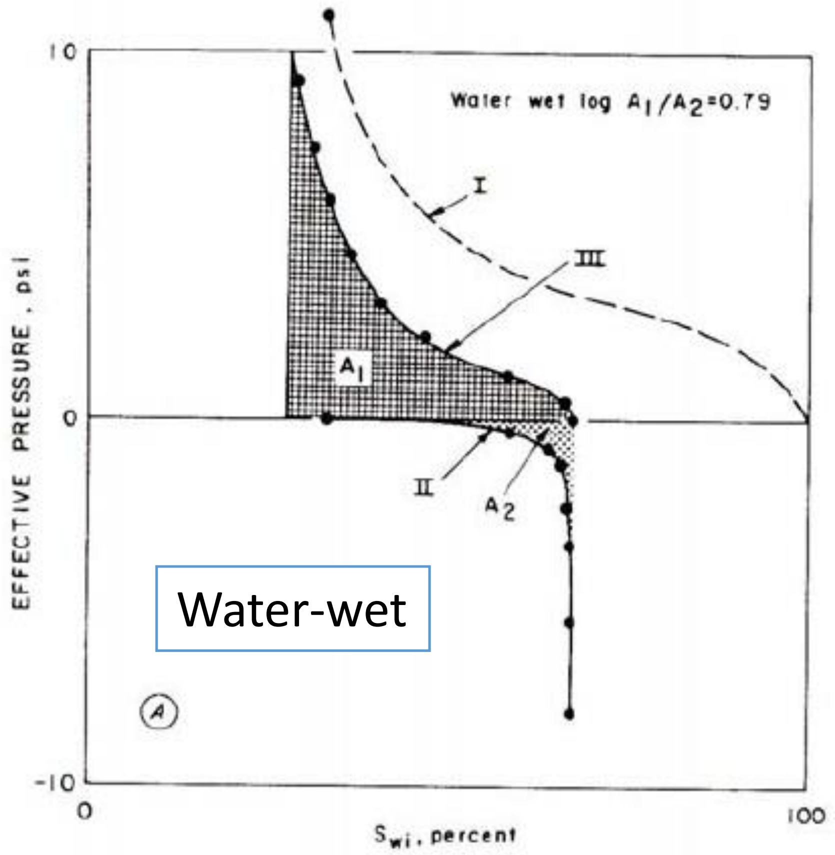
- The United States Bureau of Mines (USBM) wettability index is obtained by carrying out a number of forced water and oil displacement experiments using a centrifuge.
- The sample is saturated initially with water, and the water is displaced with oil to irreducible water saturation using the centrifuge, line-I.
- The sample, which now contains initial oil saturation and irreducible water saturation, is then centrifuged in water to residual oil saturation, line-II.
- The sample, which now contains water and residual oil saturation, is then centrifuged in oil to irreducible water saturation, line-III.
- The area under a capillary pressure curve represents the thermodynamic work required for the displacement.
- The USBM wettability index (I_{w}) ranges from -1 for a strongly oil-wet rock to +1 for a strongly water-wet rock. A wettability index of zero indicates no preferential wetting by either fluid.

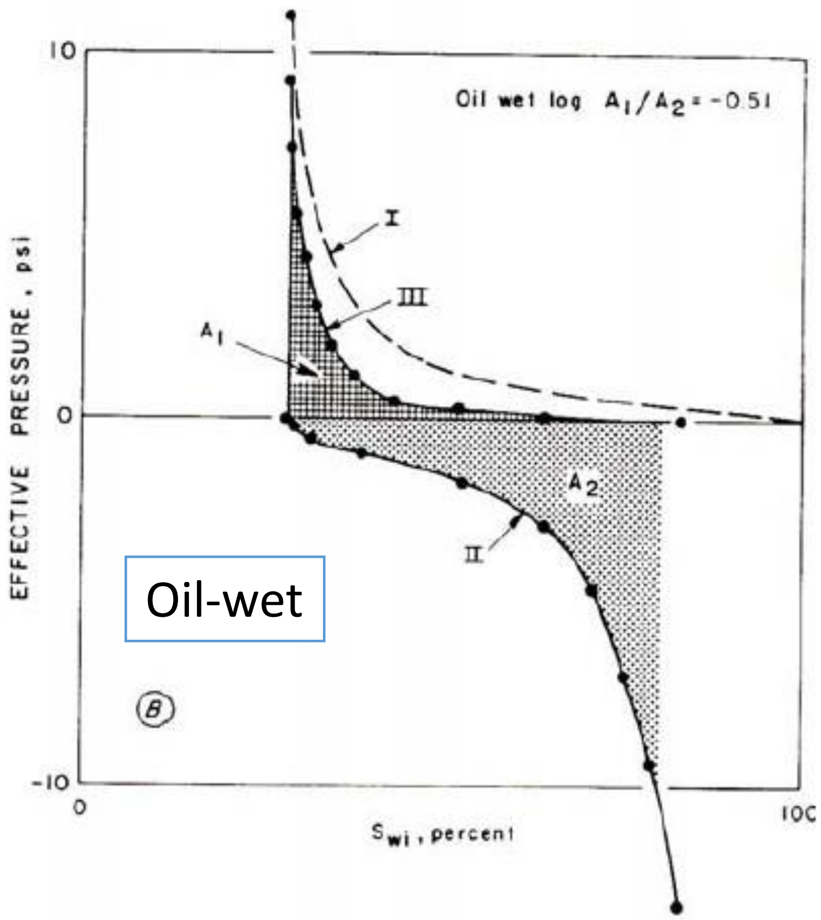


$$I_{\mathrm{w}} = \log_{10}\left(\frac{A_1}{A_2}\right)$$

USBM Wettability Index

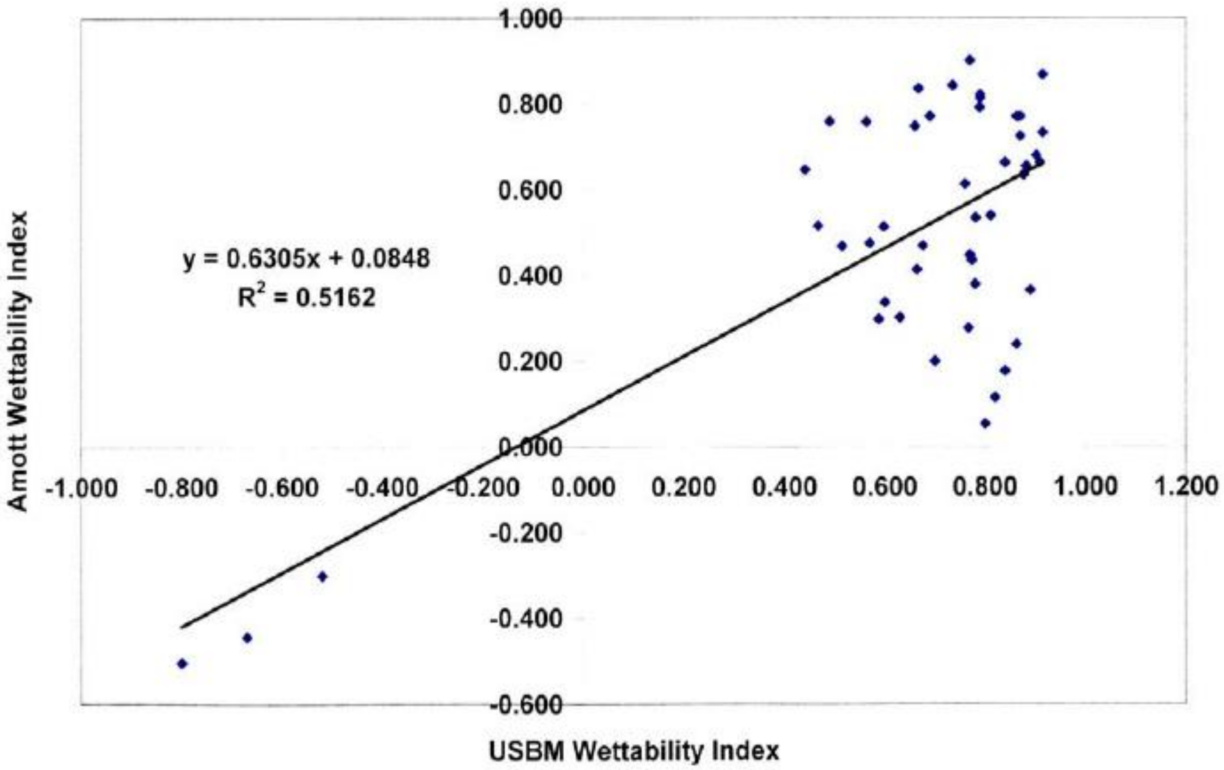
- What are the differences?
- Why are they different?





Correlation between USBM and Amott measurements

- Figure to the right compares the USBM and Amott wettability indices, of 43 outcrop rock samples and three reservoir rock samples.
- Both methods show the three reservoir rock samples to be oil wet as indicated by the negative values for both wettability indices.



Wettability of Petroleum Reservoirs

- The wettability of petroleum reservoirs span the entire spectrum from preferentially water-wet to preferentially oil-wet reservoirs.
- Treiber et al. (1972) measured the wettability of 30 sandstones and 25 carbonate reservoirs by measuring contact angles at the reservoir temperatures using the reservoir oils and synthetic brine.
- The results showed 27% of the reservoirs tested were preferentially water wet, 66% were preferentially oil-wet, and the remaining 7% were of intermediate wettability.
- 43% of the sandstones were preferentially water wet, 50% were preferentially oil wet, and 7% were of intermediate wettability.
- 84% of the carbonate reservoirs were preferentially oil wet, 8% were preferentially water wet, and 8% were of intermediate wettability.
- Based on this study, carbonates are more likely to be preferentially oil wet than preferentially water wet.
- A similar contact angle study by Chiligarian and Chen (1983) on 161 carbonate reservoirs showed 80% of the reservoirs to be preferentially oil wet, 8% to be preferentially water wet and 12% to be of intermediate wettability, being consistent with those of Treiber et al. (1972).