Advanced Petrophysics: Relative Permeability

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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 is relative permeability?
- Modeling of two-phase immiscible displacement in porous media
- Buckley-Leverett approximate solution
- How to quantify relative permeability
  - Laboratory measurements
- Assessment of relative permeability from drainage capillary pressure
- Parameters affecting relative permeability

Relative Permeability

- **Relative Permeability:** The permeability of one fluid in the presence of other immiscible fluids is known as the effective permeability to that fluid.

$$q_w = -\frac{kk_{rw}A}{\mu_w}\left(\frac{\partial P_w}{\partial x} + \rho_w g \sin\alpha\right)$$

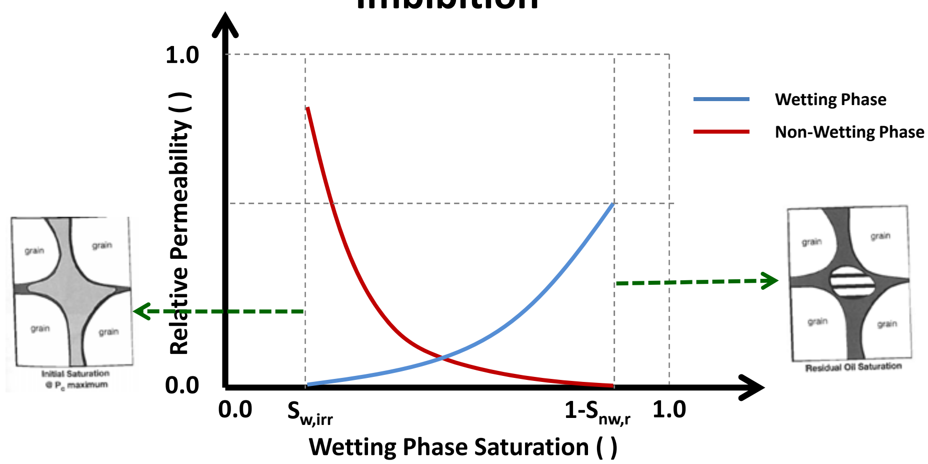
$$q_o = -\frac{kk_{ro}A}{\mu_o}\left(\frac{\partial P_o}{\partial x} + \rho_o g \sin\alpha\right)$$

$$q_g = -\frac{kk_{rg}A}{\mu_g}\left(\frac{\partial P_g}{\partial x} + \rho_g g \sin\alpha\right)$$

Relative Permeability, Imbibition Process

Saturation-dependent relative permeability

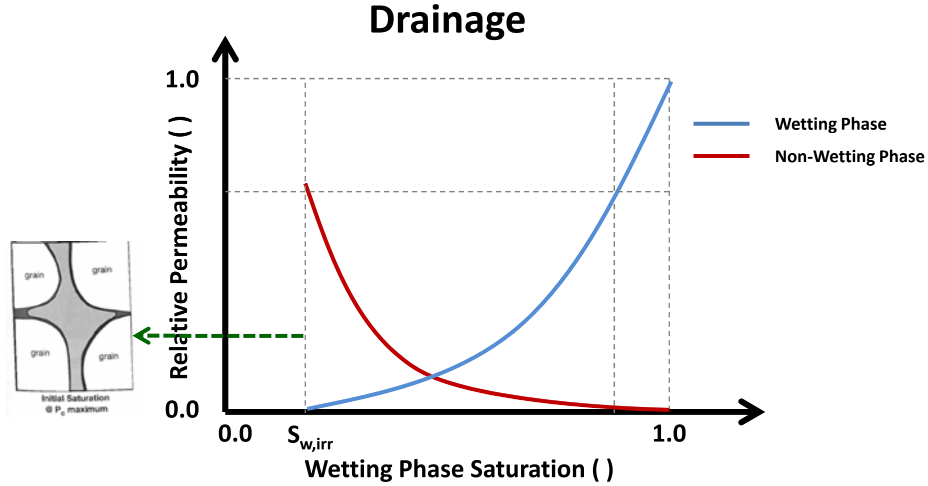
Imbibition



Relative Permeability, Drainage Process

Saturation-dependent relative permeability

Drainage



Modeling of Two-Phase Immiscible Displacement in Porous Media

OPTIONAL

- **Please watch the video (Parts 1 and 2)! The link to this video is already shared with you.**

Buckley-Leverett Approximate Solution

OPTIONAL

- **Please watch the video (Parts 1 and 2)! The link to this video is already shared with you.**

How to Estimate Relative Permeability?

- How to Estimate Relative Permeability?
  - Laboratory-based assessment of relative permeability
    - Stationary liquid method
      - Porous Plate Desaturation
      - Centrifuge Desaturation
    - Unsteady-state method
  - In-situ assessment of relative permeability
    - What are the possibilities based on what we learned so far?

Stationary Liquid Method

- **Step 1:** Install the clean, dry core sample in the Hassler apparatus. Evacuate the core and saturate with the wetting phase. Determine the absolute permeability of the core by wetting phase flow.

- **Step 2:** Displace the wetting phase with the non-wetting phase until no more wetting phase flows from the core. Calculate the irreducible wetting phase saturation and the initial non-wetting phase saturation. Measure the steady state pressure drop and the non-wetting phase injection rate and calculate the relative permeability to the non-wetting phase at the irreducible wetting phase saturation via

$$k_{rnw} = \frac{\mu_{nw} q_{nw} L}{k A \Delta P_{nw}}$$

Stationary Liquid Method

- **Step 3:** Inject a mixture of the wetting and non-wetting phases at rates qnw and qw such that the ratio, qw/qnw, is very much less than 1 until steady state is achieved. Steady state is achieved when the injected and produced qw/qnw ratios are equal and the pressure drop no longer changes with time.

- **Step 4:** Measure the pressure drop and calculate the wetting phase saturation by material balance. Calculate the relative permeabilities to the nonwetting and wetting phases at the latest wetting phase saturation via

$$k_{rw} = \frac{\mu_w q_w L}{kA\Delta P_w} \qquad k_{rnw} = \frac{\mu_{nw} q_{nw} L}{kA\Delta P_{nw}}$$

Stationary Liquid Method

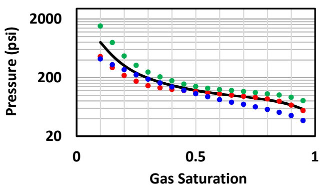
- **Step 5:** Increase the ratio qw/qnw and repeat steps 3 and 4 to calculate the relative permeabilities at higher and higher wetting phase saturations.

- **Step 6:** Inject only the wetting phase until no more non-wetting phase flows from the core. Calculate the residual non-wetting phase saturation. Measure the steady state pressure drop and the wetting phase injection rate and calculate the relative permeability to the wetting phase at residual non-wetting phase saturation.

How to minimize the capillary end effects?

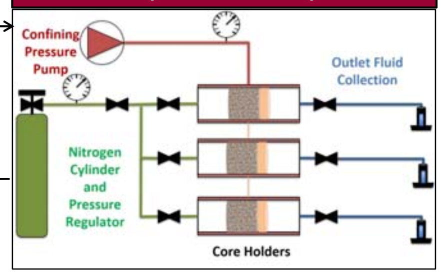
Stationary Liquid Method, Porous Plate Desaturation

MICP Data Core Grouping

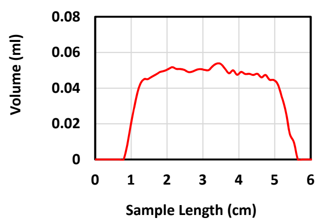


Group	Sample ID	Desaturation Pressures (psi)
I	A B	12,20,60,130
II	C# D	25,40,120, 200
III	E F G	95,130,200,480

Experimental Setup



Saturation Profile (NMR)

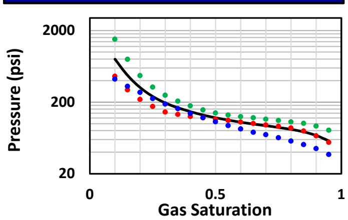


- Saturation Estimation
  - NMR T_2 Measurements
  - Gravimetric Calculations
- Gas Permeability (Pulse Decay)

Source: Gonzalez et al., 2019, SPWLA
(Heidari's research group)

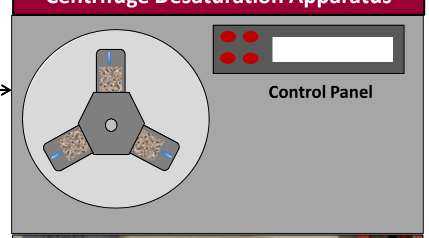
Stationary Liquid Method, Centrifuge Desaturation

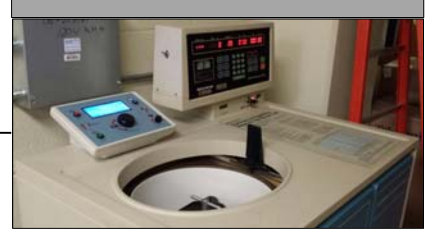
MICP Data Core Grouping



Group	Sample ID	Desaturation Speeds (rpm)
I	A B	1600, 2000, 3500, 5100
II	C# D	4200, 4900,6100,9500
III	E F G	2300, 2900, 4900, 6400

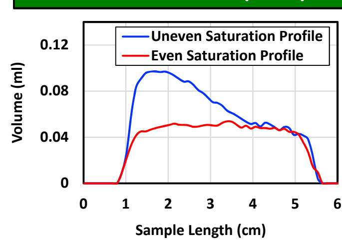
Centrifuge Desaturation Apparatus





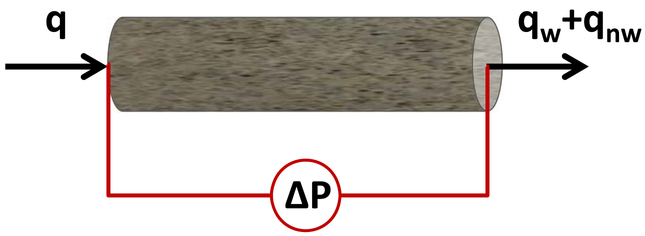
- Saturation Estimation
  - NMR T_2 Measurements
  - Gravimetric Calculations
- Gas Permeability (Pulse Decay)

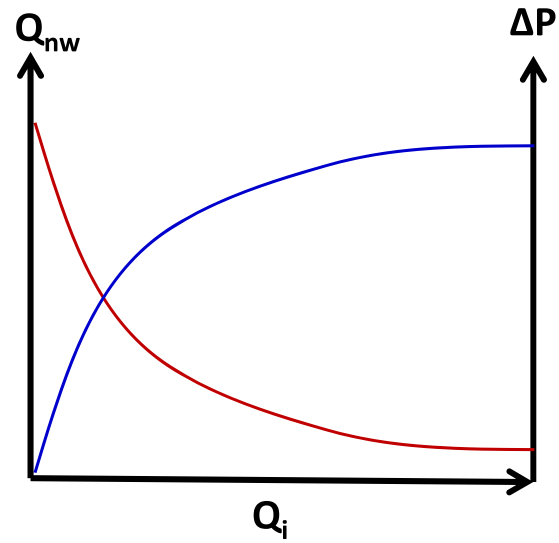
Saturation Profile (NMR)



Source: Gonzalez et al., 2019, SPWLA
(Heidari's research group)

Unsteady-state Method





Qnw(t): the cumulative non-wetting phase produced
Qi(t): the cumulative wetting phase injected

Interpretation of Data Collected from Unsteady-state Method

JBN Method

(Welge (1952) and Johnson, Bossler and Neumann (JBN, 1959))

$$k_{rnw} = \frac{f_{nw,outlet}}{\dfrac{d\left(\dfrac{1}{W_i I_r}\right)}{d\left(\dfrac{1}{W_i}\right)}}$$

W_i: dimensionless pore volume injected

I_r: relative injectivity

$$k_{rw} = \frac{\mu_w}{\mu_{nw}}\left(\frac{1}{f_{nw,outlet}} - 1\right) k_{rnw}$$

$$I_r = \frac{\left(\dfrac{q}{\Delta P}\right)}{\left(\dfrac{q}{\Delta P}\right)_s} = \frac{\left(\dfrac{q}{\Delta P}\right)}{\left(\dfrac{kA}{\mu_{nw} L}\right)}$$

$\left(\dfrac{kA}{\mu_{nw} L}\right)$: constant

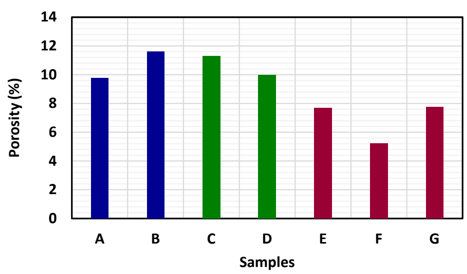
I encourage you to see the derivation or to try to derive these equations yourself!

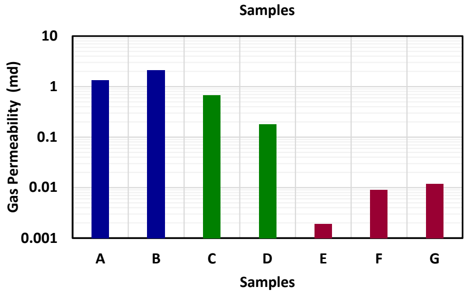
Characteristics of Unsteady-state Method

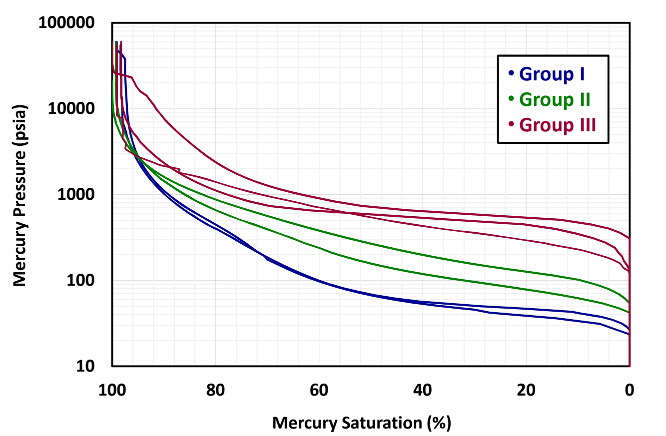
- Very fast compared to the steady-state method
- Minimizing capillary end effects is critical!
  - Can you explain the reason?

- Range of water saturation in which relative permeability can be recorded: S_{wf} to $1\text{-}S_{nwr}$
  - What rock/fluid properties control this range?

Example: Application to Multiple Tight Sand Reservoirs



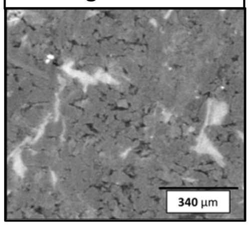




Source: Gonzalez et al., 2019, SPWLA (Heidari's research group)

Challenges in Application to Tight Rocks

Tight Rocks

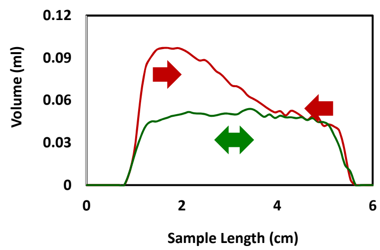


Failure to account for the desaturation mechanisms could lead to uncertainty in relative permeability measurements!

Source: Gonzalez et al., 2019, SPWLA
(Heidari's research group)

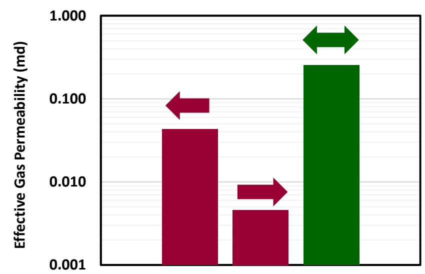
Steady-state Methods

- Low injection rates are difficult to measure.
- Stabilization time increases significantly.

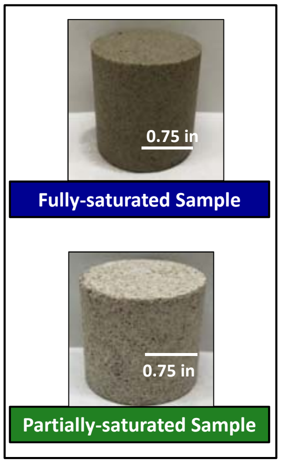


Unsteady-state Methods

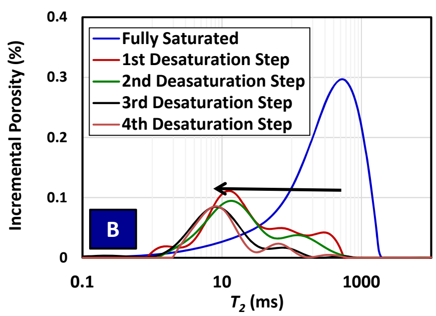
- Complex calculation methods.
- Viscous effects and capillary end effects are challenging to be taken into account.



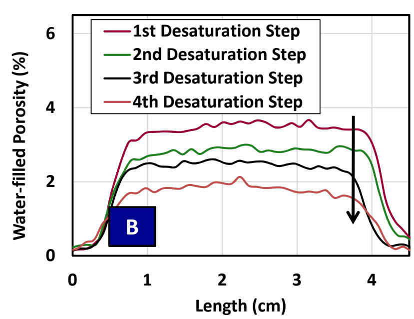
Example: Application to Multiple Tight Sand Reservoirs



NMR T_2 Distribution



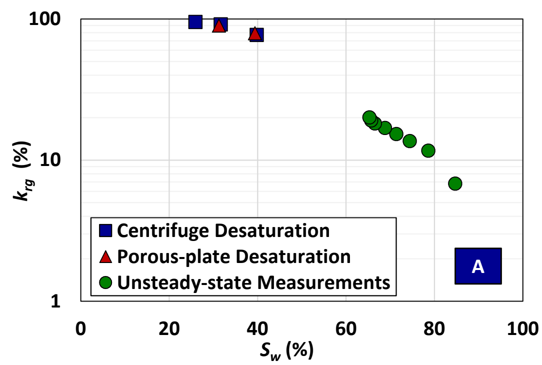
NMR Saturation Profile

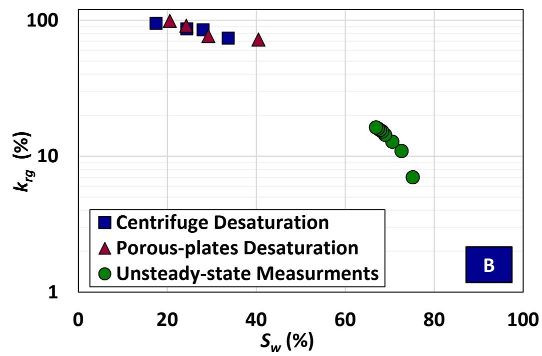


The dominant T_2 peaks shift towards faster relaxation times as water saturation decreases.

Source: Gonzalez et al., 2019, SPWLA
(Heidari's research group)

Example: Application to Multiple Tight Sand Reservoirs

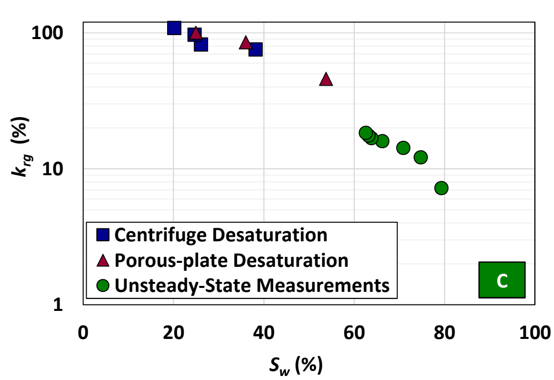


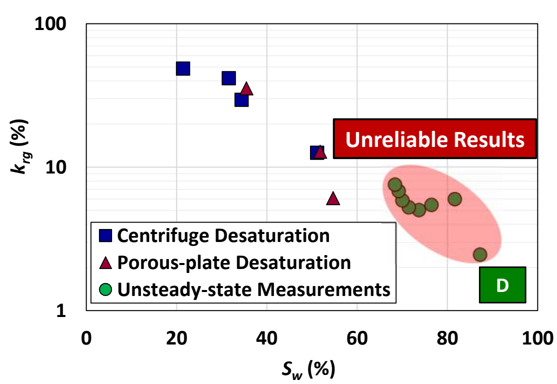


Group	Sample	Porosity (%)	Air Permeability (md)
I	A	9.78	1.35
	B	11.60	2.12

Source: Gonzalez et al., 2019, SPWLA (Heidari's research group)

Example: Application to Multiple Tight Sand Reservoirs

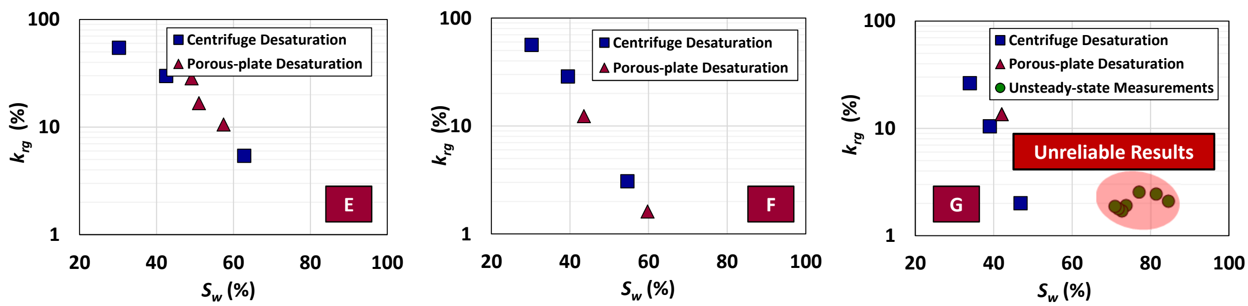




Group	Sample	Porosity (%)	Air Permeability (md)
II	C	11.3%	0.669
	D	10%	0.178

Source: Gonzalez et al., 2019, SPWLA (Heidari's research group)

Example: Application to Multiple Tight Sand Reservoirs



Group	Sample	Porosity (%)	Air Permeability (md)
III	E	7.69	0.019
	G	5.23	0.009
	F	7.76	0.012

Source: Gonzalez et al., 2019, SPWLA
(Heidari's research group)

In-situ Assessment of Relative Permeability

- Is it possible to estimate relative permeability in-situ condition?
- What are the possible options based on what we learned so far?
- What are the challenges associated with these possible options?

Assessment of Relative Permeability from Drainage Capillary Pressure

OPTIONAL

$$k_{rw}(S_w) = \frac{k_w}{k} = \frac{\int_0^{S_w} \frac{dS_w}{P_c^{2+\alpha}}}{\int_0^1 \frac{dS_w}{P_c^{2+\alpha}}}$$

$$k_{rnw}(S_w) = \frac{k_{nw}}{k} = \frac{\int_{S_w}^1 \frac{dS_w}{P_c^{2+\alpha}}}{\int_0^1 \frac{dS_w}{P_c^{2+\alpha}}}$$

- **What are the limitations of these models?**
- **Can they be addressed?**

Updated Model: Burdine (1953)

OPTIONAL

Normalized drainage relative permeability

$$\bar{k}_{rw}(S_w^*) = \frac{k_w(S_w^*)}{k_w(S_w^* = 1)} = \left(S_w^*\right)^2 \frac{\int_0^{S_w^*} \frac{1}{P_c^2} dS_w^*}{\int_0^1 \frac{1}{P_c^2} dS_w^*}$$

$$\bar{k}_{rnw}(S_w^*) = \frac{k_{nw}(S_w^*)}{k_{nw}(S_w^* = 0)} = \left(1 - S_w^*\right)^2 \frac{\int_{S_w^*}^1 \frac{1}{P_c^2} dS_w^*}{\int_0^1 \frac{1}{P_c^2} dS_w^*}$$

We need to estimate this value!

Normalized wetting phase saturation

$$S_w^* = \frac{S_w - S_{wirr}}{1 - S_{wirr}}$$

How to calculate this integral?

Assessment of Relative Permeability from Drainage Capillary Pressure

OPTIONAL

Let's use Brooks-Corey drainage capillary pressure model:

$$\ln S_w^* = -\lambda \ln P_c + \lambda \ln P_e \rightarrow \ln P_c = -\frac{1}{\lambda}\ln S_w^* + \ln P_e \rightarrow P_c = P_e \left(S_w^*\right)^{-\frac{1}{\lambda}}$$

pore size distribution index

$$\bar{k}_{rw}(S_w) = \left(S_w^*\right)^{\frac{2+3\lambda}{\lambda}}$$

$$\bar{k}_{rnw}(S_w) = \left(1 - S_w^*\right)^2 \left[1 - \left(S_w^*\right)^{\frac{2+\lambda}{\lambda}}\right]$$

$$k_{rw} = \left(\frac{S_w - S_{wirr}}{1 - S_{wirr}}\right)^{\frac{2+3\lambda}{\lambda}}$$

$$k_{rnw} = k_{rnw}\left(at\ S_w = S_{wirr}\right)\left(1 - \frac{S_w - S_{wirr}}{S_m - S_{wirr}}\right)^2 \left(1 - \left(\frac{S_w - S_{wirr}}{1 - S_{wirr}}\right)^{\frac{2+\lambda}{\lambda}}\right)$$

wetting phase saturation at which k_{rnw} becomes 0
(at critical nonwetting phase saturation)

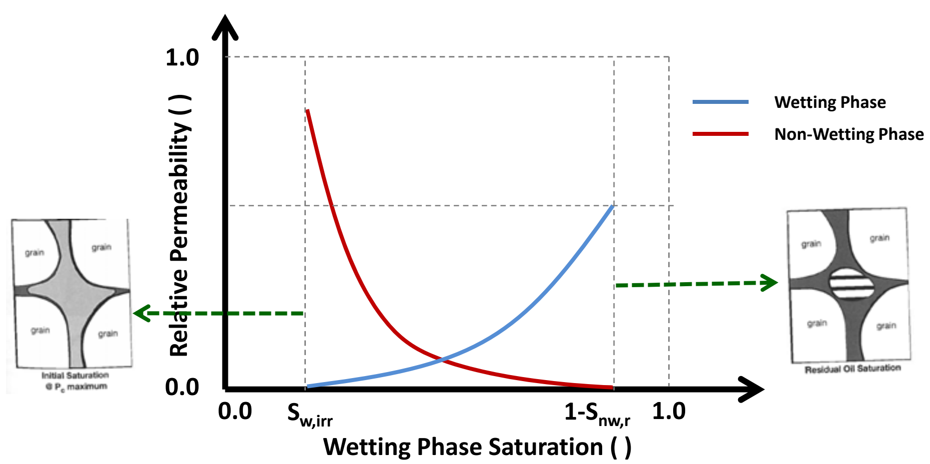
Example

Please Take Notes!

Parameters Affecting Relative Permeability

- Fluid saturation
- Saturation history
- Wettability
- Injection rate
- Viscosity ratio
- Interfacial tension
- Pore structure
- Temperature
- Heterogeneity
- …

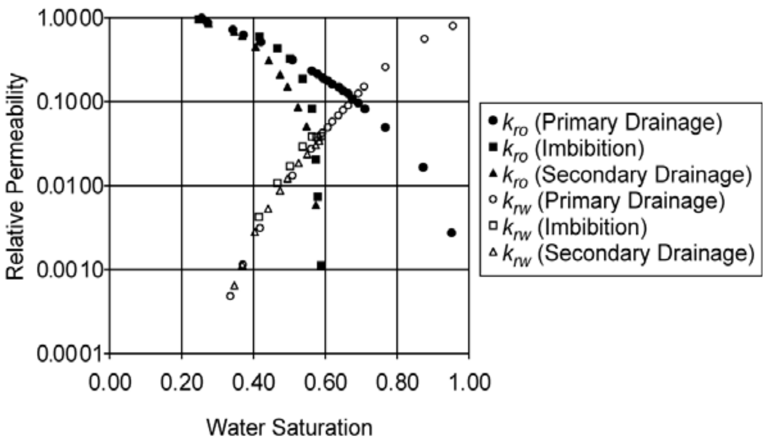
Impact of Fluid Saturation on Relative Permeability



Saturation of fluid X ↑ ⇨ Relative permeability to fluid X ?

Impact of Saturation History on Relative Permeability

Hysteresis in relative permeability



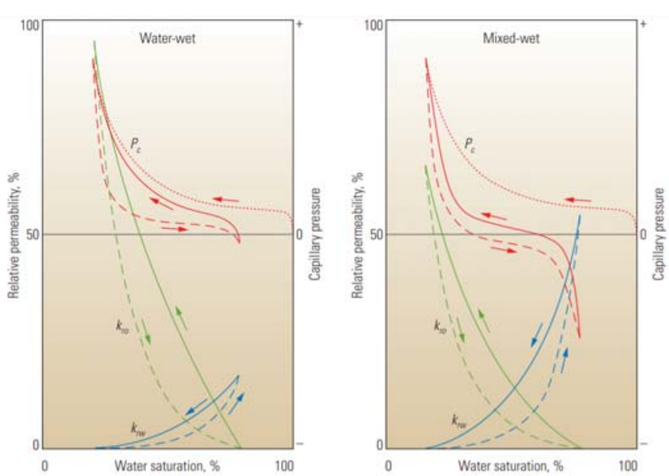
Imbibition K_{rnw} < Drainage K_{rnw}

Imbibition K_{rw} > Drainage K_{rw}

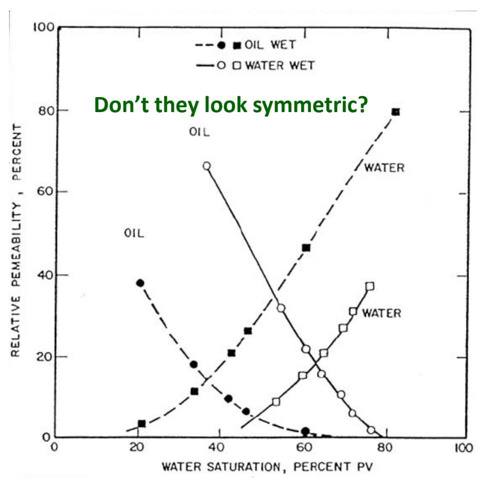
Can you explain this observation?

Source: Braun and Holland, 1995

Impact of Wettability on Capillary Pressure and Kr

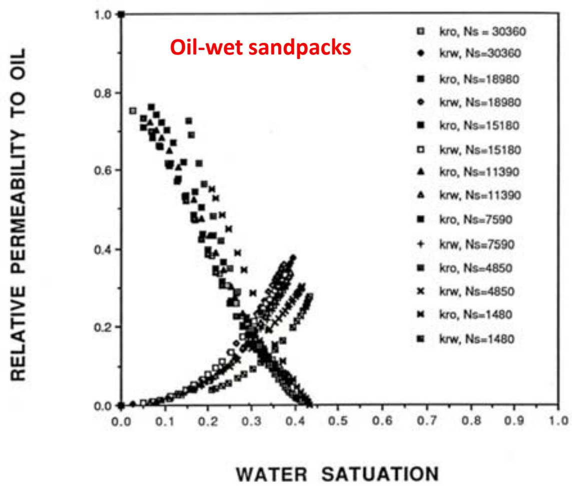


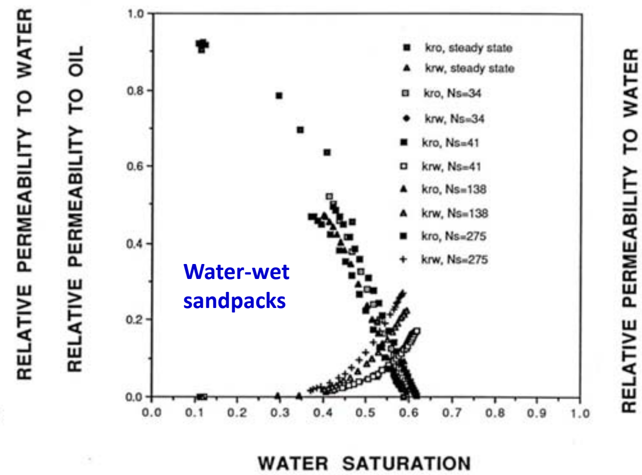
Source: Schlumberger Oilfield Review, Fundamentals of Wettability.



Source: Jennings, 1957; Peters, E. J., 2012, Advanced Petrophysics

Impact of Injection Rate on Relative Permeability

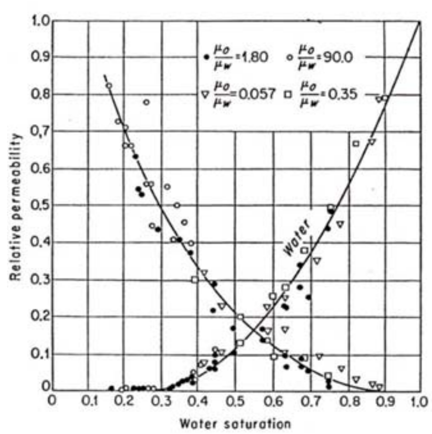




Source: Peters, E. J., 2012, Advanced Petrophysics

Impact of Viscosity Ratio on Relative Permeability

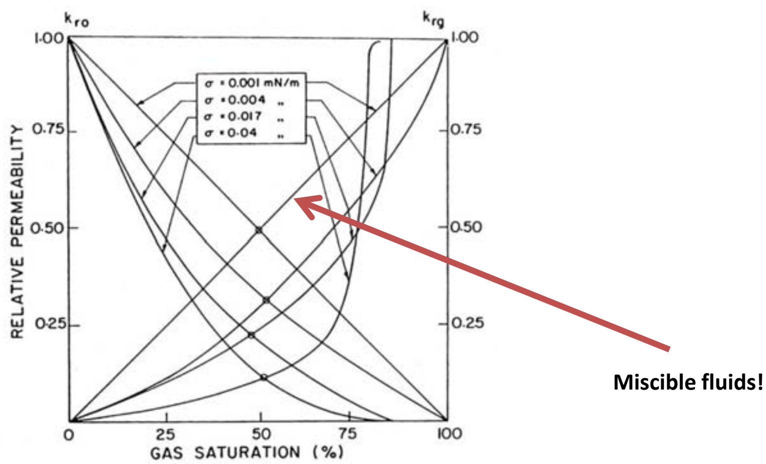
Steady-state Measurements



What about unsteady state?

Source: Jennings, 1957; Peters, E. J., 2012, Advanced Petrophysics

Impact of Interfacial Tension on Relative Permeability



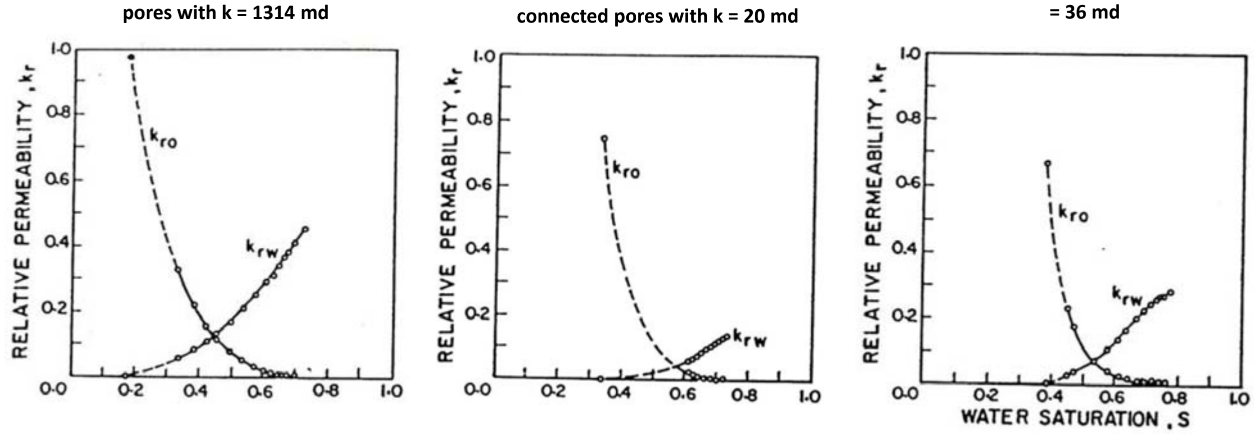
Source: Bardon and Longeron, 1978

Impact of Pore Structure on Relative Permeability

sandstone with large, well-connected pores with k = 1314 md

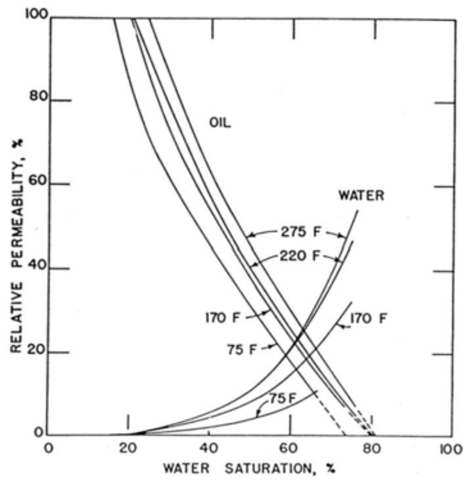
Sandstone with small, well-connected pores with k = 20 md

sandstone with a few large pores connected with small pores with k = 36 md



Source: Morgan and Gordon, 1970

Impact of Temperature on Relative Permeability



Source: Poston et al., 1970

Complementary References

- **Peters, E. J., 2012, Advanced Petrophysics. Live Oak Book Company. Chapter 8**
- **Zinszner, B. and Pellerin, F. M., 2007, A Geoscientist's Guide to Petrophysics. Editions Technip.**