# Maximizing Production After Stimulation in Tight Gas Reservoirs

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# Can Modeling Help Design Fracture Treatments?

- Fracture geometry prediction is improving
  - computing of in-situ stresses
    - Must be calibrated to field measurements
  - measuring and modeling rheology
    - Sensitive to environmental variables
  - predicting prop transport and post-closure movement
  - Modeling and predicting screenouts
    - Requires pre-frac injection and careful diagnostics
  - fracture containment mechanisms other than stress contrast
    - Can be calibrated locally based on observations

# Placing Problem Jobs

- Near-well restrictions and high injection pressures
  - Step-rate tests to separate perf restrictions from “tortuosity”
- Rapid near-well screenouts
  - Fluid stability (?)
  - Fissure PDL and proppant holdup
- Increasing pressure to limits during the pad
  - Reservoir conditioning at low rate

# Designing for Expected Conductivity

- Include major damage effects
  - non-Darcy and multiphase flow effects
  - non-uniform stress, prop crushing and traditional conductivity
  - channelized flow, saturation distributions and gravity over-ride
  - fluid stability, breaker effectiveness, cleanup, flowback and post-treatment
- Integrate reservoir deliverability and pack damage to estimate effective producing frac length

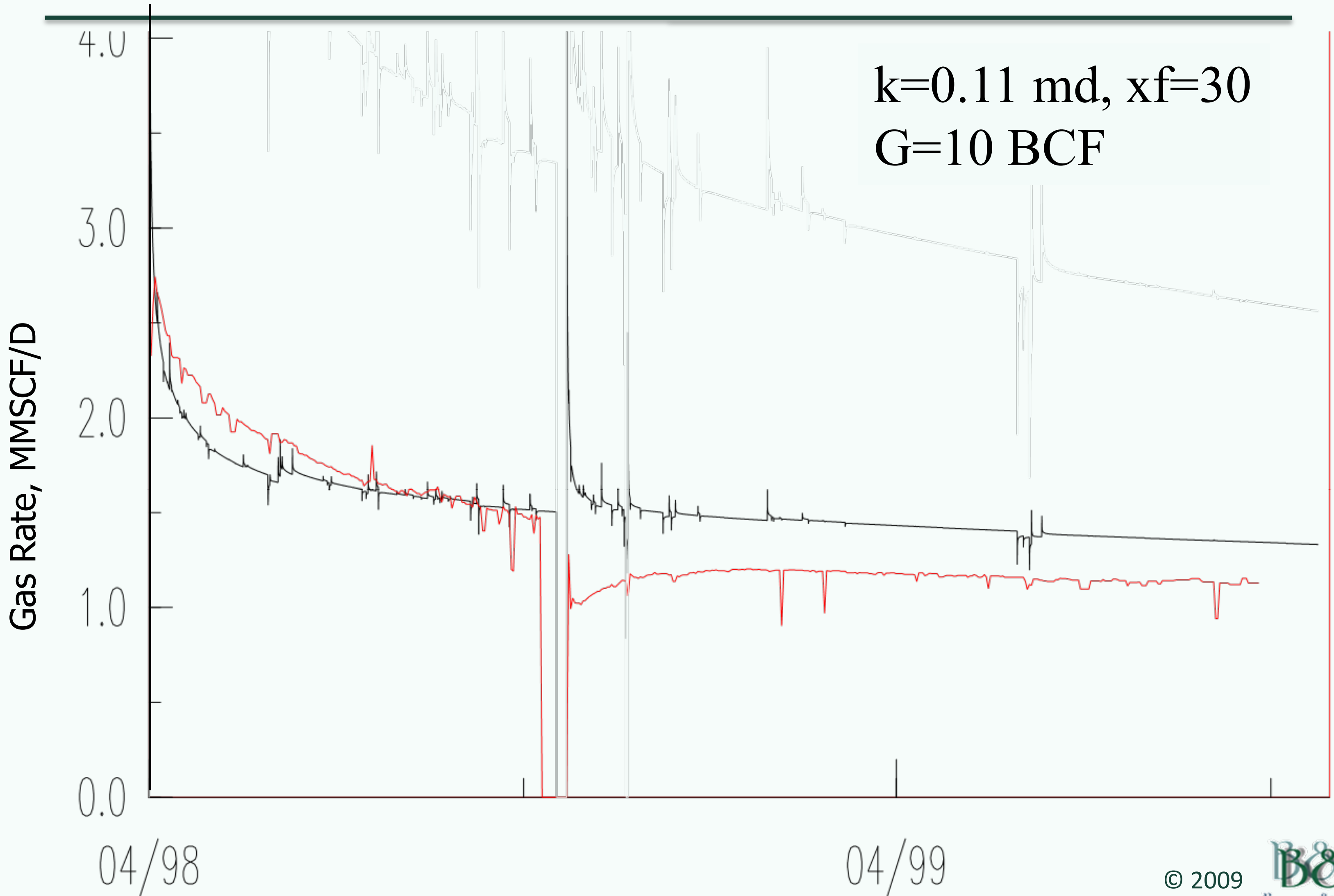
# Post-Job Analysis

- We must know what was achieved to improve the design
- Production analysis is still the best tool around
  - How the frac behaves during production pays for the treatment
- Collect the data!
- Do the work, or the design effort was wasted

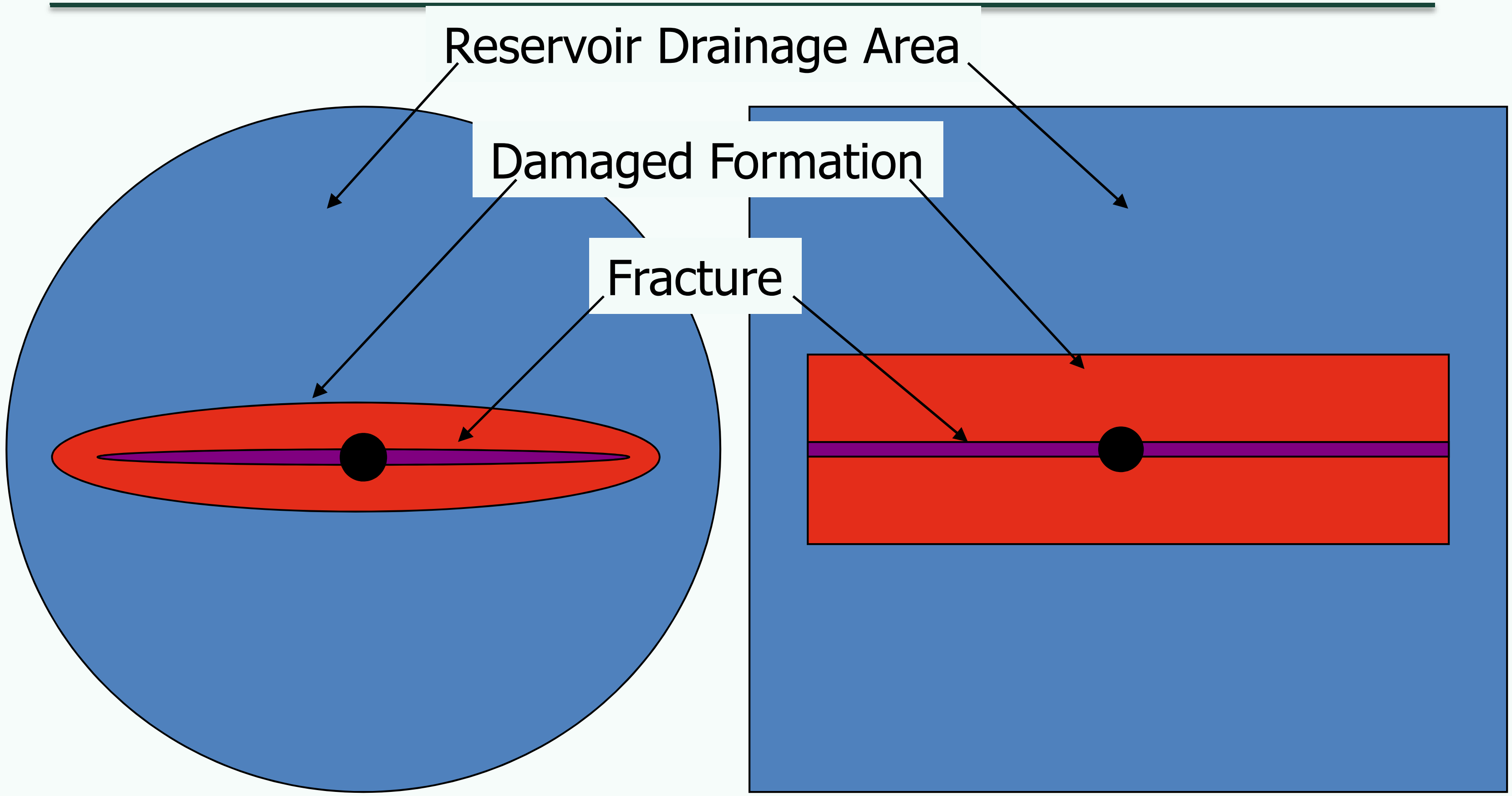
# Effect of Liquid Loading on Gas Well Production

- Impact of short-term well killing or shut-ins
  - Application of snubbing instead of killing
- Capillary pressure and phase trapping
- Proper and improper use of surfactants

# Fractured Well Performance Showing Effects of a Short Shut-In



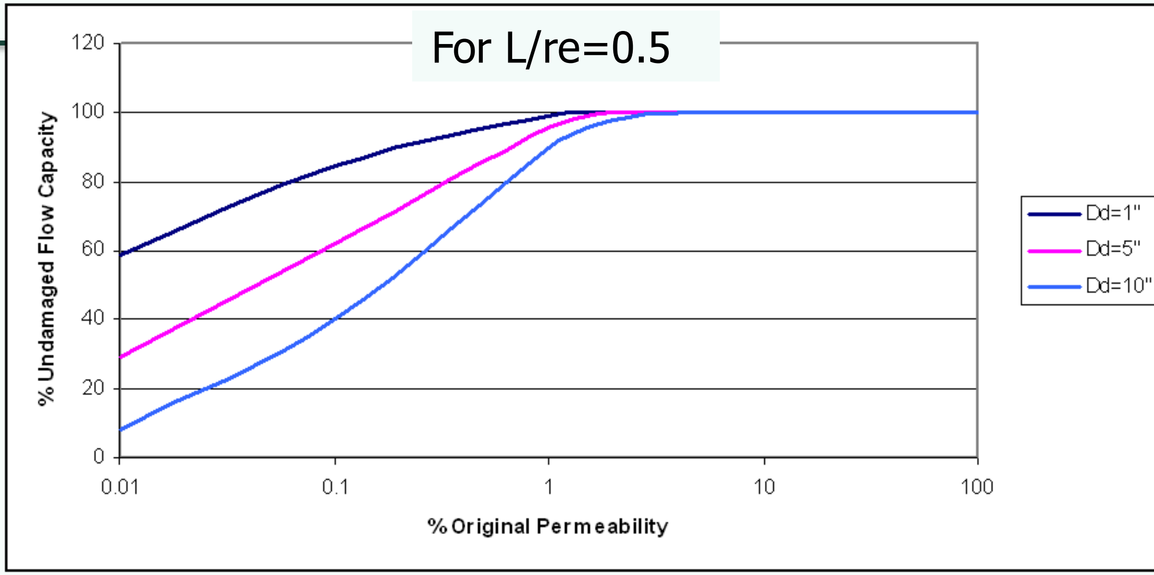
# Fracture Face Skin Damage

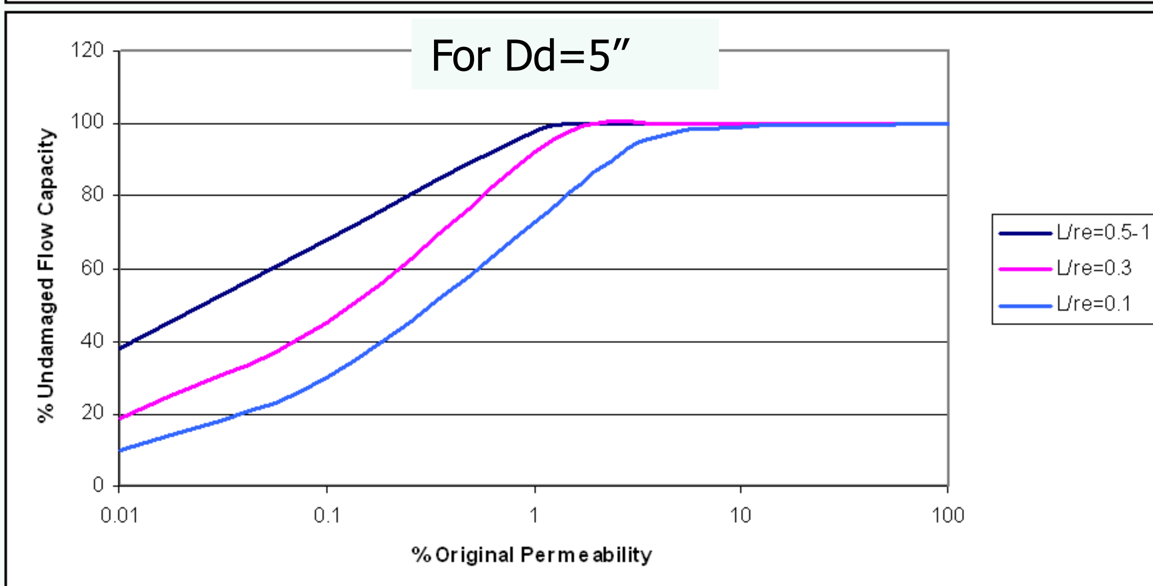



Pratts Analytical Model

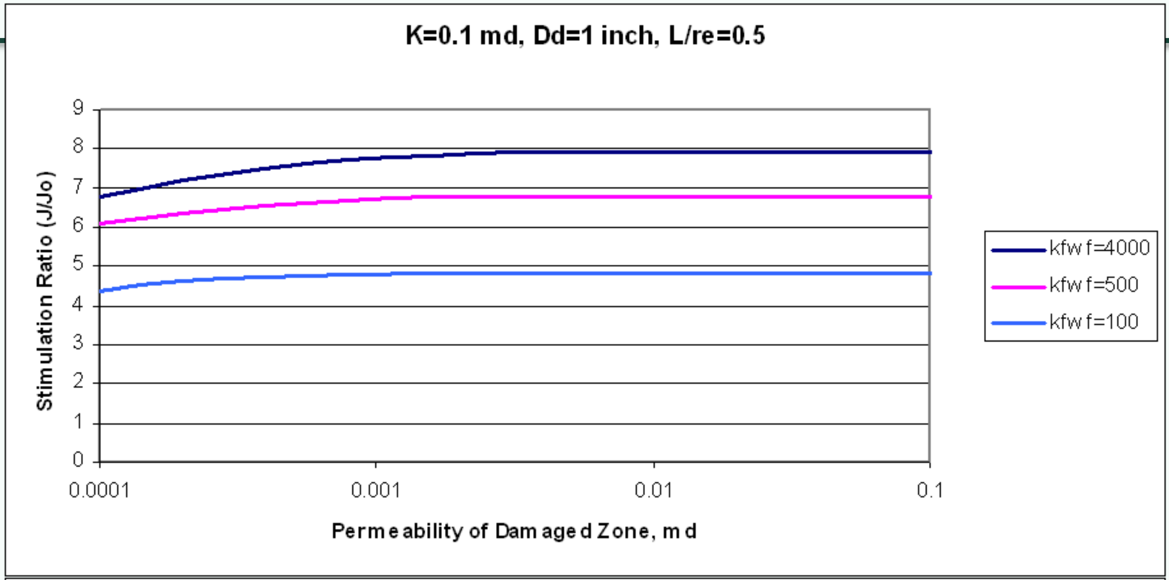
Holditch Numerical Model

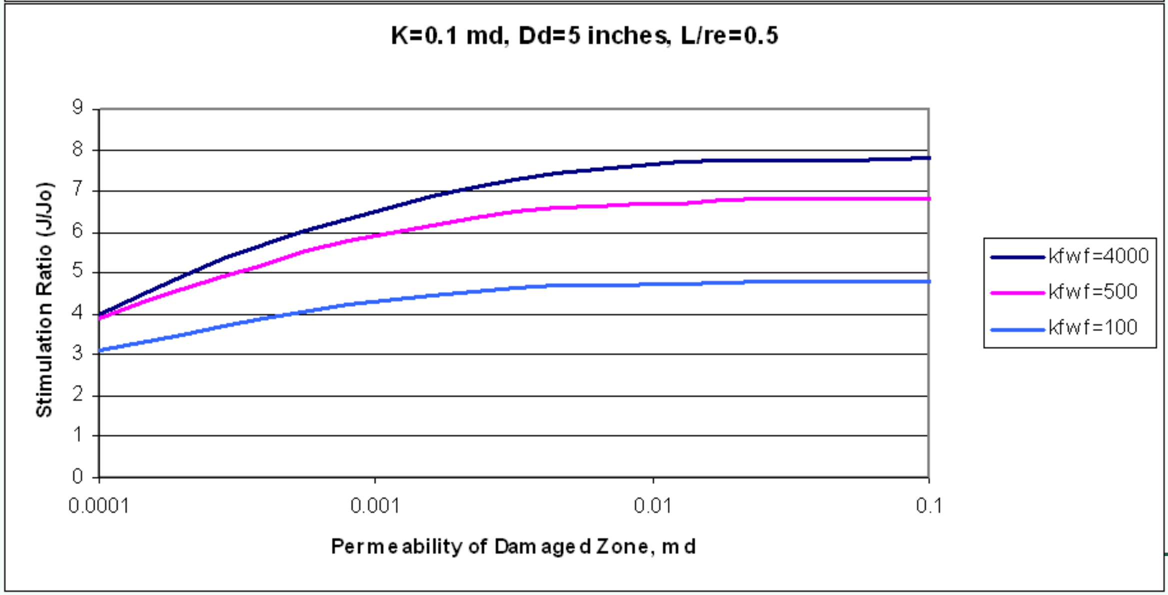
# Pratts Results Paraphrased



# Holditch Results for Face Damage



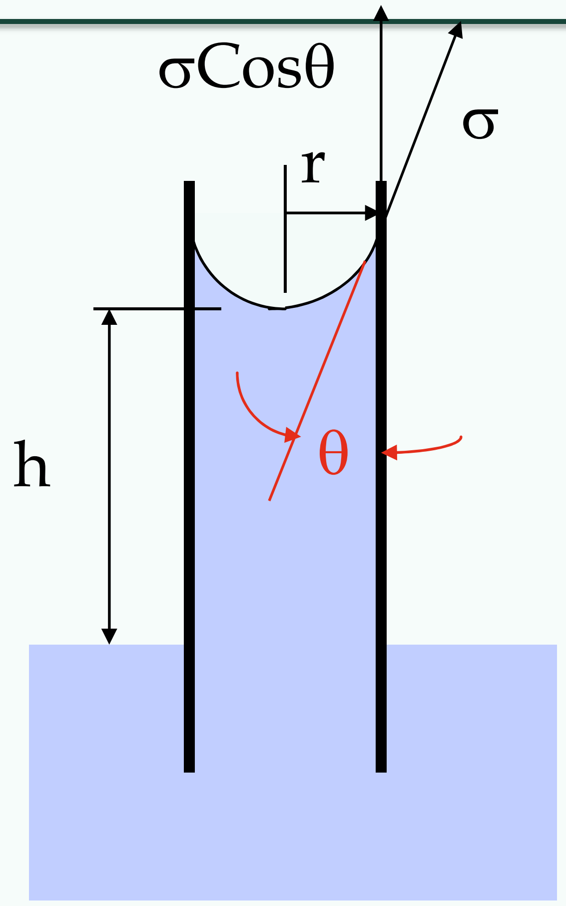
# Another Look at Face Damage

- Pratts and Holditch both assumed that the entire fracture surface area was open to flow
- Permeability is reduced at the face, but remains non-zero
- The large surface area and very low velocity (low pressure gradient) makes perm damage tolerable
- If the fracture face area is diminished (by capillary blockage), it cannot contribute to flow (perm=zero) and their conclusions are invalid
- Inflow capacity is reduced by the ratio of open face area
- Pressure gradients and damage effects are much more severe where flow can occur

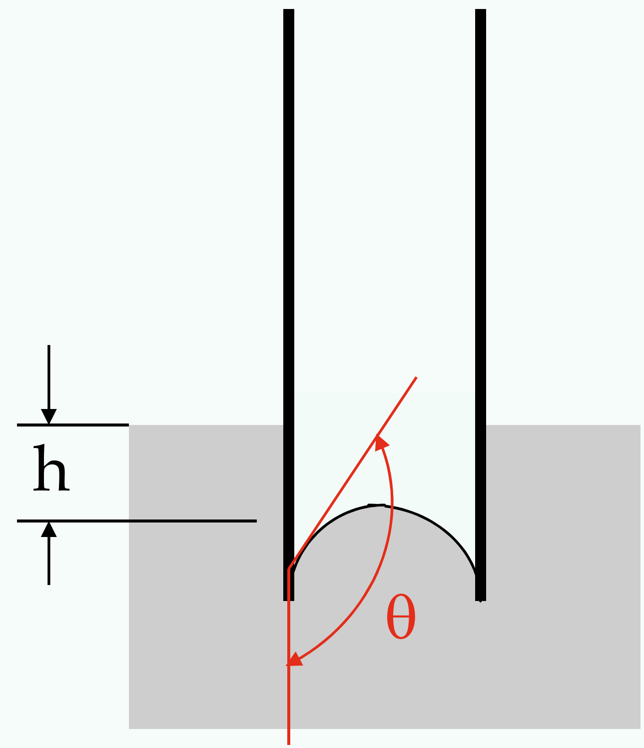
# Capillary Pressure

- The difference between the pressures of two or more immiscible phases contained in a restricted cavity is $P_c$
- Capillary pressure is related to pore size, size distribution, and wettability
- Saturation distribution within a porous medium is controlled by capillary pressure.

# Capillary Effects in Circular Tubes




Capillary Rise of
a Wetting Phase




Capillary Depression of
a Non-Wetting Phase

# Capillary Pressure Equations

At equilibrium (no movement of interface):

Force Up = Force Down

$$\textbf{Force Up} = 2\pi r \sigma \cos\theta$$

$$\textbf{Force Down} = \pi r^2 \Delta\rho g h$$

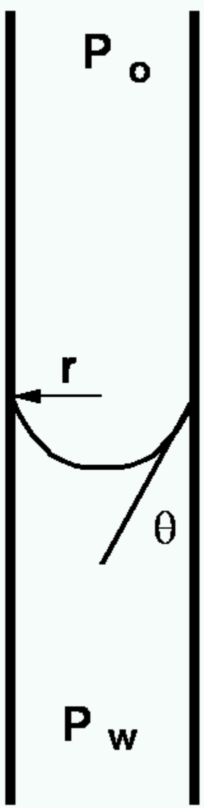
Capillary Pressure is defined as Force per Unit Area ($\pi r^2$):

$$P_c = \frac{2\pi r \sigma \cos\theta}{\pi r^2} = \frac{2\sigma \cos\theta}{r} \text{ and}$$

$$P_c = \frac{\pi r^2 \Delta\rho h\, g/g_c}{\pi r^2} = \Delta\rho h \frac{g}{g_c}$$

So: $P_c = \dfrac{2\sigma \cos\theta}{r} = \Delta\rho \dfrac{g}{g_c} h$

# Capillary Pressure and Frontal Advance Rate




$$P_c = P_o - P_w$$

$$= \frac{2\sigma Cos\,\theta}{r}$$

$$V = \frac{r^2 \Delta P}{4\mu \Delta L}$$

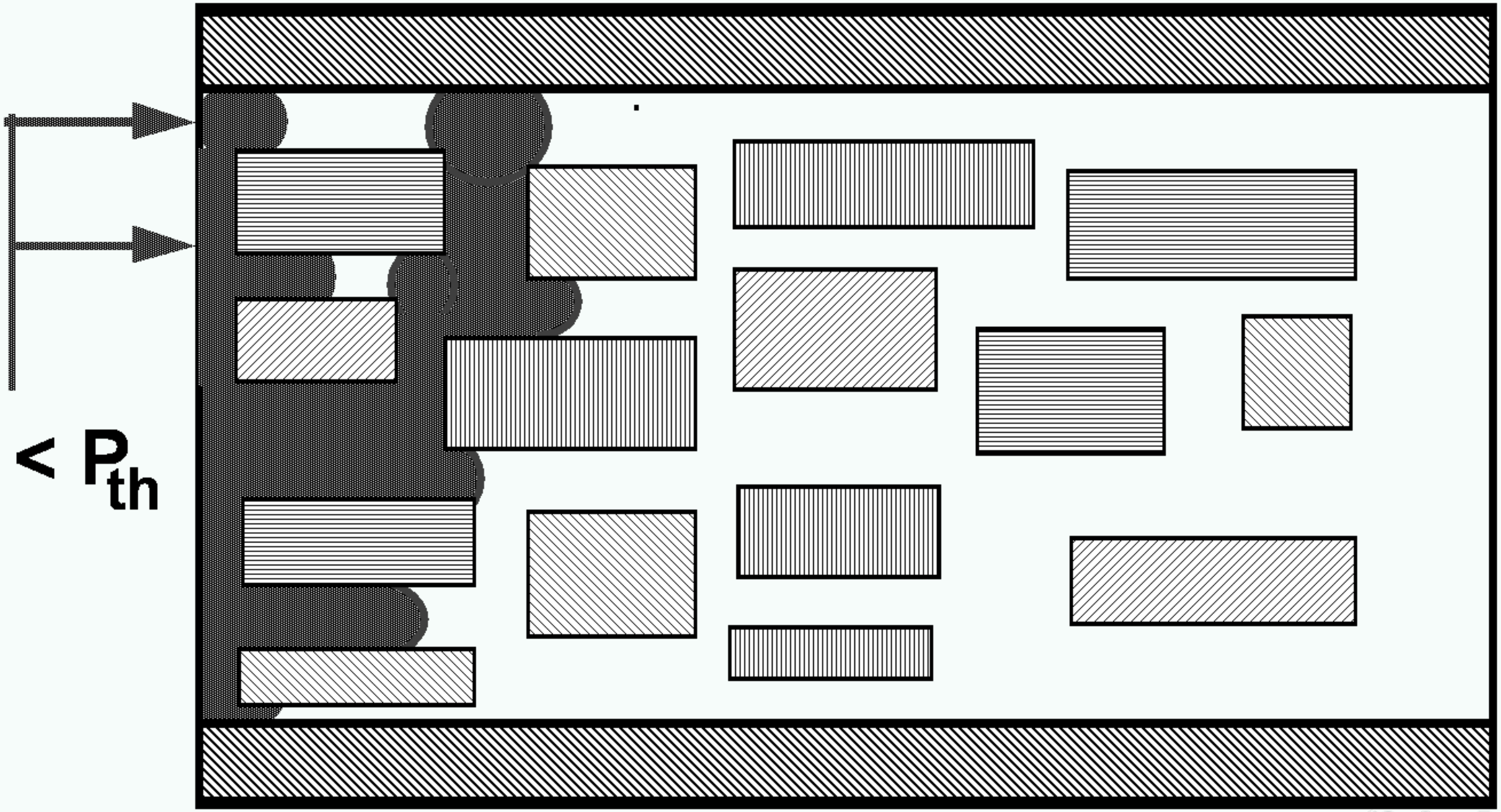
Must exceed the threshold capillary pressure to get the interface to move.

- Any pressure differential below the threshold just distends the meniscus.

Once the interface moves, the frontal advance rate is controlled by viscous flow.

- Note that both threshold pressure and velocity favor flow in large pores for any potential-driven flow.

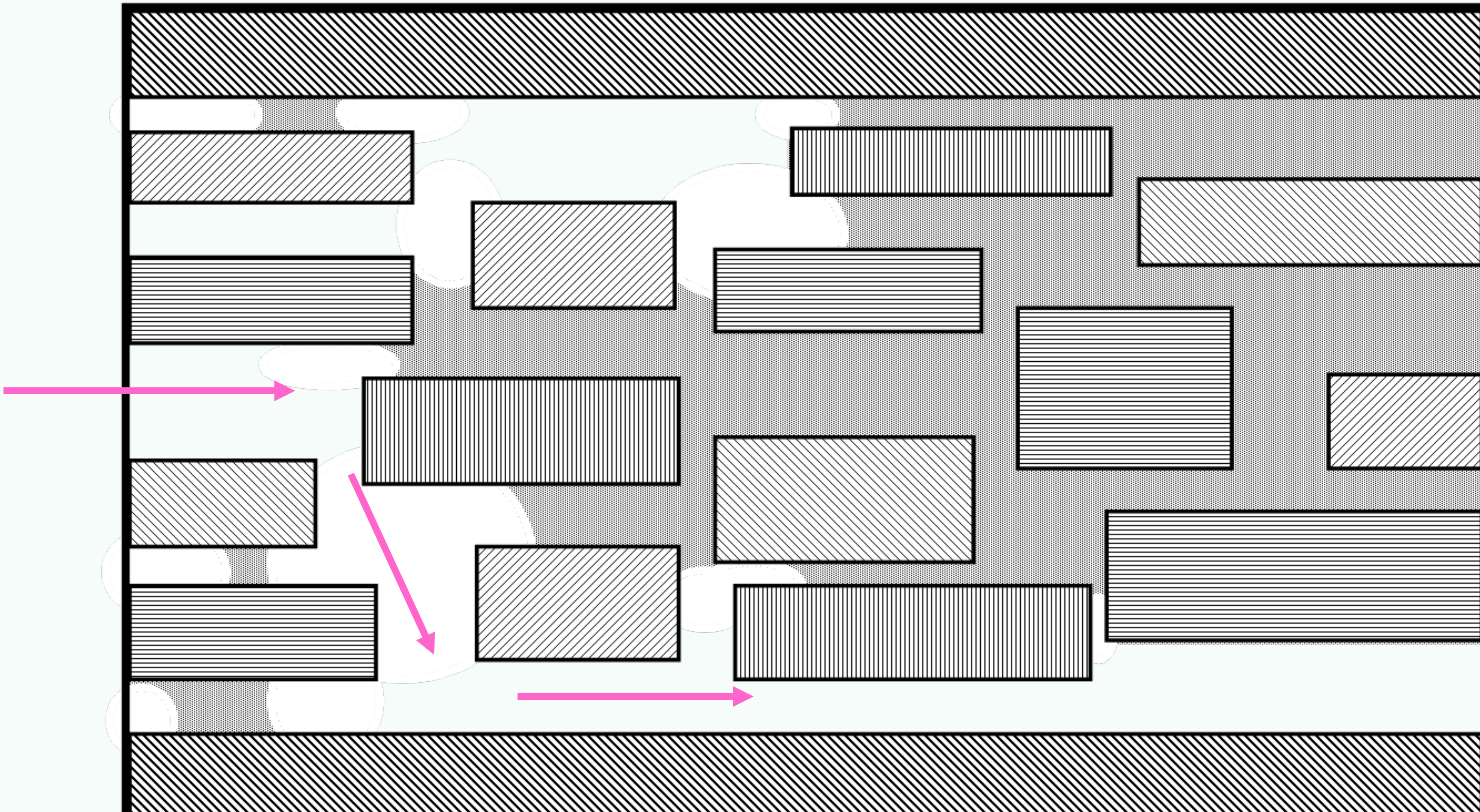
# Capillary Pressure restricts fluid entry by pore size



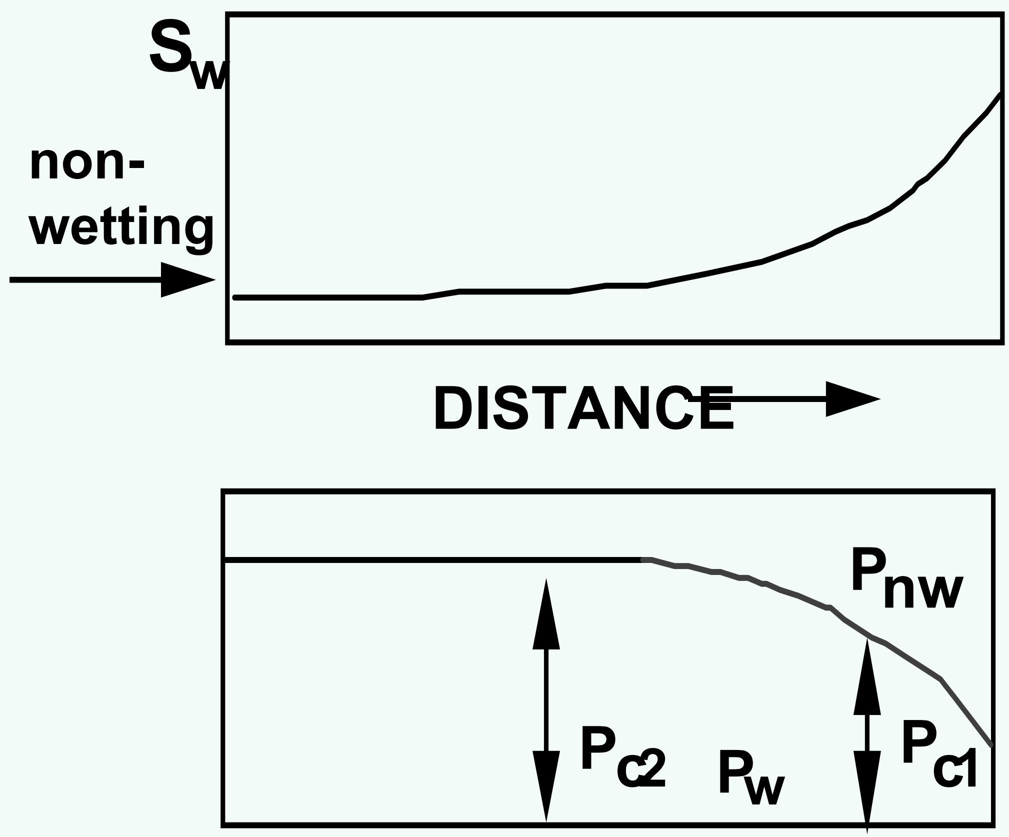
$P_o < P_{th}$

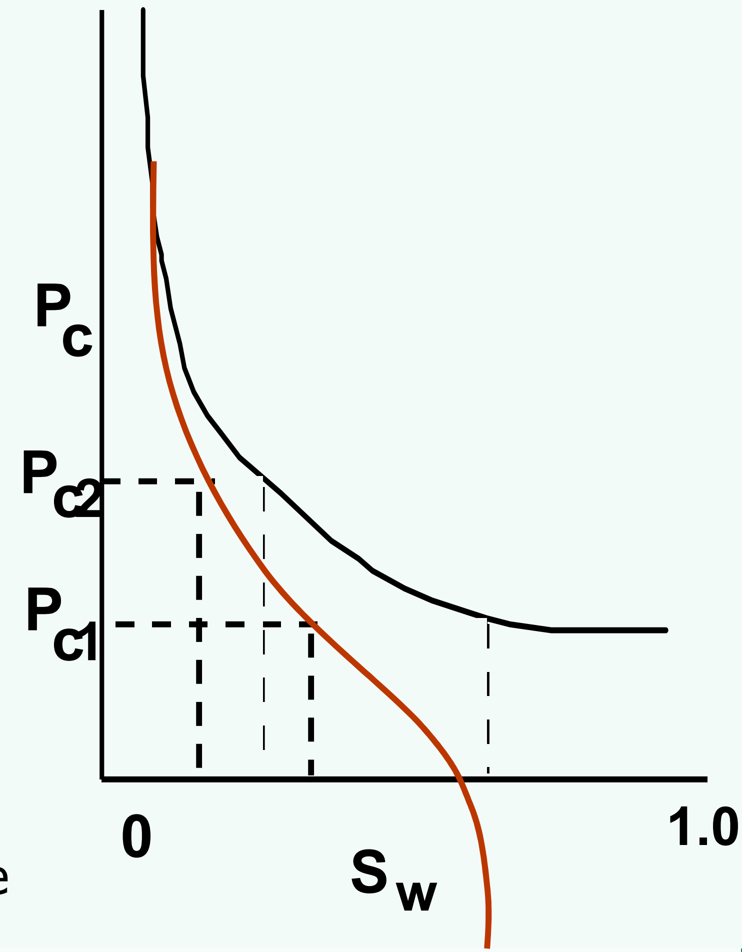
# Gas Evolution is Different From Gas Injection

Injected gas can only enter pores based on threshold entry pressure. Gas flow is restricted to few pore channels.



# What causes capillary saturation blockage after breakthrough?

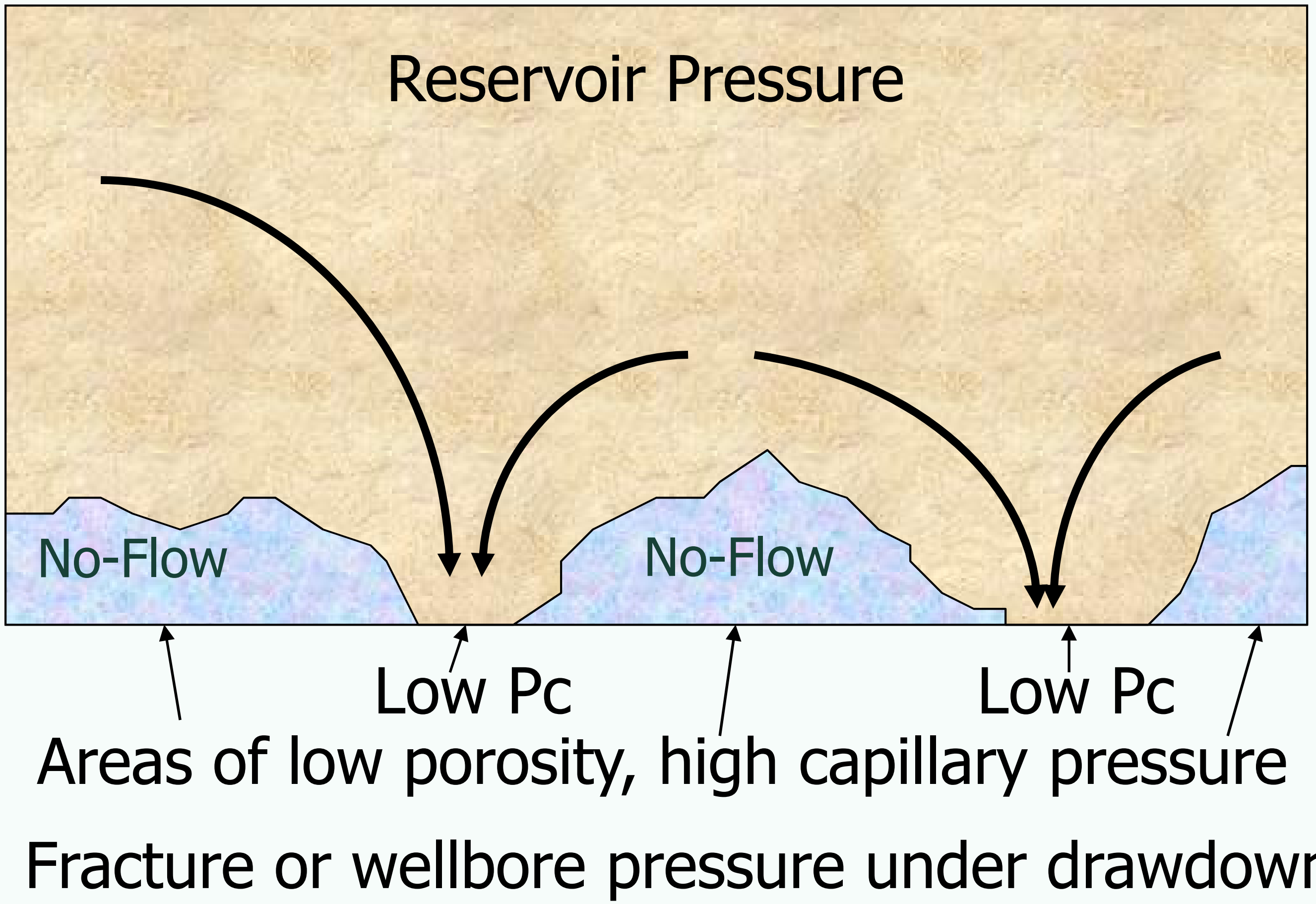



Outside the reservoir the capillary pressure approaches zero as radius of curvature of the gas bubble or oil droplet increases.

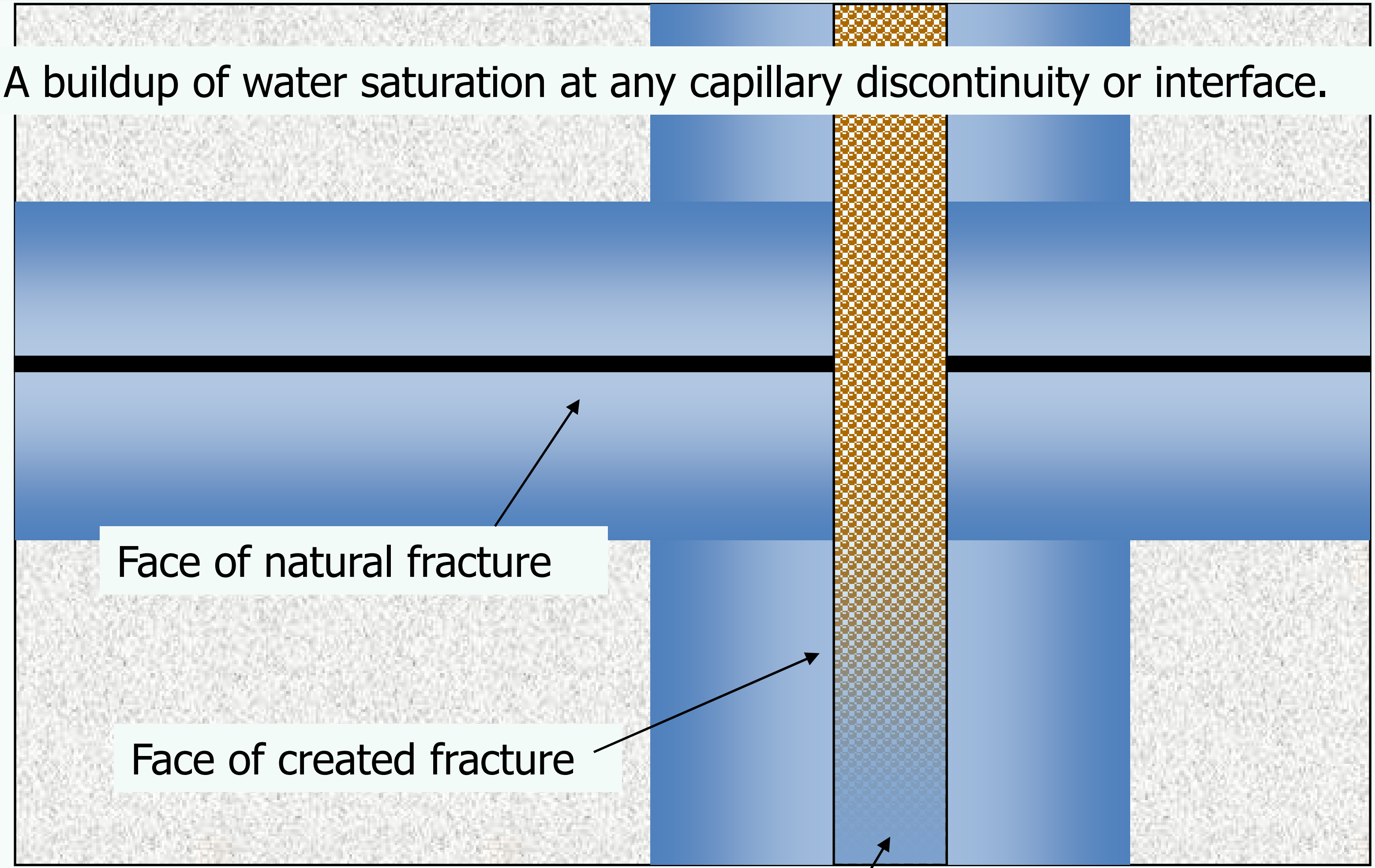
# Capillary Phase Trapping: A Potentially Serious Damage Mechanism

Capillary blocking causes loss of fracture face area

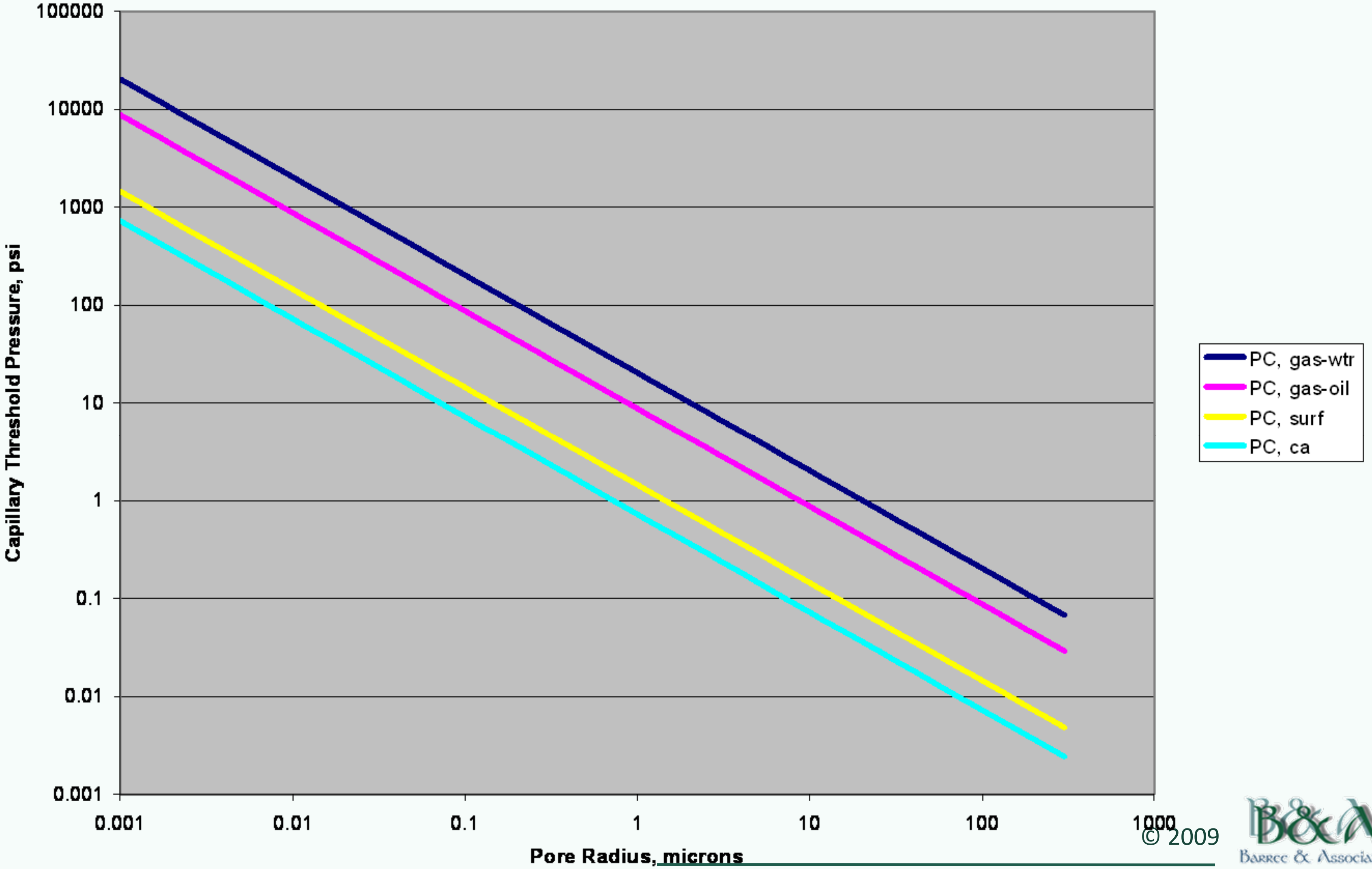


# Capillary Face Discontinuities or "Capillary End-Effect"

A buildup of water saturation at any capillary discontinuity or interface.



# Capillary Threshold Pressure for Various Fluid Systems



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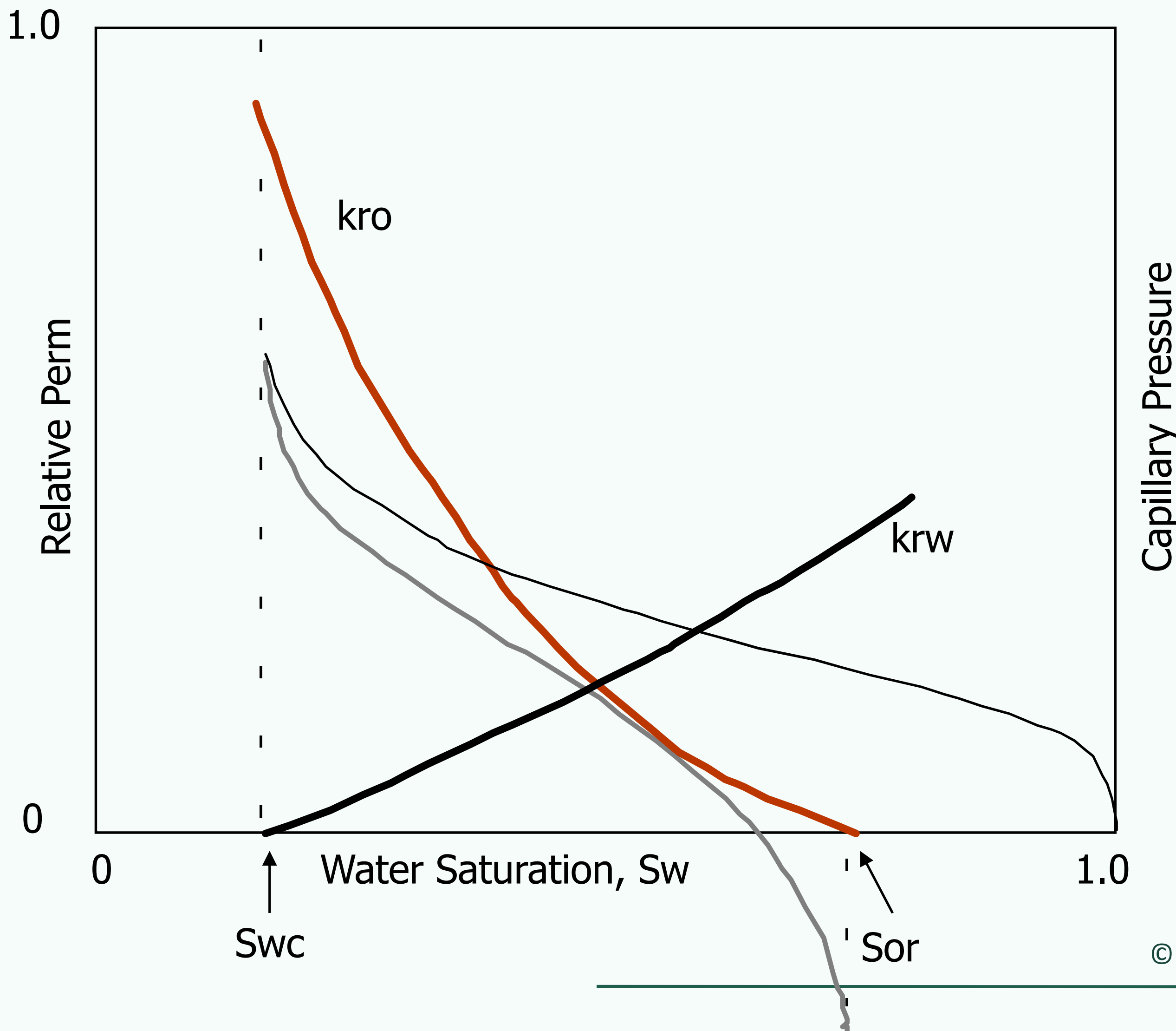
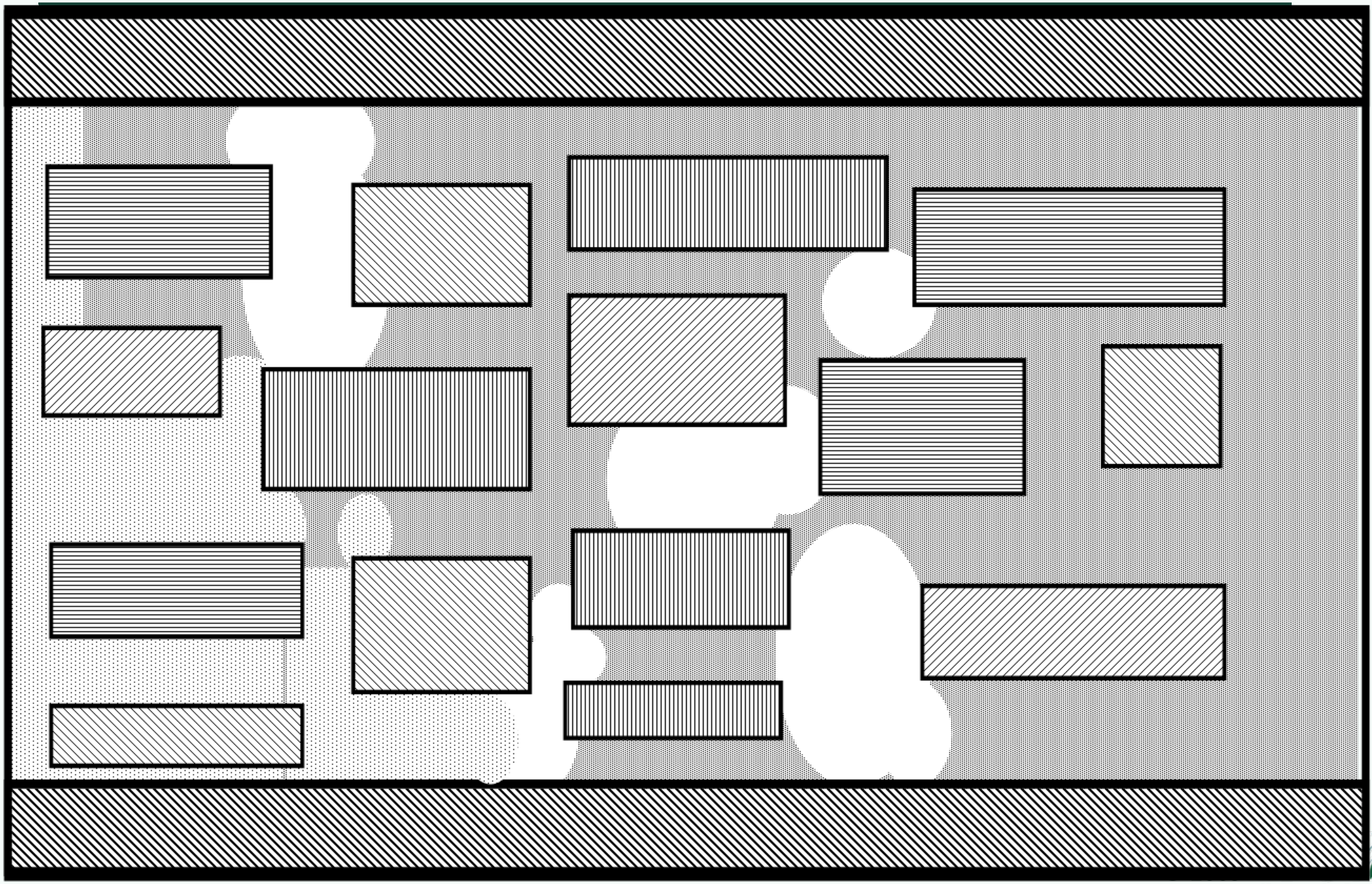
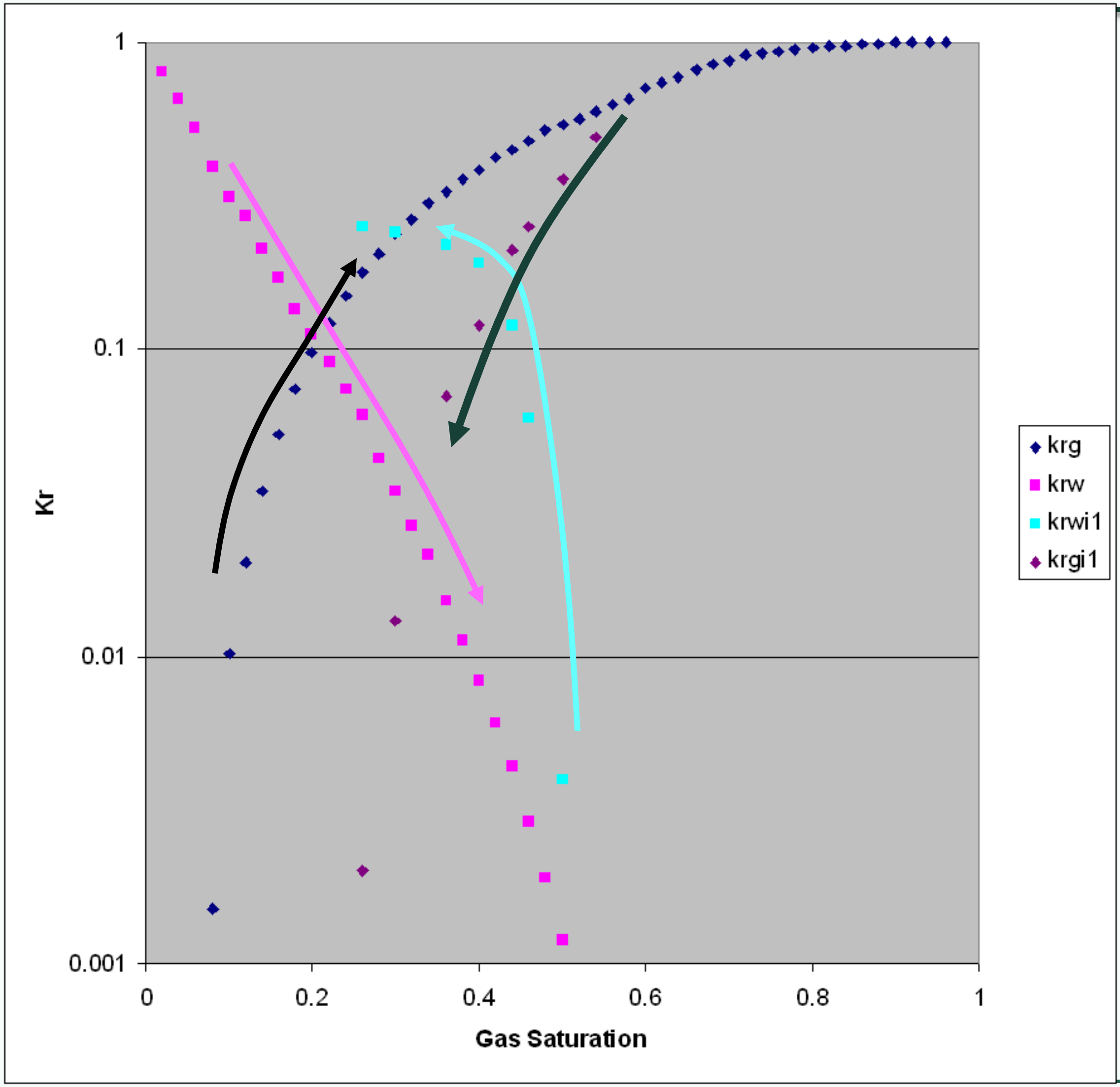
# Drainage and Imbibition Residual Saturations at Capillary Equilibrium



# Pore Throats Blocked by Gas Force Flow Through Other Channels



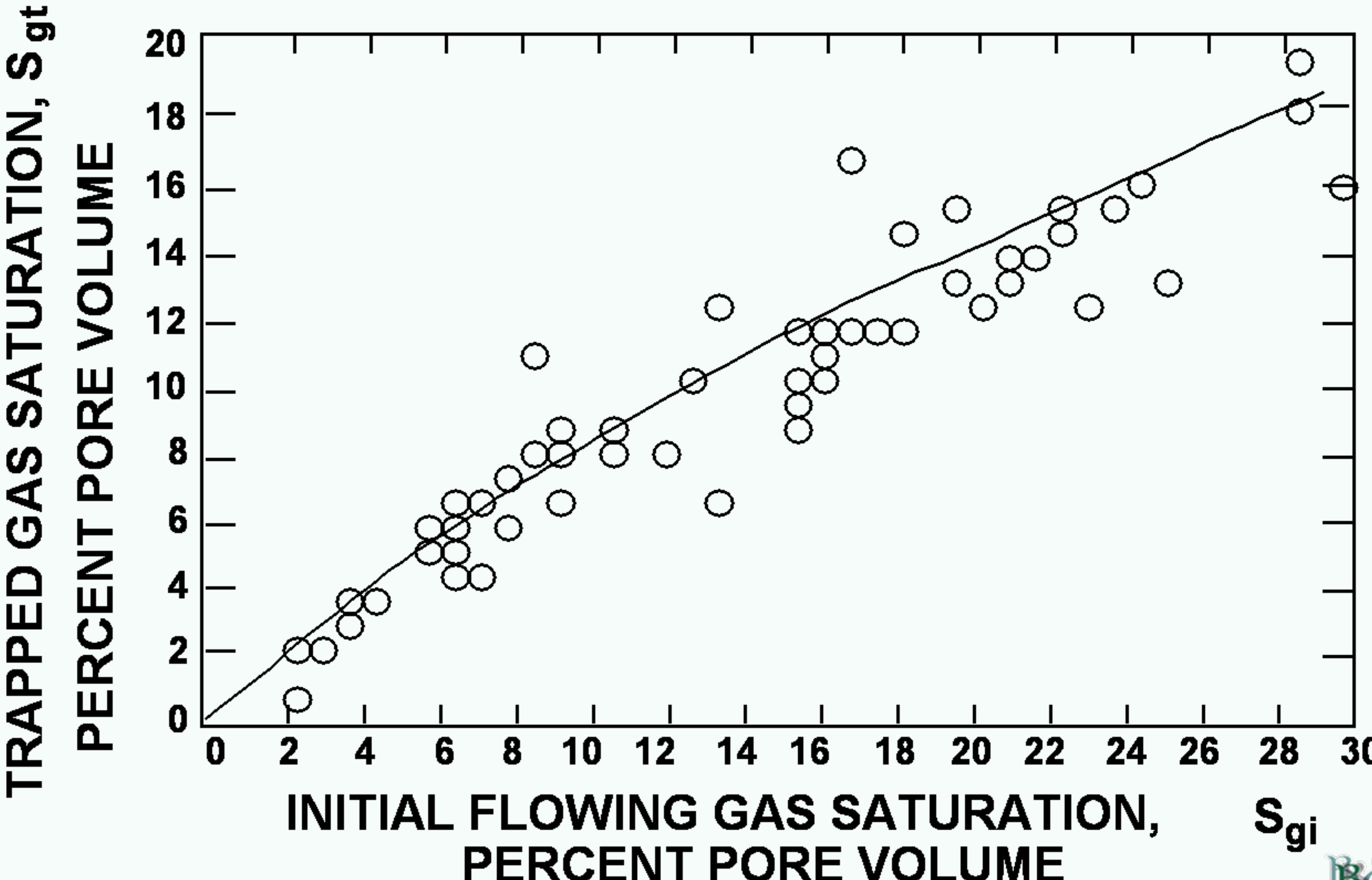
# Gas-Water Rel-Perm Hysteresis




Hysteresis curves show effects of gas blockage and entry pressure.

This can happen every time a well is killed or shut-in when liquid is injected or allowed to fall out in the tubing and imbibe.

# Trapped Gas Increases with Initial Gas Saturation



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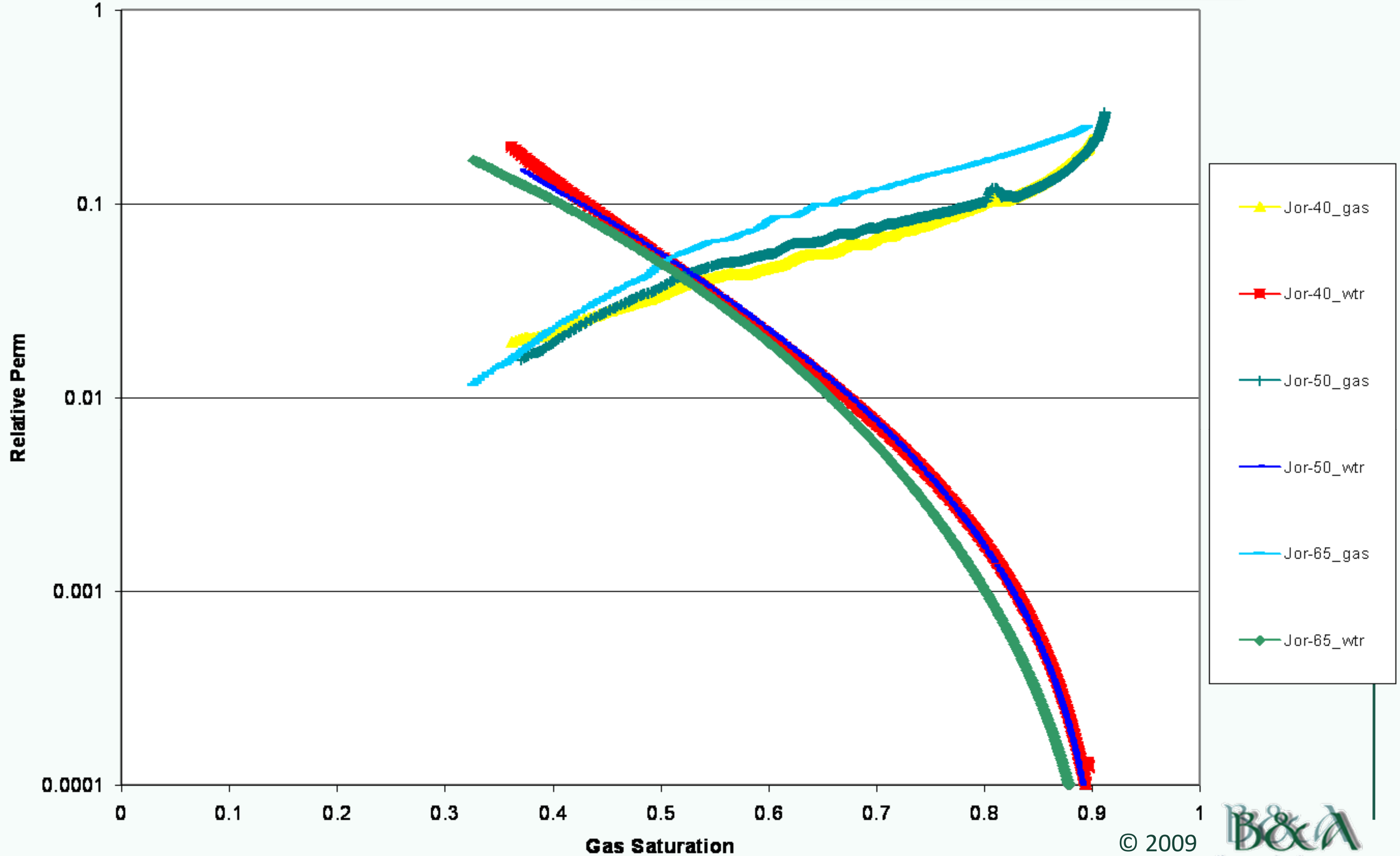
# Summary of 16/30 Jordan Sand Data: Gas-Water Displacement Tests



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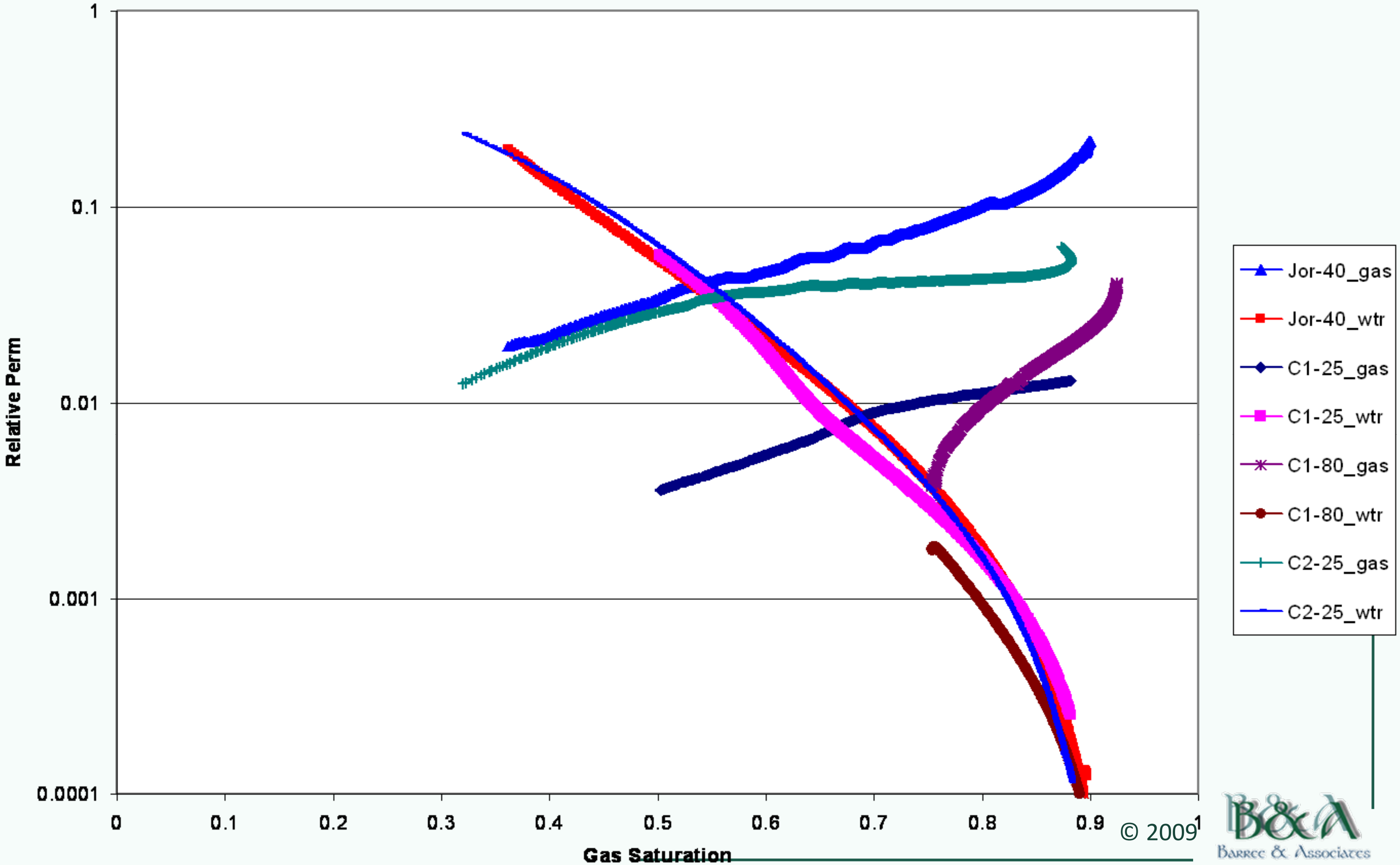
# Summary of Surfactant C Data with Saturation Offset Applied



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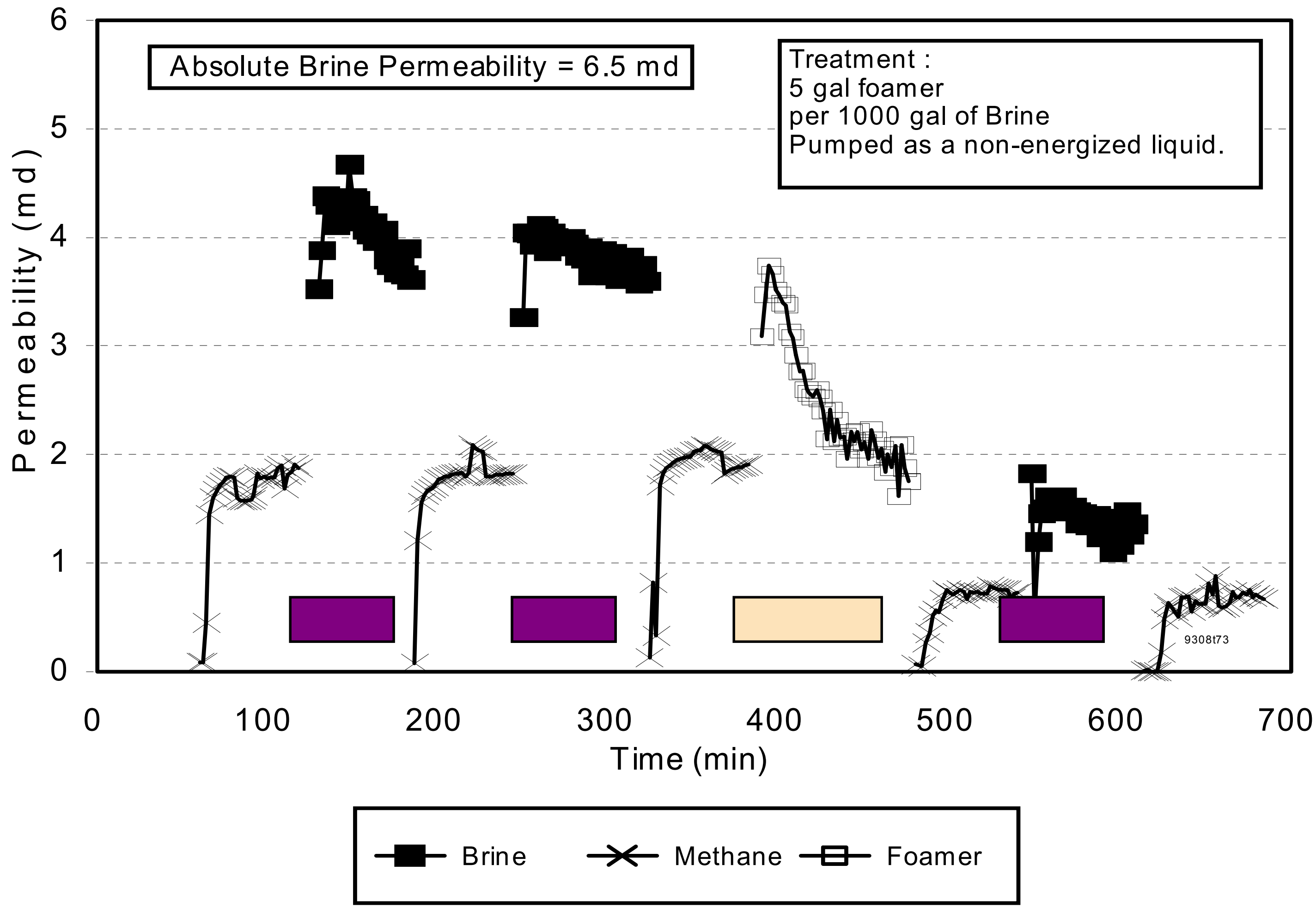
# Effects of Foamers on Gas Perm



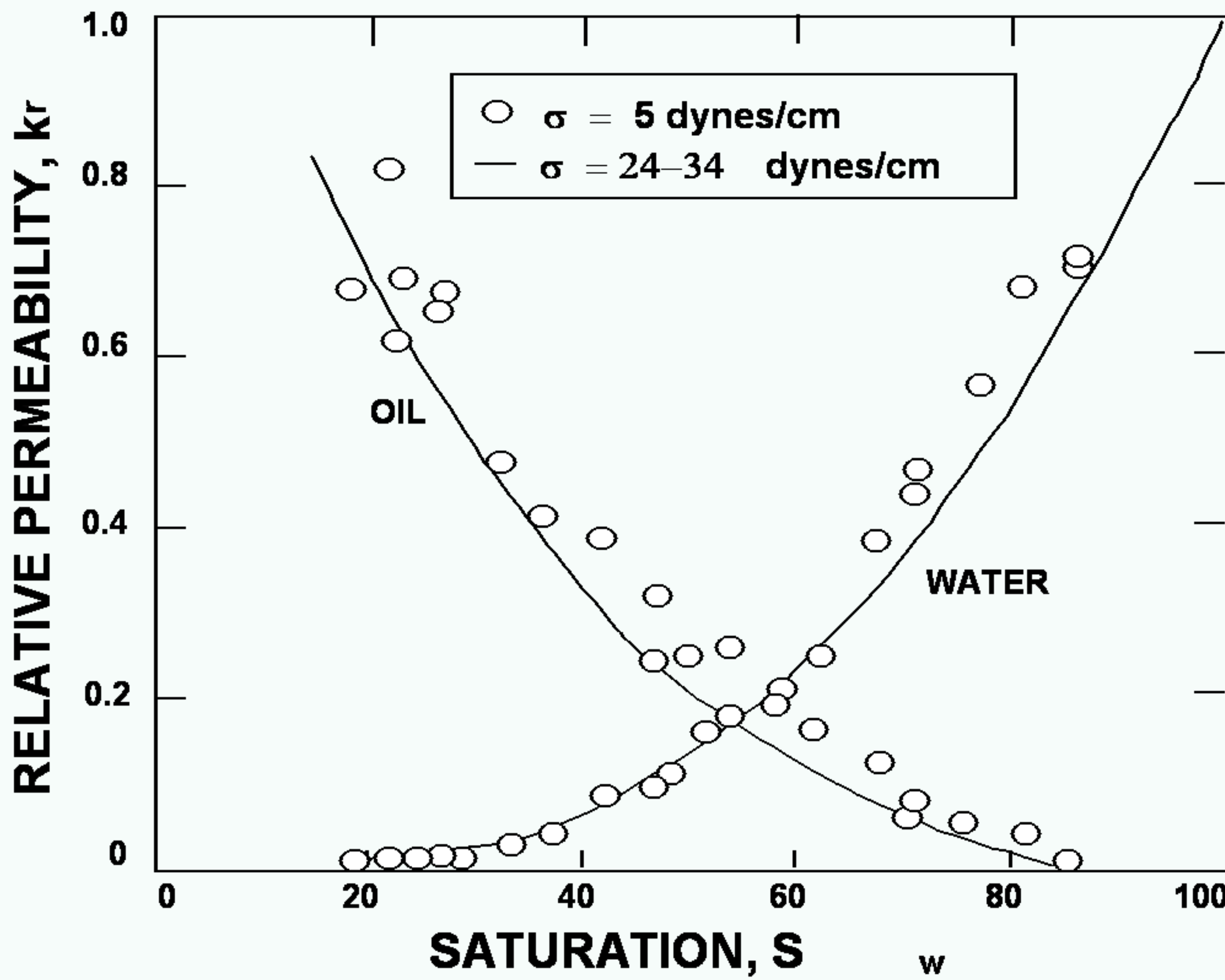
# Effect of Gas Blockage on Flowback

- Initial cleanup removes liquids and establishes gas permeability
- A shut-in or liquid-kill increases saturation around well and fracture face leading to trapped gas
- Permeability to all phases may be reduced significantly (and permanently)
- How a well is cleaned-up may as important as how it’s frac’d
- Repeated well killing (for multi-zone fracs) is to be avoided
- Dewatering is a slow process but imbibition can be very fast

# Correcting "Water Block"

- Use $CO_2$ or $N_2$ saturated fluids
- Try to lower interfacial tension (IFT) and capillary threshold pressure
- Change rel-perm curve through IFT reduction
- Add high-vapor pressure miscible fluid (MeOH) to system
- $CO_2$ "Huff-and-Puff" (for immobile water zones)
- Pump-off the well and maintain water level below perfs until system "drains"

# Moderate Changes in IFT Have Little Effect on Rel Perms



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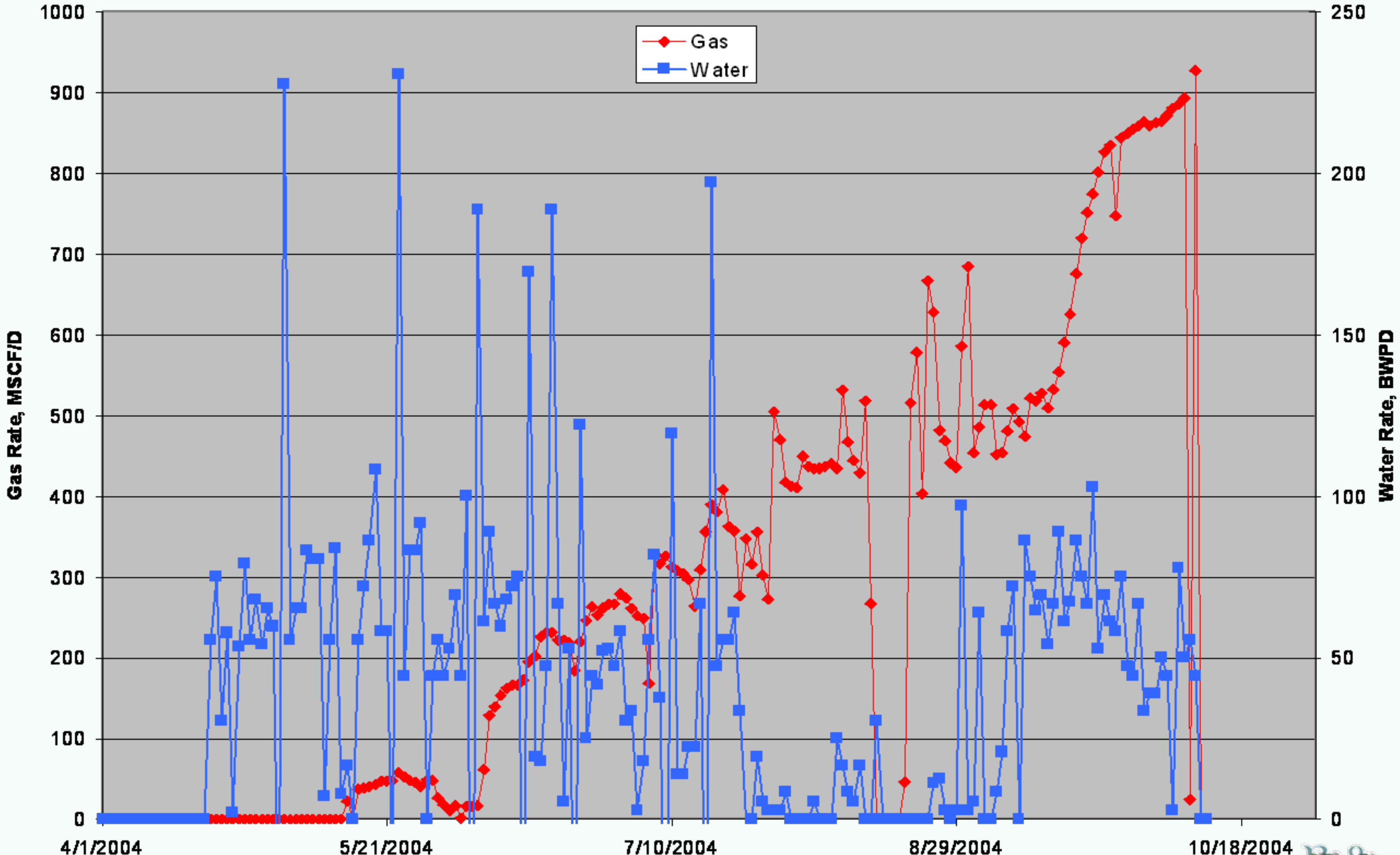
# Example Well History: Recovering from Severe Water Loading

- Well "watered out" and died after losing fluid to the gas zone because of a casing leak
- Previous operator spent months gas lifting the well to unload water with no gas response
- Gas lifting proved unsuccessful and the well was given up for dead
- New operator purchased the well and installed a surplus pumping unit on April 14
- Well initially made 70 bwpd and no gas
- One month later the well showed signs of gas

# Well Performance After Pump Installation



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# Results of Extended Rod-Pumping

- Almost 20,000 BW have been produced since the casing leak was repaired (about 8000 since
- Well continues to give up water with a current rate of about 48 bwpd
- Oil production rate has now increased to 5 bopd (about half of pre-leak rate)
- Gas rate has returned to pre-leak rate of about 1 MMSCF/D
- New operator has booked 100 MBOE additional reserves for this well

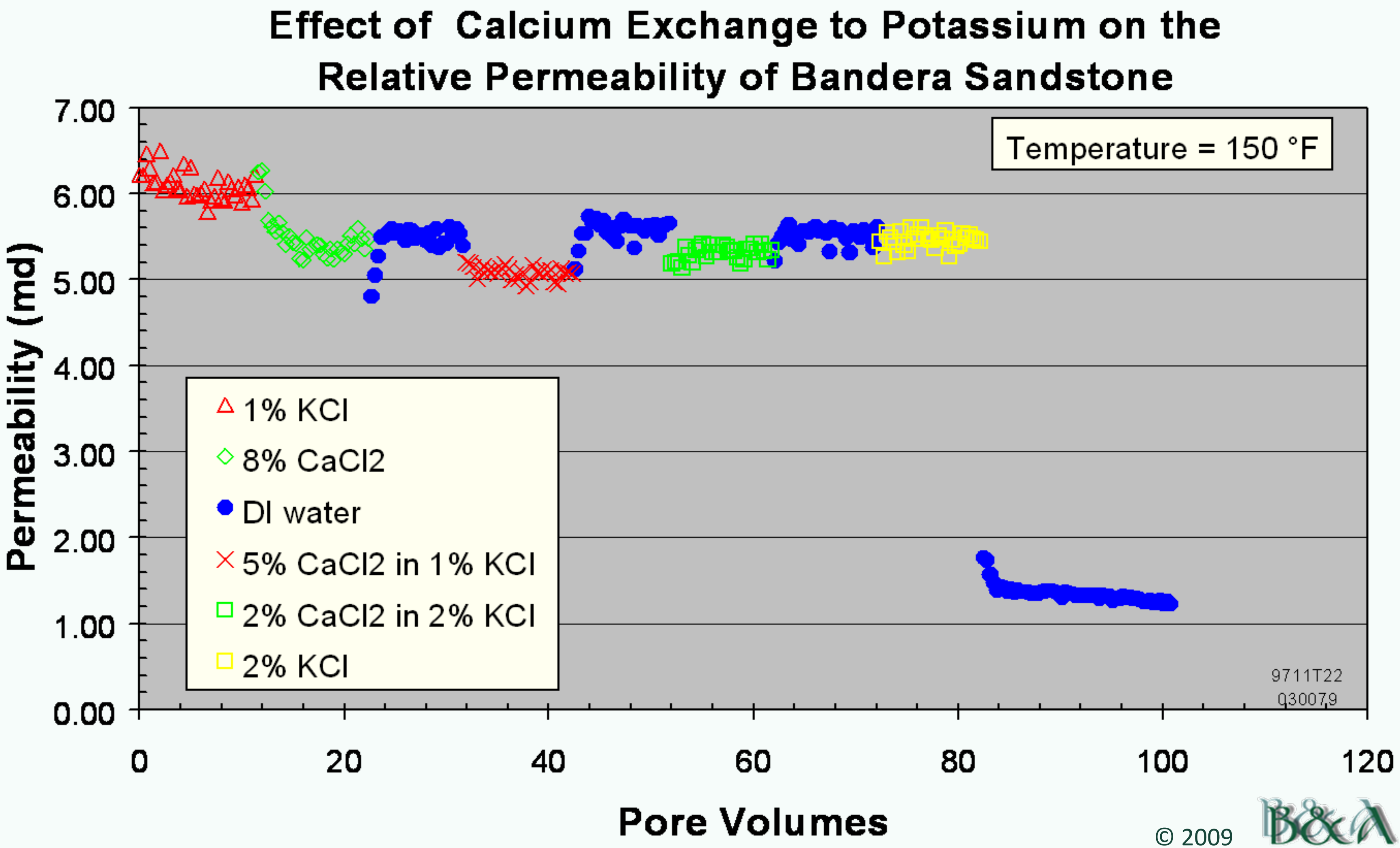
# Clay Sensitivity and Control

- Different damage mechanisms require different treatment
  - Clay swelling
  - Clay hydration and extension
  - Fines migration and plugging
  - Cation exchange effects
  - Relative permeability damage

# Formation Damage in Coal and Shale

- Identification of swelling and dispersing clays
  - Capillary suction time (CST)
  - Roller oven test
- Fluid-rock interactions and generation of fines
  - Effects of brine salinity and acid
  - Organic fluids can and will adsorb in coals
- Regained matrix permeability
  - Generally too low to measure with no damage
- Retained fracture conductivity
  - Stress effects
  - Fluid effects

# Bandera Sandstone: Effect of $CaCl_2$





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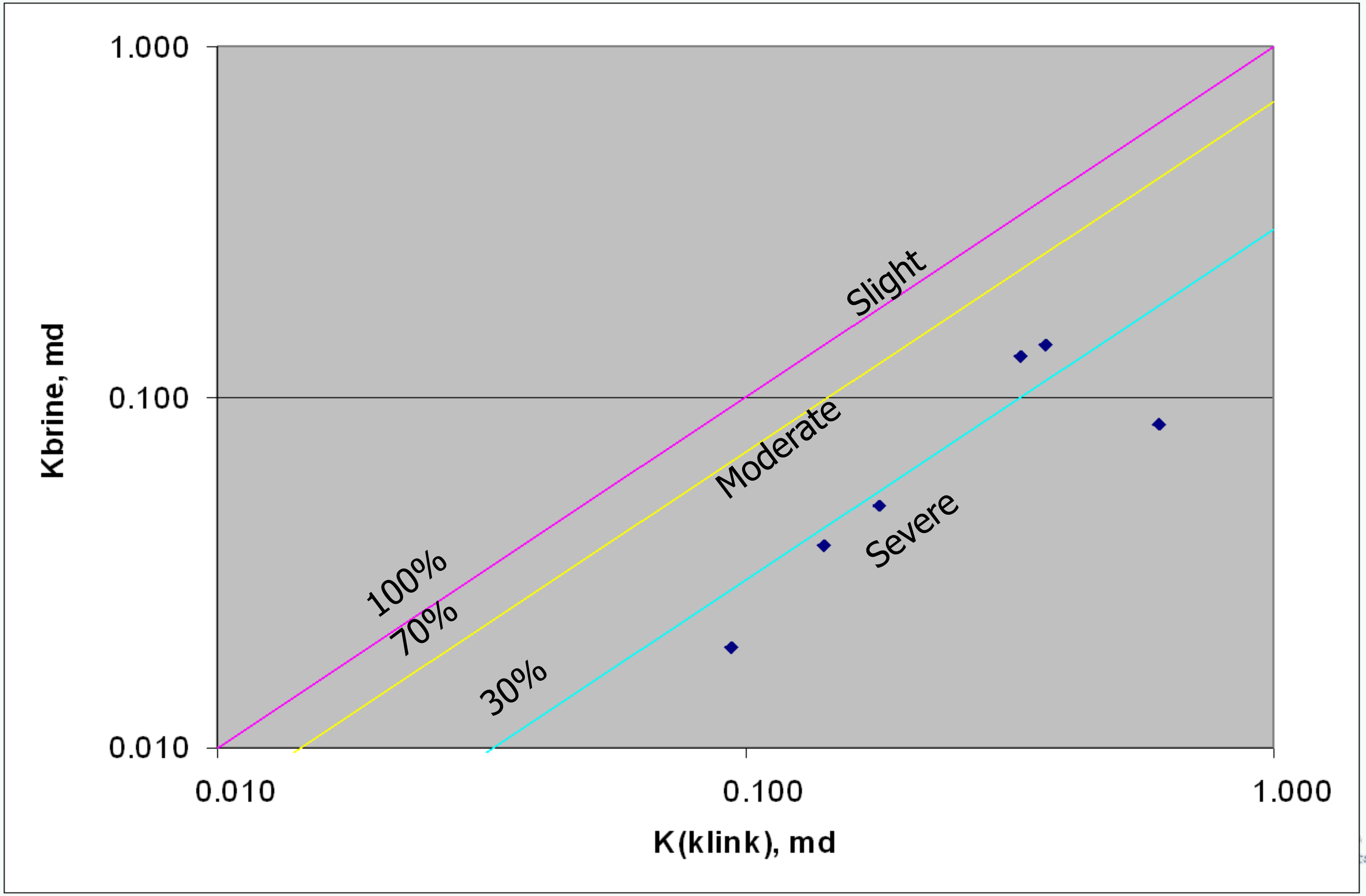
# General Plot for Characterizing Water Sensitivity



# Clay Effects on Permeability

- Will migrate
  - wrong cation, wrong salinity, wrong sequence
- Trap other migrating fines
  - degraded feldspars
- Other stabilizing mechanisms are present to prevent fresh water damage
  - Surface and interior cations
    - interior cations are very difficult to exchange
  - Other cations may be involved in “permanent” stability other than calcium

# Recommendation

- Brine sensitivity can not be anticipated from core composition analysis alone.
- Other effects, most notably, relative permeability, may be the biggest problem
- Whole core or drilled sidewall cores are the answer:
  - location directed by logs
  - flow tests can confirm key factors
  - must know connate brine composition for most meaningful understanding.

# Clay Control Additives and KCl Substitutes

- Polymeric additives for "nets" to lock migrating fines in place
- Ammonium salts enhance cation exchange and may liberate sodium or potassium
- Both are depleted by leading-edge contact and may only affect a limited reservoir volume
- Additives may work well "when they're not needed"
- Base decisions on actual identified type of clay sensitivity

# Where do we go from here?

- Improve geometry models
  - more and better fracture mapping data
  - collect and analyze more pressure data
  - conduct more post-frac tests
- Apply what we learn
  - continue to question models
  - allow models to expand to include
    - reservoir flow - falloff analysis - cleanup
    - wellbore effects - heat flow - chemistry

# Where do we go?

- Improved job execution
  - cleaner fluids
  - better quality control
- Improve post-frac performance analysis
  - pressure buildups and multi-rate tests
  - production performance analysis
    - get and archive more data
    - make this a routine for all wells
  - polymer and water recovery analysis