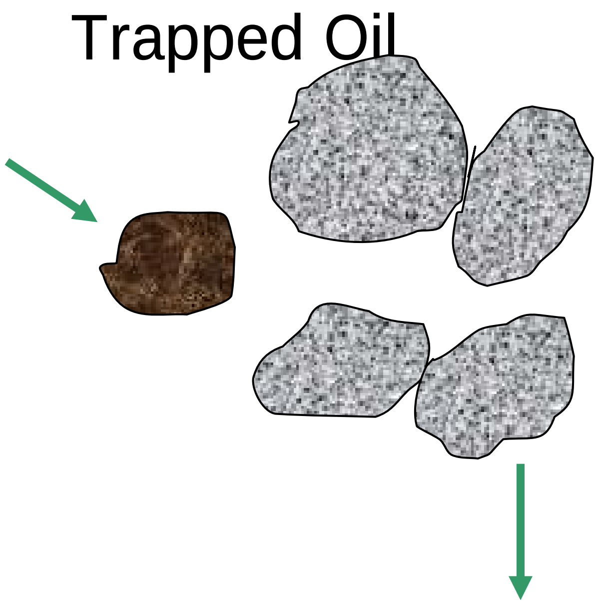
Chapter 2

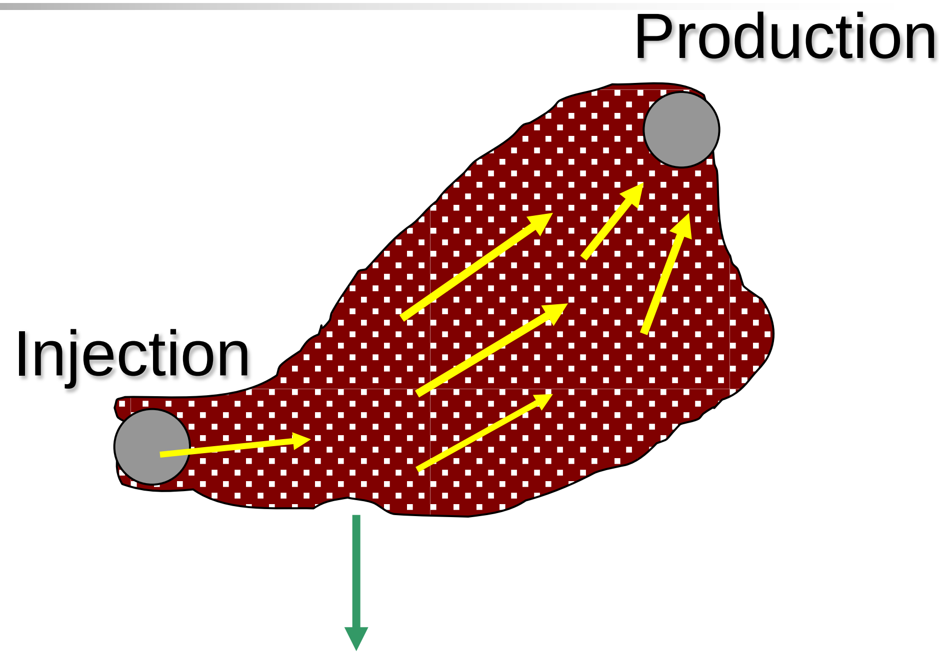
Oil Recovery Efficiency

Efficiency of a Displacement Process

- Microscopic Displacement of Fluid in a Reservoir
- Macroscopic Displacement of Fluids in a Reservoir

Efficiency of a Displacement Process





$$E = E_M \text{ (Microscopic Efficiency)} \times E_V \text{ (Volumetric Efficiency)}$$

Efficiency of a Displacement Process

- However,

$$E_V = E_A \times E_L$$

E_A = Areal Sweep efficiency

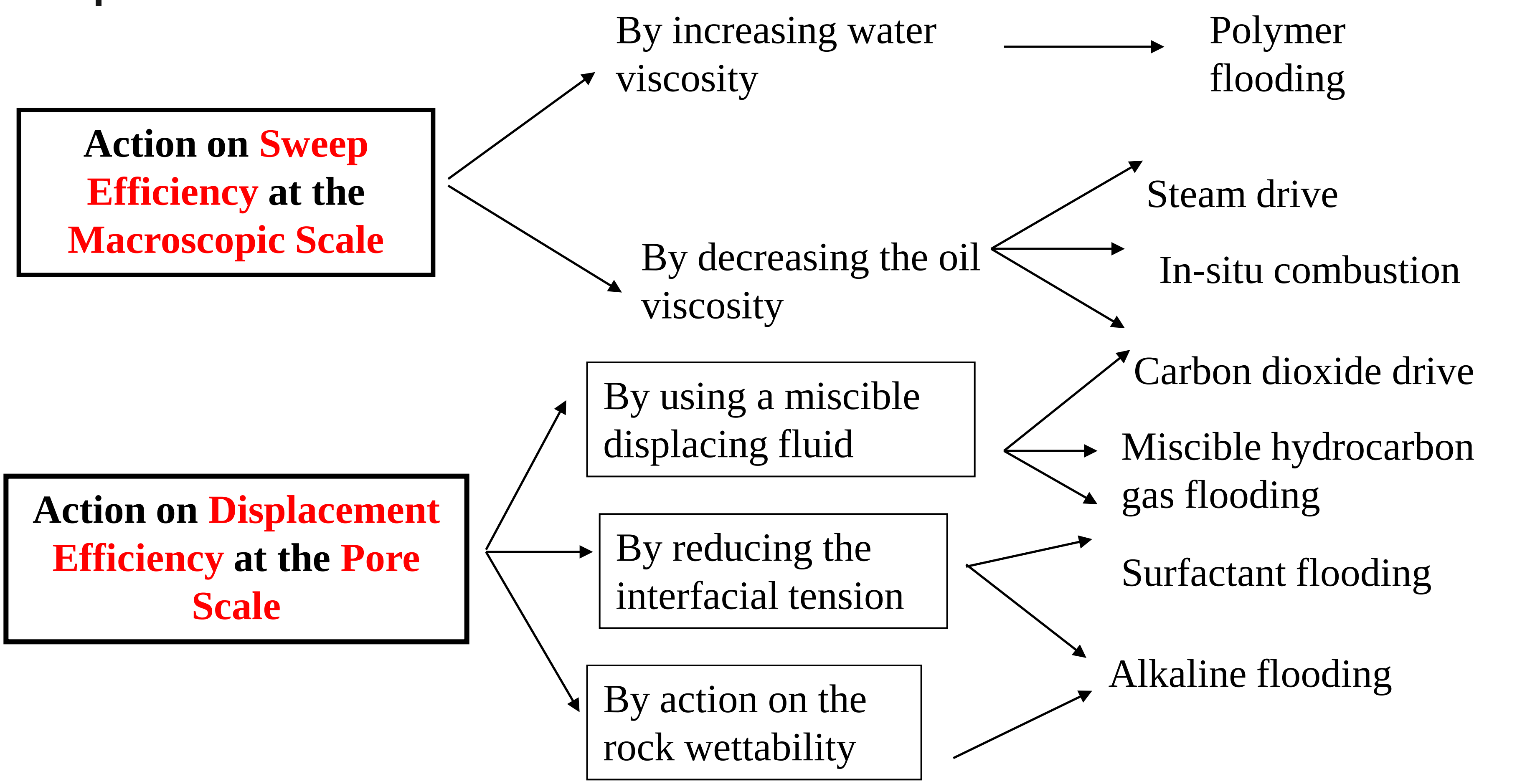
E_L = Lateral Sweep efficiency

Microscopic & Macroscopic sweep efficiencies

$$E_D = \frac{reservoir\ volume\ of\ oil\ mobilized\ by\ EOR\ agent}{reservoir\ volume\ of\ oil\ contacted\ by\ EOR\ agent}$$

$$E_v = \frac{reservoir\ volume\ of\ oil\ contacted\ by\ displacing\ agent}{reservoir\ volume\ of\ oil\ originally\ in\ place}$$

Action on Sweep & Displacement Efficiency



Microscopic Displacement of Fluids

Microscopic efficiency largely determines the success or failure of any EOR process. For crude oil it is reflected in the magnitude of Sor (i.e., the residual oil saturation remaining in the reservoir rock at the end of the process).

$$E_D = \frac{Volume\ of\ oil\ mobilized}{Volume\ of\ contacted\ oil}$$

Example

- Initial oil saturation, S_{oi}, is 0.60 and S_{or} in the swept region for a typical water flood is 0.30
- $E_D = (S_{oi} – S_{or}) / S_{oi}$
- $E_D = (0.60 – 0.30) / 0.60$
- $E_D = 0.50$
- A typical waterflood sweep efficiency, E_v, at the economic limit is 0.70. Therefore,
- $E = E_D E_V = 0.50 * 0.70 = 0.35$

Why Oil Remains

- Mobility Problem
- Capillary Number
  - **Capillary Forces**
    - Surface Tension and IFT
    - Solid Wettability
    - Capillary Pressure
  - **Viscous Forces**

Important factors relating to microscopic displacement behavior

- Capillary forces have a detrimental effect, being responsible for the trapping of oil within the pore.
- Trapping is a function of the ratio of Viscous to Capillary forces.
- The residual oil saturation decreases as the ratio (Viscous force/ Capillary force) increases.

Capillary Forces- Solid Wettability

- **Fluid distribution** in porous media are affected not only by the forces at fluid/fluid interfaces, but also by force of fluid/solid interfaces.
- **Wettability** is the tendency of one fluid to spread on or adhere to a solid surface in the presence of a second fluid.
- When two immiscible phases are placed in contact with a solid surface, one phase is usually attracted to the solid more strongly than the other phases. **The more strongly attracted phase is called the wetting phase**.

The Drainage Process and Reservoir Rocks

The magnitude of water saturation retained is proportional to the capillary pressure -- which is controlled by the rock-fluid system

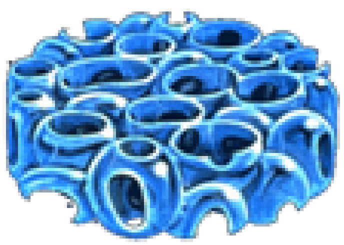
$$Sw = f\left(Pc\right)$$

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

Fluid Property (σ)

Rock - Fluid Property (θ)

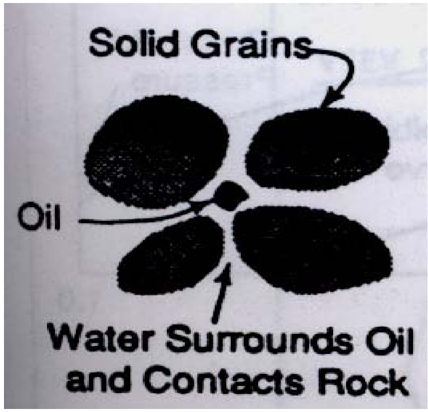
Rock Property (K & ϕ) (r)



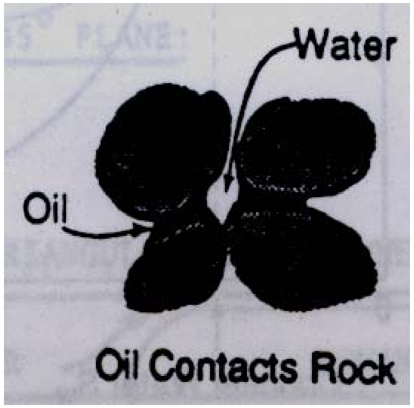
Idealized Water Film Surrounding Sand Grains

Capillary Forces- Solid Wettability

- Rock wettability affects the nature of fluid saturations and the general relative permeability characteristics of a fluid/rock system.
- The following figure shows residual oil saturations in a strongly water-wet and a strongly oil-wet rock.

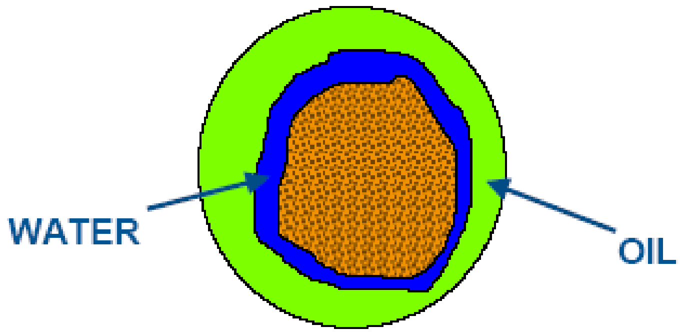


Water-wet System



Oil-wet System

Surface tension

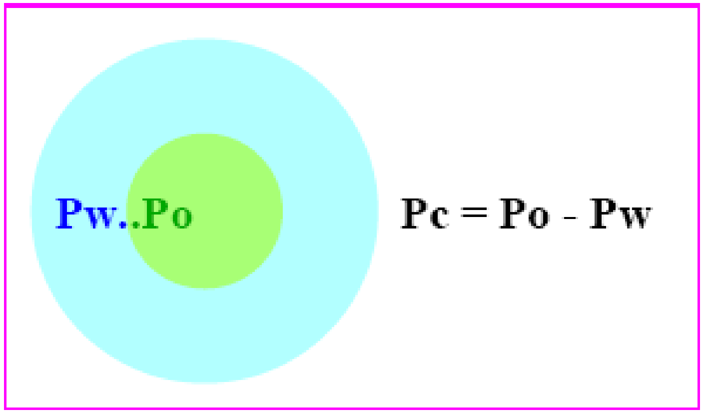


Surface forces act:

- at the interface in between 2 fluids ==> interfacial tension
- at the interface between rock and fluid => wettability
- resulting force is called « capillary force »

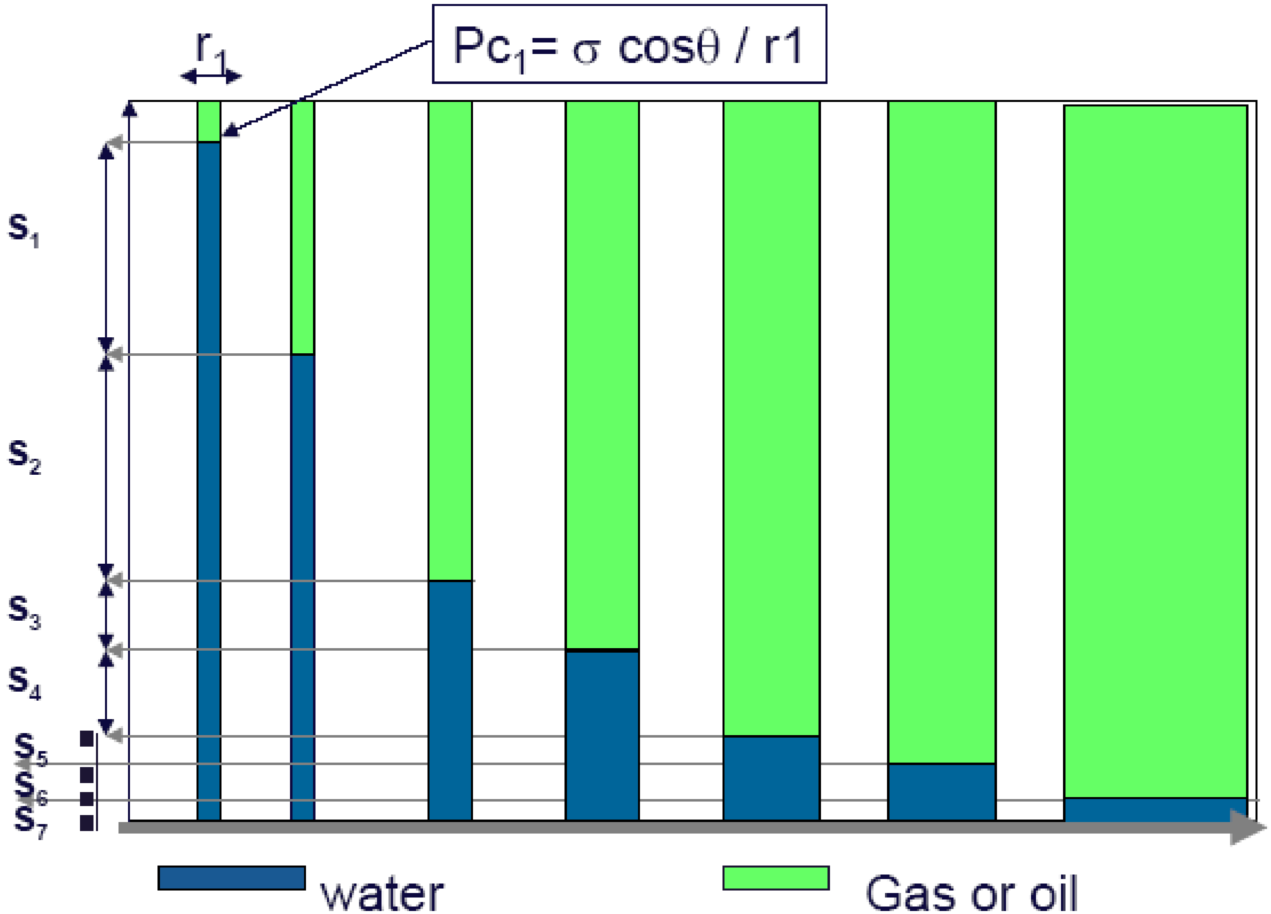
Capillary pressure

- Pressure difference in between 2 fluids seperated by an interface

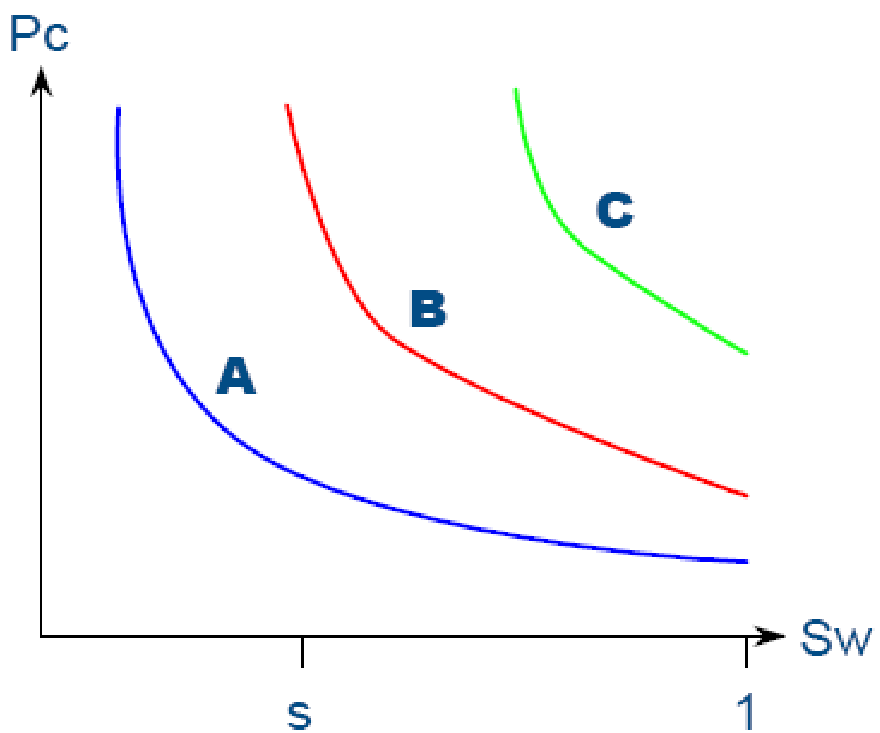


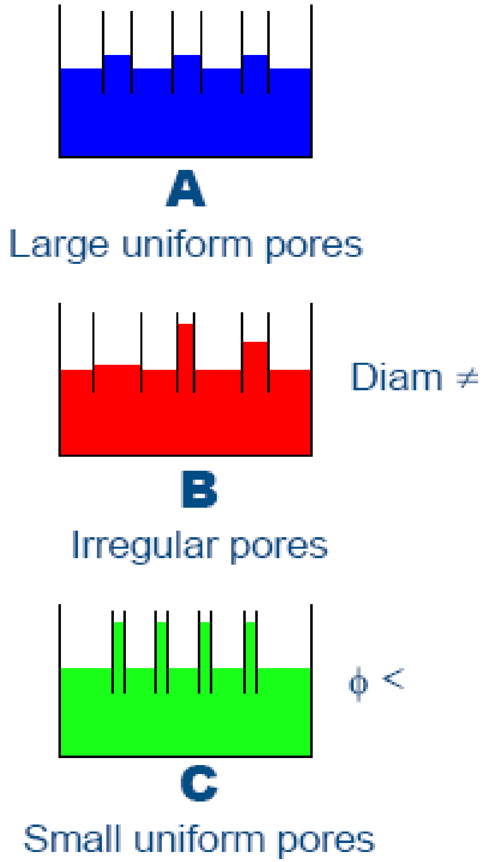
- Capillarity is a phenomenon which depends upon interactions:
  - in between fluid and porous medium: wettability
  - in between 2 fluids: interfacial tension

Tubes Analogy



Pores filling





Capillary Forces: Surface Tension & IFT

Inside a capillary tube

$$P_C = P_A - P_B = \frac{2\,\sigma\,\cos\theta}{r}$$

Depends on :

- *wettability*
- *pore size*
- *interfacial tension* σ

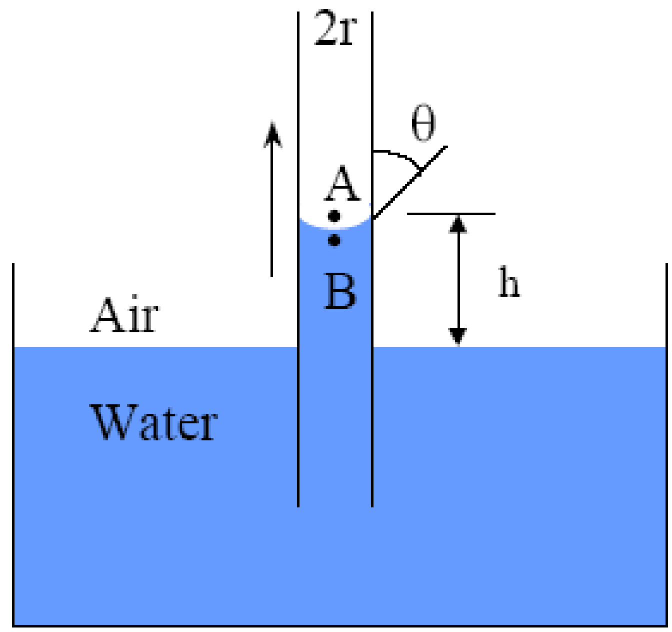
Gravité

$P_A = P_{atm}$

$P_B = P_{atm} - h\,(\rho_w - \rho_{air})\,g$

$$P_C = h\,(\rho_w - \rho_{air})\,g$$

$$h = \frac{2\,\sigma\,\cos\theta}{r\,(\rho_w - \rho_{air})\,g}$$



Capillary pressure= pressure difference in capillary medium between the wetting fluid and the non-wetting fluid

Capillary Pressure Equation

- The difference pressure between oil water at the oil/water interface

$$p_o - p_w = h(\rho_w - \rho_o)g = p_c$$

$$\sigma_{ow} = \frac{rp_c}{2\cos\theta}$$

$$or \qquad P_c = \frac{2\sigma_{ow}\cos\theta}{r}$$

Capillary Forces- Capillary Pressure

- **Capillary pressure is related to**
  - the fluid/ fluid IFT
  - Relative permeability of fluids (through θ)
  - Size of capillary (through r)
  - The phase with the lower pressure will always be the phase that preferentially wets the capillary.
- Pc varies inversely as a function of the capillary radius and increases as the affinity of the wetting phase for the rock surface increases.

Viscous Force

- Viscose forces in a porous medium are reflected in the magnetite of the pressure drop that occurs as a result of fluid flow through porous medium.
- One of the simplest approximations used to calculate the viscous force is to consider a porous medium as a bundle of parallel capillary tubes.
- With this assumption, the pressure drop for laminar flow through a single tube is given by Poiseuille’s law.

Viscous force

- Viscous forces in a porous medium are reflected in the magnitude of the pressure drop that occurs as a result of flow of a fluid through the medium.
- One of the simplest approximations used to calculate the viscous force is to consider a porous medium as a bundle of parallel capillary tubes.
- The main assumption, the pressure drop for laminar flow through a single tube is given by Poiseuille's law

$$\Delta p = -\frac{8\mu L \upsilon}{r^2 g_c}$$

Viscous Force

- Viscous forces in a porous medium can be expressed in terms of Darcy's law:

$$\Delta p = -(0.158)\left(\frac{\bar{v}\mu L\phi}{k}\right)$$

$$\Delta p = pressure\ drop, psi$$

$$\bar{v} = average\ velocity,\ ft/D$$

$$\mu = viscosity, cp$$

$$L = length, ft$$

$$\phi = porosity$$

$$k = permeability, darcies$$

- The magnitude of viscous forces can be illustrated in the following example

Example: Calculation of pressure gradient for viscous oil flow in a rock

- Calculate the pressure gradient for flow of an oil with 10 cp viscosity at an interstitial flow rate of 1 ft/D. the rock permeability is 250 md and the porosity is 0.2.

Solution: $$\Delta p = -(0.158)(\frac{\bar{v}\mu L \phi}{k})$$

$$\frac{\Delta p}{L} = -\frac{0.158 \times 1.0 \quad ft/D \times 10 \quad cp \times 0.2}{0.250 \quad darcies} = -1.264 \quad psi/ft$$

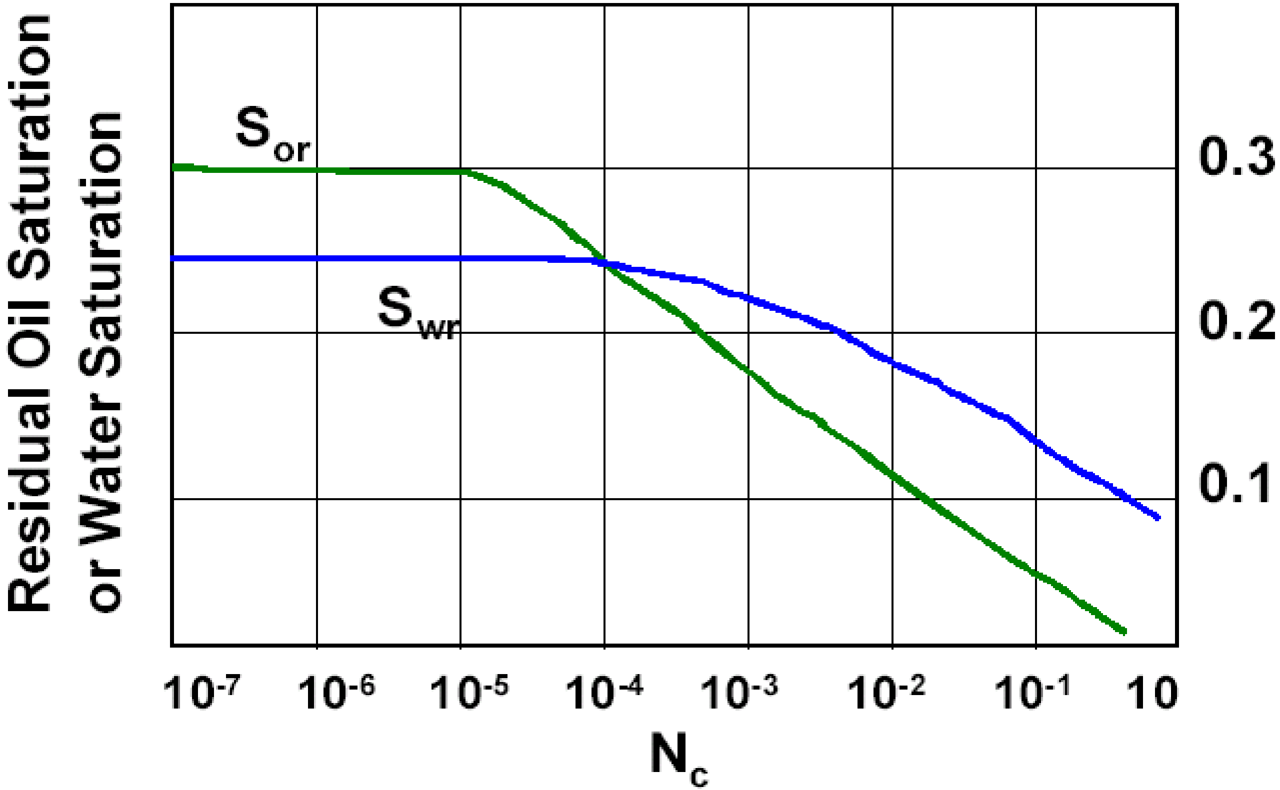
- The viscous forces yield pressure gradients in the reservoir rocks on the order of 0.1 to >1 psi/ft

Capillary Number

$$N_{ca} = \frac{v\mu_w}{\sigma_{ow}}$$

- Water floods typically operates at condtions where Nca < 10^{-6}, and Nca values on the order of 10^{-7} are probably most common.
- The relationship between trapping wetting or non-wetting phase and a local capillary number indicates experimental evidence of trapping in a permeable media. This relationship is called the capillary desaturation curve.

Trapped Oil Saturation



Typical capillary desaturation curve

Phase trapping

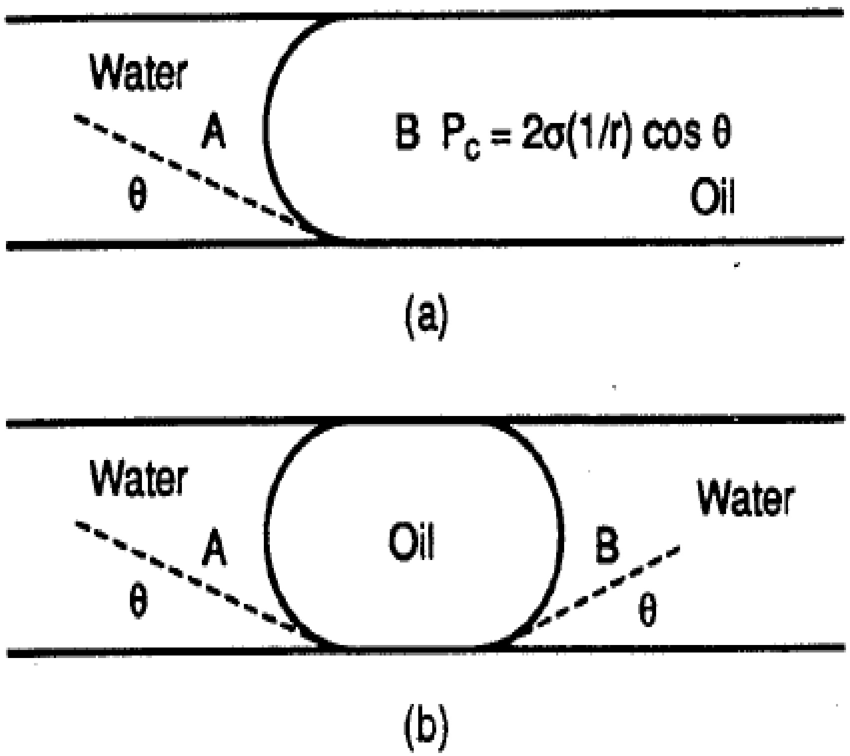
Trapping and mobilization are related to the following factors in a complex way:

1. Pore structure of the porous media
2. Fluid/rock interactions related to wettability
3. Fluid/fluid interaction reflected in IFT

Trapping a single capillary Jamin effect

- It has been recognized that the pressure required to force a nonwetting phase through a capillary system, such as a porous rock, can be quite high
- This phenomenon called the Jamin effect
- This phenomenon can be described most easily by analyzing a trapped oil droplet or gas bubble in a preferentially water-wet capillary as shown in next slide.

Oil/water interfaces: a continues phases vs. trapped drop

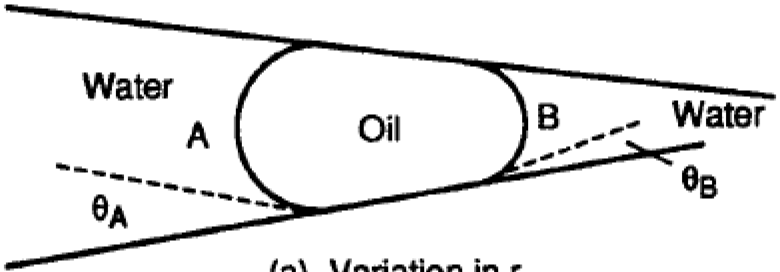


- **For a, the pressure across the interface is just the capillary pressure**

$$P_B - P_A = P_C = \frac{2\sigma_{OW} COS\theta}{r}$$

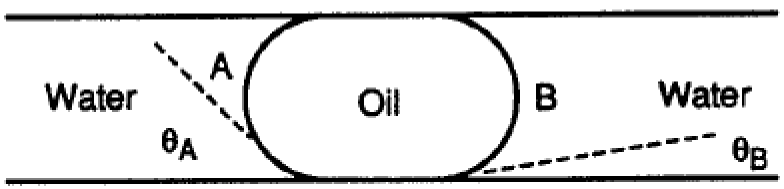
$$P_B - P_A = 0$$

Different conditions of trapping a droplet in a capillary



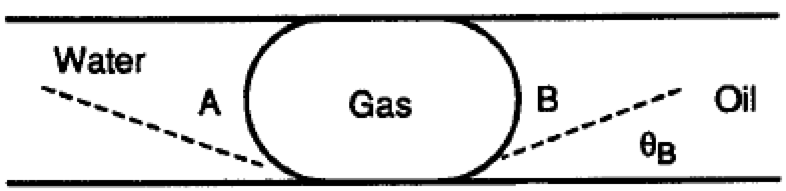
(a) Variation in r

$$p_B - p_A = 2\sigma_{ow}\cos\theta\left(\frac{1}{r_B} - \frac{1}{r_A}\right)$$



(b) Variation in θ

$$P_B - P_A = \frac{2\sigma_{OW}}{r}\left(COS\theta_B - COS\theta_A\right)$$



(c) Variation in σ

$$P_B - P_A = \frac{2}{r}\left(\sigma_{OW} COS\theta B - \sigma_{go} COS\theta_A\right)$$

Generalized expression

$$P_B - P_A = \left(\frac{2\sigma_{OW} COS\theta}{r} \right)_B - \left(\frac{2\sigma_{OW} COS\theta}{r} \right)_A$$

Example: pressure required to force an oil trap through a pore throat

- Calculate the threshold pressure necessary to force an oil drop through a pore throat that has a forward radius of 6.2 micro meter and radius of 15 micro meter. Assume that the wetting contact angle is zero and IFT is 25 dynes/sec.

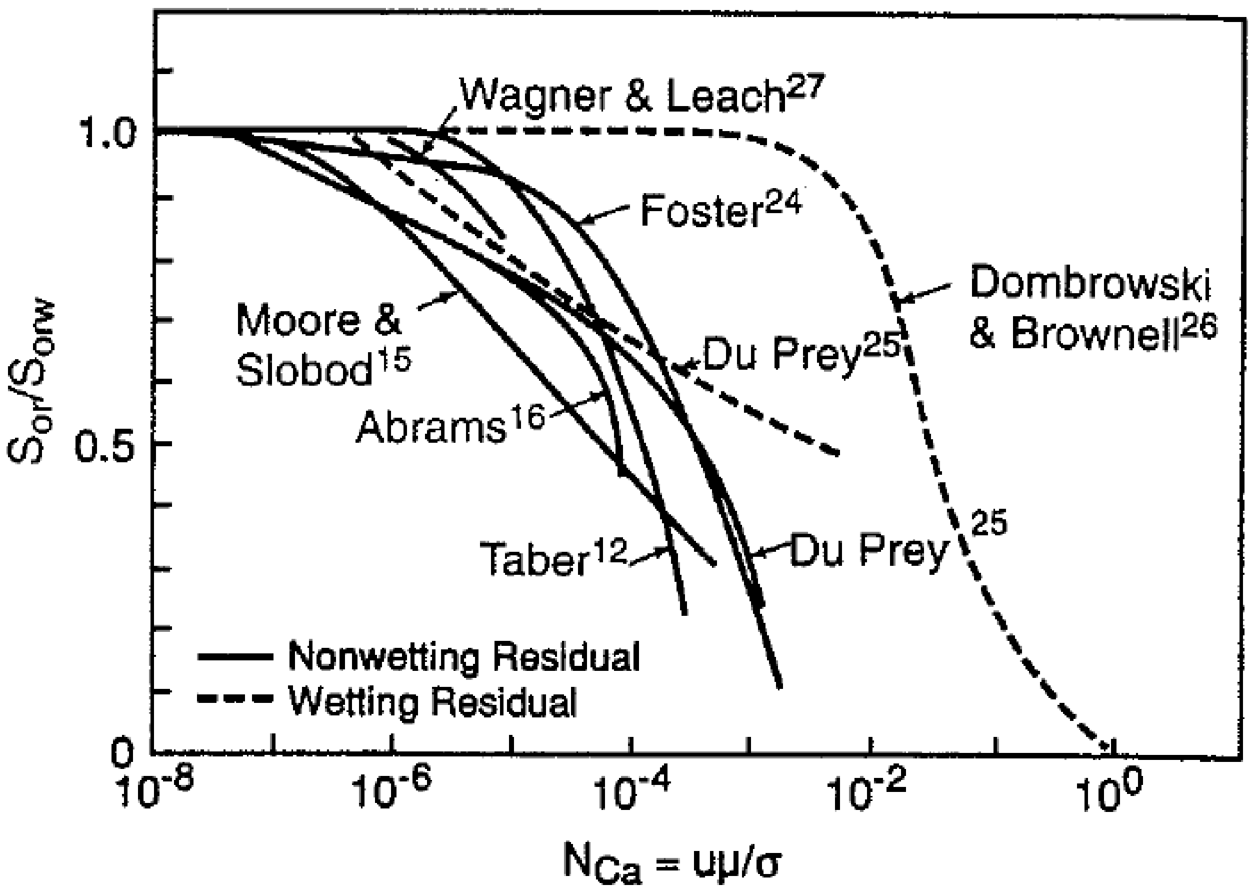
P_B-P_A=2*25(1/0.00062-1/0.0015)= - 47300 dynes/cm2

-47300*1.438*10^-5= - 0.68 psi

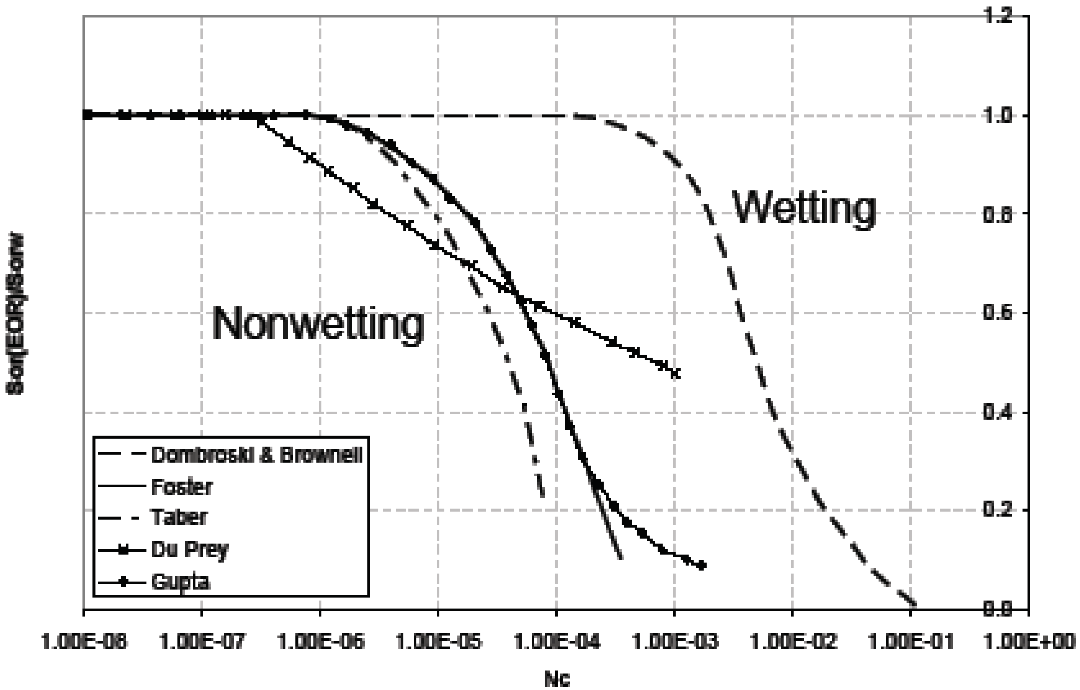
What would be the pressure gradient in psi/ft if the pressure drop length were 0.01 cm?

$$\Delta p / L = -\frac{0.68 \ \ psi}{0.01 \ cm} \times \frac{30.48 \ \ cm}{ft} = -2073 \ \ psi / \ ft$$

Mobilization of trapped phases-Alteration of viscous/capillary force ratio



Importance of capillary number in defining EOR



$$Nc = \frac{k \dfrac{\Delta p}{\Delta L}}{\sigma}$$

Dominance of Capillary Forces over Viscous Forces

Consider the displacement of oil by water from a capillary tube, at velocity v. For simplicity let us assume that $\mu = \mu_w = \mu_o$.

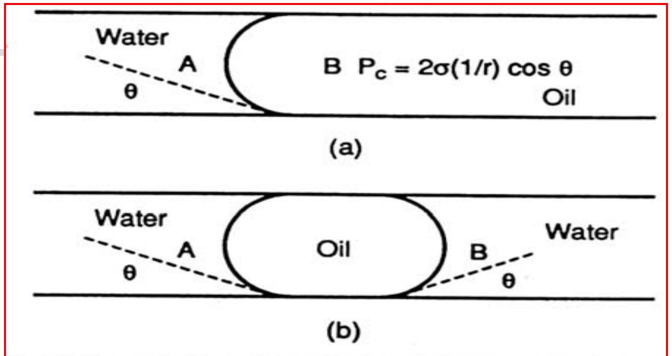


Fig. 2.13—Illustration of oil/water interfaces: continuous phases vs. trapped drop.

$$P_B - P_A = \frac{8\mu L\bar{v}}{r^2} + \frac{2\sigma\cos\theta}{r}$$

Typical values are: μ = 1.0 cp and σ = 30 mN/m and velocity = 0.3 m/d. Calculated vales of $p_B - p_A$ are listed in Table 2.2 for different r's .

TABLE 2.2—CAPILLARY AND VISCOUS FORCES FOR DIFFERENT SIZES OF PORE RADII, EXAMPLE 2.5

Pore Radii	$-8\mu L\bar{v}/r^2$		ΔP_c		$p_B - p_A$	
(μm)	dynes/cm²	psi × 10⁴	dynes/cm²	psi	dynes/cm²	psi
2.5	−22.6	−3.25	240,000	3.45	+239,977	3.45
5	−5.6	−0.81	120,000	1.73	+119,994	1.73
10	−1.41	−0.20	60,000	0.86	+59,999	0.86
25	−0.23	−0.033	24,000	0.35	+24,000	0.35
50	−0.056	−0.008	12,000	0.17	+12,000	0.17
100	−0.014	−0.002	6,000	0.086	+6,000	0.086

Note that the capillary force is much higher than the viscous force and the downstream pressure is higher.

Mobilization of trapped phases

- The fraction of oil that gets trapped depends on the value of N_{ca} in the system
- After becoming trapped, can it be remobilized by exceeding this value of N_{ca}?
- The answer is that in general it takes a higher N_{ca} to re-mobilize the oil
- This is illustrated in following Table

Reduction of trapping vs. mobilization

	Residual Oil (%PV)		
	Torpedo	Elgin	Berea
Effect of flood rate			
2 ft/D at front	41.6	48.2	49.5
200 ft/D at front	33.8	32.3	39.5
2 ft/D at front followed by 200 ft/D behind front	38.1	44.5	42.6
Effect of favorable viscosity ratio			
$\mu_o/\mu_w = 1.0$ at flood front	41.6	48.2	49.5
$\mu_o/\mu_w = 0.055$ at flood front	19.3	22.2	22.1
$\mu_o/\mu_w = 1.0$ at flood front followed by 0.055 behind front	41.0	47.5	48.8
Effect of reducing IFT			
$\sigma = 30$ dynes/cm at flood front	41.6	48.2	49.5
$\sigma = 1.5$ dynes/cm at flood front	28.5	27.5	31.5
$\sigma = 30$ dynes/cm at flood front followed by 1.5 dynes/cm behind front	41.0	46.0	48.0

Points to remember

i. It takes a much higher value of N_{ca} to mobilize the residual oil than the value of N_{ca} at which it became trapped.

ii. Variations in the N_{ca} vs. S_{or} correlation with different types of rock are significant.

iii. Wettability is important; wetting phase residuals can be more difficult to mobilize.

Macroscopic Displacement of Fluids in Reservoir

- Volumetric Displacement Efficiency Expression
- Definition & Discussion of Mobility Ratio
- Areal Displacement Efficiency
- Vertical Displacement Efficiency
- Volumetric Displacement Efficiency

Volumetric Displacement Efficiency

- Volumetric Displacement Efficiency Expressed as the product of Areal and Vertical Displacement Efficiencies

  Volumetric sweep efficiency can be considered conceptually as the product of the Areal and vertical sweep efficiencies. Consider a reservoir that has uniform porosity, thickness, and hydrocarbon saturation, but that consists of several layers. For a displacement process conducted in the reservoir, E_V can be expressed as

$$E_V = E_A * E_L$$

Volumetric Displacement Efficiency

$$E_A = \frac{Area\ contacted\ by\ displacing\ agent}{Total\ area}$$

Where ;

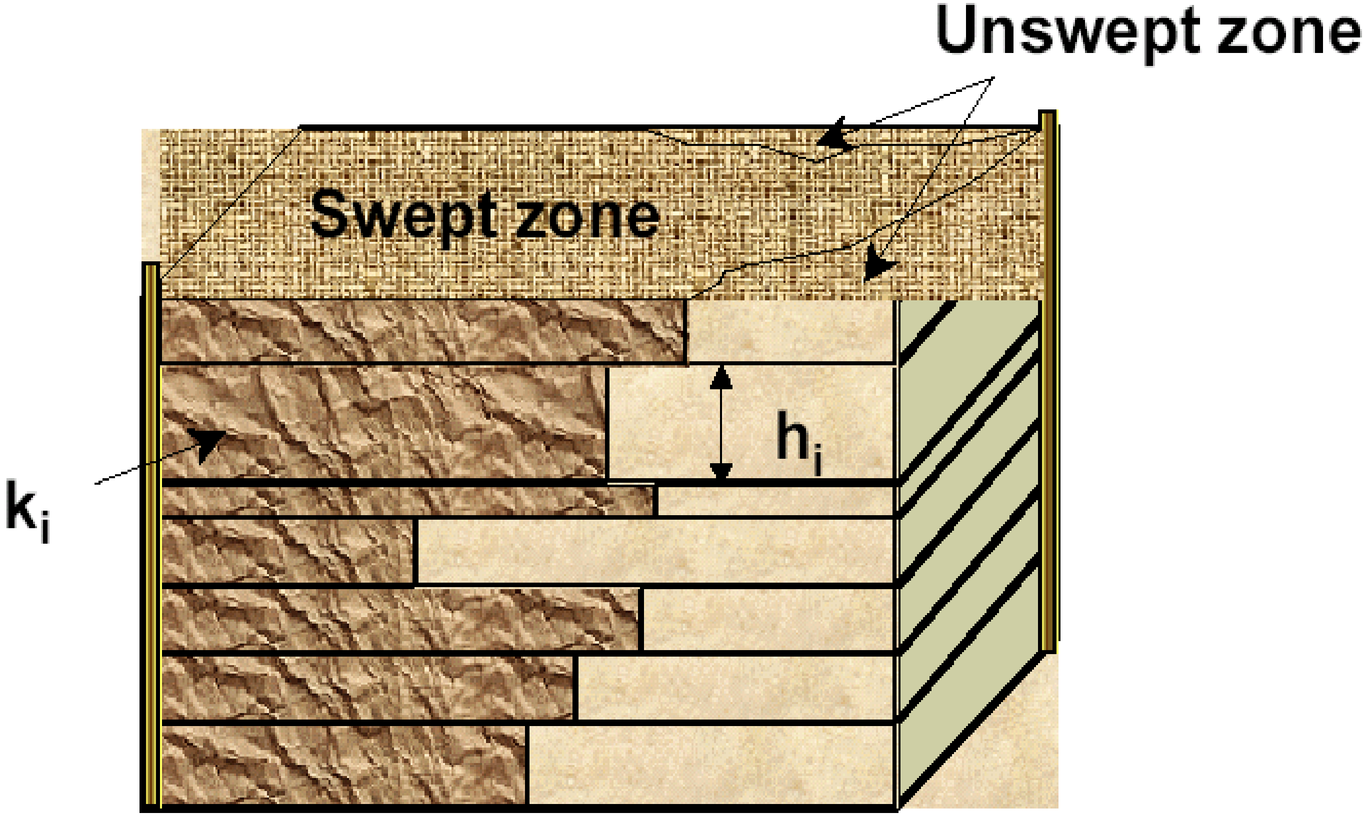
$$E_L = \frac{Length\ contacted\ by\ displacin\ gagent}{Total\ vertical\ length}$$

All efficiencies are expressed as fractions. E_A is the volumetric sweep efficiency of the region confined by the largest Areal sweep efficiency in the system.

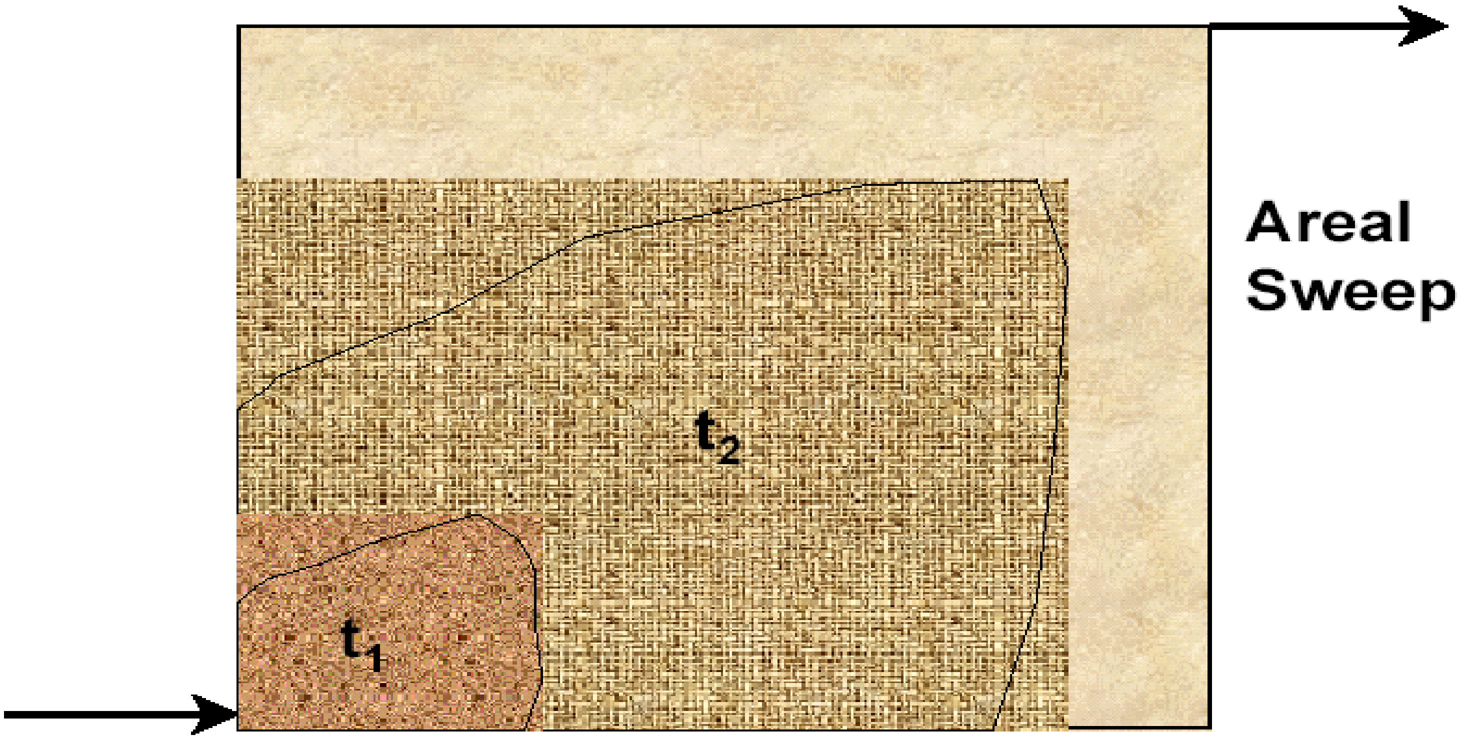
For a real reservoir, in which porosity,thickness,and hydrocarbon saturation vary areally, E_A is replaced by a pattern sweep efficiency ,

$$E_V = E_P E_L$$

This figure illustrates the concept of the vertical and areal sweep efficiency



The following figure illustrate the definition of Areal sweep efficiency



$$E_A = \frac{Areal\ contracted\ by\ displacing\ agent}{Total\ area}$$

Parameters Affecting Efficiencies

- Mobility Ratio
  - Viscous Fingering
  - Pattern
  - Heterogeneity
  - Gravity Effect

Oil Recovery Equation

E_A – **Areal Sweep Efficiency**

• The most common source of Areal sweep efficiency data is from displacements in scaled physical models.

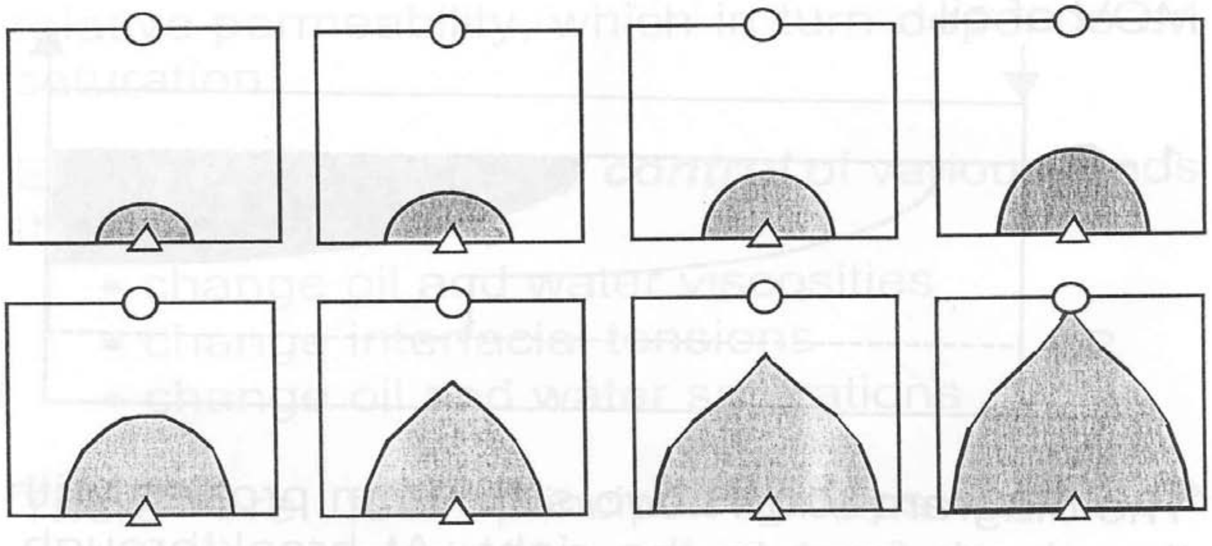
• Several correlations exist in the literature.

• Craig (1980) in his SPE monograph "the reservoir engineering aspects of waterflooding" discusses several of these methods.

•These correlations are for piston like displacements in homogeneous, confined patterns

Areal sweep efficiency

- When oil is produced from patterns of injectors and producers, the flow is such that only part of the area is such that only part of the area is swept at breakthrough. the expansion of the water bank is initially radial from the injector but eventually is focused at the producer.



The pattern is illustrated for a direct line drive at a mobility ratio of unity. At breakthrough a considerable area of the reservoir is upswept.

Mobility Definition

$$\lambda_W = \frac{k_W}{\mu_W} \qquad \lambda_O = \frac{k_O}{\mu_O}$$

Mobility controls the relative ease with which fluids can flow through a porous medium.

$$M = \lambda_D / \lambda_d$$

λ_D = mobility of the displacing fluid phase

λd = mobility of the displaced fluid phase

Mobility ratio

The mobility ratio is an extremely important parameter in any displacement process. It affects both areal and vertical sweep, with sweep decreasing as M increases for a givent volume of fluid injected.

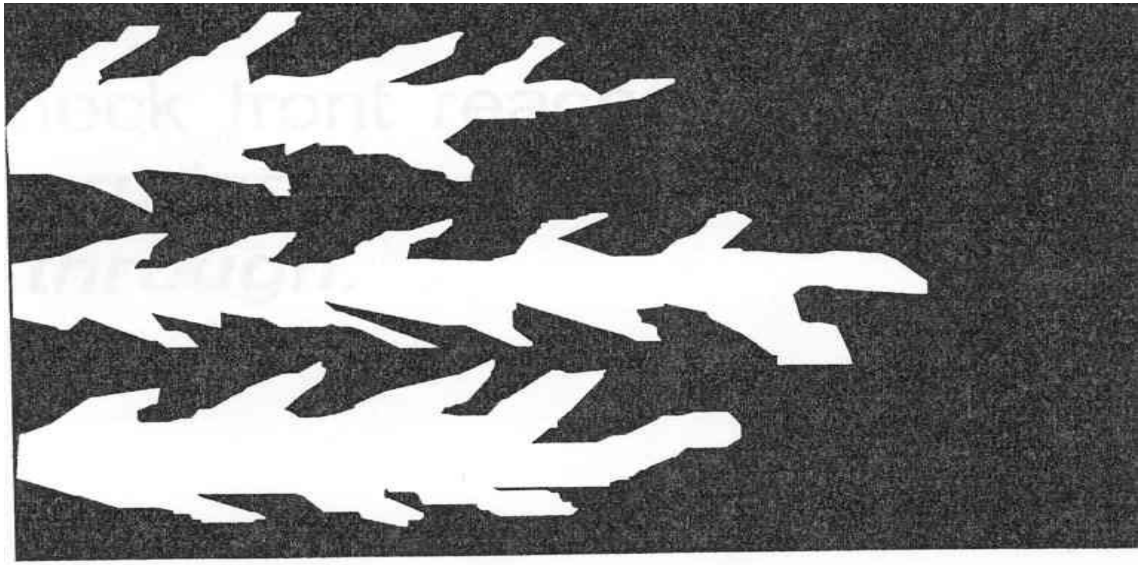
$$M = \left(\frac{v_o}{v_s}\right)$$

When the mobility

M <1 then favorable displacement
M >1 then unfavorable displacement

Viscous Fingering

- If the displacing fluid has a tendency to move faster than the displaced fluid, the fluid-fluid interface is **unstable**. tongues of displacing fluid propagate at the interface. This process is called **viscous fingering**.



Parameters Affecting Areal Displacement Efficiency

- Injection/Production well pattern
- Reservoir permeability heterogeneity
- Mobility Ratio

Flooding Patterns: A number of different injection/production well patterns have been used in reservoir displacement process

- A number of different injection/production well patterns have been used in reservoir displacement process.

- Vertical

- Horizontal

Permeability Heterogeneity

- It is often has a marked effect on Areal sweep. This effect may be quite different from reservoir to reservoir, however, and thus it is difficult to develop generalized correlations.

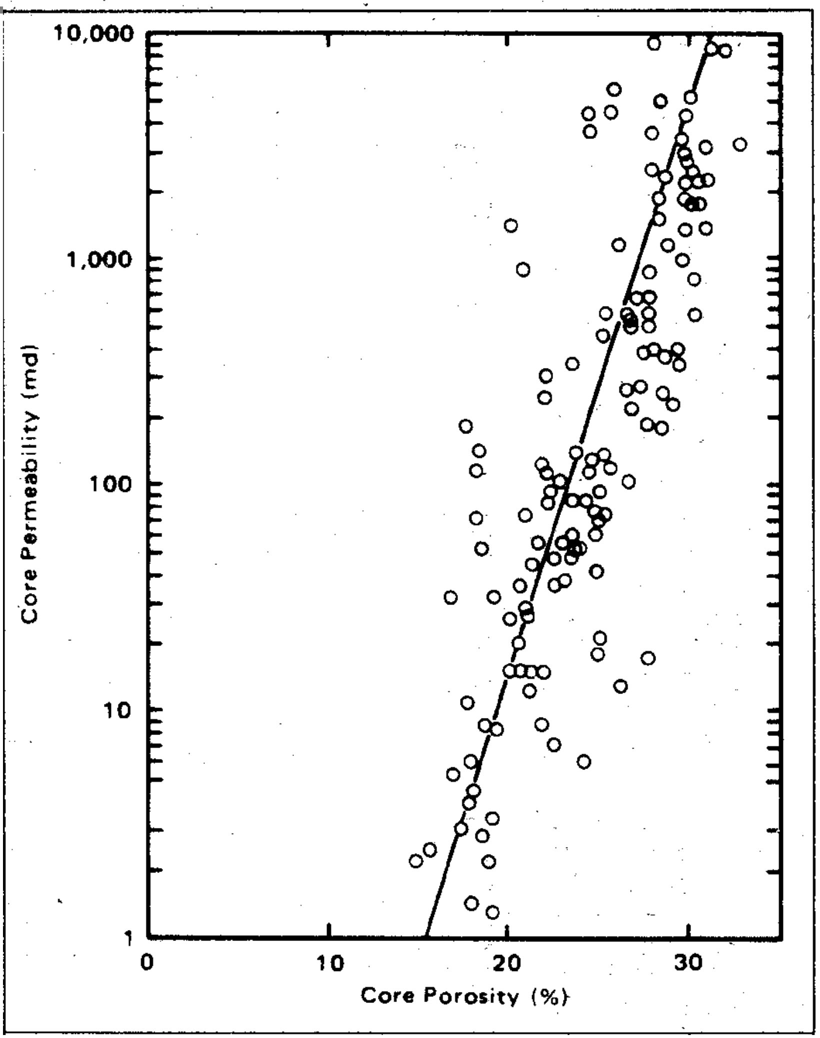
- Anisotropy in permeability has great effect on the efficiency.

Example of Heterogeneity

- Assume relationship between ϕ and k as in sandstone of Brent Field (North Sea) – see next slide
- Assume porosity range is

$$0.15 \le \phi \le 0.3$$

Porosity permeability relation



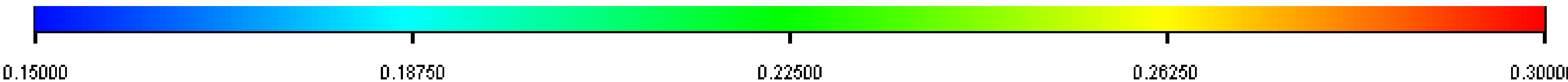
Flow Field – Rock Subdivided into Fine Grid

- Areal grid (nz = 1) – in the real world we would have a full 3-D piece of rock

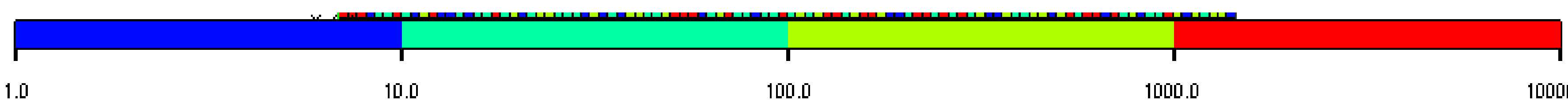
- x and y dimensions are the horizontal dimensions of the coarse grid block

- Rock contains 10,000 random heterogeneities cell – size x/100 and y/100

Color Scales of Porosity and Permeability

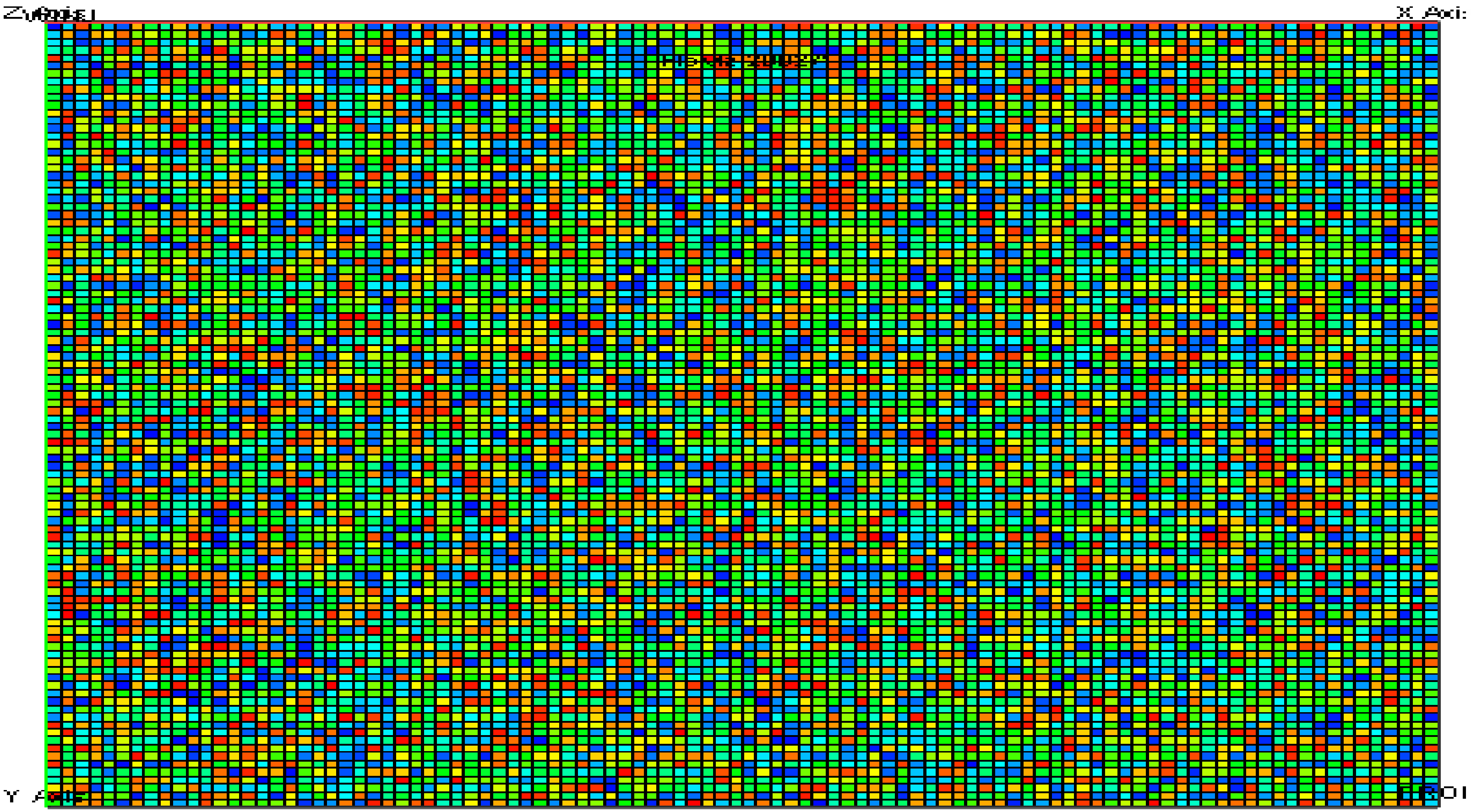


Porosity



Permeability

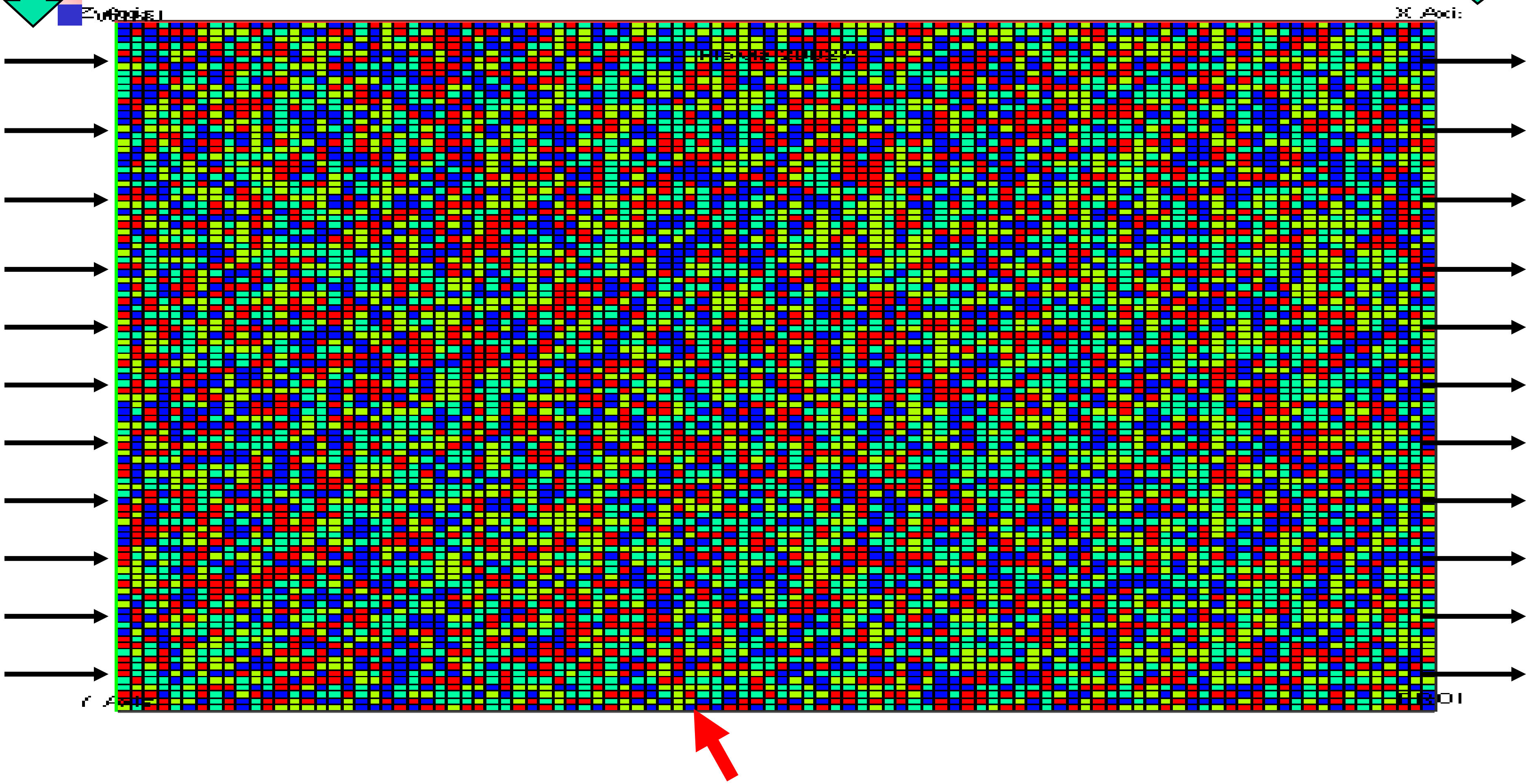
Porosity



Permeability

Flow into block

Flow out of block



Rock boundary / coarse grid block boundary

Flow Situation

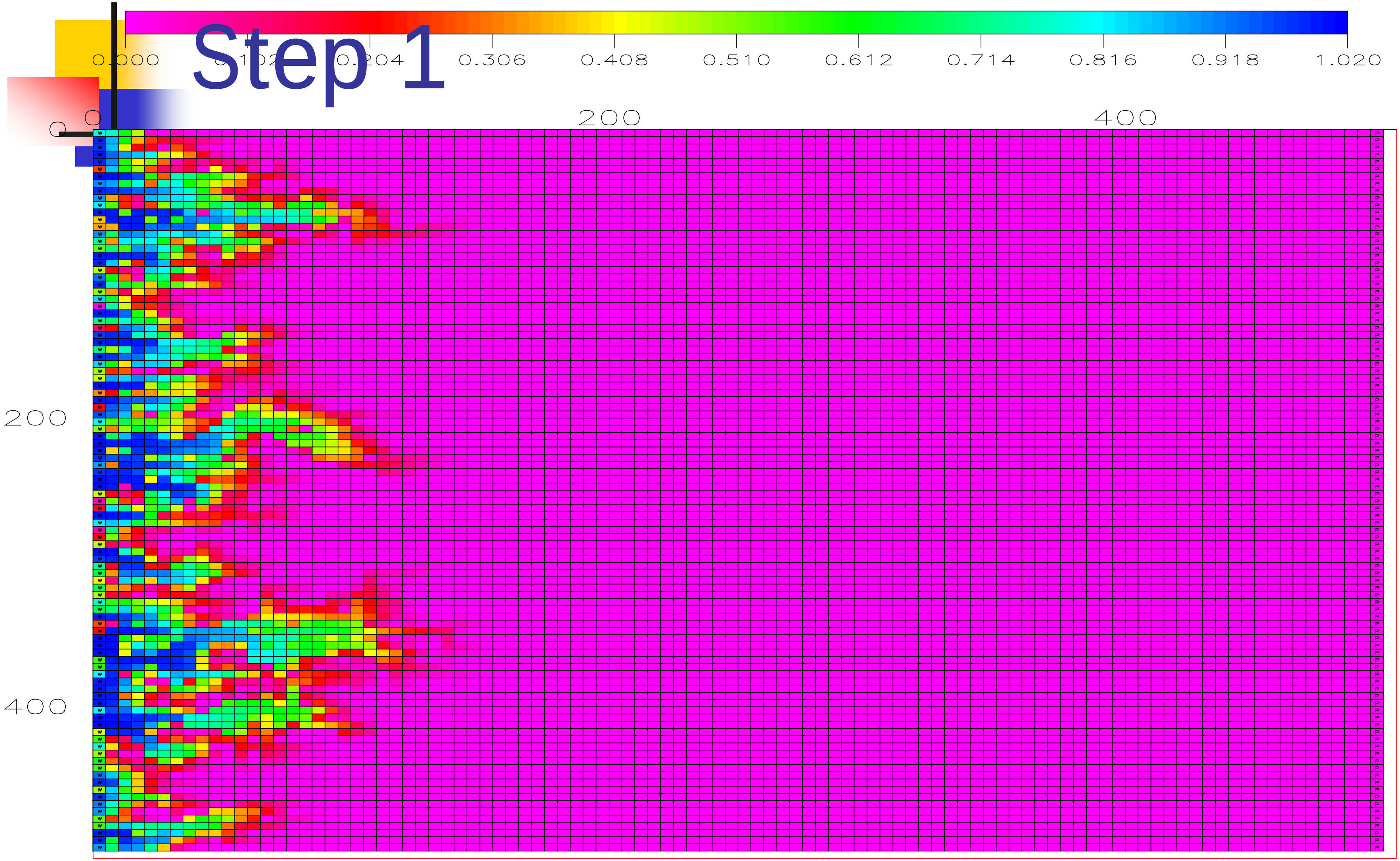
- 10,000 fine grid are represented by one grid block in the “scale up grid”
- Oil viscosity = 1 cp
- Injection fluid viscosity (3 cases) = 1, 0.2 and .05 cp
- Relative permeabilities are straight lines – corner to corner
- Flow into LHS of block – flow out of RHS
- Saturations shown at 5 times

Heterogeneous Description

10,000 Blocks

Mobility Ratio = 1.0

Step 1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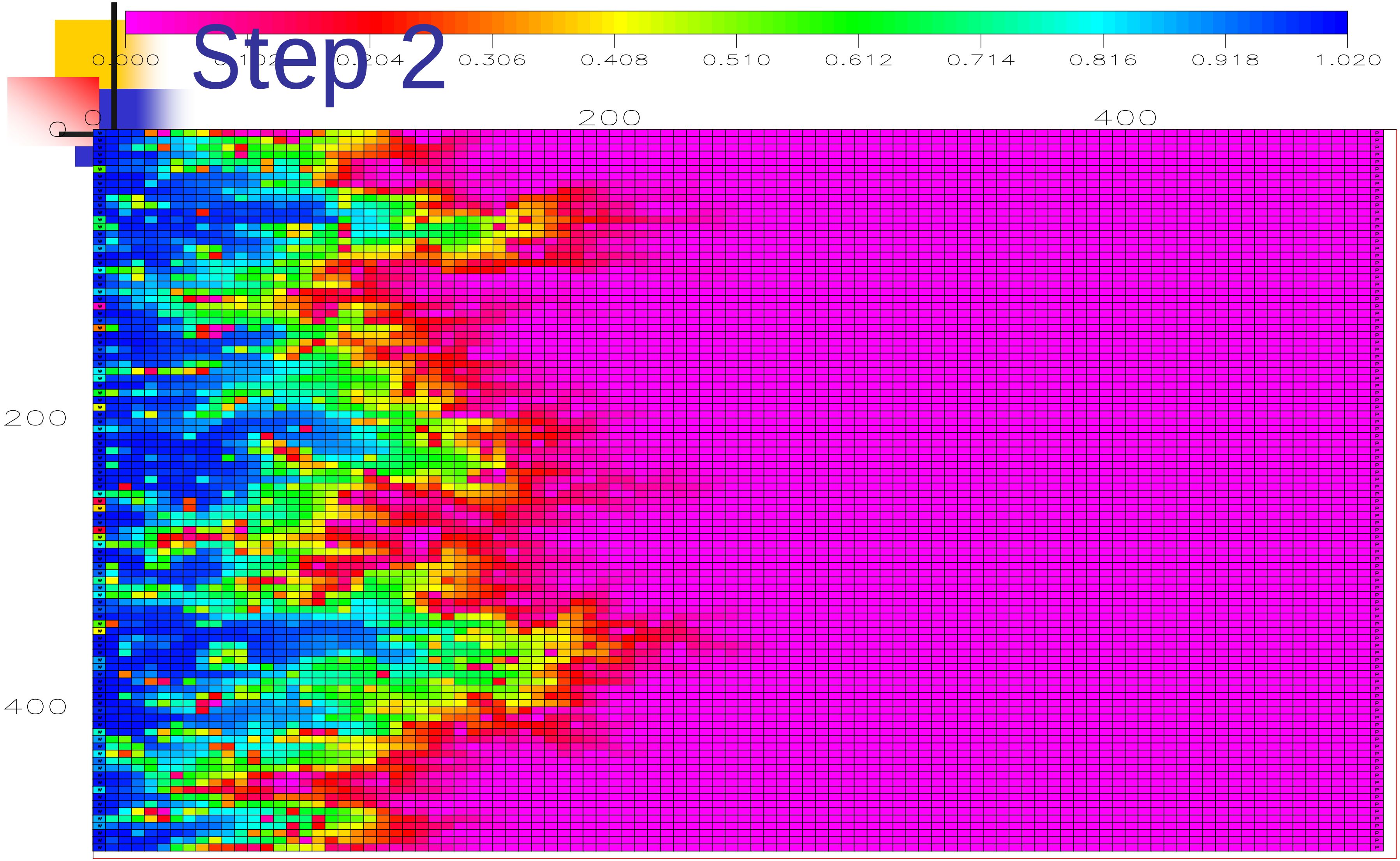
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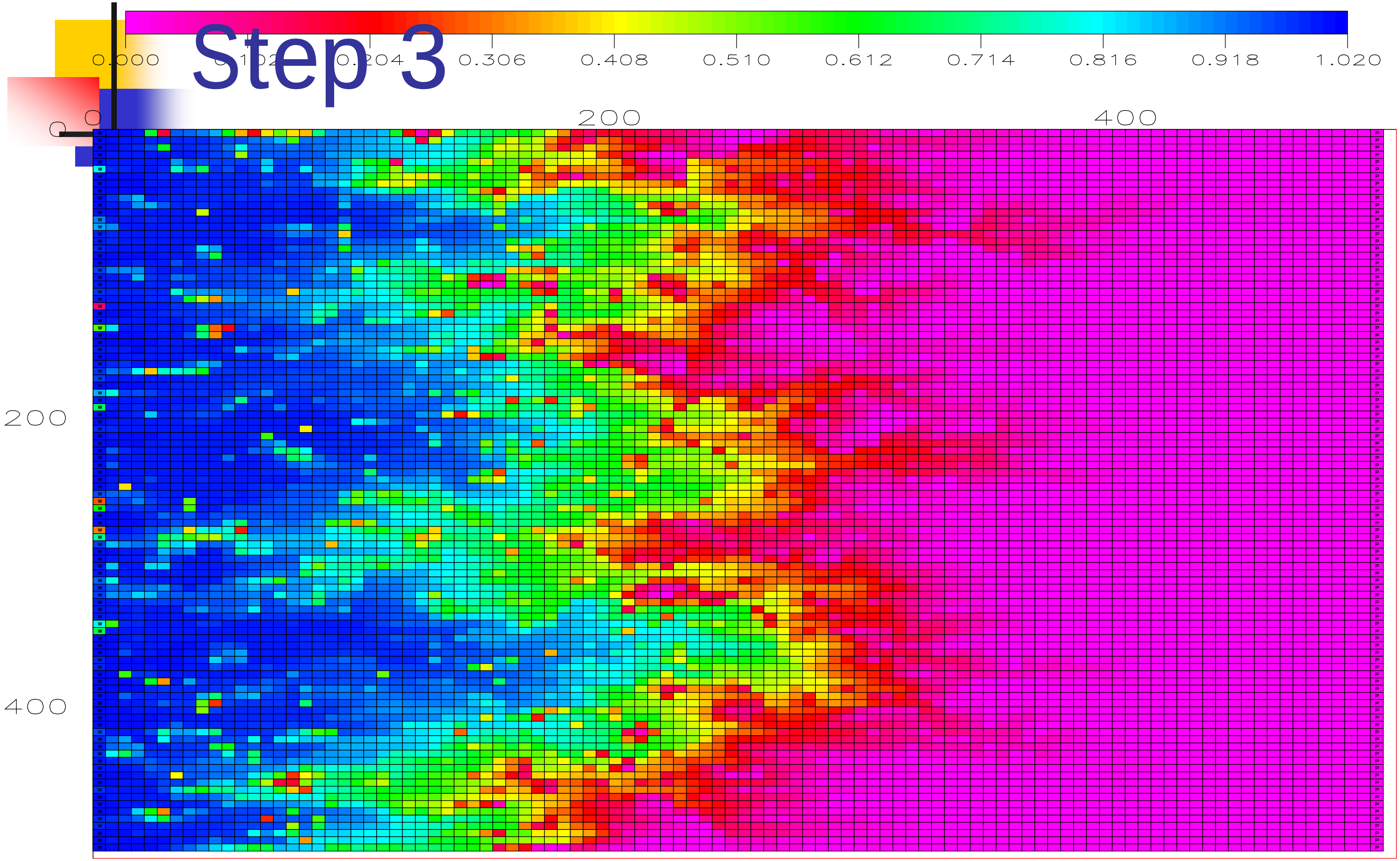
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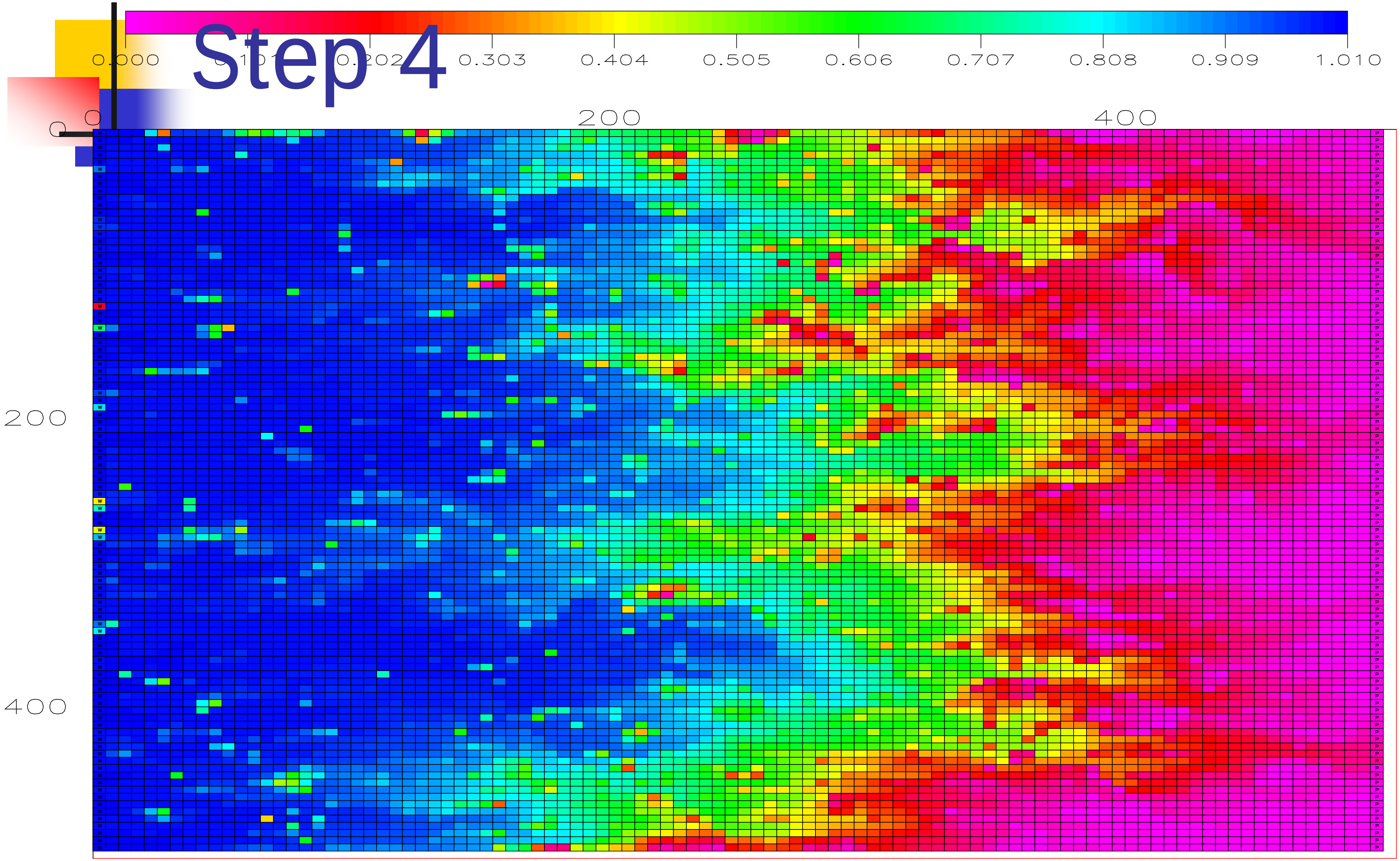

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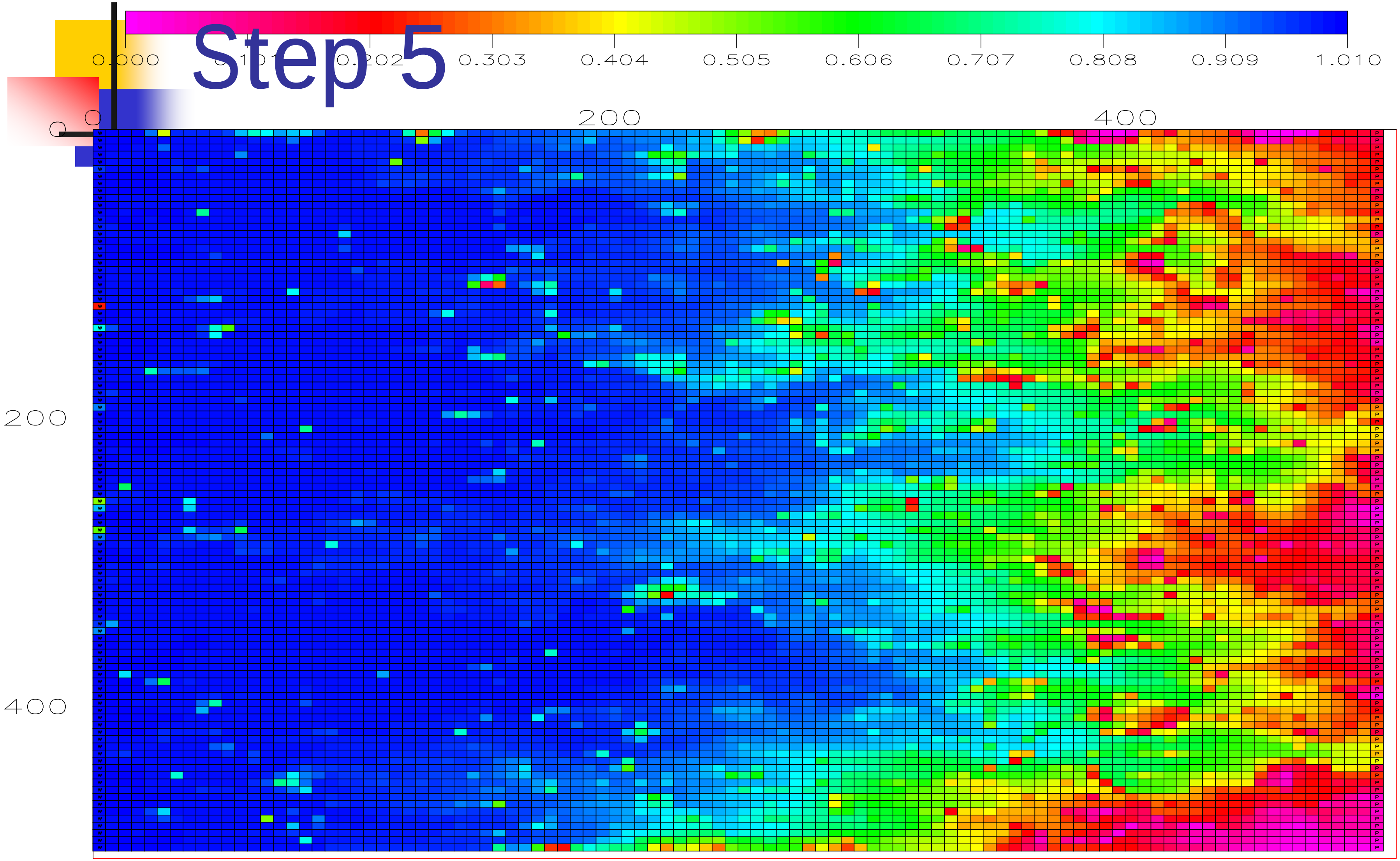
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Step 5

Homogeneous Case

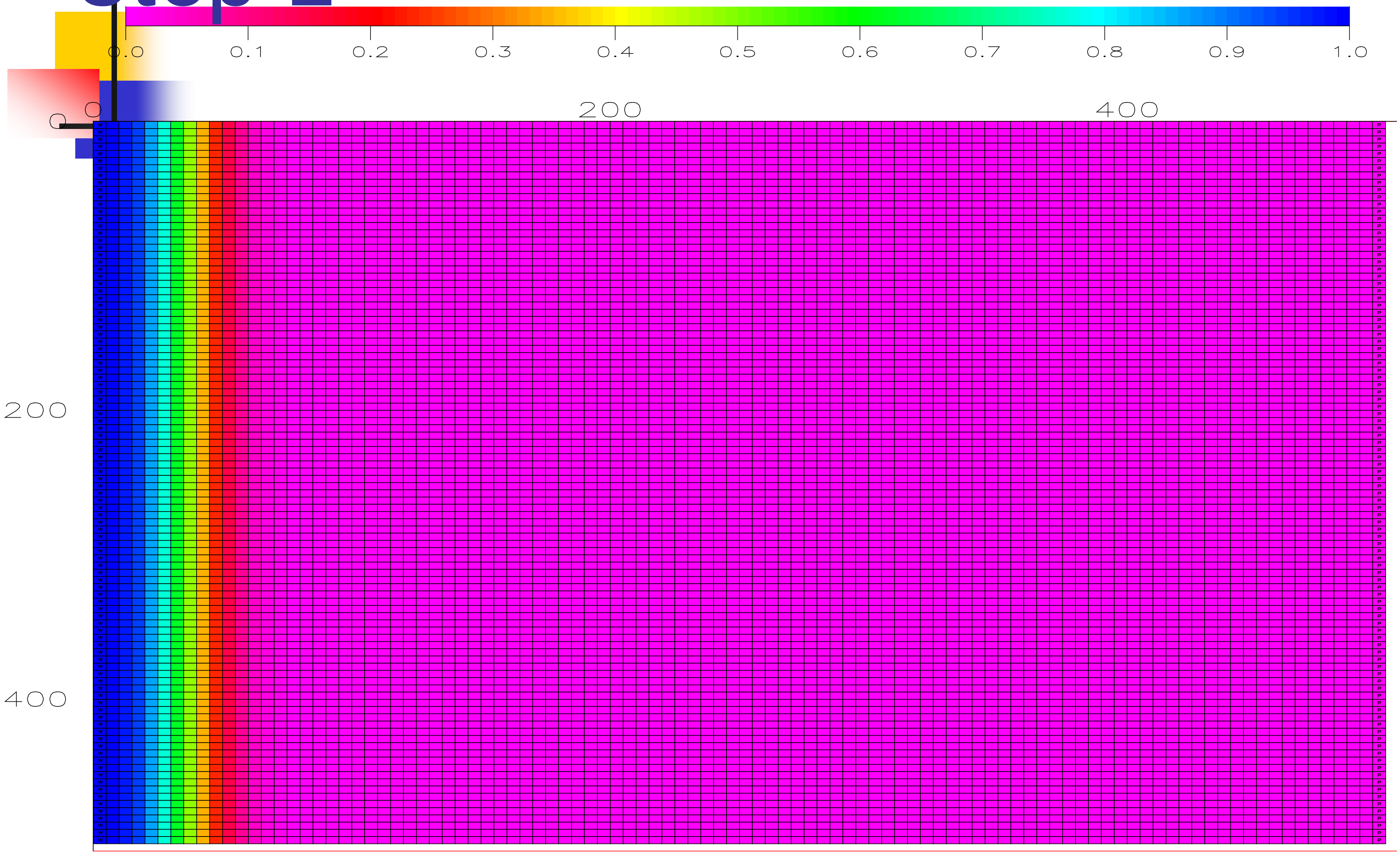
- 10,000 heterogeneous grid blocks are made homogeneous
- Permeability and porosity are average values of the 10,000 cells
- k = 1096.85 mD
- ϕ = 0.225

Homogeneous Description

10,000 Blocks

Mobility Ratio = 1.0

Step 1



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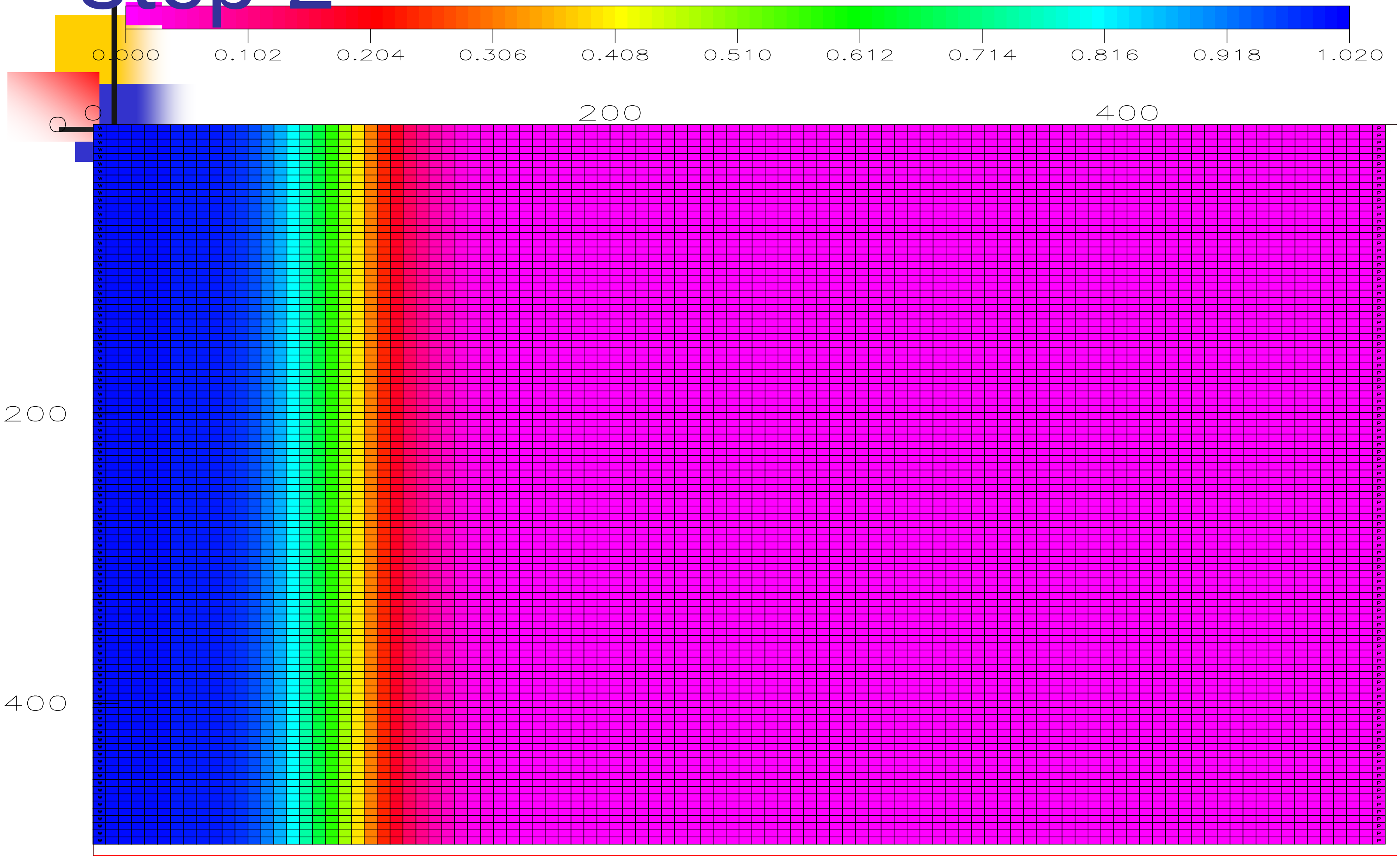

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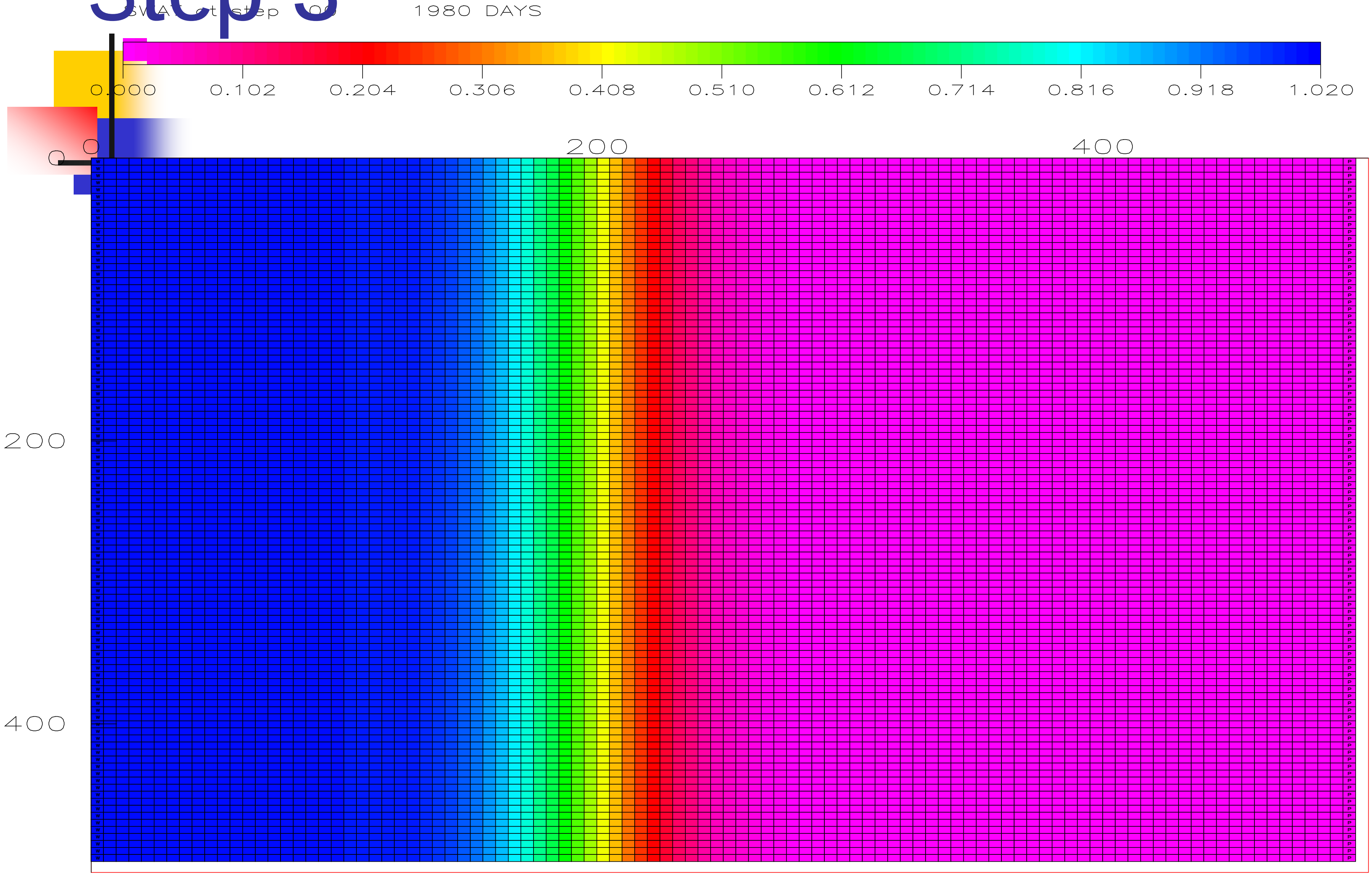
Step 3



SWAT at step
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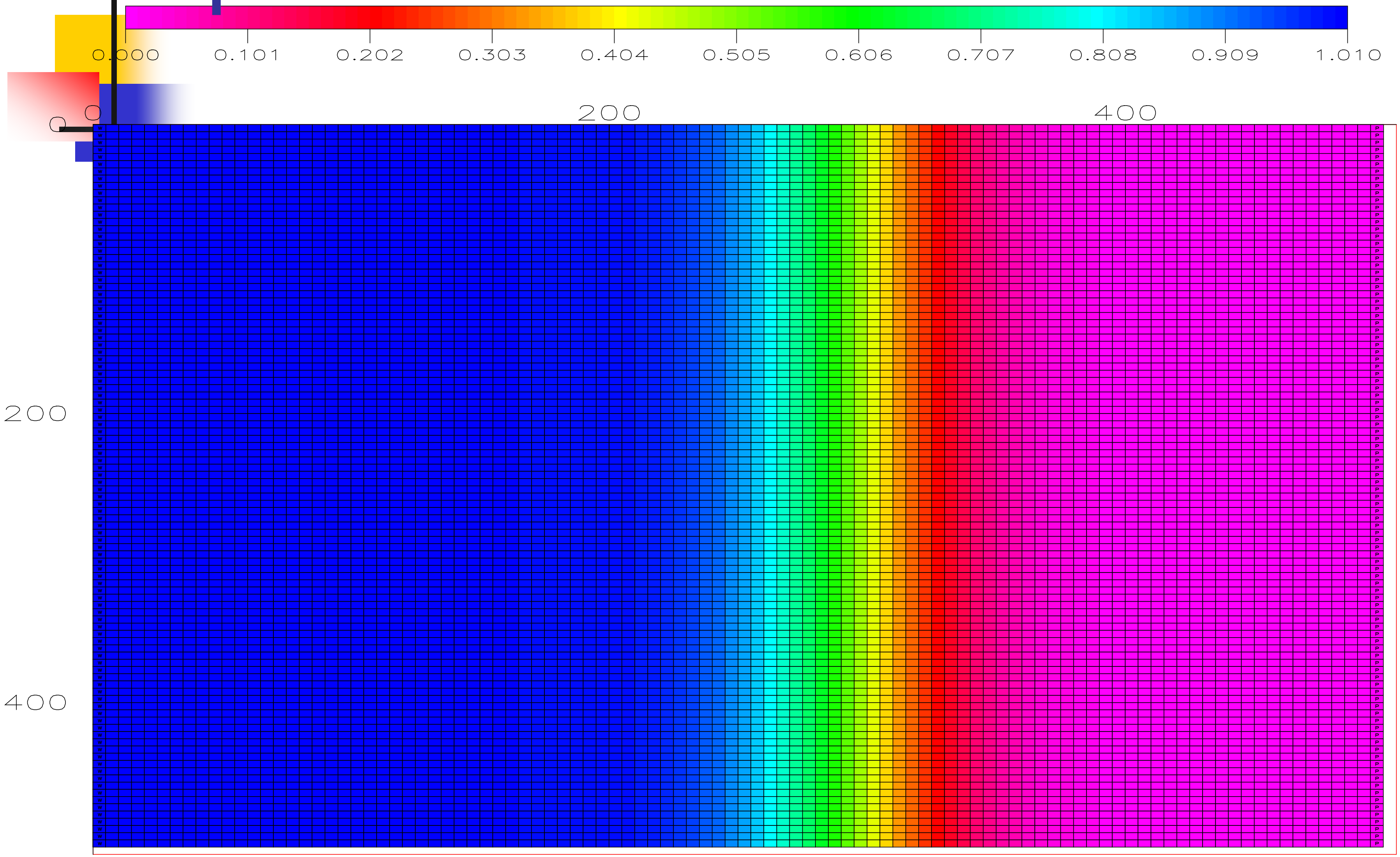
Step 4



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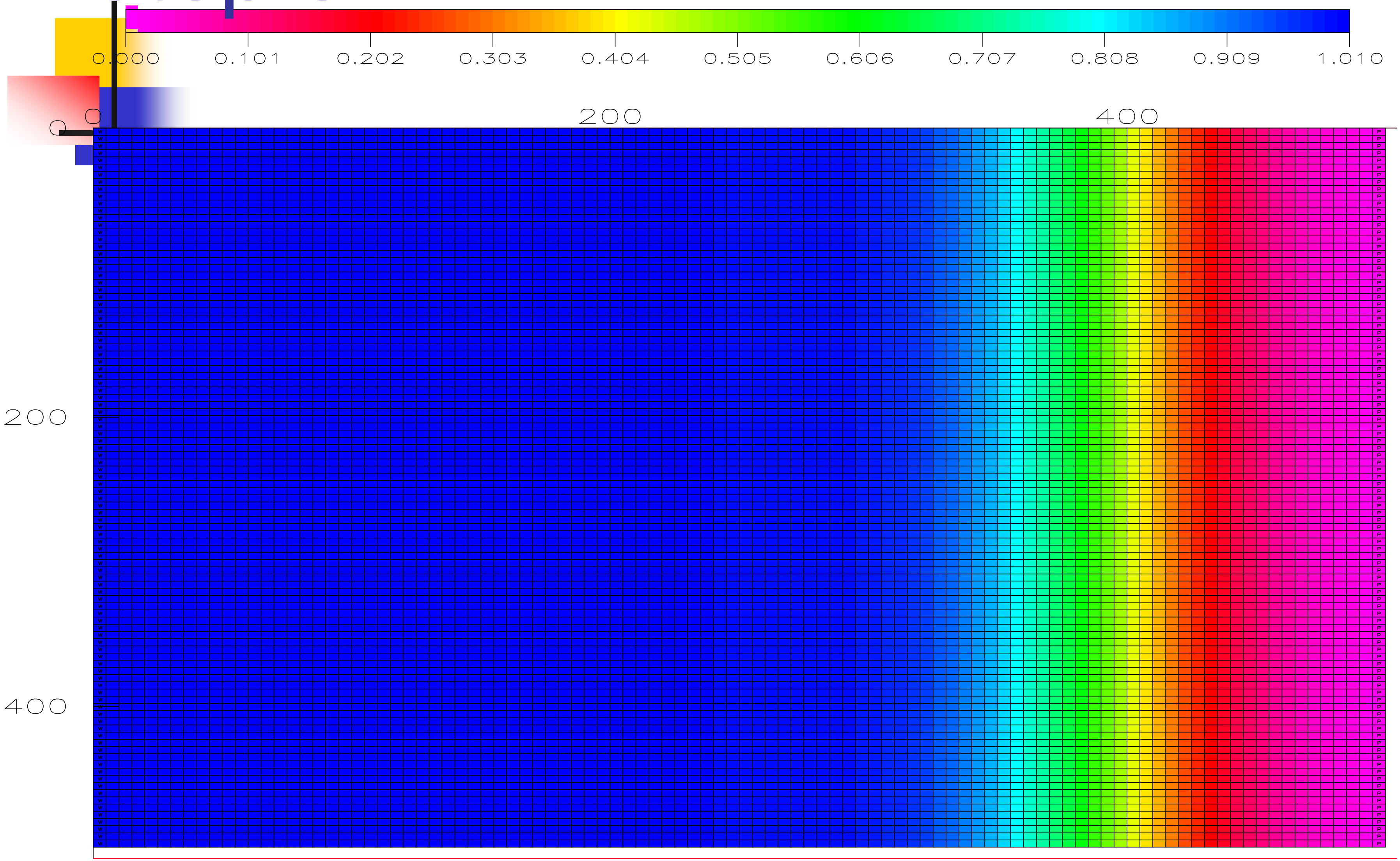
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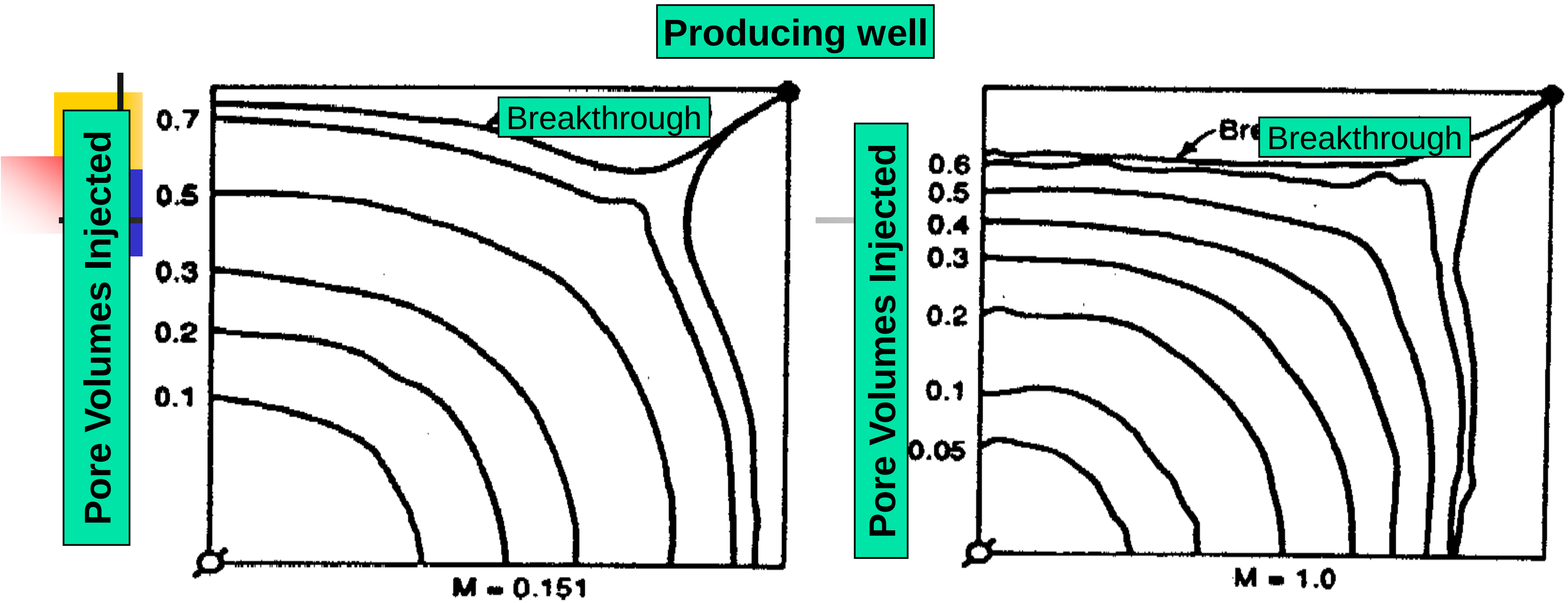
Effect of Mobility Ratio

- Physical models have been widely used for studies of Areal sweep efficiency.
- Gravity effects are eliminated by adjusting the densities of the different fluids or by using thin models so that gravity override or underride is minimized.
- The fronts, or interfaces, between displaced and displacing fluids are monitored by use of dyed fluids that be photographed or by X-ray shadow graph technique.
- The following figures show fluid fronts at different points in a flood for different mobility ratios. These results are based on photographs taken during displacements of one colored liquid by second, miscible colored liquid in a scaled model.

Areal sweep efficiency as a function of mobility ratio and injected volume

Correlations Based on Miscible Fluids, Five-Spot Pattern. The following shows fluid fronts at different points in a flood for different mobility Ratios. The Viscosity Ratio varied in different floods and, because only one phase was present, M is given by Equation.

$$M = \frac{\mu_d}{\mu_D}$$

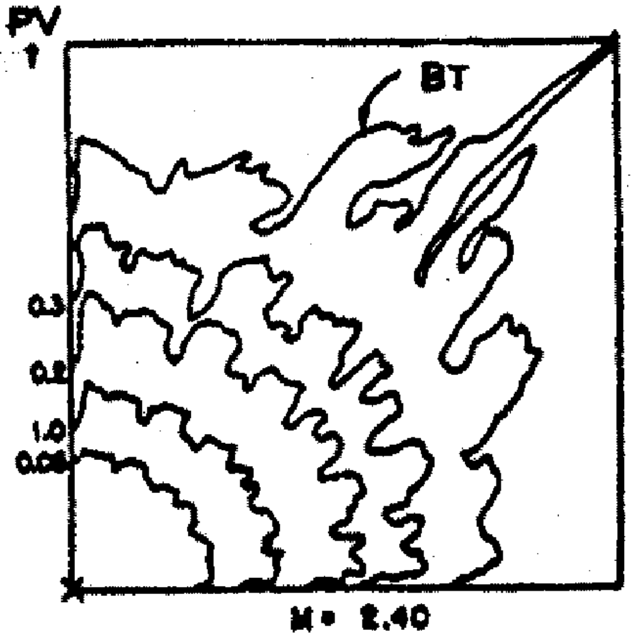


Injection well

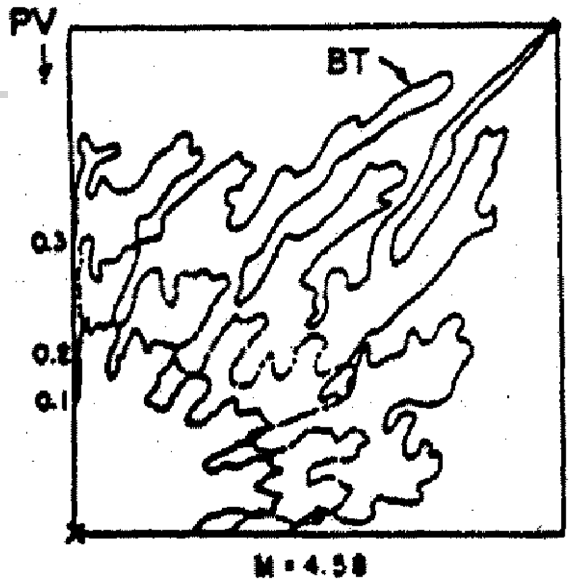
M=0.151 **M=1.0**

Miscible displacement in a quarter of

a five-spot pattern at mobility ratios<=1.0



M=2.40



M=4.58

- **PRODUCING WELL**

X INJECTION WELL

PV=PORE VOLUME INJECTED

BT=BREAKTHROUGH

Miscible displacement in a quarter of a five-spot pattern at mobility ratios>1.0,viscous fingering (from Habermann)

M=17.3

M=71.5

• **PRODUCING WELL**

X INJECTION WELL

PV=PORE VOLUME INJECTED

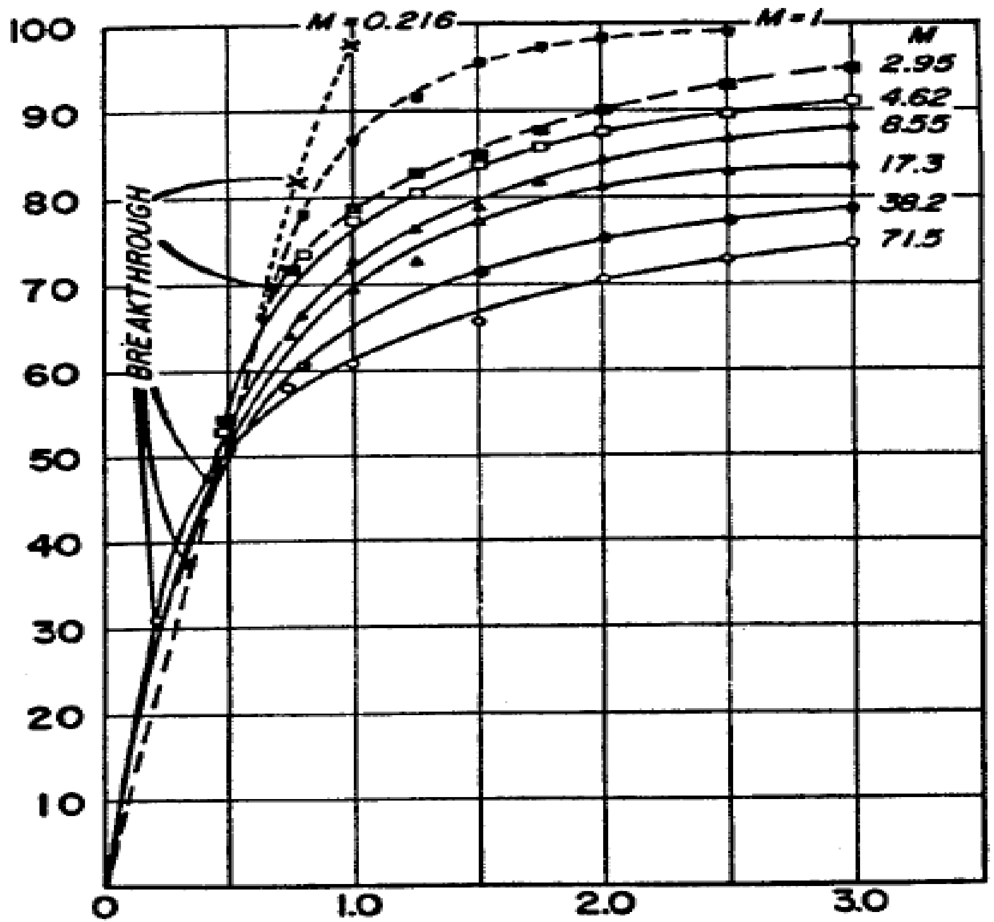
BT=BREAKTHROUGH

Miscible displacement in a quarter of a five-spot pattern at mobility ratios>1.0,viscous fingering (from Habermann)

Correlations Based on ….

Habermann presented values of EA as a function of dimensionless PVs injected, Vi/Vp,after breakthrough, as shown in the following Figure results are given for M=0.216 (favorable) to 71.5 (unfavorable).

Areal Sweep Efficiency, EA%



Pore Volume Injected, Vi/Vp

Areal sweep efficiency after breakthrough as a function of mobility ratio and PVs injected

Correlation Based on Miscible Fluids

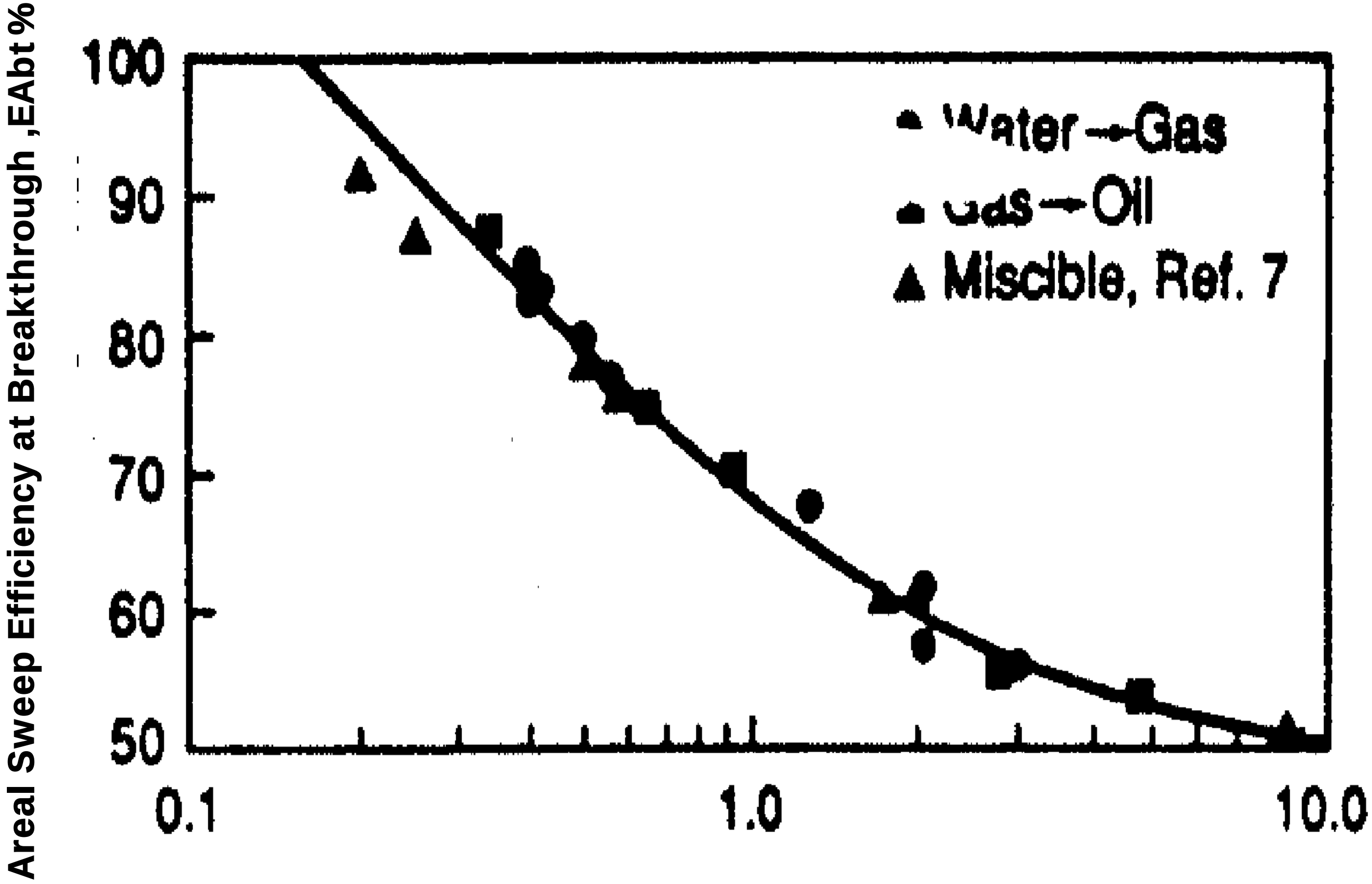
- Numerous modeling studies for patterns other than a five-spot have been reported.
- One-eight of a nine-spot pattern is shown as an example (Figure 5)
- This study was conducted with miscible liquids and the X-ray shadowgraph method

Correlations Based on Immiscible Fluids, Five –Spot Pattern

- **Craig et al.** conducted an experimental study of Areal displacement efficiency for **immiscible fluids** consisting of oil, gas, and water.. The study was conducted in **consolidated sandstone cores**, and fronts were monitored with the **X-ray** shadowgraph technique.

- Figure 6 compares Areal sweep efficiency at breakthrough as a function of mobility ratio to the data of Dyes et al., which were obtained with miscible fluids.

Figure 6: Areal sweep efficiency at breakthrough as a function of mobility ratio(immiscible fluid displacement);



Prediction of Areal Displacement Performance on the Basis of Modeling Studies

- Prediction based on Piston-Like Displacement
  - Caudle & Witte correlation
  - Claridge correlation (viscous fingering)
  - Mahaffey et. Al model (dispersion)
    - Parallel plate glass model
- Mathematical Modeling-Numerical

Prediction of Areal Displacement Performance on the Basis of Modeling Studies

- **Prediction Based on Piston –Like Displacement**.

  Caudle and Witte published results from laboratory models of a **five-spot pattern** in which displacements were conducted with **miscible** liquids.

  The performance calculations are restricted to those floods in which piston-like displacement is a reasonable assumption; i.e., the displacing phase flows only in the swept region and the displaced phase flows in the upswept region. No production of displaced phase occurs from the region behind the front.

Prediction Based on Piston Like Displacement

- E_A is given as a function of M for various values of injected PVs.

- The ratio Vi/V_{pd} is a dimensionless injection volume defined as injected volume divided by displaceable PV, V_{pd}.

- For a waterflood, V_{pd} is given by

$$V_{pd} = Ah\Phi(S_{oi} - S_{or})$$

- E_A as a function of M for different values of the fractional flow of the displacing phase ,f_D, at the producing well.

Prediction Based on Piston–Like Displacement

- conductance ratio, γ , as a function of M for various values of E_A.
- Conductance is defined as injection rate divided by the pressure drop across the pattern, $\frac{q}{\Delta p}$
- At any mobility ratio other than M=1.0,conductance will change as the displacement process proceeds.
- For a favorable mobility ratio, conductance will decrease as the area swept, EA, increases. The opposite will occur for unfavorable M values.
- The conductance ratio, is the conductance at any point of progress in the flood divided by the conductance at that same point for a displacement in which the mobility ratio is unity (referenced to the displaced phase).

Conductance ratio

$$\gamma = \frac{\left(\dfrac{q}{\Delta p}\right)_x}{\left(\dfrac{q}{\Delta p}\right)_i}$$

The subscript i refers to initial conditions,

Q is the steady state reservoir flow rate and

Δp is the pressure difference between injector and producer

- At any point in the flood for constant Δp

$$q = q_i \gamma$$

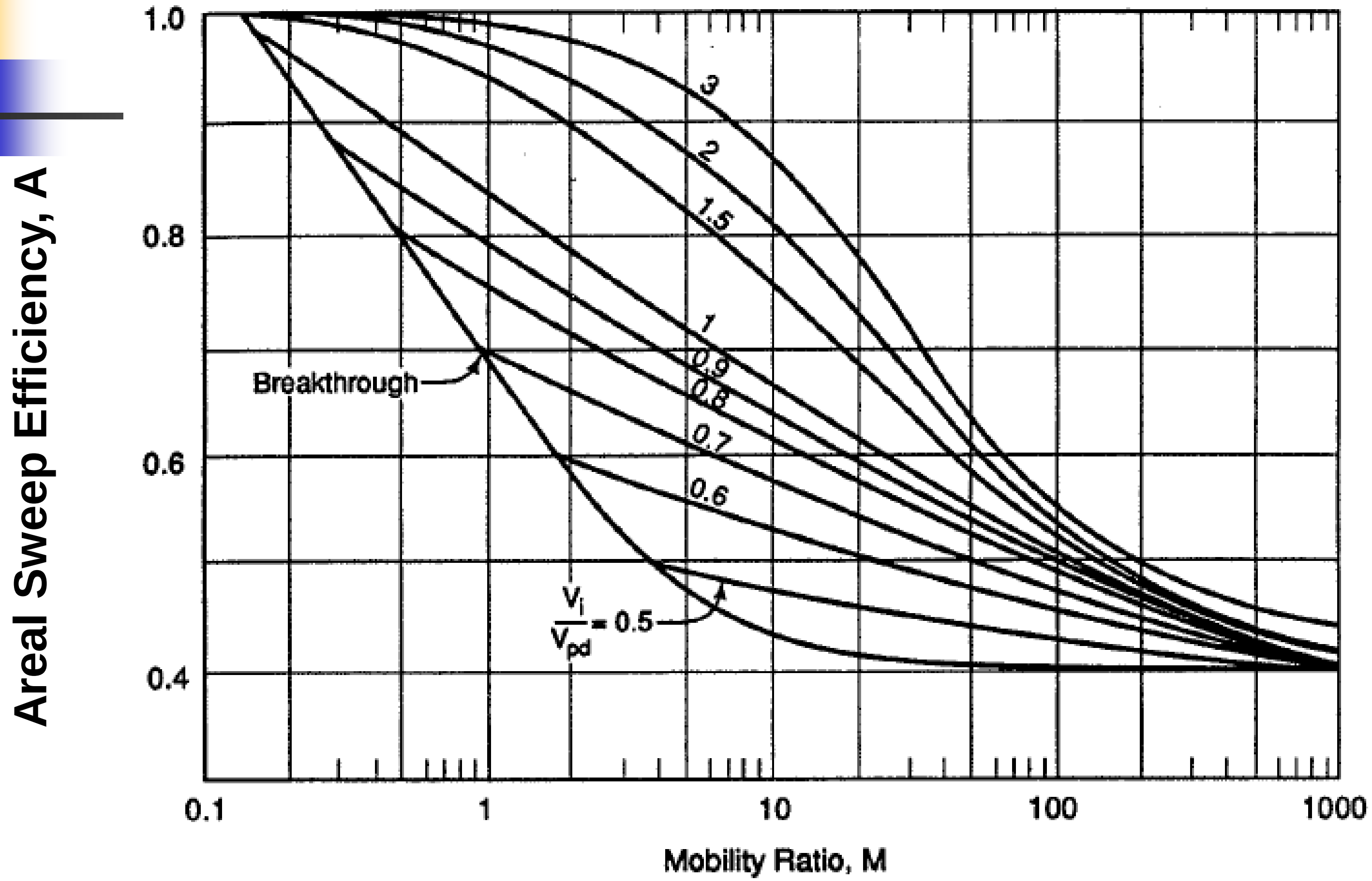
Prediction Based on Piston –Like Displacement

- Performance calculations can be performed.
- Areal sweep as a function of volume injected is available.
- Fractional production of either phase can be determined.
- Rate of injection may be determined as a function of E_A
- initial injection rate.

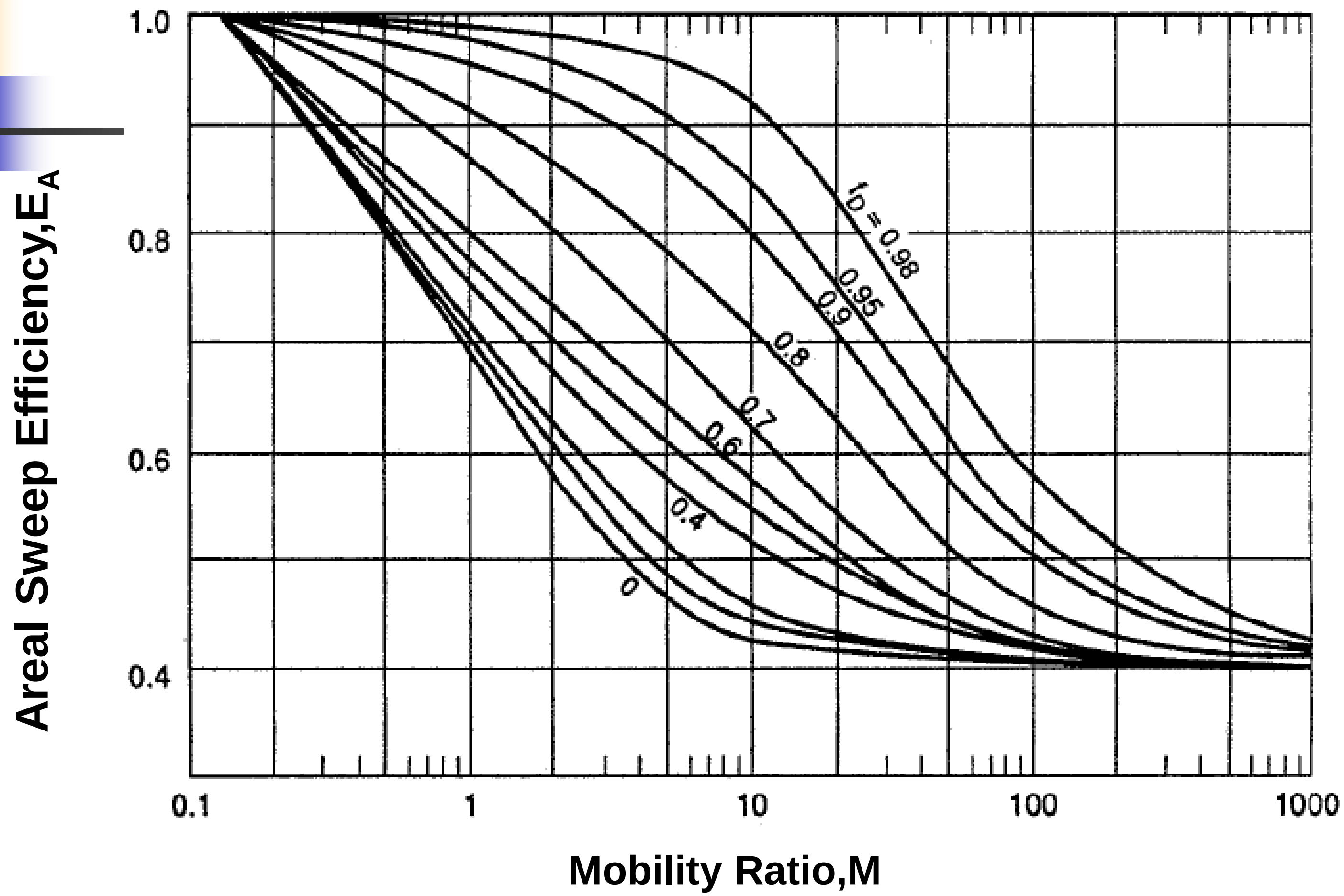
Prediction Based on Piston –Like Displacement

$$q_i = \frac{0.001538 k\, k_{rd}\, h \Delta p}{\mu_d (\log \frac{d}{r_w} - 0.2688)}$$

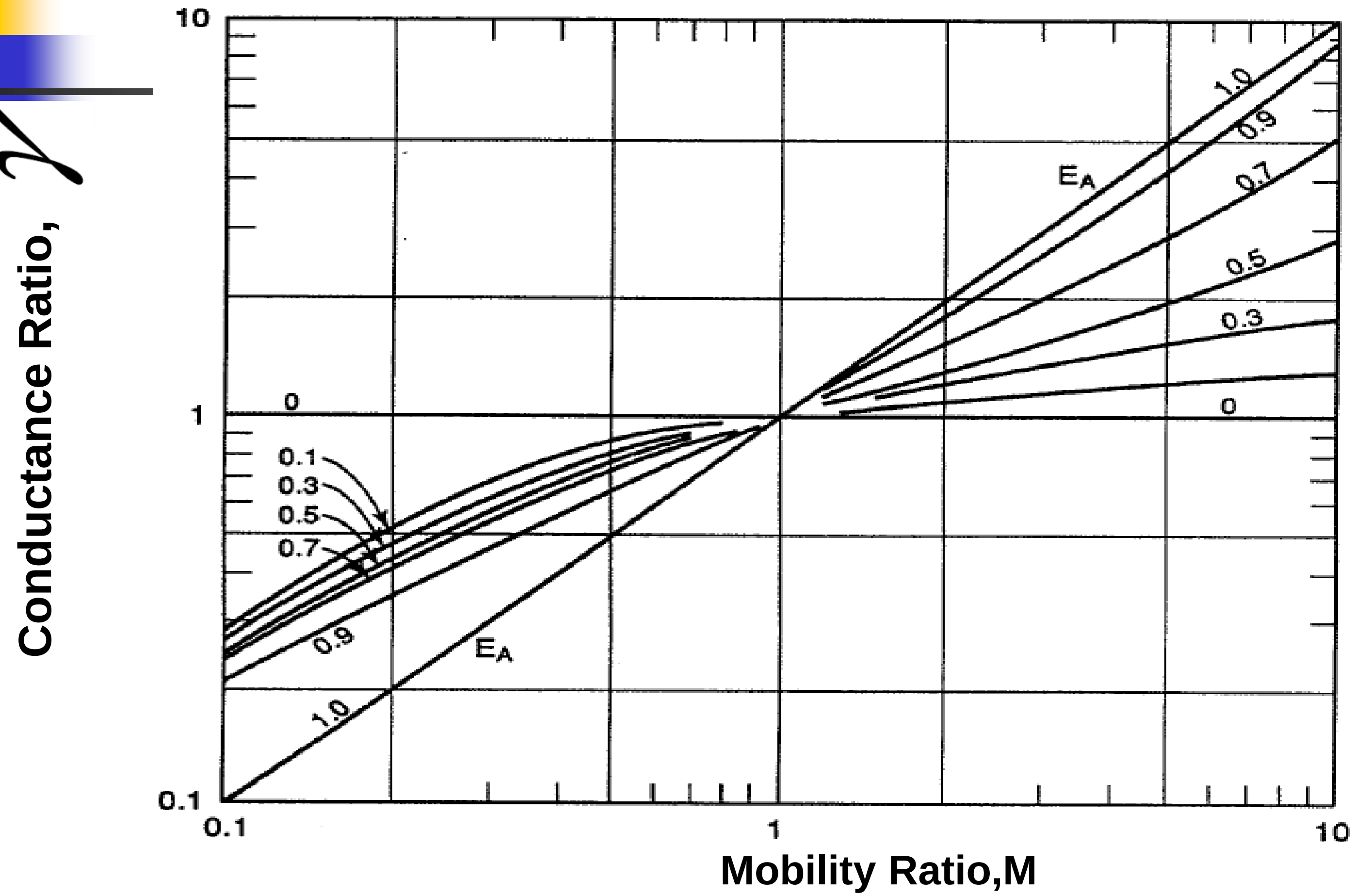
q_i = injection rate at start of a displacement process, B/D
k = absolute rock permeability ,md
k_{rd}= relative permeability of displacing phase
h = reservoir thickness ,ft
Δp = pressure drop, psi
μ = viscosity of displacing phase, cp
d = distance measured between injection & production wells,ft
r_w= wellbore radius, ft



Areal Sweep efficiency as a function of mobility ratio and injected volume.



Areal sweep efficiency as a function of mobility ratio and fractional flow at displacing phase



Conductance ratio as a function of mobility ratio and Areal sweep.

Example 1

Given M=2.08, initial Δp=69 bar and initial reservoir flow rate = 31.8 m^3/day.

Find Δp at breakthrough and when 1.5 pore volume has been displaced. Assume constant flow rate.

Solution:

Areal sweep efficiency at breakthrough is 0.6

With EA=.6 and M=2.08, figure 8 gives γ = 1.4

$$\Delta p = \frac{(q/\gamma)}{(q/\Delta p)_i} = \frac{69}{1.4} = 49.3 \quad bar$$

From a cumulative volume injected of 1.5 times the displaceable pore volume the pressure drop will be:

Δp=69/1.8=38.3 bar

Example: Performance Calculations Based on Physical Modeling Results

- **A waterflood is conducted in a five-spot pattern in which the pattern area is 20 acres. Reservoir properties are:**

$$h = 20\ ft$$
$$\phi = 0.2$$
$$S_{oi} = 0.8$$
$$S_{or} = 0.25$$
$$\mu_o = 10\ \ cp$$
$$\mu_w = 1\ \ cp$$
$$B_o = 1.0\ \ RB/STB$$
$$k = 50\ \ md$$
$$k_{rw} = 0.27(at\ \ ROS)$$
$$k_{ro} = 0.94(at\ \ S_{wi})$$
$$\Delta p = 1250\ \ psi$$
$$r_w = 0.5\ \ ft$$

Required

Use the method of Caudle and Witte to calculate:

(1) the barrels of oil recovered at the point in time at which the producing WOR=20 ,

(2) the volume of water injected at the same point

(3) the rate of water injection at the same point in time

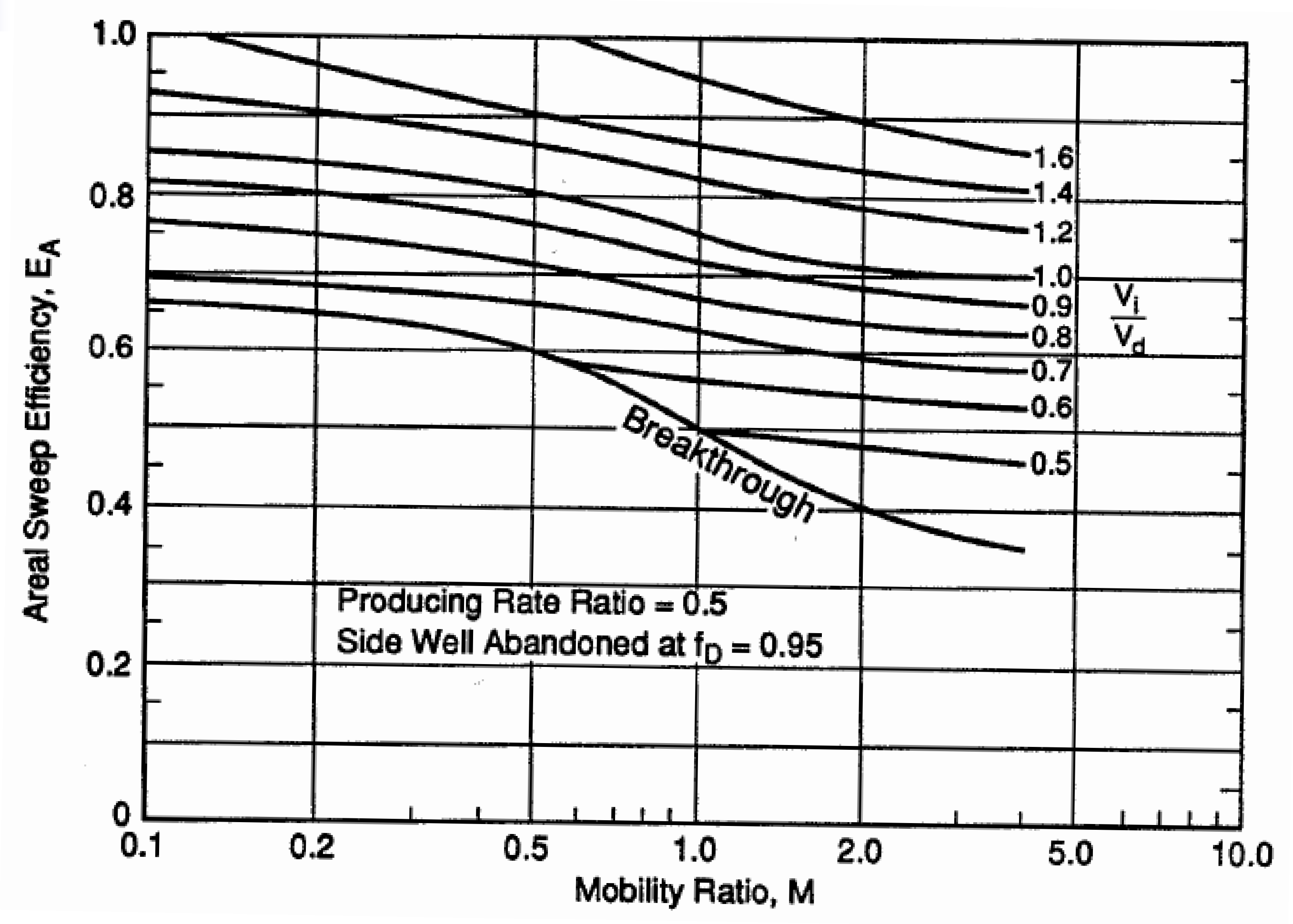
Solution

1. Calculate oil recovered
   - $M=2.9$, $f_D=20/21=.95$ From Fig 8, $E_A=.94$
   - Np=321000 STB
2. Calculate total water injected. From Fig 6, Vi/Vpd=2.5 (at $E_A=.94$)
   - Vpd = Vp (Soi – Sor) = 341300 bbl
   - Vi = Vpd x 2.5 = 853300 bbl
3. Calculate water injection rate at the same point in time. From

$$q_i = \frac{0.001538k\,k_{rd}\,h\Delta p}{\mu_d(\log\frac{d}{r_w} - 0.2688)}$$

   - qi=63.4 B/D
   - From Fig. 9, γ=2.7, from $q = i\gamma$ = 63.4x2.7 = 171 B/D

Areal sweep efficiency as a function of mobility ratio- seven points pattern



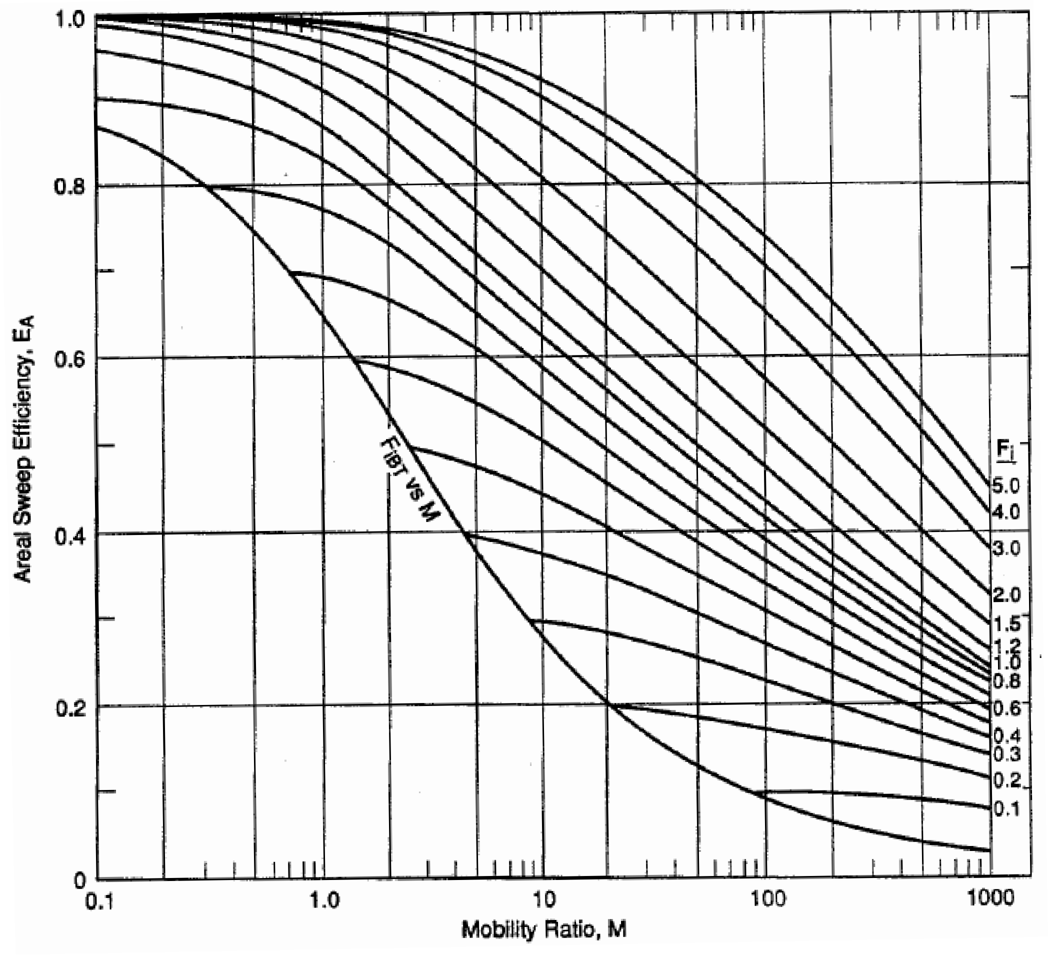
Claridge model for viscous fingering

- Claridge developed a correlation by combining the Caudle and Witte data with the model of viscous fingering derived by Koval.

- Recovery efficiency is given in displaceable PV's of oil produced as a function of displaceable PV's of fluid injected, F_i, and mobility ratio, M.

- The curves are presented in the following figure

Claridge correlation for Areal sweep efficiency



$$F_{ibt} = \left[0.9/(M + 1.1)\right]^{1/2}$$

$$\frac{N_p / V_{pd} - F_{ibt}}{1.0 - N_p / V_{pd}} = \left(\frac{1.6}{F_{\mu}^{0.61}}\right)\left(\frac{F_i - F_{ibt}}{1.0 - F_{ibt}}\right)^{1.28/F_{\mu}^{0.26}}$$

$$F_{\mu} = \left[0.78 + 0.22\left(\frac{\mu_o}{\mu_s}\right)^{1/4}\right]^4$$

- Where F_i=dimensionless displaceable PV's injected
- F_{ibt}=dimensionless displaceable PV's of solvent injected at the time of solvent breakthrough at the producing well
- The FVF's are one

Example: application of Claridge correlation

A miscible displacement is to be conducted in 20 acre five spot pattern in a reservoir with the following properties.

$h=20$ ft

$\varphi=0.20$

$S_{oi}=0.75$ $\mu_o=2.0$cp $\mu_s=0.04$ cp

$B_o=B_s=1.0$ RB/STB

A very large solvent slug is to be injected. Calculate oil recovery out to a solvent injection of 1.0 PV.

Solution

1. **First calculate M** $M = \mu_o / \mu_s = 2.0 / 0.04 = 50$
2. **Calculate F_{ibt}, Fμ, and Vpd**

$$F_{ibt} = \left(\frac{0.9}{M + 1.1} \right)^{1/2} = \left(\frac{0.9}{50 + 1.1} \right)^{1/2} = 0.133PV$$

$$F_{\mu} = \left[0.78 + 0.22 \left(\frac{\mu_o}{\mu_s} \right)^{1/4} \right]^4 = \left[0.78 + 0.22(50)^{1/4} \right] = 3.47$$

$$V_{pd} = Ah\phi S_{oi} = 4.65x10^5 bbl$$

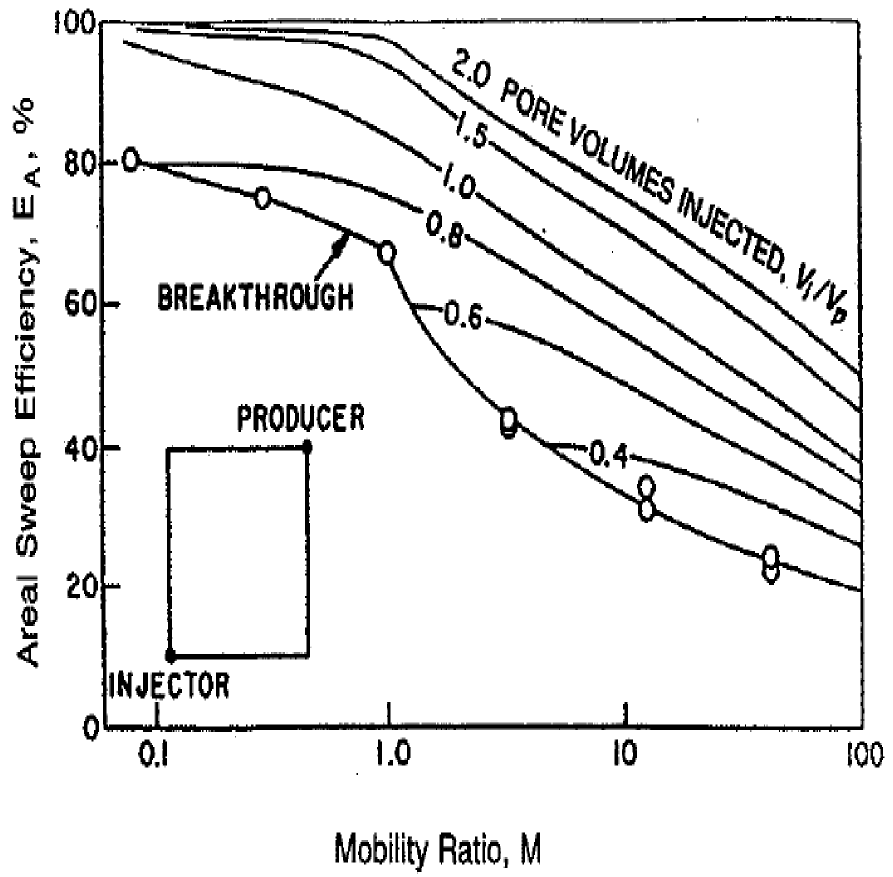
Results: Oil production as a function of volume injected

$$\frac{N_p/V_{pd} - F_{ibt}}{1.0 - N_p/V_{pd}} = \left(\frac{1.6}{F_\mu^{0.61}}\right)\left(\frac{F_i - F_{ibt}}{1.0 - F_{ibt}}\right)^{1.28/F_\mu^{0.26}}$$

F_i	N_p/V_{pd}	N_p(bbl)
0.133	0.133	$6.19\text{x}10^4$
0.15	0.15	$6.96\text{x}10^4$
0.25	0.224	$1.04\text{x}10^5$
0.50	0.353	$1.64\text{x}10^5$
0.75	0.439	$2.04\text{x}10^5$
1.00	0.503	$2.3\text{x}10^5$

Mahaffey et al. experiments

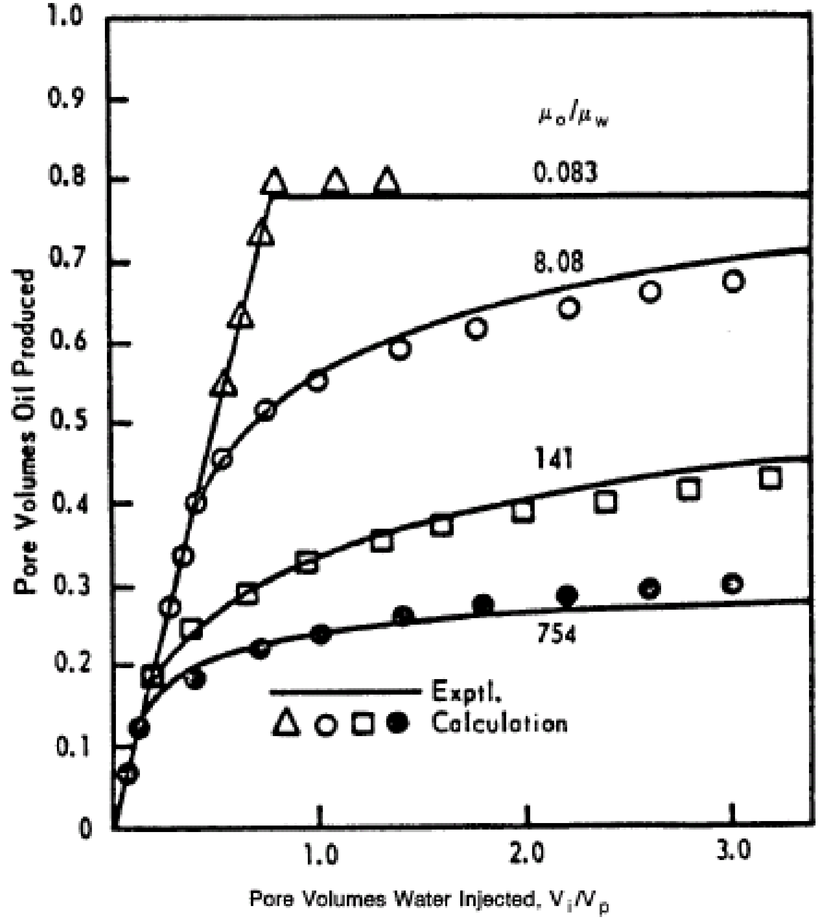
- This study was conducted in a parallel plate glass model scaled so that dispersion effects were at or near the molecular diffusion level.
- Miscible displacement data for a five spot pattern are shown.



Calculation of E_A with Mathematical Modeling

- Models are based on Numerical analysis methods and digital computers
  - Douglas et al-2D immiscible displacement method. This method is based on the numerical solution of the PDE's that describe the flow of two immiscible phases in two dimensions
  - Higgins and Leighton mathematical model is based on frontal advance theory

Mathematical modeling: Comparison of calculated and experimental results, 5 spot pattern (Douglas et al.)

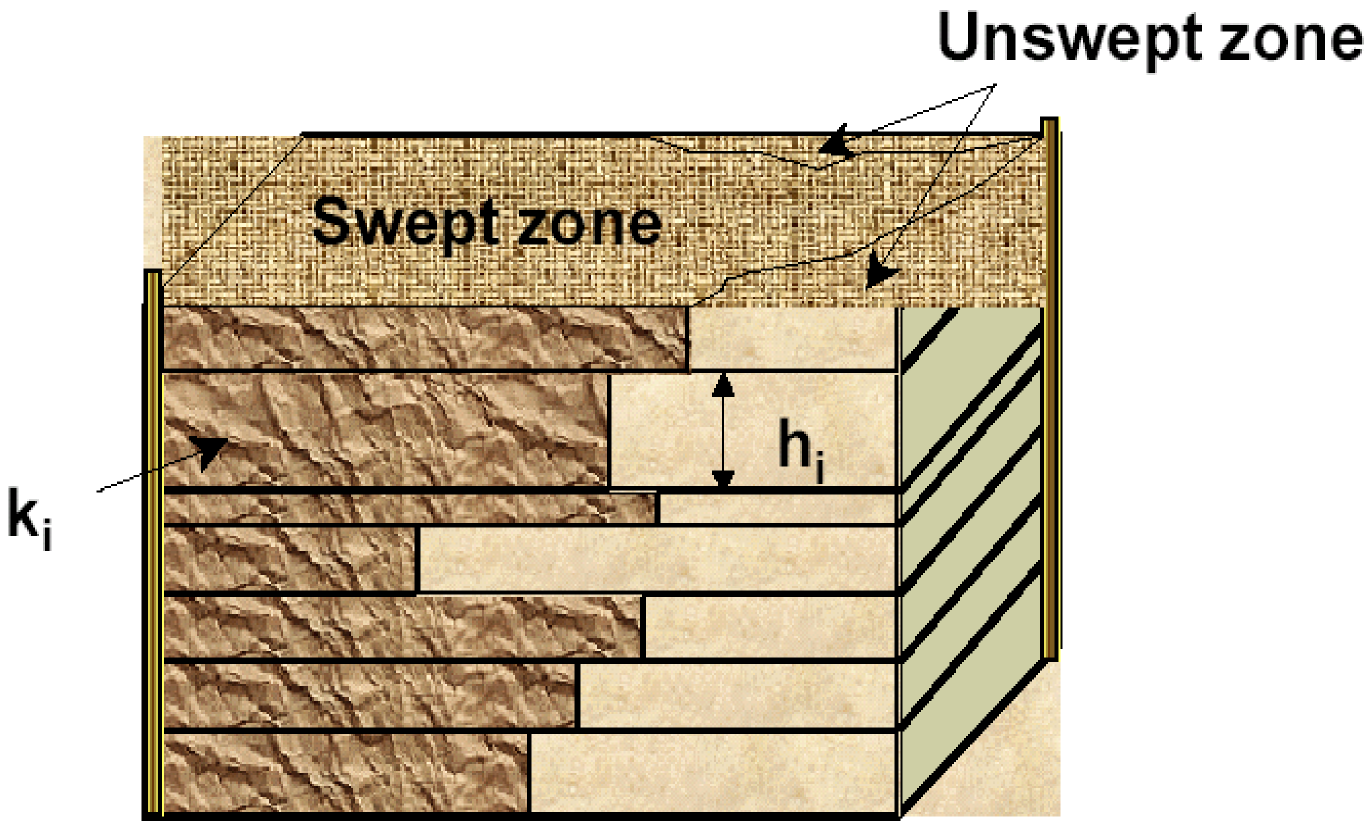


Vertical Displacement Efficiency

Vertical sweep (displacement) efficiency, pore space invaded by the injected fluid divided by the pore space enclosed in all layers behind the location of the leading edge (leading Areal location) of the front.

Areal sweep efficiency, must be combined in an appropriate manner with vertical sweep to determine overall volumetric displacement efficiency. It is useful, however, to examine the factors that affect vertical sweep in the absence of Areal displacement factors.

Vertical Displacement Efficiency



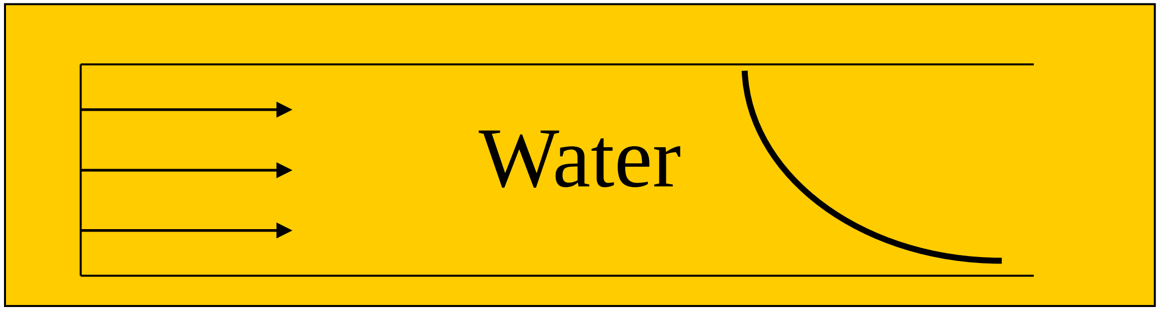
Vertical Displacement Efficiency

- Vertical Displacement Efficiency is controlled primarily by four factors:
  - Heterogeneity
  - Gravity effect
    - Gravity segregation caused by differences in density
  - Mobility ratio
  - Vertical to horizontal permeability variation
  - Capillary forces

Gravity Segregation in Horizontal Bed

- Water tongue

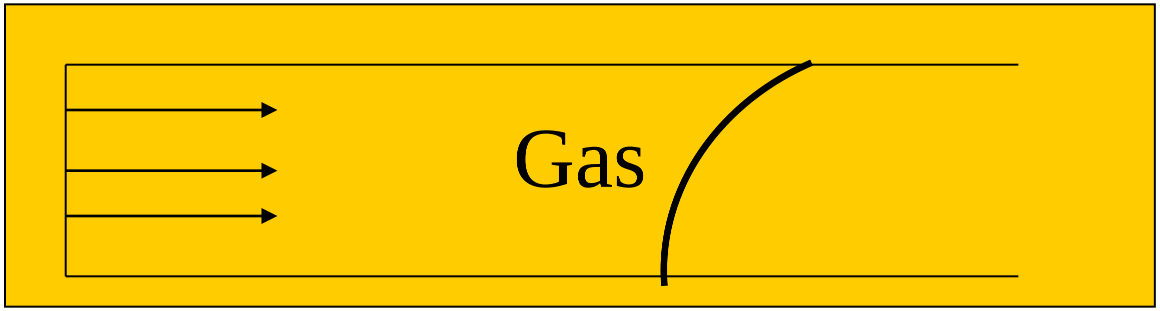
Gravity Underride (b)



$$\rho_D > \rho_d$$

- Gas umbrella

Gravity Override



$$\rho_D < \rho_d$$

Effect of Gravity Segregation and Mobility Ratio on Vertical Displacement Efficiency

- **Gravity segregation** occurs when the injected fluid is less dense than the displaced fluid

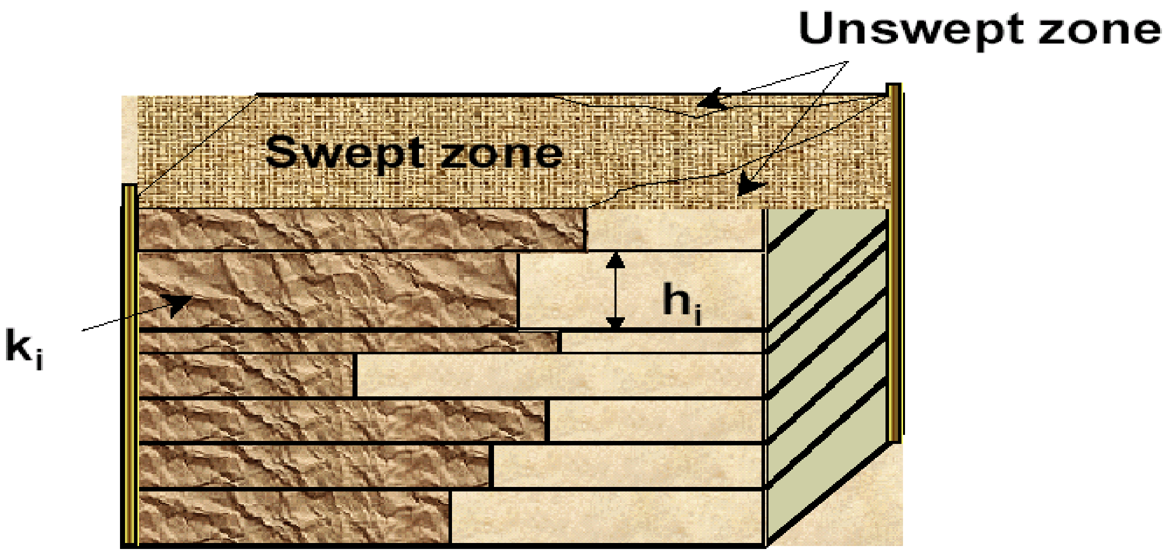
- Gravity override is observed in steam displacement, in-situ combustion, CO2 flooding, and solvent flooding processes.

- **Gravity segregation** also occurs when the injected fluid is more dense than the displaced fluid, such as waterflood.

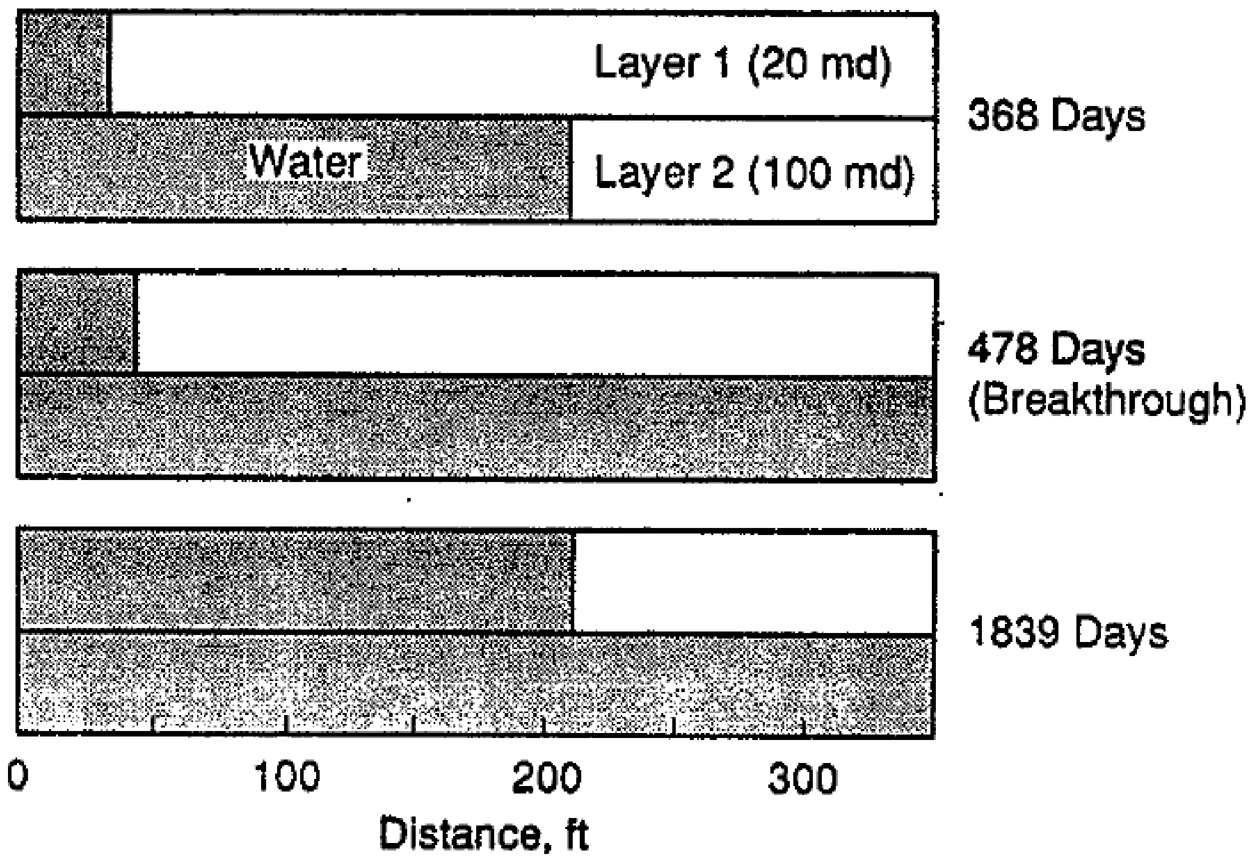
- **Gravity segregation** leads to early breakthrough of the injected fluid and reduced vertical sweep efficiency.

Heterogeneity

Observation of thre figure indicates a stratified reservoir with layers of different permeability. The displacement of the fluid is and an idealized piston-flow type. Due to the permeability contrast the displacing fluid will break through earlier in the first layer, while the entire cross-section will achieve sweep-out at a later time, when layer #4 breaks through.



Heterogeneity:Location of the water front at different Location



Experimental Result

- Craig et al. studied vertical sweep efficiency by conducting a set of scaled experiments in linear systems and five-spot models. Both consolidated & unconsolidated sands were used.
- The linear models used were from 10 to 66 in. long with length/height ratios ranging from 4.1 to 66.
- Experiments were conducted with miscible and immiscible liquids having mobility ratios from 0.057 to 200.
- Immiscible water floods were conducted at M<1.
- Vertical sweep was determined at breakthrough by material balance and visual observation of produced effluent

Craig et al. Results

- Results of the linear displacements are shown in the next Figure, where E_l at breakthrough is given as a function of dimensionless group called a viscous/gravity ratio.

$$R_{v/g} = \left(\frac{u\mu_d}{kg\Delta\rho}\right)\left(\frac{L}{h}\right)$$

Where u= linear Darcy velocity,

μ_d=viscosity of displaced phase

$\Delta\rho$=density difference between displacing and displaced phases

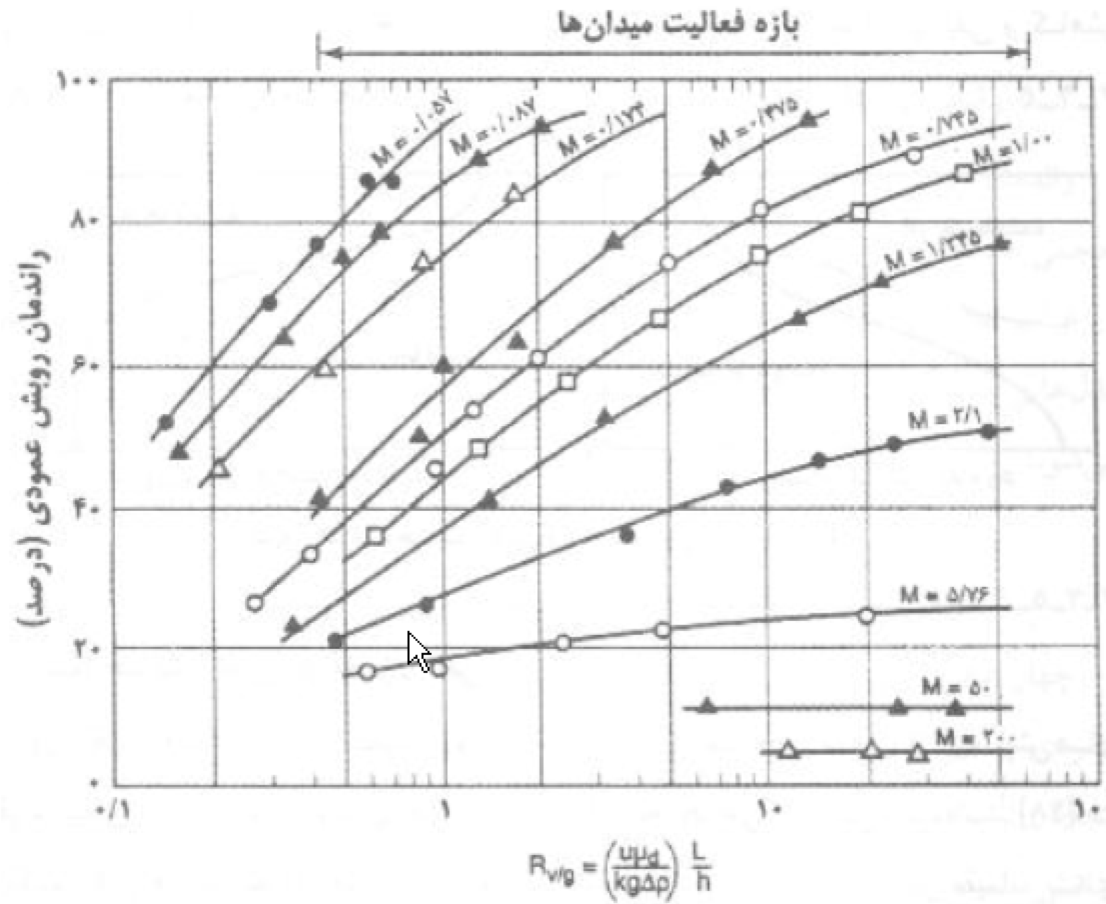
Craig et al. Results

- In customary units

$$R_{v/g} = \left(\frac{2050 u \mu_d}{k \Delta\rho} \right) \left(\frac{L}{h} \right)$$

Where u= linear Darcy velocity in bbl/day-ft^2,
μ_d=viscosity of displaced phase
K = permeability in millidarcies
$\Delta\rho$=density difference between displacing and displaced phases in grams per cubic centimeter
L and h are in feet

Vertical sweep efficiency at breakthrough as a function of the ratios of viscous/gravity forces, Linear system (from Craig et al.)



$$R_{v/g} = \frac{2050\ u\ (B/D \cdot ft^2)\ \mu_d\ (cp)\ L\ (ft)}{k\ (md)\ \Delta\rho\ (g/cm^3)\ h\ (ft)}$$

Observations

- At small $R_{v/g}$ values, the displaced phase tends to override or underride, depending on the magnitude of the liquid densities, which leads to early breakthrough of the displacing phase, even for M=1.
- As $R_{v/g}$ becomes relatively large in magnitude, with M=1.0, E_I approaches 100%
- The presented data where obtained for the case in which the horizontal permeability is equal to vertical permeability.
- If permeability in V and H are not equal $k=SQRT(K_H*K_V)$ as suggested by Stalkup

Example: Relative Importance of Gravity Segregation in a Displacement Process

A miscible displacement process will be used to displace oil from a linear reservoir having the following properties:

L=300ft H=10ft Φ=0.20

Soi=0.75 Siw=0.25

Ko=200md (effective permeability to oil at interstitial water solution

Determine the effect of gravity segregation on the vertical sweep efficiency if the oil is displaced miscibility by solvent with a density of 0.7 g/cc and a viscosity of 2.3 cp at reservoir temperature.

The density of oil is 0.85 g/cc and viscosity is 2.3 cp. A frontal advance rate of 0.075 ft/day is considered. Consider displacement at frontal advance rate of 0.375 ft/D. This is equivalent to a Darcy velocity of 0.075 ft/D.

Calculate the viscous/gravity ratio.

Solution

$$u = 0.075\ ft / D\left(\frac{1}{5.615\ ft^3 / bbl}\right) = 0.0134\,B(\,D -\ ft^2\,)$$

$$R_{v/g} = \frac{(2050)(0.0134)(2.3)(300)}{(200)(0.85 - 0.70)(10)} = 63$$

Caculate M

$$M = \frac{k_D}{\mu_D}\frac{\mu_d}{\mu_d} = \frac{\mu_d}{\mu_D} = 2.3 / 2.3 = 1.0$$

From the figure $E_I(\text{at breakthrough}) = 0.86$

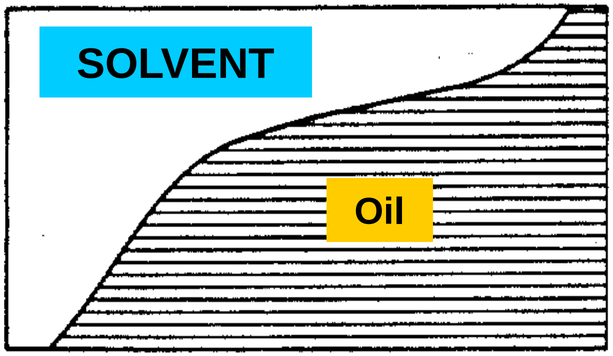
If the frontal advance rate were .0075 ft/day, the value of $R_{v/g}$ would be 6.3 and E_I=.70

- Note: increasing the permeability from 200 to 4000 md has the same effect as reducing the frontal advance rate from 0.075 to 0.00375 ft/day

Flow Regions in Miscible Displacement at Unfavorable Mobility Ratios

Flow experiments in a vertical cross section in horizontal porous media have shown that four flow regions, are possible when the mobility ratio is unfavorable.

Region I occurs at very low $R_{V/g}$ values and is characterized by a single gravity tongue, with the displacing liquid either underriding or overriding the displaced liquid. Vertical sweep is a strong function of $R_{V/g}$ .At large values, in region II, a single gravity tongue still exists, but vertical sweep is relatively insensitive to the value of the viscous/gravity ratio.



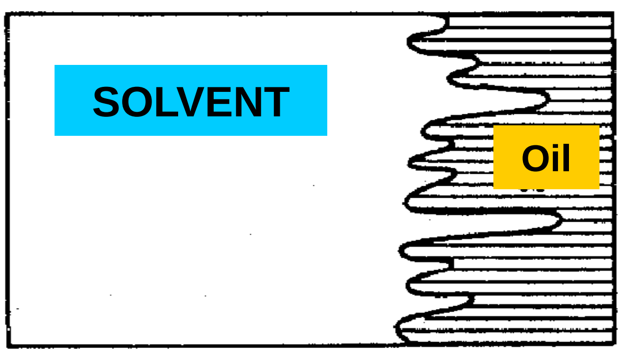
(A) REGIONS I AND II

Flow Regions in Miscible Displacement at Unfavorable Mobility Ratios

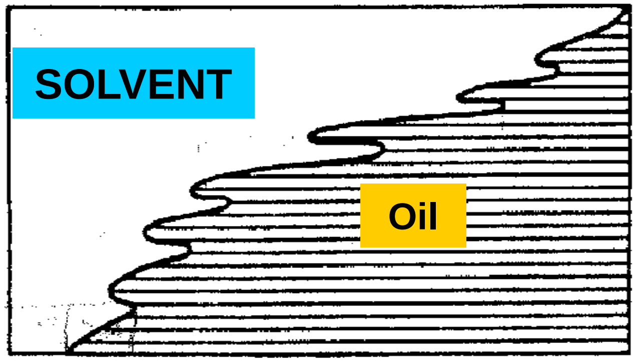
The transition to region III occurs at a particular critical $R_{V/g}$ value.

In region III, viscous fingers are formed along the primary gravity tongue and appear as secondary fingers along the primary gravity tongue. Vertical sweep is improved by the formation of the viscous fingers in this region.

In region IV ,flow is dominated by the viscous forces and by viscous fingering. A gravity tongue does not form because of the strong viscous fingering. The vertical sweep in this region is relatively insensitive to $R_{V/g}$

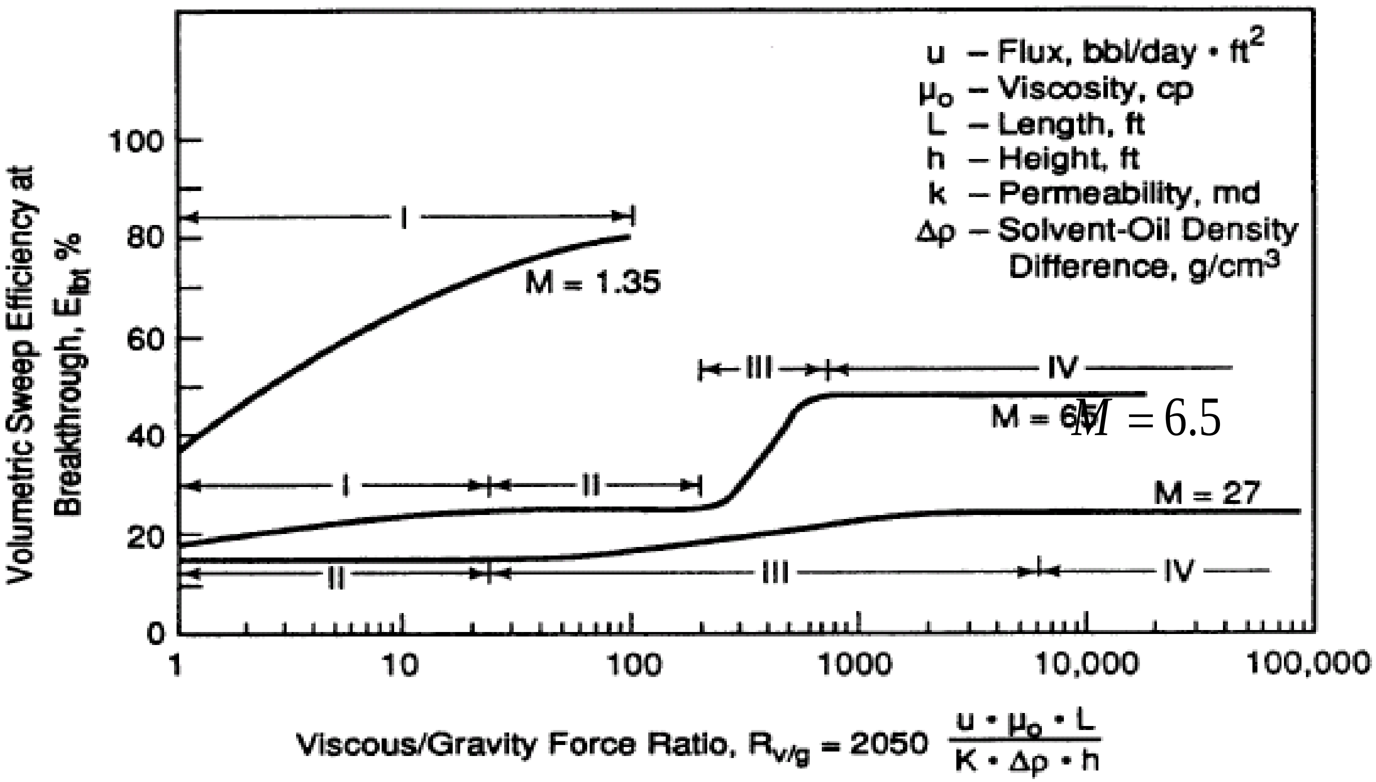


(C) REGION IV



(B) REGION III

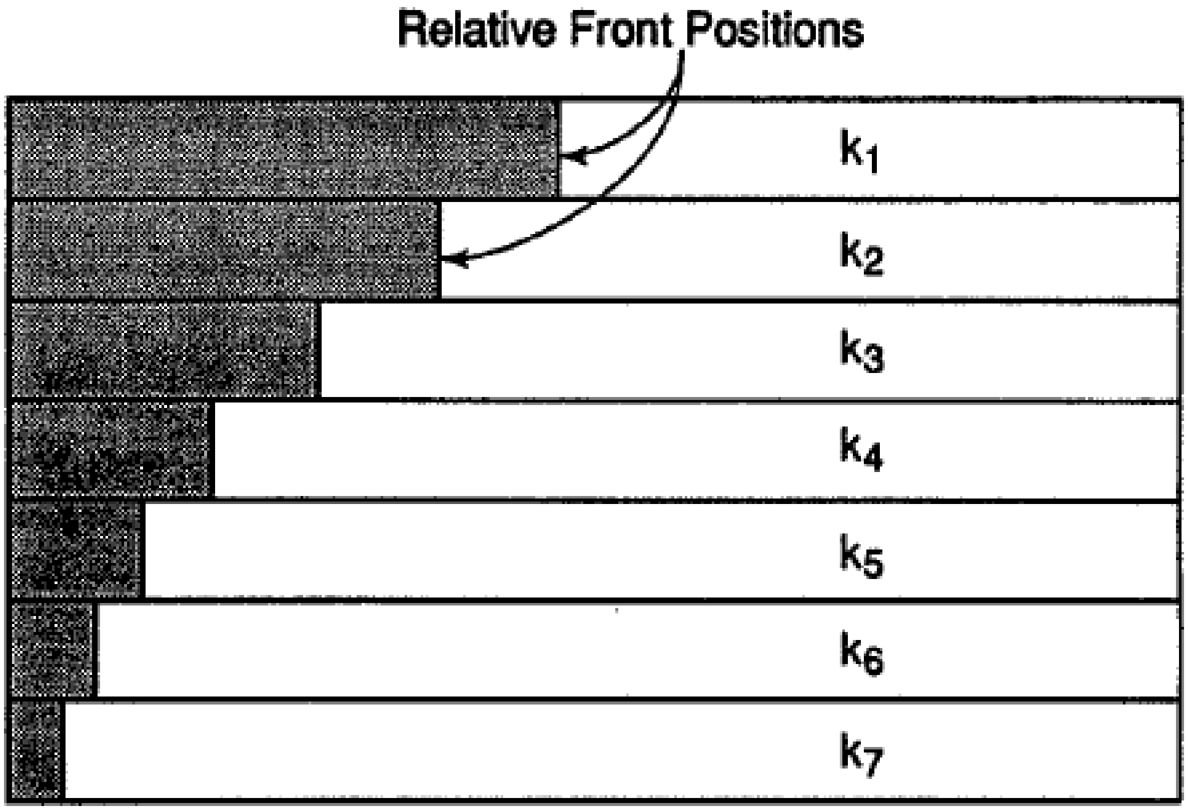
Flow Regimes in Miscible Displacement



Heterogeneity: Dykstra-Persons model

- The reservoir is represented by no communicating layers and by neglecting gravity segregation.
- Piston like displacement in a linear reservoir flooded at constant pressure drop.
- The model is based on subdividing the reservoir into n layers of equal thickness that have different permeabilities.
- Layers are arranged in order of descending permeability as shown next.

Heterogeneity: Dykstra-Persons model



Heterogeneity: Dykstra-Persons model

- For M=1

$$E_I = \frac{n_j + \sum_{k=j+1}^{n} \frac{k_k}{k_j}}{n}$$

- Where n=total number of layers, nj=number of layers flooded out, and k=permeability

Heterogeneity: Dykstra-Persons model

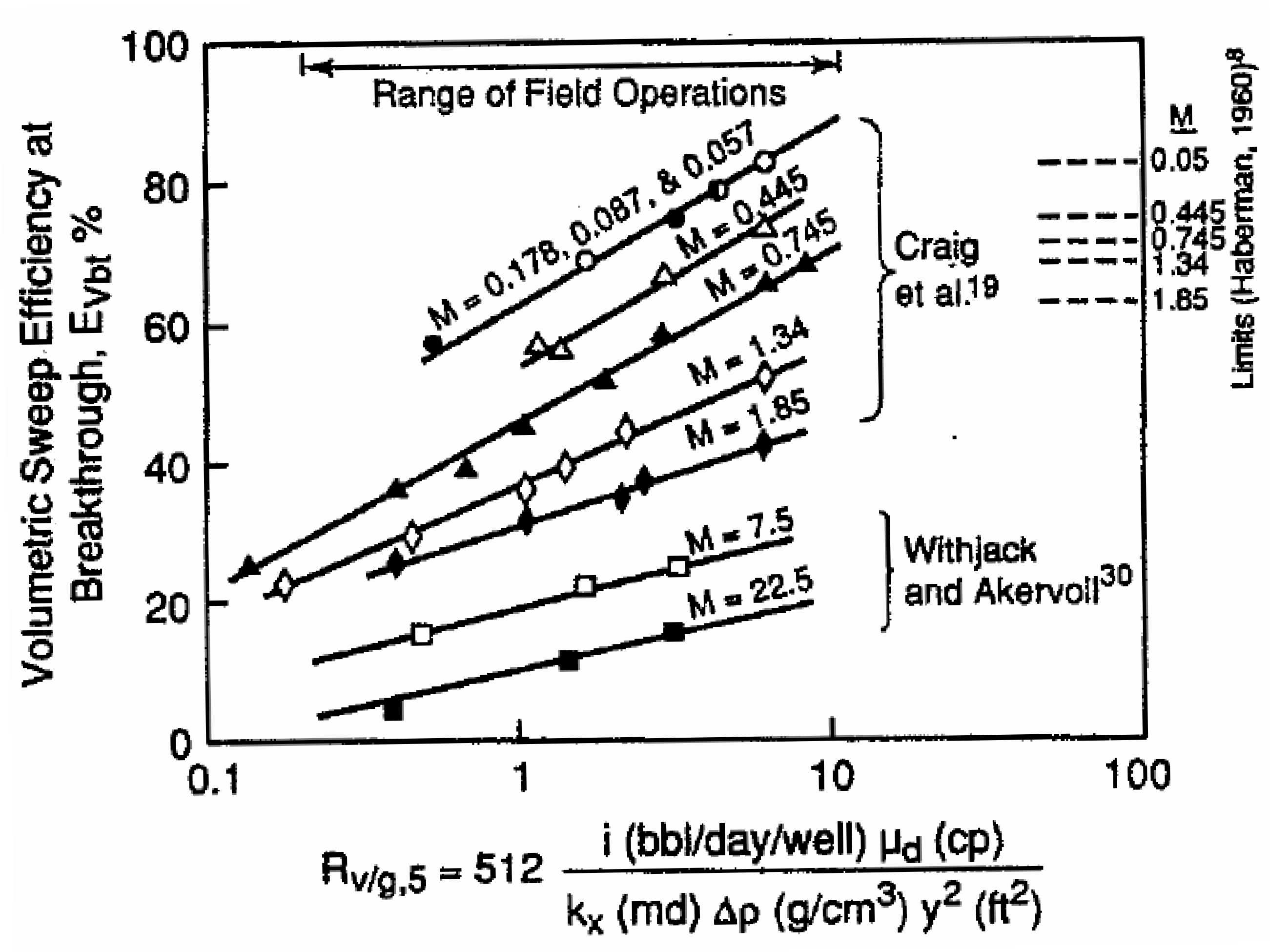
For other M

$$E_I = \frac{n_j + \frac{(n-n_j)M}{M-1} - \frac{1}{M-1}\sum_{k=j+1}^{n}\left[M^2 + \frac{k_k}{k_j}\left(1-M^2\right)\right]^{1/2}}{n}$$

Volumetric Efficiency

- Methods of estimating volumetric displacement efficiency in a 3D reservoir fall into two classifications.
- Direct application of 3D models
  - Physical
  - mathematical
- Layered reservoir model.
  - The reservoir is divided into a number of no communicating layers.
  - Displacement performance is calculated in each layer with correlations of 2D.
  - Performance in individual layers are summed to obtain volumetric efficiency

Volumetric Displacement Efficiency



Calculation of volumetric sweep with Numerical Simulators

Dynamic study: before and after history matching

Example

* production data
initial model — current model