Note Title 8/27/2018

"RESERVOIR"

1. Geologic & Petrophysical
   - * Barriers
     - To Vertical Flow
       - $k_v$ low $\Rightarrow 0$ "shaly" (& other types)
     - To Areal Flow
       - Faults ($T_F = 0 \rightarrow 0 \quad > 0$)
       - Stratigraphic (pinchouts)

   Defines RFUs
   - Depl.
   - EOR

   - * Spatial Variation of Rock (& Fluid) Properties

Mapping
Well bore logs
Petrel
Geostatisticians

- $\underbrace{k_z \quad k_x \quad k_y}_{f(x,y,z)}$ Anisotropy in all direction

Core
$k_h(\phi)$
$k_v(\phi)$


- $\phi(x,y,z)$
- $S_w(x,y,z)$

$S_{HC}(x,y,z) = 1 - S_{wc}$ ← connate ("initial")

└ Henning Omre, NTNU

# ② FLUID "SYSTEMS" & "PROPERTIES"

TPG4145

## Fluid Systems

- Reservoir "Gas" (RG) $RF_g \propto (p_{R\,abandonment})$
  (Dry & Wet)

- Reservoir "Oil" (RO) $p_{Ri} \geq p_b$ } $p_b(x_{Ri}(Z, X, Y_i; T_R))$

- Aquifer (AQ)
  - Transition Zone ($Z < Z_{FWL}$

    $S_w$ from 100% to $k_{rw} \sim 0$

    $p_w = p_o$

    Free Water Level "(OWC / GWC)"

    Shallowest Z where $S_w = 100\%$
    "OWC, GWC"

  - Below FWC "Paleo" Zone

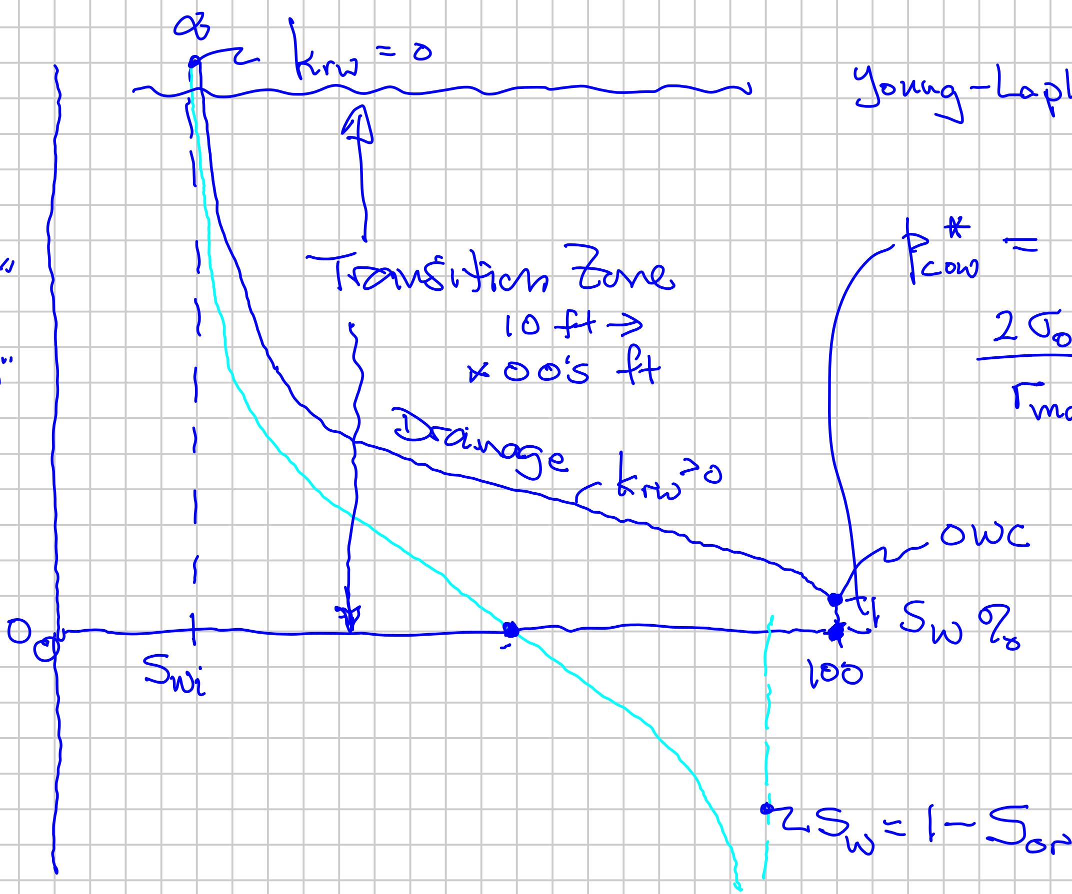
    $k_{ro} \sim$ low $\rightarrow 0$

$P_{cow} = p_o - p_w$

or

Depth "k" "PSD"

$= \dfrac{P_{cow}}{(\rho_w - \rho_o) g}$




Young-Laplace

$P^*_{cow} = \dfrac{2\sigma_{ow}}{r_{max}}$

Transition Zone : $\left[ k_{ro} > 0 \text{ \& } k_{rw} > 0 \right]$ $k_{ro} = 0$

$k_{ro} \approx 0$ to $k_{rw} \approx 0$

— RG ("Gas Cap") & RO ("Oil Rim" Zone)

- Saturated Fluid System

  Gas-Oil Contact transition $p_{R,GOC} = p_{d,GOC} = p_{b,GOC}$

  Most "common" situation assumption

  RG in Gas Cap Uniform $y_{Ri} \sim \text{constant}(X, Y, Z)$

  RO in Oil Zone Uniform $x_{Ri} \sim$ —— " ——

  – May have a smaller gas-oil transition zone

$$\text{Depth} = \frac{P_{cgo}}{(\rho_o - \rho_g) g}$$

because usually $(\rho_o - \rho_g) > (\rho_w - \rho_o)$

$$P_{cgo}(S_o) < P_{cow}(S_o)$$

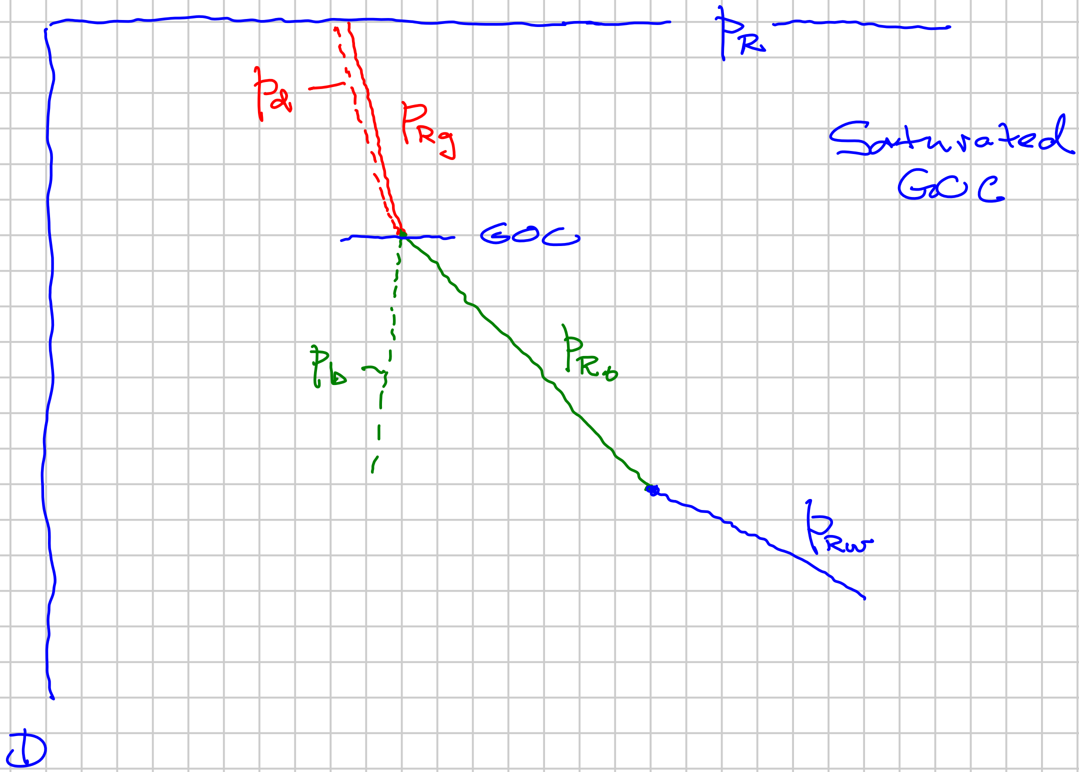
Lab $P_{c\,air\text{-}w}$ $\Rightarrow$ $(P_{cgo})_R = P_{ca\text{-}w} \cdot \dfrac{(\sigma_{go})_R}{(\sigma_{a\text{-}w})_L}$

$(\sigma_{ow})_R \sim 40 - 20$ mN/m

$(P_{cow})_R = P_{ca\text{-}w} \cdot \dfrac{(\sigma_{ow})_R}{(\sigma_{a\text{-}w})_L}$

$(\sigma_{go})_R \sim 40 \to < 1$

70 mN/m




Undersaturated Gas-Oil Contact


Strong Compositional Variation with Depth $z_{Ri}(Z)$ substantial

Final Eq. is reached by molecules moving around to minimize total energy.

no force field

Chemical Energy $\mu_i$

Molecular Diffusion $q_i = D_i \left( \frac{d\mu_i}{dZ} \right)$

Eq. reached $q_i \Rightarrow 0$

In force field $a$ = const.

$$\phi_i = \mu_i + M_i \, a \, \Delta Z$$

$$q_i = D_i \left( \frac{d\phi_i}{dZ} \right) \Rightarrow q_i = 0$$

Muskat 1930s : $\mu_i \simeq$ simplified liquid model

Sage Lacey 1937 : $\mu_i \sim$ more rigorous model

⋮

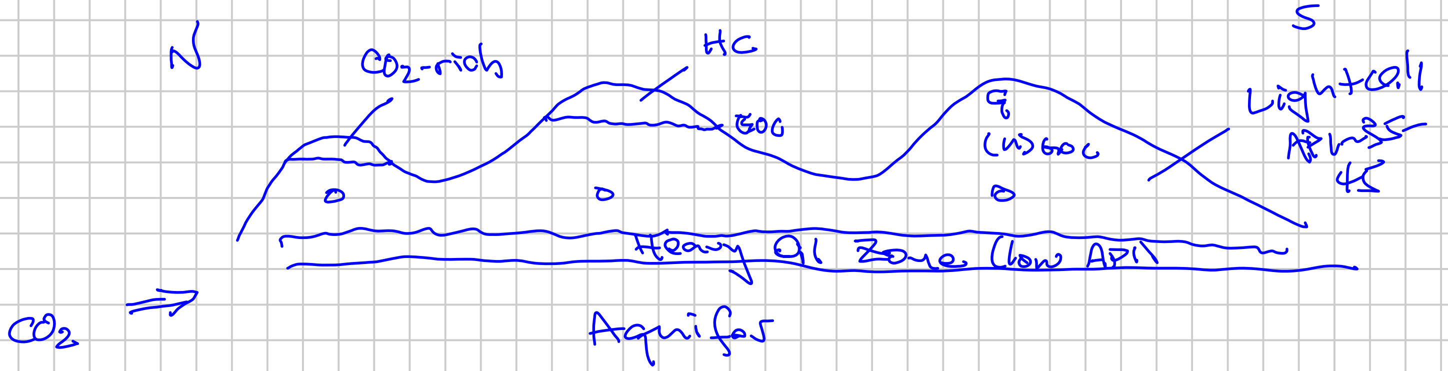
1980 : Tom Schulte (Shell)

$z_{Ri} \left( Z ; \mu_i^{\text{Cubic EOS}} \right)$

- Brent Field
- Birba Oman

- Non-Equilibrium Fluid Systems

Italy Val d'Agri


N
S
CO2-rich
HC
GOC
(?) GOC
Light oil
API ~35-45
Heavy Oil Zone (low API)
Aquifer
CO2

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# CONVENTIONAL vs UNCONVENTIONAL RESERVOIRS

## CONVENTIONAL

| RESERVOIR TYPE (Name) | ROCK | FLUID |
|---|---|---|
| 1. GAS (Dry \| Wet \| "Retrograde" Gas Condensate) | (1) $k > 0.1 - 1$ md (0.01) | |
| 2. OIL | "C" | $\mu < 100$ cp |
| 3. GAS + OIL | (2) $1-\phi$ | |

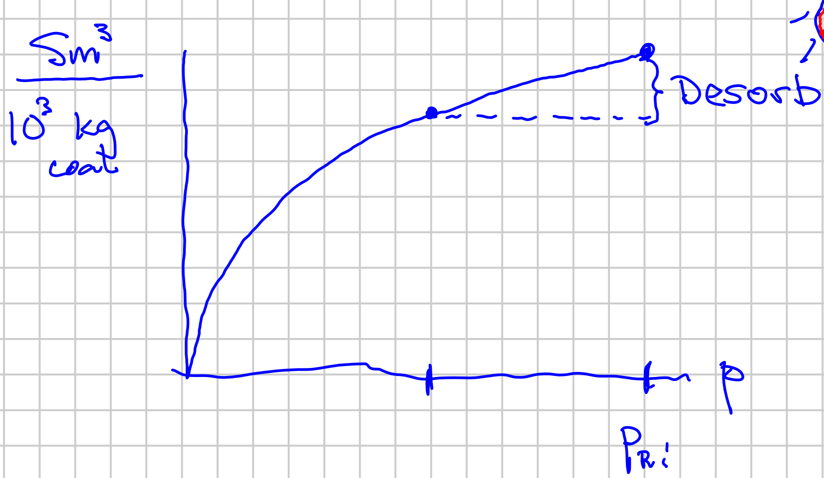
"High" Mobility $= \frac{kh}{\mu}$ ($\lambda h$)

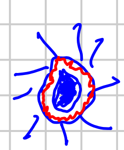
## UNCONVENTIONALS

| | | | |
|---|---|---|---|
| 1. HEAVY OIL (SAGD) | $p_{Ri}$ low | $1-\phi$, $k > 1000$ md | $\mu_o \gtrsim 1000$ cp "U" $\downarrow$ 10 |
| 2. Tight / Ultra-Tight (Shale) | $p_{Ri}$: high | "U" $k < 0.001$ $\rightarrow 10^{-5}$ md | $\mu_o < 1$ cp Shale Gas - Sorbed Gas |
| 3. Naturally Fractured | | $2-\phi$ "U" $k_m \sim 0.01-10$ md | $\mu \lesssim 10$ cp |

$$\frac{\phi_m}{\phi_t} = 90-99\%$$

4. Coal Bed Methane (CBM)



Adsorbed Methane

U

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# RECOVERY FUNDAMENTALS

$\underbrace{\text{Depletion} \mid \text{EOR}}_{\text{IOR}}$

STB Sm³

N/HCPV

RB m³

## DEPLETION

- Initial Reservoir Pressure — $p_{Ri}$
- PVT {
  - Initial Solution OGR (GOR)
  - Initial "Oil FVF" ($\bar{B}_{oi}$ (RO) or $r_{si}/B_{gdi}$ (RG)) } N/HCPV G/HCPV — $r_{si}$ $R_{si}$ — STB/RB HCPV
- Total Water Volume (AQ, NGR, $S_{wc}$)
- PVT : Oil $c_o$ | Oil Shrinkage; Gas $c_g$ ($B_g$) } $\mu$
- LNX (# RFUs) Contrast in RFU "D" = $\left[\left(\frac{kh}{8+s}\right)\Delta p / HCPV\right]_{RFU}$
- Rock Compressibility ("high" $p_{Ri}$)
- Gas-Oil Relative Permeabilities (RO SGD) — Solution Gas Drive

# EOR

① – Volumetric Sweep ("Conformance")
"Macroscopic" Sweep

• Vertical (layering) $k_h(Z)$, gravity ($k_v(Z)$)

Orders of magnitude variation $k_h(Z)$

• Areal

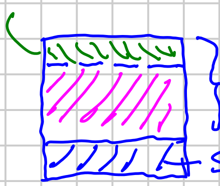
- Well placement ("pattern")
- Well type
- ( $k_x$ $k_y$ anisotropy)

② Microscopic Sweep
"Pore-Level" — " —

In the volumetrically swept volume

Residual Oil + $S_{or}$ where $k_{ro} \to 0$

Injectant →



$S_{HC}$ ($S_o$)

$S_{wc}$

Buckley-Leverett 80% $S_{oi} = 1 - S_{wc}$
1942

at BT Inj $\boxed{50\%}$ $S_{of}$. > $S_{orw} = 25\%$

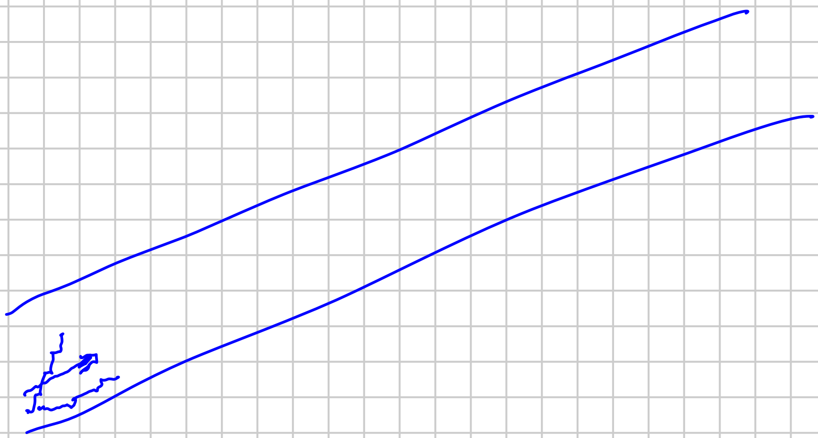
Keep Injecting Many (∞) PVs

$S_{orw}$.

• Oil-Water wettability
• Pore size distribution ($k_{rw}$ & $k_{ro}$)

- Gravity $v_z$ strong

$S_{oi} \rightarrow S_{or}$



(a) BL: Immiscible, Equilibrium $S_{oi} \rightarrow S_{of} \rightarrow S_{or}$
O-W O-G

(b) Non-Equilibrium Gas-Oil Displacement (Complex PVT)

Pore-Level

$RF_o = 100\%$

- Develop "Miscibility" $S_{org} \rightarrow 0$ 100% RF microscopic
  - Vaporizing Gas Drive (VGD)
    - Gas Inj in a Gas Condensate R
    - Gas Inj in an Oil R, (10%)
      - High $p_{inj}$, Light Oils, Lean $C_1$-rich inj gas
  - Condensing/Vaporizing Gas Drive (90%)
    Aaron Zick 1986
- Immiscible (Swelling | Vaporizing)
  $S_{org}$ from $(S_{org})_{Eq.Gas}$ → 20 10 0%
  25% BL

  Many PVs of gas passing over the oil