Naturally Fractured Reservoirs

PRODUCTION MECHANISM OF A FRACTURED RESERVOIR

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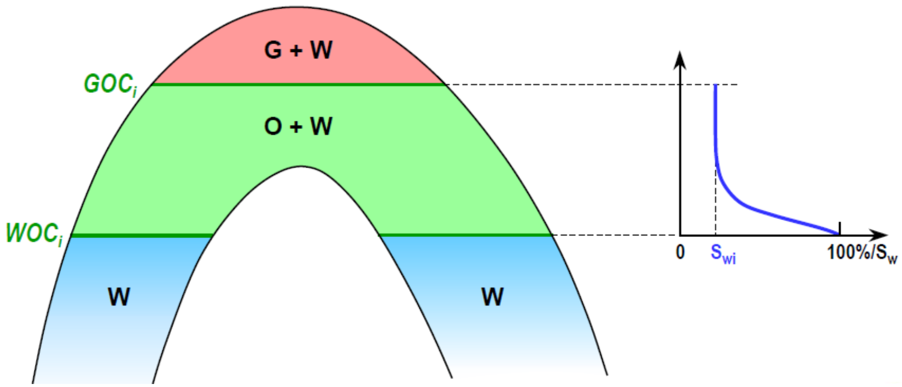
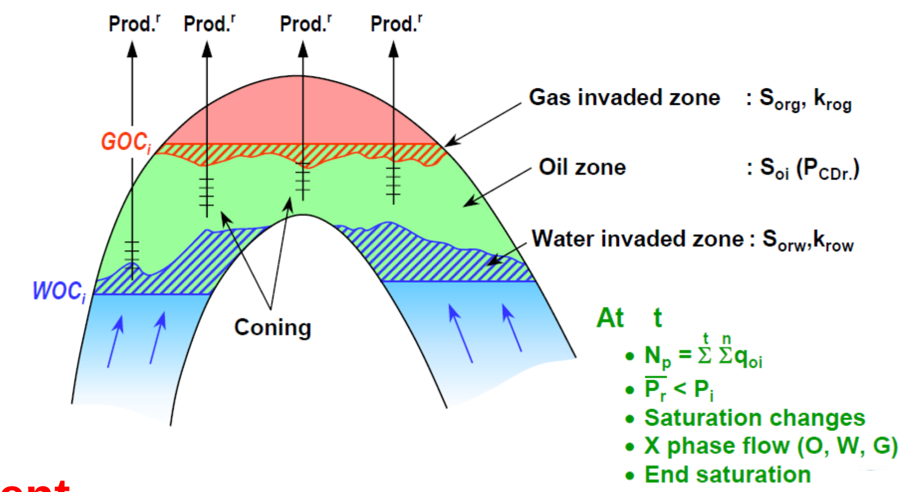
Production Mechanisms of a Conventional Oil Reservoir

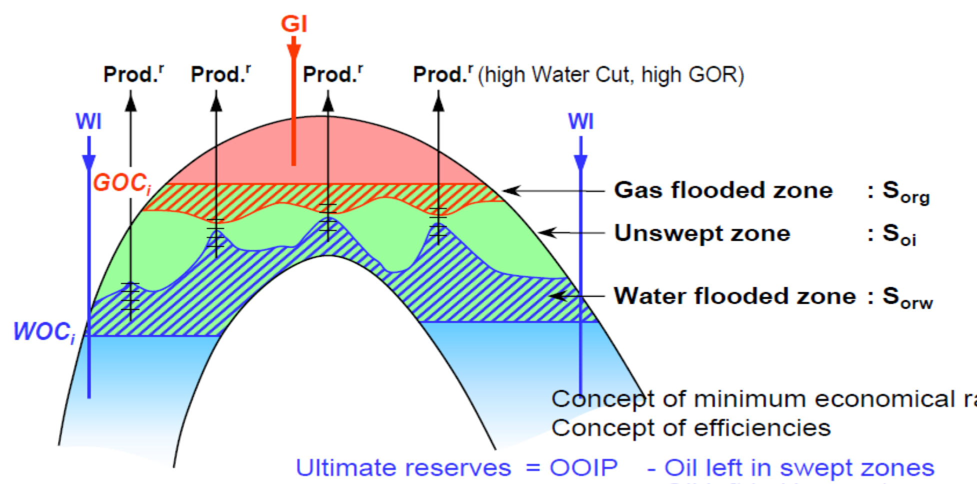
Initial Conditions



During Development



Abandonment



Concept of minimum economical rate
Concept of efficiencies

Ultimate reserves = OOIP - Oil left in swept zones
- Oil left in Unswept zones
= $N_1 + N_2 + N_3$

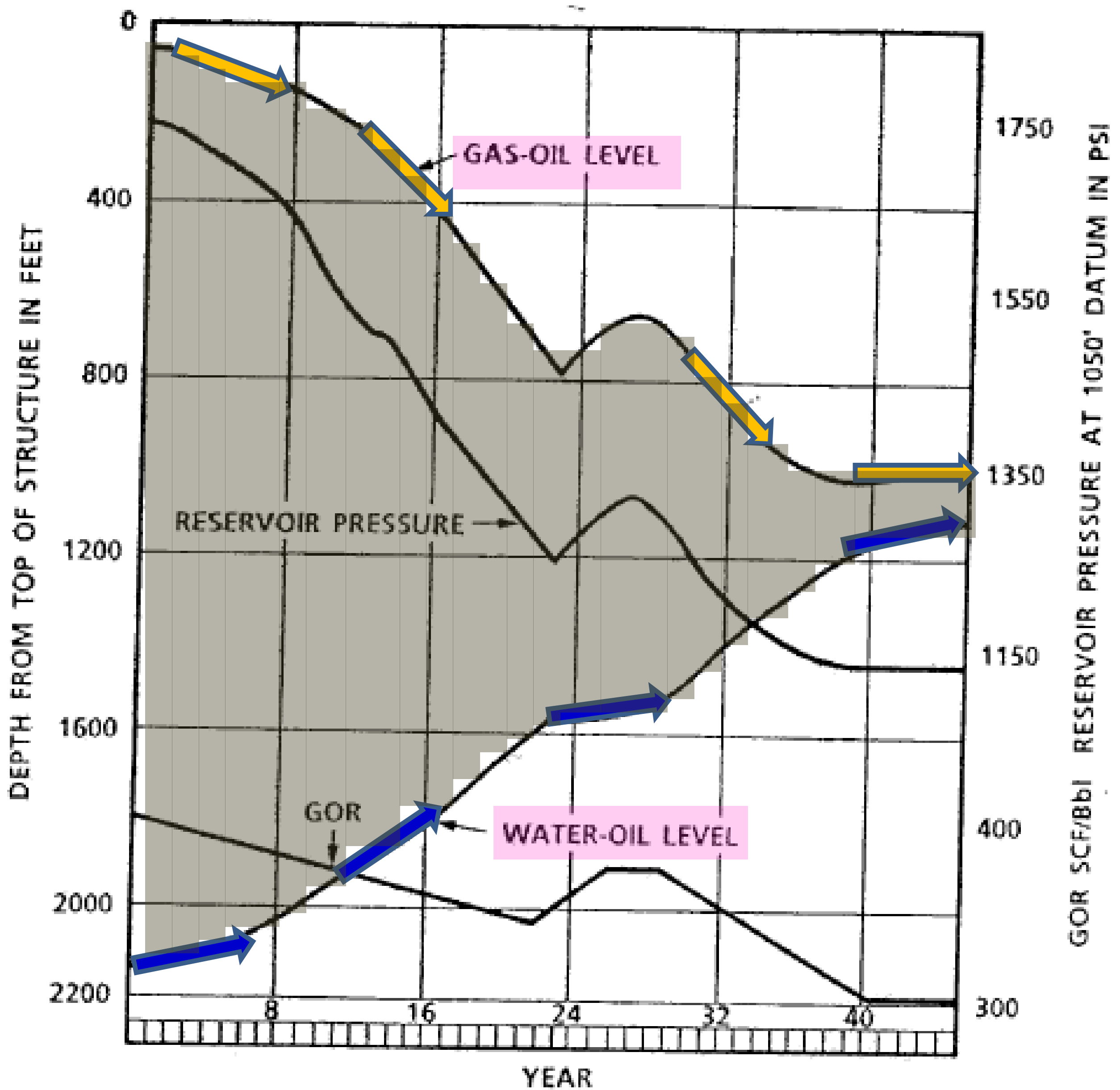
Natural Depletion Recovery for a Conventional Reservoir

- **Natural Depletion**
  - IMPLEMENTATION : Just open the well
  - PERFORMANCES :P_R, Rates (Oil, Gas, Water, or GOR, WOR) versus time
  - LIMITATIONS : - Pressure decline (economical rate) - Limiting WC- Limiting GOR

- **Natural Depletion Recovery Mechanisms**
  - Rock and fluid expansion
  - Solution gas drive
  - Gas cap expansion
  - Natural water influx
  - Gravity drainage
  - Combination drive

Conventional vs. Fractured reservoirs

- ❑The reservoir gas-oil ratio, GOR us. Recovery
- ❑The rate of pressure decline per unit of oil produced
- ❑The absence of transition zones in a fractured reservoir
- ❑Pressure drop around a producing wellbore in a fractured reservoir is very low
- ❑The free-water oil production in a fractured reservoir is essentially a function of production rate
- ❑Constant PVT properties with depth



0
400
800
1200
1600
2000
2200
DEPTH FROM TOP OF STRUCTURE IN FEET
GAS-OIL LEVEL
RESERVOIR PRESSURE
GOR
WATER-OIL LEVEL
8
16
24
32
40
YEAR
1750
1550
1350
1150
400
300
GOR SCF/Bbl
RESERVOIR PRESSURE AT 1050' DATUM IN PSI

Reservoir Description During Depletion

- Static Zonation: Before reservoir production begins (GOC, WOC)

- Dynamic Zonation:
  - It will result from reservoir production conditions during field exploitation
  - continuously changing during reservoir production due to:
    - the exchange of matrix-fracture fluid,
    - fluid segregation in fractures,
    - changes in phases provoked by gas liberation,
    - fluid produced from reservoir.

- Fracture zoning: Fracture network practically saturated with only one phase

- Matrix zoning: The matrix block may be saturated with one, two or even three phases.

- The matrix-fracture interaction and fluid exchange will depend on the relative position of the single block in the reservoir and the respective water-oil and gas-oil contact.

Reservoir zoning- Dynamic Conditions

(a): Zone distribution
(b): Pressure distribution
(c): Matrix saturation distribution

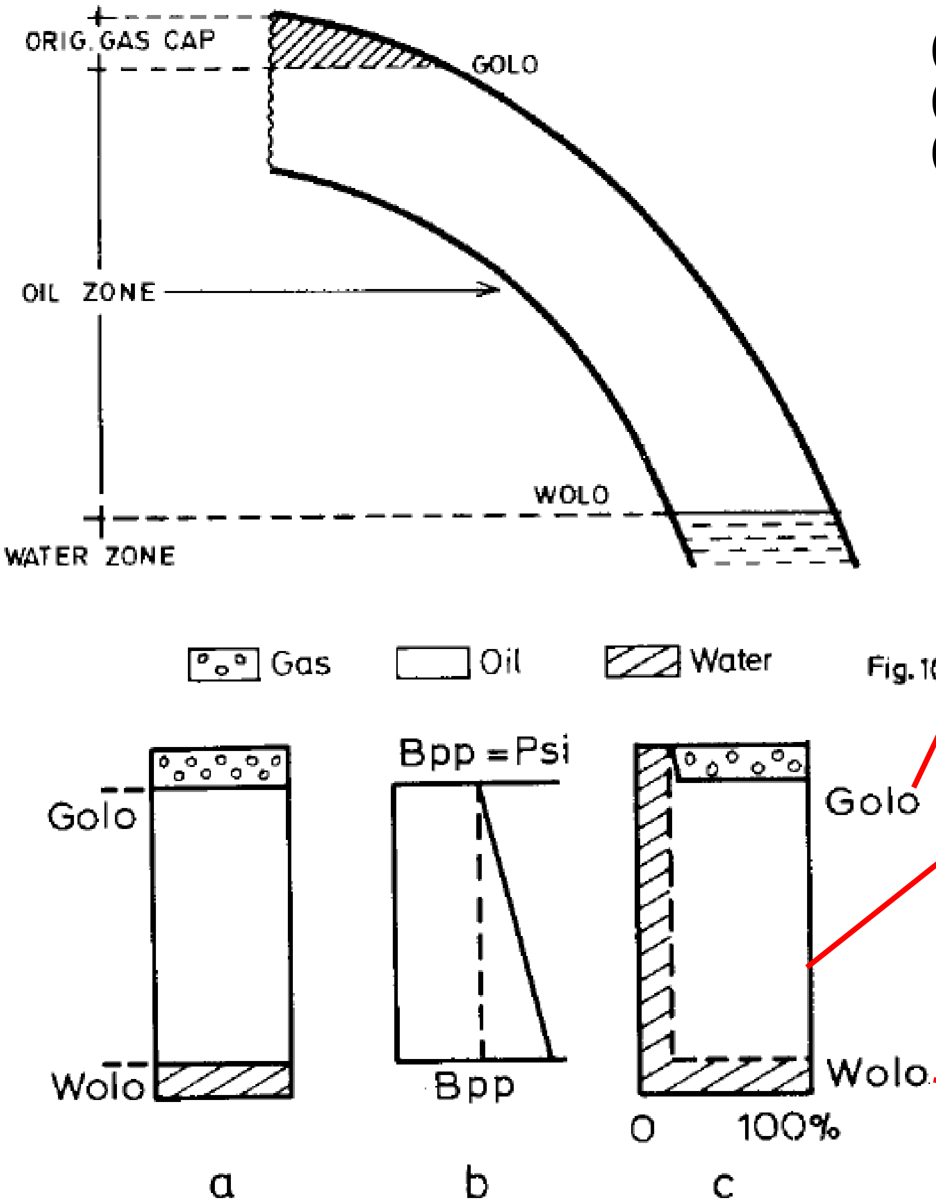
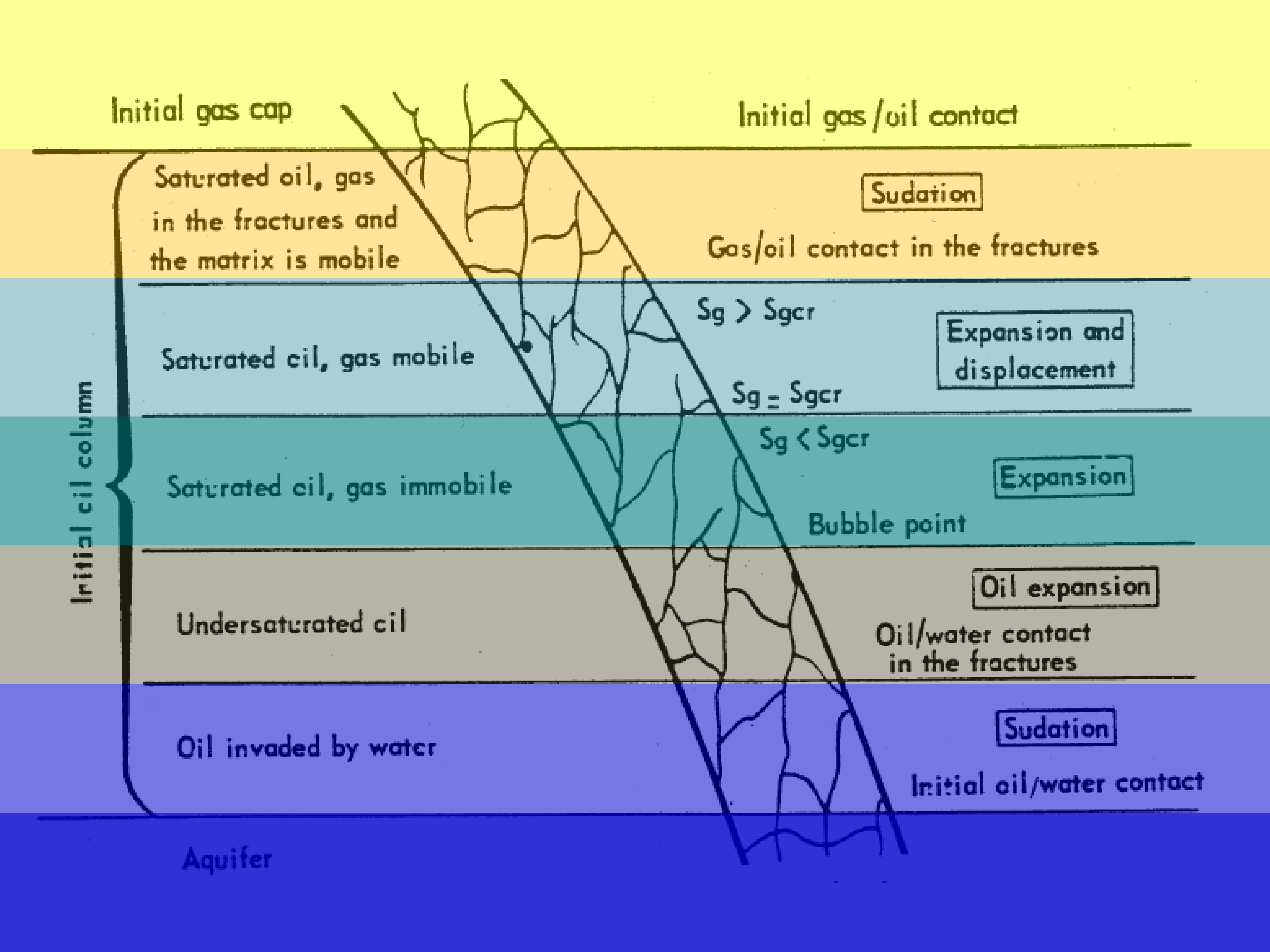


Fig. 10.6

Above GOLO, gas saturates the fractures, and gas with interstitial water saturates the matrix.

between WOLO and GOLO the matrix blocks are saturated with oil and interstitial water and the fractures with oil only

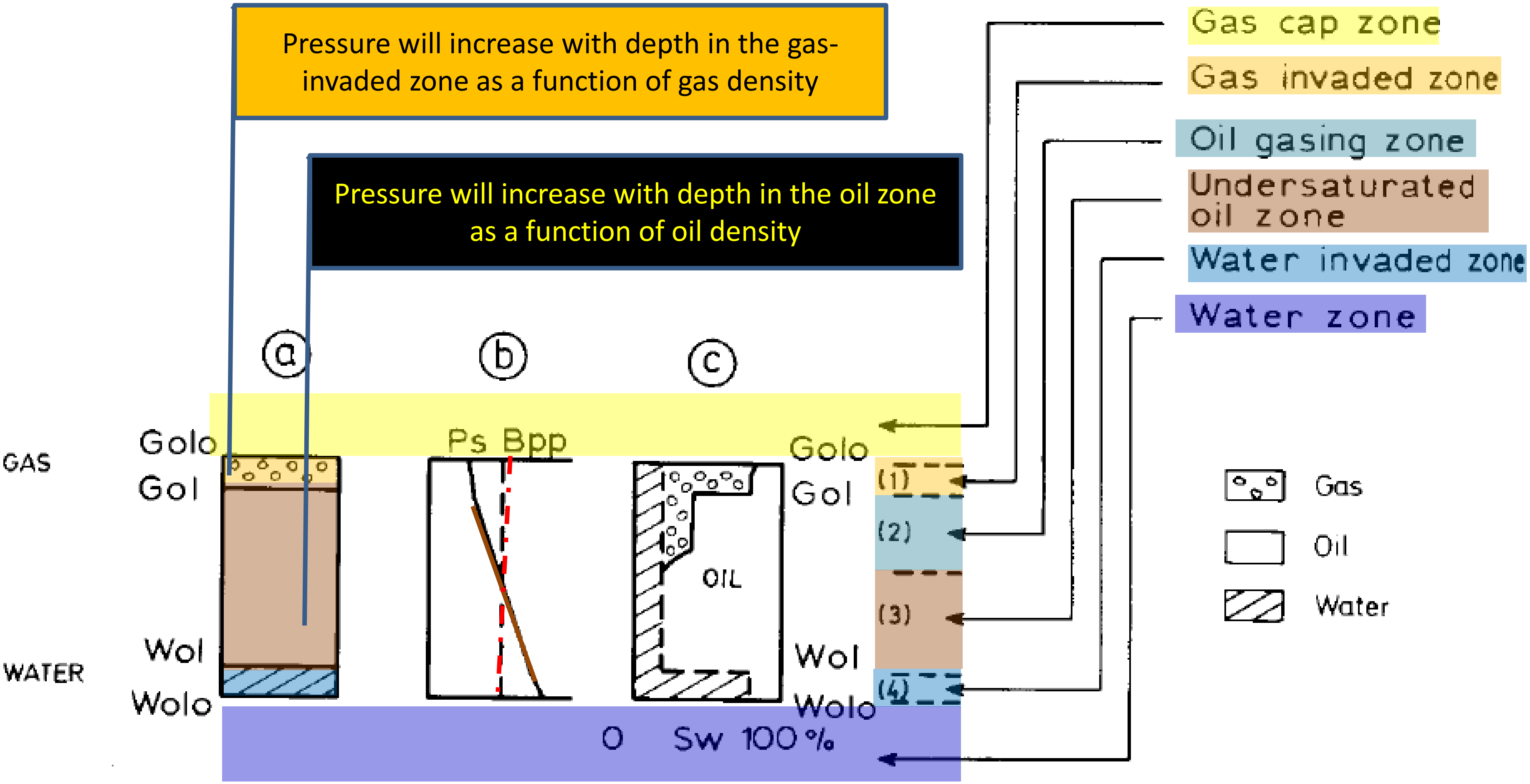
Below WOLO the matrix pores are saturated with water



Initial gas cap
Initial gas/oil contact
Saturated oil, gas in the fractures and the matrix is mobile
Sudation
Gas/oil contact in the fractures
Sg > Sgcr
Saturated oil, gas mobile
Expansion and displacement
Sg = Sgcr
Sg < Sgcr
Initial oil column
Saturated oil, gas immobile
Expansion
Bubble point
Oil expansion
Undersaturated oil
Oil/water contact in the fractures
Oil invaded by water
Sudation
Initial oil/water contact
Aquifer

Reservoir zoning- Dynamic Conditions

In oil gasing zone: $P_s < B_{pp}$



(a): zone distribution through fluid contact in fractures

(b): pressure vs. depth in reservoir and relationship P_s vs. B_{pp}

(c): Matrix saturation distribution

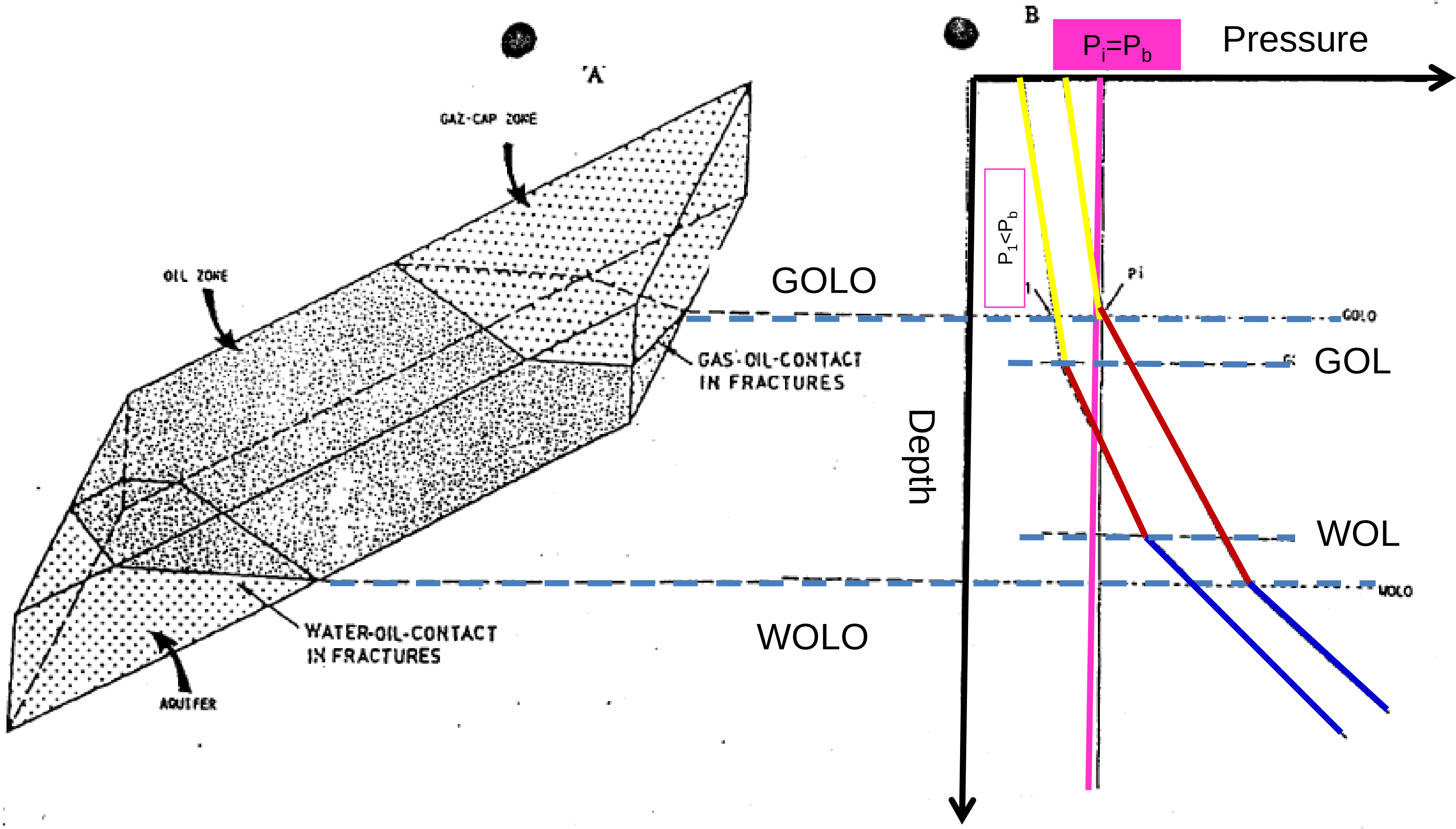


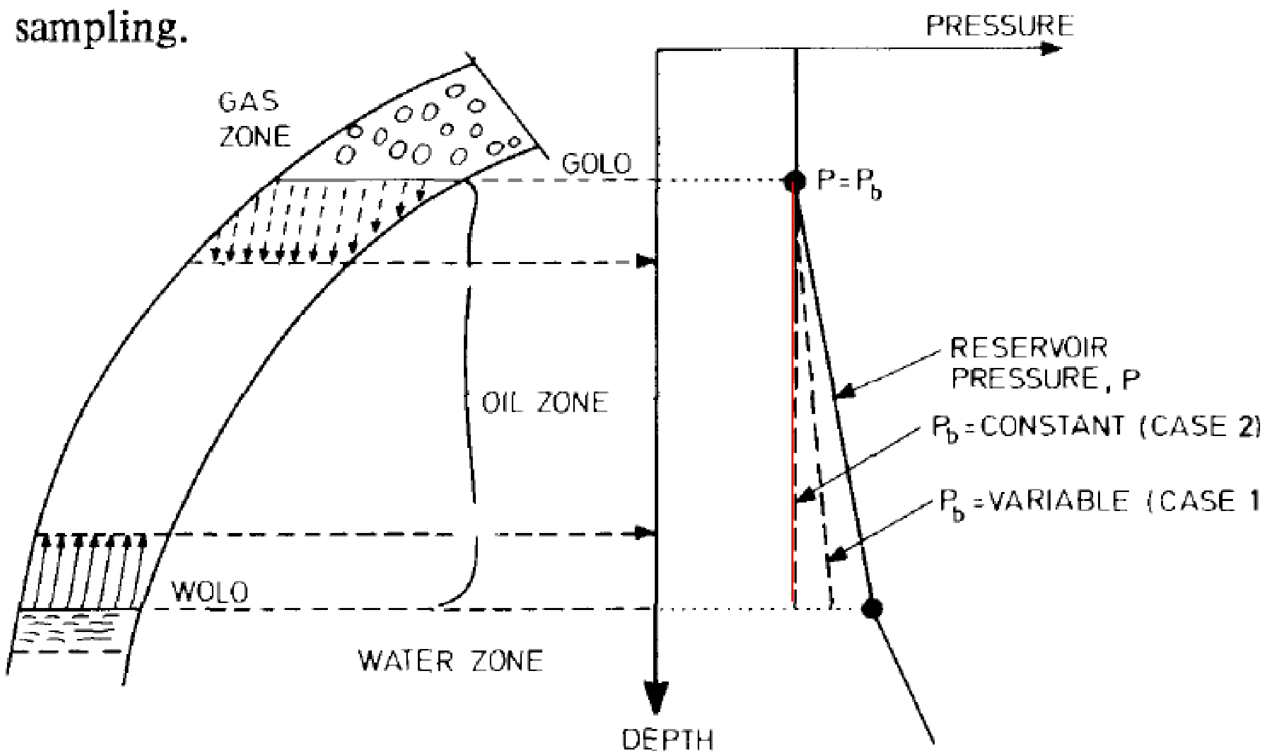
Fig 67 Fractured reservoir initial distribution of the three zones : gas-cap ,oil zone and water zone a) zones controlled by original limits GOLO and WOLO b) pressure distribution (continuous line) in the three zones @ initial conditions (P_i $=P_B$) ;pressure distribution (dotted line) after pressure depletion @ $P_1 < P_i = P_B$

Constant PVT properties with depth
Oil Circulation and Implications on PVT Properties

❑At the original gas-oil contact level (GOLO) the **reservoir pressure** is equal to the **saturation pressure**; but below this level the saturation pressure may either in:

1. vary with depth (as in a conventional reservoir), or in
2. remain constant along the entire oil column (typical for a fractured reservoir having a very good intercommunicating fractured network).

sampling.



- The constant value of $\mathbf{P_b}$ with the depth is the result of a convection process inside the reservoir due to the combined effect of pressure and the thermal gradient in a fractured reservoir.
    1. Oil contracts under the influence of increasing pressure
    2. Oil expands under the influence of the increasing temperature

- Thus, for a given system, a state of disequilibrium may develop if the expansion, resulting from the increase of temperature with depth, is counter-balanced by the contraction, due to the increase of pressure with depth.
- As a result, a further convection process may develop inside the reservoir, causing the heavier oil from the upper part of the reservoir to move rapidly through the fractures towards the lower part, while the light oil of the lower part of the reservoir moves upwards.
- A homogeneity of PVT properties with depth will be the result of this continuous fluid circulation throughout the fracture network. This process needs an excellent intercommunication between fractures over the entire reservoir. Otherwise, a segregation process of oil will take place along the reservoir depth, and consequently, a variation of PVT properties with depth.

Segregation vs. Convection of Oil in a Fractured Reservoir

❑The variation of the volumetric mass (in isothermal conditions) of a compressible liquid under the influence of a pressure variation (as discussed by Saidi and van Golf-Racht) is,

$$\delta_T = \delta_o e^{c\Delta P} \qquad (10.11)$$

❑The isobaric variation of the volumetric mass of a compressible liquid under a temperature variation is,

$$\delta_p = \delta e^{\lambda \Delta T} \qquad (10.12)$$

δ_T : volumetric mass under constant temperature
δ_p : volumetric mass under constant pressure,
c :the compressibility

Condition of Convection and Segregation

$$\begin{Bmatrix} \delta_p - \delta_T \text{ if positive} - \text{convection} \\ \delta_p - \delta_T \text{ if negative} - \text{segregation} \end{Bmatrix} \qquad (10.13)$$

c. Example

Considering the following temperature and pressure data in a reservoir,

$$\lambda = 6.4 \times 10^{-4}\ \text{vol/vol/°F}$$

$$C = 1.45 \times 10^{-5}\ \text{vol/vol/psi}$$

$$T_G = 0.02\text{°F/ft}$$

$$P_G = 0.3\text{psi/ft}$$

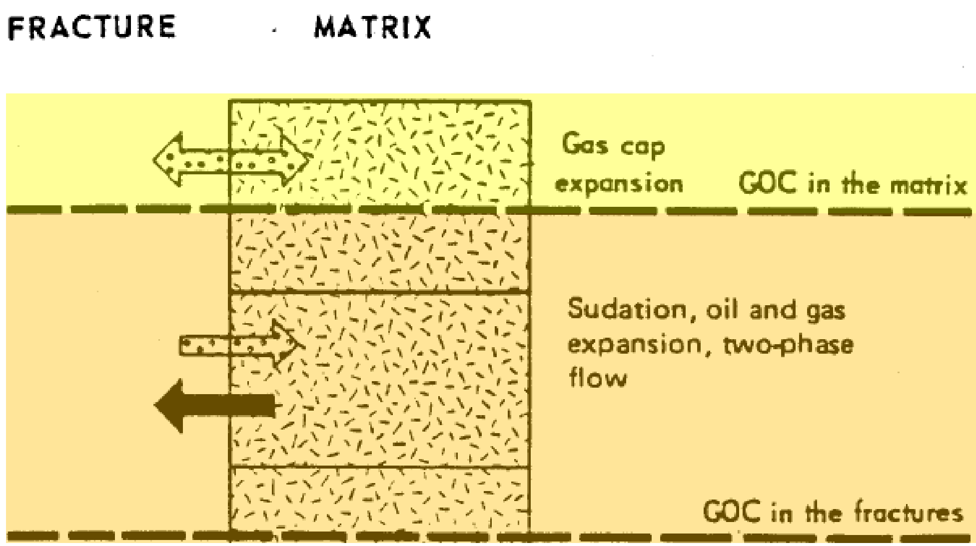
the result is,

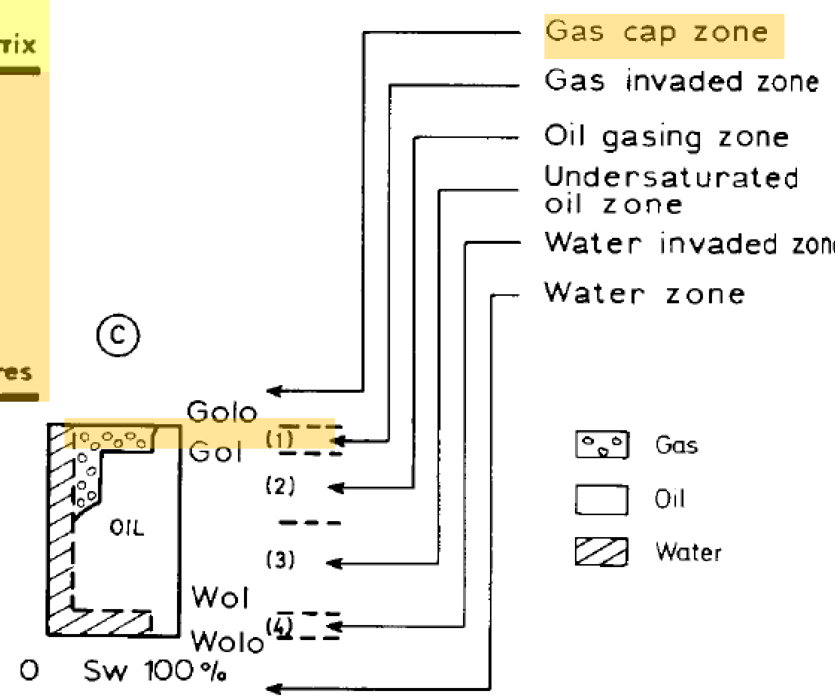
$$6.4 \times 10^{-4} \times 0.02 - 1.45 \times 10^{-5} \times 0.3 = 3.45 \times 10^{-5} > 0$$

Since the result is positive, the PVT properties are uniform and therefore, $P_b = \text{const}$ with the depth.

Gas Invaded Zone

- In the gas-invaded zone the gas saturation increases to a value equivalent to $S_g = 1 - S_{Wi} - (S_{or})_g$
- The magnitude of residual oil (S_{or}), depends on conditions of gas front advancement (figure 1 0 . 7c) and on specific characteristics of drainage displacement.



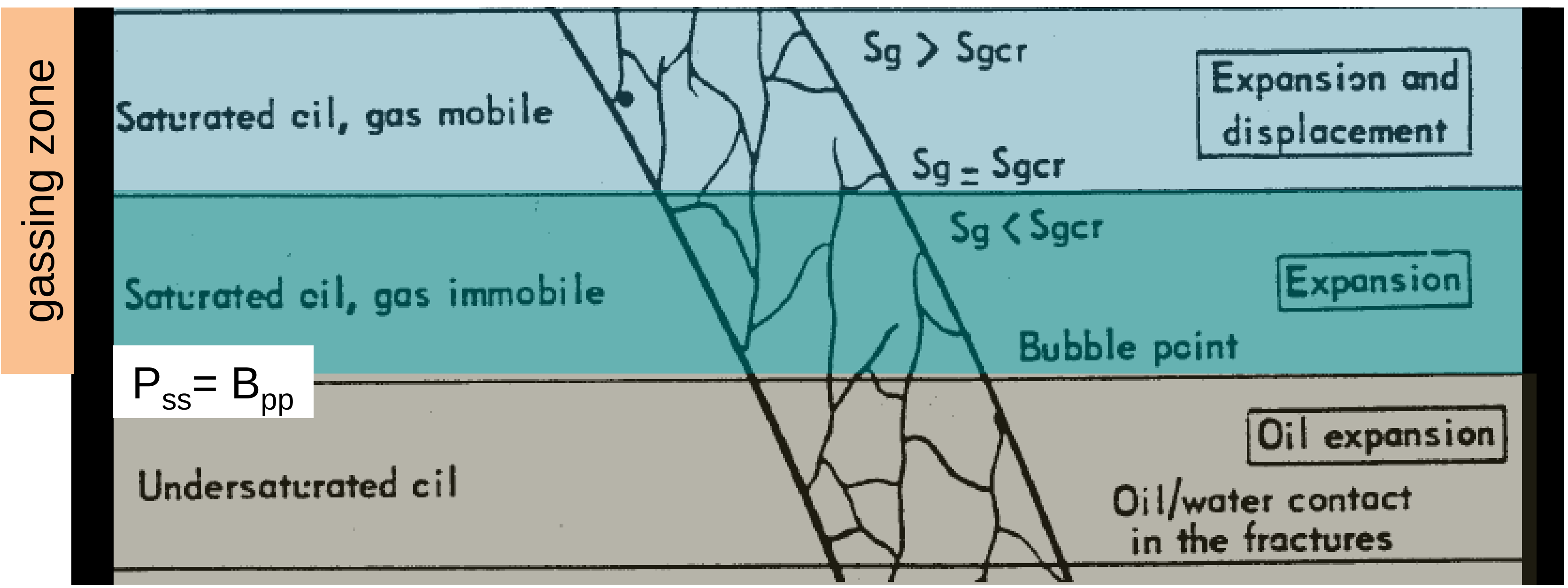


Oil Zone

Sub-zones between GOC &WOC

As a result of pressure variation with depth the oil zone may be divided into two

- the gassing zone, between GOL and $P_{ss}= B_{pp}$
- the under-saturated zone, between $P_s = B_{pp}$ and WOL

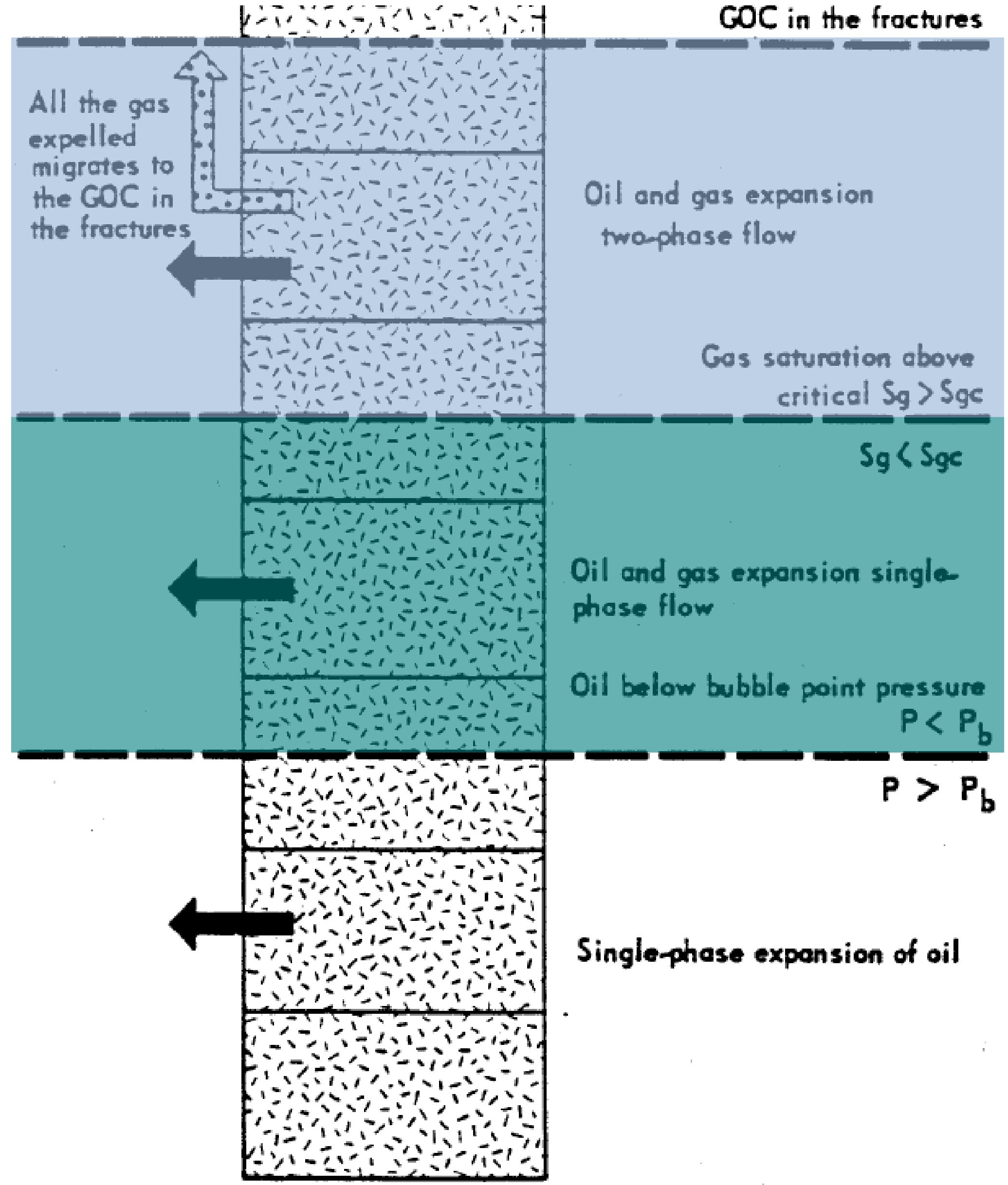


Oil Zone- Gassing Zone

- Because $P_S < B_{PP}$, a volume of gas will be liberated from the oil
- The driving mechanism will be influenced in this case by the presence of free gas in matrix blocks and in the oil saturated fractured network.
- The fluid interchange between matrix and fractures will become a complex process influenced by gravity and capillary pressures and developing phenomena of convection, super-saturation.
- The phenomena taking place in a fractured reservoir are substantially more complex than the equivalent solution gas drive in a conventional reservoir.

Oil Zone- Gassing Zone

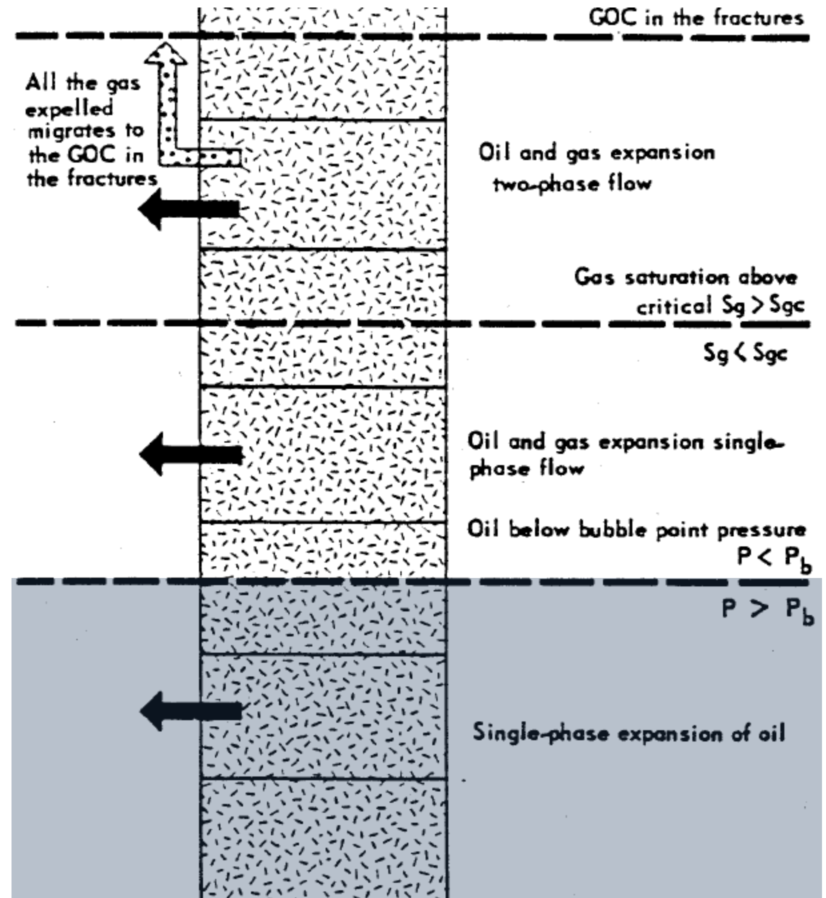
- In the oil gassing zone the saturation in gas corresponds to the oil recovered from the matrix as a result of reservoir pressure decline below bubble point pressure. The oil remaining in this zone at a given stage of reservoir depletion is expected to be substantially higher than the residual oil in the gas-cap zone.



Oil Zone- Under-saturated Zone

- As a result of reservoir pressure being higher than bubble point pressure ($P_s > B_{pp}$), the entire fracture-matrix system is saturated with only one movable phase, oil.
- The matrix-facture fluid interchange is the unique result of fluid expansion associated to reservoir depletion and compressibility of the fracture-matrix system fluids and rock.

- In the under-saturated oil zone only two phases - oil and interstitial water – exist since the gas has not yet been liberated from the oil

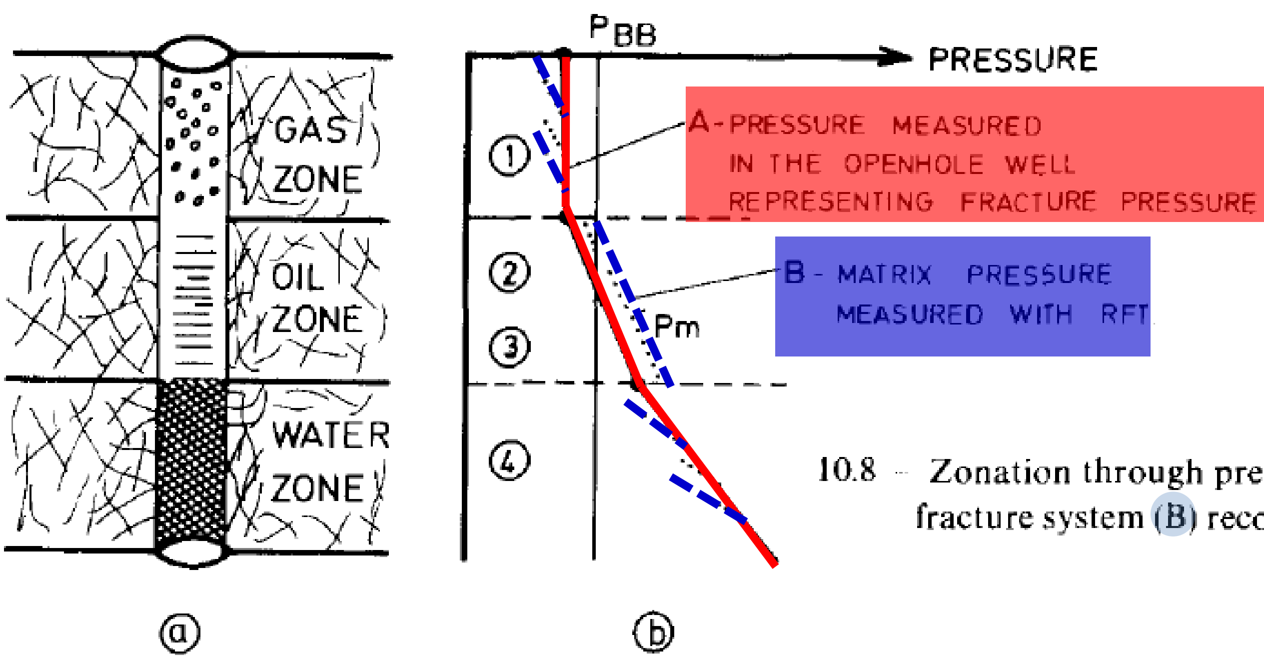


Water Invaded Zone

- In the water-invaded zone there is a saturation in water (interstitial and invaded) and a saturation in residual oil $(S_{or})_w$ as a result of imbibition displacement of oil contained in blocks by water saturating the surrounding fractures.

The Role of Fracture Pressure vs. Depth

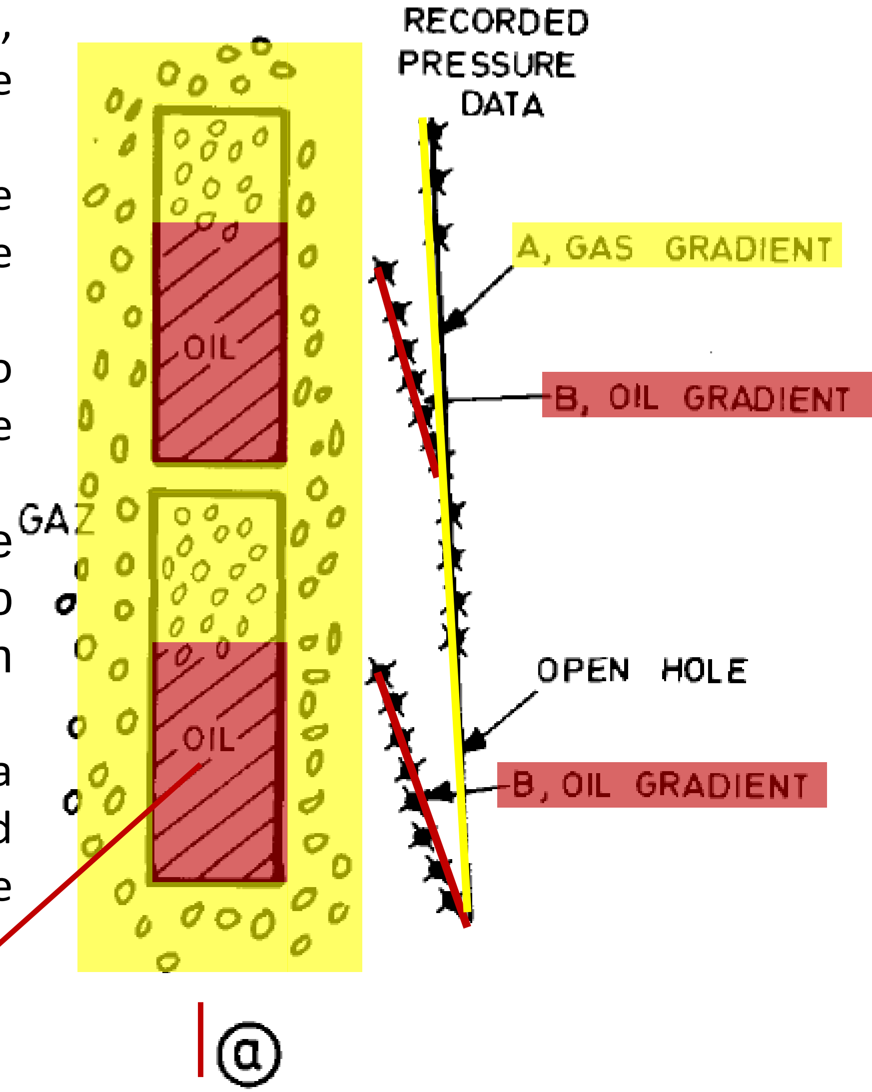
- Reservoir zoning may be continuously evaluated by pressure recording vs. depth in an open hole observation well.
- The four zones may be delimited if the pressure vs. depth variation (expressed by curve A in figure 10.8b) is associated with the bubble point pressure $\mathbf{B_{pp}}$.
- Matrix pore pressure: repetitor formation tester (RFT)
- Pore pressure (blue dashed line) deviates from line A (red line) as a result of local saturation distributions in each block



10.8 – Zonation through pressure data: (A) recorded in fracture system (B) recorded in matrix blocks.

Zoning vs. Pressure Distribution
blocks in the gas-invaded zone

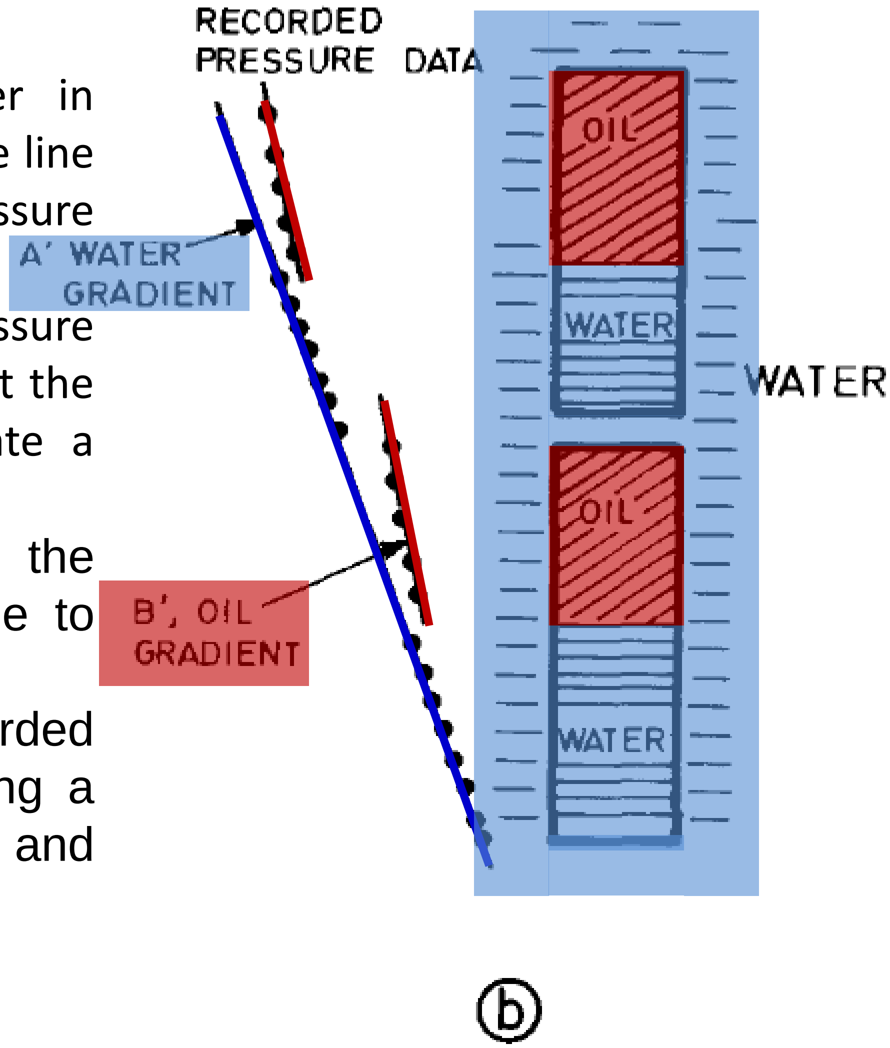
- ❑the matrix pore pressure will not stay on line A, and its deviation will correspond to the mobile phase gradient.
- ❑the upper part of the block will have the same pressure gradient as the gas saturating the surrounding fractures.
- ❑At any depth the difference between the two gradients indicates the limit of drainage displacement in the block.
- ❑In gasr-invaded zones, by means of the pressure gradients B, it becomes possible to evaluate the gravity drainage performance in situ.
- ❑A comprehensive analysis of the recorded data vs. time may also help in establishing a valid scaling factor between lab data and effective field behaviour data.



oil in the hold-up zone

Zoning vs. Pressure Distribution
blocks in the water-invaded zone

- ❑line A‘ represents the presence of water in fractures measured in the open-hole well, while line B’ represents the matrix intergranular pore pressure recorded by RFT.
- ❑Where water displaced the oil, the pore pressure and fracture have the same water gradient, but the non-displaced zone containing oil will indicate a pore pressure following the oil gradient.
- ❑In water-invaded zones, by means of the pressure gradients B', it becomes possible to evaluate the inhibition performance in situ.
- ❑A comprehensive analysis of the recorded data vs. time may also help in establishing a valid scaling factor between lab data and effective field behaviour data.



Zoning vs. Pressure Distribution

blocks in the oil zone (gassing and under-saturated zones)

- In the oil zone, the pressures of both gassing and undersaturated zones are less depressed than fracture voids.
- in the undersaturated zone the difference in pressure $\Delta P = P_m - P_f$ generates the oil production by single phase expansion mechanism (Fig. 10.8b, zone 3)

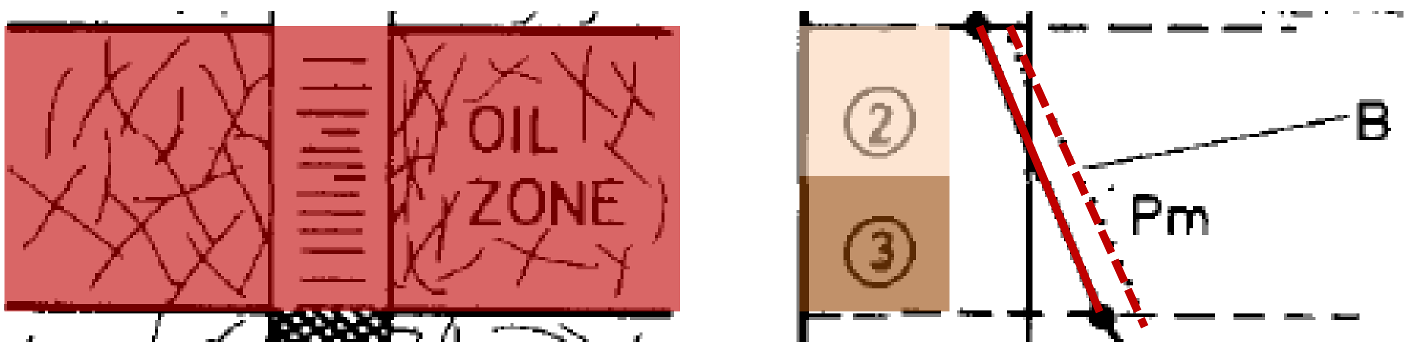
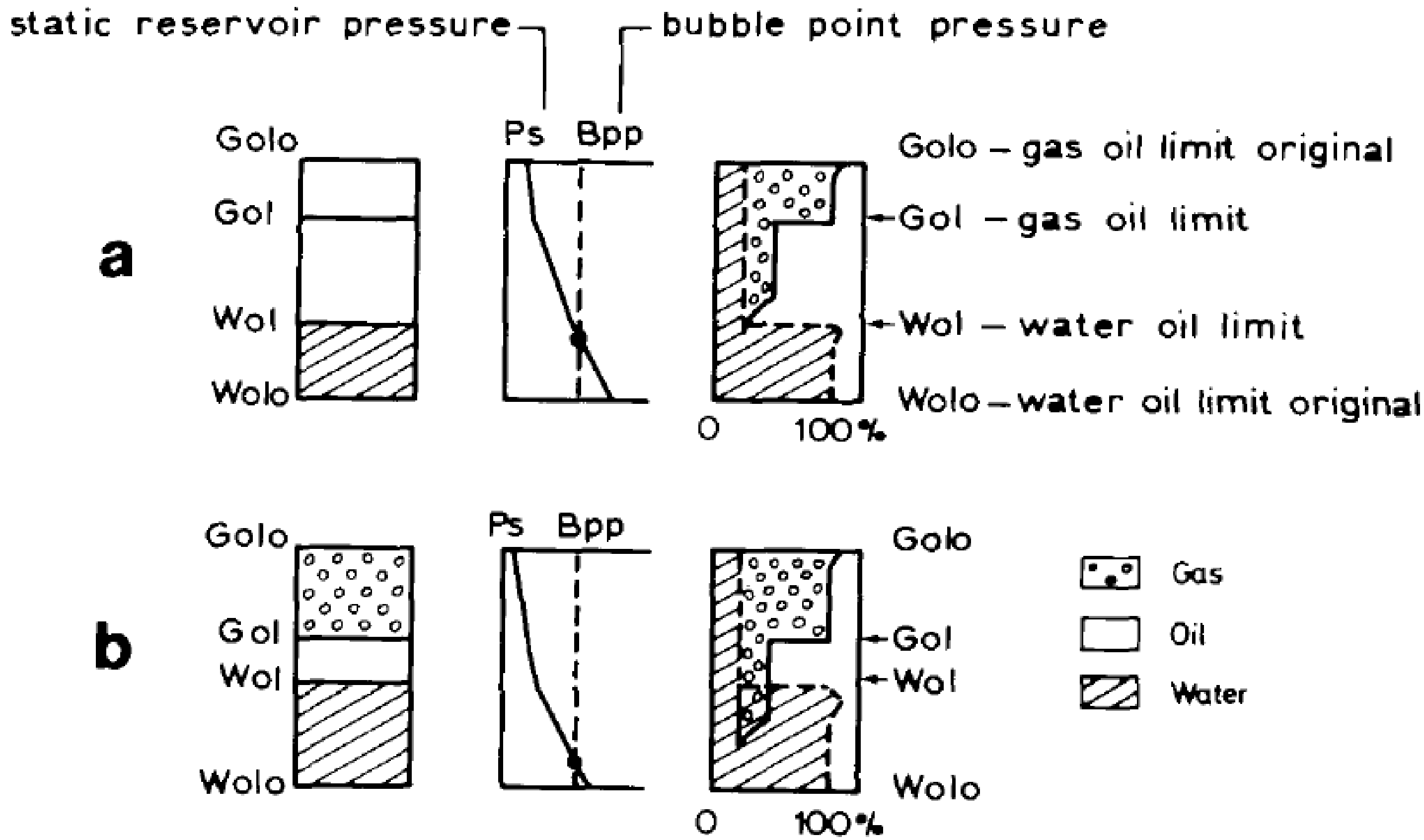


Fig. 10.8b

Zoning at a Late Stage of Reservoir Depletion

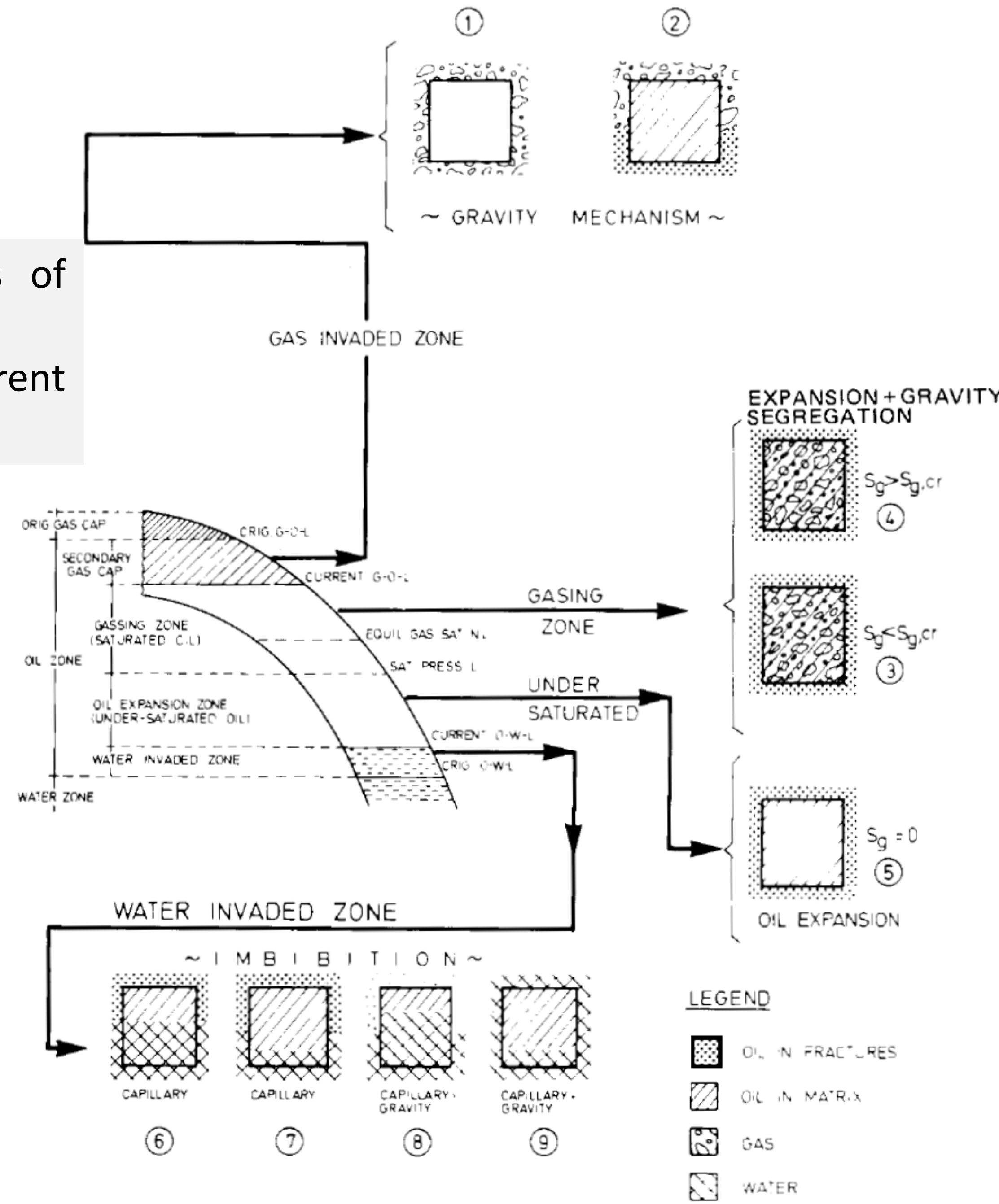
In an advanced stage of reservoir production (figure 10.10 a and b) a superposition of zones becomes possible especially if the reservoir height is not very significant. A stage may be reached when reservoir pressure is below B,, in the water-invaded zone



10.10 – Zonation at later stage of depletion: a) before and b) after the interference of gas-cap invaded zone with water-invaded zone

RESERVOIR ZONING VS. PRODUCTION MECHANISM

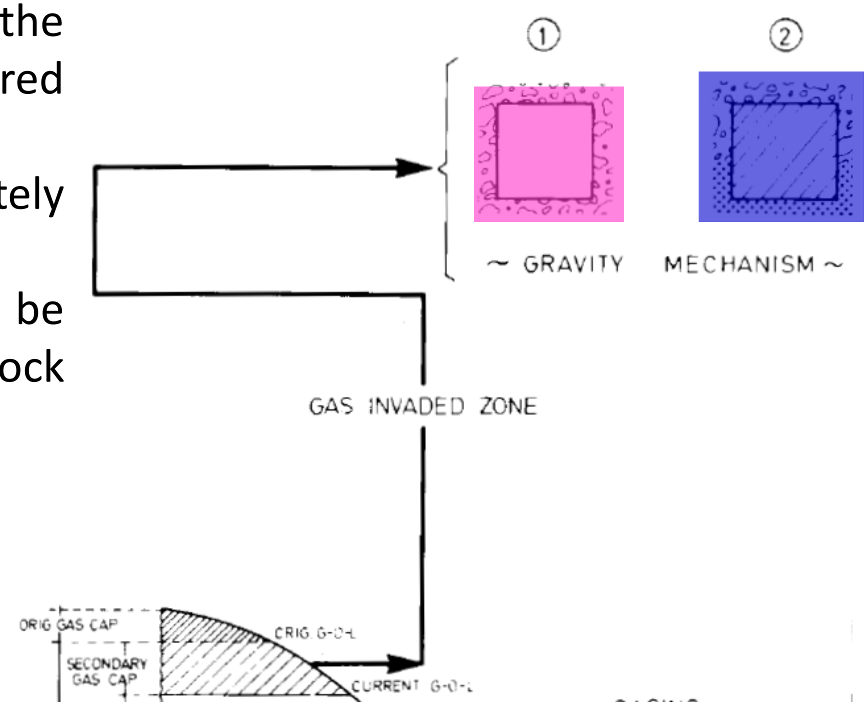
- ❑Different fluid saturations of matrix and fractures.
- ❑The presence of four different production mechanisms



10.11 – Schematisation of four basic zones and production mechanism in nine blocks taken as examples.

Gas-invaded zone
Gravitational drainage displacement mechanism

- Between GOLO and the current GOL (where the secondary gas-cap is developing in the fractured network)
- The matrix blocks will be partially or completely surrounded by gas.
- The capillary pressure and block height will be the main parameters upon which the block holdup zone depends.



$$U = \frac{g\,(H - Z)\,\Delta\rho - P_c}{\frac{\mu_g}{KK_{rg}}\left[MH + (1 - M)\,Z\right]}$$

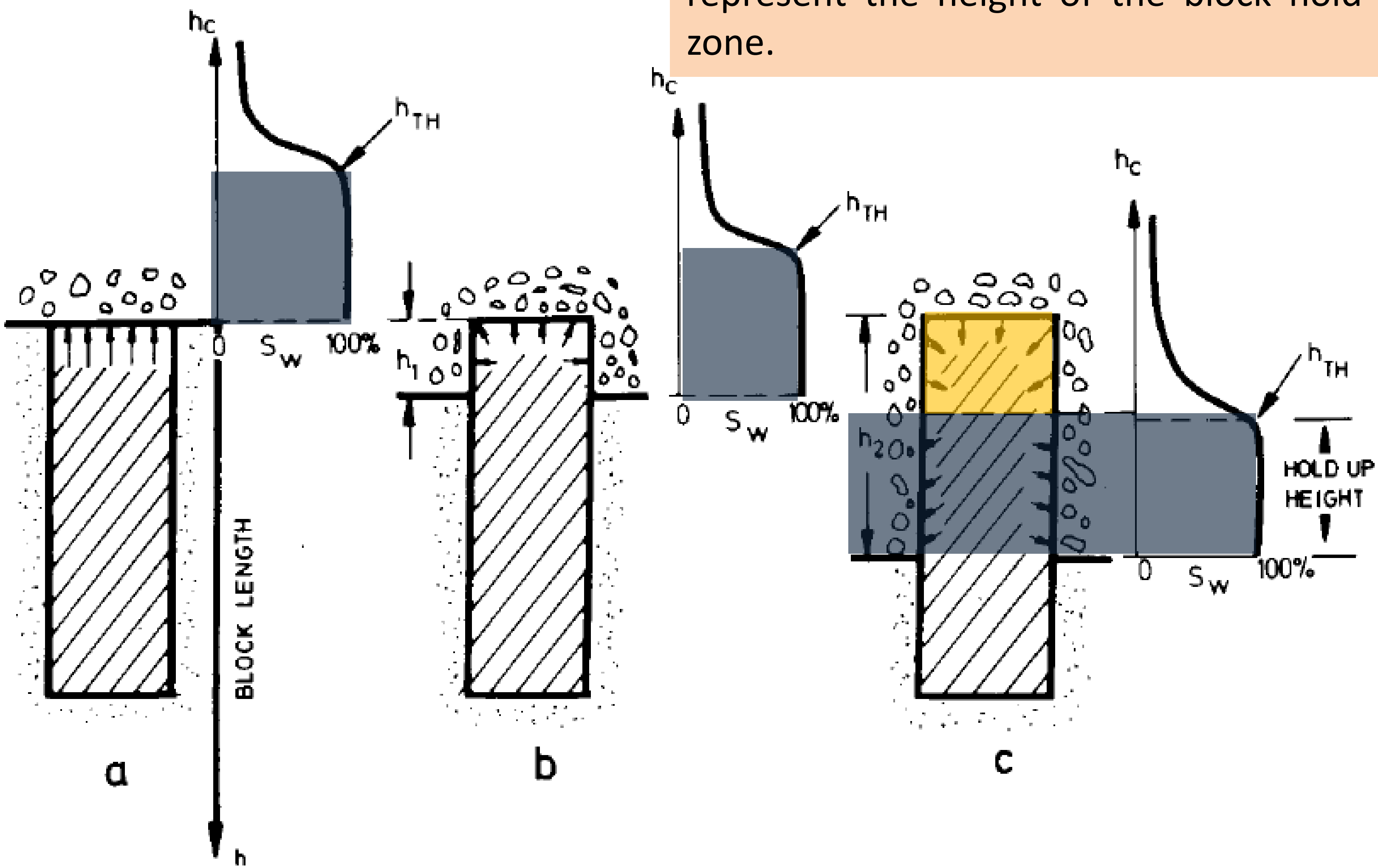
$$U = \frac{g\left[H_g - (H - Z)\right]\Delta\rho - P_c}{\frac{\mu_g}{KK_{rg}}\left[MH + (1 - M)\,Z\right]}$$

Gas-invaded Zone
Production Mechanism

- the oil producing mechanism in the matrix blocks of the gas-cap is gravity drainage
- The forces which resist the displacement of oil by gas are related to:
    - pore distribution
    - the average pore diameter (which influences the capillary height (h_C) and threshold height (h_{TH})).

(a,b): h_{TH} ~ h_c, displacement does not take place if the gas is in contact with the upper block surface or even if it reaches a depth of $h_1 < h_{TH}$

(c) when the block is surrounded at a depth of $h_2 > h_{TH}$ ~ h_c will recovery take place. In this case, recovery is limited only to the matrix block height $h_2 - h_{TH}$ while h_{TH} will represent the height of the block hold-up zone.



10.12 – Role of gas-oil contact advancement in drainage displacement.

Gas-invaded Zone
Production Mechanism

- It is essential to know the relationship of capillary height vs. block height in order to calculate block recovery behavior.
- Since gas-oil interfacial tension increases with reservoir depletion, the holdup height may increase in the absence of a pressure maintenance by gas injection.
- An oil re-imbibition process may take place when some of the oil produced through gas gravity drainage may re-imbibe into lower blocks which have been partially desaturated. In fact, during the descent of oil drops (displaced by gas) through fractures, the oil may enter into contact with the gassing zone blocks which are partially saturated with gas and oil. The re-imbibition of these blocks with oil is, in effect a reduction of the overall oil production in the reservoir.

Gas-invaded Zone
Production Mechanism- the Interaction Effect of the Blocks

This effect was experimentally developed by **Saidi** and may be called block-block interaction, as a result of oil entering (supplied) into the upper face of a tilted block, or infiltrating from the surrounding fractures after having left an upper located block.

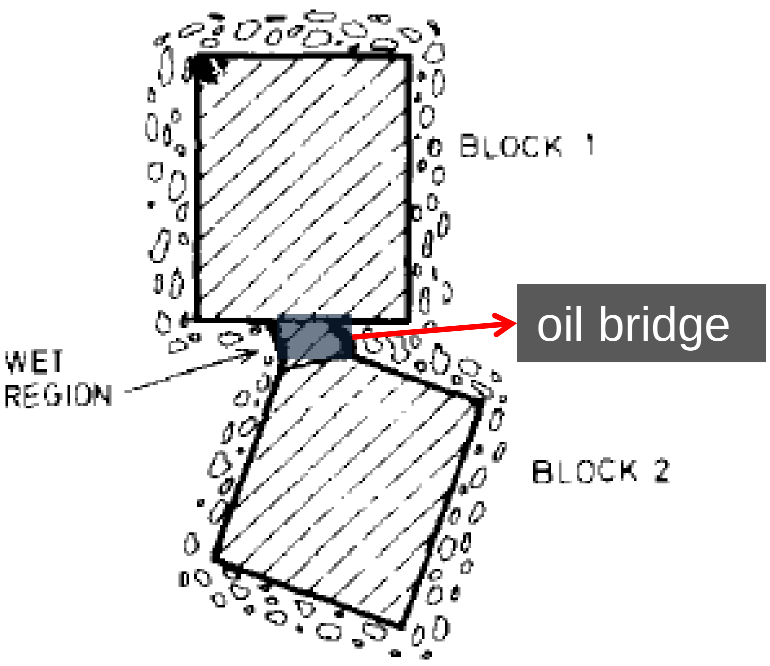
❑Description of phenomenon

❖Between the two adjacent blocks 1 and 2 (both located in the gas-invaded zone), a wet region may create an oil bridge.

❖ Oil bridge creates a continuous oil phase among the blocks due to irregularities in fractures.

❖Oil bridge is represented by a film of oil remaining between the blocks in the case of narrow fractures.

❖The oil flow from block 1 to 2, due to capillary continuity, is controlled by capillary pressure gradients and the potential difference of gravity



The rate of effective permeability K_O , depends on matrix saturations S_O^* and is expressed by,

$$q = -\frac{k_o(S_o^*)}{\mu_o}\left(\Delta\rho g - \frac{dP_c}{dZ}\right) \quad (10.1)$$

where,

$$q = -\frac{k_o(S_o^*)}{\mu_o}\left(\Delta\rho \times g - \frac{dP_c}{dS_o^*} \cdot \frac{dS_o^*}{dZ}\right) \quad (10.2)$$

$$S_o^* = (S_o - S_{or})/(1 - S_{cw} - S_{or})$$

- The oil produced from the matrix in fractures but re-imbibed in the lower matrix blocks during the descent of oil in the fractured network is disregarded in this rate q.
- Such a reimbibition will evidently reduce the efficiency of the gas-invaded zone producing through the drainage displacement mechanism.

Gas-invaded Zone
Production Mechanism- the Interaction Effect of the Blocks
Definition of rates

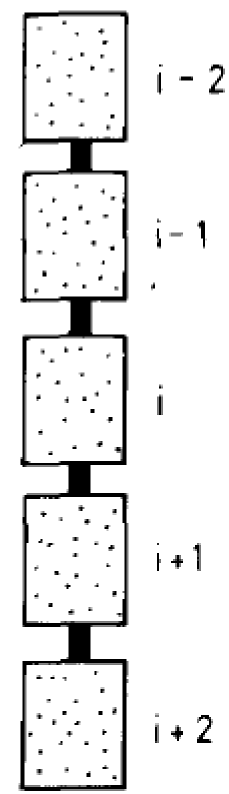
In the case of continuity of flow over several blocks forming a stack of blocks of different dimensions and physical characteristics, in the block i the rate may be expressed as follow:

The drainage rate of single block is

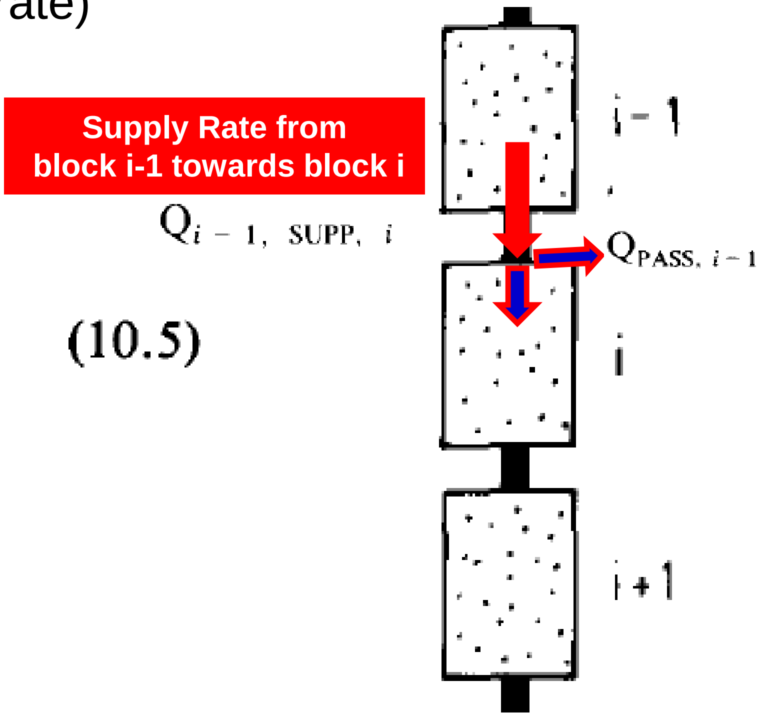
$$Q_{DR} = A \frac{(Hg - Z)\,\Delta\gamma - P_c}{\frac{\mu_g}{kk_{rg}}\,[MH + (1 - M)\,Z]} \qquad (10.4)$$

or by rearranging the terms as,

$$Q_{DR} = A \frac{(Hg - Z)\,\Delta\gamma - P_c}{\frac{\mu_o}{kk_{ro}}\,\frac{1}{M}\,[MH - (1 - M)\,Z]} = A\,\frac{k_o}{\mu_o}\,\frac{(H - Z) - h_c}{\left[H - \left(\frac{1}{M} - 1\right)Z\right]}\,\Delta\gamma \qquad (10.4')$$



- The maximum drainage rate (gravitational rate)
  - $P_c = 0$ (equivalent to $h_c << H$)
  - $Z = 0$ (equivalent to $z << H$)



$$Q_{GR} = Q_{MAX} = A \frac{k_o}{\mu_o} \Delta \gamma \quad (10.5)$$

* If $Q_{i-1, SUPP, i} < Q_{MAX, i}$, all oil coming from above is sucked into block i.

* If $Q_{i-1, SUPP, i} > Q_{MAX\, i}$, some of the oil (the excess) passes through the fractured

❑**Reinfiltration rate** is then equal to the rate of supply under the condition that the supply rate is lower than the maximum drainage rate.

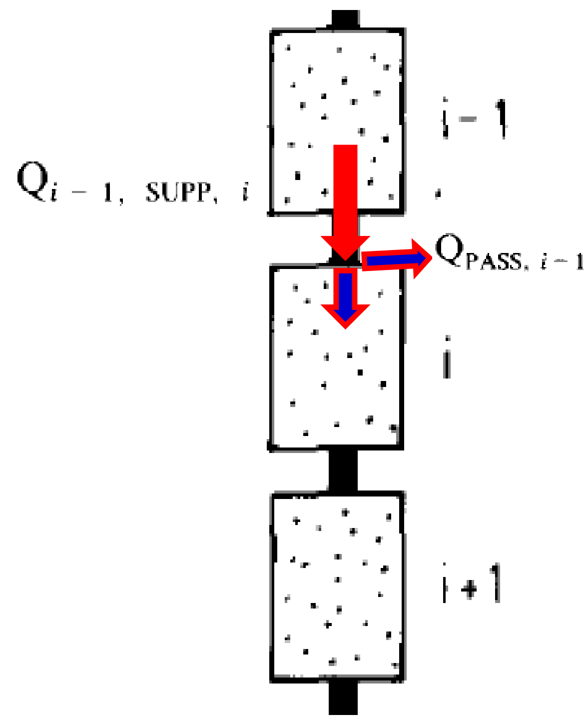
$$Q_{REINF,\, i} = Q_{i-1,\, SUPP} \text{ if } Q_{i-1,\, SUPP,\, i} < Q_{MAX,\, i} \qquad Q_{MAX} = A \frac{k_o}{\mu_o} \Delta \gamma$$

❑**Passing rate** is the excess of the rate which moves through the fractured network.

$$Q_{PASS,\, i} = Q_{i-1,\, SUPP,\, i} - Q_{DR,\, i}$$

and takes place only if,

$$Q_{i-1,\, SUPP,\, i} > Q_{MAX,\, i}$$



Gas-invaded Zone

Production Mechanism- the Interaction Effect of the Blocks

Degree of block interaction

- ❑Full interaction corresponds to α= 1
  - ❖The total supply rate of block i - 1 is sucked into block i
- ❑Partial interaction corresponds to 0 < α < 1
  - ❖Reinfilterate rate
  - ❖Passing rate
- ❑Non-interaction corresponds to α = 0 (a single block without any interaction with adjacent blocks)

$\alpha = 1$ – corresponds to $Q_{i-1,\,\mathrm{SUPP},\,i} < Q_{\mathrm{MAX},\,i}$

$\alpha < 1$ – corresponds to $Q_{i-1,\,\mathrm{SUPP},\,i} > Q_{\mathrm{MAX},\,i}$

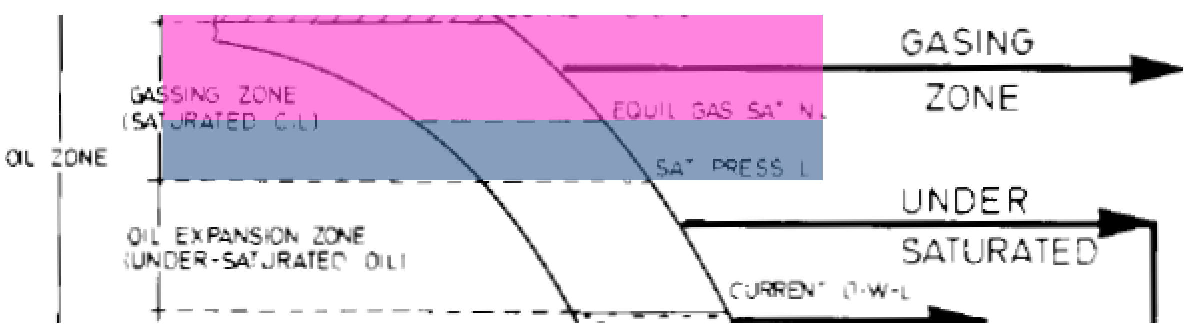
Gas-invaded Zone
Production Mechanism
Gravity drainage from stacks of equal blocks

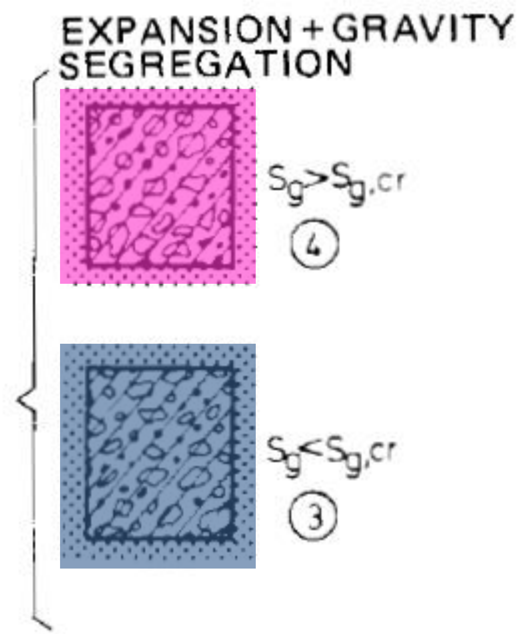
- The drainage process described by a single block behaviour may be unrealistic since it is too rapid and too optimistic compared with stacked blocks.

Gassing Zone

Liberated gas expansion + buoyancy + imbibition + convection mechanisms

- Between current GOL and B_{pp}
- In the gassing zone the oil-saturated blocks are surrounded by fractures saturated with oil. The matrix pore pressure is lower than the bubble point pressure.
- Two sub-zone in oil gassing zone
  - The upper sub-zone $S_g > S_{gcr}$
  - The lower sub-zone $S_g < S_{gcr}$
- Segregation of gas inside the matrix block
- The interchange of fluids between matrix and fractures
- Complex matrix-fracture transfer due to the circulation of liberated gas in fractures saturated with oil, as well as the contact between the heavier oil of fractures with the lighter oil remaining in the matrix.
- Super-saturation





Gassing Zone
Production Mechanisms

- The presence of fractures changes the production mechanism from a conventional solution gas-drive to a more complex production mechanism and flowing process.

- The liberated gas from matrix blocks percolates upward in fractures

- Besides the simple expansion of fluids and rock, it is possible to have:
    i. Oil circulation due to convection phenomena,
    ii. Displacement of matrix oil by fracture oil as a result of differences in densities between the oil in matrix and that in fractures,
    iii. Gas diffusion between oil in matrix and fissures, as a result of higher gas concentration in matrix oil

Gassing Zone

Production Mechanisms

A different concept of solution gas-drive as a result of diffusion (non-dispersion)

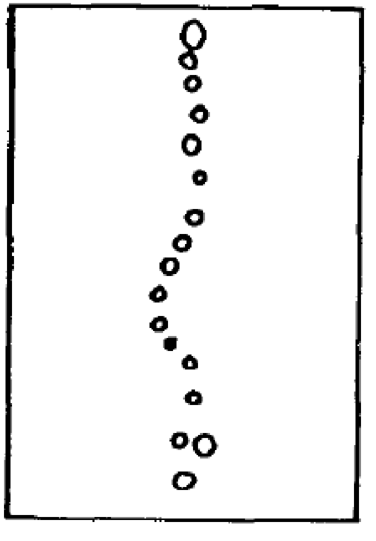
Dumore Theory (supported by experimental results) : at a low reservoir pressure decline rate

$$\left(\frac{dp}{dt}\right) < 10^{-6}\ \frac{at}{sec}$$

a super-saturation phenomena would be developed in the pores. In other words, it would be a pressure (super-saturation pressure) at which gas would remain in a liquid phase below its equilibrium bubble point (obtained from conventional PVT experiments).

Analyzing the Super-saturation Phenomena

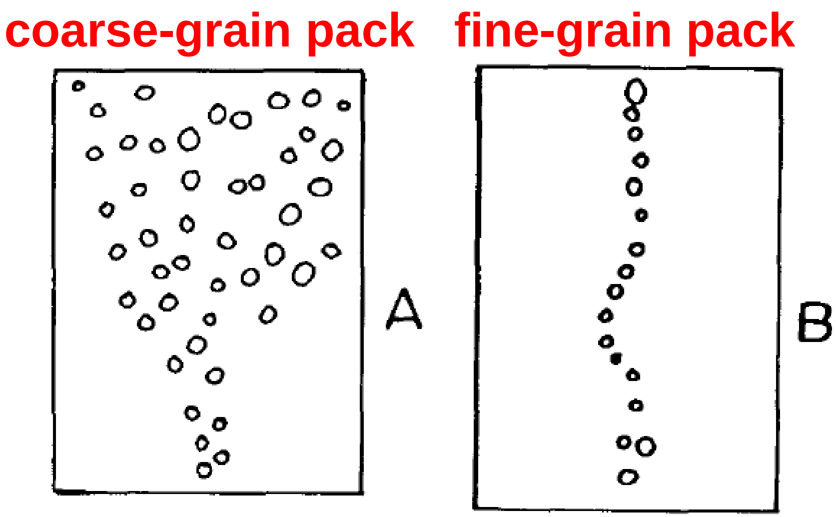
- The largest pore having a lower capillary pressure would be the first pore in which a gas bubble would develop.
- Because of super-saturation, a gas concentration gradient exists between the bubble of gas in the large pore and its surrounding. If the reservoir pressure drops at a very low decline rate there will be enough time for the diffusion of gas through liquid in the surrounding area to feed the bubbles of gas. In this manner the bubbles of gas grow larger and larger until the gas bubble channel reaches the upper boundary of a block, where it delivers gas to fractures.
- During such a process, the spherical drainage of a bubble changes into a cylindrical drainage, and at any time a new gas nucleus will develop into the largest pore undergoing a similar process, since the pore pressure is below the bubble pressure, but greater than a critical super-saturation pressure.



- A mathematical derivation was developed based on physical characteristics and Fik's law for unsteady and steady-state periods, and preliminary studies indicate that for a pressure decline rate(10^{-6} atm/sec) and a non-homogeneous reservoir rock a gas saturation of about 1% would be developed in the gassing zone.
- If diffusion takes place in the under-saturated part of the reservoir, where the bubble point pressure drops considerably below the original value, the free-gas saturation is low when this part of the reservoir becomes a gassing zone. If, on the contrary, the pressure deline rate is high, super-saturation oil capacity is low and if in addition the reservoir rock is homogeneous, a tendency of gas dispersion phenomena occurs and a classic solution gas-drive calculation must be applied even in the fractured reservoir.

Basic Experiment

- In a coarse-grain pack : gas dispersion
- In a fine-grain pack: gas channel
- It was observed that the gas phase is not a continuous stream of upward moving gas, but rather an agglomeration of small mutually interconnected gas channels and thus forming a continuous stream.
- In a non-homogeneous grain pack the non-dispersed single channel follows a more tortuous pattern than in a more uniform grain pack.
- The transition of upward gas flowing from dispersion to non-dispersion conditions is restricted to a particular permeability interval or a particular permeability porosity ratio.
- The upward gas flow at low rates is governed mainly by gravity and capillary forces alone, which helps a non-dispersion state of flow

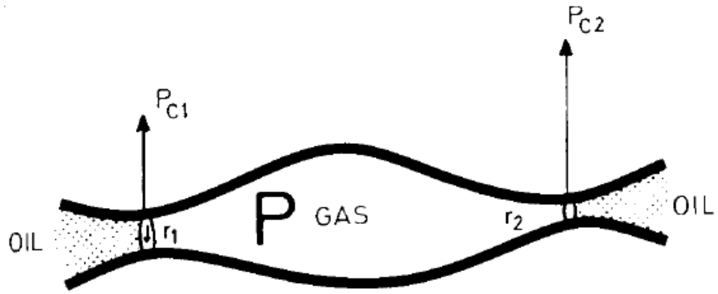


10.21 Bubbles of gas liberated. A) Dispersion B) Non-dispersion

Qualitative Explanation of Dispersion and Non-dispersion

If the two capillary pressures are respectively

$$P_{c1} \cong \frac{2\sigma}{r_1} \text{ and } P_{c2} \cong \frac{2\sigma}{r_2}$$



then the following applies:

$$\text{when } r_2 \ll r_1 \rightarrow P_{c2} \gg P_{c1} \rightarrow \text{if} \begin{cases} P > P_{c2} - \text{dispersion state} \\ P_{c2} > P > P_{c1} - \text{non-dispersion state} \end{cases}$$

$$\text{when } r_2 = r_1 \rightarrow P_{c2} = P_{c1} \rightarrow \text{if} \begin{cases} P > P_{c1} - \text{dispersion since,} \\ \qquad \text{automatically } P > P_{c2} \end{cases}$$

- ❑If pores are uniform and of large radii, this is equivalent to small capillary forces and a state of dispersion will take place.
- ❑If pores are non-uniform and of small radii, there is a great chance that a non-dispersion condition of gas flow will take place.

Associated with Leverett's expression, the limit of the states of dispersion and non-dispersion could be expressed by a transition capillary magnitude,

$$\sigma \sqrt{\Phi/K} \cong 1.5 \times 10^4 \sim 2 \times 10^4 \text{ dyne/cm}^2$$

Classic Production Mechanism (dispersion of liberated gas)

- **Classic case of Solution gas drive mechanism**: the liberated gas in the matrix will depend on the relationship between the relative permeability of gas vs. gas saturation.

The liberated gas in the matrix lock

- **$S_g < S_{gcr}$**
  - the liberated gas becomes immobile
  - the liberated gas expansion will drive the oil out of the matrix block towards the fractures.

- **$S_g > S_{gcr}$**
  - the liberated gas becomes mobile
  - the mechanism will be a combination between solution gas-drive and segregation.
  - some of the liberated and segregated gas will leave the matrix and drive some of the oil towards the fractures.
  - the desaturation in oil of the matrix blocks increases
  - the oil from the surrounding fractures may be re-imbibe the matrix
  - the resaturation in oil of the same block will reduce the single block production performance.

Diffusion

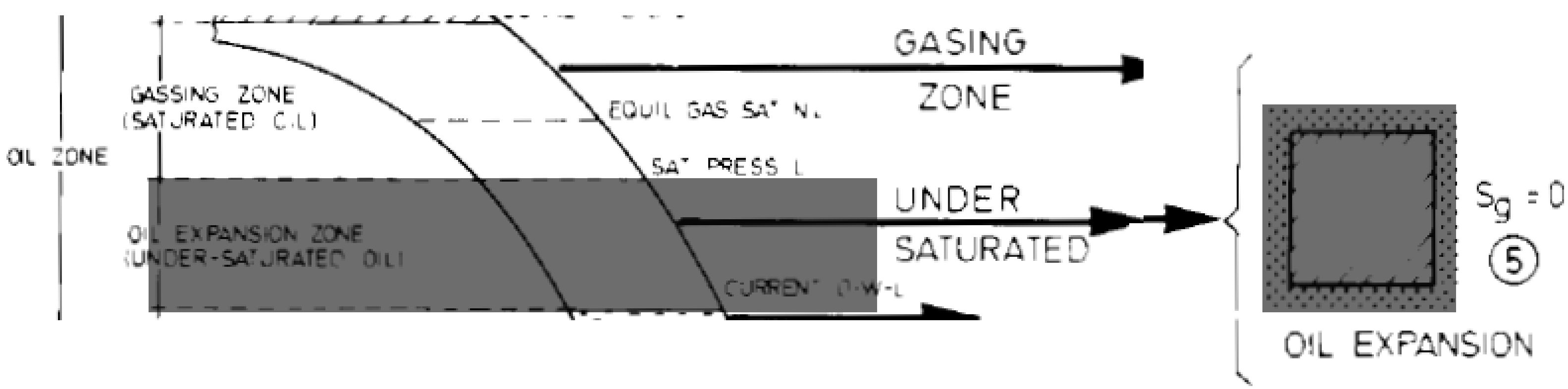
Convection is a result of contrasting oils within the fracture network. Diffusion is due to the contrast in hydrocarbon properties between fracture and matrix: it can take place between gas and oil, thus enchancing sudation, or between oils with different compositions.

This phenomenon has been observed in several Iranian fields (Ref. 8) where the saturation pressure has been found to change by as much as 35 bars during ten years of single-phase depletion.

Under-saturated Zone
Simple Expansion Drive Mechanism

- Between the level of B_{PP} and the level of the current WOL
- Single-phase oil
- Driving force: P_m-P_f
- the production mechanism is the result of the single phase expansion of matrix oil under the pressure difference between the matrix and fractured network.
- The expansion drive mechanism will be bigger if the compressibility and pressure decline rate are higher while production rate increases if block dimensions are smaller.

$$C_{oe} \cong C_o + C_w \frac{S_{wm}}{1 - S_{wm}} + C_{pm} \frac{1}{1 - S_{wm}}$$



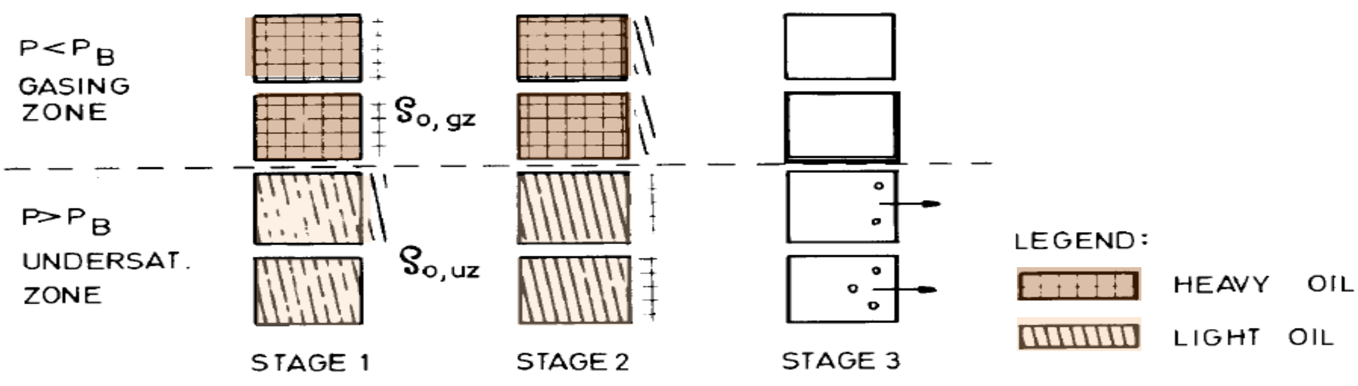
Convection Process in Gassing and Under-saturated Zones

Stage 1: Low dissolved gas, higher density
Stage 2: Instability and convective mixing, contact of low dissolved gas oil with the lighter oil (higher content in dissolved gas) in the matrix block.
Stage 3: The convectional mixing causes more of the dissolved gas to transfer from matrix to fissure than does molecular diffusion

Two Extreme Cases

1. Convection will not take place in the under-saturated zone, and thus no additional dissolved gas will be produced from this zone. The gas produced in the gas-cap will only be the result of the gasing zone.

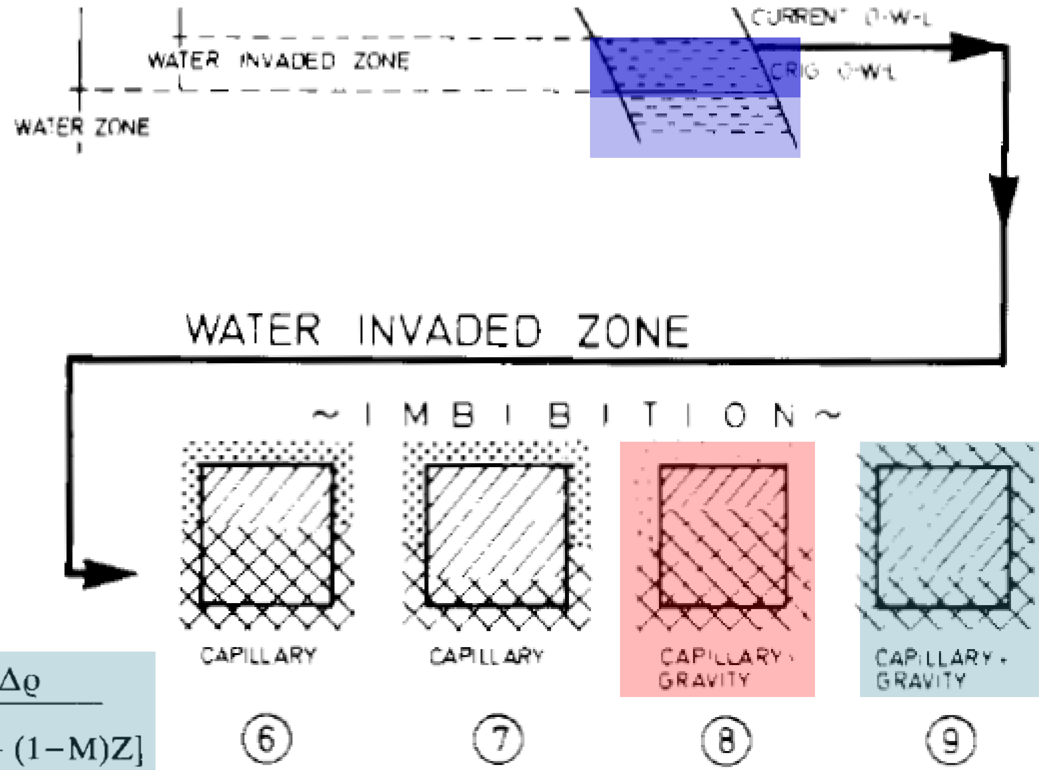
2. A very strong (infinitely rapid) convection takes place in the under-saturated zone. A maximum transfer of gas from matrix to fractures takes place.



Water-invaded Zone

Gravitational + Capillary Imbibition Displacement Mechanisms

- Between the current WOL and the original WOLO
- Oil is recovered through gravitational and capillary imbibition.
- Oil recovered from the matrix pores as a result of progressive exposure of the matrix pores to a water environment in the fractures, is rate sensitive to rate of water table advancement.
- often during displacement one or another of these forces may prevail.



$$U = \frac{P_c + g(H_w - Z)\Delta\rho}{\mu_w / KK_{rw}\,[MH + (1 - M)Z]}$$

$$u = \frac{P_c + g(H-Z)\Delta\varrho}{\frac{\mu_w}{k\,k_{rw}} Z + \frac{\mu_o}{k\,k_{ro}} (H-Z)} = \frac{P_c + g(H-Z)\Delta\varrho}{\frac{\mu_w}{k\,k_{rw}} [MH + (1-M)Z]}$$

Table 10.1 *Production mechanism*

Zone (Fig. 10.7)	Saturation				
	Matrix	Fractures network	Production mechanism	Block no. fig 10.11	Observations
Gas invaded (1)	oil	gas	Gravity drainage	1	$P < P_{BB}$
»	»	gas + oil	»	2	$P < P_{BB}$
Gasing zone (2)	oil gas	oil	• expansion of liberated gas	3 & 4	»
$Sg < Sga$	oil + gas	oil	• convection	3	• immobile gas
$Sg > Sga$	»	oil		4	• mobile gas
under-saturated oil (3)	oil	oil	monophase expansion	5	$P > P_{BB}$
water invaded (4)	water & oil	water & oil	capillary imbibition	8 6	Fracture water – oil contact below critical
			gravity & imbibition	7,9	Fracture water – oil contact above critical