Material Balance

Hamidreza Salimi

Content

- Material-balance (MB) concept
- Drive Mechanisms
- MB for gas reservoirs
- MB for oil reservoirs

Refs: Applied Petroleum-Reservoir Engineering, Craft & Hawkins
Fundamentals of Reservoir Engineering, Dake
Lecture notes of Wim Swinkels
Lecture notes of Willem Schulte

Material-Balance Concept

- Since reservoir volume is constant, the sum of volume changes (including production and injection) of the oil, free gas, and water must equal zero

- In other words, expansion should be equal to voidage:
  - the net voidage (production minus injection minus influx) must be made up by expansion of the in-place materials
  - a volume balance which equates the cumulative observed production, expressed as an underground withdrawal, to the expansion of the fluids in the reservoir resulting from a finite pressure drop

Material Balance

- Equations that link pressure to net withdrawals
- Constrained by conservation of mass
- Thus production balanced by
  - oil expansion
  - dissolved gas liberation
  - expansion of gas cap
  - expansion of connate water
  - water influx
  - compaction of pore volume
- Combined with dynamic processes provides basis for reservoir prediction

Drive Mechanisms

- Fluid Expansion
  - Occurs as reservoir undergoes pressure depletion
- Solution Gas Drive
  - When reservoir pressure falls below bubble-point, gas is liberated from hydrocarbon liquid phase. Expansion of gas phase contributes to displacement of liquid phase.
- Water Drive
  - For reservoirs connected to natural aquifers, reservoir pressure declines, water starts to expand and flow into reservoir
- Gas-Cap Drive
  - Volume of free gas in upper part of structure expands into oil zone to displace oil downdip
- Compaction Drive
  - Pressure depletion generates an increase in effective pressure acting over rock. Depending on formation compressibility, this increase may induce a decrease in pore volume providing some energy

- MB applied to gain an understanding of reservoir-drive mechanisms under primary-recovery conditions

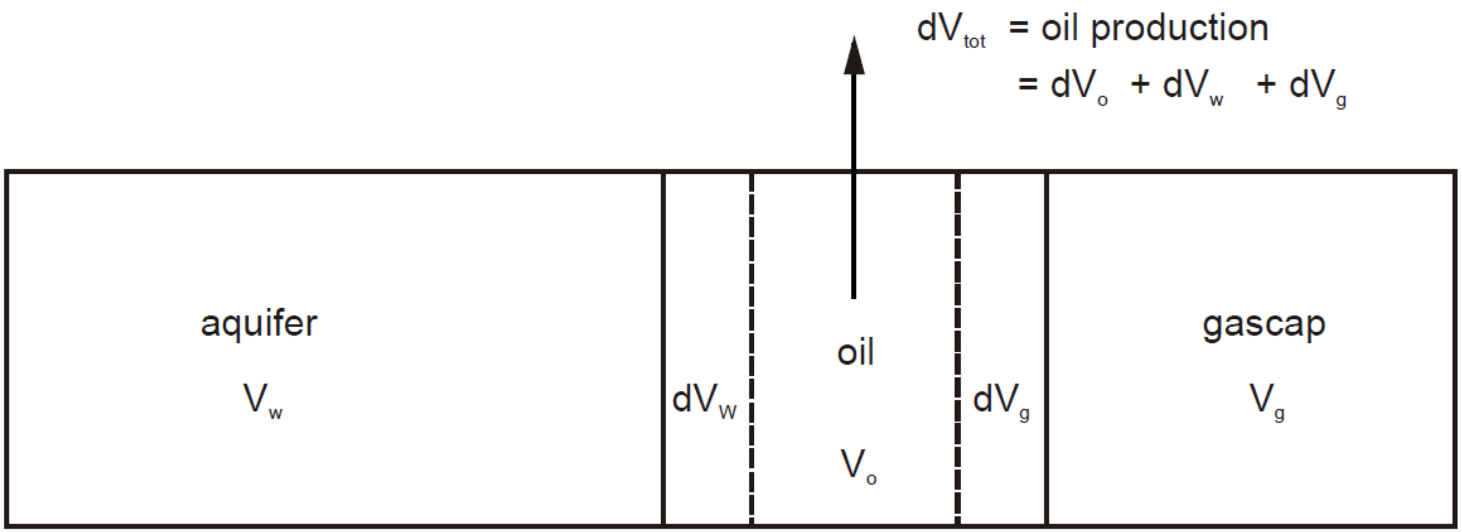
Fluid and Rock Properties for Expansion

- Solution gas/oil ratio (R_s)
- Oil-formation-volume factor (B_o)
- Gas-formation-volume factor (B_g)
- Total-formation-volume factor (B_t)
- Formation compressibility (c_f)
- Water compressibility (c_w)

Nomenclature-Definitions

- OIP/GIP: oil/free gas in place
- N/G: original OIP/GIP
- N_p: cumulative oil production
- G_p: cumulative gas production
- W_p: cumulative water production
- W_i: cumulative water influx/injection
- G_i: cumulative gas injection
  - Note: All except for OIP/GIP are at standard conditions

Primary Oil Recovery Resulting from Oil, Water, and Gas Expansion



$$dV_{tot} = \text{oil production} = dV_o + dV_w + dV_g$$

$$dV_{tot} = c_o V_o \Delta P + c_w V_w \Delta P + c_g V_g \Delta P$$

Typical values for compressibility factors at 2000 psia (138 bar):

$$c_o = 15\times10^{-6}\ 1/\text{psi},\ c_w = 3\times10^{-6}\ 1/\text{psi},\ c_g = 500\times10^{-6}\ 1/\text{psi}$$

Contribution to oil production by oil and water expansion only significant if V_o and V_w are large. In contrast, because of its very high compressibility, relatively small volume of gas cap contributes significantly to oil production.

Gas Reservoirs (Expansion Factor)

Calculates expansion factor by using z

Expansion factor: $E = \frac{V_{sc}}{V} = B_g$

Expansion factor: $E = \frac{V_{sc}}{V} = \frac{z_{sc} T_{sc} P}{z T P_{sc}} = a \frac{P}{zT}$

for field units E = 35.37 P/zT (vol/vol)

Standard conditions:

T_{sc} = 16 °C or 60 °F

P_{sc} = 101 kPa or 14.7 psi

Gas initially in place (GIIP): $G = V\varphi(1 - S_{wc})E_i$

Gas Reservoir (Depletion, No Water Influx)

- Hydrocarbon pore volume: $HCPV = V\varphi(1 - S_{wc}) = G/Ei$

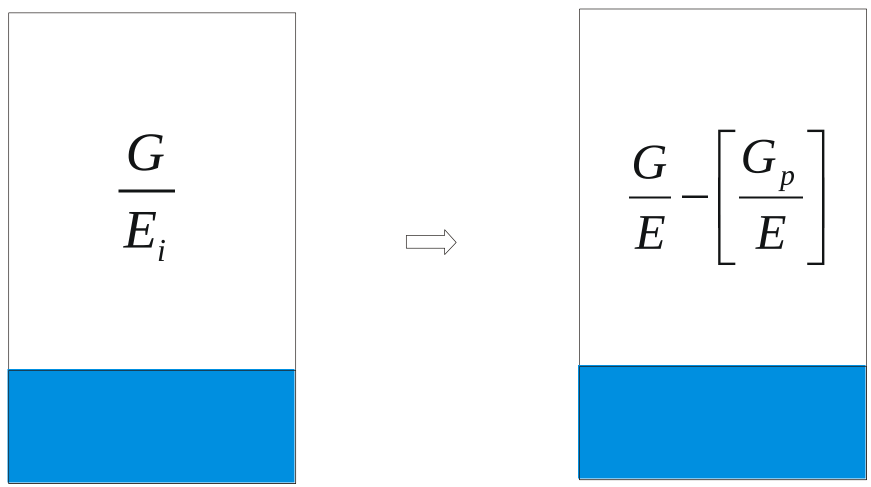
Production (sc) = GIIP – Unproduced Gas (sc)

$G_p =$ G – (HCPV)E

$G_p =$ G – G/E_i E

$$\frac{G_p}{G} = 1 - \frac{E}{E_i}$$

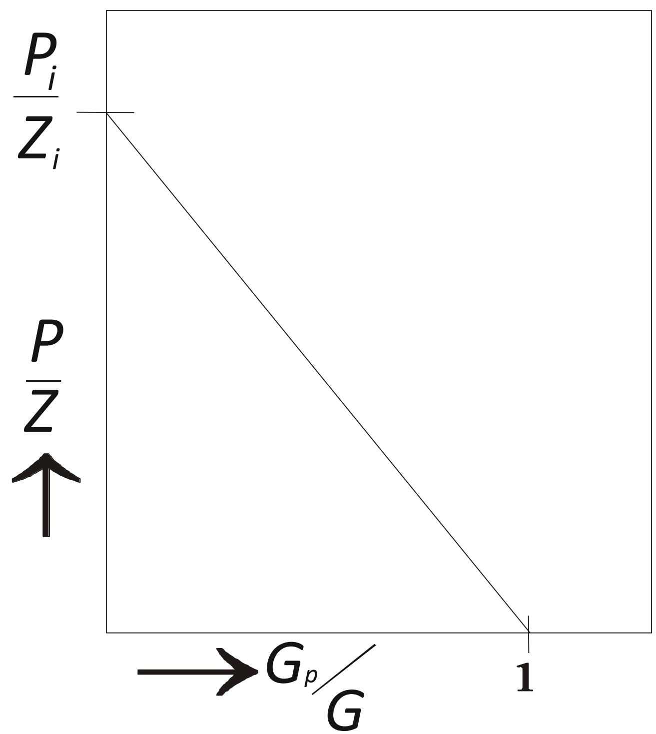
$$\frac{P}{z} = \frac{P_i}{z_i}\left(1 - \frac{G_p}{G}\right)$$



Gas Reservoirs

- Relation between production and pressure over time

$$\frac{P}{z} = \frac{P_i}{z_i}\left(1 - \frac{G_p}{G}\right)$$



Connate-Water Expansion and Grain-Pressure Increase

- Total change in hydrocarbon pore volume

$$\mathrm{d(HCPV)} = -\mathrm{d}V_w + \mathrm{d}V_f$$

  - Negative sign is because expansion of connate water leads to reduction in HCPV

$$\mathrm{d(HCPV)} = -\left(c_w V_w + c_f V_f\right)\Delta P$$

$$V_f = PV = \frac{HCPV}{(1 - S_{wc})} = \frac{G}{E_i(1 - S_{wc})}$$

$$V_w = PV \times S_{wc} = \frac{G S_{wc}}{E_i(1 - S_{wc})}$$

$$\frac{G_p}{G} = 1 - \left(1 - \frac{\left(c_w S_{wc} + c_f\right)\Delta P}{1 - S_{wc}}\right)\frac{E}{E_i}$$

Gas Reservoirs

$$\frac{G_p}{G} = 1 - \left(1 - \frac{(c_w S_{wc} + c_f)\Delta P}{1 - S_{wc}}\right)\frac{E}{E_i}$$

For typical reservoirs, reduction in hydrocarbon pore volume, due to connate water expansion and rock compaction, is negligible:

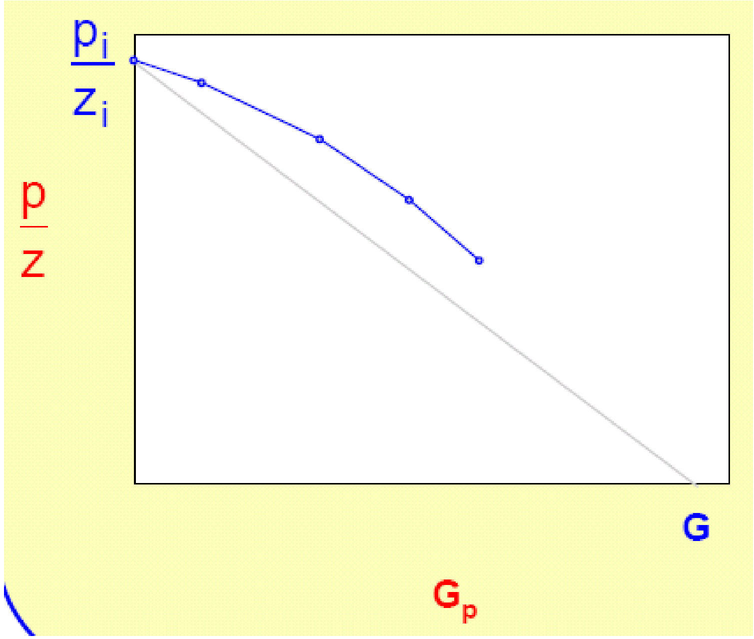
c_w = 3×10^{-6} 1/psi, c_f = 10×10^{-6} 1/psi, S_{wc} = 0.2, ΔP = 1000 psi, the term in parenthesis becomes:

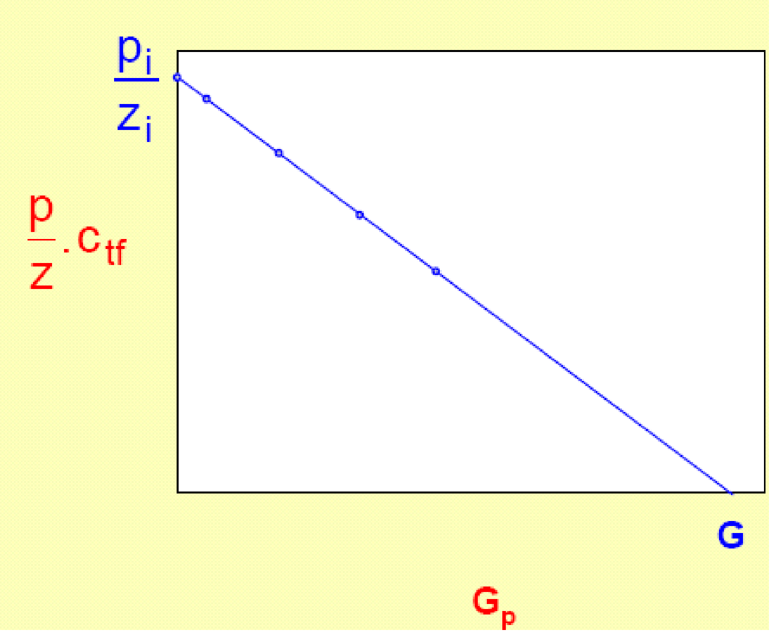
$$1 - \frac{(3\times 0.2 + 10)}{0.8} \times 10^{-6} \times 10^{3} = 1 - 0.013$$

Not always, e.g., shallow unconsolidated reservoirs (c_f = 100×10^{-6} 1/psi

Compaction Drive

- Impact of compaction on P/Z plot

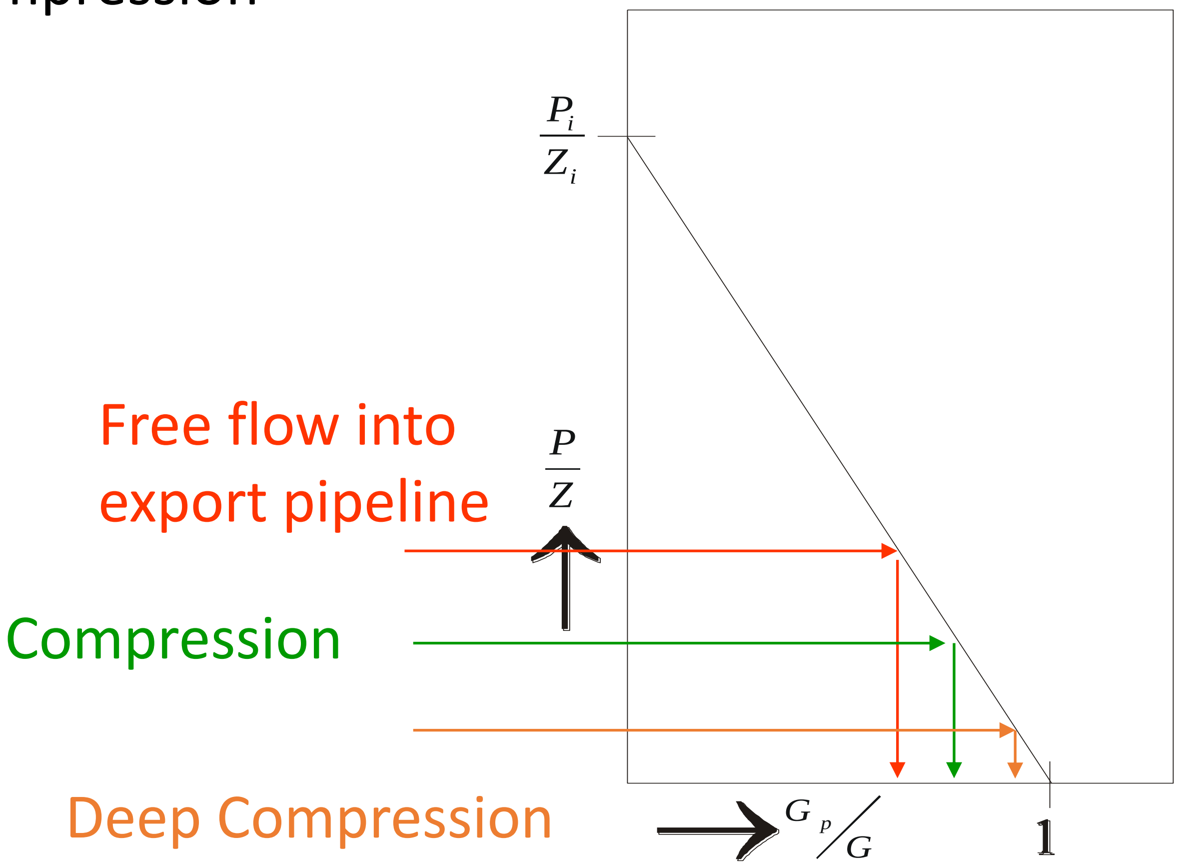




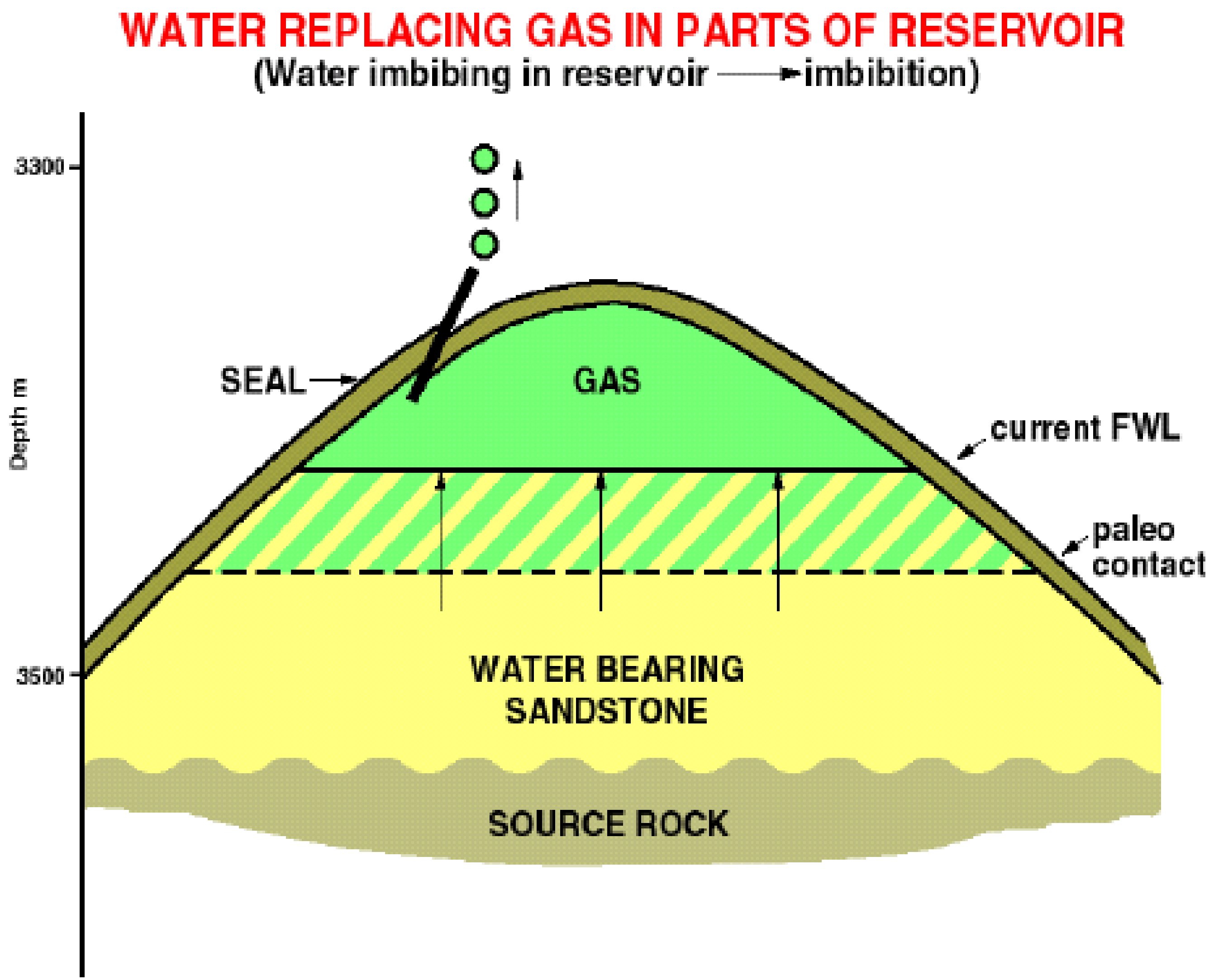
By including bracket term (c_{tf}) in P/Z

Groningen Gas Field

Improving recovery by lowering the abandonment pressure using compression

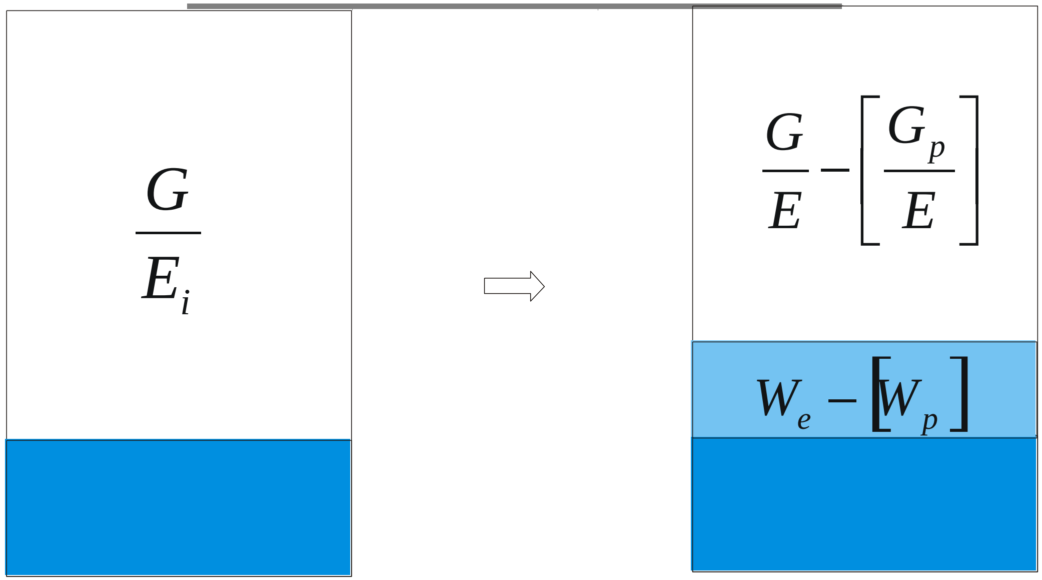


Water Influx



Gas Reservoir with Water Influx

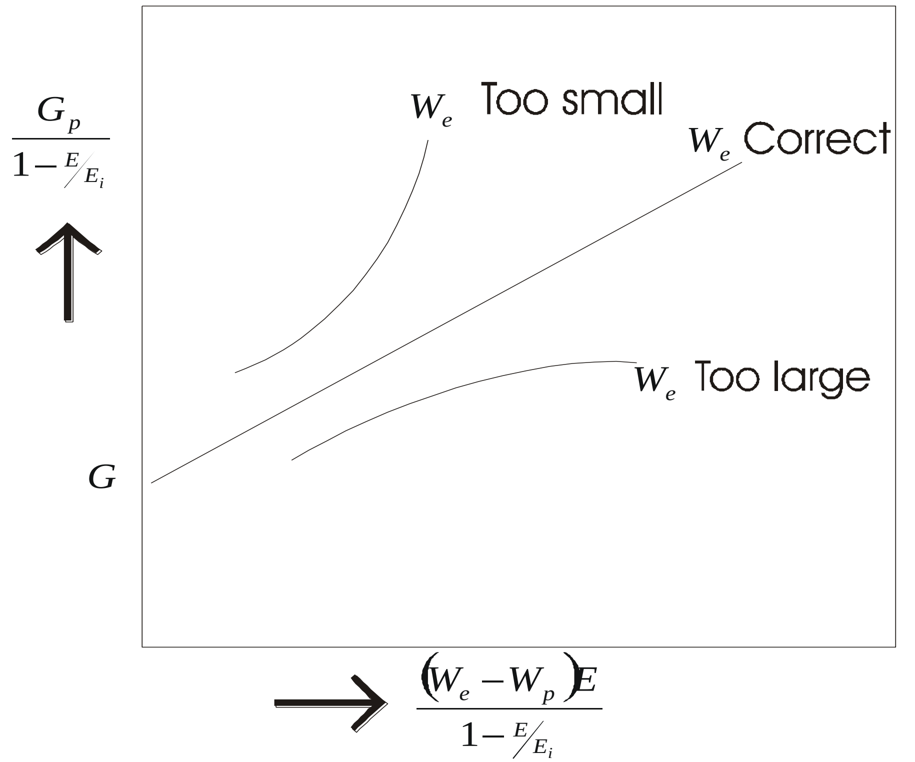
	Standard Conditions	Reservoir Conditions
Gas	G_p	$\frac{G_p}{E}$
Oil	—	—
Water	W_p	W_p



$$\frac{G}{E_i} = \frac{G - G_p}{E} + W_e - W_p$$

Gas Reservoir with Water Influx

- Linear plot $$\frac{G_p}{1-E/E_i} = G + \frac{(W_e - W_p)E}{1-E/E_i}$$

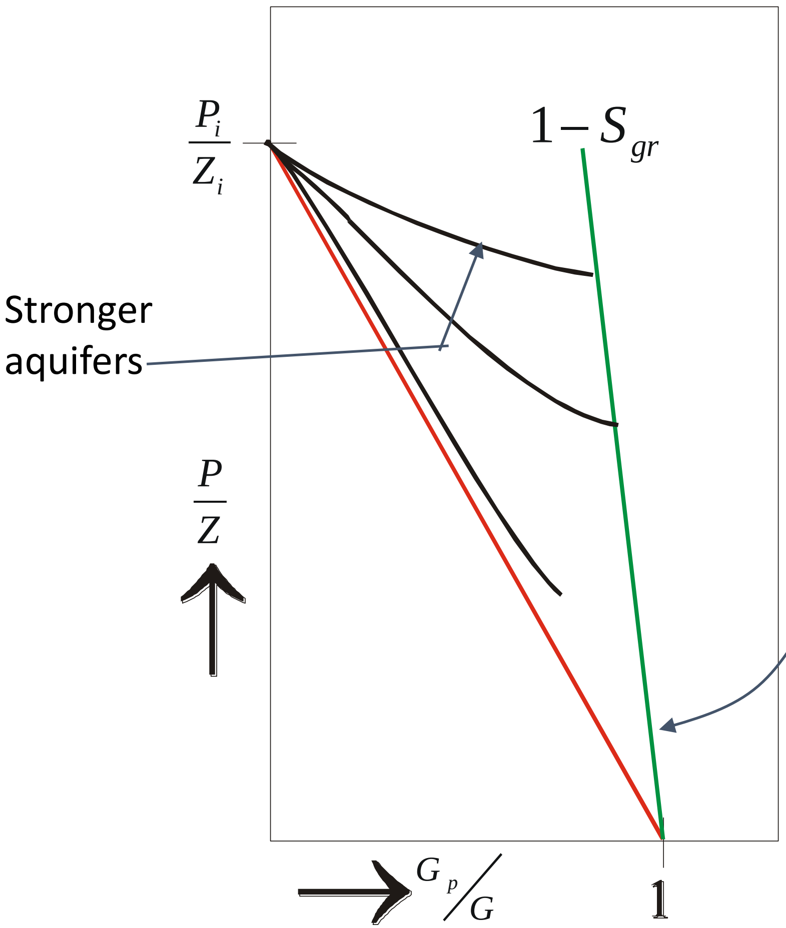


Note that you may have inaccuracy in G and W_e
Note: linearity is independent of uncertainty in G

Gas Reservoir with Water Influx

- Rewrite MBE:

$$\frac{P}{Z} = \frac{\frac{P_i}{Z_i}\left(1-\frac{G_p}{G}\right)}{\left(1-\frac{E_i}{G}\left(W_e - W_p\right)\right)}$$



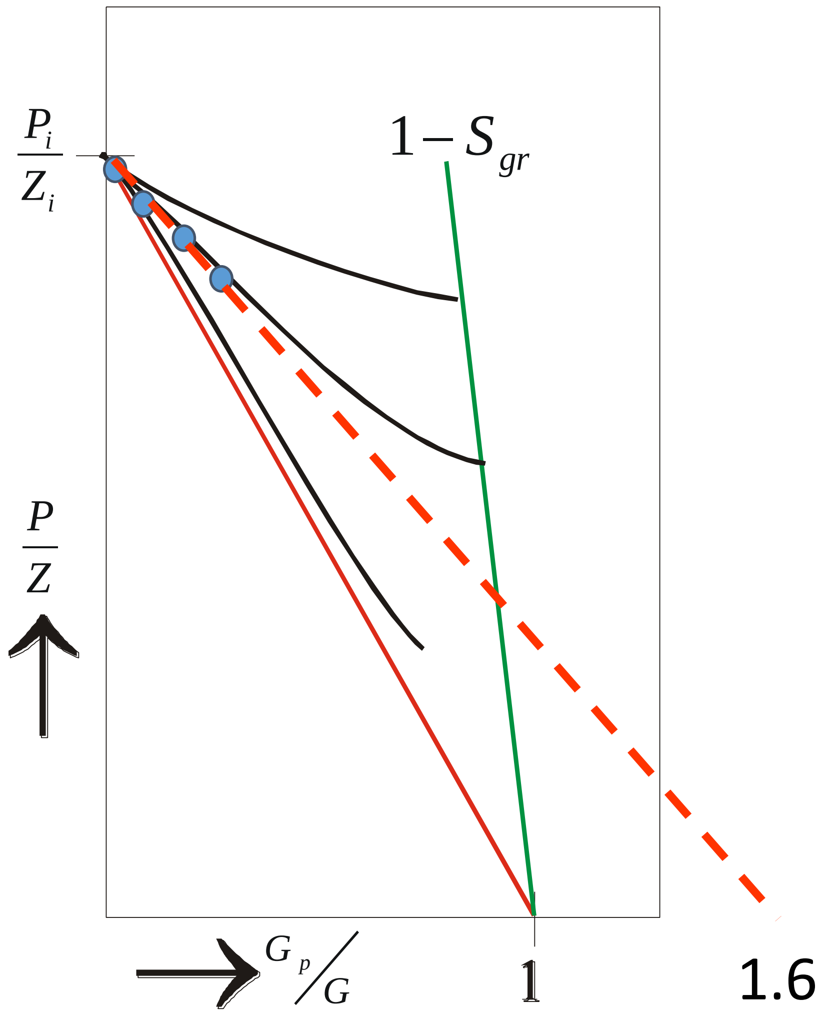
The aquifer influx does not allow a large pressure drop

ultimate possible under an effective waterdrive

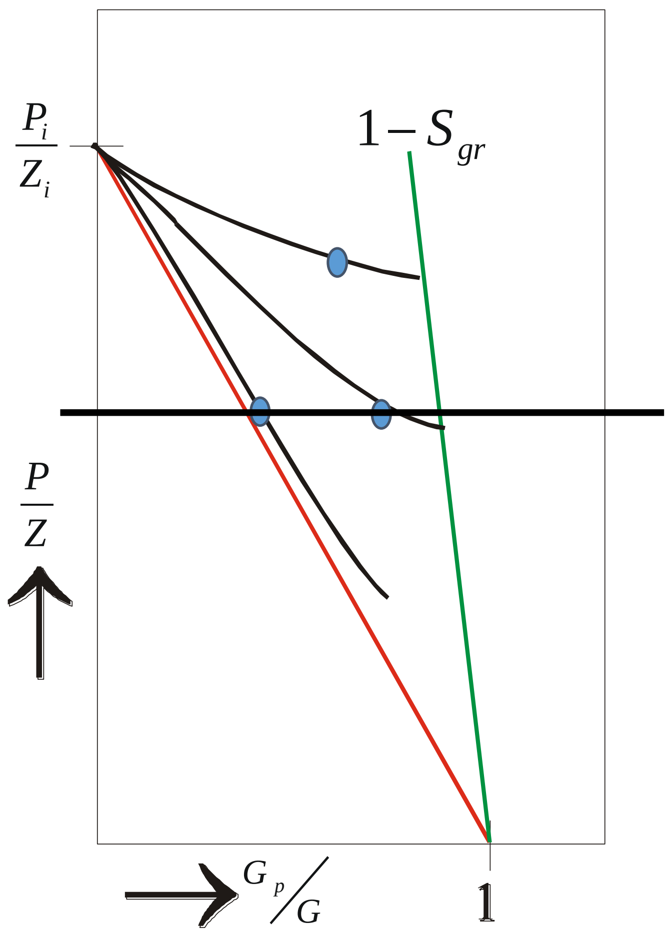
S_{gr} is fixed, but the associated trapped / immobile gas is also a linear function of P/Z

Gas Reservoir with Water Influx

- Errors if aquifer not accounted for



Gas Reservoir with Water Influx



At given final pressure Some water influx is Beneficial

Oil Reservoirs

- Oil MBE is more complex than gas MBE as there are more phases involved
  - Oil
  - Dissolved gas
  - Free gas
  - Water
- Volume balance can be evaluated as

Underground withdrawal = expansion of oil + originally dissolved gas

+ expansion of gas-cap gas

+ reduction in HCPV due to connate-water expansion and decrease in pore volume

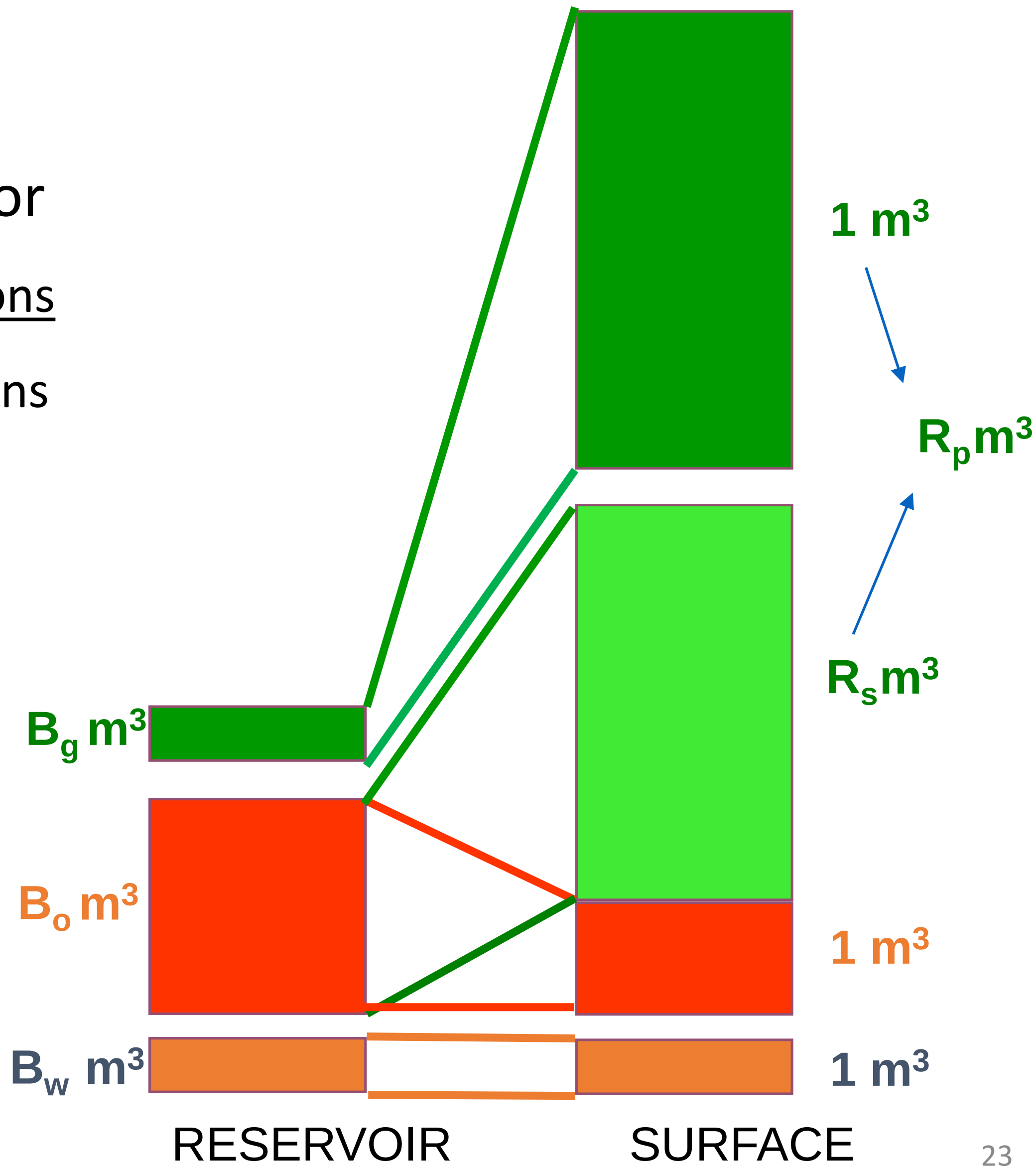
Reservoir and Surface Volumes

B = Formation Volume Factor

= $\frac{\text{volume at reservoir conditions}}{\text{volume at standard conditions}}$

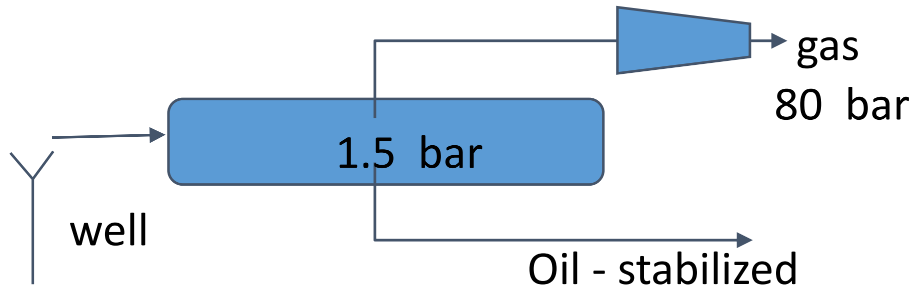
R = Gas : Oil Ratio

= $\frac{\text{volume of gas at standard conditions}}{\text{volume of oil at standard conditions}}$

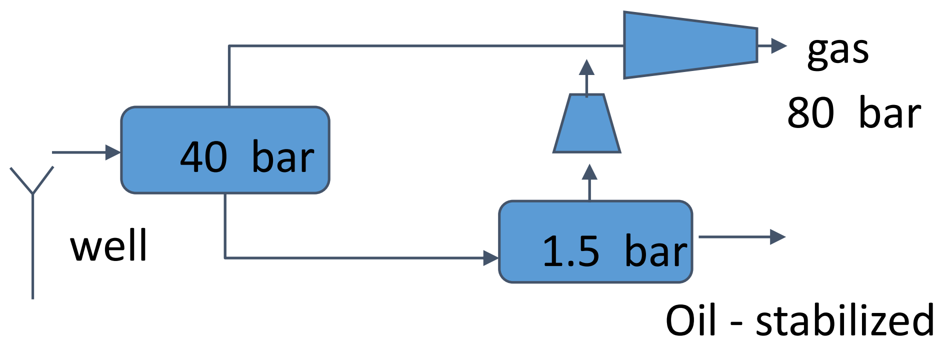


B_o and B_g are dependent on surface facilities

Option 1:



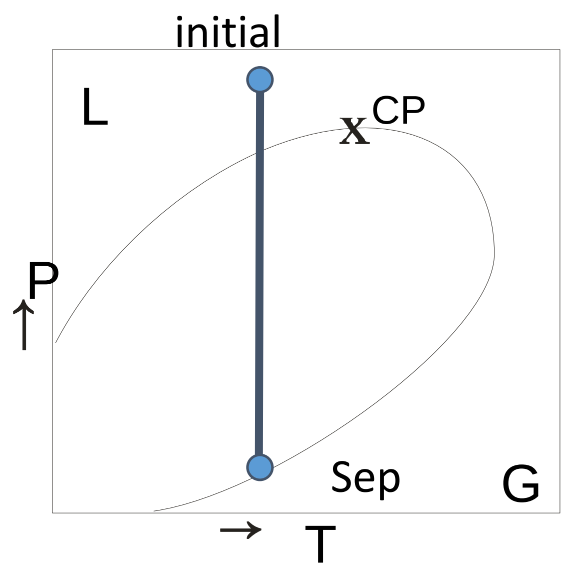
Option 2:

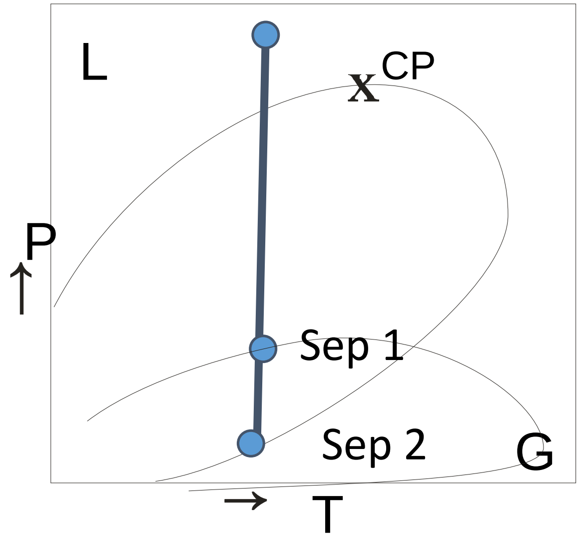


Option 2 gives a lower Bo and more liquid reserves

Hydrocarbon Phase Behavior

Explanation in phase diagram





<u>The extreme case:</u>

Single step to atmospheric:

All you have is gas – no liquids

<u>Two steps:</u>

At first step:

take only the liquid to next separator

This liquid has a different PVT diagram

Result: liquids in the tank

Task of the facility engineer: optimize liquid yield while considering energy and facility cost

Expansion of Fluids

Expansion of fluids as we go from initial pressure to a lower pressure

Expansion of oil and dissolved gas:

- Liquid expansion:

$$N(B_o - B_{oi})$$

- Expansion of gas-cap gas:

$$N(R_{si} - R_s)B_g$$

- Expansion of gas-cap gas:
  - Total volume of gas cap gas is mNB_{oi} (rb), which is $G = mNB_{oi}/B_{gi}$ at scf
  - This amount of gas at lower pressure $mNB_{oi}B_g/B_{gi}$ (rb)
  - Therefore, expansion of gas-cap is

$$mNB_{oi}\left(\frac{B_g}{B_{gi}} - 1\right)$$

Change in HCPV
(Connate-Water Expansion and Pore-Volume Reduction)

Total volume change: d(HCPV) = − dV_w + dV_f or

d(HCPV) = $-(c_w V_w + c_f V_f)\Delta P$ where

V_f is total pore volume = HCPV/(1 − S_{wc}) and

V_w is connate water volume = $V_f \times S_{wc}$

Total HCPV including gascap is $(1+m)NB_{oi}$

then HCPV reduction can be expressed as

$$-\mathrm{d(HCPV)} = (1+m)NB_{oi}\left(\frac{c_w S_{wc} + c_f}{1 - S_{wc}}\right)\Delta P$$

Underground Withdrawal

Observed surface production during pressure drop ΔP is N_p stb of oil and N_pR_p scf of gas (N_pR_s comes from dissolved gas and remaining $N(R_p$-$R_s)$ is from gas cap.

Total underground withdrawal at reservoir condition is

$$N_p\left(B_o + \left(R_p - R_s\right)B_g\right)$$

Equating this withdrawal with the sum of volume changes leads

$$N_p\left(B_o + \left(R_p - R_s\right)B_g\right)$$
$$= NB_{oi}\left[\frac{(B_o - B_{oi}) + (R_{si} - R_s)B_g}{B_{oi}} + m\left(\frac{B_g}{B_{gi}} - 1\right)\right.$$

MB Expressed as Linear Equation

Presented by (Havlena and Odeh)

Production: $F = N_p\,(B_o + (R_p - R_s)B_g) + W_p\,B_w$

Expansion of oil and dissolved gas: $E_o = (B_o - B_{oi}) + (R_{si} - R_s)\,B_g$

Expansion of gas-cap gas: $E_g = B_{oi}(B_g/B_{gi} - 1)$

Expansion of connate water and reduction in pore volume:

$$E_{f,w} = (1+m)B_{oi}\left(\frac{c_w S_{wc} + c_f}{1 - S_{wc}}\right)\Delta P$$

Using these terms, MB equation can be written as

$$F = N\,(E_o + mE_g + E_{f,w}) + W_e\,B_w$$

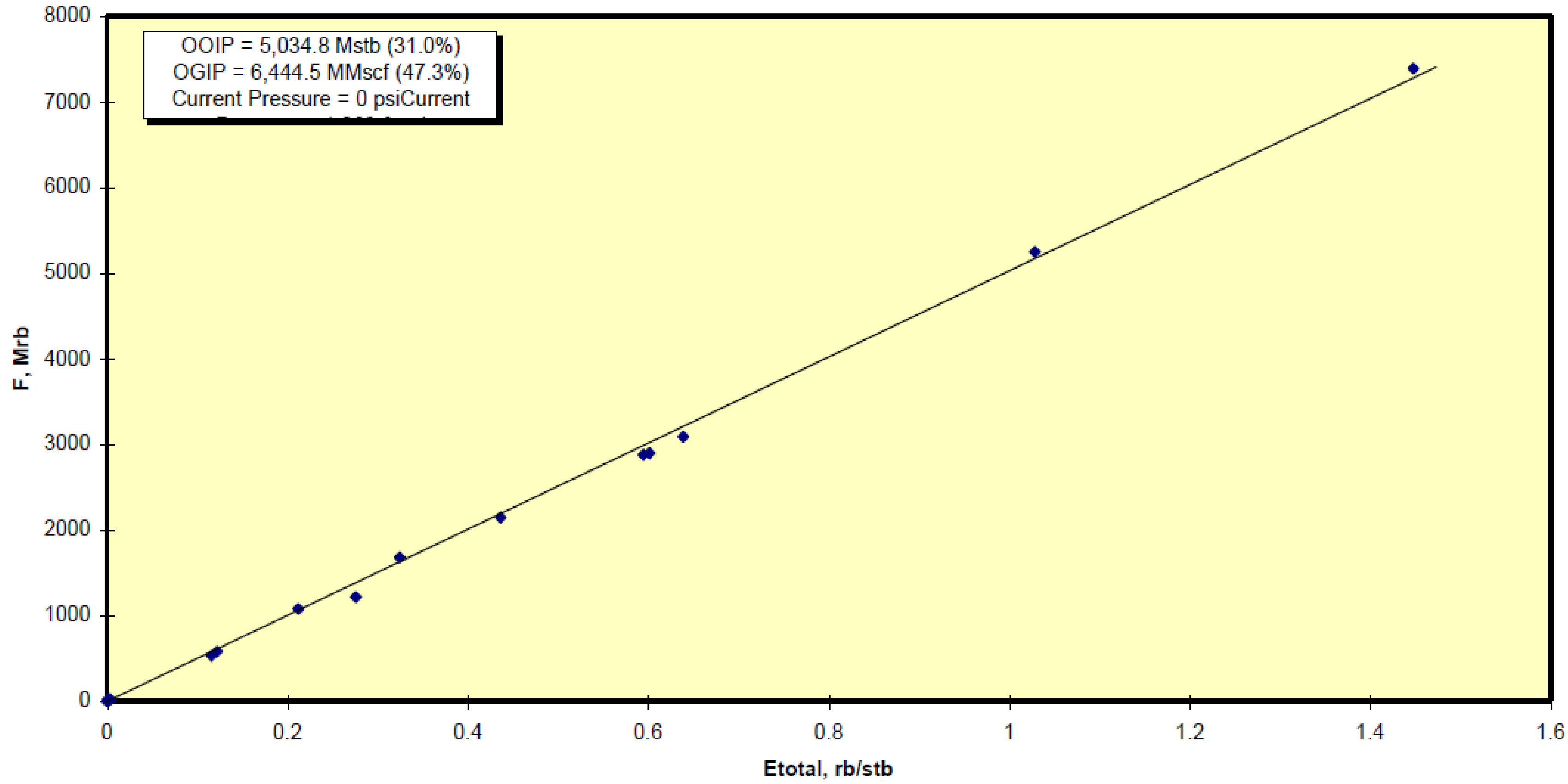
Consider it for different drive mechanisms (solution gas drive, gas-cap drive, water drive)

Solution-Gas Drive

- Mechanisms: expansion of oil and release of its own gas
  - No gas cap: $m = 0$
  - No water influx
- A. above bubble point:
  - $R_s = R_{si} = R_p$ therefore
  - $F = N\,(E_o + E_{f,w})$
- So plot F versus $(E_o + E_{f,w})$ should be straight line with slope of N (STOIIP)
- B. below bubble point:
  - Free gas: $R_s < R_{si}$
  - No initial gas cap
  - $F = N\,(E_o + E_{f,w})$
- So plot F versus $(E_o + E_{f,w})$ should be straight line with slope of N (STOIIP)

Plot of F vs. E_{total}

Should yield a straight line with a *y* intercept of zero and a slope of the original oil in place

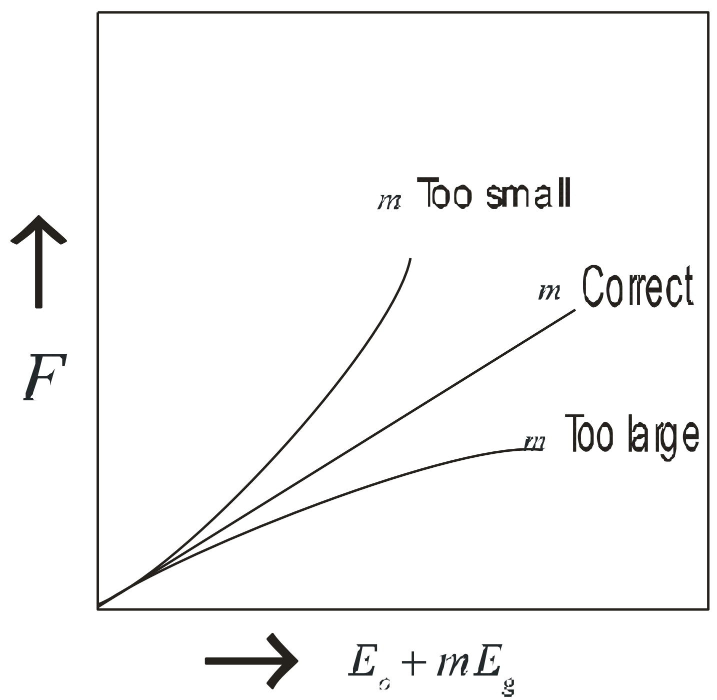


Gas-Cap Drive

- Mechanisms: free gas
  - Pore compressibility negligible
  - No water influx

$$F = N\,(E_o + mE_g)$$

- So plot F versus $(E_o + mE_g)$, slope is N, select m such that a straight line results



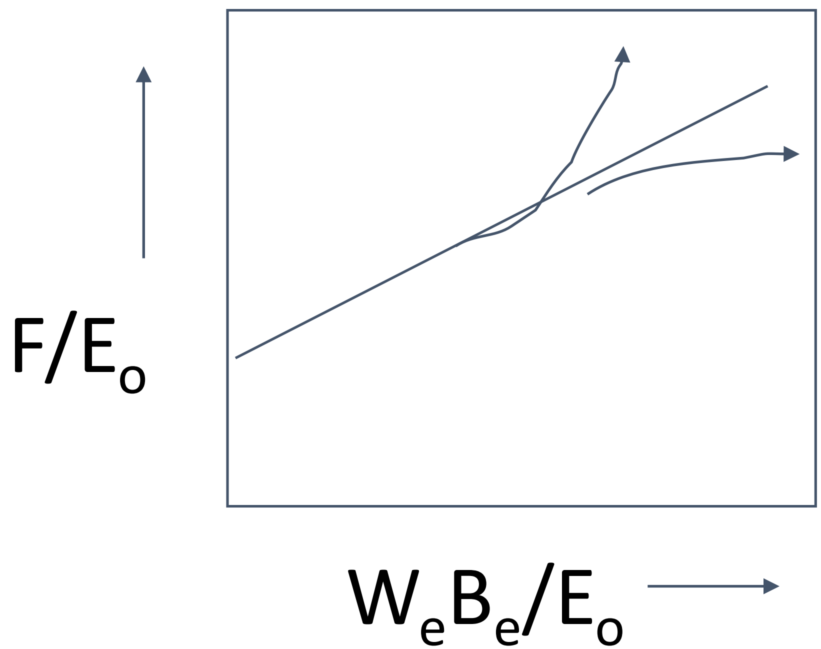
Water Drive

- Mechanisms: water influx, aquifer or injector
  - Pore compressibility negligible

$$F = N\,(E_o) + W_e\,B_w$$

So, plot F/E_o versus W_eB_w/E_o should give a straight line

A good method to verify your aquifer model, which can be complex and a function of pressure and time



Disadvantages MBE

- no flow dynamics
- assumes uniformity of
  - pressure
  - saturation
  - composition
- NO distribution of fluids therefore no real predictive power
- alternative
  - reservoir simulation (history matching)

But ALWAYS do it as sanity check