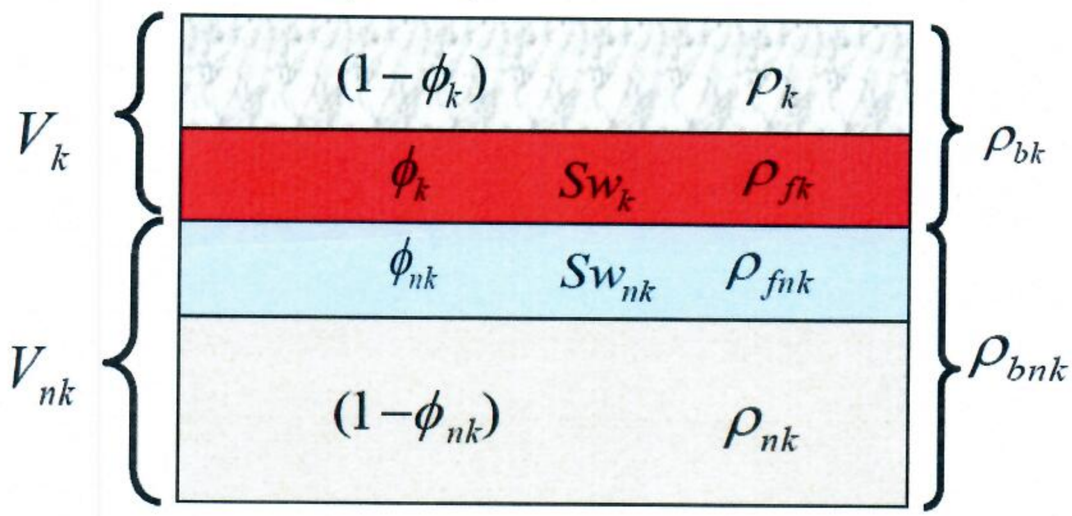
Petrophysical Model for Source Rocks.

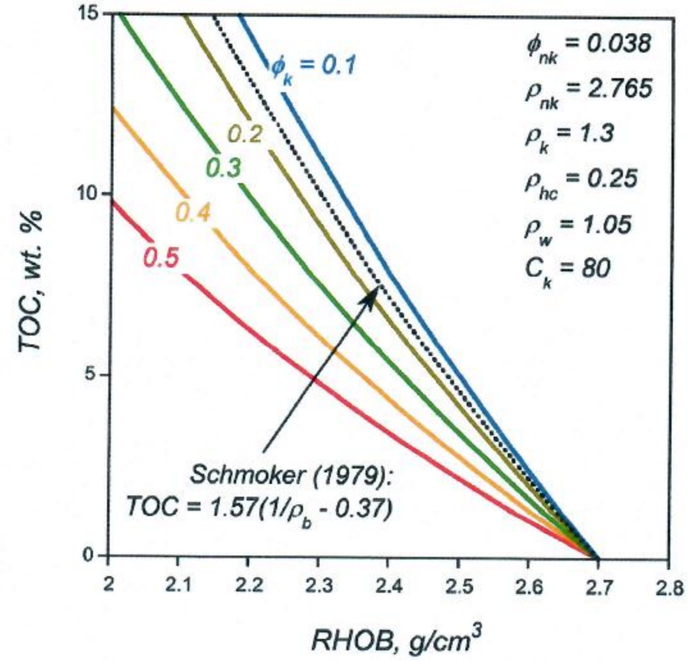
In 2012, Lev + I published an innovative concept "A New Petrophysical Model for Orgnic Shales". The main idea was hydrocarbons occupied organic porosity and water occupied inorganic porosity. This eliminated the need for Archie type resistivity based approach.

Conceptual Model

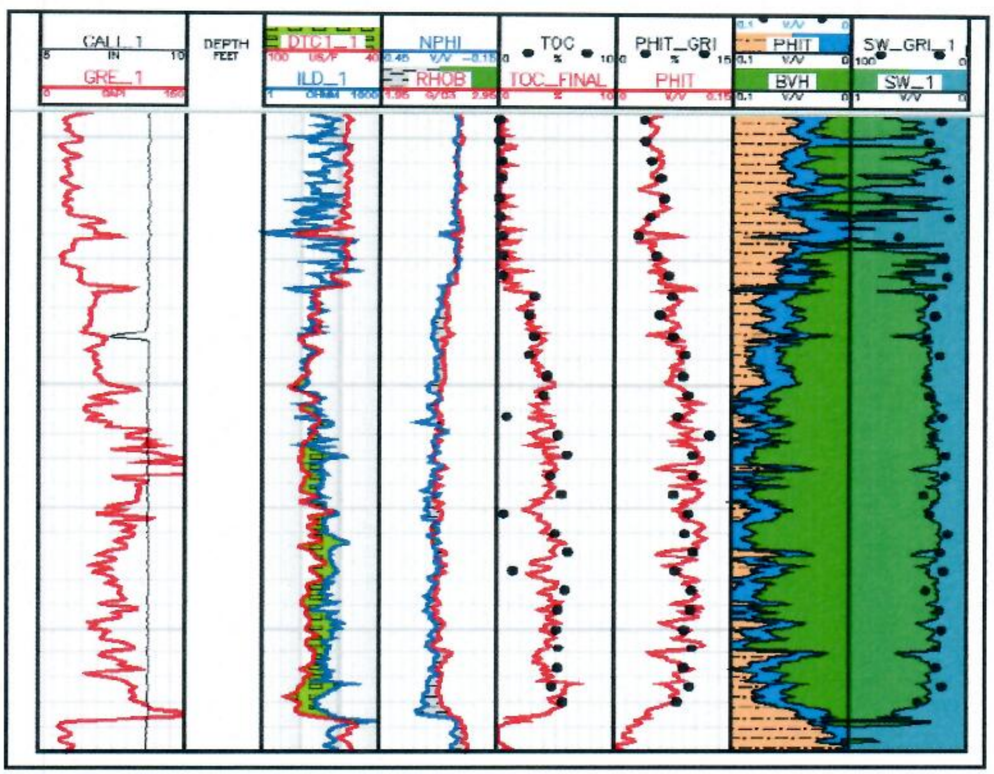


The model decoupled kerogen porosity that is consistent with thermal maturity and constraint by physical bounds from total porosity.

MODEL

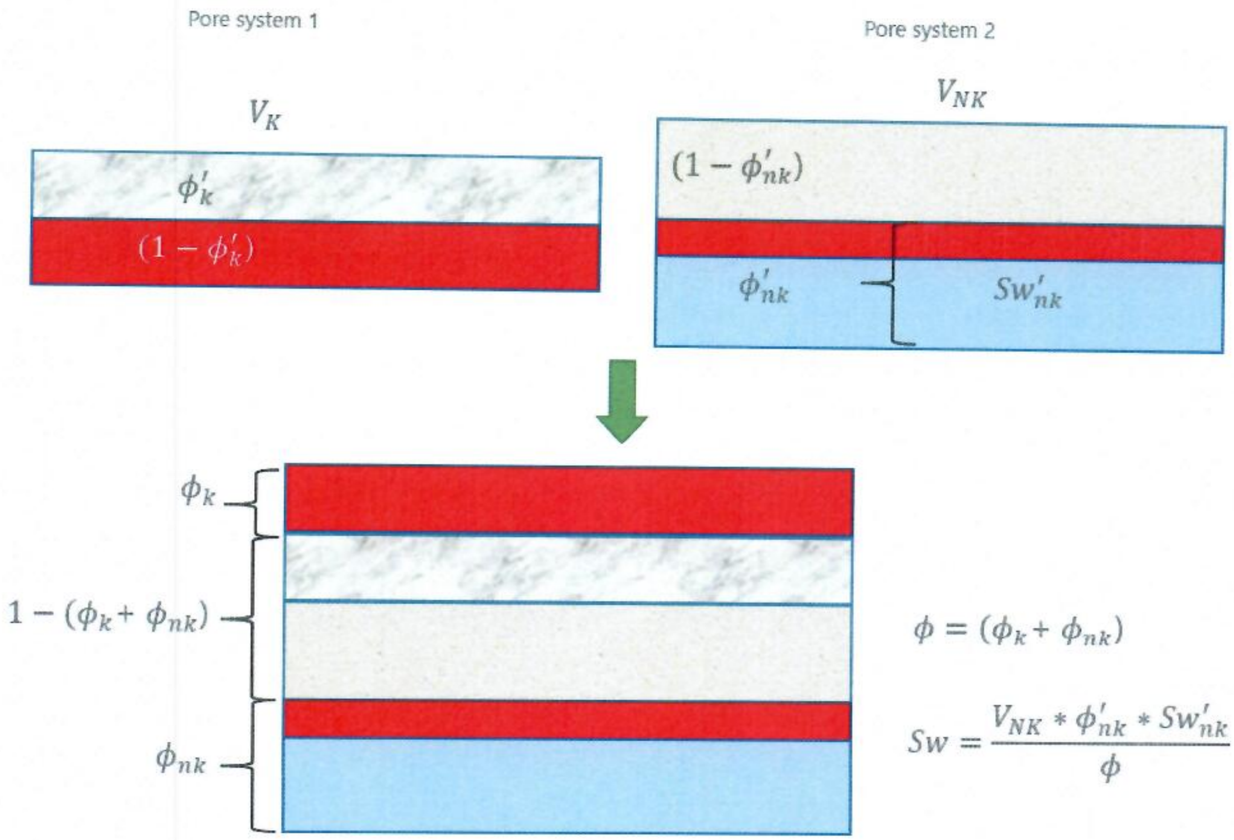


MODEL APPLICATION



while there was consensus about hydrocarbons occupying organic ϕ, the fluids in the host rock was up for debate. Hence this update to the model allowing for both HC & water to exist in the inorganic porosity.

The New Model (Update)



This model eliminates the issues faced by conventional Archie derivative models. The need for R_w, m, n, a, R_t, V_{cl} → no longer is required. Rather two parameters are introduced to obtain a solution.

$$\left.\begin{array}{l} 1.\ S'_{wnK} \\ 2.\ \phi'_{nK} \end{array}\right\} \rightarrow \text{when TOC or Kerogen} = 0.$$

There are ways to estimate this as described earlier or some may find creative ways to introduce these parameters. But the good thing is this model can be used as a calibration tool to estimate them by calibrating to core data.

<u>MODEL INPUTS</u>

1. C_K → % of org. carbon in Kerogen
2. ρ_{nK} → density of inorg. rock
3. ρ_K → density of kerogen
4. ρ_{hc} → hydrocarbon density
5. ρ_w → water density.
6. ρ_b → bulk density
7. TOC → from logs.
8. ϕ'_{nK} → from core or estimate
9. S'_{wnK} → from core or $f(V_{cl})$

Computation:

(1) Kerogen Volume K

$$K = \frac{TOC\ \rho_{nk}}{TOC\ (\rho_{nk} - \rho_k) + C_k \rho_k}$$

(2) Matrix density.

$$\rho_m = K\rho_k + (1-K)\rho_{nk}$$

(3)

$$\phi_k = \frac{ay - bx}{cy - bx}$$

Where

$a = \rho_m - \rho_b$ $\quad b = \rho_m - \rho_{fnk}$

$c = \rho_m - \rho_k$ $\quad x = A\,\phi'_{nk}$ $\quad A = (1-K)$

$y = 1 - \phi'_{nk} + A\,\phi'_{nk}$ $\quad \rho_{fnk} = S'_{wnk}(\rho_w - \rho_{nc}) + \rho_{nc}$

(4)

$$\phi_{nk} = \frac{A\,\phi'_{nk}(1-\phi_k)}{(1 - \phi'_{nk} + A\,\phi'_{nk})}$$

(5)

$$\phi = \phi_k + \phi_{nk}$$

(6)

$$\phi_k' = \frac{\phi_k}{K(1-\phi) + \phi_k}$$

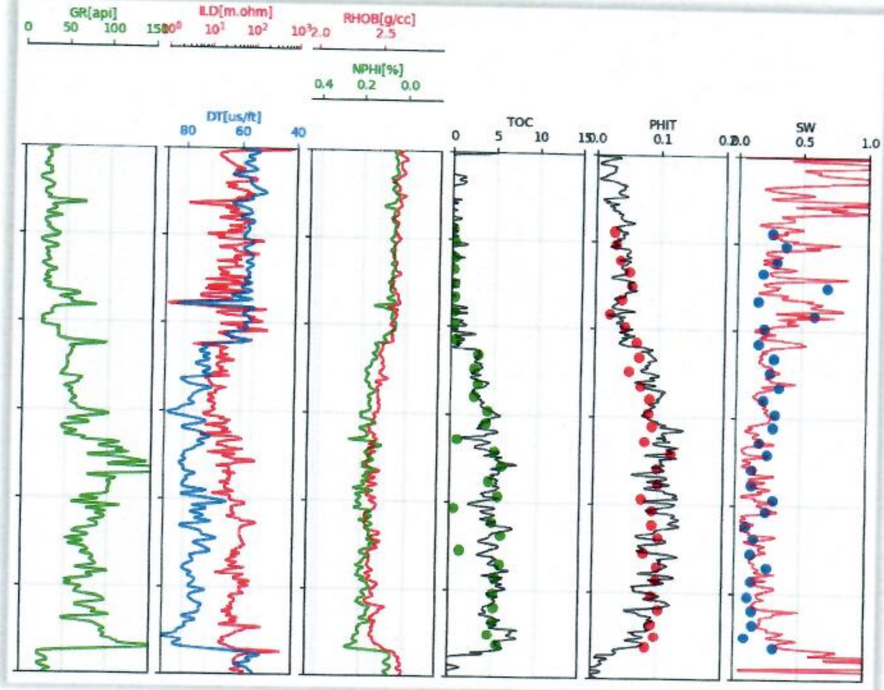
(7)

$$S_w = \frac{V_{nk}\,\phi_{nk}\,S'_{wnk}}{\phi}, \quad V_k = \frac{K(1-\phi)}{(1-\phi_k')}$$

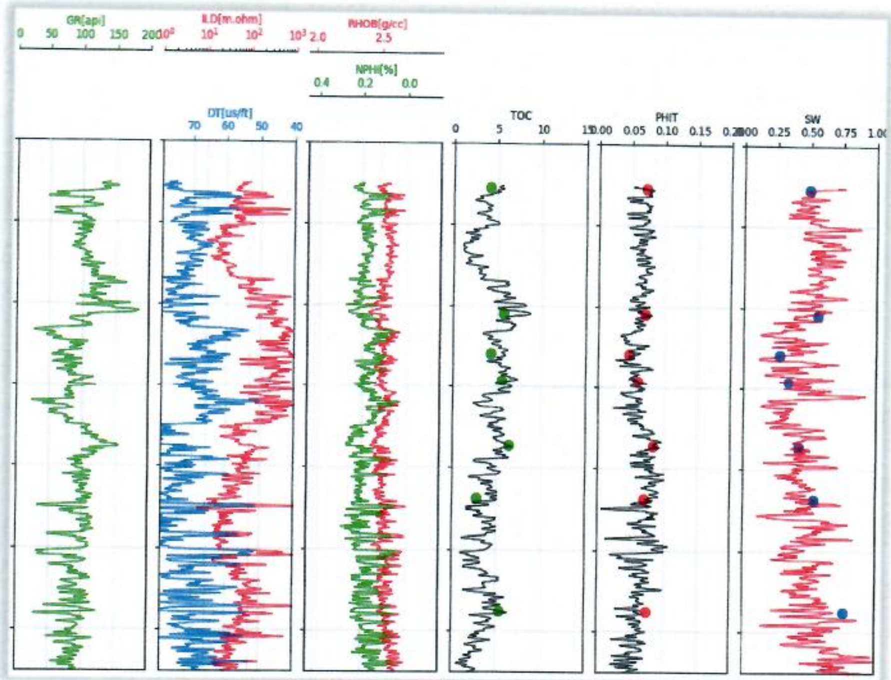
$$V_{nk} = 1 - V_k$$

Model Application:

Shale Play 1



Shale Play 2



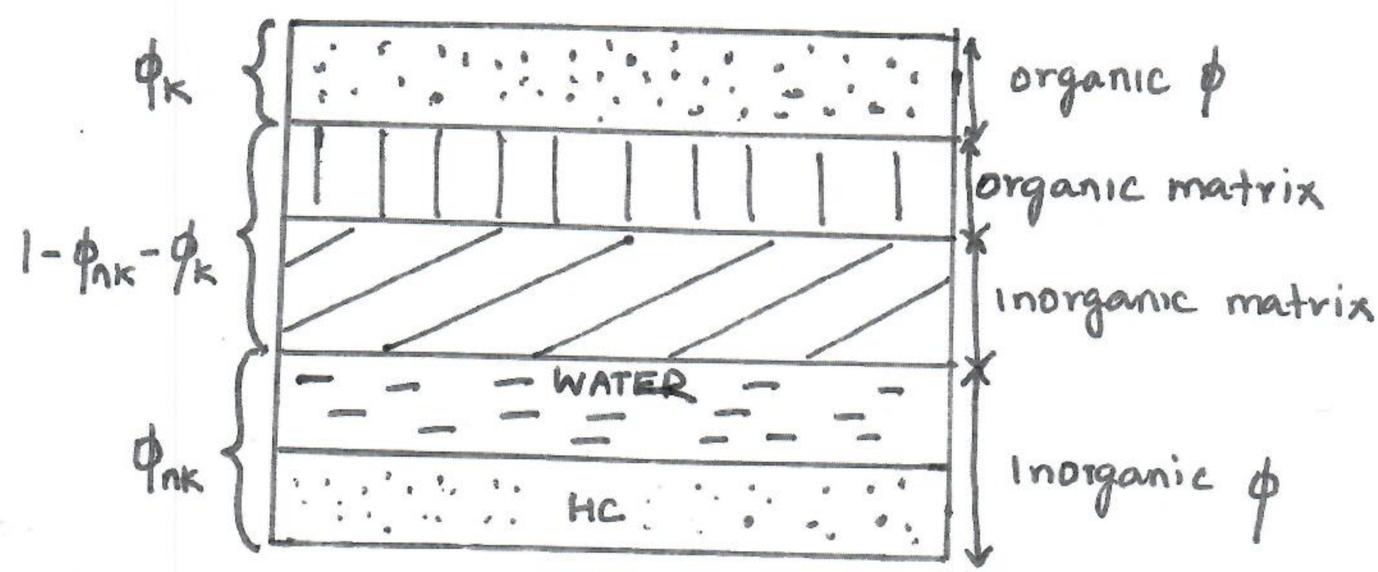
APPENDIX – Model Derivation

SOURCE ROCK PETROPHYSICAL MODEL

UPDATE : HYDROCARBONS IN ORGANIC POROSITY
WATER + HYDROCARBONS IN INORGANIC POROSITY

Let us consider the total system

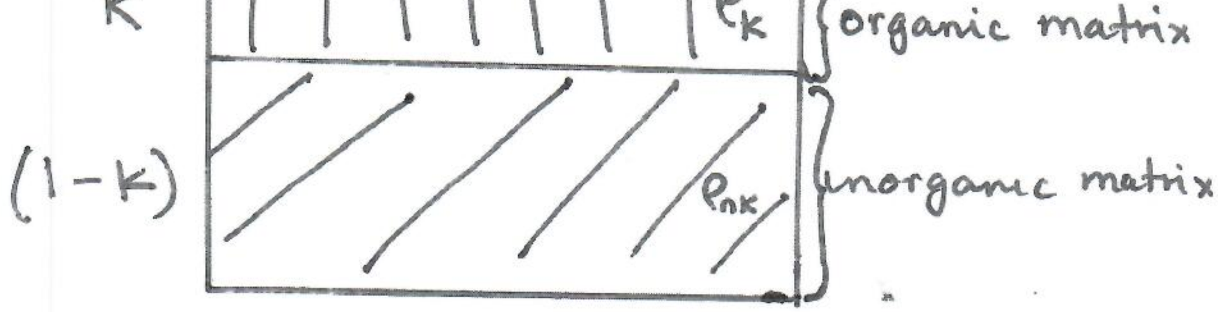
SYSTEM ①



Total porosity $\phi_t = \phi_K + \phi_{nK}$

Lets just take a subset of System ① of only the matrix portion.

System ②



$K \rightarrow$ volume of kerogen (or any orgnic matter)

If ρ_K = density of kerogen and

ρ_{nK} = density of inorganic rock (usually from XRD)

then from mass balance

$$\rho_m = k\rho_K + (1-k)\rho_{nK} \quad - (1)$$

expressing in wt %.

$$1 = \boxed{\frac{k\rho_K}{\rho_m}} + \frac{(1-k)\rho_{nK}}{\rho_m}$$

TOC is the wt % of organic carbon. If C_K is the organic carbon % in kerogen,

$$TOC = \frac{C_K \, k \rho_K}{\rho_m} \quad - (2)$$

$$k = \frac{\rho_{nK} - \rho_m}{\rho_{nK} - \rho_K} \quad \text{from (1)}$$

$$\therefore k = \frac{TOC\,\rho_m}{C_K \rho_K} = \frac{TOC\,\rho_{nK}}{TOC\,(\rho_{nK} - \rho_K) + C_K \rho_K} \quad - (3)$$

Also from (1) & (2)

$$\rho_m = k\rho_k + (1-k)\rho_{nk} \qquad (1)$$

$$TOC = \frac{c_k \, k \, \rho_k}{\rho_m} \qquad (2)$$

can be combined to give.

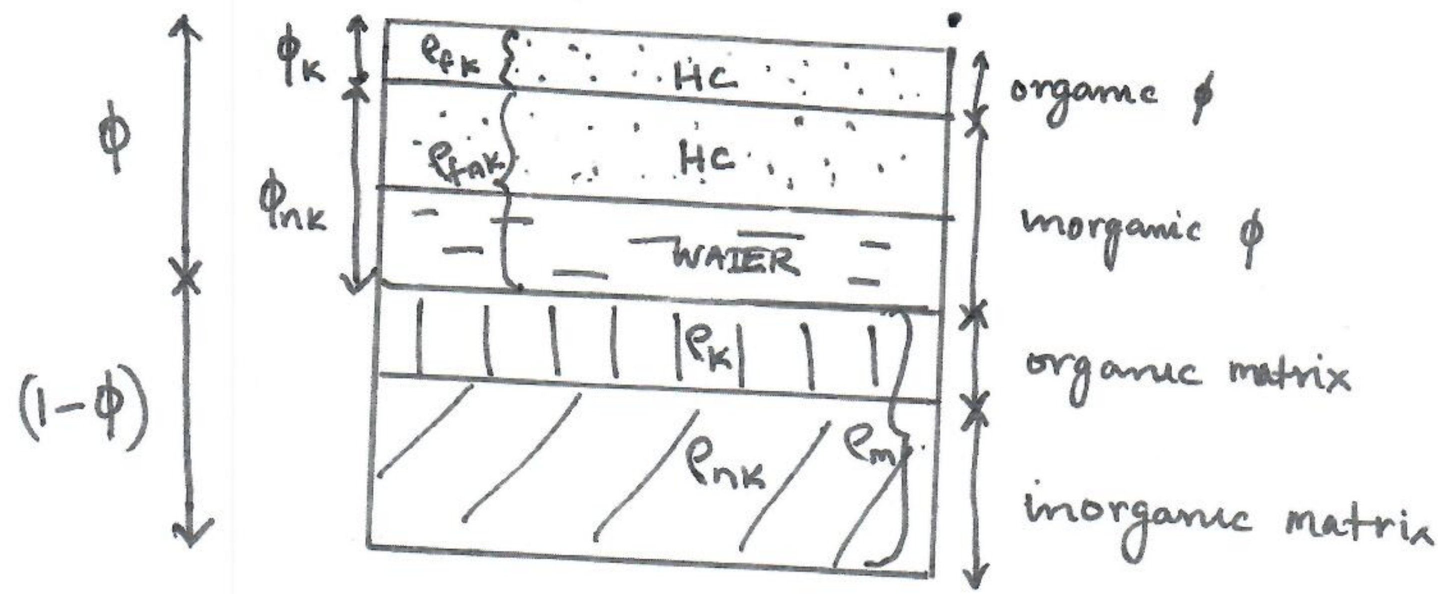
$$\rho_m = \frac{c_k \rho_k \rho_{nk}}{TOC(\rho_{nk} - \rho_k) + c_k \rho_k} \qquad - (4)$$

So after computing TOC from logs,

1. Use eqn (3) to compute kerogen volume
2. use k or TOC to compute ρ_m from eqns (1) or (4)

$\rho_{nk} \rightarrow$ obtained from XRD

Lets rearrange system ①



Total $\phi = \phi_k + \phi_{nk}$

Mass balance

$$\rho_b = \phi_{nk}\rho_{fnk} + \phi_k \rho_{fk} + (1 - \phi_{nk} - \phi_k)\rho_m$$

$$\rho_b = \phi_{nk}\rho_{fnk} + \phi_k \rho_{fk} + \rho_m - \rho_m\phi_{nk} - \rho_m \phi_k$$

$$\rho_b - \rho_m = \phi_{nk}(\rho_{fnk} - \rho_m) + \phi_k(\rho_{fk} - \rho_m)$$

$$\rho_m - \rho_b = \phi_{nk}(\rho_m - \rho_{fnk}) + \phi_k(\rho_m - \rho_{fk})$$

$$\phi_k(\rho_m - \rho_{fk}) = \rho_m - \rho_b - \phi_{nk}(\rho_m - \rho_{fnk})$$

$$\phi_k = \frac{(\rho_m - \rho_b) - \phi_{nk}(\rho_m - \rho_{fnk})}{(\rho_m - \rho_{fk})} \quad - ⑤$$

The assumptions for fluid.

① Kerogen/org. ϕ contains only HC

$$\therefore \quad \rho_{fK} = S'_{wK}\rho_w + (1-S'_{wK})\rho_{hc}$$

$$S_{wK} = 0$$

$$\therefore \quad \rho_{fK} = \rho_{hc}.$$

② Inorg ϕ contains both HC & water.

$$\rho_{fnK} = S'_{wnK}\rho_w + (1-S'_{wnK})\rho_{hc}$$

The '' or prime represents values in the individual domain (explained later).

$$\therefore \quad \rho_{fnK} = S'_{wnK}(\rho_w - \rho_{hc}) + \rho_{hc}.$$

If there is invasion in the system, it is assumed to invade only the In-organic ϕ since org. ϕ is HC wet.

If invasion:

$$\rho_{fnK} = S_{xo}\rho_{filt} + (1-S_{xo})\left[S'_{wnK}(\rho_w - \rho_{hc}) + \rho_{hc}\right]$$

Lets define the domain system porosities
Earlier we said

$$\phi_t = \phi_k + \phi_{nk}$$

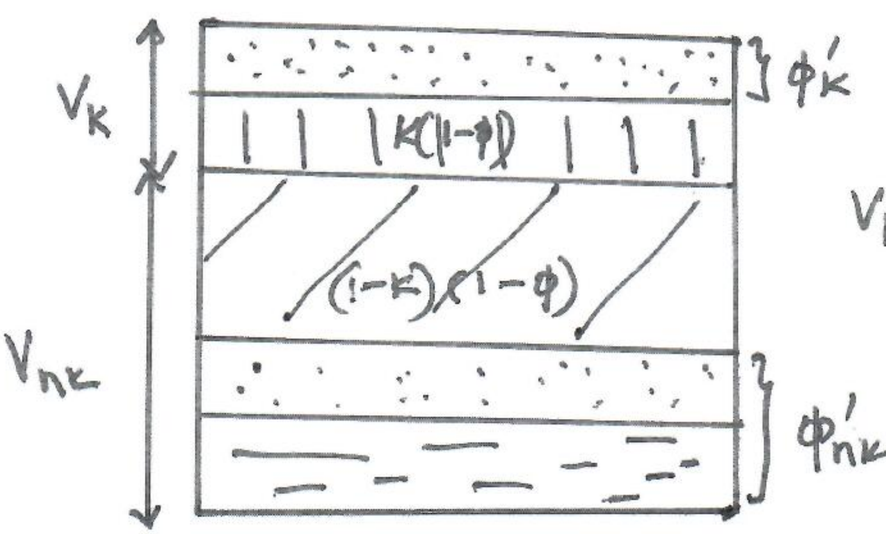
ϕ_k & ϕ_{nk} are the porosities in their def. of the total system, in essence

$$\phi_t = \text{organic } \phi + \text{inorganic } \phi.$$

We now define something called domain specific system → denoted by " ' ".

ϕ_k' → Kerogen domain ϕ → w.r.t. → V_k

ϕ_{nk}' → In orgainc domain ϕ. → w.r.t → V_{nk}.



$$V_k + V_{nk} = 1$$

In this system $\phi = V_k \phi_k' + (1-V_k)\phi_{nk}'$

$$\phi = V_k \phi_k' + (1-V_k)\phi_{nk}'$$

$\therefore$

$$\phi_k = V_k \phi_k'$$

$$\phi_{nk} = (1-V_k)\phi_{nk}'$$

$$V_{nk} = (1-K)(1-\phi) + \phi_{nk}' V_{nk}$$

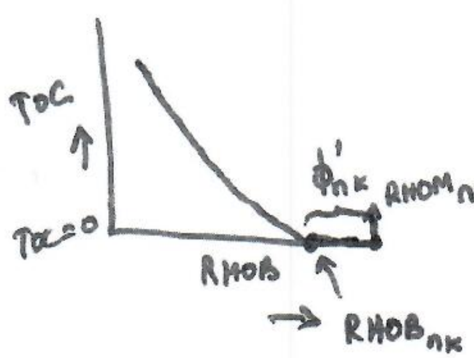
$$V_{nk} = \frac{(1-K)(1-\phi)}{(1-\phi_{nk}')} \quad — (6)$$

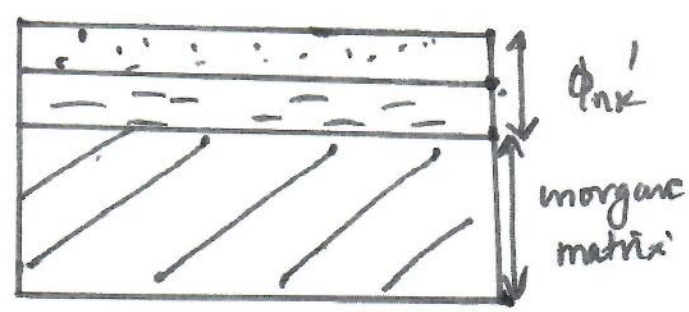
$$\phi_{nk} = (1-V_k)\phi'_{nk}$$

$$\phi_{nk} = \phi_{nk}' * V_{nk} \quad — (7)$$

ϕ_{nk}' is what we get from core data as we extrap at TOC = 0

TOC = 0





From (7)

$$\phi_{nk} = \phi'_{nk} \times V_{nk}$$

$$\phi_{nk} = \phi'_{nk} * \frac{(1-k)(1-\phi)}{(1-\phi'_{nk})}$$

$$\phi'_{nk} = \frac{\phi_{nk}(1-\phi'_{nk})}{(1-k)(1-\phi)}$$

$$\phi'_{nk}(1-k)(1-\phi) = \phi_{nk}(1-\phi'_{nk})$$

Let $A = (1-k)$, also $\phi = \phi_{nk} + \phi_k$

$$A\phi'_{nk}(1-\phi_{nk}-\phi_k) = \phi_{nk}(1-\phi'_{nk})$$

$$A\phi'_{nk}(1-\phi_k) = \phi_{nk}(1-\phi'_{nk}+A\phi'_{nk})$$

$$\phi_{nk} = \frac{A\phi'_{nk}(1-\phi_k)}{(1-\phi'_{nk}+A\phi'_{nk})} \quad -(8)$$

From (5)

$$\phi_k = \frac{(\rho_m - \rho_b) - \phi_{nk}(\rho_m - \rho_{fnk})}{(\rho_m - \rho_{fk})}$$

From (8)

$$\phi_{nk} = \frac{A\,\phi'_{nk}(1-\phi_k)}{(1-\phi'_{nk} + A\,\phi'_{nk})} \quad \text{where } A = (1-K)$$

Let
$$a = \rho_m - \rho_b$$
$$b = \rho_m - \rho_{fnk}$$
$$c = \rho_m - \rho_{fk}$$
$$x = A\,\phi'_{nk}$$
$$y = 1 - \phi'_{nk} + A\,\phi'_{nk}$$

$$\therefore \quad \phi_k = \frac{a - \phi_{nk}\,b}{c} \Rightarrow \frac{a - \frac{bx(1-\phi_k)}{y}}{c}$$

$$\phi_k = \frac{ay - bx + bx\,\phi_k}{cy}$$

$$\phi_k = \frac{ay - bx}{cy - bx} \longrightarrow (9)$$

So after computing

Volume of Kerogen k, matrix density ρ_m

↳ from core data determine ϕ'_{nk} by extrapolating $TOC \to 0$ in TOC vs RHOB plot. (or even TOC vs ϕ plot).

↳ assume an initial estimate of S'_{wnk}. Again (extrapolate $TOC \to 0$ in core TOC vs S_w plot). Also one can use V_{cl} and establish a transform for S_{wnk} from V_{cl}.

Then

↳ compute ϕ_k from (9)

↳ once ϕ_k is computed, compute ϕ_{nk} from (8)

Then total porosity

$$\phi = \phi_k + \phi_{nk}$$

once total porosity ϕ is computed, we can then solve for kerogen domain organic ϕ, ϕ_k'.

$$\phi_K = V_K \phi_K'$$

$$V_K = K(1-\phi) + V_K \phi_K'$$

$$V_K = \frac{K(1-\phi)}{(1-\phi_K')}$$

$$\phi_K = \frac{\phi_K' K (1-\phi)}{(1-\phi_K')}$$

$$(1-\phi_K')\phi_K = \phi_K'[K(1-\phi)]$$

$$\phi_K = \phi_K'[K(1-\phi) + \phi_K]$$

$$\phi_K' = \frac{\phi_K}{K(1-\phi) + \phi_K} \quad - (10)$$

So from previous steps we can solve for

$\rightarrow \phi$ $-(\phi_{nk}+\phi_k)$

$\rightarrow \phi_{nk}$ $-⑧$

$\rightarrow \phi'_{nk}$ - estimate or core data calibration

$\rightarrow \phi_k$ $-⑨$

$\rightarrow \phi'_k$ $-⑩$

The total water saturation of the system S_w is given by.

$$S_w = \frac{V_{nk}\,\phi_{nk}\,S_{wnk}'}{\phi} \qquad -(11)$$

Remember.

$$V_k = \frac{K(1-\phi)}{(1-\phi_k')} \quad \& \quad V_{nk} = 1-V_k \qquad -(12)$$

Also

$$V_k = \frac{\phi - \phi_{nk}'}{\phi_k' - \phi_{nk}'}$$

$$\left(\text{from} \quad \phi = V_k\,\phi_k' + (1-V_k)\,\phi_{nk}'\right)$$