LIFTING THE FOG OF CONFUSION SURROUNDING DETERMINISTIC PETROPHYSICS

Paul Spooner, Lloyd's Register

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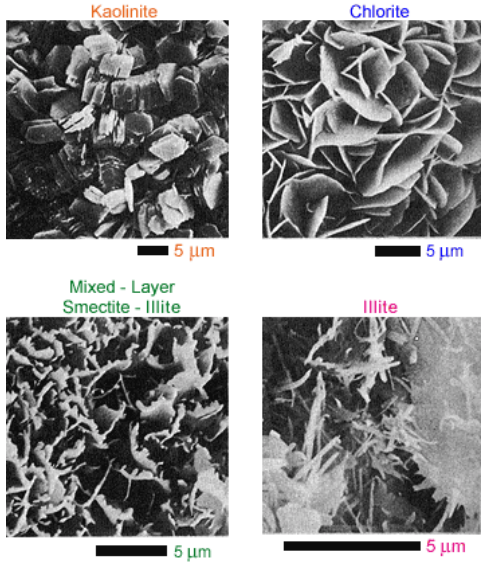
Lifting The Fog of Confusion Surrounding Clay and Shale in Petrophysics

Paul Spooner, SPWLA 55th Annual Logging Symposium, May 18-22, 2014, paper VV

- Shale is a rock, typically defined as an indurated, finely laminated, sedimentary rock, composed primarily of clay, mud and silt.
  - This definition does not describe mineralogy, it describes grain size
  - 'Clay' (in English) refers to clay sized particles, i.e. < 1/256 mm.
- 'Clay' (in English) can also refer to mineralogy, and it is the dual use of this word that is at the heart of the confusion.
  - 'Clay' minerals are a group of hydrous aluminium silicates with a sheet-like structure (phyllosilicates), which adsorb water on their surfaces and have a high CEC (Cation Exchange Capacity).
  - In shales most of the clay sized particles are composed of clay minerals
- This distinction is important because there is so much confusion in the industry where Vshale and Vclay are frequently interchanged



From Wilson, 1982. Courtesy SPE

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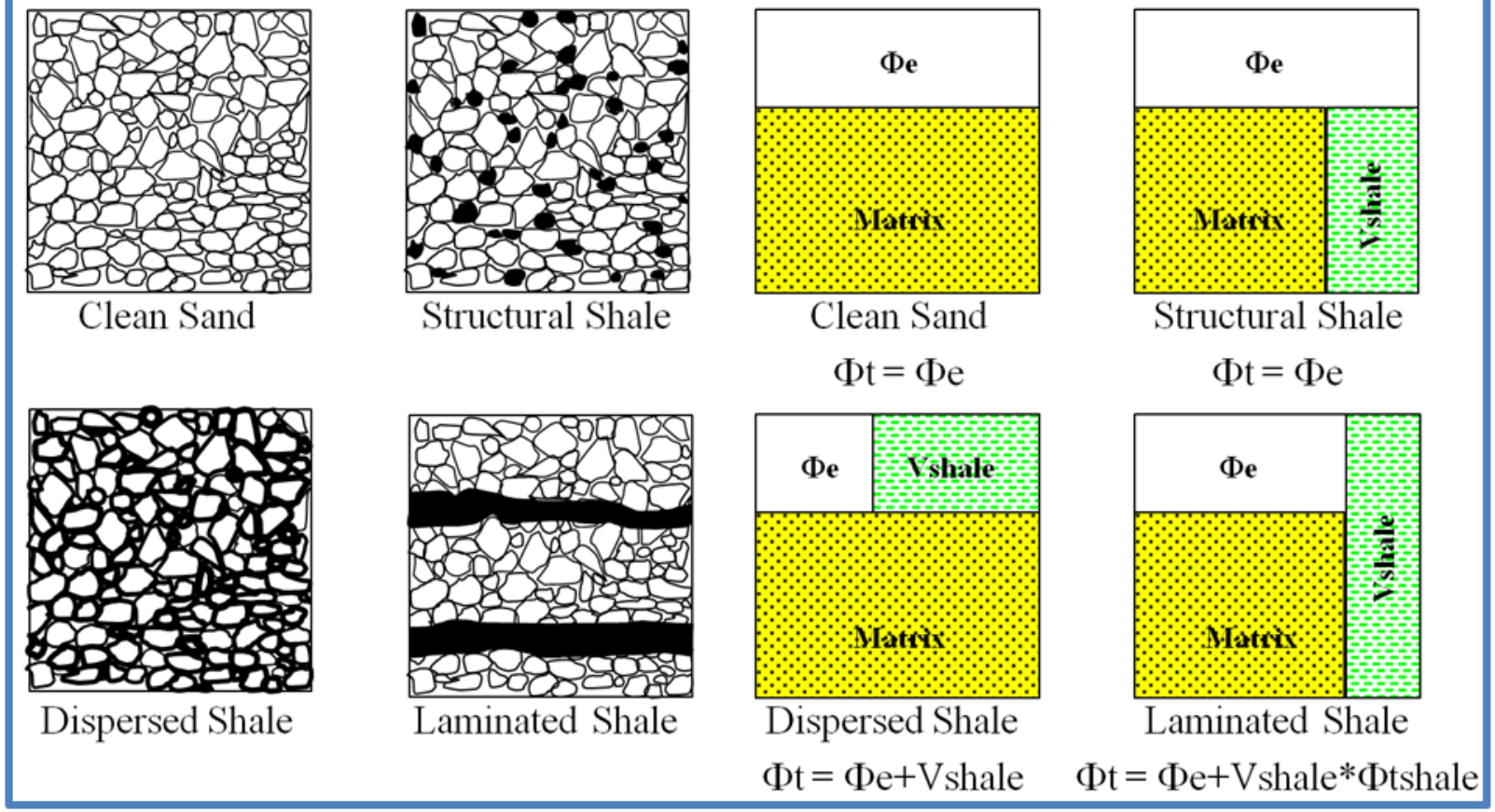
Shale Distribution models, like the one shown, are often used to illustrate shaley-sand interpretation methods, but these models are misleading as they confuse shale and clay.



- Tool response equations have no terms for 'structural', dispersed' or 'laminated' clays (or shales)
- It is the minerals, fluids and their volumes that matter, e.g.

$$\rho_b = \rho_1 * v_1 + \rho_2 * v_2 + \rho_3 * v_3 + \ldots$$

- So, assuming $\Phi e = \Phi t$ -'clay water' (we'll discuss this in the 2nd half)
  - Structural model implies that the 'Shale' must be <u>100% silt</u>
  - Dispersed model implies that the 'Shale' must be <u>100% clay</u>
  - Laminated model is correct in terms of clay, but it is expressed in terms of shale
- *But shale and clay are not the same!*

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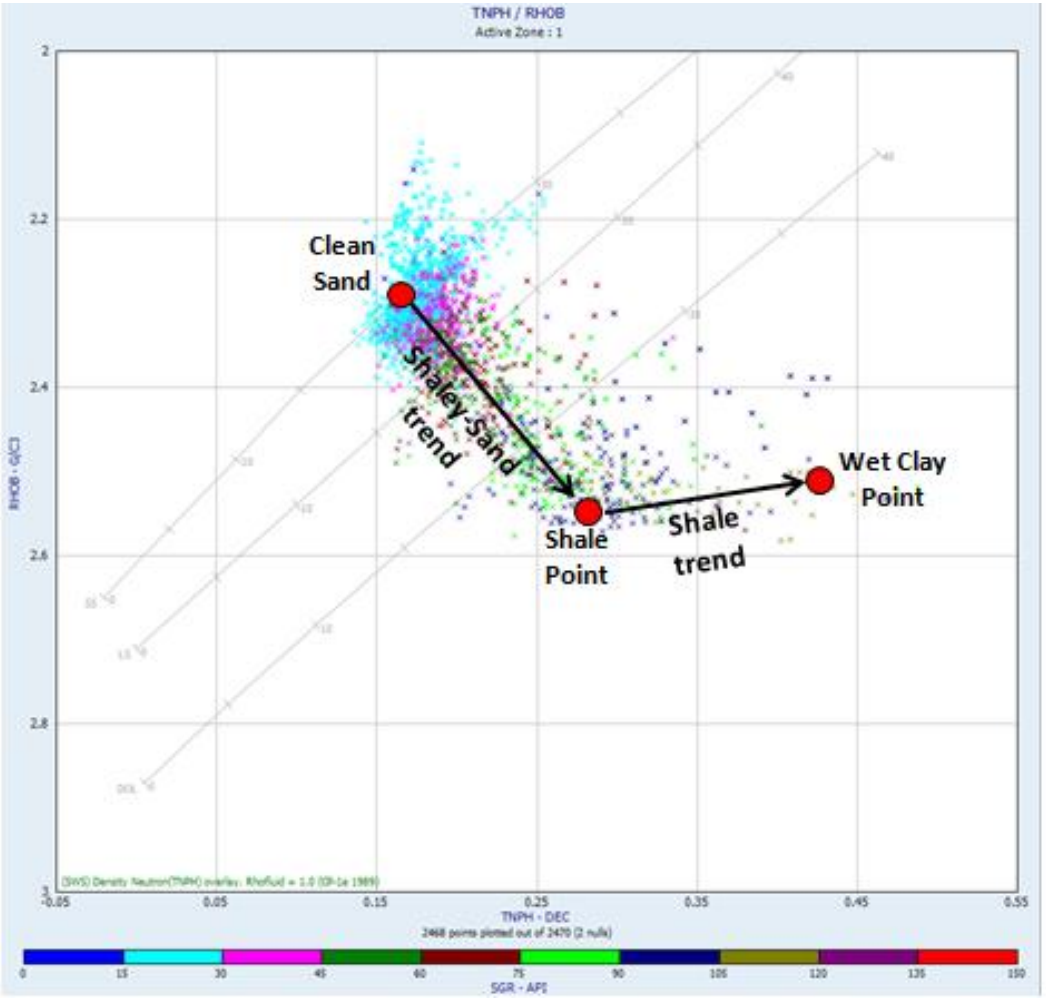

- In a typical shaley-sand we see 2 trends forming an ‘L’ or ‘V’ shape, the Shaley-Sand trend and the Shale trend.
- The Shale Point is the intersection of the two trends, it is the shale in the shaley-sand.
- The shaley-sand trend is a linear volumetric mix of clean sand and shale, i.e. 50% shale by volume will plot half way through this trend.
- The shale trend is important as it provides the means to identify the Wet Clay Point.

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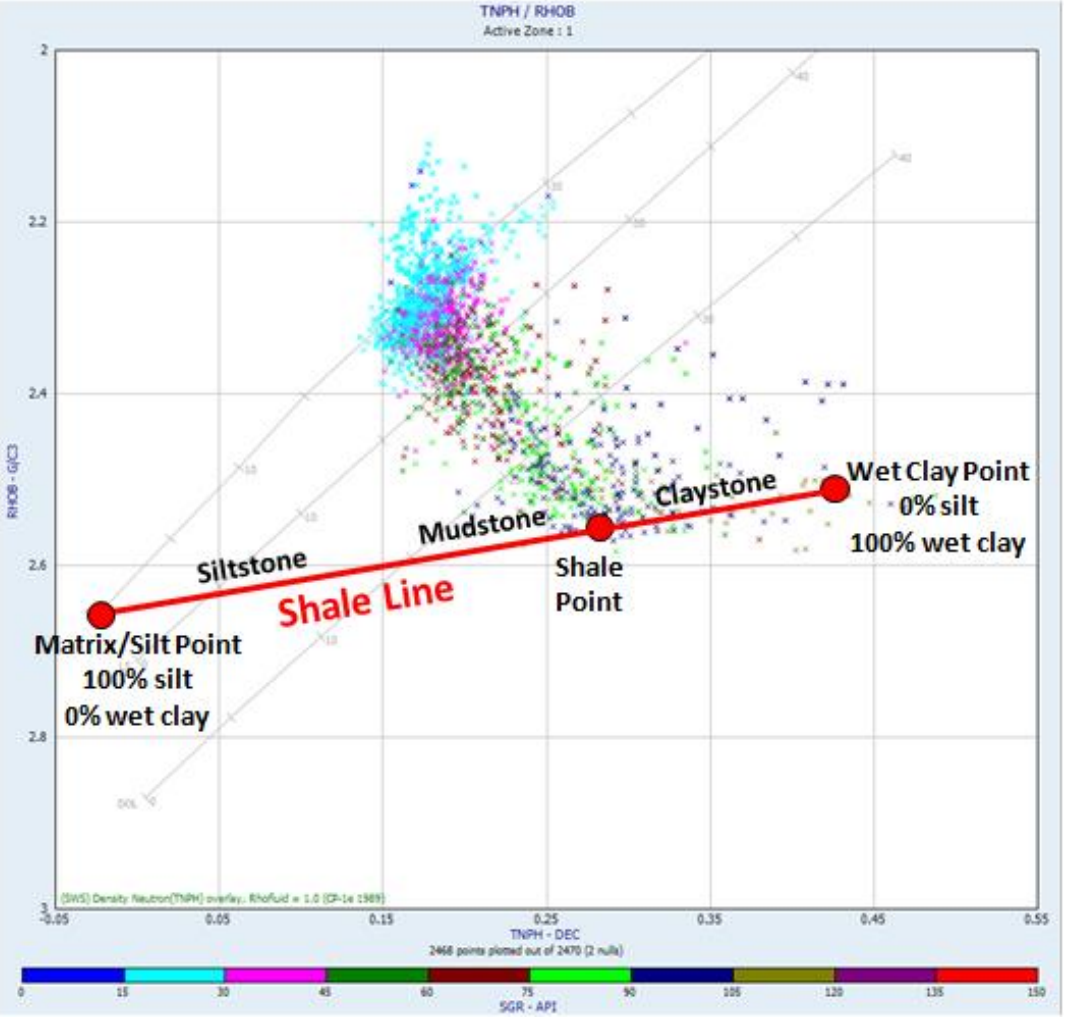
- Shale is a mix of silt, i.e. matrix, and wet clay.
- The 'Shale Line' runs from the Matrix Point (100% silt, 0% wet clay, 0% porosity) to the Wet Clay Point (100% wet clay, 0% silt).
- The location of the Shale Point on the Shale Line depends on the amount of clay and silt in the shale. If the shale is 30% silt and 70% wet clay, the shale point is 70% along the shale line from the Silt Point.
- This reflects the general classification of shale as siltstone, mudstone or claystone.



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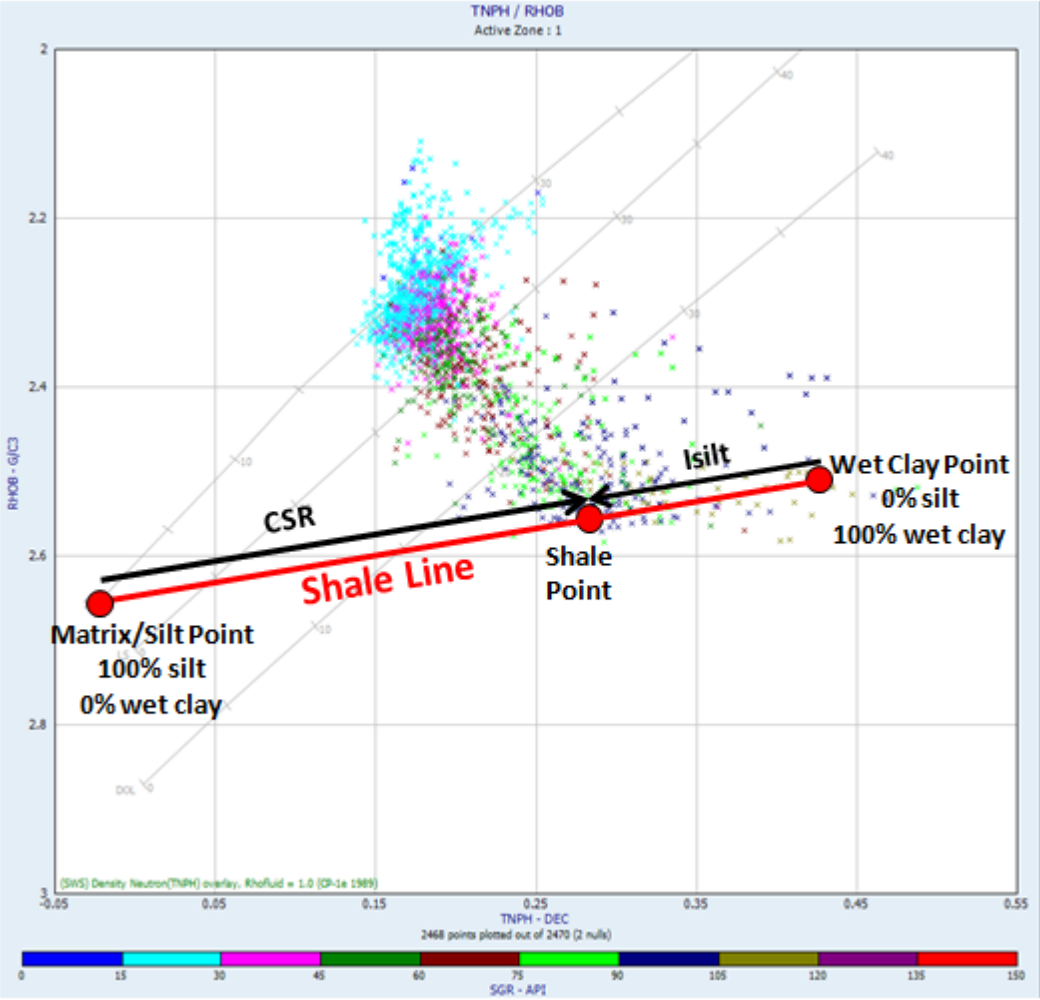

- The Clay Shale Ratio, CSR (sometimes called the Clay:Silt Ratio), is the amount of clay in the shale.
- CSR is how far along the Shale Line the Shale Point is located.
- If shale is 70% clay and 30% silt then CSR is 0.7.
- Silt Index, Isilt, is another way to express the same concept, it would be 0.3.
- Within a linear shaley-sand trend CSR is constant.

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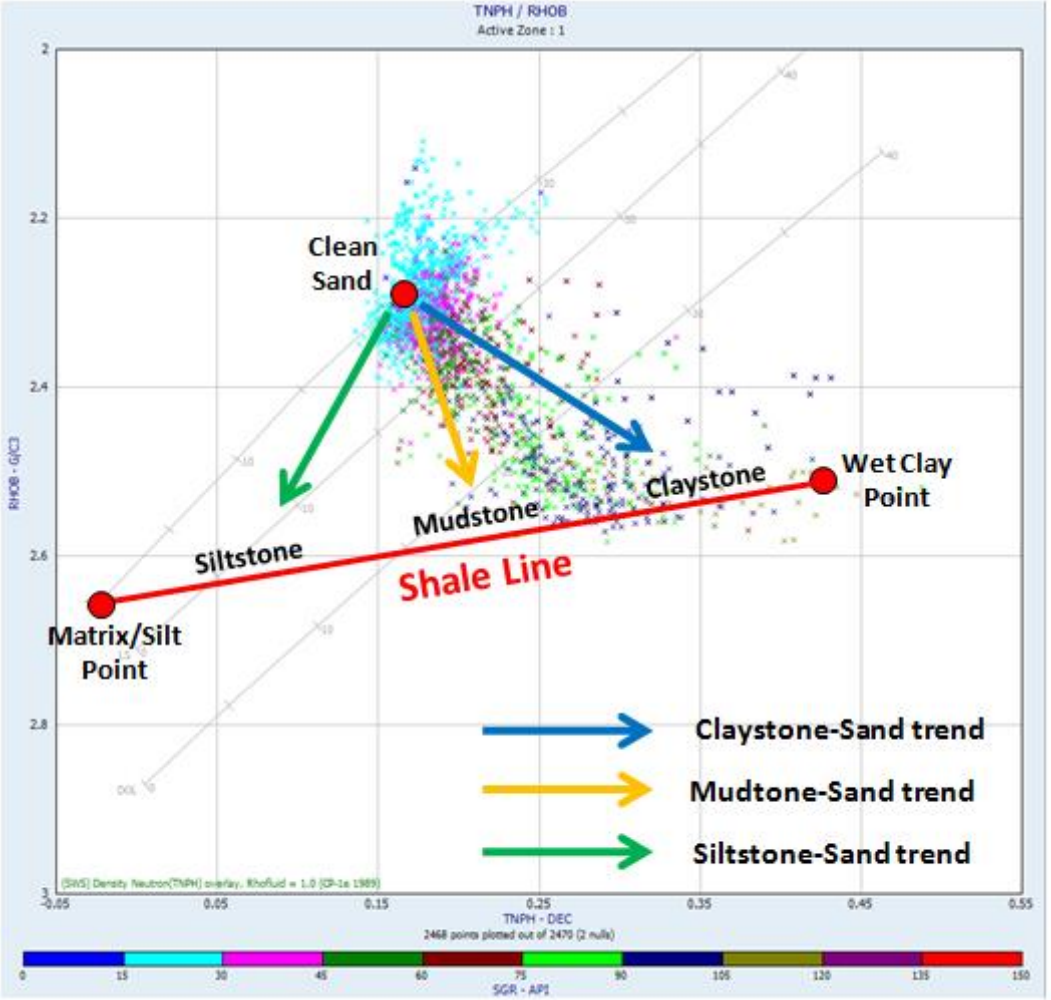

- CSR affects the Shaley-Sand trend.
- Shale with a high clay content will produce a shaley-sand trend toward claystone.
- Shale with similar clay and silt content will produce a shaley-sand trend toward mudstone.
- Shale with a high silt content will produce a shaley-sand trend toward siltstone.
- ‘Laminated’, ‘Structural’ and ‘Dispersed’ shale trends are often identified in the data, but are these real or just the effect of changing CSR?

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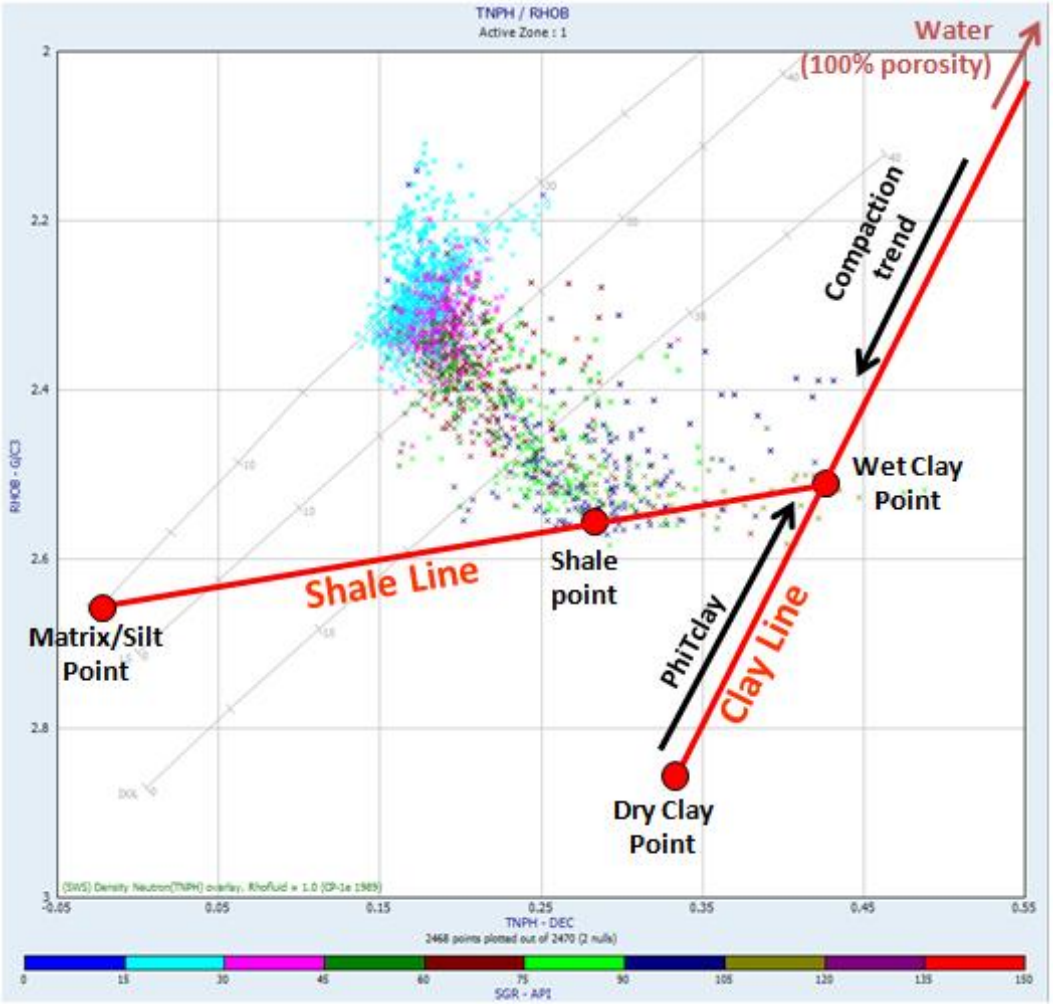

- The Clay Line runs from the Dry Clay Point up through the Wet Clay Point to the Water Point.
- Dry Clay Point is controlled by clay mineralogy.
- Wet Clay Point is controlled by the clay porosity, how much water it holds, PhiTclay.
- PhiTclay can be determined from the Dry Clay density and Wet Clay density.
- The Shale Point, and hence Shaley-Sand trend, are affected by changes in clay mineralogy and ‘wetness’, even when CSR is constant.
- Hence, this can also be misinterpreted as changes in ‘Laminated’, ‘Structural’ and ‘Dispersed’ shale trends .

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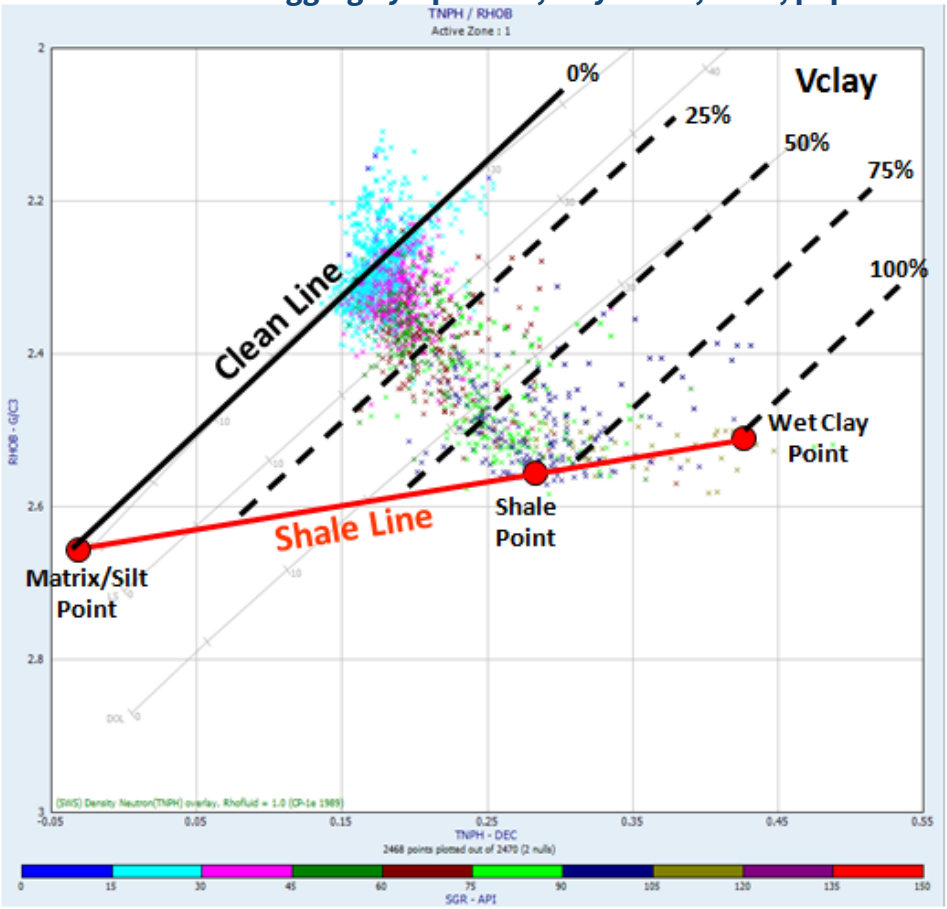
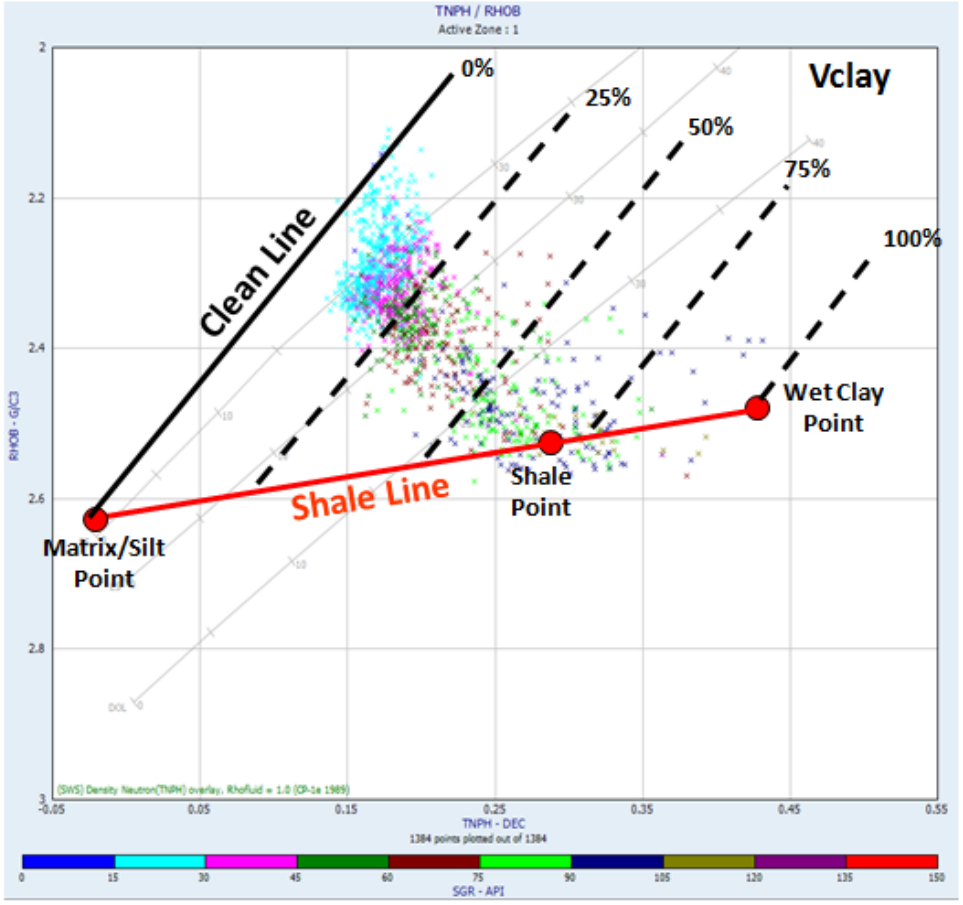




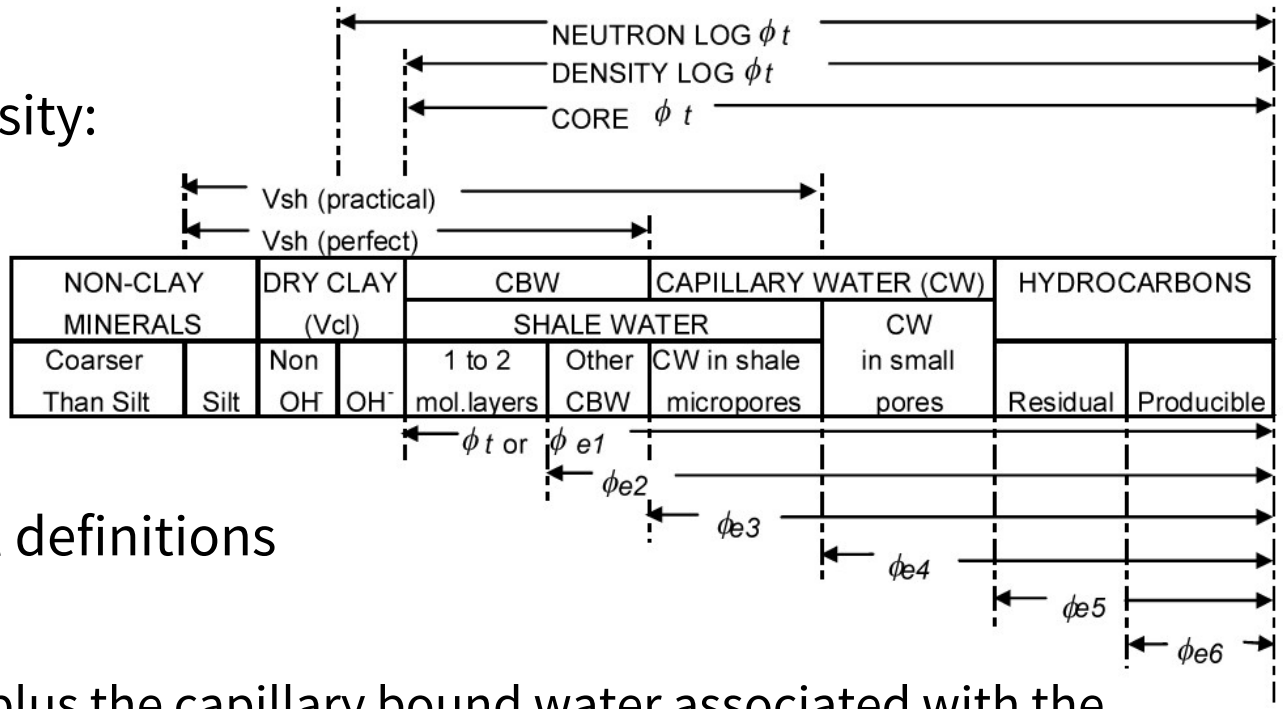
- Vclay is determined by linear interpolation from the clean line (Vclay = 0%) to the Wet Clay Point (Vclay = 100%). Changing the slope of the Clean Line accounts for hydrocarbon effect.

Lifting The Fog of Confusion Surrounding Total and Effective Porosity in Petrophysics

Paul Spooner, SPWLA 59th Annual Logging Symposium, June 2-6, 2018, paper RRR

- Wikipedia has 6 definitions of Effective Porosity:

From Wikipedia - based on the Eslinger & Pevear concept
(Eslinger, Pevear, 1988)



- Φe1 is oven dried core porosity
- Φe2 is humidity core porosity
- Φe3 and Φe4 are the 'normal' petrophysical definitions
  - Φe3 is Φt minus 'clay water'
  - Φe4 is Φt minus 'shale water', i.e. clay water plus the capillary bound water associated with the silt in the shale but excluding the capillary bound water associated with the silt in the sand….. but how can we discriminate that from logs? Even NMR cannot do that.
- Φe5 and Φe6 only consider pore space available to store hydrocarbons
  - They exclude all the bound water…. how do we measure that if Sw>Swirr? NMR in every well?
  - They often also refer to 'connected' porosity….. how do we measure that? NMR cannot do that. Density vs sonic? The difference is often due to the non-linear response of sonic to porosity.

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- In Petrophysics it is confusing to use 2 different definitions of Effective Porosity:
- Φt minus 'clay water' (Φe3) is based on a mineral model
  - This is the definition used by all commercial non-deterministic solvers
  - This is the definition used by all commercial NMR interpretations
  - This is the definition used by some commercial deterministic models
- Φt minus 'shale water' (Φe4) is based on a rock model
  - This is the definition used by some other commercial deterministic models

- Maybe we should standardize on a single definition?

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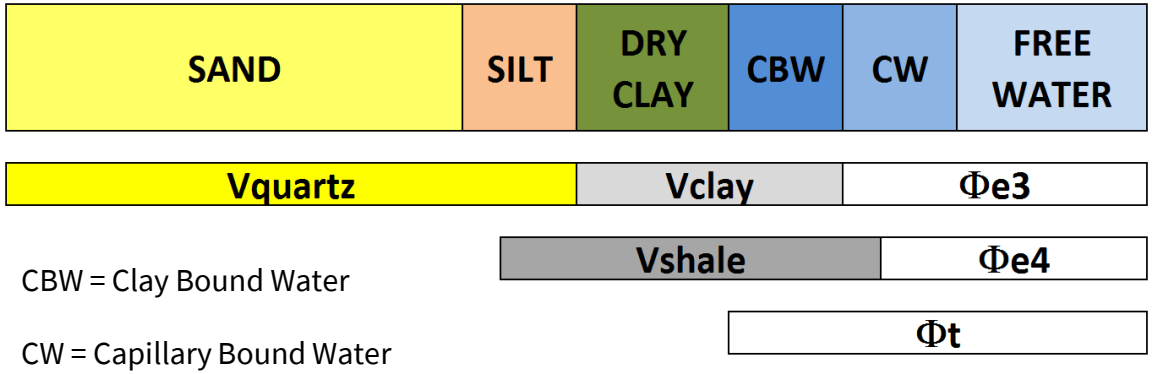
- For a given rock as shown:

  If Vsand = 0.5, Vsilt = 0.12, Vdclay = 0.15, Vcbw = 0.04, Vcw = 0.04, Vfw = 0.15

  Then Vquartz = 0.62, Vclay = 0.19, Φt = 0.23 and Φe3 = 0.19

  Also if Vshale = 0.30 then Φe4 = 0.18



CBW = Clay Bound Water

CW = Capillary Bound Water

- We can then compare different methods of calculating Φt and Φe from the density log:
- Φt first – this intuitively feels correct as we 'correct' Φt to get Φe
  - Method 1 – calibrate directly to core
  - Method 2 – $\Phi t = (\rho_{ma}-\rho_b)/(\rho_{ma}-\rho_{fl})$ and $\Phi e4 = \Phi t - Vsh*\Phi t_{sh}$ where $\Phi t_{sh} = (\rho_{ma}-\rho_{sh})/(\rho_{ma}-\rho_{fl})$
  - Method 3 – Φt same as Method 2 and $\Phi e3 = \Phi t - Vcl*\Phi t_{cl}$ where $\Phi t_{cl} = (\rho_{ma}-\rho_{cl})/(\rho_{ma}-\rho_{fl})$
  - Method 4 – replace ρ_{ma} in Methods 2 or 3 with a shale or clay corrected Grain Density
- Φe first
  - Method 5 – solve the tool response equations directly for Φe

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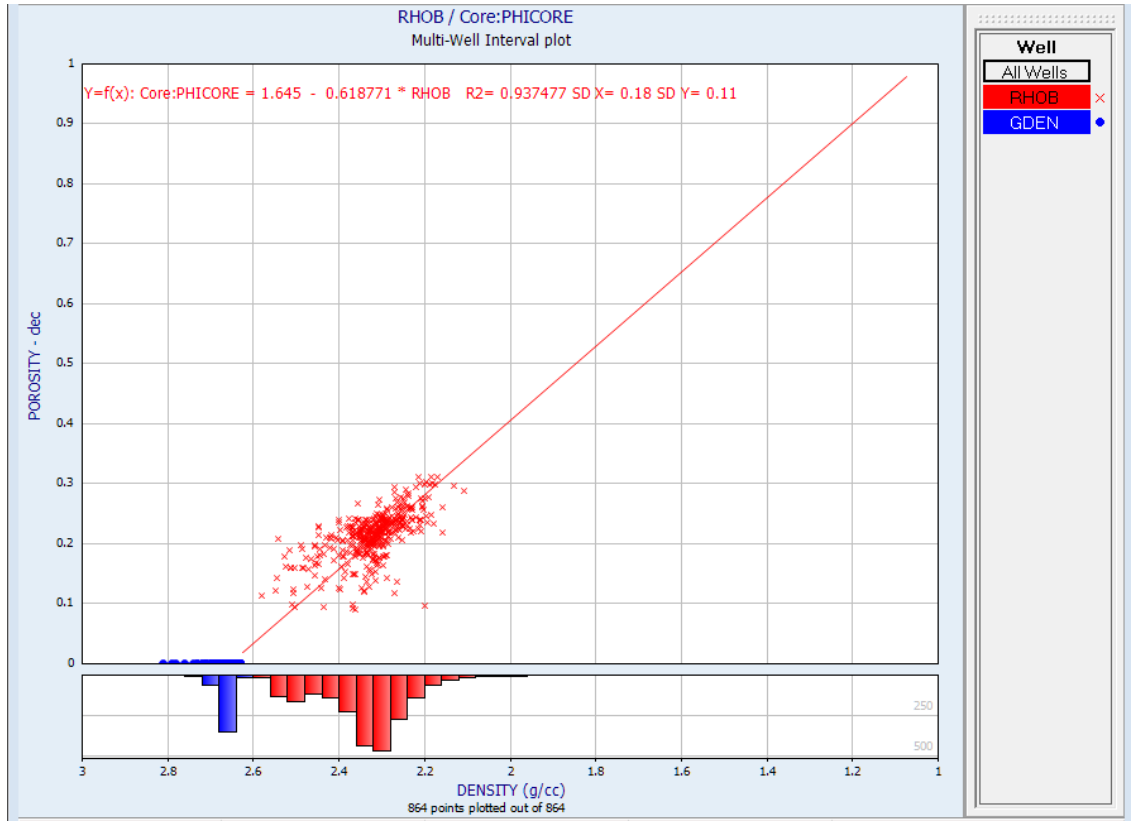
Method 1: Crossplot Regression of density log against core porosity

- This assumes a fixed ρ_{ma} and ρ_{fl}
  - May be robust in homogeneous formations
  - Less robust in heterogeneous formations
    - Changing mineralogy
    - Changing clay content
    - Changing Net-To-Gross
    - Changing fluid types
    - Changing fluid saturations
    - Non cored intervals
- Does not address differences in resolution
  - Problematic in thinly bedded shaley-sands
  - Logs 'see' a different volumetric average
  - Core may be preferentially plugged in clean sands



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Methods 2 and 3:

- Both give the wrong Φt:
  - $(\rho_{ma}-\rho_b)/(\rho_{ma}-\rho_{fl})$ gives the wrong Φt as it ignores the clay minerals
- Both give the wrong water volume
  - $(\rho_{ma}-\rho_{sh})/(\rho_{ma}-\rho_{fl})$ gives the wrong shale water vol as it uses the wrong matrix point
  - $(\rho_{ma}-\rho_{cl})/(\rho_{ma}-\rho_{fl})$ produces wrong clay water vol as it uses the wrong matrix point
- But both Methods <u>do</u> give the right Φe …. Remarkably, 2 wrongs make a right!
- However, this can lead to several problems
  - Comparing the wrong Φt to core Φt can cause parameters to be wrongly picked, e.g. Vcl
  - Using the wrong Φt in SwT equations will give the wrong SwT
  - If ρ_{fl} is solved as a function of Sxo then that might be wrong as well
  - The correct Φt still has to be calculated from Φe using the correct water volumes
  - So, even when done correctly, its still Φe first anyway!

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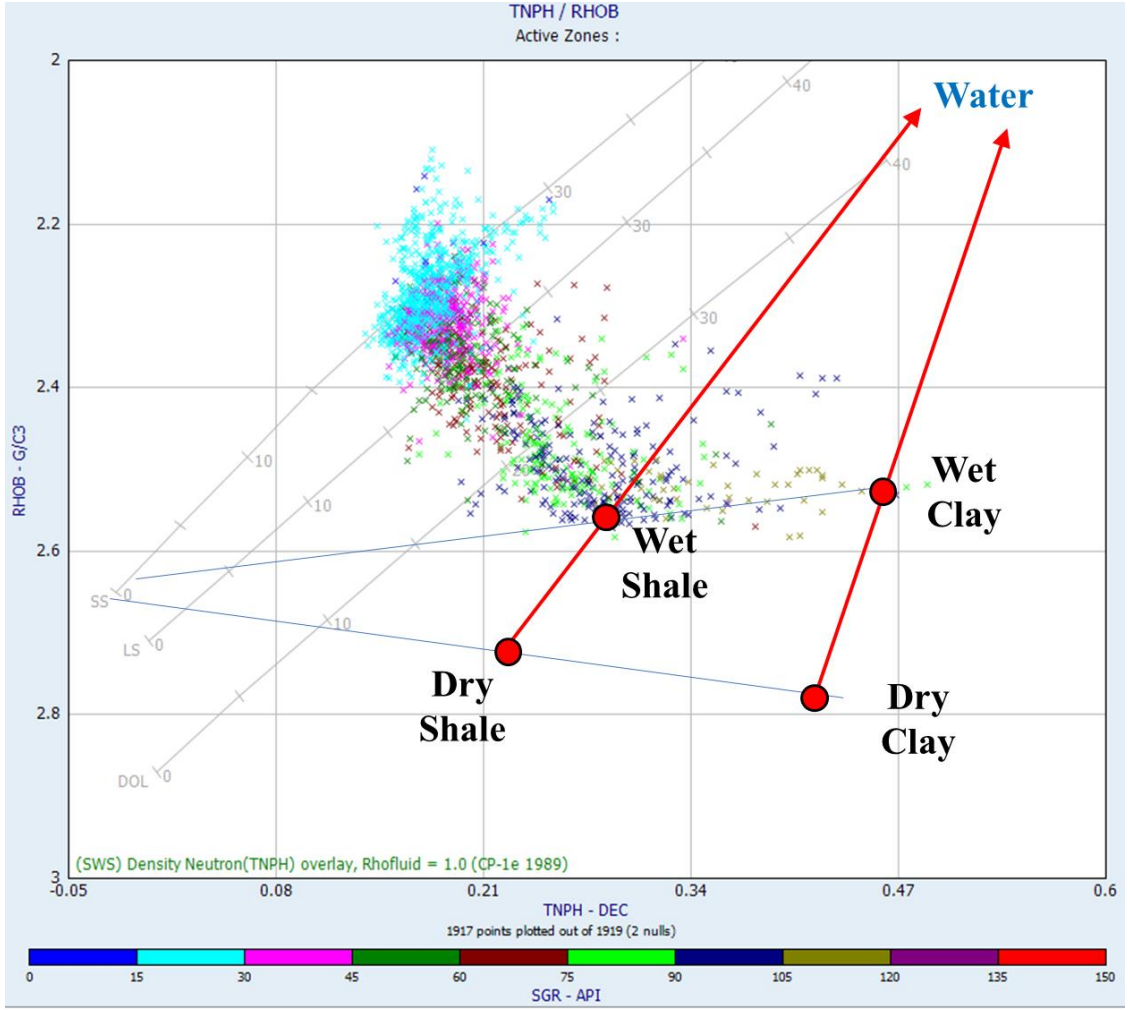
- **Methods 2 and 3**:
- Correct Shale and Clay Water volumes should be calculated using the Dry and Wet points, not ρ_{ma}
  - $\Phi t_{sh} = (\rho_{dsh} - \rho_{sh})/(\rho_{dsh} - \rho_{fl})$
  - $\Phi t_{cl} = (\rho_{dcl} - \rho_{cl})/(\rho_{dcl} - \rho_{fl})$
  - Dry clay density can be inferred from knowledge of the clay mineralogy
  - Dry shale density by interpolation from dry clay density
- Φt is then re-calculated again after Φe
  - $\Phi t = \Phi e + Vsh^* \Phi t_{sh}$
  - $\Phi t = \Phi e + Vcl^* \Phi t_{cl}$
- This last step is usually ignored



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Method 4:

- Various forms of shale or clay correction to ρ_{ma} are in common use, e.g.
  - $Gd = (1-Vsh)^* \rho_{sand} + Vsh^* \rho_{sh}$
  - $Gd = (1-Vcl)^* \rho_{sand} + Vcl^* \rho_{cl}$
  - $Gd = (1-(Vsh^*CLYsh))^* \rho_{sand} +(Vsh^*CLYsh^* \rho_{dcl})$ where CLYsh is the volume of dry clay in wet shale
- All of these give the wrong Grain Density
  - Many of these mix up dry and wet terms so they are inconsistent
  - Grain Density is given by $(\rho_1{}^*v_1 + \rho_2{}^*v_2 +\ldots+ \rho_n{}^*v_n)/(v_1 + v_2 +\ldots+ v_n)$,
    - i.e. it is the dry rock density normalized by $(1-\Phi t)$
  - So using any volumetric sum ignoring the porosity gives the wrong Grain Density
- So they give the wrong Φt

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Method 5:

- The definition of bulk density is $\rho_1 * v_1 + \rho_2 * v_2 + \ldots + \rho_n * v_n$
- For 2 minerals, matrix and wet clay, and 2 fluids, water and hydrocarbon
  - $\Phi e = (\rho_{ma} - \rho_b - Vcl*(\rho_{ma} - \rho_{clay}))/(\rho_{ma} - \rho_w * Sxo - (1 - Sxo * \rho_{hc}))$ and $\Phi t = \Phi e + Vcl * \Phi t_{cl}$
  - This produces a fully consistent result with all the porosities and volumes correct
  - i.e. the tool response equation yields Φe not Φt
- Treating shale as a 'mineral', i.e. matrix, shale, water and hydrocarbon
  - $\Phi e = (\rho_{ma} - \rho_b - Vsh*(\rho_{ma} - \rho_{shale}))/(\rho_{ma} - \rho_w * Sxo - (1 - Sxo * \rho_{hc}))$ and $\Phi t = \Phi e + Vsh * \Phi t_{sh}$
  - This also produces a fully consistent result with all the porosities and volumes correct
- Note that there are no terms for structural, dispersed or laminated!
  - The bulk density log response is <u>not</u> influenced by the distribution of the clays or shales
- We should solve Sxo iteratively as it is a function of porosity and varies with invasion
  - It is more robust to incorporate Rxo data than rely entirely on porosity logs (ND)

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Neutron Density Porosity:

- 2 corrected porosities (ΦDC and ΦNC) are often averaged using a variety of methods
  - $\Phi e = (\Phi DC+\Phi NC)/2$ (without gas) $\Phi e = ((\Phi DC^2+\Phi NC^2))^{1/2}/2$ (with gas)
  - $\Phi t = \Phi e + Vsh*\Phi t_{sh}$ where $\Phi t_{sh} = \delta*\Phi D_{sh} + (1-\delta)*\Phi N_{sh}$ where δ is 0.5 to 1
  - These are empirical averages that do not correctly solve the problem
- Neutron Porosity
  - Often simply corrected in a similar manner to Methods 2 & 3 but this is wrong
  - The full tool response equation also includes Matrix, Excavation and Salinity corrections
  - The matrix correction should include the silt from both the sand and the shale volumes
  - Therefore, for Method 5, we should use the Vcl option, not Vsh
- 2 equations solved together
  - 2nd variable can be one of the common parameters, e.g. ρ_{ma}, ρ_{hc}, Sxo or Vcl
  - ρ_{ma} makes an excellent 2nd variable as it is good way to QC the interpretation

$$\emptyset e3 = \frac{\rho ma - \rho b - Vcl*(\rho ma - \rho cl)}{\rho ma - \rho w*Sxo - (1-Sxo)*\rho hc}$$

$$\emptyset e3 = \frac{\emptyset N - Vcl*Ncl + Nma + Exfact + Nsal}{Sxo + (1-Sxo)*Nhc}$$

Thank You

Questions ?

Please contact:
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