Gaffney, Cline & Associates

CLASTICS; How to choose the right petrophysical evaluation method using standard logs

London Petrophysical Society: Petrophysics 101

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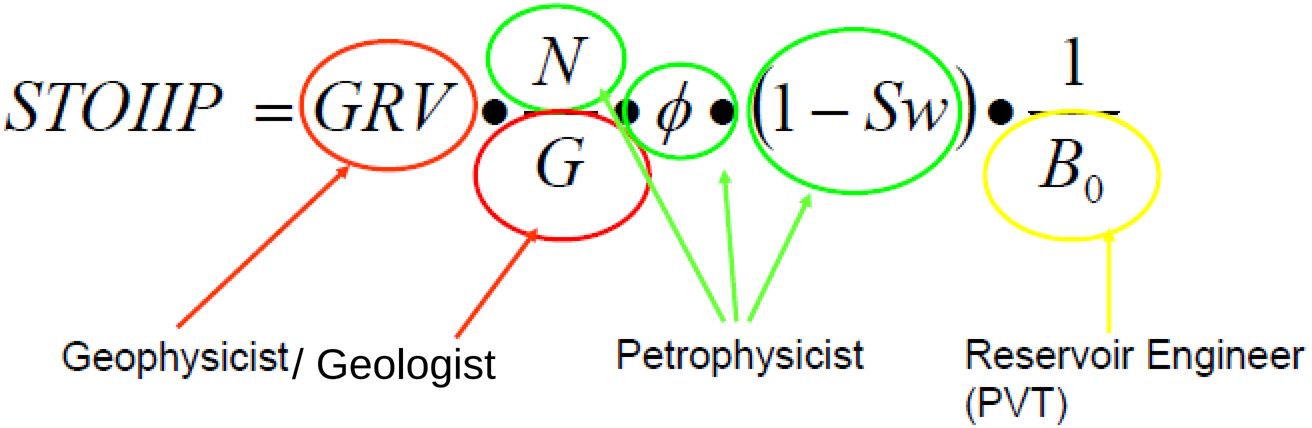
17th March 2016

Petrophysics: key inputs to volumes evaluation



$$STOIIP = GRV \bullet \frac{N}{G} \bullet \phi \bullet (1 - Sw) \bullet \frac{1}{B_0}$$

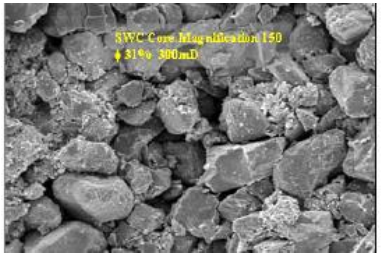
Geophysicist/ Geologist

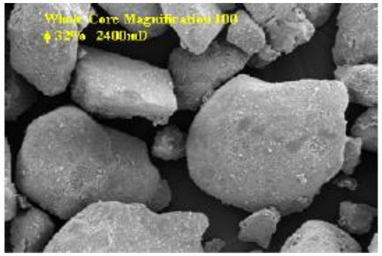
Petrophysicist

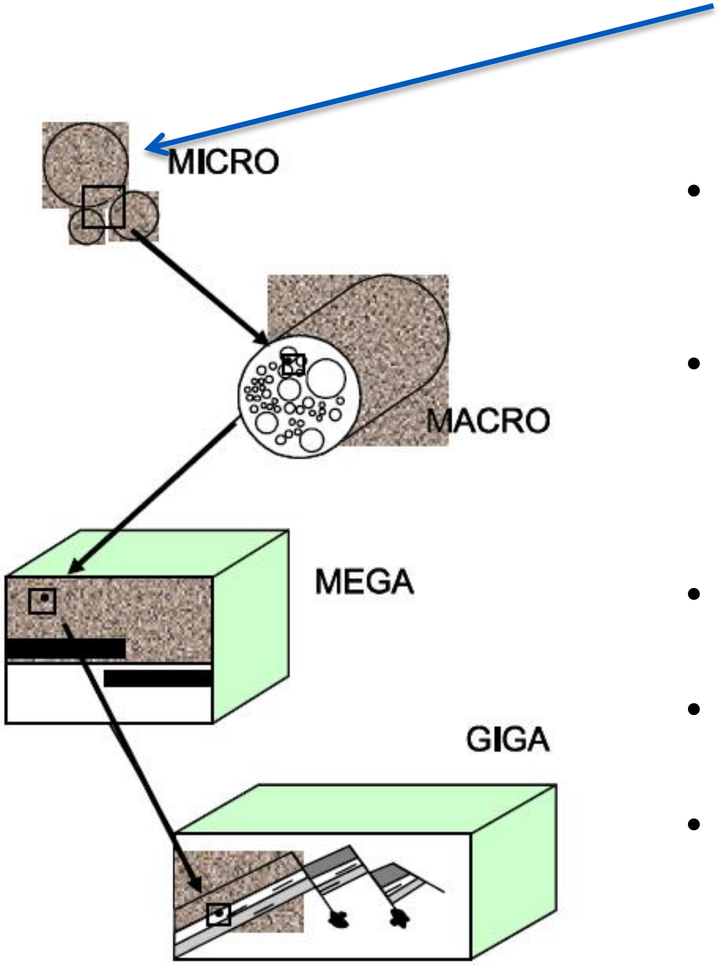
Reservoir Engineer
(PVT)

Oil initially in place	STOIIP	
Gross rock volume	GRV	
Net to Gross	N/G	logs, welltests, core (permeability)
Porosity	ϕ	logs, core (stressed porosity)
Water saturation	Sw	logs, core (Archie m & n, Dean-Stark Sw) saturation-height (core capillary pressure)
Formation volume factor	B_o	laboratory measurements on fluids

Clastic Reservoirs: data measured at different scales

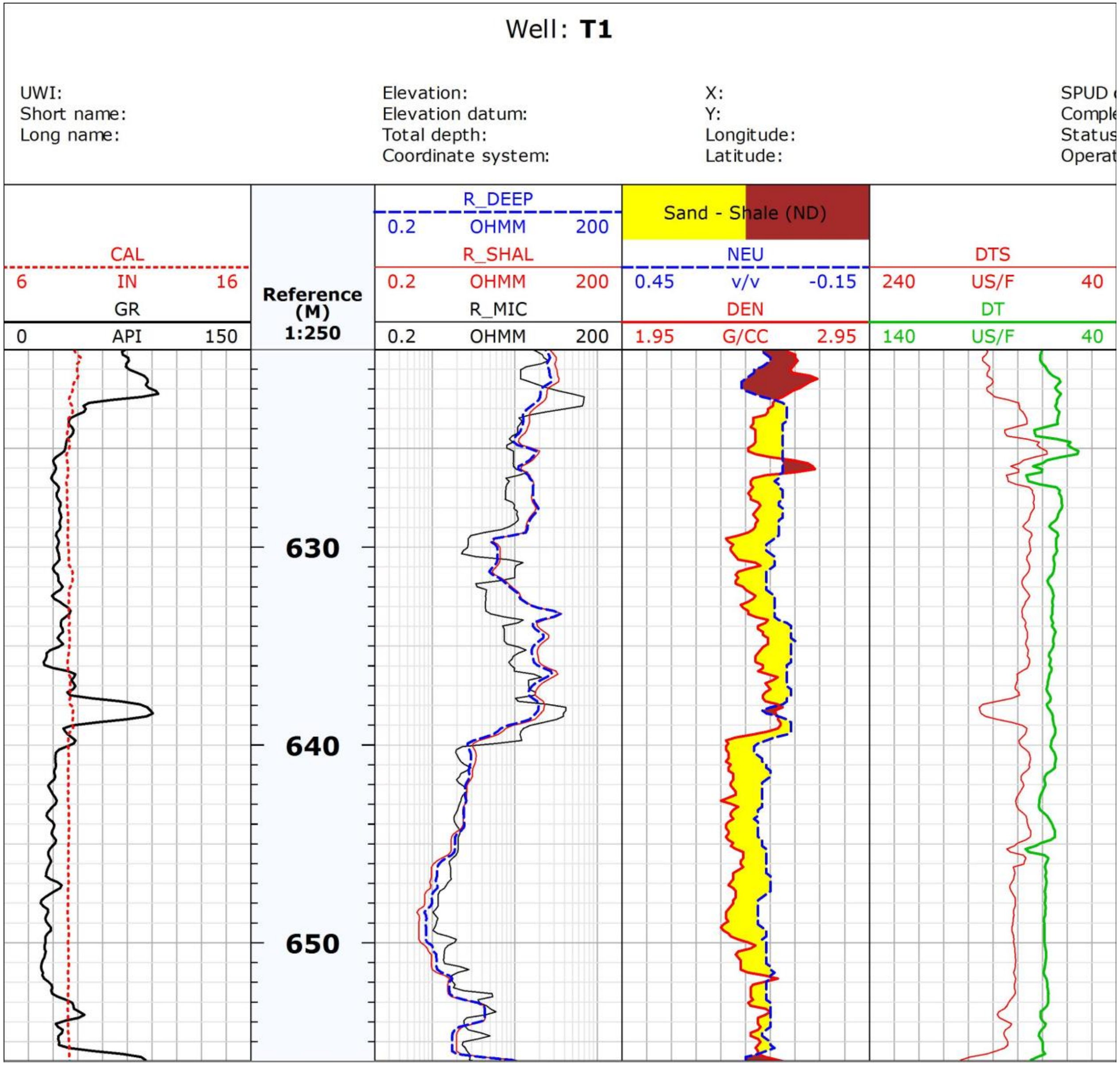






- Micron Scale: pore throats
- Macroscopic Scale (cm): core plug data
- Mega Scale (m): log data
- PLT data
- Giga Scale: geocellular grid cells
  welltests (extended range)

Well logs: basic log suite



Volume of Shale

- In the Total Porosity System, Vsh is used only to eliminate shale intervals from the analysis (i.e a lithology cut-off)

- In the Effective Porosity System, Vsh is used in the quantification of porosity and water saturation from logs and any uncertainties or errors in the calculation of Vsh are continued on throughout the petrophysical evaluation.

- Some petrophysicists try to differentiate between Volume of Shale and Volume of Clay, but for practical purposes, they are often regarded as the same property. Vsh calculation is never an absolute measurement beyond laboratory core analysis.

Volume of Shale

- Vsh (Gamma Ray)
  - Linear

$$V_{sh} = I_{GR} = \frac{GR_{\log} - GR_{\min}}{GR_{\max} - GR_{\min}}$$

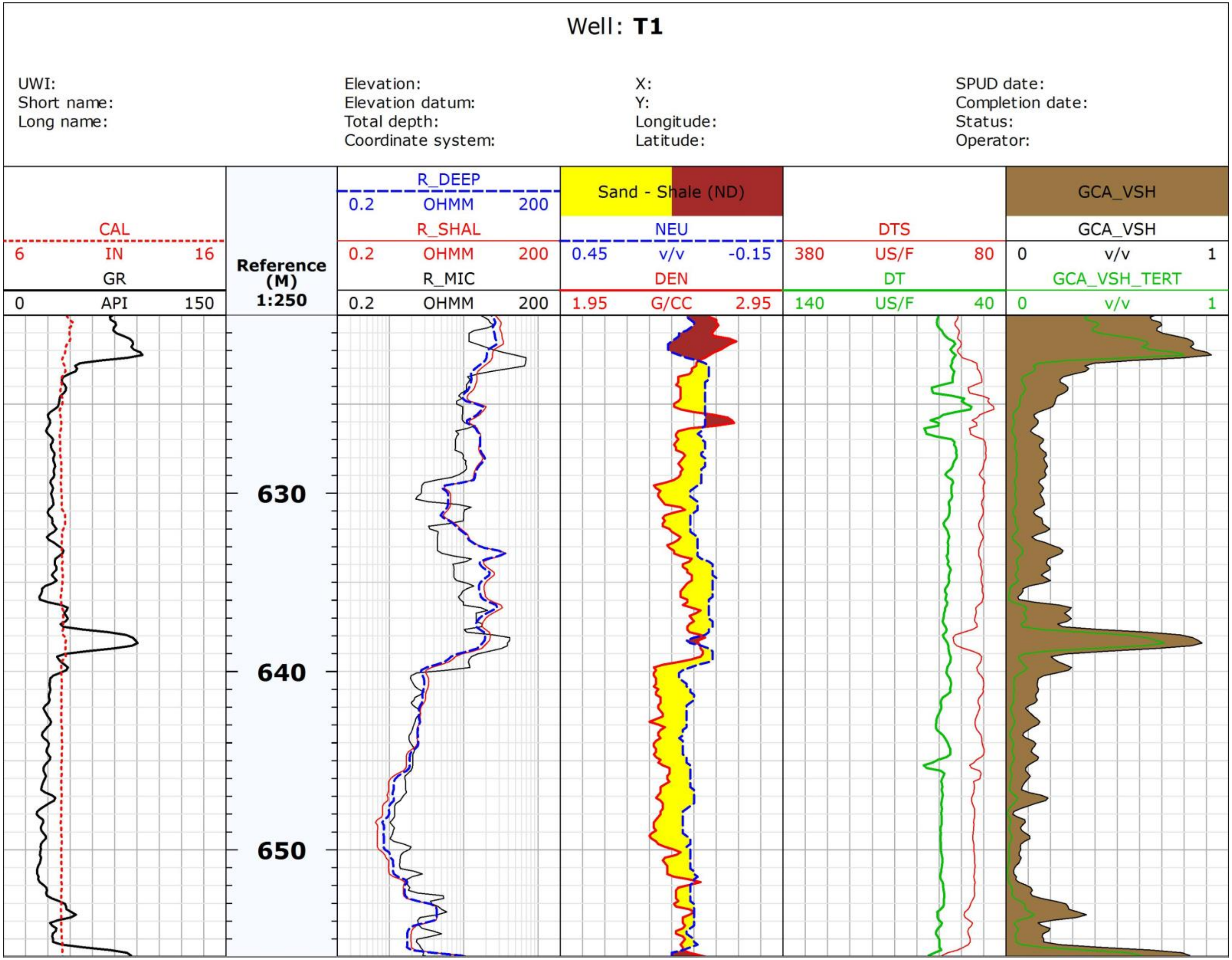
  - Non linear

    (Larionov, Tertiary sands)

$$V_{sh} = 0.083(2^{3.7 I_{GR}} - 1)$$

- Vsh (Density/Neutron)
  - Preferred where sands contain radioactive minerals (e.g Potassium Feldspars)
  - Not recommended for gas sands – will cause an underestimate of Vsh.

Vsh Evaluation



Which Porosity?

- **Total Porosity (Phit)**:

  Takes account of electrochemically (clay) bound water, capillary bound water and free fluids.

  Simplest approach, calibration to core data is straightforward.

- **Effective Porosity (Phie)**:

  Attempts to eliminate the non contributing porosity fraction attributed to clay within the reservoir.

  Takes account of capillary bound water and free fluids.

For most reservoir simulator intialisation purposes, electrochemically or clay bound water is part of the binding solids and only capillary bound water, immoveable hydrocarbons and free fluids are assigned to the effective pore space

Which Porosity/Permeability? – ensure consistency with the simulator

absolute permeability tensor (usually to brine)

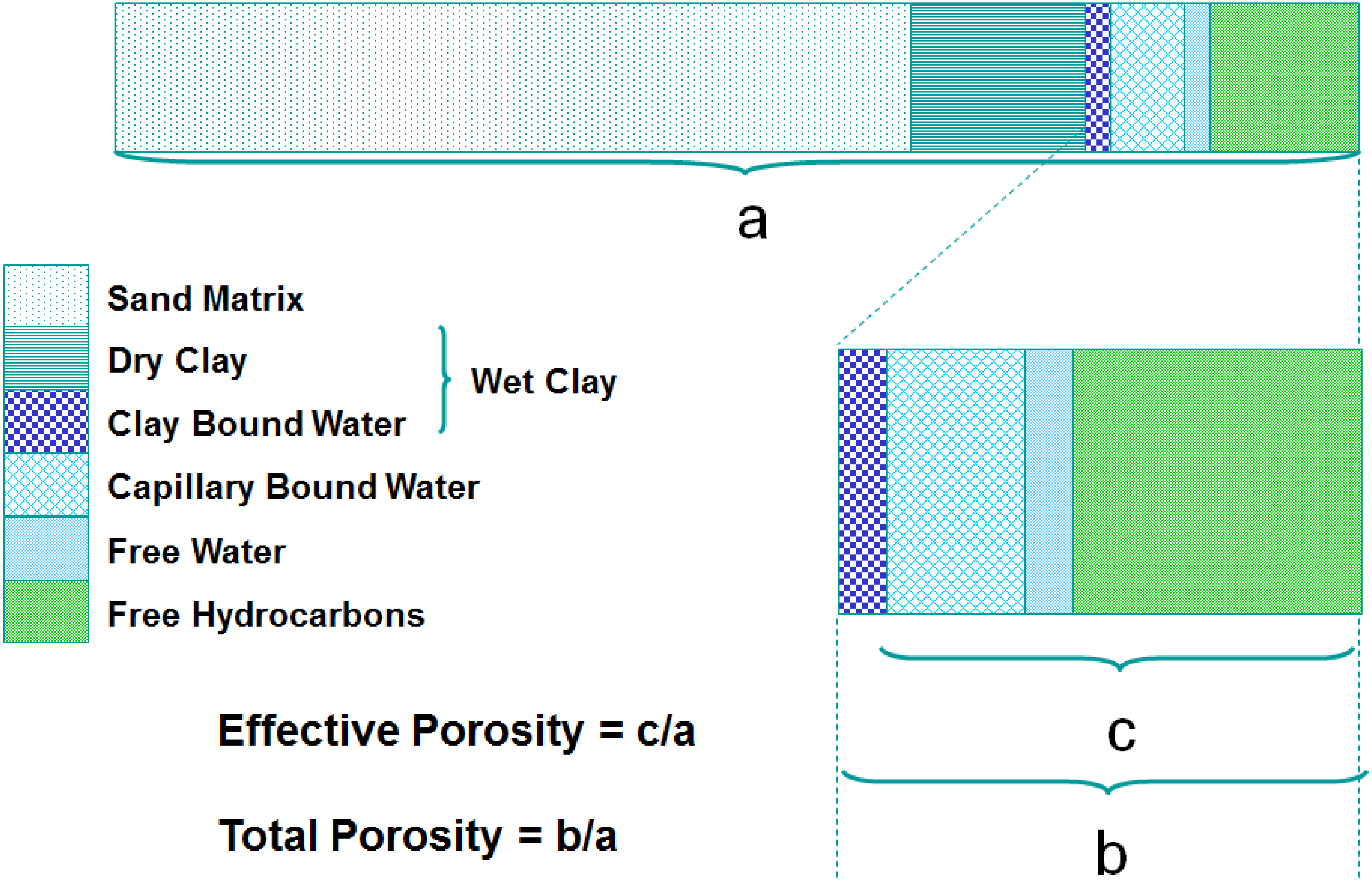
$$\sum_{p=1}^{n_p} \nabla \cdot \left(\rho_p y_{c,p} \frac{\boldsymbol{k} k_{rp}}{\mu_p} \left(\nabla P_p + \rho_p g \nabla D\right)\right) = \sum_{p=1}^{n_p} \left(\frac{\partial}{\partial t}\left(\phi_e \rho_p y_{c,p} S_p\right)\right) + q_c$$

effective porosity

…………. the partial differential equation that forms the basis for dynamic simulation

Courtesy of Worthington and Hattingh , SPE 160248, 2012

Porosity: total and effective



Effective Porosity = c/a

Total Porosity = b/a

$$\phi_e = \phi_t - V_{sh}\phi_{tsh} = \phi_t(1 - S_{wb})$$

Porosity Evaluation

- **Total porosity (Phit)**
  - Preferred approach where conventionally dried core plug data are available
  - Phit from logs can be compared to and calibrated with overburden-corrected core analysis data.
  - Phit from QC’ed Density Log is recommended log analysis approach.

$$\mathit{Phit} = (\mathit{Rhomatrix} - \mathit{Rhob}) / (\mathit{Rhomatrix} - \mathit{Rhofluid})$$

- **Effective porosity (Phie)**
  - Effective Porosity measurements on core can be unreliable – humidity drying is poorly calibrated
  - Effective Porosity from logs demands a robust Vsh interpretation and an estimate of shale porosity
  - More reliable to use Total Porosity for both core and log evaluation
  - Effective Porosity can be estimated from Total Porosity later.

$$\mathit{Phie} = \mathit{Phit} - \mathit{Vsh} * \underbrace{((\mathit{Rhomatrix} - \mathit{Rhoclay})/(\mathit{Rhomatrix} - \mathit{Rhofluid}))}_{\textit{Total porosity of clay fraction}}$$

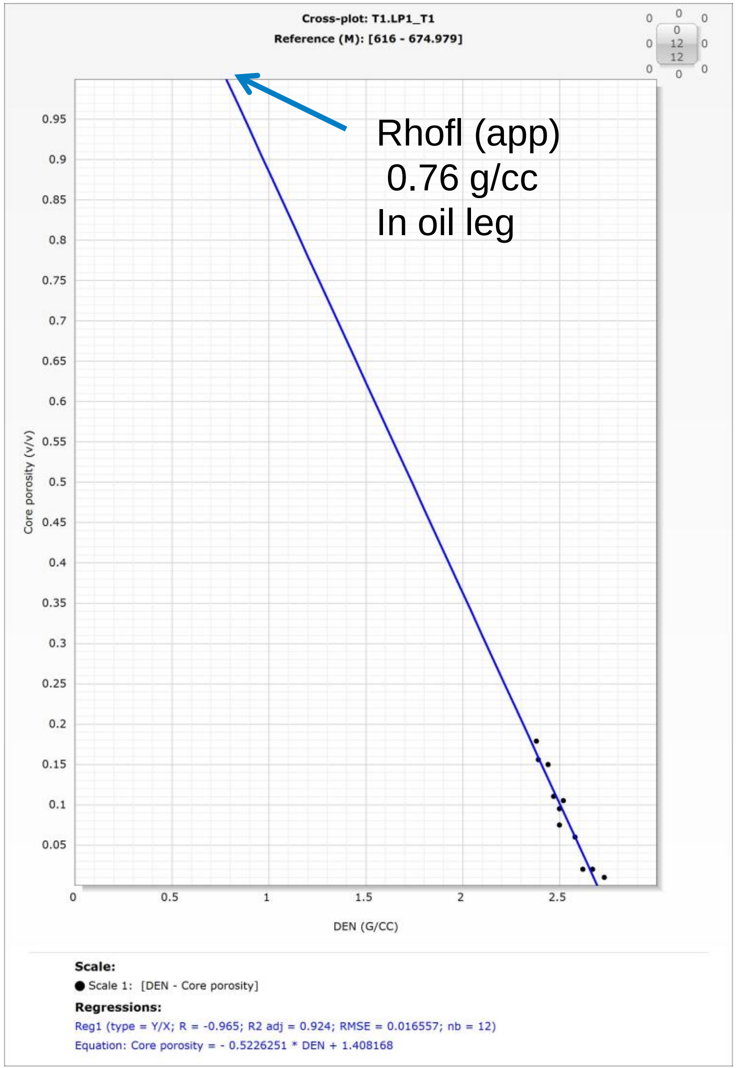
Porosity: Phit evaluation integration with core data

- ***Phit = (Rhomatrix - Rhob) / (Rhomatrix - Rhofluid)***

Rhomatrix:
from statistical analysis of core grain density data (2.64 ~ 2.67 g/cc)

Rhofluid (apparent):
from plot of core porosity against density log per fluid type.

$$\rho_f = Sxo \cdot \rho_{mf} + (1-Sxo) \cdot \rho_{hc}$$

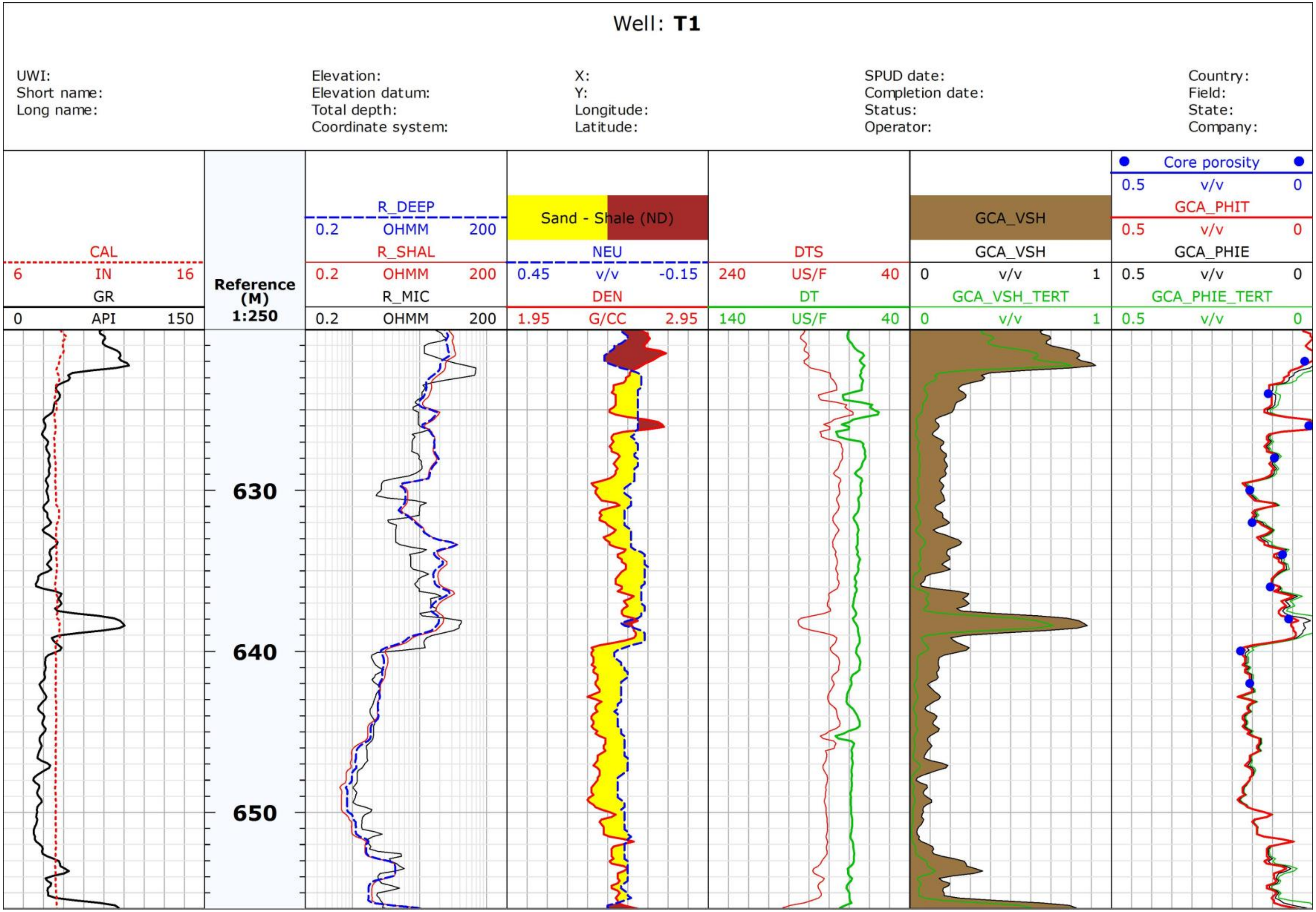

Cross-plot: T1.LP1_T1
Reference (M): [616 - 674.979]

Rhofl (app)
0.76 g/cc
In oil leg

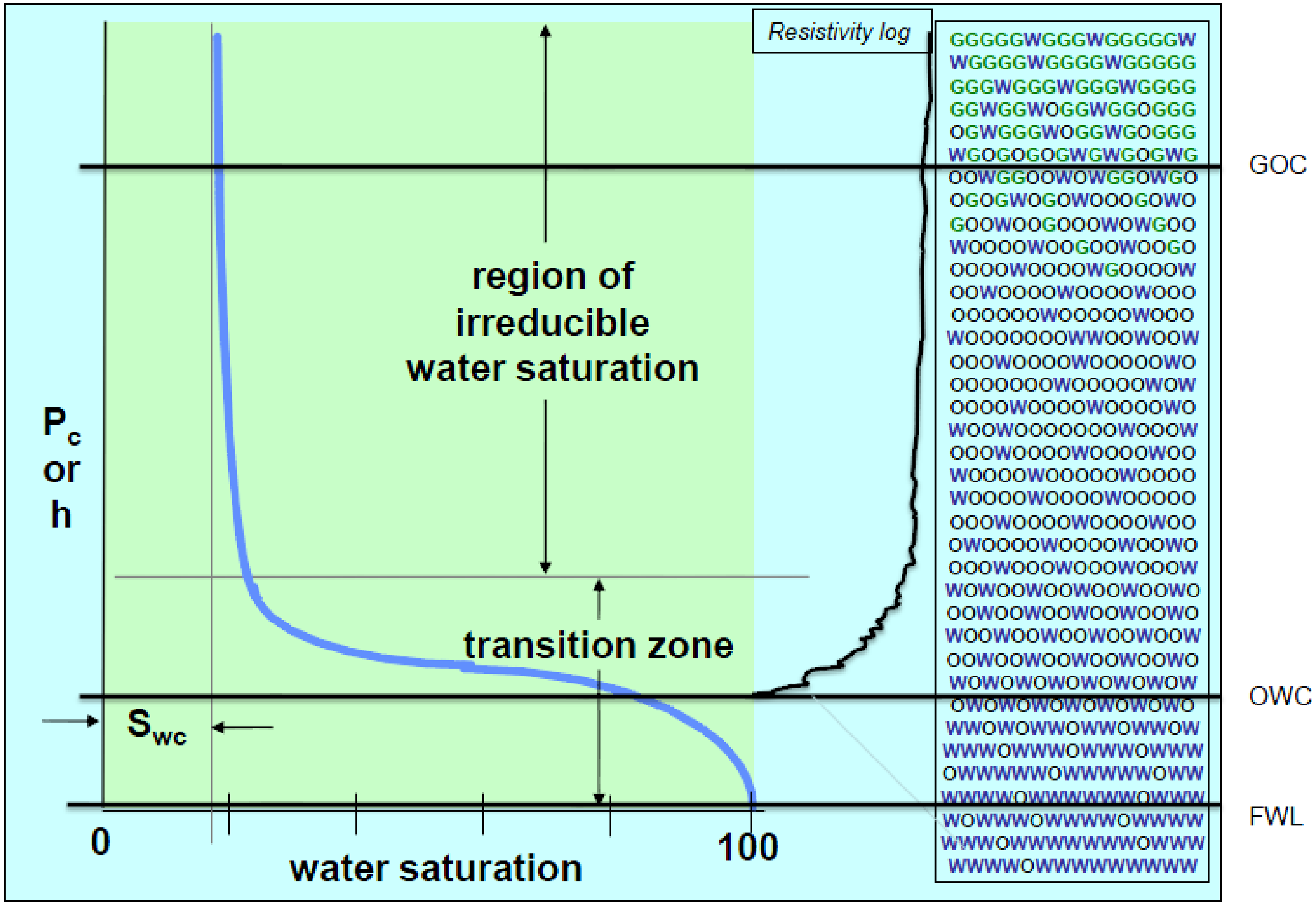
Scale:
● Scale 1: [DEN - Core porosity]

Regressions:
Reg1 (type = Y/X; R = -0.965; R2 adj = 0.924; RMSE = 0.016557; nb = 12)
Equation: Core porosity = - 0.5226251 * DEN + 1.408168

Porosity Evaluation



Water Saturation: distribution in the reservoir



1

Archie's (1942) equation

$$F = \phi^{-m} = \frac{Ro}{Rw}$$

&

$$Sw = \left(\frac{Ro}{Rt}\right)^{\frac{1}{n}}$$

↓

$$Sw = \sqrt[n]{\frac{Rw}{Rt \times \phi^{m}}}$$

Based on core data, but applicable to logs and has stood the test of time.

Archie: m & n considerations

$$Sw = ((a.Rw.\emptyset\hat{}(-m))/Rt)\hat{}(1/n)$$

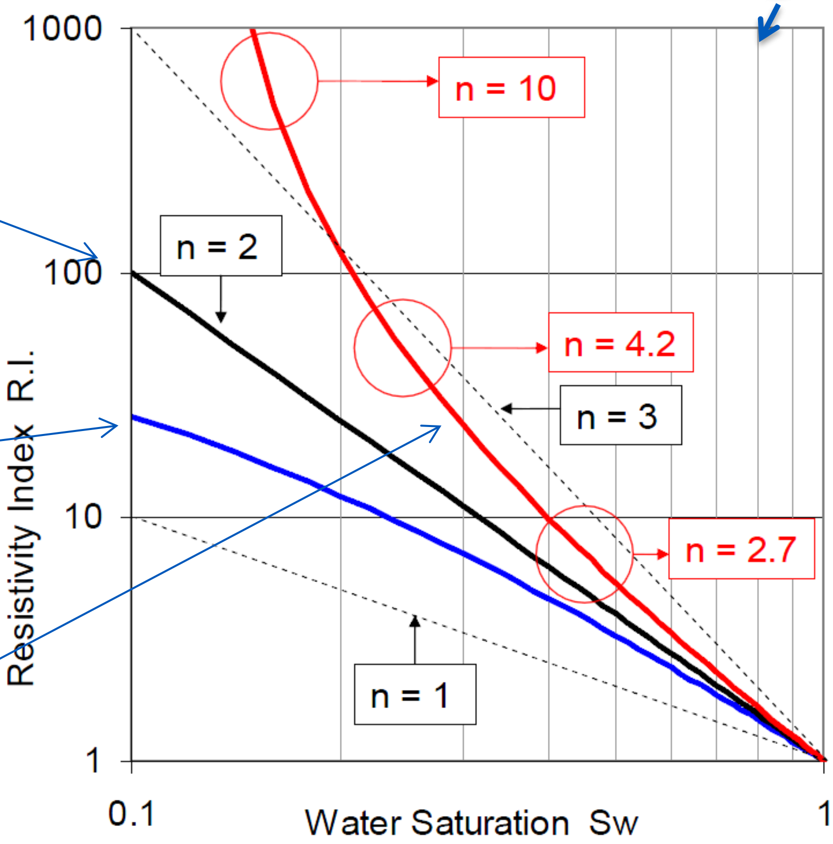
- m (cementation/tortuosity exponent) derived from FRF SCAL data
- n (saturation exponent) derived from RI SCAL data
- m variable with porosity system and in general decreases with better quality rock,
- n is dependent on wettability – increases with oil wetness as the conductive brine phase becomes disrupted
- n can reduce as a function of grain surface rugosity and clay presence

- m ↑ Sw ↑
- n ↑ Sw ↑

Archie: n Saturation Exponent

- Archie rocks are where resistivity ratio vs. saturation plots as a straight line in log-log scale. The slope of the line is equal to n.
- The blue curve is typical of shaly sands. Increased conductivity is caused by clay-water interaction
- The red curve is typical of strongly oil-wet carbonates which deviate from Archie behaviour

$$Sw = ((a.Rw.\emptyset^{\wedge}(-m))/Rt)^{\wedge}(1/n)$$



Montaron, 2009, Petrophysics, Vol. 50

Archie: Sources of Water Resistivity (Rw)

$$Sw = ((a.\boxed{Rw}.\emptyset \wedge (-m))/Rt) \wedge (1/n)$$

- Pickett plot over water leg
  - Graphical solution of Archie for case Sw =100%

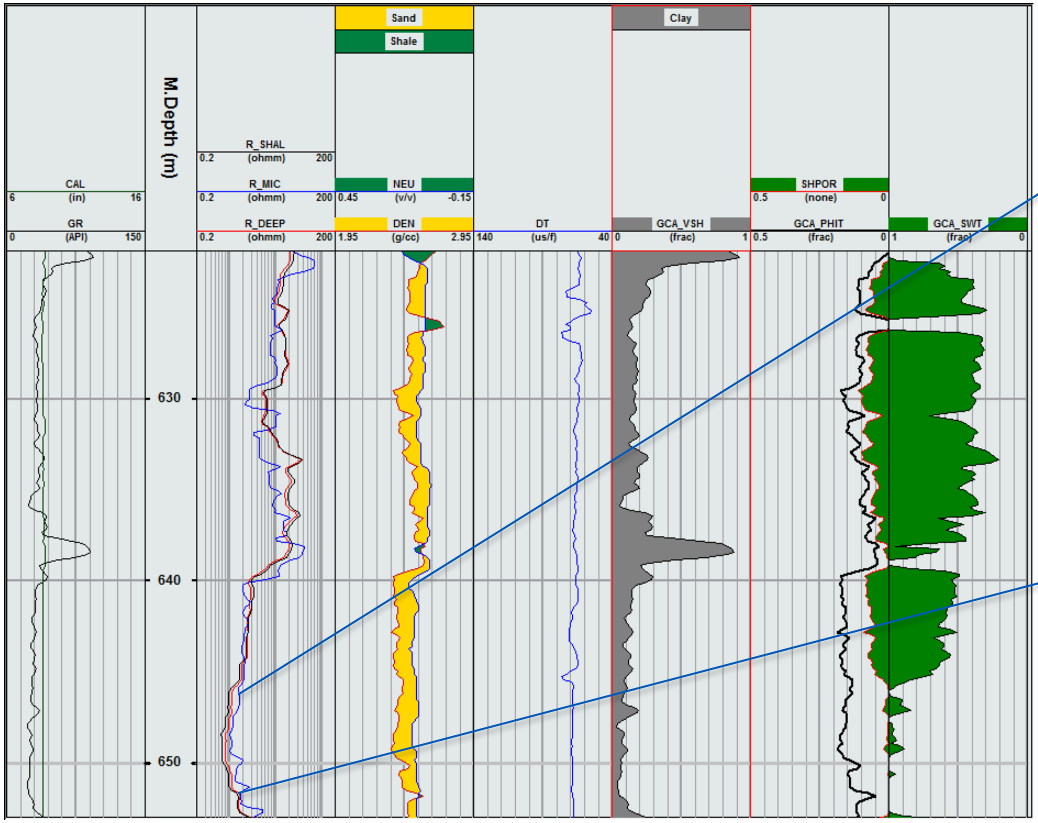
- Formation water samples
  - be careful of mud filtrate contamination
  - be sure to differentiate between results quoted as Total Dissolved Solid (TDS), ppm Chlorides and ppm NaCl eqv.
  - N.B.: ppm NaCl equivalent = 1.645 * ppm total chlorides.

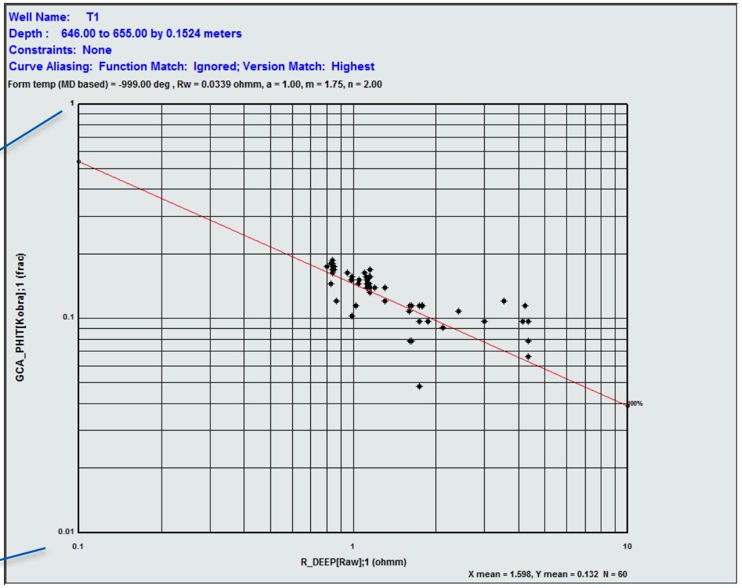
- Spontaneous potential (SP log)

- Rw is dependent on temperature (variable) and salinity (constant)
- Rw expressed in Ohmm and salinity in ppm NaCl eqv.

Archie: Water Resistivity, Rw from Pickett plot

A plot of porosity against deep resistivity on a log-log scale





Well Name: T1

Depth : 646.00 to 655.00 by 0.1524 meters

Constraints: None

Curve Aliasing: Function Match: Ignored; Version Match: Highest

Form temp (MD based) = -999.00 deg , Rw = 0.0339 ohmm, a = 1.00, m = 1.75, n = 2.00

X mean = 1.598, Y mean = 0.132 N = 60

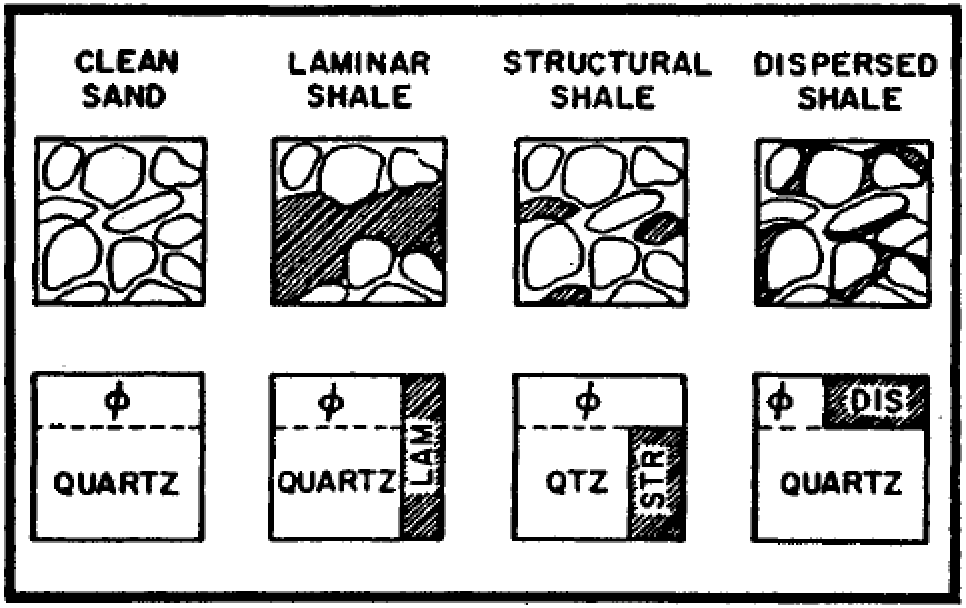
Rw ~ 0.034 Ohmm
m can be also be estimated
from the slope of the gradient

Archie's Equation: Limitations

- Assumes that the formation itself has no electronic conduction
- Does not account for vuggy porosity
- Starts to become unstable as formation water salinities decrease < 20,000 -30,000 ppm NaCl eqv.
- Affected by conductive minerals e.g pyrite, glauconite
- Affected by presence of conductive clays in the formation

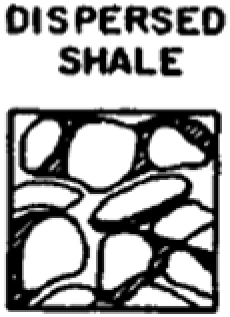
- Archie is not a universal equation for all rock types

Saturation from Resistivity: Shaly Sands



Shaly Sand Evaluation: Total Porosity System

$$Sw = ((a.Rwe.\emptyset{}^\wedge(-m^{*}))/Rt){}^\wedge(1/n^{*})$$



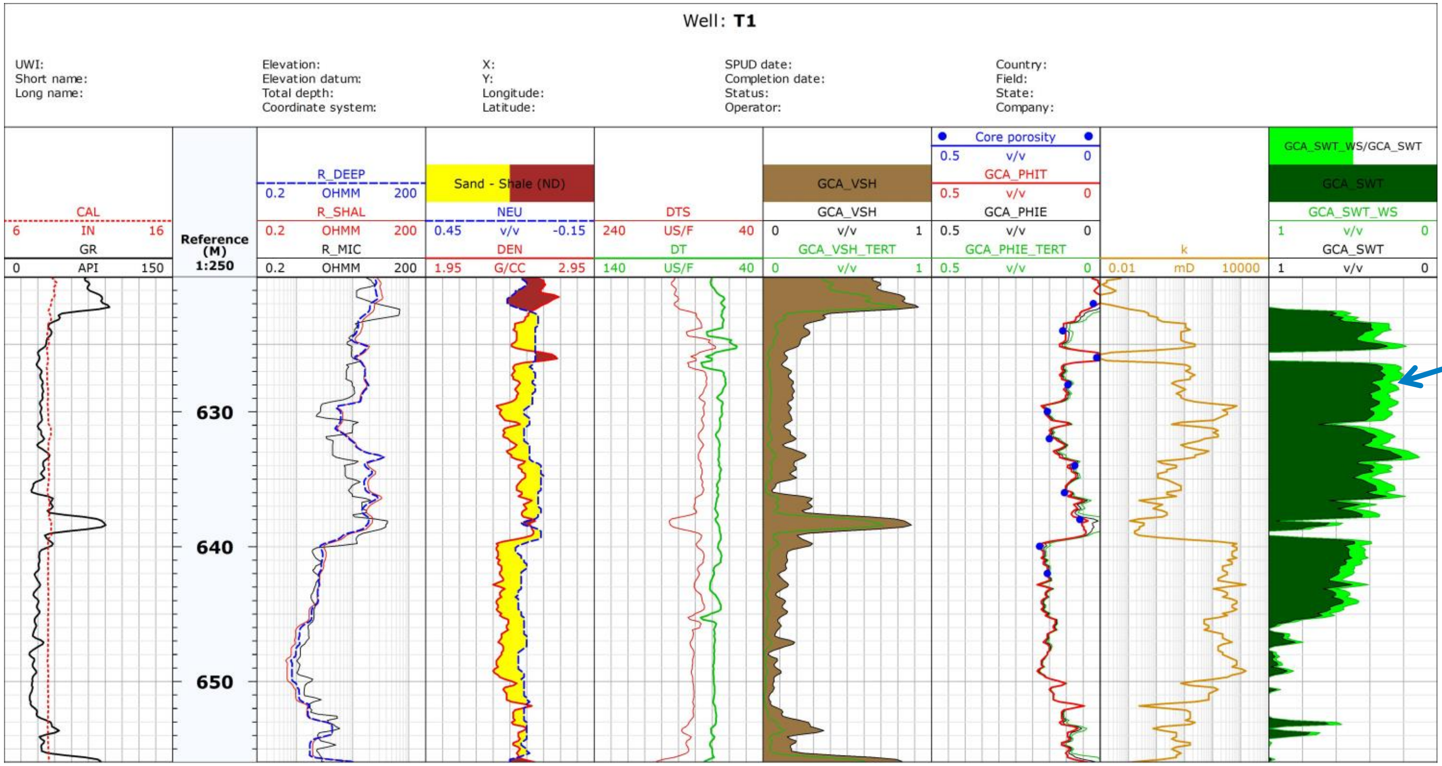
Combined term Rwe can be expanded from Archie Eqn.
to cover the effects of water conductivity and dispersed clay conductivity

$$Rwe = 1/(\frac{1}{Rw} + B.Qv/Sw)$$

Where: B is mobility of clay counter ions…..*function of Temp & Rw*
Qv is the clay conductivity…..*from SCAL*
m^* is clay corrected Archie m….*from SCAL*
n^* is clay corrected Archie n…..*from SCAL*

Sw now appears on both sides of the equation,
but computers handle this effortlessly through iteration
.. we now have the Waxman – Smits equation in its simplest form !

Shaly Sand Evaluation: Waxman Smits



Example;

Having determined the
B.Qv clay conductivity term
by means of SCAL or log analysis

The Waxman-Smits Eqn.
has the potential to produce a
lower Sw value than Archie

If no conductive clay present,
then Sw (W-S) = Sw (Archie)

Saturation in Shaly Sands: Summary

Clean sand: Archie Eqn.

Shaly Sand

Total porosity system (PHIT)

Waxman- Smits Eqn.
Juhasz Eqn*.
Dual Water Eqn.

Require:
- B.Qv

from SCAL
or log analysis

*Juhasz eqn formulated to enable evaluation independent of core Qv measurements, but requires Vsh.

Shaly Sand

Effective porosity system (PHIE)

Indonesia Eqn**.

Mod.Simandoux Eqn.

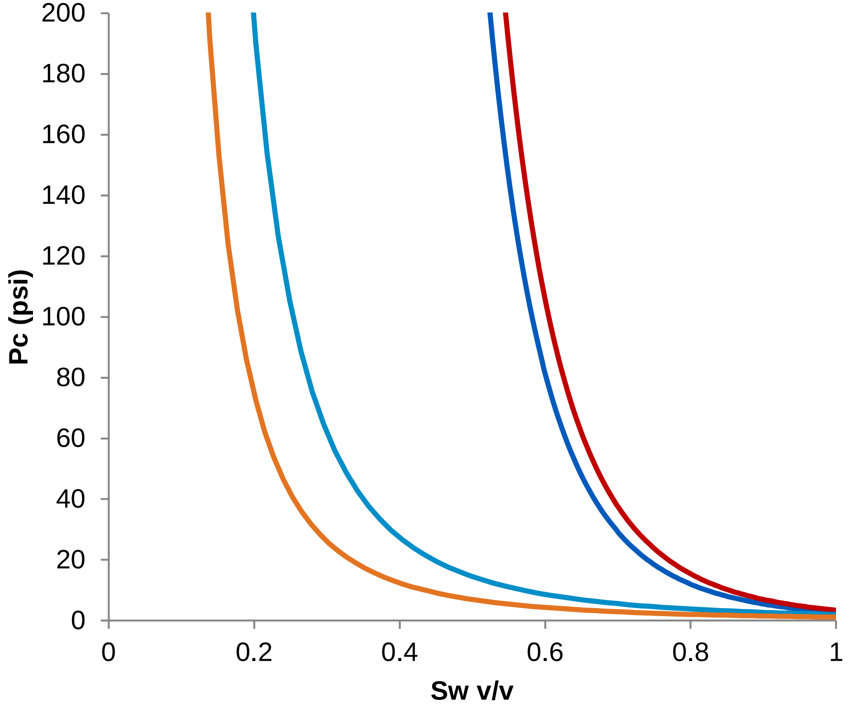
Require:
- Vsh
- Rsh

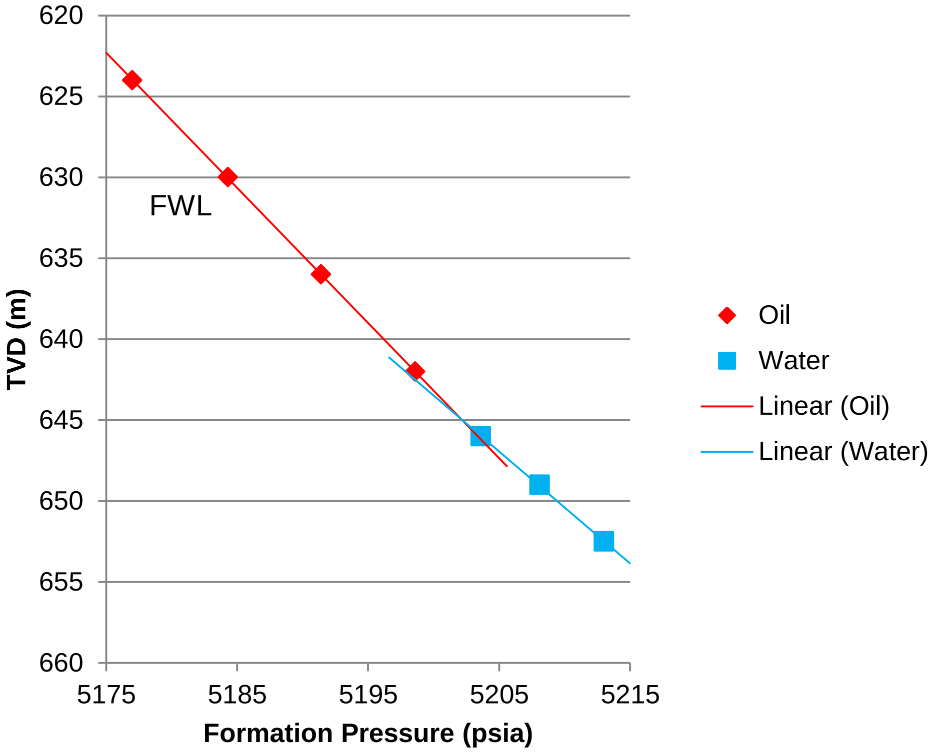
from log analysis

**Indonesia eqn formulated for evaluation of shaly sands with low salinity formation water.

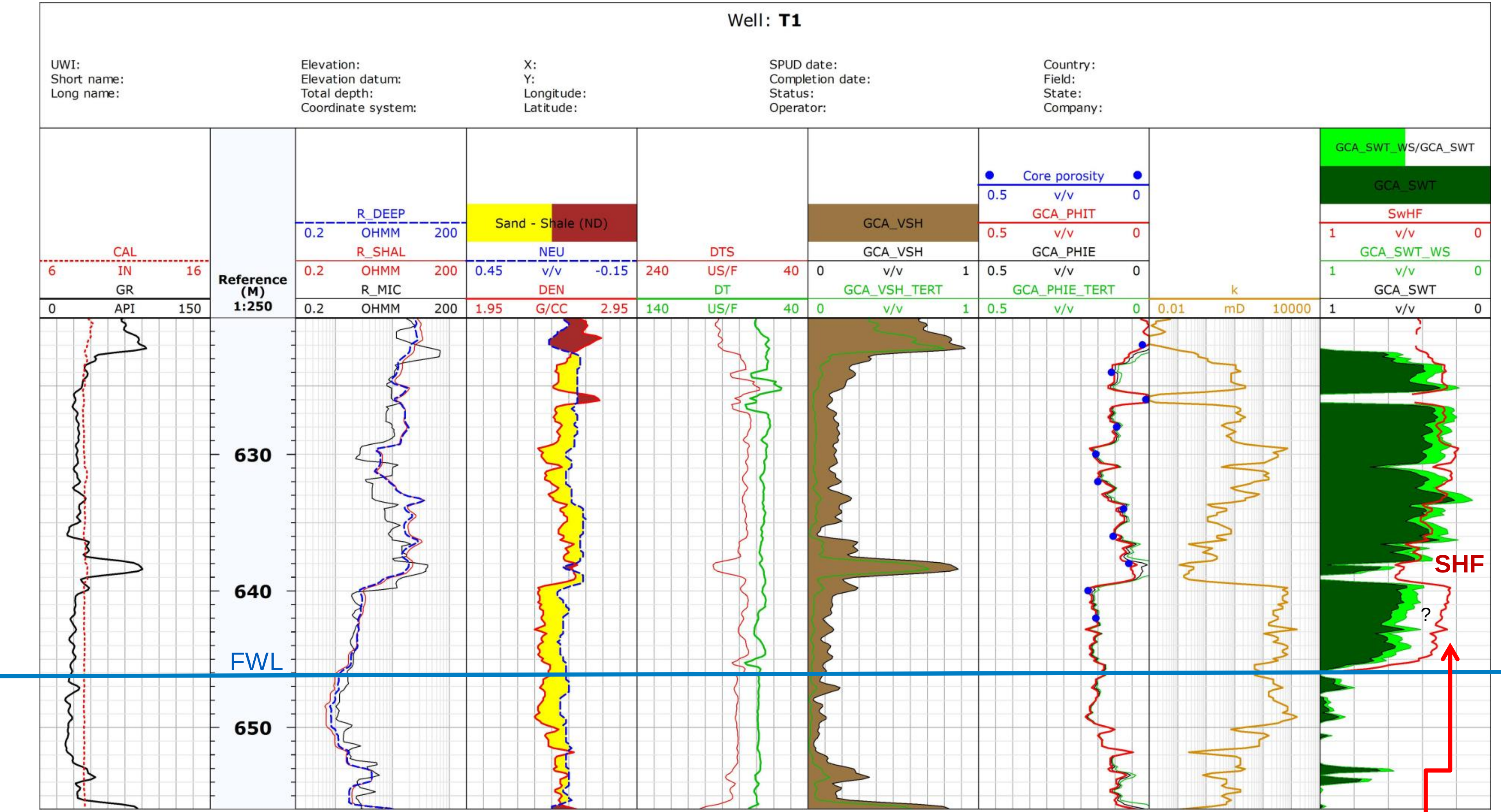
Laminated sand/shale (thin beds): Advanced interpretation techniques e.g Thomas Stieber cross-plot analysis to evaluate lamination volume and true resistivity of sand laminae. Multicomponent induction resistivity logs allow differentiation of horizontal and vertical resistivity.

Saturation: integration with capillary pressure data; Sat-Ht function and FWL





Integrated Evaluation



Difference between Sw from Sat-Ht function (SHF) and Sw from logs indicates possibility of a swept or flushed zone

Alternative means of saturation estimation

- Dean Stark: direct extraction of water phase from uninvaded core
  - only reliable with OBM systems

- Saturation-Height Function estimation from capillary pressure data from core
  - Need to identify Free Water Level in order to apply the
  - Very useful to independently verify the Sw derived from log data

- Pulsed Neutron measurements from advanced logging tools
  - works through casing
  - useful for remaining oil saturation determination after sweep

- Dielectric logs – can measure remnant oil saturation in invaded zone

- Nuclear Magnetic Resonance
  - Requires significant levels of processing

Outline Evaluation Workflow

- **Organise**
  - Log data, logging parameters, core data, mudlogging data, make log QC plots.
- **Edit**
  - Depth match logs, edit washouts, depth shift core data.
- **Correct**
  - Environmental corrections to logs (only if necessary – don’t double correct), Establish Rt from Resistivity curve arrays (tornado charts), compaction correct core data.
- **Think**
  - What porosity system? Shaly Sand? Laminated Sands?
  - Select appropriate petrophysical models.

Continued…

- **Evaluate and Integrate**
  - Appropriate Vsh, Porosity, Saturation methods.
  - Core analysis data – calibrate porosity, SCAL data – calibrate water saturation from resistivity with FRF/RI
- **Groundtruth**
  - Check Vsh against lithology from geological descriptions.
  - Compare log porosity to corrected core data.
  - Compare log Sw to Sw from Capillary Pressure Data (Sat-Ht).
- **Communicate**
  - To the users of your interpretation – methods, uncertainties, assumptions and ranges.
- **Document**
  - Write up as you go, saves re-work.

- Useful Reference:

Well Logging and Formation Evaluation , Toby Darling, 2005, Elsevier, Gulf Professional Publishing.

ISBN:0-7506-7883-6

Acknowledgements to Phil Gibbons, GCA for log evaluation examples.