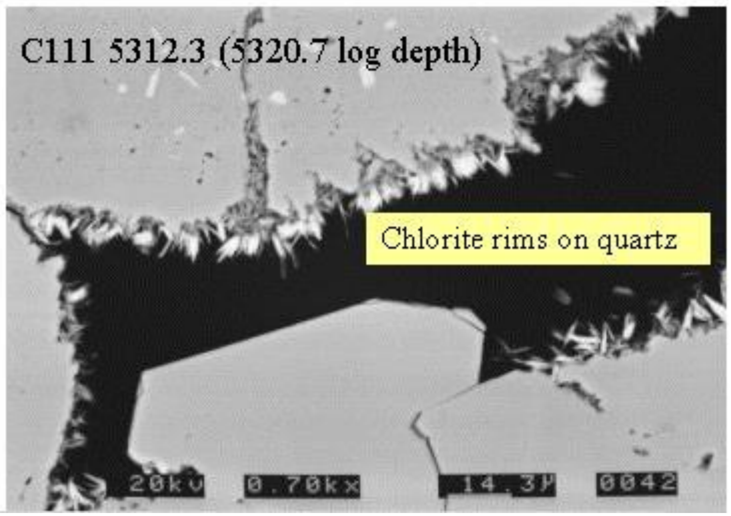
Formation Evaluation Society of Malaysia (FESM)
A Chapter of the Society of Petrophysicists and Well Log Analysts (SPWLA)
"Master Seminar on Clay" Wednesday 22nd April 2015

A Review of Log-Based Techniques for Measuring Clay Volume

Sherif Farag
Schlumberger

Richard Holland
Lundin



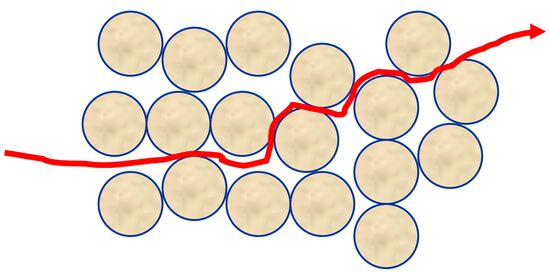
The Effect of Archie's 'm' and 'n'

$$S_w^{\,n} = \frac{R_o}{R_t}$$

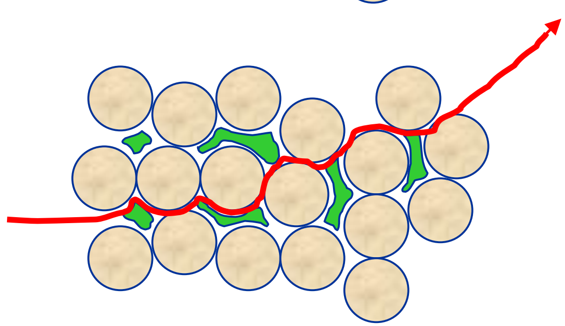
Gustavus E. Archie, 1907-1978

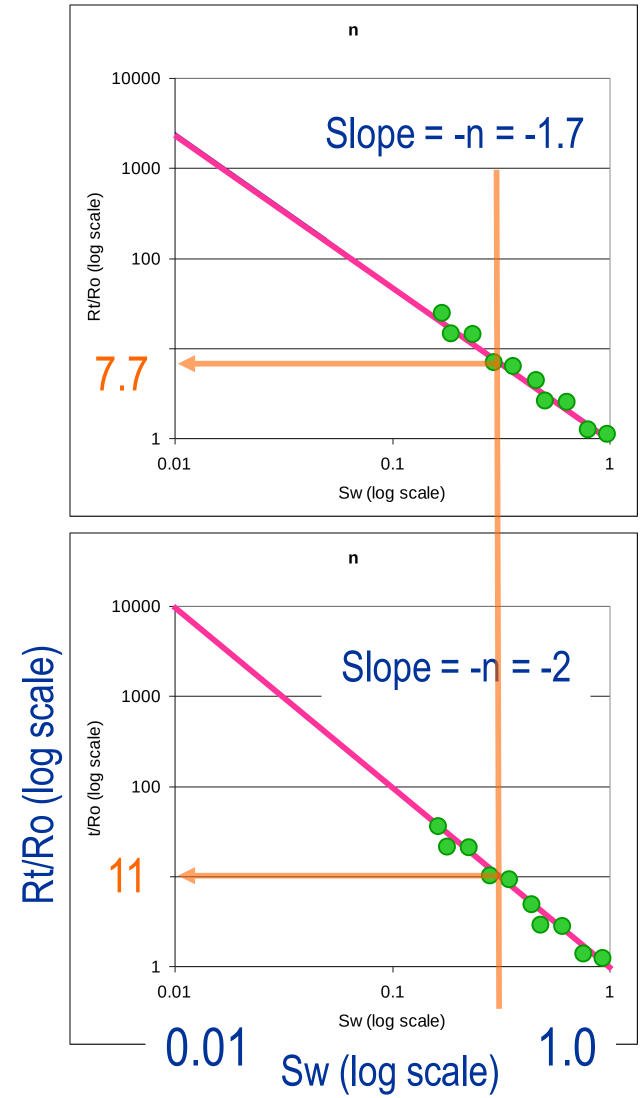
$$R_t = \frac{a}{\phi^m}\frac{R_w}{S_w^{\,n}}$$

Effect of m (tortuosity)



Effect of m+n (tortuosity)





Clays Coating the Grains

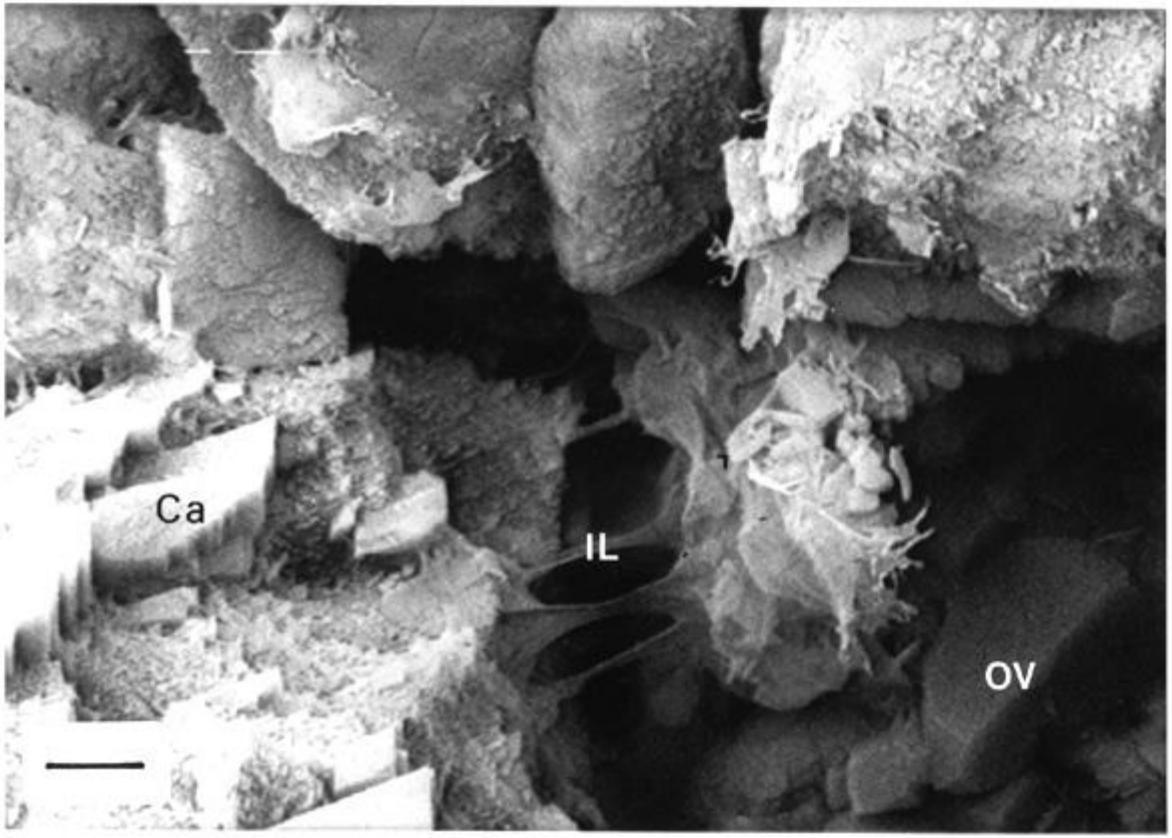
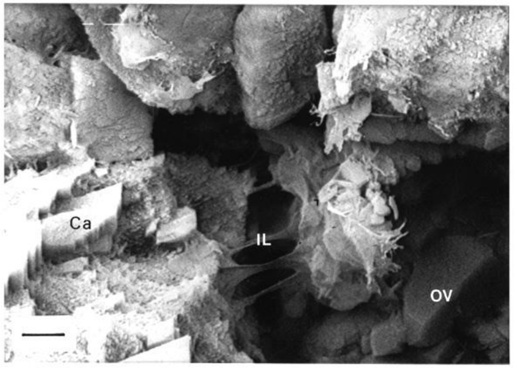


Figure 22--Bridging illite (IL), which appears to consist of very thin membrane covering most of framework grains and authigenic calcite (Ca) and quartz (OV). Some illite is whiskery. Sotong 5G-5.1, 2175.0 m msl. SEM photograph. Scale bar = 3 μm.

UPPER OLIGOCENE - LOWER MIOCENE SANDSTONE RESERVOIRS, SOUTHERN MALAY BASIN[1]
Khalid Ngah[2]
Search and Discovery Article #10008 (2000)
[1] Adaptation for online presentation of part of Ph.D. Thesis submitted to Imperial College, University of London, 1990.
[2] Kaysham Resources SDN BHD, Kuala Lumpur, Malaysia.
Special appreciation is expressed to the management of PETRONAS and to R.C. Selley and R. Stoneley Imperial College, University of London
http://www.searchanddiscovery.com/documents/khalid/

The Effect of Clay



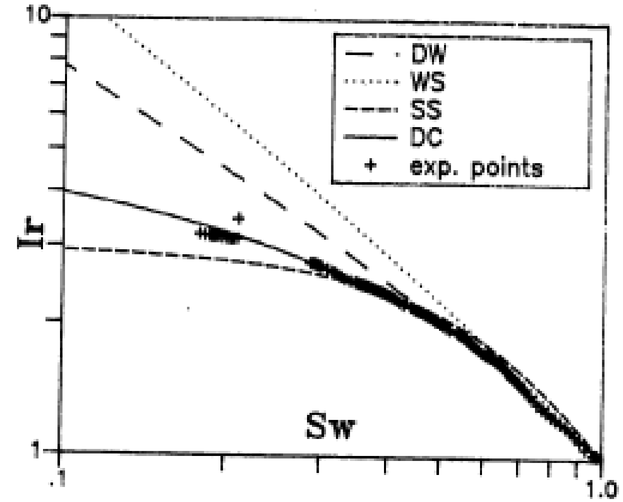
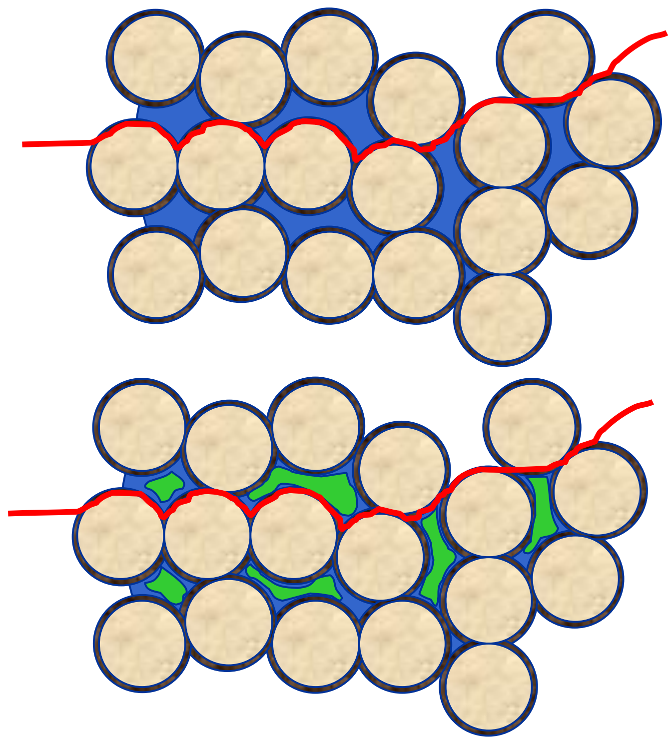
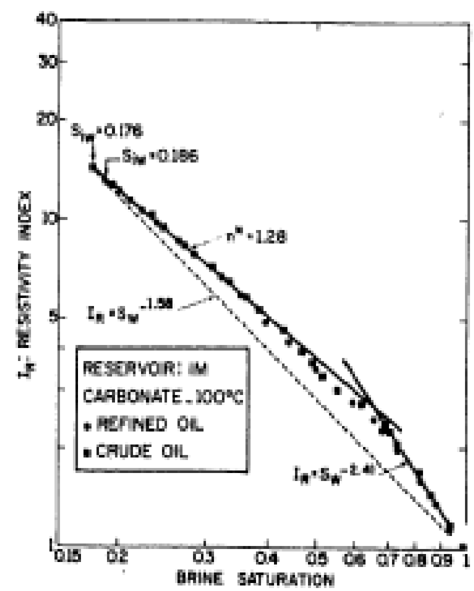


Fig 7 — Resistivity Index curve CON5•2
Cw= 0.354 S/m

Clay coating sand grains, current path (m and n) dominated by clay





Popular Saturation Equations

- Indonesia Equation

$$\frac{1}{Rt} = \left(\frac{V_{cl}^{\left(1-\frac{V_{cl}}{2}\right)}}{\sqrt{R_{cl}}} + \frac{\phi_e}{\sqrt{R_w}} \right)^2 S_w^{\ 2}$$

- Waxman-Smits Equation

$$\frac{1}{R_t} = \frac{S_w^{\ 2}}{F^* R_w} + \frac{B Q_v S_w}{F^*}$$

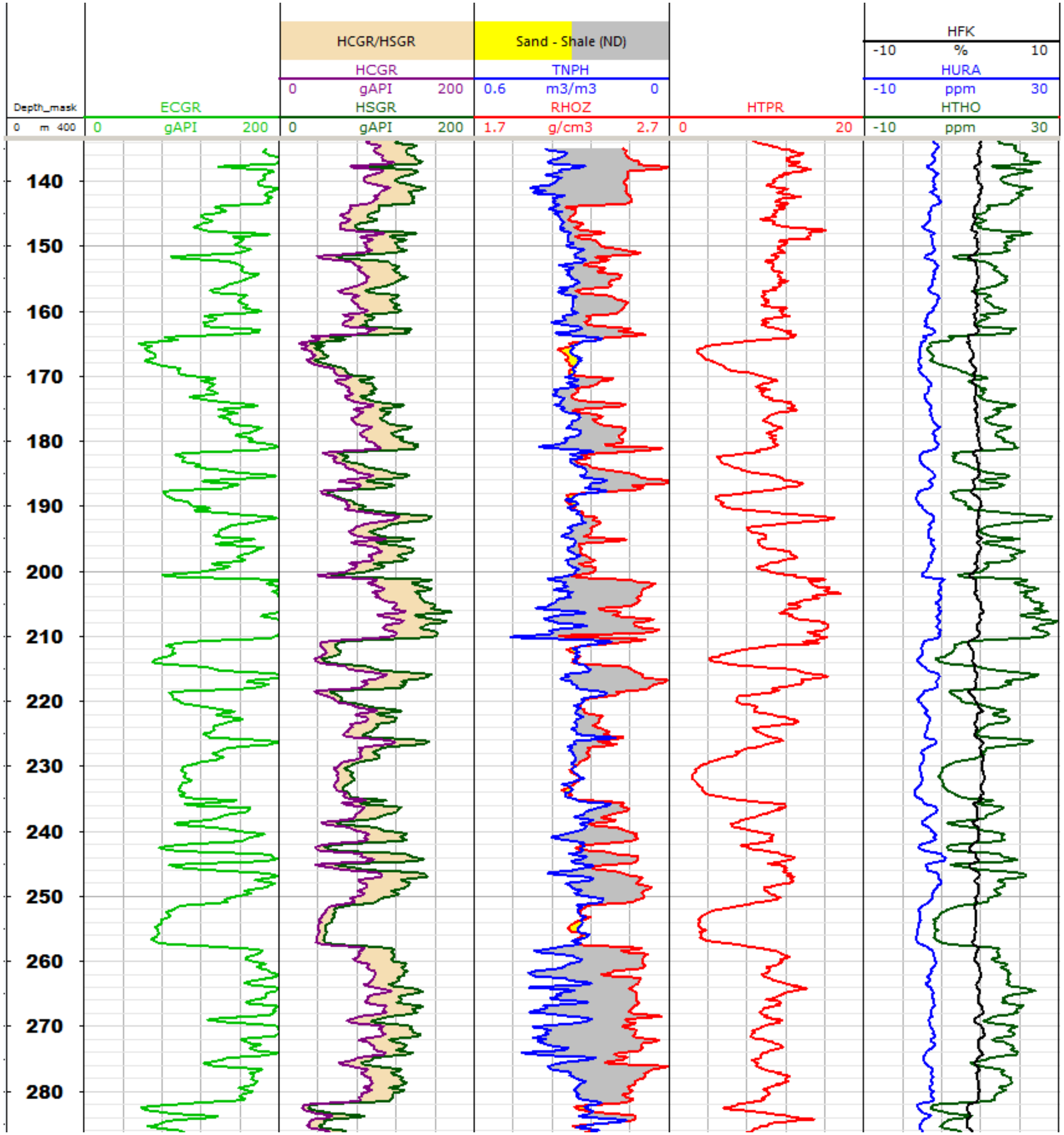
- Dual Water Equation

$$C_t = \frac{\phi_t^m S_{wt}^n}{a} \left(C_w + \frac{S_{wb}}{S_{wt}} (C_{wb} - C_w) \right)$$

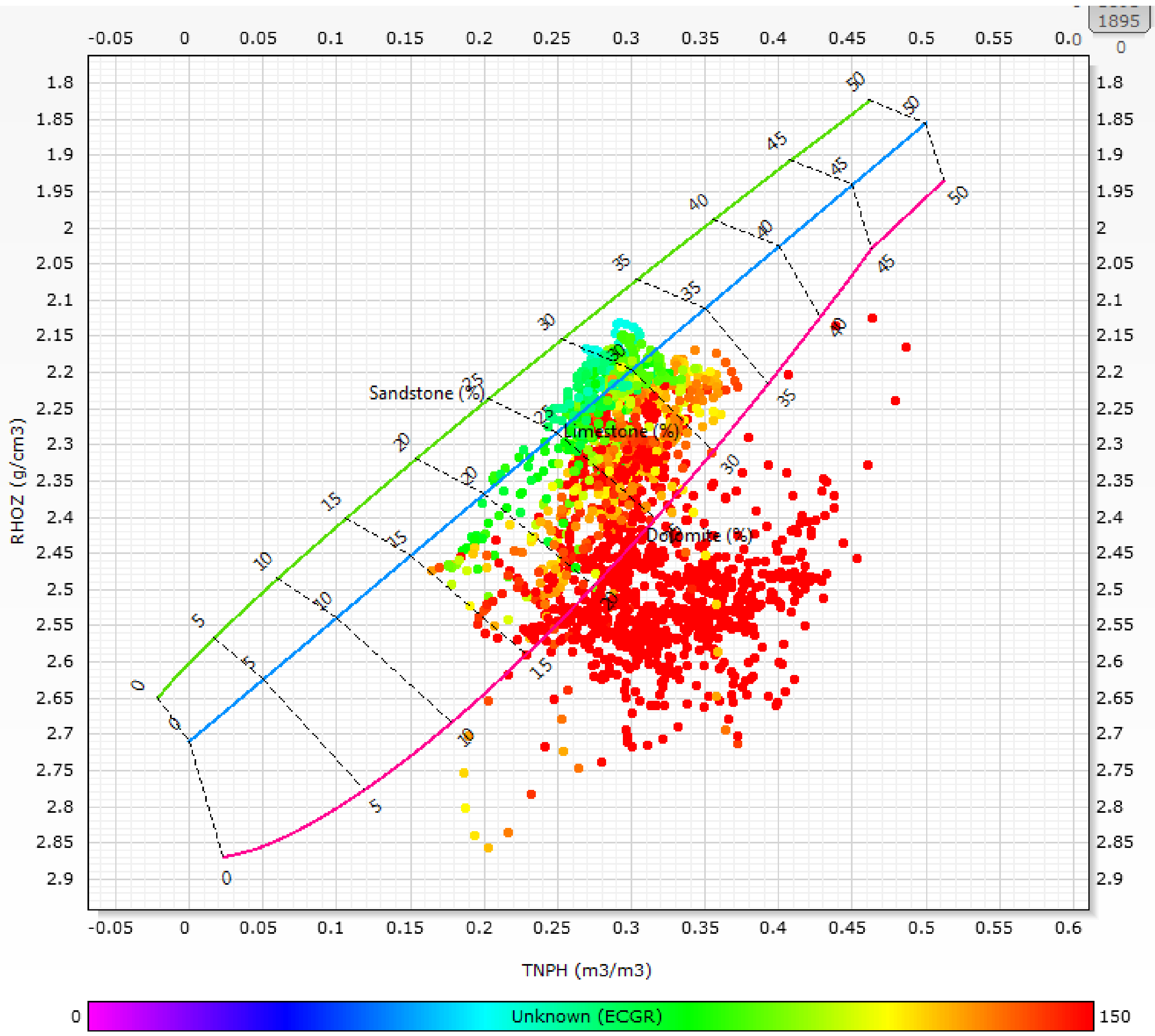
Clay Volume from Logs

- Triple combo logs (GR – Density – Neutron Porosity)
  - Clay is radioactive, dense and absorbs neutron
- Natural GR Spectroscopy
  - Sensitive to the fraction of Thorium, Uranium and Potassium
  - Clay type from the relationship between Th vs K ???
- Neutron – GR Spectroscopy
  - Sensitive to elements in the rock
  - Elemental composition interpreted to give mineralogy
- Clay-bound water
  - NMR Swb can be used directly in dual water model
  - Suitable T2 cutoff is required (default 3ms)
- Grain size
  - Can be derived from NMR with suitable calibration
  - Easier to calibrate to core than clay-bound water
- The electrical effect of the clay
  - This is actually what we need for saturation calculation
  - Dispersive dielectric measurements are sensitive to CEC

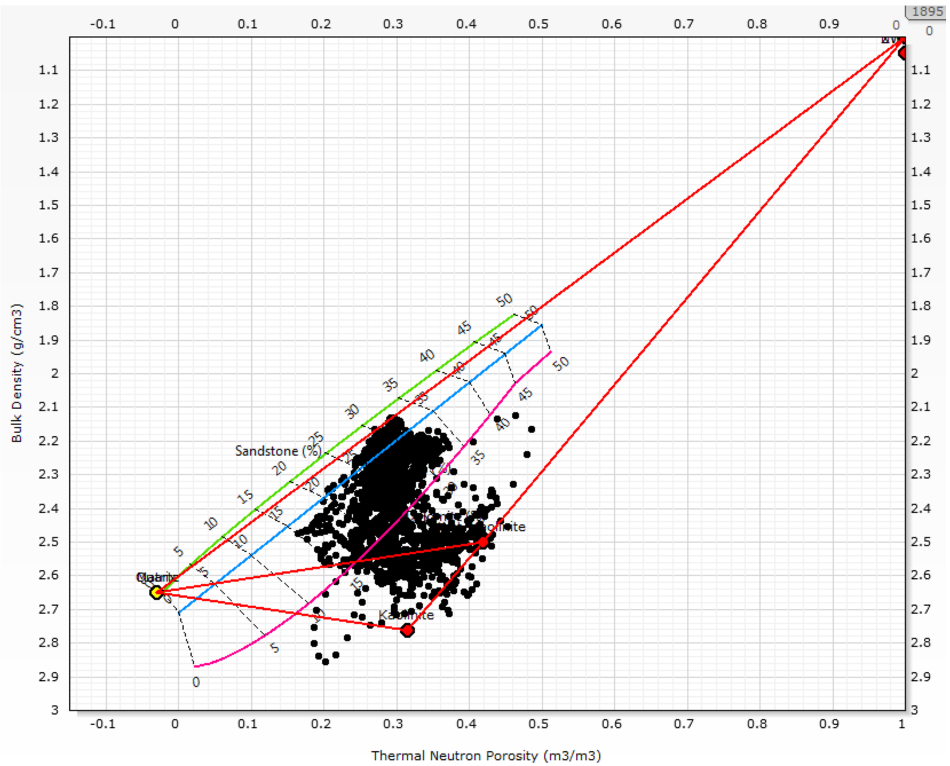
Density – Neutron - Natural GR

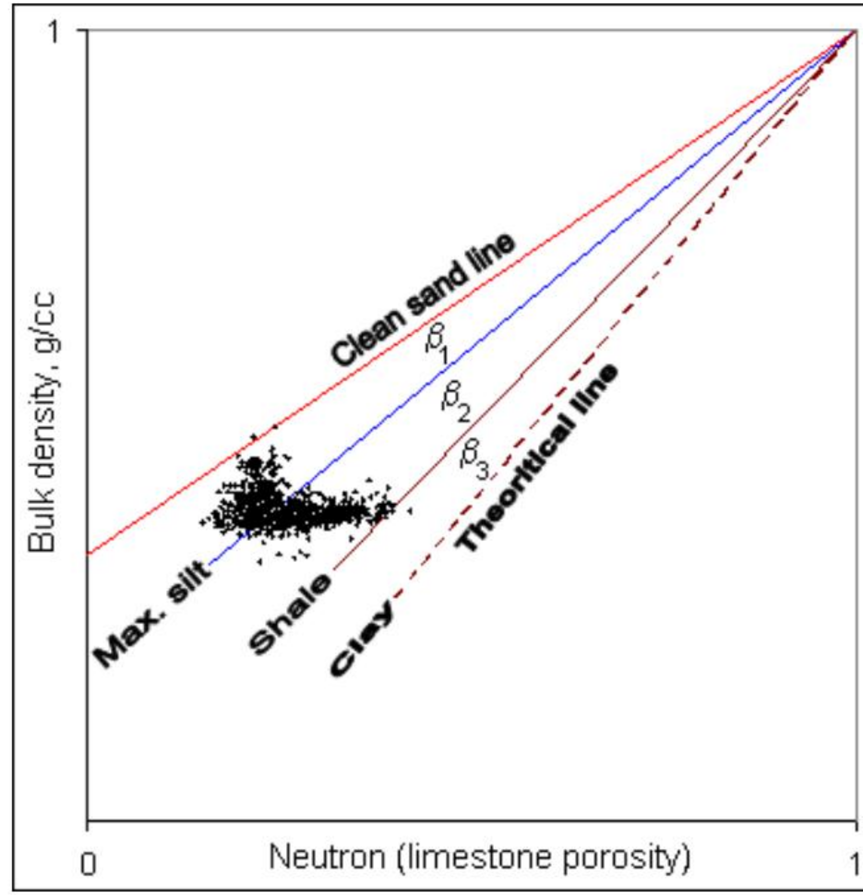


Density – Neutron Crossplot



Graphical Methods from Density-Neutron



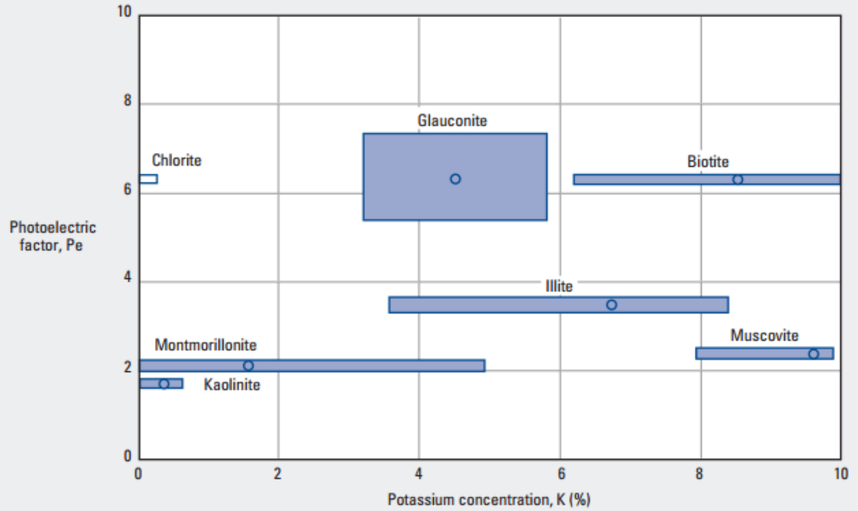


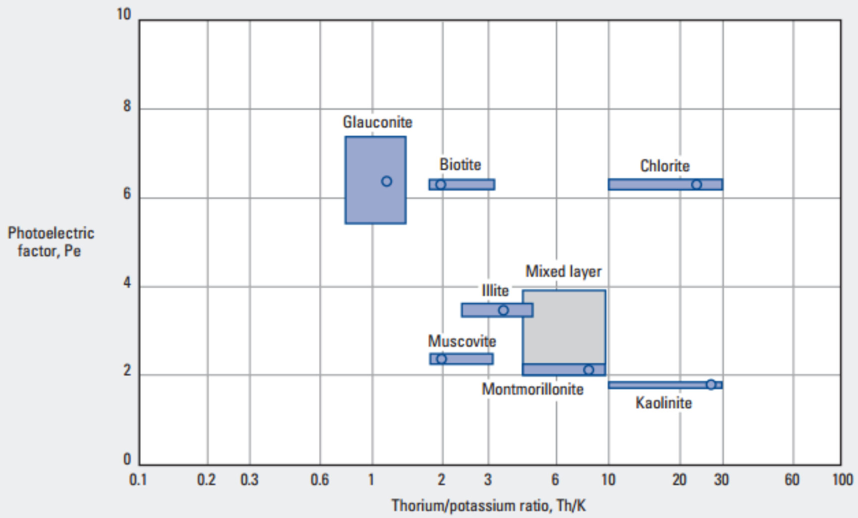
SPWLA 51st Annual Logging Symposium, June 19–23, 2010

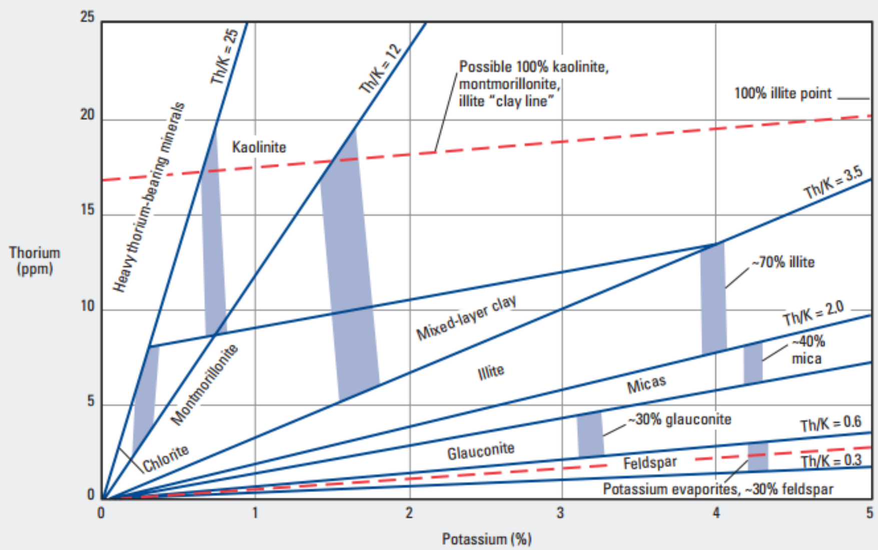
STATE-OF-THE-ART PERMEABILITY DETERMINATION FROM WELL LOGS TO PREDICT DRAINAGE CAPILLARY WATER SATURATION IN CLASTIC ROCKS

Chiew F. Choo, *PETRONAS Carigali Sdn. Bhd.*

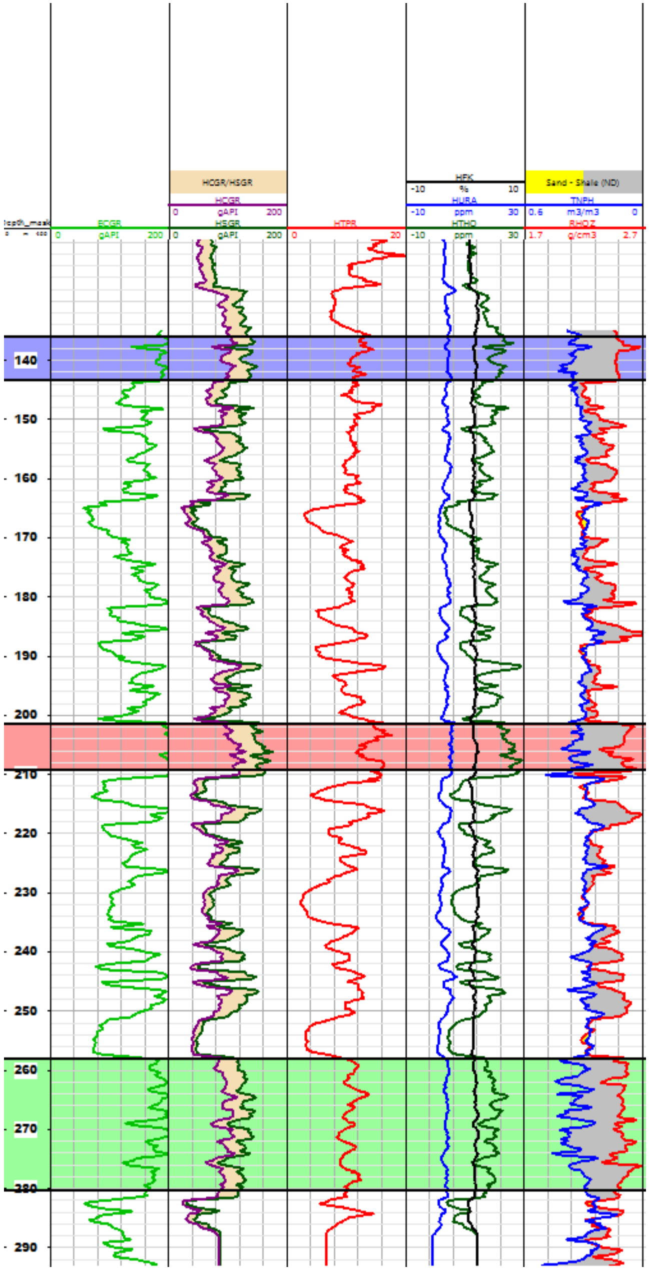
Natural GR: Lith-1 and Lith-2 (CP-18, CP-19)

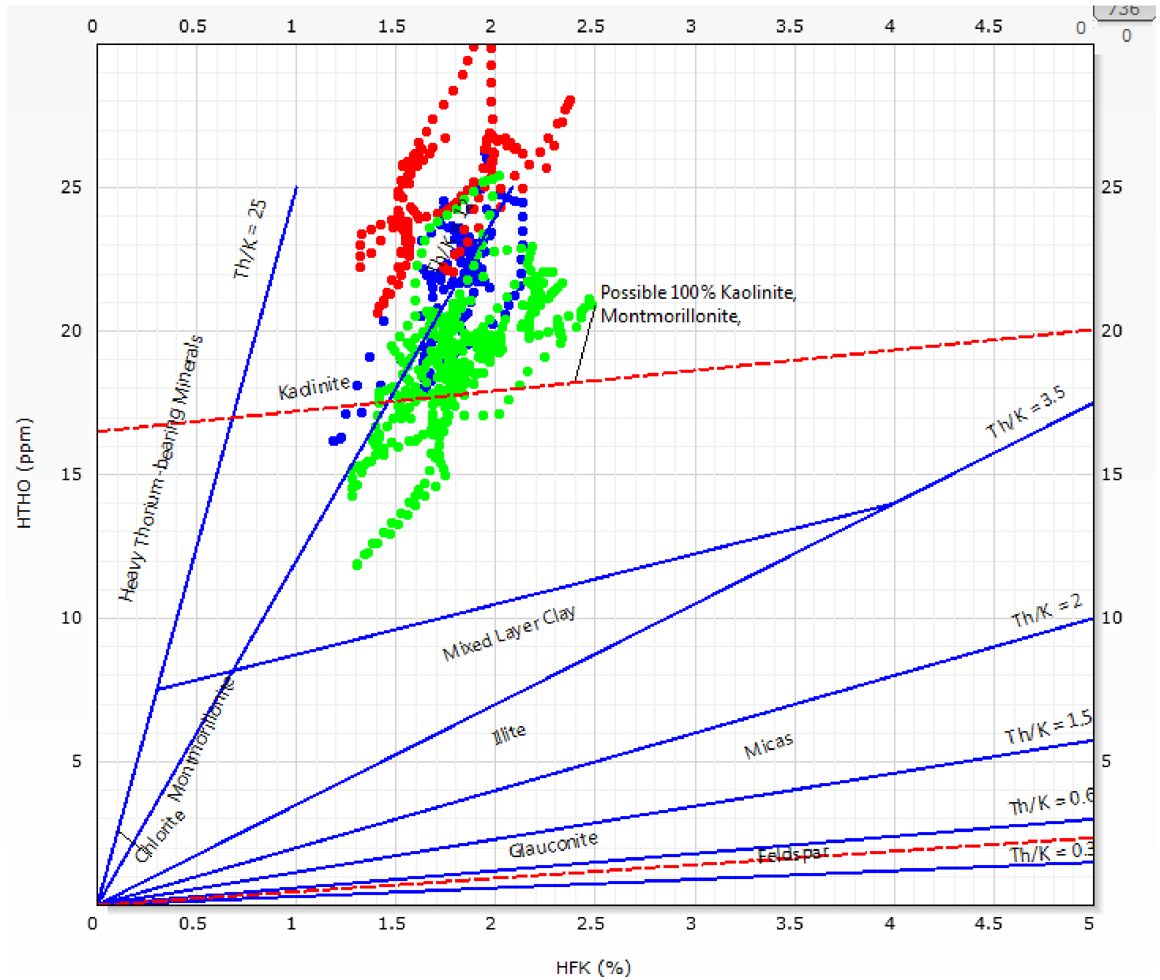




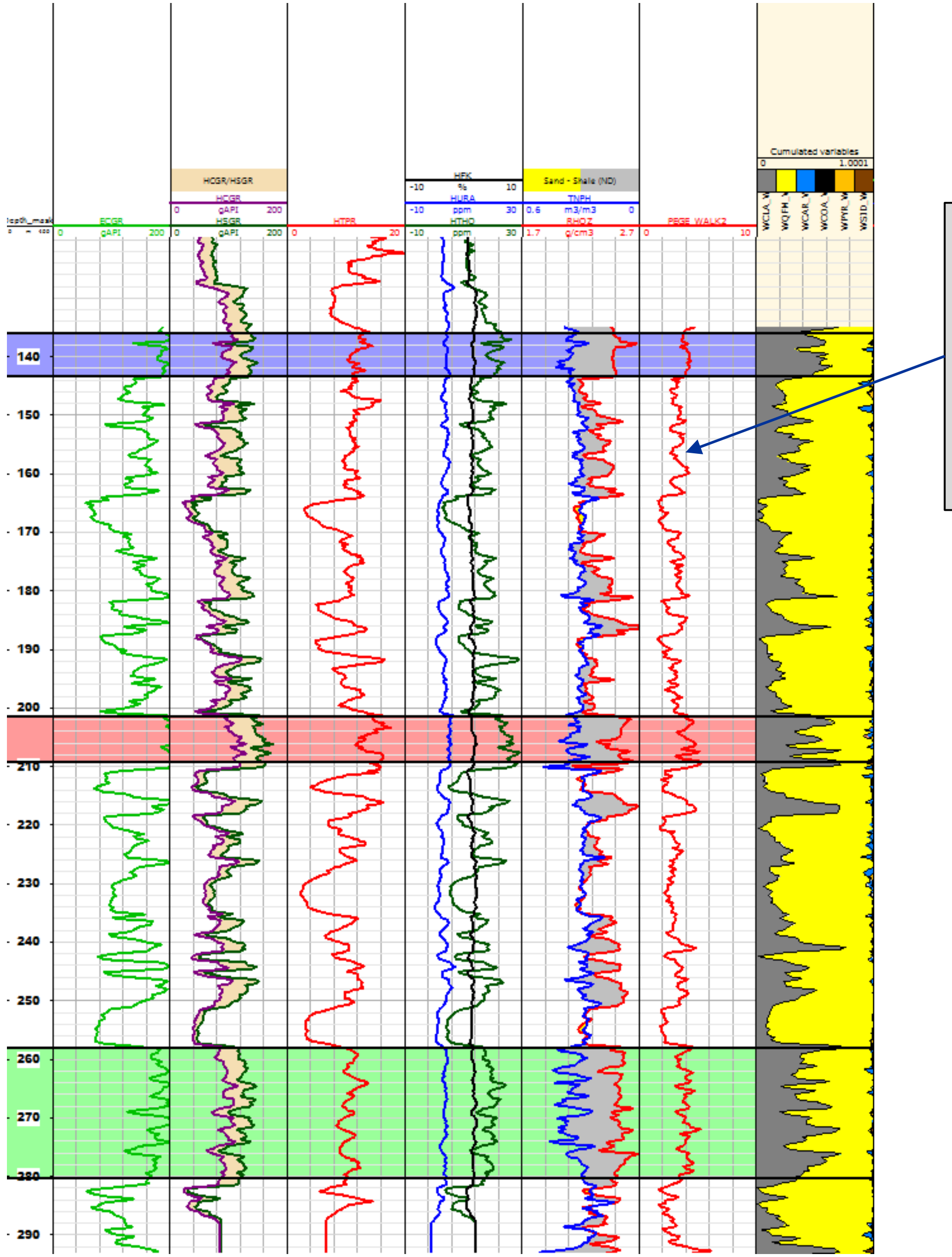


Clay Typing From GR Spectroscopy





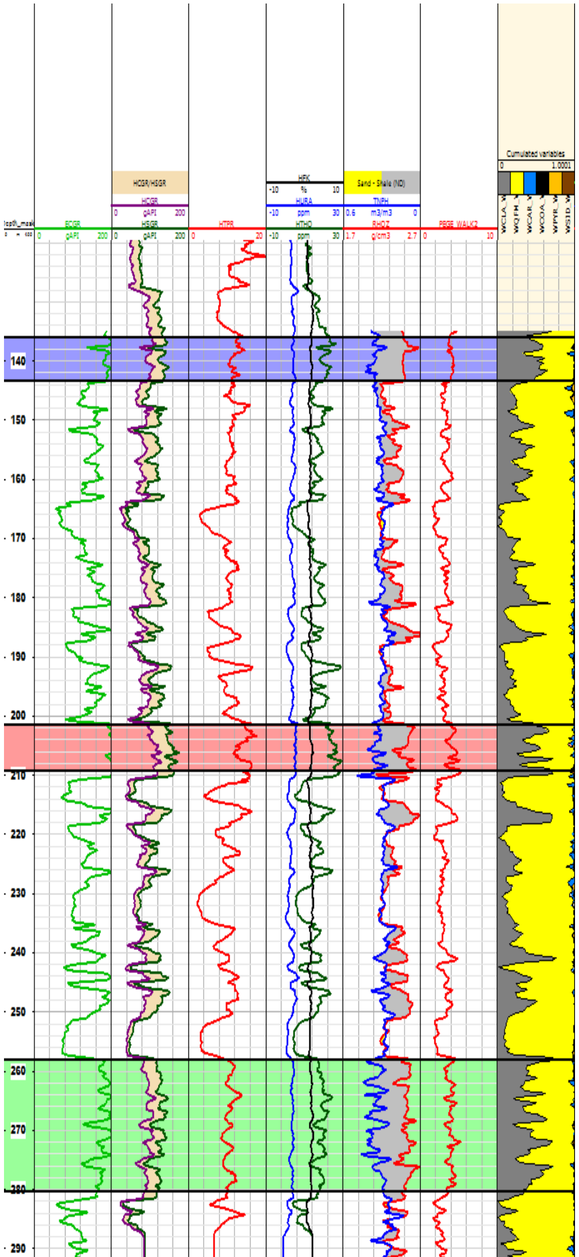
PEF from Neutron-GR Spectroscopy

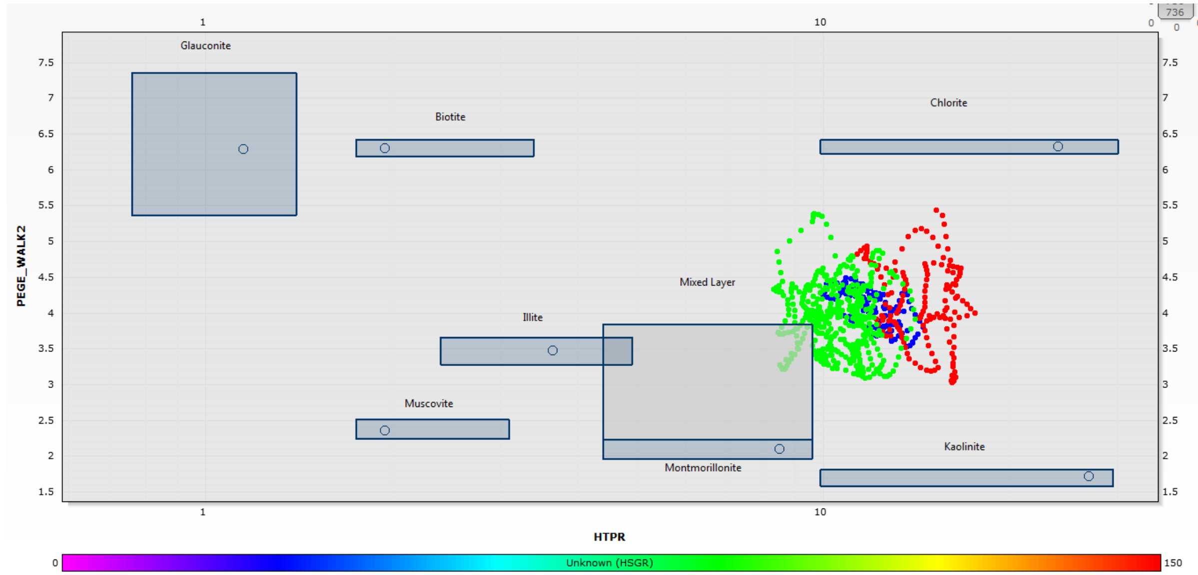


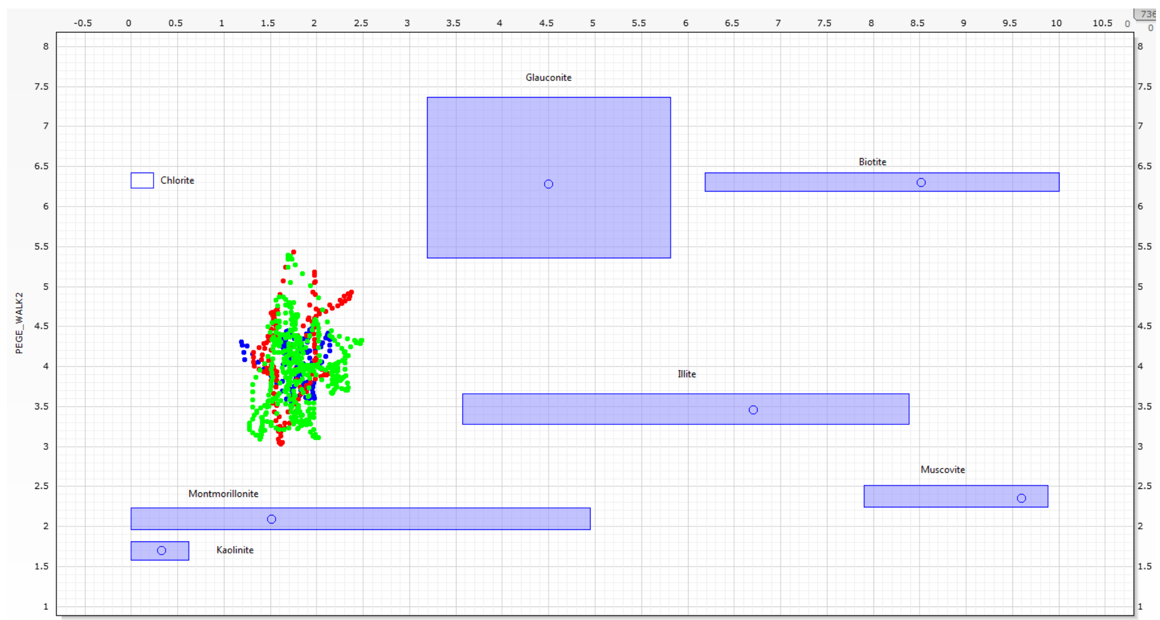
PEF from
N-GR Spectroscopy

Not sensitive to
Barite in the mud

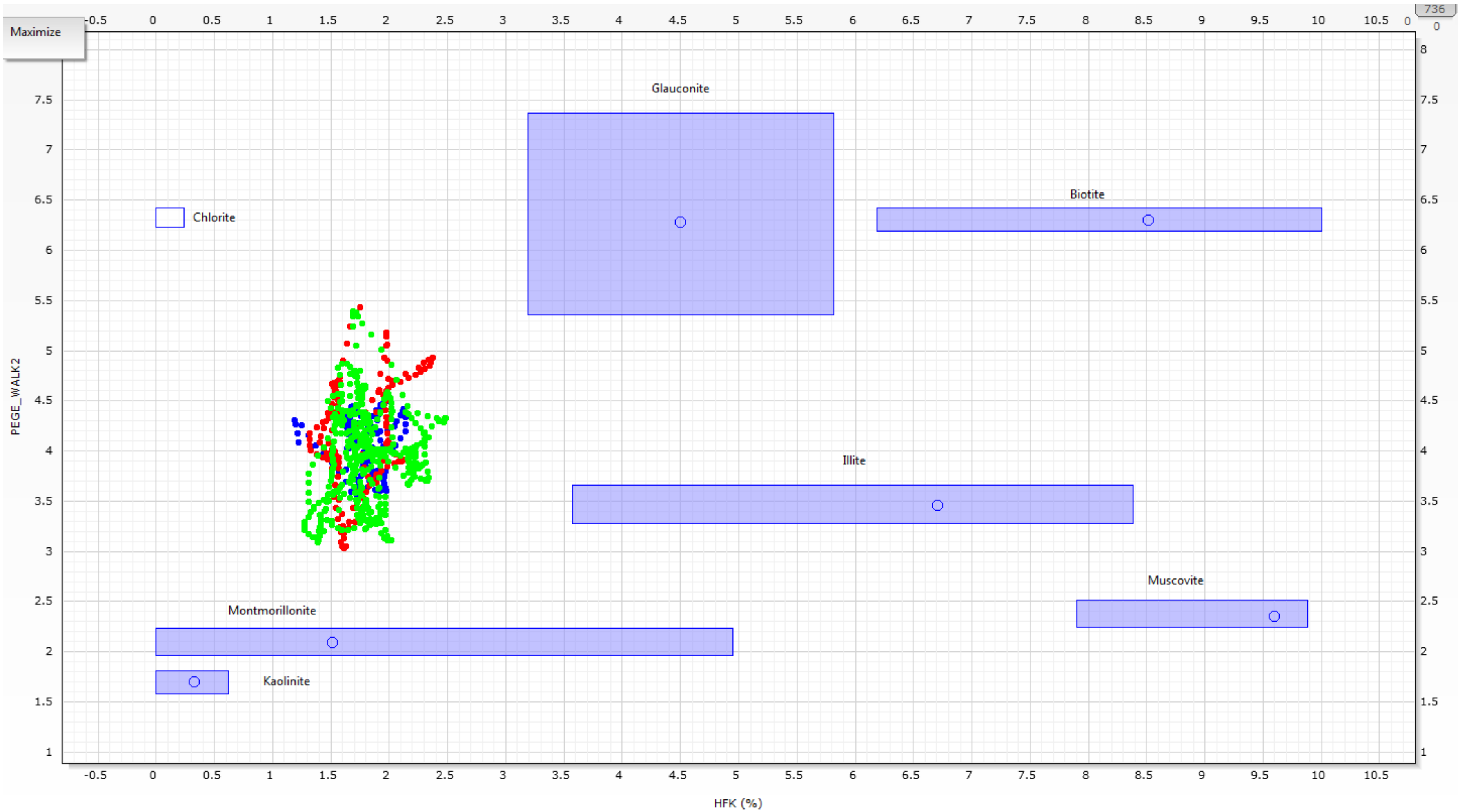
PEF vs TH/K and PEF vs K



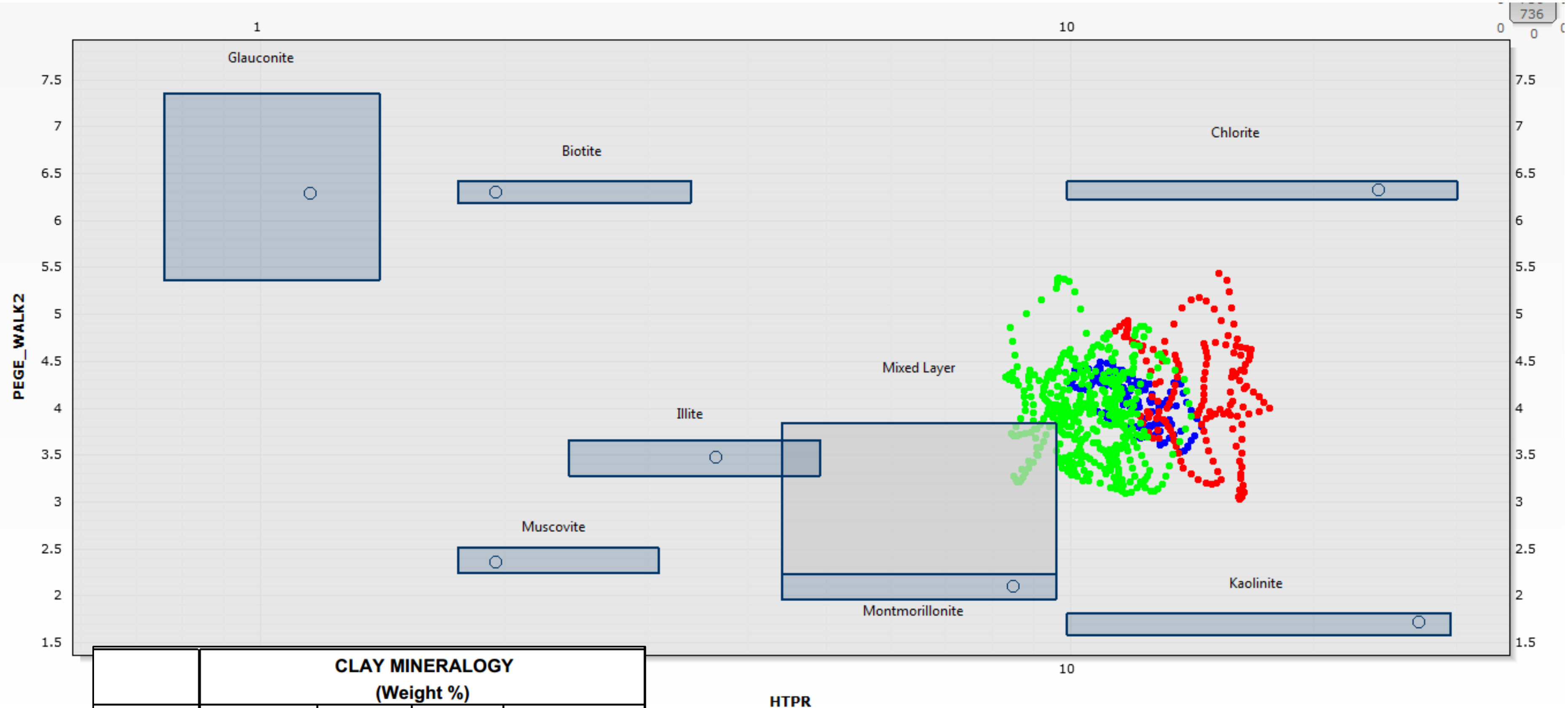




PEF vs K

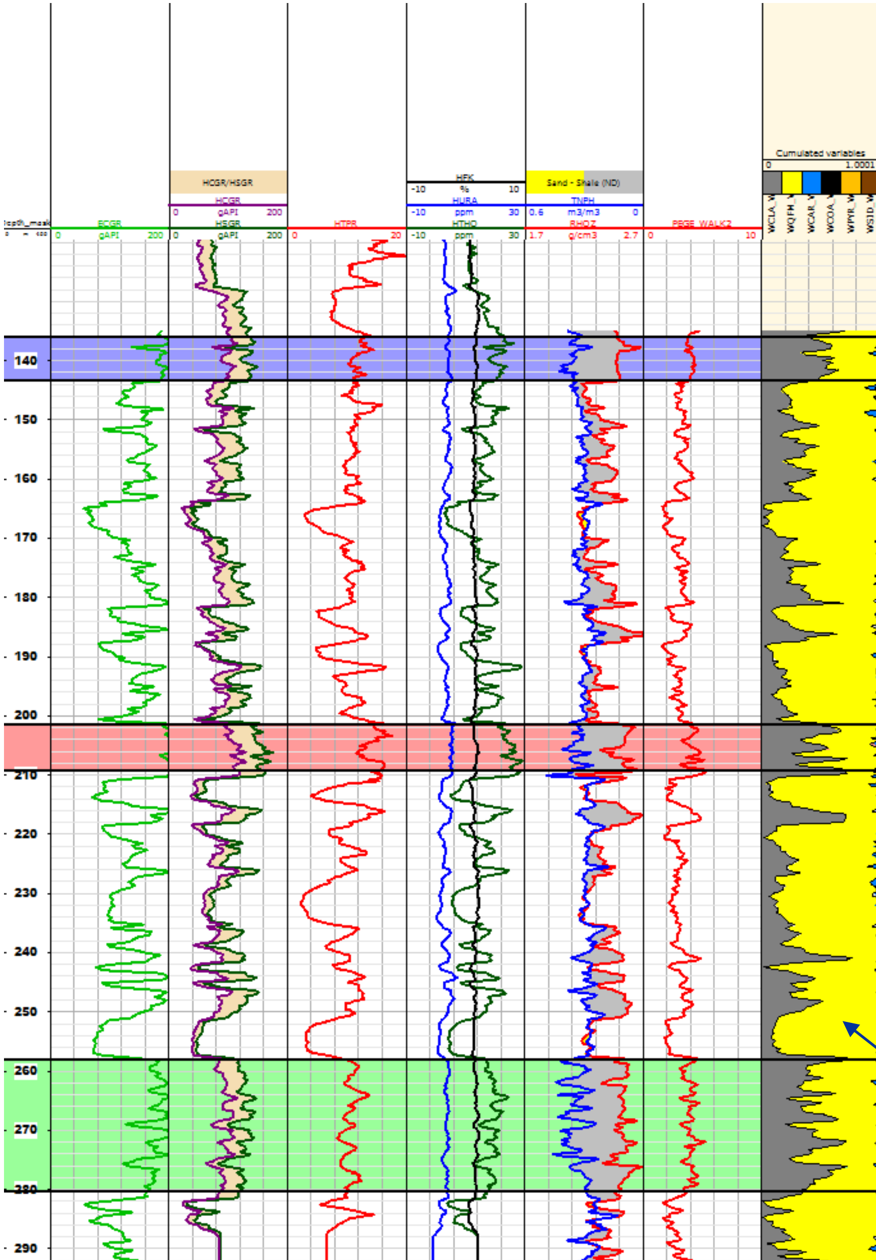

Maximize
Glauconite
Biotite
Chlorite
Illite
Muscovite
Montmorillonite
Kaolinite
PEGE_WALK2
HFK (%)
736

PEF vs TH/K



	CLAY MINERALOGY (Weight %)			
Total Clay	Illite + Mica	Kaolinite	Chlorite	Mixed Layer Illite/Smectite *
15.9	2.7	8.2	2.7	2.3
21.4	3.4	12.0	1.7	4.3
24.2	3.0	14.5	3.8	2.9
25.5	3.7	15.7	3.2	2.9
26.4	2.9	11.8	8.1	3.6
22.0	2.8	9.3	7.5	2.4
17.6	3.9	9.4	2.0	2.4
28.4	6.5	14.9	2.0	5.0
16.8	1.2	5.2	8.7	1.7

We can conclude that the clay type does not vary much



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22.0	2.8	9.3	7.5	2.4
17.6	3.9	9.4	2.0	2.4
28.4	6.5	14.9	2.0	5.0
16.8	1.2	5.2	8.7	1.7

Neutron Spectroscopy Total Clay Volume

Neutron Spectroscopy: Elemental Composition

Elemental abundance in earth's crust

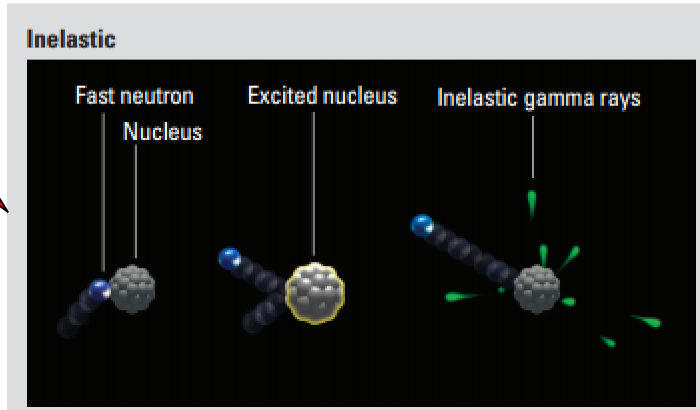
O	*46.7*
Si	***27.6***
Al	***8.1***
Fe	***5.1***
Ca	***3.7***
Na	***2.8***
K	***2.6***
Mg	***2.1***
S, Ti, Gd, Mn	

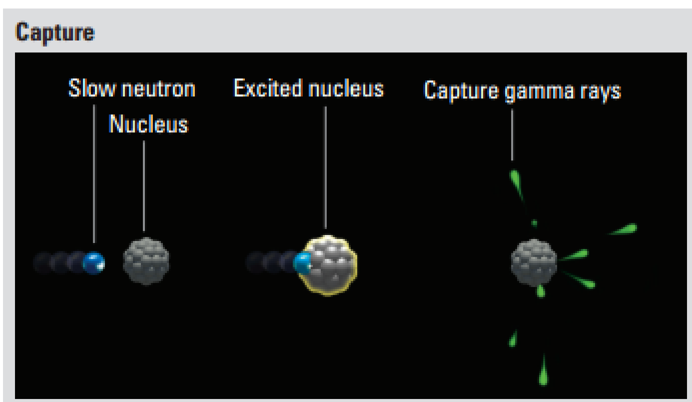
> 99 %

Carbon

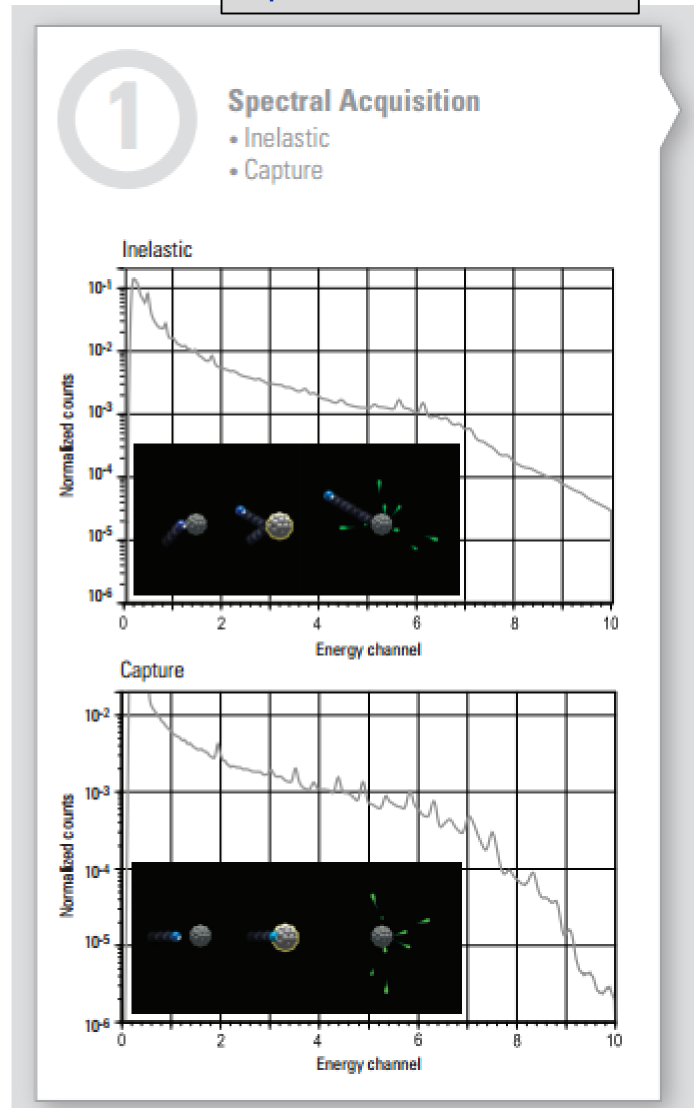
Neutron – Gammaray Spectroscopy

Neutron Source

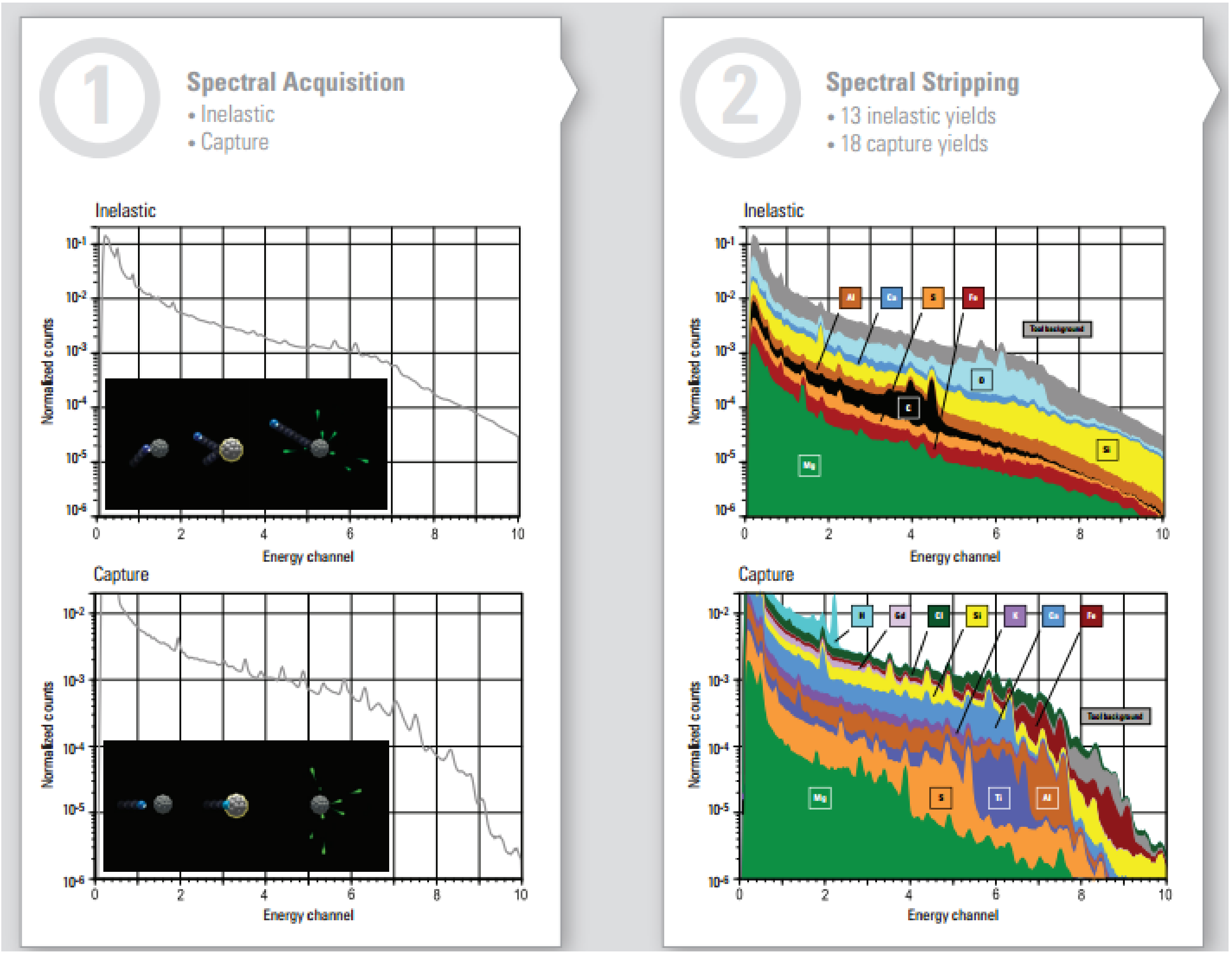




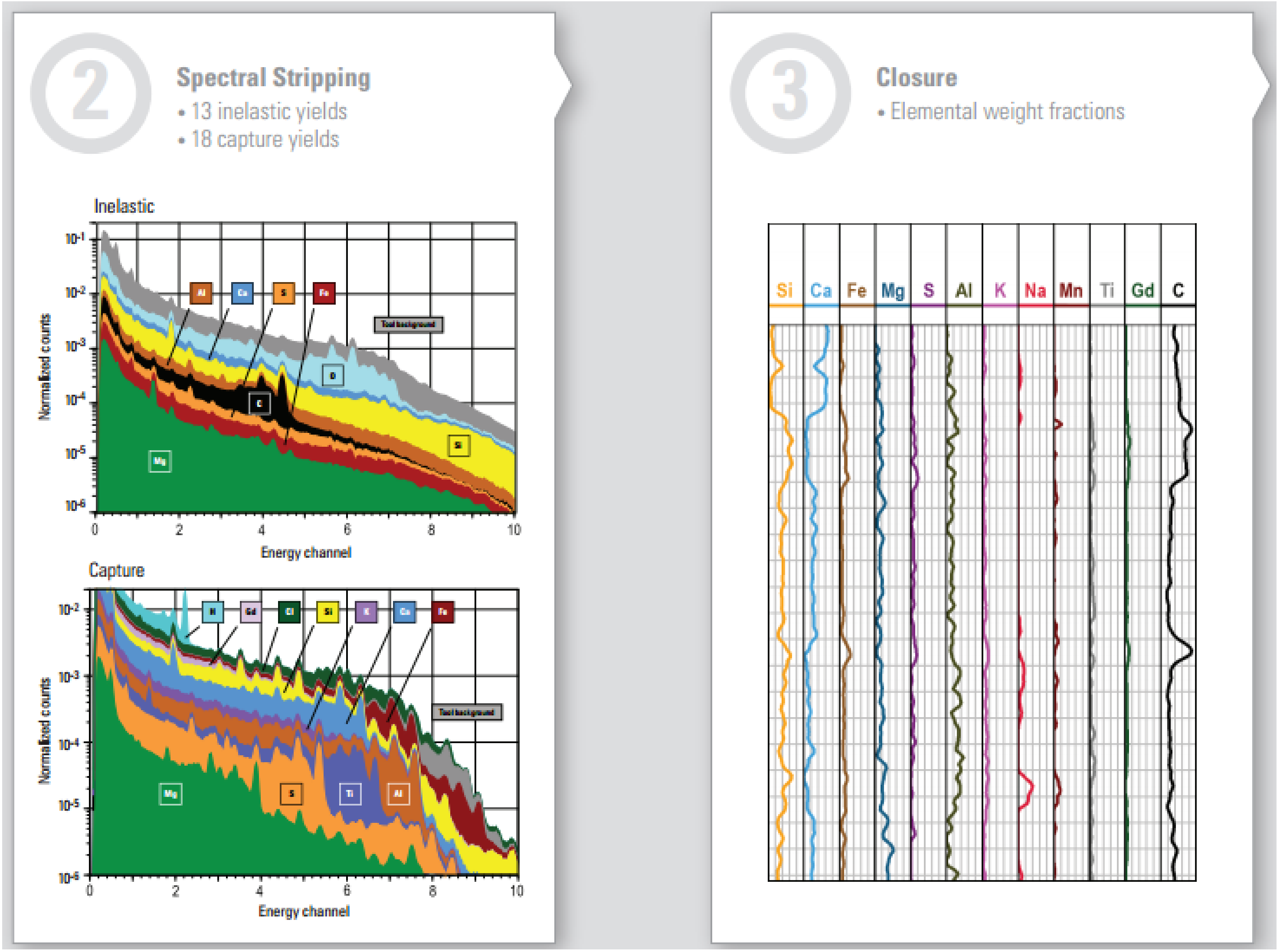
Spectral GR Detector



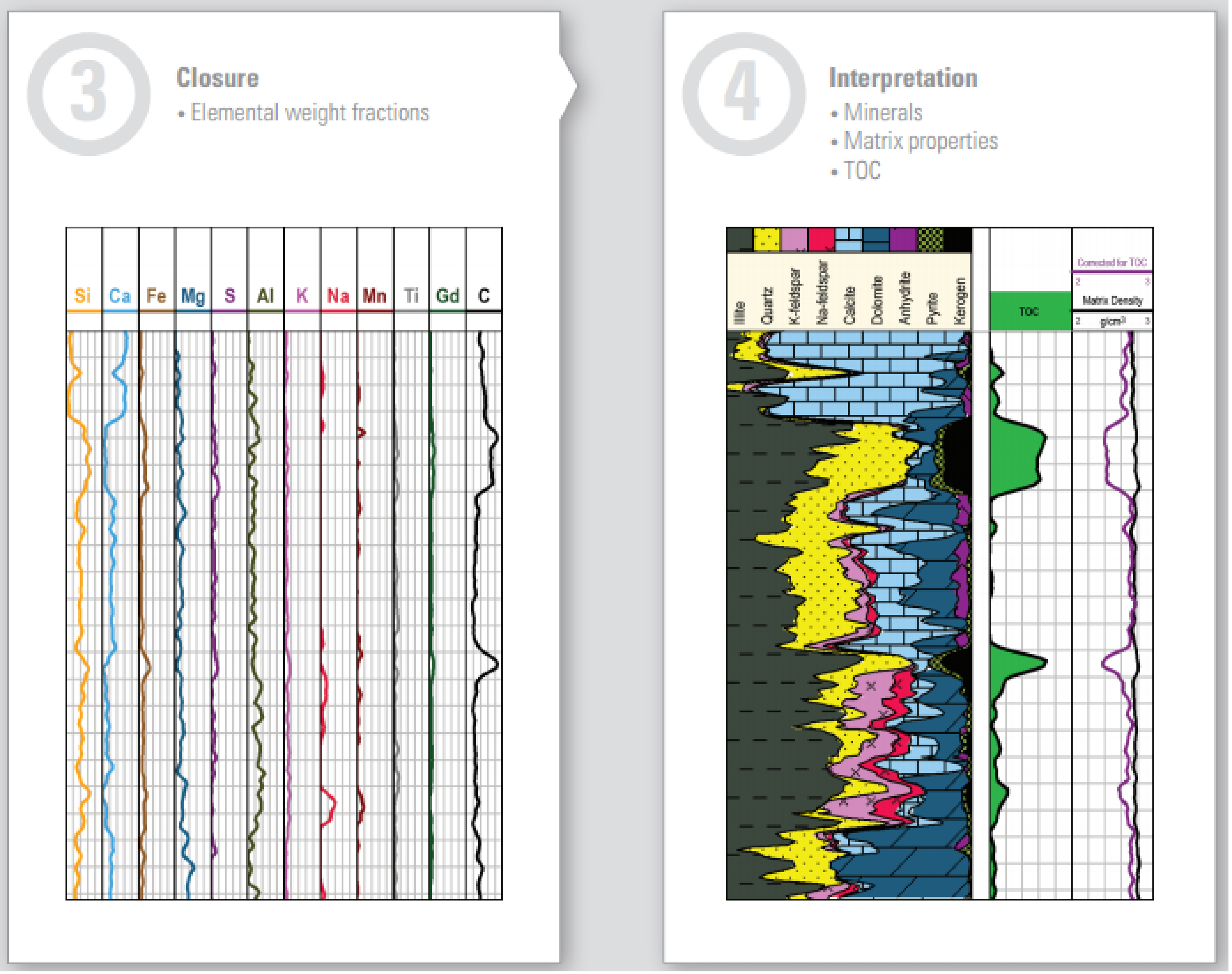
Each Element Generates a Unique GR Spectrum



Spectrum Analysis : Element Concentrations



Elements to Minerals Interpretation



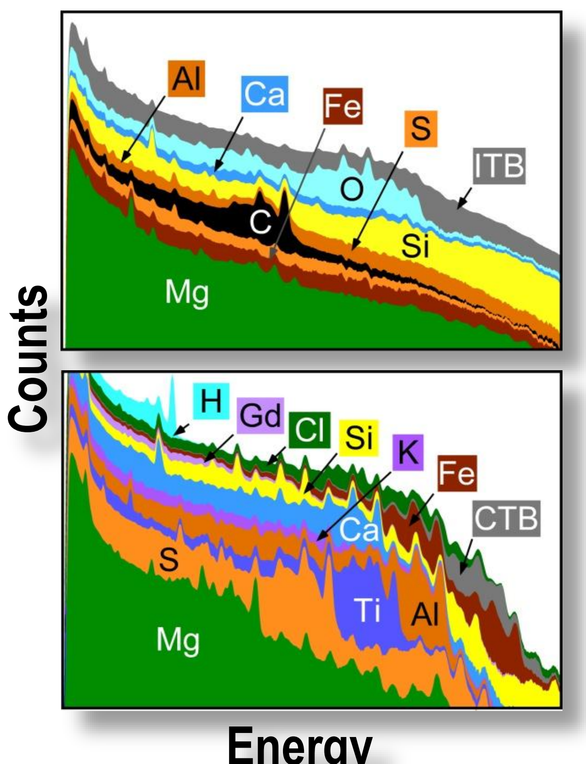
Neutron – GR Spectroscopy

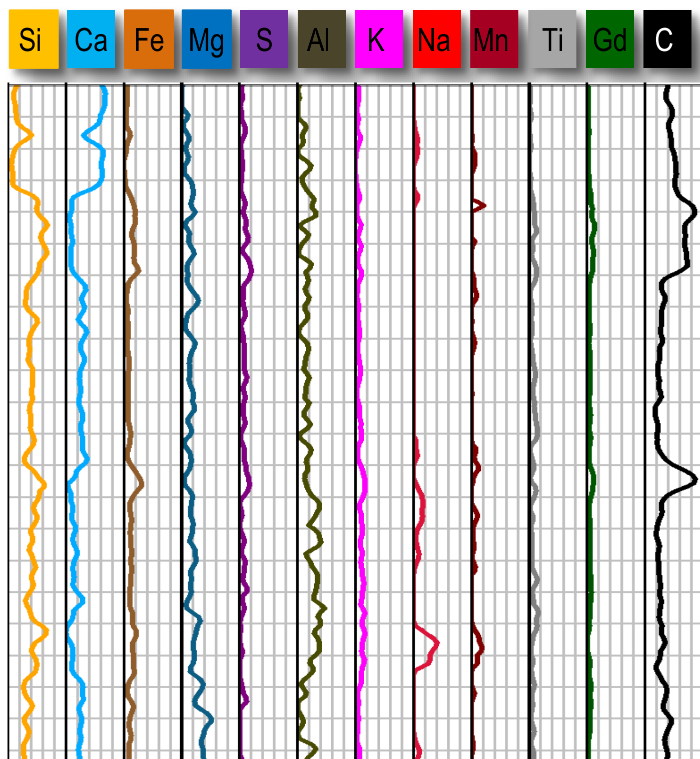
Spectra Acquisition
- Spectra

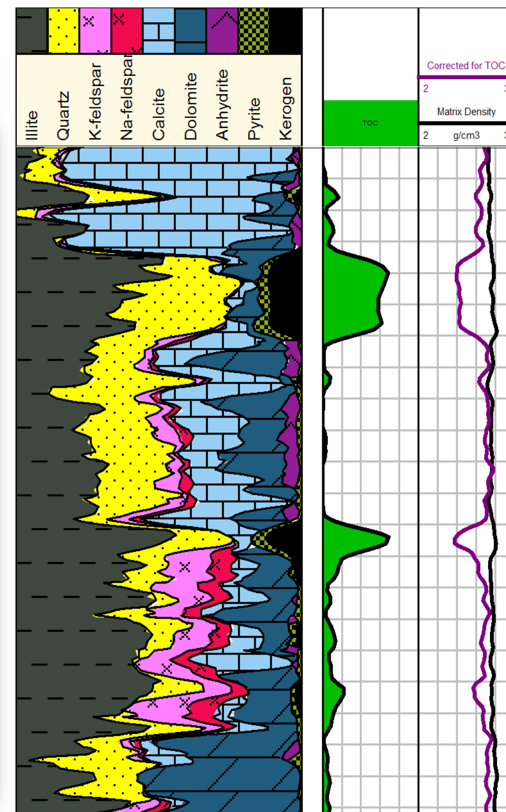
Spectral Stripping
- Elemental Yields

Closure
- Dry Weight Elements

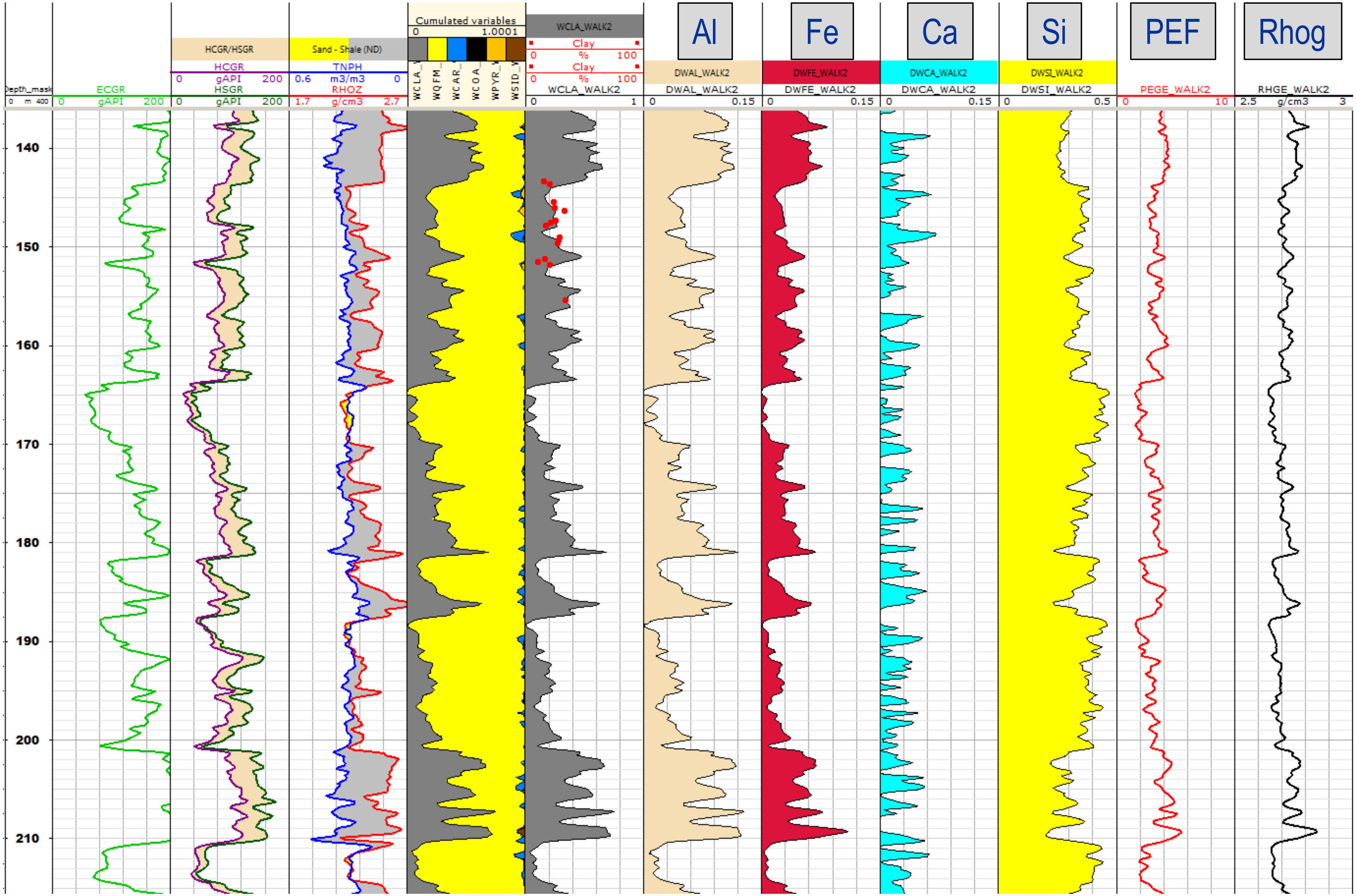
Interpretation
- Minerals
- Matrix Properties
- TOC



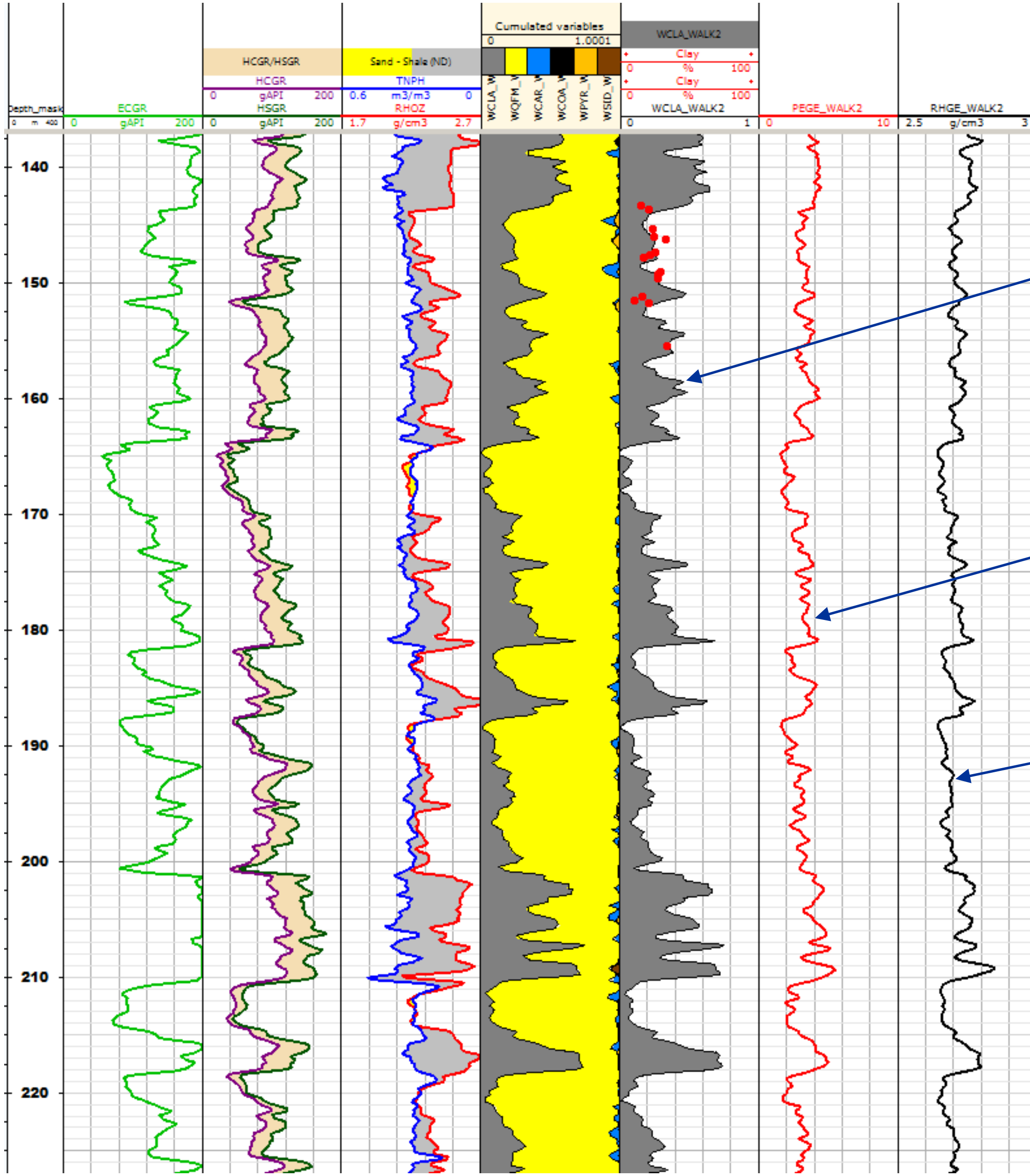




Dry Weight Clay Fraction From Neutron Spectroscopy



Dry Weight Clay Fraction From Neutron Spectroscopy

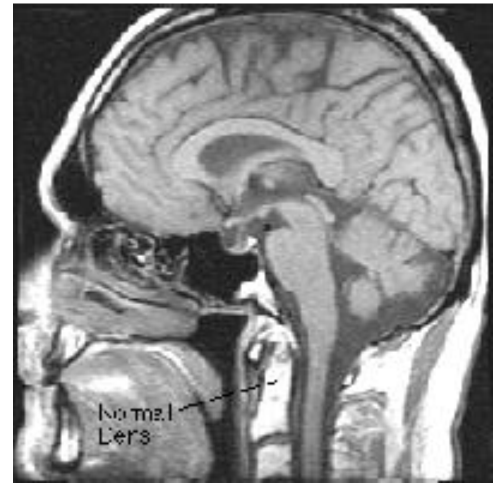


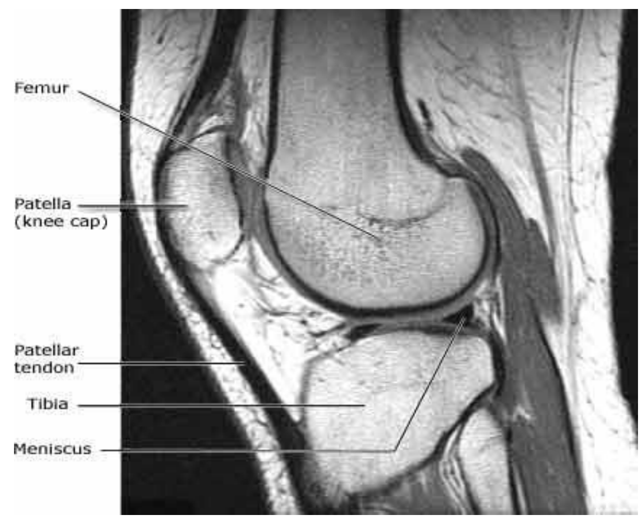
Dry Weight Clay Volume.
Directly comparable to XRD or FTIR

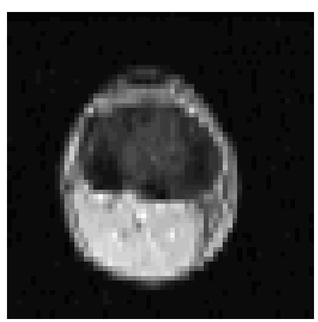
PEF_Spectroscopy

Grain Density
(more on this soon)

Modern MRI Images

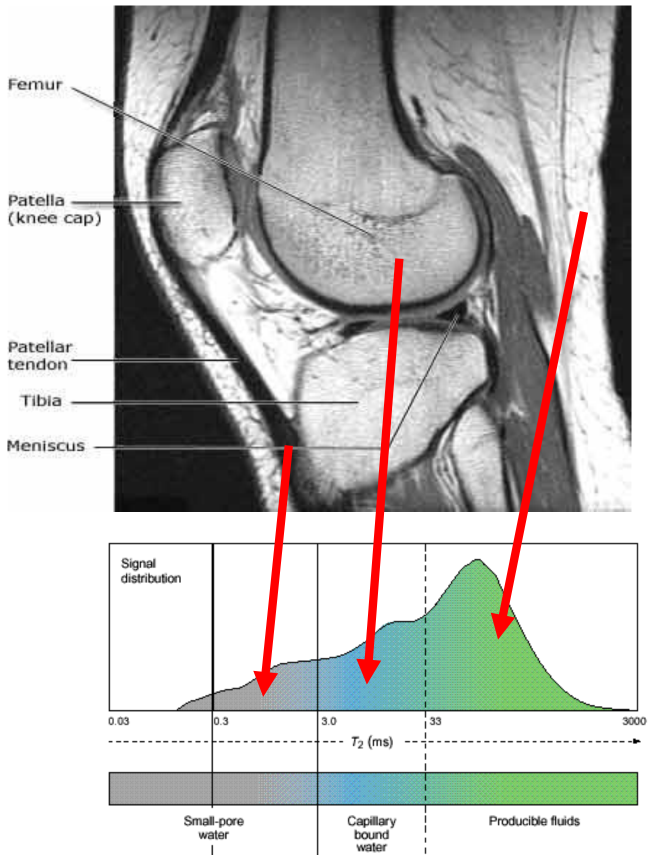






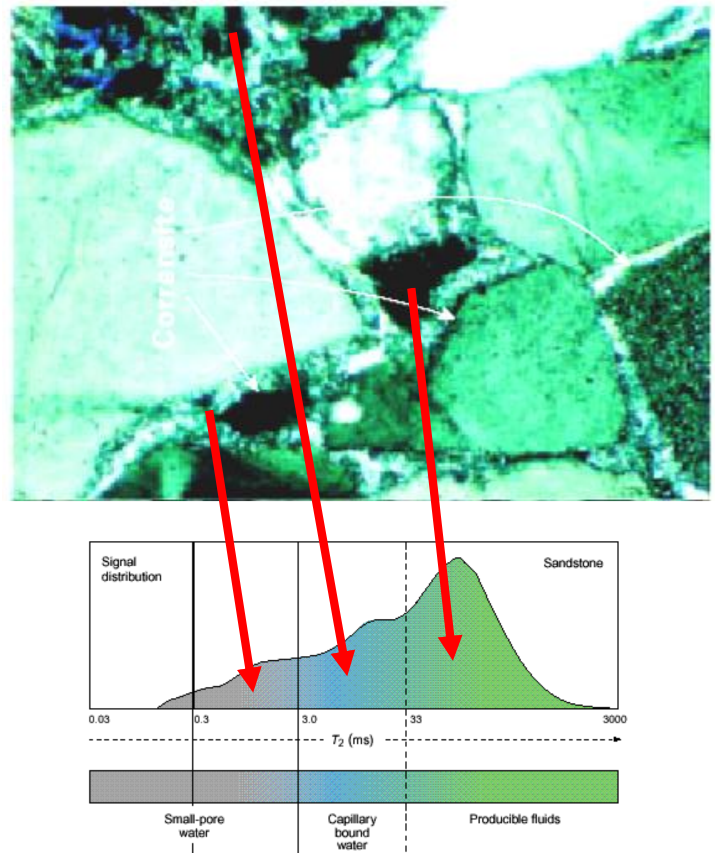
Volume of measurement

MRI



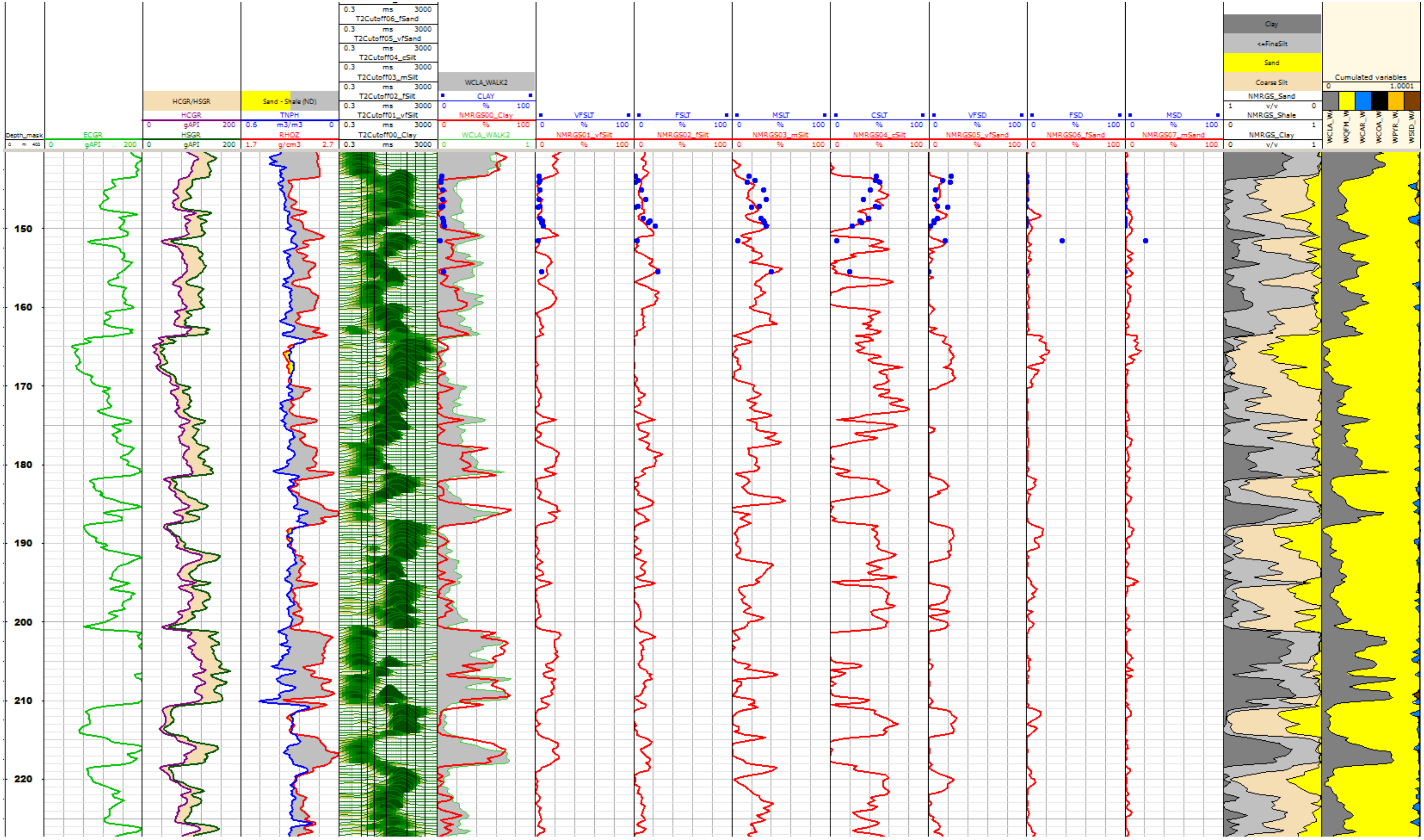
Each pixel in Image has an amplitude and T2

Logging tool

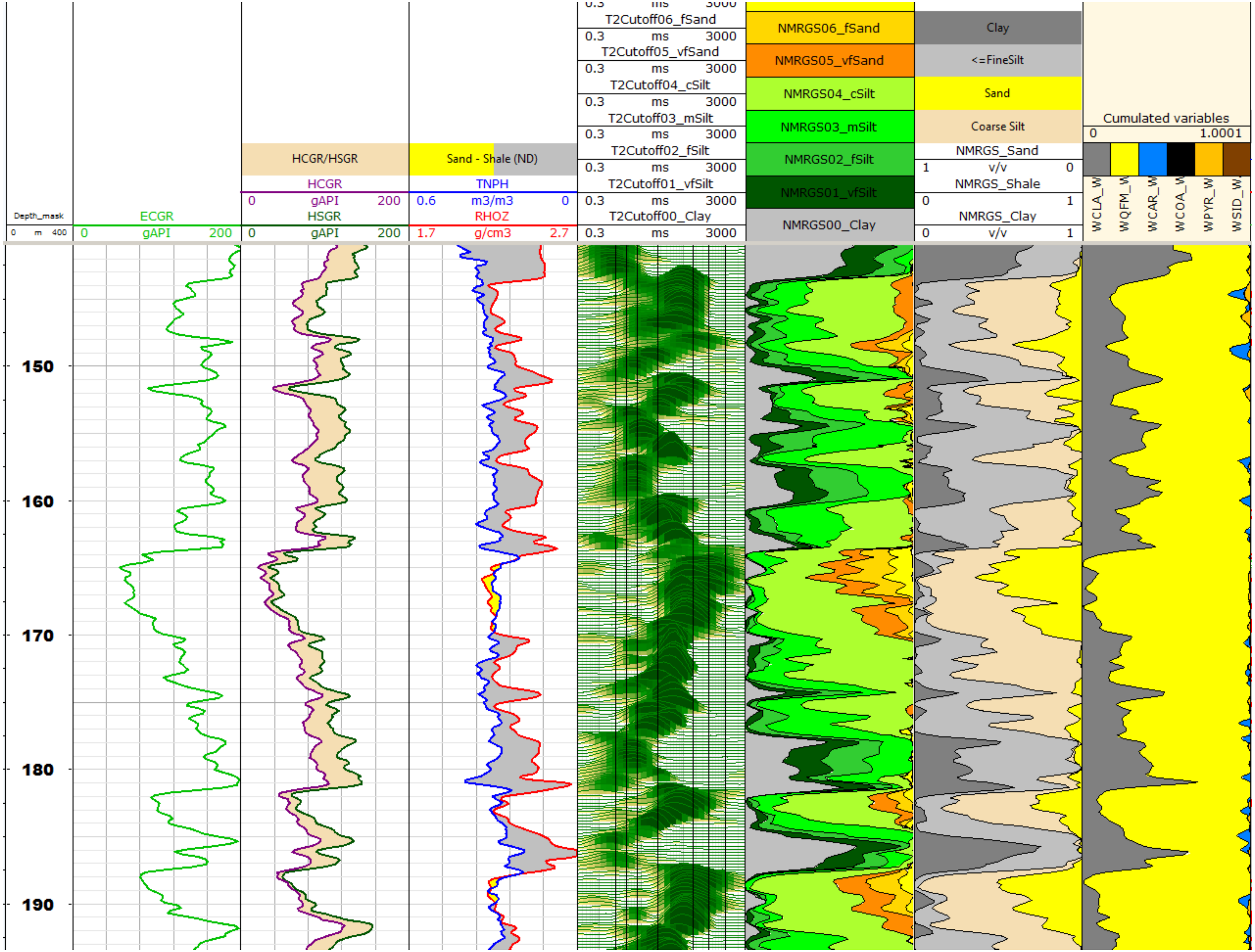


Volume of investigation is several cubic inches so it can include millions of pores.

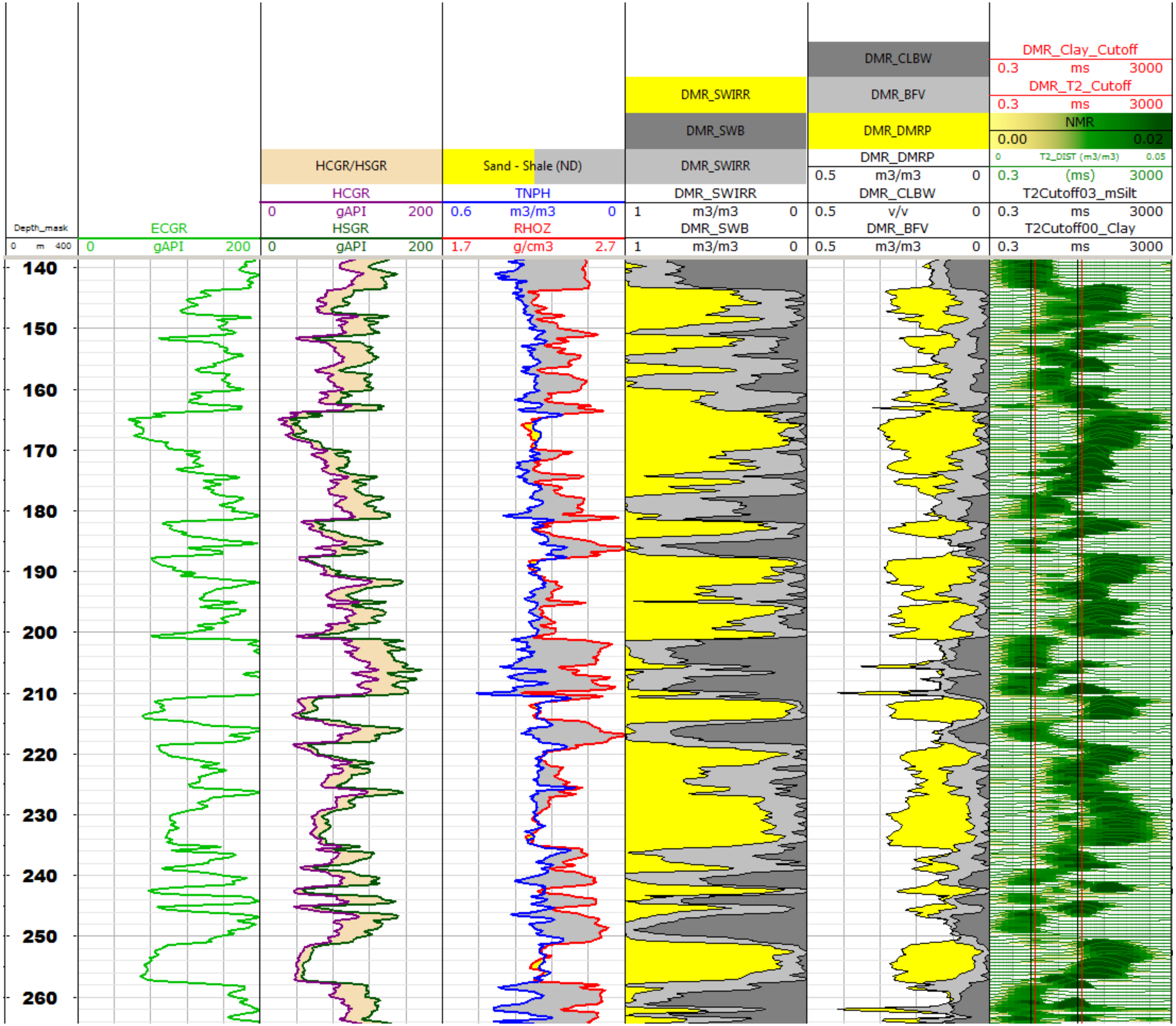
NMR Grain Size Calibration



NMR Grain Size Example

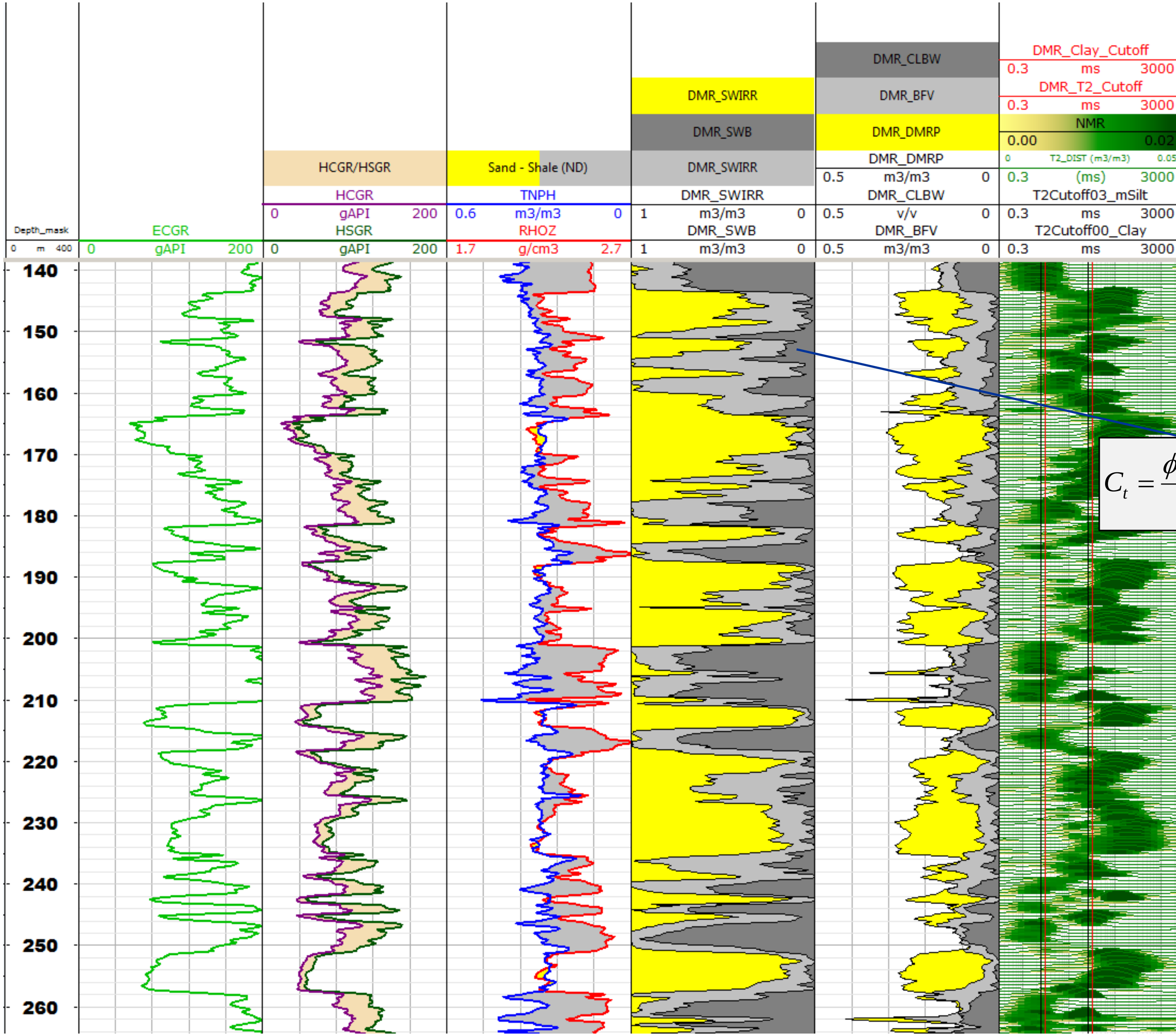


Swb From NMR



Depth_mask
0 m 400
ECGR
0 gAPI 200
HCGR/HSGR
HCGR
0 gAPI 200
HSGR
0 gAPI 200
Sand - Shale (ND)
TNPH
0.6 m3/m3 0
RHOZ
1.7 g/cm3 2.7
DMR_SWIRR
DMR_SWB
DMR_SWIRR
DMR_SWIRR
1 m3/m3 0
DMR_SWB
1 m3/m3 0
DMR_CLBW
DMR_BFV
DMR_DMRP
DMR_DMRP
0.5 m3/m3 0
DMR_CLBW
0.5 v/v 0
DMR_BFV
0.5 m3/m3 0
DMR_Clay_Cutoff
0.3 ms 3000
DMR_T2_Cutoff
0.3 ms 3000
NMR
0.00 0.02
0 T2_DIST (m3/m3) 0.05
0.3 (ms) 3000
T2Cutoff03_mSilt
0.3 ms 3000
T2Cutoff00_Clay
0.3 ms 3000
140
150
160
170
180
190
200
210
220
230
240
250
260

Swb From NMR

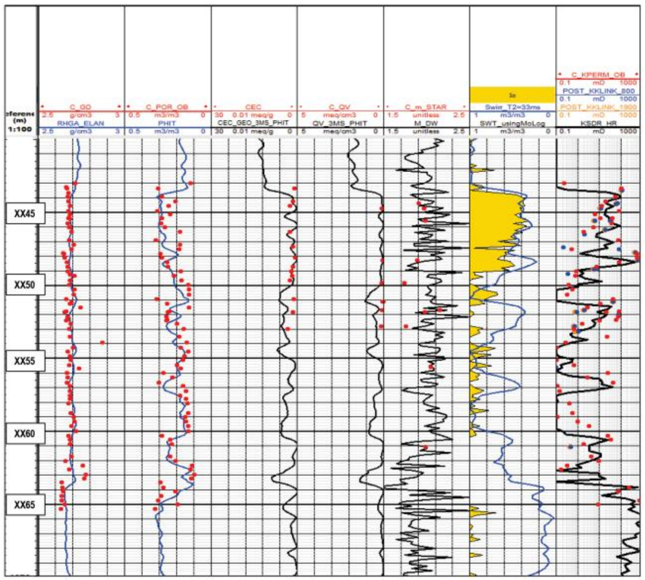


Dual Water

$$C_t = \frac{\phi_t^m S_{wt}^n}{a}\left(C_w + \frac{S_{wb}}{S_{wt}}\left(C_{wb} - C_w\right)\right)$$

CEC From NMR and N-Spectroscopy Logs

Willy Tan et al. computed Qv and CEC using NMR and N-GR Spectroscopy and went on to derive m using Sxo from a **Dielectric** measurement.



$$CEC_{BulkRock} = \frac{Q_v * \emptyset_T}{\rho_{grain} * (1 - \emptyset_T)}$$

N-GR Spectroscopy

NMR

$$Q_v = \frac{S_{wb}}{\alpha v_Q^H}$$

functions of temperature and water salinity

$$C_{xo} = \phi^{m_0} S_{xo}{}^{n} \left[\left(\frac{S_{xo} - \alpha v_Q^H Q_v}{S_{xo}} \right) C_{mf} + \frac{\beta Q_v}{S_{xo}} \right]$$

PETROPHYSICS, VOL. 55, NO. 1 (FEBRUARY 2014); PAGE 14–23; 8 FIGURES

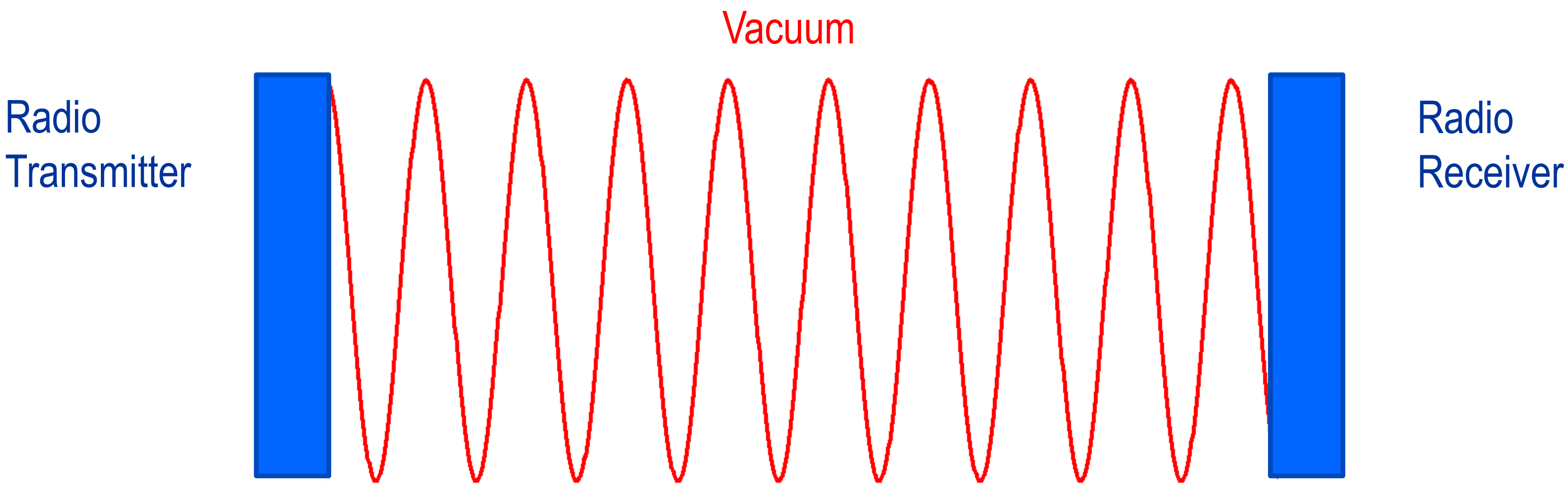
Solving Complex Dual-Water Equation using Dielectric-NMR-Spectroscopy and Conventional Logs

Willy Tan[1], Ryan Lafferty[2], and Thomas J. Neville[3]

Dielectric

Oilfield Review Spring 2011

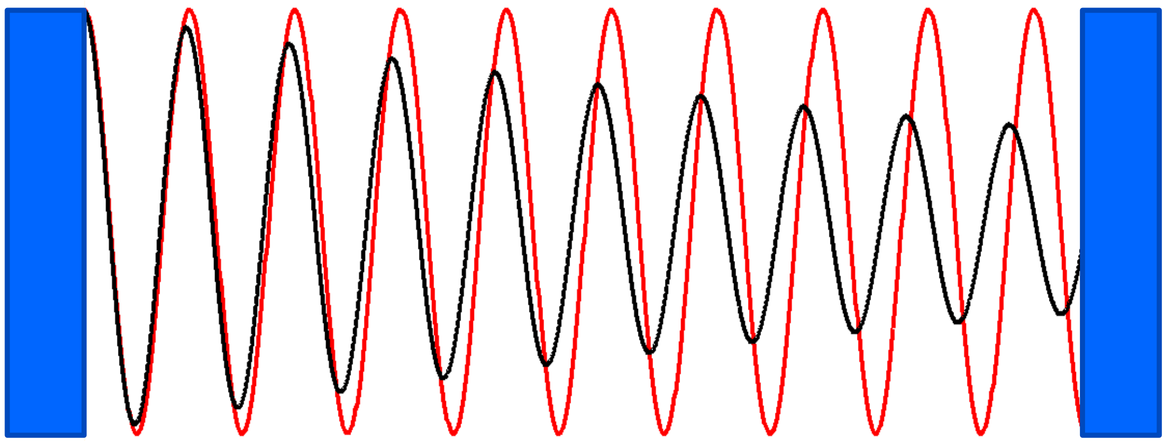
High Frequency Electromagnetic Waves



Principle of the Dielectric Scanner

Vacuum

Radio Transmitter



Radio Receiver

Material with a specific Dielectric Permittivity and Conductivity

A Amplitude
Ø Phase

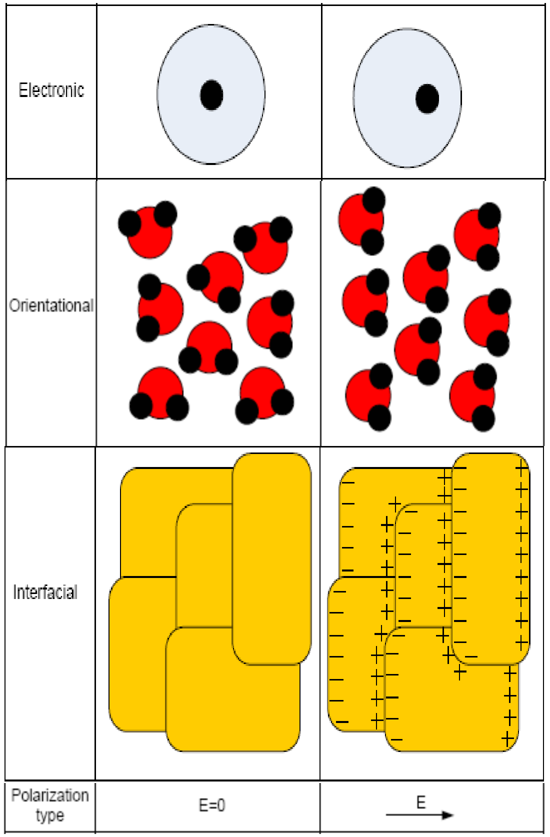
σ Conductivity
ε Relative Permittivity

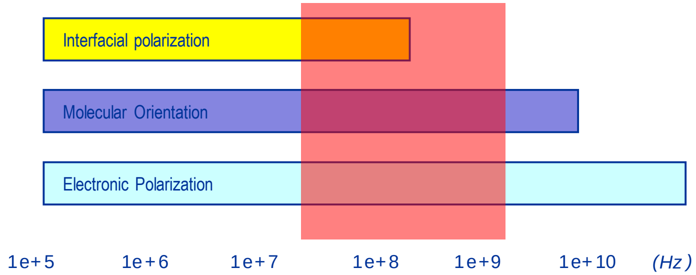
- **Dielectric dispersion** is the variation of relative permittivity and conductivity as a function of frequency

Dielectric Permittivity ε

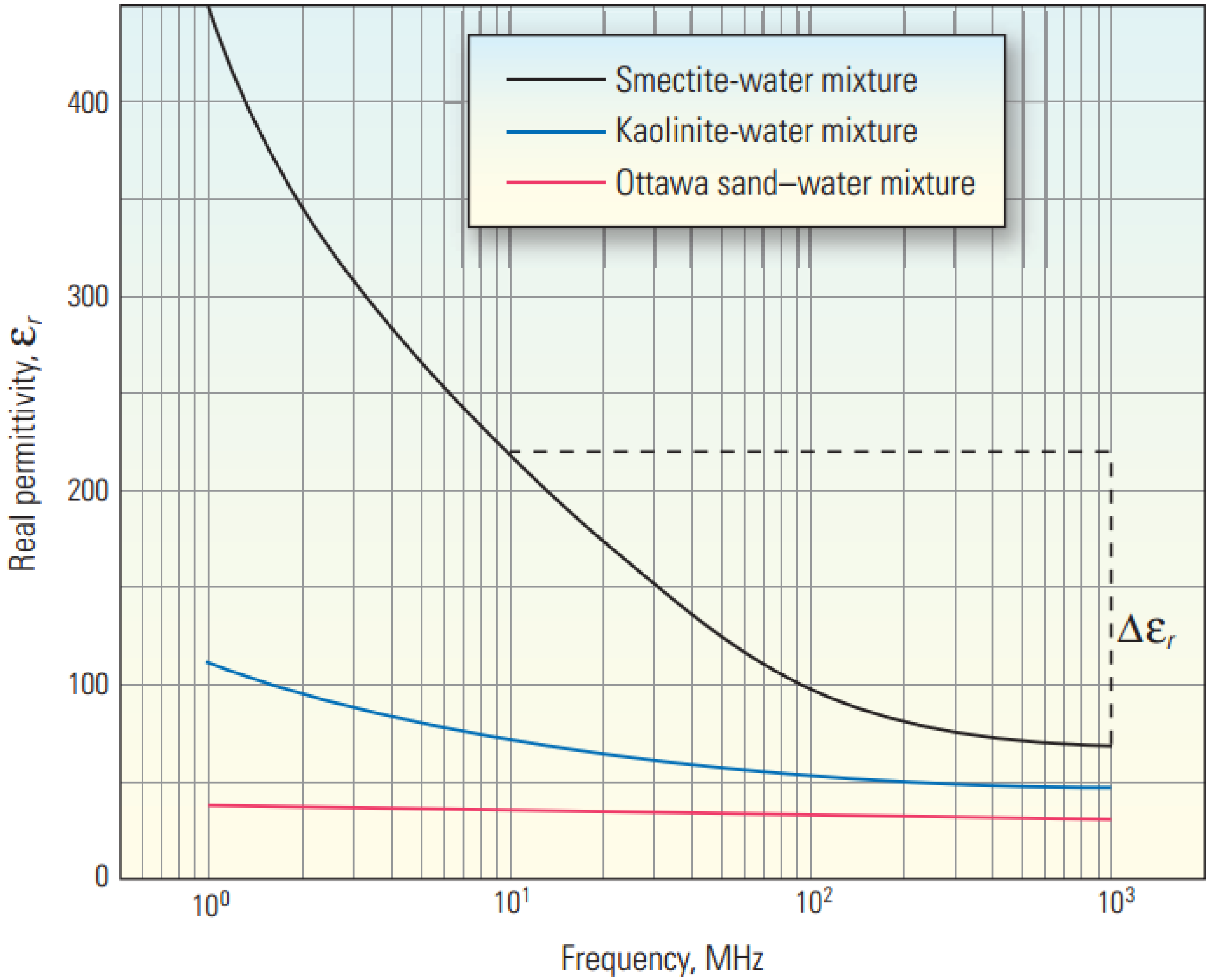
- Oil : ε ~ 2
- Rock : ε ~ 5-9
- Water : ε ~ 50-80

- Big contrast between water and oil
- Different frequencies sensitive to different properties



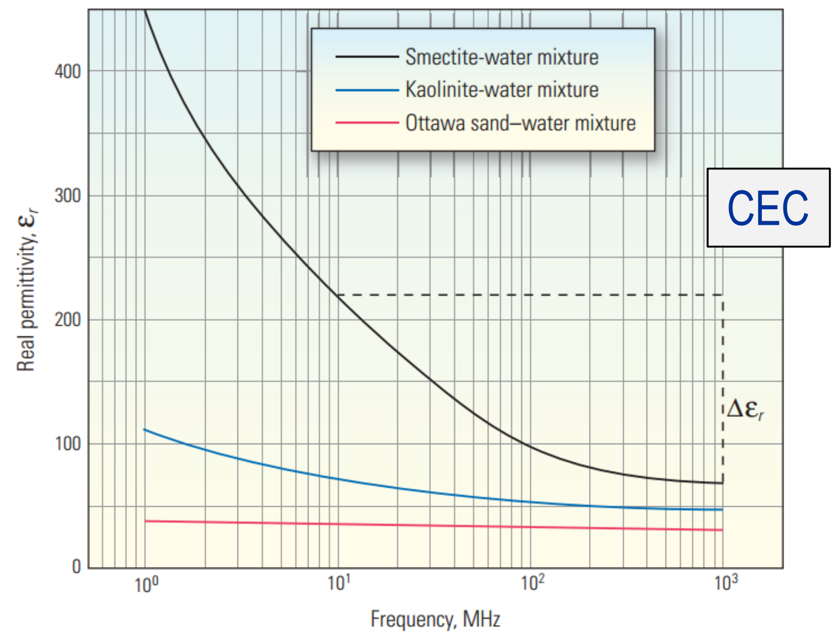


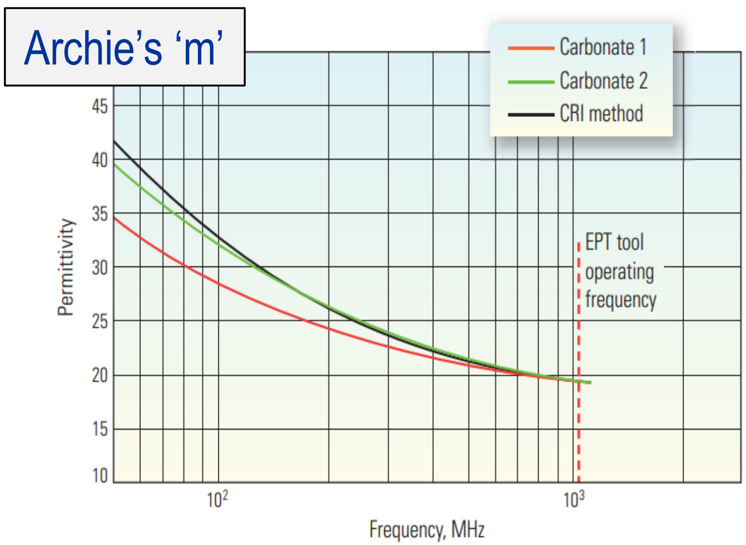
Dielectric Permittivity vs CEC

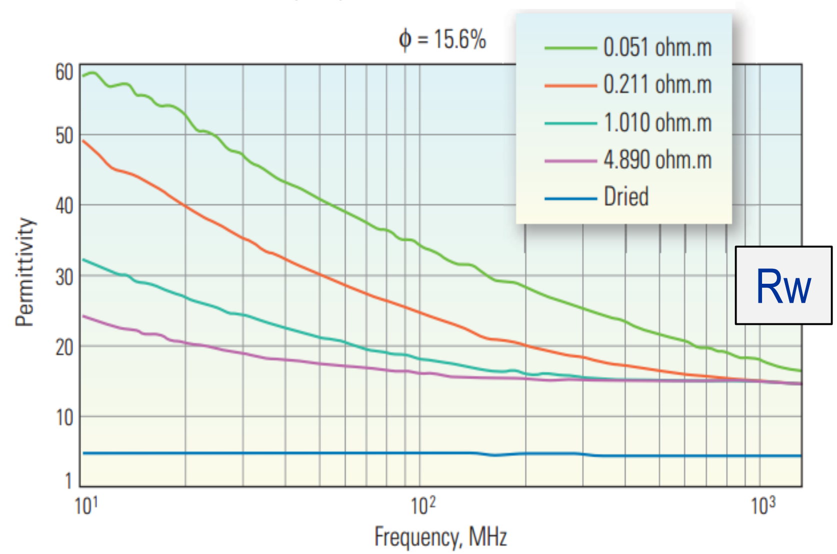


Unfortunately CEC is not alone

Variation in 'm' and Rw also cause dielectric dispersion







Equivalent Conductivity Solution

Measure Sw by one or more other methods that don't require resistivity

All log measurements are in the invaded zone except resistivity

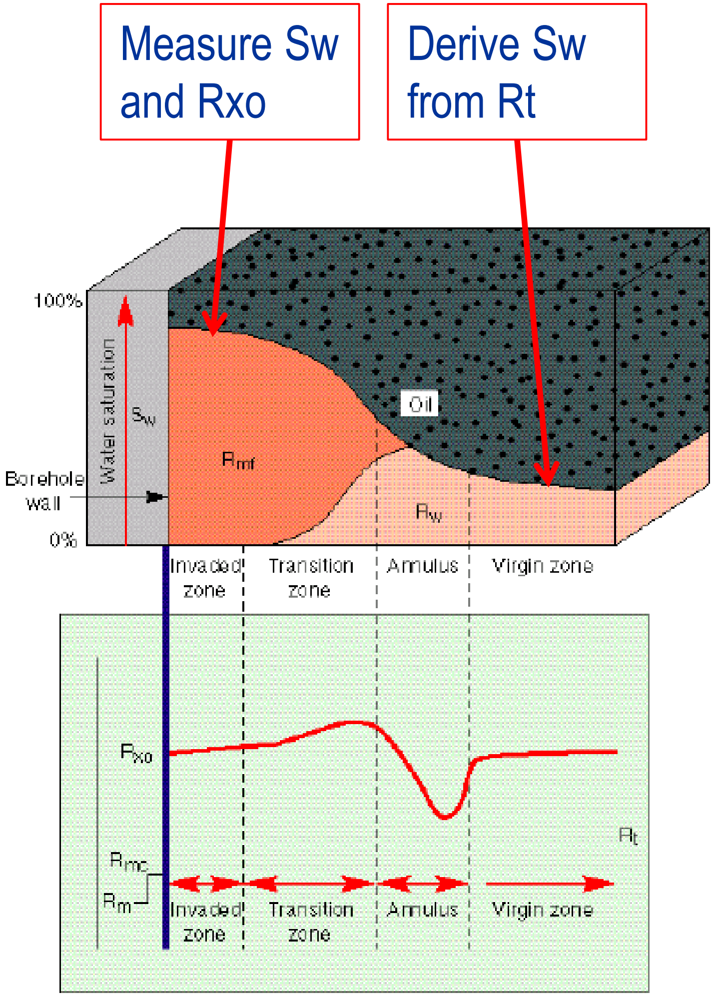
So
1- Measure Sxo and Rxo in the invaded zone
2- Derive a relationship between Rxo and Sxo
3- Apply this relationship to Rt to derive Sw.

This is complicated in water based mud due to different filtrate and formation water resistivity

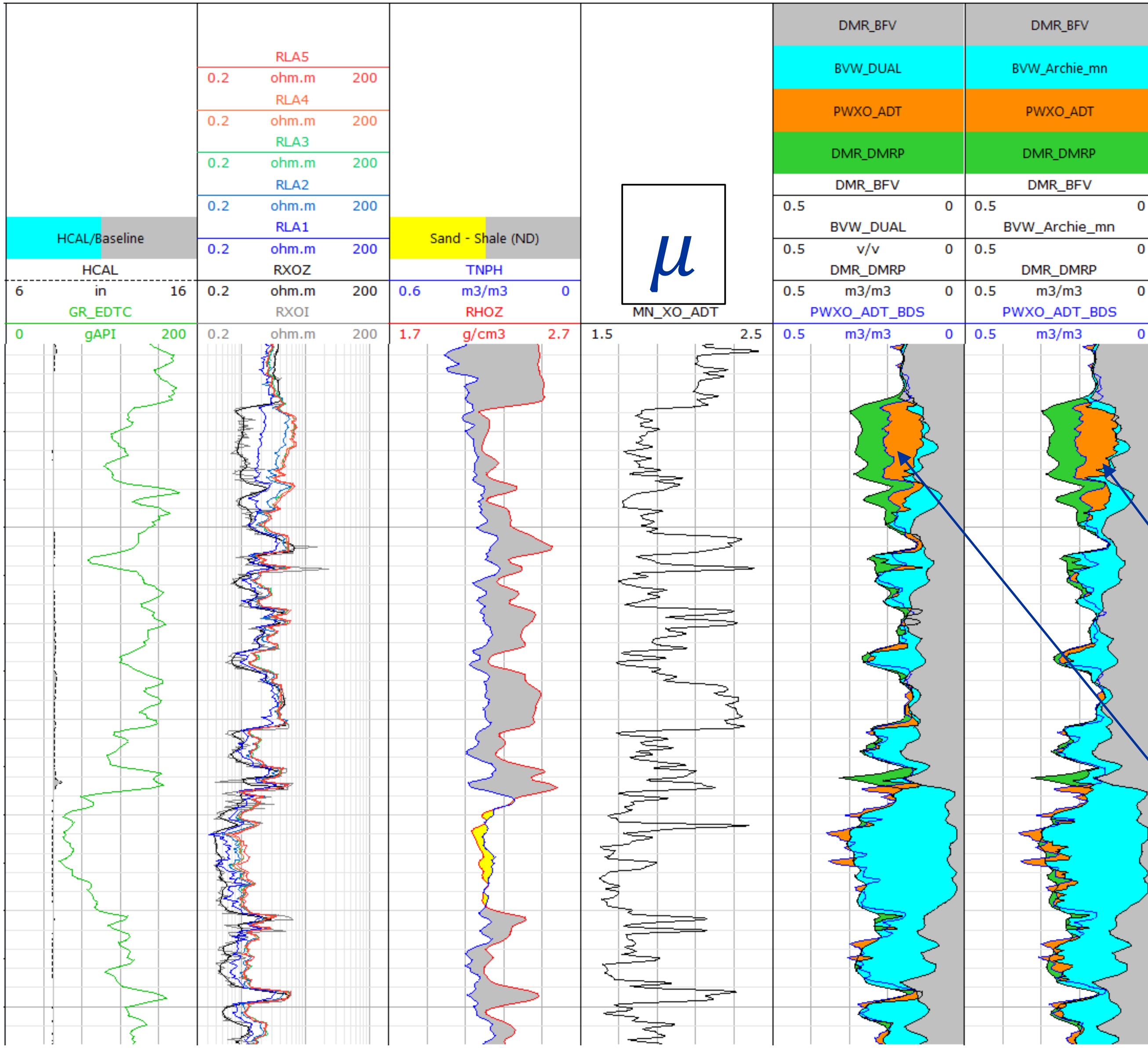
We still need to know Rw

Archie's n may be different between drainage and imbibition

m=n (μ) can vary with Sw



"μ" from Dielectric Includes CEC Excess Conductivity, m and n



Archie

$$S_w^n = \frac{1}{\phi^m}\frac{R_w}{R_t}$$

$$\mu = n = m$$

$$(S_w \phi)^{\mu} = \frac{R_w}{R_t}$$

$$(V_w)^{\mu} = \frac{R_w}{R_t}$$

Dual Water

$$C_t = \frac{\phi_t^m S_{wt}^n}{a}\left(C_w + \frac{S_{wb}}{S_{wt}}(C_{wb} - C_w)\right)$$

Summary

- Triple combo logs (GR – Density – Neutron Porosity)
  - Clay is radioactive, dense and absorbs neutrons
- Natural GR Spectroscopy
  - Low cost and widely used
  - Difficult to derive quantitative total clay volume
  - Clay type ??
- Neutron – GR Spectroscopy
  - Elemental composition interpreted to give mineralogy
  - Dry weight mineral fractions, convenient for XRD and FTIR comparison
  - The most accurate of the techniques presented without core calibration
- Clay-bound water
  - NMR Swb can be used directly in dual water model
  - Useful when only the porosity associated with the clay is needed
  - T2 cutoff required
- Grain size
  - Can be derived from NMR with suitable calibration
  - Easier to calibrate to core than clay-bound water
- The electrical effect of the clay (and Rw and Archie parameters)
  - This is actually what we need for saturation calculation
  - Dielectric measurements are still considered exotic and few users are comfortable with them
  - Not suited to other applications such as predicting fines migration, rock properties etc.