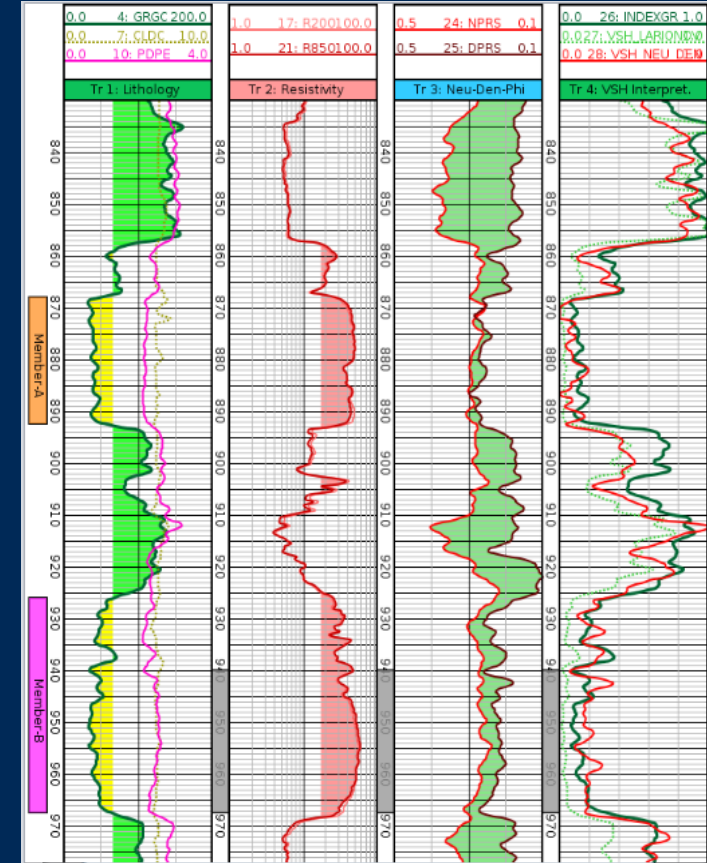


Crossplots

R_w Calculation Methods



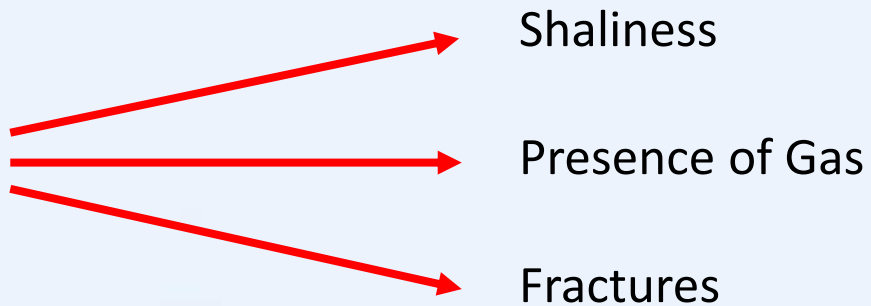
Crossplots

- **Graphical / Mathematical Approach**
 - ✓ 2D Plots
 - ✓ 3D Plots
- **Various Properties (Units)**
 - ✓ Density, Transit time, Porosity, Pe
- **Addressing Properties**
 - ✓ More accurate Porosity
 - ✓ Lithology
- **No Unique Interpretation**

Porosity Crossplots

- Neutron-Density
- Sonic-Neutron
- Sonic-Density
- Density-Photoelectric

Complicating Factors:



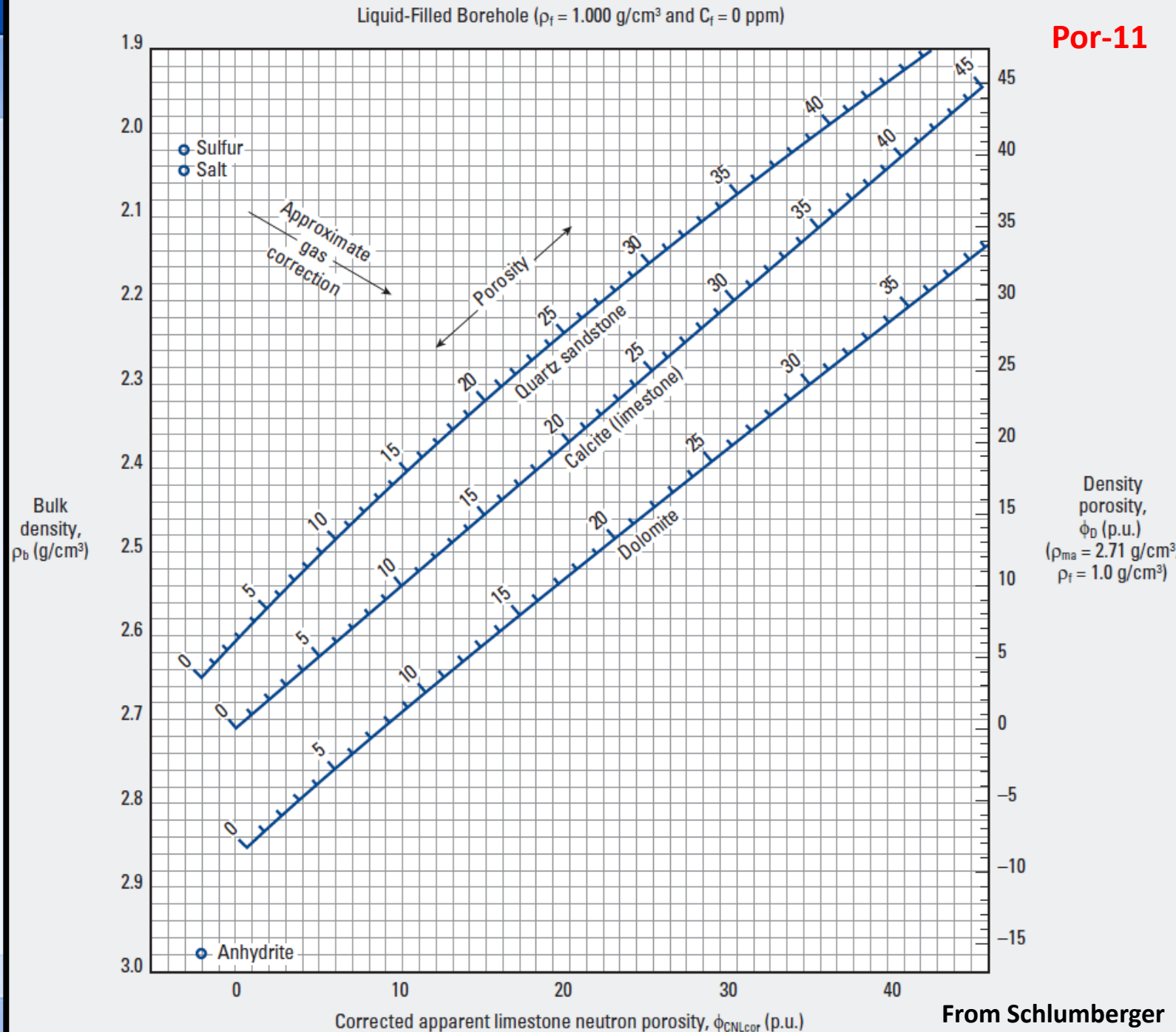
Neutron-Density Crossplot

- Most Common
- For clean, liquid saturated formations
- Water based muds: Fresh mud ($\rho_f=1.0 \text{ gr/cm}^3$), Salt mud ($\rho_f=1.1 \text{ gr/cm}^3$)
- Charts Por-11 & Por-12

Crossplots

N-D Crossplot

- Neutron Limestone
- Bulk density or LS DPHI
- SW-NE are lith. Lines
- NW-SE are porosity lines
- 2 more & less likely lith. Possibilities
- True porosity
- Lithology %



Crossplots

Example

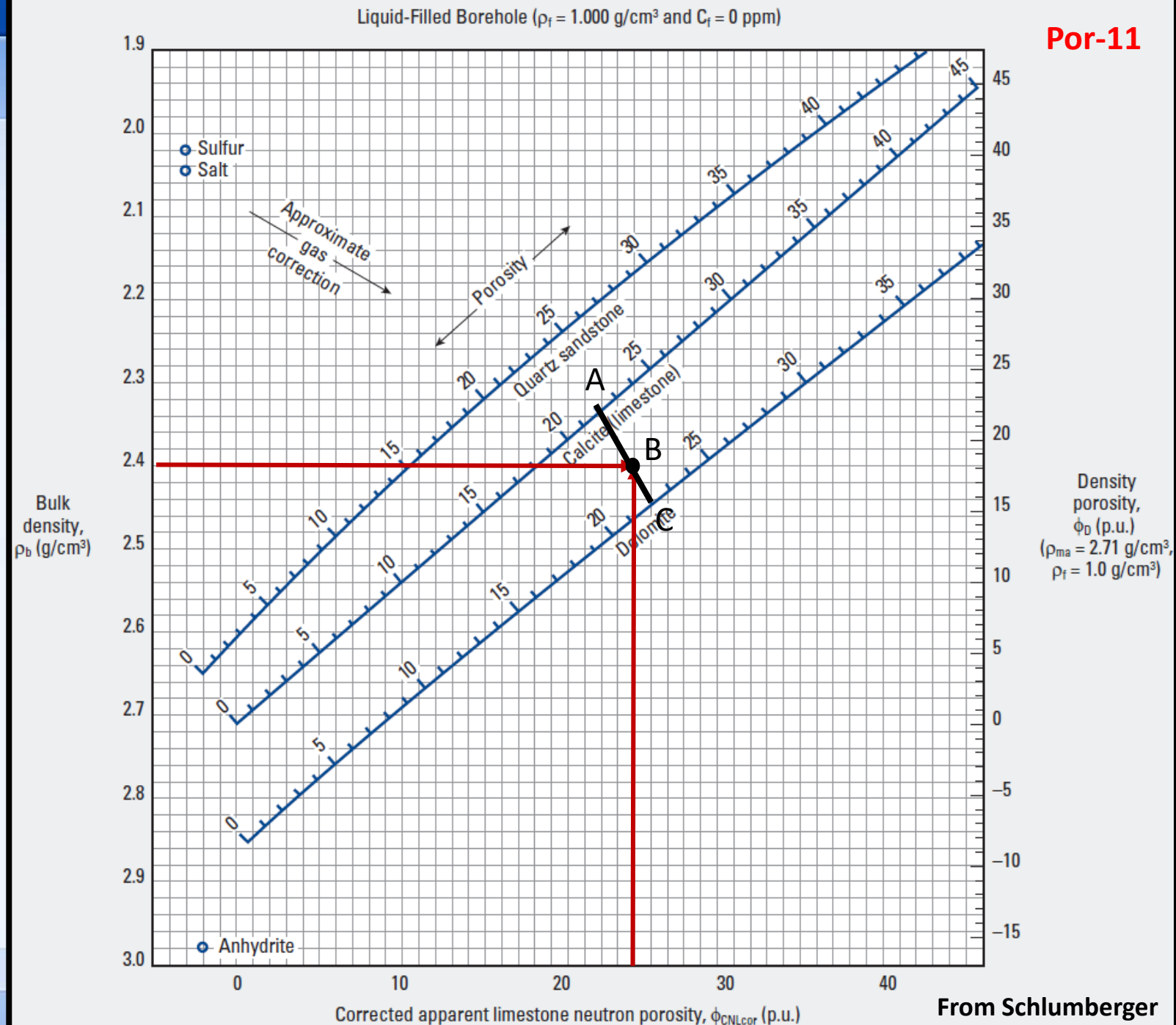
$$\rho_b = 2.4 \text{ gr/cm}^3 \quad \phi_{\text{NLS}} = 24\%$$

More likely: Dol, LS

$$\text{LS \%} = \text{BC/AC} = 1.0/2.5 = 40\%$$

$$\text{DOL \%} = \text{AB/AC} = 1.5/2.5 = 60\%$$

Less Likely: Dol, SS



Crossplots

N-D Crossplot

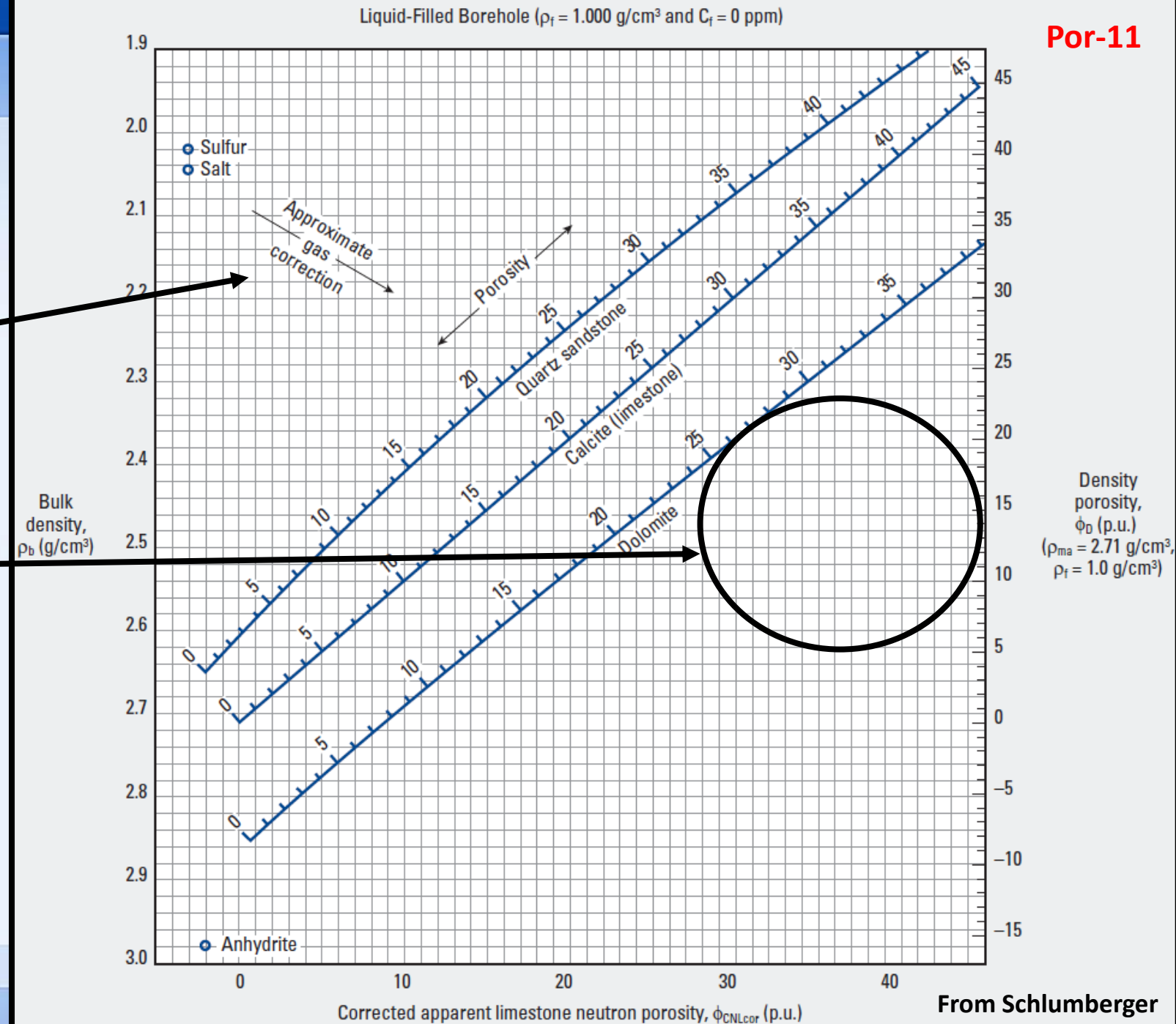
Gas

Shale

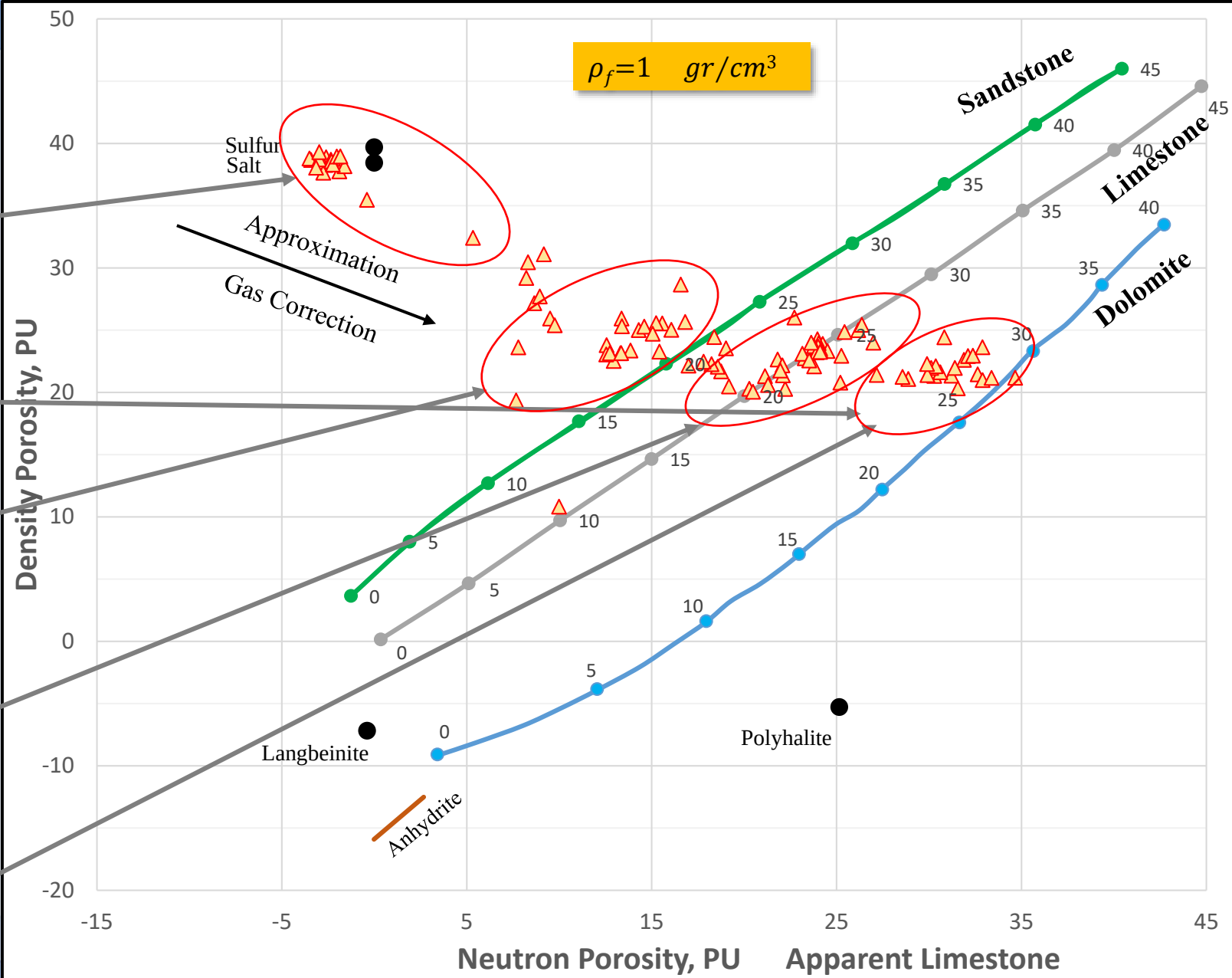
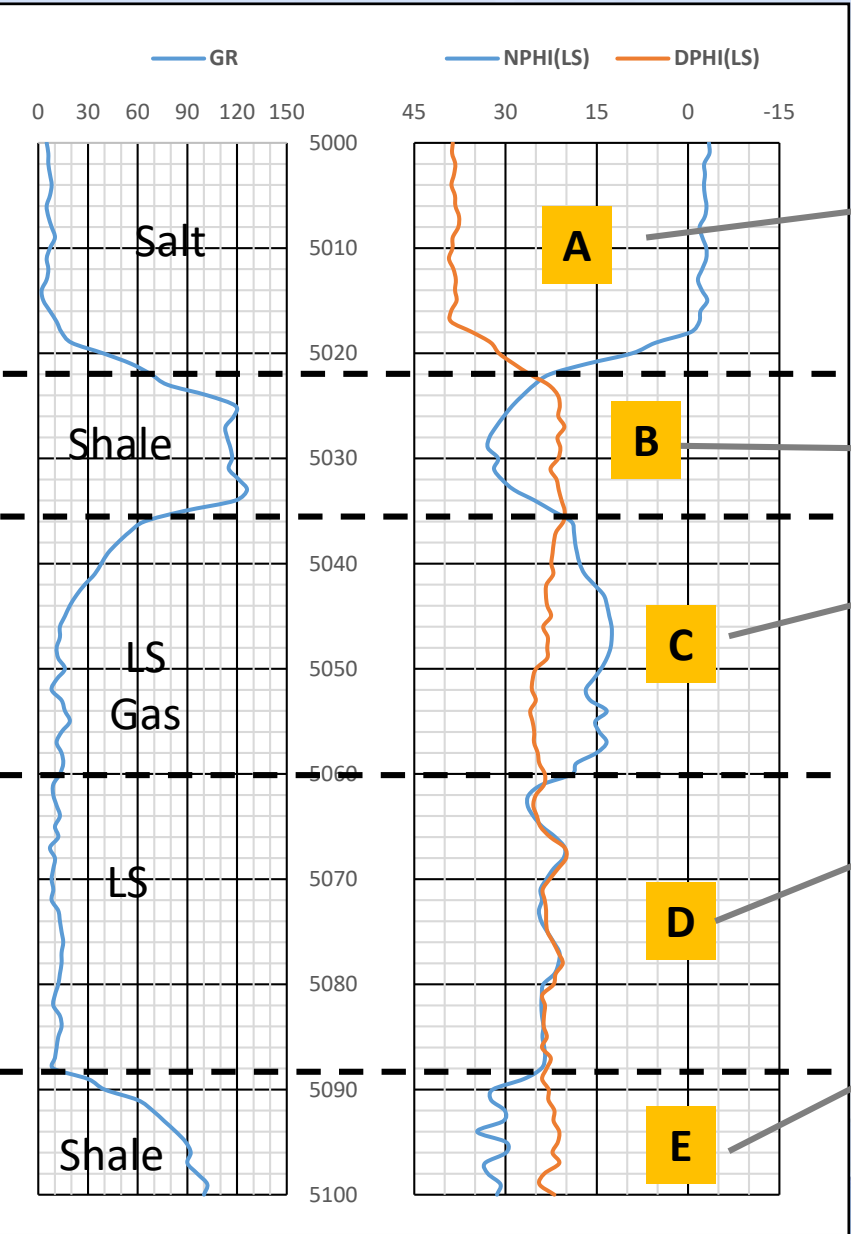
Shales tend to behave like dolomite, use GR discriminator to distinguish them.

Fracture:

N-D logs measure total porosity,
no effect



Crossplots



Sonic-Neutron Crossplot

- For clean, liquid saturated formations
- Water based muds:
- Chart Por-20

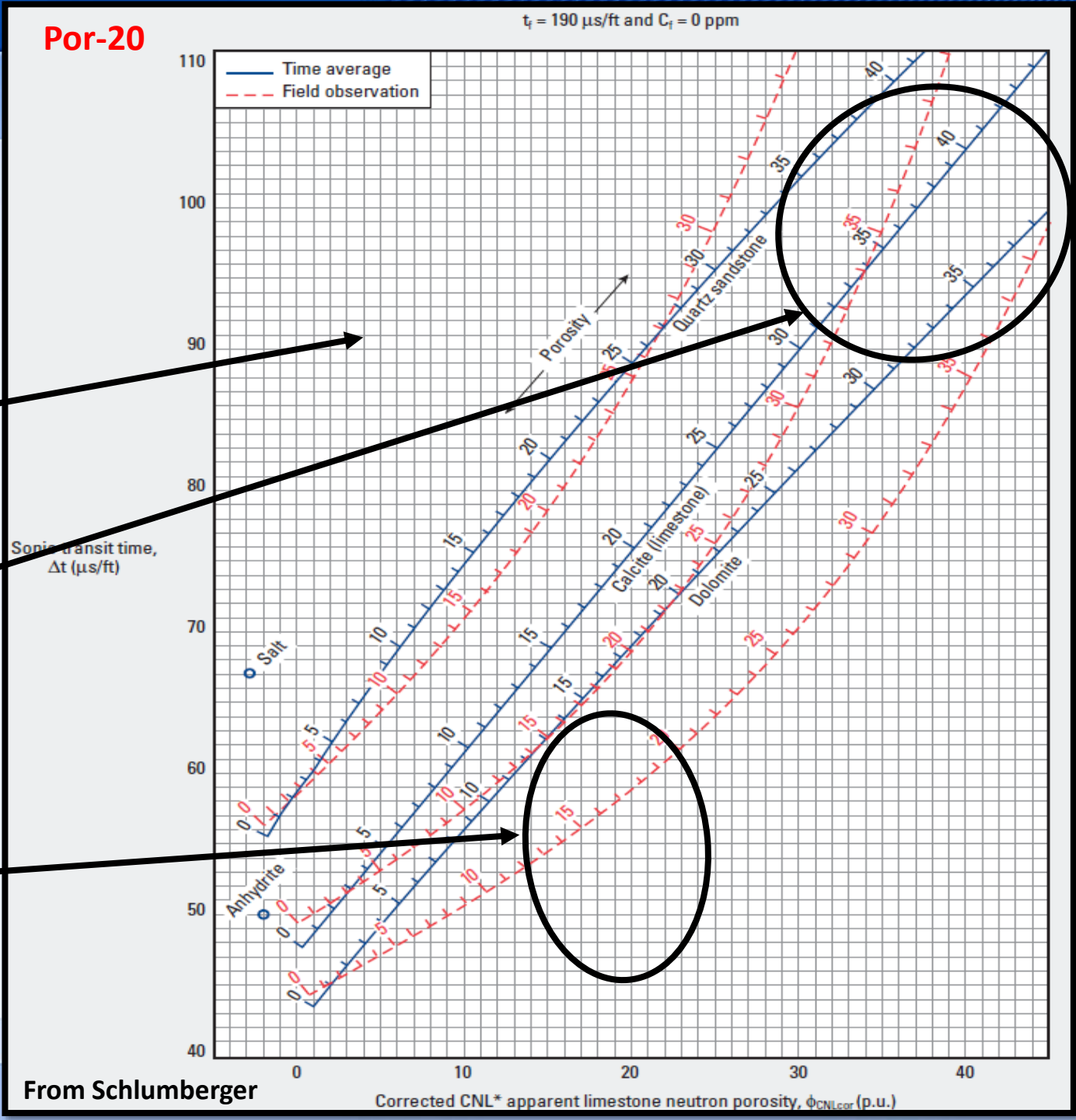
Crossplots

Sonic-Neutron
Crossplot

Gas

Shale

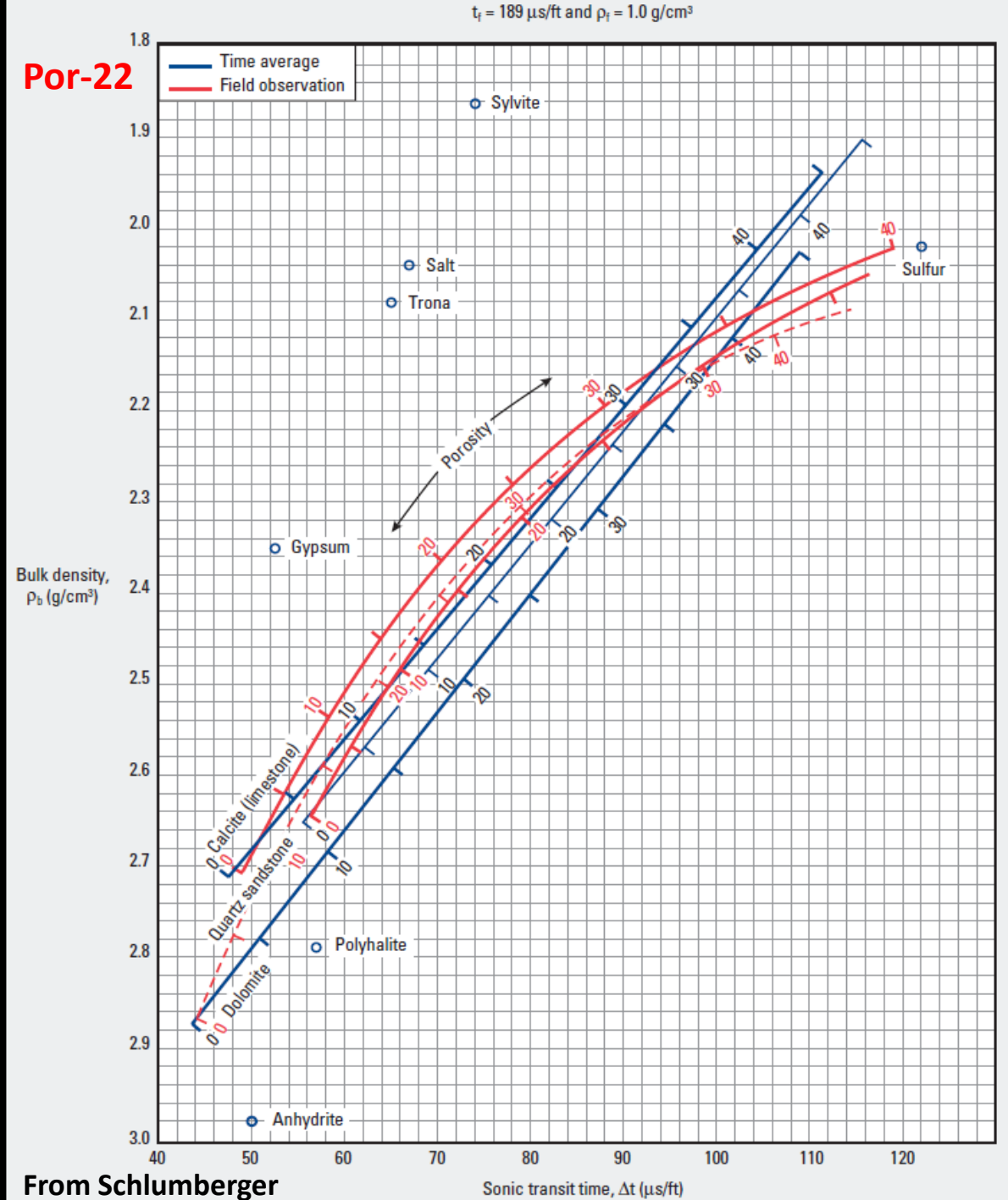
Fractures



Crossplots

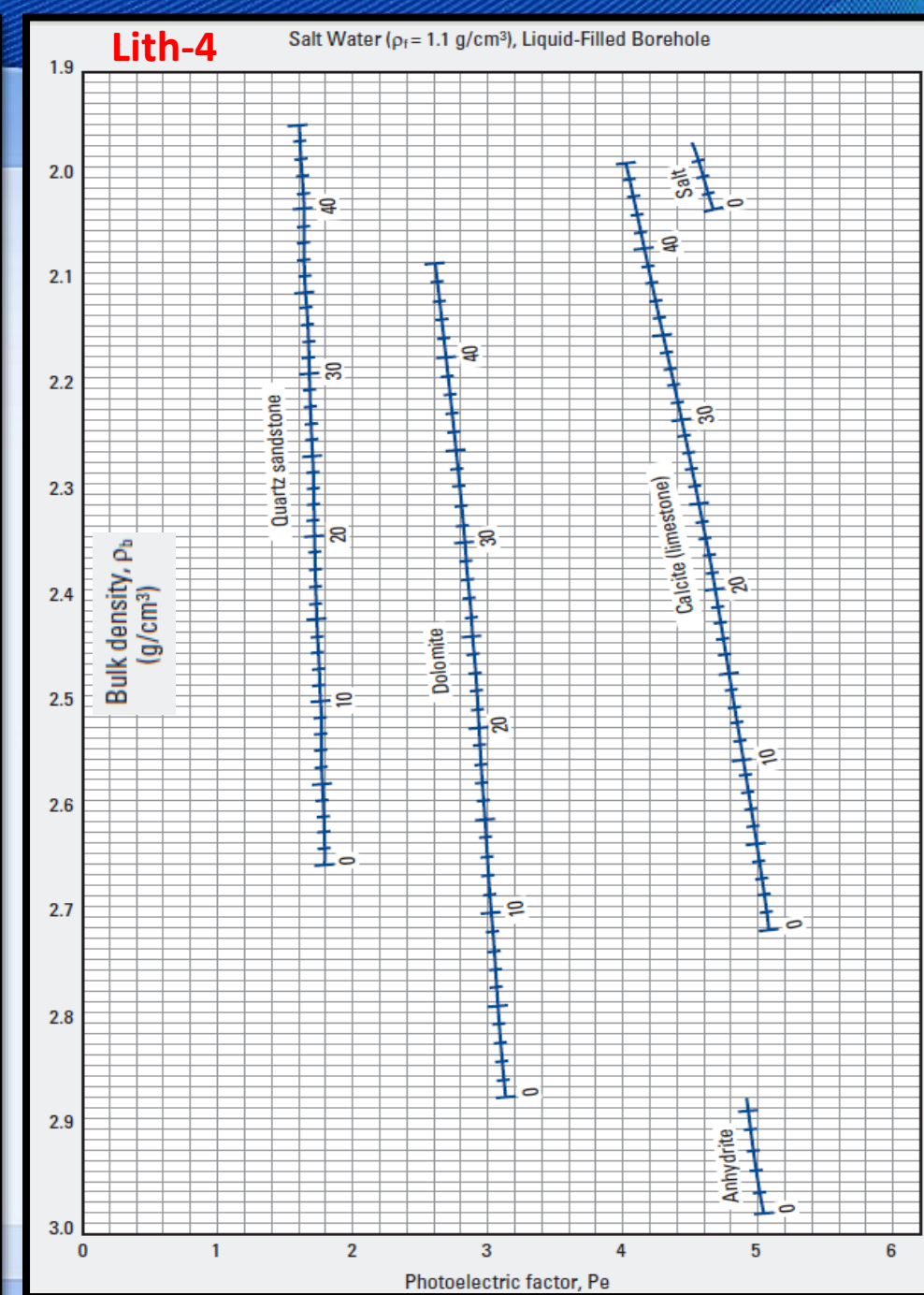
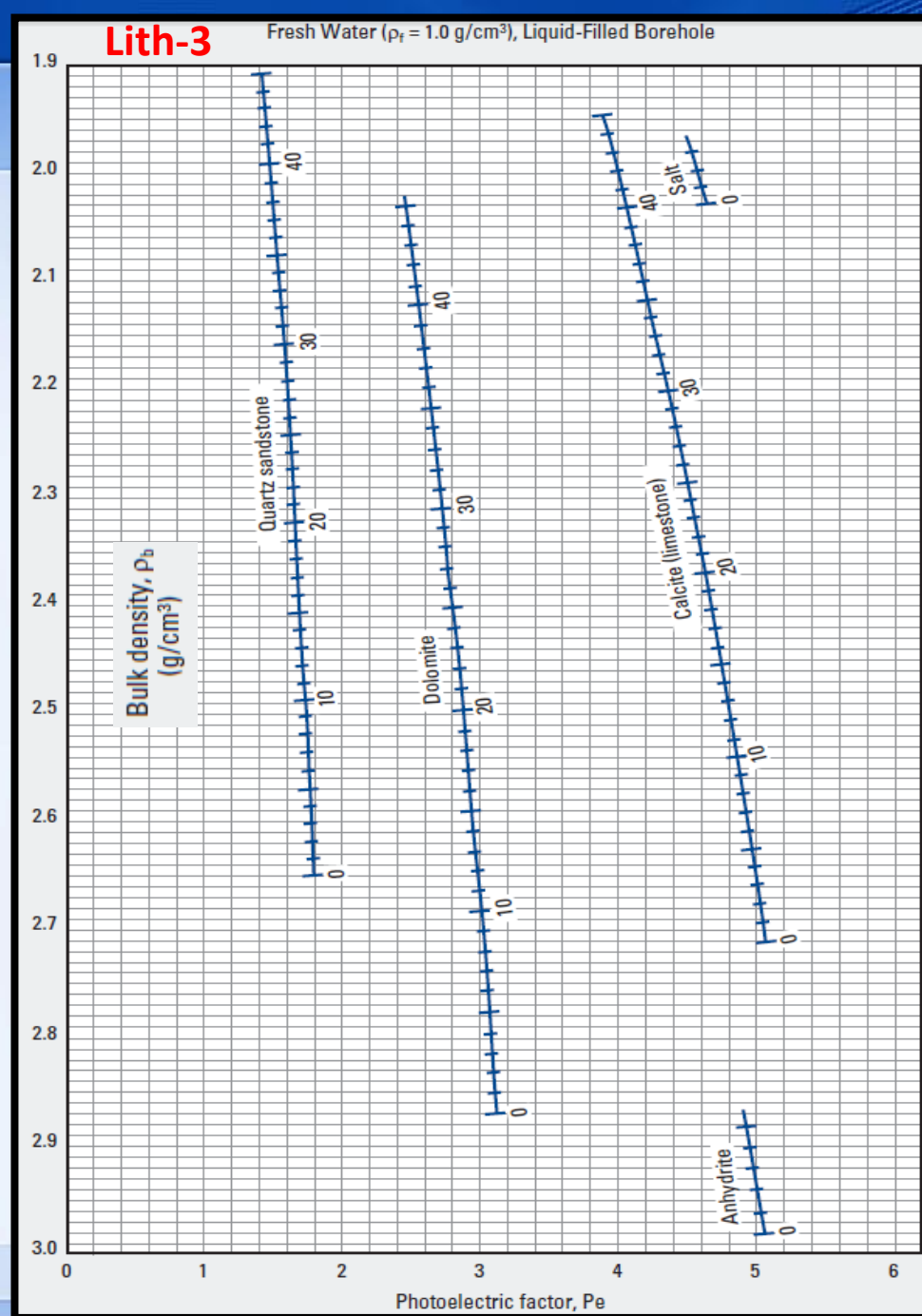
Sonic-Density Crossplot

- Poor porosity resolution
- Poor lithology resolution
- Useful for evaporates



Crossplots

Density- P_e Crossplot



From Schlumberger

3-Measurement Crossplots

- 2D Plots
- 3 Mineral Matrix
- Multiple logs (D,N,S D,N,Pe)
 - ✓ M-N Plot
 - ✓ MID Plot
 - ✓ $\rho_{\text{maa}} - U_{\text{maa}}$

Crossplots

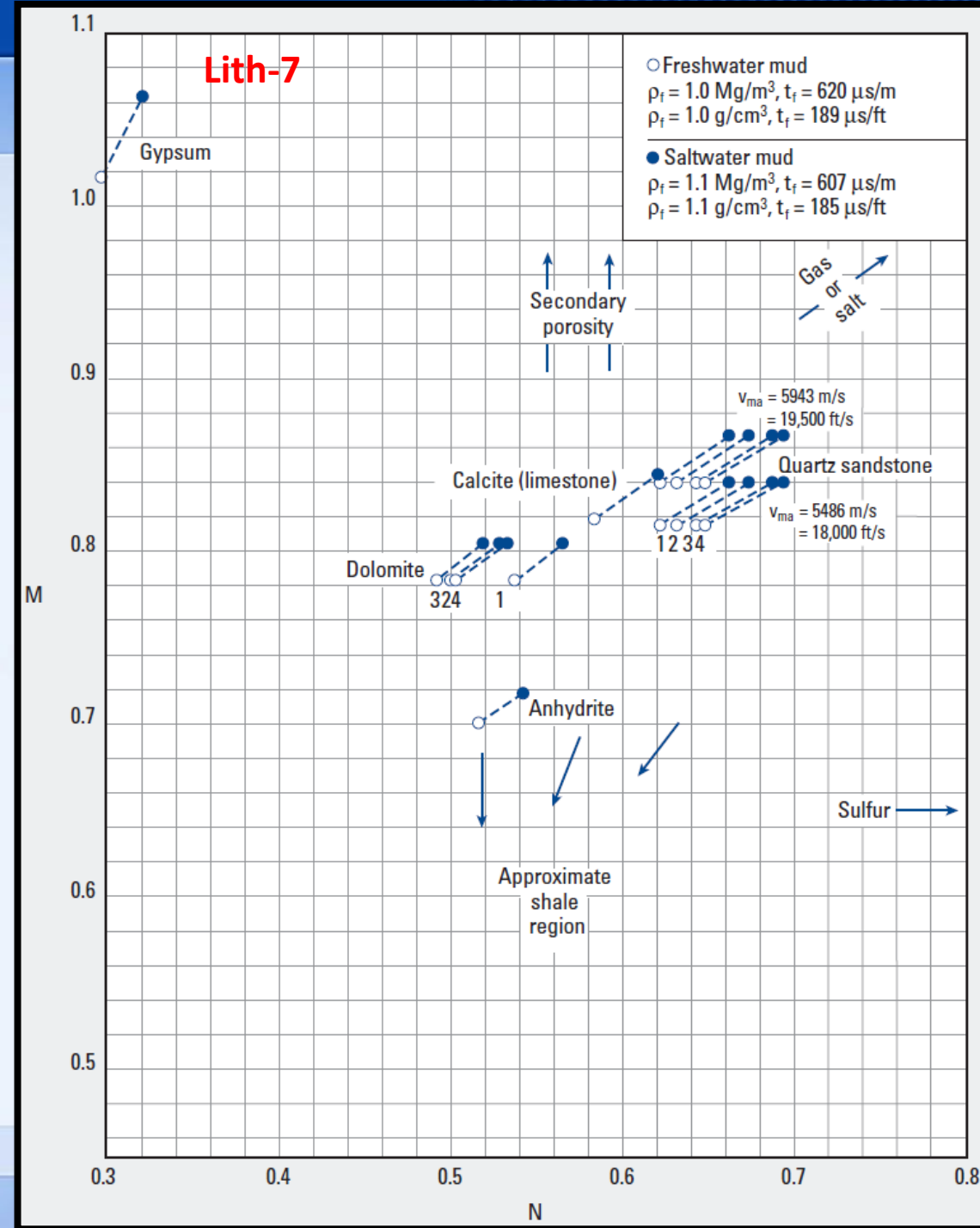
M-N Plot

$$M = \frac{\Delta t_f - \Delta t}{(\rho_b - \rho_f) \times 100}$$

$$N = \frac{\phi_{Nf} - \phi_N}{(\rho_b - \rho_f)}$$

ϕ_N is in fraction

ϕ_{Nf} is assumed to be 1.0



1. $\phi=0$
2. $\phi < 12 \text{ p.u}$
3. $12 < \phi < 27 \text{ p.u}$
4. $27 < \phi < 40 \text{ p.u}$

From Schlumberger

Crossplots

Example

Fresh-mud filtrate with $\rho_f = 1.0 \text{ g/cm}^3$, $\Delta t_f = 189 \mu\text{s/ft}$,

$\Delta t = 69 \mu\text{s/ft}$, $\rho_b = 2.5 \text{ g/cm}^3$, $\phi_N = 10\%$,

$\Delta t - \rho_b$ crossplot?

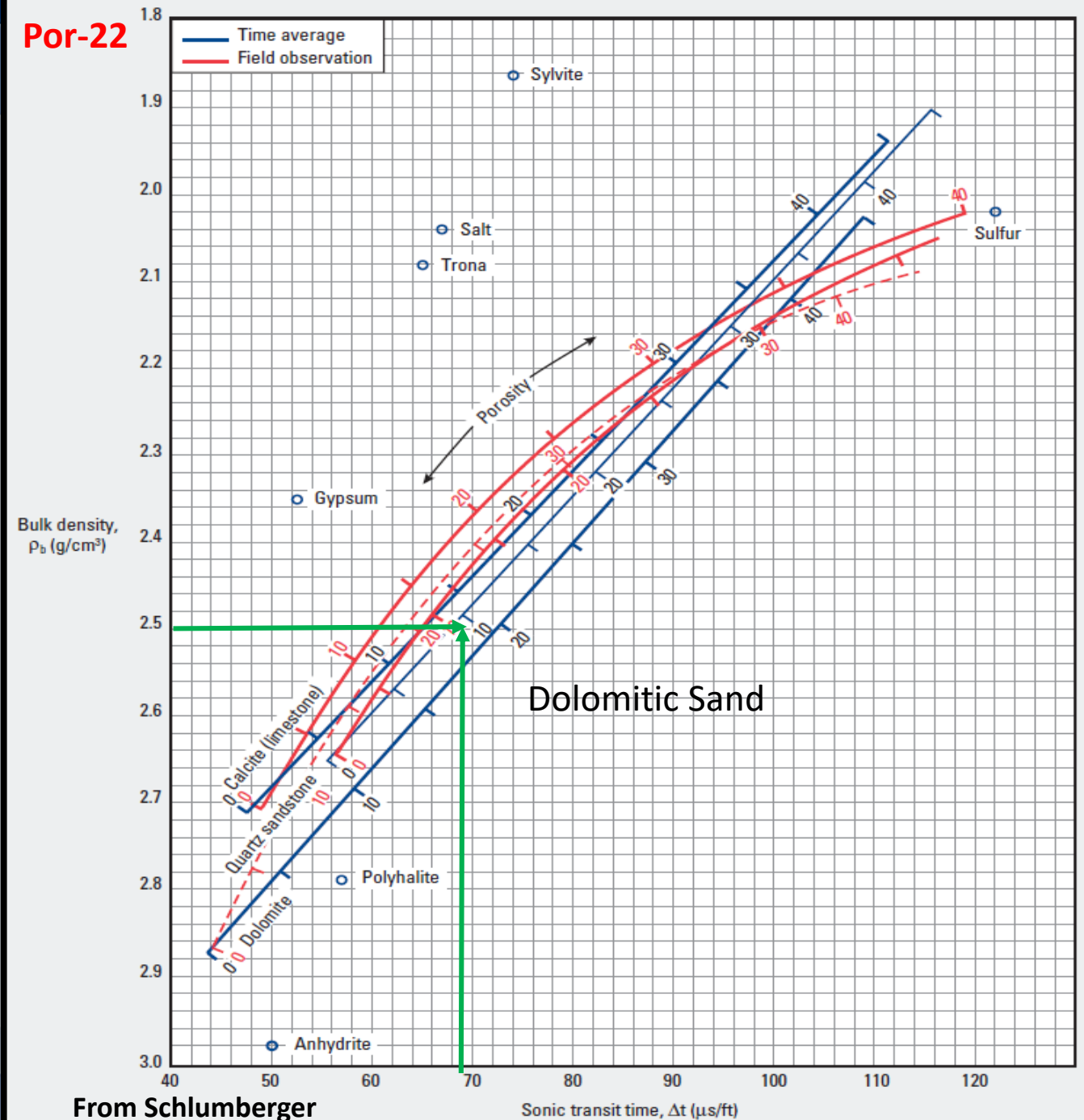
$\Delta t - \phi_N$ crossplot?

$\phi_N - \rho_b$ crossplot?

M-N plot?

Lithology mixture?

Por-22



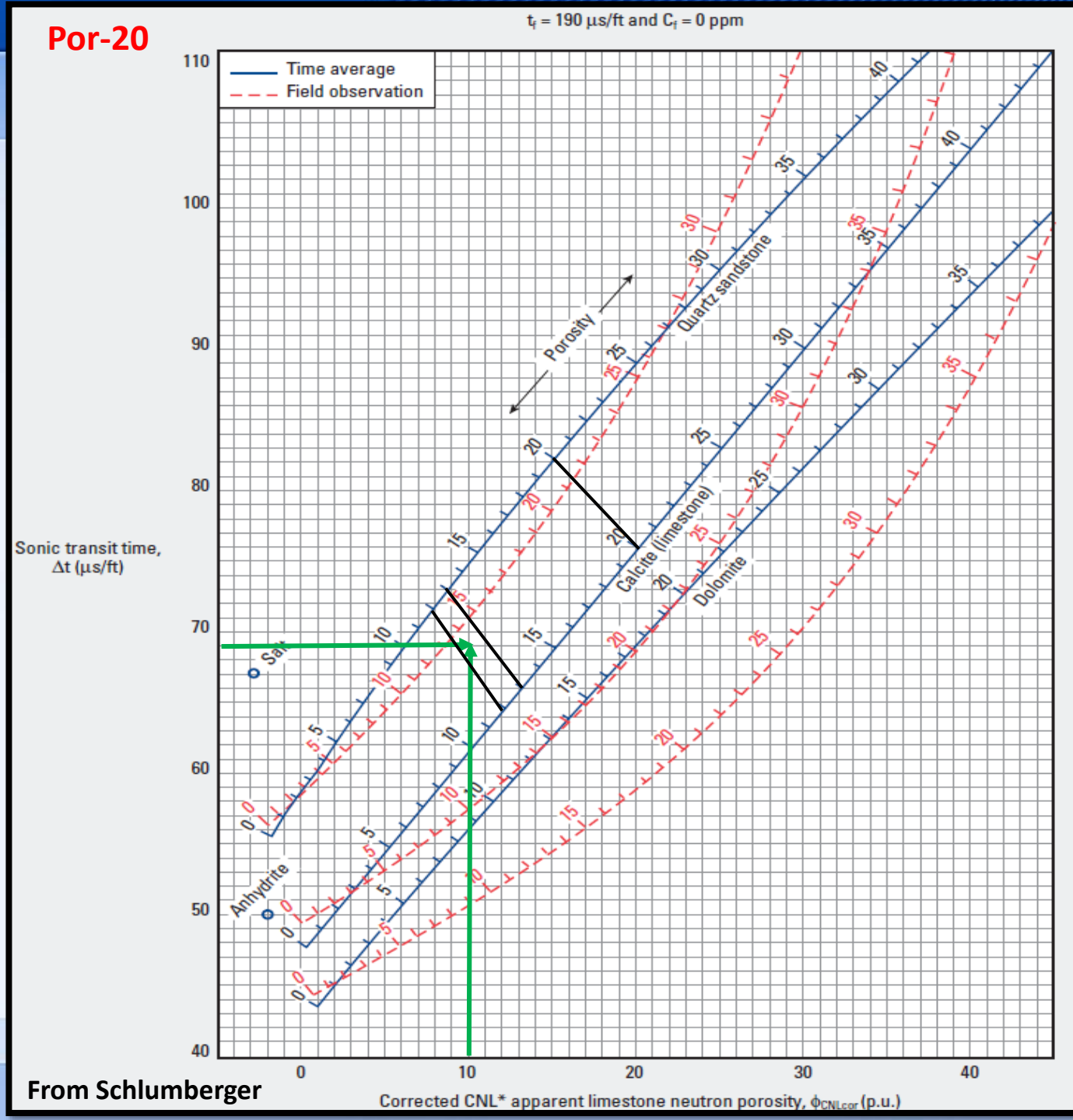
Crossplots

Example

Limy sand (more likely)
Dolomitic sand (less likely)

PHI=12.5%

Por-20

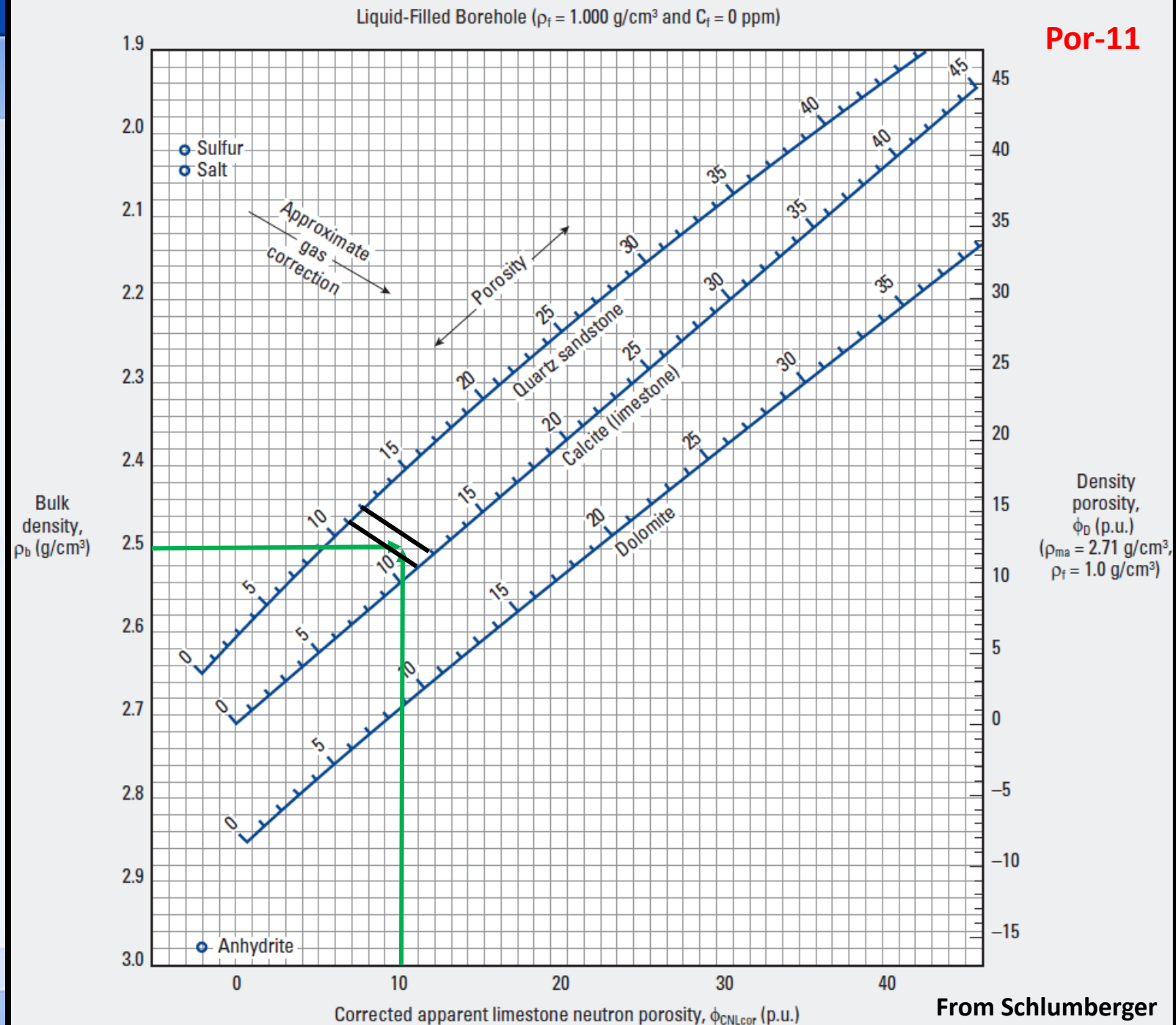


Crossplots

Example

Sandy lime (more likely)
Dolomitic sand (less likely)

PHI=11.5%



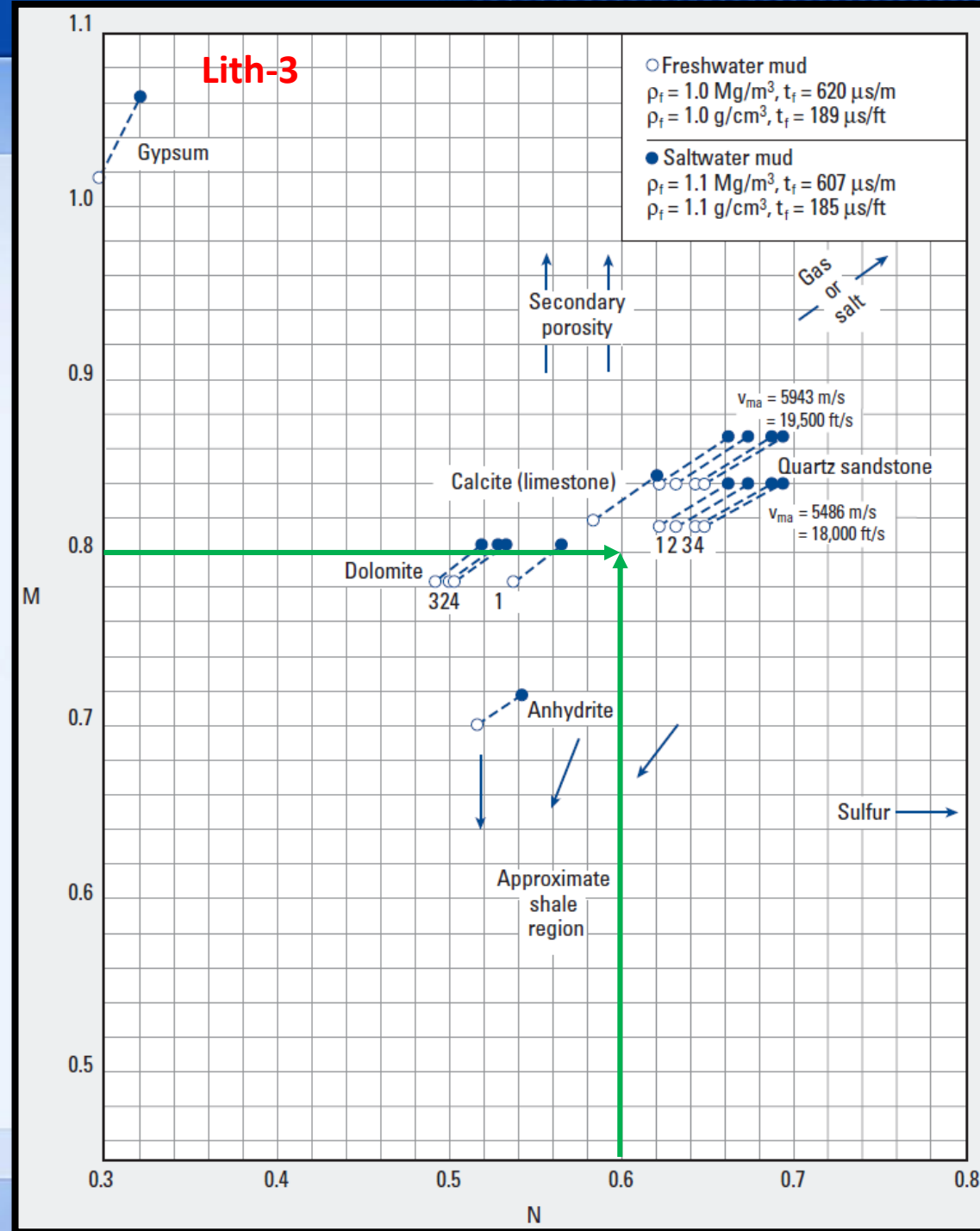
Crossplots

Example

$$M = \frac{\Delta t_f - \Delta t}{(\rho_b - \rho_f) \times 100} = \frac{189 - 69}{(2.5 - 1.0) \times 100} = 0.8$$

$$N = \frac{\phi_{Nf} - \phi_N}{(\rho_b - \rho_f)} = \frac{1.0 - 0.1}{(2.5 - 1.0)} = 0.6$$

Dolomite-Sand mixture



From Schlumberger

Crossplots

MID Plot

$$\rho_{maa} = \frac{\rho_b - \phi_x \times \rho_f}{1 - \phi_x}$$

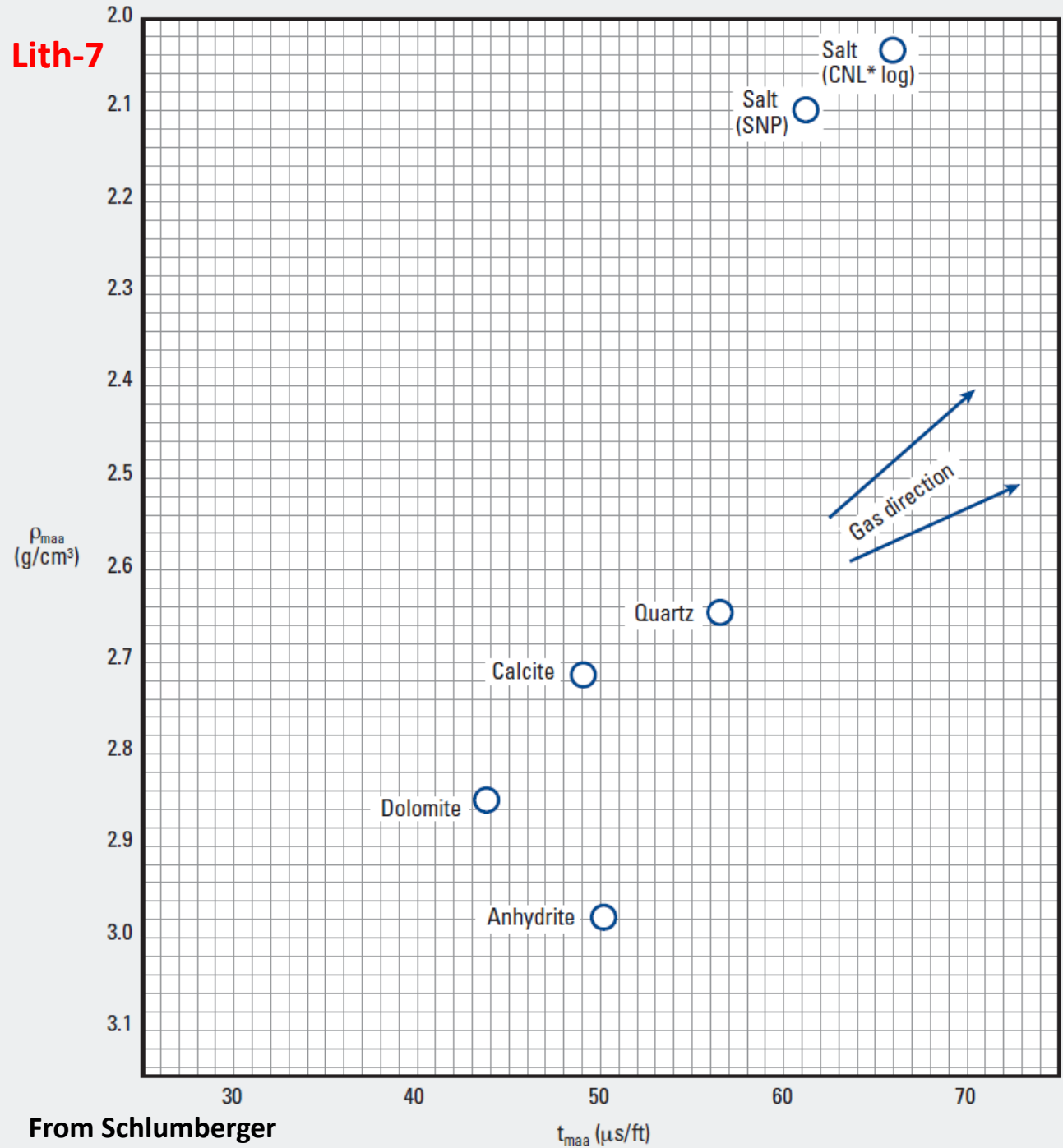
$$\Delta t_{maa} = \frac{\Delta t - \phi_x \times \Delta t_f}{1 - \phi_x}$$

$$\phi_x = \frac{\phi_{NLS} + \phi_{DLS}}{2}$$

ϕ_x is in fraction

Limestone scale

Lith-7



From Schlumberger

Crossplots

$\rho_{maa} - U_{maa}$ Plot

$$\rho_{maa} = \frac{\rho_b - \phi_x \times \rho_f}{1 - \phi_x}$$

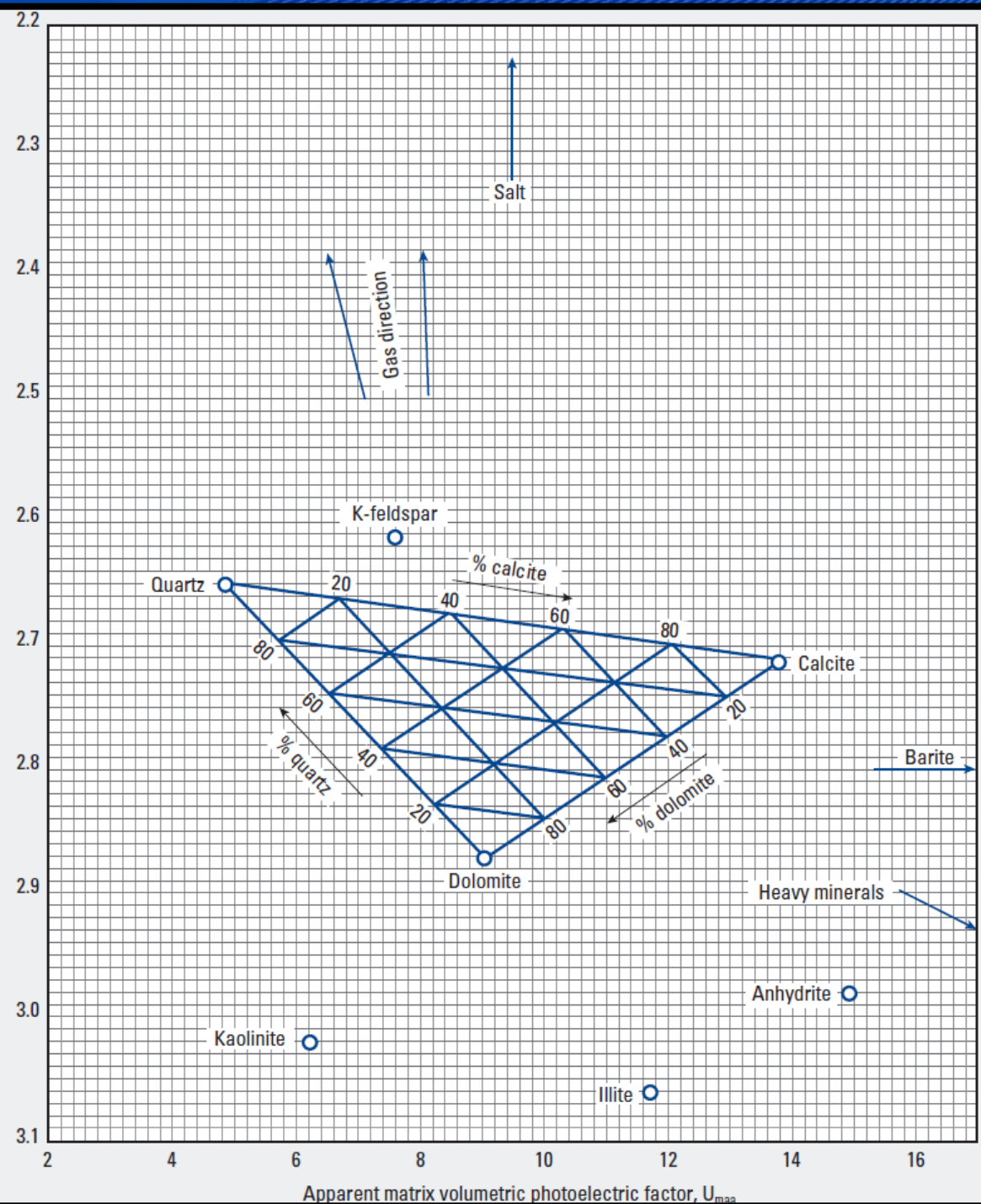
$$U_{maa} = \frac{P_e \times \rho_b}{1 - \phi_x}$$

$$\phi_x = \frac{\phi_{NLS} + \phi_{DLS}}{2}$$

ϕ_x is in fraction

Lith-6

Apparent matrix
grain density,
 ρ_{maa} (g/cm³)



From Schlumberger

Crossplots

Example

Fresh-mud filtrate with $\rho_f = 1.0 \text{ g/cm}^3$,
 $\rho_b = 2.368 \text{ g/cm}^3$, $\phi_{NLS} = 25\%$, $P_e = 3.3 \text{ barns/e}$

What is the lithology?

$$\phi_D = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} = \frac{2.71 - 2.368}{2.71 - 1.0} = 20\%$$

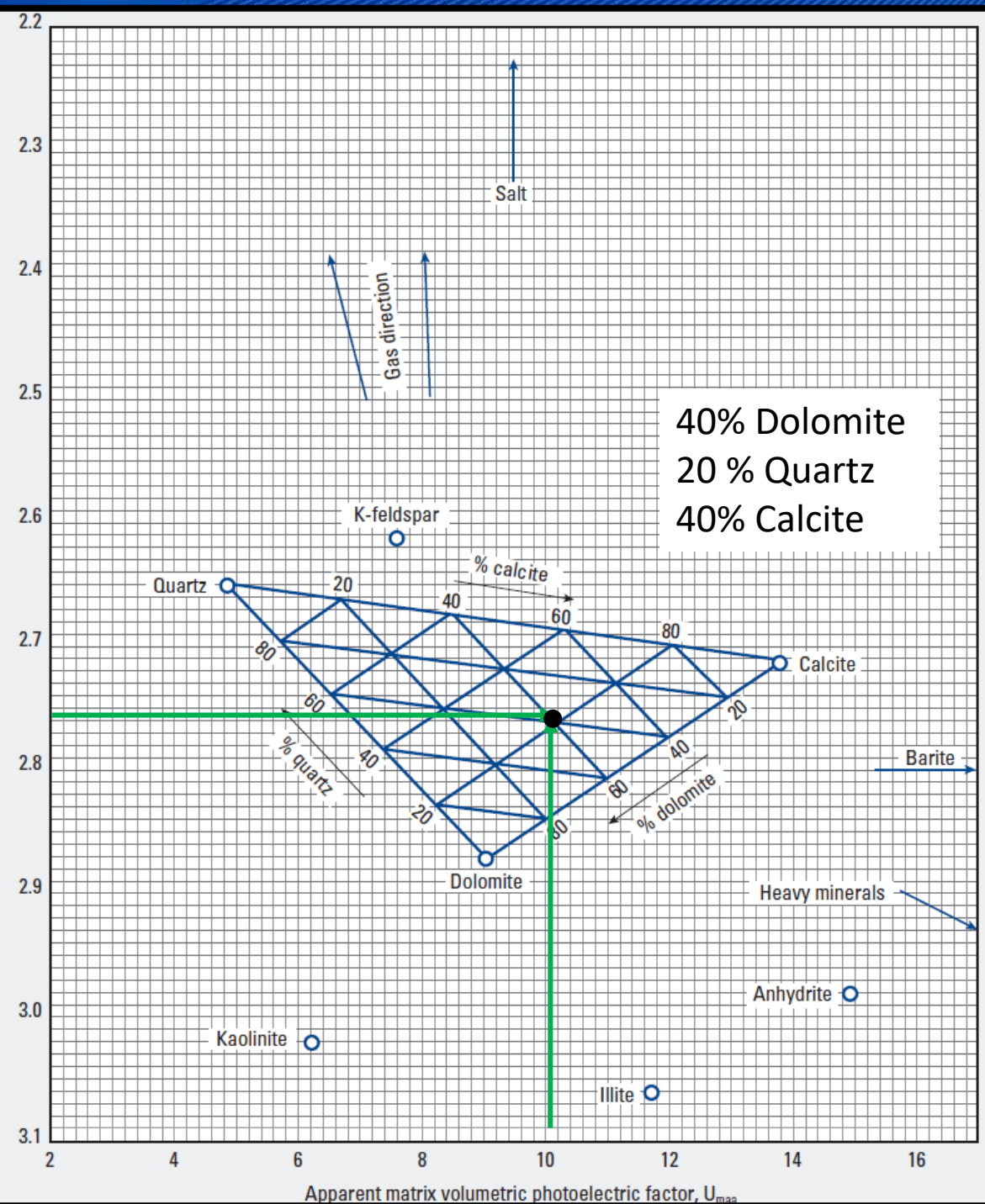
$$\phi_x = \frac{\phi_{NLS} + \phi_{DLS}}{2} = \frac{0.25 + 0.2}{2} = 0.225$$

$$\rho_{maa} = \frac{\rho_b - \phi_x \times \rho_f}{1 - \phi_x} = \frac{2.368 - 0.225 \times 1.0}{1 - 0.225} = 2.765$$

$$U_{maa} = \frac{P_e \times \rho_b}{1 - \phi_x} = \frac{3.3 \times 2.368}{1 - 0.225} = 10.08$$

Lith-6

Apparent matrix
grain density,
 $\rho_{maa} \text{ (g/cm}^3\text{)}$

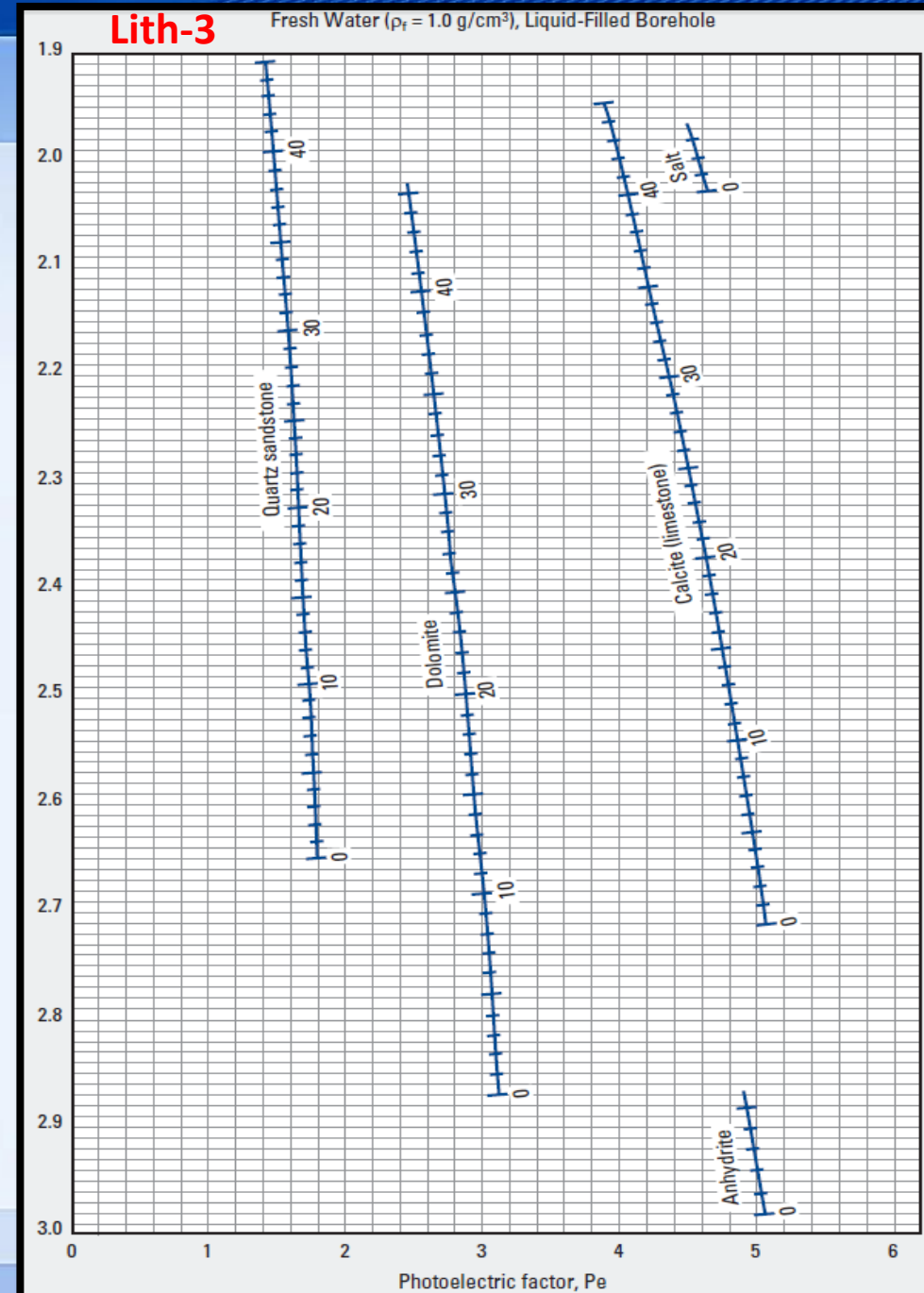


Crossplots

Class Example

Fresh-mud filtrate with $\rho_f = 1.0 \text{ g/cm}^3$,
 $\rho_b = 2.368 \text{ g/cm}^3$, $\Phi_{NLS} = 25\%$, $P_e = 3.3 \text{ barns/e}$

What is the lithology using Pe-Density Crossplot?



From Schlumberger

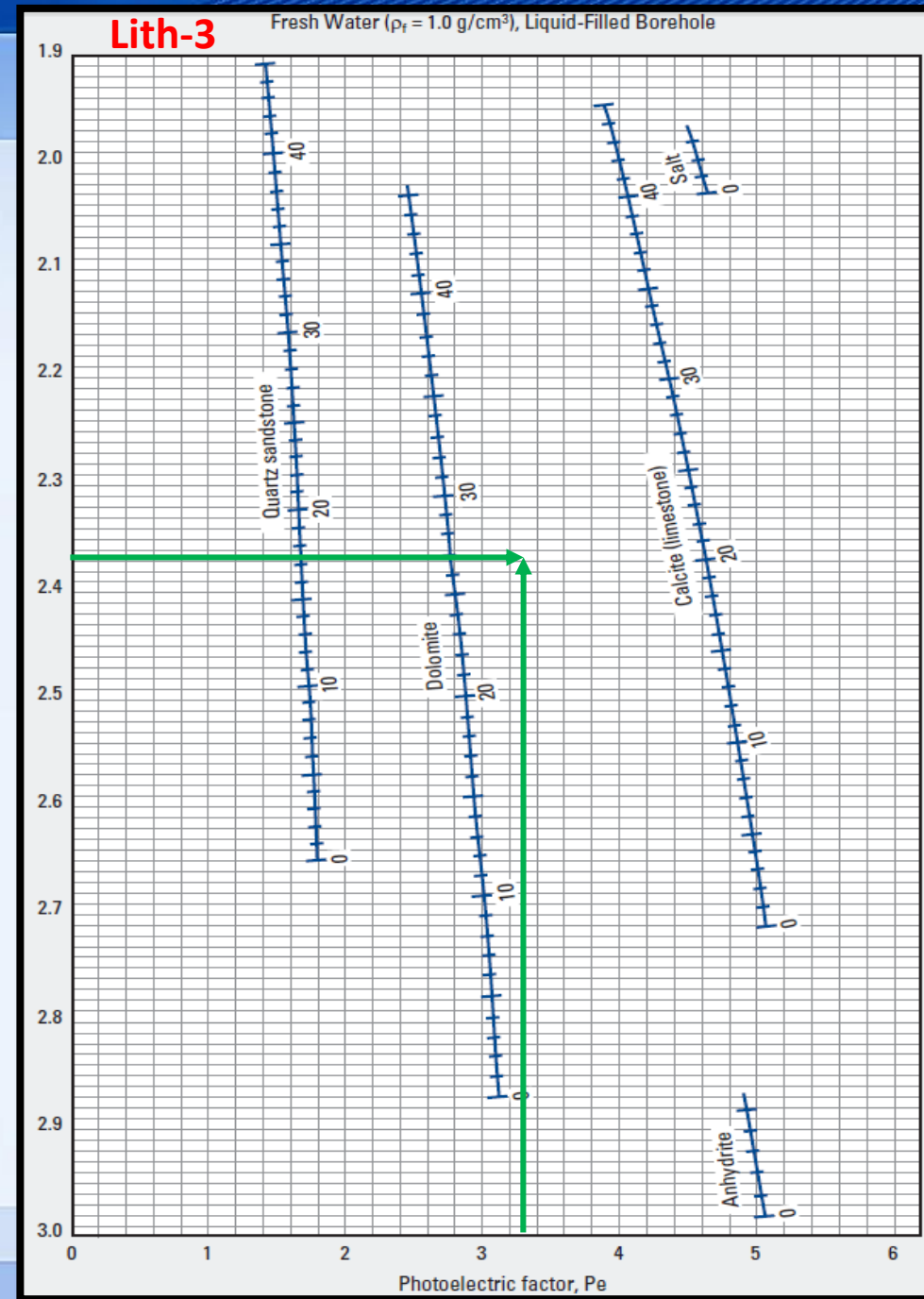
Crossplots

Class Example

Fresh-mud filtrate with $\rho_f = 1.0 \text{ g/cm}^3$,
 $\rho_b = 2.368 \text{ g/cm}^3$, $\Phi_{NLS} = 25\%$, $P_e = 3.3 \text{ barns/e}$

What is the lithology using Density-Pe Crossplot?

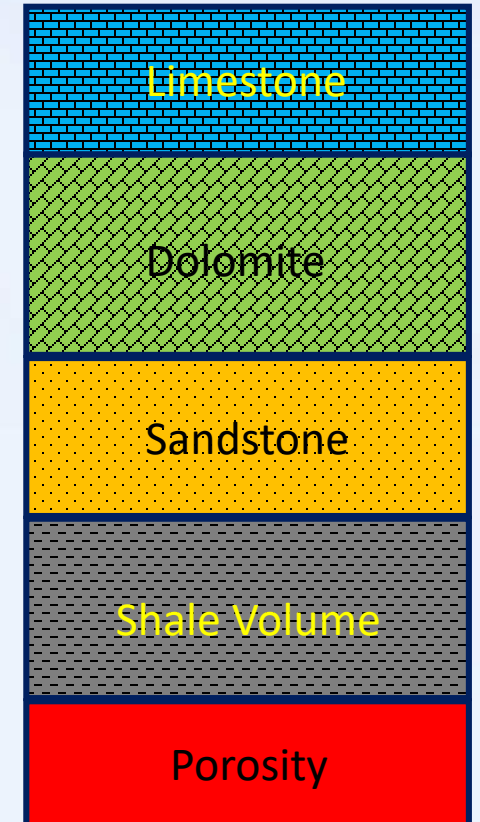
Limy Dolomite (most likely)
Sandy Limestone (less likely)



From Schlumberger

Computational Analysis

Unity	{	$V_{SS} + V_{Dol} + V_{LS} + V_{sh} + \emptyset = 1$
Neutron Log		$\emptyset_{N,SS}V_{SS} + \emptyset_{N,Dol}V_{Dol} + \emptyset_{N,LS}V_{LS} + \emptyset_{N,sh}V_{sh} + \emptyset_{N,\emptyset}\emptyset = 1$
Density Log		$\rho_{ma,SS}V_{SS} + \rho_{ma,SS}V_{Dol} + \rho_{ma,SS}V_{LS} + \rho_{ma,SS}V_{sh} + \rho_{fluid}\emptyset = 1$
Pe Log		$U_{SS}V_{SS} + U_{Dol}V_{Dol} + U_{LS}V_{LS} + U_{sh}V_{sh} + U_{fluid}\emptyset = 1$
GR Log		$GR_{SS}V_{SS} + GR_{Dol}V_{Dol} + GR_{LS}V_{LS} + GR_{sh}V_{sh} + GR_{fluid}\emptyset = 1$



Unit Volume of Rock

Crossplots

Computational Analysis

Unity

$$V_{SS} + V_{Dol} + V_{Ls} + V_{sh} + \phi = 1$$

Neutron Log

$$\phi_{N,SS}V_{SS} + \phi_{N,Dol}V_{Dol} + \phi_{N,Ls}V_{Ls} + \phi_{N,sh}V_{sh} + \phi_{N,\phi}\phi = 1$$

Density Log

$$\rho_{ma,SS}V_{SS} + \rho_{ma,Dol}V_{Dol} + \rho_{ma,Ls}V_{Ls} + \rho_{ma,sh}V_{sh} + \rho_{fluid}\phi = 1$$

Pe Log

$$U_{SS}V_{SS} + U_{Dol}V_{Dol} + U_{Ls}V_{Ls} + U_{sh}V_{sh} + U_{fluid}\phi = 1$$

GR Log

$$GR_{SS}V_{SS} + GR_{Dol}V_{Dol} + GR_{Ls}V_{Ls} + GR_{sh}V_{sh} + GR_{fluid}\phi = 1$$

GR of clean SS (either read it from the log or assume a reasonable value)

$$V_{SS} + V_{Dol} + V_{Ls} + V_{sh} + \phi = 1$$

$$-1.5\%V_{SS} + 2.5\%V_{Dol} + 0V_{Ls} + \phi_{N,sh}V_{sh} + 100\%\phi = 1$$

$$2.65V_{SS} + 2.87V_{Dol} + 2.71V_{Ls} + \rho_{ma,sh}V_{sh} + \rho_{fluid}\phi = 1$$

$$4.79V_{SS} + 9.05V_{Dol} + 13.78V_{Ls} + U_{sh}V_{sh} + U_{fluid}\phi = 1$$

$$GR_{SS}V_{SS} + GR_{Dol}V_{Dol} + GR_{Ls}V_{Ls} + GR_{sh}V_{sh} + GR_{fluid}\phi = 1$$

TABLE 24.1—LITHOLOGY INDICATORS FOR COMMON MINERALS (Schlumberger 2005b)

Mineral	ρ_b	ρ_{ma}	ϕ_{CNL}	Δt_{ma}	M	N
Sand	2.65	2.648	-1.5	55.5	0.84	0.64
Limestone	2.71	2.710	0.0	47.5	0.85	0.60
Dolomite	2.87	2.876	2.5	43.5	0.80	0.53
Anhydrite	2.96	2.977	0.0	50.0	0.72	0.52
Halite	2.17	2.032	0.0	67.0	1.24	1.02
Sylvite	1.98	1.863	0.0	74.0	1.41	1.23
Gypsum	2.32	2.351	60	52.0	1.05	0.31

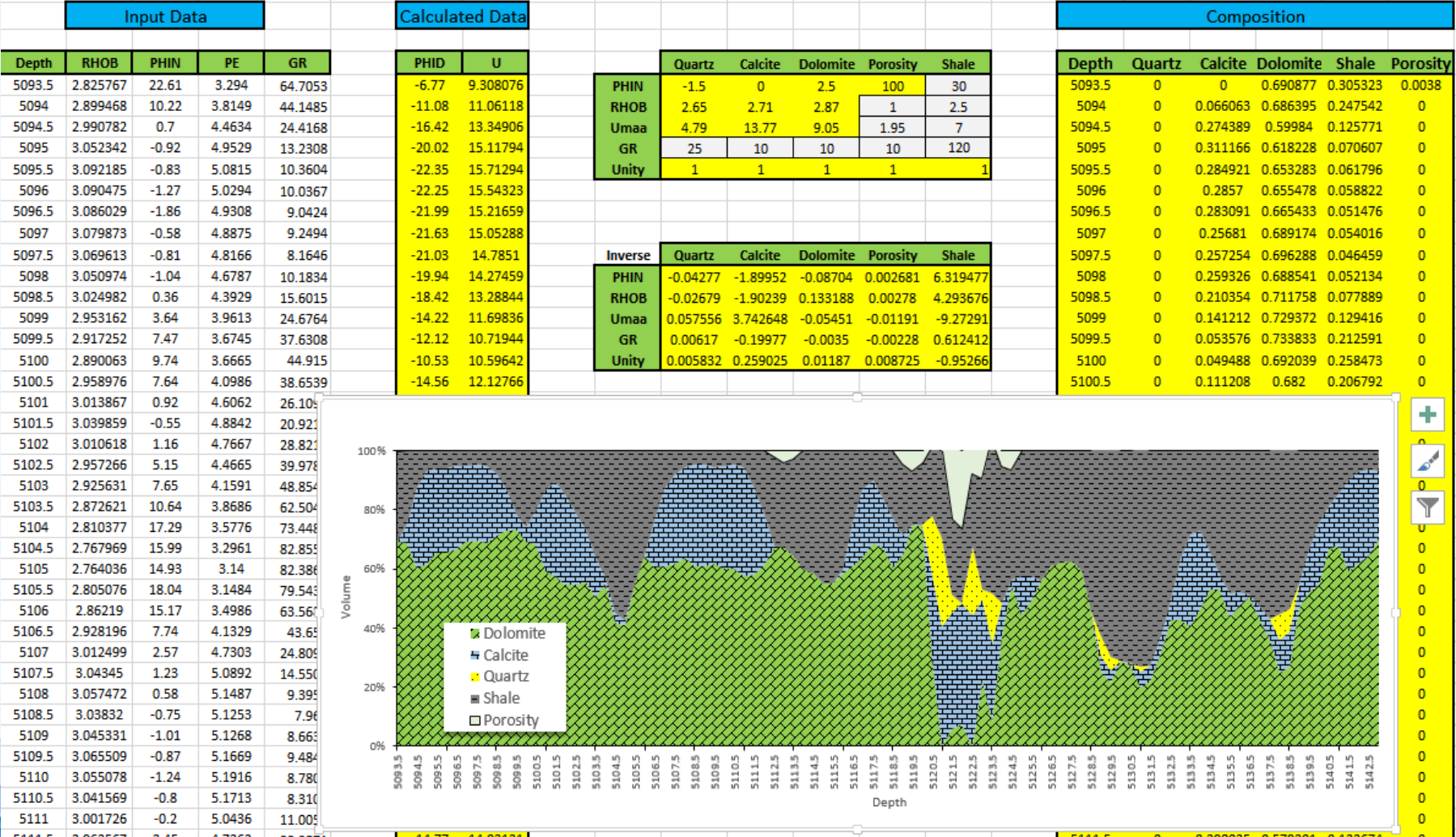
TABLE 24.2—DENSITY AND PHOTOELECTRIC INDEX FOR COMMON MINERALS (Schlumberger 2005b)

Mineral	P_e	ρ_{maa}	U_{maa}	ρ_b	U
Dolomite	3.14	2.88	9.11	2.88	9.05
Limestone	5.08	2.71	13.78	2.71	13.78
Sandstone	1.81	2.65	4.79	2.65	4.79

Luckily your are saved!

Computational Analysis-Composition

Do NOT change the values/formulas in the Yellow areas!



R_w Calculation Methods

- Direct measurement from a water sample (DST, Produced water at separator)
- Computation from chemical analysis of a water sample
- ✓ • From SP log
- ✓ • From sonic log (R_{wa})
- The ratio technique
- Crossplots (Pickett plot, Hingle plot)
- R_w catalogs from AAPG and SPWLA

R_w from Chemical Analysis

- If Na^+ and Cl^- are the only ions present in a solution, computation of an R_w value is estimated by entering the chart **Gen-6** with a total NaCl concentration and a temperature and exiting with an R_w value in $\Omega\cdot\text{m}$.
- When working with formation waters that contain ions other than Na^+ and Cl^- , the effect of these other ions on the electrical behavior of the electrolyte must be considered. The two factors that must be taken into consideration are **(1)** the charge carried by the ion and **(2)** its mobility through an electrolyte in the presence of an electric field.
- A practical method of dealing with this problem is to use multipliers (Chart **Gen-4**) for each ion to compute its effective charge-carrying power relative to Na^+ and Cl^- .

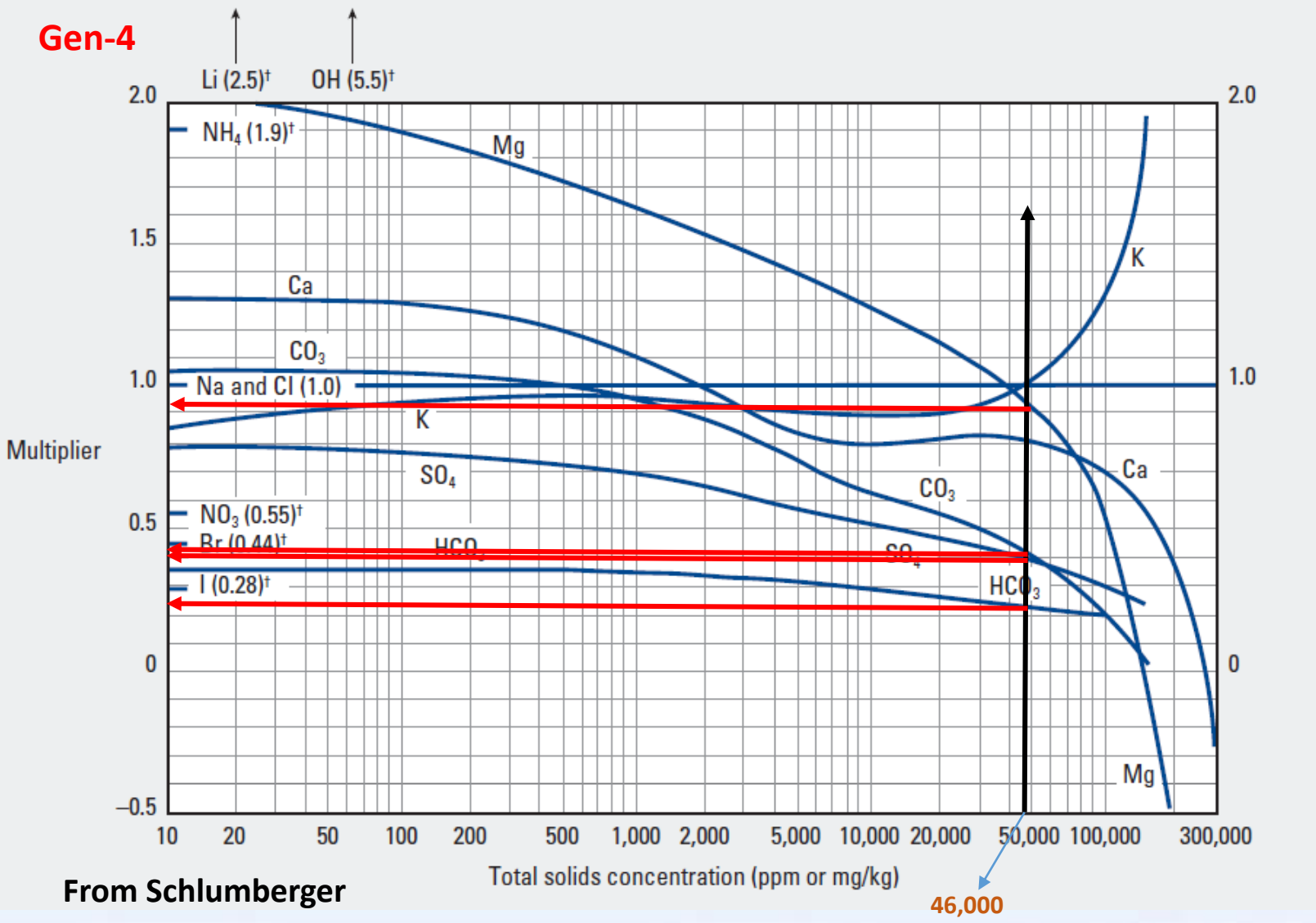
R_w Calculation Methods

Example

Water sample from a well has the following chemical analysis at 75 °F. What is the water resistivity of the formation if T_f=125 °F

Ion	Symbol	Concentration (ppm)
Sodium and chloride	Na ⁺ and Cl ⁻	25,000
Carbonate	CO ₃ ⁻	2,000
Sulfate	SO ₄ ⁻	5,000
Bicarbonate	HCO ₃ ⁻	10,000
Magnesium	Mg ⁺⁺	4,000
Total		46,000

Ion	Concentration (ppm)	Multiplier	Effective Concentration
Sodium and chloride	25,000	1.00	25,000
Carbonate	2,000	0.40	800
Sulfate	5,000	0.37	1,850
Bicarbonate	10,000	0.20	2,000
Magnesium	4,000	0.95	3,800
Total	46,000		33,450



R_w Calculation Methods

Example (Continued)

Ion	Concentration (ppm)	Multiplier	Effective Concentration
Sodium and chloride	25,000	1.00	25,000
Carbonate	2,000	0.40	800
Sulfate	5,000	0.37	1,850
Bicarbonate	10,000	0.20	2,000
Magnesium	4,000	0.95	3,800
Total	46,000		33,450

Equivalent NaCl Concentration

Alternative of using Gen-6:

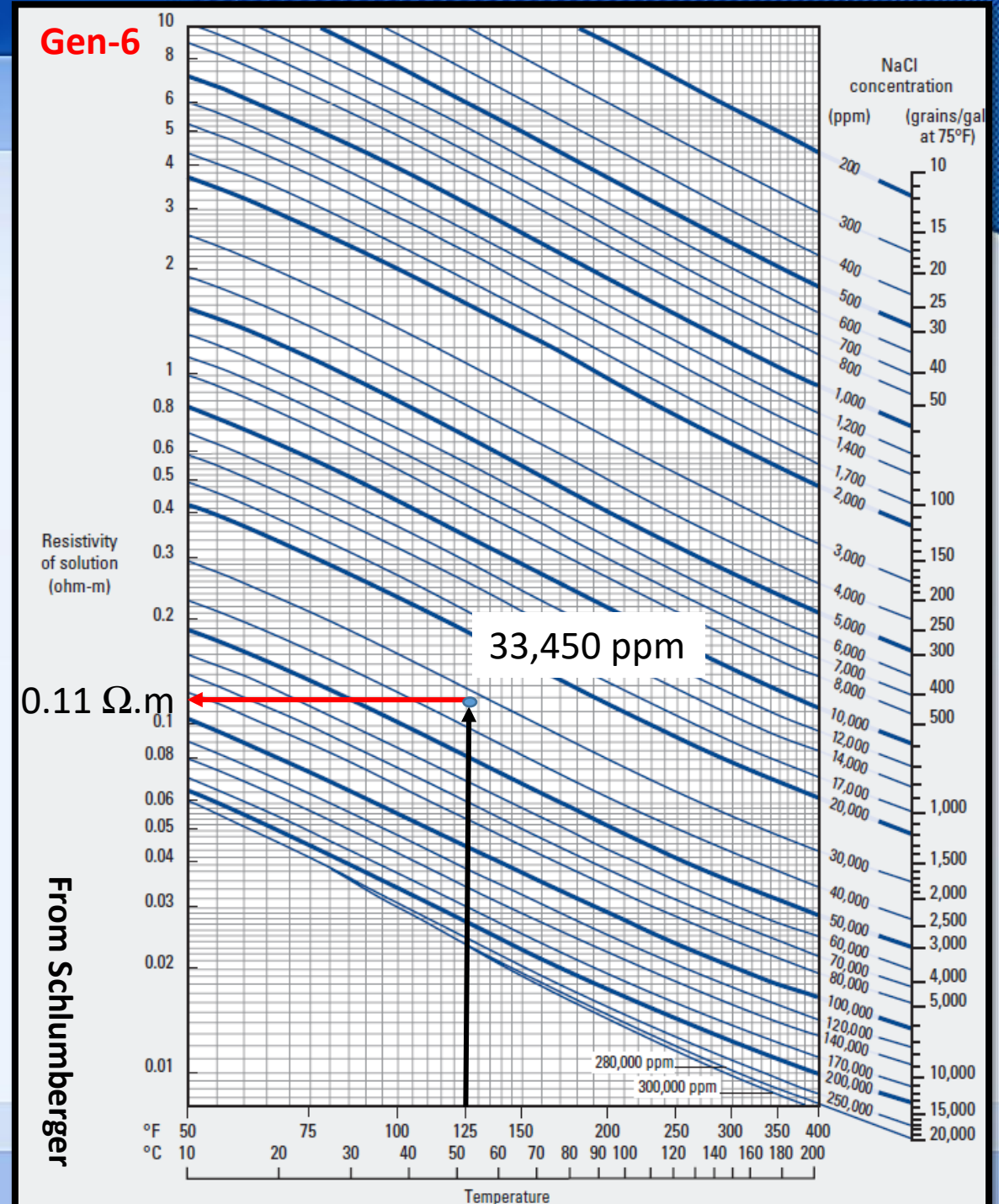
$$x = \frac{3.562 - \log(R_{w,75} - 0.0123)}{0.955} \quad ppm(NaCl) = 10^x$$

$$R_2 = R_1 \frac{T_1 + 6.77}{T_2 + 6.77} \text{ } ^\circ\text{F}$$

$$R_{w,75} = 0.1866 \text{ ohm.m}$$

$$R_{w,125} = 0.1158 \text{ ohm.m}$$

Gen-6



Ratio Technique

$$S_w^n = F \frac{R_w}{R_t}$$

$$S_{xo}^n = F \frac{R_{mf}}{R_{xo}}$$

Only in water zone



$S_w = S_{xo} = 100\%$

$$\frac{R_{mf}}{R_{xo}} = \frac{R_w}{R_t}$$



$$R_w = R_t \times \frac{R_{mf}}{R_{xo}}$$

Other Applications of Ratio Technique

$$S_{xo} > S_w \Rightarrow \frac{R_{xo}}{R_t} < \frac{R_{mf}}{R_w} \quad \text{In HC zones}$$

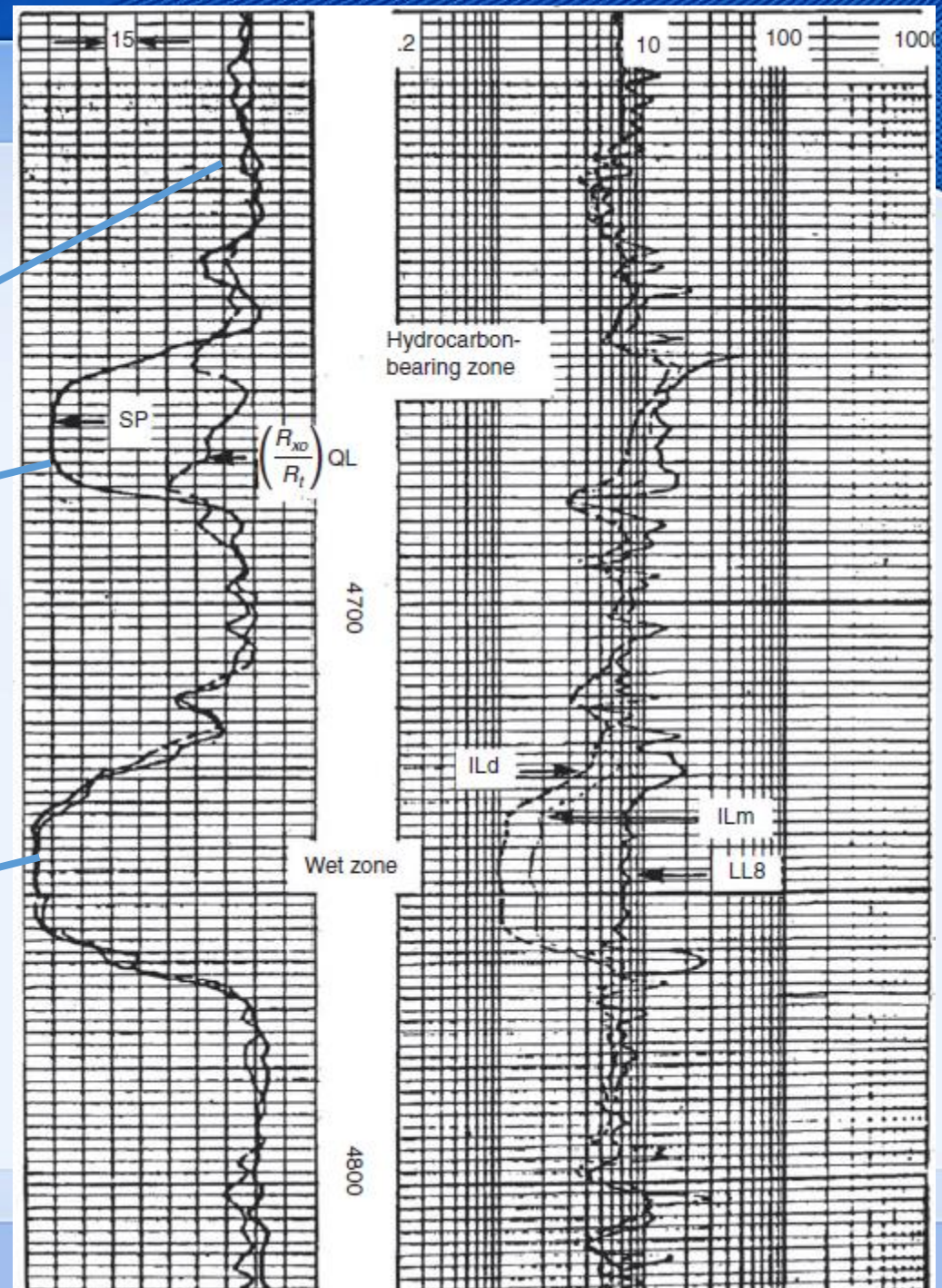
$$\frac{R_{xo}}{R_t} \cong 1 \quad \text{In Shales}$$

Ratio Technique

SP with R_{xo}/R_t

R_{xo}/R_t separates from
the SP curve

R_{xo}/R_t tracks the
SP curve

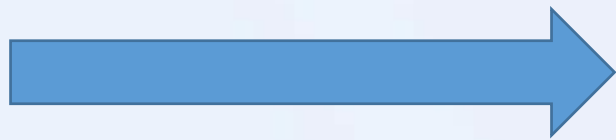


Pickett Plot

$$S_w = \sqrt[n]{\frac{a R_w}{\phi^m R_t}}$$

$$\log S_w = \frac{1}{n} (\log a R_w - m \log \phi - \log R_t)$$

In water zone



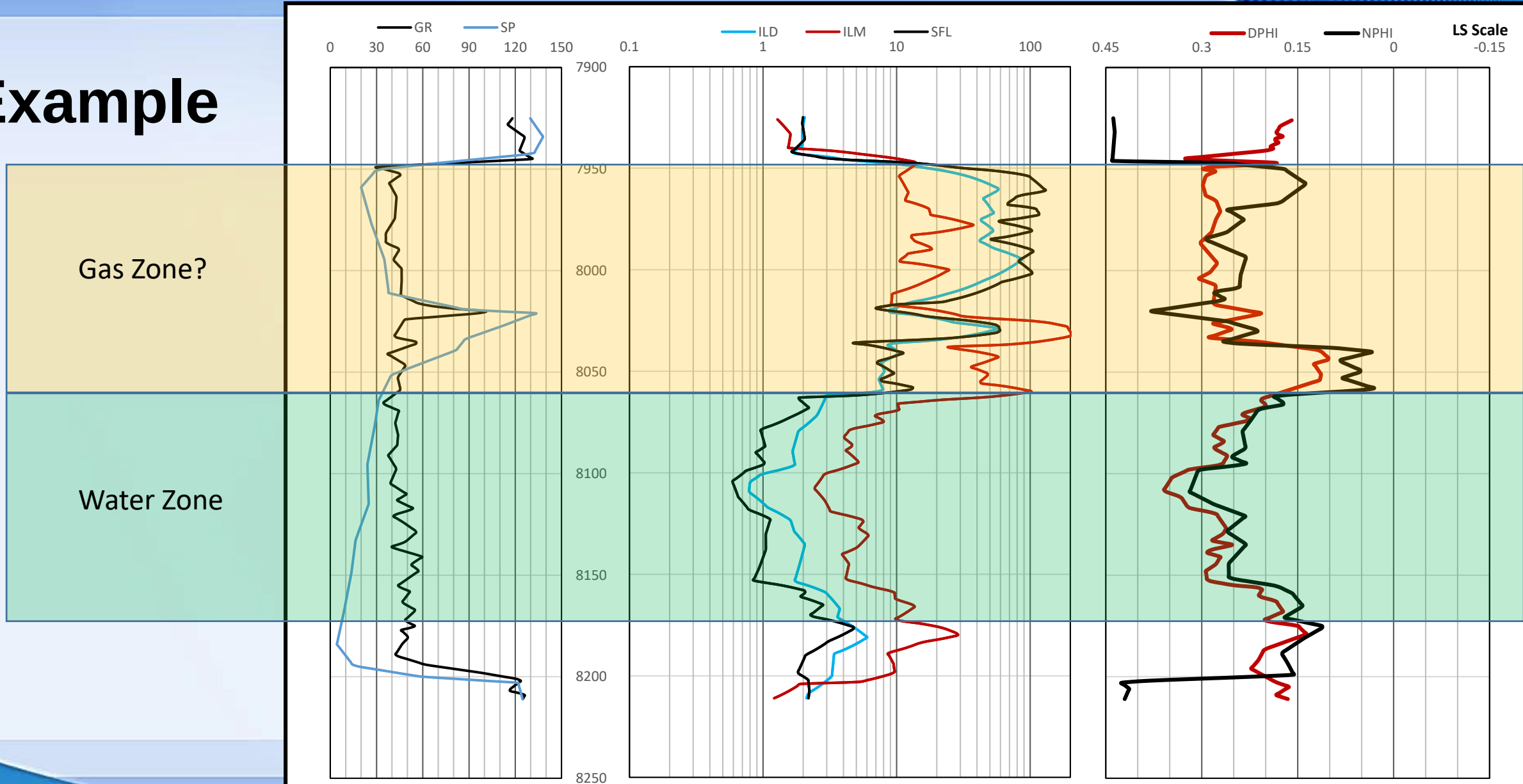
$S_w = 100\%$

$$\underbrace{\log R_t}_Y = \underbrace{\log a R_w}_{\text{Int.}} - \underbrace{m}_{\text{Slope}} \underbrace{\log \phi}_X$$

a, m, R_w can be found by trial and error on log-log plot.

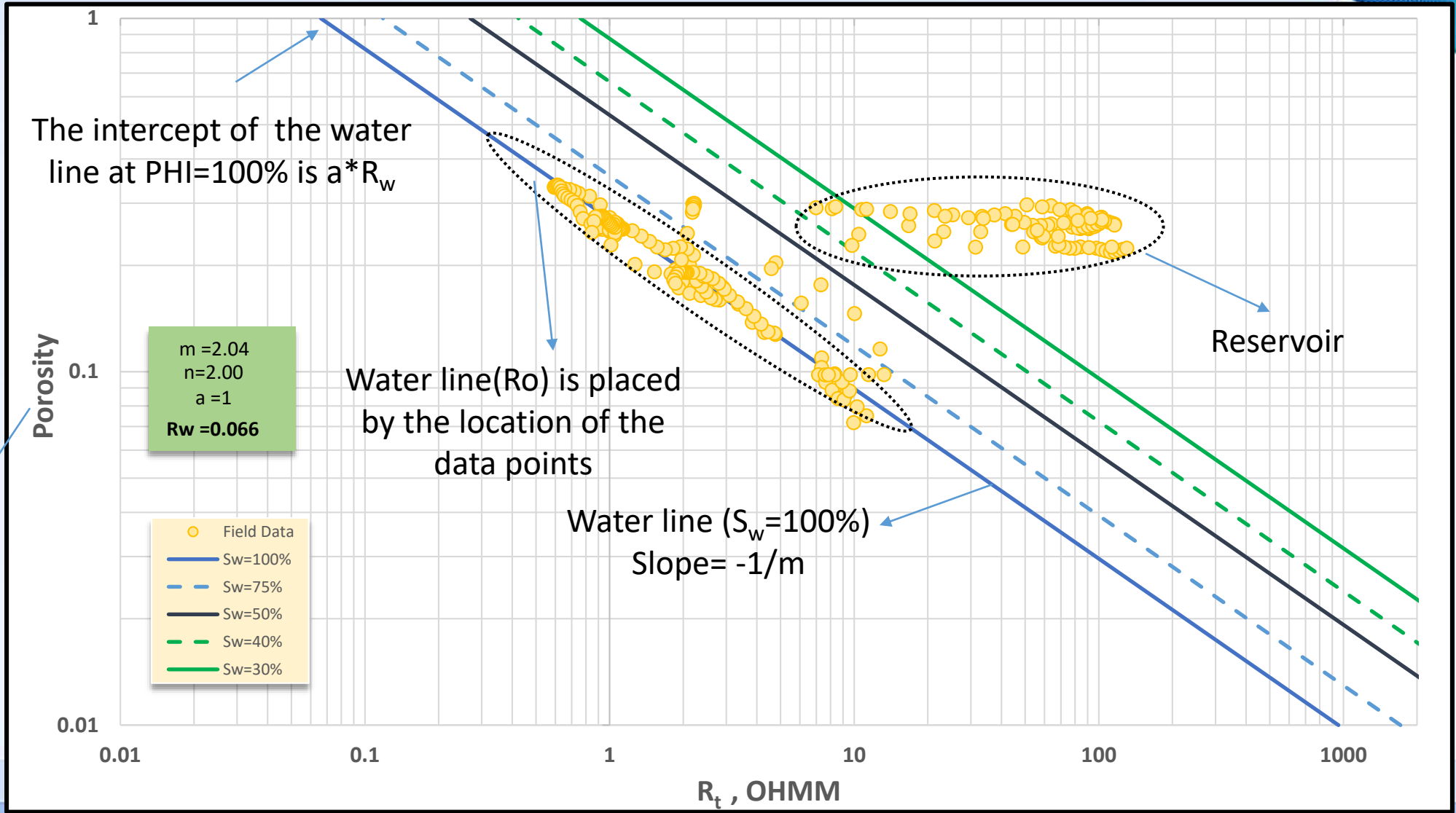
R_w Calculation Methods

Example



Pickett Plot

PHIX or
PHID or
PHIS



Pickett Plot

*Advantages:

- Water saturation can be predicted without prior knowledge of R_w , a , or m . R_w is directly predicted (if tortuosity factor (a) is known or estimated) from the intercept of the water-bearing line at a porosity of 1.0 ($\phi = 100\%$).
- Cementation exponent (m) is directly predicted from the slope of the water-bearing line.
- Reservoir zone can be seen easily on the plot. Hydrocarbon-bearing points lie away from the line, moved horizontally to the right from the water-bearing line by their increased resistivity. The horizontal distance of a point from the water bearing line depends on the water saturation (S_w) of that point.

*Limitations:

- Presence of water zone is required to find the water (R_o) line.
- A wide range of porosity must be present to positively determine a water-bearing line. Formation lithology and water resistivity must be constant over the intervals compared in the plot.

Bulk Volume of Water (BVW)

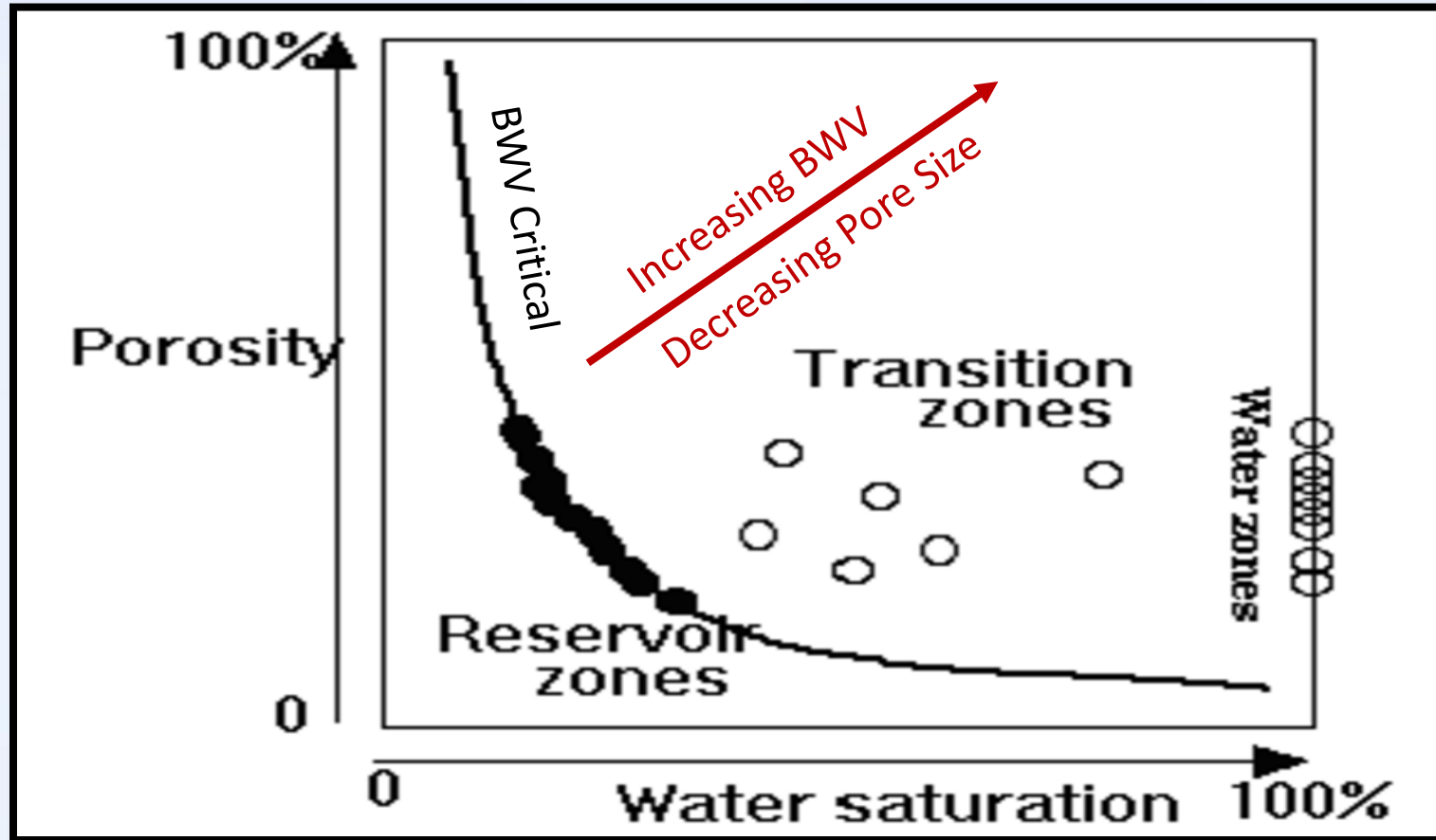
- Calculating S_w from Archie's equation or Pickett plot, is not sufficient to determine whether the HC zone will produce HC, water, or HC with water cut.
- The production is controlled by factors such as pore size, capillary pressure, wettability, surface tension.
- BVW is a useful measure controlled by pore size indicating the productivity.
- BVW is product of porosity in water saturation: $BVW = \phi \times S_w$
- If a reservoir is at S_{wirr} , it produces water free HC. BVW @ this saturation is "Irreducible BVW (BVWi)".
- To find if a zone is likely producing water free or not, we can use Buckle's plots.

Common BVWi Values

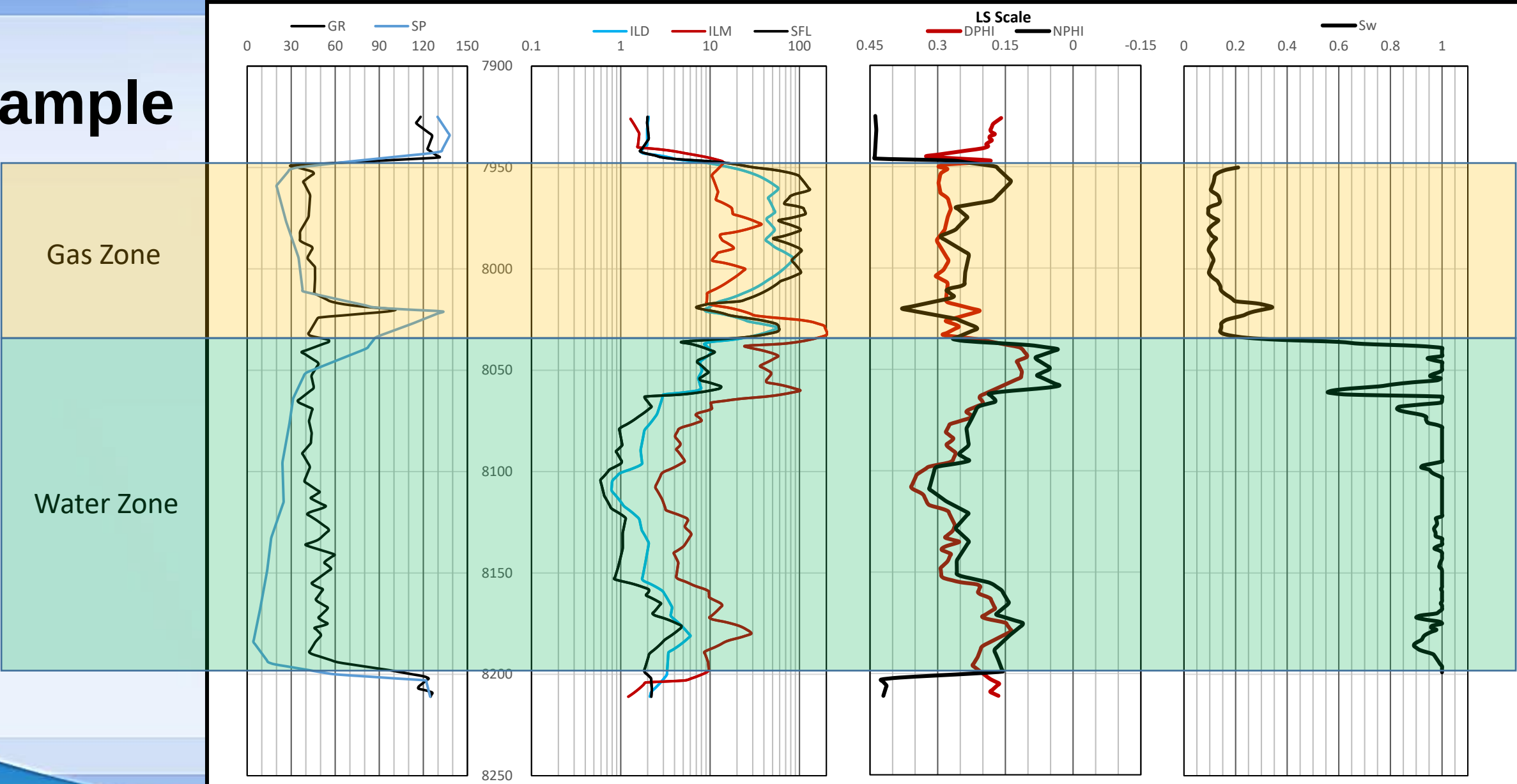
Grain Size (millimeters)		Bulk Volume Water (BVW)
coarse	1.0 to 0.5 mm	0.02 to 0.025
medium	0.5 to 0.25 mm	0.025 to 0.035
fine	0.25 to 0.125 mm	0.035 to 0.05
very fine	0.125 to 0.0625 mm	0.05 to 0.07
silt	< 0.0625 mm	0.07 to 0.09
(after Fertl and Vercellino, 1978)		
Carbonate Porosity		Bulk Volume Water (BVW)
Vuggy		0.005 to 0.015
Vuggy & Intercrystalline (intergranular)		0.015 to 0.025
Intercrystalline (intergranular)		0.025 to 0.04
Chalky		0.05

From Asquith

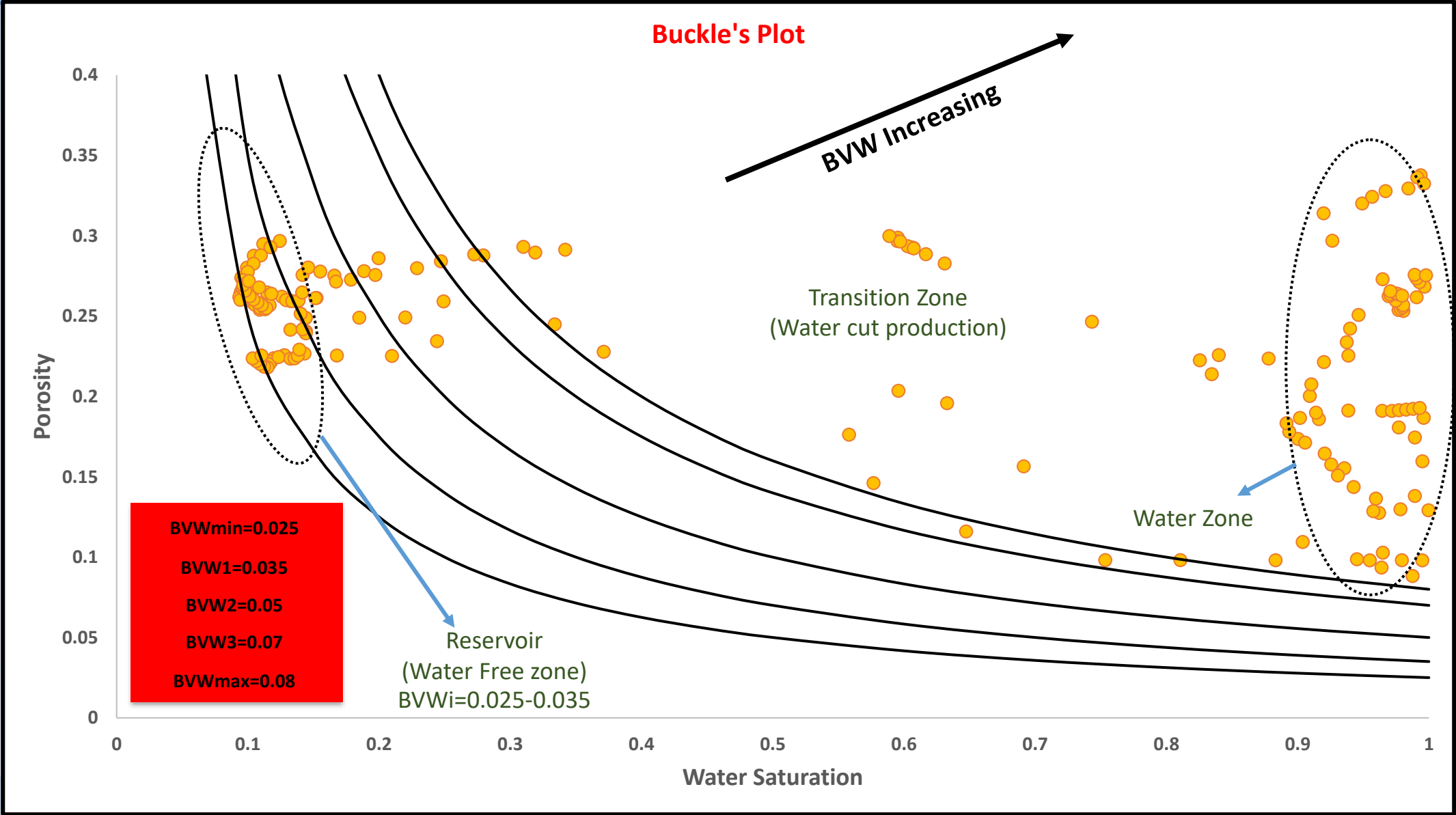
Buckle Plot



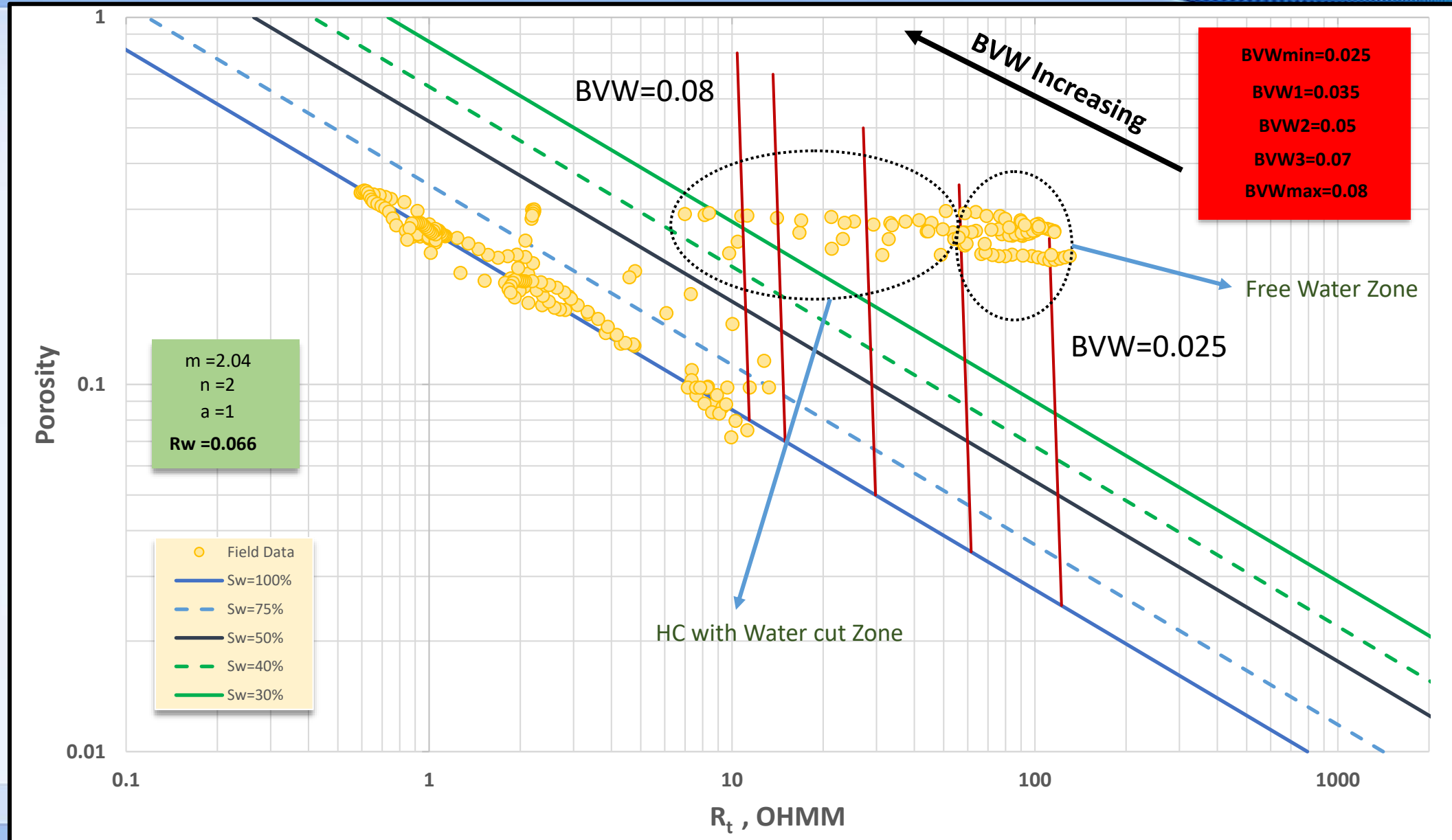
Example



Example



Example



Useful Charts

○Lith-3

○Lith-4

○Lith-6

○Lith-7

○Por-11

○Por-12

○Por-20

○Por-22

○Gen-4

○Gen-6