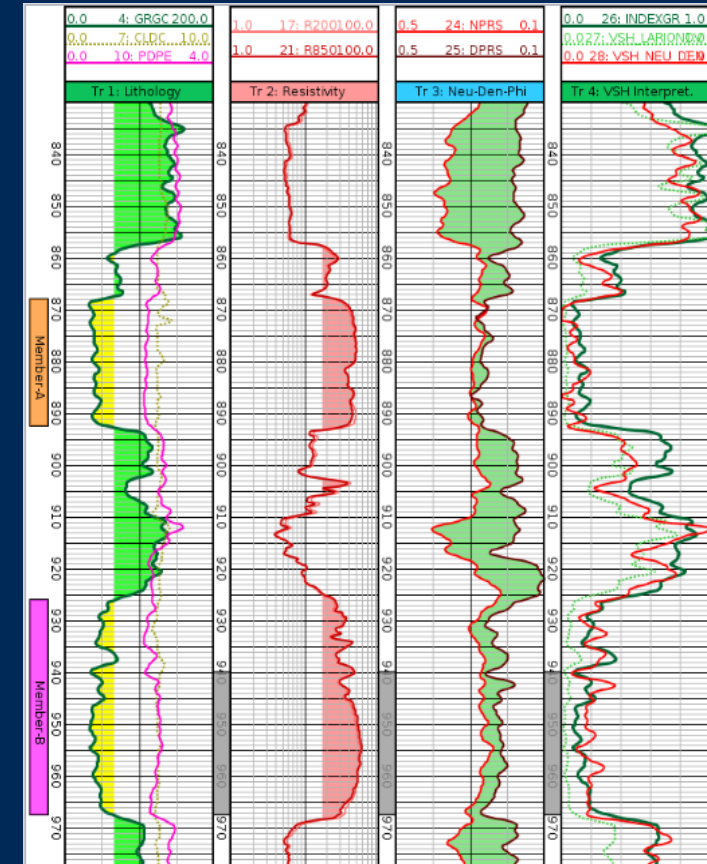
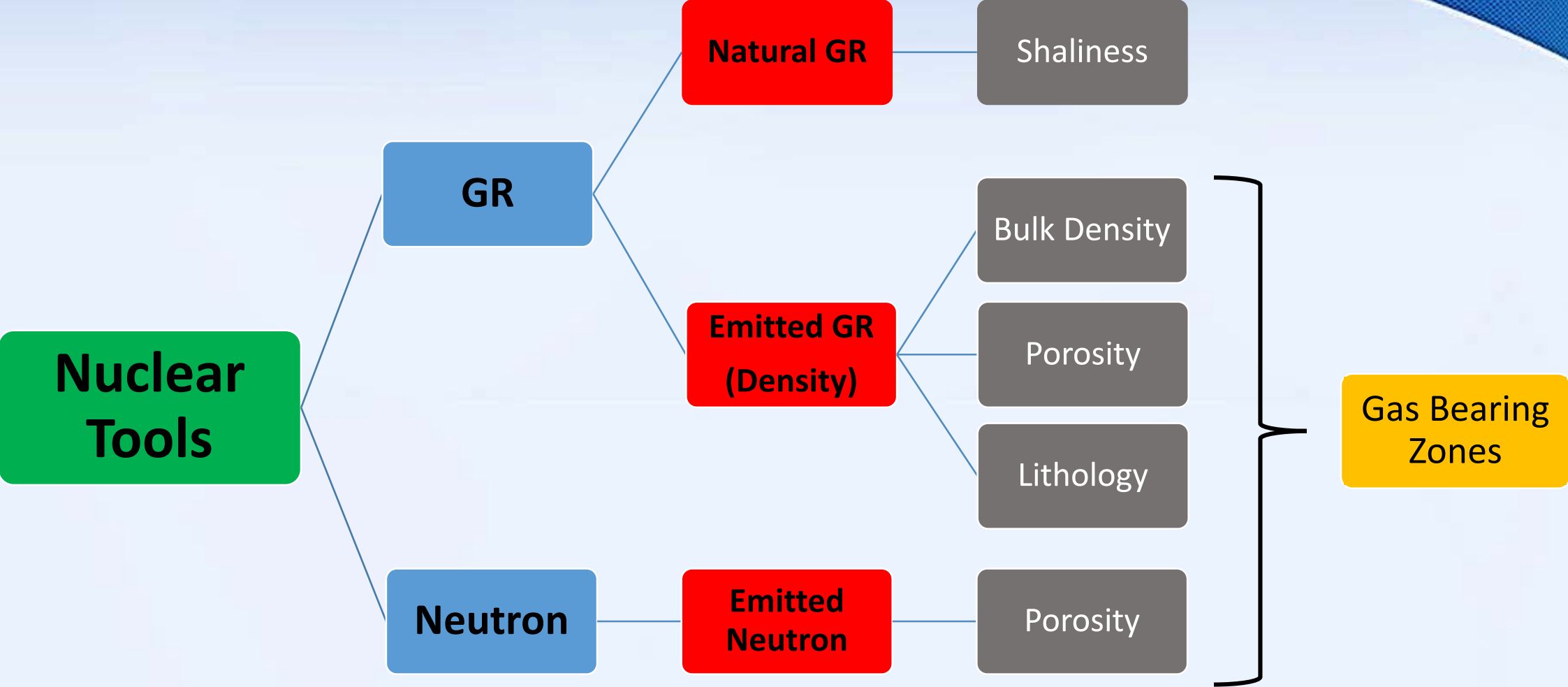


Density-Neutron Logs



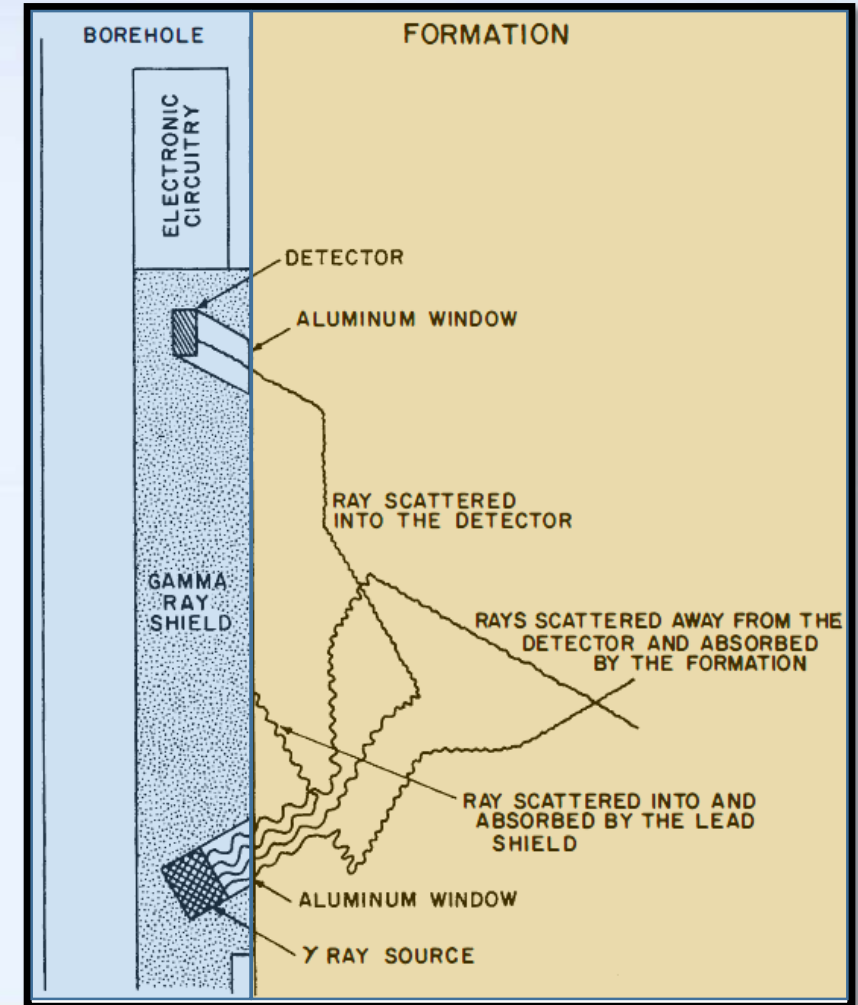


Density Log Application

- ☐ Porosity measurement
- ☐ Lithology identification
- ☐ Gas detection (with neutron log)
- ☐ Mechanical properties (with sonic log)

Density Tool Principle

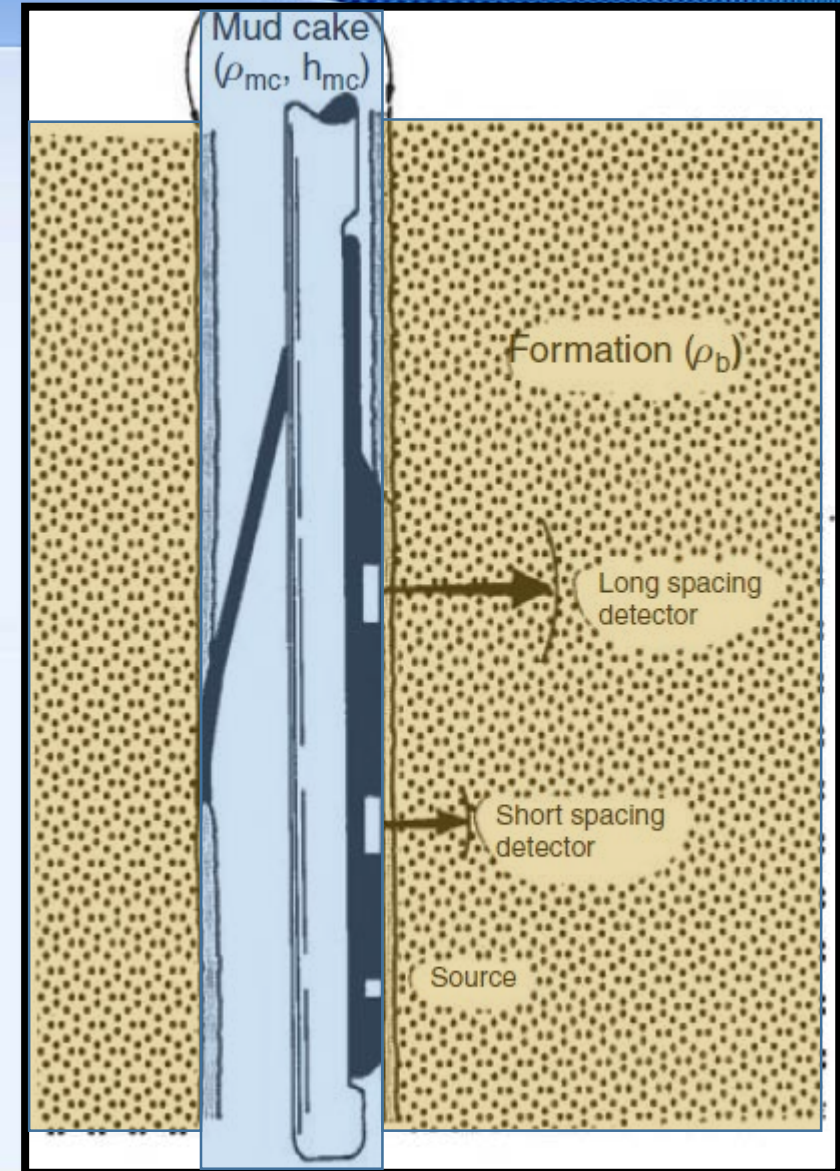
- 1) Gamma rays are emitted from a radioactive source (Cs 137 or Co 60) with medium energy (0.662 MeV from Cs137).
- 2) Gamma rays collide with the formation electrons and lose their energy.
- 3) Detectors (near and far) measure the energy of the backscattering rays.
 - High-energy backscattered rays due to the **Compton Scattering Effect** are related to the density (ρ_b).
 - Low-energy backscattered rays due to the **Photoelectric Effect** are related to the lithology.



Bassiouni, 1994

Density Tools

- It was accepted as a porosity measurement tool in 1960s.
- **Compensated Formation Density (FDC):**
 - Two detectors
 - Compensated for borehole effect
- **Lithodensity Tool (LDT):**
 - Two detectors
 - Measures bulk density and P_e



From Schlumberger

GR Interaction with Matter

1) Pair Production:

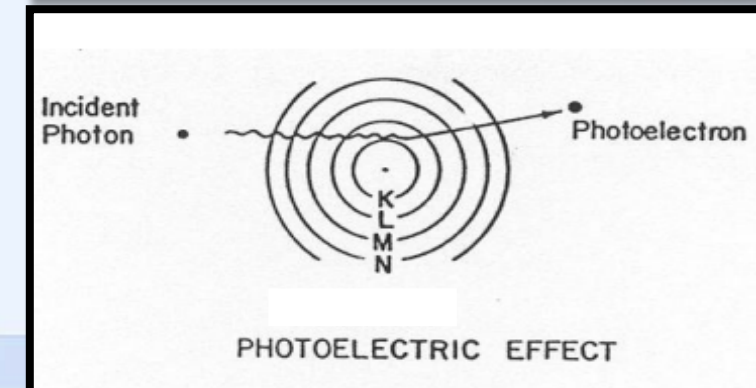
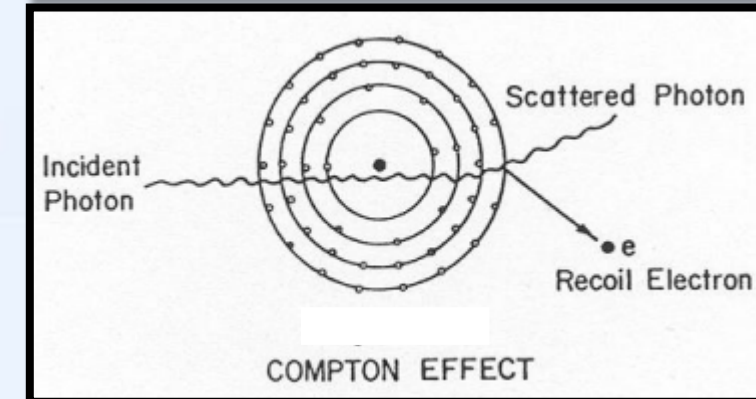
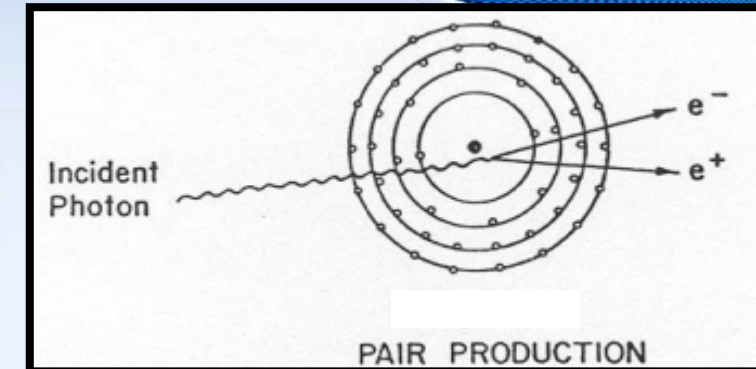
- ✓ GR with high energy (above 1.022 MeV) interacts with the nucleus.
- ✓ Gets absorbed and an electron-positron pair is formed and emitted.
- ✓ It is not detected in density tools (have energy above 0.622 MeV).

2) Compton Scattering:

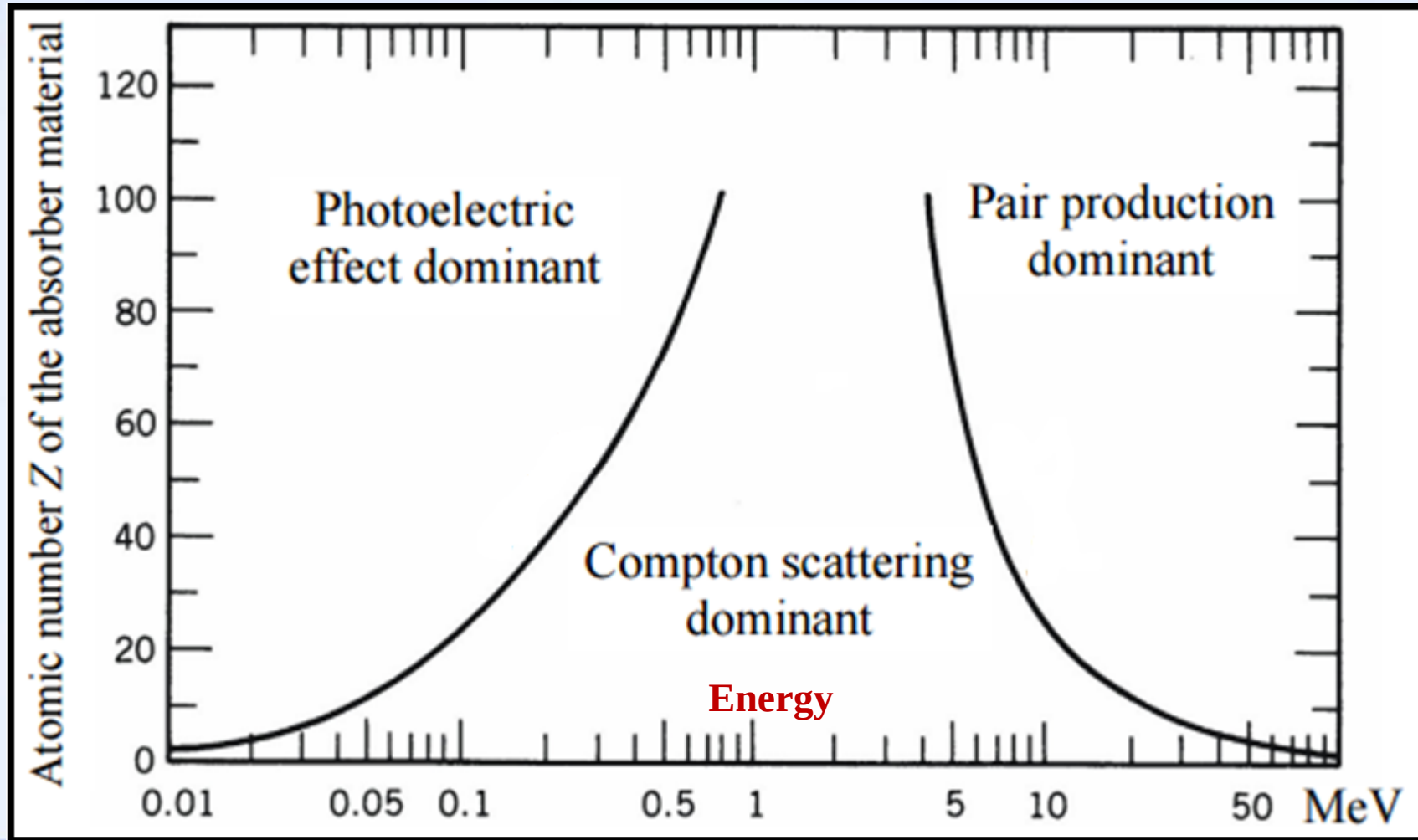
- ✓ GR with medium/high energy interacts with the electron.
- ✓ A GR with lower energy and an electron are scattered.
- ✓ Accounted for rock electron density.

3) Photoelectric Effect:

- ✓ GR with low energy interacts with the atom.
- ✓ A photoelectron is scattered.
- ✓ Accounted for atomic number & lithology.



GR Interaction with Matter



Effect of Atomic Number on GR Spectrum

$$Z_1 < Z_2 < Z_3$$

$$\rho_{b1} = \rho_{b2} = \rho_{b3}$$

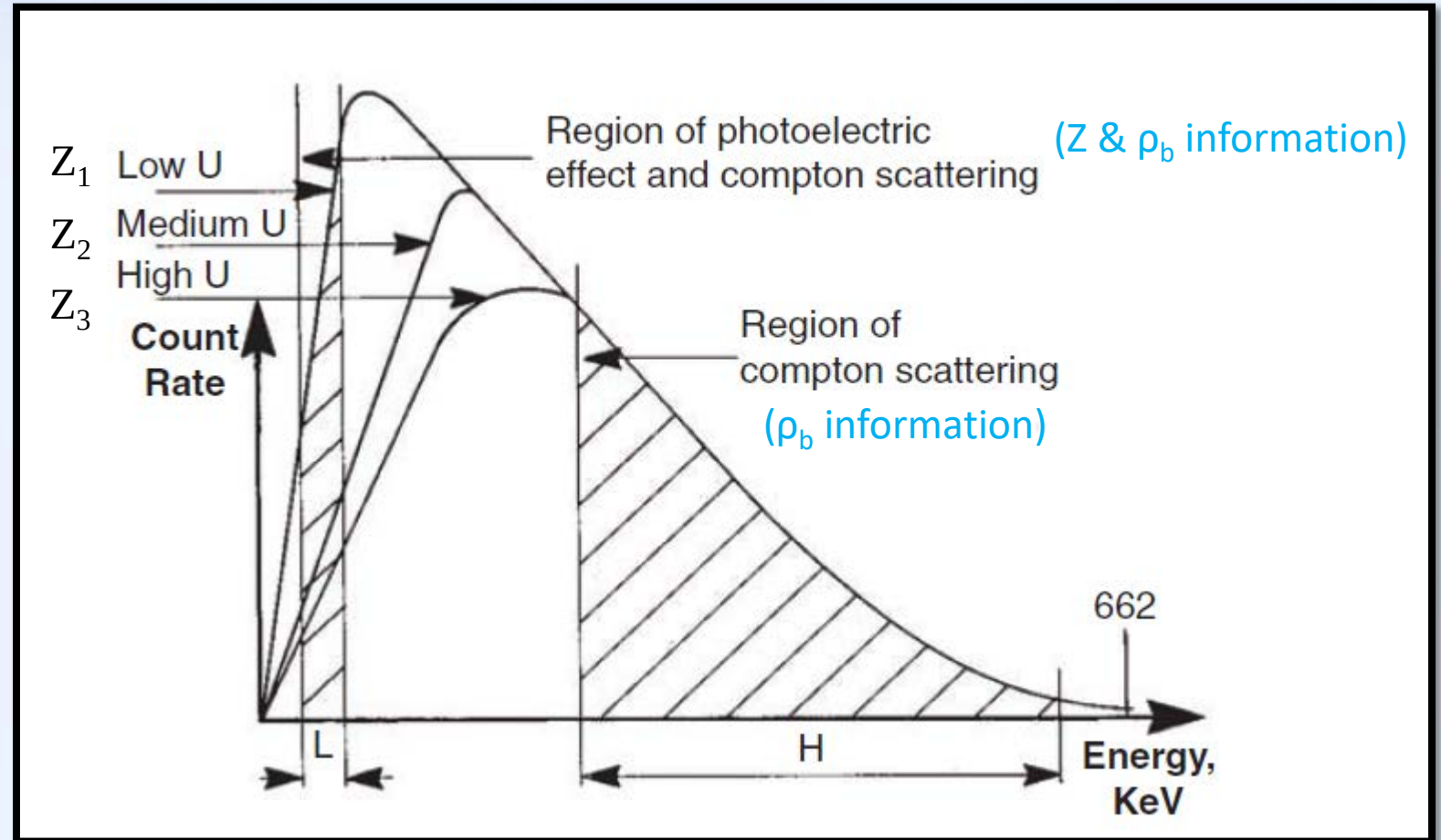
$$U = P_e \times \rho_e$$

$$P_e = (0.1 \times Z_{eff})^{3.6}$$

U : Absorption Rate: barns/cm³

ρ_e : electron/cm³

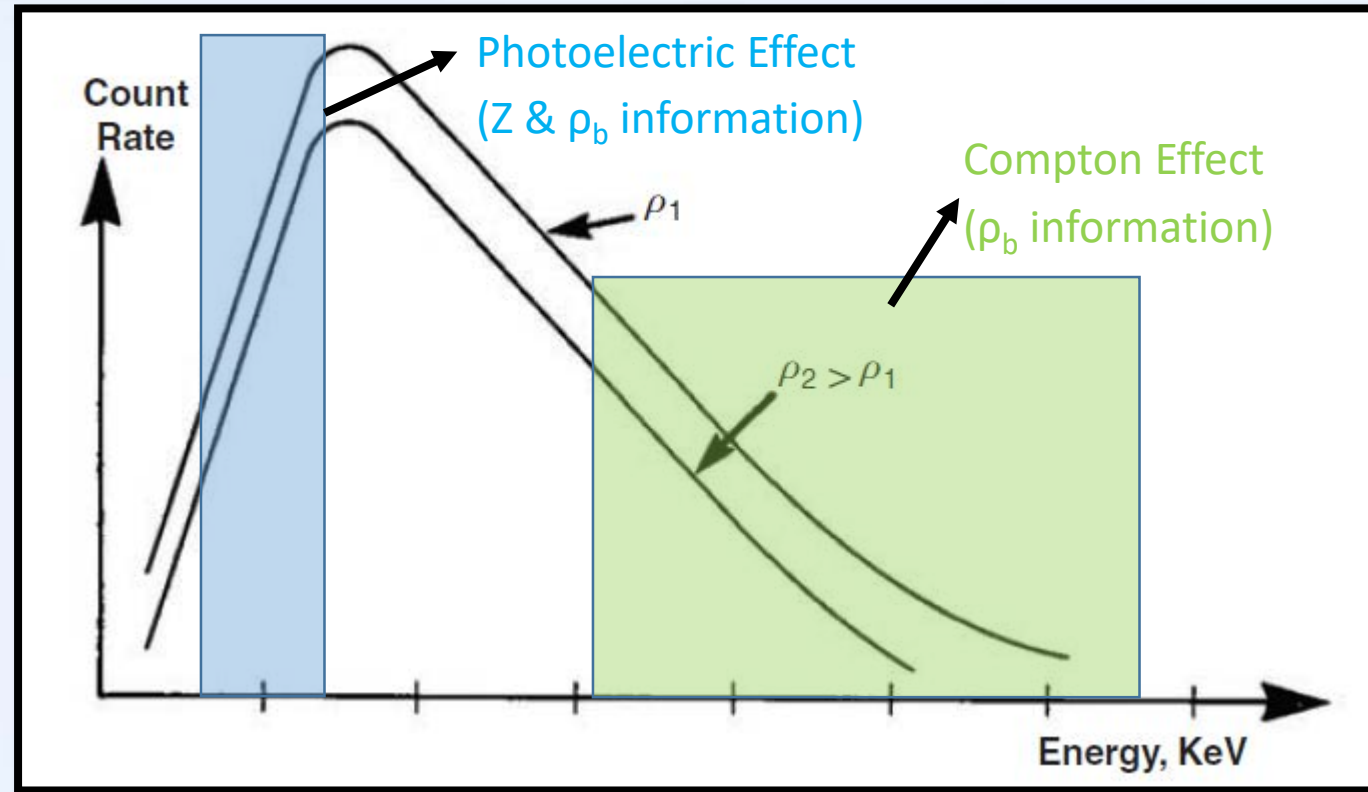
P_e : barns/electron



Bateman, 2012

Effect of Density on GR Spectrum

$$Z_1 = Z_2$$
$$\rho_{b1} < \rho_{b2}$$



Bateman, 2012

Bulk Density

- Campton Scattering depends only on the electron density of formation.
- Electron density is related to the bulk density:

Z = Atomic number
 A = Atomic weight
 ρ_b = Bulk density of the material
 $\frac{2Z}{A} \approx 1$ for all elements except hydrogen (≈ 2)

$$\rho_e = \frac{2Z}{A} \rho_b$$

- Calibrated for fresh water filled limestone formation:

$$\rho_a = 1.0704 \rho_e - 0.1883$$

ρ_a = Apparent bulk density of the material

- $\rho_b \approx \rho_a$ for common sedimentary rocks.
- Calibrated for SS & Dol formation: $\rho_b \approx \rho_a$

TABLE 17.2—APPARENT DENSITY VALUES FOR VARIOUS MINERALS AND FLUIDS					
Compound	Formula	Actual Density ρ_b	$\frac{2Z}{A}$ Mol. Wt.	ρ_e	ρ_a (as seen by tool)
Quartz	SiO ₂	2.654	0.9985	2.650	2.648
Calcite	CaCO ₃	2.710	0.9991	2.708	2.710
Dolomite	CaCO ₃ MgCO ₃	2.870	0.9977	2.863	2.876
Anhydrite	CaSO ₄	2.960	0.9990	2.957	2.977
Sylvite	KCl	1.984	0.9657	1.916	1.863
Halite	NaCl	2.165	0.9581	2.074	2.032
Gypsum	CaSO ₄ 2H ₂ O	2.320	1.0222	2.372	2.351
Anthracite	Coal	1.400	1.030	1.442	1.355
Coal		1.800		1.852	1.796
Bituminous		1.200		1.272	1.173
Coal		1.500	1.060	1.590	1.514
Fresh Water		1.000		1.110	1.00
Salt Water	200,000 ppm	1.146	1.0797	1.237	1.135
"Oil"	$n(\text{CH}_2)$	0.850	1.1407	0.970	0.850
Methane	CH ₄	ρ_{meth}	1.247	$1.247 \rho_{\text{meth}}$	$1.335 \rho_{\text{meth}} - 0.188$
"Gas"	C _{1,1} H _{4,2}	ρ_g	1.238	$1.238 \rho_g$	$1.325 \rho_g - 0.188$

Source: Schlumberger

Photoelectric Index, P_e

- Photoelectric absorption depends on both electron density and the average atomic number.
- Two parameters U and ρ_e are measured in low energy photoelectric effect window.

$$U = P_e \times \rho_e$$

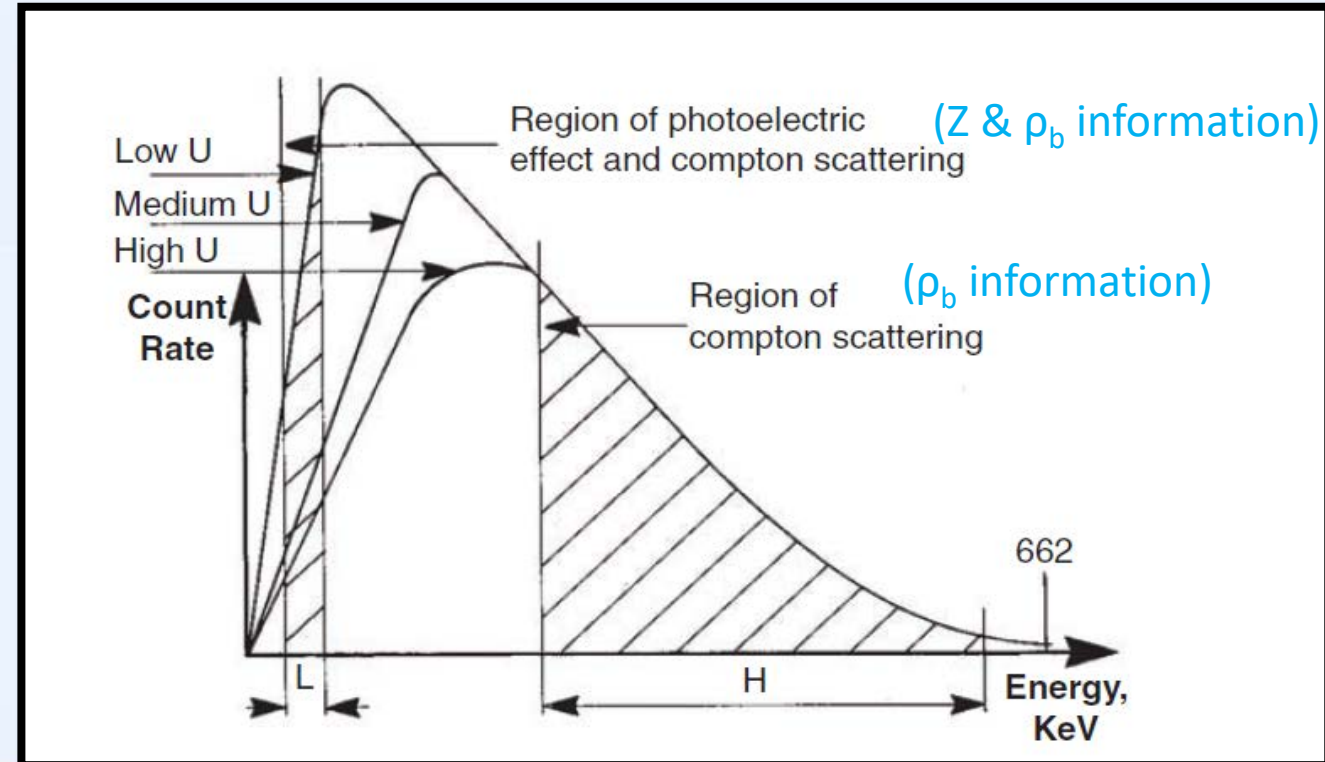
U : Absorption Rate: barns/cm³

ρ_e : electron/cm³

$$P_e = (0.1 \times Z_{eff})^{3.6}$$

P_e : barns/electron

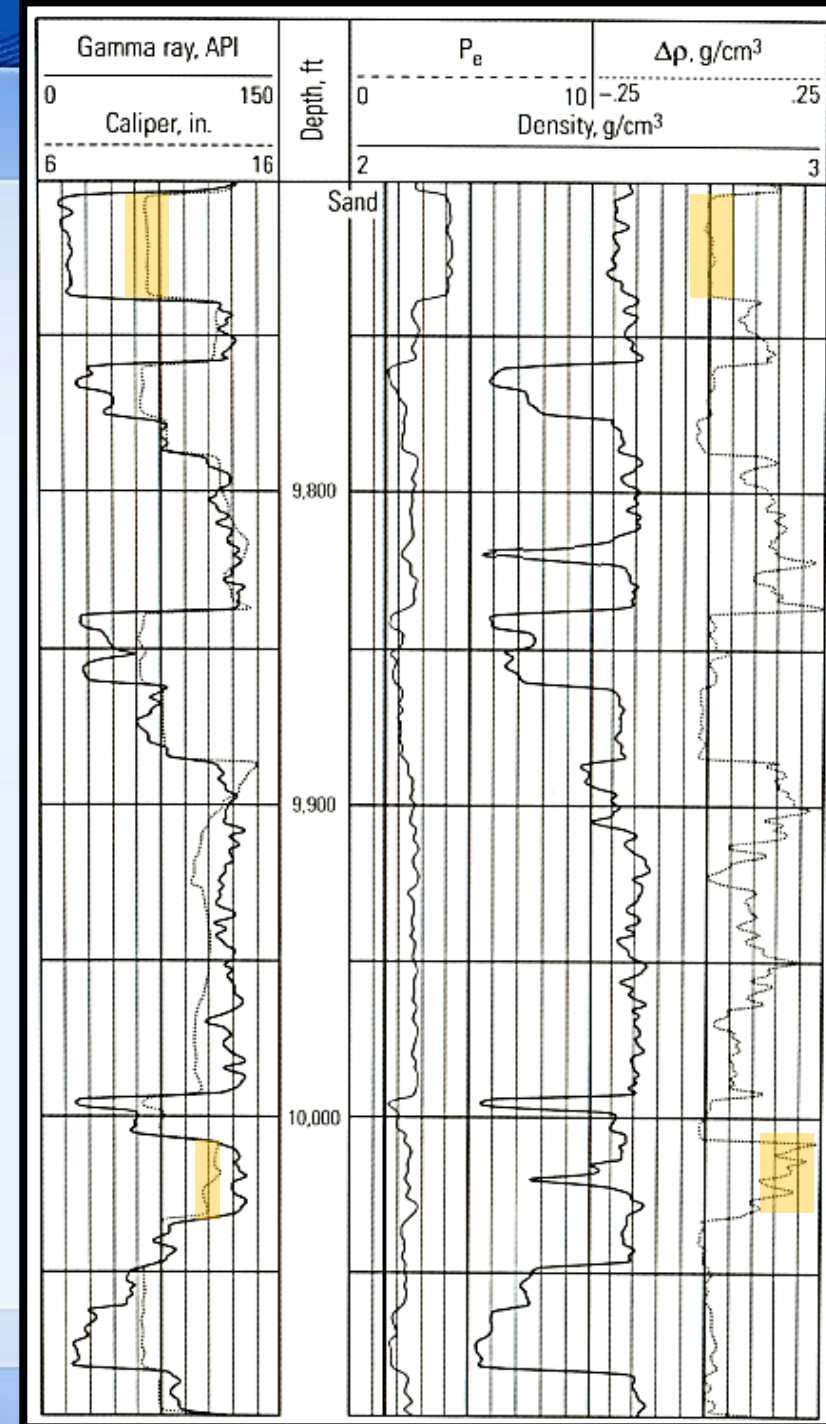
Matrix	P_e
Quartz/Chert	1.81
Calcite	5.08
Dolomite	3.14
Anhydrite	5.05
Halite	4.65
Shale	1.8-6.3



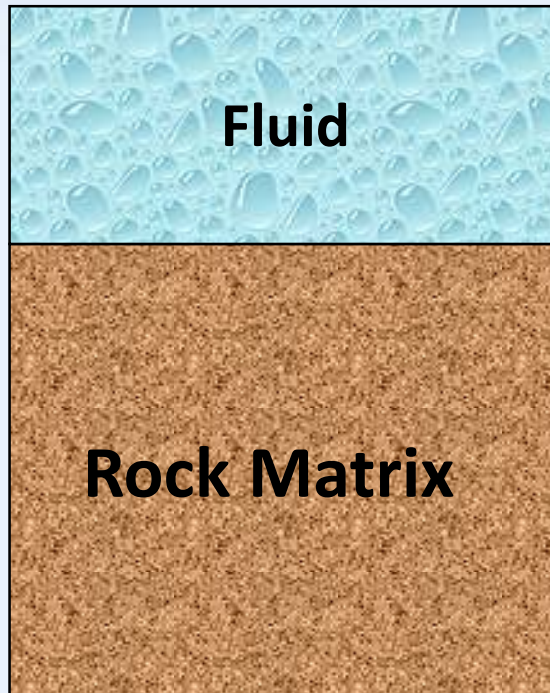
Bateman, 2012

Log Presentation

- Linear
- Increasing from left to right
- RHOB (gr/cc)
- Accompanied with correction: DRHO
- DRHO is “quality measurement” i.e.:
cave in, poor pad contact
- Not reliable if $DRHO > 0.2 \text{ gr/cc}$



Density Porosity

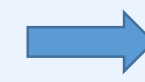


ϕ
 ρ_f

$1-\phi$

ρ_{ma}

$$\rho_b = \phi \rho_f + (1 - \phi) \rho_{ma}$$



$$\phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f}$$



PHID(ϕ_D) curve is obtained from here!

Matrix	ρ_{ma} gr/cc
Sandstone	2.65
Limestone	2.71
Dolomite	2.87
Anhydrite	2.98
Salt	2.03
Shale	2.1-2.8

Mud	ρ_f gr/cc
Fresh water	1.00
Salt water	1.1-1.2
Oil	0.8-0.9

Fluid is considered the mud filtrate since DOI of density tool is within the flushed zone.

Density Log

ϕ_D From Chart

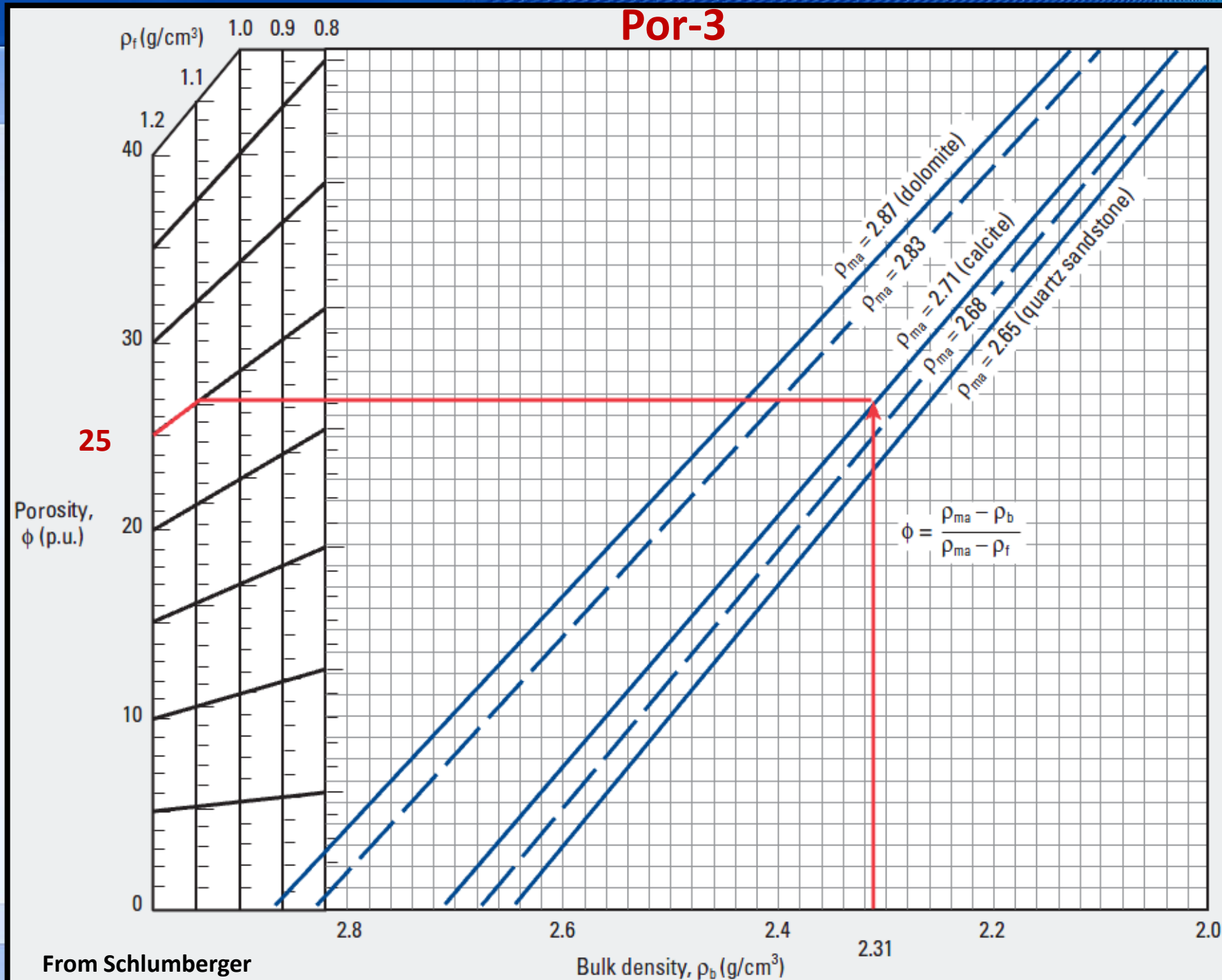
$$\rho_{ma} = 2.71 \text{ gr/cm}^3$$

$$\rho_b = 2.31 \text{ gr/cm}^3$$

$$\rho_f = 1.1 \text{ gr/cm}^3$$

$$\phi_D = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f}$$

$$\phi_D = \frac{2.71 - 2.31}{2.71 - 1.1} = 25\%$$



Gas Effect on Density Porosity

- If gas is present in the formation, significant amount of gas remains in the invaded zone.
- Gas density is significantly low compared to water or oil.
- Gas reduces the mean fluid density of invaded zone (which is usually assumed 1.0 or 1.1 gr/cc).
- This fluid density assumption of 1.0-1.1 gr/cc causes overestimation of the porosity.

$$\phi_D = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f}$$

Example

A gas bearing sandstone formation filled with 1.0 gr/cm³ mud filtrate is reported to have bulk density of 2.2 gr/cm³. If the residual gas saturation is known to be 40% :

- 1) Calculate apparent porosity assuming there is no residual gas:
- 2) Calculate true porosity if gas density is 0.1 gr/cm³.
- 3) Calculate porosity if gas pressure is low and hence gas density is negligible.

$$1) \quad \phi_D = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \quad \phi_D = \frac{2.65 - 2.2}{2.65 - 1} = 27\%$$

Example

$$\rho_b = \overbrace{\phi(1 - S_{xo})\rho_g + \phi S_{xo}\rho_{mf}}^{\phi\rho_f} + (1 - \phi)\rho_{ma}$$

$$\phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - (1 - S_{xo})\rho_g - S_{xo}\rho_{mf}}$$

2)

$$\phi = \frac{2.65 - 2.2}{2.65 - (0.4) \times 0.1 - 0.6 \times 1} = 22\%$$

3)

$$\phi = \frac{2.65 - 2.2}{2.65 - 0.6 \times 1} = 21.95\%$$

Compare with 27% in part 1!

Where can we find S_{xo} and ρ_g ?

$$\rho_g$$

$$\phi(1 - S_{xo})$$

$$\rho_{mf}$$

$$\phi S_{xo}$$

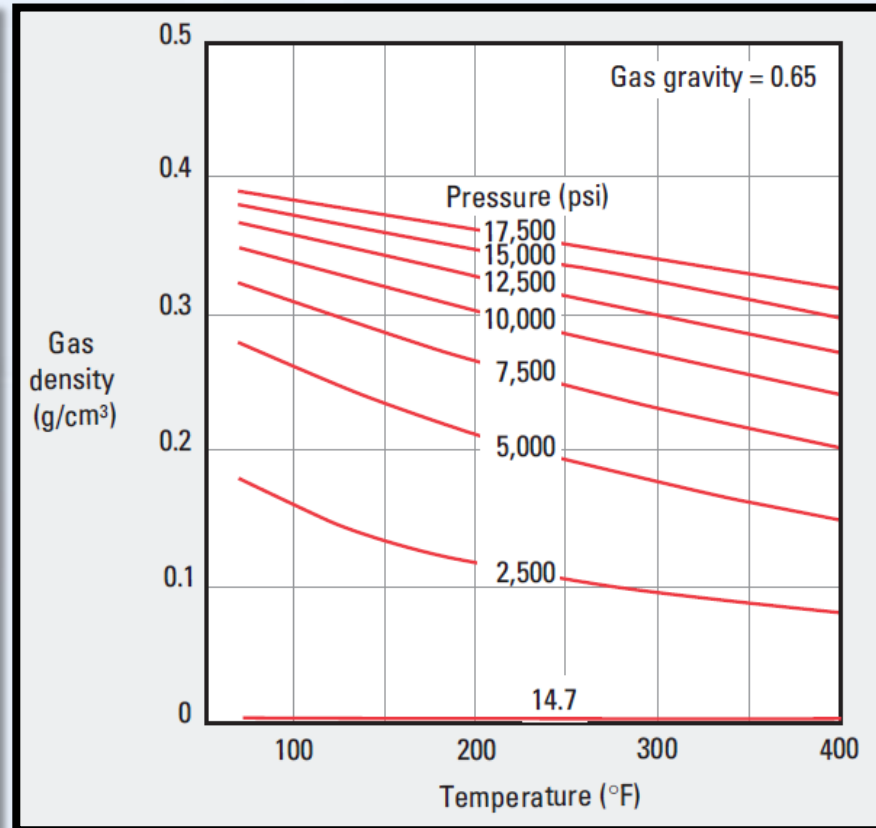
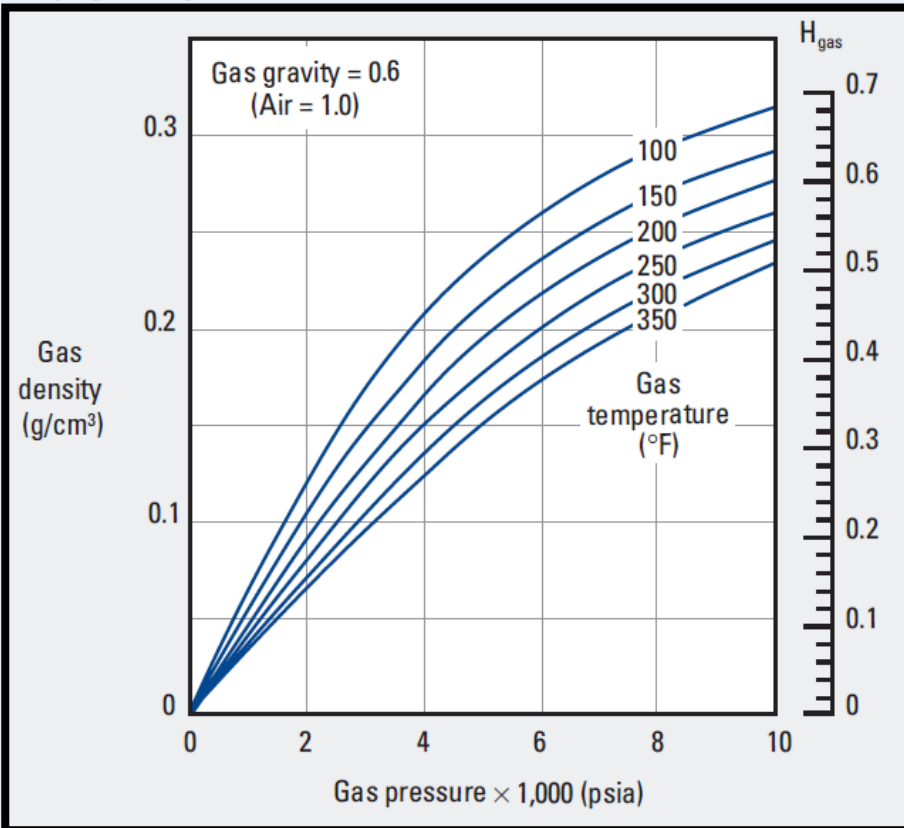
$$1 - \phi$$

$$\rho_{ma}$$



Gas Density

Gen-8



From Schlumberger

OR

$$\rho_g = \frac{0.18}{(7644/\text{depth in ft}) + 0.22}$$

gr/cm³

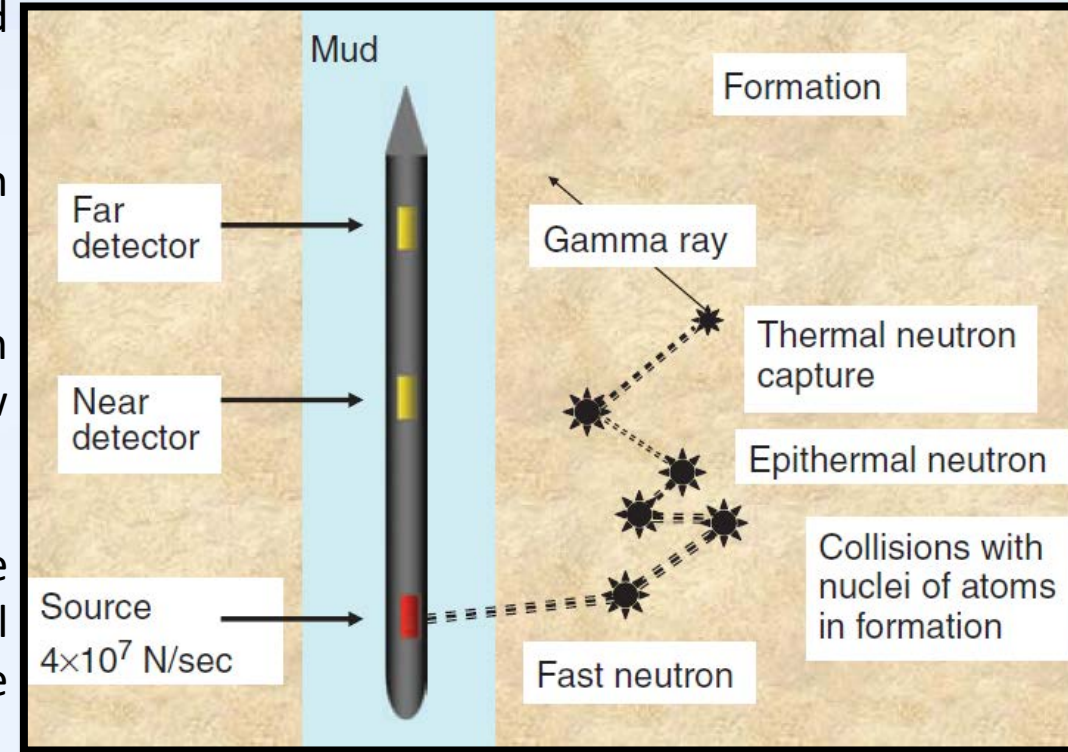
Neutron Log Application

- ☐ Identifying porous zones
- ☐ Porosity measurement
- ☐ Gas zone detection (with density log)
- ☐ Lithology identification

Neutron Tool Principle

1) Neutrons are emitted from a chemical (Pu-Be or Am-Be) or pulsed source.

- Fast Neutrons: Near the chemical sources, neutrons are found with substantially at their initial energy of several MeV ($>4\text{MeV}$).
- Epithermal Neutrons: Fast neutrons losing energy with each collision, the neutrons reach to an intermediate energy level of few eV (0.1-100 eV).
- Thermal Neutrons: Neutron slows down to a point ($<0.1\text{ eV}$) where it has the same energy as the surrounding matter; this energy level is a direct function of the absolute temperature. At this stage, the neutron is ripe for capture.



Bateman, 2012

2) Detectors count neutrons scattered back from the formation.

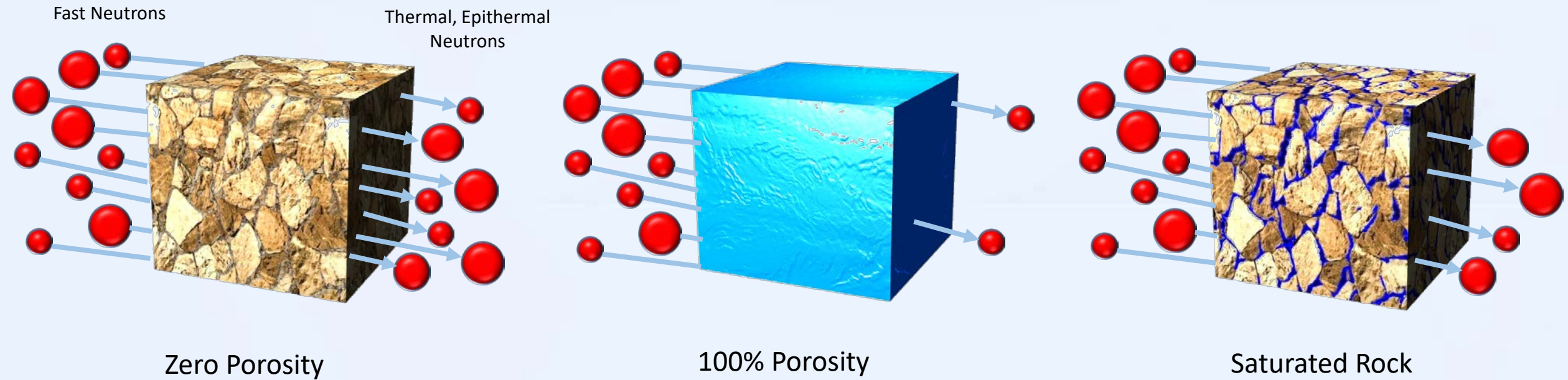
High counts: Low porosity

Low counts: High porosity

Thermal Neutrons

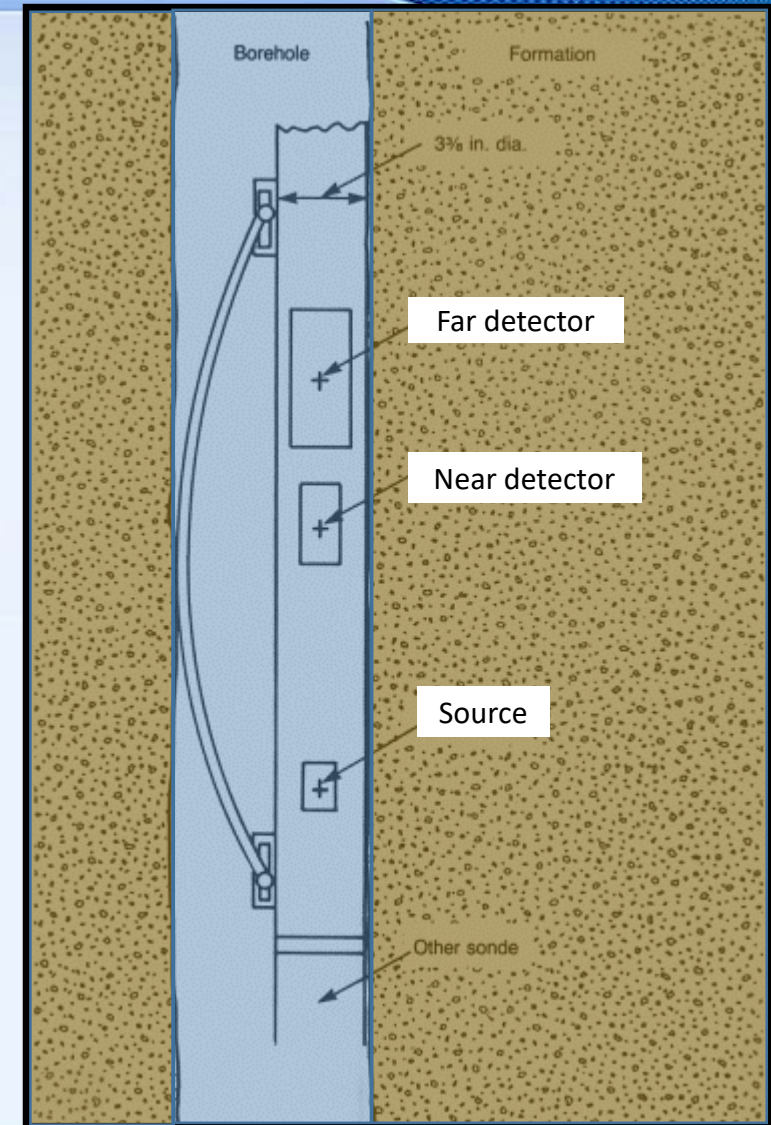
- Collisions cause neutrons to lose energy (slow down).
- Energy loss by collision is dependent on mass difference.
- Hydrogen, the element with only a proton for a nucleus, is the best material for slowing down a neutron.
- “Billiard Ball Effect” reveals that when two balls collide, the maximum energy loss occurs when two balls are of equal mass. The neutron and the proton, being of equal mass, account for the prodigious powers of the hydrogen nucleus to slow neutrons.
- The more hydrogen (porosity), the more slowing down of energy to the thermal level and the more capturing by formation.
- Other elements (except Cl) have minor effect on the neutron tool, requiring compensation.

Neutron Response



Neutron Tools

- **GNT (Gamma Ray Neutron Tool)**
 - One detector
 - Qualitative indicator of porosity
 - Severe issues with mud and formation salinity and hole size
- **SNP (Sidewall Neutron Porosity)**
 - One detector
 - Salinity problem was solved
 - Mudcake effects
- **CNL (Compensated Neutron Log)**
 - Two detectors
 - Overcame the previous problems
 - Applicable open/cased holes



Lithology Effect on Neutron Porosity

- Neutron tool responds to the hydrogen mostly.
- Neutron tool also responds to other elements (minerals) to a lesser extent.
- Thus, Neutron tool reads different porosity values in different formations with same porosity.
- For that, the neutron porosity is scaled (calibrated) to Limestone (mostly) or Sandstone.

The neutron porosity is an APPARENT POROSITY
and needs to be converted to TRUE POROSITY.

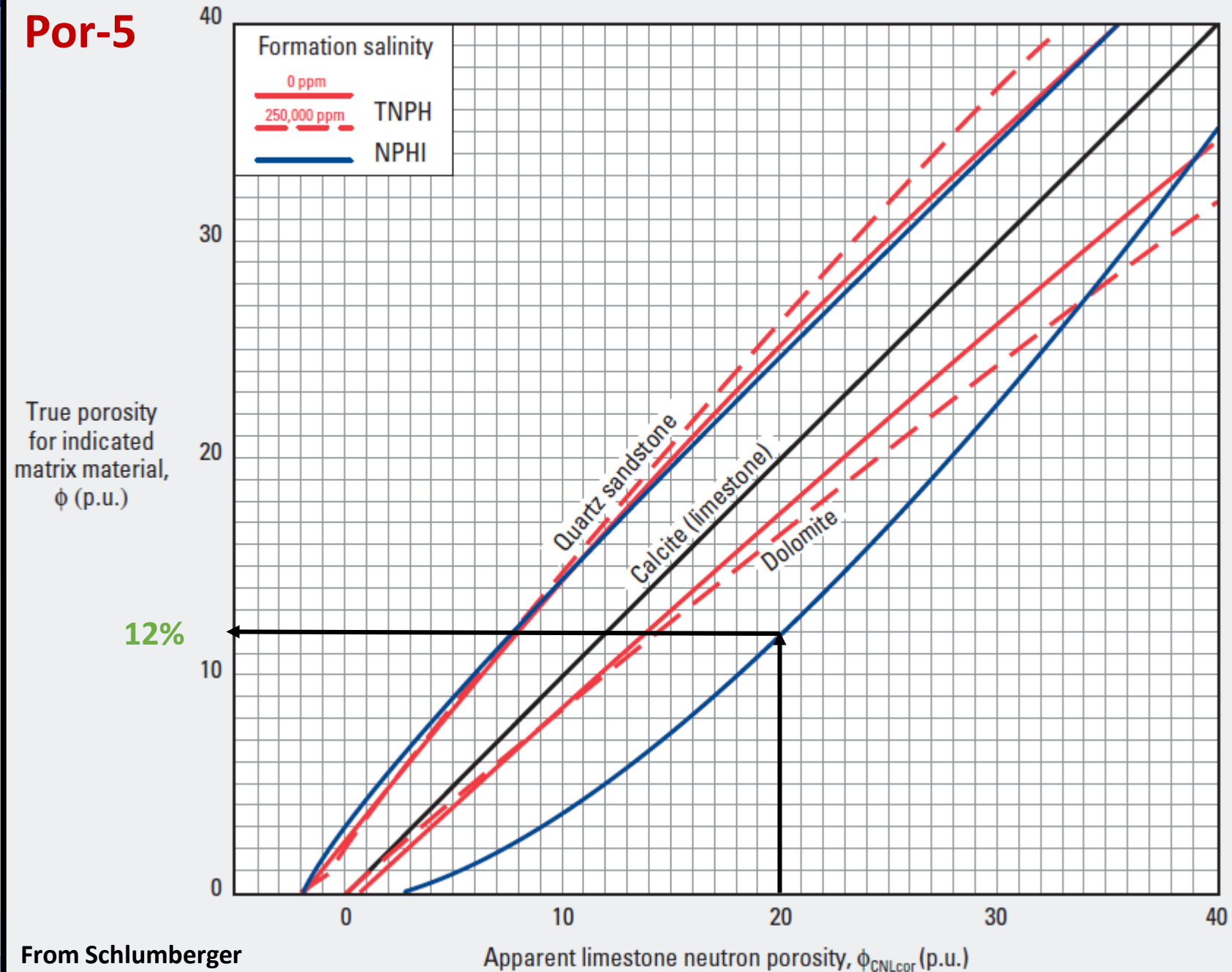
Example

NPHI (Neutron porosity) of a water zone is reported 20% with LS scale. If the matrix is **dolomite**, what is the true porosity?

12%

What if the matrix is LS or SS?

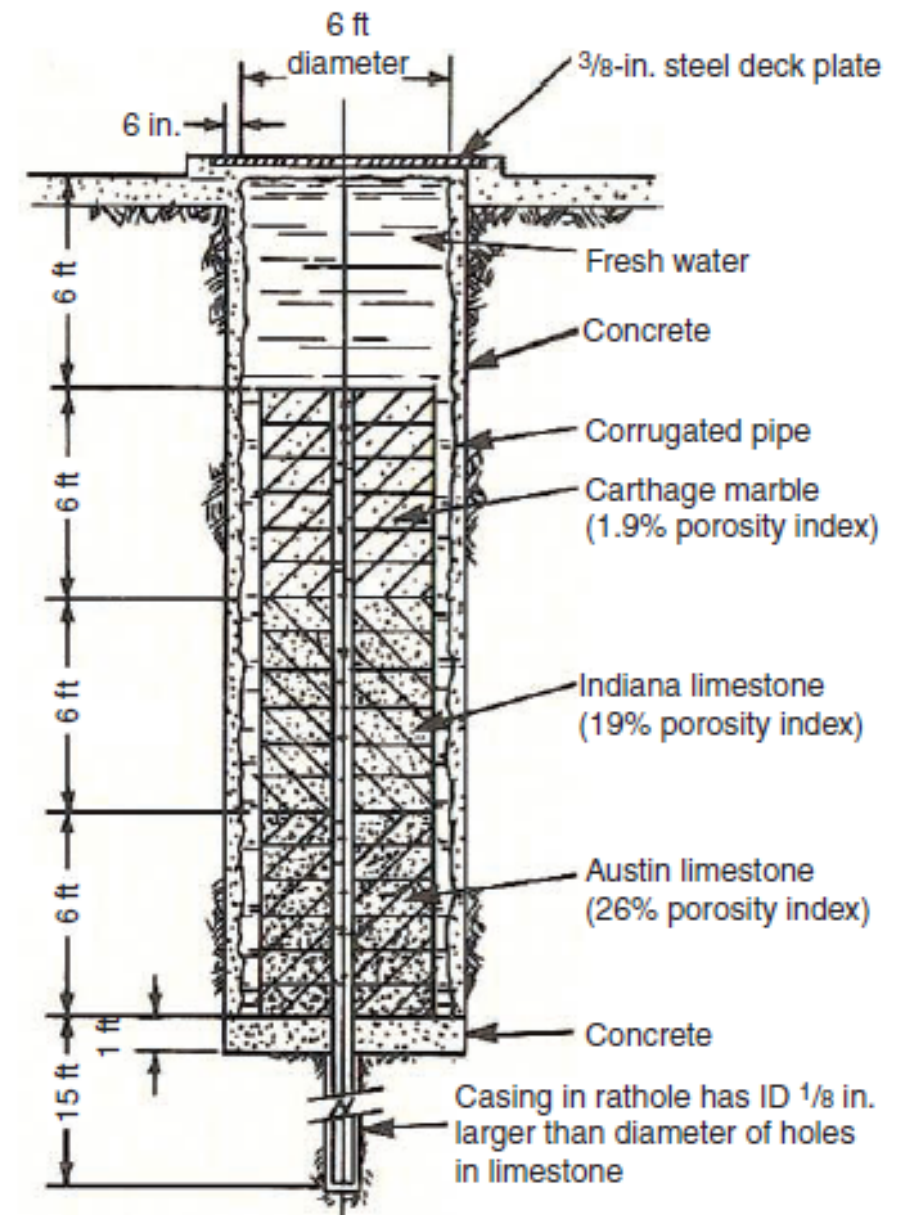
Por-5



CNL Tool Calibration

- Apparent LS neutron and true porosities are equal in clean, water-bearing zones where the lithology is limestone.
- Apparent neutron and density porosities should agree in clean, water-bearing zones where the lithology is known.
- Apparent neutron limestone porosity for salt ($\Phi_{\text{NLM}} = -1.5\%$), and anhydrite ($\Phi_{\text{NLM}} = 0\%$), can be used as benchmarks.

NLM: Neutron Limestone Matrix



Carthage marble, Austin limestone, and Indiana limestone sections are each composed of 6 regular octagonal blocks, 5 ft across, 1 ft thick, with 7 7/8-in. ($\pm 1/16$ in.) center bore hole.

Gas Effect on Neutron Porosity

- Gas has a lower hydrogen concentration than water or oil because of its lower density.
- Neutron tool detects gas as water with smaller volume (porosity).
- Thus, in gas zones, the neutron tool reads porosity abnormally low.



Meanwhile, Density tool reads porosity in gas zones abnormally high!

Shale Effect on Neutron Porosity

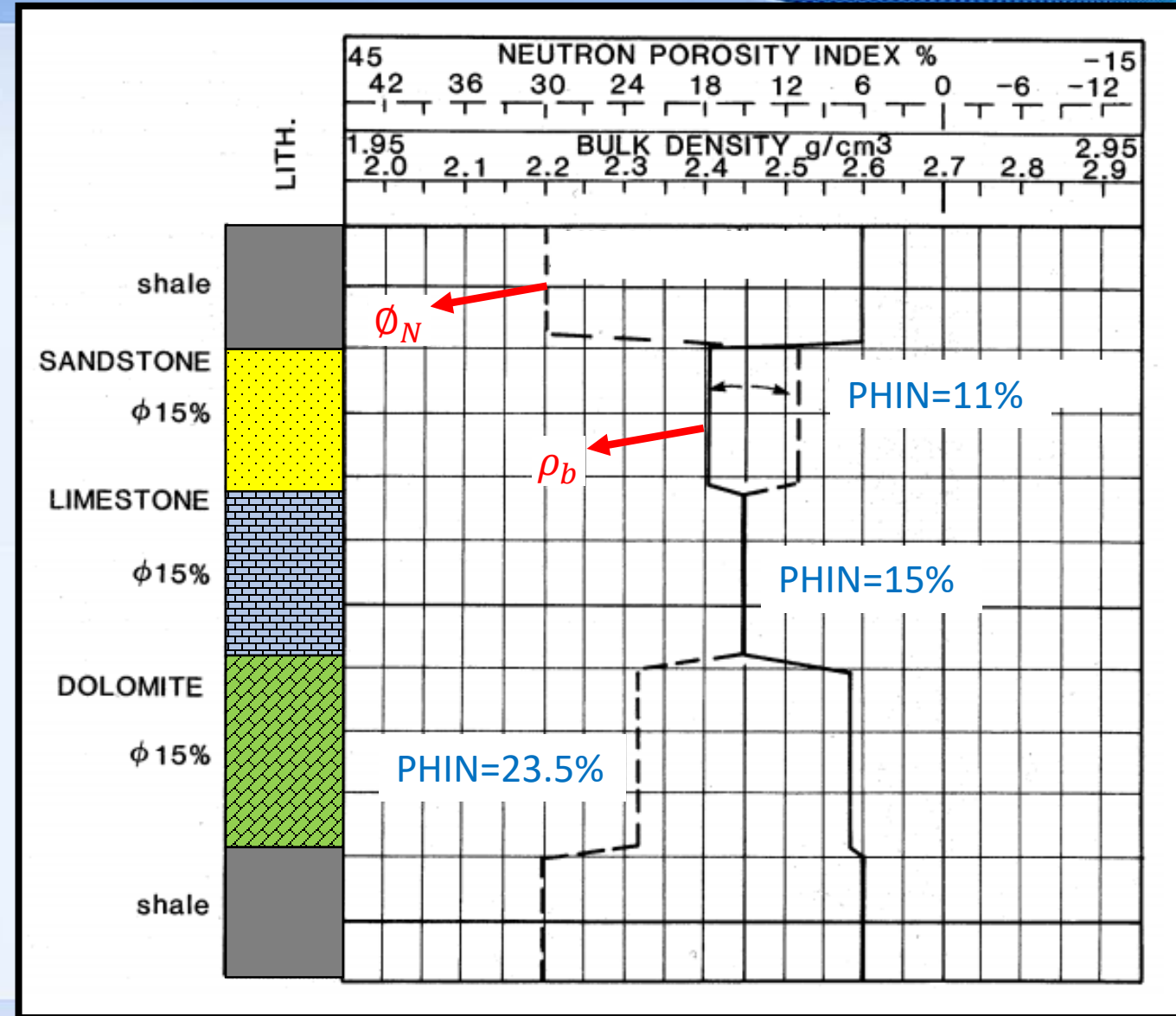
- Shale has bound water in its structure.
- Neutron tool responds to presence of hydrogen in the bound water.
- The bound water is not mobile, thus does not represent effective porosity.
- Therefore, in shale zones, Neutron porosity is abnormally high.

NPHI Scales

- **NPHI is usually plotted on limestone or sandstone scale (dolomite scale is rare).**
- **Limestone Scale:**
 - ✓ In 100% water saturated limestone formation, the limestone scale reads the correct porosity.
 - ✓ In 100% water saturated sandstone formation, the limestone scale reads the wrong porosity (≈ 4 P.U lower) and has to be corrected.
 - ✓ In 100% water saturated dolomite formation, the limestone scale reads the wrong porosity (≈ 7.5 P.U higher) and has to be corrected.
- **Sandstone Scale:**
 - ✓ In 100% water saturated sandstone formation, the sandstone scale reads the correct porosity.
 - ✓ In 100% water saturated limestone formation, the sandstone scale reads the wrong porosity (higher) and has to be corrected.
 - ✓ In 100% water saturated dolomite formation, the sandstone scale reads the wrong porosity (higher) and has to be corrected.

NPHI & RHOB Curves

- Calibrated for LS filled with 100% fresh water.
- Neutron scale : -15% to 45% Porosity.
- Density scale: 1.95 to 2.95 gr/cm³.
- In LS zones, both curves overlay.
- Other scalings are possible.

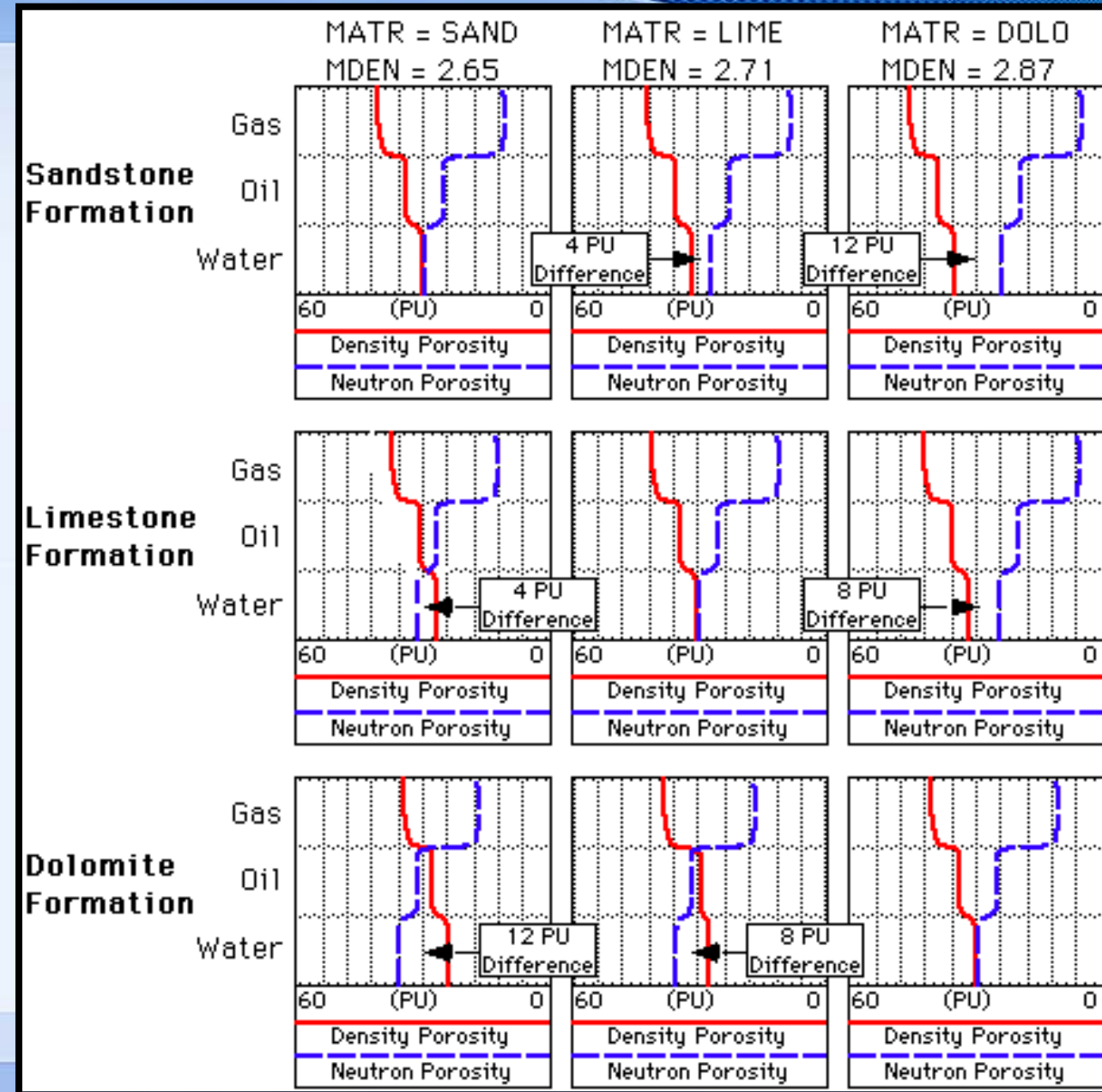


NPHI & DPHI Curves

- If the lithology and apparent lithology scale are the same, in water zone, ϕ_N overlays ϕ_D .
- In Gas bearing zones, no matter what lithology or scale is, ϕ_D is significantly higher than ϕ_N .
- $\phi_{NLS} = \phi_{NSS} - 4 \text{ P.U}$ Neutron App. SS to App. LS
- $\phi_{NLS} = \phi_{NDol} + 7.5 \text{ P.U}$ Neutron App. DOL to App. LS

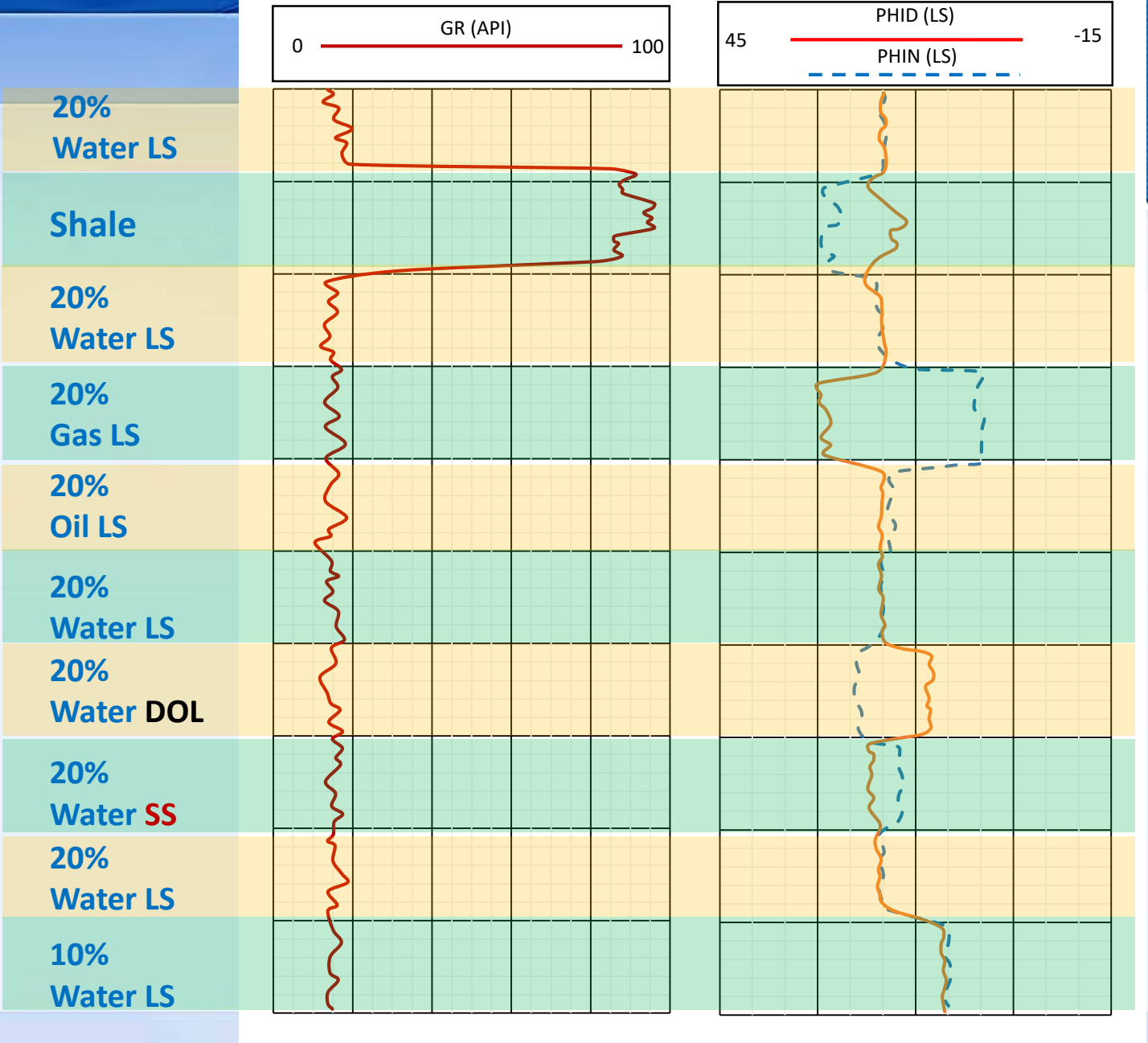
True Lithology

Apparent Lithology (Porosity)



Neutron-Density Log

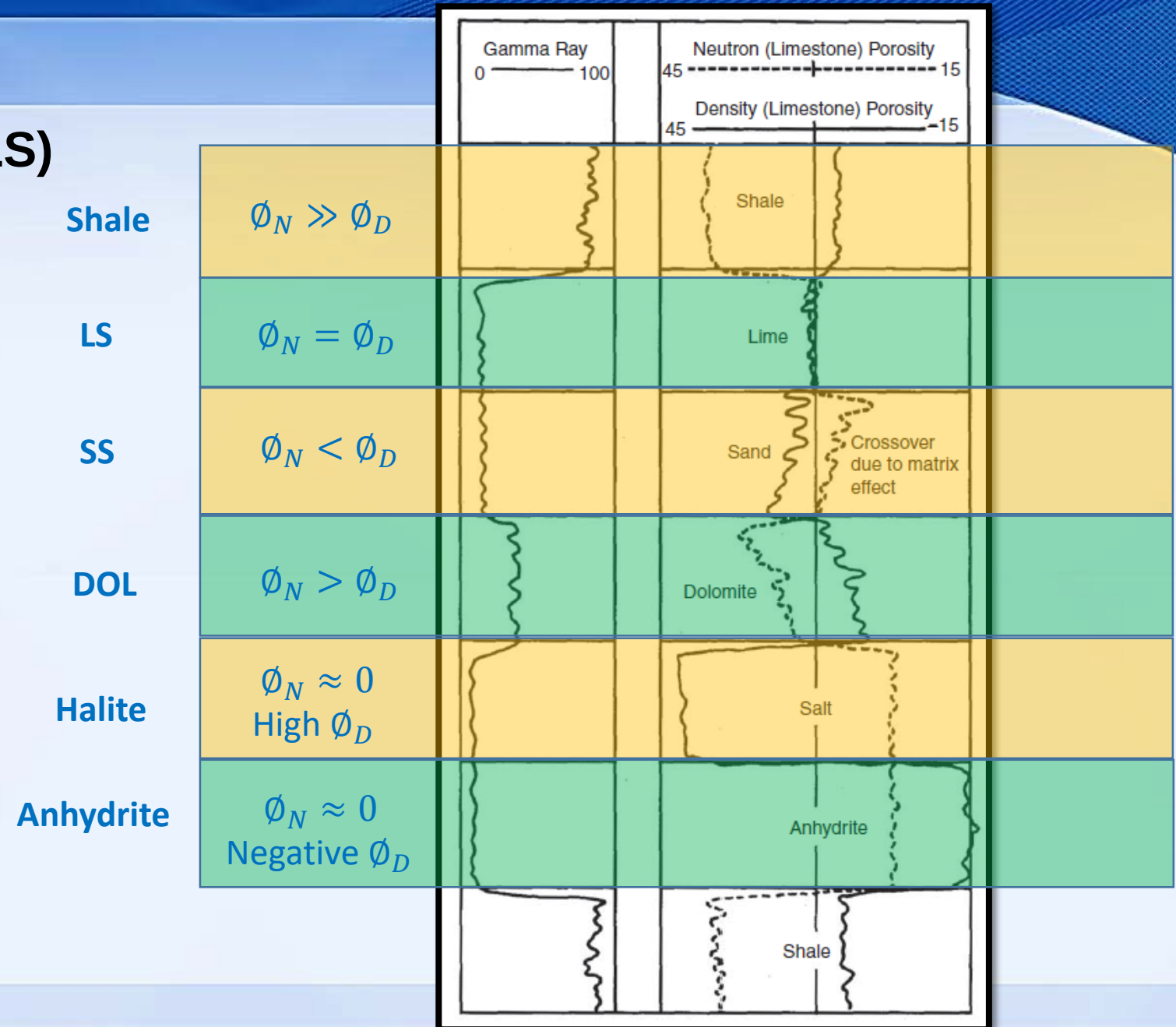
Neutron-Density Overlay (LS)



Neutron-Density Log

Neutron-Density Overlay (LS)

- In Carbonate, Evaporate formations
- When lithology is not known
- From -15% to 45% porosity
- Equivalent to 2.95 to 1.95 gr/cm³



Neutron-Density Log

Neutron-Density Overlay (SS)

- In shale sand sequence formations
- From 0% to 60% porosity
- Equivalent to 2.65 to 1.65 gr/cm³

Shale

$$\phi_N \gg \phi_D$$

Gas

$$\phi_N \ll \phi_D$$

Oil

$$\phi_N < \phi_D$$

Water

$$\phi_N = \phi_D$$

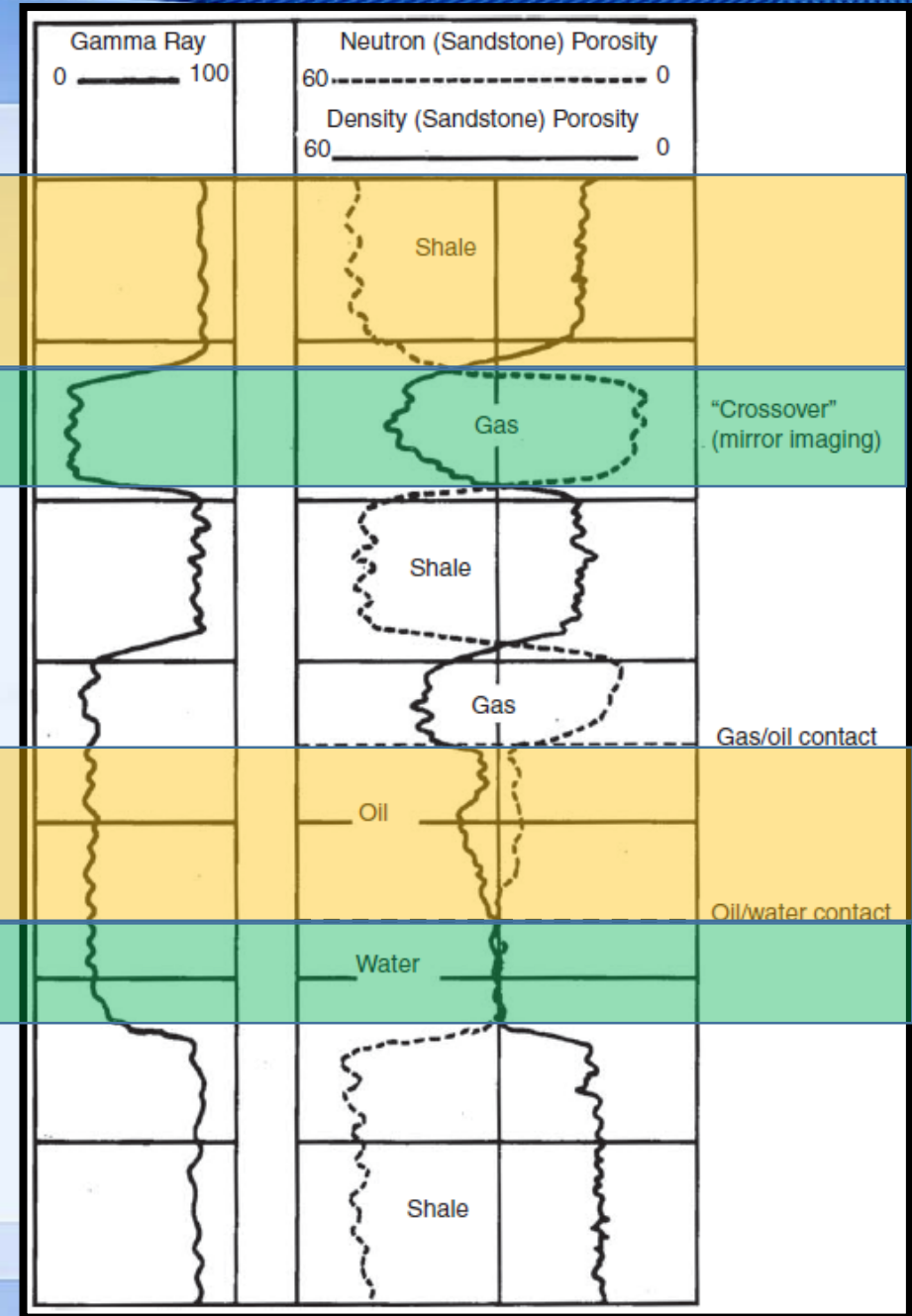


Table to Memorize

Rock/Mineral	ρ_b (gr/cm ³)	Neutron Porosity	PE (barns/electron)
Quartz	2.65	Moderate to high	1.81
Chert	2.65	Low	1.81
Calcite	2.71	Low	5.08
Dolomite	2.87	Moderate	3.14
Halite	2.03	Low	4.63
Anhydrite	2.98	Low	5.05
Gypsum	2.36	High	3.97
Shale	2.1-2.8	Moderate to high	1.8-6.3

Porosity Correction

1) Shaliness Correction

$$\phi_{D,corr} = \phi_D - \phi_{D,sh} \times V_{sh}$$

$$\phi_{N,corr} = \phi_N - \phi_{N,sh} \times V_{sh}$$

→ Similarly for sonic porosity

2) Hydrocarbon Effect

For Liquids

$$\phi_T = \frac{(\phi_D + \phi_N)}{2}$$

For Gas

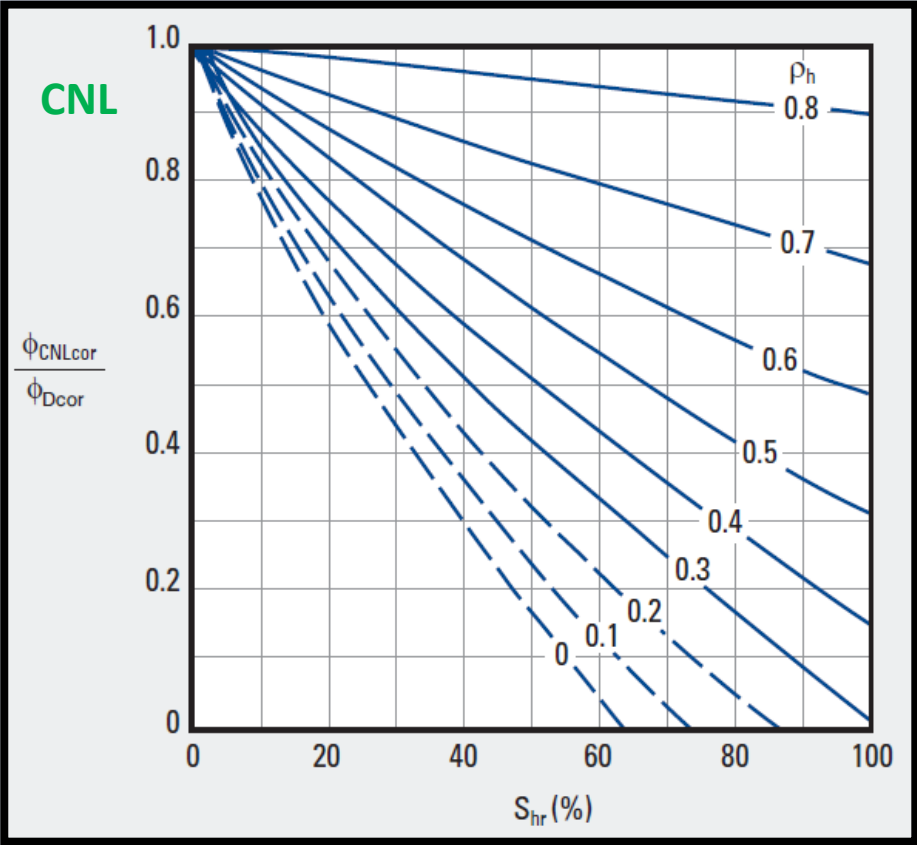
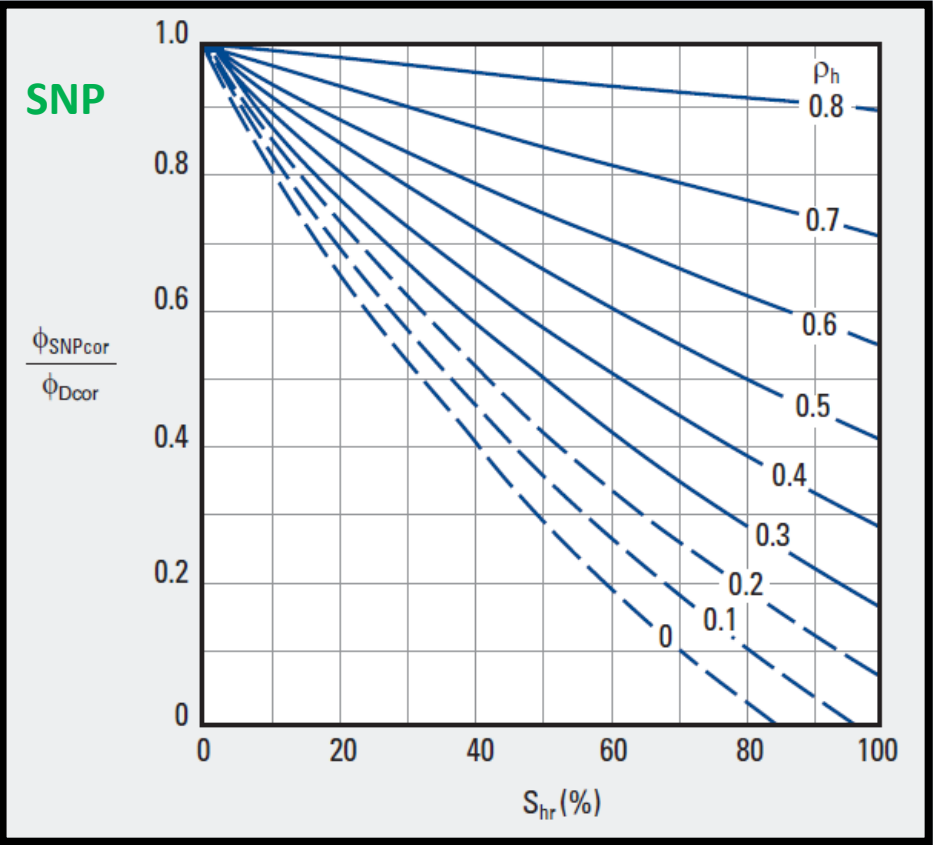
$$\phi_T = \sqrt{\frac{(\phi_D^2 + \phi_N^2)}{2}}$$

True Porosity

Note: D & N porosities should be corrected for shale first, then corrected for fluid effect.

Por-27

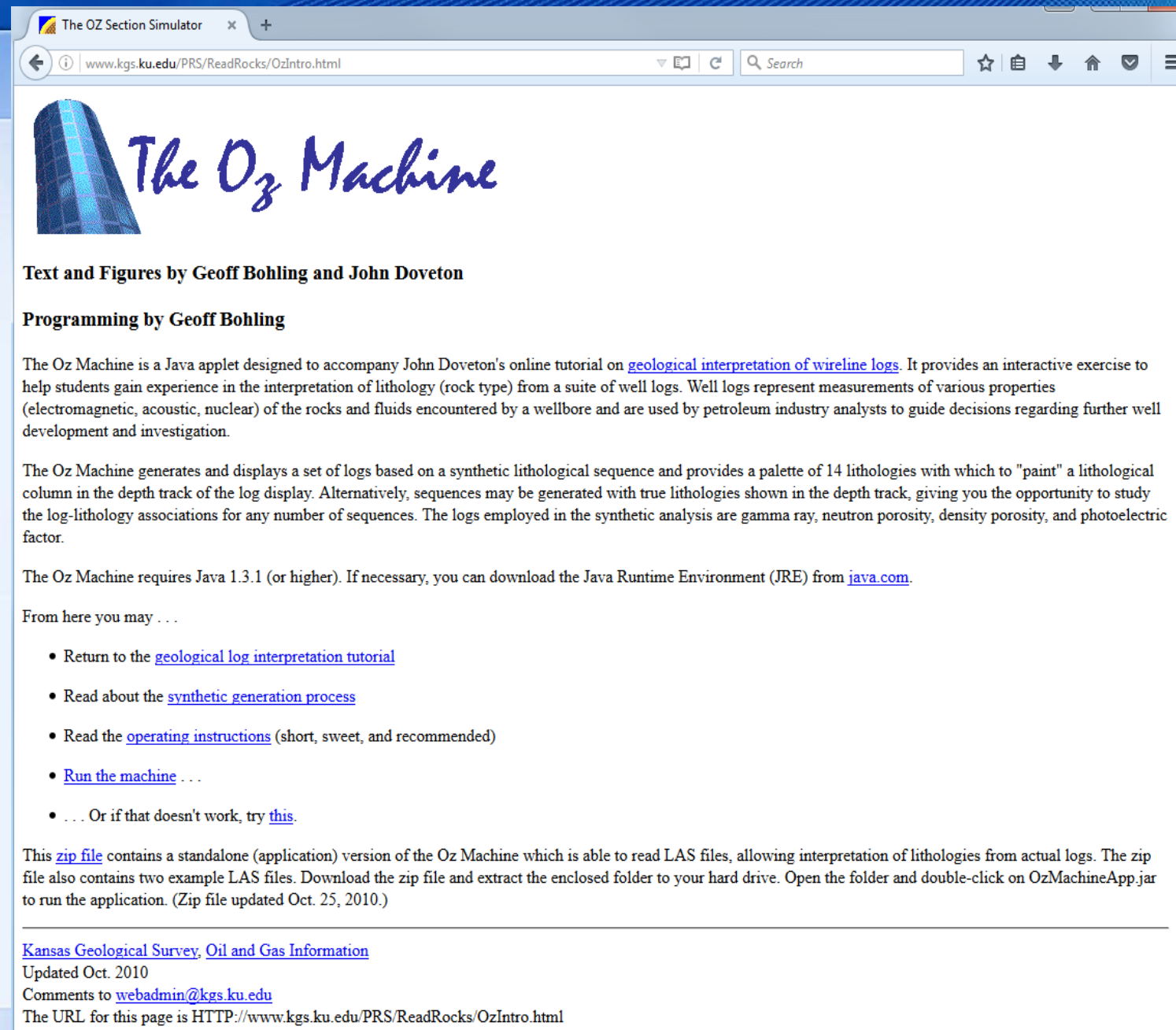
Hydrocarbon Density



From Schlumberger

Practice at Home

- Download the software
- Contains couple of logs with lithology solution
- Practice

A screenshot of a web browser displaying the 'The Oz Machine' page. The browser's address bar shows the URL 'www.kgs.ku.edu/PRS/ReadRocks/OzIntro.html'. The page features a logo with a blue wireframe cylinder and the text 'The Oz Machine' in a purple script font. Below the logo, the text 'Text and Figures by Geoff Bohling and John Doveton' is displayed. A section titled 'Programming by Geoff Bohling' follows. The main text describes 'The Oz Machine' as a Java applet for interpreting lithology from well logs. It mentions that the applet generates logs based on a synthetic lithological sequence or true lithologies. A list of links is provided for further resources, including a geological log interpretation tutorial, synthetic generation process, operating instructions, and a link to run the machine. At the bottom, there is a link to a standalone application version of the Oz Machine, a footer with contact information for the Kansas Geological Survey, and the URL for the page.

The Oz Machine

Text and Figures by Geoff Bohling and John Doveton

Programming by Geoff Bohling

The Oz Machine is a Java applet designed to accompany John Doveton's online tutorial on [geological interpretation of wireline logs](#). It provides an interactive exercise to help students gain experience in the interpretation of lithology (rock type) from a suite of well logs. Well logs represent measurements of various properties (electromagnetic, acoustic, nuclear) of the rocks and fluids encountered by a wellbore and are used by petroleum industry analysts to guide decisions regarding further well development and investigation.

The Oz Machine generates and displays a set of logs based on a synthetic lithological sequence and provides a palette of 14 lithologies with which to "paint" a lithological column in the depth track of the log display. Alternatively, sequences may be generated with true lithologies shown in the depth track, giving you the opportunity to study the log-lithology associations for any number of sequences. The logs employed in the synthetic analysis are gamma ray, neutron porosity, density porosity, and photoelectric factor.

The Oz Machine requires Java 1.3.1 (or higher). If necessary, you can download the Java Runtime Environment (JRE) from [java.com](#).

From here you may . . .

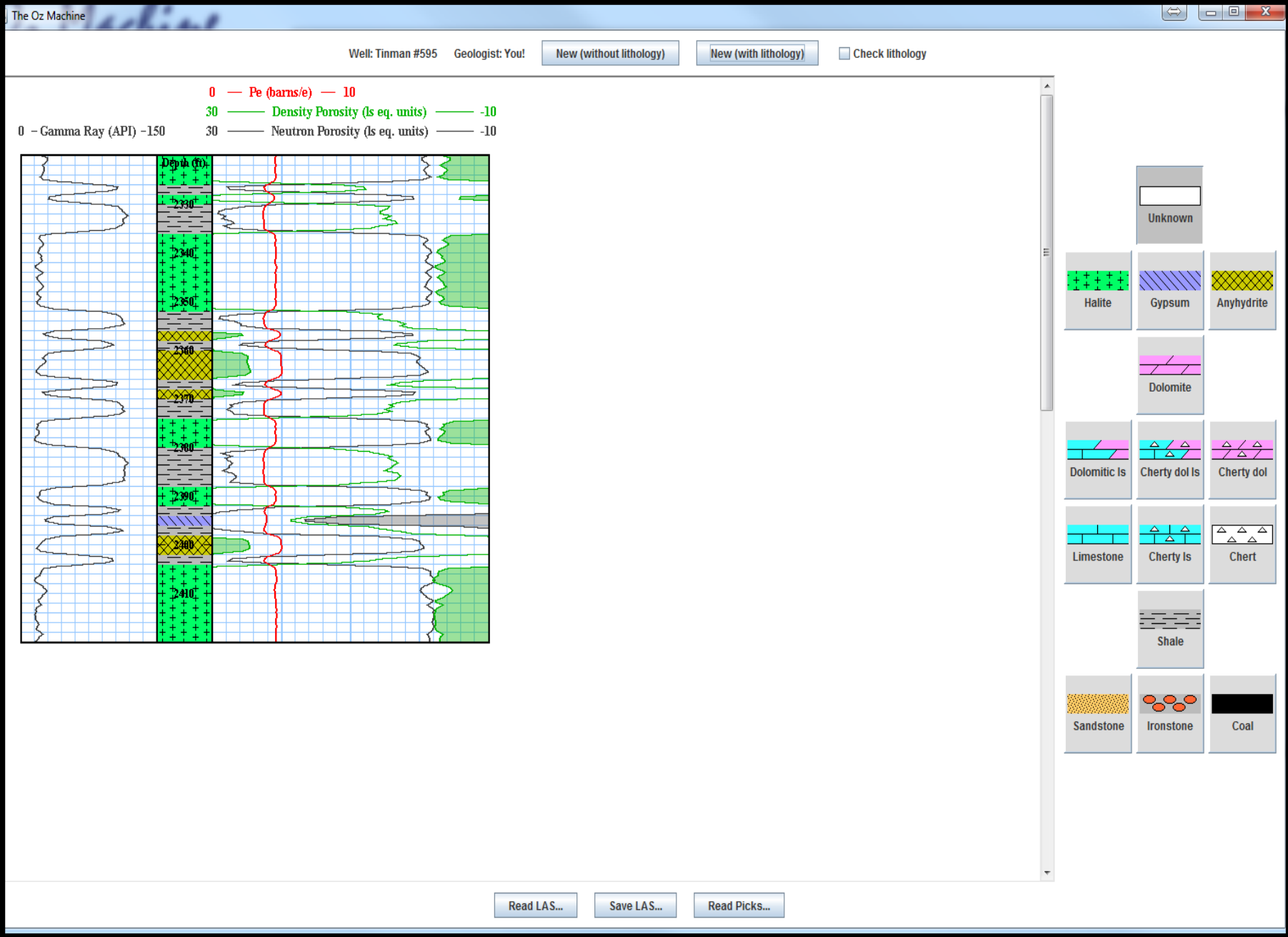
- Return to the [geological log interpretation tutorial](#)
- Read about the [synthetic generation process](#)
- Read the [operating instructions](#) (short, sweet, and recommended)
- [Run the machine](#) . . .
- . . . Or if that doesn't work, try [this](#).

This [zip file](#) contains a standalone (application) version of the Oz Machine which is able to read LAS files, allowing interpretation of lithologies from actual logs. The zip file also contains two example LAS files. Download the zip file and extract the enclosed folder to your hard drive. Open the folder and double-click on OzMachineApp.jar to run the application. (Zip file updated Oct. 25, 2010.)

[Kansas Geological Survey, Oil and Gas Information](#)
Updated Oct. 2010
Comments to webadmin@kgs.ku.edu
The URL for this page is [HTTP://www.kgs.ku.edu/PRS/ReadRocks/OzIntro.html](http://www.kgs.ku.edu/PRS/ReadRocks/OzIntro.html)

Neutron-Density Log

Practice at Home



Neutron-Density Log

Class Example

What is the lithology?

- A:

Anhydrite
- B:

Anhydrite
- C:

Dolomite
- D:

Dolomite
- E:

Shaly SS.
- F:

Sandstone
- G:

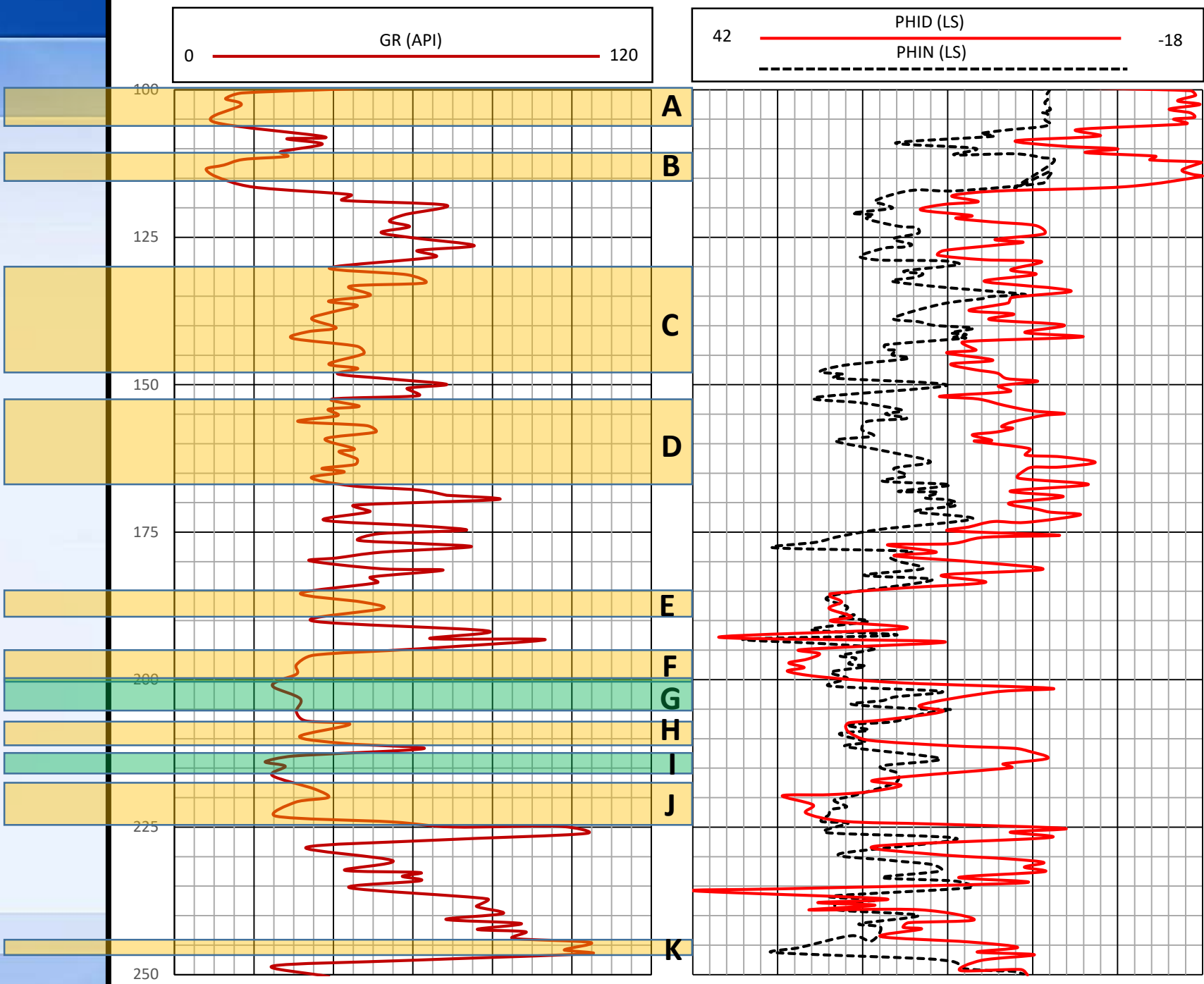
Dolomite
- H:

Limestone
- I:

Dolomite
- J:

Sandstone
- K:

Shale



Neutron-Density Log

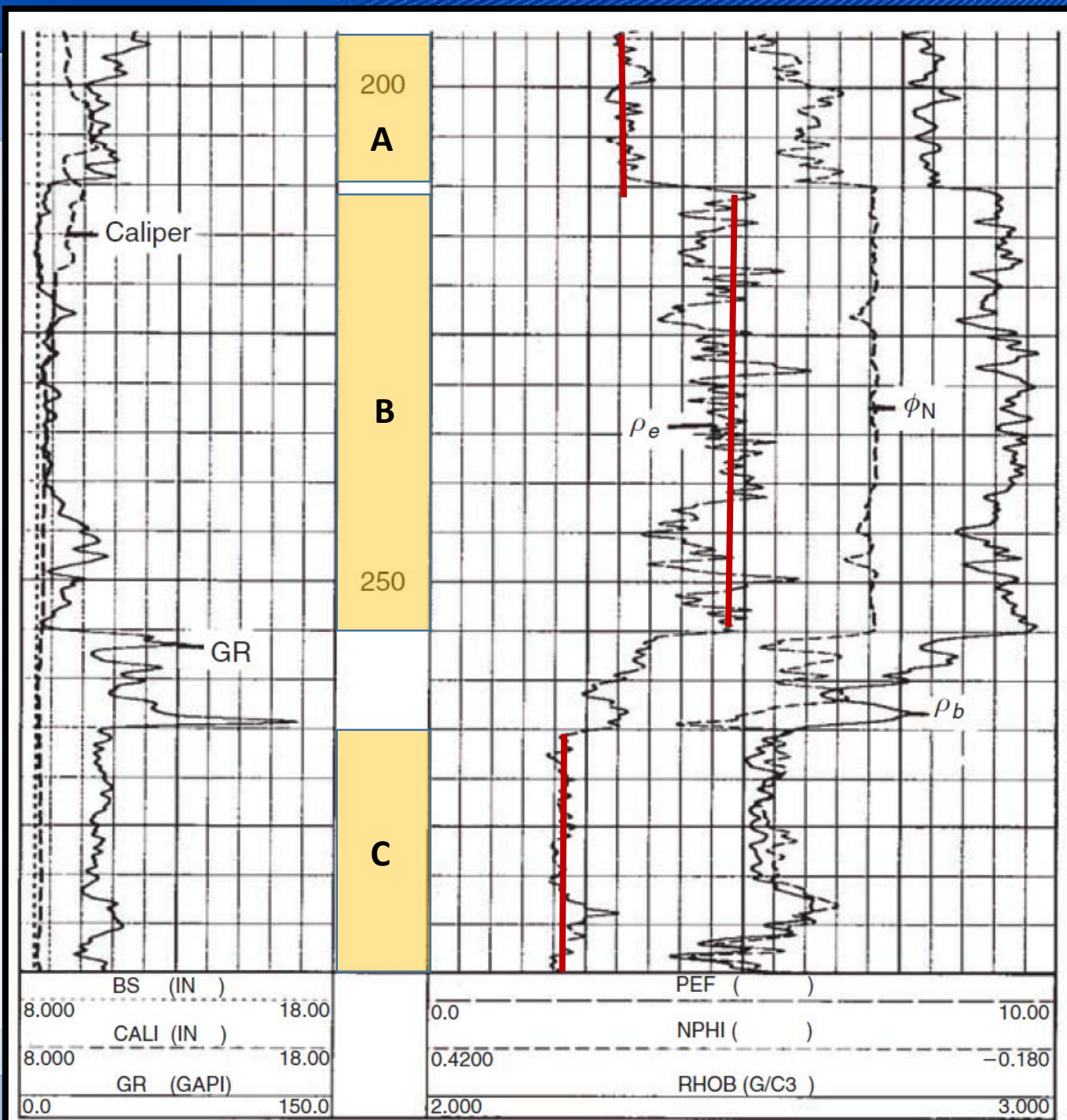
Example

What is the lithology?

A: $P_e \approx 3$ & $\phi_N > \phi_D$ Dolomite

B: $P_e \approx 4.7$ & $\phi_N \approx 0$ $\phi_D \ll 0$ Anhydrite

C: $P_e \approx 2.1$ & $\phi_N < \phi_D$ Sandstone



Neutron-Density Log

Example

Neutron Porosity of an unknown lithology zone is reported 20% in SS scale. What is the apparent porosity in Dol and LS scale?

OR

$$\phi_{\text{NLS}} = \phi_{\text{NSS}} - 4 \text{ P.U}$$

$$\phi_{\text{NLS}} = 20 - 4 = 16\%$$

$$\phi_{\text{NDol}} = \phi_{\text{NSS}} - 11.5 \text{ P.U}$$

$$\phi_{\text{NLS}} = 20 - 11.5 = 8.5\%$$

Por-5

