POROSITY LOGS

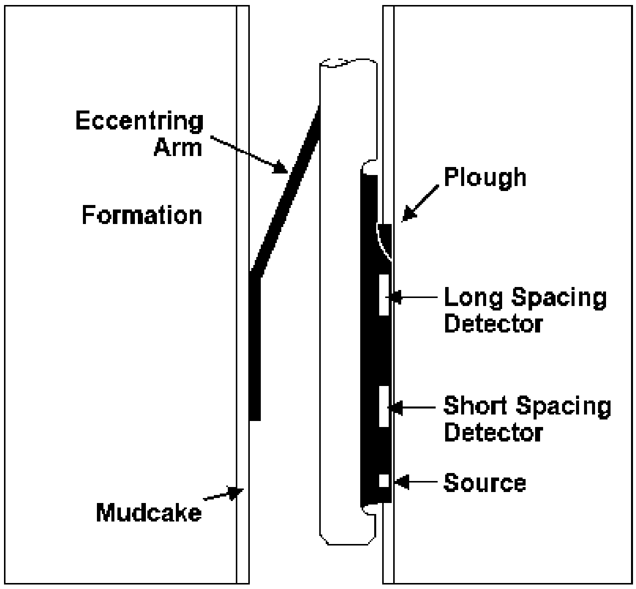
- Rock porosity can be obtained from the;
  - Sonic log
  - Density log
  - Neutron log
- For all these devices, the tool response is affected by the formation porosity, fluid and matrix.
- If the fluid and matrix effects are known or can be determined, the tool response can be related to porosity. Therefore, these devices are usually referred to as ***porosity logs***.
- None of these logs measure porosity directly.
- The density and neutron logs are nuclear measurements. The sonic log use acoustic measurements.
- A combination of these logs gives good indications for lithology and more accurate estimates of porosity.
- Porosity calculating from porosity log is not very accurate method, but has the advantage of providing continuous porosity data.
- When the porosity are obtained from porosity log, they can be calibrated with porosity data obtained from core-sample and serve as additional dependable source of porosity distribution evaluation.

Density Log

- The formation density compensated (FDC) log is a porosity log that measures *bulk density* of the formation.

❖ ***FDC Log Uses***

– Porosity/Lithology Determination.
– Detect gas-bearing zone.
– Evaluation of shaly sands and complex lithology.
– Determination of hydrocarbon density.



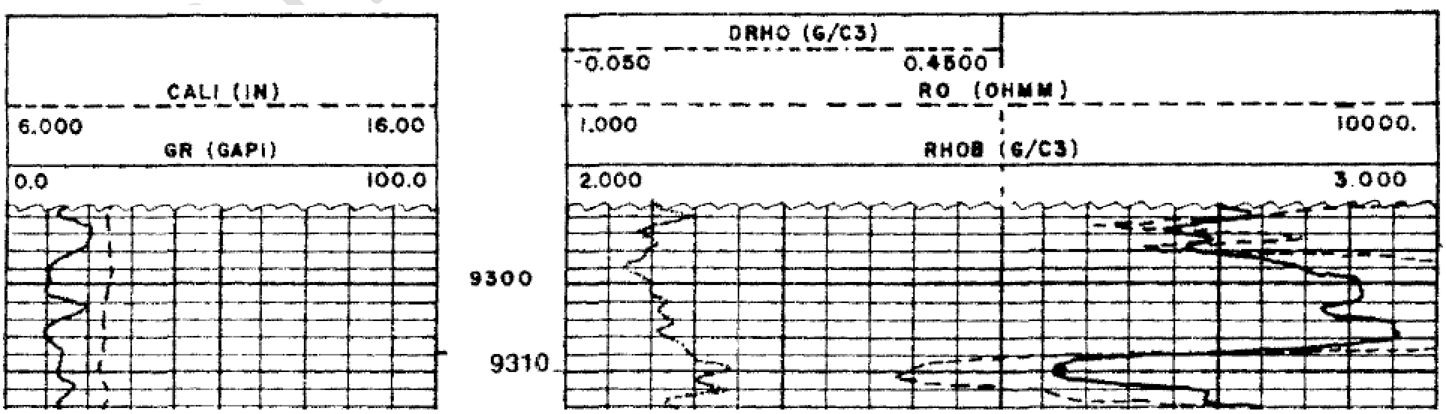
▪ **Principle**

- The density logging device is a contact tool which consists of a medium-energy gamma ray source that emits gamma rays into a formation. The gamma ray source is either Cobalt-60 or Cesium-137.
- Gamma ray collides with electrons in the formation. At each collision a gamma ray particle loses some of its energy to the electrons.
- The interaction between incoming gamma ray particles and electrons in the formation called "***Compton Scattering***".
- Two detectors, located a fixed distance from the gamma ray source, are counted the number of scattered (returning) gamma rays as an indicator of formation density.

- The number of Compton Scattering collisions is a direct function of the number of electrons in a formation (electron density).
- So, electron density can be related to bulk density *(ρ_b)* of a formation in (gm/cm^3).

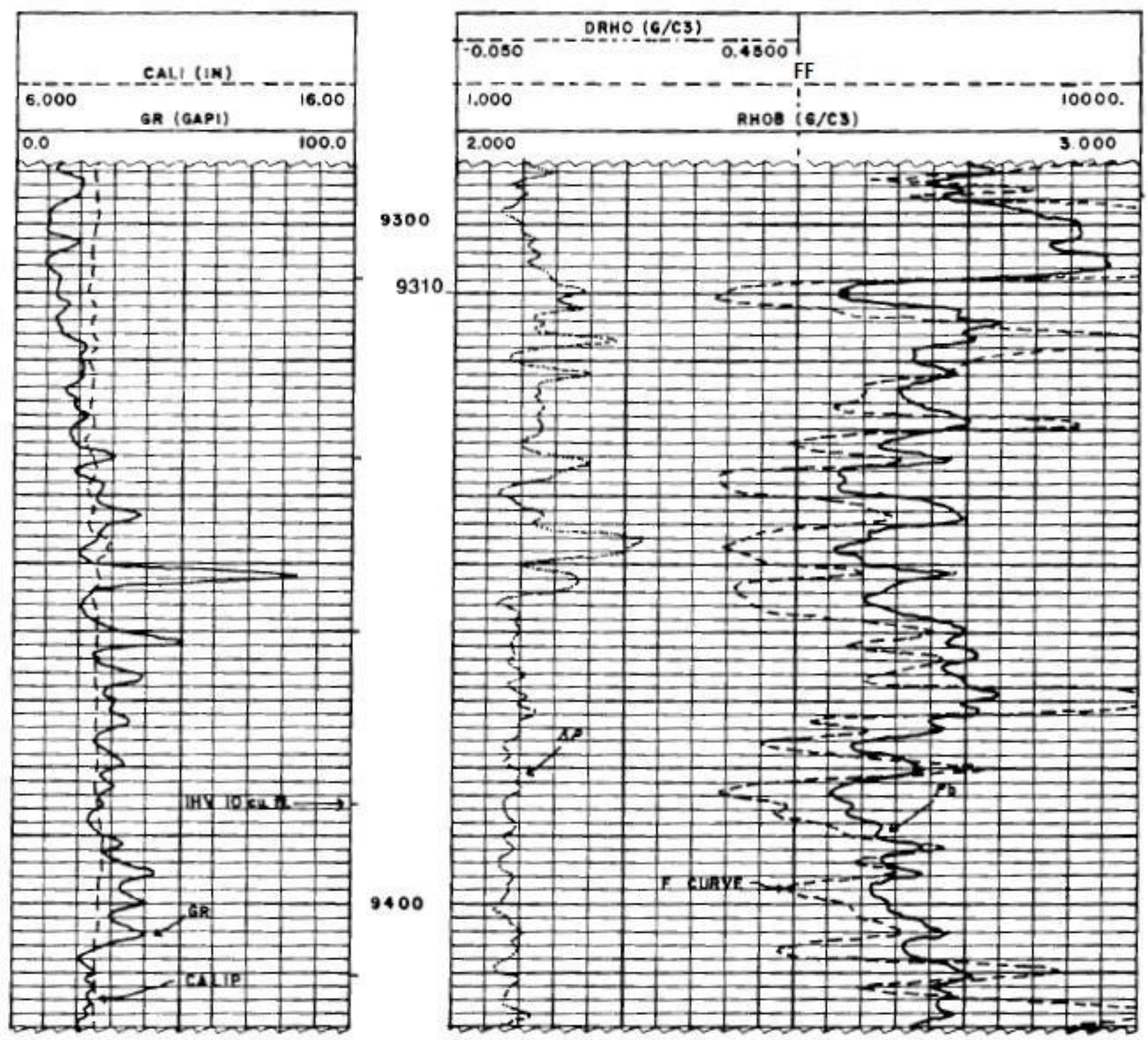
FDC Log Presentation

- The bulk density curve is recorded in tracks #2 and #3 along with a correction curve *($\Delta\rho$).*
- Because the modern density log is a compensated log (dual detectors), the correction curve ($\Delta\rho$) records how much correction has been applied to the bulk density curve (ρ_b), due to borehole irregularities.
- *When the* correction curve ($\Delta\rho$) e*xceeds 0.2 gm/cc, the value of the bulk density obtained from the bulk density curve* (ρ_b) *should be considered invalid.*
- A density derived porosity curve is sometimes present in tracks #2 and #3 along with the bulk density (ρ_b) and correction ($\Delta\rho$) curves. Track # 1 contains a gamma ray log and a caliper log.



Example…1: bulk density log with a gamma ray and caliper and formation factor curve (F).

- **Track #1**-This track includes both the gamma ray and caliper logs. Note that both scales read left to right: the gamma ray values range from 0 to 100 API gamma ray units. and the caliper measures the bore hole size from 6 to 16 inches.
- **Tracks #2 and #3**-The bulk density curve *(*ρ_b*),* correction curve *(*$\Delta\rho$) and formation factor curve (FF) are recorded in this track, where the scales increase in value from left to right.
- The bulk density (ρ_b) scale ranges in value from 2.0 gm/cc to 3.0 gm/cc and is represented by a solid line.
- The density correction curve $\Delta\rho$ ranges in value from -0.05 gm/cc to +0.45 in increments of 0.05 gm/cc, but only uses the left half of the log track.
- The formation factor curve (F) ranges in value from 1 to 1000 and is represented by a dashed line.
- For example at depth 9310 ft. read a bulk density value (ρ_b) of *2.56* gm/cc.


CALI (IN)
6.000 16.00
GR (GAPI)
0.0 100.0
9300
9310
9400
IHV 10 cu ft
GR
CALIP
DRHO (G/C3)
-0.050 0.4500
FF
1.000 10000.
RHOB (G/C3)
2.000 3.000
F CURVE

- **Porosity from Density Log**

- Formation bulk density(ρ_b) is a function of matrix density(ρ_{ma}), porosity and formation fluid density(ρ_f) (salt mud, fresh mud. or hydrocarbons).
- To determine porosity, either by **chart** (**por-5**) or by equation, the matrix density and type of fluid in the borehole must be known.
- The formula for calculating density porosity is:

$$\varphi_D = \frac{\rho_m - \rho_b}{\rho_m - \rho_f} \ldots\ldots\ldots..(1)$$

Where;

ρ_{ma} = matrix (or grain) density

ρ_b = Bulk density as measured by the log.

ρ_f = Fluid density

<table>
<tr><th colspan="2">Fluid/lithology Type</th><th>ρ (gm/cc)</th></tr>
<tr><td>fresh water mud</td><td rowspan="4">ρ_f gm/cc</td><td>1</td></tr>
<tr><td>Salt water mud</td><td>1.15</td></tr>
<tr><td>Oil</td><td>0.85 (If unknown.)</td></tr>
<tr><td>Gas</td><td>0.7 (If unknown.)</td></tr>
<tr><td>Sandstone</td><td rowspan="5">ρ_m gm/cc</td><td>2.65</td></tr>
<tr><td>Limestone</td><td>2.71</td></tr>
<tr><td>Dolomite</td><td>2.87</td></tr>
<tr><td>Anhydrite</td><td>2.96</td></tr>
<tr><td>Salt (Halite) NaCl</td><td>2.165</td></tr>
</table>

Example….2: Using **chart por-5** for converting bulk density *(ρ_b)* to porosity using values picked from a density log in **Example..1**.

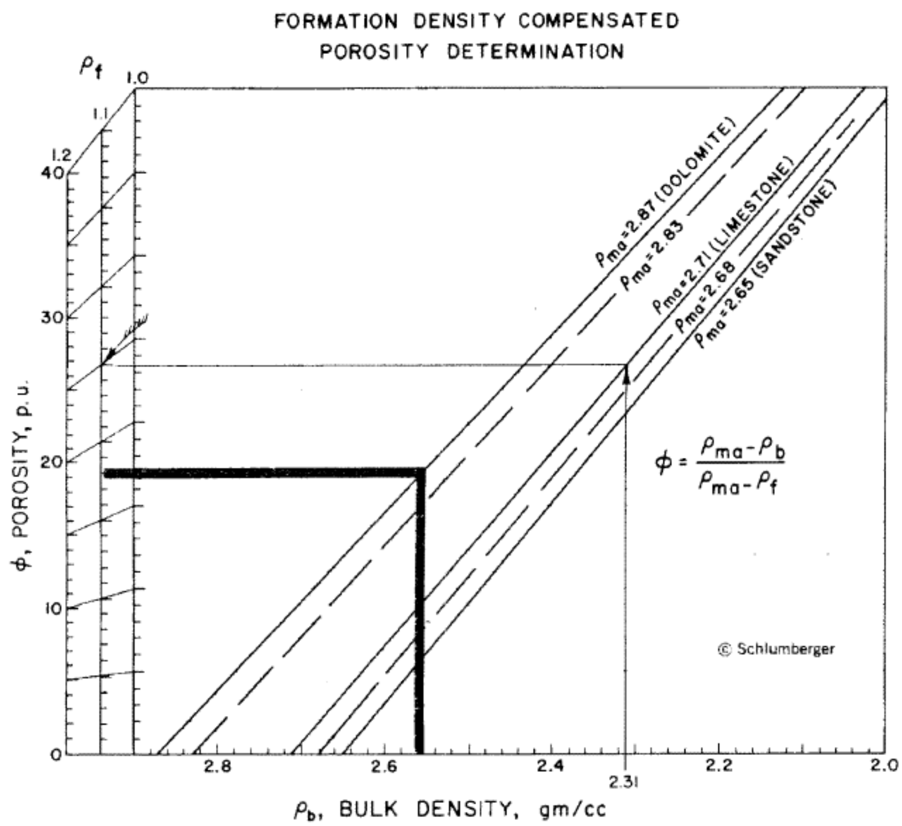
Given; ρ_{ma} = 2.87 gm/cc (dolomite; from table)

ρ_f = 1.1 gm/cc (fluid density for salt mud)

ρ_b = 2.56 gm/cc at a depth of 9310 ft (from log: Fig. above)

Procedure:

1. Find a value for bulk density *(ρ_b)=2.56 gm/cc* on the horizontal scale.
2. Follow the value vertically until it intersects the diagonal line representing the matrix density *(ρ_{ma})* used (in this case 2.87 for dolomite).
3. From that point, follow the horizontal line to the left where the porosity value is represented on the porosity scale at a fluid density (ρ_{fl}) of 1.1 In this case, the porosity is 18%.



Shaly Formation

- After the volume of shale (V_{sh}) is determined from GR log, it can be used to correct the porosity obtained from density log for shale effect.
- Hilchie (1978) suggests that for shale to significantly affect log-derived water saturations (i.e. water saturation from Archie equation), shale content must be greater than 10 to 15 %.
- Remember that, porosity is one of the Archie's Eq. parameters, therefore, porosity determined from porosity log must be corrected to shale effect.

$$Sw^n = \frac{a\,R_w}{\varphi^m\,R_t} \qquad (Archie\ Eq)$$

- The first step in shaly sand analysis is to determine the volume of shale from a gamma ray log.
- After the volume of shale (V_h) is determined, it can then be used to correct the porosity log for shale effect.
- Porosity from density log in a shaly formation is calculated using the following equation:

$$\varphi_{Dc} = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} - V_{cl}\left(\frac{\rho_{ma} - \rho_{cl}}{\rho_{ma} - \rho_f}\right) \ldots\ldots (2)$$

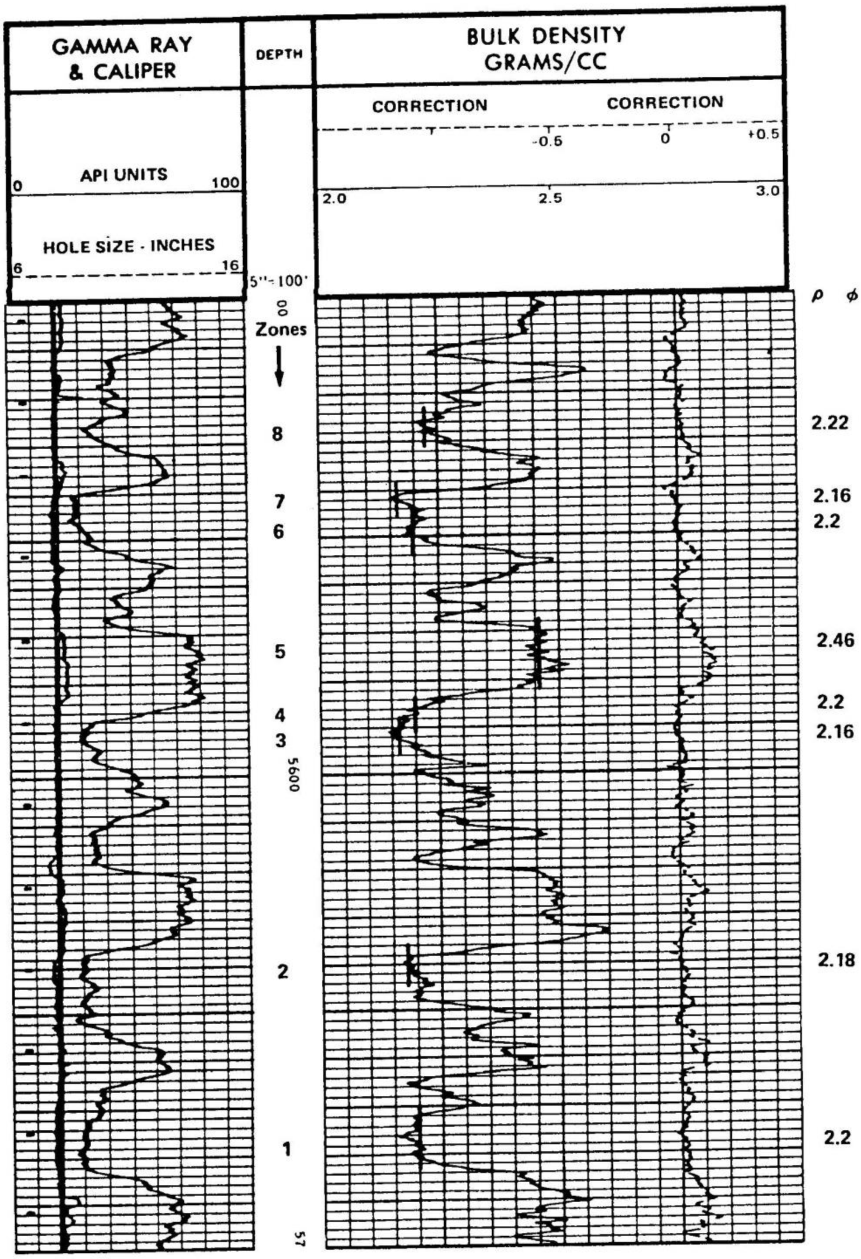
Where;

φ_{Dc}= Corrected density for clay effect.

V_{cl} = Volume of clay.

ρ_{cl} = Density value of adjacent clay formation. (i.e. at maximum GR reading). From figure of **Example….1,** GR max. at depth 9352 ft = 82 API, so $\rho_{cl} = 2.725\ gm/cc$

Example…3: calculate formation porosity at depth 5600 ft.



Steps:

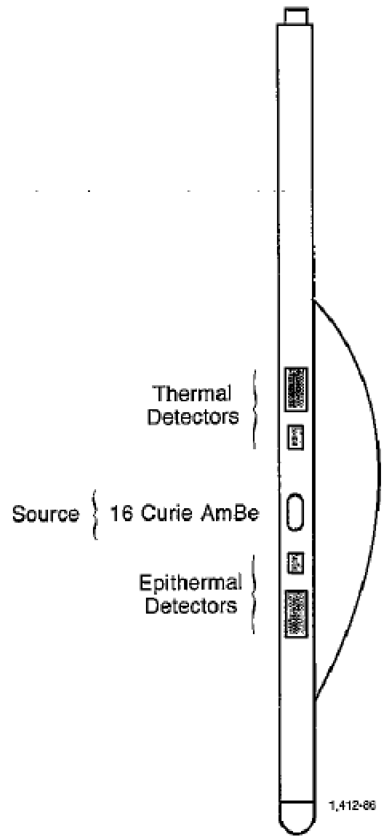
1. *Read* ρ_b *value at depth 5600 ft*
2. *Read GRmin and GRmax from GR log.*
3. *Calculate Vsh at depth 5600 ft.*
4. *Calculate porosity using chart por-5 or using Eq.(1).*
5. *If Vsh at depth 5600 ft less than 10% , porosity, go to step 4.*
6. *If Vsh at depth 5600 ft greater than 10%, read the value of* ρ_{cl} *, go to step 7.*
7. *Correct the porosity value from step(4) to shale effect using Eq(2).*

Neutron Log

- Neutron log is porosity log that measure the *hydrogen ion concentration* in a formation.
- In clean formations (i.e. shale-free) where the pores are filled with water or oil, the neutron log reflects the amount of liquid-filled porosity.

❖ **Principle**

- Neutrons are created from a *chemical source* in the neutron logging tool.
- The *chemical source* may be a mixture of *americium* and *beryllium* which will continuously emit neutrons.
- These neutrons collide with the nuclei of the formation material, and result in a neutron losing some of its energy.
- Because the hydrogen atom is almost equal in mass to the neutron, maximum energy loss occurs when the neutron collides with a hydrogen atom. Therefore, the maximum amount of energy loss is a function of a formation's hydrogen concentration.
- Because hydrogen in a porous formation is concentrated in the fluid-filled pores, energy loss can be related to the formation's porosity.



- When pores are filled with the gas, rather than oil or water, neutron porosity will be lowered. This occurs because there is less concentration of hydrogen in gas compared to oil or water. A lowering of neutron porosity by gas is called *gas effect.*

- Neutron log responses vary depending on:
  - ✓ differences in detector types.
  - ✓ spacing between source and detector.
  - ✓ lithology--i.e. sandstone, limestone. and dolomite.
- These variations in response can be compensated for by using the appropriate chart (**Neutron Porosity Equivalence Curves**).

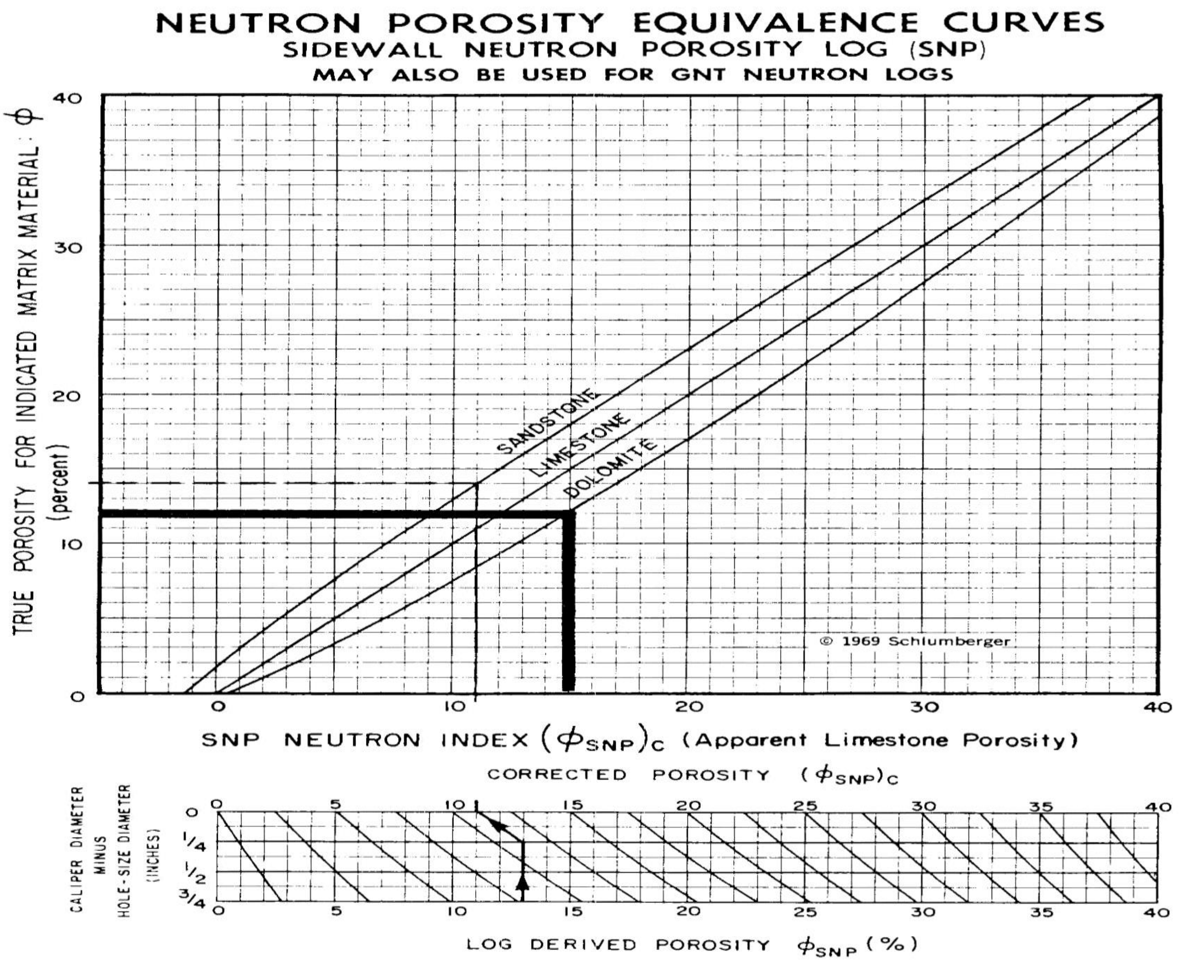
❖ **CNL & SNP Log**

- The first modern neutron log was the **Sidewall Neutron Log SNP**.
- The Sidewall Neutron Log has both the source and detector in a pad which is pushed against the side of the borehole.
- The most modern of the neutron logs is a **Compensated Neutron Log CNL** which has a neutron source and two detectors.
- The advantage of Compensated Neutron logs over Sidewall Neutron logs is that they are <u>less affected by borehole irregularities</u>.
- Both the Sidewall and Compensated Neutron logs can be recorded in apparent limestone, sandstone or dolomite porosity units.
- If a formation is limestone and the neutron log is recorded in apparent limestone porosity units, apparent porosity is equal to true porosity. However. when the lithology of a formation is sandstone or dolomite, apparent limestone porosity *must* be corrected to true porosity by using the appropriate chart (**Neutron Porosity Equivalence Curves**).

Example..4// Correcting of Sidewall Neutron Porosity (SNP) for lithology by using charts. **Given**: The lithology is dolomite. Also. the apparent limestone porosity is 15%. The value for apparent limestone porosity is read directly from a Sidewall Neutron Porosity Log (SNP).

Procedure:

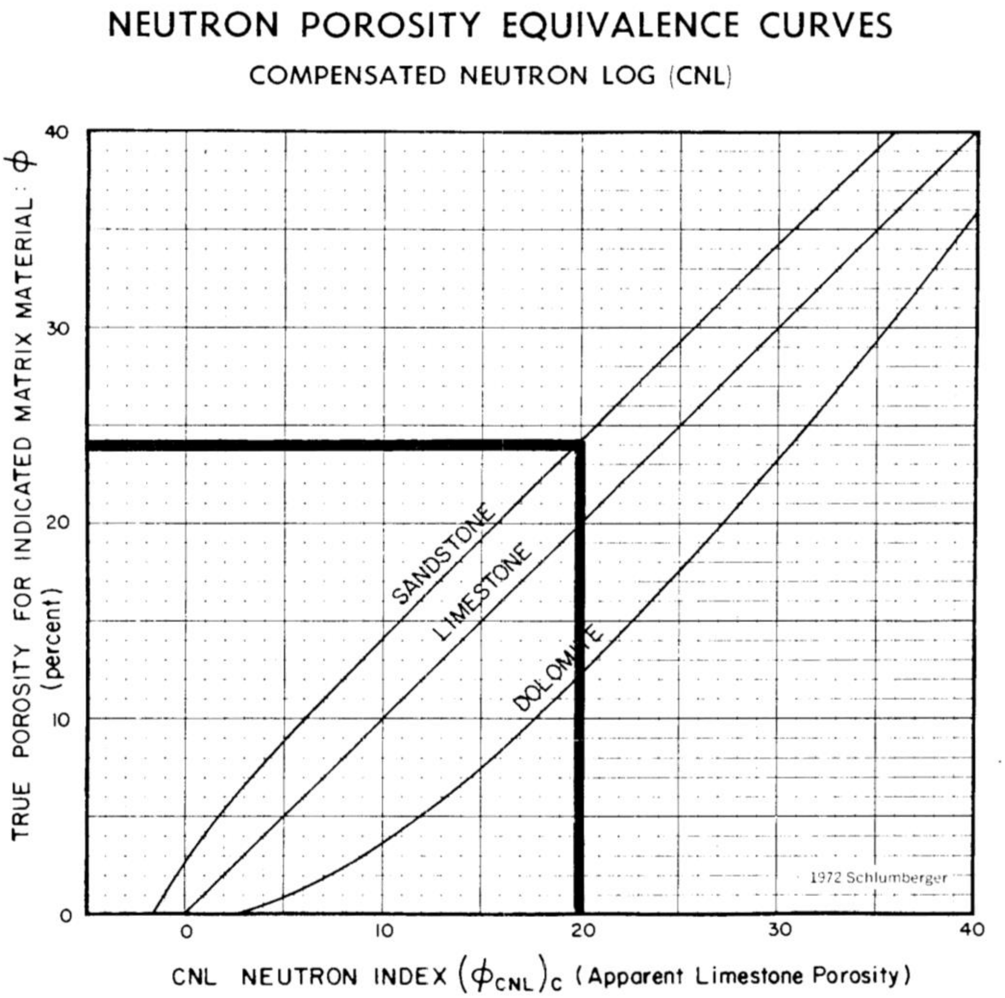
1. Find the value for apparent limestone porosity (read from an SNP log) along the scale at the bottom of the correction chart. In this example the value is 15 %.
2. Follow the value vertically until it intersects the diagonal curve representing dolomite.
3. From that point, follow the value horizontal1y to the left and read the true porosity *Φ* on the left-hand scale: 12%.



Example..5// Correcting of Compensated Neutron Porosity (CNL) for lithology by using charts. **Given**: The lithology is sandstone. Also. the apparent limestone porosity is 20%. The value for apparent limestone porosity is read directly from a Compensated Neutron Porosity (CNL).

Procedure:

1. Find the value for apparent limestone porosity (read from an CNL log) along the scale at the bottom of the correction chart. In this example the value is 20 %.
2. Follow the value vertically until it intersects the diagonal curve representing sandstone.
3. From that point, follow the value horizontal1y to the left and read the true porosity Φ on the left-hand scale: 24%.



- **In shaly formation,** the value of neutron porosity must be corrected in clay formation by the following equation;

$$\varphi_{Ncorr} = \varphi_{Nlog} - V_{clay} * \varphi_{Nclay} \dots \dots (3)$$

Where;

φ_{Ncorr} = Corrected neutron porosity.

$\varphi_{N\log}$ = Neutron log reading of the interval.

V_{clay}= Volume of clay.

φ_{Nclay} = neutron log of the adjacent clay formation.

☒ Combination Neutron-Density Log

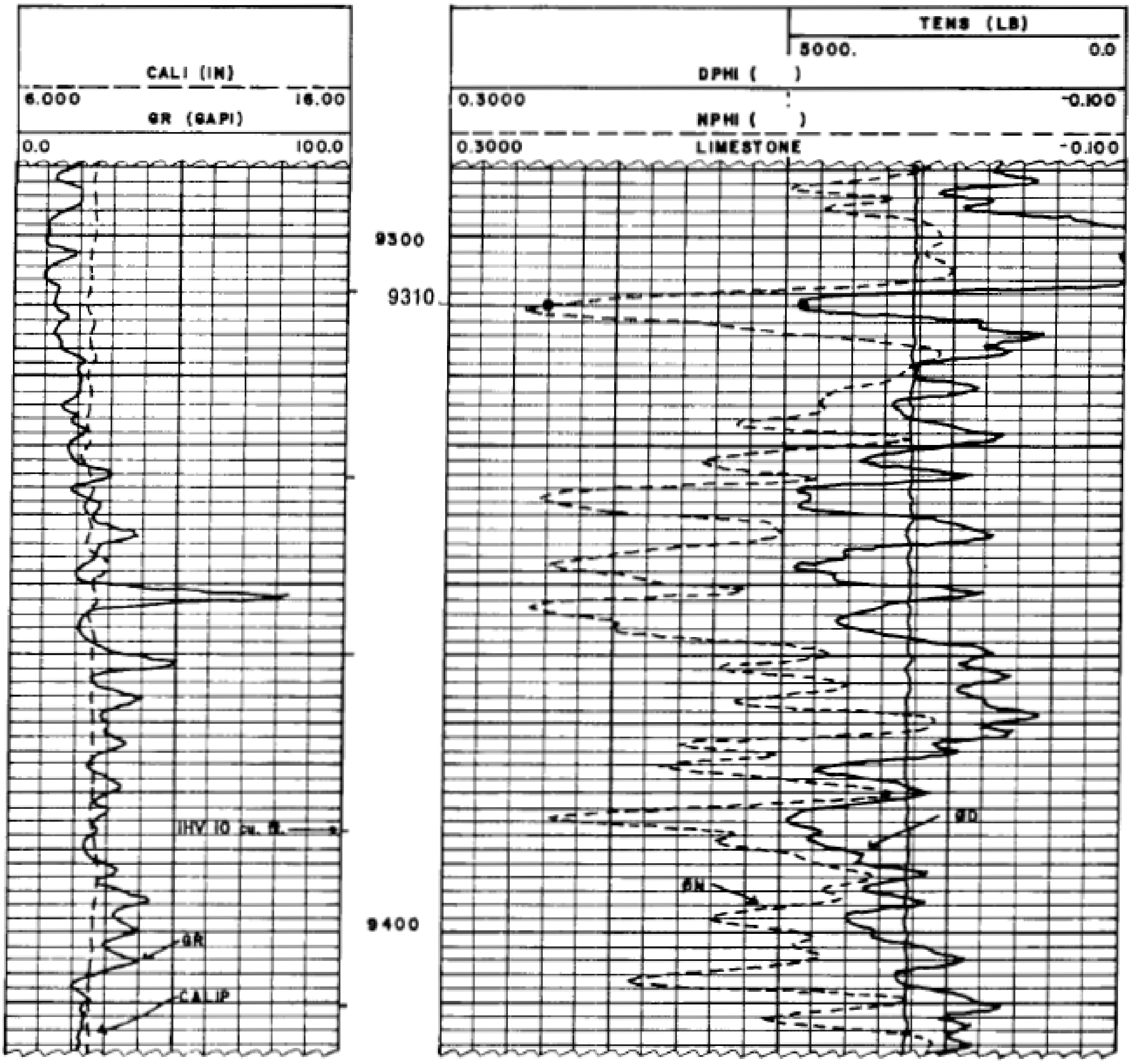
- The Combination Neutron-Density Log is a combination porosity log. Besides its use as a porosity device, it is also used to determine lithology and to detect gas-bearing zones.
- The Neutron-density Log consists of neutron and density curves recorded in tracks #2 and #3 and a caliper and gamma ray log in track # 1.
- Both the neutron and density curves are normally recorded in limestone porosity units with each division equal to either two percent or three percent porosity: however, sandstone and dolomite porosity units can also be recorded.

Example..6// Example of a Combination Neutron-Density with gamma ray log and caliper.

Track # 1--This track contains both GR log with scale (0-100) API and caliper log with scale (6 – 16) inches.

Tracks #2 and #3-Both neutron porosity and density porosity curves. The scale for both is the same, ranging from - 10% to + 30% in increments of *2%.* and is measured in limestone porosity units. On this log the density porosity is represented by a solid line and the neutron porosity is represented by a dashed line.

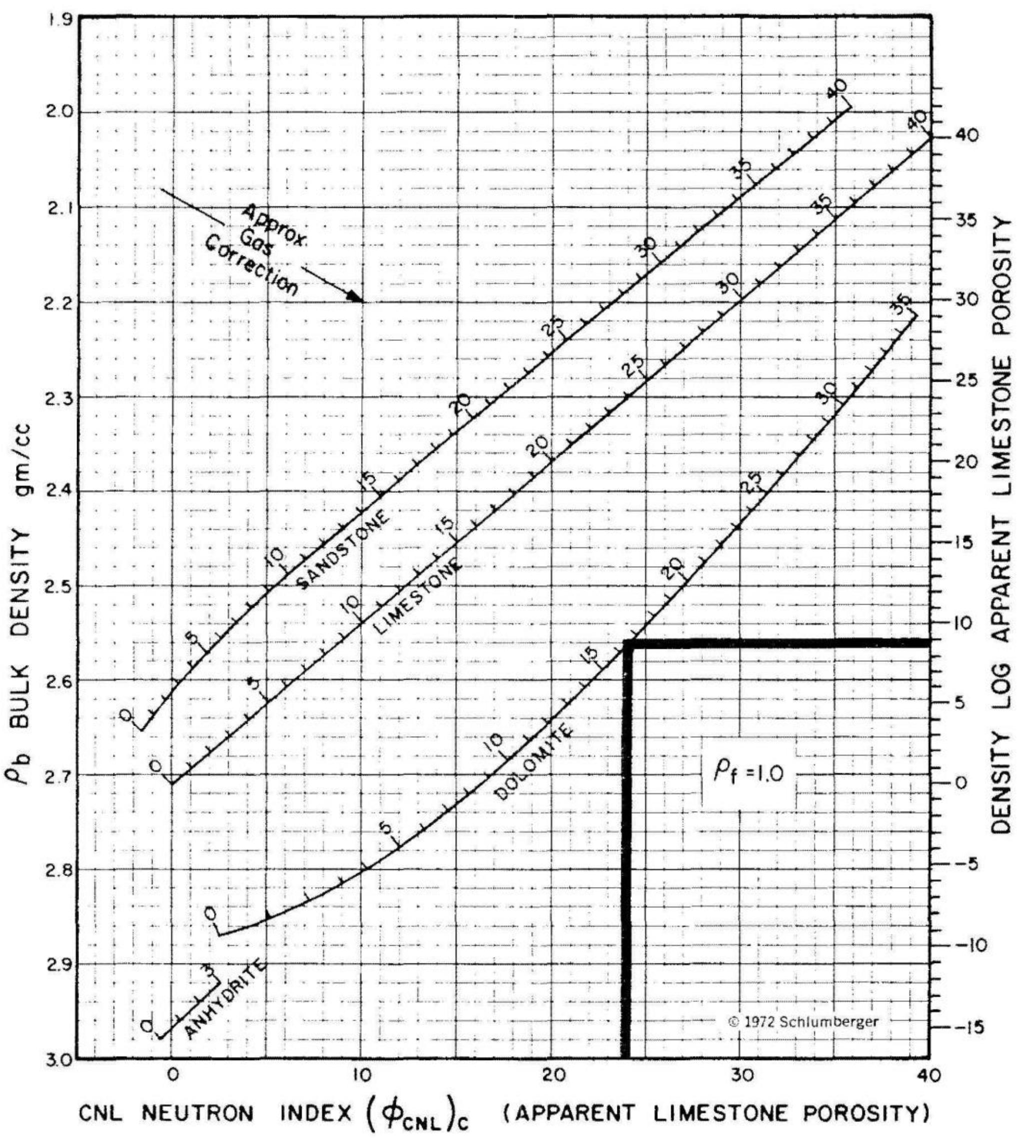
- The porosity can he obtained by first reading apparent limestone porosities from the neutron and density curves (for example: at depth 9324 ft. PHID = 3.5% and PHIN=8%), then these values are cross-plotted on a neutron-density porosity **chart** (**CP-1c , and CP-1d**) to find true porosity and lithology.


CALI (IN)
6.000 16.00
GR (GAPI)
0.0 100.0
TENS (LB)
5000. 0.0
DPHI ( )
0.3000 -0.100
NPHI ( )
0.3000 -0.100
LIMESTONE
9300
9310
9400
IHV 10
GR
CALIP
ΦD
ΦN

Example…7// Using Chart (CP-1c) for correcting Neutron-Density Log porosities for lithology. **Given**; ρ_f= 1 gm/cc (fresh muds) PHID =9%, PHIN=24% at depth 9310 ft.(From Example 4)

Procedure:

1. Locate the neutron porosity value on the bottom scale (24%) and find the density porosity value on the right-hand scale (9%).
2. Follow the values until they intersect on the chart. In this example, the values meet on the lithology curve for dolomite, and the intersection shows a true porosity value of 16.5%.



- Examination of the neutron-density porosity charts (CP-1d and CP-1d) reveals that the porosity values are only slightly affected by changes in lithology. Therefore, porosity from a Neutron-Density Log can be calculated *mathematically*.
- The alternate method of determining neutron-density porosity is to use the root mean square formula,

$$\varphi_{N-D} = \sqrt{\frac{\varphi_N^2 + \varphi_D^2}{2}} \ldots\ldots\ldots\ldots..(4)$$

Where:

φ_{N-D}= neutron-density porosity
φ_N = neutron porosity (limestone units)
φ_D= density porosity (limestone units)

Example…8// From Example…4, at depth 9324 ft. PHID = 3.5% and PHIN=8%, if ρ_f= 1.1 gm/cc, calculate the porosity.

From cross-plot (CP-1d), indicates that the lithology is a limey dolomite and the porosity is ***6%.***

From Equation: we calculate a porosity of ***6.2%.*** This calculated porosity value compares favorably with the value obtained from the crossplot method.

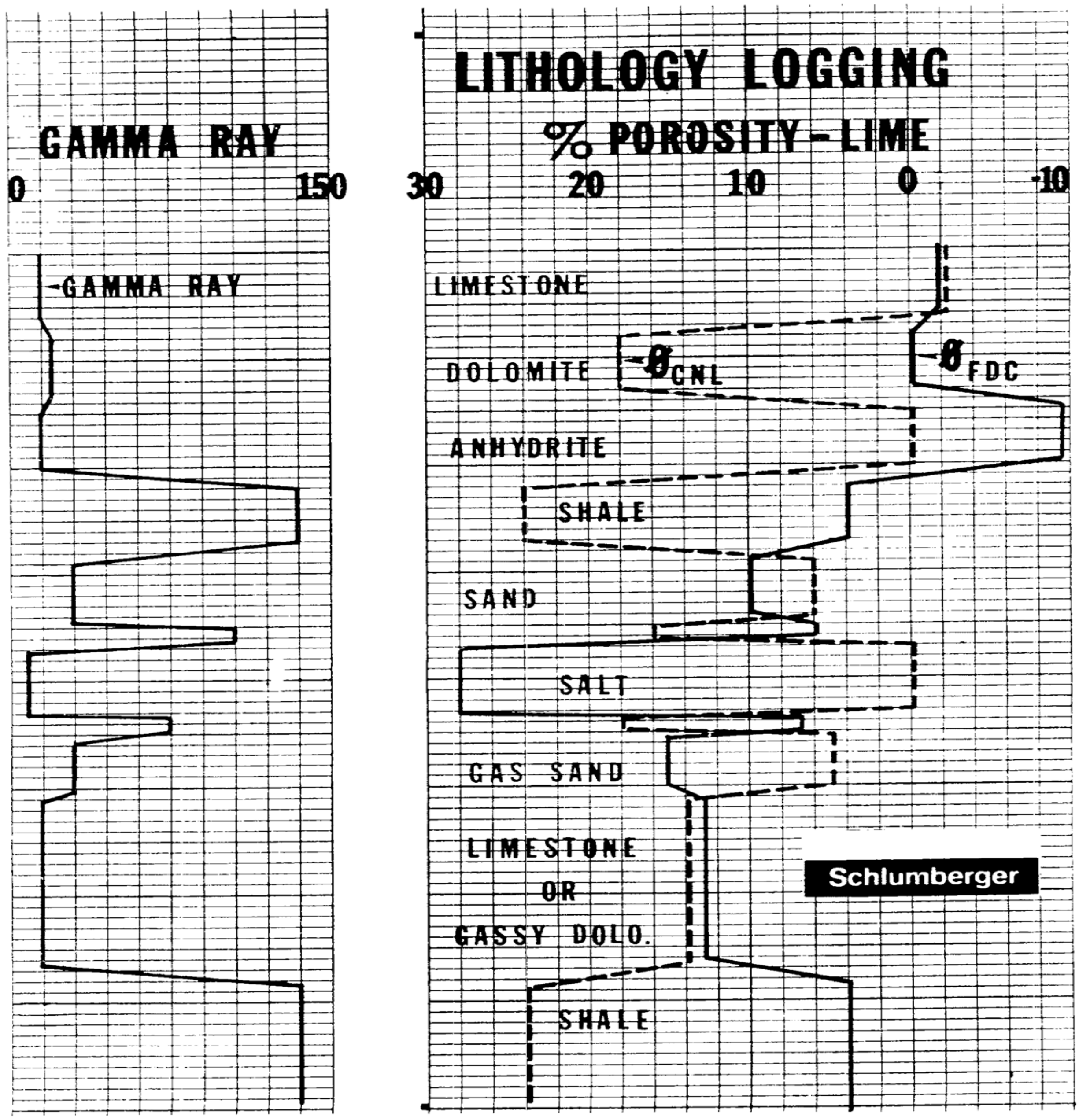
- When a Neutron-Density Log records a density porosity of less than (0%) the following formula should be used to determine neutron-density porosity;

$$\varphi_{N-D} = \frac{\varphi_D + \varphi_N}{2} \ldots\ldots\ldots\ldots.(5)$$

Note: Eq.5 used in Gas Bearing formations and when a Neutron-Density Log records a density porosity of less than (0%), while Eq.4 used in Oil or Water Bearing formations.

Example…9// **A.** Using Combination Gamma Ray Neutron-Density Log as a tool for determining lithology**.**

B. Using Combination Gamma Ray Neutron-Density Log as a tool for detection water/oil/gas bearing zone**.**

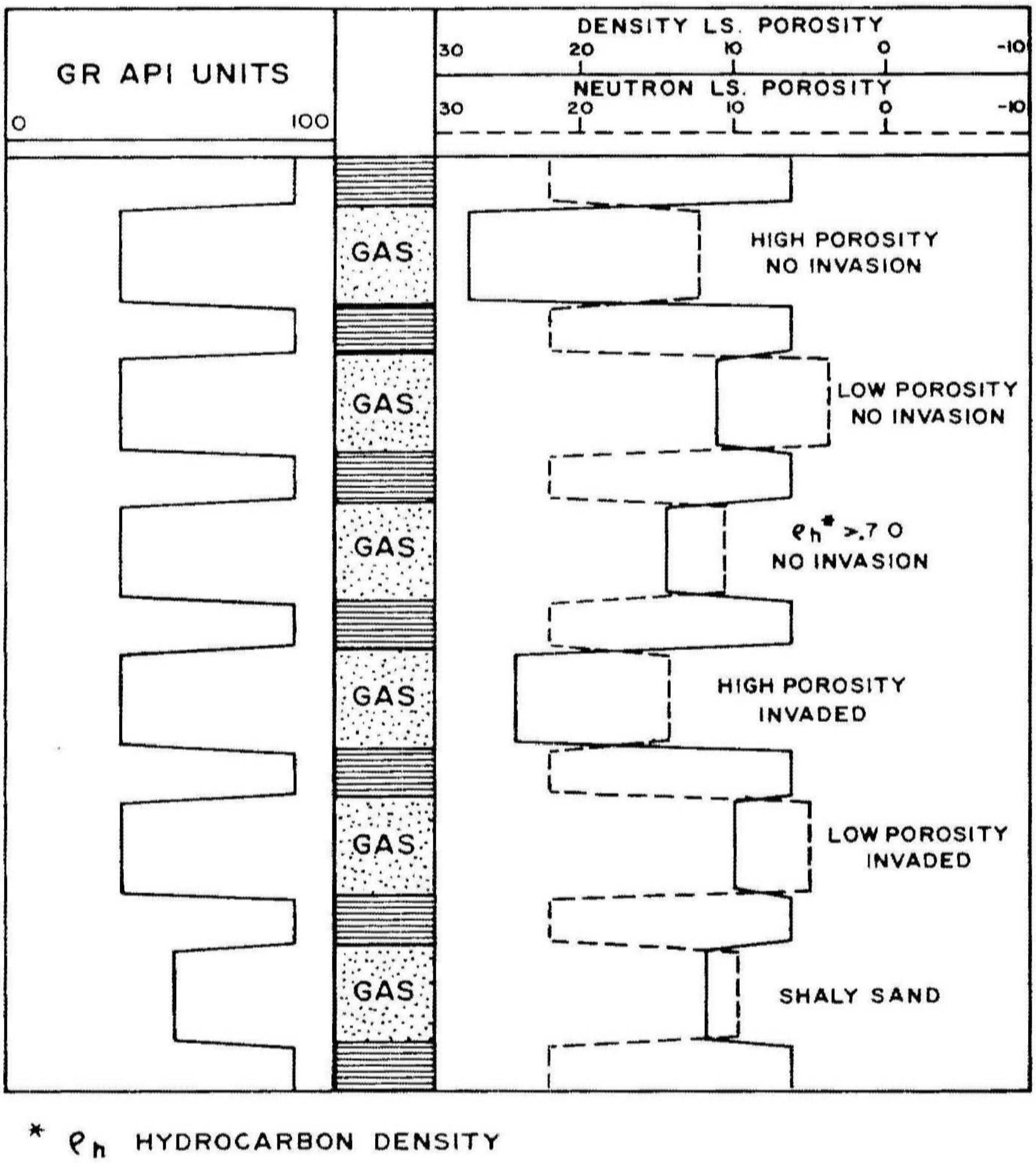


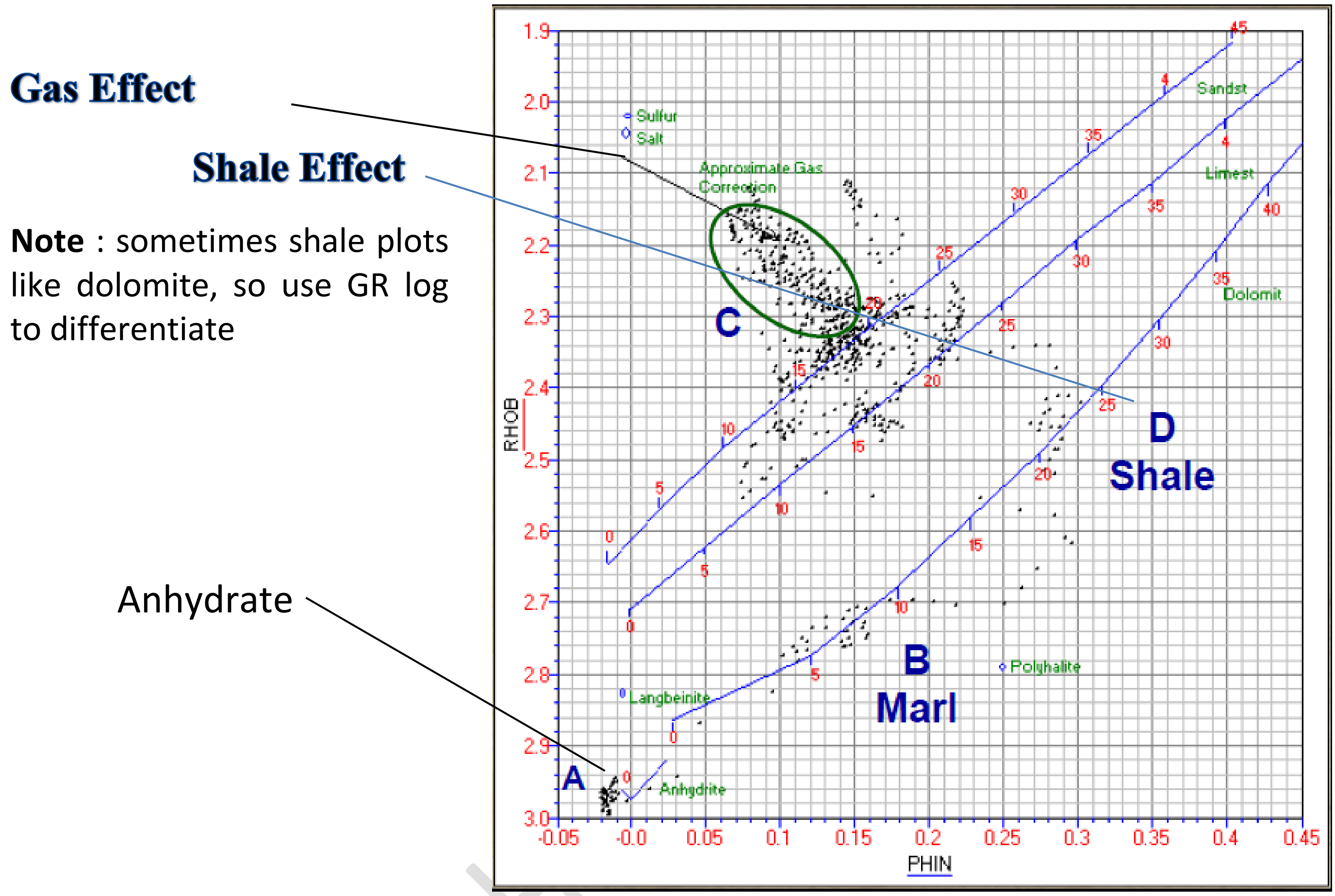
A. The relationship between log responses on the Gamma Ray Neutron-Density Log and rock type provides a powerful tool for the subsurface geology. By identifying rock type from logs, facies maps can be construct for the field.

Lithology	ϕ_N and ϕ_D
Sandstone	Neutron-Density crossover ($\phi_N > \phi_D$) of 6 to 8 porosity units
Limestone	Neutron and density curves overlay ($\phi_N \approx \phi_D$)
Dolomite	Neutron-density separation ($\phi_N < \phi_D$) of 12 to 14 porosity units
Anhydrite	Neutron porosity is greater than density porosity ($\phi_N > \phi_D$) by 14 porosity units; $\phi_N \approx 0$
Salt	Neutron porosity is slightly less than zero. Density porosity is 40 porosity units (0.40) or more. Watch for washed out hole (high Caliper) and bad density data

B. The *oil or water-bearing sand* has a density log reading of four porosity units more than the neutron log. In contrast, the gas-bearing sand has a density reading of up to 10 porosity units more than the neutron log. Where an *increase* in density porosity occurs along with a *decrease* in neutron porosity in a gas-bearing zone, it is called *gas effect.* Gas effect is created by gas in the pores. Gas in the pores causes the density log to record too high a porosity (i.e. gas is lighter than oil or water) and causes the neutron log to record too Iowa porosity (i.e. gas has a lower concentration of hydrogen atoms than oil or water). The effect of gas on the Neutron-Density Log is a very important log response because it helps the engineers to detect gas-bearing zones.

Example…10// Neutron-Density responses log responses in gas-bearing sandstones, show how gas effect varies with depth of invasion, porosity, hydrocarbon density and shale content.





- **Estimation of Hydrocarbon Density** From neutron and density logs

✓ **Used Chart: CHART (CP-10).**

✓ This chart estimate the density of the saturating hydrocarbon from a comparison of neutron and density measurements, and the hydrocarbon saturation in the portion of the rock investigated by the neutron and density logs (invaded or flushed zone).

✓ The neutron log (either CNL or SNP log) and the density log must be corrected for environmental effect and lithology before entry into the charts.

✓ To use, enter the appropriate chart with the ratio of neutron porosity to density porosity, and the hydrocarbon saturation. The intersection defines the hydrocarbon density in g/cm^3.

Example…9: ΦCNL_{cor} = 15 p.u. ΦD_{cor} = 25 p.u. and Sh_r = 30%

Therefore, ρh = 0.28 g/cm^3

- Schlumberger (1974) proposed an equation to compute the **total porosity** from neutron and density logs that may be expressed as:

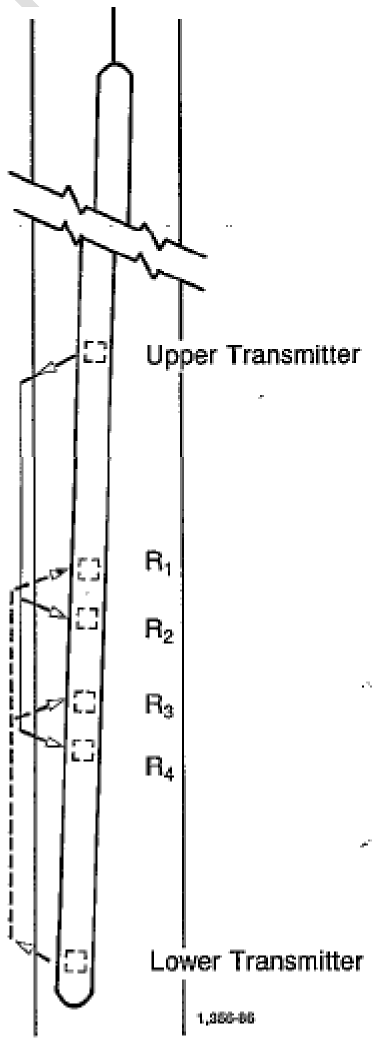
$$\varphi_{ND} = \varphi_t = \frac{\varphi_{Ncorr} + \varphi_{Dcorr}}{2} \ldots\ldots..(6)$$

- **Effective porosity** is the total porosity less the fraction of the pore space occupied by clay. In very clean sands, total porosity is equal to effective porosity**.**

$$\varphi_e = \varphi_t * (1 - V_{clay}) \ldots\ldots..(7)$$

Sonic Log

- The sonic log is a porosity log that measures interval transit time (Δt) of a compressional sound wave traveling through one foot of formation.
- The sonic log device consists of one or more sound transmitters, and two or more receivers.
- Modern sonic logs are **borehole compensated** devices (**BHC**). These devices greatly reduce the effects of borehole size variations, as well as errors due to tilt of the sonic tool.
- Interval transit time (Δt) in microseconds per foot is the reciprocal of the velocity of a compressional sound wave in feet per second.
- Interval transit time (Δt) is recorded in tracks #2 and #3. A sonic derived porosity curve is sometimes recorded in tracks #2 and #3, along with the Δt curve. Track # 1 contains a caliper log and a gamma ray log or an SP log.
- The interval transit time (Δt) is dependent upon both <u>lithology</u> and <u>porosity</u>. Therefore a formation's matrix velocity must be known to derive sonic porosity either by chart (**CHART Por-3**) or by the following formula (*Wyllie et.al.* 1958, equitation):



$$\varphi s = \frac{\Delta t_{log} - \Delta t_{ma}}{\Delta t_{fl} - \Delta t_{ma}} \ldots \ldots \ldots (8)$$

Where;

φs = Sonic (acoustic) porosity = primary porosity

Δt_{log} = Sonic travel time from the log.

Δt_{ma} = Matrix travel time.

Lithology	Δt_{ma} (µsec/ft)	Lithology	Δt_{ma} (µsec/ft)
limestone	47.6	Salt	67
Dolomite	43.5	Anhydrite	50
Sandstone	55.5		

Δt_{fl} =is the interval transit time in the fluid within the formation. [For fresh water mud = 189 (µsec/ft) and for salt-water mud = 185 (µsec/ft)].

- The Wyllie et al (1958) formula for calculating sonic porosity can be used to determine porosity in consolidated sandstones and carbonates formations.
- When sonic log is used to determine porosity in unconsolidated sands, an empirical compaction factor or C_p should be added to the Wyllie et al (1958) equation:

$$\varphi s = \frac{\Delta t_{log} - \Delta t_{ma}}{\Delta t_{fl} - \Delta t_{ma}} . \frac{1}{C_P} \dots\dots\dots (9)$$

C_P = The compaction factor is obtained from the following formula:

$$C_P = \frac{\Delta t_{sh}}{100} \dots\dots\dots\dots (10)$$

Where:

Cp = compaction factor

Δt_{sh} = interval transit time for adjacent shale.

Note: Eq.9 used only when Δt_{sh} > 100 (µsec/ft).

- When vuggy or fracture porosity are calculated by the Wyllie formula, porosity values *will be too low*. This will happen because the sonic log only records matrix porosity rather than vuggy or fracture secondary porosity.
- The percentage of vuggy or fracture secondary porosity can be calculated by subtracting *sonic porosity* from *total porosity.* Total porosity values are obtained from density or neutron log.
- The percentage of secondary porosity, called-SPI or secondary porosity index, can be a useful mapping parameter in carbonate exploration.

$$SPI = \varphi_s - \varphi_t \dots\dots\dots\dots (11)$$

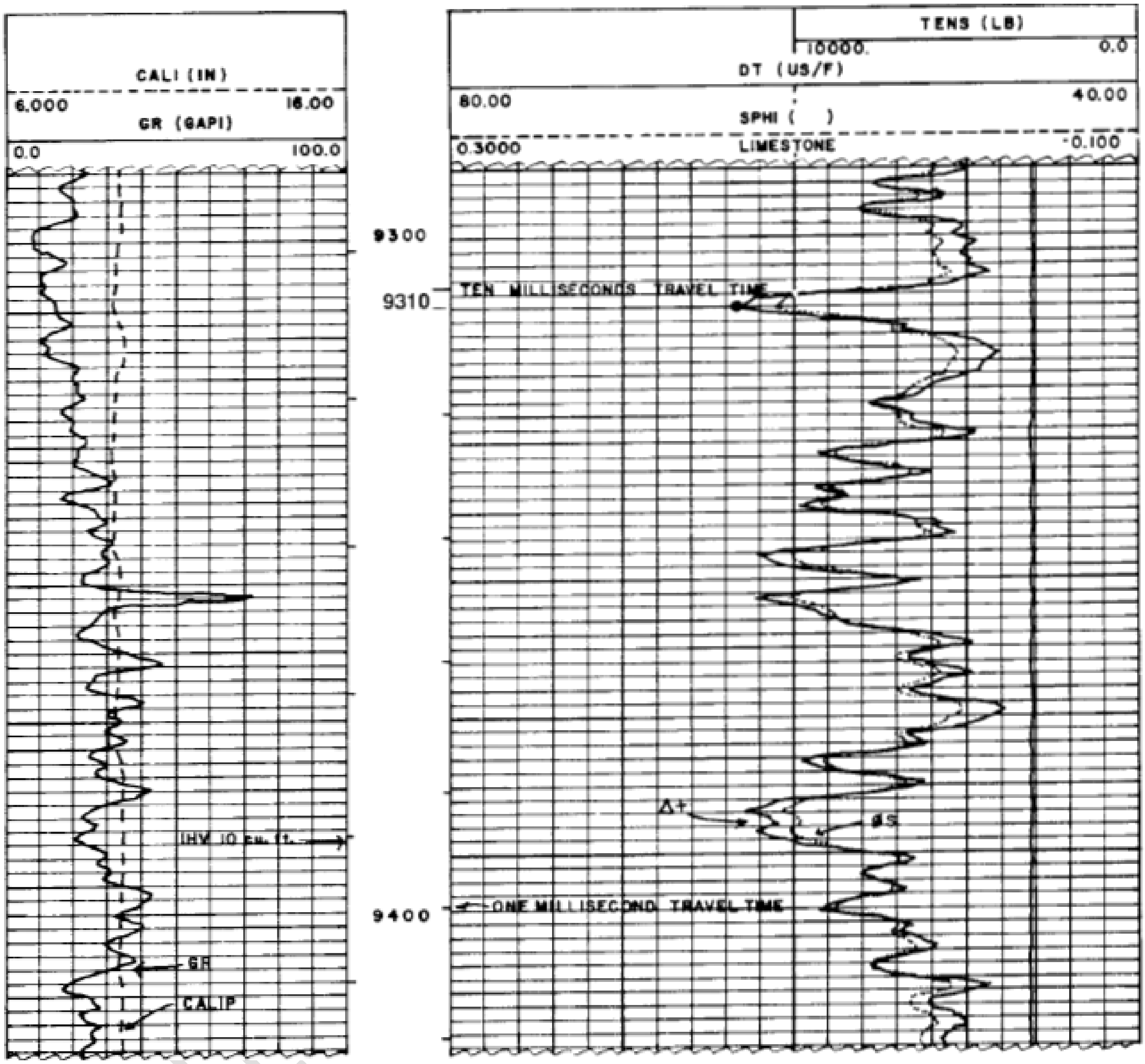
- The interval transit time (Δt) of a formation is increased due to the presence of hydrocarbons (i.e. *hydrocarbon effect).* If the effect of hydrocarbons is not corrected, the sonic derived porosity *will be too high*. The following empirical corrections suggested for hydrocarbons effect:

$$\varphi = \varphi_{sonic} * 0.7 \dots\dots\dots (12) \qquad gas$$

$$\varphi = \varphi_{sonic} * 0.9 \dots\dots\dots (13) \qquad oil$$

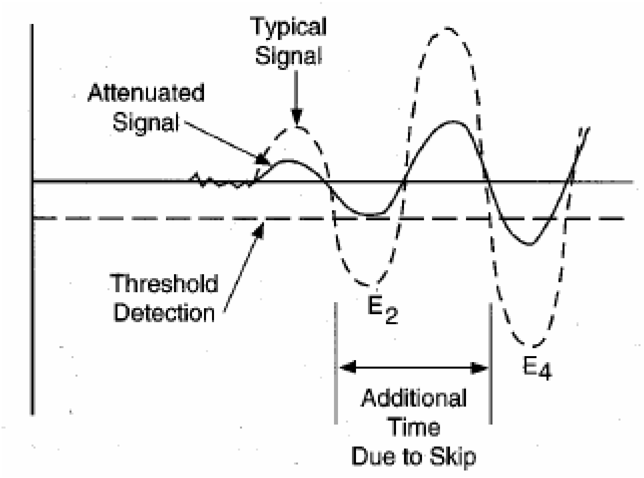
Example…..11// sonic log with gamma ray log and caliper.

- **Track # 1**--This track contains both GR log with scale (0-100) API and caliper log with scale (6 – 16) inches.
- **Tracks #2 and #3**-Both the interval transit time (Δt) scale and the porosity scale are shown in this track. Sonic log interval transit time (Δt) is represented by a solid line, on a scale ranging from 40 to 80 *µsec/ft.* increasing from *right-to-left.*
- The sonic porosity measurement (limestone matrix) is shown by a dashed line, on a scale ranging from --10% to + 30% porosity increasing from *right-to-left.*
- At the sample depth used in Figure below (9310 ft), read a sonic log interval transit time (Δt) value of 63 µsec/ft.

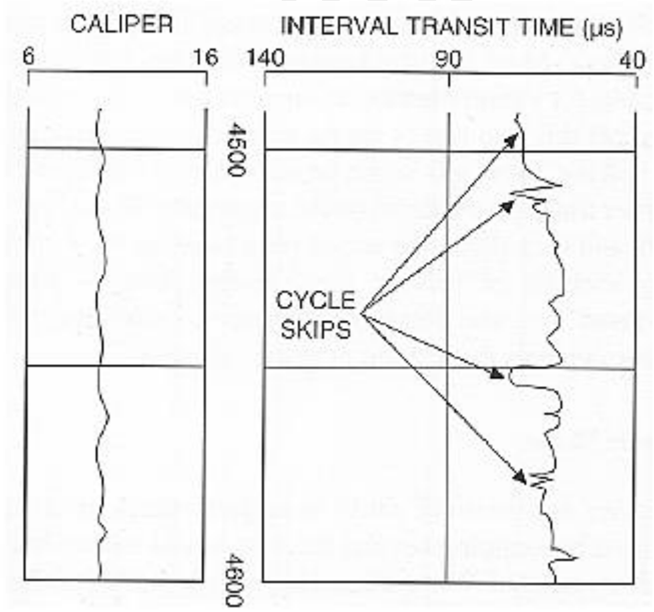

CALI (IN)
6.000
16.00
GR (GAPI)
0.0
100.0
TENS (LB)
10000.
0.0
DT (US/F)
80.00
40.00
SPHI ( )
0.3000
-0.100
LIMESTONE
9300
9310
TEN MILLISECONDS TRAVEL TIME
IHV 10 cu. ft.
Δt
ϕS
9400
ONE MILLISECOND TRAVEL TIME
GR
CALIP

Cycle Skipping.

Cause: Dampening of first arrival at far receiver



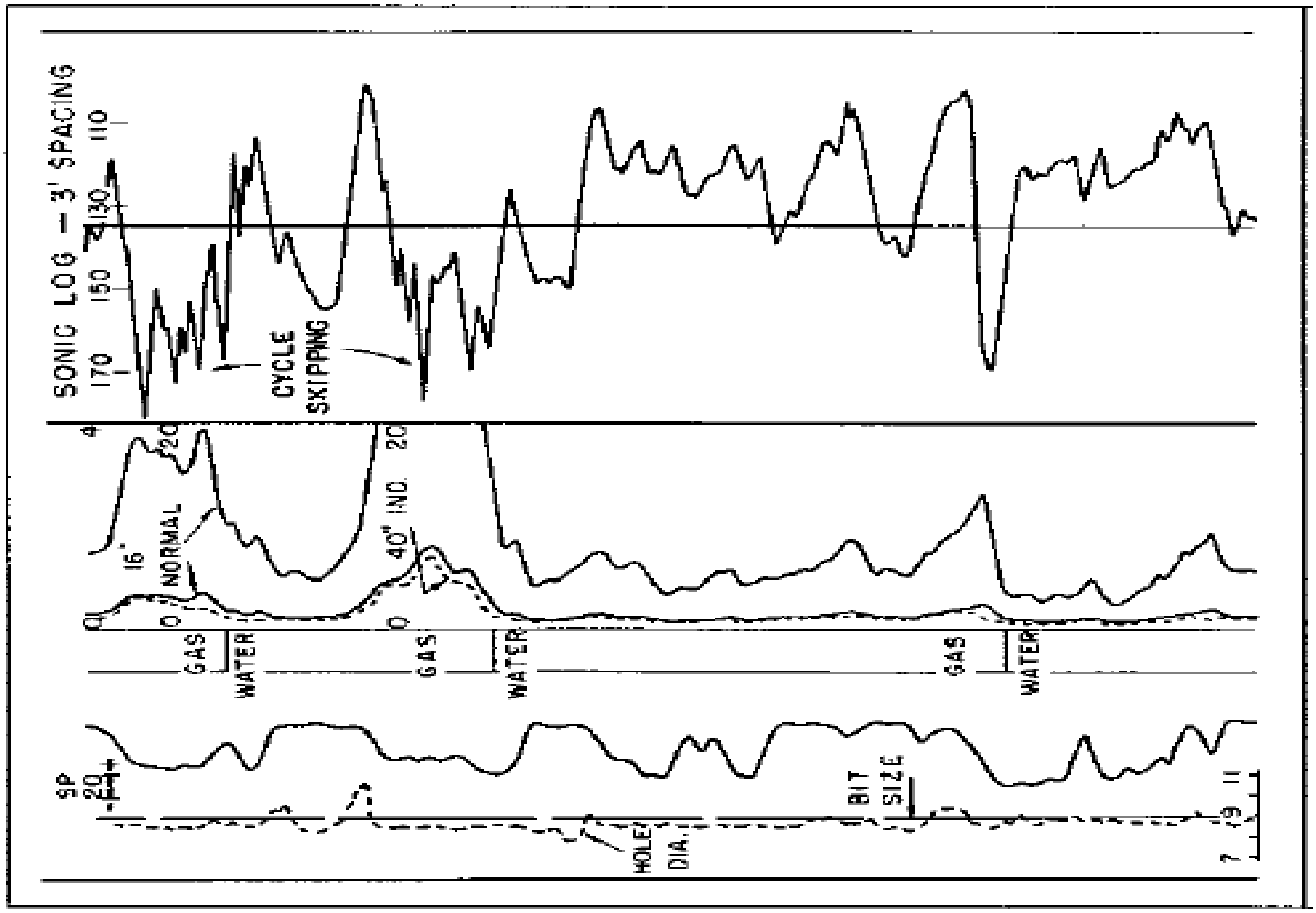
Effect: Sonic curve shows spiking or an abrupt change towards a higher travel time.

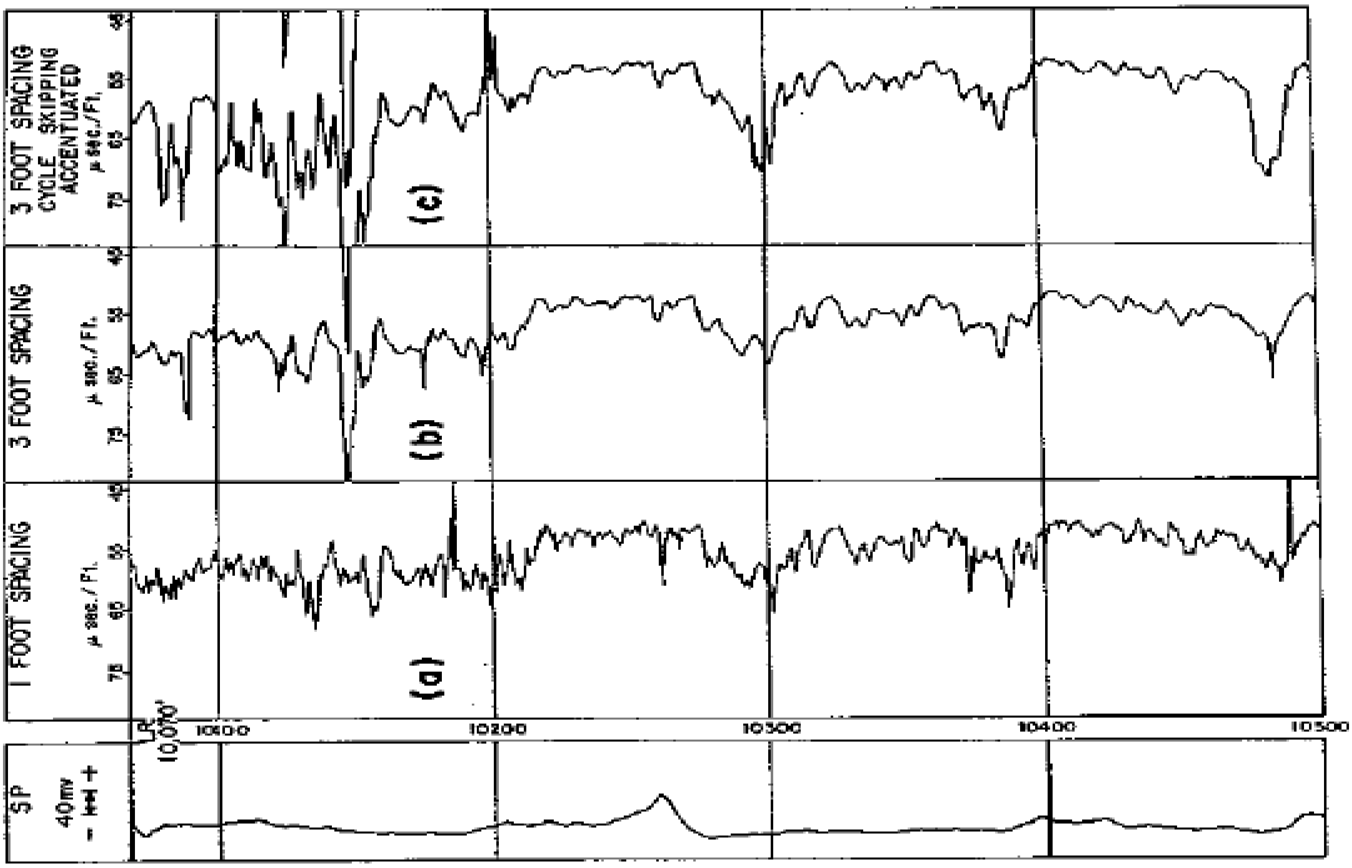


Occurs in: (1) series of thin beds of different velocities; (2) gas bearing zone; (3)Unconsolidated formations; (4)fractured formations.

تحدث هذه الظاهرة نتيجة ضعف الموجة الأنكسارية عند وصولها جهاز الألتقاط الثاني فلا تسجل الموجة وأنما تسجل الموجات الأنكسارية الثانوية وهذا تأخير في وصول الموجة بسبب زيادة مفاجئة في تسجيل الزمن (t) .ضعف الموجة الأنكسارية الأولية يعود الى عوامل عديدة منها وجود طبقات غير متماسكة او وجود طبقات كلسية متشققة

Fig. 1 shows an example of cycle skipping. **Fig.2a** shows an example of cycle skipping associated with fractured formations. **Fig.2b** shows cycle skipping in the interval of 10090 to 10150 ft.


SONIC LOG — 3' SPACING
CYCLE SKIPPING
16" NORMAL
40" IND.
GAS
WATER
GAS
WATER
GAS
WATER
SP
BIT SIZE
HOLE DIA.


3 FOOT SPACING CYCLE SKIPPING ACCENTUATED
(c)
3 FOOT SPACING
(b)
1 FOOT SPACING
(a)
μ sec./Ft.
10100
10200
10300
10400
10500
SP
40mv