



Porosity Logs

General

- Type of porosity logs
 - Sonic log
 - Density log
 - Neutron log
- 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





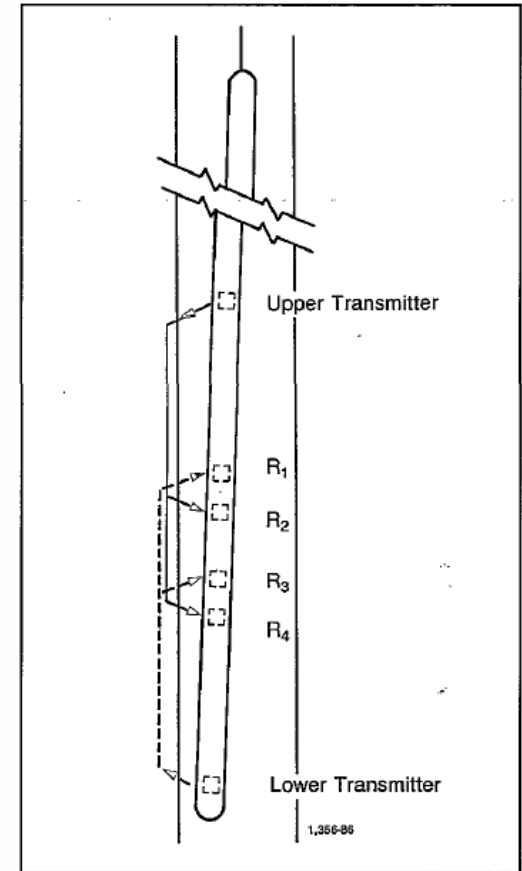
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Sonic log

General

Sonic

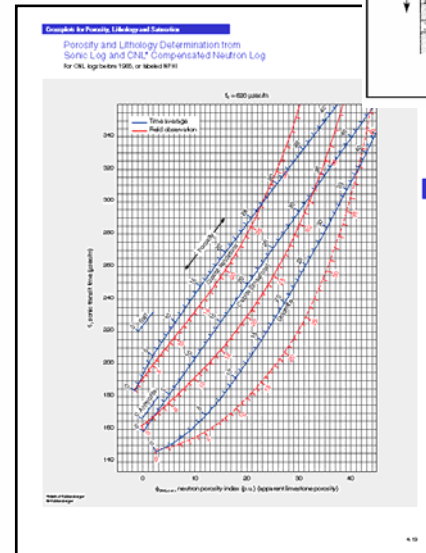
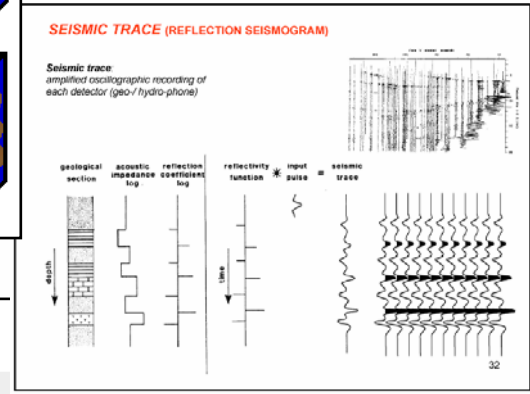
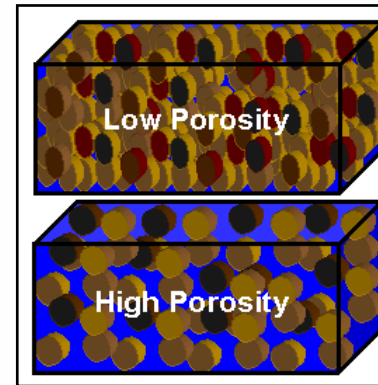
- A log that measures interval transit time (Δt) of a compressional sound wave travelling through the formation along the axis of the borehole
- The acoustic pulse from a transmitter is detected at two or more receivers. The time of the first detection of the transmitted pulse at each receiver is processed to produce Δt .
- The Δt is the transit time of the wave front over one foot of formation and is the reciprocal of the velocity
- Interval transit time is both dependent on lithology and porosity
- Sonic log is usually displayed in track 2 or 3
- Units: $\mu\text{sec}/\text{ft}$, $\mu\text{sec}/\text{m}$
- Mnemonics: DT, AC
- Symbol: ϕ



General

Sonic

- Interpretation goals:
 - Porosity
 - Lithology identification (with *Density* and/or *Neutron*)
 - Synthetic seismograms (with *Density*)
 - Formation mechanical properties (with *Density*)
 - Detection of abnormal formation pressure
 - Permeability identification (from waveform)
 - Cement bond quality



Sonic Porosity

Formula

- From the Sonic log, a sonic derived porosity log (SPHI) may be derived:

- Wyllie Time-average

$$\phi_s = \left(\frac{\Delta t_{\log} - \Delta t_{\text{matrix}}}{\Delta t_f - \Delta t_{\text{matrix}}} \right)$$

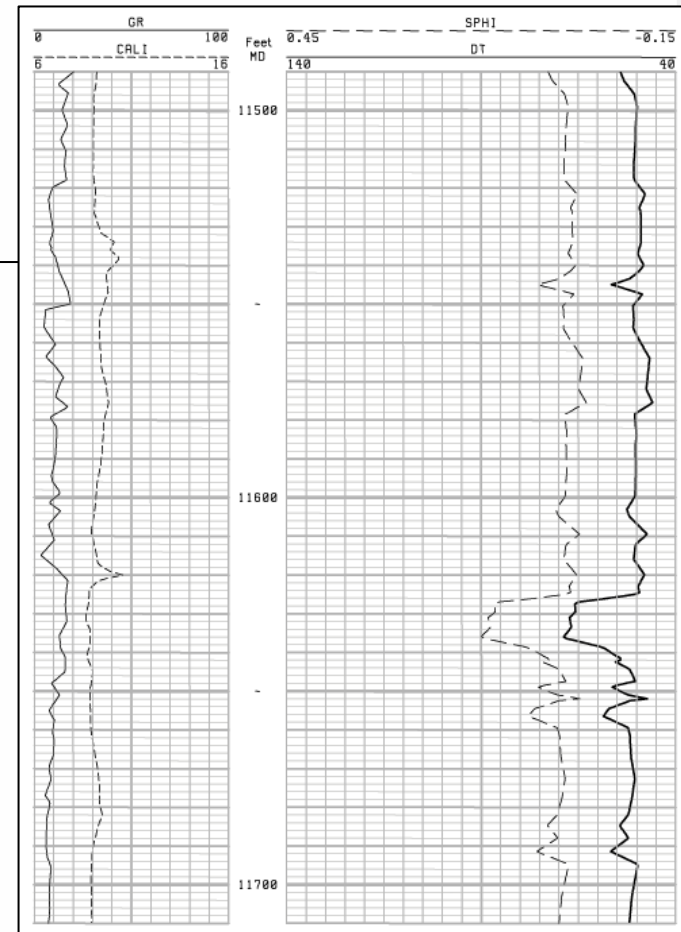
- Raymer-Hunt-Gardner

$$\phi_s = \frac{5}{8} \times \left(\frac{\Delta t_{\log} - \Delta t_{\text{matrix}}}{\Delta t_{\log}} \right)$$

- For unconsolidated formations

$$\phi_s = \left(\frac{\Delta t_{\log} - \Delta t_{\text{matrix}}}{\Delta t_f - \Delta t_{\text{matrix}}} \right) \times \frac{1}{C_p}, \text{ with } C_p = \frac{\Delta t_{\text{sh}} \times C}{100}$$

- This requires a formation matrix transit time to be known
- SPHI Units: percent, fraction
- Cp = Compaction factor
- C = constant, normally 1.0



- Hydrocarbon effects:
 - The Dt is increased due to HC therefore:
 - $\phi = \phi_s \times 0.7$ (gas)
 - $\phi = \phi_s \times 0.9$ (oil)



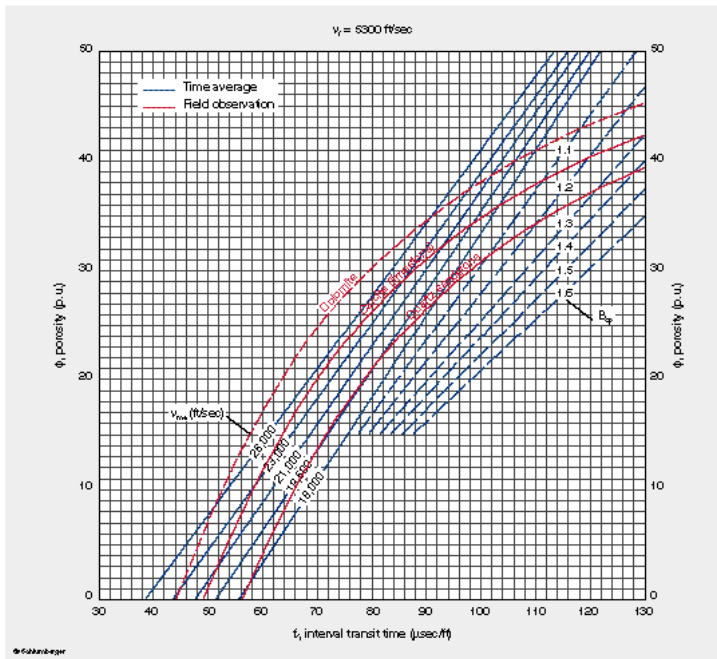
Sonic Porosity Charts

Porosity

Porosity Evaluation from Sonic

Schlumberger

Por-3
(English)



Por

These two charts (Por-3) convert sonic log interval transit time, t_i , into porosity, ϕ . Two sets of curves are shown. The blue set employs a weighted-average transform. The red set is based on empirical observation (see Reference 20). For both, the saturating fluid is assumed to be water with a velocity of 5300 ft/sec (1615 m/sec).

To use, enter the chart with the interval transit time from the sonic log. Go to the appropriate matrix velocity or lithology curve and read the porosity on the ordinate.

For rock mixtures such as lity sandstones or cherty dolomites, intermediate matrix lines may be required. When using the weighted-average transform in unconsolidated sand, a lack-of-compaction correction, B_c , must be made. To accomplish this, enter the chart with the interval transit time; go to the appropriate compaction correction line, and read the porosity on the ordinate. If the compaction correction is unknown, it can be determined by working backward from a nearby clean water sand whose porosity is known.

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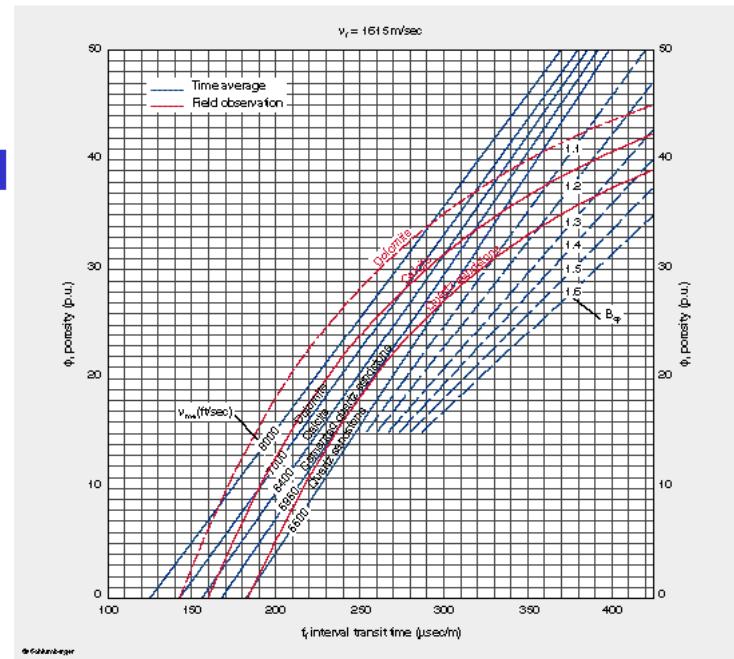
3.3

Porosity

Porosity Evaluation from Sonic

Schlumberger

Por-3m
(Metric)



Por

Example: $t_i = 76 \mu\text{sec}/\text{ft}$ [249 $\mu\text{sec}/\text{m}$]

$v_{ma} = 19,500 \text{ ft}/\text{sec}$ [5950 m/sec] \rightarrow sandstone

Therefore, $\phi = 18\%$

(by either weighted average or empirical transform)

For more information see References 18, 19 and 20.

Lithology	v_{ma} (ft/sec)	v_{ma} (m/sec)	v_{ma} (ft/sec)	v_{ma} (m/sec)
Sandstone	19,000-19,500	58.5-59.5	5400-5944	162-182
Limestone	21,000-23,000	64.0-70.0	6400-7000	195-213
Dolomite	22,000-24,000	67.0-73.0	7000-7920	213-241

3.4



Sonic Porosity

	V_{ma} (ft/sec)	V_{ma} (m/s)	Δt_{ma} (μ s/ft)	Δt_{ma} (μ s/m)	Δt_{ma} (μ s/ft) commonly used	Δt_{ma} (μ s/m) commonly used
Sandstone	18 – 19.5	5.5 – 5.95	55.5 - 51	182 – 167	55.5 or 51	182 or 167
Limestone	21 – 23	6.4 – 7.0	47.6 – 43.5	156 – 143	47.5	156
Dolomite	23	7.0	43.5	143	43.5	143
Anhydrite	20	6.1	50	164	50	164
Salt	15	4.575	66.7	219	67	220
Freshwater mud filtrate	5.28	1.610	189	620	189	620
Saltwater mud filtrate	5.40	1.649	185	607	185	607
Gas	1.08	0.33	920	3018	920	3018
Oil	4.35	1.32	230	755	230	755
Casing (iron)	17.5	5.33	57	187	57	187



Sonic

Secondary Effects

- Environmental effects:
 - Enlarged borehole, formation fractures, gas in the borehole or formation, or improper centralization can produce signal attenuation resulting in "cycle skipping" or DT spikes to higher values
 - Improper centralization, lack of standoff, or excessive logging speed can result in "road noise", or DT spikes to either higher or lower values
- Interpretation effects:
 - Lithology: porosity calculated from sonic depends on the choice of matrix transit time, which varies with lithology
 - Porosity calculations for uncompacted formations may yield porosity values higher than the actual values when using the Wyllie equation. Use instead the Raymer-Hunt-Gardner equation or correct for decompaction
 - Porosity calculated in gas bearing zones will be slightly higher than the actual values because the traveltime in gas is higher than in water

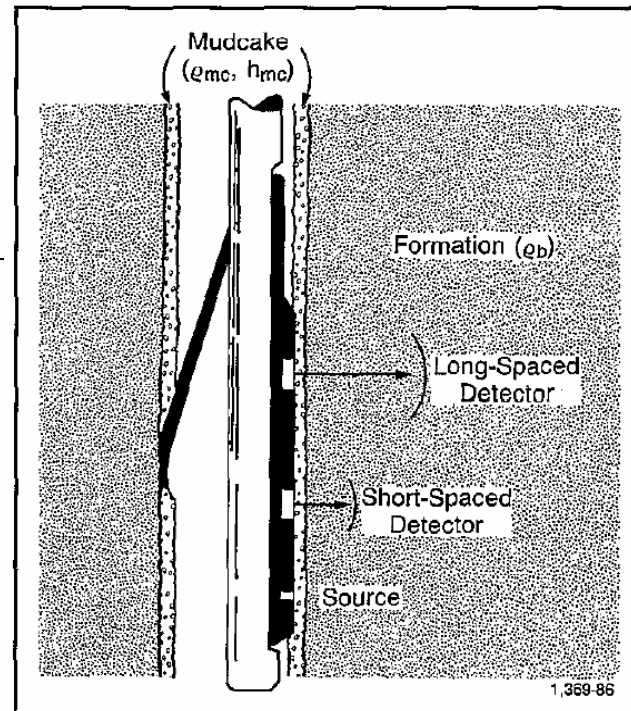




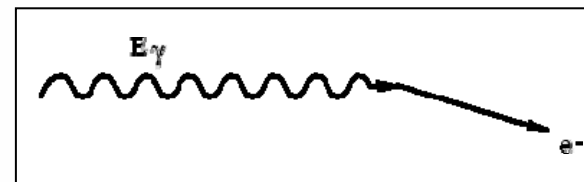
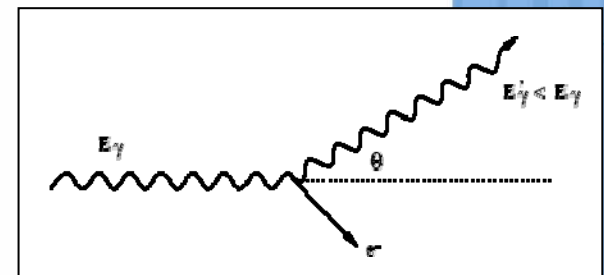
Density Log

General Density

- Gamma rays emitted from a chemical source (Ce^{137} , Co^{60}) interact with electrons of the elements in the formation.
- Two detectors count the number of returning gamma rays which are related to formation electron density
- For most earth materials, electron density is related to formation density through a constant
- Returning gamma rays are measured at two different energy levels
 - High energy gamma rays (Compton scattering) determine bulk density and therefore porosity
 - Low energy gamma rays (due to photoelectric effect) are used to determine formation lithology
- Low energy gamma rays are related to the lithology and show little dependence on porosity and fluid type
- Symbol for density: ρ (rho)



High energy
Compton scattering

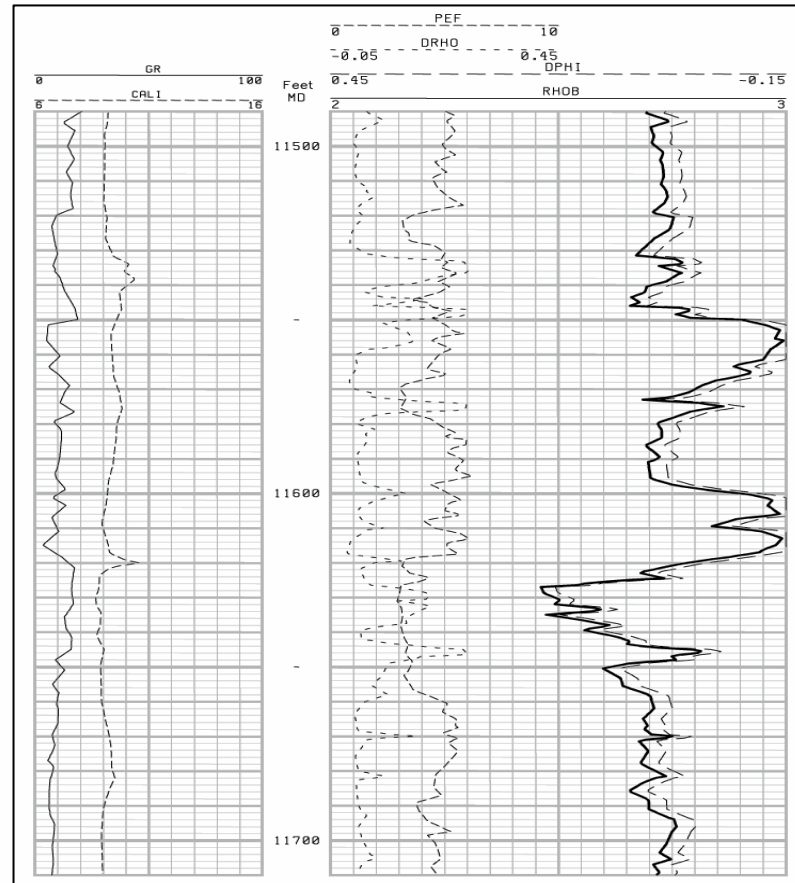


Low energy
Photoelectric absorption



General Density

- Bulk Density:
 - Units: g/cm³, kg/m³
 - Mnemonics: RHOB, DEN, (ZDEN)
- Density Porosity:
 - Units: %, v/v decimal
 - Mnemonics: DPHI, PHID, DPOR
- Density Correction:
 - Units: g/cm³, kg/m³
 - Mnemonics: DRHO
- Photoelectric effect:
 - Units: b/e (barns per electron)[†]
 - Mnemonics: PE, Pe, PEF

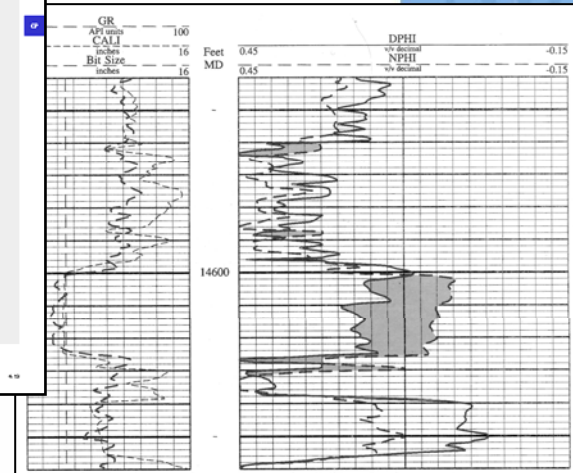
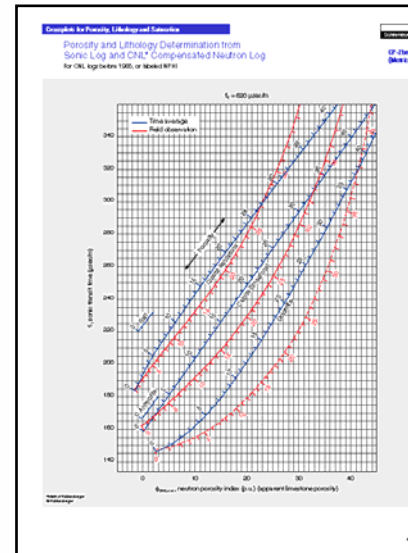
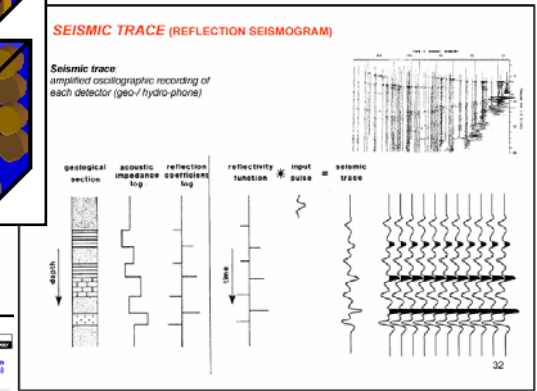
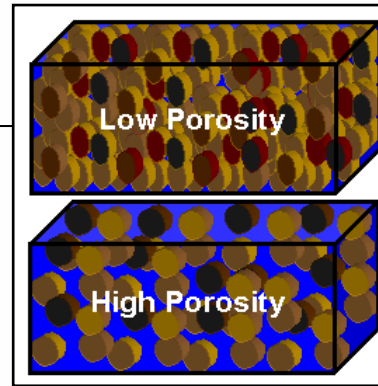


[†]A barn is a unit of area, abbreviated mostly as "bn" or "b", equal to 10⁻²⁸ m². Although not an official SI unit, it is widely used by nuclear physicists, since it is convenient for expressing the cross sectional area of nuclei and nuclear reactions. A barn is approximately equal to the area of a uranium nucleus



General Density

- Interpretation goals
 - Porosity
 - Lithology identification (from *PEF* and/or with *Sonic* and/or *Neutron*)
 - Gas indication (with *Neutron*)
 - Synthetic seismograms (with *Sonic*)
 - Formation mechanical properties (with *Sonic*)
 - Clay content (shaliness)(with *Neutron*)

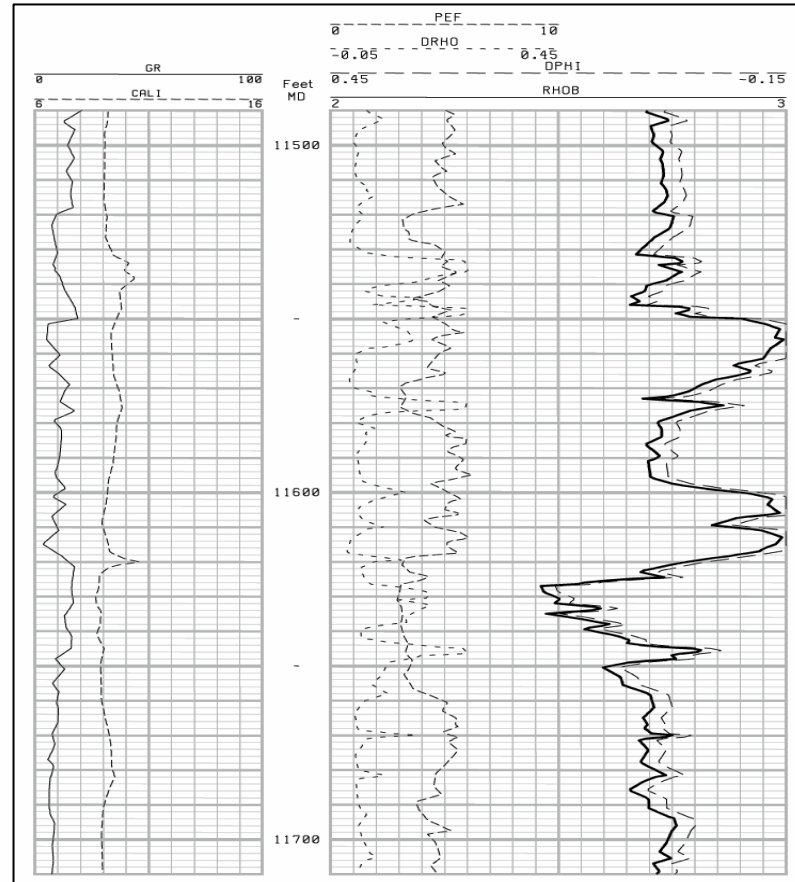


Density Porosity Formula

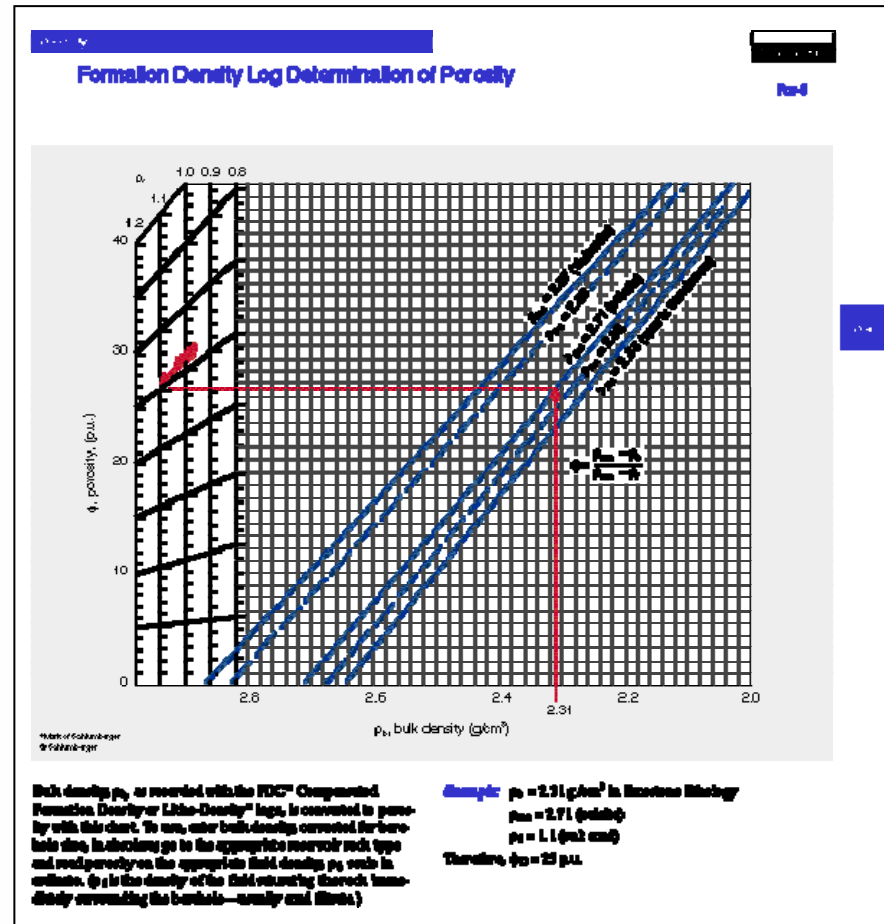
- Formation bulk density (ρ_b) is a function of matrix density (ρ_{ma}), porosity and formation fluid density (ρ_f)
- Density porosity is defined as:

$$\phi_{den} = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f}$$

- The matrix density and the fluid density need to be known



Density Porosity Chart



Density Porosity

	Matrix density (g/cm ³)	Fluid density (g/cm ³)	PEF (b/e)
Sandstone	2.65		1.81
Limestone	2.71		5.08
Dolomite	2.87		3.14
Anhydrite	2.98		5.05
Halite	2.04		4.65
Coal	~1.2		0.2
Barite	4.09		267
Gas		0.2	0.95
Oil		~0.85	0.12
Water		1.0 – 1.2	0.36 – 1.1



Density

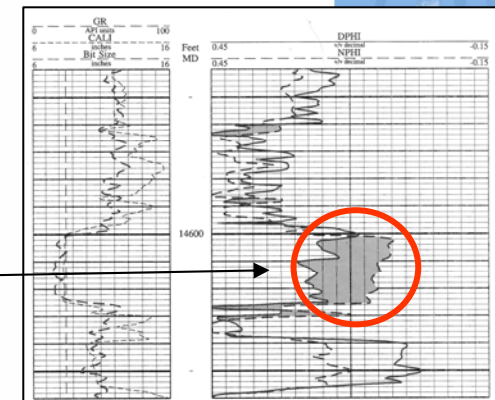
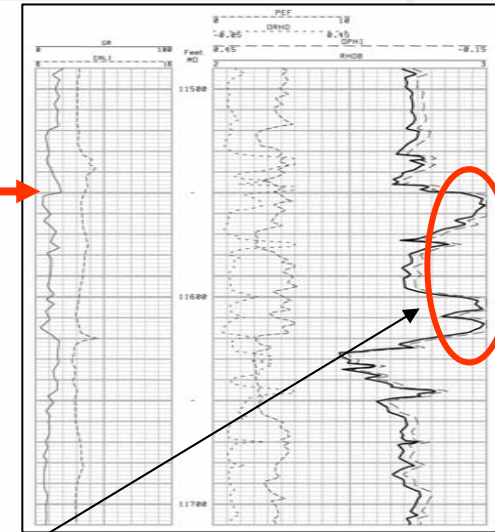
Secondary Effects

- Environmental effects:

- Enlarged borehole: $RHOB < Fm. \text{ Bulk Density}$ ($DPHI > PHI_{\text{actual}}$)
- Rough borehole: $RHOB < Fm. \text{ Bulk Density}$ ($DPHI > PHI_{\text{actual}}$). This is due to the sensor pad losing contact with the borehole wall. Other indications for a rough borehole will be highly variable Caliper curve, and a high-valued density correction (DRHO)
- Barite muds: $RHOB > Fm. \text{ Bulk Density}$ ($DPHI < PHI_{\text{actual}}$) and $PEF > PEF_{\text{actual}}$

- Interpretation effects:

- Lithology: porosity calculated from density depends on the choice of matrix density, which varies with lithology (DPHI might be negative)
- Fluid content: porosity calculated from density depends on the choice of fluid density, which varies with fluid type and salinity. In routine calculations, zone of investigations is assumed to be 100% filled with mud filtrate
- Hydrocarbons: Presence of gas (light HC) in the pore space causes DPHI to be more than the actual porosity. In Density-Neutron combinations, this causes a "cross-over", where the NPHI values are less than the DPHI values
- In all three cases above, the RHOB value from the tool is correct, but the calculated DPHI is erroneous





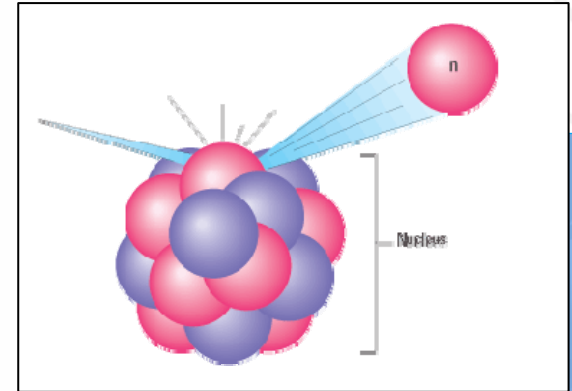
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Neutron Log

General

Neutron

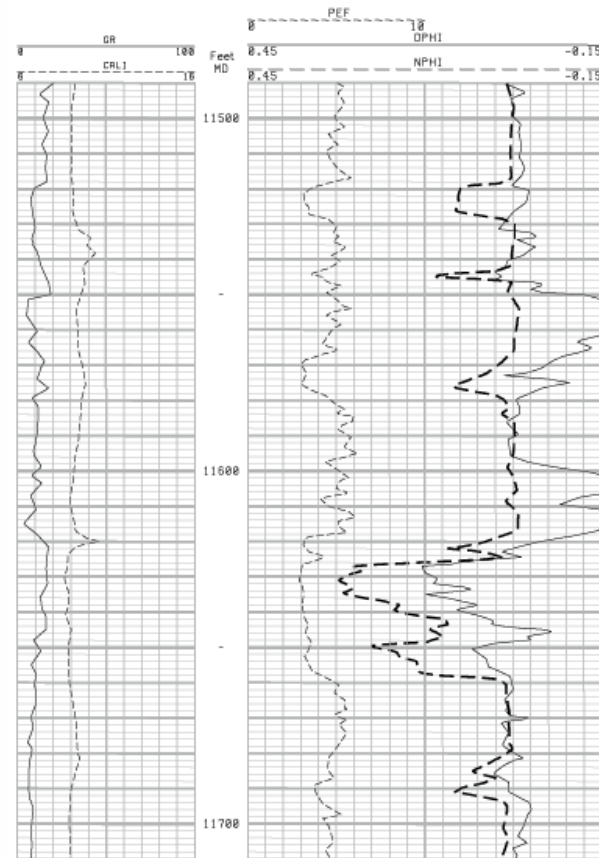
- Neutron logs measure the hydrogen content in a formation. In clean, shale free formations, where the porosity is filled with water or oil, the neutron log measures liquid filled porosity (ϕ_N , PHIN, NPFI)
- Neutrons are emitted from a chemical source (americium – beryllium mixture). At collision with nuclei in the formation, the neutrons lose energy. With enough collisions, the neutron is absorbed and a gamma ray is emitted
- Since a neutron is slightly heavier than a proton, the element which closely approximates the mass of a neutron is hydrogen. In neutron-hydrogen collisions the average energy transferred to the hydrogen nucleus is about $\frac{1}{2}$ that of the energy originally contained in the neutron. Whereas, if the scattering nucleus was oxygen (mass 16 amu) the neutron would retain 77% of its energy
- Materials with large hydrogen content like water or hydrocarbons become very important for slowing down neutrons. Since hydrogen in a porous formation is concentrated in the fluid-filled pores, energy loss can be related to the formation's porosity



General

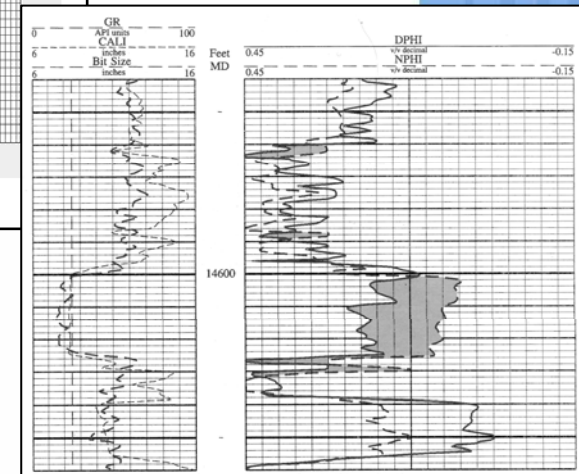
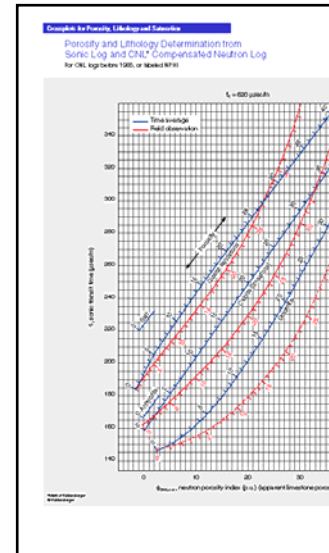
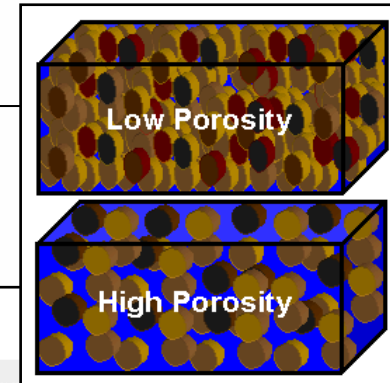
Neutron

- Neutron curves commonly displayed in track 2 or 3
- Displayed as Neutron Porosity (NPHI, PHIN, NPOR)
- Units: porosity units (p.u.) (calibrated with a standard, different for all tools), v/v decimal, fraction or %
- Neutron logs are not calibrated in basic physical units. Therefore, specific logs need to be interpreted with specific charts



General Neutron

- Interpretation goals:
 - Porosity (displayed directly on the log)
 - Lithology identification (with *Sonic* and *Density*)
 - Gas indication (with *Density*)
 - Clay content, shaliness (with *Density*)
 - Correlation, especially in cased holes



Neutron Porosity

Secondary Effects

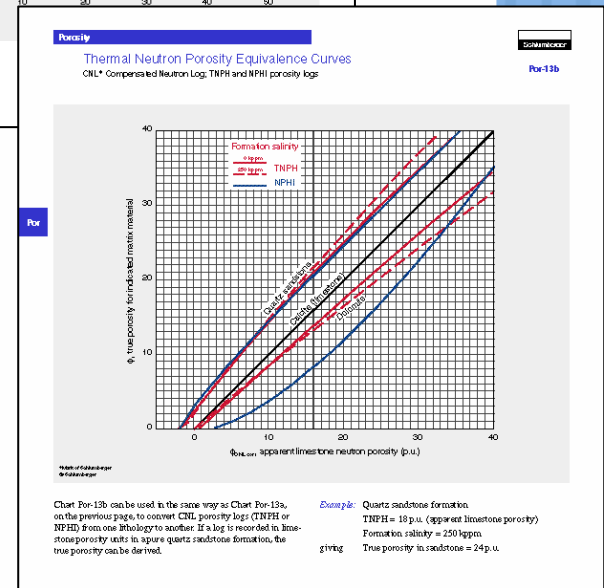
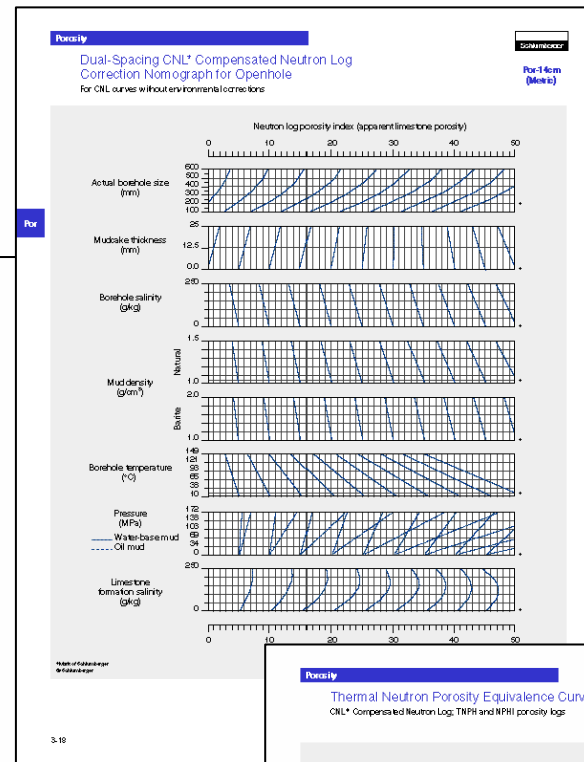
- Environmental effects:

- Enlarged borehole: $NPHI > PHI_{actual}$
- Mudcake: $NPHI < PHI_{actual}$
- Borehole salinity: $NPHI < PHI_{actual}$
- Formation salinity: $NPHI > PHI_{actual}$
- Mud weight: $NPHI < PHI_{actual}$
- Pressure: $NPHI > PHI_{actual}$
- Temperature: $NPHI < PHI_{actual}$

Pressure and temperature have the greatest effect. Neutron less affected by rough borehole

- Interpretation effects:

- Shaliness: $NPHI > PHI_{actual}$ in shaly zones
- Gas: $NPHI < PHI_{actual}$ in gassy zones.
- Lithology: In general, for logs recorded in limestone porosity units, if the actual lithology is sandstone, the log porosity is less than the actual porosity. If the actual lithology is dolomite, the log porosity is greater than the actual porosity





Porosity Combinations

Porosity determination

Given t_{ma} , ρ_{ma} or ϕ_{ma} , correct total porosities can be calculated from the appropriate logs, in water-filled formations and with no secondary porosity* present

* The porosity created through alteration of rock, commonly by processes such as dolomitization, dissolution and fracturing



But...

- Matrix lithology often unknown
- Complex mineralogical composition
- Presence of other pore fluids than water
- Even geometry of pore structures affect the tools

So, we need additional information

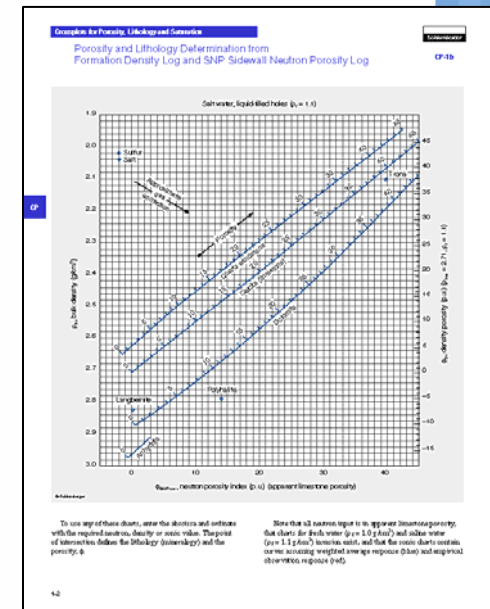
- Fortunately, sonic, density and neutron logs respond different on
 - Matrix minerals
 - Pore fluids
 - Geometry of pore structure
- Combination of logs may unravel complex matrix and fluid mixtures and thereby provide a more accurate determination of porosity
- A.o. crossplots are a convenient way to demonstrate how various combinations of logs respond to lithology and porosity



Introduction

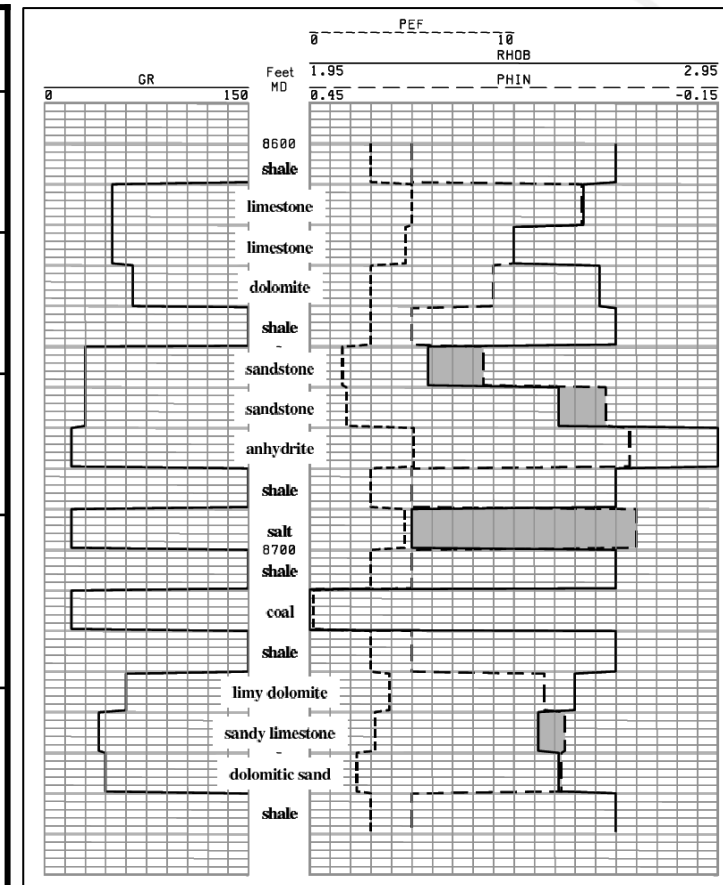
Porosity combinations

- When using a single porosity measurement, lithology must be specified, through the choice of a matrix value, for the correct porosity to be calculated
- When using two or more measurements, lithology may be predicted (along with porosity), but with some ambiguity
- Measurement preferences (in order of choice):
 - Two measurements:
 - Neutron and Density
 - Quick-look Lithology and Porosity
 - Neutron and Sonic
 - Spectral density (bulk density and Pe)
 - Density and Sonic
 - Three measurements:
 - Neutron and spectral density
 - Neutron; Density, and Sonic
 - MID (Matrix Identifications) Plots
 - M-N Plots



Quick-look (ϕ_N & ϕ_D)

Lithology	ϕ_N and ϕ_D	Pe
Sandstone	Neutron-Density crossover ($\phi_N > \phi_D$) of 6 to 8 porosity units	<2
Limestone	Neutron and density curves overlay ($\phi_N \approx \phi_D$)	~5
Dolomite	Neutron-density separation ($\phi_N < \phi_D$) of 12 to 14 porosity units	~3
Anhydrite	Neutron porosity is greater than density porosity ($\phi_N > \phi_D$) by 14 porosity units; $\phi_N \approx 0$	~5
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	4.7



Note: Both ϕ_N and ϕ_D should be calculated with respect to limestone. ϕ_N is recorded on limestone matrix and ϕ_D is calculated with a ρ_{ma} of 2.71 g/cm³ or scaled to approx. the Neutron porosity scale

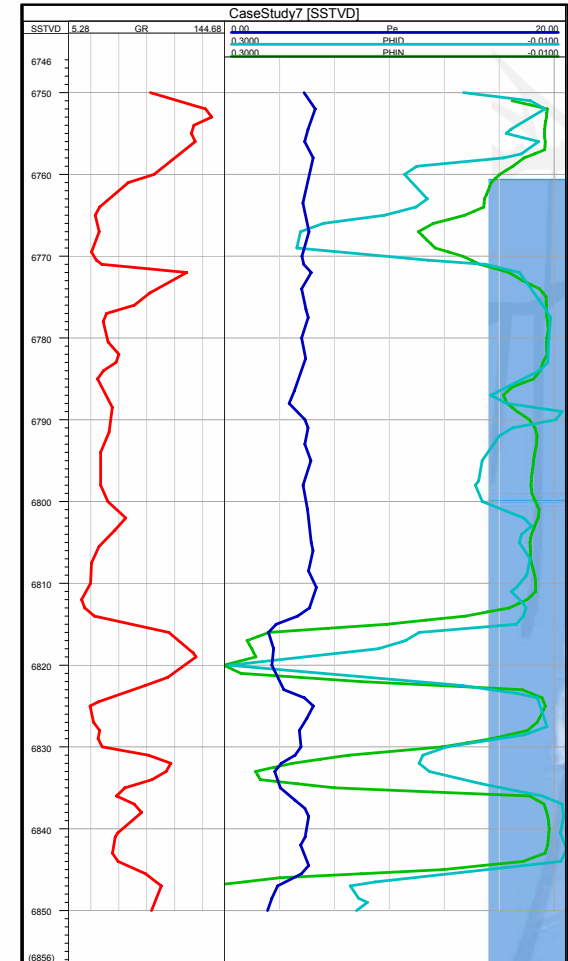


Neutron-Density: Special Case

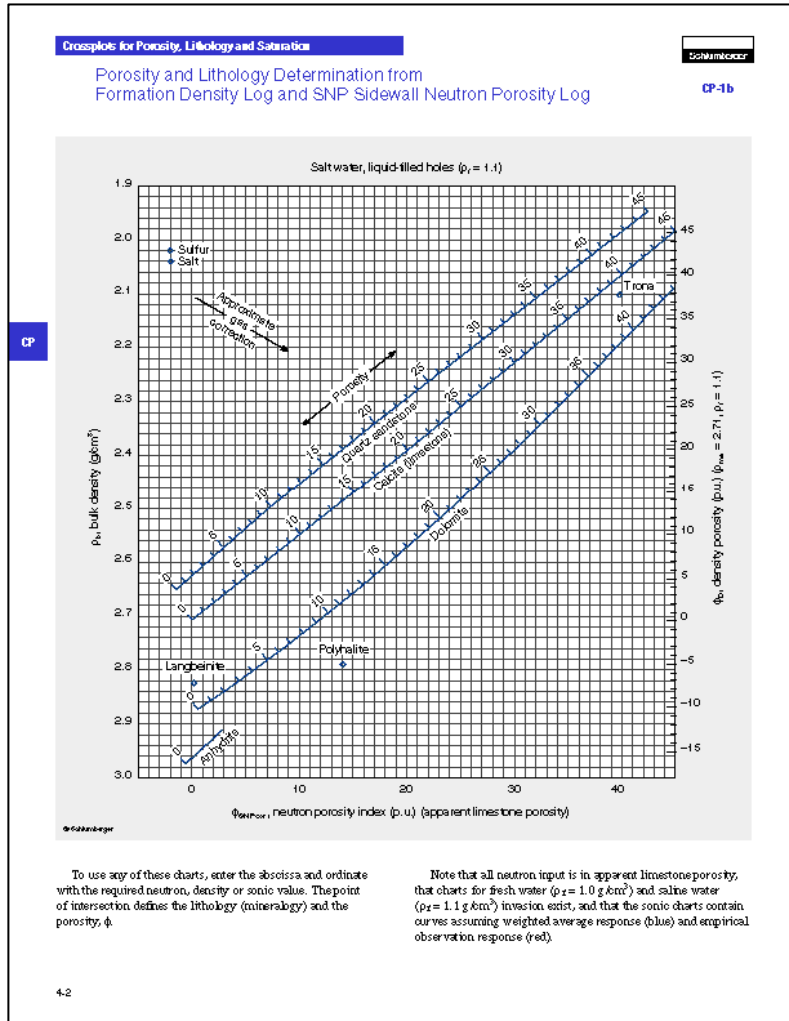
- Gas detection:
 - Density porosity is too high
 - Neutron porosity is too low
 - Neutron porosity < Density porosity
 - Cross-over
 - Be aware, cross-overs may also be caused by lithological differences as an affect of the scaling

Porosity of a gas-bearing formation

$$\phi_{ND} = \sqrt{\frac{\phi_N^2 + \phi_D^2}{2}} \approx \frac{1}{3} \times \phi_N + \frac{2}{3} \times \phi_D$$



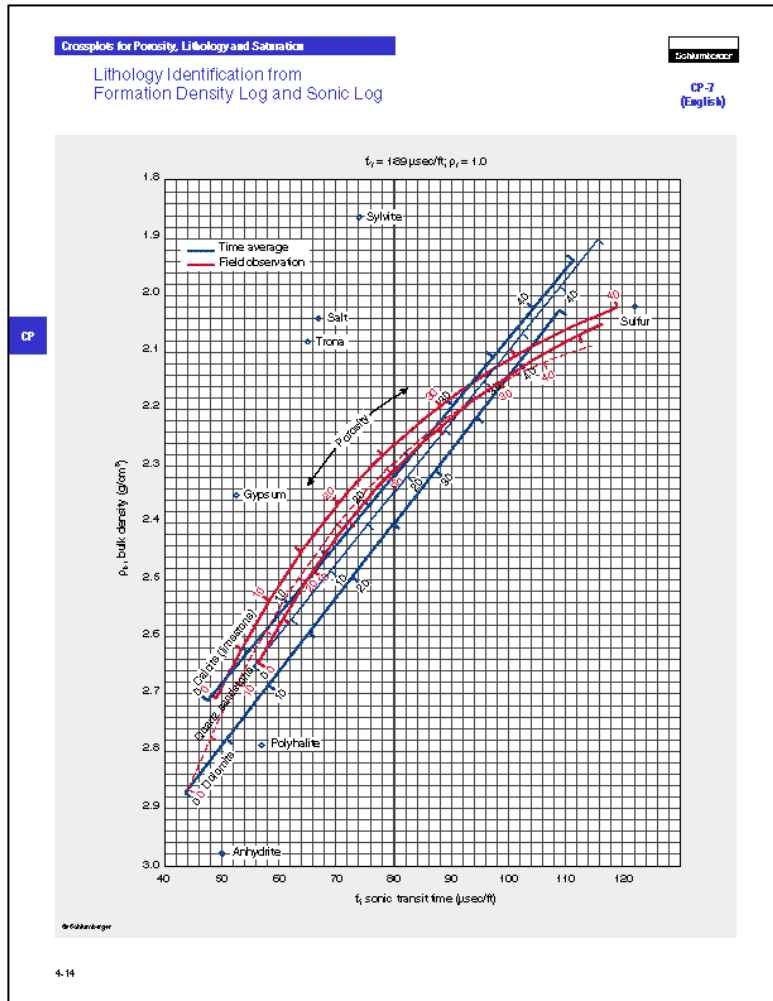
Neutron-Density crossplot



- Advantage:
 - Given two possible lithology pair solutions, the porosity remains relatively invariant between the solutions
 - The combination of neutron and density is the most common of all porosity tool pairs
- Disadvantage:
 - In rough holes or in heavy drilling muds, the density data might be invalid



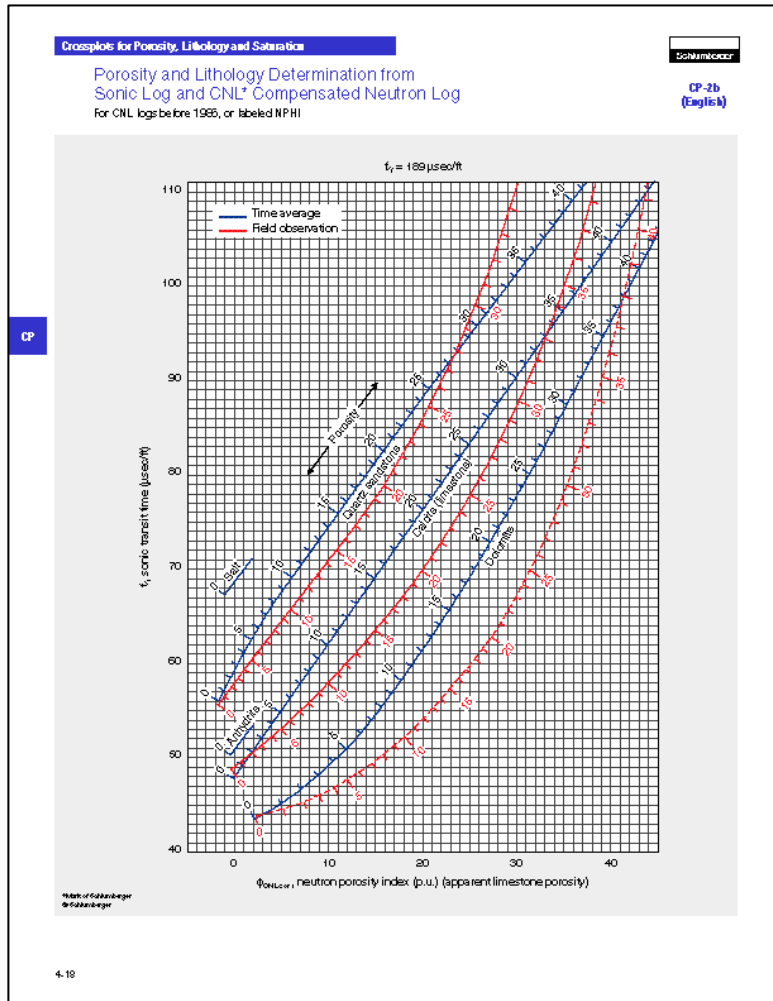
Sonic-Density crossplot



- Advantage:
 - Potential reservoirs plot along the closely spaced lithology lines, while shales tend to fall toward the lower right of the plot
 - Quite useful for determining some evaporite minerals
- Disadvantage:
 - The choice of the lithology pair has a significant effect on the estimation of the porosity
 - The lithology lines are closely spaced, so any uncertainty in the measurements produces large changes in lithology and porosity estimates



Sonic-Neutron crossplot



- Advantage:

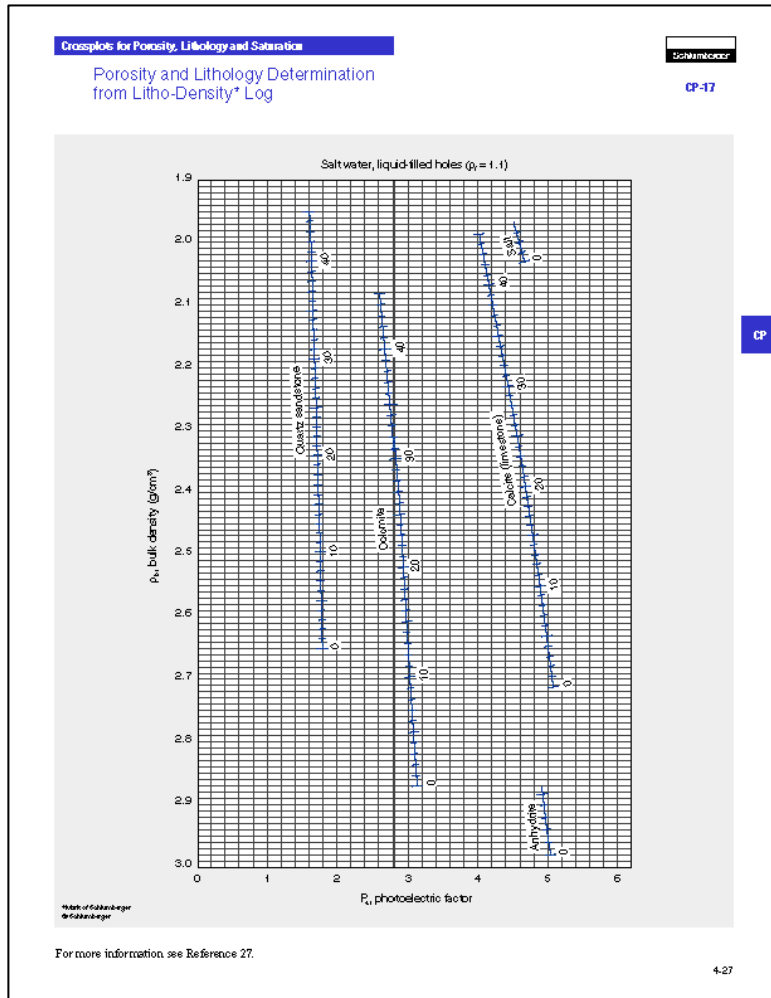
- Given two possible lithology pair solutions, the porosity remains relatively invariant between the solutions
- The sonic is less sensitive to rough holes than the density

- Disadvantage:

- The combination of sonic and neutron data is not common



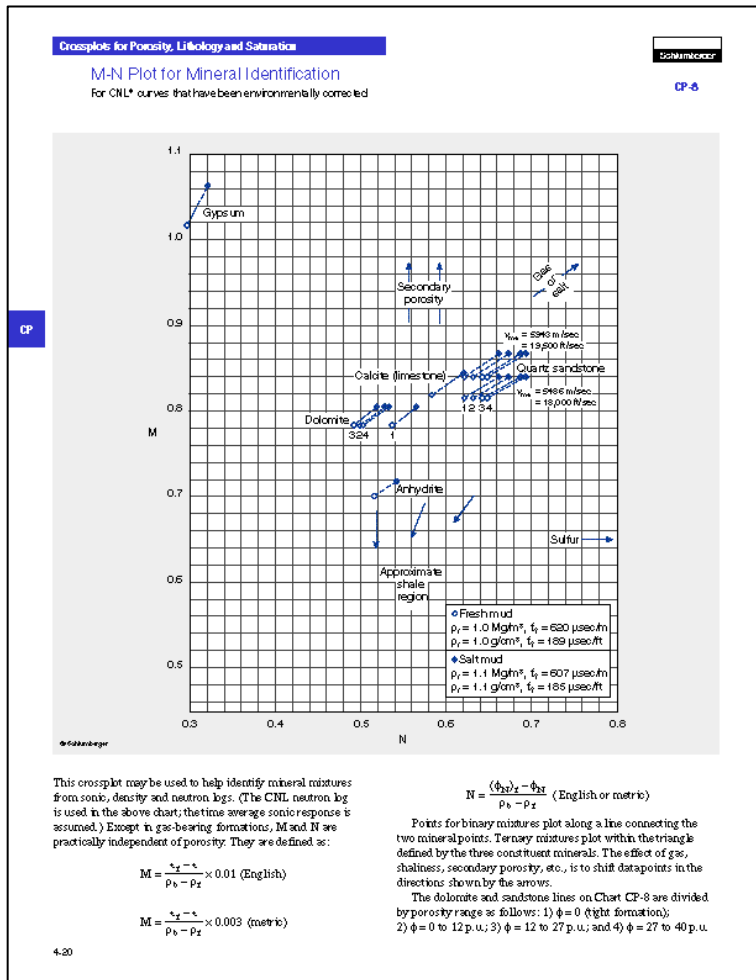
Density-Photoelectric crossplot



- Advantage:
 - Both measurements are made with the same logging tool; both will be available in newer wells
- Disadvantage:
 - The choice of the lithology pair has a significant effect on the estimation of the porosity
 - In rough holes or in heavy drilling mud the data may be invalid
 - The P_e will not be present in wells logged before 1978



M-N Lithology plots



- Three-measurement lithology technique
- Combination of the three porosity measurements
- Single mineralogy
- Binary mixtures
- Ternary mixtures

$$M = \frac{\Delta t_f - \Delta t}{\rho_b - \rho_f} \times 0.01 \text{ or } 0.003 \quad N = \frac{\phi_{Nf} - \phi_N}{\rho_b - \rho_f}$$

English Metric

Δt = from log

Δt_f = formation fluid

ρ_b = from log

ρ_f = formation fluid

ϕ_N = from log

ϕ_f = fluid, usually 1.0



Lithology and Porosity

- Result:
 - Approximate idea of Lithology
 - Value for the Total Porosity
- But...
 - We want a value for the Effective Porosity

$$\phi_e = \phi_t \times (1 - V_{sh})$$



Volume of shale

- The volume of shale in a sand is used in the evaluation of shaly sand reservoirs.
- It can be calculated by
 - Spontaneous Potential
 - Gamma Ray



V_{sh} by SP

$$V_{sh} = 1.0 - \frac{PSP}{SSP}$$

or

$$V_{sh} = \frac{PSP - SSP}{SP_{shale} - SSP}$$

- With
 - PSP, Pseudostatic Spontaneous Potential (max. SP of shaly formation)
 - SSP, Static Spontaneous Potential of a nearby thick clean sand
 - SP_{shale} , value of SP in shale, usually assumed to be zero



PSP definition

- **pseudostatic spontaneous potential**

1. *n.* [Formation Evaluation]

The ideal spontaneous potential (SP) that would be observed opposite a shaly, permeable bed if the SP currents were prevented from flowing. In the middle of a thick, permeable bed whose resistivity is not too high, the SP reads close to the pseudostatic spontaneous potential (PSP). In other conditions, however, the SP may be significantly less than the PSP. The PSP ignores other potential sources and assumes that a surrounding shale is a perfect cationic membrane. The ratio of the PSP to the static spontaneous potential is known as the SP reduction factor, alpha. Alpha is less than 1 and is a function of the shaliness, or cation-exchange capacity, within the sand. The higher this cation-exchange capacity, the larger the internal membrane potential. The latter has the opposite polarity to the liquid-junction potential and reduces the SP.

The PSP, and alpha, are reduced when hydrocarbons are introduced into shaly sands, because the cation-exchange capacity in the sands is forced into a smaller conductive pore volume and therefore has a larger relative effect.

Conclusion: PSP is difficult to determine



V_{sh} by GR

Gamma Ray Index

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

I_{GR} = Gamma Ray index

GR_{log} = GR reading from the log

GR_{min} = minimum GR

GR_{max} = maximum GR

$V_{shale} = I_{GR}$, Linear response, 1st order estimate

$V_{shale} = 0.08(2^{3.7 \cdot I_{GR}} - 1)$, Larionov (1969), Tertiary rocks

$V_{shale} = \frac{I_{GR}}{3 - 2 \times I_{GR}}$, Steiber (1970)

$V_{shale} = 1.7 - [3.38 - (I_{GR} - 0.7)^2]^{1/2}$, Clavier (1971)

$V_{shale} = 0.33 \times (2^{2 \cdot I_{GR}} - 1)$, Larionov (1969), for older rocks

