

15. THE NEUTRON LOG

15.1 Introduction

The *neutron log* is sensitive mainly to the amount of hydrogen atoms in a formation. Its main use is in the determination of the porosity of a formation.

The tool operates by bombarding the formation with high energy neutrons. These neutrons undergo scattering in the formation, losing energy and producing high energy gamma rays. The scattering reactions occur most efficiently with hydrogen atoms. The resulting low energy neutrons or gamma rays can be detected, and their count rate is related to the amount of hydrogen atoms in the formation.

In formations with a large amount of hydrogen atoms, the neutrons are slowed down and absorbed very quickly and in a short distance. The count rate of slow neutrons or capture gamma rays is low in the tool. Hence, the count rate will be low in high porosity rocks.

In formations with a small amount of hydrogen atoms, the neutrons are slowed down and absorbed more slowly and travel further through the rock before being absorbed. The count rate of slow neutrons or capture gamma rays in the tool is therefore higher. Hence, the count rate will be higher in low porosity rocks.

Figure 15.1 shows a typical neutron tool.

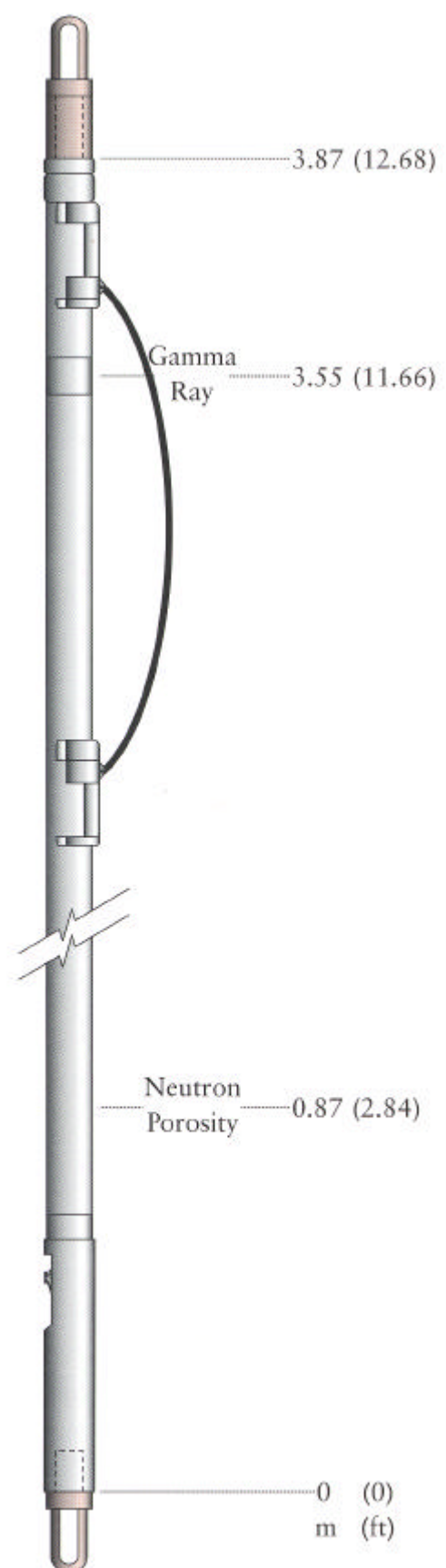


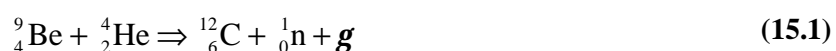
Figure 15.1 A typical neutron tool.

15.2 Theory

In neutron logging there are three processes of interest: neutron emission, neutron scattering and neutron absorption.

15.2.1 Neutron Emission

The neutron tool emits high energy (4.5 MeV) neutrons from a radioactive source. They move very fast, and their energy is related to their speed. They are called *fast neutrons*. The neutron sources used in logging are a mixture of two elements (i) a source of alpha radiation such as radium, plutonium or americium, and (ii) beryllium-9. The alpha particles from the radium, plutonium or americium interact with the beryllium-9 in an atomic reaction that produces carbon-12, a fast neutron and gamma rays.



15.2.2 Neutron Scattering

The fast neutrons interact with the nuclei of atoms within the formation. The interaction is a form of elastic scattering involving the neutrally charged neutron and a stationary positively charged nucleus. At each interaction (collision) the neutron loses some energy and slows down, and the nucleus of the atom in the formation material gains energy. Such collisions occur with nuclei of ALL elements. However, the process of energy transfer (i.e., energy loss from the neutron) is most efficient when the masses of the neutron and the nucleus are the same, and becomes much less efficient when the nuclei of the formation material are more massive than the neutron. The neutron has approximately the same mass as hydrogen nuclei (the lightest element). Hence the neutrons lose energy by elastic scattering most efficiently by interaction with hydrogen nuclei, and lose energy much less efficiently by interaction with more massive nuclei such as silicon or oxygen. Figure 15.2 shows the efficiency of several elements in slowing down fast neutrons.

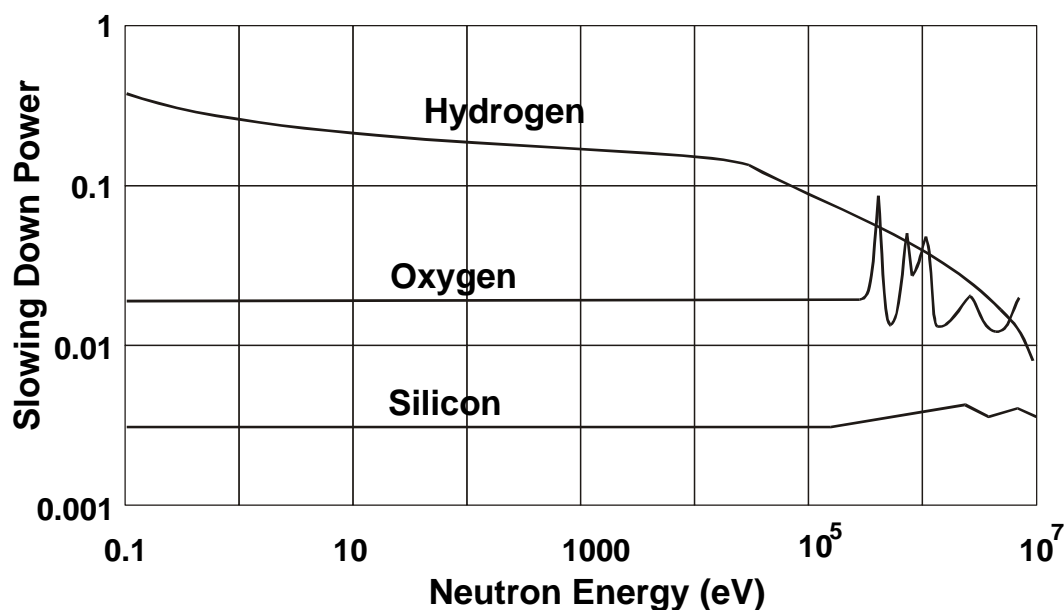


Figure 15.2 The fast neutron slowing efficiency of hydrogen, silicon and oxygen atoms as a function of neutron energy for a clean sandstone, $f = 0.15$.

The initially fast neutrons (>0.5 MeV) quickly lose their energy and become slower (Fig. 15.3), passing through stages called *intermediate neutrons* (10^2 to 10^5 eV), *epithermal neutrons* (0.1 to 100 eV), and finally *thermal neutrons* (<0.1 eV). In solid materials containing reasonable amounts of low atomic mass elements, this process can happen very quickly for a given neutron (of the order of microseconds). However, the time taken to slow down to a given energy will vary from neutron to neutron, depending on the chance collisions with nuclei. Thermal neutrons are so called because they have energies which are those that a particle has as a result of it existing at room temperatures. In other words, they only have the small energies associated with the random kinetic motion associated with room temperatures.

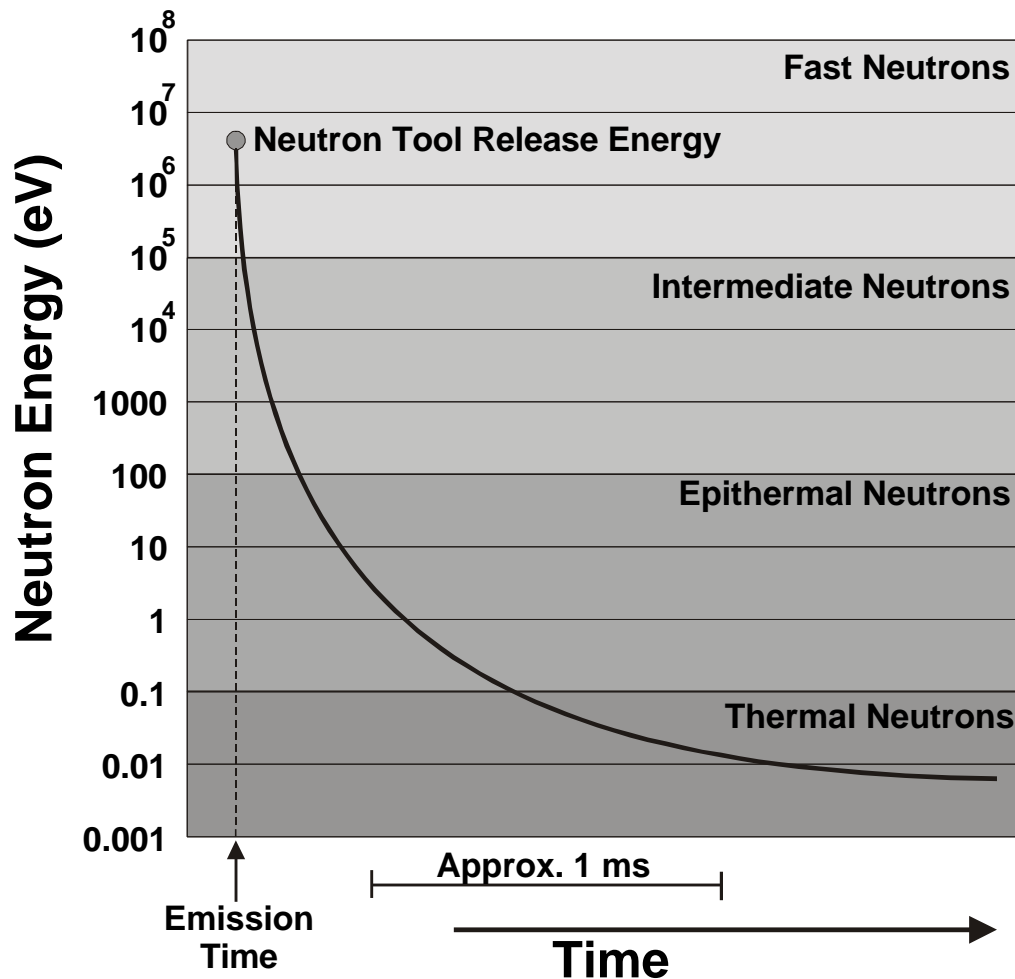


Figure 15.3 The slowing of fast neutrons with time by elastic collision with formation nuclei.

When the neutrons attain epithermal or thermal energies, collisions occur much less frequently because the neutrons are moving from nucleus to nucleus much more slowly. Within a few microseconds of being exposed to the fast neutron source, the formation has slowed the incoming neutrons down to epithermal and thermal levels, and a cloud of these thermal neutrons exists in the formation surrounding the source. Collisions continue resulting in little further loss of energy and the slow diffusion of the thermal neutrons from the zone around the detector. During this process the neutrons are absorbed by the formation nuclei.

15.2.3 Neutron Absorption

Thermal (and to some extent epithermal) neutrons can be absorbed by the nuclei of the formation atoms. The efficiency of neutron absorption varies from element to element. The only elements which exhibit significant neutron absorbing behaviour and exist in reasonable quantities in rocks are hydrogen and chlorine. The process of neutron absorption by hydrogen and chlorine are



and



In neutron logging, some tools measure the epithermal neutrons, some the thermal neutrons and some the gamma rays emitted when a neutron is absorbed.

15.2.4 Hydrogen Index

We can define a partial concentration of hydrogens per unit mass $(C_H)_{mass}$ of a material as the mass of hydrogen atoms in the material divided by the mass of all the atoms of all elements in the material.

$$(C_H)_{mass} = \frac{n_H A_H}{\sum_i n_i A_i + n_H A_H} \quad (15.4)$$

where: A_H = the atomic mass of hydrogen atoms in the material
 A_i = the atomic mass of non-hydrogen element i
 n_H = the number of hydrogen atoms in a molecule of the material
 n_i = the number of non-hydrogen atoms of element i in a molecule of the material
Note: i is summed over every non-hydrogen element in the material.

Thus, for pure water (H₂O), where the atomic mass of hydrogen is 1.0 and the atomic mass of oxygen is 16.0, the partial concentration of hydrogen $(C_H)_{mass} = (2 \times 1.0) / (1 \times 16.0 + 2 \times 1.0) = 1/9$.

It is simple to obtain the partial concentration of hydrogens per unit volume $(C_H)_{vol}$, by multiplying the partial concentration of hydrogens per unit mass by the density of the material, $(C_H)_{vol} = \mathbf{r}_b \times (C_H)_{mass}$. Hence, the partial concentration of hydrogens per unit volume $(C_H)_{vol} = \mathbf{r}_{bwater} / 9 = 1/9$, because the density of pure water is 1.000 g/cm³.

Now, the *Hydrogen Index* of a material is defined as the partial concentration of hydrogens per unit volume *relative to water*. So, if the hydrogen index of water is constrained by the definition to be unity, and water has a partial concentration of hydrogens per unit volume of 1/9, the hydrogen index of a material is

$$HI = \frac{9 n_H A_H}{\sum_i n_i A_i + n_H A_H} \mathbf{r}_b \quad (15.5)$$

where: A_H = the atomic mass of hydrogen atoms in the material
 A_i = the atomic mass of non-hydrogen element i

n_H = the number of hydrogen atoms in a molecule of the material
 n_i = the number of non-hydrogen atoms of element i in a molecule of the material
Note: i is summed over every non-hydrogen element in the material.

Table 15.1 shows Eq. (15.5) in practice for a few minerals and fluids commonly found in reservoirs.

Table 15.1 Hydrogen index calculations for some reservoir minerals and fluids.

Compound	Formula	A_i	n_i	n_H	r_b	HI
Pure water	H ₂ O	16	1	2	1.000	1.000
Oil	(CH ₂) _x	12	1	2	0.780	1.003
Methane	CH ₄	12	1	4	r_m	$2.25 \times r_m$
Gas	C _{1.1} H _{4.2}	12	1.1	4.2	r_g	$2.17 \times r_g$
Quartz	SiO ₂	28, 16	1, 2	0	2.654	0.000
Calcite	CaCO ₃	40, 12, 16	1, 1, 3	0	2.710	0.000
Gypsum	CaSO ₄ .2H ₂ O	40, 32, 16	1, 1, 6	4	2.320	0.4855

Note the following:

- If the tool is in 100% water (a large tank of the stuff, say), the $HI = 1.000$. This is equivalent to a rock of 100% porosity saturated with water. So we have a fixed point that $HI = 1$ represents $f = 1$.
- If the tool is in a pure limestone rock with zero porosity, the $HI = 0.000$, because there are no hydrogen atoms in the solid matrix of calcite. So we have a second fixed point where $HI = 0$ represents $f = 0$.
- If the tool is in a pure limestone with a given porosity f , the hydrogen index will be directly proportional to the amount of water in the formation. Hence $HI = f$ for completely water saturated limestones.

Thus the hydrogen index is a proxy measure of porosity if the solid minerals of the formation contain no hydrogen and if the pores are completely saturated with water. But, it is the hydrogen index that controls the count rate observed by the neutron tool. Hence we have a tool that can measure porosity in water saturated formations where the matrix minerals contain no hydrogen.

In practice, it is not only hydrogen that affects the passage of neutrons in a formation. As we can see from Fig. 15.2, other rock forming elements have an effect on the slowing down of neutrons in the formation, but their effect is small compared with hydrogen, and when it comes to neutron absorption, both chlorine and hydrogen have a part to play. The small errors that are introduced by assuming that it is just hydrogen that affects neutrons are overcome by calibrating the tool. The tool is calibrated in pure limestone, and hence does not give true porosities. Instead it gives equivalent porosities that would occur if the rock was measuring limestone. This will be discussed in further detail in Section 4.

The Hydrocarbon Effect. Note in Table 15.1 that the hydrogen indices of water and oil are approximately the same because the effect of their different compositions on the partial concentration of hydrogens per unit volume is approximately balanced by the difference in their density.

As with the formation density tool, the zone of investigation of the neutron tool is constrained to the flushed zone. Hence, the tool will measure the hydrogen index associated mainly with the mud filtrate,

together with whatever remains of the hydrocarbons and formation water in the formation. Imagine, for example that we are in an oil zone in a limestone, the mud filtrate almost completely replaces the formation fluids such that there is a saturation of mud filtrate S_{XO} , and a residual saturation of hydrocarbons $(1 - S_{XO})$. The porosity read by the neutron tool is related to the actual porosity in the formation by

$$f_N = f [HI_{mf} S_{XO} + HI_{hc} (1 - S_{XO})] \quad (15.5)$$

If the hydrocarbon is oil, this equation reduces to $f_N \approx f$, because, as we have seen in Table 15.1 the hydrogen index of water and oils is similar; $HI_{mf} \approx HI_{hc}$. This is true whether the mud filtrate is oil-based or water-based.

$$f_N = f [1.00 \times S_{XO} + 1.003 \times (1 - S_{XO})] \approx f \quad (15.6)$$

If the hydrocarbon is methane gas with a density of 0.1 g/cm^3 , the equation reduces to

$$f_N = f [1.00 \times S_{XO} + 2.25 \times 0.1 \times (1 - S_{XO})] \quad (15.7)$$

If the saturation in the flushed zone $S_{XO} = 0.7$, Eq. (15.7) reduces to $f_N = 0.77 f$. This is known as the *hydrocarbon effect in the neutron log*.

The Chlorine Effect. Some types of neutron tool measure the thermal neutrons and gamma rays produced during the capture of neutrons. There are only two elements that are found in reservoirs that contribute significantly to neutron absorption; hydrogen and chlorine. The presence of hydrogen in the fluids is what we want to measure, so this is not a problem.

However, if the drilling mud, mud filtrate or formation fluids contain a significant amount of dissolved chloride ions, as is often the case, the tool will measure a lower flux of neutrons and hence overestimate the porosity. This is called the *chlorine effect*, and is present in wells drilled or logged in the presence of drilling muds containing dissolved chlorine, or in formations where the formation waters are particularly salty.

The Shale Effect. Shale contain clays that have a significant amount of surface absorbed (bound) water. Hence shales can contain a significant proportion of hydrogens despite being low porosity. The apparent porosity read from the neutron tool in shale formations is therefore always significantly higher than it really is. This is called the *shale effect* or the *bound-water effect*, and will be discussed further later in this chapter.

15.3 Tool Operation

There are three main types of neutron tool, which are:

- The Gamma Ray/Neutron Tool (GNT)
- The Sidewall Neutron Porosity Tool (SNP)
- The Compensated Neutron Log (CNL)

15.3.1 *Gamma Ray/Neutron Tool (GNT)*

This tool has a neutron source and a single detector that is sensitive to high energy capture gamma rays and thermal neutrons and is non-directional. The tool can be run in either open or cased holes, and in both cases is run centered. A 3-3/8 inches diameter tool is used in open holes, and a 1-11/16 or 2 inch diameter tool is used in cased holes. The source to detector spacing varies between tool manufacturers, but is in the range 15.5 to 19.5 inches. Because the tool is centered, the detected neutrons and gamma rays have to travel through both mudcake and drilling mud. Hence, this tool is highly sensitive to changes in borehole quality, temperature, type of drilling mud, and mudcake thickness. Correction curves are available from the tool manufacturers to correct the log data for temperature, hole diameter, and the effect of drilling mud and mudcake.

Because the tool measures the thermal neutrons and the capture gamma rays, it is effected by the process of neutron capture by chlorine. Since drilling mud, mud filtrate and formation waters may contain significant amounts of dissolved chloride ions, the measurement can give erroneous values. Erroneous values take the form of overestimated porosities in formations either drilled with muds containing dissolved chloride ions, or salty formation fluids.

15.3.2 *Sidewall Neutron Porosity Tool (SNP)*

This tool is designed for use in open holes only. The tool has a source and a single detector with a 16 inch spacing, which are mounted on a skid that is pressed against the borehole wall. Often this will be the same carrier that holds the formation density source and detector. Because the tool is pressed against the borehole wall, the drilling mud does not affect the measurement, and the attenuation due to the mudcake is reduced. However rough holes can cause misalignment of the either the source of the detector with the borehole wall, and hence give erroneous readings.

The detector is sensitive to epithermal neutrons. These neutrons are not yet slow enough to take part in absorption reactions with hydrogen and chlorine. Hence, the SNP tool readings are unaffected by the presence of chlorine in high salinity muds and formation fluids.

15.3.3 *Compensated Neutron Log (CNL)*

This tool is designed to be sensitive to thermal neutrons, and is therefore affected by the chlorine effect. It has two detectors situated 15 in and 25 in from the source. The detector further from the source is larger to ensure that adequate count rates are observed. The critical measurement for this tool is the difference in the thermal neutron population, which results from neutron capture and neutron scattering. The tool readings are presented in limestone porosity units in the same way as the sidewall neutron porosity tool. The CNL tool has a very strong source of neutrons to ensure that the measured count rates are sufficiently high to obviate any significant errors associated with statistical fluctuations

in the count rate despite the longer source-detector spacing for this tool compared to the GNT and SNP tools. The stronger source permits a deeper depth of investigation as well as allowing the tool to operate in cased holes. The CNL tool is run eccentric in the hole by an arm which presses the tool against the side of the borehole. This means that the tool is insensitive to the type of mud in the hole, but implies that the readings are only for one portion of the borehole wall. The CNL log is shown in Fig. 15.4.

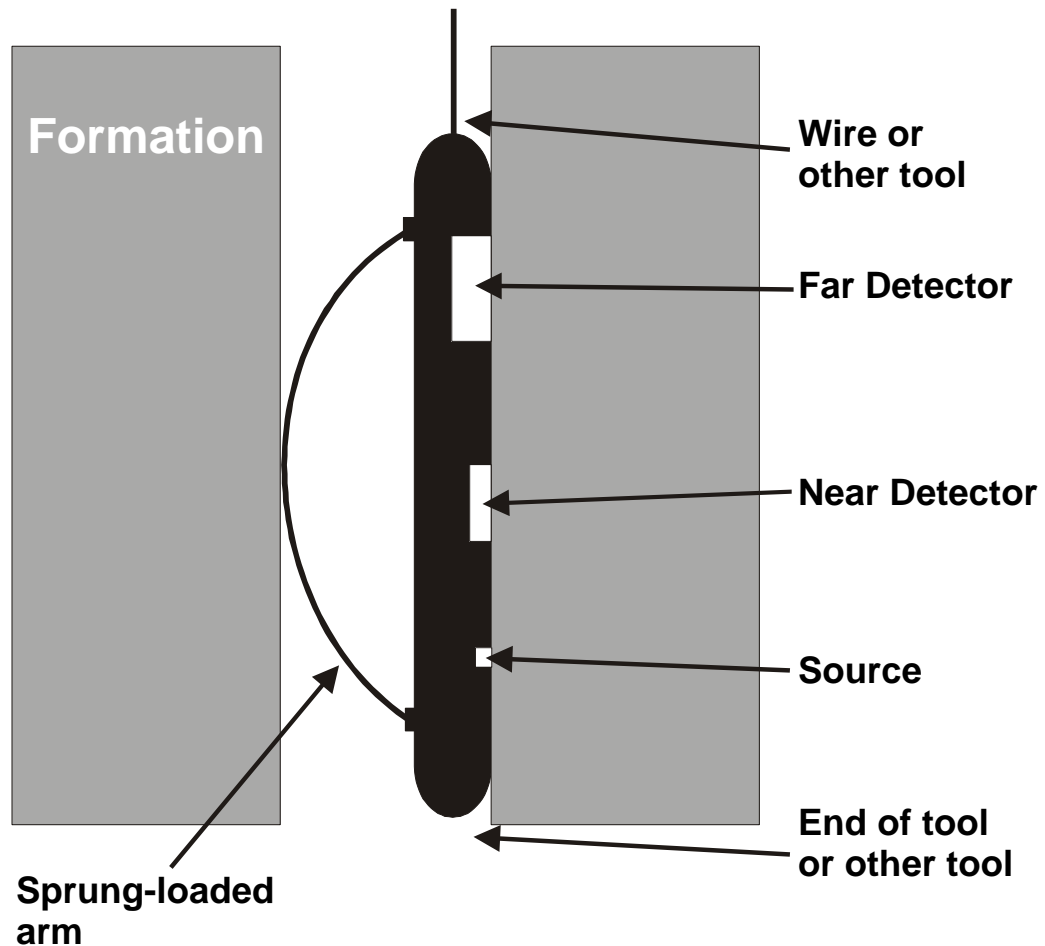


Figure 15.4 The CNL tool (Schlumberger).

15.4 Log Presentation

The data from all tool types are recorded in tracks 2 and 3.

The data from the GNT tool is given in API units as shown in Fig. 15.5.

The data from the SNP tool is given in equivalent limestone porosity units, with the scale running from approximately -10% to 30%, as shown in Fig. 15.6.

Data from the CNL tool is given in equivalent limestone porosity units, with the scale running from approximately -10% to 30%, as shown in Fig. 15.7.

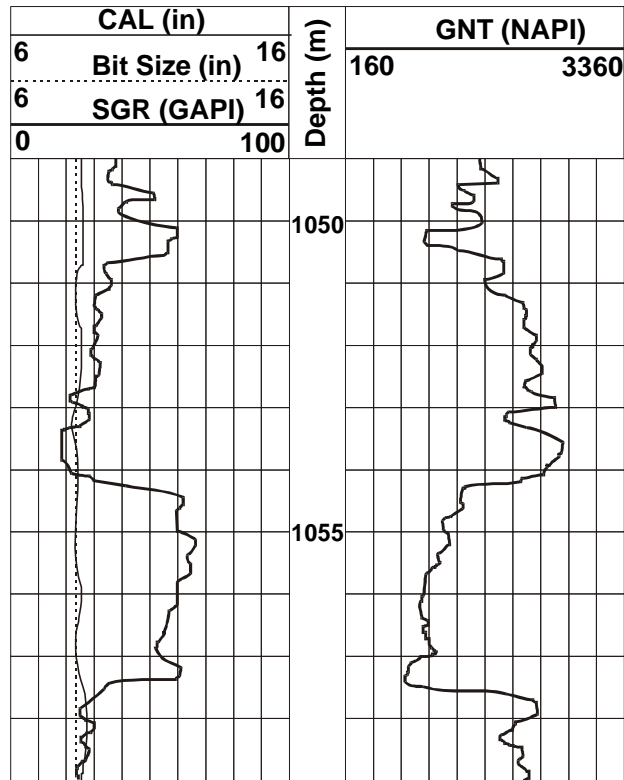


Figure 15.5 Log presentation for the GNT tool.

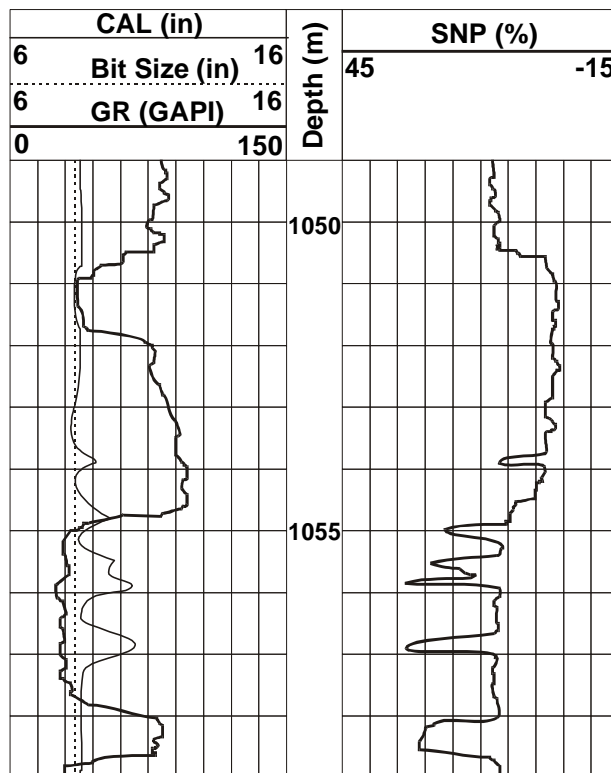


Figure 15.6 Log presentation for the SNP tool.

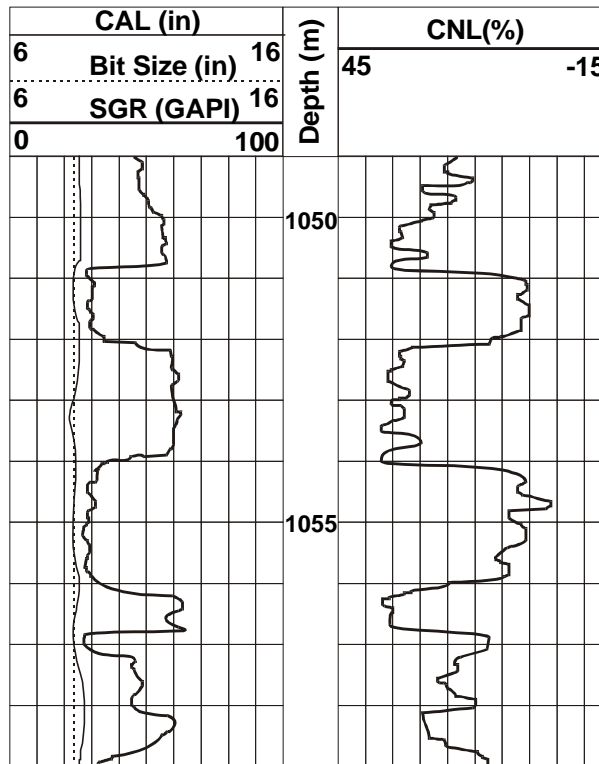


Figure 15.7 Log presentation for the CNL tool.

15.5 Calibration

15.5.1 The GNT Tool

The primary standard for this tool is the API Neutron Calibration Pit at the University of Houston. This pit contains three blocks of carbonate with accurately known porosities that are filled with fresh water that are drilled to accept a tool. The tool is calibrated in 19% porosity Indiana limestone, for which an API value of 1000 API neutron units is defined. The response of the tool is then checked in 1.9% Carthage Marble, 26 % Austin limestone, and 100% fresh water. A tool tested at Houston is used as a secondary reference for the calibration of other tools at the wireline company's workshops around the globe. A wellsite check on the calibration of a tool is also carried out before and after running the tool using a neutron source of accurately known radioactivity.

15.5.2 The SNP and CNL Tools

These tools are calibrated in blocks of limestone, sandstone and dolomite of high purity and accurately known porosity in test pits. The tools are calibrated, not to give readings in API neutron porosity units, but to give the porosity directly in percent. Limestone is chosen as the calibrating lithology, so the readings are given in limestone porosity units.

IMPORTANT The common use of limestone porosity units as the calibrating unit for these logs means that the reading of porosity in a limestone formation will be exact, but the reading of porosity in these units in any other formation lithology will need correction (Fig. 15.8).

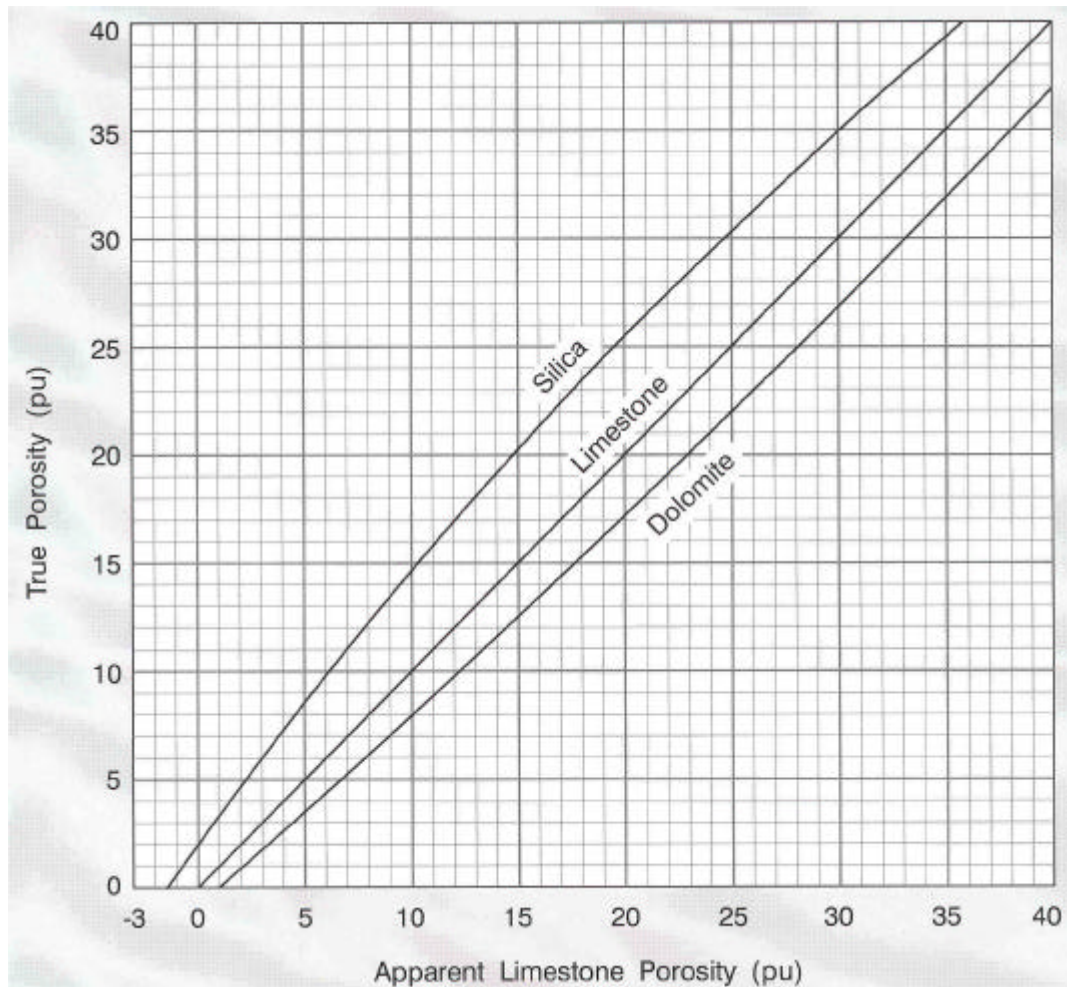


Figure 15.8 Correction chart for obtaining porosity values for lithologies other than limestone.

The SNP tool is calibrated at the wellsite uses a U-shaped polyethylene baffle (artificial formation) with a two position baffle, where the geometry of the block and baffle arrangements are known to result in readings equivalent to 11% porosity and 22% porosity.

The calibration of the CNL tool is checked at the wellsite before and after each logging run by the use of a neutron source of accurately known activity placed a standard distance from each detector.

15.6 Depth of Investigation

The depth of penetration of the tool readings depends directly upon the amount of hydrogens in the formation. Thus, for porous rocks that contain water or hydrocarbons (i.e., many hydrogens), there is much neutron scattering and absorption, and hence the depth of investigation is small. For low porosity rocks containing water or hydrocarbons, there are fewer hydrogens in the formation and the depth of investigation is larger.

The presence of gas in a formation increases the depth of investigation because, although the gas may contain hydrocarbons, the gas has a very low density compared to liquid water and oil, and hence a very low hydrogen index.

The presence of shales decreases the depth of investigation because even low porosity shales contain many waters (i.e., hydrogen) that are bound to the surface of the clay crystals.

The depth of investigation of the CNL tool in a water saturated formation of 35% porosity is about 12 inches, and that of the SNP tool in the same formation is about 8 inches.

15.7 Vertical Resolution

As with most tools the vertical resolution is defined by the source detector spacing for single detector tools and the spacing between the two detectors for dual detector tools. The vertical resolution of neutron tools is a little greater than these spacings. For the GNT tool the vertical resolution is 16 inches or 20 inches depending upon which of the two source-detector spacings possible for this tool are used. The vertical resolution of the SNP tool is 16 inches, and for the CNL tool is 10 inches.

As usual, the true bed resolution (the thinnest bed for which the true neutron porosity reading in that bed is measured) is approximately three times the vertical resolution (i.e., 36 to 48 inches). Thinner beds will be noticed by the tool, but the apparent porosity will not be the same as the true porosity of the bed.

The measuring point for these tools is half way between the source and the detector for single detector tools, and half way between the two detectors for the dual detector tool.

15.8 Borehole Quality

The GNT tool is run centered in the borehole, and is therefore sensitive to the effect of caving and wash-out due to the attenuation of gamma rays and neutrons by the larger annulus of drilling mud around the tool. As the diameter of the borehole increases, more of the signal that the tool measures represents the borehole, and less comes from the formation. Clearly, there is a degree of caving where the signal measured by the tool is no longer representative of the formation, and then the tool cannot be used. This problem is accentuated by the presence of chloride ions in the drilling mud (i.e., a salt water-based mud), where attenuation by the drilling mud can lead to grossly erroneous porosity readings.

The SNP and CNL tools are run pressed up against the borehole wall. In this case, the roughness of the borehole wall due to caving or wash-out can result in the detectors or source not being pressed directly up against the borehole wall. This will cause erroneous porosity readings.

15.9 Mud Type

The tools can be used in most types of mud.

The GNT tool is sensitive to chloride-rich muds, and its results must then be corrected for the drilling mud, mudcake and mud filtrate.

The SNP tool is not sensitive to the chloride effect and is run pressed against the borehole wall. The mudcake tends to increase the apparent porosity because the mudcake has a high hydrogen index. This effect can be corrected for.

The detectors of the CNL tool are sensitive to the chloride effect. However, the tool is run pressed against the borehole wall so the effect of the drilling mud is not included in the measurement. Furthermore, the use of two detectors automatically compensates for the effect of chloride-rich mudcake and mud filtrate.

The density of the mud also affects the readings, because high density muds attenuate the radiation to a greater extent. This is usually only a problem for the GNT tool, where the effect can be compensated for using correction charts.

15.10 Uses of the Neutron Log

15.10.1 Determination of Porosity

The main use of the neutron log is to provide porosity information.

The tool is sensitive to the amount of hydrogens in the formation and to a less extent upon other elements. It is assumed that the contribution to the measurement by elements other than hydrogen is negligible, and that the contribution to the measurement from hydrogen comes entirely from the fluids fully occupying the pore space.

However, in real rocks elements other than hydrogen that exist in the rock matrix do contribute to the measurement (e.g., chlorine in formation water, mud filtrates and in some evaporite formations), and hydrogen is present in the matrix (e.g., bound water in shales).

The problem is partially overcome by calibrating the tool to give the porosity in limestone units. Pure limestone saturated with fresh water is chosen because it contains no elements which contribute significantly to the measured signal other than hydrogen.

The porosities that are read by the tool are accurate in limestone formations that contain fresh water.

The porosities that are read by the tool in other lithologies or with other fluids need to be corrected by a chart such as that shown in Fig. 15.8.

There are three effects that are not corrected for in the log data, that need to be briefly mentioned.

The Hydrocarbon Effect. The presence of hydrocarbon liquid (oil) does not effect the tool response as it has approximately the same hydrogen index as fresh water. Hydrocarbon gas, however, has a much lower hydrocarbon index resulting from its low density, and its presence will give rise to *underestimations* in porosity (Fig. 15.9).

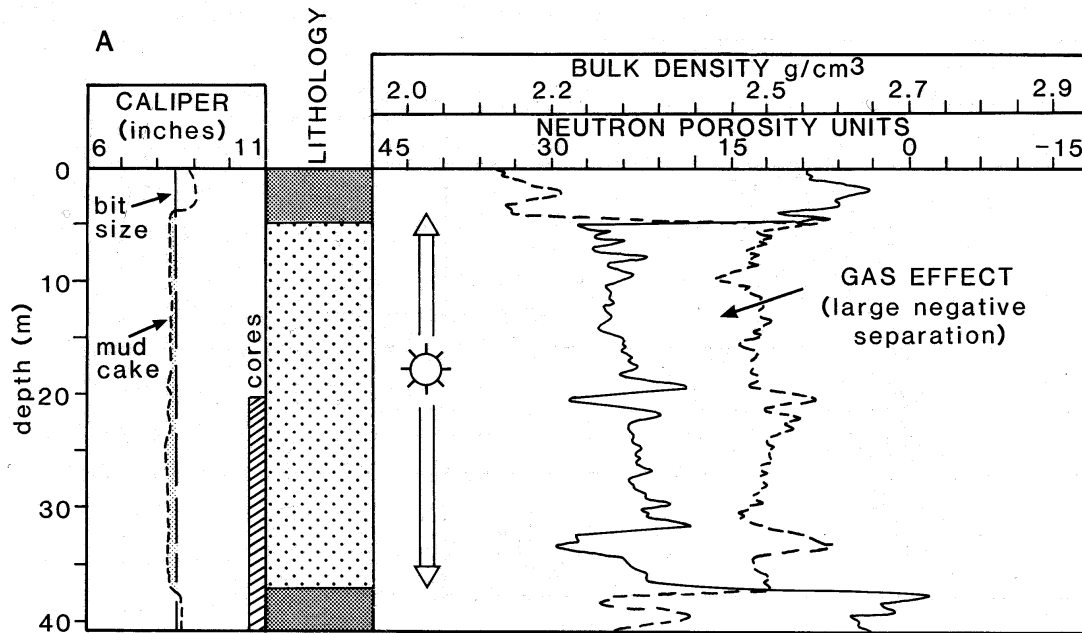


Figure 15.9 The Hydrocarbon gas effect in the neutron log.

The Shale Effect. Shale contain clays that have a significant amount of bound water molecules on their surfaces. This increases the hydrogen index of the formation. Even very low porosity shales can give erroneously high porosity readings due to the presence of these bound waters.

The Chloride Effect. Chlorine is a good absorber of neutrons, and can lead to overestimations of porosity if present either as formation fluid or mud filtrate.

15.10.2 Determination of Lithology

The direct use of the neutron log to identify lithologies depends upon the recognition of which lithologies may contain hydrogen atoms (Table 15.2).

Table 15.2 Lithological and fluid indicators for the neutron tool.

Type	Examples
Fresh and salt water	Formation water Drilling mud Mudcake Mud filtrate
Hydrocarbons	Gasses Oils Oil-based drilling mud Oil-based mud filtrate Oil-based mudcake Coal Organic-rich deposits
Bound water	Shales
Water of Crystallization	Evaporites
Hydrated minerals	Igneous and metamorphic rocks

Figure 15.10 shows typical log responses in common lithologies.

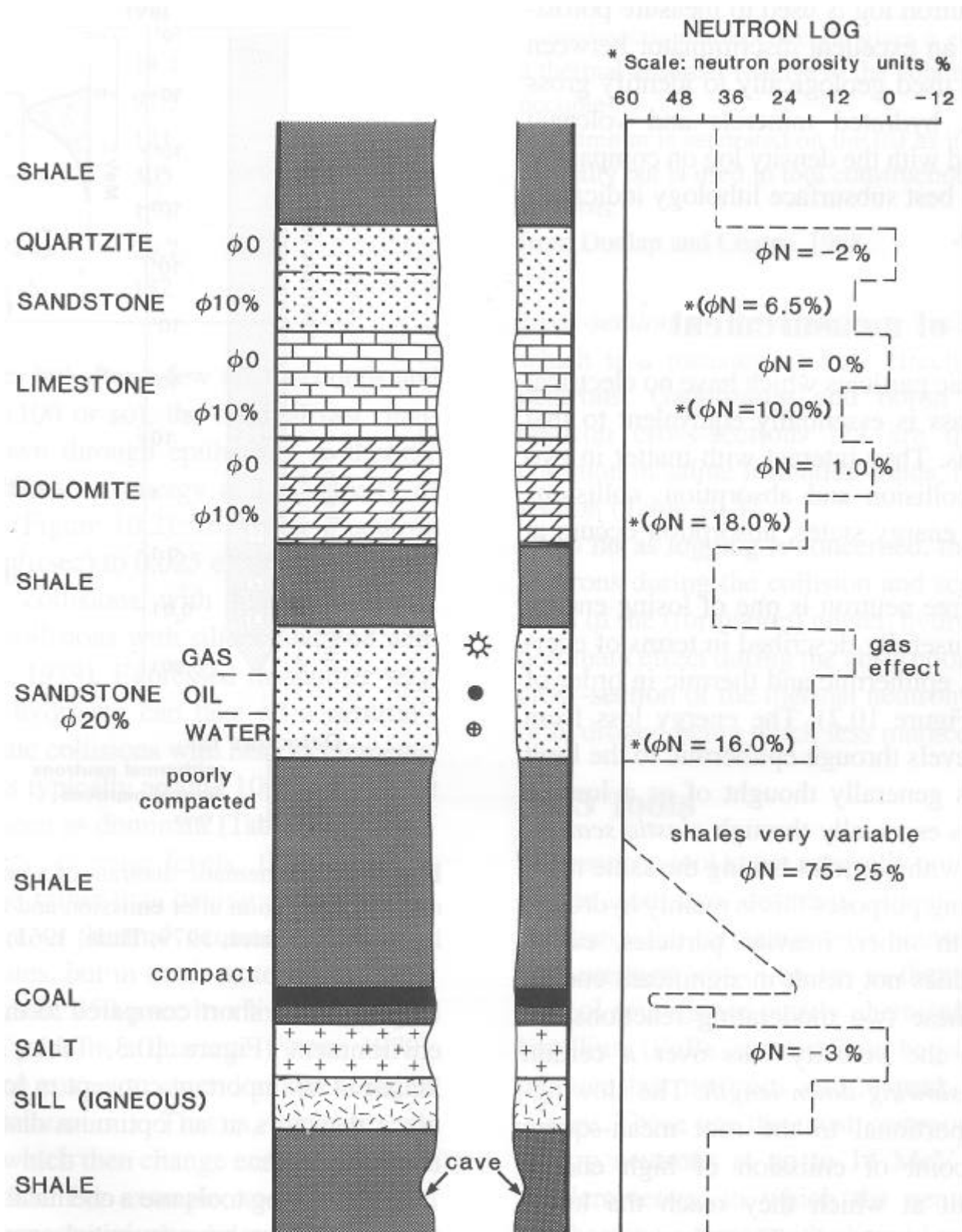


Figure 15.10 Typical neutron log responses in common lithologies.

The values of apparent porosity in shales varies considerably, but is usually higher than the apparent porosity in carbonate or sandstone rocks (i.e., 45 to 75%). This clearly high and unrealistic porosity is a partial indicator of shale, and can become diagnostic when combined with the gamma ray log. One may see a slight decrease in the apparent porosity in shales due to compaction, but only over large depth intervals.

The apparent neutron limestone porosity is affected by the amount of shale and sand, or shale and limestone in a mixture of the two. Hence we can recognize coarsening-up and fining-up sequences in the neutron log (Fig. 15.11). While one can calculate a shale volume from the neutron log directly, it is not recommended because of the effect of hydrocarbon gasses which may be present to disturb the log.

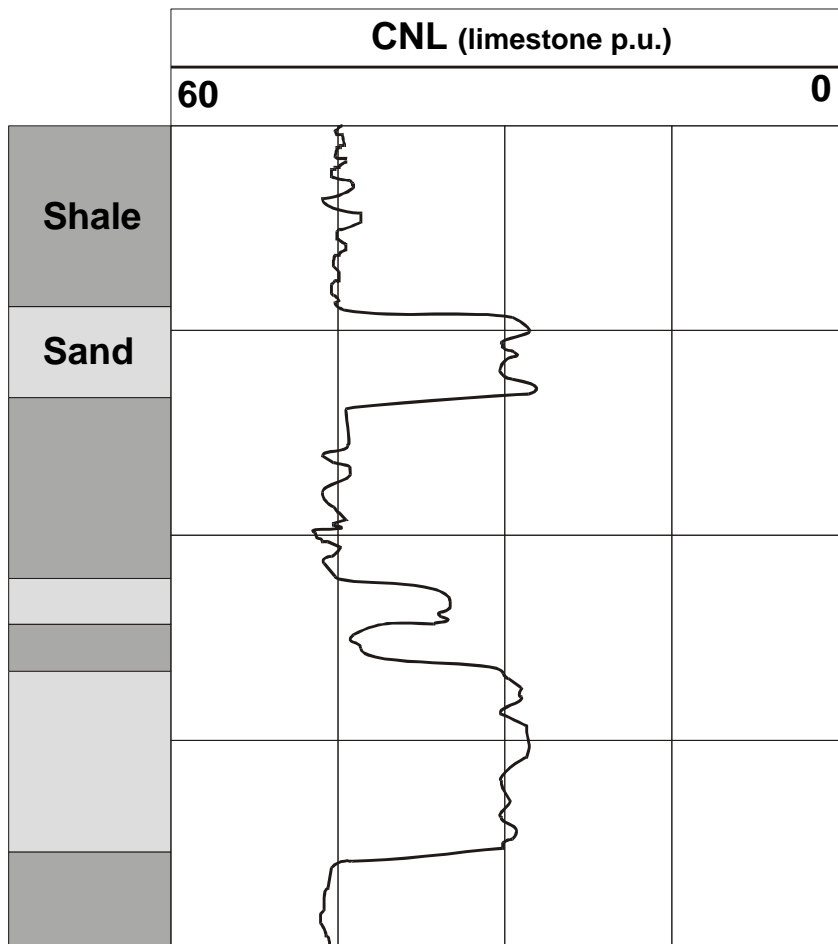


Figure 15.11 The neutron log response to mixtures of shales and sandstones.

Organic mater, often present in shales may cause an even higher apparent neutron limestone porosity than the bound water in the shales alone (Fig. 15.11).

The neutron log can detect evaporites by either their waters of crystallization. The most common example is gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), but also include kainite, carnalite and polyhalite. The first three of these give apparent limestone porosities of about 60%, while polyhalite give about 25%. The apparent limestone porosities for halite, anhydrite, and sylvite are very low (-3, -2, and -3 respectively) as they contain no water. Note that there is no effect of the chlorine atom in halite or sylvite (Fig. 15.12).

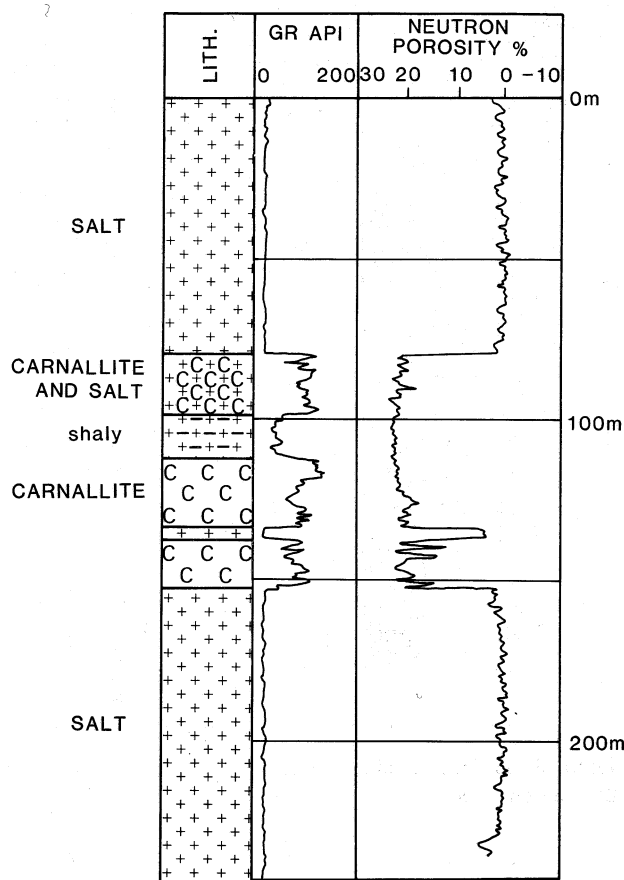


Figure 15.12 The neutron log response to evaporites (after Rider, 1997).

Hydrated minerals are not common in basins. The only occurrence is occasional chamosite in Liassic shales in the North Sea. Hydrated minerals may be seen in neutron logs used for non-hydrocarbon purposes, such as geothermal reservoir assessment in metamorphic and igneous provinces. However, volcanic and intrusive rocks show high apparent neutron porosities due to hydrated minerals, and these horizons in reservoirs can be very useful for correlation purposes.

15.11 Lithological Identification using the Neutron-Density Combination

15.11.1 Compatible Scales and the Density-Neutron Cross-plot

This is a hugely important technique, and together with the litho-density log forms the best downhole lithological identification technique available to the petrophysicist.

Both the formation density log and the neutron log give a direct measurement of TOTAL porosity. Hence, if they are plotted on compatible scales, they should overlie each other (Fig. 15.13).

Note that the compatible scale here is Density (1.95 to 2.95 g/cm³) and Neutron (-15 to 45% limestone porosity units). This is the most commonly used scale range, although other wider or more restricted ones are possible.

Note also that good superimposition will ONLY occur for clean limestone formations 100% saturated with fresh water.

To construct a compatible scale we follow the following steps:

- For limestone with 0% porosity, the density log reads 2.71 g/cm³ and the neutron log reads zero.
- For limestone with 100% porosity, the density log reads 1.00 g/cm³ and the neutron log reads 100.

These two points can be plotted on a graph of density (from the density log) on the y-axis against neutron porosity (from the neutron log) on the x-axis. We can join up the two points with a straight line, and calibrate the line for porosity (Fig. 15.14). The graph is called the *density-neutron crossplot* and the line is called the *clean limestone line*.

The clean limestone line only works for clean limestones because of the effect of non-hydrogen elements in the matrix on the neutron porosity values, and the different grain densities. However, we can take account of the different densities and correct the neutron porosity units using Fig. 15.8, to obtain lines of the cross-plot for clean sandstones and clean dolomite, the *clean sandstone* and *clean dolomite* lines.

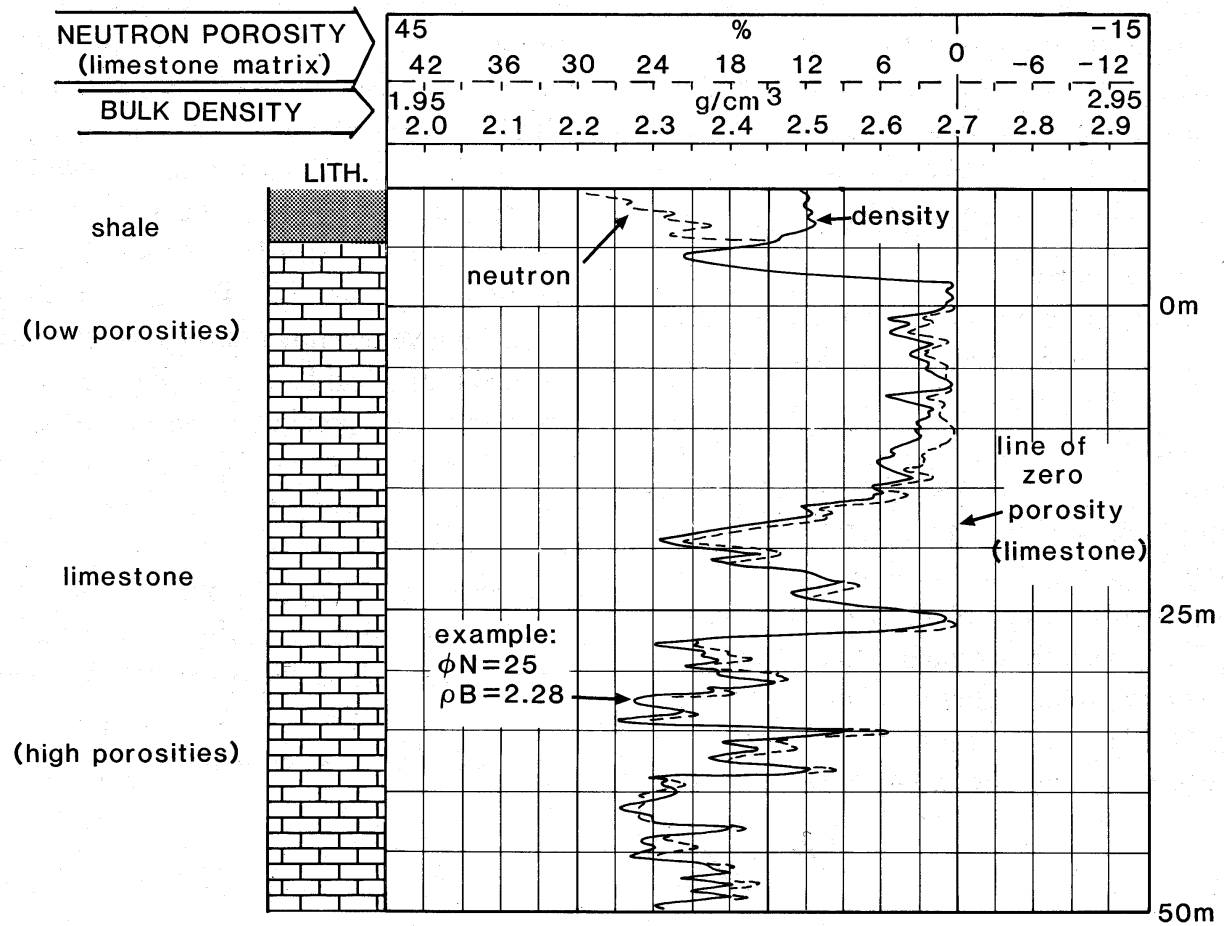


Figure 15.13 The density and neutron log responses for clean formations on a compatible scale (after Rider, 1997).

One can see from the cross-plot that for density and neutron logs plotted on compatible scales, there will be a *separation* of the density and the neutron logs for sandstone and dolomite, but no separation for limestone (Fig. 15.15). The sandstone separation is called *negative* and the dolomite separation is in the other direction and slightly larger, and is called *positive*.

The separations are caused by the relative positions of both logs.

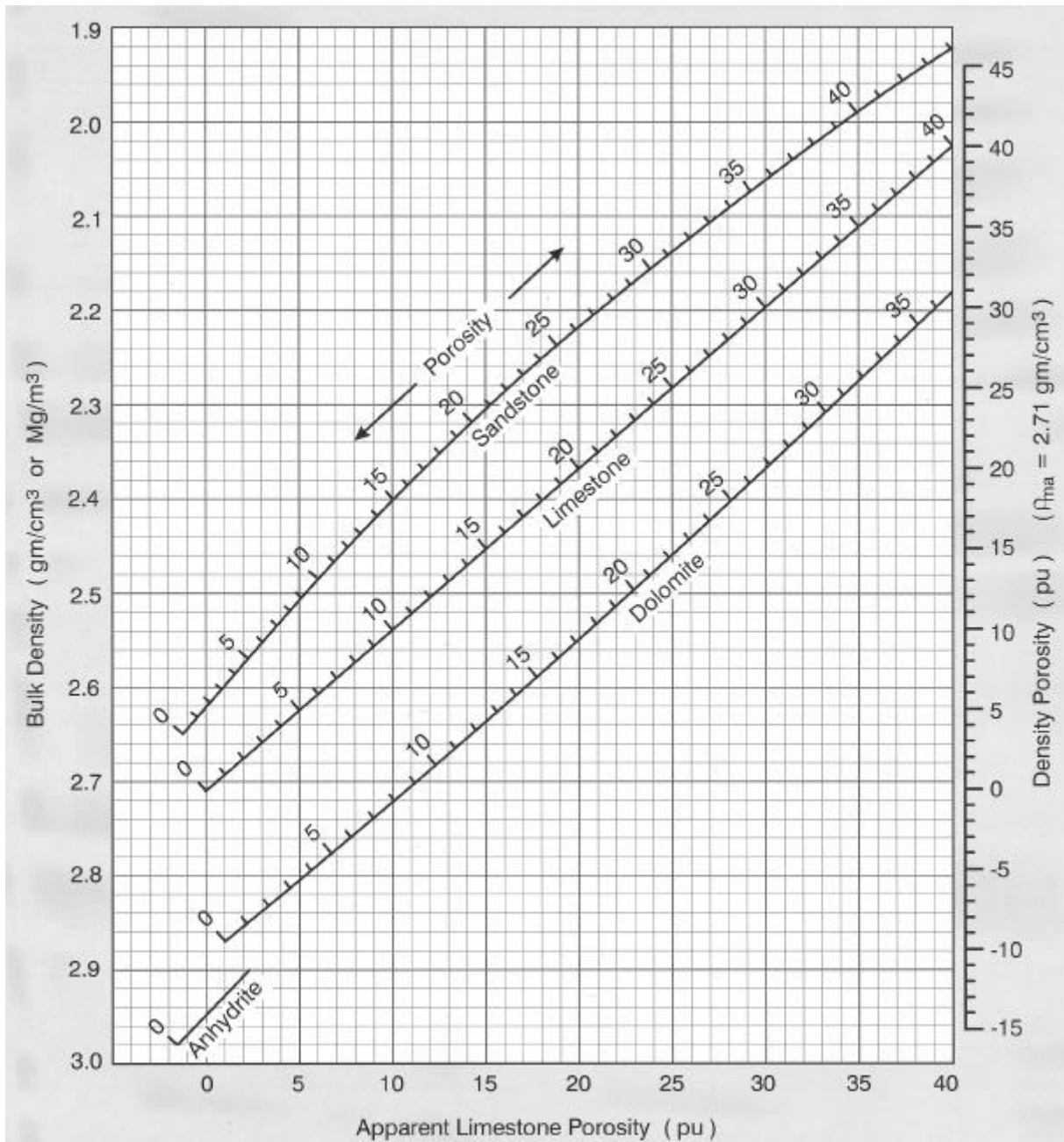


Figure 15.14 The density-neutron crossplot.

15.11.2 Clean Formations

- There is no separation for pure limestones, and the porosity value that the log gives is accurate.
- There is a small negative separation for clean sandstones.
- There is a moderate positive separation for pure dolomites.

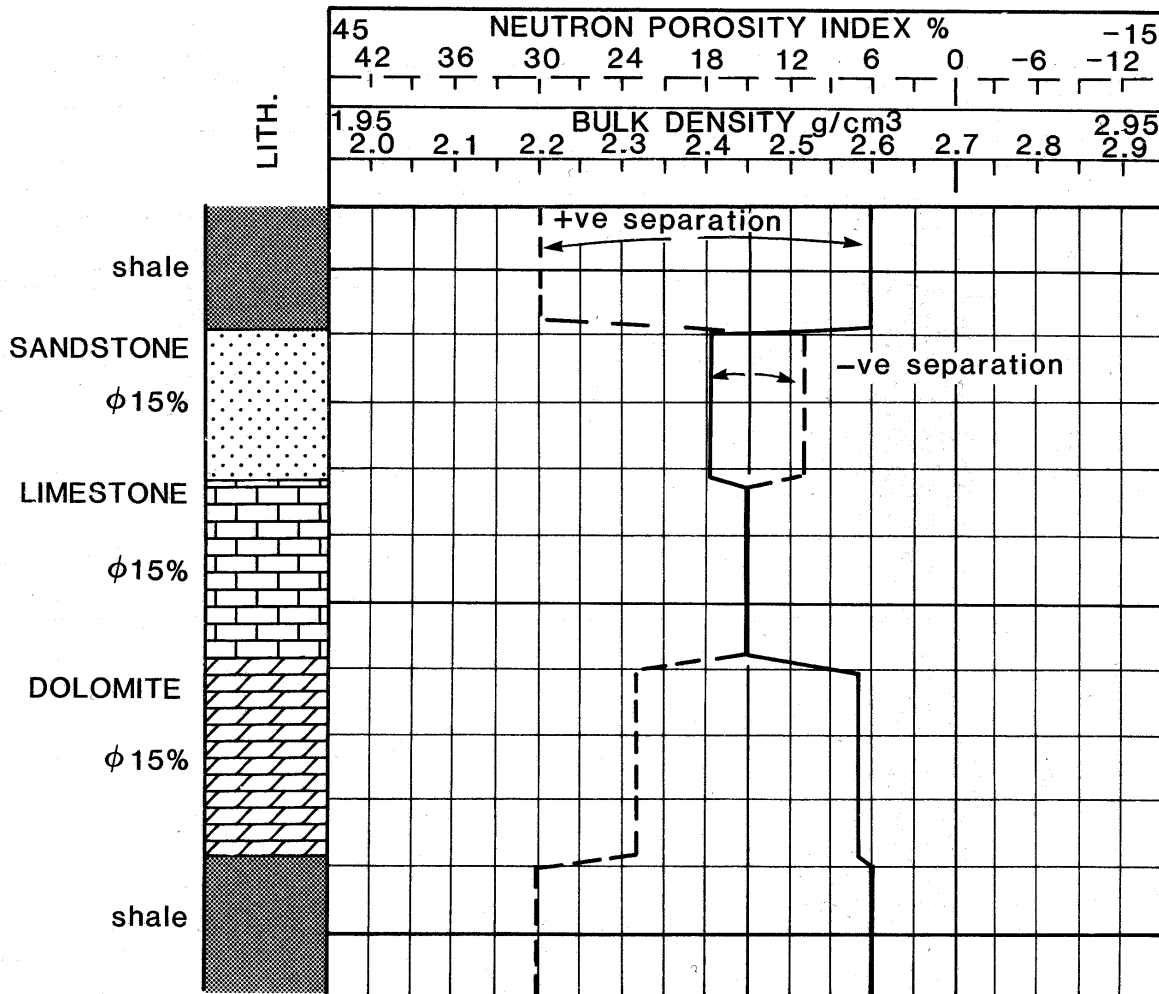


Figure 15.15 The density-neutron combination idealized responses.

15.11.3 Shaly Formations

If shale is present in the formation, the neutron log reads much higher porosities than it would otherwise do because of the effect of bound water. This gives a large positive separation.

This large positive separation is diagnostic of shales.

If the shale volume decreases due to the intermixture of sandstone, the large positive separation decreases, crosses-over and becomes eventually the small negative separation associated with pure sandstone.

Thus, a sequence of clearly defined sand and shale formations shows switching between positive and negative separations in the logs.

Often the beds will not be well defined, but coarsen-up or fine-up gradually. This can be seen by a gradual switch from one separation to another. Hence the characteristic patterns (reviewed in the chapter on the gamma ray log) can be recognized in the separations, and conclusions may be drawn concerning the depositional environment.

The size of the separation is actually THE BEST quantitative estimator of shale volume. It is better than the shale volume derived from the gamma ray log. We can write an equation for shale volume based on separations

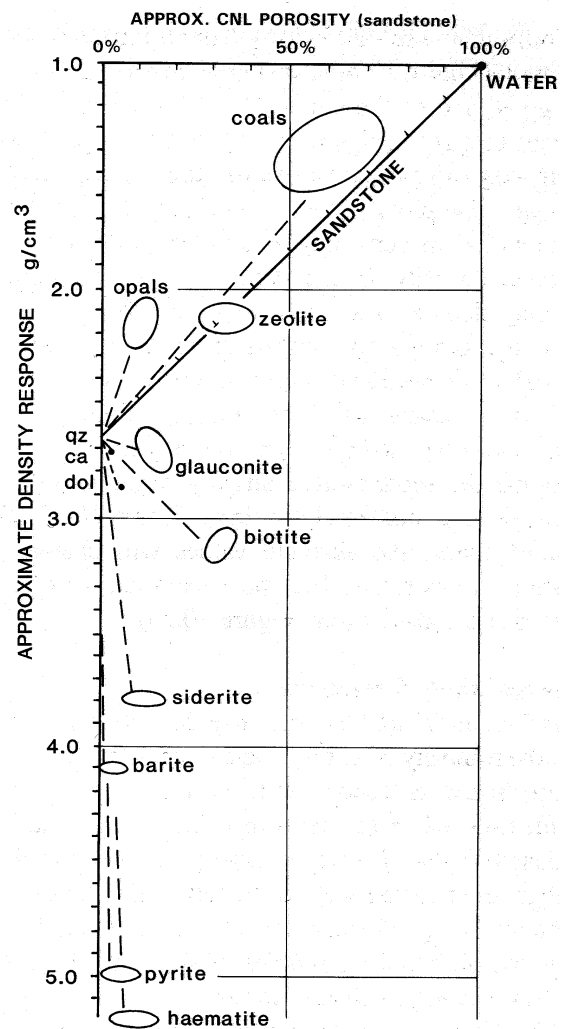
$$V_{sh} = \frac{\Omega_{log} - \Omega_{sand}}{\Omega_{sh} - \Omega_{sand}} \tag{15.8}$$

where Ω stands for the separation measured in 100% sandstone, 100% shale, and at the point of interest in the log. Note that the separations may ALL be measured on the limestone porosity scale, ALL on the density scale, or ALL using a simple ruler on the log! Each is valid, but you must keep it consistent for the whole equation.

15.11.4 Distinctive Lithologies

Certain minerals have unusual combinations of density and neutron porosity. These unusual combinations can be used to identify them on a combination log. Examples are given in Fig. 15.16.

Coals are a good example of a distinctive combination of density and neutron porosity values. They have unusually low densities combined with unusually high apparent neutron porosity values associated with their hydrogen content.



15.11.5 Evaporites

Remember from the section about the formation density tool that evaporites can often be recognized because their often pure nature leads to well constrained density values. Evaporites have apparent neutron porosity values which are either very high or very low. The combination of well constrained density values and very high or very low apparent neutron porosity values is a characteristic and diagnostic combination for evaporites (Fig. 15.17).

Fig 15.16 Distinctive minerals on a density-neutron log.

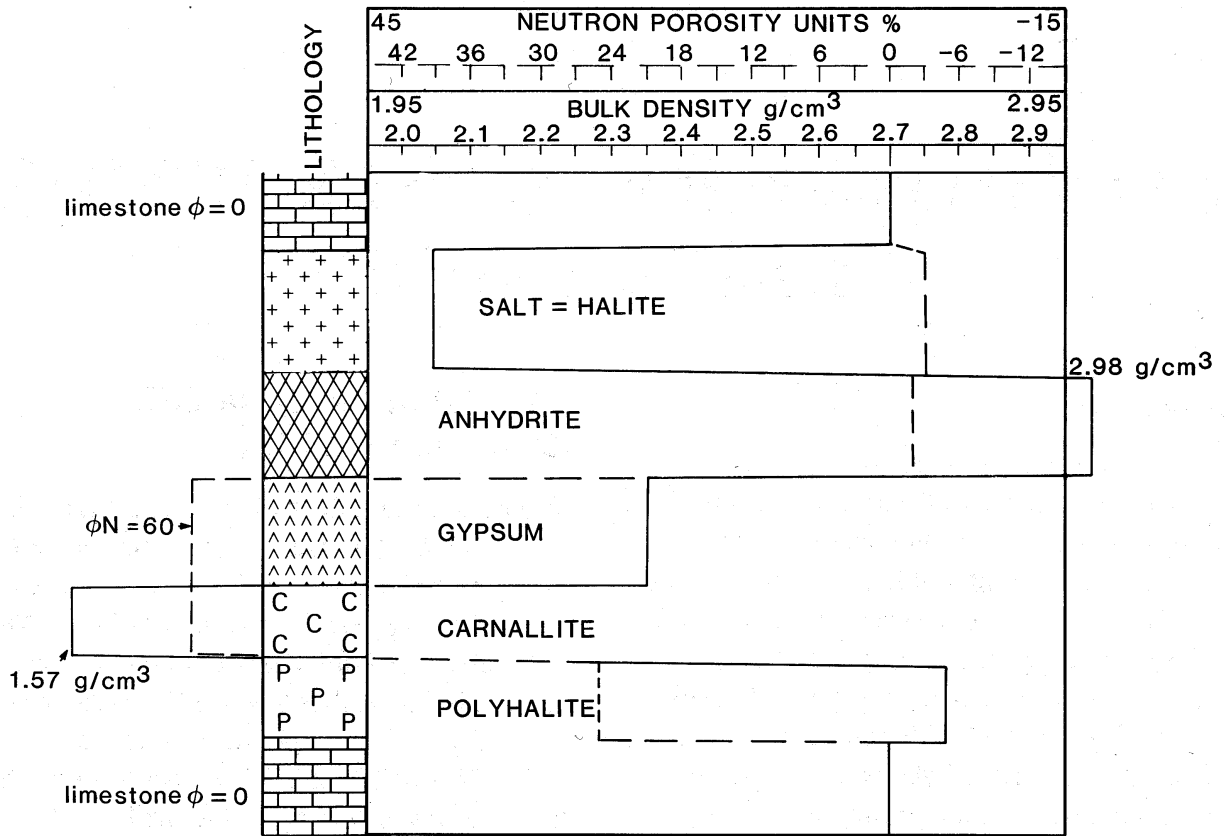


Fig 15.17 Distinctive evaporites on a density-neutron log.