9
THE DENSITY AND PHOTOELECTRIC FACTOR LOGS

9.1 The density log, generalities

The log

The density log is a continuous record of a formation's *bulk density* (Figure 9.1). This is the overall density of a rock including solid matrix and the fluid enclosed in the pores. Geologically, bulk density is a function of the density of the minerals forming a rock (i.e. matrix) and the volume of free fluids which it encloses (i.e. porosity). For example, a sandstone with no porosity will have a bulk density of 2.65g/cm^3, the density of pure quartz. At 10% porosity the bulk density is only 2.49g/cm^3, being the sum of 90% quartz grains (density 2.65g/cm^3) and 10% water (density 1.0g/cm^3).

Principal uses

Quantitatively, the density log is used to calculate porosity and indirectly, hydrocarbon density. It is also used to calculate acoustic impedance. Qualitatively, it is a useful lithology indicator, can be used to identify certain minerals, can help to assess source rock organic matter content (even quantitatively) and may help to identify overpressure and fracture porosity (Table 9.1).

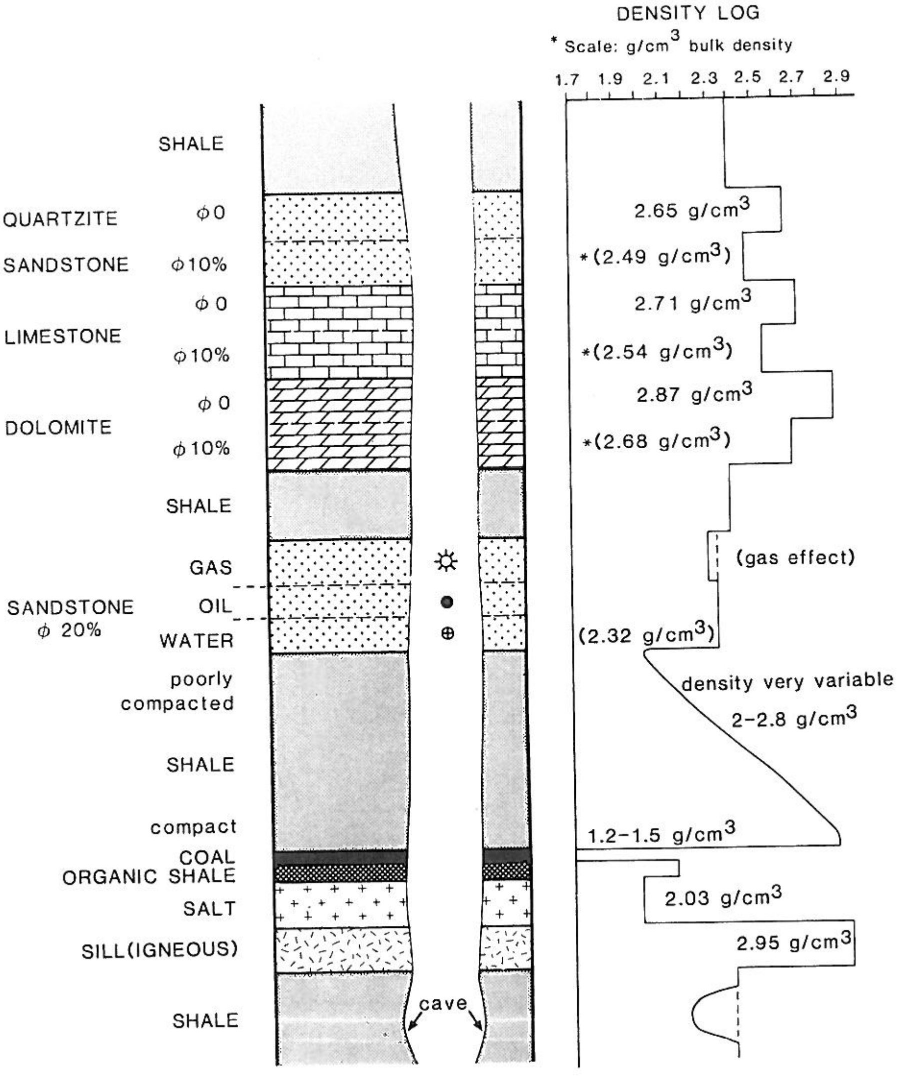

Figure 9.1 The density log: some typical responses. The density log shows *bulk density*. *Density and porosity with fresh formation-water density 1.0g/cm^3 (cf. Figure 10.1, which is on a compatible scale of neutron porosity).

Table 9.1 The principal uses of the density log.

	Discipline	Used for	Knowing
Quantitative	Petrophysics	Porosity	Matrix density Fluid density
	Seismic	Acoustic impedance	(Use raw log)
Qualitative and semi-quantitative	Geology	General Lithology Shale textural changes Mineral identification	Combined with neutron* Average trends Mineral densities
	Reservoir geology	Overpressure identification Fracture recognition	Average trends Sonic porosities
	Geochemistry	Source rock evaluation	Density – O.M. calibration

*using density log combined with neutron log on compatible scale

9.2 Principles of measurement

The logging technique of the density tool is to subject the formation to a bombardment of medium-high energy (0.2–2.0 MeV) collimated (focused) gamma rays and to measure their attenuation between the tool source and detectors. Such is the physical relationship that the attenuation (Compton scattering, *see* Section 7.2) is a function of the number of electrons that the formation contains – its electron density (electrons/cm^3) – which in turn is very closely related to its common density (g/cm^3) (Table 9.2). In dense formations, Compton scattering attenuation is extreme and few detectable gamma rays reach the tool's detectors, while in a lesser density the number is much higher. The change in counts with change in density is exponential over the average logging density range from about 2.0–3.0 g/cm^3 (Figure 9.2). Detector counts in modern tools are converted directly to bulk density for the log printout (Figure 9.5). However, although electron density, as detected by the tool, and real density are almost identical, there are differences when water (hydrogen) is involved. For this reason, the actual values presented on the density log are transformed to give actual values of calcite (2.71g/cm^3) and pure water (1.00g/cm^3) (Table 9.2). (There are still slight differences between log density and real density, especially when chlorine is involved.)

9.3 Tools

The standard density tools have a collimated gamma ray source (usually radiocaesium which emits gamma rays at 662 keV, but radiocobalt is also used) and two detectors (near and far) which allow compensation for borehole effects when their readings are combined and compared in calculated ratios. The near detector response is essentially due to borehole influences which, when removed from the

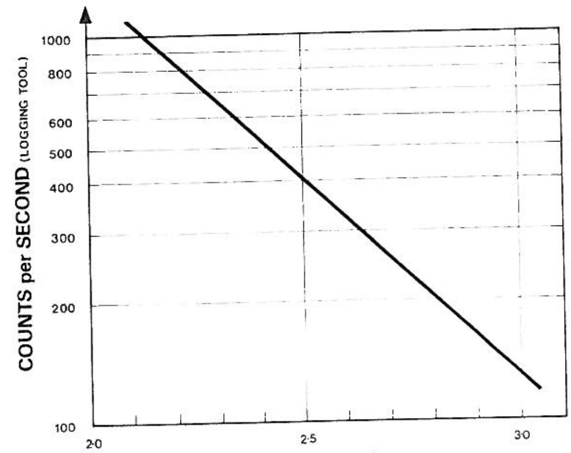

Figure 9.2 Correlation between the density-tool radiation count (counts per second) and bulk density. A high density gives a low count. (Re-drawn from Desbrandes, 1968).

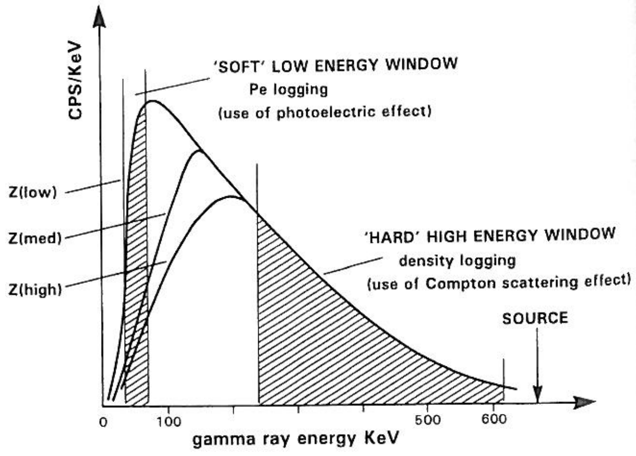

Figure 9.3 Density and lithodensity (photoelectric) logging in relation to gamma ray energy. Density logging uses the high energy regions where Compton scattering occurs. Photoelectric logging uses the low energy region where the photoelectric effect is dominant. CPS = counts per second. KeV – kilo electron volts. Z = atomic number. (Modified from Ellis, 1987).

Table 9.2 Density, electron density and tool given density for some common compounds (from Schlumberger, 1989a).

Compound	Formula	Actual density ρ_b, g/cm^3	Tool density based on electron density (ρe), g/cm^3	*Density given on log g/cm^3
Quartz	SiO_2	2.654	2.650	2.648
Calcite	$CaCO_3$	2.710	2.708	2.710
Dolomite	$CaCO_3MgCO_3$	2.850	2.863	2.850
Halite	NaCl	2.165	2.074	2.032
Gypsum	$CaSO_42H_2O$	2.320	2.372	2.351
Anhydrite	$CaSO_4$	2.960	2.957	2.977
Sylvite	KCl	1.984	1.916	1.863
Coal bituminous		1.200	1.272	1.173
		1.500	1.590	1.514
Coal anthracite		1.400	1.442	1.355
		1.800	1.852	1.796
Fresh water	H_2O	1.000	1.110	1.000
Salt water	200,000 ppm	1.146	1.273	1.135
Oil	$n(CH_2)$	0.850	0.970	0.850
Methane	CH_4	0.000677	0.00084	
Gas	$C_{1.1}H_{4.2}$	0.000773	0.00096	

*Density given on log = 1.0704 (ρe) – 0.1883

Table 9.3 Modern density tools.

1. Density measurement

Name	Symbol	Company
Formation Density Compensated	FDC	Schlumberger
Compensated Densilog	CDL	Western Atlas, Halliburton
Compensated Density	CDS	BPB

2. Density and Photoelectric measurement

Name	Symbol	Company
Litho-Density Tool	LDT	Schlumberger
Compensated Z-Density	ZDL	Western Atlas
Photoelectric Density	PDS	BPB
Spectral Density Tool	HSDL	Halliburton

far detector response enhance the formation effects (Figure 9.6). The most recent density tools (Table 9.3) use more efficient scintillation detectors which separate high (hard) and low (soft) gamma ray energy levels (Figure 9.3). This allows a better evaluation of borehole effects, so providing a more accurate density measurement as well as the additional photoelectric factor value (Section 9.7). Source and detectors are mounted on a plough-shaped pad which is pressed hard against the borehole wall during logging (Figure 9.4). Density-log readings therefore refer to only one sector on the borehole wall.

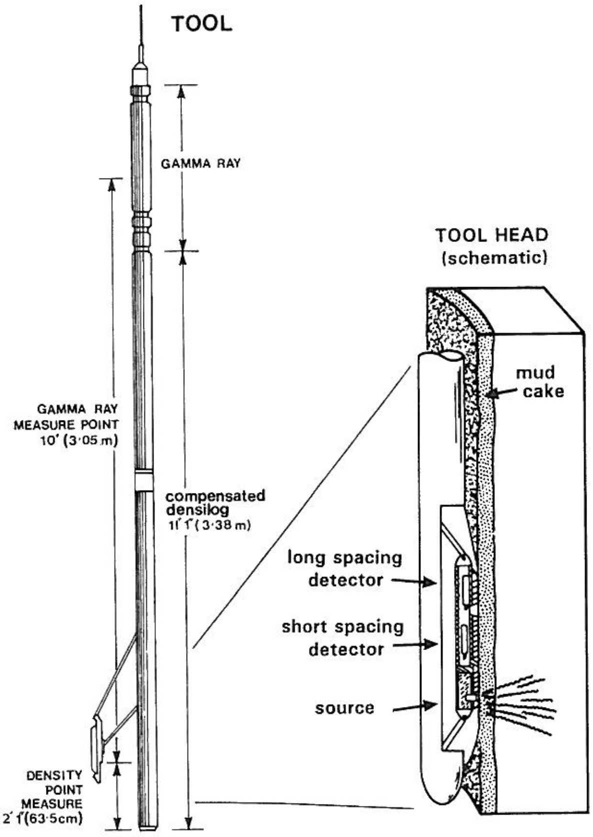

Figure 9.4 A density tool (Densilog from Atlas Wireline) and a tool head (modified from Dresser Atlas, 1982 and Ellis, 1987).

10
THE NEUTRON LOG

10.1 Generalities

The log

The neutron log provides a continuous record of a formation's reaction to fast neutron bombardment. It is quoted in terms of *neutron porosity units*, which are related to a formation's *hydrogen index*, an indication of its richness in hydrogen.

Formations modify neutrons rapidly when they contain abundant hydrogen nuclei, which in the geological context are supplied by water (H_2O). The log is therefore principally a measure of a formation's water content, be it bound water, water of crystallization or free pore-water. This hydrogen richness is called the hydrogen index (*HI*) which is defined as the weight % hydrogen in the formation/wt % hydrogen in water, where *HI* water = 1 (Table 10.8). However, the oilfield interest in water is as a pore fluid filler and porosity indicator so that the neutron log response is given directly in *neutron porosity units*. Neutron porosity is real porosity in clean limestones, but other lithologies require conversion factors. Since it is calibrated to limestones, the log is sometimes called the Limestone Curve (Figure 10.1).

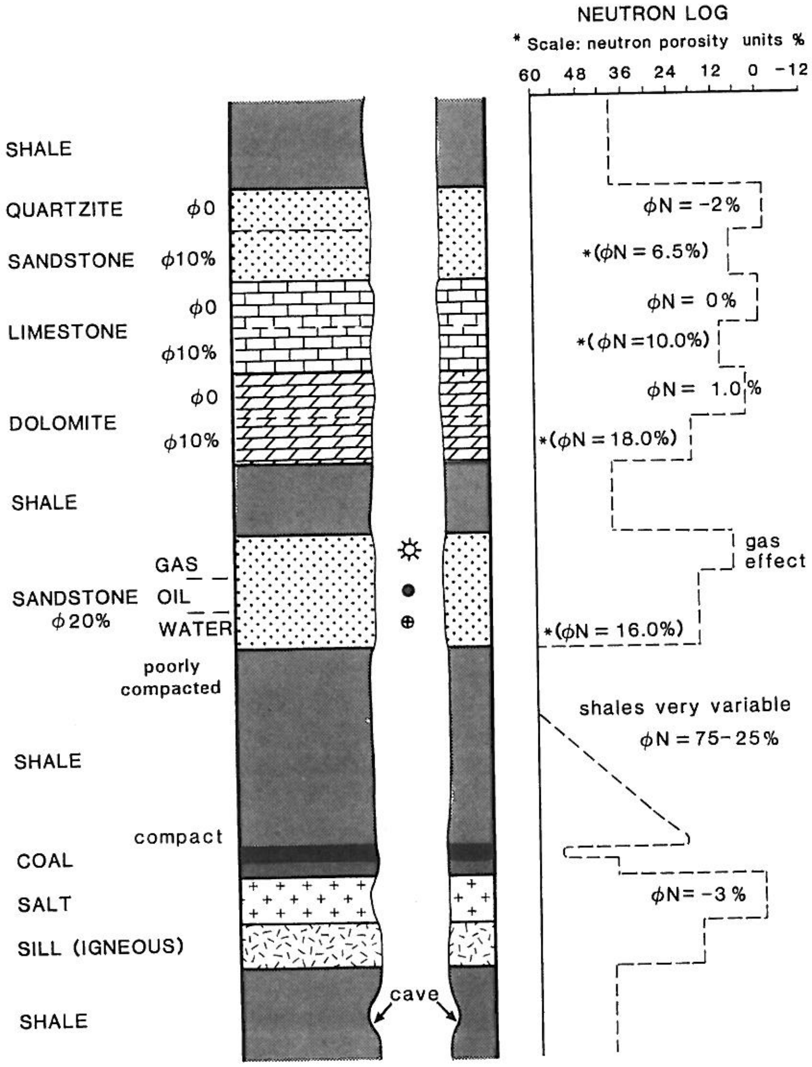

Figure 10.1 The neutron log: some typical responses. The neutron log shows *hydrogen index* which is converted to *neutron porosity units*.
* Porosity with fresh water and the Schlumberger CNL tool (cf. Figure 9.1 which is on a compatible scale of porosity).

Table 10.1 The principal uses of the neutron log.

	Discipline	Used for	Knowing
Quantitative	Petrophysics	Porosity	Matrix Hydrogen index
Qualitative	Petrophysics	Identification of gas	Lithology
	Geology	Lithology – shales	Gross lithology
		Evaporites	Neutron evaporite values
		Hydrated minerals	
		Volcanic and intrusive rocks	Calibration
		General lithology	Combined with density*

*using neutron log combined with density log on compatible scales.

Principal uses

Quantitatively, the neutron log is used to measure porosity. Qualitatively, it is an excellent discriminator between gas and oil. It can be used geologically to identify gross lithology, evaporites, hydrated minerals and volcanic rocks. When combined with the density log on compatible scales, it is one of the best subsurface lithology indicators available (Table 10.1).

10.2 Principles of measurement

Neutrons are subatomic particles which have no electrical charge but whose mass is essentially equivalent to that of a hydrogen nucleus. They interact with matter in two principal ways, by collision and absorption: collisions are mainly at higher energy states, absorption occurs at lower energy.

The lifetime of a free neutron is one of losing energy and can therefore be usefully described in terms of energy state, namely fast, epithermic and thermic in order of decreasing energy (Figure 10.2). The energy loss from fast neutron energy levels through epithermic to the limit of thermic energy, is generally thought of as a loss of velocity which occurs especially through *elastic scattering*, that is collisions with particles having the same mass as neutrons. For logging purposes this is mainly hydrogen nuclei. Collision with other, heavier particles, called *inelastic scattering*, does not result in significant energy loss (Table 10.2). These two moderating reactions are considered to cause the velocity loss over a certain trajectory called the *slowing-down length*. The slowing-down length is proportional to the root mean-square distance from the point of emission of high energy neutrons to the point at which they reach the lower limit of epithermal energy levels. This distance can be calculated from a knowledge of the combined capture cross-sections of the constituent elements of the material traversed. In a hydrogen rich medium, slowing-down length will be short compared to that in a hydrogen free environment (Figure 10.3, Table 10.2). Slowing-down length is an important concept in logging as it is used to place detectors at an optimum distance from the tool's neutron source.

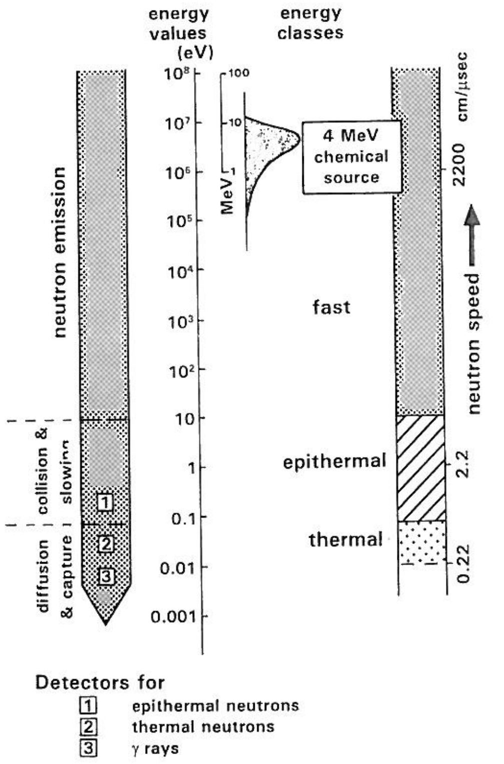

Figure 10.2 Schematic diagram of a neutron life, showing the energy degradation after emission and the neutron tool detector levels. (From Serra, 1979; Tittle, 1961; Owen, 1960).

Most logging tools use a chemical source producing *fast neutrons*. These have an initial energy of around 4 MeV (see Tools), which means that they have an initial velocity of approximately 2800 cm/µsec (Figure 10.2). With this energy and velocity, the neutrons have considerable

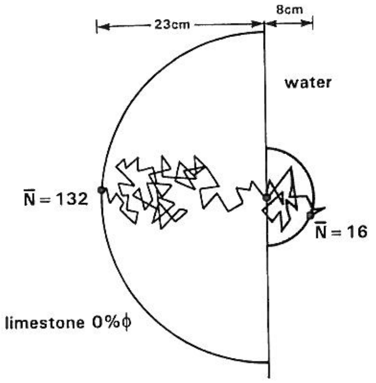

Figure 10.3 Schematic trajectories of a neutron in a limestone with no porosity and pure water. The slowing down length in the limestone is far greater than in water (modified from Ellis, 1987).

Table 10.2 Neutron slowing-down parameters (*number of collisions involved during change from 4.2 Mev to 1 eV). (from Ellis 1987).

Moderator	*no. of collisions
H	14.5
C	91.3
O	121
Ca	305
H_2O	15.8
Limestone 20% ϕ	29.7
Limestone 0% ϕ	132

Table 10.3 Thermal neutron capture cross-sections of some elements, (note the values for H and Cl as well as B and Gd).

Element	Capture cross-section, barns	*cross-section* atomic weight
H	0.33	0.33
C	0.0034	0.00028
O	0.00027	0.000017
Na	0.53	0.023
Mg	0.063	0.0027
Al	.23	0.0085
Si	.16	0.0057
Cl	33.2	0.94
K	2.10	0.054
Ca	0.43	0.011
B	759	70.3
Gd	49,000	312
Cd (shield material)	2,450	21.9

– cross-section/atomic weight gives a guide to the effect of a thermal absorber relative to the volume of formation it occupies.
– Cadmium is separated on the list as it is rarely encountered naturally but is used in tool construction as a thermal absorber.
from Dunlap and Coates, 1988.

penetration capabilities but after a few microseconds and successive collisions (100 or so), the original fast neutrons have slowed down through epithermic to thermic levels with about 0.25 eV of energy and a velocity of around 0.22 cm/μsec (Figure 10.2). To reduce a neutron from 2 MeV (2200 cm/μsec) to 0.025 eV (0.22 cm/μsec) requires 18 (elastic) collisions with hydrogen nuclei but 257 (non-elastic) collisions with silicon and 368 with calcium nuclei (Serra, 1979). Expressed in another way, elastic collision with hydrogen can take all a neutron's energy but in non-elastic collisions with heavier elements, the energy reduction is typically around 10% to 25%: the effect of hydrogen is seen as dominant (Table 10.2).

At the lower energy, thermic levels, the neutron is thought of as diffusing, rather than having a velocity. For example, in a vacuum, a thermal neutron will diffuse randomly for 13 minutes, but in earth materials the time varies: 5 μsec in rock salt, 450 μsec in a limestone without porosity and 900 μsec in a quartzite (Serra, 1979). The period of diffusion comes to an end as the neutrons undergo *absorption* interactions. That is, they are captured by other nuclei which then change energy state and, mostly, become unstable. For example, some nuclei, on capturing a neutron, spontaneously de-excite and emit gamma rays of capture, the so-called n,γ capture radiation (an effect used in pulsed neutron logging) (Figure 10.2). The rapidity of neutron absorption depends on the *capture cross-section* of the absorbing nuclei of the formation, which is a measure of how effective it is at capturing neutrons. Gadolinium and boron have large thermal neutron cross-sections but are quite rare: chlorine, common in saline formation fluids, has a moderate cross-section (Table 10.3).

As far as logging is concerned, the dominant effect on neutrons during the collision and scattering phase, is the mass of the (formation) nuclei, hydrogen dominating: the dominant effect during the absorption phase is the capture cross-section of the thermal neutron absorbers, the effect of hydrogen being much less marked (Table 10.3).

10.3 Tools

The neutron tool today generally consists of a fast neutron source and two detectors (Figure 10.4). The source bombards the formation with neutrons and the detectors measure their loss of energy as they pass through it.

Tool sources are mostly chemical, such as plutonium-beryllium (PuBe) or americium-beryllium (AmBe), which produce fast neutrons with a peak energy level around 4 Mev. These are the most common. Infrequently, high energy neutrons at up to 14 MeV are produced using accelerometers, in which the neutrons are created by bombarding a target with charged particles.

Historically, the first neutron tools consisted of a source and just a single detector but these were quite affected by borehole environment and most tools now