Rock Physics

From mm. to Km. scale

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Radioactivity logging

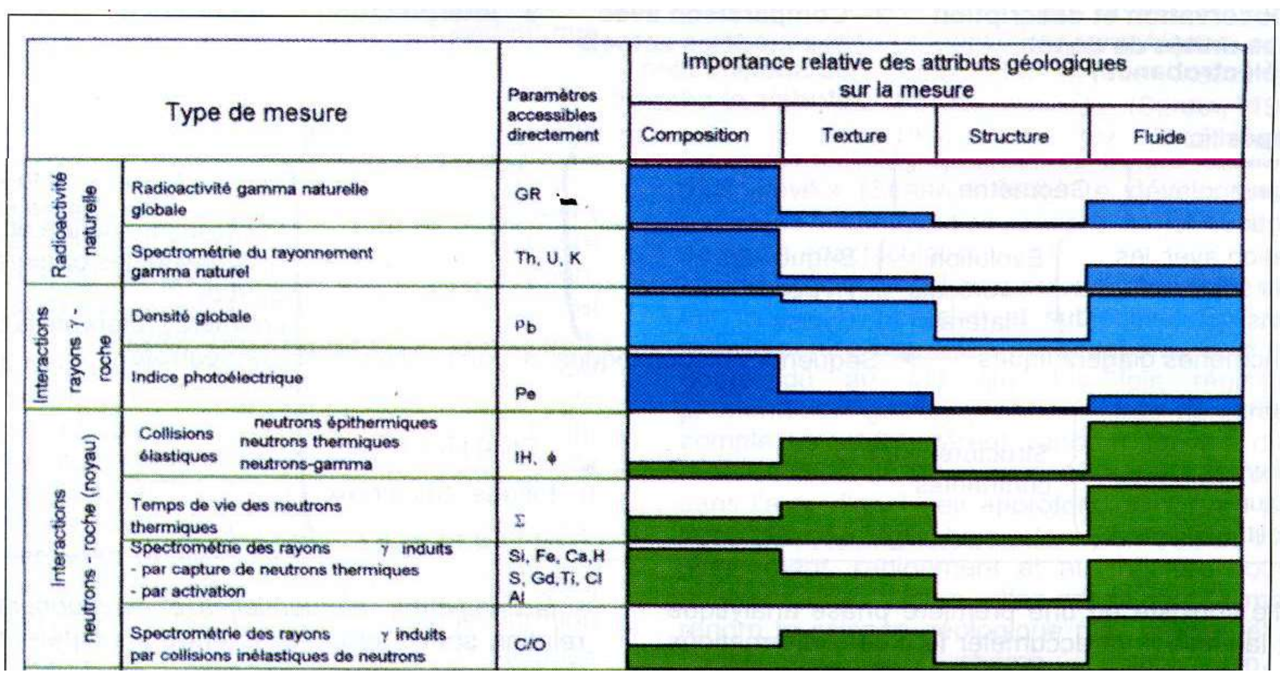
Some slides from P. Glover and S. Gautier.

Contents :

I. Radioactivity theory

➢ Radioactivity logging

Radioactivity is used in several different types of logging tool. There are those that measure the **natural radiation** generated by the formation (passive method), such as the total and spectral **gamma ray logs**, and those that measure the **response of the formation to radiation** generated by the tool, such as the **neutron**, **density and litho-density logs** (active method).



(Serra et Abbott, 1980)

I. **Radioactivity theory**

- Radioactivity theory

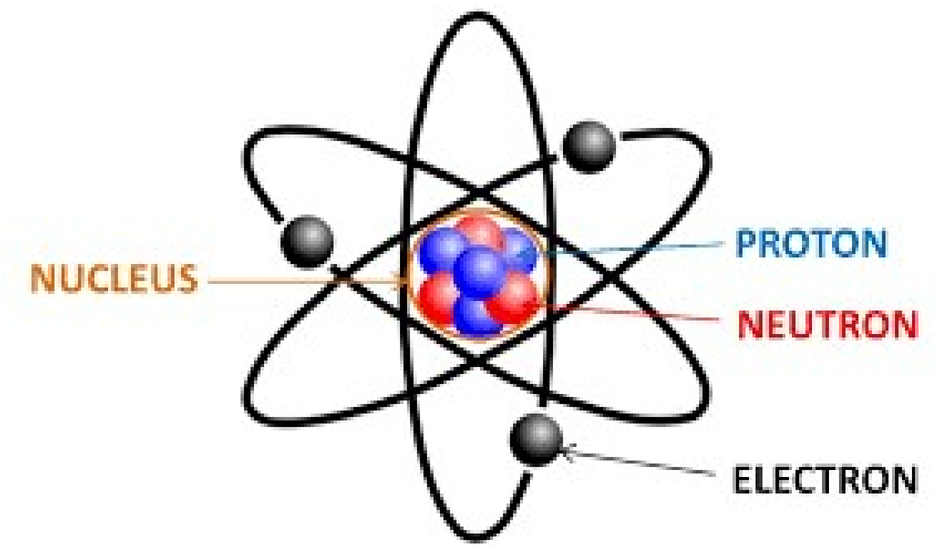
- Radioactivity is a fundamental property of the structure of all matter.

Element code

Atomic number

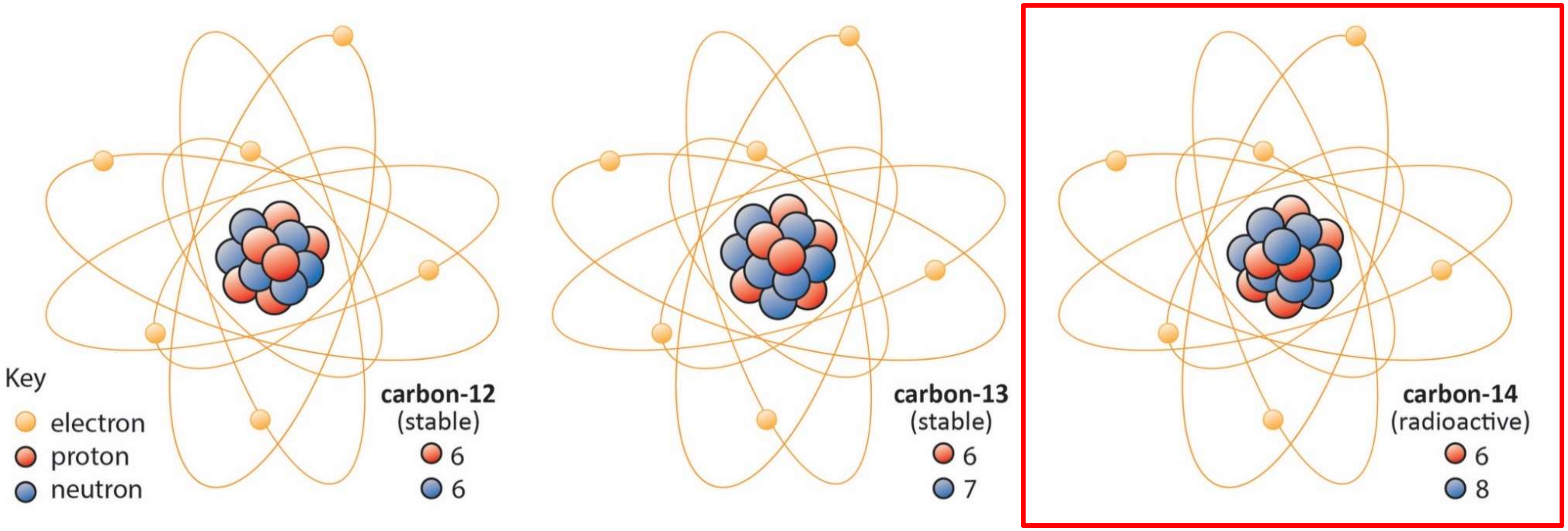
Atomic mass number

$_{Z}X^{A}$



I. **Radioactivity theory**

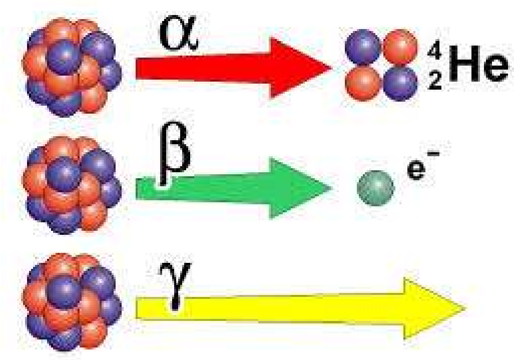
- Radioactivity theory-Isotopes



I. **Radioactivity theory**

- Radioactivity theory-Isotopes

There are five main methods whereby an unstable isotope can gain stability by losing energy. These are:



- Emission of an α **particle**, which is a helium nucleus $_2He^4$, and carries two positive charges.
- Emission of a β- particle, which is a negatively charged high energy electron originating in the nucleus together with an anti-neutrino, ν.
- Emission of a β+ particle, which is a positively charged high energy positron originating in the nucleus together with an neutrino, ν.

Particle radiaction

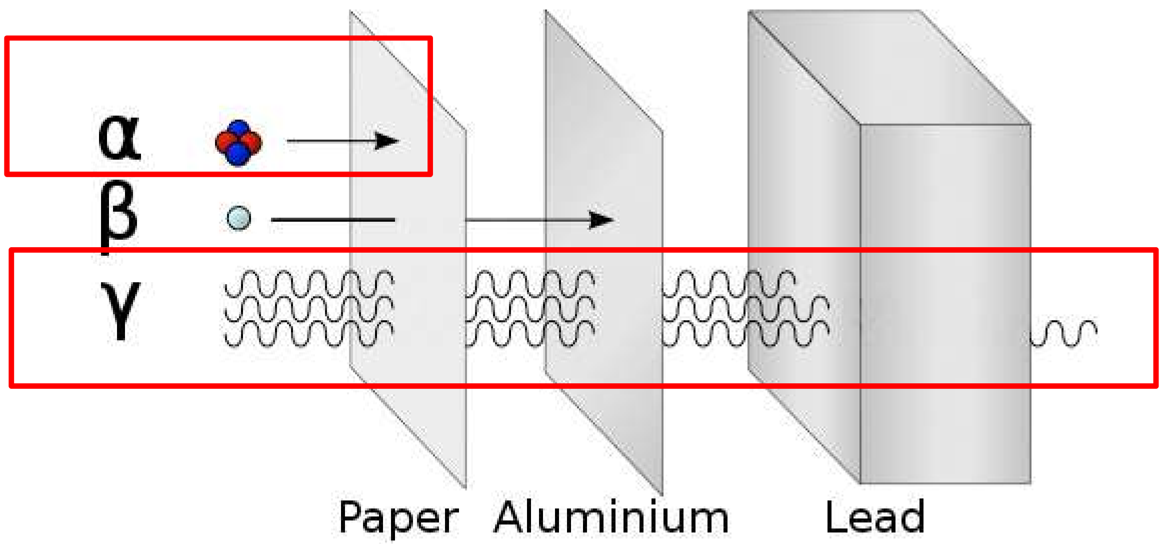
- **Emission of a gamma rays, γ, which are high energy photons (electro-magnetic waves) and have no mass and carry no charge.**
- Electron capture, which involves an electron being captured by the nucleus.

Electro-magnetic radiation

Under some circumstances neutrons may also be expelled from a material, but this is not a spontaneous decay.

I. **Radioactivity theory**

- Radioactivity theory-Isotopes



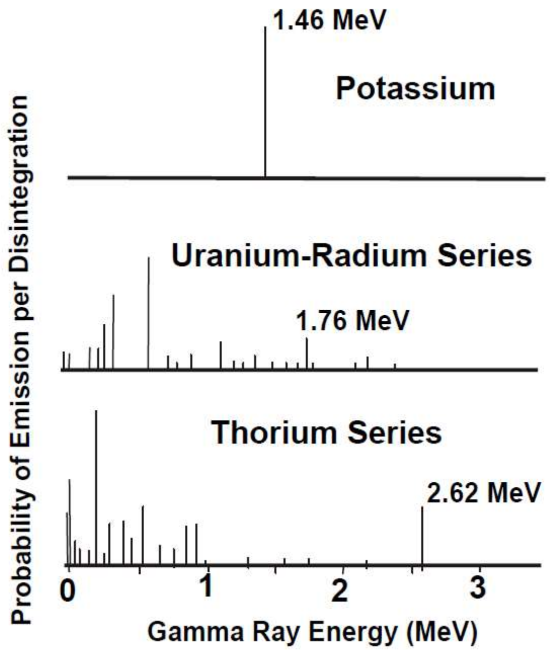
Gamma rays are the most important in petrophysical logging because they have the highest penetration of all the radiations except neutrons. Their penetration ability means that they can be detected through several centimetres of cement casing. Alpha and beta particles have very limited penetration ability, being stopped immediately by any solid material.

I. **Radioactivity theory**

➢ Radioactivity theory-Isotopes

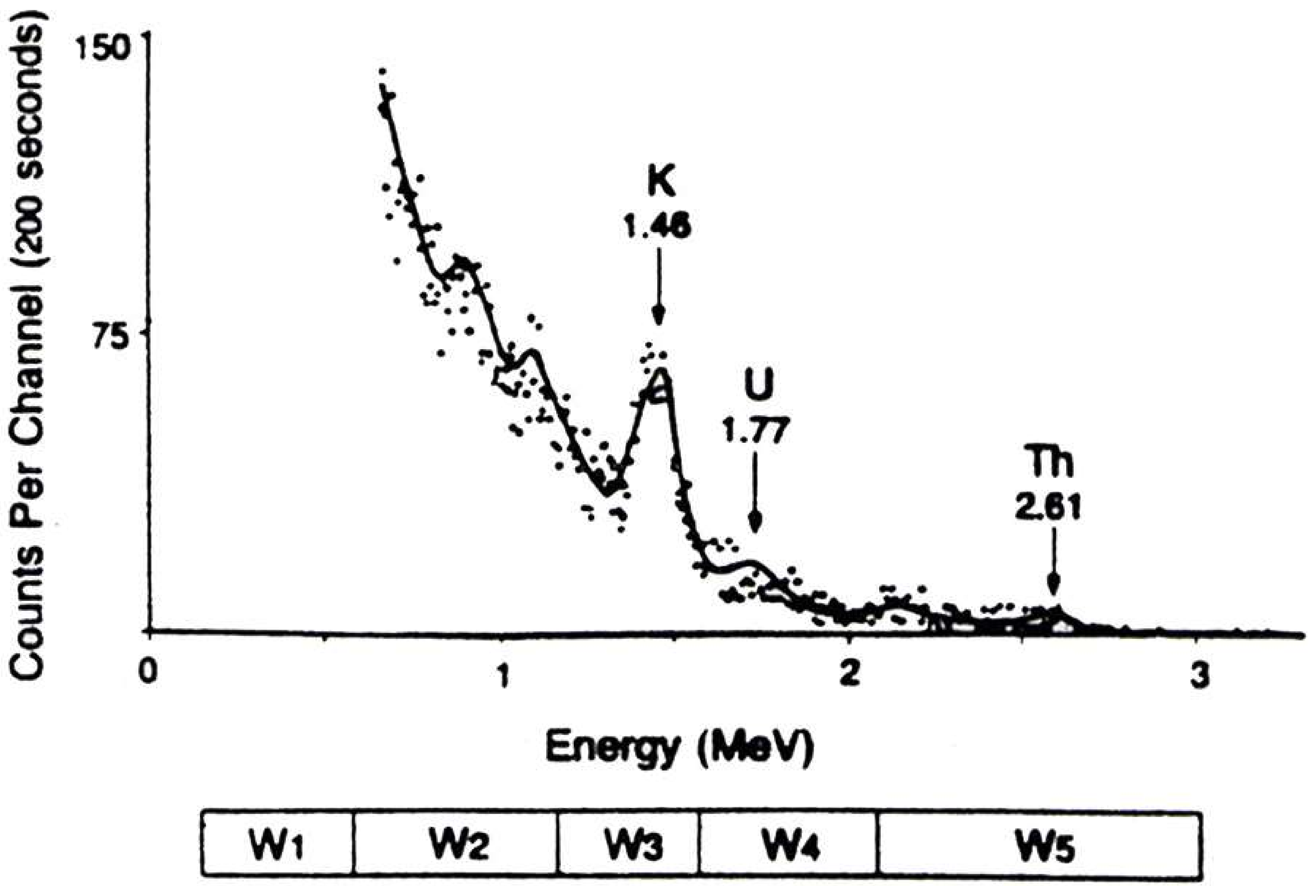
Most isotopes found naturally in rocks are either stable, present in insignificant amounts, or generate insignificant amounts of radiation. There are, however, a few which are significant. These are:

- The Potassium isotope ${}_{19}K^{40}$ (the stable forms are ${}_{19}K^{39}$ and ${}_{19}K^{41}$).
- The Thorium series isotopes.
- The Uranium-Radium series isotopes.



I. **Radioactivity theory**

➢ Radioactivity theory-Isotopes



I. **Radioactivity theory**

➢ Radioactivity and minerals

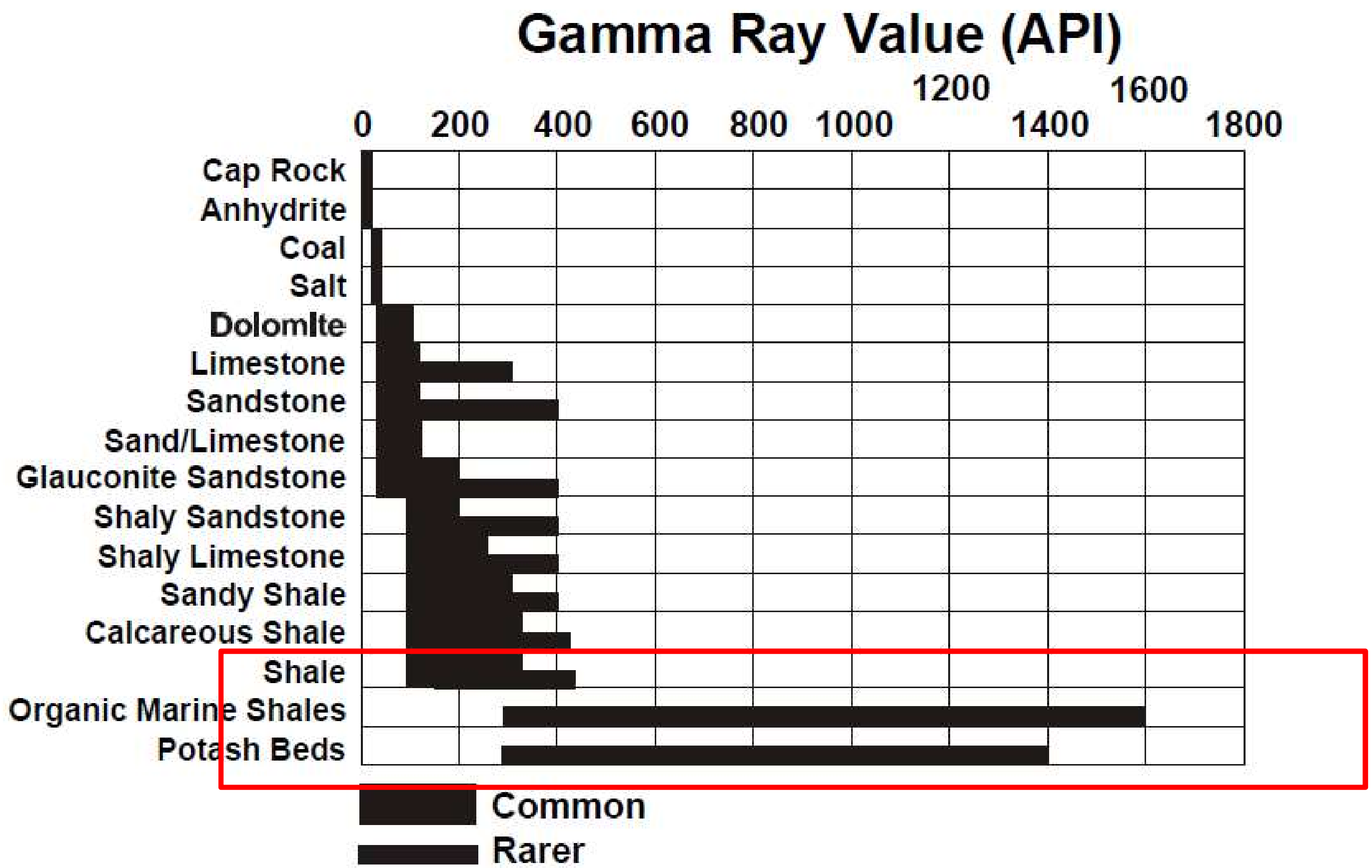
Table 10.1 Gamma radiation from common minerals and lithologies (after Pirson, 1963).

Mineral or Lithology	Composition	Gamma Radiation (API Units)
Pure Mineral		
Calcite	$CaCO_3$	0
Dolomite	$CaMg(CO_3)_2$	0
Quartz	SiO_2	0
Lithology		
Limestone	-	5-10
Dolomite	-	10-20
Sandstone	-	10-30
Shale	-	80-140
Evaporites		
Halite	$NaCl$	0
Anhydrite	$CaSO_4$	0
Gypsum	$CaSO_4(H_2O)_2$	0
Sylvite	KCl	500
Carnalite	$KCl\,MgCl_2(H_20)_6$	220
Langbeinite	$K_2SO_4(MgSO_4)_2$	290
Polyhalite	$K_2SO_4MgSO_4(CaSO_4)_2(H_2O)_2$	200
Kainite	$MgSO_4KCl(H_2O)_3$	245
Others		
Sulphur	S	0
Lignite	$CH_{0.849}\,N_{0.015}\,O_{0.221}$	0
Anthracite	$CH_{0.358}\,N_{0.009}\,O_{0.022}$	0
Micas	-	200-350

Figure 10.2 shows the range of gamma ray values generated by common lithologies. Note the particularly high values for potash beds, which contain a large amount of potassium-40, and organic shales, which contain enhanced uranium associated with their organic nature.

I. **Radioactivity theory**

- Radioactivity and rocks



I. **Radioactivity theory**

➢ Scattering and attenuation

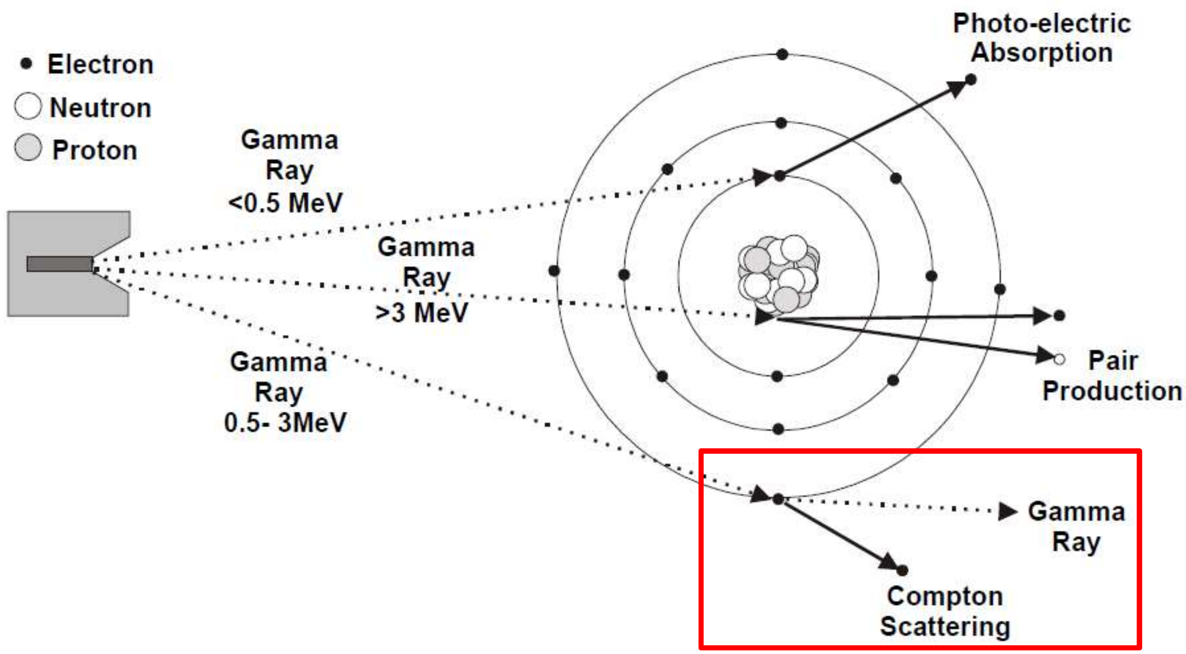
Once the gamma rays have been emitted they travel through materials (formation, fluids, mud cake and drilling mud) and interact with them. There are three processes that occur, and each is applicable to gamma rays with a given energy range. These are:

- **Gamma rays with energy >3 MeV.** These interact with the nucleus of the materials that they are travelling through and are converted into an electron and a positron in the process (*pair production*). The efficiency of the process is low, so these gamma rays may be measured by a sensor. However, they contribute only small amounts to the overall signal.
- **Gamma rays with energy 0.5 to 3 MeV.** These gamma rays undergo *compton scattering*, where a gamma ray interacts with the electrons of the atoms through which they are passing, ejecting the electron from the atom, and losing energy in the process. A gamma ray in this range may undergo several of these collisions reducing its energy from its initial value to an energy of less than 0.5 MeV in a stepwise fashion.
- **Gamma rays with energy <0.5 MeV.** These gamma rays collide with electrons of the atoms through which they are passing, and are adsorbed. The gamma ray energy is either used to promote the electron to a higher energy level or to eject it from the atom. This process is called *photo-electric adsorption*, and is important in the Litho-Density tool.

I. **Radioactivity theory**

➢ Scattering and attenuation

Figure 10.3 shows the processes of scattering and absorption schematically.



The number of collisions, hence the reduction in gamma ray energy, and the number of gamma rays adsorbed is directly related to the number of electrons in the materials through which the gamma rays pass.

- High count rates =low electron densities
- low count rates = high electron densities.

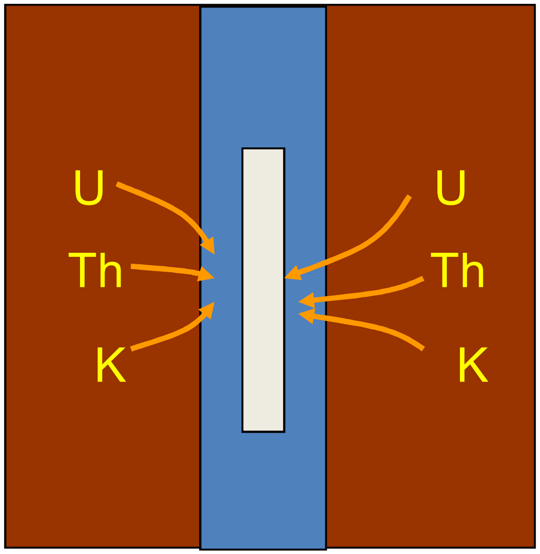
The electron density is, of course, related to the mean atomic number and bulk density of the material.

II. **Natural Gamma ray log**

➢ Gamma ray

- The *gamma ray* log measures the **total natural gamma radiation** emanating from a formation. This gamma radiation originates from potassium-40 and the isotopes of the Uranium-Radium and Thorium series. The gamma ray log is commonly given the symbol *GR*.

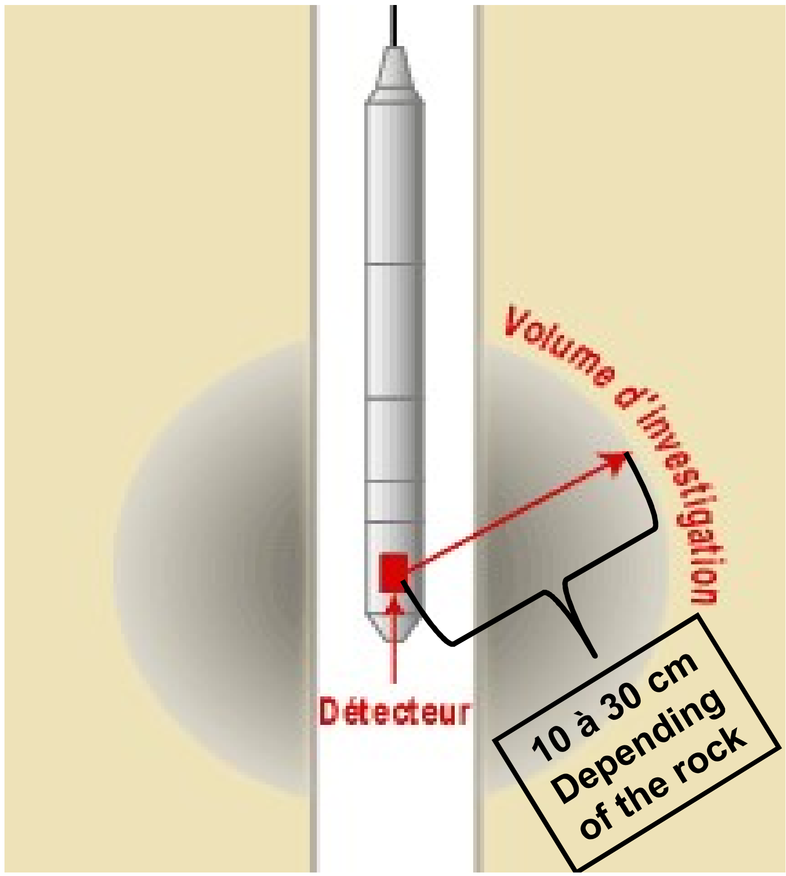
- Once the gamma rays are emitted from an isotope in the formation, they progressively **reduce in energy** as the result of collisions with other atoms in the rock (*compton scattering*). Compton scattering occurs until the gamma ray is of such a low energy that it is completely absorbed by the formation.



II. **Natural Gamma ray log**

➢ Total gamma ray

- The initial intensity of gamma ray emission, which is a property of the elemental **composition of the rock**.
- The amount of compton scattering that the gamma rays encounter, which is related to the **distance between the gamma emission and the detector and the density of the intervening material**.

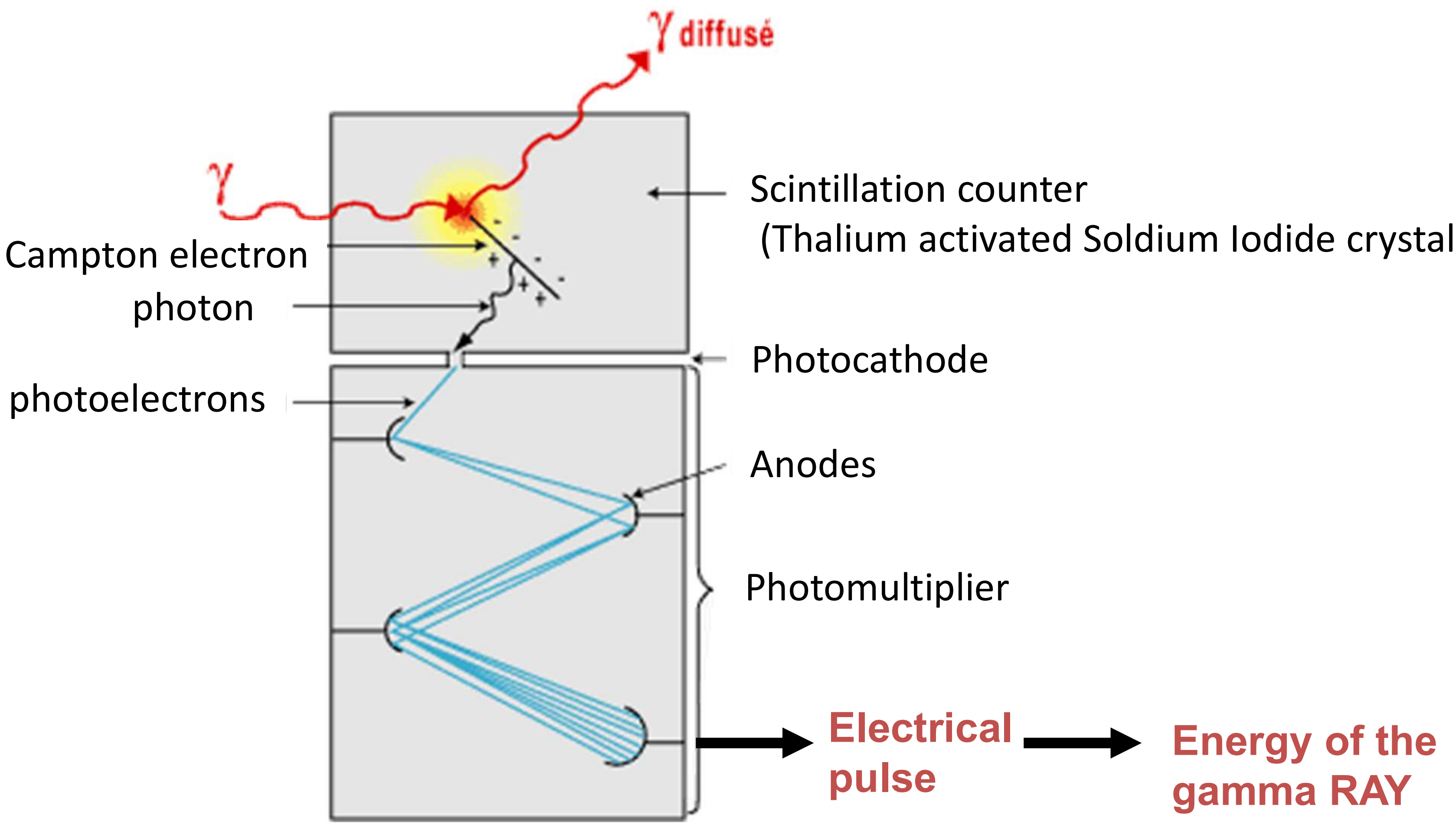


Vi ≈ 0.5 m^3

II. **Natural Gamma ray log**

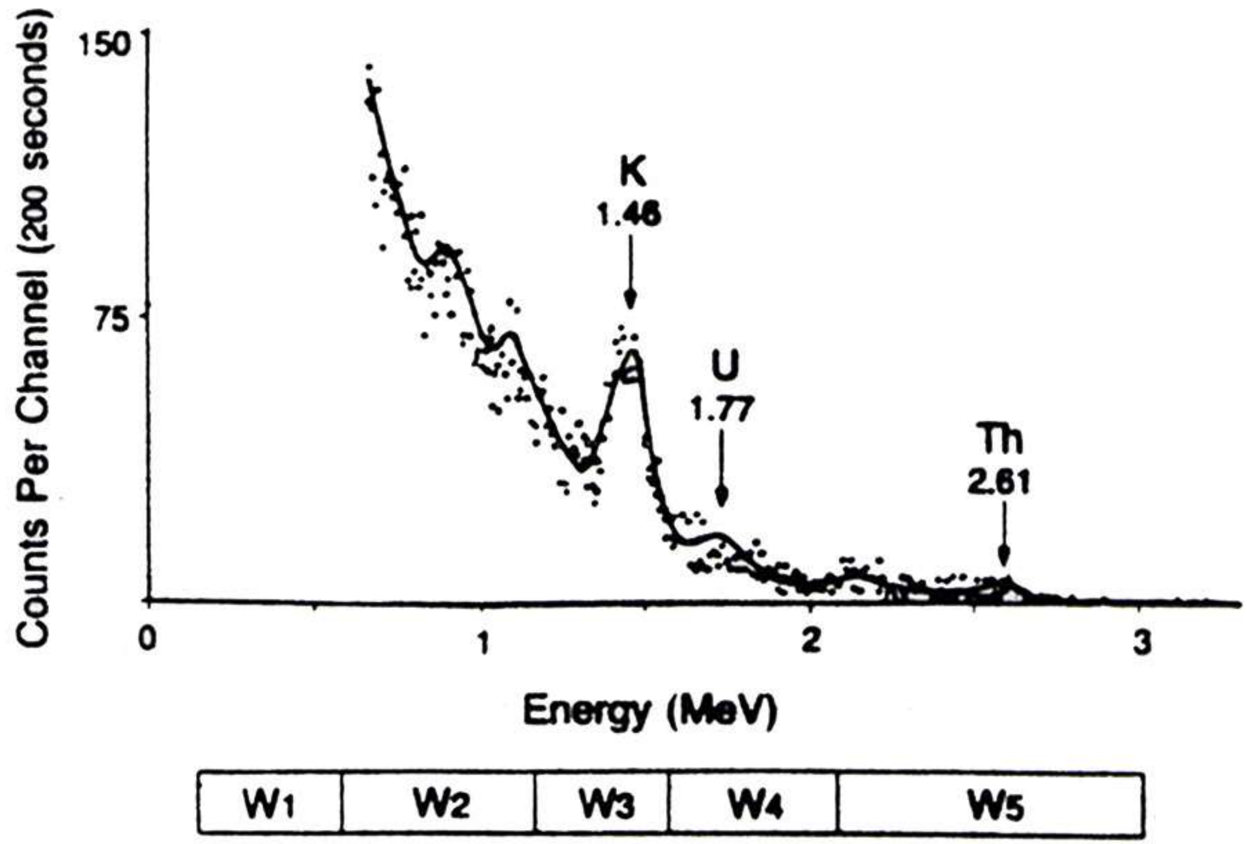
➢ Principles

The tool consists simply of a highly sensitive gamma ray detector in the form of a scintillation counter.



II. **<u>Natural Gamma ray log</u>**

- Principles: spectral gamma ray

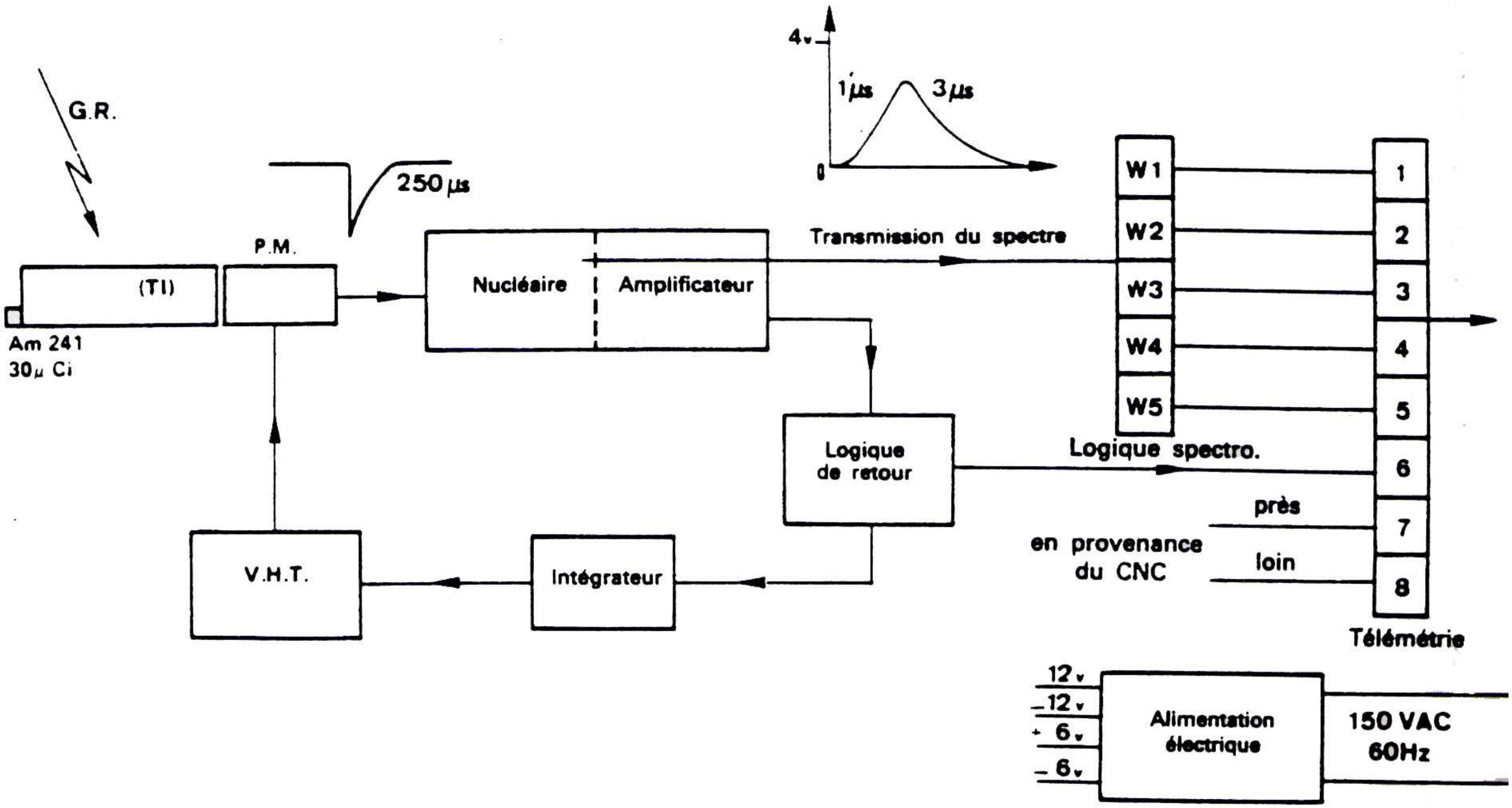


K U Th

II. **Natural Gamma ray log**

- Principles

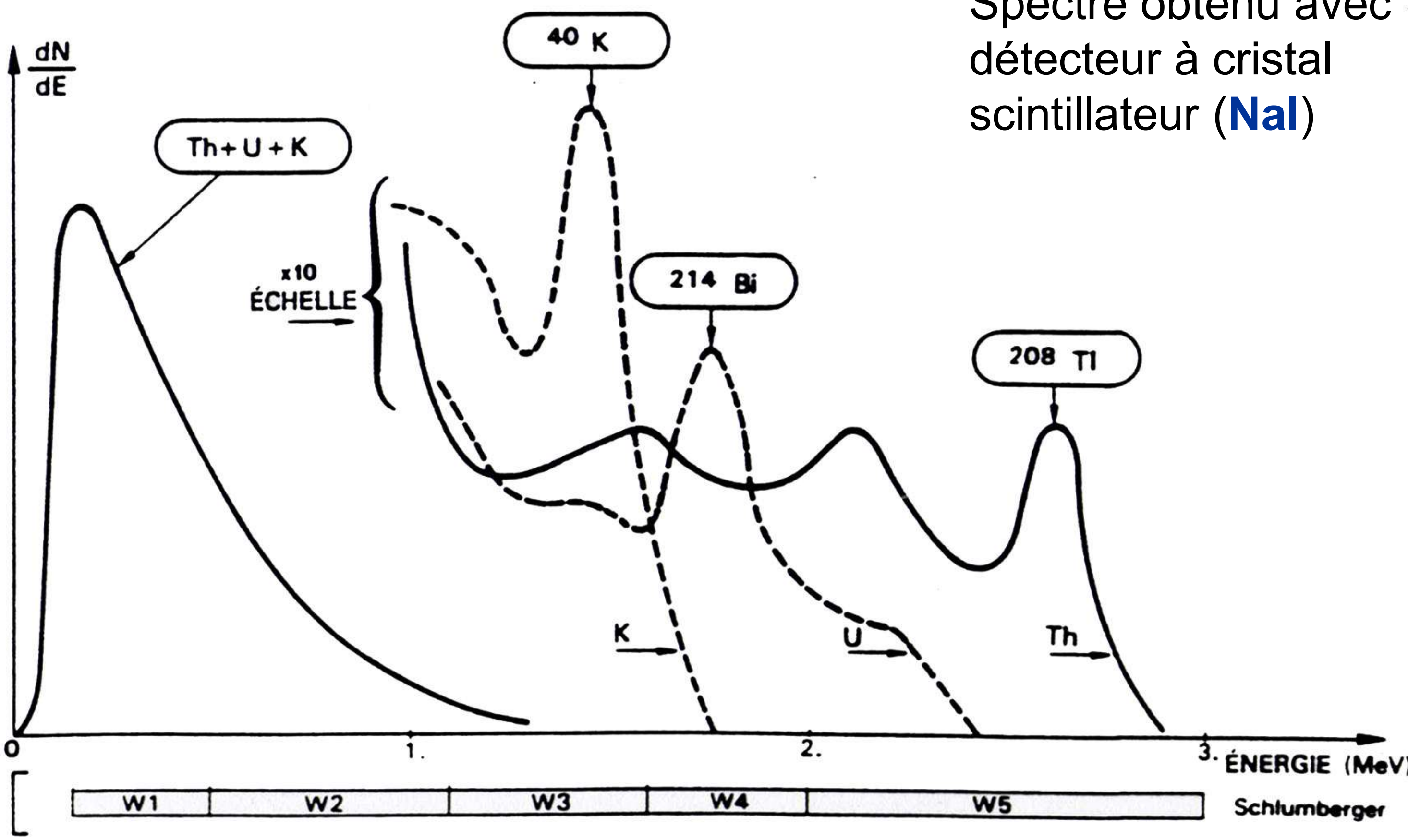
Time =1 sec



➡ Logs : **K, U, Th** et **T**γ **With depth**

II. Natural Gamma ray log

➢ Principles



Spectre obtenu avec détecteur à cristal scintillateur (**NaI**)

- Total Gamma ray : Th+U+K …
- Spectral Gamma ray : (Th,U,K) ➔ (Th+U+K)

II. **Natural Gamma ray log**

- Unit

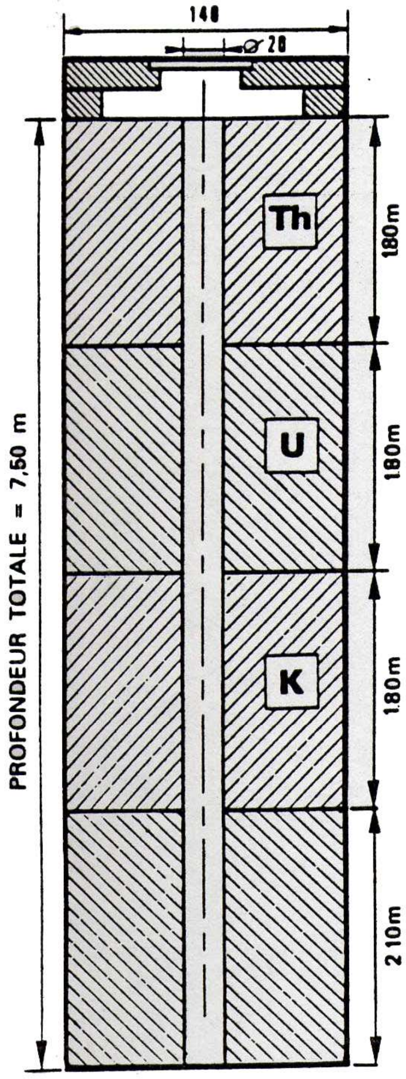
- Unit: API

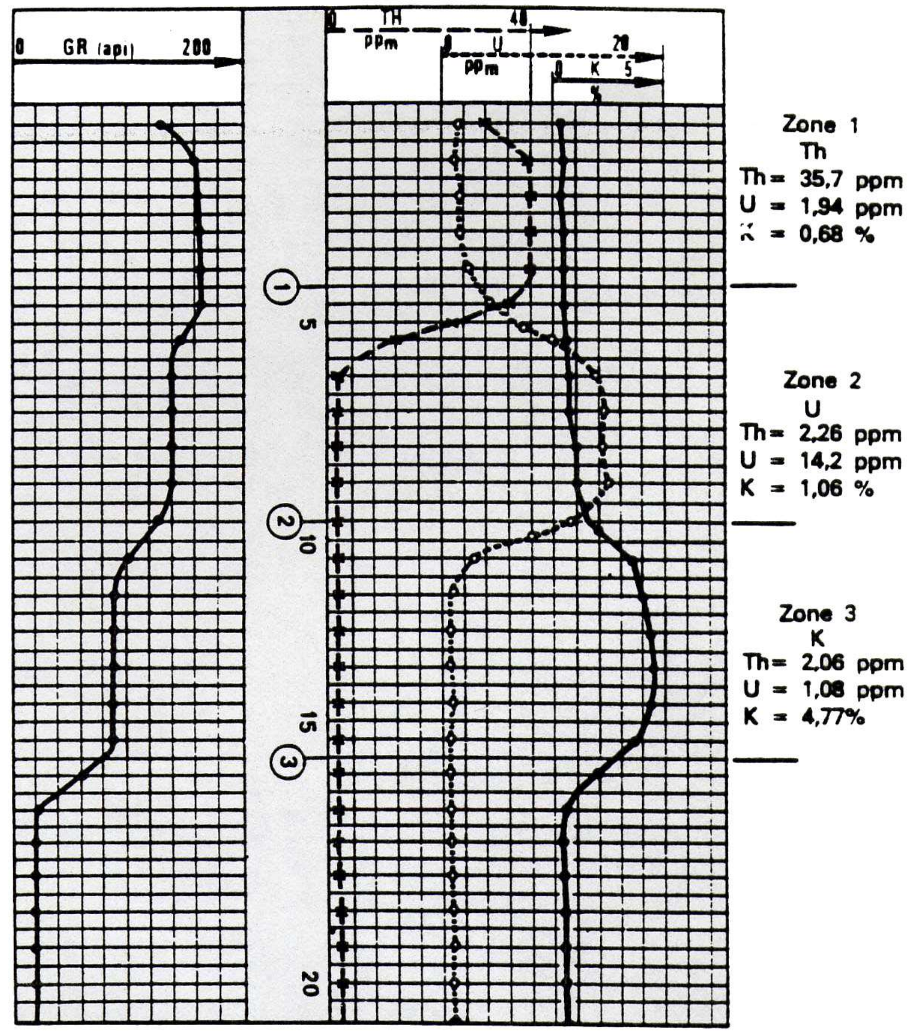
API unit is defined empirically by calibration to a reference well at the University of Houston. This reference well is an artificial one that is composed of large blocks of rock of accurately known radioactivity ranging from very low radioactivity to very large radioactivity.

The API unit is 1/200th of the difference between the highest activity formation in the reference well, and the lowest.

II. **Natural Gamma ray log**

- Calibration

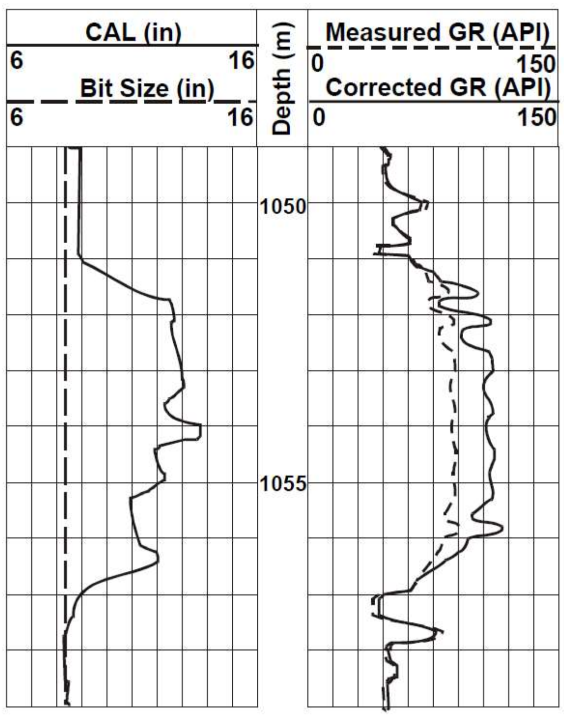


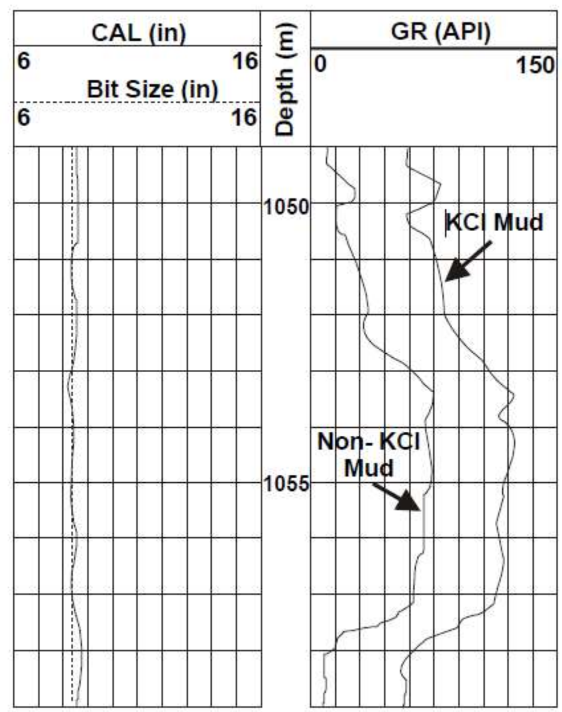


II. **Natural Gamma ray log**

- Factor affecting gamma ray logs

- Logging speed
- Borehole quality/diameter
- Mud type





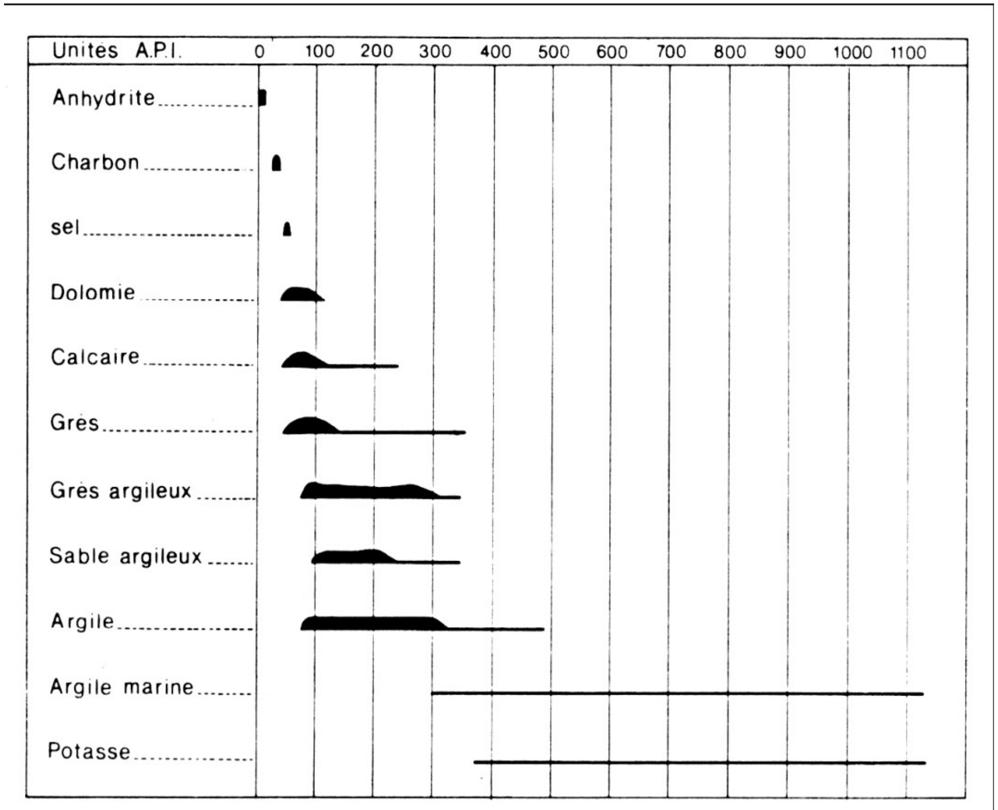
II. **Natural Gamma ray log**

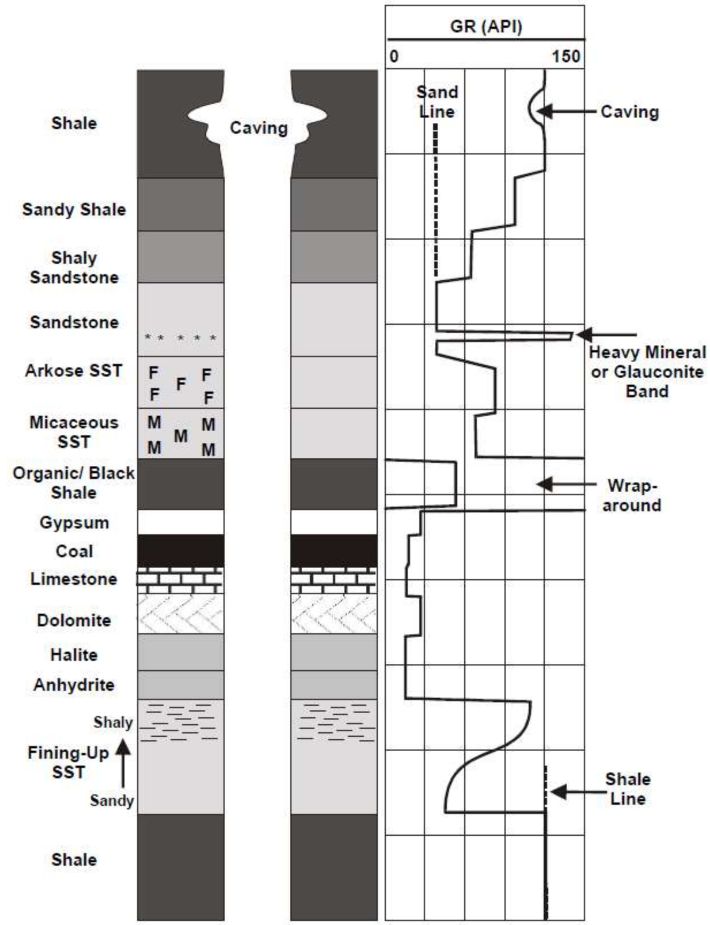
- Uses of gamma ray log

- Determination of Lithology
- Determination of Shale Content
- Depth Matching
- Cased Hole Correlations
- Recognition of Radioactive Mineral Deposits
- Recognition of Non-Radioactive Mineral Deposits
- Radio-isotope Tracer Operations
- Facies and Depositional Environment Analysis

II. **Natural Gamma ray log**

➢ Determination of Lithology





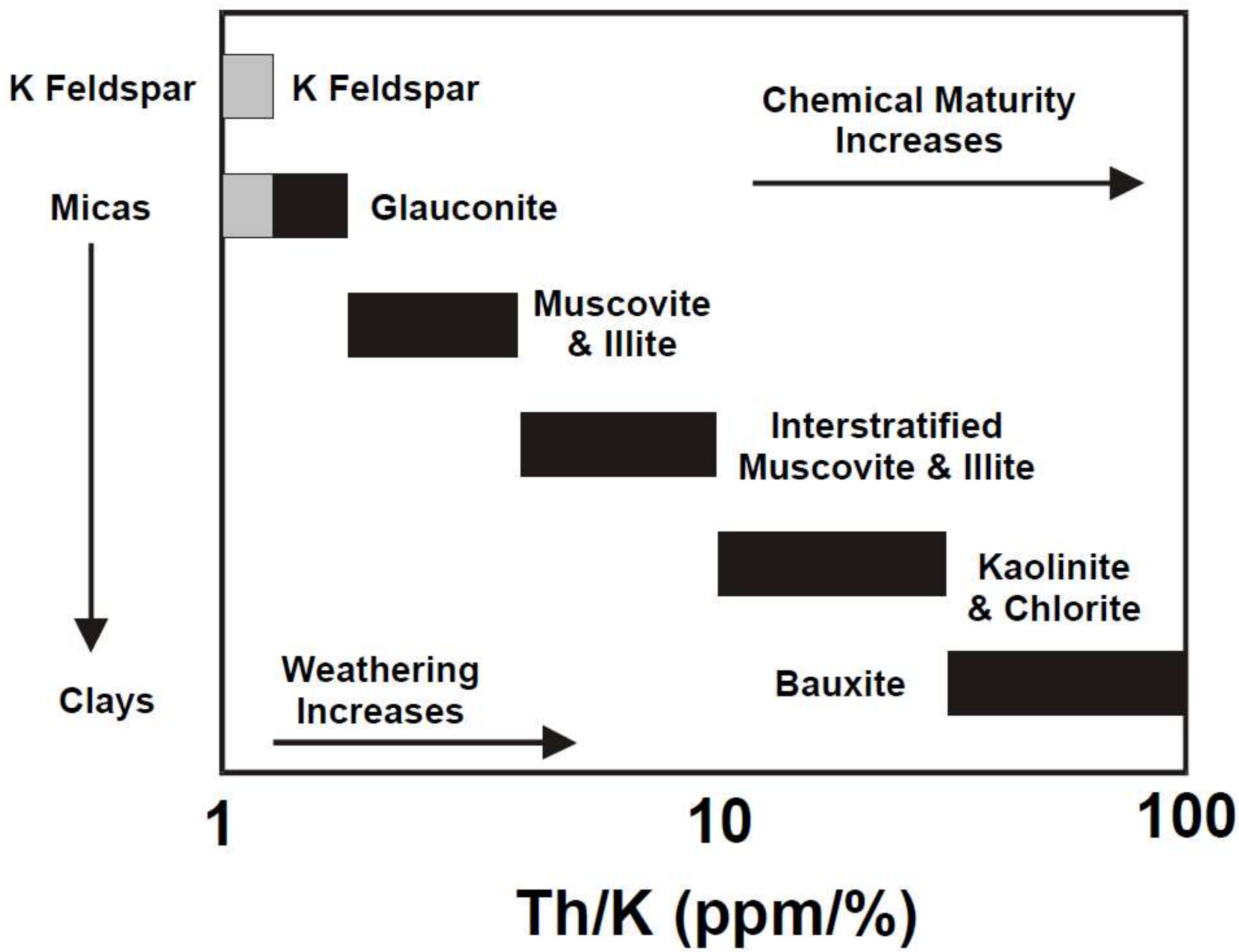
II. **Natural Gamma ray log**

➢ Determination of Lithology

Nom	Formule chimique		Teneur en K (en % de poids)
— FELDSPATHS			
• Roches alcalines			
Microcline	$KAl\,Si_3\,O_8$	triclinique	16 (idéale) à 10,9 (a)
Orthose	$KAl\,Si_3\,O_8$	monoclinique	14 (idéale) à 11,8 (a)
Anorthose	$(Na, K)\,Al\,Si^3\,O^8$		
— MICAS			
• Muscovite (1)	$KAl_2\,(Al\,Si_3\,O_{10})\,(OH, F)_2$		9,8 (idéale) à 7,9 (a)
• Biotite (1)	$K\,(Mg\,Fe)_3\,(Al\,Si_3\,O_{10})\,(OH, F)_2$		6,2 à 10,1 (moyenne 8,5)
• Illite	$K_{1-1.5}\,Al_4\,Si_{7-6.5}\,Al_{1-1.5})\,O_{20}\,(OH)_4$		3,51 à 8,31 (moyenne 6,7)
• Glauconite	$K_2\,(Mg, Fe)_2\,Al_6\,(Si_4O_{10})_3\,(OH)_{12}$		3,2 à 5,8 (moyenne 4,5)
• Phlogopite	$KMg_3\,(Al\,Si_3\,O_{10})\,(F, OH)_2$		6,2 à 10,1 (moyenne 8,5)
— ROCHES FELDSPATHOÏDES			
• Métasilicates			
Leucite	$KAl\,(SiO_3)_2$		17,9 (idéale)
• Orthosilicates			
Néphéline	$(Na, K)\,Al\,Si\,O_4$		4 à 8
Kaliophilite	$KAl\,Si\,O_4$		
— AUTRES MINERAUX ARGILEUX*			
Montmorillonite (1)			0 à 4,9 (b) (moyenne 1,6)
Chlorite (1)			0 à 0,35 (moyenne 0,1)
Kaolinite (1)			0 à 0,6 (c) (moyenne 0,35)

II. **<u>Natural Gamma ray log</u>**

➢ Determination of Lithology



II. Natural Gamma ray log

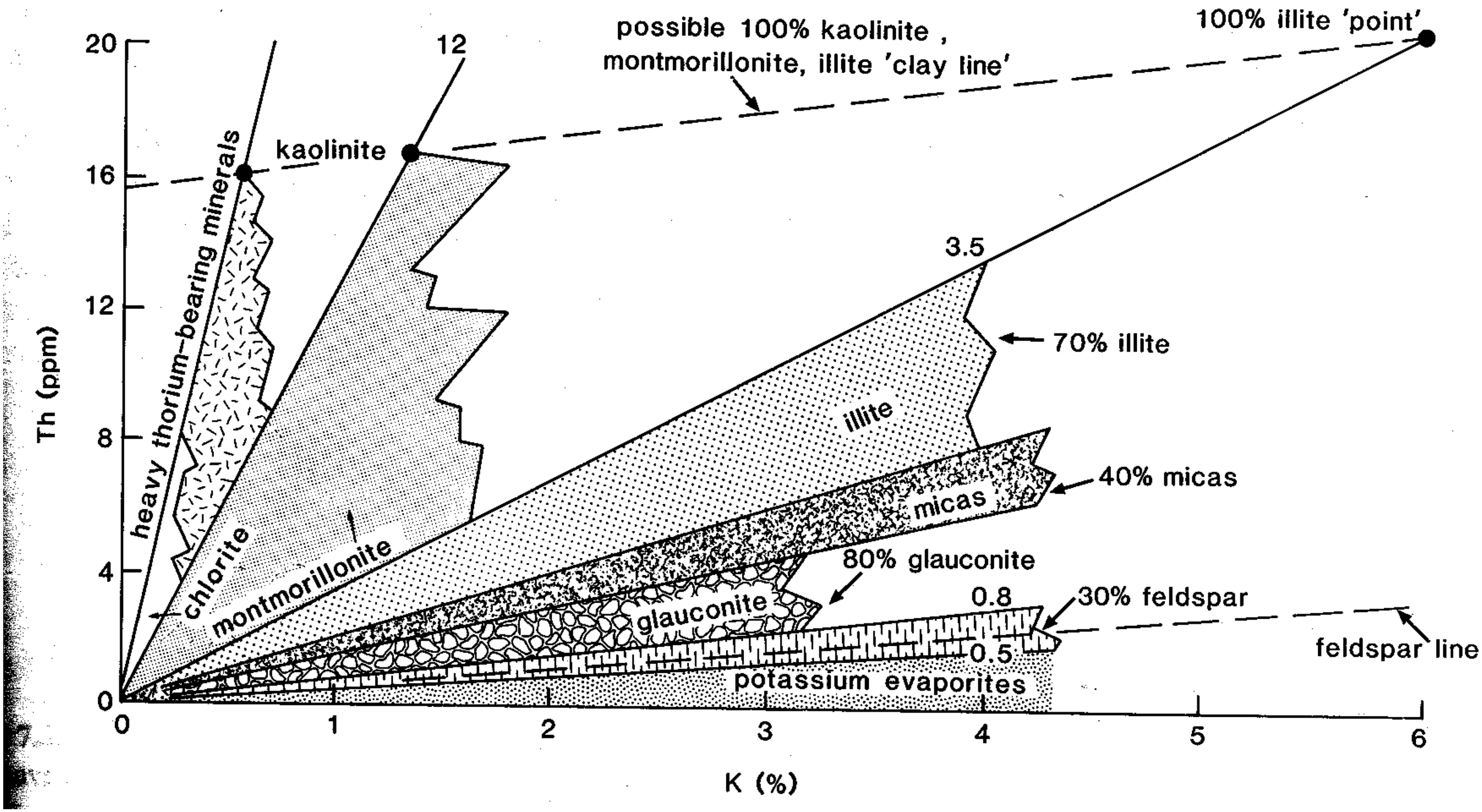
➢ Determination of Lithology : sandstones

Radioactive sandstones fall into one of six main groups, which are classified below:

- **Clay-Bearing Sandstones.** If clay minerals are known to be present in the rock
- **Arkose sandstones.** These contain feldspars, which have a significant potassium content, but a low thorium content. The Th/K ratio will therefore be low (<1 ppm/%)
- **Micaceous sandstones.** These contain mica, which has a potassium composition that is less than feldspars and a thorium content that is higher. The Th/K ratio is usually between 1.5 and 2.5 ppm/%.
- **Graywackes.** These contain both feldspars and micas, and give Th/K ratios intermediate between 1 and 2.5 ppm/%.
- **Greensands.** These contain glauconite, which is a mica group mineral containing iron, magnesium and potassium. It has Th/K ratios between 1 and 1.5 ppm/%.
- **Heavy mineral-bearing sandstones.** The heavy minerals are often abundant in either U or Th or both. The U and Th values are usually sufficiently high to ensure high U/K and Th/K ratios even if thesandstones also contains potassium in the form of feldspars, micas or glauconite. Typically Th/Kvalues will be above 25 ppm/%, and U/K values will be above 20 ppm/%.

II. **Natural Gamma ray log**

- Determination of Lithology : sandstones



II. **Natural Gamma ray log**

- Determination of Lithology : carbonate

Table 12.1 Interpretation of spectral gamma ray data in carbonates.

K	Th	U	Explanation
Low	Low	Low	Pure carbonate, no organic matter or oxidizing environment.
Low	Low	High	Pure carbonate, organic matter, reducing environment.
Low	High	Low	Not a carbonate, or shaly carbonate with rarer low K high Th clay minerals, no organic matter or oxidizing environment.
Low	High	High	Not a carbonate or shaly carbonate with rarer low K high Th clay minerals, organic matter, reducing environment.
High	Low	Low	Glauconite carbonate, no organic matter or oxidizing environment. Also consider K-bearing evaporites.
High	Low	High	Algal carbonate, or glauconite present, organic matter, reducing environment.
High	High	Low	Shaly carbonate, no organic matter or oxidizing environment.
High	High	High	Shaly carbonate, organic matter, reducing environment.
Note: Stylolites can locally concentrate U, clays and organic matter.			

II. **Natural Gamma ray log**

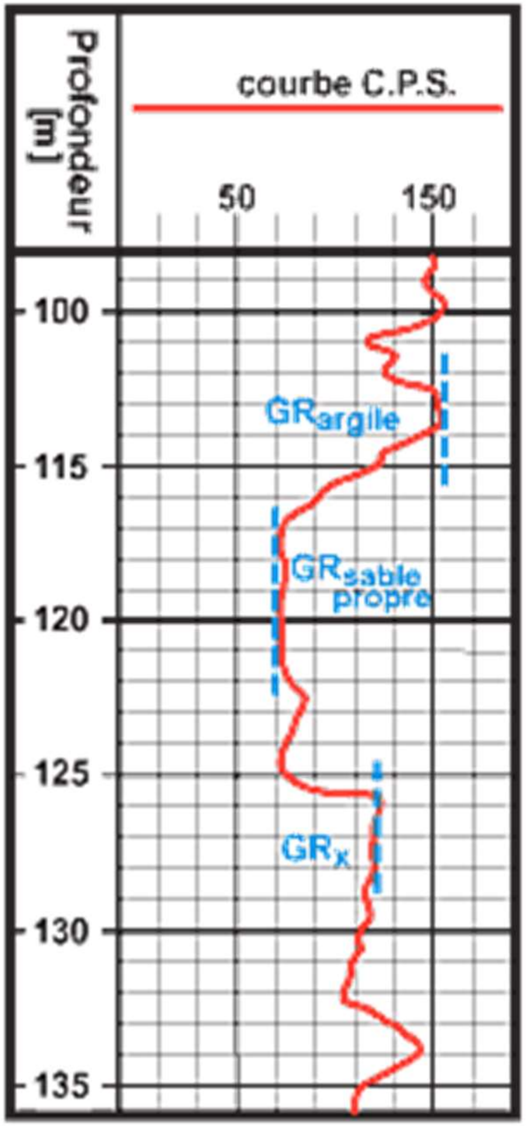
- Determination of Lithology : evaporites

Table 12.2 Potassium-bearing evaporites.

Name	Composition	K (wt%)	Density [FDC] (g/cm^3)	Pe [LFDC] (b/e)	Porosity [CNL] (%)	ΔT [Sonic] (μs/ft)
Sylvite	KCl	52.44	1.86	8.51	-3	74
Langbeinite	$K_2SO_4(MgSO_4)_2$	18.84	2.82	3.56	-2	52
Kainite	$MgSO_4\ KCl(H_2O)_2$	15.7	2.12	3.5	>60	-
Glaserite	$(K\ Na)_2SO_4$	24.7	2.7	-	-	-
Carnalite	$KCl\ MgCl_2(H_2O)_6$	14.07	1.57	4.09	>60	83
Polyhalite	$K_2SO_4\ MgSO_4\ (CaSO_4)_2\ (H_2O)_2$	13.37	2.79	4.32	25	57.5

II. **Natural Gamma ray log**

- Determination of Shale Content



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

$\boldsymbol{I_{GR}}$ → Gamma ray index

$\boldsymbol{GR_{log}}$ → Gamma ray reading at the depth of interest

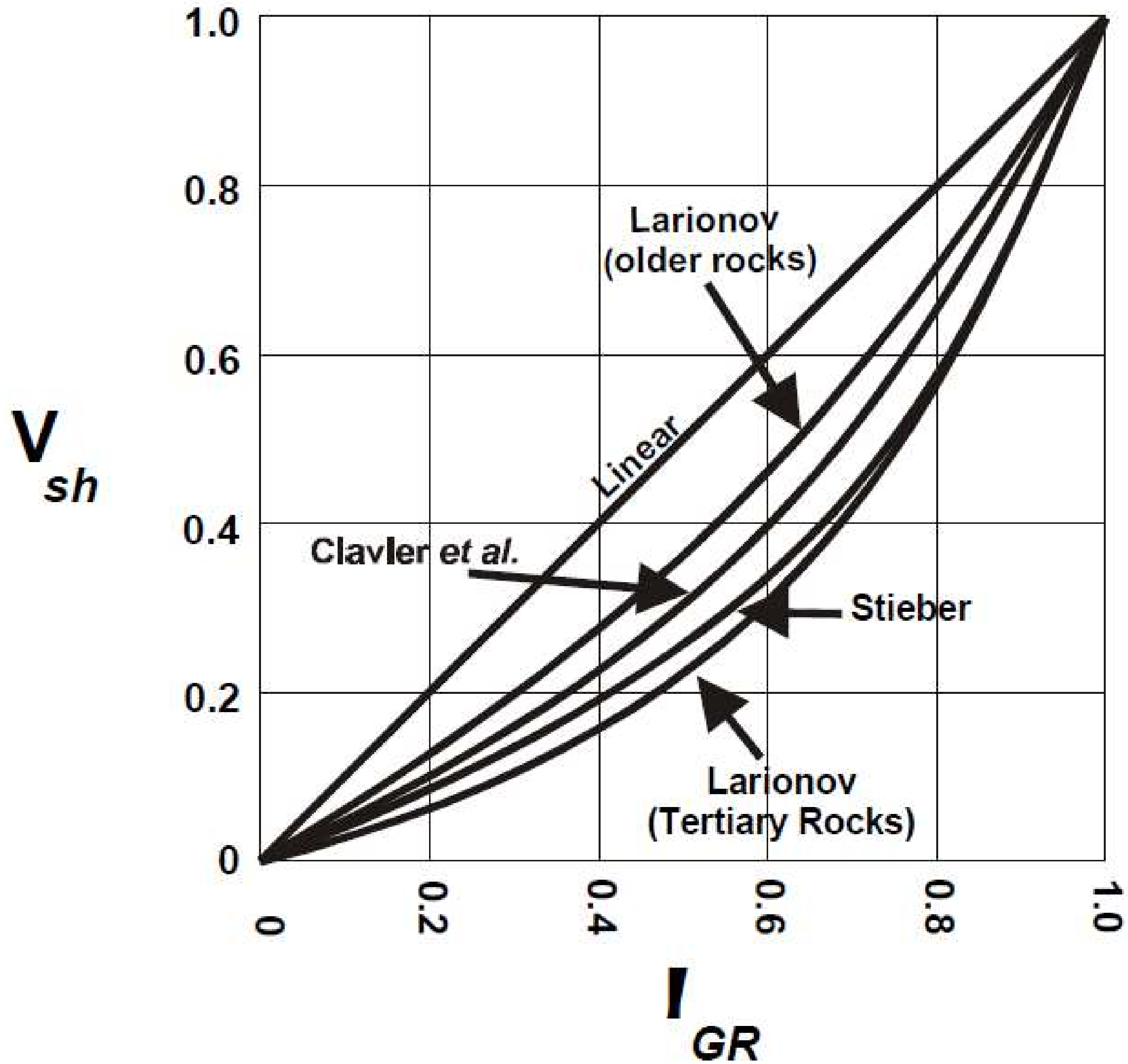
$\boldsymbol{GR_{min}}$ → the minimum gamma ray reading (usually the mean minimum through a clean sandstone or carbonate formation)

$\boldsymbol{GR_{max}}$ → the maximum gamma ray reading (usually the mean maximum through a shale or clay formation)

IGR = (120-70)/(155-70) = 0.59 = 59%

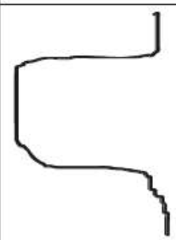
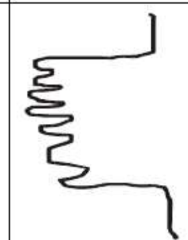
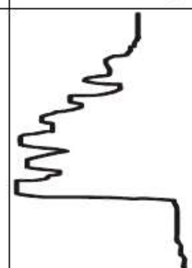
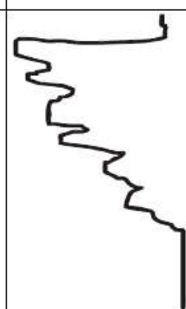
II. **Natural Gamma ray log**

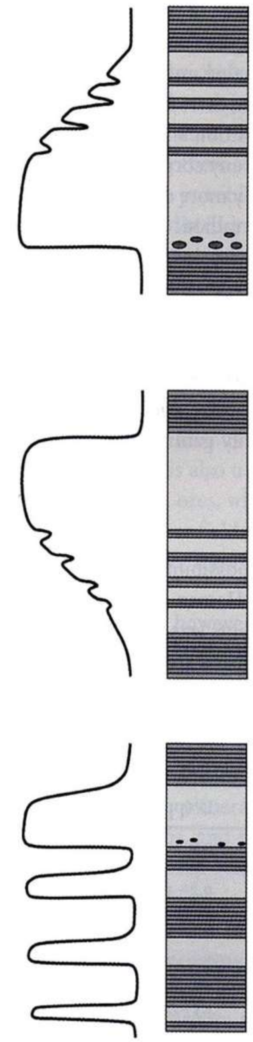
- Gamma ray index (IGR) vs Volume of shale (Vsh)



II. **Natural Gamma ray log**

- Facies and Depositional Environment Analysis

Shape	Smooth	Environments	Serrated	Environments
Cylinder Represents uniform deposition.		Aeolian dunes Tidal sands Fluvial Channels		Deltaic distributaries Turbidite channels Proximal deep-sea fans
Bell Shape Fining upwards sequences.		Tidal sands Alluvial sands Braided streams Fluvial channels Point bars		Lacustrine sands Deltaic distributaries Turbidite channels Proximal deep-sea fans
Funnel Shape Coarsening upward sequences.		Barrier bars Beaches Crevasse splays		Distributary mouth bars Delta marine fringe Distal deep-sea fans



(D'après Rider, 1996)

III. **Density log**

➢ Formation density log

The *formation density* log measures the bulk density of the formation. Its main use is to derive a value for the total porosity of the formation. It s also useful in the detection of gas-bearing formations and in the recognition of evaporites.

- A formation with a high bulk density, has a high number density of electrons. It attenuates the gamma rays significantly, and hence a low gamma ray count rate is recorded at the sensors.
- A formation with a low bulk density, has a low number density of electrons. It attenuates the gamma rays less than a high density formation, and hence a higher gamma ray count rate is recorded at the sensors.

$$n_e = \frac{NZ}{A}\rho_b$$

n_e = number density of electrons in the subtance $\left[\frac{electrons}{cm^3}\right]$

N = Avogadro's number ($\approx 6.02 \times 10^{23}$)

Z = Atomic number $(no\ unit)$

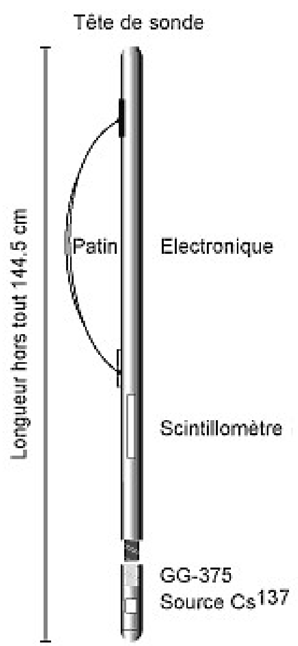
A = Atomic weight $\left[\frac{g}{mol}\right]$

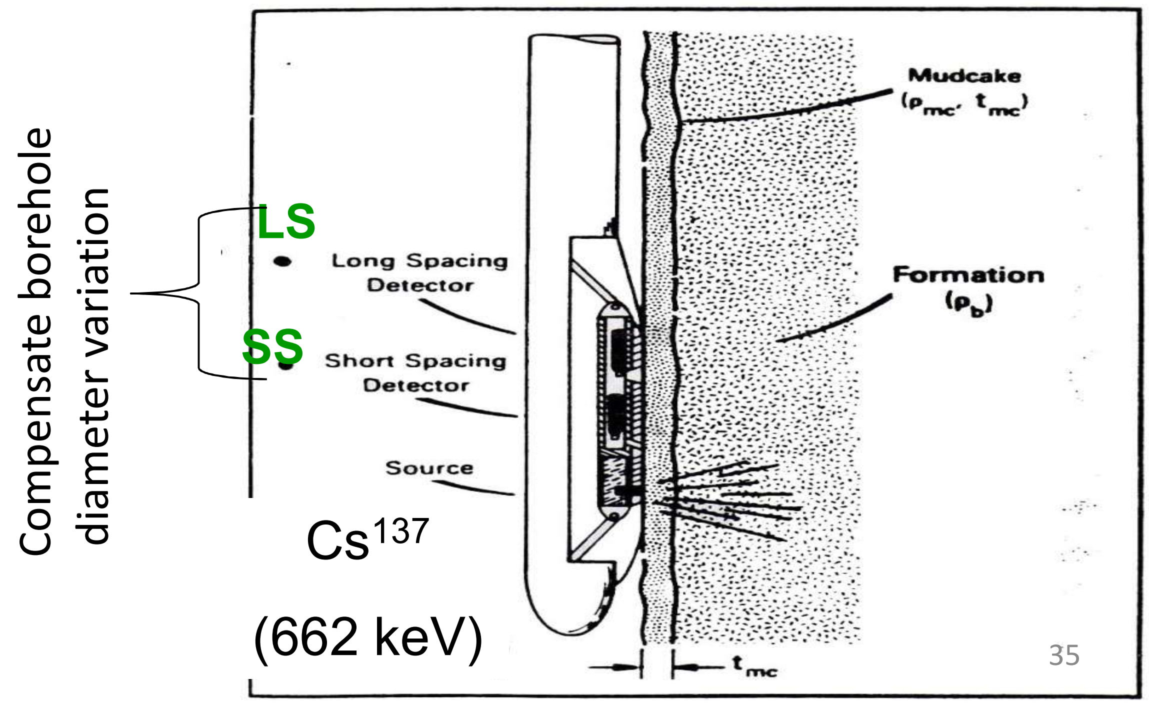
ρ_b = bulk density of the material $\left[\frac{g}{cm^3}\right]$

III. **Density log**

➢ Principle

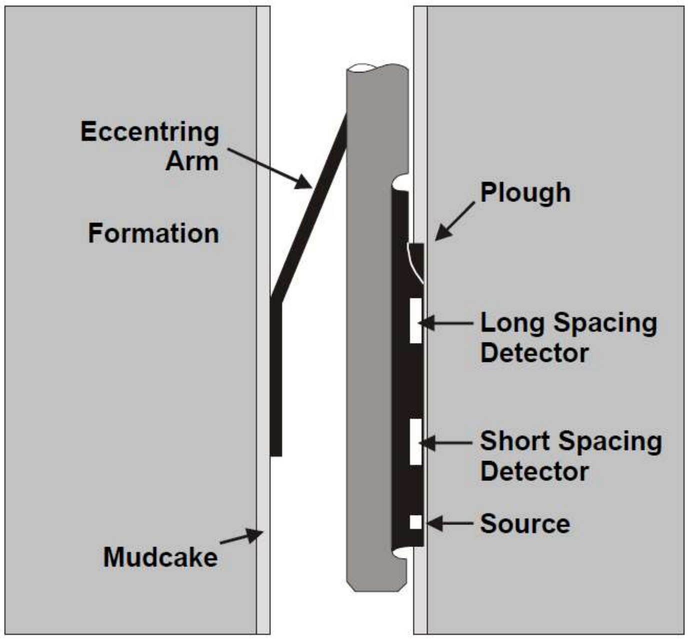
- The tool consists of:
- **A radioactive source.** This is usually caesium-137 or cobalt-60, and emits gamma rays of medium energy (in the range 0.2 – 2 MeV). For example, caesium-137 emits gamma rays with a energy of 0.662 MeV.
- **A short range detector.** This detector is very similar to the detectors used in the natural gamma ray tools, and is placed 7 inches from the source.
- **A long range detector.** This detector is identical to the short range detector, and is placed 16 inches from the source.

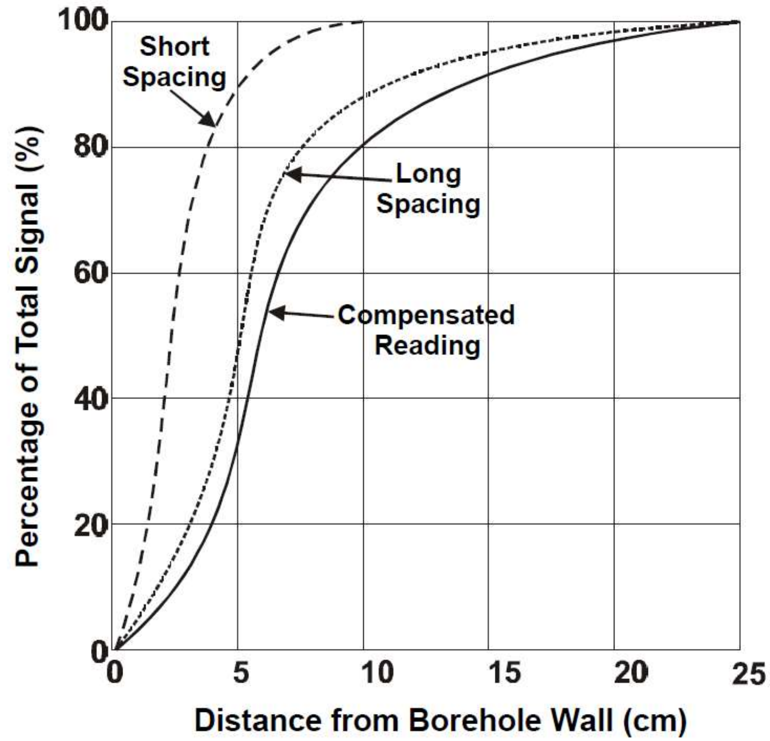




III. **Density log**

- <u>Principle</u>





$$Density = \Delta\rho = \rho_{LS} - \rho_{SS}$$

III. **Density log**

➢ Factor affecting the log density

- Logging Speed (400 m/h)

➔vertical resolution = 26 cm

- Borehole quality

- Mud type

- Mud thickness (correction needed)

III. **Density log**

- Uses of formation density log

- The main use of the formation density log is to determine porosity.

- Identification of Lithology

- Identification of Evaporites

- Shale Compaction, Age, and Unconformities

- Overpressure

- Recognition of Accessory Mineralogies

III. **<u>Density log</u>**

- <u>Porosity</u>

<u>Determination of porosity</u> :

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

With : $\rho_f = \rho_{mf} S_{X0} + \rho_{hc}(1-S_{X0})$

S_{XO}=*Saturation of the mud filtrate in the invaded zone*

ρ_f= *fluid density*

ρ_{ma}= *matrix density*

ρ_b= *rock density*

ρ_{mf}= *density of the mud filtrate*

ρ_{hc}= *density of the hydrocarbon or water*

III. **Density log**

- Uses of formation density log

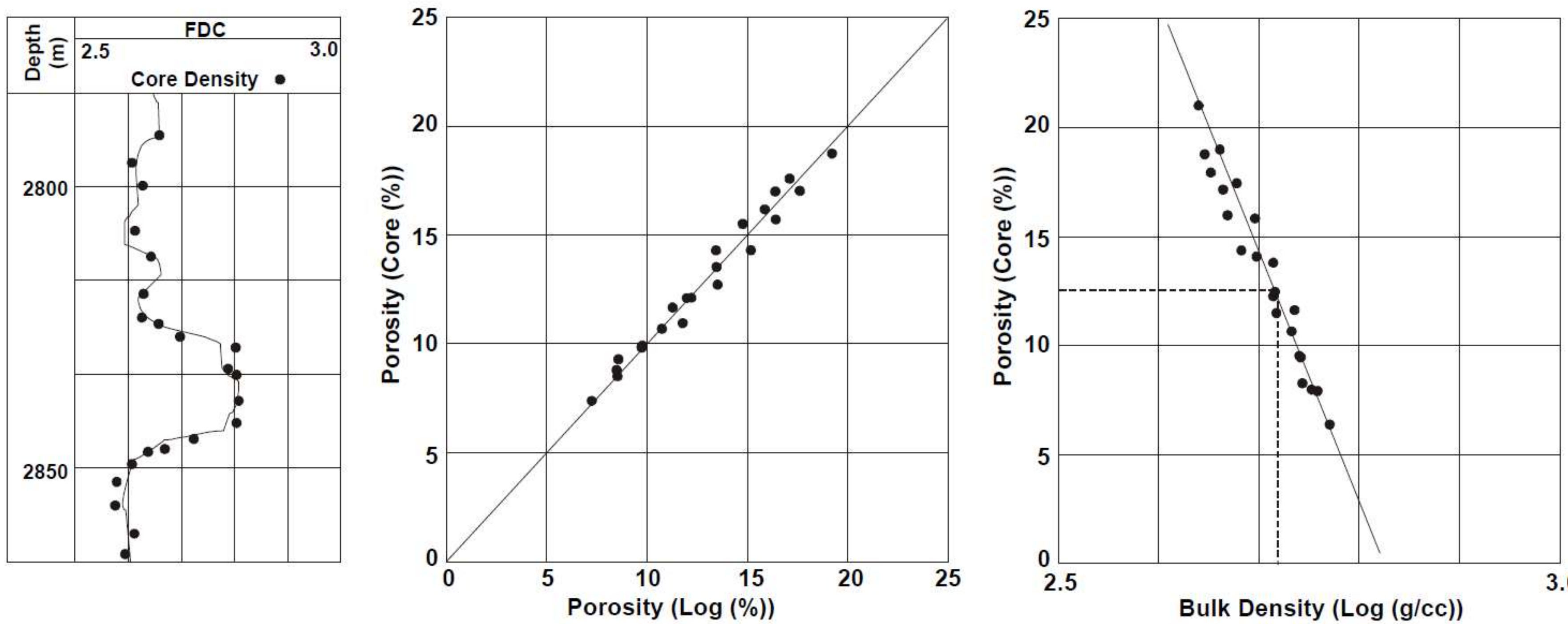
Mineral	Grain Density (g/cm^3)
Quartz	2.65
Calcite	2.71
Dolomite	2.87
Biotite	2.90
Chlorite	2.80
Illite	2.66
Kaolinite	2.594
Muscovite	2.83

Mineral	Grain Density (g/cm^3)
Halite*	2.16
Gypsum*	2.30
Anhydrite*	2.96
Carnalite*	1.61
Sylvite*	1.99
Polyhalite*	2.78
Glauconite	2.30
Kainite	2.13

*Evaporites

III. **Density log**

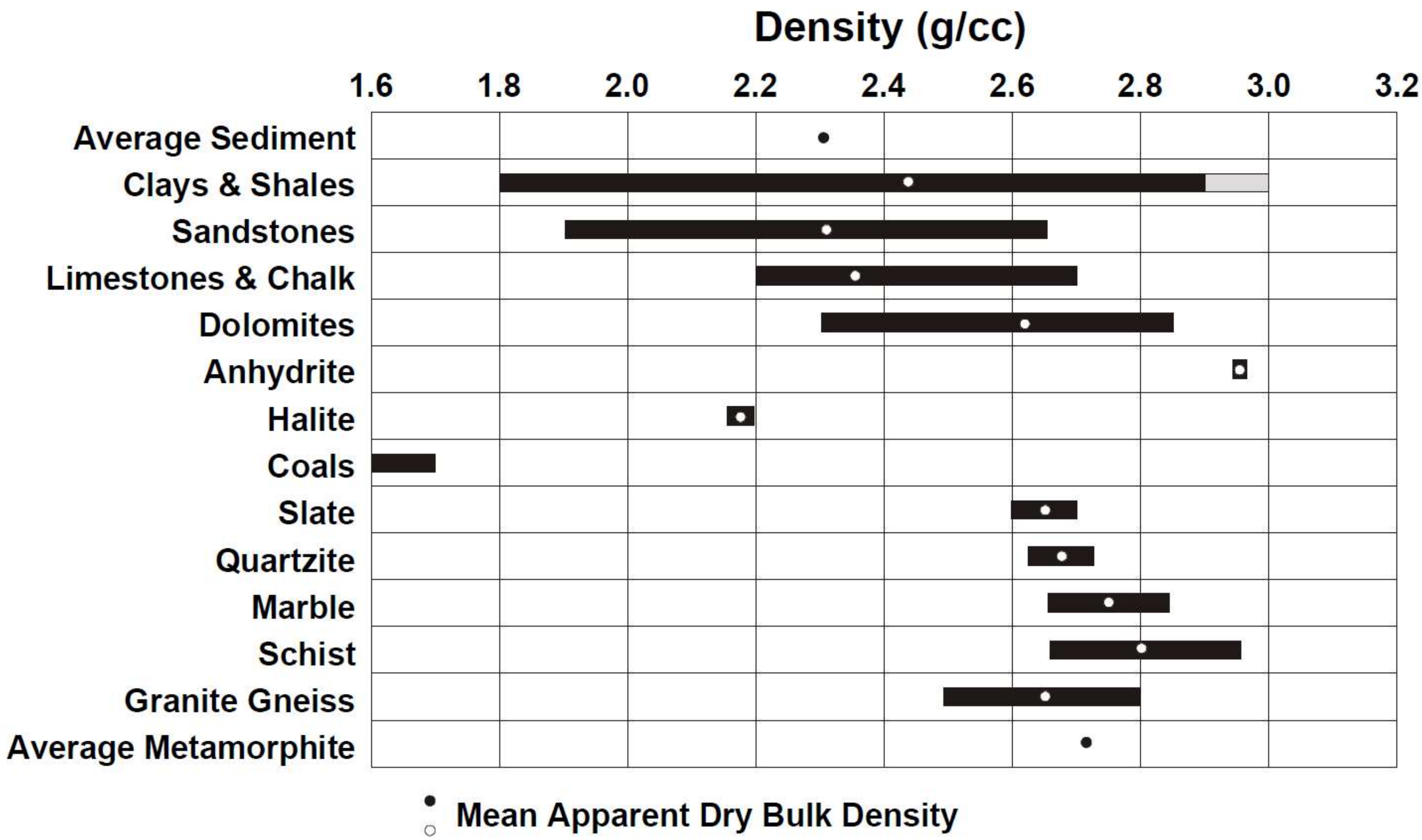
➢ Calibration with core porosity



III. **Density log**

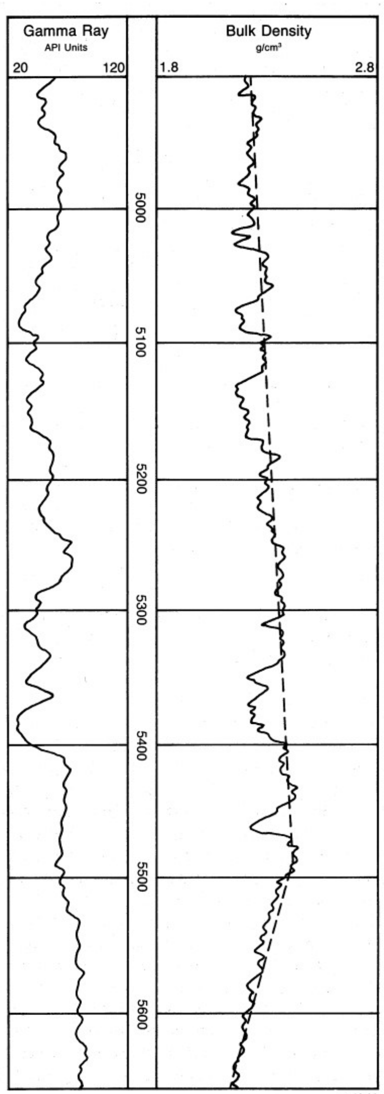
- <u>Identification of Lithology</u>

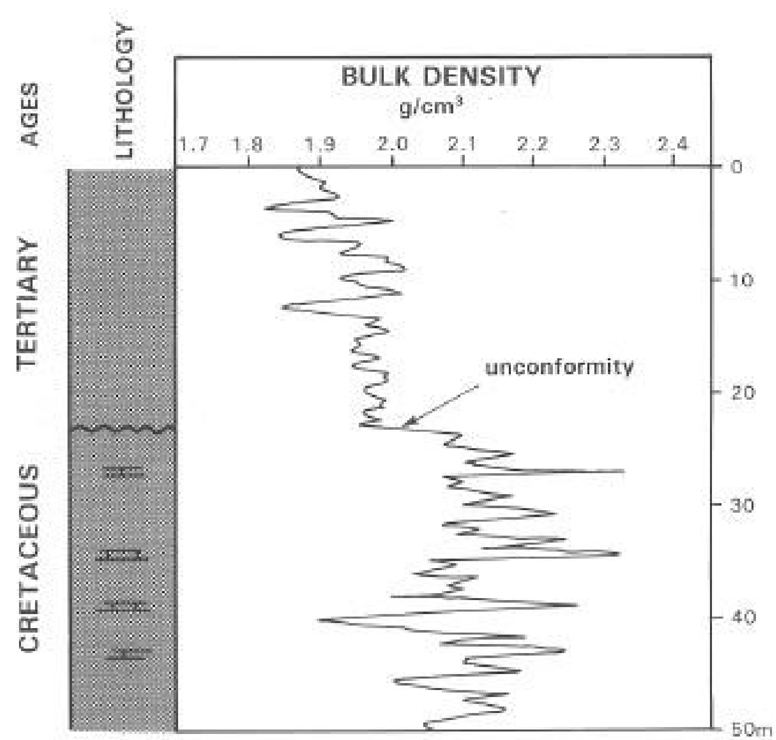
  - <u>Identification of Evaporites</u>



III. **Density log**

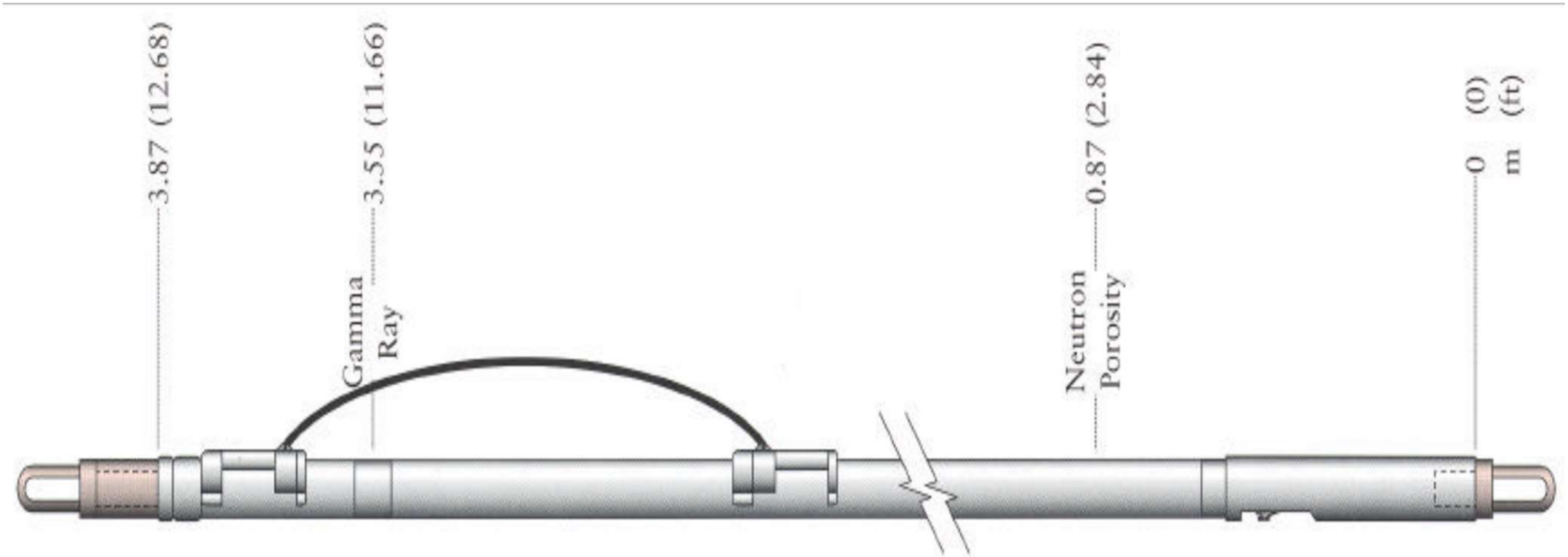
- Shale Compaction, Age, and Unconformities Overpressure





IV. **Neutron log**

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



IV. **Neutron log**

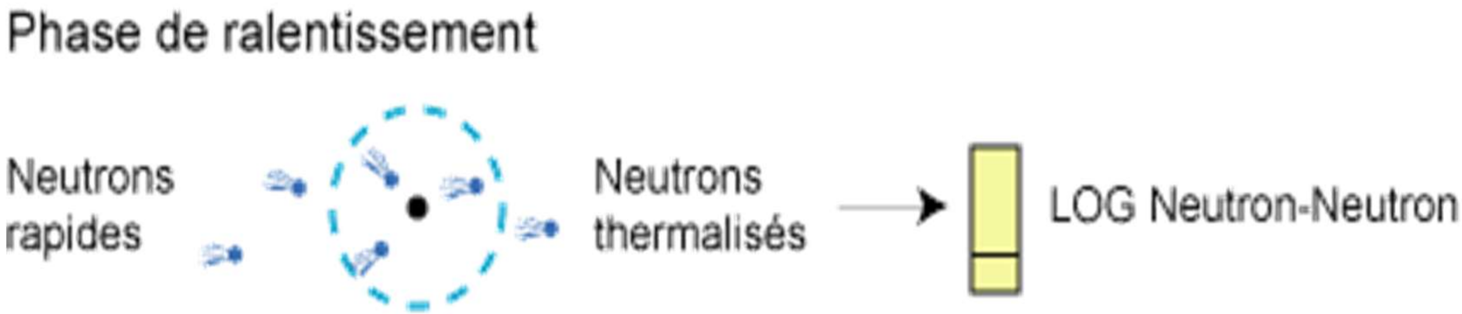
➢ Principle

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.

$$ {}_{4}^{9}Be + {}_{2}^{4}He \Longrightarrow {}_{6}^{12}C + {}_{0}^{1}n + \gamma $$

IV. **Neutron log**

- Principle: Neutron Scattering



Energy= **0.025 eV** speed =**2200 m/s**

Energy **<0,025 ev**

IV. **Neutron log**

➢ Tools

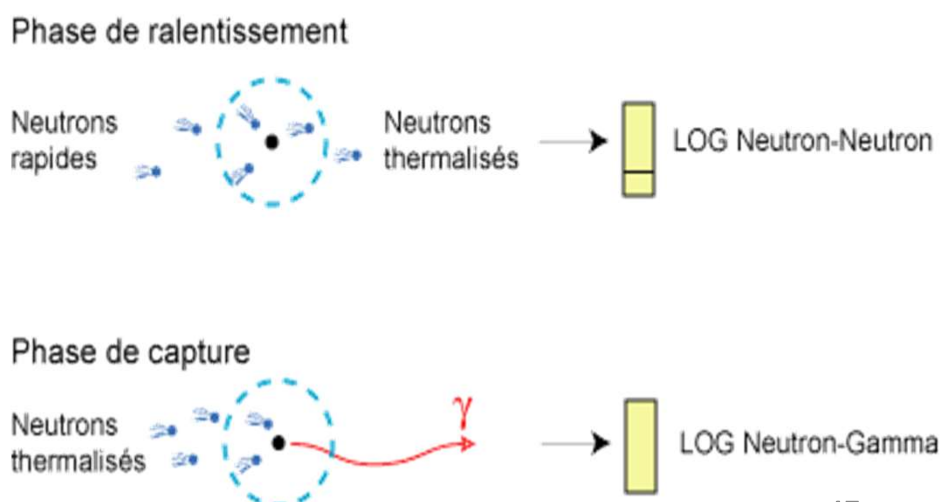
There are 2 main types of neutron tool, which are:

-Gamma ray-neutron tool (Neutron source, Gamma ray detector)

➔run in open and cased hole, sensible to chlorine

-Neutron Neutron tool (neutron source, Neutron detector)

➔ Operate in cased hole.



IV. **Neutron log**

- Principle: Neutron Scattering

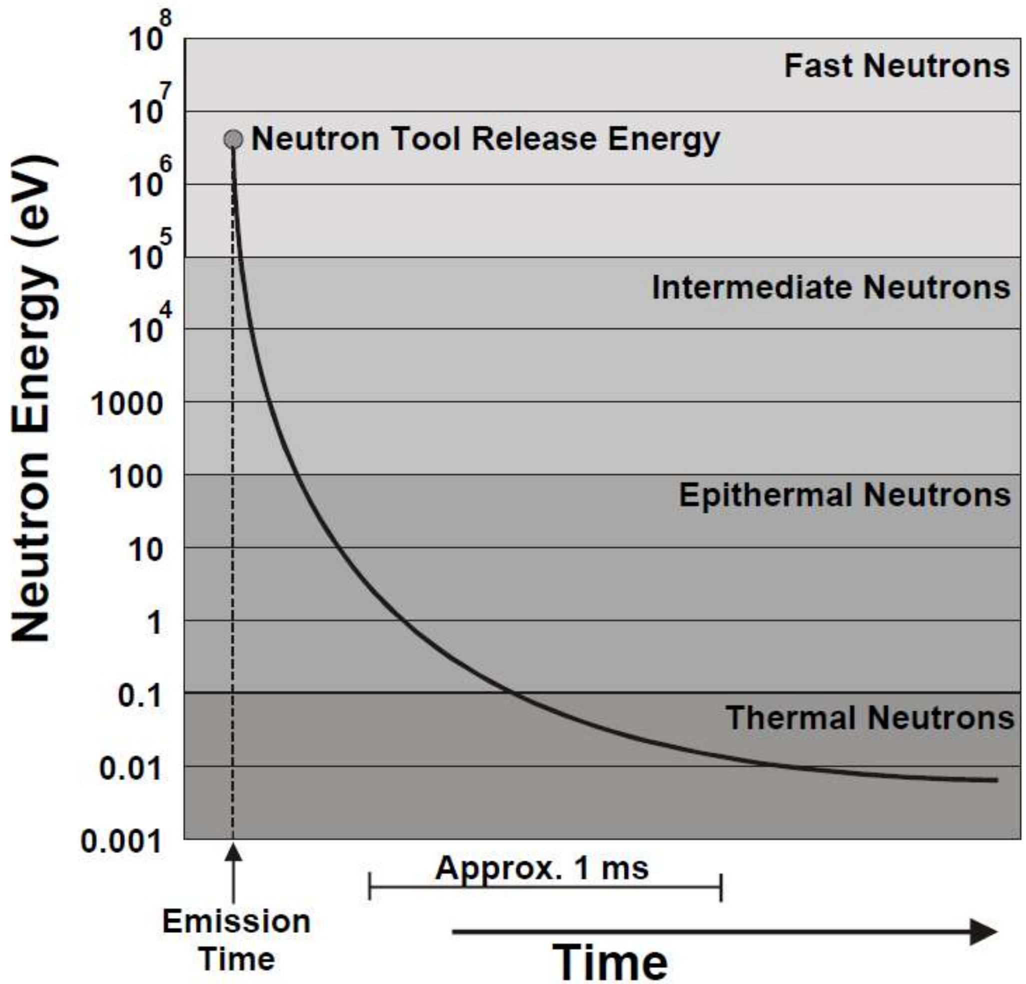


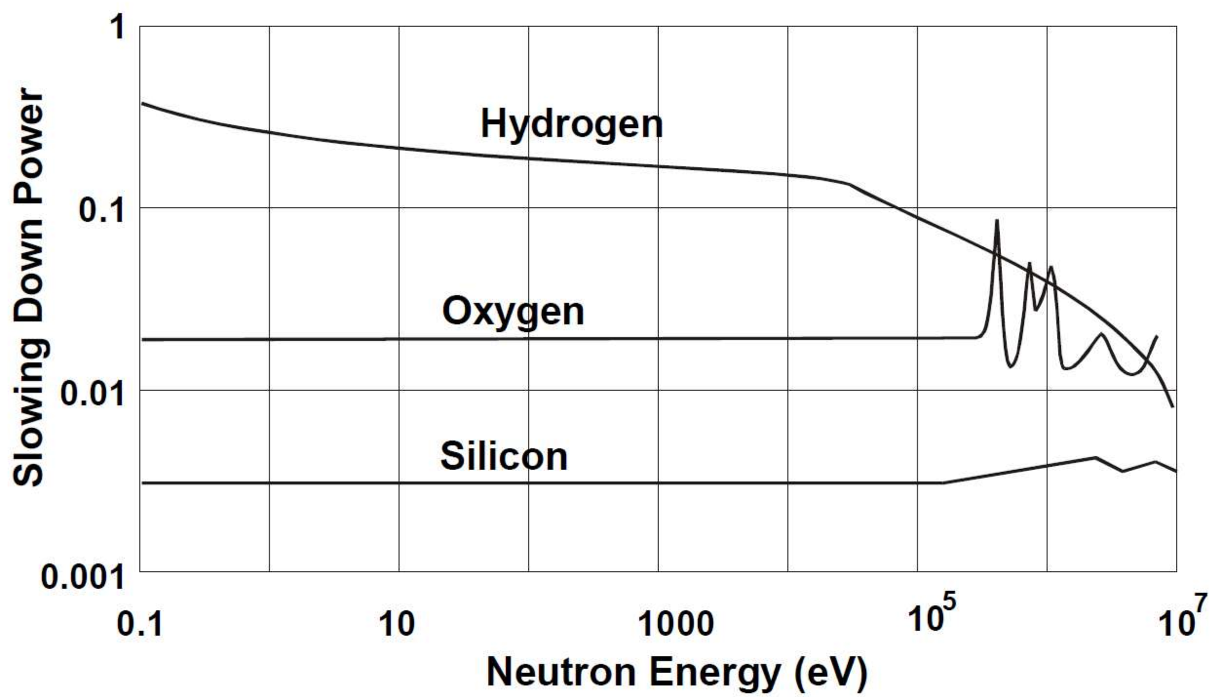
Figure 15.3 The slowing of fast neutrons with time by elastic collision with formation nuclei.

IV. **Neutron log**

- Principle: Neutron Scattering

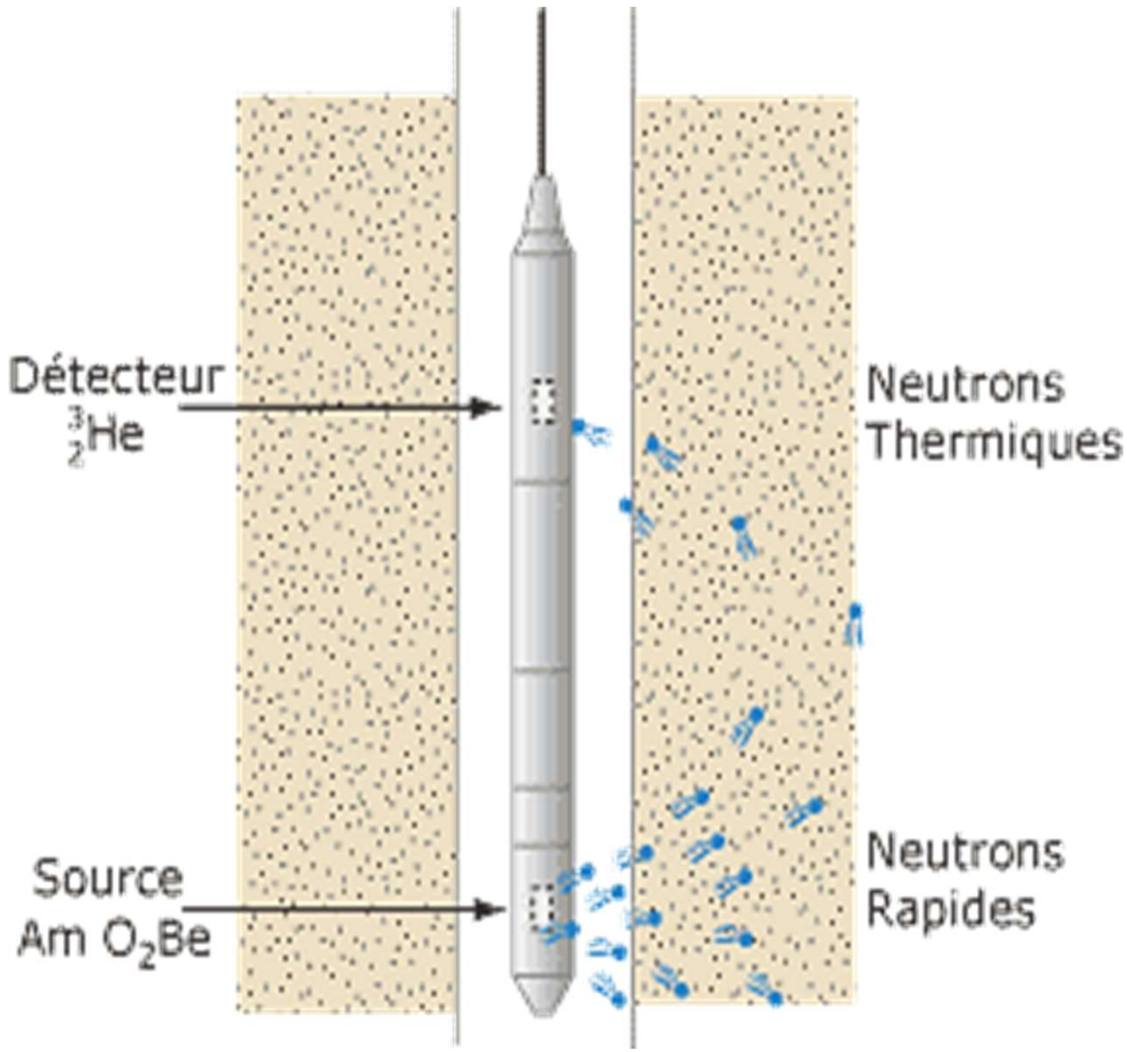
Energy loss from the neutron is most efficient when the masses of the neutron and the nucleus are the same, and becomes much less efficient when the nuclei of the formation material are more massive than the neutron.

➔ **Detection of Hydrogen**



IV. **Neutron log**

- Principle: Neutron Scattering



IV. **Neutron log**

➢ Hydrogen index

We can define a **partial concentration of hydrogens** per unit mass $(CH)_{mass}$ 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.

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

$\boldsymbol{A_H}$ = Atomic mass of hydrogen atoms in the material

$\boldsymbol{A_i}$ = Atomic mass of non-hydrogen element i

$\boldsymbol{n_H}$ = number of hydrogen atoms in a molecule of a material

$\boldsymbol{n_i}$ = number of non-hydrogen atoms of element i in a molecule of the material

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 *(CH)mass* = (2X1.0)/(1X16.0 + 2X1.0) = 1/9.

IV. **Neutron log**

- Hydrogen index

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 :*

$$HI = \frac{9 n_H A_H}{\sum_i n_i A_i + n_H A_H} \rho_b$$

A_H = Atomic mass of hydrogen atoms in the material

A_i = Atomic mass of non-hydrogen element i

n_H = number of hydrogen atoms in a molecule of a material

n_i = number of non-hydrogen atoms of element i in a molecule of the material

i is summed over every non-hydrogen element in the material

IV. **Neutron log**

➢ Hydrogen index

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

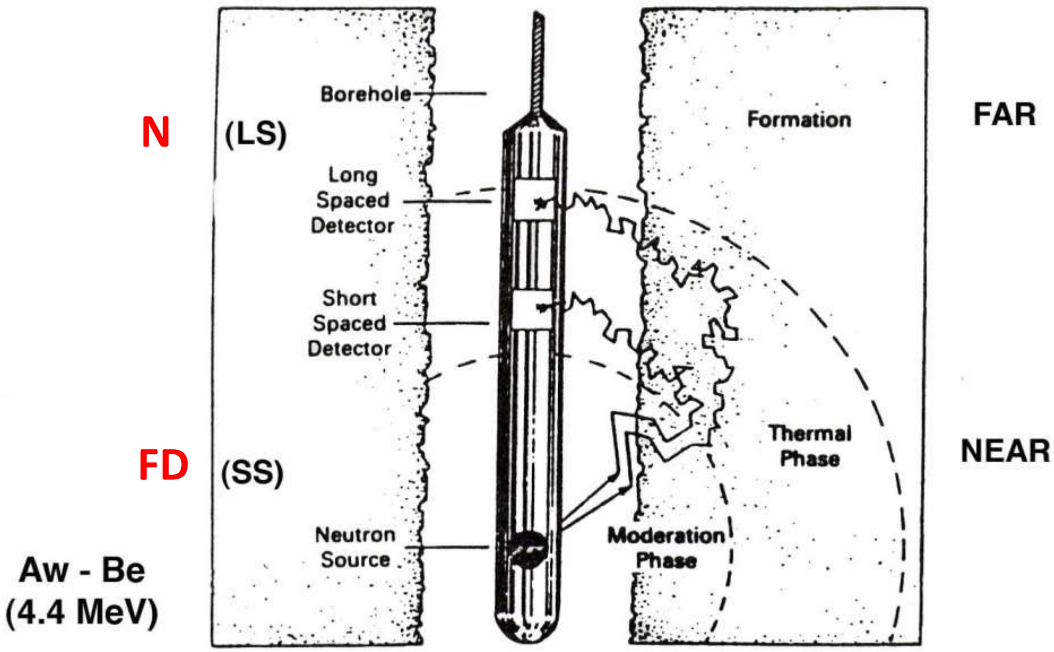
Compound	**Formula**	A_i	n_i	n_H	ρ_b	***HI***
Pure water	H_2O	16	1	2	1.000	1.000
Oil	$(CH_2)_x$	12	1	2	0.780	1.003
Methane	CH_4	12	1	4	ρ_m	$2.25\times\rho_m$
Gas	$C_{1.1}H_{4.2}$	12	1.1	4.2	ρ_g	$2.17\times\rho_g$
Quartz	SiO_2	28, 16	1, 2	0	2.654	0.000
Calcite	$CaCO_3$	40, 12, 16	1, 1, 3	0	2.710	0.000
Gypsum	$CaSO_4.2H_2O$	40, 32, 16	1, 1, 6	4	2.320	0.4855

The porosity read by the neutron tool is related to the actual porosity in the formation by :

$$\phi_N = \phi\left[HI_{inf}S_{XO} + HI_{hc}(1 - S_{XO})\right]$$

IV. **Neutron log**

- Porosity vs Hydrogen index



IV. **Neutron log**

- Factor affecting Neutron log

Neutron logs are affected :

- **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.

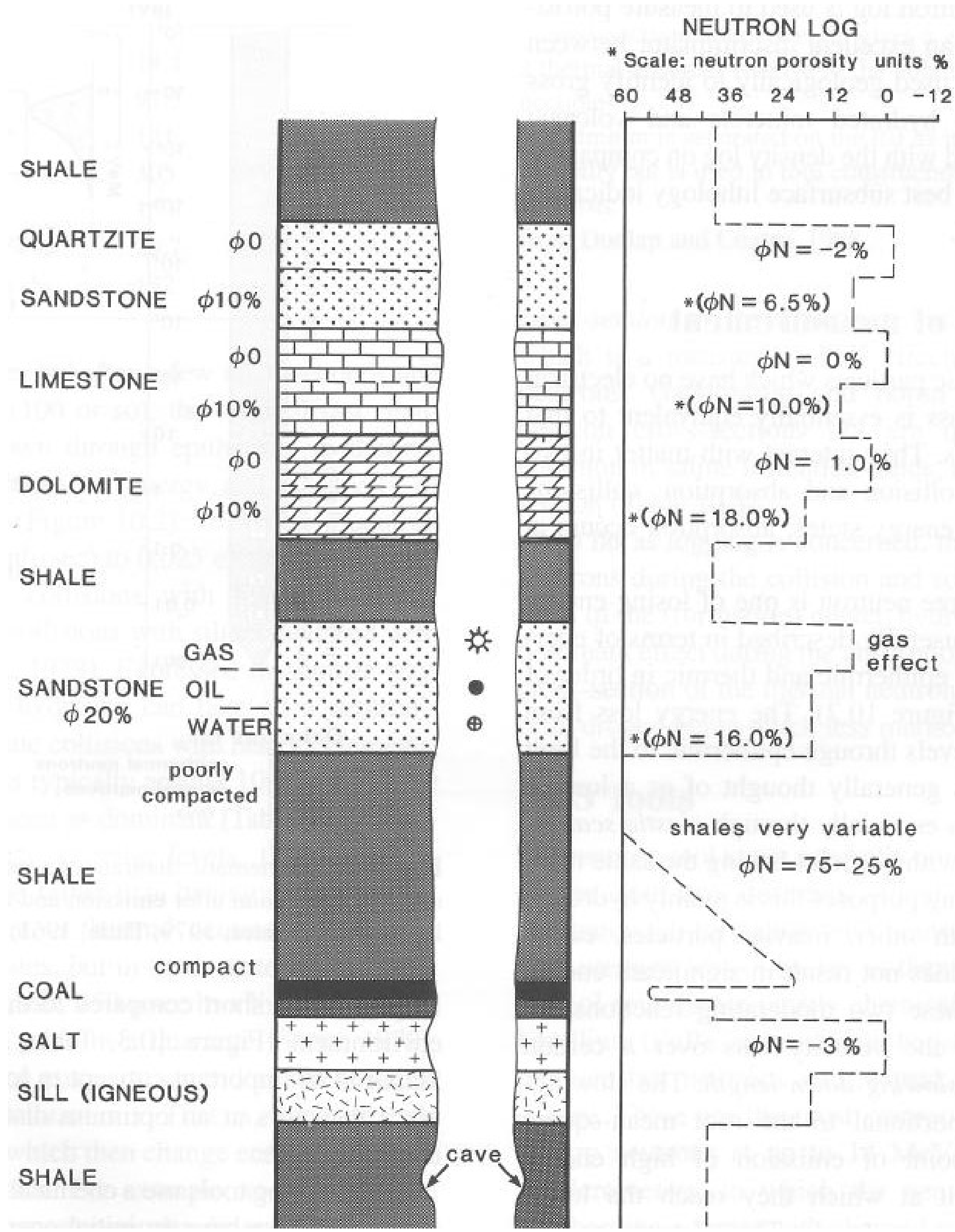
- **The Chloride Effect.** Chlorine is a good absorber of neutrons, and can lead to overestimations of porosity if present either as formation fluid or mud filtrate.

- Borehole Quality

- Mud Type

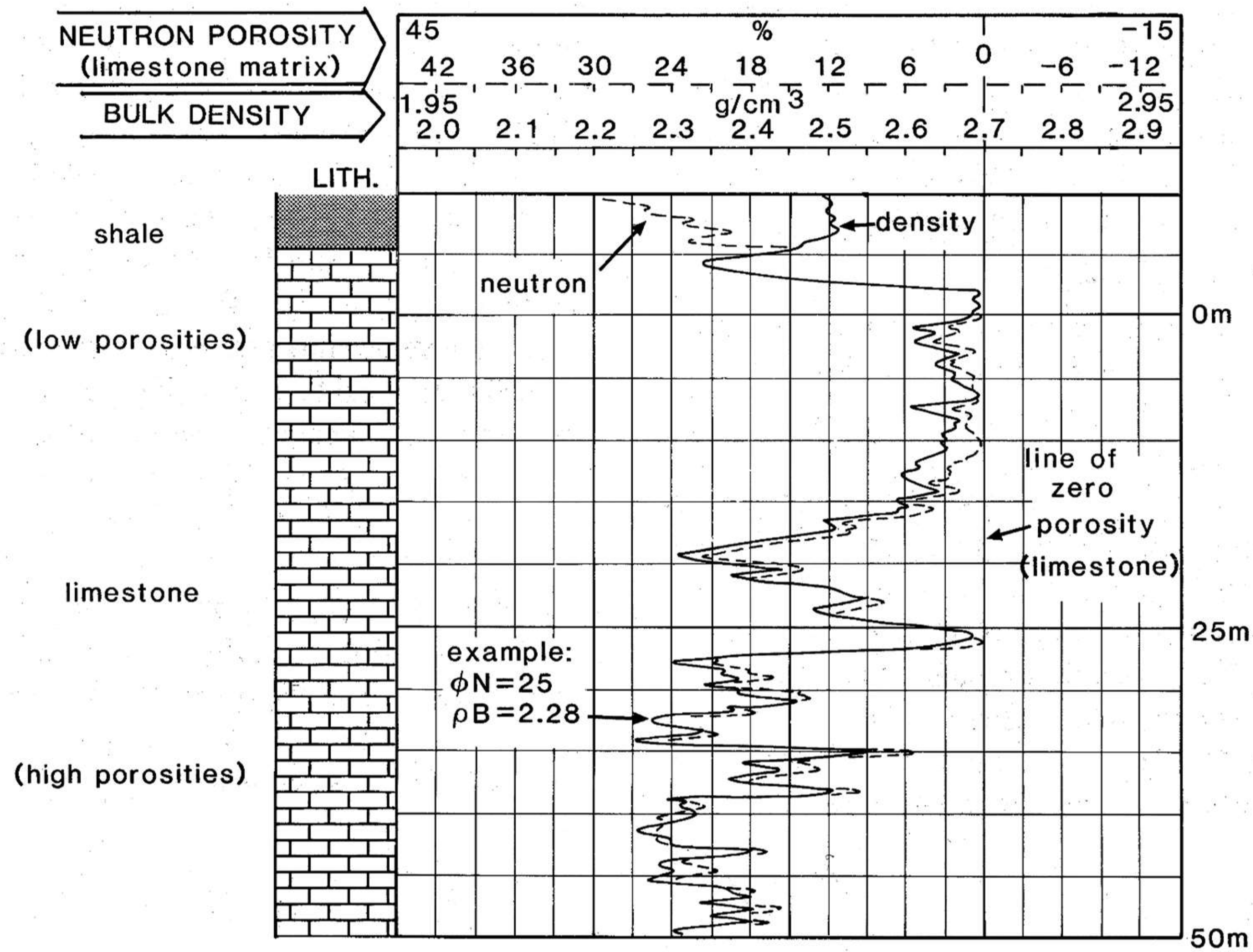
- **Presence of Gas (underestimate the porosity) (gas density =0.1)**

Ⅳ. **Neutron log**



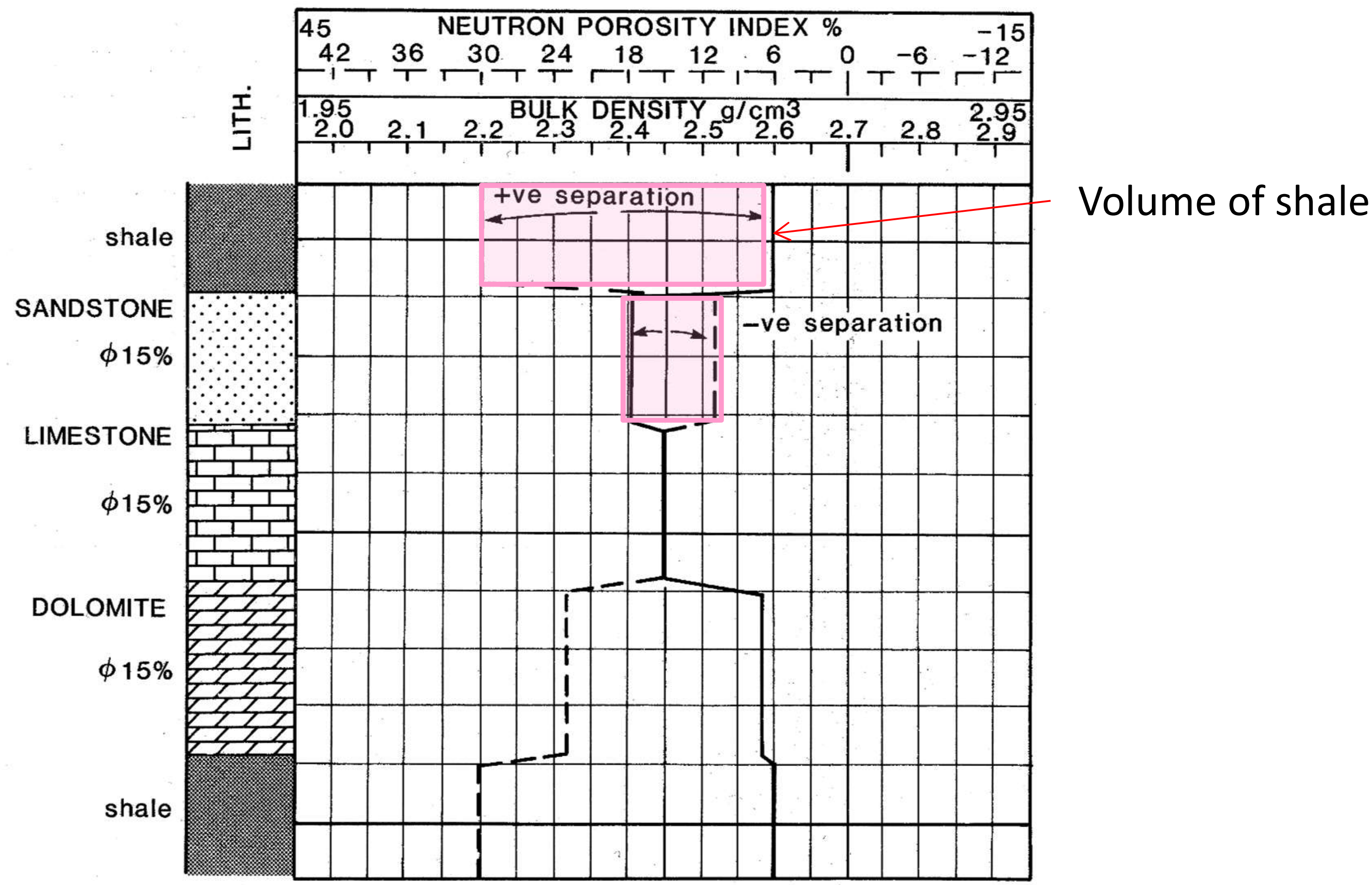
IV. **Neutron log**

- Relation Gamma ray & Neutron



IV. **<u>Neutron log</u>**

- Relation Gamma ray & Neutron



IV. **Neutron log**

- Relation Gamma ray & Neutron