Gamma Ray Logging

Tool Physics and Application

by

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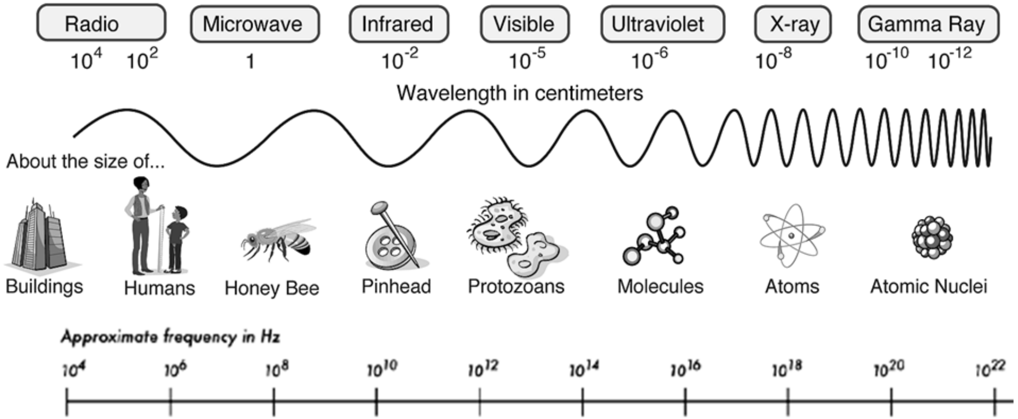
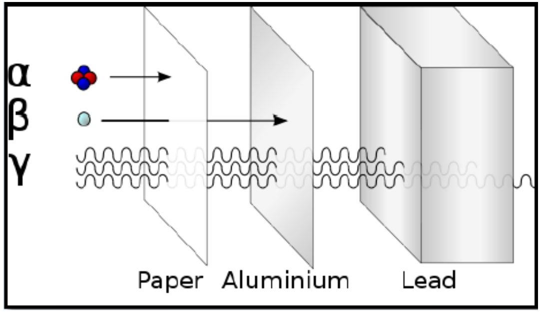
Radiation

- Simply put, radiation is the release of energy in the form of moving waves or streams of particles.
- This energy can be low-level, like microwaves and cell phones; or high level like X-rays or cosmic rays from outer space.
- There are electromagnetic radiation which are radio waves, microwaves, infrared, visible light, ultraviolet light, x-rays and gamma rays and nuclear radiation where a subatomic particle or energy are emitted from the nucleus of atoms.
- Nuclear radiation is sometimes called ionizing radiation, as it is energetic enough to knock electrons off atoms; alpha, beta and gamma radiations are the examples.



Nuclear Radiation

- Every element in the periodic table has a specific number of protons and neutrons. But sometimes an atom will have too many or too few neutrons. When this happens, it becomes unstable, or “radioactive”.
- Radioactive atoms want to become stable again. So they release energy until they get back to a balanced state. This process is known as radioactive decay and there are three main types:
  - α-radiation: atomic nucleus shoots out an alpha particles, which consists of two protons and two neutrons; alpha particles are heavy and travel small distances
  - β-radiation: atomic nucleus shoots out an electron; beta particles are lighter and travel further.
  - γ-radiation: extremely high energy photon escapes the nucleus; gamma radiation is actually a wave and it travel farthest of all.
- Unlike alpha and beta radiation, which have both energy and mass, gamma rays are pure energy, they are weightless packets of energy called photons.
- Gamma rays are emitted spontaneously by some radioactive elements and are similar to visible light but have much higher energy.

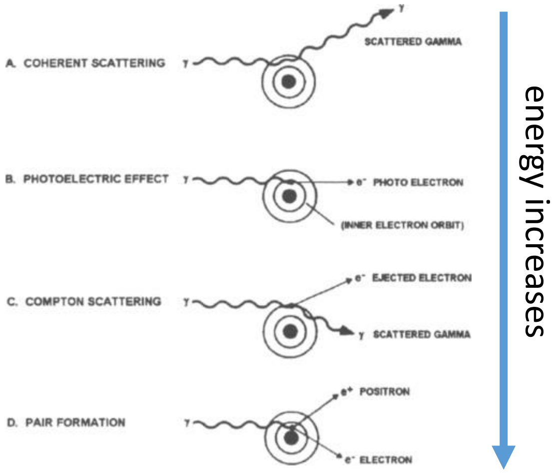


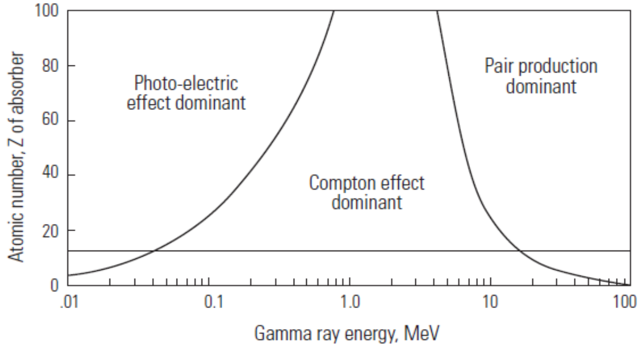
Gamma rays have so much penetrating power that several inches of a dense material like lead, or even a few feet of concrete may be required to stop them.

Gamma Ray Scattering

There are three types of gamma ray interactions in earth formations that are of interest:

- The **photoelectric effect** results from interaction of a gamma ray with an atom in the material. In this process the incident gamma ray disappears and transfers its energy to a bound electron. If the incident gamma ray energy is large enough, the electron is ejected from the atom and begins interacting with the adjacent material. For most earth formations, the photoelectric effect becomes the dominant process for gamma ray energies below about 100 keV.
- **Compton scattering**, which involves interactions of gamma rays and individual electrons. It is a process in which only part of the gamma ray energy is imparted to the electron; the remaining gamma ray is of reduced energy. Unlike the photoelectric effect, the cross section for Compton scattering changes relatively slowly with energy (660 keV).
- The third and final gamma ray interaction is **pair production**. Like the photoelectric process, pair production is one of absorption rather than scattering. In this case the gamma ray interacts with the electric field of a nucleus, and if the gamma ray energy is above the threshold value of 1022 keV, it disappears and an electron-positron pair is formed.





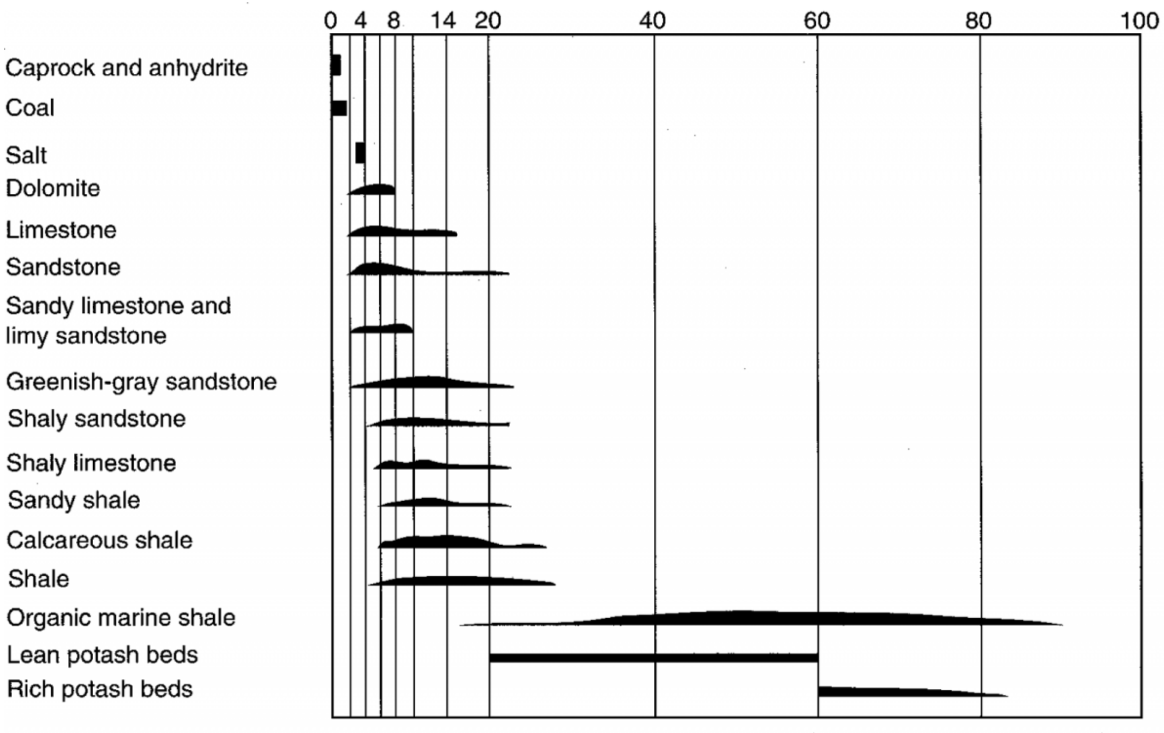
Regions of dominance of the three principal gamma ray scattering mechanisms as a function of energy and the atomic number, Z, of the scattering material

Outline

- Gamma-Ray Emission in Sedimentary Rocks
- Gamma-Ray Logging Tools
- Gamma-Ray Tool Principles
- Spectral Gamma-Ray Logging
- Gamma-Ray Log Presentation
- Gamma-Ray Calibration
- Factor Affecting Tool Response
- Gamma-Ray Application

Gamma Ray Emission in Sedimentary Rocks

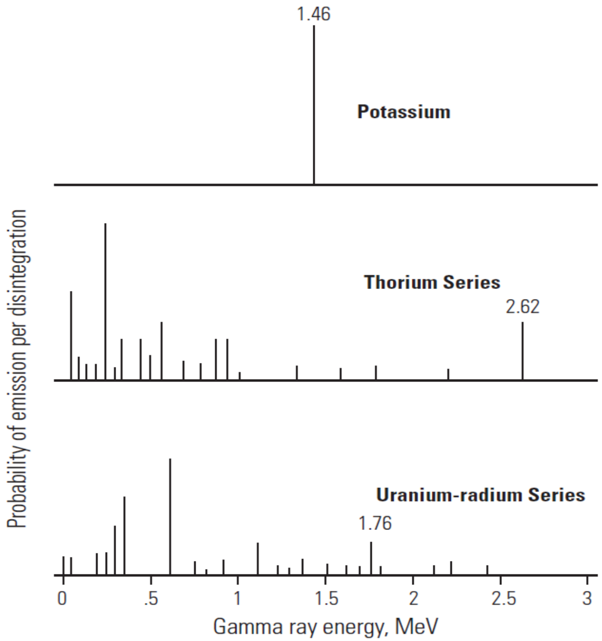
- To the right, the distribution of relative radioactivity level for various rock types are shown



(from Bigelow after Russell)

Gamma Ray Emission in Sedimentary Rocks

- Sedimentary rocks tend to emit Gamma rays. Nearly all the natural gamma ray radiation encountered in the earth is emitted by the radioactive potassium isotope (potassium-40, fairly common element in the earth's crust) and by the radioactive elements of the uranium-radium and thorium series.
- Each type of decay is characterized by a specific energy (wavelength), and the frequency of occurrence of each decay energy is different. To the right, the energies of the gamma rays emitted by potassium, uranium and thorium series are shown.
- Thorium and uranium both decay through two different series of a dozen or more intermediate isotopes to a stable isotope of lead. This gives rise to complicated gamma ray spectra with emissions at many different energies. The prominent gamma ray emission from the uranium series is due to an isotope of bismuth, while that of the thorium series is from thallium.
- The radioactive particles Uranium, Potassium, Thorium are very fine grains. During deposition these particles deposit with shale because shale is also fine grain rock. That's why the value of GR is high in Shale.
- Shale-free sandstones and carbonates have low concentrations of radioactive material and give low gamma ray readings, unless a radioactive contaminant such as volcanic ash or granite wash is present or formation waters contain dissolved radioactive salts. As shale content in the formation increases, the gamma ray log response increases because of the concentration of radioactive material in shale.
- Clean sandstone might also produce a high gamma ray response if the sandstone contains potassium feldspars, micas, glauconite, or uranium-rich waters. In this case the spectral gamma ray log can be run in place of the standard gamma ray log.



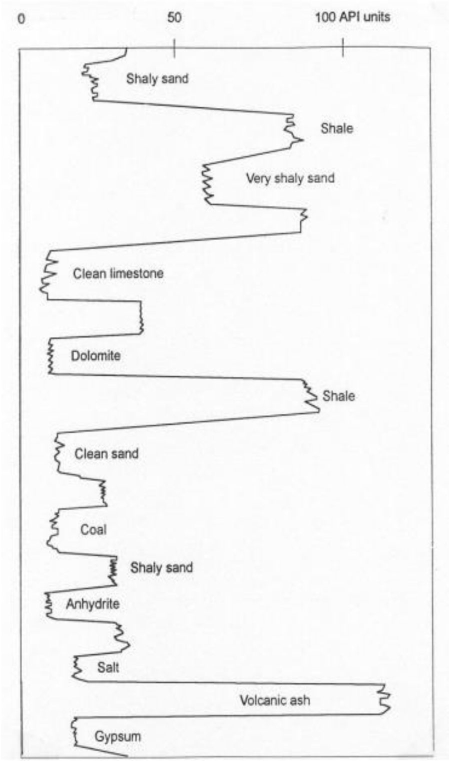
The distribution of gamma rays from the three naturally occurring radioactive isotopes.

Gamma Ray Emission in Sedimentary Rocks

- Limestone, Anhydrite ≈ 15-20 API
- Sandstone, Dolomite ≈ 20-30 API
- Clay minerals:
  - Average Shale ≈ 100 API
  - Shale is a good source of 40K.
  - Shales are clay rich (50-60%) sedimentary rocks.
  - An average shale contains 56% Clay, 24% quartz, 9 % carbonates and 6% Feldspar
  - An average shale has 2% K, 6 ppm U and 12 ppm Th

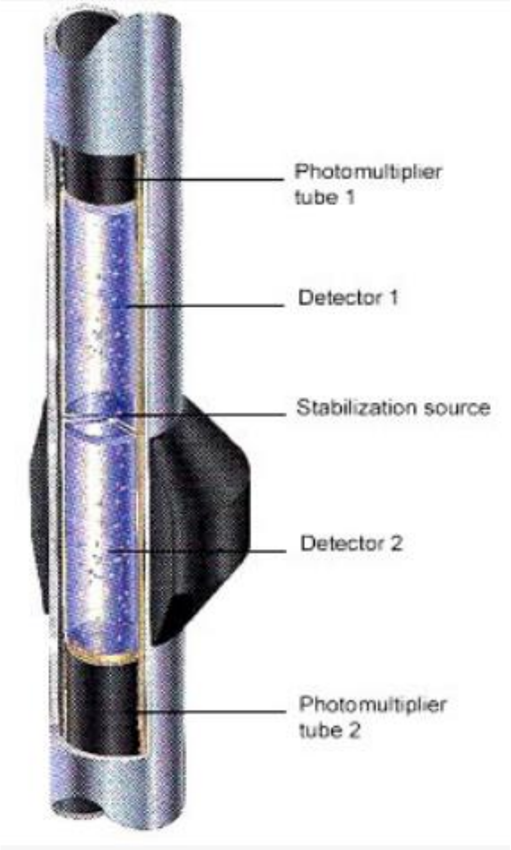
Clay Minerals	K, %	U, ppm	Th, ppm
Bauxite	-	3-30	10-130
Glauconite	5.08-5.30	-	-
Bentonite	< 0.5	1-20	6-50
Montmorillonite	0.16	2-5	14-24
Kaolinite	0.42	1.5-3	6-19
Illite	4-8	1.5	-
Mica	6.7-9.8	-	< 0.01

- Feldspars:
  - Rich in 40K (up to 11.8%)



Gamma Ray Logging Tools

- The gamma ray tool is a passive logging tool. It records naturally occurring radiation of gamma rays from the formation, the intensity of natural radioactivity of rocks. No energy is provided by the logging tool, and it can be run in both open and cased holes.
- Gamma ray is measured in two common ways of natural (total natural radioactivity) and spectral (identifying the contribution of each three source elements of U, Th, K)
    1. The GR tool uses a simple gamma ray detector to measure the total radioactivity of the formation, can not distinguish between radioactive elements.
    2. Spectral gamma tools additionally quantify the concentrations of the radioisotopes present by recording their energy.
- The two types of devices have similar depths of investigation and suffer from minor environmental effects.
- The calibration of both types of devices is made with respect to artificial “shale” formations in the laboratory.



Gamma Ray Tool Principles

The gamma ray measurement device accepts gamma rays from almost a hemisphere that includes the formation and the drilling mud between the formation and the sensor. Gamma rays may therefore come from the formation at any angle from horizontal to almost vertically, and indeed may come from the drilling mud itself.

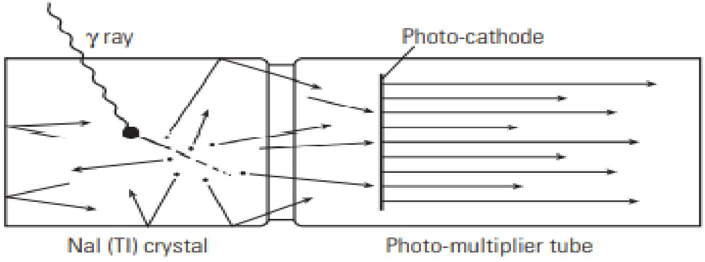
- The active detector element is sensitive to ionizing radiation such as energetic electrons. When these particles travel within the crystal lattice, they impart their energy to a cascade of secondary electrons which are finally trapped by impurity atoms.
- As the electrons are trapped, visible or near-visible light is emitted.
- The light flashes are then detected by a photomultiplier tube optically coupled to the crystal and transformed into an electrical pulse.

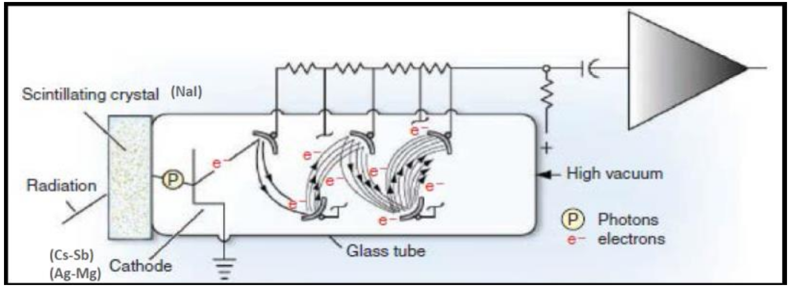
Today, majority of GR tools use scintillation detectors, and they are much more efficient than the Geiger-Mueller counters used in the past:

- Gamma ray strikes the sodium iodide crystal.
- After strike, a single photon of light is emitted.

The emitted light is then strikes a cesium-antimony/silver-magnesium photocathode.

- Each photon, after hitting the photocathode, releases a bundle of electrons.
- Electrons are accelerated in an electrical field to strike another electrode to produce an even bigger shower of electrons.
- This process (electrons hitting electrodes) is repeated as much as a small current conducted through a measurement resistor to give a voltage pulse that signals a gamma ray has struck the crystal.
- Number of pulses are recorded per unit of time representing GR log.





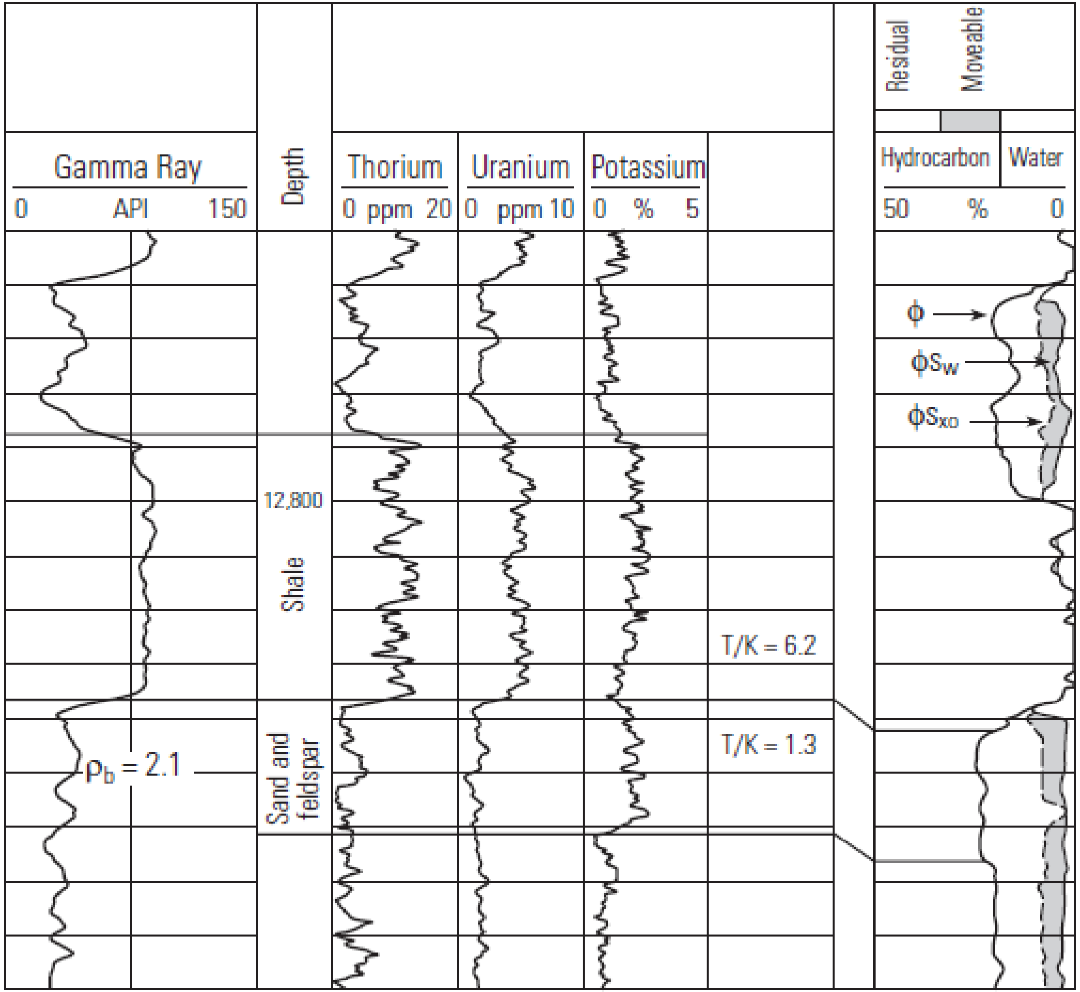
Bateman, 2012

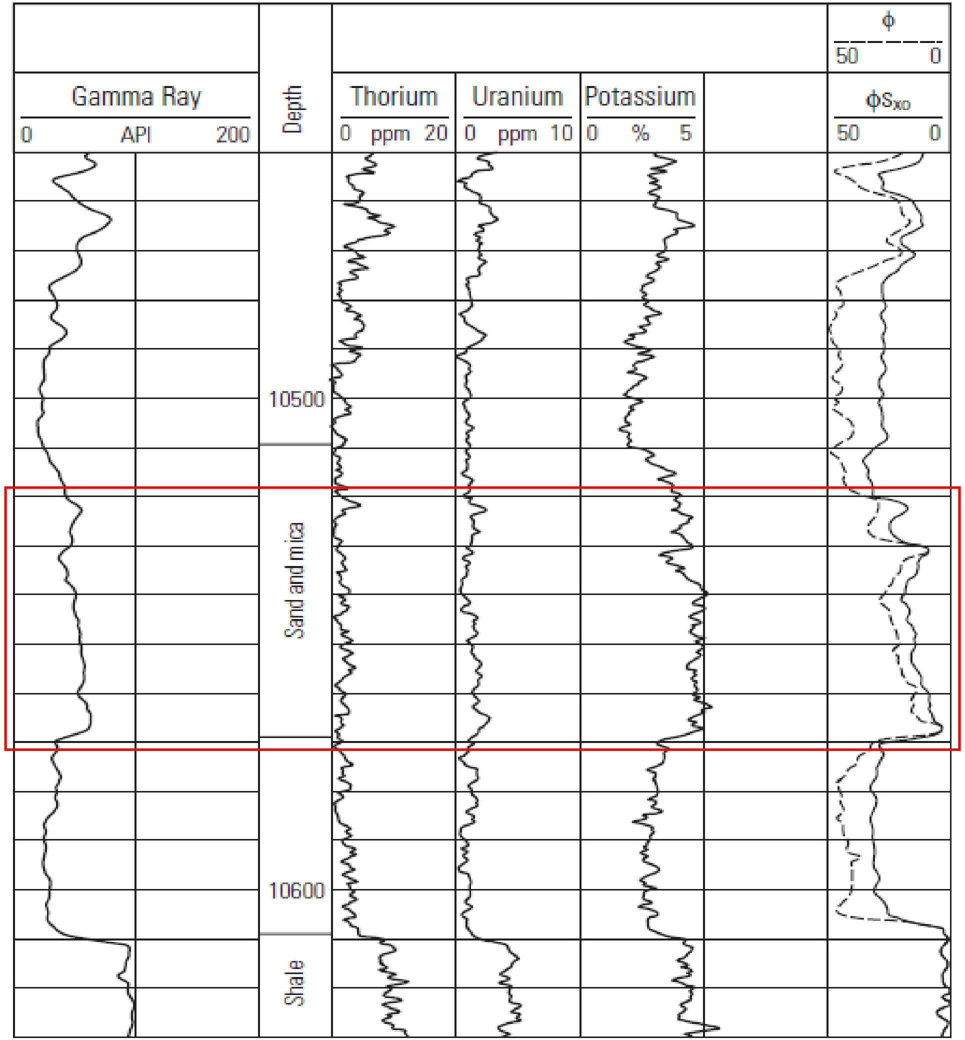
Spectral Gamma Ray Logging

- SGR is capable to determine the amounts of Thorium, Uranium and Potassium in the formation.
- These are usually presented on tracks 2 and 3 of the log. The thorium and uranium concentrations are presented in parts per million (ppm) and the potassium concentration in percent (%).
- A total (standard) GR curve is recorded and presented in track 1 and 'uranium free' measurement (CGR) can also be provided on track 1. It is simply the summation of gamma rays from thorium and potassium.
- The thorium and potassium response of the Natural Gamma Ray log is often a much better shale indicator than the simple GR log or other shale indicators.
- **Thorium** concentration on earth crust is 12 ppm, insoluble, stable, found with heavy minerals, *found with shales*.
- **Potassium** concentration on the earth crust is 2.6%, soluble with water – found as $\mathrm{K_2O}$, *first constituents of shales*, *found with feldspar and micas*.
- **Uranium** concentration on the earth crust is 3 ppm, soluble with water – found as $\mathrm{UO_2}$, deposited in anoxic, anaerobic environments, makes forms with organic carbon, deposited in the fractures and stylolites, *not related with shale or clay content*, found with accessory minerals (a constituent mineral present in small quantity).
- Dewan (1983) has suggested the use of only the thorium and potassium components instead of total GR in the shale volume equations, because uranium salts are soluble and can be transported and precipitated in the formation after deposition.
- If potassium minerals are present in the sandstone, Dewan (1983) suggested the use of only the thorium component in the shale volume equations.

A log showing the effect of feldspar on the **spectral** and **total gamma ray** logs.

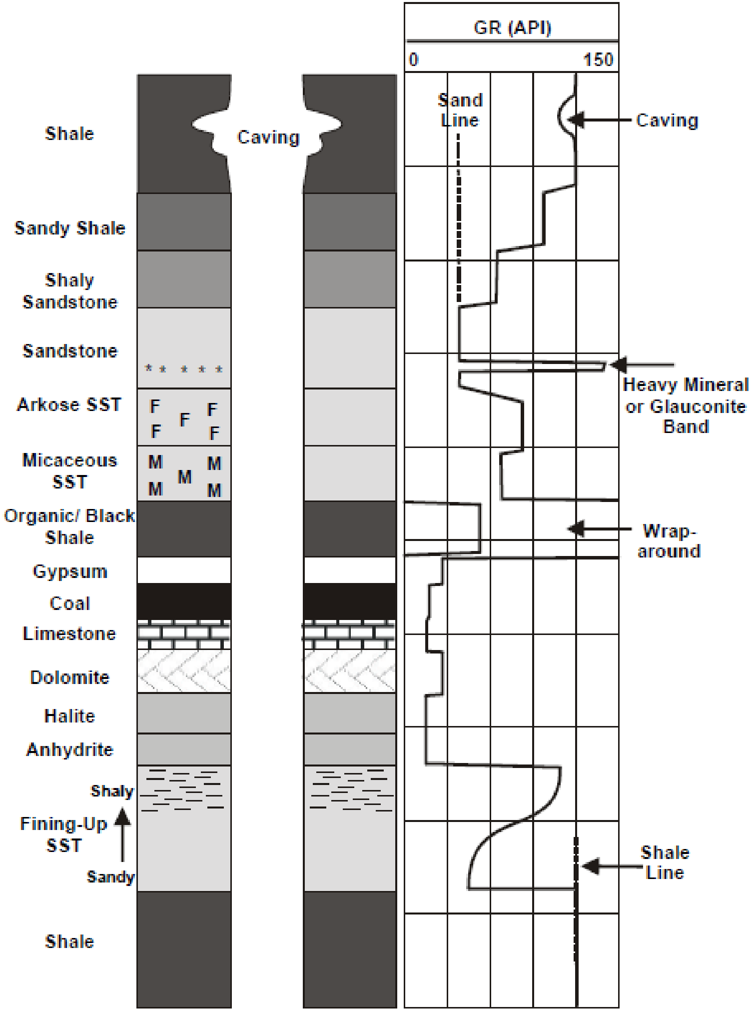
- Shales, organic rich shales and volcanic ash show the highest gamma ray values.
- Halite, anhydrite, coal, clean sandstone, dolomite and limestone have low gamma ray values.
- **But!** Clean sandstone may contain feldspars (arkose sandstones), micas (micaceous sandstones) or both (greywackes), glauconite, heavy minerals, any of which will give the sandstone higher gamma ray values than would be expected from a clean sandstone.

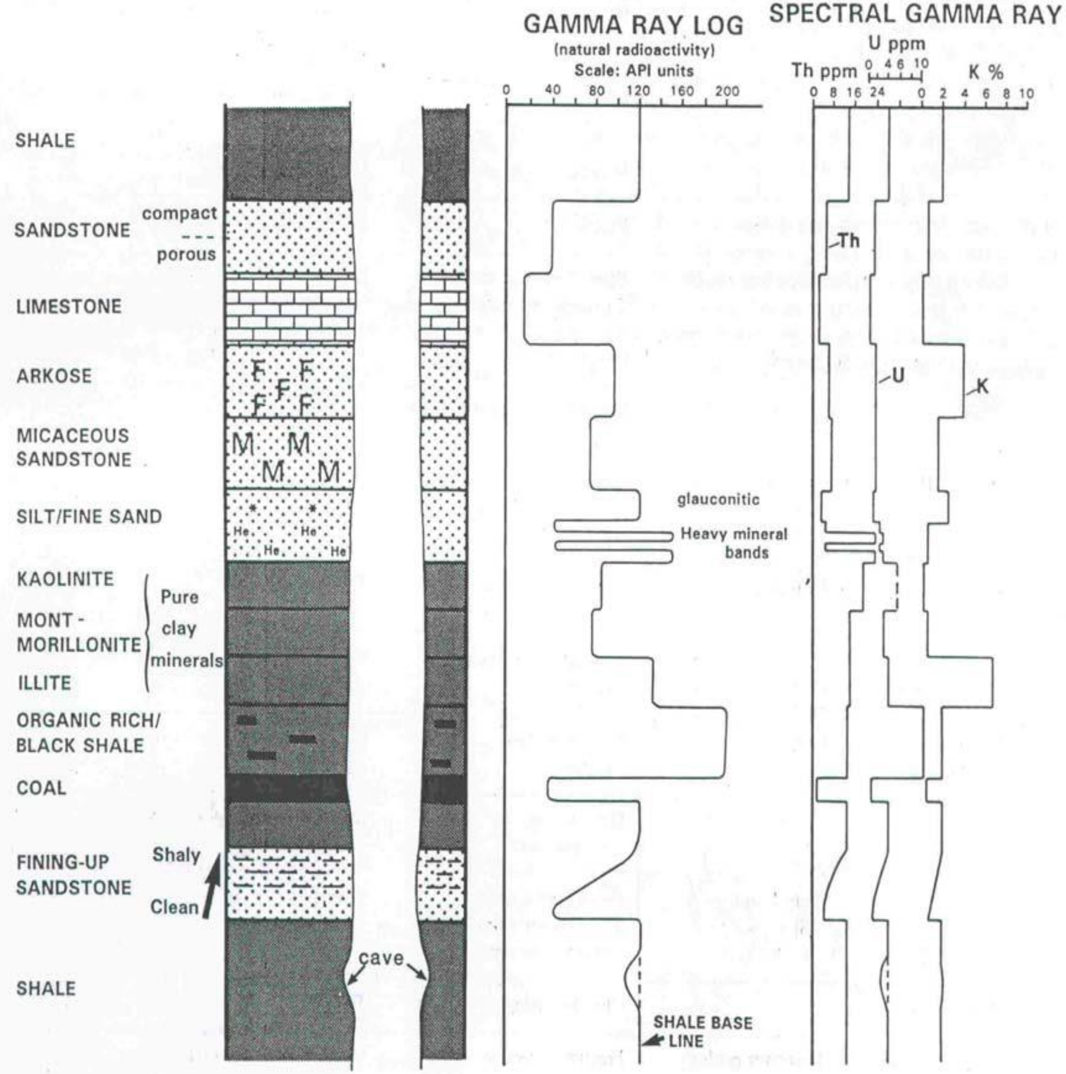




A **spectral gamma ray log** indicating the concentration of Th, U, and K.

- The zone indicated as containing mica shows an abnormally high K content.
- In the zone, the GR curve would incorrectly imply the presence of a non-negligible amount of clay.


GR (API)
0
150
Shale
Caving
Sand Line
Caving
Sandy Shale
Shaly Sandstone
Sandstone
Heavy Mineral or Glauconite Band
Arkose SST
Micaceous SST
Organic/ Black Shale
Wrap-around
Gypsum
Coal
Limestone
Dolomite
Halite
Anhydrite
Shaly
Fining-Up SST
Sandy
Shale Line
Shale

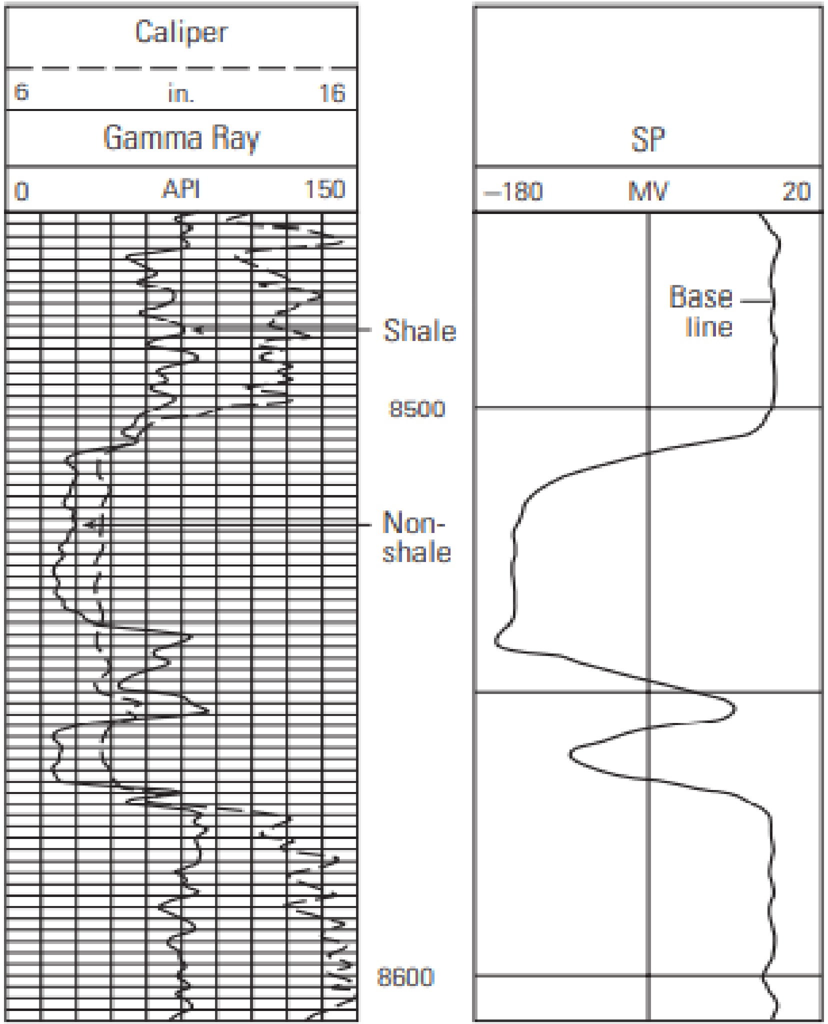

GAMMA RAY LOG
(natural radioactivity)
Scale: API units
0 40 80 120 160 200
SPECTRAL GAMMA RAY
U ppm
0 4 6 10
Th ppm
0 8 16 24
K %
0 2 4 6 8 10
SHALE
SANDSTONE
compact
porous
LIMESTONE
ARKOSE
MICACEOUS SANDSTONE
SILT/FINE SAND
glauconitic
Heavy mineral bands
KAOLINITE
MONT-MORILLONITE
ILLITE
Pure clay minerals
ORGANIC RICH/ BLACK SHALE
COAL
FINING-UP SANDSTONE
Shaly
Clean
SHALE
cave
SHALE BASE LINE
Th
U
K

GR Log Presentation

- The total gamma ray log is usually recorded in track 1 with the caliper log.
- The gamma ray log is commonly given the symbol GR and reported in pseudo-units called API units. In the former USSR countries, including Azerbaijan, mkR/h unit is used.
- Although the API scale goes from 0 to 200 API, it is more common to see 0 to 100 API and 0 to 150 API used in log presentations, as data greater than 150 API is not common, and can always be handled by the use of wrap-around.
- When gamma ray logging is carried out through the cement casing, a scale of 0 to 50 API is most often used, as a result of the lower values measured due to the attenuation of the gamma count rate by the casing.

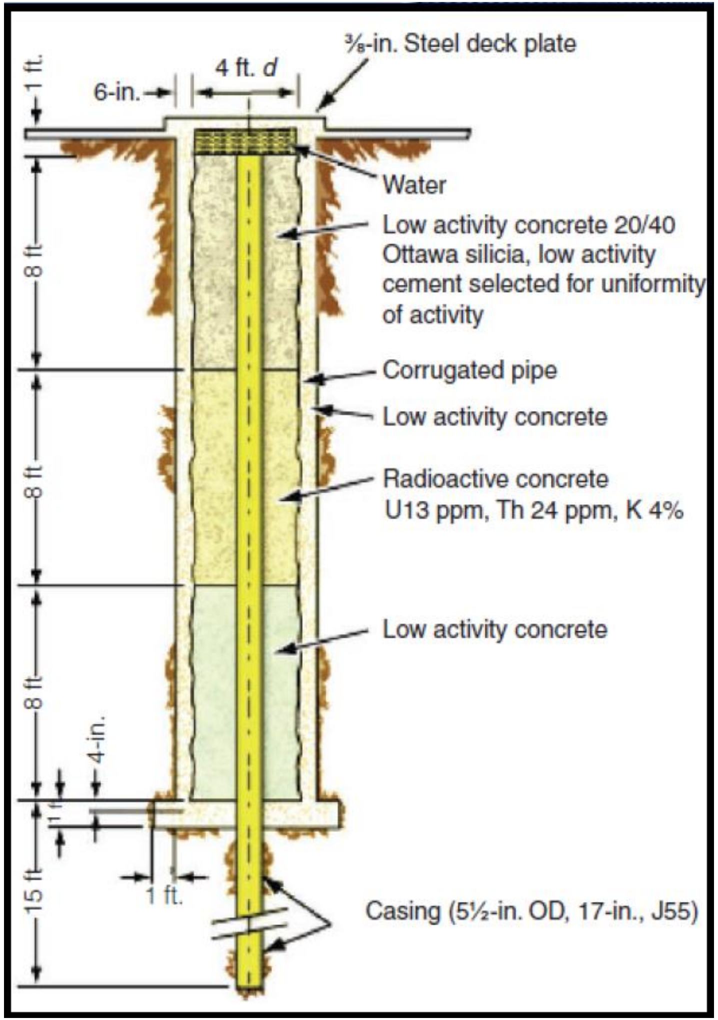
Equipment	Old Unit	API Units Per Old Unit
GNT - F or -G Gamma Ray	1 µgm Ra-eq/ton	16.5
GNT-J, -K Gamma Ray, GLD-K	1 µgm Ra-eq/ton	11.7

Conversion from old units to API units for Schlumberger gamma ray logs



GR Calibration

- The API unit is defined empirically by calibration to a reference well containing an artificial shale 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.
- A cylinder 4 ft in diameter and 24 ft long contains a central 8 ft section consisting of cement mixed with 13 ppm uranium, 24 ppm thorium, and 4% potassium sandwiched by 8 ft sections of pure Portland cement on either side.
- This 24 ft sandwich is cased with 5-1/2 in J55 casing.
- The API standard defines the difference in radioactivity between the pure cement and the radioactive cement mixture as 200 API units, 1 API is 1/200th of the calibrated, standard response.
- 200 API is twice as typical GR reading in shale.



Factors Affecting GR Tool Response

1. Radiation intensity of the formation

   Two formations having the same amount of radioactive material per unit volume, but having different densities, will show different radioactivity levels with the less dense formations appearing to be slightly more radioactive.

2. Counter's efficiency

   It is a detector to measure the gamma radiation originating in the volume of formation near the sonde. Scintillation counters are now generally used as a counter. They are much more efficient than the Geiger-Mueller counters used in the past.

3. Time constant and logging speed

4. Borehole environment (correction is required!)
   - *Tool position in the hole (centered/eccentered)*
   - *Hole size (washout/mud cake)*
   - *Mud density*
   - *Casing size and weight*
   - *Cement thickness*

* In sedimentary formations, the depth of investigation of the GR logging tool is about 1 ft.

$$GR = \frac{\sum \rho_i V_i A_i}{\rho_{\mathrm{b}}}$$

ρ_i density of each radioactive mineral

V_i bulk volume factor of the minerals

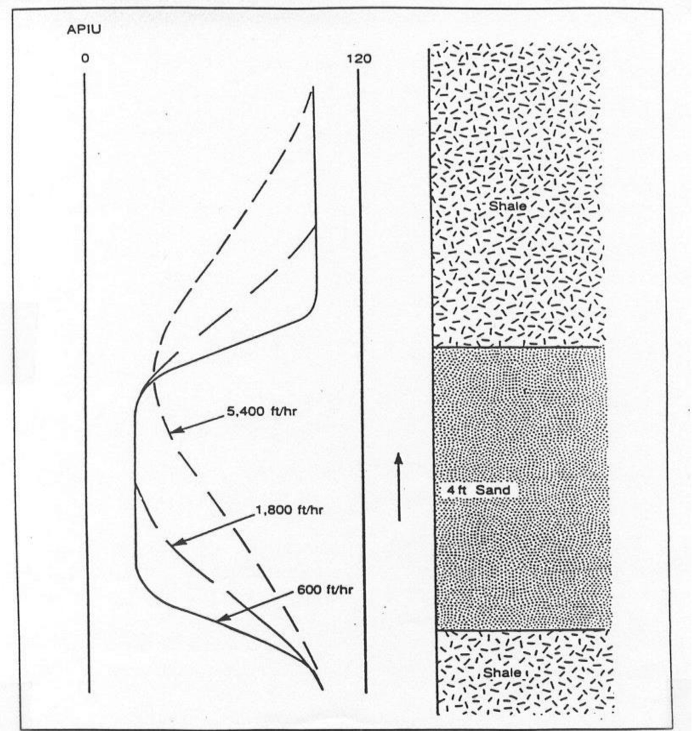
A_i proportionality factor corresponding to the radioactivity of the minerals

ρ_{b} bulk density of the formation

Time Constant and Logging Speed

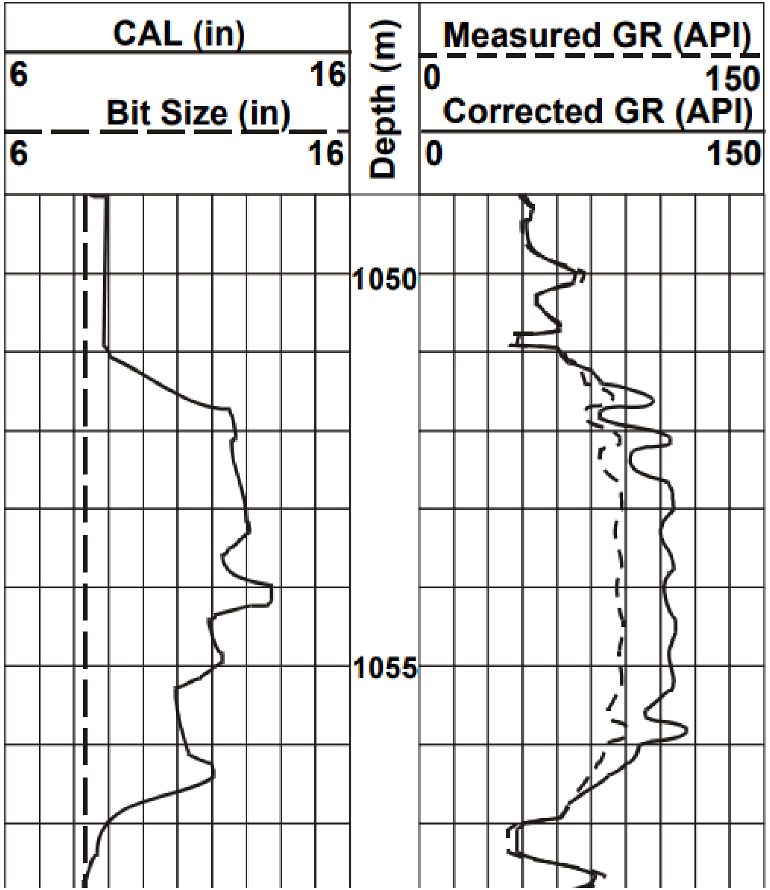
- Gamma Ray Logs never repeat exactly! The minor variations are statistical fluctuations due to the random nature of the radioactive pulses reaching the detector. Typical variation ranges are 5-10 API Units in shales, and 2-4 units in clean formations
- It is possible to reduce statistical fluctuations by optimizing the time constant and logging speed.
- Time constant is the unit time (in sec.) that pulses has been counted on the detector.
- Time constant and logging speed requires to be adjusted in a way that log resolution and logging time is optimized.
- Common applied logging speeds and time constants are:

Logging Speed, ft/hr	Time Constant, sec
3600	1
1800	2
1200	3
900	4



Borehole Effect

- Borehole Quality The gamma ray log usually runs centered in the borehole. If the borehole suffers from caving, the gamma ray log can be badly affected.
- In intervals that suffer from caving, there is more drilling mud between the formation and the gamma ray detector to attenuate the gamma rays produced by the formation.
- Note that barite muds are a particular problem as barite is very efficient at absorbing gamma rays.



GR Log

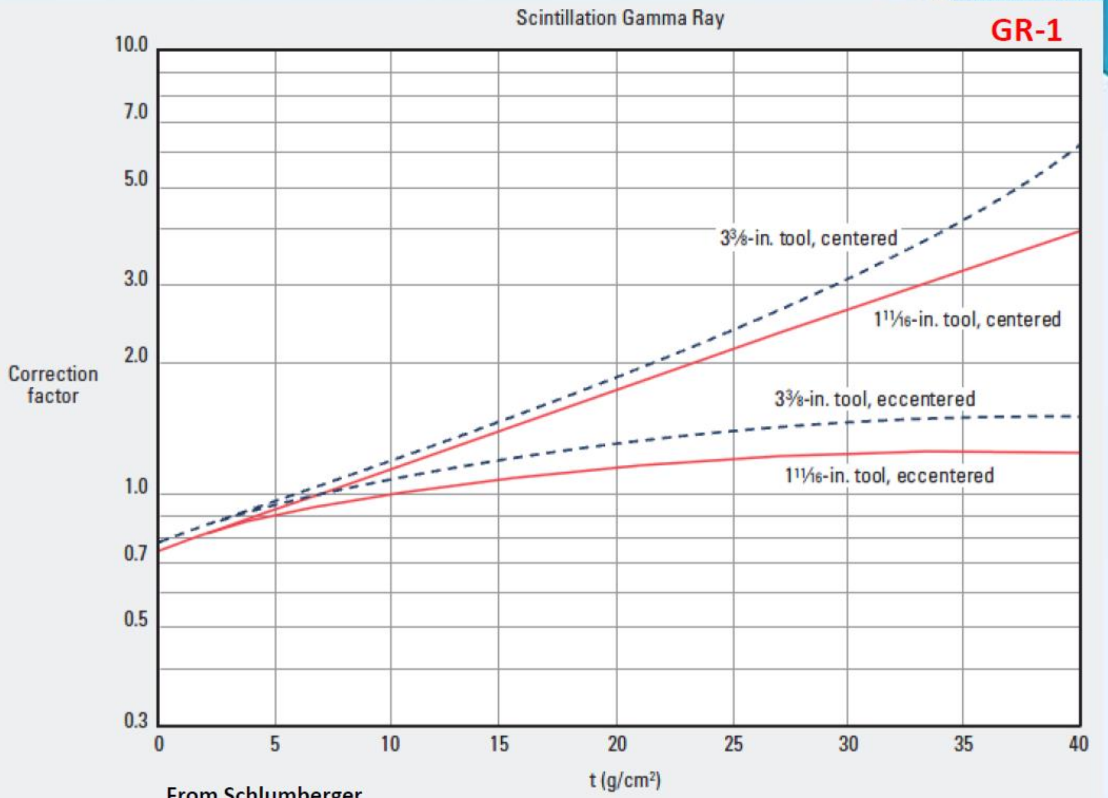
Gamma Ray Correction Chart (Open Hole)

$$t = \frac{W_{mud}}{8.345}\left(\frac{2.54(d_h)}{2} - \frac{2.54(d_{tool})}{2}\right)$$

$W_{mud}: Mud\ wight\ ppg$

$d_h: wellbore\ diameter, in$

$d_{tool}: tool\ OD, in$



From Schlumberger

GR Log

Example

What is the corrected GR for the given information:

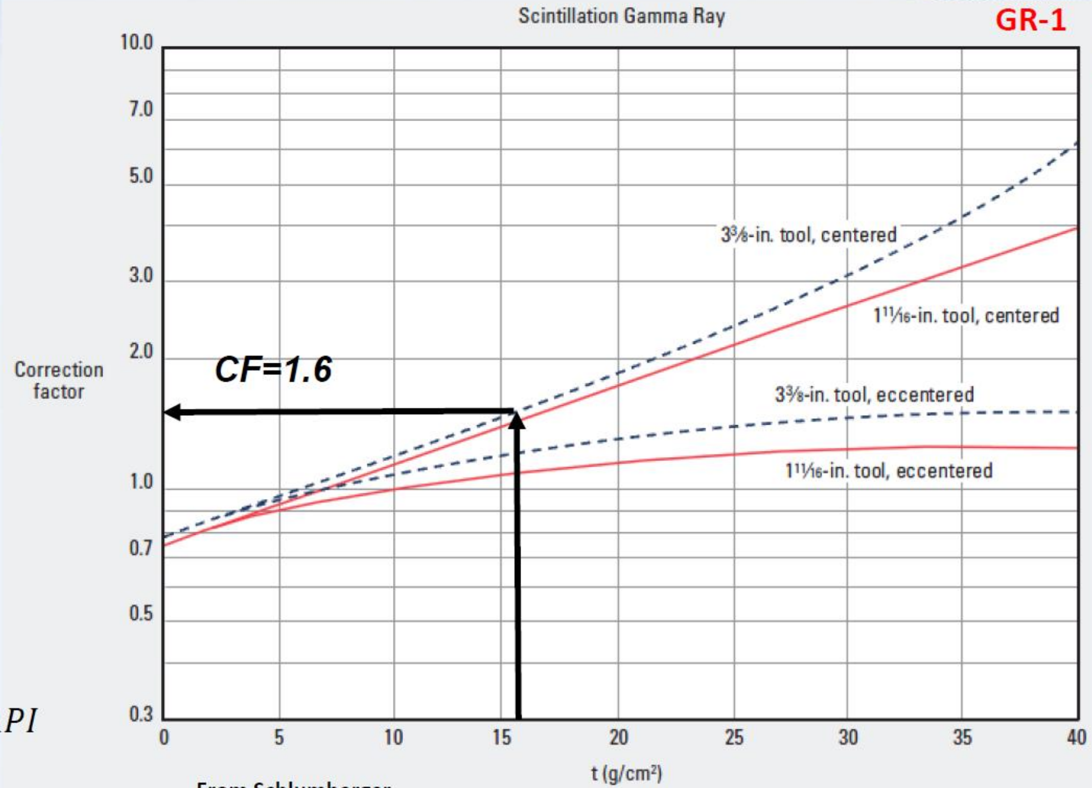
W_{mud}: $12\ ppg$ $\quad$ d_h: $12, in$ $\quad$ GR: $50, API$

d_{tool}: $3_{3/8}\ OD, in$ $\quad$ *Tool is centered.*

$$t = \frac{W_{mud}}{8.345}\left(\frac{2.54(d_h)}{2} - \frac{2.54(d_{tool})}{2}\right)$$

$$t = \frac{12}{8.345}\left(\frac{2.54(12)}{2} - \frac{2.54(3_{3/8})}{2}\right) = 15.8$$

$$GR_{cor.} = GR \times CF \qquad GR_{cor} = 50 \times 1.6 = 80\ API$$



From Schlumberger

GR Log

Gamma Ray Correction Chart (Cased Hole)

$$t = \frac{2.54}{2}\left[\frac{W_{mud}}{8.345}(d_{IDcsg} - d_{tool}) + \rho_{csg}(d_{ODcsg} - d_{IDCSG}) + \rho_{cement}(d_h - d_{ODCSG})\right]$$

$W_{mud}: Mud\ wight\ ppg$

$d_h: wellbore\ diameter, in$

$d_{tool}: tool\ OD, in$

$d_{IDcsg}: Casing\ ID, in$

$d_{ODcsg}: Casing\ OD, in$

$\rho_{cement}: Cement\ density, gr/cm^3$

$\rho_{csg}: Casing\ density, gr/cm^3$

From Schlumberger

Gamma Ray Application

- GR is used for identifying the lithology, shale content (clay mineral) and evaluating the shale volume. Combination of SP/GR with resistivity logs gives an indication of the thickness of porous media.
- Depth matching within the well, the high vertical resolution of the gamma ray log makes it extremely useful for depth matching and fine scale correlation. The gamma ray log is combinable with all tools, and is almost always used as part of every logging combination run because of its ability to match the depths of data from each run.
- The correlation is done through the determination of bed boundaries, making stratigraphic correlations to be possible.
- Cased hole correlations, the gamma ray tools are the standard device used for the correlation of logs in cased and open-holes.
- It is frequently used to complement the SP log and as a substitute for the SP curve in wells drilled with salt mud, air, or oil-based muds.
- Recognition of radioactive mineral deposits
- Recognition of non-radioactive mineral deposits
- Radio-isotope tracer operations, monitor movement of injected radioactive material
- Facies and depositional environment analysis

Determination of Shale Content

- Gamma ray log can be used to calculate volume of shale in porous reservoirs.
- The volume of shale expressed as a decimal fraction or percentage.
- First, we need to calculate gamma ray index.
- The gamma ray log has several nonlinear empirical responses as well a linear responses. The non linear responses are based on geographic area or formation age. All non linear relationships are more optimistic that is they produce a shale volume value lower than that from the linear equation.

$$I_{GR} = Gamma\ ray\ index$$

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

$$GR_{Log} = gamma\ ray\ record\ \ from \log$$

$$GR_{\min} = gama\ ray\ \ for\ clean\ sand$$

$$GR_{\max} = gamma\ ray\ \ for\ shale$$

Determination of Shale Content

- For very hard compacted formation at depth of 8,000 ft or more, gamma ray index is considered equal to shale volume, linear model:

$$V_{sh} = I_{GR}$$

- For tertiary sediment rocks at depth of less than 4,000 ft, the shale volume is:

$$V_{sh} = 0.083(2^{3.7 I_{GR}} - 1)$$

- For older rocks at depth of 4,000-8,000 ft, the shale volume is:

$$V_{sh} = 0.33(2^{2 I_{GR}} - 1)$$

- Clavier Model:

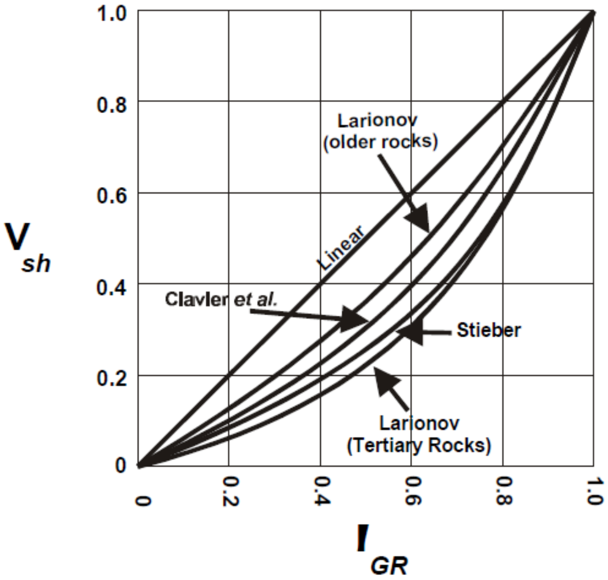
$$V_{\mathrm{sh}} = 1.7 - \sqrt{3.38 - (0.7 + I_{\mathrm{GR}})^2}$$

- Steiber Model:

$$V_{\mathrm{sh}} = \frac{I_{\mathrm{GR}}}{3 - 2I_{\mathrm{GR}}}$$

- Bateman Model:

$$V_{\mathrm{sh}} = I_{\mathrm{GR}}^{(I_{\mathrm{GR}} + \mathrm{GR\_Factor})} \qquad \mathrm{GR\_Factor} = 1.2 - 1.7$$



These models are based on:
- Age of the shale (tertiary, …)
- Shale distribution (laminar, dispersed, structural)

$$\mathrm{NTG} = 1 - V_{\mathrm{sh}}$$

Depositional Environment

- Shaliness in the formation does not change suddenly, the change is gradual with depth.
- Gradual changes of shaliness are indicative of the litho-facies and the depositional environment of the rock and are associated with changes in grain size and sorting.

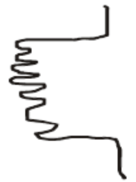
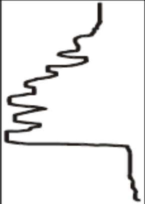
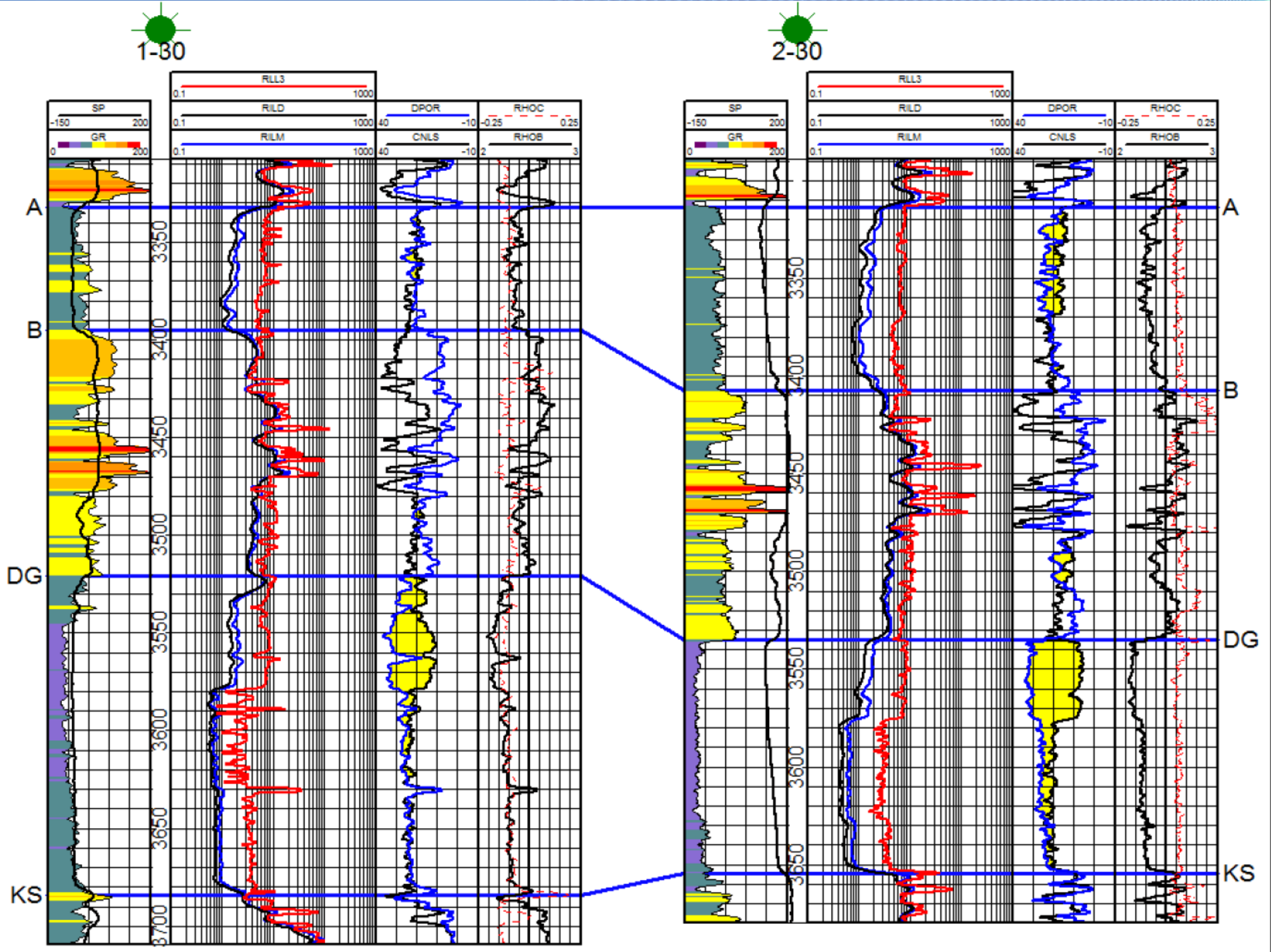
Shape	Smooth	Environments	Serrated	Environments
Cylinder Represents uniform deposition.		Aeolian dunes Tidal sands Fluvial Channels		Deltaic distributaries Turbidite channels Proximal deep-sea fans
Bell Shape Fining upwards sequences.		Tidal sands Alluvial sands Braided streams Fluvial channels Point 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

Figure 11.8 The gamma ray log and depositional environments.

Correlation



GR Log

Shale Mineral Identification