11. THE TOTAL GAMMA RAY LOG

11.1 Introduction

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.

Hence, the gamma ray intensity that the log measures is a function of:

- 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.

The tool therefore has a limited depth of investigation.

Note that 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 (beware: some drilling muds are very radioactive!).

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.

11.2 Principles

The tool consists simply of a highly sensitive gamma ray detector in the form of a scintillation counter. The scintillation counter is composed of a thalium activated single sodium iodide crystal backed by a photomultiplier. When a gamma ray strikes the crystal a small flash of light is produced. This flash is too small to be measured using conventional electronics. Instead, it is amplified by a photomultiplier, which consists of a photocathode and a series of anodes held at progressively higher electrical potentials, all of which are arranged serially in a high vacuum. The flash of light hits the photocathode and causes a number of *primary electrons* to be produced. These few electrons still represent too small a signal to be measured. The primary electrons are accelerated towards the first anode. For every electron that hits the anode, a number of *secondary electrons* are emitted (between 4 and 8 usually). These electrons are accelerated towards the next anode, where each of the secondary electrons produce even more secondary electrons. This process is repeated for each of say 10 anodes. If 6 electrons are emitted at each anode for each incident electron, we can see that a single incident gamma ray ultimately produces 6^{10} = 60,466,176 electrons, which represents a current that can be amplified further by conventional amplifiers.

The whole process takes an extremely short time, but during this time the photomultiplier is *saturated* and is insensitive to further gamma rays. However, the small incident flux of gamma rays produced from rocks ensures that saturation is rarely if ever reached for down-hole tools. Since the flash of light and the number of primary electrons is proportional to the energy of the gamma ray, the final current from the scintillation counter is also proportional to the energy of the incident gamma ray. Hence, there will be a threshold gamma ray energy below which the scintillation counter is insensitive to gamma rays.

Scintillation counters are relatively small devices, which means that the gamma ray tool can have a high vertical resolution.

11.3 Calibration

Intuitively, we might expect the units for gamma ray logging to be in gamma counts per second. However, this results in extremely unwieldy values. Conventionally, the gamma ray log is reported in pseudo-units called API units. The 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.

Tools are run in the Houston well (*test pit*), and are used as standards to calibrate further tools at local test pits. A further calibration check is also carried out at the well-site before and after the log is run, by using a radioactive source of accurately known radioactivity a fixed distance from the tool.

It should be noted that logs from the USSR and its satellite countries used counts per second as its gamma ray logging units until recently. As with all USSR logs, the interpretation and correction of these logs to API units is not straightforward.

11.4 Log Presentation

The total gamma ray log is usually recorded in track 1 with the caliper log, bit size and SP log. In this case, the other tracks most often include resistivity, density, neutron or sonic logs (Fig. 11.1).

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.

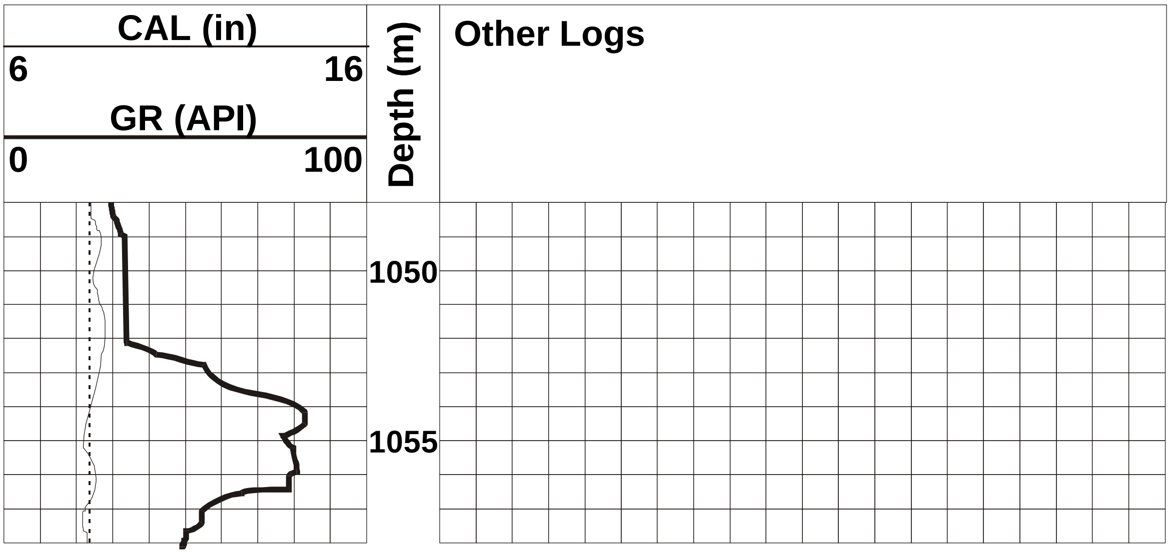


Figure 11.1 Gamma log presentation.

11.5 Depth of Investigation

The gamma rays are attenuated by compton scattering by all materials between the atom that emitted the gamma ray and the detector, which includes the rock itself and the drilling mud. The degree of attenuation depends upon the number density of atoms in the material, and this is related to the density of the material. As we have seen in Chapter 10, there is a distribution of gamma ray energies, but at distance from the emitting atom increases, the energy of the gamma rays decreases but compton scattering until they are too low to be measured by the scintillation counter. Clearly, therefore, there is a maximum depth of investigation for the tool that depends upon formation and mud density.

For average values of drilling mud and formation density, we can say that approximately 50% of the gamma ray signal comes from within 18 cm (7 inches) of the borehole wall, increasing to 75% from within 30 cm (1 foot). Hence, the depth of investigation, if defined at 75% of the signal, is 30 cm. However, this will decrease for denser formations of the same radioactivity, and increase for less dense formations of the same radioactivity.

Note that the zone of sensitivity is almost hemispherical, so the 30 cm depth of investigation applies both horizontally (perpendicular to the borehole wall) and sub-vertically (sub-parallel with the borehole wall). This has implications for the vertical resolution of the tool.

11.6 Logging Speed

Radioactive emissions are random, and hence fluctuate in an unpredictable way with time. If the count rates are high, this causes no real problems as there are sufficiently many counts in a reasonable time interval for the fluctuations to average out. In gamma ray logging, the count rate is low so the fluctuations have to be taken into account. For each measurement depth, the tool must linger long enough to measure enough count in order to obtain good quality data. In gamma ray logging a time averaging procedure is adopted to minimize the statistical fluctuations. The output from the detector is measured as a gamma ray count rate, which is averaged over a time defined by a *time constant* T_c.

In order to increase the quality of the log data T_c should be as large as possible. However, as the logging tool is constantly moving, a large T_c will result in the bluring of bed boundaries, which as implications for the vertical resolution of the tool. As there are large costs associated with running logs slowly, thee is a compromise to be reached between logging speed and log quality. In practice, the product of logging speed in feet per second and T_c in seconds is conventionally held constant at 1 foot. Hence, the gamma ray measurement is averaged over this one foot interval, and the log data is shifted down by 1 foot to compensate. Note that the log data is therefore recorded at the bottom of the one foot interval over which it is averaged.

Table 11.1 illustrates the effect of the interplay between the statistical fluctuations, the gamma count rate and T_c for a single formation with a constant radioactivity. In this example we assume that the logging speed is 1 foot per second × T_c. If the time constant is set to one third of a second, there are 9 measurements with an apparent vertical resolution of 4 inches, but these measurements fluctuate wildly between 9 and 18 counts per second. If the time constant is one second, there are 3 measurements covering the logged interval with an apparent vertical resolution of 12 inches, but a much smaller error in the measurements themselves (i.e., the range has dropped to 12 to 14 counts per second). If the time constant is any higher, the measured value of counts per second becomes very well constrained, but the vertical resolution degrades rapidly, 3 foot in this case. Clearly the T_c = 1 s case is a good balance between logging variability (error) and resolution.

Table 11.1 Variations in count rate in gamma ray logging.

Counts	**No. of Counts**	**Period (s)**	**Count Rate (per second)**	**No. of Counts**	**Period (s)**	**Mean Count Rate**	**No. of Counts**	**Period (s)**	**Mean Count Rate**
	T_c = 0.333 s			**T_c = 1 s**			**T_c = 3 s**		
• • • •	4	0.333	12	14	1	14	39	3	13
• • • • • •	6	0.333	18						
• • • •	4	0.333	12						
• • • • •	5	0.333	15	12	1	12			
• • •	3	0.333	9						
• • • •	4	0.333	12						
• • • • •	5	0.333	15	13	1	13			
• • •	3	0.333	9						
• • • • •	5	0.333	15						
Mean Count Rate (per second)	-	-	13	-	-	13	-	-	13
Range of Count Rate (per second)	-	-	9 -18	-	-	12-14	-	-	13-13
Standard Deviation (per second)	-	-	3	-	-	1	-	-	-

Note that the apparent vertical resolution is not the one encountered in practice because of the geometry of the sensor arrangement. In practice one must add about 2 feet to the apparent vertical resolution to obtain the real one.

Figure 11.2 shows gamma ray log data across a boundary between two formations of different radioactivity for various values of logging speed *V* in ft/hr and for a time constant of 2 s. Note that even at *V*=0 there is a gradual change from the gamma ray count in one formation and that in the next due to the finite sensor size and the geometry of its sensitive zone. Increasing logging speeds show an increased bluring of the boundary.

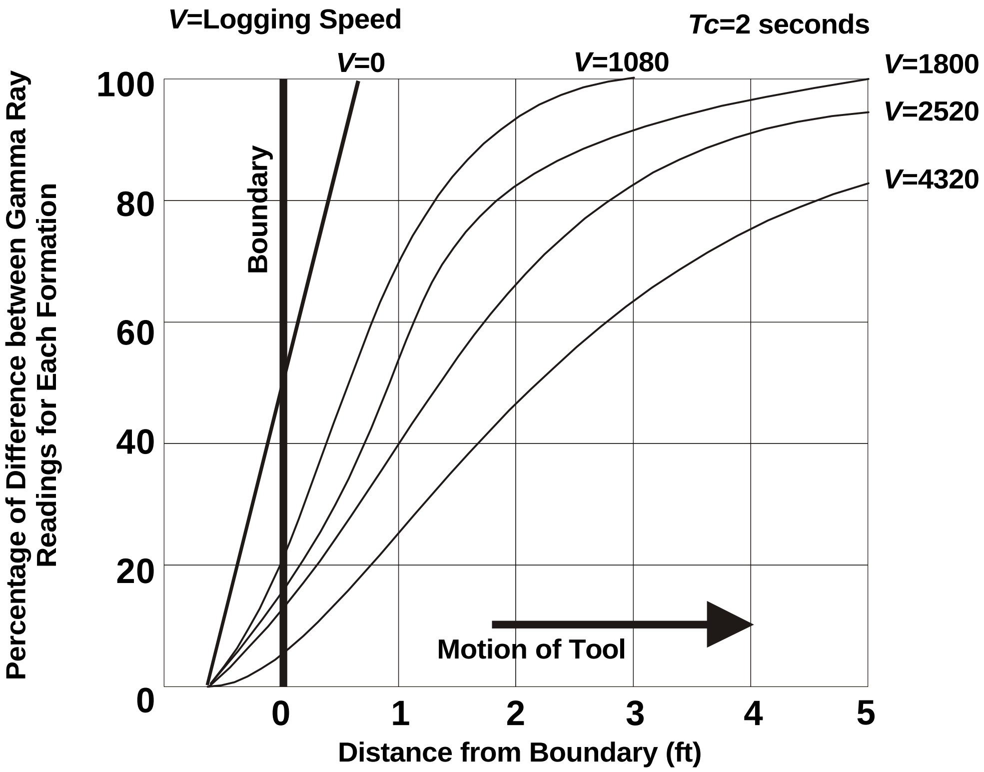


Figure 11.2 Effect of logging speed in bed boundaries.

11.7 Vertical Resolution

There are three factors governing the vertical resolution:

- The size of the detector, which is quite small (about 5-10 cm diameter).
- The effect of the time constant as described in Section 10.6. For conventional logging, with the product of logging speed and time constant set to 1 foot, the contribution to degradation in the vertical resolution from his cause is 1 foot.
- The hemispherical zone of sensitivity of the sensor. As the sensor is sensitive to gamma rays from a hemispherical zone, and its approximate depth of investigation of about 30 cm (1 foot) for formations of average density, we can see that the degradation in vertical resolution from this source will be about 2 foot.

Hence, the vertical resolution of the tool is just over 3 foot (90 cm).

This is quite a high vertical resolution for an open-hole tool, and so the gamma ray tool is good at defining thin beds, for fine correlation, and for depth matching between logging runs.

11.8 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. Hence, the log is underestimated, as shown in Fig. 11.3.

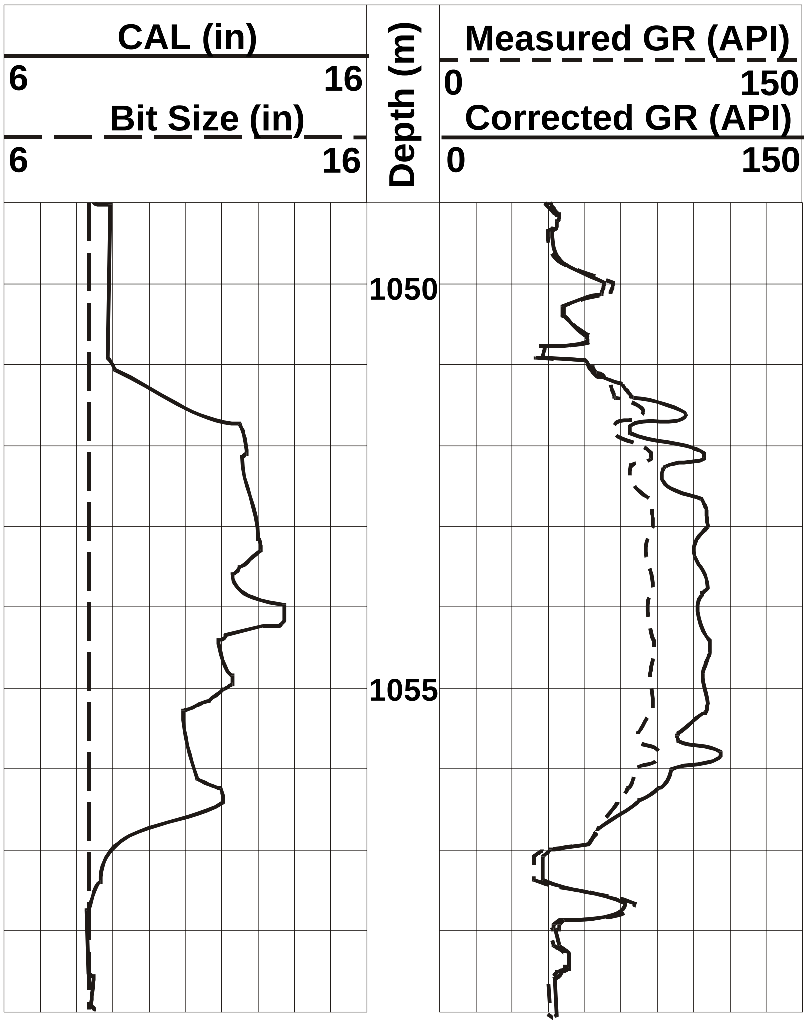


Figure 11.3 Effect of caving on the gamma ray log.

Note that the denser the mud used, the greater the underestimation will be, because of increased compton scattering in the drilling mud. Barite muds are a particular problem as barite is very efficient at absorbing gamma rays.

The measured overestimation may usually be corrected if the caliper log for the well is known. Figure 11.3 also shows the corrected gamma ray log. Comparison of the two show the degree to which the caving has affected the gamma ray reading. Corrections are carried out using correction charts supplied by the logging tool company. Each tool design has its own set of charts, which are drawn up for a range of drilling fluids and tool geometries. Figure 11.4 shows an example of such a correction chart. Note that the tool can also be run in eccentred mode (pressed up against the borehole wall). When run in eccentred mode the corrections are much smaller as the drilling mud contributes less to the gamma ray signal, and has less opportunity to attenuate the gamma rays.

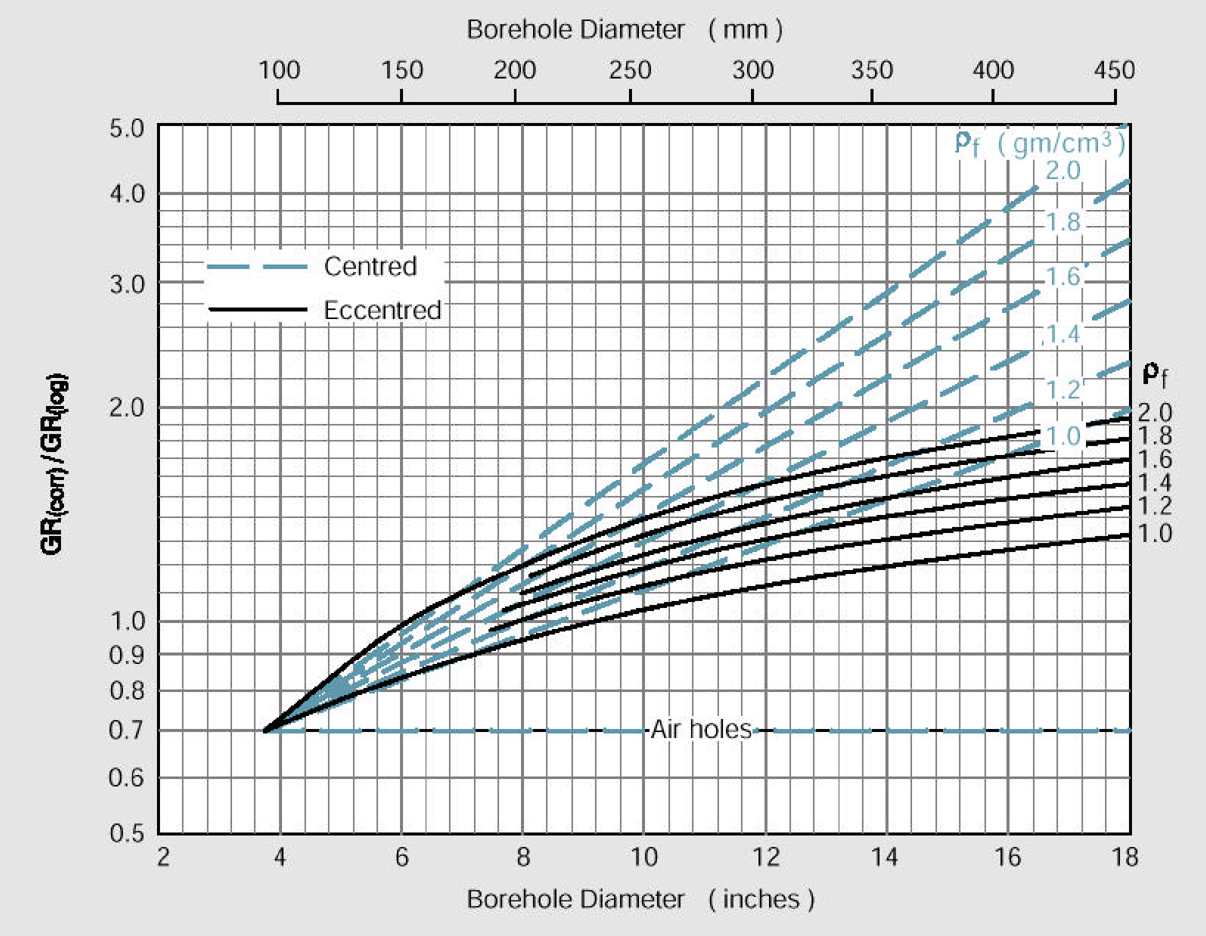


Figure 11.4 Gamma ray log correction chart for a 3.75 inch tool in an 8 inch hole with a KCl-free drilling mud with a mud weight of r_f g/cm^3 as a function of borehole diameter (courtesy of Reeves Wireline Ltd.).

11.9 Mud Type

The density of the drilling mud (*mud weight*) effects the signal because higher density muds attenuate gamma rays more. This effect is taken account of by the borehole correction done in the previous section. However, extra care should be taken with barite drilling muds, as barite is very efficient at attenuating gamma rays and will give an anomalously low gamma ray reading.

In the discussion so far, we have assumed that the drilling mud attenuates the gamma ray signal, but does not contribute to it. While this is true of many drilling muds, it is not generally true. Potassium chloride-based drilling muds are not uncommon. These muds have a natural gamma radioactivity associated with potassium-40. The radiation from KCl drilling muds contributes to the total gamma ray count rate measured, increasing it considerably.

In good quality 'on-gauge' boreholes the gamma ray log is consistently increased by a constant amount. This is not a significant problem as a glance at the log header information would tell us that KCl mud was used and we should expect slightly higher values of the gamma ray log than usual.

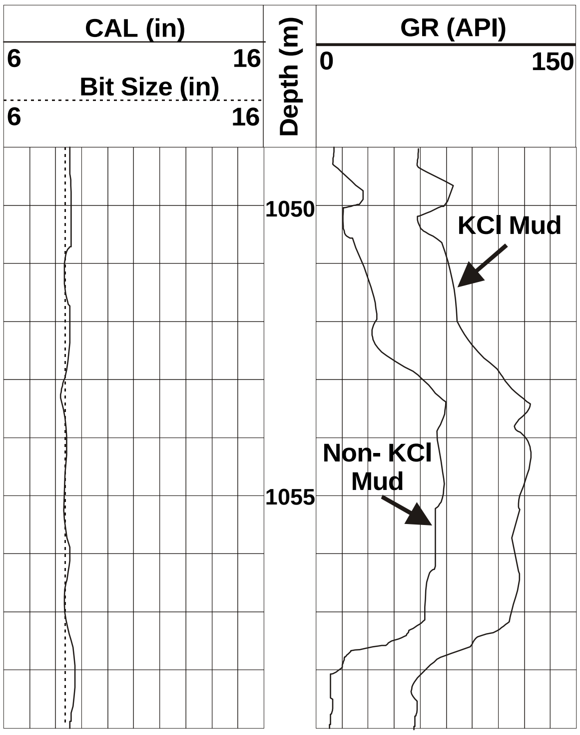


Figure 11.5 Effect of KCl drilling mud on the gamma ray log in an on-gauge borehole.

Problems may arise if the borehole diameter varies, leading to varying amounts of drilling-fluid between the formation and the sensor with depth. In caved holes in radioactive formations there is usually no effect observed as the caving effectively replaces a radioactive formation with radioactive drilling fluid. However, a significant local increase in the gamma ray log can be observed where very low radioactivity formations, such as some evaporites, have been washed out.

11.10 Uses of the Total Gamma Ray Log

The gamma ray log is an extremely simple and useful log that is used in all petrophysical interpretations, and is commonly run as part of almost every tool combination. Consequently, every well may have as many as 5 independent sets of gamma ray log data. The high vertical resolution of the gamma ray log makes it extremely useful for depth matching and fine scale correlation. The main uses of the gamma ray log are outlined in the following sections. The first three applications are by far the most important.

11.10.1 Determination of Lithology

The gamma ray log is an extremely useful tool for discrimination of different lithologies. While it cannot uniquely define any lithology, the information it provides is invaluable when combined with information from other logs.

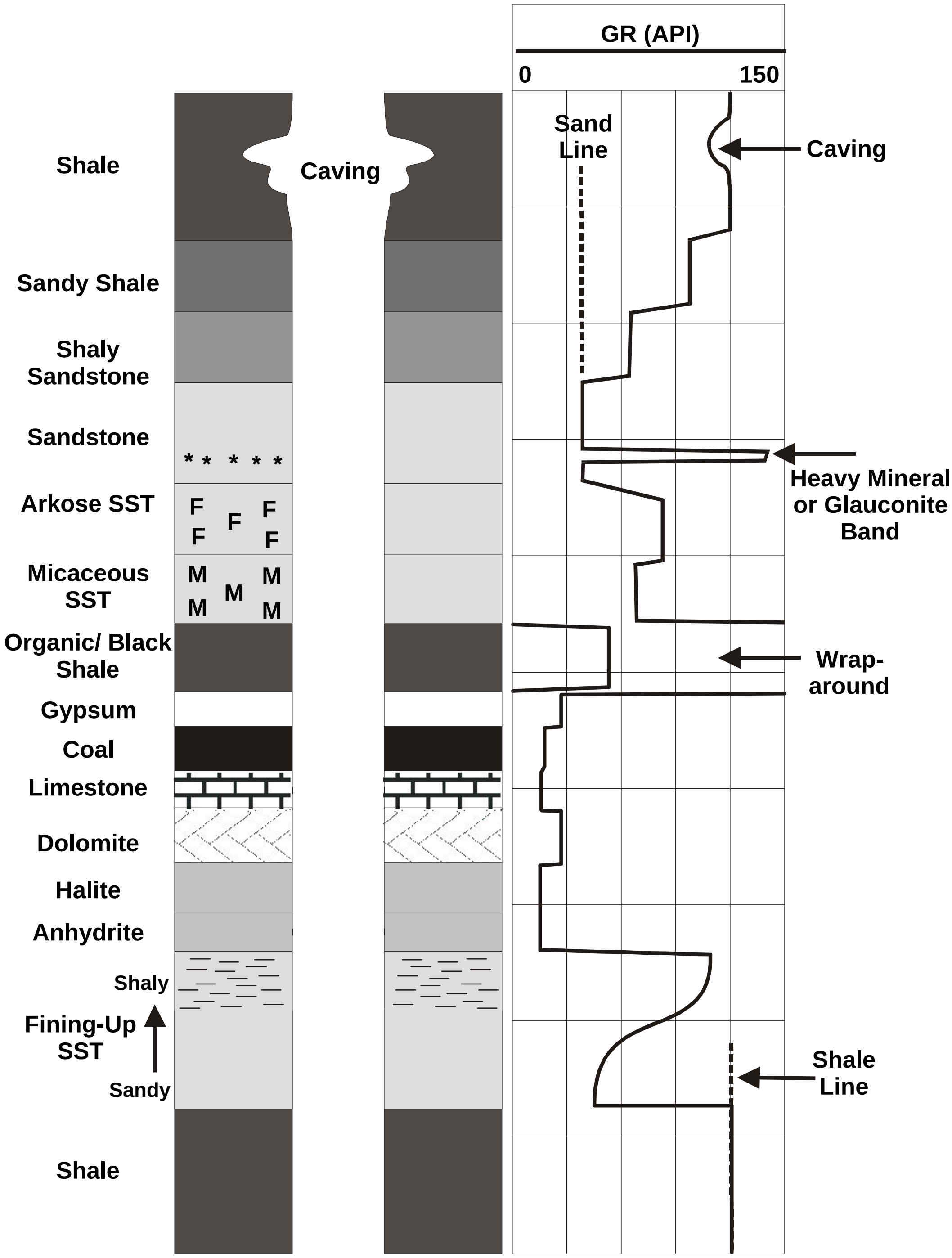


Figure 11.6 Effect of different lithologies on the gamma ray log.

Its main use is the discrimination of shales by their high radioactivity. Figure 11.6 shows how different lithologies affect the total gamma ray log. Note that shales, organic rich shales and volcanic ash show the highest gamma ray values, and halite, anhydrite, coal, clean sandstones, dolomite and limestone have low gamma ray values. Care must be taken not to generalize these rules too much. For example a clean sandstone may contain feldspars (arkose sandstones), micas (micaceous sandstones) or both (greywackes), or glauconite, or heavy minerals, any of which will give the sandstone higher gamma ray values than would be expected from a clean sandstone.

11.10.2 Determination of Shale Content

In most reservoirs the lithologies are quite simple, being cycles of sandstones and shales or carbonates and shales. Once the main lithologies have been identified, the gamma ray log values can be used to calculate the shaliness or *shale volume* V_{sh} of the rock. This is important as a threshold value of shale volume is often used to help discriminate between reservoir and non-reservoir rock.

Shale volume is calculated in the following way: First the *gamma ray index* I_{GR} is calculated from the gamma ray log data using the relationship

$$I_{GR} = \frac{GR_{\log} - GR_{\min}}{GR_{\max} - GR_{\min}} \qquad \textbf{(11.1)}$$

where: I_{GR} = the gamma ray index
$GR_{\log}$ = the gamma ray reading at the depth of interest
$GR_{\min}$ = the minimum gamma ray reading. (Usually the mean minimum through a clean sandstone or carbonate formation.)
$GR_{\max}$ = the maximum gamma ray reading. (Usually the mean maximum through a shale or clay formation.)

Many petrophysicists then assume that $V_{sh} = I_{GR}$. However, to be correct the value of I_{GR} should be entered into the chart shown as Fig. 11.7, from which the corresponding value of V_{sh} may be read.

It should be noted that the calculation of shale volume is a 'black art' as much depends upon the experience of the petrophysicist in defining what is the minimum (*sand line*) and the maximum (*shale line*) values, noting that the sand line and/or shale line may be at one gamma ray value in one part of the well and at another gamma ray value at deeper levels.

Once the shale volume has been calculated, a threshold shale volume may be defined which will divide the well into a number of reservoir and non-reservoir zones. This zonation is combined with the zonation that will also take place on the basis of porosity, permeability and hydrocarbon saturation.

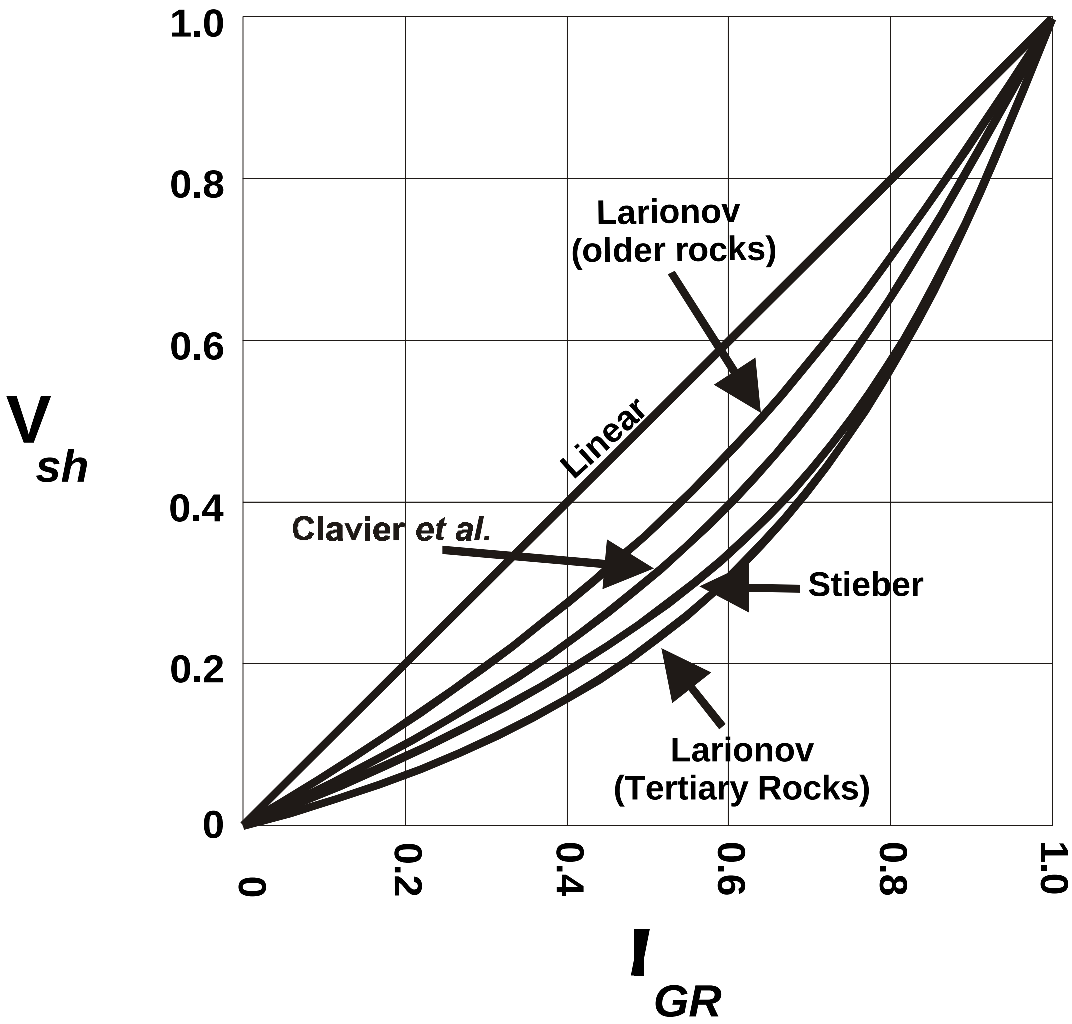


Figure 11.7 Calculation of shale volume.

10.10.3 Depth Matching

The gamma ray tool is run as part of almost every tool combination. It has a high reliability and a high vertical resolution. The tool will also show a useful decrease when opposite casing. For all these reasons, the tools is commonly used to match the depths of data from a given depth interval made at different times with different tool combinations. The depth matching may rely on the characteristic sudden reduction in gamma ray values when the tool encounters the casing of the section of borehole above the interval of interest, but more usually relies on matching the patterns in the gamma ray response from the gamma ray tools run with each tool combination.

10.10.4 Cased Hole Correlations

A different type of depth matching relates open hole measurements to cased hole and production logging measurements. Clearly, we would want to match accurately the depths at which open-hole data are taken and the depths at which cased-hole or production logging data are taken. The gamma ray log and the Casing Collar Locator allow this matching to be performed, ensuring that accurate depth control is maintained during cased-hole logging, and while perforating the correct depths. Note that the gamma ray readings will be less in the cased holes due to the attenuation of gamma rays by the cement casing.

11.10.5 Recognition of Radioactive Mineral Deposits

The gamma ray log can be used to recognize certain radioactive deposits, the most common of which are potash deposits and uranium ores.

Potassium-40 emits gamma rays with the single energy of 1.46 MeV. This results in there being a linear relationship between the gamma ray count rate and the content of potassium in the formation. In potash deposits, the gamma ray reading after hole size correction gives approximately 15 API units per 1%wt. K_2O.

There is no simple relationship between the gamma ray reading and the abundance of uranium in a formation, because the energy spectrum also includes radiation from other elements in the uranium-radium series.

11.10.6 Recognition of Non-Radioactive Mineral Deposits

Particular deposits have a very low natural radioactivity. The gamma ray log can also be used to indicate these. Formations with extremely low natural radioactivities are the non-radioactive evaporites (salt, anhydrite and gypsum), and coal beds. Note that some evaporites have a large concentration of potassium and can be very radioactive. These rare evaporites are given in Table 10.1.

11.10.7 Radio-isotope Tracer Operations

Deliberate doping of fluids with radioactive tracers is sometimes carried out to find the location of pipe leaks, thief zones and channeling behind the casing. The gamma ray log is sometimes employed as a detector in these cases.

11.10.8 Facies and Depositional Environment Analysis

We have seen that the gamma ray log is often used to measure the shaliness of a formation. In reality the shaliness often does not change suddenly, but occurs gradually with depth. Such gradual changes are indicative of the litho-facies and the depositional environment of the rock, and are associated with changes in grain size and sorting that are controlled by facies and depositional environment as well as being associated with the shaliness of the rock. Figure 11.8 analyses the shape of gamma ray log responses for various depositional environments.

All possible combinations of these shapes may be encountered.

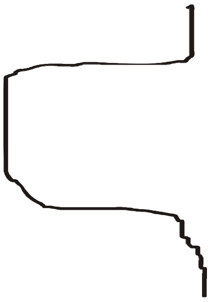
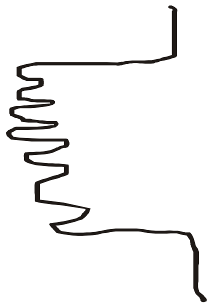
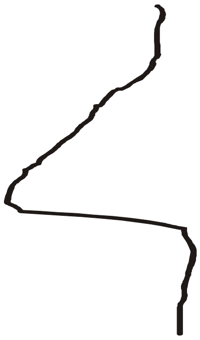
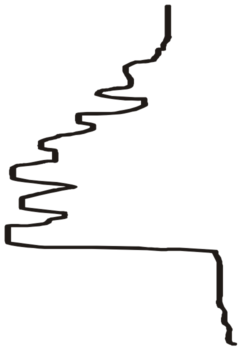
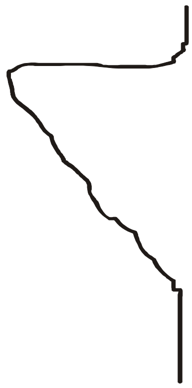
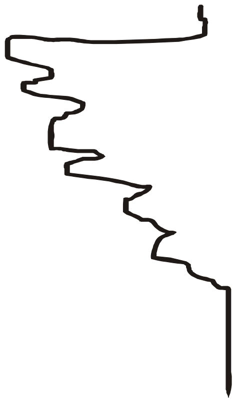
Shape	**Smooth**	**Environments**	**Serrated**	**Environments**
Cylinder Represents uniform deposition.		Aeolian dunes Tidal sands Fluvial Channels		Deltaic distributaries Turbidite channels Proximal deep-sea fans
Bell Shape Fining upwards sequences.		Tidal sands Alluvial sands Braided streams Fluvial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