7

THE GAMMA RAY AND SPECTRAL GAMMA RAY LOG

7.1 Generalities

The log

The gamma ray log is a record of a formation's radioactivity. The radiation emanates from naturally-occurring uranium, thorium and potassium (*see below*). The simple gamma ray log gives the radioactivity of the three elements combined, while the spectral gamma ray log shows the amount of each individual element contributing to this radioactivity.

The geological significance of radioactivity lies in the distribution of these three elements. Most rocks are radioactive to some degree, igneous and metamorphic rocks more so than sediments. However, amongst the sediments, shales have by far the strongest radiation. It is

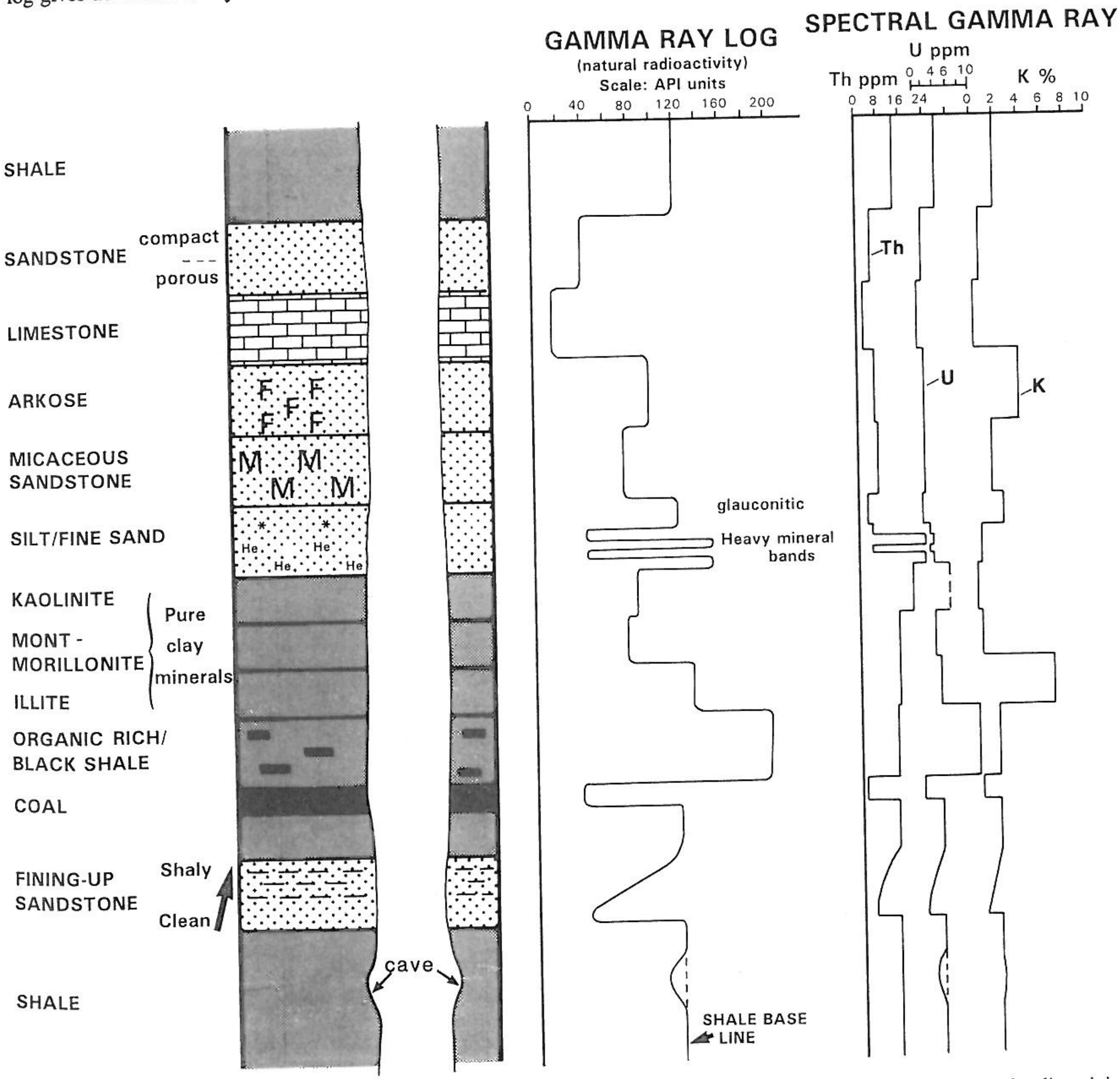

Figure 7.1 The gamma ray log and spectral gamma ray log: some typical responses. The gamma ray log shows natural radioactivity. The spectral gamma ray log gives the abundances of the naturally radioactive elements, thorium, Th and uranium, U in parts per million (ppm) and potassium, K in %. F - feldspar, M = mica, * = glauconite.

for this reason that the simple gamma ray log has been called the 'shale log', although modern thinking shows that it is quite insufficient to equate gamma ray emission with shale occurrence. Not all shales are radioactive, and all that is radioactive is not necessarily shale (Figure 7.1) – *see* Section 7.6.

Principal uses

The gamma ray log is still principally used quantitatively to derive shale volume. Qualitatively, in its simple form, it can be used to correlate, to suggest facies and sequences and, of course, to identify lithology (shalyness). The spectral gamma ray can be used additionally to derive a quantitative radioactive mineral volume and a more accurate shale volume. Qualitatively it can indicate dominant clay mineral types, give indications of depositional environment, indicate fractures and help to localize source rocks (Table 7.1*a*,*b*).

Table 7.1(a) Principal uses of the gamma ray log.

	Discipline	**Used for**	**Knowing**
Quantitative	Petrophysics	Shale volume (Vsh)	gamma ray (max) gamma ray (min)
Qualitative	Geology	Shale (shaliness)	gamma ray (max) gamma ray (min)
		Lithology	typical radioactivity values
		Mineral identification	Mineral radioactivity
	Sedimentology	Facies	Clay/grain size relationship
	Sequence Stratigraphy	Parasequence & condensed sequence identification	Clay/grain size & organic matter/radioactivity relationships
	Stratigraphy	correlation	–
		Unconformity identification	–

Table 7.1(b) Principal uses of the spectral gamma ray log.

	Discipline	**Used for**	**Knowing**
Quantitative	Petrophysics	Shale volume (V_{sh})	Th (max), Th (min) for pure shale
		Radioactive mineral volume	V_{sh} (Th), K (max), K (min) for shale
Semi-quantitative and qualitative	Geology	Dominant clay material	Th, K, U content of individual clay minerals
		Detrital clay mineral suite	Radioactive content of individual clay minerals
	Sedimentology & Sequence Stratigraphy	Condensed section recognition from excess uranium	Normal U and Th content or Th/U ratio of shales
		Climatic changes?	Th/K ratio changes in shale
	Reservoir geology	Fracture detection	Uranium contribution to radioactivity
	Geochemistry	Marine source rock identification	Uranium content of organic matter

7.2 Natural gamma radiation

Natural radiation in rocks comes essentially from only three elemental sources: the radioactive elements of the thorium family, of the uranium-radium family and of the radioactive isotope of potassium ^{40}K (Adams and Weaver, 1958).

Quantitatively, potassium is by far the most abundant of the three elements (Table 7.2) but its contribution to the overall radioactivity in relation to its weight is small. In reality, the contribution to the overall radioactivity of the three elements is of the same order of magnitude, the abundance seeming to be the inverse of the contribution in energy: a small quantity of uranium has a large effect on the radioactivity, a large quantity of potassium a small effect.

Each of the three sources emits gamma rays spontaneously. That is, they emit photons with no mass and no charge but great energy (this being the definition of a gamma ray). The energy in the case of uranium, thorium and potassium emissions occurs in the spectrum from 0 – 3MeV (million electron volts).

Table 7.2 Abundance and relative radiation activity of the natural radioactive elements.

	K	Th	U
†Relative abundance in the earth's crust	2.59%	~12ppm	~3ppm
*Gamma rays per unit weight	1	1300	3600

†Serra (1979), Serra *et al.*, (1980)
*Adams and Weaver (1958)

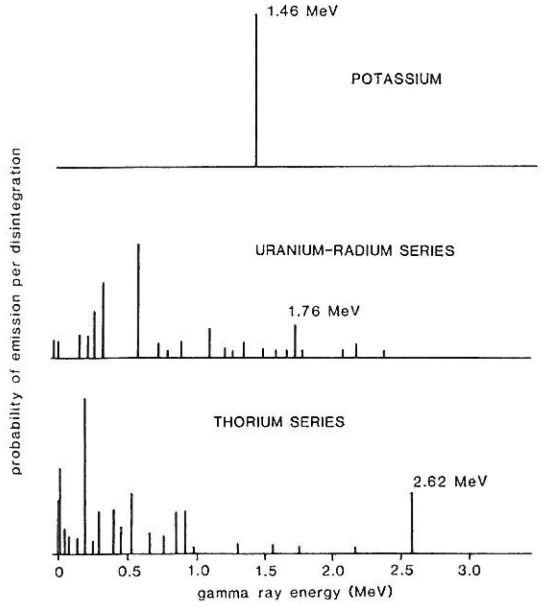

Figure 7.2 The gamma ray emission spectra of naturally radioactive minerals. The principal peaks used to identify each source are indicated. (After Tittman *et al.*, 1965, re-drawn from Schlumberger, 1972).

The radiation from ^{40}K is distinct, with a single energy value of 1.46 MeV (Figure 7.2). Both thorium and uranium emit radiations with a whole range of energies, but with certain peak frequencies. These peaks are especially distinct at the higher energy levels of 2.62 MeV for thorium and 1.76 MeV for uranium (Figure 7.2).

The spectra and the energy levels illustrated are those at the point of emission. One of the characteristics of gamma rays is that when they pass through any material their energy is progressively absorbed. The effect is known as Compton scattering, and is due to the collision between gamma rays and electrons which produces a degrading (lowering) of energy (Figure 7.3). The higher the common density through which the gamma rays pass, the more rapid the degradation or loss of energy (in reality it depends on the material's electron density, which is very similar to common density).

In borehole logging, when radiations are observed by the tool, they have already passed through the formation and probably also the drilling mud, both of which cause Compton scattering. Thus, the discrete energy levels at which gamma rays are emitted become degraded, and a continuous spectrum of values is observed (Figure 7.4). When each of the radioactive minerals is present, their radiations become mixed and the resulting spectrum is very complex. However, a glance at the original spectra (Figure 7.2) will show that the final complex, mixed spectrum, even after Compton scattering, will still contain diagnostic peaks, especially in the 1-3 MeV region. The original distinct peaks of potassium at 1.46 MeV, uranium

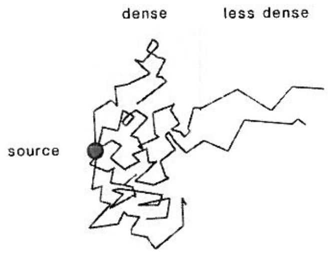

Figure 7.3 Schematic drawing of the Compton scattering of gamma rays. The effect is more marked in denser matter (cf. Lavenda, 1985).

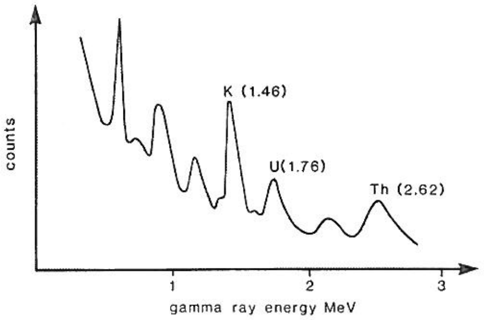

Figure 7.4 Complex spectrum observed from a radioactive source containing potassium, thorium and uranium, after Compton scattering. (After Hassan *et al.*, 1976).

and for Tertiary clastics

$$V_{sh} = 0.083(2^{3.7V_{sh}(t)} - 1.0) \qquad (6)$$

where V_{sh} = shale volume.

Radioactive mineral volume

Attempts to quantify the presence of radioactive minerals such as feldspars or mica are based on two assumptions: (1) all thorium radioactivity is from shale, and (2) radioactive detrital minerals show only potassium radioactivity.

For the quantification, the potassium values are normalized for shale volume using the maximum and minimum method as for thorium. The normalized potassium value will give shale volume + radioactive minerals volume. Subtracting the shale volume derived from the thorium log will leave the volume of radioactive minerals (Schenewerk *et al.*, 1980).

$$\text{Volume of radioactive minerals}$$

$$= \frac{K(\text{log value}) - K(\min) - V_{sh}\left[(K(\max) - (\min))\right]}{a} \qquad (7)$$

where $K(\min)$ = potassium % in clean formation; $K(\max)$ = potassium % in pure shale and a = empirical factor for the formation concerned.

The two strictly quantitative methods outlined above are essentially used in petrophysical applications. Other, geologically applicable, qualitative and semi-quantitative uses of the gamma ray spectral log are described below.

7.10 Qualitative and semi-quantitative uses of the spectral gamma ray log

Shale and clay minerals

A certain amount of literature exists on the possibility of identifying individual clay minerals using the spectral gamma ray log. Most results have local significance only, are inconclusive or unsuccessful. As was shown previously (Geochemical behaviour, Section 7.5) the potassium content of the clay minerals varies considerably between species but is moderately constant within species (Table 7.8). Thorium, too, varies with each species but with slightly less consistency (Table 7.13). The intent is to find if these variations enable the individual species to be identified qualitatively, and eventually quantitatively.

The interval of the Muddy 'J' formation of Eastern Wyoming has been studied by Donovan and Hilchie (1981). They found a fairly good correlation between potassium radioactivity and illite content. However, they also found that while there was no correlation between clay mineral content and total gamma radiation, there was a strong correlation between total counts and uranium content. The essential radiation was therefore coming from uranium. The evidence suggested that the uranium source was principally smectite, its presence being caused by the exchange of the uranyl ion from the formation waters. Uranium radioactivity was therefore related to the presence of smectite. Almost exactly the opposite was found in the analysis of shales around the North Sea (Dypvik and Eriksen, 1983). The authors found that potassium and thorium were the dominant contributors to gamma ray activity with uranium being of minor importance (cf. Table 7.14).

A complex quantitative approach to clay-mineral identification has been proposed (Quirein *et al.*, 1982). The authors suggest that clay mineral species, along with feldspar and evaporites, can all be identified relatively simply by their Th/K ratios (Figure 7.27). There is certainly a tendency for this behaviour (cf. Tables 7.8, 7.13) and it is the basis for using just thorium as a shale indicator (*see* 'Quantitative uses'). However, individual clay minerals do not fall into such a simple classification. Such a classification demands a strict chemical control for the distribution of the elements. As was indicated, potassium is chemically involved in the clay lattice, but the exact behaviour of thorium in terms of clay-mineral composition is not clear. This method has no experimental justification and the precision for the identification of specific clay minerals is not justified (Hurst, 1990).

Local variations, complexity of clay-mineral mixtures and many other contributory variables allow no convincingly clear picture as yet for precise clay-mineral identification. The use of the spectral gamma ray log for this purpose is not yet available. Qualitative uses are, however, available (*see below*).

Dominant clay mineral and detrital mineral content: use of the Th/K ratio

The method described previously for quantifying radioactive mineral volume (Section 7.9) was based on the proposition that thorium occurs effectively only in clays and is thus a clay volume indicator, while potassium occurs in both clays and radioactive minerals. The method was applied quantitatively to sandstones but may be used semi-quantitatively for both sandstones and mudstones: the lithologies should be interpreted separately. That is, the Th/K ratio will be largely a function of detrital mineral content in sands, but of clay mineral content in shales (in that these are potassium rich). In both lithologies, the usual value for the Th/K ratio is 4–6 (Myers, pers comm), deviations from this band will be the result of certain detrital mineral or clay mineral abundances. For instance, a sandstone with a low Th/K ratio (of less than 4), will generally be dominated by feldspars, micas or glauconite: with high ratios, (greater than 6), it is likely that heavy minerals dominate.

In mudstones, a low Th/K ratio (of less than 4), probably indicates that illites dominate the clay minerals, while high ratios (more than 6) probably indicate that kaolinite dominates. For example a study of the Permian

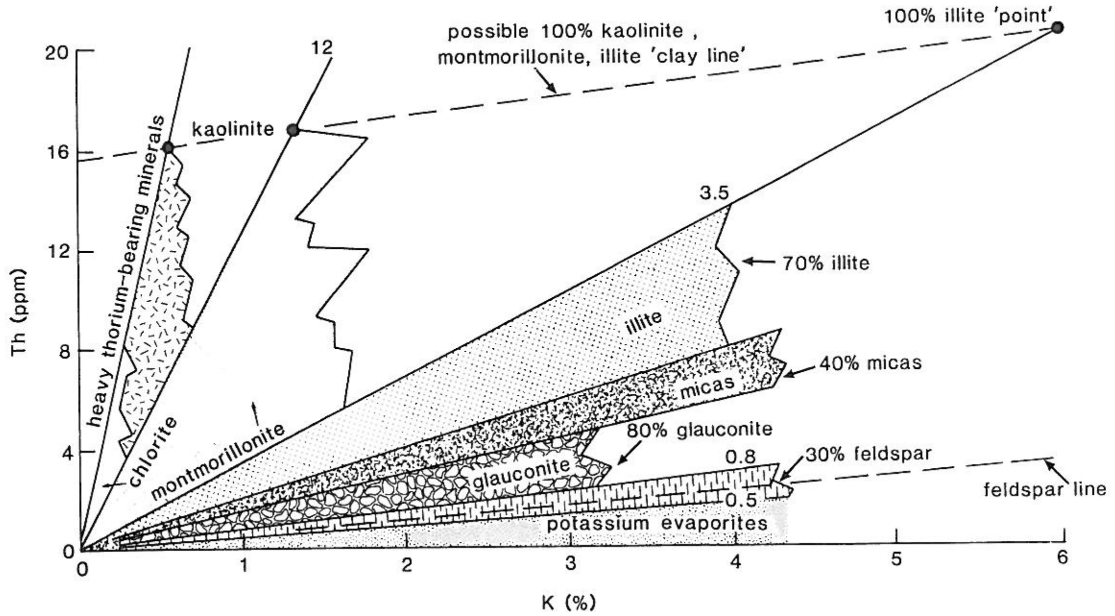

Figure 7.27 Graph of the theoretical distribution of clay minerals, heavy minerals and evaporites, in terms of potassium and thorium content. (Re-drawn from Quirein *et al.*, 1982).

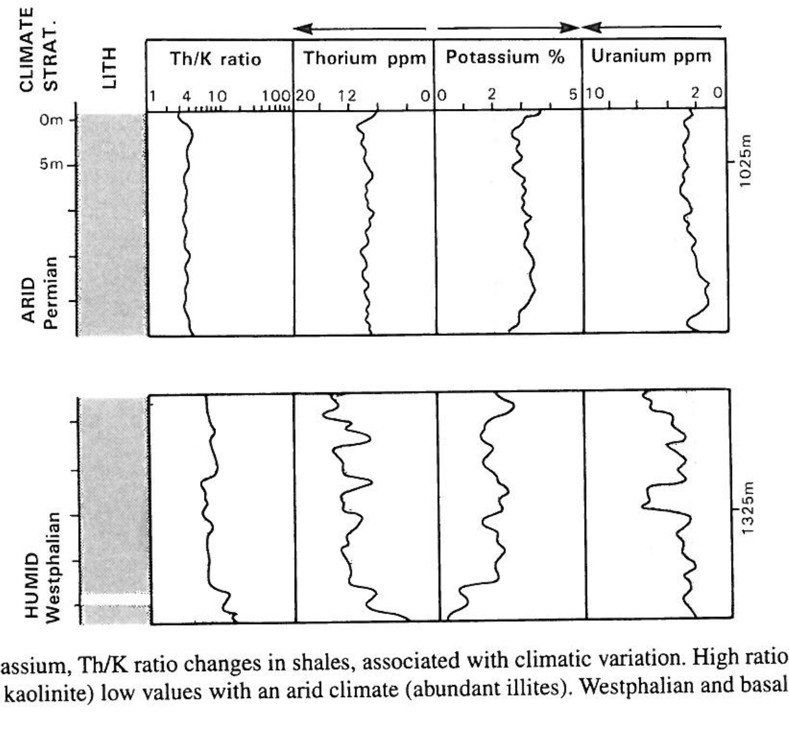

Figure 7.28 Thorium/potassium, Th/K ratio changes in shales, associated with climatic variation. High ratios are associated with a humid climate (abundant kaolinite) low values with an arid climate (abundant illites). Westphalian and basal Permian, central UK.

to Cretaceous of central Kansas (Doveton, 1991), shows that low Th/K ratios (high potassium) are typical of the aeolian Permian shales and silts, where the high potassium content comes from feldspars, rock fragments and illites, while high Th/K ratios (low potassium) occur in the marine, Lower Cretaceous because the shales are dominated by kaolinite and illite with some chlorite, smectite and mixed layer clays, all generally low in potassium content.

This example contains an often observed aspect of Th/K ratios: when they change *progressively* in shale sections, it is an indication of climatic change (it is in effect a progressive change in clay mineralogy). The example (Figure 7.28) shows two sections from the same well over a 300 m interval. The Th/K ratio decreases progressively upwards in the shales. The lowest section is from the deltaic coal-bearing Westphalian which had a humid climate. The top section is from the Permian with an arid climate (Figure 7.28). Within a sandstone sequence, similar progressive changes are more likely to indicate mineralogical variations than climatic ones and for instance, channel lags often show a high Th/K ratio because of the heavy minerals they contain.