CHAPTER TEN

GAMMA RAY

1. Introduction

Gamma ray logs are used for three main purposes:

- correlation
- evaluation of the shale content of a formation
- mineral analysis

The gamma ray log measures the natural gamma ray emissions from radioactive formations. Since many gamma rays can pass through steel casing, the log can be run in both open and cased holes. In related applications, induced gamma rays are measured (i.e., pulsed neutron logging), but these are not discussed in this section.

Figure 10-1 shows a gamma ray log. It is normally presented in track 1 on a linear grid and is scaled in API units. Gamma ray activity increases from left to right. Modern gamma ray tools are in the form of double ended subs that can be sandwiched into almost any logging tool string. Gamma ray tools consist of a gamma ray detector and the associated electronics for passing the gamma ray counts or count rates to the surface.

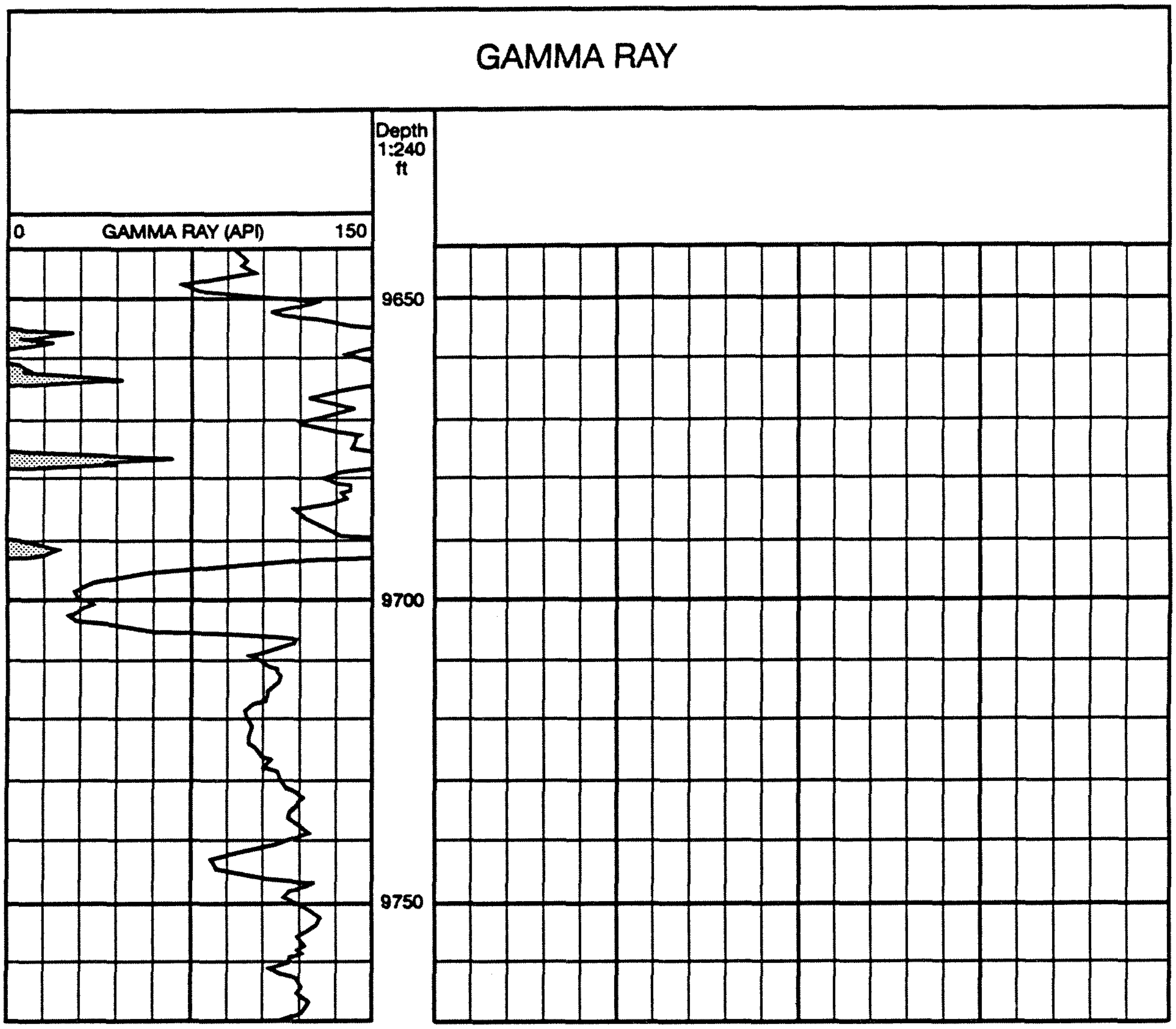


Figure 10-1. Gamma ray log.

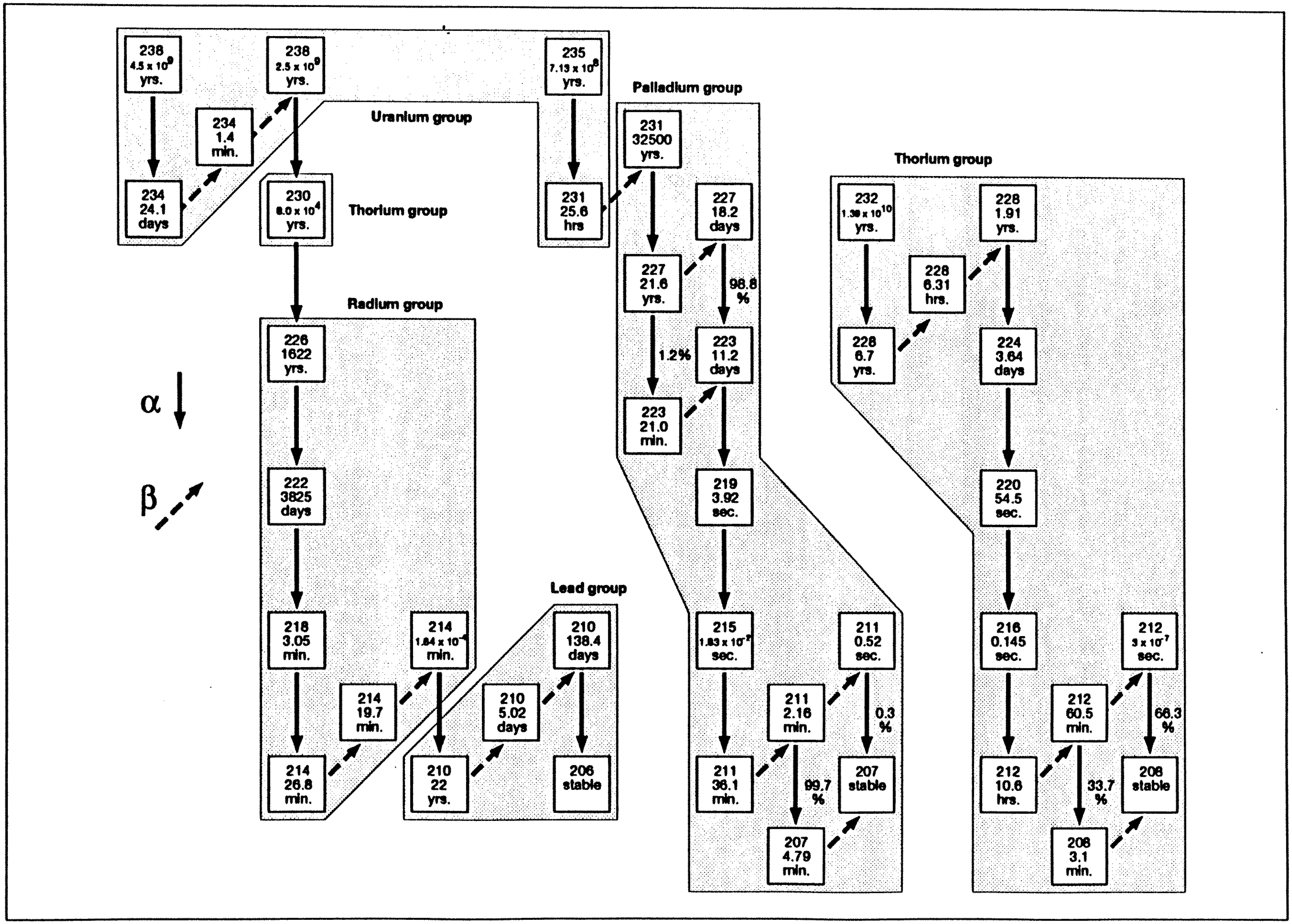


Figure 10-2. Naturally-occuring radioisotopes.

2. Origin of Natural Gamma Rays

Gamma rays originate in three sources in nature. These are the radioactive elements of the Uranium Group, the Thorium Group, and potassium. Uranium 235, uranium 238 and thorium 232 all decay, via long chains of daughter products, to stable lead isotopes as illustrated in Figure 10-2.

An isotope of potassium, ^{40}K, decays to argon and emits a gamma ray as shown in Figure 10-3. It should be noted that each type of decay is characterized by a gamma ray of a specific energy (wave length, frequency, or color) and that the frequency of occurrence for each decay energy is different. Figure 10-4 shows this relationship between gamma ray energy and frequency of occurrence. This is an important concept since it is used as the basis for analysis of data from the natual gamma spectroscopy tools.

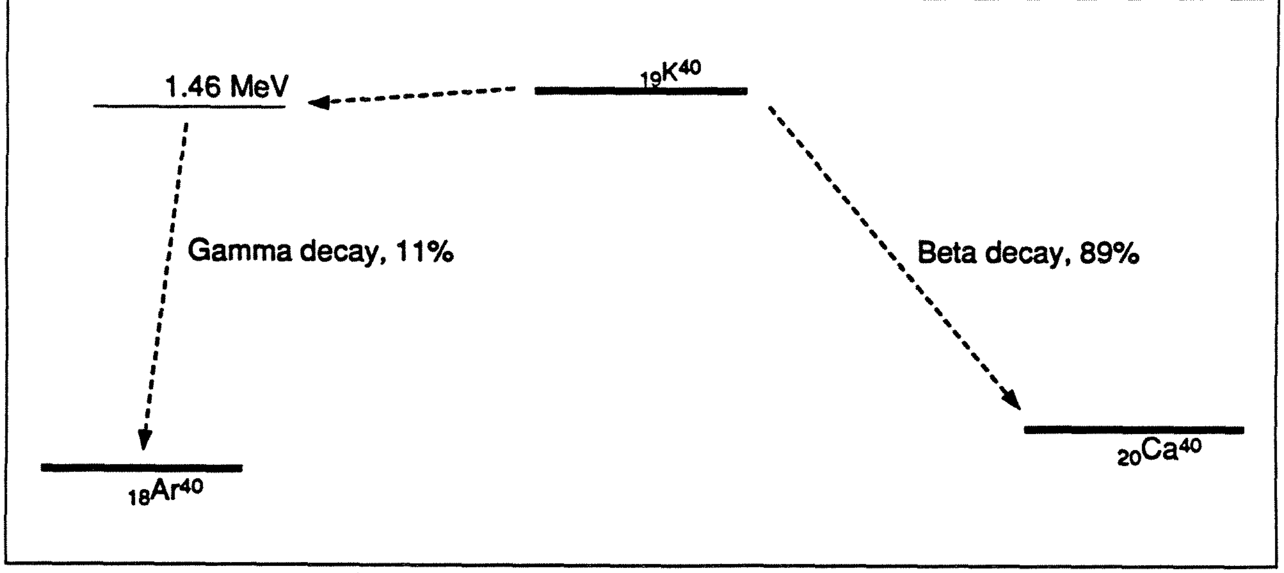


Figure 10-3. Decay modes of K^{40}.

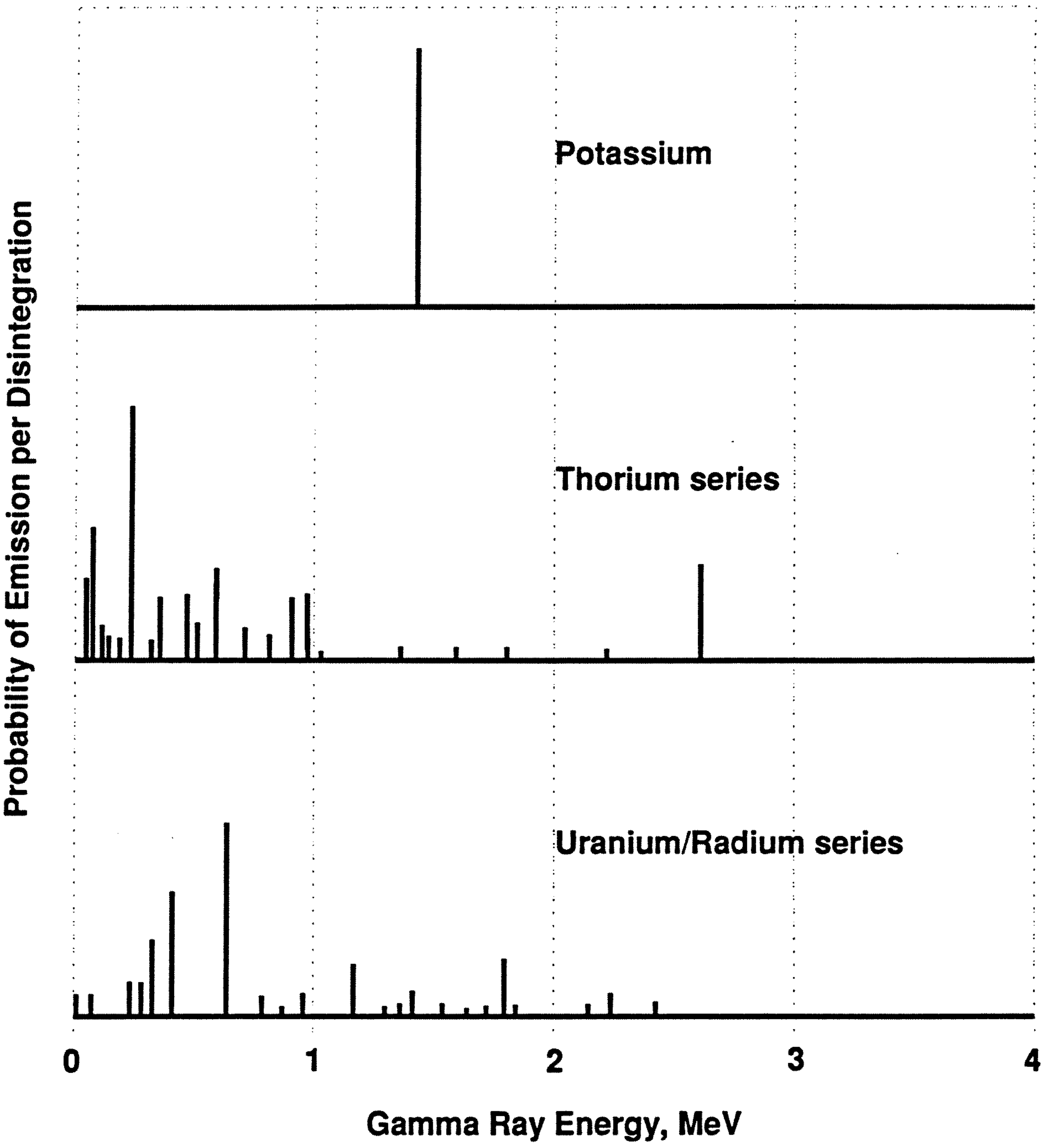


Figure 10-4. Emission spectra for potassium, thorium, and uranium series.

3. Abundance of Naturally Occurring Radioactive Minerals

An "average" shale contains 6 ppm uranium, 12 ppm thorium and 2% potassium. Since the various gamma ray sources produce different numbers and energies of gamma rays, it is more informative to consider this mix of radioactive materials on a common basis by referring to potassium equivalents (the amount of potassium that would produce the same number of gamma rays per unit of time). Reduced to a common denominator, the average shale contains uranium equivalent to 4.3% potassium, thorium equivalent to 3.5% potassium, and 2% potassium. This "average" shale is a rare find. A shale is a mixture of clay minerals, sand, silts and other extraneous materials; thus, there can be no "standard" gamma ray activity for shale. Indeed, the main clay minerals vary enormously in their natural radioactivity. Kaolinite has almost no potassium whereas illite contains between 4% and 8% potassium. Montmorillonite contains less than 1% potassium. Natural radioactivity may also be due to the presence of dissolved potassium or other salts in the water contained in the pores of the shale.

4. Operating Principle of Gamma Ray Tools

Traditionally, two types of gamma ray detectors have been used in the logging industry: Geiger-Mueller and scintillation detectors. Today most gamma ray tools use scintillation detectors containing a sodium iodide (NaI) crystal (Figure 10-5); newer and more efficient crystal materials are constantly being discovered but the principles of operation are the same. When a gamma ray strikes the crystal, a single photon of light is emitted. This tiny flash of light then strikes a photocathode (probably made from cesium antimony or silver-magnesium). Each photon hitting the photocathode releases a bunch of electrons.These, in turn, are accelerated in an electric field to strike another electrode producing an even bigger "shower" of electrons. This process is repeated through a number of stages until a final

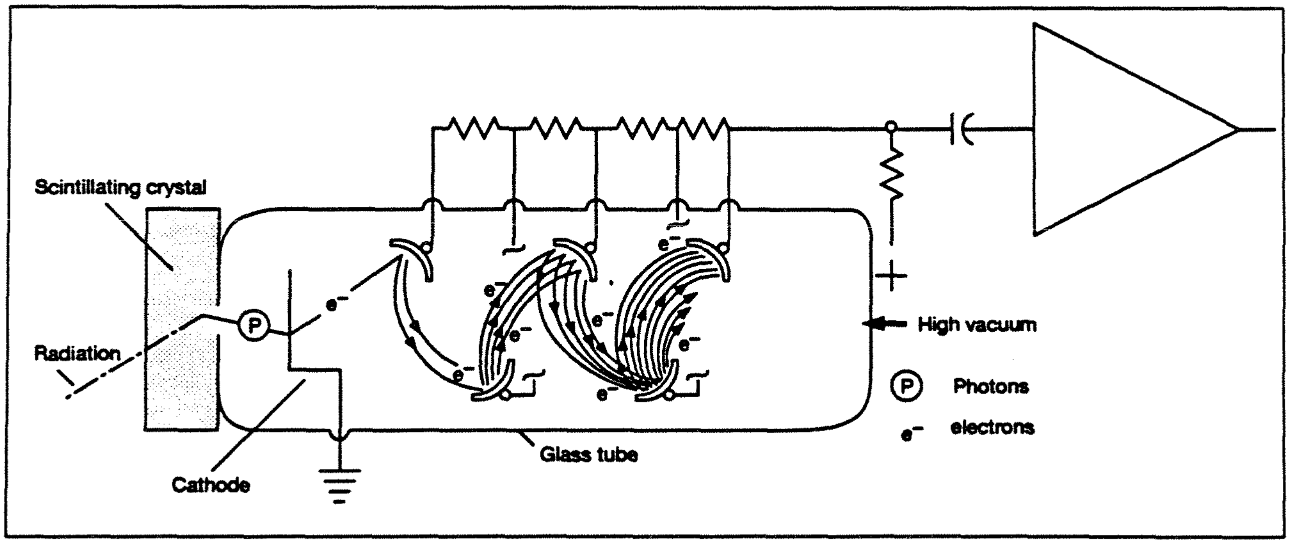


Figure 10-5. Scintillation gamma ray detector.

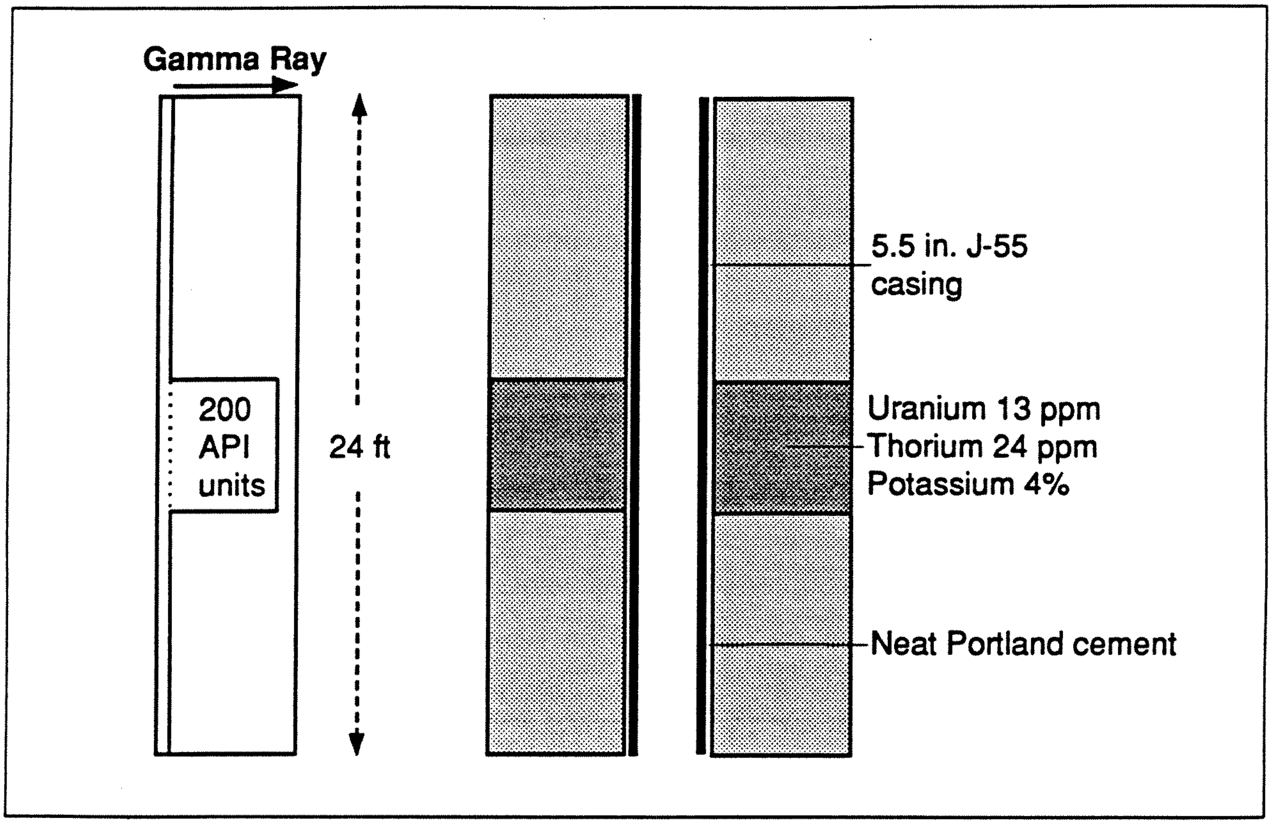


Figure 10-6. API gamma ray standard.

electrode conducts a small current through a measure resistor to produce a voltage pulse that can be measured. Each detected gamma ray produces a single pulse. The "dead time" of these systems vary but are typically very short, and they can register many counts/second before being "swamped" by numerous near-simultaneous gamma rays.

5. Calibration of Gamma Ray Detectors and Logs

One of the problems of gamma ray logging is the choice of a standard calibration system, since all logging companies use counters of different sizes that are encased in steel housings that vary in transparency to gamma rays. On very old logs, the scale might be quoted in μgm of radium per ton of formation. For many reasons this was found to be an unsatisfactory method of calibration, so a standard was devised by the American Petroleum Institute (API). A test pit at the University of Houston contains the "artificial shale" illustrated in Figure 10-6. A cylinder, which is 24 ft long and 4 ft in diameter, contains a central 8 foot section consisting of cement mixed with 13 ppm uranium, 24 ppm thorium and 4% potassium. Above and below are 8 foot sections of neat Portland cement, and all 3 layers are cased with 5.5in J-55 casing. The API standard defines 200 API units as the difference in radioactivity between the neat cement and the radioactively doped cement. Any logging service company may place its tool in this pit to make a calibration.

Field calibration is performed using a portable jig or blanket that contains a radioactive source, usually a small amount of ^{226}Ra or ^{232}Th. The source produces a known increase in radioactivity over the background count rate. This increase is equivalent to a known number of API units.

6. Time Constants and Block Filtering

All radioactive processes are subject to statistical variations. For example, if a source of gamma rays emits an average of 100 gamma rays per second over a period of hours, the source will emit 360,000 gamma rays (100/second × 60 seconds × 60 minutes). However, if the count is measured for any one particular second, the actual count might be less than 100 or more than 100. Gamma rays can be counted for a very short interval of time, resulting in a poor estimate of the real count rate, or the gamma rays can be counted for a long time resulting in a more accurate estimate. In well logging, long measurement times mean slow logging speeds, since the amount of time a detector is opposite a point is inversely related to tool velocity.

Most computerized logging units make records of measurements from 2 to 120 times per foot. A gamma ray tool moving at 1800 ft/hr (30 ft/min) will sample 6 inches of formation each second; it will "look" at each 3 inch interval for only 1/2 second (if sampled 4 times per foot, and leaving aside consideration of the physical length of the detector). If plotted as measured, this data will produce an extremely statistical or "noisy" gamma ray log.

The original method for handling the statistics inherent to nuclear data was to average the data over 1 to 4 seconds, depending on the logging speed. These "time constants" smoothed the gamma ray log nicely to a usable form, albeit with some loss of vertical resolution and slight changes in effective measure point. With the advent of computerized logging units, a similar method was employed: the gamma ray data is block filtered over several samples above and below the measure point. The result is a more usable and repeatable gamma ray log at the proper depth, with slightly less bed boundary resolution.

If the logging speed is doubled, the amount of time the detector "sees" a given point is reduced in half; there is a corresponding increase in statistical effects. To achieve the same repeatability as with the slower logging speed, one must increase the length of the block filter. Figure 10-7 shows the effects of changing logging speed and filter lengths on a gamma ray log.

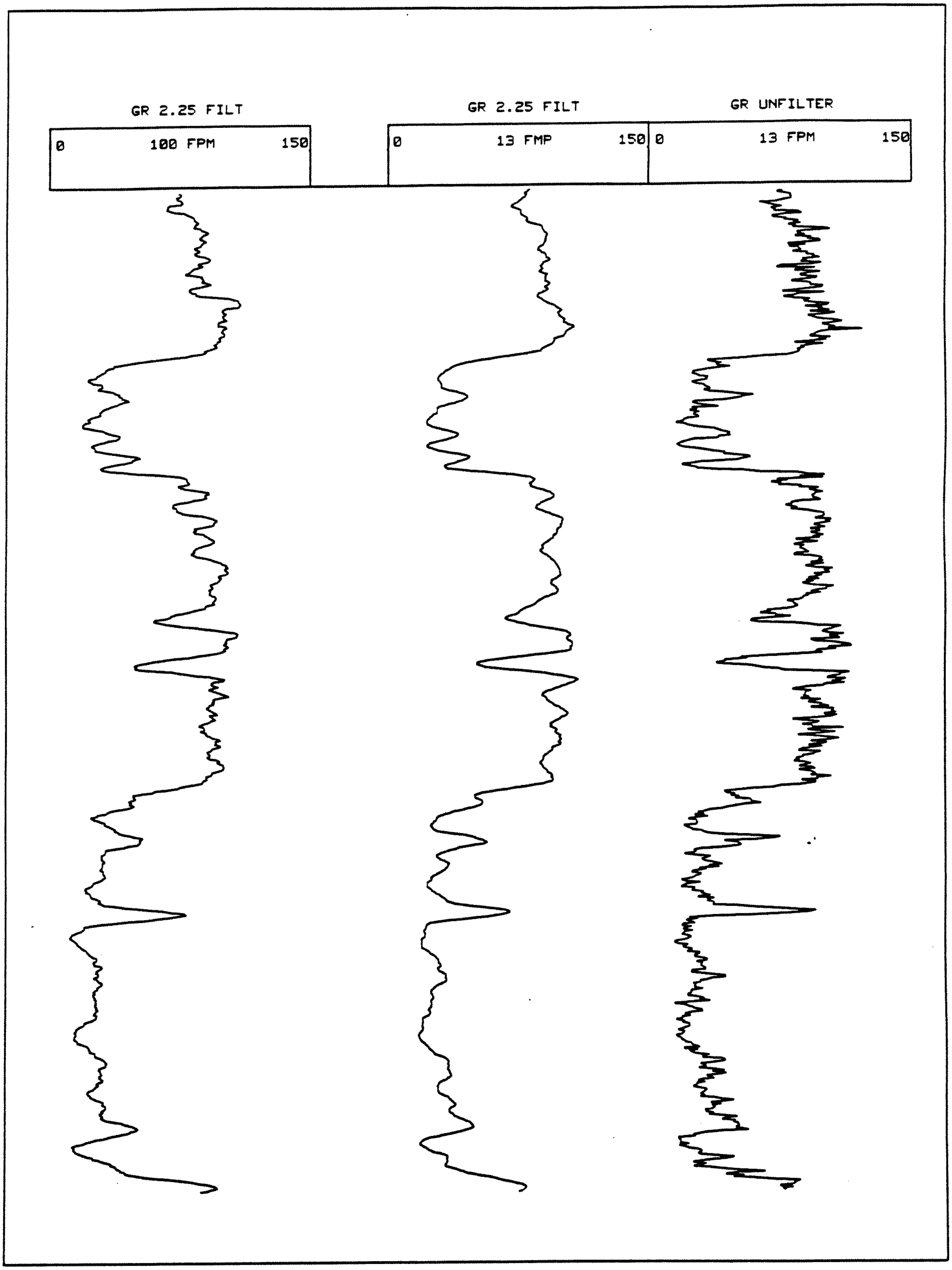


Figure 10-7. Effect of logging speed and filter length on gamma ray log.

7. Perturbing Effects on Gamma Ray Logs

Gamma ray logs are subject to a number of perturbing effects including:

- sonde position in the hole (centering/eccentering);
- hole size;
- mud weight;
- casing size and weight; and
- cement thickness.

Since there are innumerable combinations of hole size, mud weights and tool positions, logging service companies publish charts to correct their gamma ray logs back to a "standard" set of conditions (3-5/8 in. tool, centered in a water-filled 8 in. hole). Figure 10-8 applies to logs run in open hole and corrects for hole size and mud weight.

Question # 1

Use Figure 10-8 to estimate GR_{corr} under the following conditions:

GR_{log} = 67 API

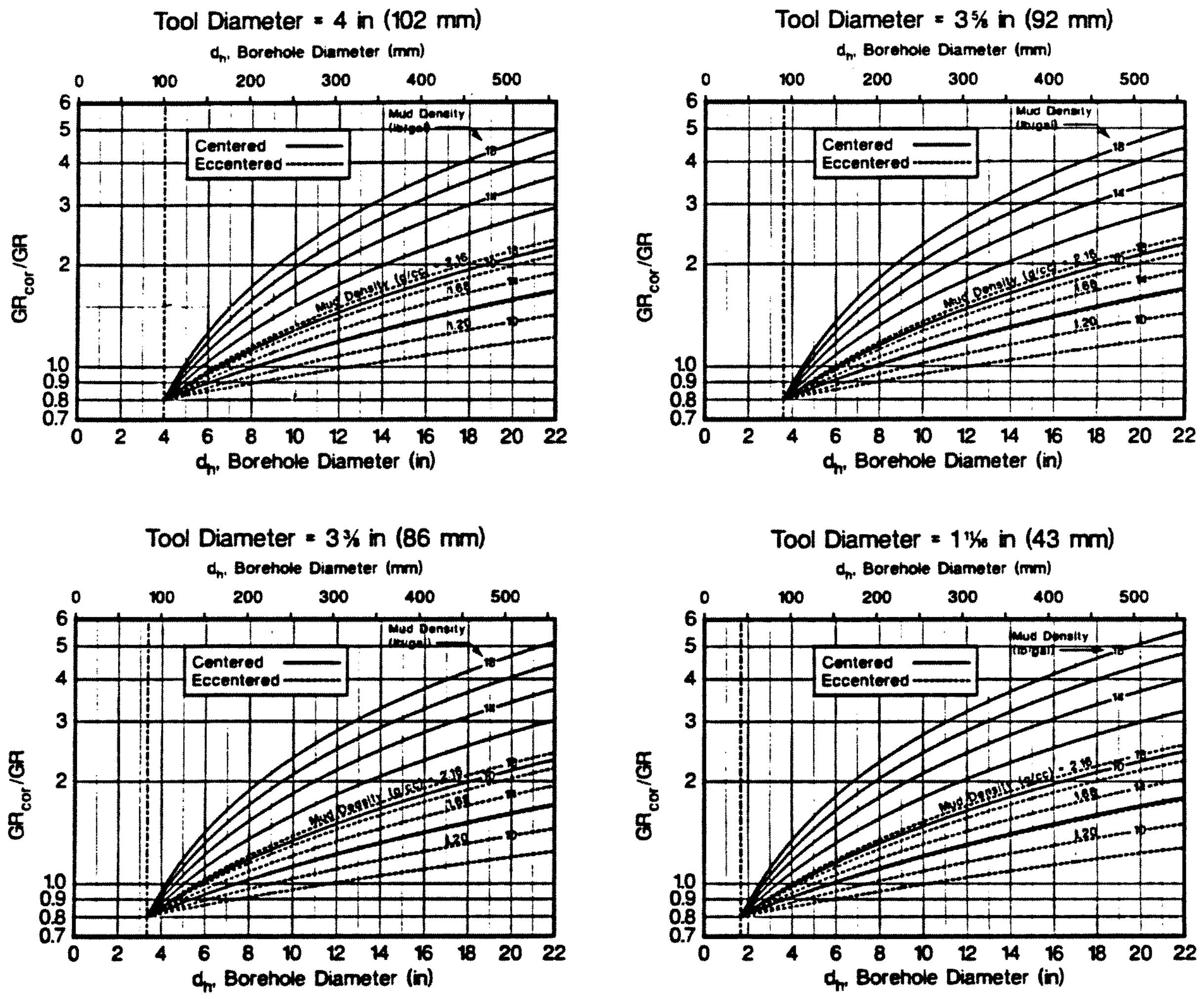
Hole size = 8 inches

Mud weight = 16 lbs/gal

Tool is centered.

Note that if a gamma ray log is run with a neutron and density, it is run usually eccentered; if it is run with a laterolog it is usually centered; if it is run with an induction log it is usually near-centered.

Gamma Ray Borehole Corrections



Tool Diameter = 4 in (102 mm)

Tool Diameter = 3⅝ in (92 mm)

Tool Diameter = 3⅜ in (86 mm)

Tool Diameter = 1 11/16 in (43 mm)

Figure 10-8. Gamma ray corrections.

8. Estimating Shale Content from Gamma Ray Logs

Since radioactive isotopes are often associated with the clay minerals in shales, it is a commonly accepted practice to use the relative gamma ray deflection as a shale volume indicator. The simplest procedure is to scale the gamma ray between its minimum and maximum values from 0 to 100% shale. The *Gamma Ray Index* is defined as a linear scaling of the GR between GR_{min} and GR_{max} such that:

$$\text{Gamma Ray Index} = \frac{GR - GR_{min}}{GR_{max} - GR_{min}} \qquad \text{(Eq. 10-1)}$$

A number of studies have shown that this is not necessarily the best method and have proposed modifications. If this index is called *I*, then the alternative relationships can be stated in terms of *I*:

Relationship	**Equation**	
Linear	$V_{sh} = I$	
Clavier	$V_{sh} = 1.7 - [3.38 - (I + .7)^2]^{1/2}$	
Steiber	$V_{sh} = I/[N\text{-}(N\text{-}1)\, I]$	(general form)
	$V_{sh} = 0.5 \cdot I/[1.5 - I]$	(if N = 3)
Bateman	$V_{sh} = I^{(I + GRfactor)}$	

where the GR_{factor} is a number (1.2–1.7) chosen to force the result to imitate the behavior of either the Clavier or the Steiber relationship. Figure 10-9 illustrates comparatively the difference between these alternative relationships.

Question # 2

On the gamma ray log shown on Figure 10-10, choose a value for GR_{min}, GR_{max} and then compute V_{sh} in Sand C using the Linear, Clavier and Steiber (N = 3) methods.

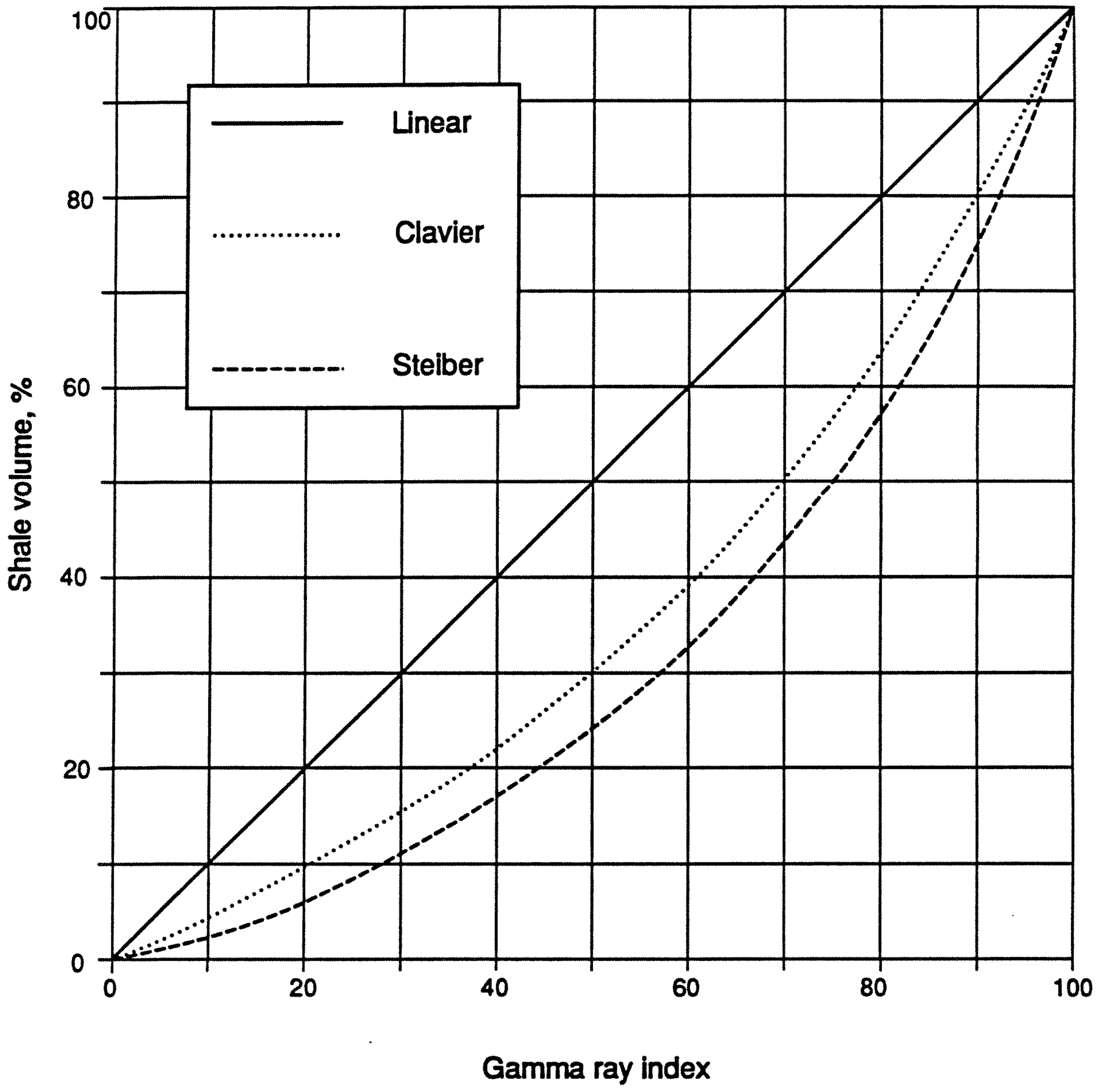


Figure 10-9. Several relationships for shale volume, V_{sh}, from gamma ray index, I.

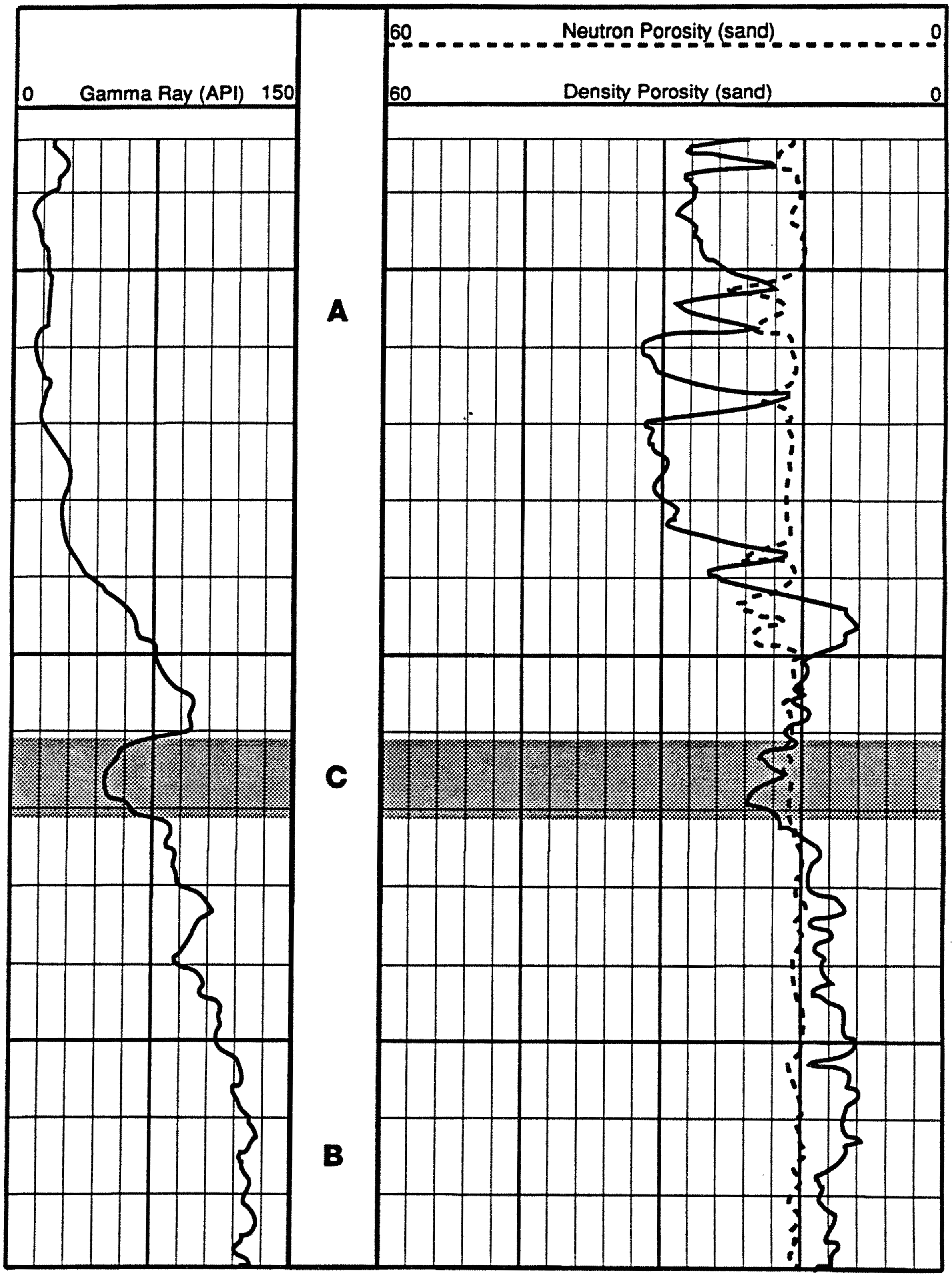


Figure 10-10. Gamma ray log for Question #2.

9. Gamma Ray Spectroscopy

Each type of radioactive decay produces a unique gamma ray. These various gamma rays have characteristic energies or frequencies. The simple method of just counting how many gamma rays a formation produces can be taken a step further to count both the number and energy of detected gamma rays. If the number of occurrences is plotted against the energy, a spectrum will be produced that is characteristic of the formation logged.

Figure 10-11 shows such a spectrum, where energies from 0 to approximately 3 MeV have been split into 256 specific energy "bins". The number of gamma rays in each bin is plotted on the Y-axis. This spectrum can be thought of as a mixture of the three individual spectra belonging to uranium, thorium and potassium. Some unique mixture of these three radioactive "families" will have the same spectrum as the observed one. The trick is to find a method of discovering that unique mixture. Fortunately the computers in logging trucks are capable of quickly finding a "best fit" and producing continuous curves showing the concentration of U, Th and K.

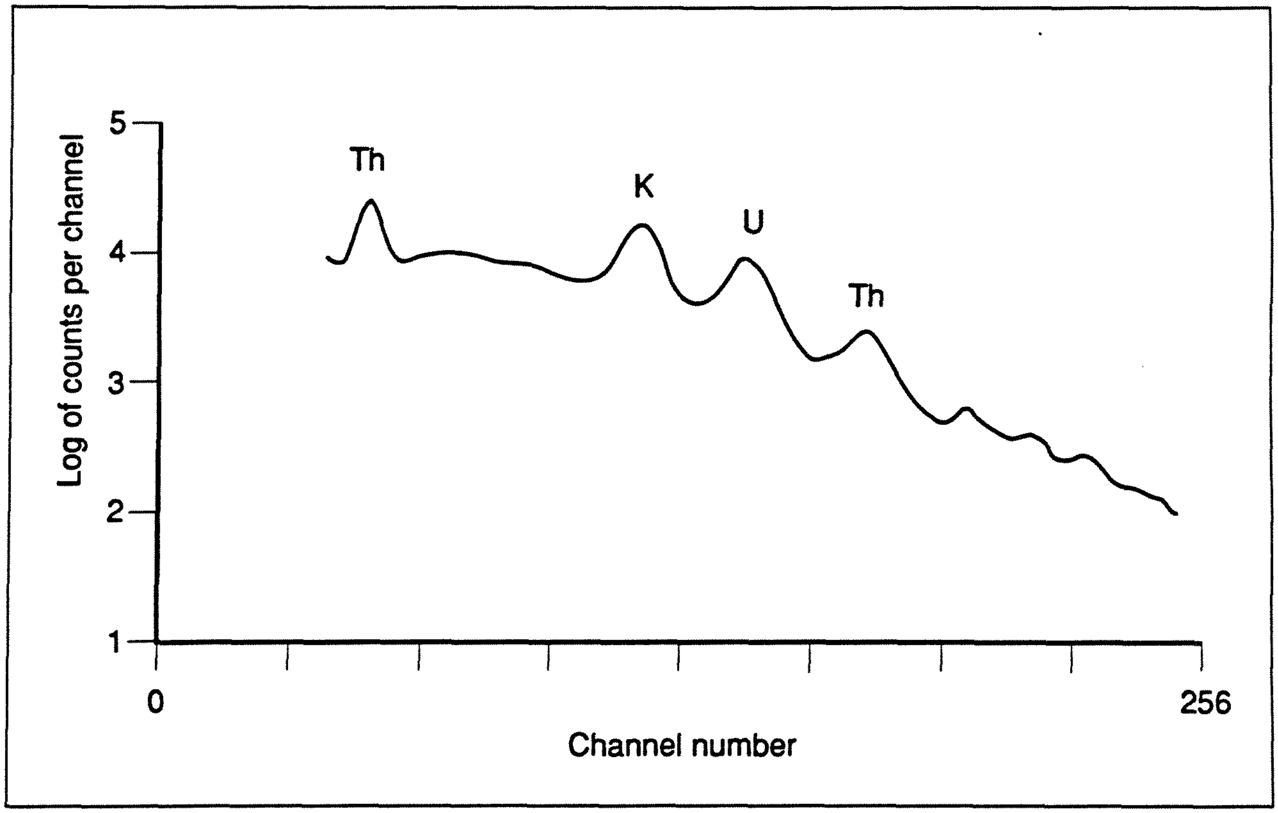


Figure 10-11. Typical gamma ray spectral data.

Figure 10-12 illustrates a spectral gamma ray log. Note that in the track 1 both total gamma ray activity (SGR) and a "uranium free" version of the total activity are displayed (in API units). The concentrations of U, Th and K are displayed in tracks 2 and 3. The units may be in counts/sec, ppm or %.

Question # 3

In the example shown in Figure 10-12, determine which elements are responsible for the high activity seen on the total gamma ray intensity curve at the point marked "A."

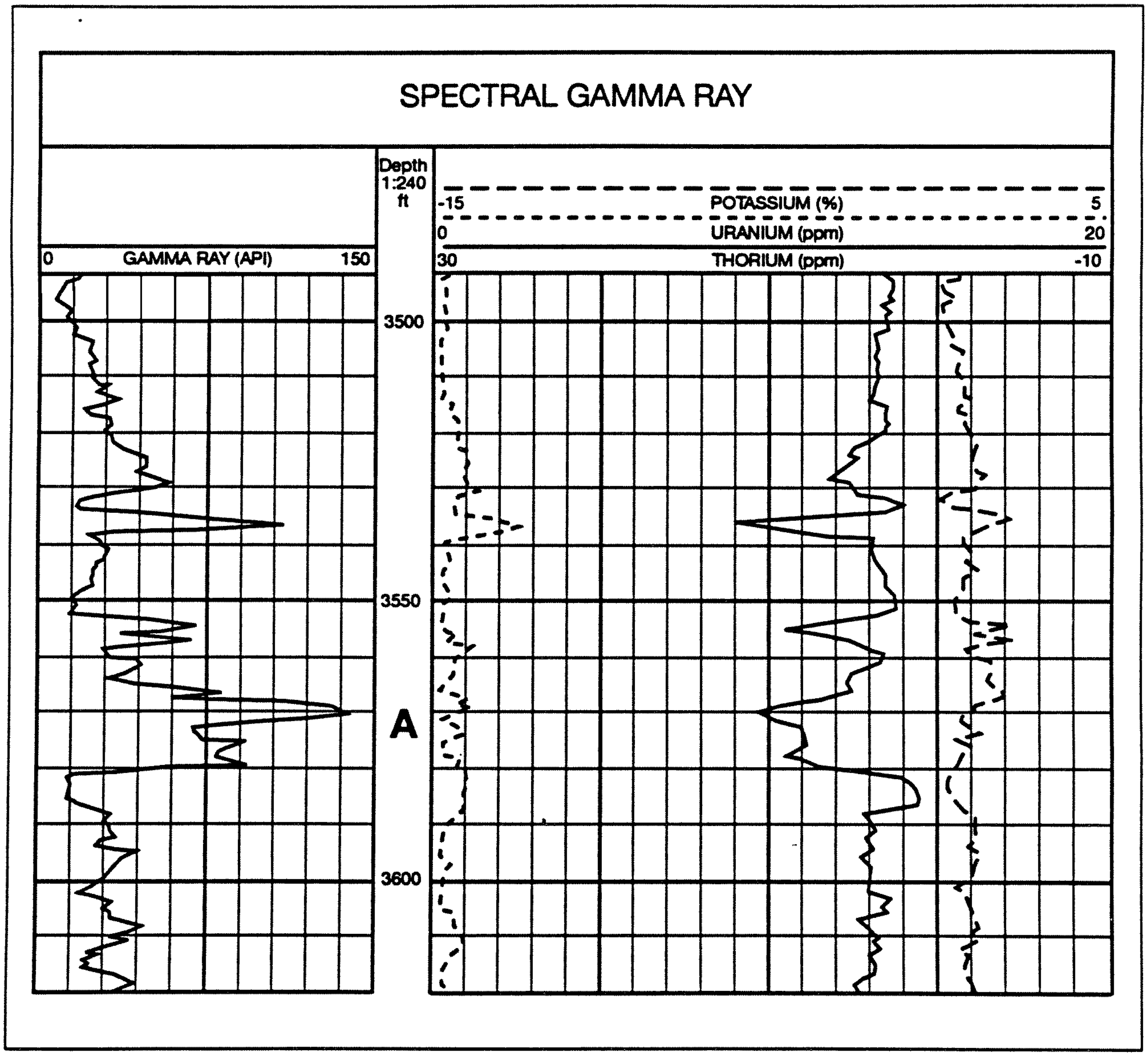


Figure 10-12. Spectral gamma ray log.

10. Interpretation of Spectral Gamma Ray Logs

Two general techniques are in use for the interpretation of spectral natural gamma ray logs. One is the use of the uranium curve (or the ratios U/Th, U/K, and Th/K) as an indicator of fractures. Another technique is to apply the U, Th and K concentrations with other log data to determine mineralogy and clay type.

Figure 10-13 illustrates the variation of the Th/K ratio in minerals ranging from K-feldspar to bauxite. Figure 10-14 "maps" a number of radioactive minerals as a function of their thorium and potassium contents.

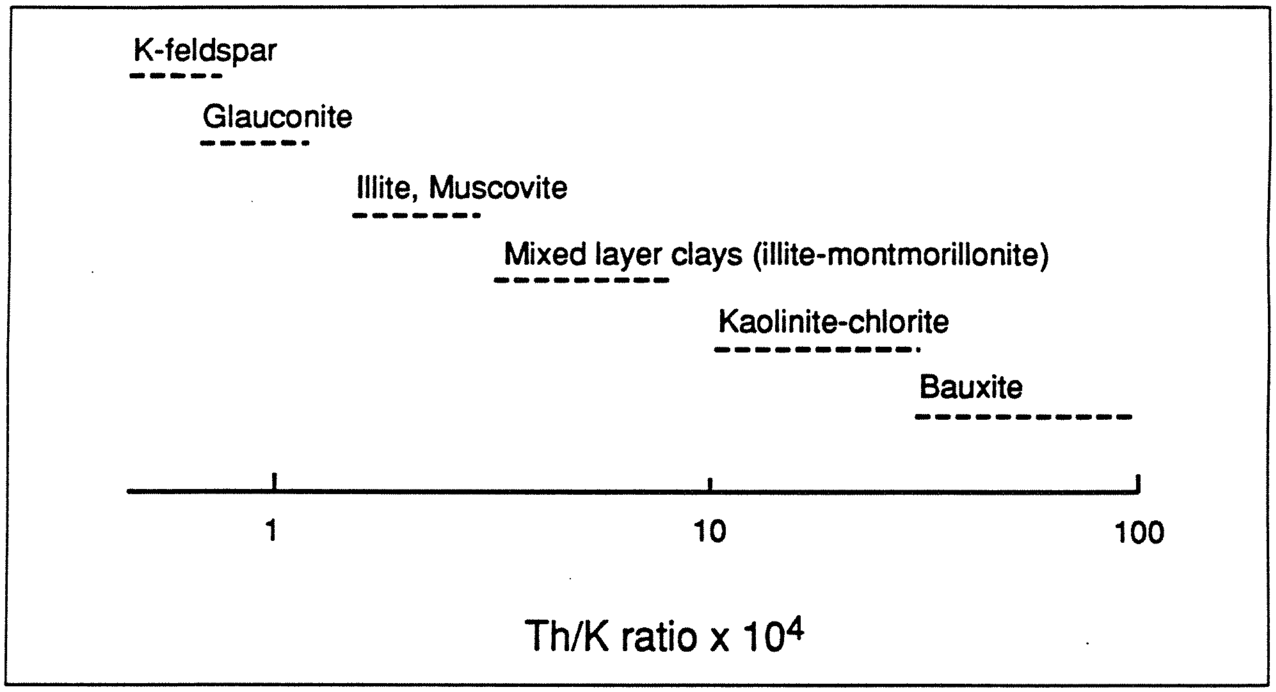


Figure 10-13. Thorium/potassium ratio ranges for several minerals.

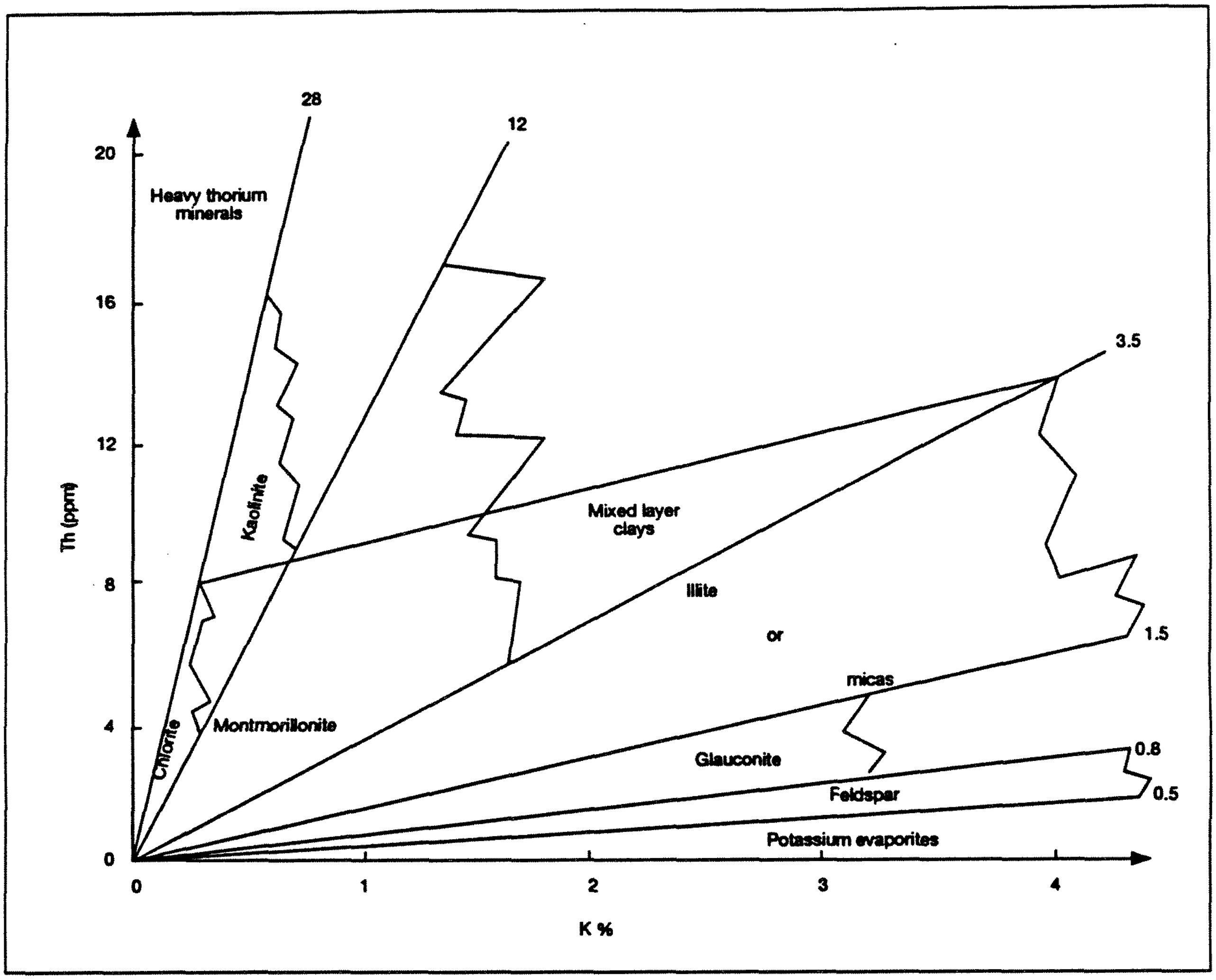


Figure 10-14. Thorium-potassium crossplot for mineral identification.

If the photoelectric absorption coefficient (P_e) is available then plots of the sort shown in Figure 10-15 can assist in mineral identification.

Other elemental ratios can be useful indicators. For example, a low U to Th ratio indicates reduced black shales. Uranium by itself may indicate a high organic carbon content, which in turn may indicate the presence of gas. Adams & Weaver proposed a classification method for sediments from Th and Th/U (Figure 16).

Field presentations of spectral gamma ray logs can assist the analyst in the task of mineral identification by offering curve plots with ratios of the three components (U, Th & K) already computed.

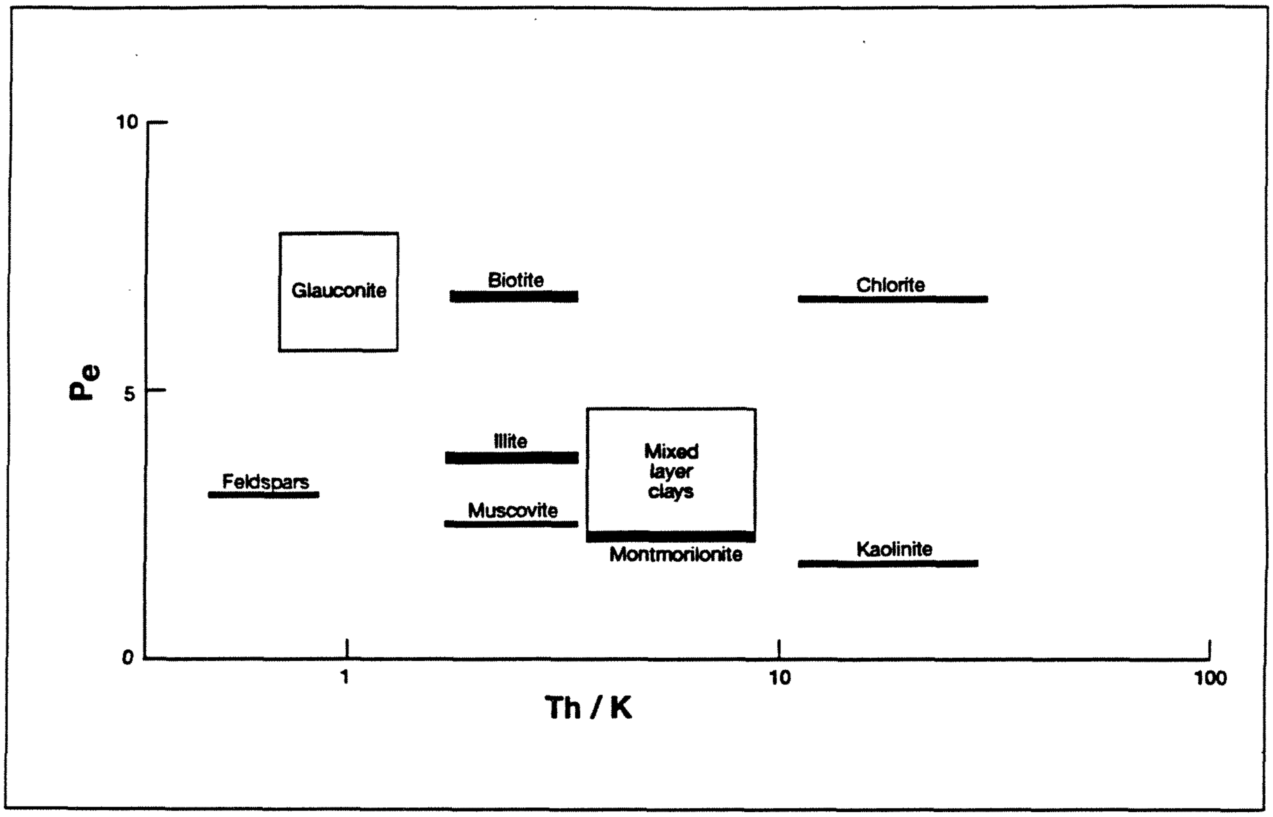


Figure 10-15a. Mineral identification by P_e and Th/K ratio.

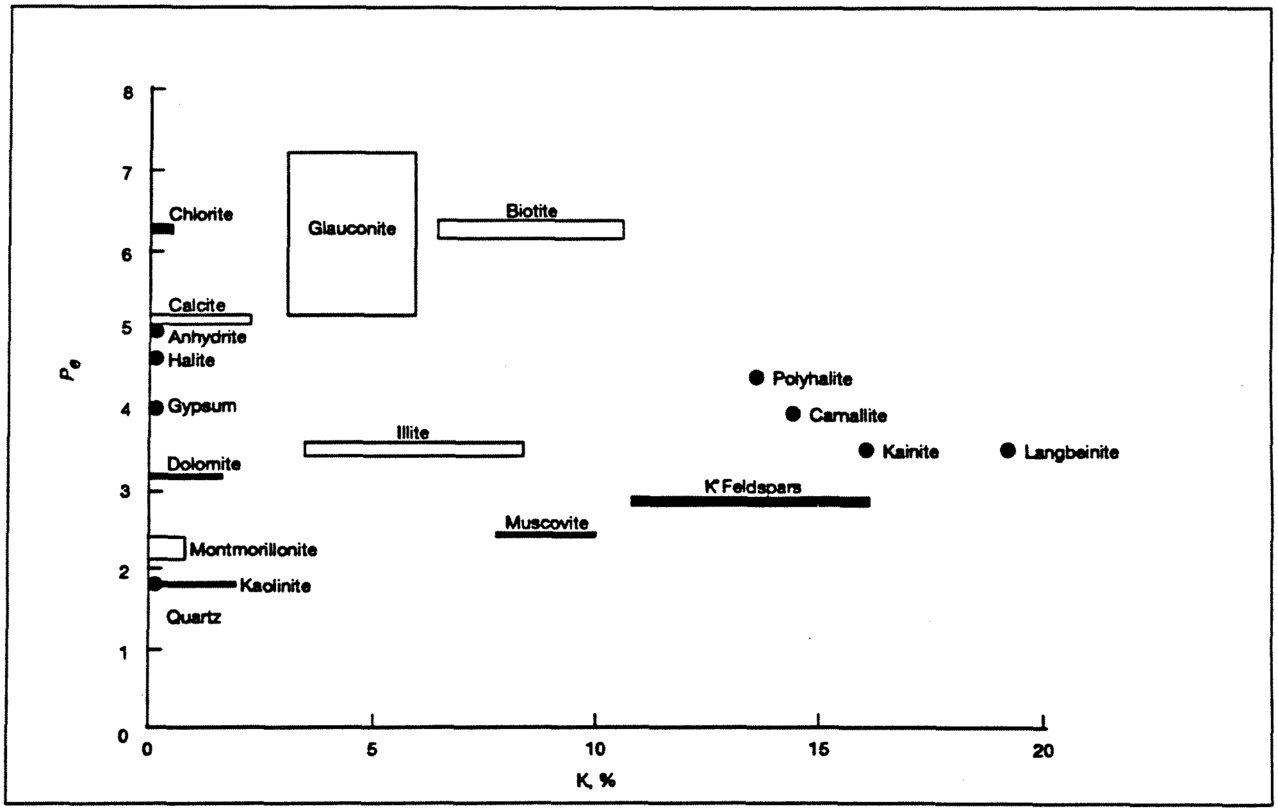


Figure 10-15b. Mineral identification by P_e and potassium content.

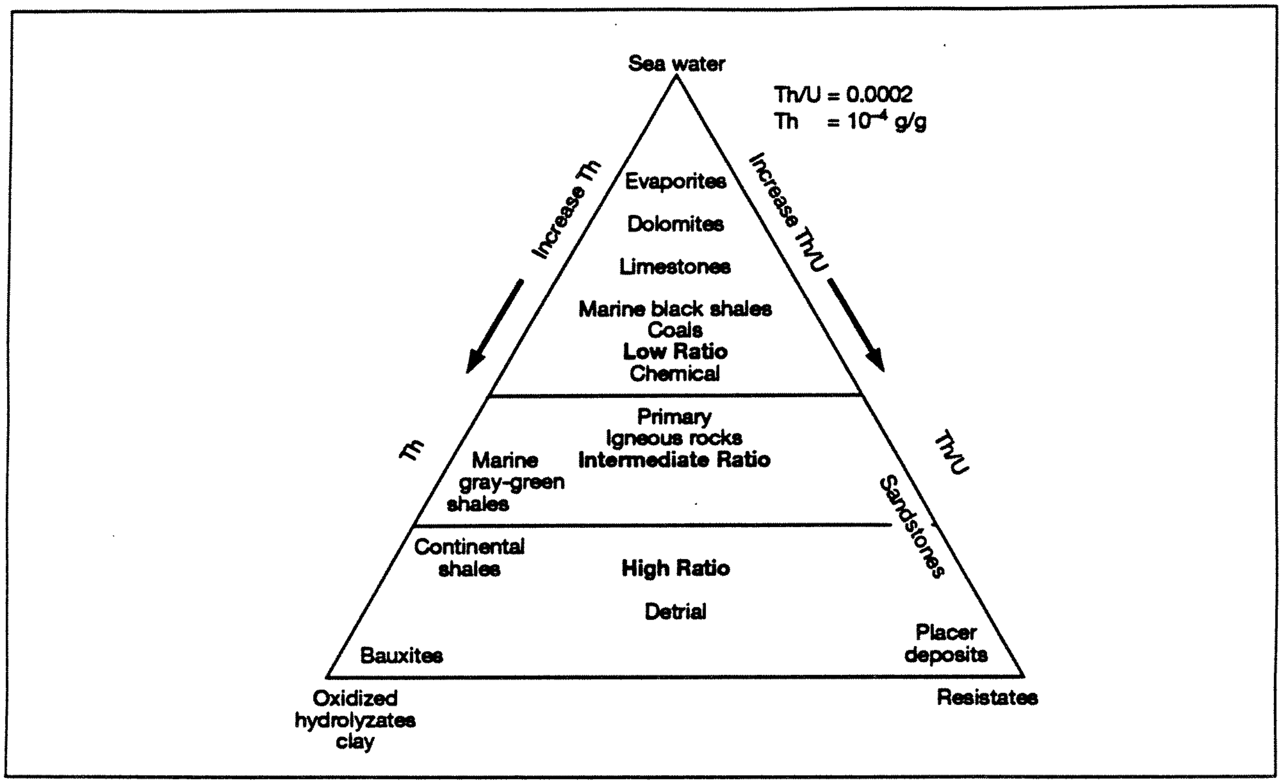


Figure 10-16. Sediment classification by thorium and uranium content.

Appendix A

Potassium, Uranium, and Thorium in Rocks and Minerals

Natural Gamma Ray Emitters--Uranium

Nuclide	Mode of Disintegration	Half Life
$_{92}U^{238}$	α	4.51 x 10^9 yr
$_{90}Th^{234}$	ß	24.1 d
$_{91}Pa^{234m}$	ß+IT	1.18 min
$_{91}Pa_{234}$	ß	6.66 hr
$_{92}U^{234}$	α	2.48 x 104^4 yr
$_{90}Th^{230}$	α	8 x 10^4 yr
$_{88}Ra^{226}$	α	1620 yr
$_{86}Em^{222}$	α	3.82 d
$_{84}Po^{218}$	α,ß	3.05 min
$_{85}At^{218}$	α,ß	2 sec
$_{86}Em^{218}$	α	1.3 sec
$_{82}Pb^{214}$	ß	26.8 min
$_{83}Bi^{214}$	α,ß	19.7 min
$_{84}Po^{214}$	α	1.6 x 10^{-4} sec
$_{81}Ti^{210}$	ß	1.32 min
$_{82}Pb^{210}$	ß	19.4 yr
$_{83}Bi^{210}$	α,ß	5.01 d
$_{84}Po^{210}$	α	138.4 d
$_{81}Ti^{206}$	ß	4.2 min
$_{82}Pb^{206}$	Stable	

Uranium-Bearing Minerals

Autunite	$Ca(UO_2)_2(PO_4)_2 \cdot (10\text{-}12H_2O)$
Tyuyamunite	$Ca(UO_2)_2(VO_4)_2 \cdot (5\text{-}8H_2O)$
Carnotite	$K_2(UO_2)_2(UO_4)_2 \cdot (1\text{-}3H_2O)$
Baltwoodite	U-silicate high in K
Weeksite	U-silicate high in Ca

Natural Gamma Ray Emitters--Thorium

Nuclide	Mode of Disintegration	Half Life
${}_{90}Th^{232}$	α	1.42×10^{10} yr
${}_{88}Ra^{228}$	ß	6.7 yr
${}_{89}Ac^{228}$	ß	6.13 hr
${}_{90}Th^{228}$	α	1.91 yr
${}_{88}Ra^{224}$	α	3.64 d
${}_{86}Em^{220}$	α	51.5 sec
${}_{84}Po^{216}$	α	0.16 sec
${}_{83}Pb^{212}$	ß	10.6 hr
${}_{83}Bi^{212}$	α,ß	60.5 min
${}_{84}Po^{212}$	α	0.30 sec
${}_{81}T^{208}$	ß	3.10 min
${}_{82}Pb^{208}$	Stable	

Thorium-Bearing Minerals

Name	Composition	ThO_2 Content
Cheralite	$(Th,Ca,Ce)(PO_4SiO_4)$	30%, variable
Huttonite	$ThSiO_4$	81.5%, ideal
Pilbarite	$ThO_2 \cdot UO_3 \cdot PbO \cdot 2SiO_2 \cdot 4H_2O$	31%, variable
Thorianite	ThO_2	Isomorphous with UO_2
Thorite	$ThSiO_4$	25 to 63%, 81.5% ideal
Thorogummite	$Th(SiO_4)_{1-x}(OH)_{4-x}$, $x<0.25$	24 to 58% or more
Allanite	$(Ca,Ce,Th)_2(Al,Fe,Mg)_3Si_3O_{12}$	0 to 3%
Bastnaesite	$(Ce,La)Co_3F$	Less than 1%
Betafite	$\sim (U,Ca)(Nb,Ta,Ti)_3O_9 \cdot nH_2O$	0 to 1%
Brannerite	$\sim (U,Ca,Fe,Th,Y)_3Ti_5O_{16}$	0 to 12%
Euxenite	$(Y,Ca,Ce,U,Th)(Nb,Ta,Ti)_2O_5$	0 to 5%
Eschynite	$(Ce,Ca,Fe,Th)(Ti,Nb)_2O_6$	0 to 17%
Fergusonite	$(Y,Er,Ce,U,Th)(Nb,Ta,Ti)O_4$	0 to 5%
Monazite	$(Ce,Y,La,Th)PO_4$	0 to 30%, usually $\sim$ 8%
Samarskite	$(Y,Er,Ce,U,Fe,Th)(Nb,Ta)_2O_6$	0 to 4%
Thucholite	Hydrocarbon mixture with U, Th, rare earth elements	
Uraninite	UO_2 with Ce, Y, Pb, Th, etc.	0 to 14%
Yttrocrasite	$\sim (Y,Th,U,Ca)_2(Ti,Fe,W)_4O_{11}$	7 to 9%
Zircon	$ZrSiO_4$	Usually less than 1%

Potassium, Uranium and Thorium Distribution in Rocks and Minerals

Materials	**K (%)**	**U (ppm)**	**Th (ppm)**
Allanite		30-700	500-5000
Apatite		5-150	20-150
Epidote		20-50	50-500
Monazite		.5-3E+3	25-200E+3
Sphene		100-700	100-600
Xenotime		0.5-34E+3	Low
Zircon		.3-3E+3	.1-2.5E+3
Andesite (average)	1.7	0.8	1.9
Andesite (Oregon)	2.9	2.0	2.0
Basalt, alkali	0.61	0.99	4.6
Basalt, plateau	0.61	0.53	1.96
Basalt, alkali olivine	<1.4	<1.4	3.9
Basalt, tholeiites (orogene)	<0.6	<0.25	<0.05
Basalt, tholeiites (non-orogene)	<1.3	<0.50	<2.0
Basalt in Oregon	1.7	1.7	6.8
Carbonates, range (average)	0-2,(0.3)	0.1-9,(2.2)	0-7, (1.7)
Carbonate, pure lime, chalk, dolo	<0.1	<1.0	<0.5
Carbonate, clean W.TX dolomite	0.1-0.3	1.5-10	<2.0
Carbonate, clean Florida lime	<0.4	2.0	1.5
Carbonate, clean TX lime, Cretac.	<0.3	1.5-15	<2.0
Carbonate, Hunton lime, OK	<0.2	<1.0	<1.5
Carbonate, West Texas	<0.3	<1.5	<1.5
Clays, bauxite		3-30	10-130
Clays, glauconite	5.08-5.3		
Clays, bentonite	<0.5	1-20	6-50
Clays, montmorillonite	0.16	2-5	14-24
Clays, kaolinite	0.42	1.5-3	6-19
Clays, illite	4.5	1.5	
Clays, mica, biotite	6.7-8.3		<0.01

Materials	K (%)	U (ppm)	Th (ppm)
Clays, mica, muscovite	7.9-9.8		<0.01
Diabase, Virginia	<1.0	<1.0	2.4
Diorite, quartzodirite	1.1	2.0	8.5
Dunite, Washington	<0.02	<0.01	<0.01
Felsdpar, plagioclase	0.54		<0.01
Feldspar, orthoclase	11.8-14.0		<0.01
Feldspar, microcline	10.9		<0.01
Gabbro (mafic igneous)	0.46-0.58	0.84-0.90	2.7-3.85
Granite, (silicic igneous)	2.75-4.26	3.6-4.7	19-20
Granite, Rhode Island	4.5-5.0	4.2	25-52
Granite, New Hampshire	3.5-5.0	12-16	50-62
Granite, preCambr.(MN,OK,CO)	2-6	3.2-4.6	14-27
Granodiorite	2.0-2.5	2.6	9.3-11.0
Granodiorite (Colorado,Idaho)	5.5	2.0-2.5	11.0-12.1
Peridodite	0.2	0.01	0.05
Phosphates		100-350	1-5
Rhyolite	4.2	5.0	
Sandstones, range (average)	0.7-3.8,(1.1)	0.2-0.6,(0.5)	0.7-2.0,(1.7
Silica, quartz, quartzite (pure)	<0.15	<0.4	<0.2
Sands, Gulf Coast beaches	<1.2	0.84	2.8
Sands, Atlantic Coast (FL, NC)	0.37	3.97	11.27
Sands, Atlantic Coast (NJ, MA)	0.3	0.8	2.07
Shales, common, range (average)	1.6-4.2,(2.7)	1.5-5.5,(3.7)	8-18,(12)
Shale, average of 200 samples	2.0	6.0	12.0
Shales, Colorado oil shales	<4.0	up to 500	1-30
Schist (biotite)		2.4-4.7	13-25
Syenite	2.7	2500	1300
Tuffs , feldspathic	2.04	5.96	1.56

NOTE: Numbers indicate typical values. If a range of values is shown, the number in parentheses is the median value.