12.   THE SPECTRAL GAMMA RAY LOG

12.1   Introduction

The *spectral gamma ray* log measures the natural gamma radiation emanating from a formation split into contributions from each of the major radio-isotopic sources. Analysis of the sources of the natural gamma radiation give us added information concerning the composition and likely lithology of the formation.

The spectral gamma ray log is commonly given the symbol *SGR*.

A typical spectral gamma ray tool is shown in Fig. 12.1.

12.2   Principles

It will be remembered that the amplitude of the output from the gamma ray sensor is proportional to the energy of the incident gamma ray. We can use this information to measure the proportion of the total gamma radiation coming from each of potassium-40, the uranium-radium series, and the thorium series for a particular formation.

Figure 10.1 shows that the energy distributions from each of the major contributors to the natural gamma radiation from a formation are different. The labeled peaks in Figure 10.1 are the energies that are dominant (most gamma rays have this energy). When the radiation has traveled through the rock and drilling fluid to the sensor, the energy distributions shown in Figure 10.1 are added together because the rock contains different amounts of each of radio-isotopes. The energy distributions are also spread out in energy space as the result of compton scattering. However, the energy peaks from each of the major contributors to the gamma radiation are still recognizable (Fig. 12.2).

Figure 12.1 The Spectral Gamma Ray Sonde (SGS). (Courtesy of Reeves Wireline Ltd.)

The spectral gamma ray tool uses the same sensor as the total gamma ray tool. The output from the sensor is fed into a multi-channel analyzer that calculates the amount of radiation coming from the energies associated with each of the major peaks. This is done by measuring the gamma ray count rate for 3 energy windows centred around the energies 1.46 MeV for potassium-40, 1.76 MeV for the uranium-radium series, and 2.62 MeV for the thorium series. These readings represent the gamma ray radioactivity from each of these sources. Their sum should be the same as the total gamma ray value measured by the total gamma ray tool, and is coded *SGR* if measured with a spectral gamma ray tool. Any combination of the three components can be summed and analyzed. However, the most important is the sum of the potassium-40 and thorium radiation, which is called the *computed gamma ray response* (*CGR*).
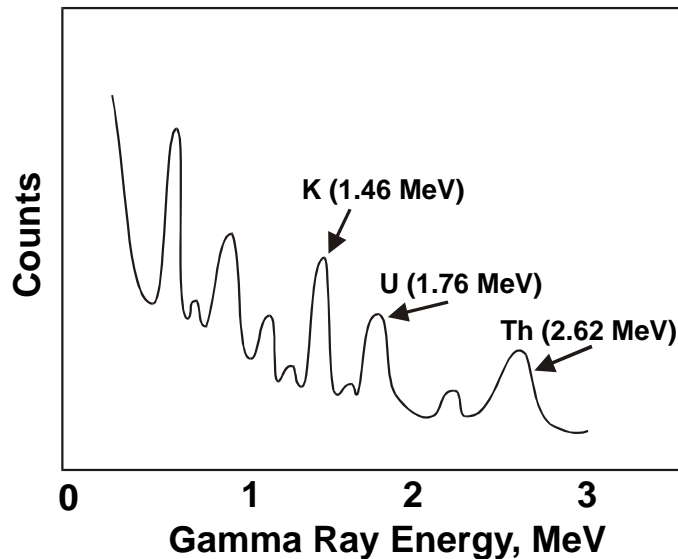

Figure 12.2 Measured gamma ray energy spectrum from a formation after compton scattering.

12.3   Calibration

The spectral gamma ray tool is calibrated using 4 sources of accurately known composition, one each containing only K^{40}, U^{238}, and Th^{232}, and one containing a mixture. Each of the sources is placed next to the detector and the tool is used to make a measurement. The calibration is designed such that the calibrated readings of the tool accurately report difference in the amount of radiation from each of the radiation sources, and the total count rate is calibrated to the Houston test pit.

12.4   Log Presentation

The format for reporting the spectral gamma ray data is more complex than for the total gamma ray log because it contains much more detailed information.

Track 1 is used to record the derived total gamma ray log (*SGR*), which is a sum of all the radiation contributions, as well as the computed gamma ray log (*CGR*), which is the sum of the potassium and thorium responses, leaving out the contribution from uranium.

Tracks 2 and 3 are used to record the calculated abundances associated with the radiation from the individual contributions from each of K^{40}, U^{238}, and Th^{232}. It should be noted that potassium is reported as a percentage, while U^{238} and Th^{232} are reported in parts per million (ppm).

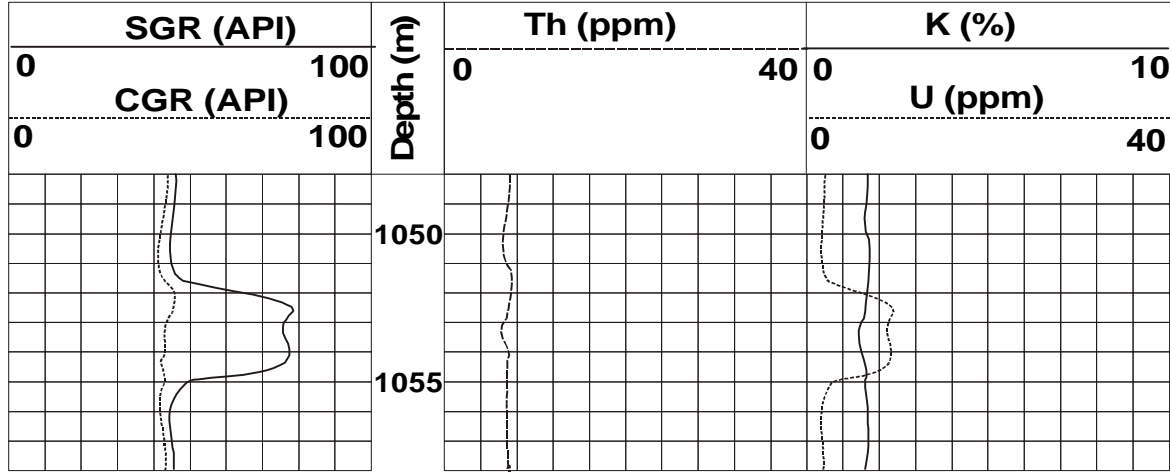Figure 12.3 shows a typical spectral gamma ray log.

Figure 12.3 The presentation of the spectral gamma ray log.

12.5   Depth of Investigation

The depth of investigation is controlled by the same fundamental physics as for the total gamma ray tool, and is identical to the total gamma ray tool (i.e., about 1 ft).

12.6   Logging Speed

While all the arguments concerning logging speed for the total gamma ray tool are also appropriate for the spectral tool, the statistical fluctuations must now be applied to proportions of the total gamma count rate. If good quality data for each of K^{40}, U^{238} and Th^{232} are to be obtained, the logging speed must consequently be lower. In practice, the log is usually run 2 to 3 time more slowly that the total gamma ray log. However, this results in very high quality *SGR* logs.

12.7   Vertical Resolution

The vertical resolution is often better than the total gamma ray tool as a consequence of the slower logging speeds. Resolutions as low as 1 foot have been obtained with some tools.

12.8   Borehole Quality

As with the total gamma ray log, the spectral tool can be run centered in the borehole or pushed up against the borehole wall (eccentred). If the borehole suffers from caving, the spectral gamma ray log can be badly affected in the same way as the total gamma ray tool, although the effect is not as bad for

the eccentred version. Correction charts for the spectral gamma ray tools are also supplied by the logging tool company for centred and eccentred configurations.

12.9   Mud Type

The density of the mud has a bearing on the detection rate, as a higher density mud absorbs the gamma rays more efficiently and reduces count rate. This is taken into account by the borehole correction, which is done for a given drilling mud density (mud weight). The worst effects are seen when barite mud is used, as barite is efficient at adsorbing gamma rays. Again, the eccentred version is less susceptible to mud weight.

The problem with KCl-based drilling mud is also apparent with the spectral tool. However, the effect of the KCl mud will only be apparent in the *SGR*, *CGR* and potassium logs. Again, the eccentred version is less susceptible to KCl mud.

12.10 Uses of the Spectral Gamma Ray Log

The spectral gamma ray log is an extremely useful log, especially for subtle lithological and compositional analysis, which benefits from its high vertical resolution. In the analysis of spectral gamma ray data, use is commonly made of the ratios of the abundances of the main radioactive sources. For example the Th/K ratio. It should be noted, however, that this is not a dimensionless ratio as the Th is measured in ppm and the K is measured in percent. Thus Th=12 ppm and K=4%, gives Th/K=3, where the units are usually not mentioned, but are actually parts per ten thousand (ppm/%).

12.10.1   Determination of Lithology

12.10.1.1   Discriminating between Sands, Shales and Accessory Minerals

It was seen in the discussion concerning the total gamma ray log that clean sands can sometimes produce high gamma ray readings which would confuse them with shales. Such sandstones include those containing feldspars, micas, glauconite, and heavy minerals including uranium-bearing ores. The extra information supplied by the spectral gamma ray tool can, in most cases, help recognize these situations, and calculate the amount of the particular radioactive minerals present.

Radioactive sandstones fall into one of six main groups, which are classified below, and may be recognized using Figs. 12.4 and 12.5.

Clay-Bearing Sandstones.   If clay minerals are known to be present in the rock, they may be identified using Fig. 12.5.

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/%), as shown in Fig. 12.4.

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 the sandstones also contains potassium in the form of feldspars, micas or glauconite. Typically Th/K values will be above 25 ppm/%, and U/K values will be above 20 ppm/%.
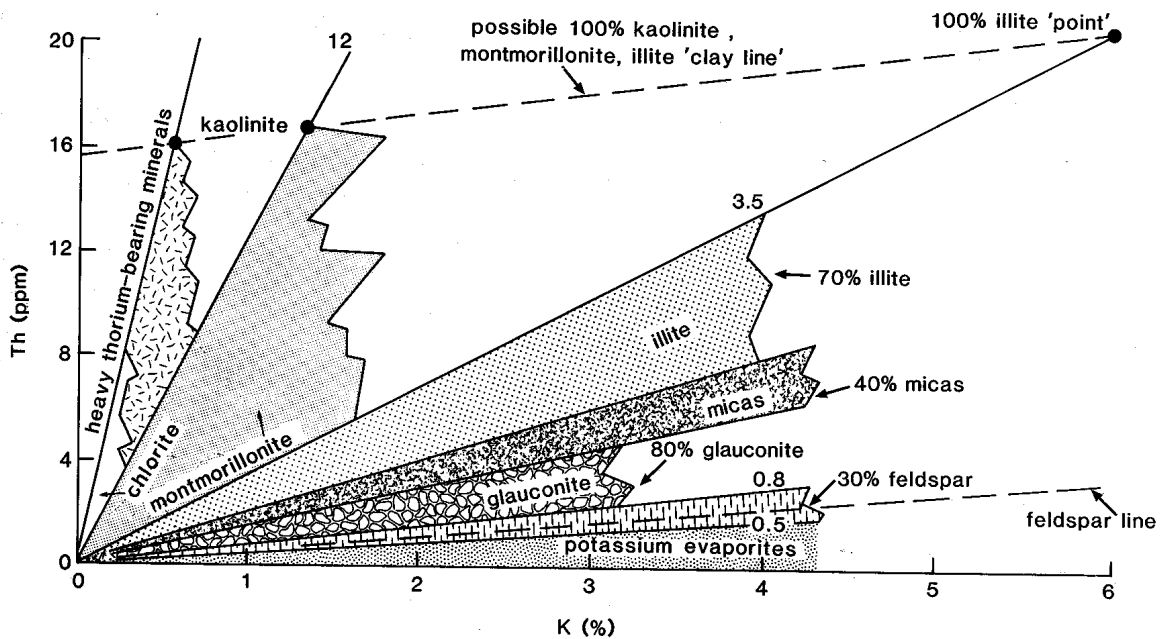
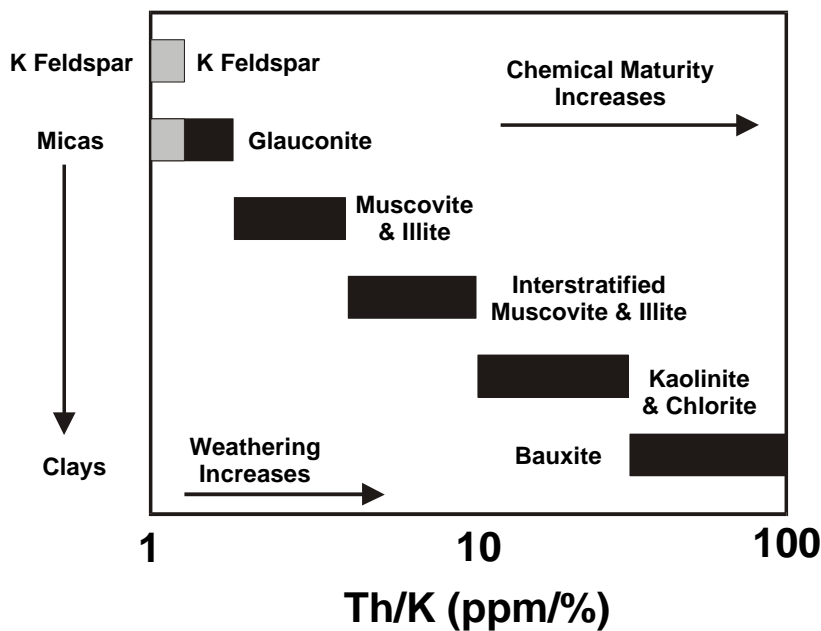**Figure 12.4** Thorium/potassium cross-plot for mineral identification using spectral gamma ray data.

Figure 12.5 Thorium/potassium ratio plot for mineral identification using spectral gamma ray data.

The fact that sands that do not contain clays are sometimes radioactive, as seen above, indicates that there will be occasions when the shale volume calculated from the total gamma ray log (*GR*) or the total gamma ray log from the spectral tool (*SGR*) will be misleading. However, we can calculate the shale volume from the individual readings of the spectral gamma ray log (K, Th, and U), and from the computed gamma ray log (*CGR*).

$$V_{sh}\big|_{CGR} = \frac{CGR - CGR_{\min}}{CGR_{\max} - CGR_{\min}} \tag{12.1}$$

$$V_{sh}\big|_{K} = \frac{K - K_{\min}}{K_{\max} - K_{\min}} \tag{12.2}$$

$$V_{sh}\big|_{Th} = \frac{Th - Th_{\min}}{Th_{\max} - Th_{\min}} \tag{12.3}$$

$$V_{sh}\big|_{U} = \frac{U - U_{\min}}{U_{\max} - U_{\min}} \tag{12.4}$$

Equations (12.1) to (12.3) are better shale indicators than Eq. (11.1), since the random contribution of U is eliminated. Equation (12.4), is almost never used.

12.10.1.2   Carbonate Formations

In pure carbonates, thorium will usually be absent because the common thorium ions are insoluble, and potassium will also be negligible. So we can say that, if the formation has very low Th and K abundances, the rock may be a pure carbonate. The rock, however, may contain uranium. Uranium usually indicates material of an organic origin as organisms are extremely good at concentrating and storing uranium. Uranium ions are either soluble or insoluble depending upon their oxidation state. Highly oxidized uranium ions, from oxidizing environments (such as deserts) are insoluble. Thus a carbonate, which also has low U abundance, comes from an oxidizing (maybe desert) environment. Conversely, non-oxidized uranium ions from sub-surface depositional environments are more soluble, and hence can be present in carbonates.

It should be noted that oxidizing environments are not conducive to the conservation of organic material, while reducing environments not only favour the conservation of organic material, they aid the conversion of the organic material to hydrocarbons. The source organic material for hydrocarbons in carbonate rocks is often algal mats that are incorporated in the deposited rocks in a sub-sea (reducing) environment and contain a significant amount of uranium.

In clay-bearing carbonate rocks high total gamma readings are not related only to the clay fraction, but are also due to the presence of uranium-radium series isotopes of organic origin. High total gamma ray readings are therefore not a reliable indicator of the shaliness of a carbonate. However, if the spectral gamma ray log indicates the presence of K and Th together with the U, it may be said that the K and Th contributions are associated with the clay content of the shaly carbonate, while the U is associated with some organic source which was deposited in a reducing environment that favours the

conservation of organic material. Similarly, high K and Th values together with low U indicates a shaly carbonate, deposited in an oxidizing environment which is not a favourable environment for the conservation of organic material.

Note that K and Th must be present **together** for a clay to be indicated. The presence of K and no Th (with or without U) is usually an indicator of the remains of algal mats in the carbonate, or of glauconite. Thus, when calculating the shaliness of a carbonate, it is better to use the *CGR* (Eq. 12.1) as in the case of sandstones in 12.10.1.1 above.

The actual values of K and Th in the shaly carbonate will depend upon the type of clay present, as shown in Fig. 12.4.

Note that isolated intervals of any combination of high U, K and Th in carbonate rocks may correspond to stylolites, which tend to concentrate uranium, organic matter, and clay minerals.

Table 12.1 shows the main interpretations of the spectral gamma ray data for carbonate rocks.

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.			

12.10.1.3   Evaporites

Large total gamma ray values are commonly associated with shales and certain types of potassium-bearing evaporite. We can discriminate between these because the potassium-bearing evaporites have much larger potassium abundances and zero thorium resulting from the insolubility of thorium ions in

water. Evaporites are deposited in oxidizing environments, so the uranium is usually also very low or zero. Some K-bearing evaporites are shown in Table 12.2.

Table 12.2 Potassium-bearing evaporites.

Name	Composition	K (wt%)	Density [FDC] (g/cm^3)	Pe [LFDC] (b/e)	Porosity [CNL] (%)	DT [Sonic] (ms/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

12.10.2   Unconformity Detection

The mean Th/K ratio of large intervals of formations is usually approximately constant. This is because it depends ultimately upon the depositional conditions. Hence any sudden changes in the mean Th/K ratio can act as an indicator of sudden change in depositional environment, such as at an unconformity.

12.10.3   Inter-well Correlation

Volcanic ashes (bentonitic intervals) are considered to be deposited at exactly the same time over a wide area. They can therefore be used to correlate between wells. Peaks in the thorium abundance log are generally considered the best signature in this correlation.

12.10.4   Recognition of Igneous Rocks

The values of Th and U from the spectral gamma ray log are used together with the density from the density log and the sonic wave travel time from the sonic log to identify and discriminate between igneous rocks. Most igneous rocks show a Th/U ratio close to 4, as shown in Fig. 12.6. The exception is syenite (Th/U=0.52). Note the progression from low values of both Th and U for ultramafic rocks to higher values as the rocks become more acidic, but with constant Th/U.

12.10.5   Diagenesis

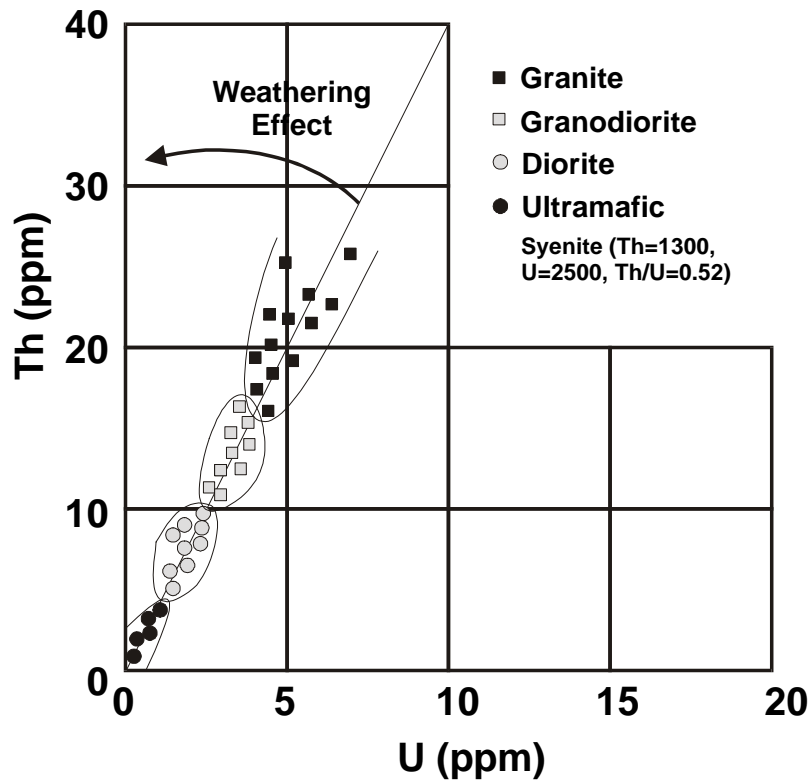Diagenesis is studied using the Th/K ratio derived from spectral gamma ray logs.

Figure 12.6 Thorium-Uranium cross-plot for igneous rocks. (Courtesy of Schlumberger).

12.10.6   *Sedimentology*

The spectral gamma ray log provides a large amount of data that can help discriminate between depositional environments and allow grain size and mineralogical composition to be constrained. Some of the more important sedimentologically relevant data are shown in Table 12.3.

Table 12.3 Sedimentological inferences from spectral gamma ray data.

SGR Observation	Sedimentological Inference
Presence of glauconite	Marine, mainly continental shelf origin.
Phosphatic deposits	Marine, mainly continental shelf origin, with warm water in a reducing environment.
Uranium	Low energy, reducing conditions
Clay type	Analysis of depositional environment.
Bauxite	Warm, humid, continental environment with good drainage.
Feldspars	Indicator of the degree of evolution of sand facies, only found in abundance close to the igneous source.

12.10.7   *Estimation of Uranium Potential*

Direct measurement of the amount of uranium present in the rocks, and its variation.

12.10.8   Cation Exchange Capacity

The cation exchange capacity of the rock may be calculated by knowing the type and quantity of clays present in the rock from spectral gamma ray data.

12.10.9   Radioactive Scaling

Unusually raised U contents are frequently observed in the perforated intervals of old wells due to the build-up of uranium salts.

12.10.10   Hydrocarbon Potential

Organic matter is good at concentrating uranium. If this is deposited in a reducing environment it can be preserved and transformed to hydrocarbons. Hence, there is a correlation between the presence of uranium and hydrocarbons. It is possible to evaluate the total organic carbon content of rocks from the uranium content derived from the spectral gamma ray log providing the relationship is calibrated using core data. The hydrocarbon potential of the rock may then be derived from the total organic carbon content.

12.10.11   Fracture Detection

Uranium is soluble in reducing conditions. Dissolved uranium salts may then be precipitated along fractures, causing local peaks in the uranium spectral gamma ray log. However, local uranium peaks do not unambiguously indicate fractures, so their presence must be checked on image logs.

12.10.12   Stylolite Detection

Stylolites concentrate clay minerals, organic matter and uranium, and can be compacted into thin bands which show up as thin peaks in the uranium spectral gamma ray log.

12.10.13   Phosphate Detection

Uranium is also associated with phosphates, which are encountered with evaporites.