Applications of Natural Gamma Ray Spectrometry Tool for Petrophysical Analysis of Hydrocarbon Reservoir in Oil & Gas Industry

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Abstract: Gamma ray tool used for petrophysical analysis in Oil & Gas industry is for natural radioactivity in rocks in subsurface. Potassium (^{40}K), uranium (^{236}U) and thorium (^{232}Th) are three decay series of isotopes are abundant in rocks and are detected by Natural Gamma Ray Spectrometry (NGS) tool. Potassium, thorium and uranium spectra of Gamma ray is obtained by NGS tool with NaI crystal of photo multiplier tube. NGS tool has five windows for counting the gamma rays of low energy and high energy level. Tool has a master calibration in Clamart (France). Secondary calibrators are used to check the operation of the tool and its stability. Natural Gamma Ray Spectrometry measures the contribution of gamma ray of each individual series of Thorium, Uranium and Potassium separately. Also, it measures concentration of Thorium and Uranium in ppm and potassium in percentage in any rock. Applications of NGS are many folds. This is very good shale indicator. Also, it differentiates between shale and potassium salts (Evaporites) with help of cross plots of K% versus bulk density, neutron porosity and sonic transit time. From the ratio of Th/K obtained from NGS tool against rocks, it distinguishes feldspathic sandstone, micaceous sandstone or quartzite sandstone. Feldspar contain high potassium and low thorium as a result Th/K ratio is very low against Feldspathic sandstone whereas the ratio is high in Micaceous sandstone due to high thorium in mica and low potassium. NGS tool play an important role to find the origin of carbonate either in pure chemical origin or organic by measuring the uranium. Low uranium indicates it is of chemical origin whereas rich content of uranium in carbonate indicates it is reducing environment and of organic origin. NGS also shows Th/K ratio abruptly high in case of unconformities. It is possible to find the organic content from measurement of uranium and from that its hydrocarbon potential in source rock after proper calibration with core data.

Key words: Shale and Evaporite, Carbonate series, Th/K ratio, Unconformity, Organic matter and Uranium concentration,

1. INTRODUCTION

Two types of Gamma ray tool are available in Oil industry. One is conventional Gamma ray tool and other is Natural Gamma ray Spectrometry (NGS). Conventional Gamma ray tool measures the total gamma ray but could not recognize the contribution of gamma ray of individual series of potassium, thorium and uranium separately. This is the ambiguity of normal Gamma Ray tool. This ambiguity is removed by Natural Gamma Ray Spectrometry (NGS) tool. It measures the contribution of gamma ray of each individual series of isotopes. Also, it measures concentration of Thorium and Uranium in ppm and potassium in percentage in any rock.

NGS tool in well logging industry is known as Lithology tool and it has many applications in petroleum industry**.** It identifies evaporating minerals and distinguishes it from shale as evaporating minerals contain more concentration of potassium than that of shale. NGS also identify type of sandstone whether it is feldspathic, micaceous or mixed. Detection of unconformities by NGS tool is another advantage for exploration of hydrocarbon. Depositional environment of Carbonate rock origin either in organic or inorganic and its source rock finding after measuring the percentage of organic matter through uranium concentration by NGS tool is another milestone in exploration business of oil industry.

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2. ORIGIN OF NATURAL RADIOACTIVITY IN ROCKS AND GAMMA RAY EMISSION SPECTRA

The isotopes of short life time disappear long ago but there are some radio isotopes in rocks having a sufficient long life and they disintegrate GR which have discrete energy levels. Potassium (^{40}K) is an isotope (half-life is 1.3 x 10^9 years) which is abundant in sedimentary rocks of Shale and Evaporites. Uranium (^{238}U) is another isotope (half-life is 4.4 x 10^9 years) found in sandstone and specially in organic Limestone. Thorium (^{232}Th) isotope (half-life is1.4 x 10^9 years) is found in monazite sand. Due to geological processes this natural radioactive isotopes are abundant in rocks within the earth's crust.

Potassium ^{40}K disintegrate to give Argon ^{40}A which is stable after emitting Gamma radiation of energy single spectrum of 1.46 Mev (figure 1). For Uranium and Thorium series, the process is more complex which gives a series of isotope some of which are gamma ray emitters. Thorium – 232 and Uranium – 238 decay series are not discussed here.

The conventional gamma ray tool lowered in borehole for petrophysical analysis is having limited option. The natural gamma radiation (counts per second or in API unit) from rocks below the surface is combination of total radiated gamma ray emitted from K ^{40}, Th ^{232} & U ^{238} series. The disadvantage of conventional gamma ray tool is that it cannot detect separately Gamma ray counts from each individual series of Potassium, Uranium and Thorium. Also, it is not able to quantify the presence of individual quantity of potassium, thorium and uranium in rocks. These demerits of conventional Gamma radiation tool are removed by 'Natural Gamma Ray Spectrometry' tool which can identify Gamma radiations from each of three decay series and quantify the amount of Thorium (Th) & Uranium (U) in ppm (parts per million) and potassium (K) in percentage within the rock below surface at any depth within a borehole.

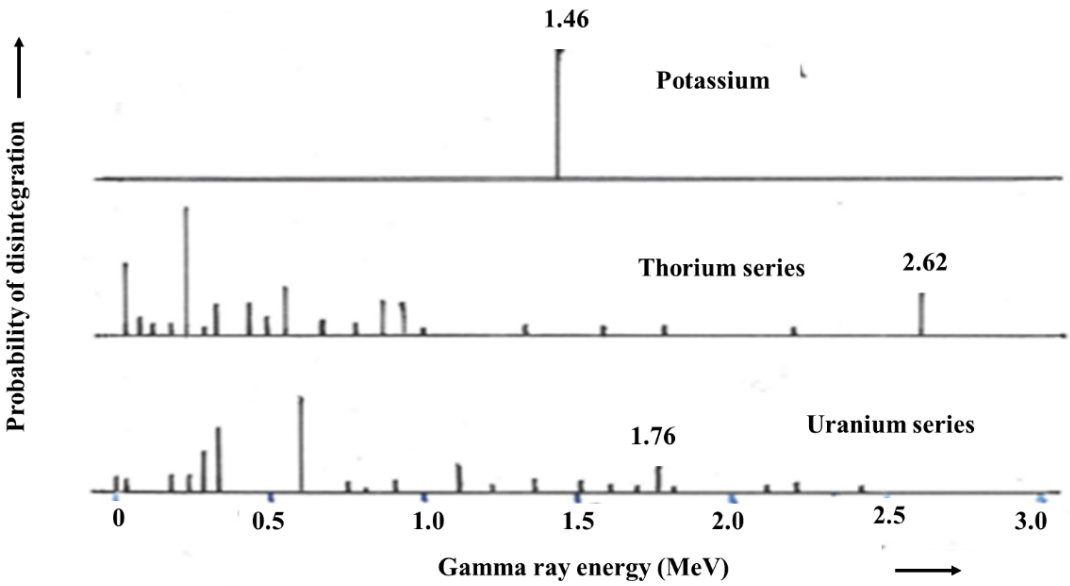

Figure 1: Gamma Ray emission Spectra of three Radioactive decay series (courtesy of Schlumberger)

Figure1 is showing the discrete energy level of gamma ray radiated. K^{40} is having single gamma radiated by 1.46 MeV from Ar ^{40} isotope. Th ^{232} is characterized by so many gamma radiations from their decay products in which Thallium (^{208}TI) emits GR whose energy is 2.62 MeV. U^{232} is another decay series of uranium in which Bismuth (^{214} Bi) emits GR at 1.76 MeV.

The detector has an intrinsic resolution broadening the picks. The observed continuous spectrum is shown in figure 2. The amplitudes of the three spectra will depend on radioactive components present so that a quantitative evaluation of Th, U and K can be found out. In the spectrum there are two regions:

1. High energy region – it is concerned with picks of 2.62 MeV from thorium series, 1.76 MeV energy level from Uranium decay series and 1.46 MeV from Potassium.
2. Low energy region – it is the concerned with of pair production and Compton scattering in the rock itself plus lower energy GR radiation from 2 decay family namely Thorium and Uranium decay series.

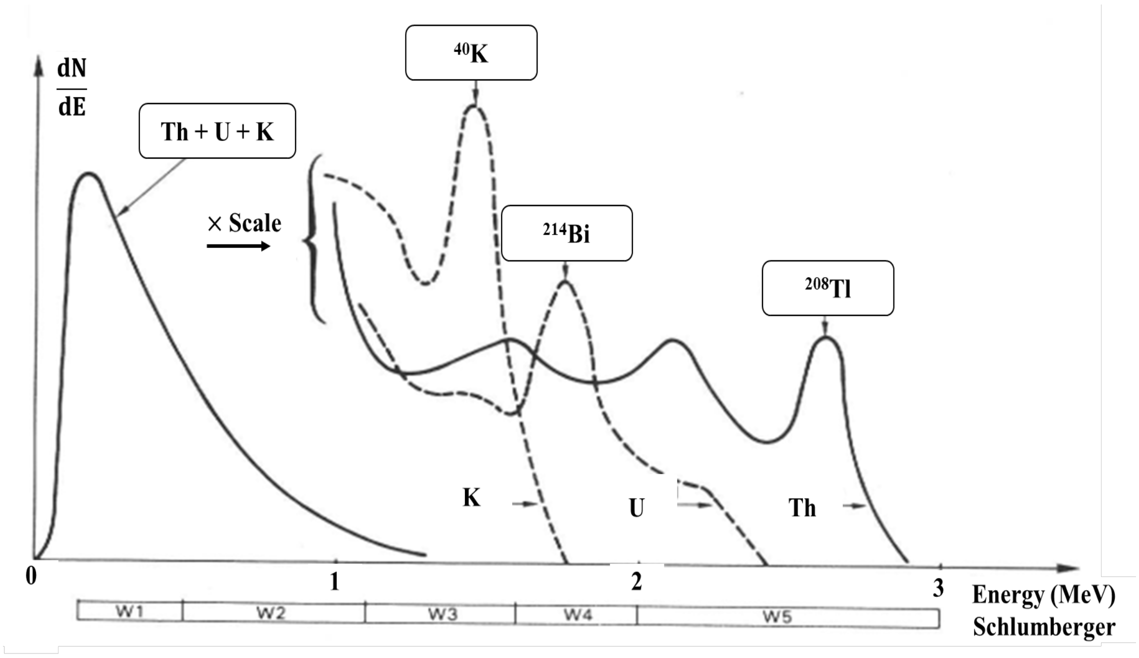

Figure 2: Potassium, Thorium and Uranium response curve with the NaI crystal detector position of the windows. (from Serra et al,1980)

3. EVAPORATING ENVIRONMENT

Evaporite minerals and shales both contain potassium. But there is a distinct difference between them. Evaporites has much higher concentration of potassium than that of clay minerals in shales. No thorium content in evaporite as thorium is insoluble (Clark, S.P., Peterman, Z.E. and Heier, K.S 1966). Therefore, against Evaporites, Th-curve would be flat or almost zero while K-curve has higher percentage of Potassium and Uranium curve is nearly zero. Against shale K-curve would be high but not so high as observed in Evaporite minerals. Figure 3 is well log data of NGS -Litho Density -Neutron porosity of well X of ONGC, India. NGS shows a very good distinguishable of Shale and Evaporite.

Figure 3 shows that the depth interval of log motif from 4045- 4048 feet, Gamma Ray (GR) curve in the first track is nearly 60 API, Thorium (Th) and Uranium (U) in 2nd track are 4 and 2 ppm respectively and Potassium(K) in 2nd track is 2% whereas in depth interval 4063- 4065 ft, the GR-curve is showing 165 API, Th is 2ppm, U is nearly zero and K > 10% which gives an indication of evaporite mineral. From log data and cutting samples while drilling in a well X of ONGC, India tells us that the interval 4045-4048 feet is shale whereas the interval 4063 -4065feet is Potassium salts (Sylvite). Due to presence of high content of potassium in the interval 4063-4065 feet, Gamma ray is showing high.

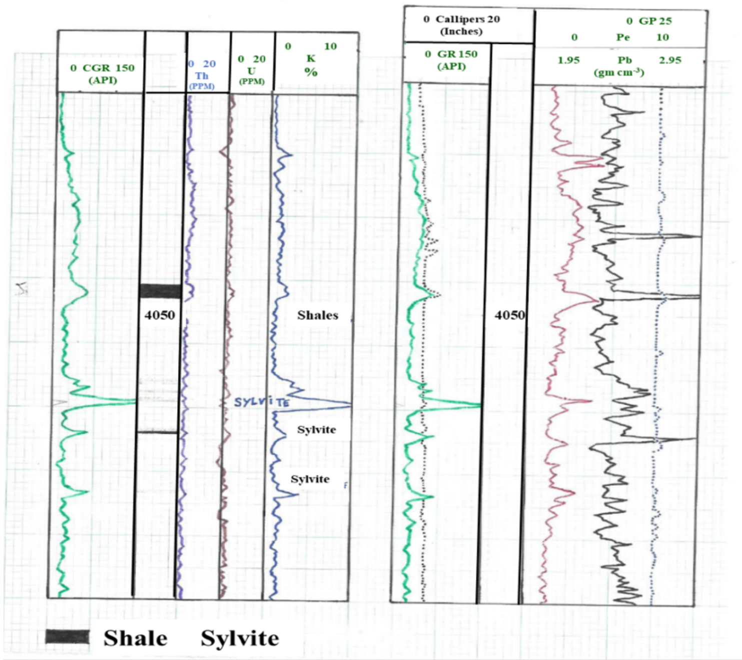

Figure 3 shows NGS response in an evaporitic interval of well X of ONGC well, India

Table 1: showing different types of Potassium minerals of Evaporites obtained by courtesy of Schlumberger.

NAME	COMPOSITION	K (% wt)	P_b (g/cm^3)	P_e (b/e)	Φ_n (%)	Δt (μs/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, $(H_2O)_3$	15.7	2.12	3.5	> 60	
Carnallite	$MgCl_2$, KCl, $(H_2O)^6$	14.07	1.57	4.09	> 60	83
Polyhalite	K_2SO_4, $MgSO_4$, $(CaSO_4)$, $(H_2O)_2$	13.37	2.79	4.32	25	5.75
Glaserite	$(KNa)_2$, SO_4	24.7	2.7			

K- Potassium, P_b - Bulk density, P_e - Photo electric coefficient, Φ_n - Neutron Porosity, Δt - Sonic transit time.

Table1 is showing different types of evaporite minerals with K (% wt). If these evaporites are sufficiently thick beds, K-curve in NGS log will be nearly exact values as shown in the Table 1.

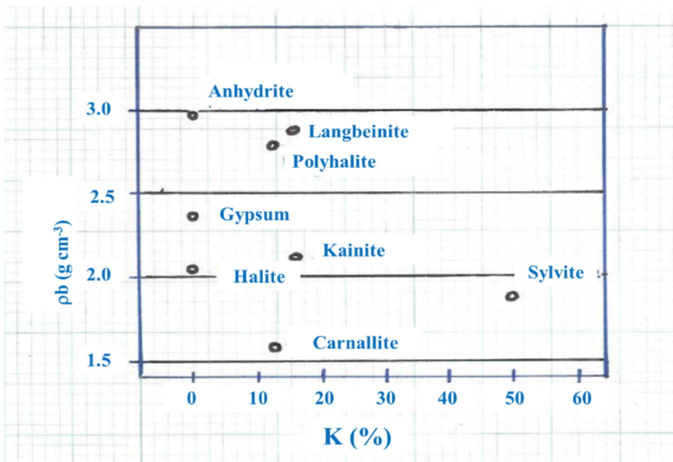

Figure 4.a: Cross plot technique of Potassium (K) versus Bulk density (ρb) to determine evaporite minerals

Otherwise, we should run NGS tool with Litho Density (P_b), Neutron porosity (Φ_n) and Sonic (ΔT) for detection of evaporites. Cross plot between P_b versus K%, Φ_n versus K% and Δt versus K% are sufficient to distinguish the type of evaporate. (Figure 4a, b, c).

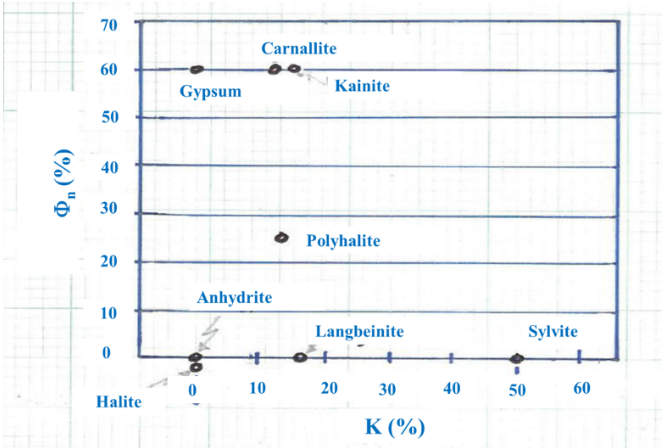

Figure 4 b: Cross plot technique of Potassium (K) versus Neutron porosity (φ_n) to determine evaporite minerals

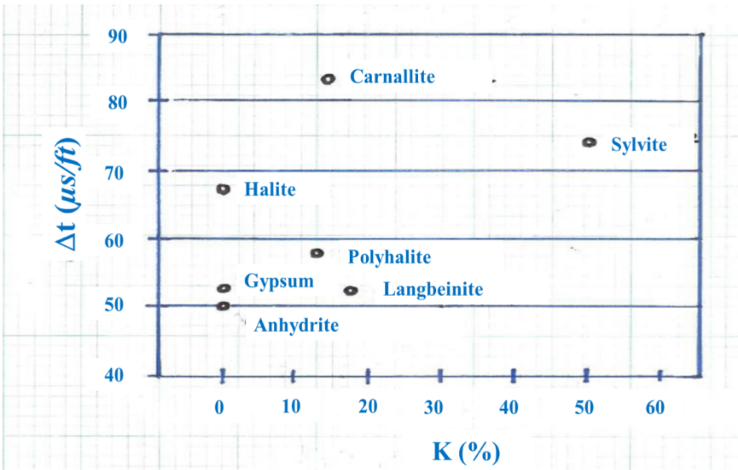

Figure 4.c: Cross plot technique of Potassium (K) versus Sonic Transit Time (DT) to determine evaporite minerals.

4. SAND SHALE SERIES/CARBONATE SHALE SERIES

Pure sandstone for log analysis is considered to be quartz in which clay minerals percentage is less than 5% as a result presence of Potassium (K), Thorium (TH) and Uranium (U) in pure sandstone are very low due to which gamma ray activity in pure sandstone is very low. From GR curve against sandstone showing very low, it is considered to be that grains presence in sandstone are coarse grains sizes and they are well sorted, chemically and texturally matured of detrial origin. On the other hand, pure shales are just opposite in which GR activity is high. NGS tool identifies that GR activity in shale is high due to presence of high concentration of Potassium as clay minerals are present in shale. But sometimes it is observed that sandstone also shows high radioactivity of GR. From depositional environment of sedimentology, it is observed that some clay minerals are also present in sandstone and log analysist called them Shaly-sand. Feldspathic sandstone or Micaceous sandstone also contain good amount of Potassium minerals due to which radioactivity of GR exist in those types of sandstone. Also, monazite sandstone found in beach area are having thorium minerals which shows high GR activity. NGS tool specifically identified Thorium and Uranium in ppm and Potassium in percentage and therefore, are able to identify the origin of radioactivity from which it is easier to interpret the lithological analysis.

From ordinary GR tool, volume of shalyness or shale indicator is as follows:

$$(V_{sh})_{GR} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}} \times 100 \quad (1)$$

But this shale indicator could not speak about the individual presence of Uranium, thorium or Potassium and therefore, it was difficult task to interpret the lithology. But now good shale indicators obtained from NGS tool are as follows:

$$(V_{sh})_{Th} = \frac{Th - Th_{min}}{Th_{sh} - Th_{min}} \quad (2)$$

$$(V_{sh})_{K} = \frac{K - K_{min}}{K_{sh} - K_{min}} \quad (3)$$

$$(V_{sh})_{CGR} = \frac{CGR - CGR_{min}}{CGR_{sh} - CGR_{min}} \qquad \text{[CGR is combination of Th and K]} \quad (4)$$

It is clear that $(V_{sh})_{Th}$, $(V_{sh})_{K}$, $(V_{sh})_{CGR}$ are good Shale indicator because now individual Th, U, and K can be obtained from which we can interpret lithology.

4.1 Carbonate - Shale Series

Figure 5 presents the NGS log data of a well Y, India which display the three curves. Blue continuous curve is the counts of Gamma rays radiated from Thorium series, black dash line curve is the Gamma ray counts radiated from combination of the Thorium and Potassium series and the pink continuous curve represents the total Gamma ray counts radiated from combination of Thorium, Uranium and Potassium. The intervals marked in figure 5 are shales and dolomites. Against shale it is observed that potassium is very high due to presence of clay minerals in shales whereas Uranium is very low. Against Dolomite bed, it is observed that Uranium is very high and Potassium is low. Uranium high may be due to organic carbon or presence of phosphatic minerals.

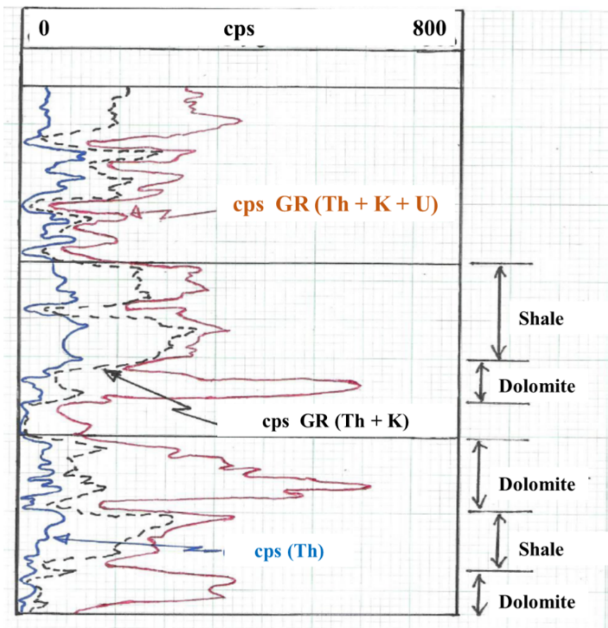

Figure 5: Formation response due to Thorium, Thorium & Potassium, Thorium-Potassium-Uranium of NGS data of well Y, India

4.2 Sand Shale series

Table 2 showing potassium bearing minerals in sand-shale series

Name		Chemical Formula	K content (% weight)
○ FELDSPARS			
	Microcline	$KALSi_3\,O_8$	16 to 11
Alkali	Orthoclase	$KALSi_3\,O_8$	14 to 12
	Anorthoclase	$(Na,K)\,ALSi_3\,O_8$	
○ MICAS			
Muscovite		$KAL_2(ALSi_3\,O_{10})\,(OH,F)_2$	10 to 8
Biotite		$K(Mg,Fe)_3(ALSi_3\,O_{10})\,(OH,F)_2$	6 – 10
Illite		$K_{1-1.5}Al_4\,(Si_{7-6.5}\,AL_{1-1.5})O_{20}\,(OH)_4$	3.5 – 8
Glauconite		$K_2(Mg,Fe)_2AL_6(Si_4O_{10})_3(OH)_{12}$	3.2 – 5.8
Phlogopite		$KMg_3(ALSi_3O_{10})(F,OH)_2$	6.2 – 10
○ FELDSPATHOIDS			
Metasilicates	Leucite	$KAL\,(SiO_3)_2$	17.9
Orthosilicates	Nephelite	$(Na,K)\,ALSiO_4$	4 to 8
○ OTHER CLAY MINERALS*			
Montmorillonite			0 –4.9
Chlorite			0 – 0.35
Kaolinite			**0 – 0.6**

4.2.1 Feldspathic Sand stone

If sandstone contains minerals of microcline, orthoclase, Anorthoclase in certain percentages which are Feldspathic minerals (Table 2), then this type of sandstone is called Feldspathic Sandstone. Feldspathic sandstone can be distinguished from the ratio of Th/K (Figure 6 and table 2). As Potassium is very high in feldspar and Thorium is low, the ratio of Th/K is very low in the order of $1x10^{-4}$ as shown in figure 6.

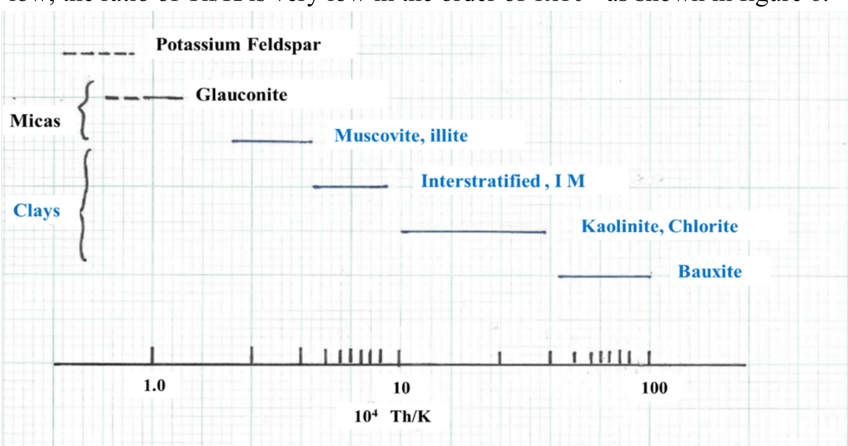

Figure 6: Mineralogical identification by the Th/K ratio given by NGS tool (from Hassan & Hossin, 1975)

4.2.2 Micaceous Sandstone

Micas contain potassium and percentage of K in potassium bearing minerals in Micaceous sandstone is comparatively lower than Feldspathic sandstone as shown in table 2. Th content in micas is higher as a result Th/K ratio is higher in Micaceous sandstone than in comparison to Feldspathic sandstone and it is in the order of 2.5x 10^{-4} shown in figure 6.

5. CARBONATE SERIES

Two types of carbonate rock are found in sedimentary rocks. One is chemical origin and other is organic.

Chemical origin of carbonate: If carbonate is of chemical origin, then thorium could not be present in carbonate because thorium is insoluble. If NGS log shows that Thorium is flat and nearly zero, and also potassium is flat, then this carbonate is pure carbonate. Also, if NGS log shows that it is Uranium free, then it is considered that pure carbonate is precipitated in oxidizing environment and therefore it is of chemical origin.

Organic origin of carbonate and source rock: If NGS shows that uranium is having variable percentages against carbonate rock, it indicates that carbonate is deposited in reducing environment favorable to organic matter and therefore, this carbonate is of organic origin and chance of organic matter converted into Kerogen and later under pressure and temperature transformed into hydrocarbon. If Th and K are present with U, this indicates the presence of Clay in the carbonate rock. So, carbonate as a source rock can be found out from NGS log data and also the depositional environment can be found out. Figure 7 is NGS log motif of well A, India showing radioactivity of GR is due to mainly presence of uranium in carbonate series. Through the interval, Thorium and Potassium are flat or nearly zero, but uranium in ppm is very high above 90 mts in carbonate series. CGR is counts of GR radiated from Thorium & Potassium series.

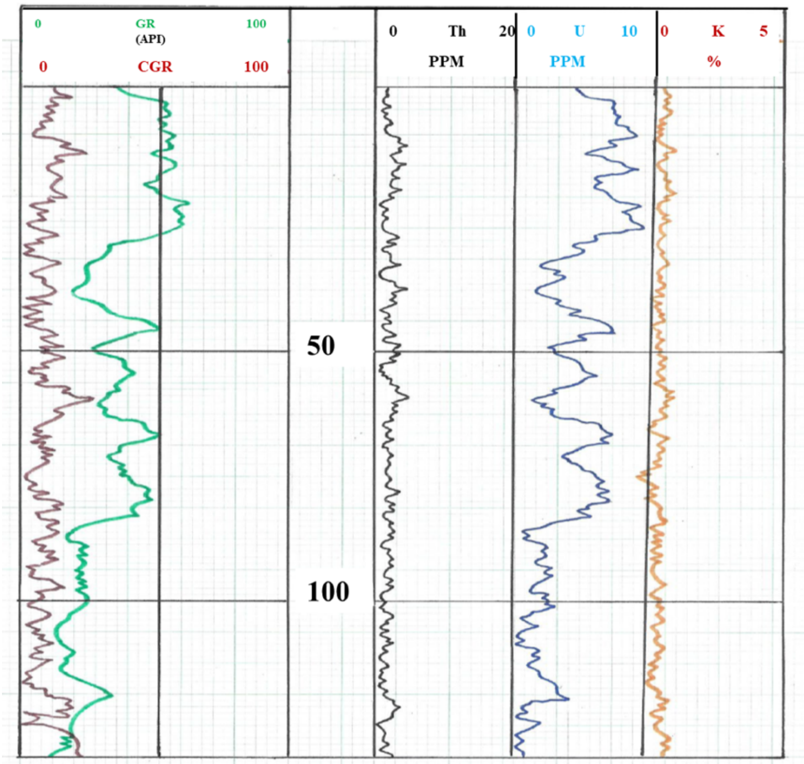

Figure 7: NGS in Carbonate series showing that radioactivity is mainly due to Uranium of well A, India

6. NGS LOG HELPS TO IDENTIFY UNCONFORMITIES

Conventional logs like resistivity, SP, Density, Neutron porosity and Sonic could not identify the unconformities as shown in figure 8. Micro resistivity image tool can alone identify unconformities from its dip direction which changes abruptly. But this tool is very costly. NGS tool can identify easily if Th/K ratio log is carried out. There is a abrupt changes of Th/K ratio against unconformities. Figure 8 is the log motif of well Z, India showing that the interval below 3900 m is unconformities as ratio of Th/K is abruptly high below the interval 3900m.

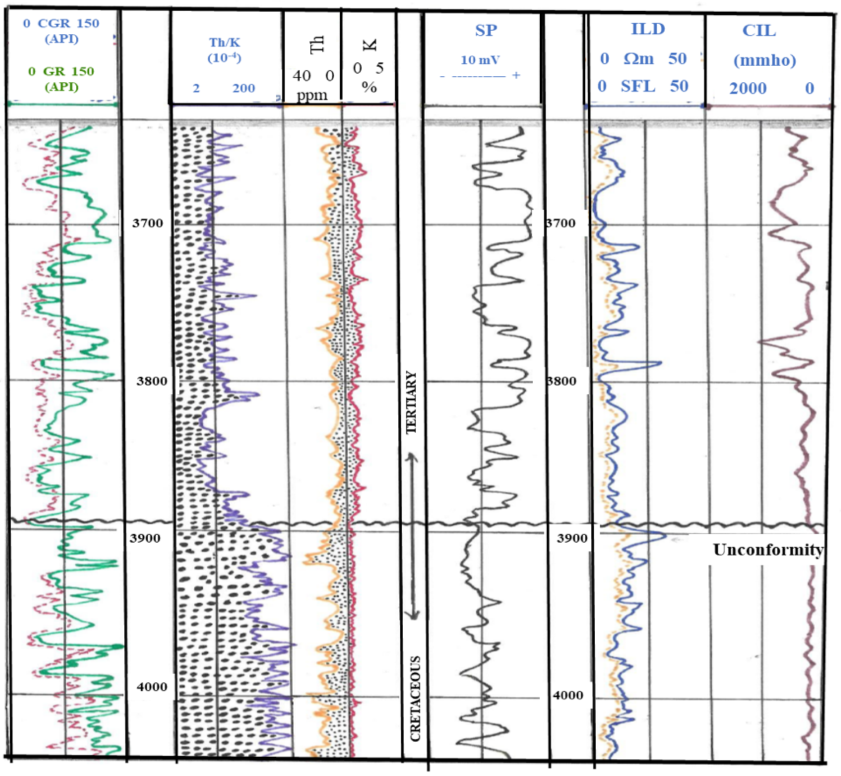

Figure 8 Unconformity identified by NGS tool and not seen by other logs of well Z, India

7. HYDROCARBON POTENTIAL

It is observed that there is a relation between organic matter and Uranium content. If we do calibration with core sample, then estimation of organic matter content of source rock from its uranium content and from that Hydrocarbon potential can be found out (Figure 9 A and 9 B).

Point a in both figure 9 A and 9 B is on the line of 75 percent Humic, 25 percent Sapropelic. From the coordinate of **point a** in figure 9 A, it indicates that total organic matter is 25% and Uranium is 0.0064 %. The same **point a** in figure 9 B yields 7.0 gallons oil per ton.

Point b in both figure 9 A and 9 B is on the line of 25 percent Humic, 75 percent Sapropelic. From the coordinate of **point b** in figure 9 A, it indicates that total organic matter is 25% and Uranium is 0.0027 %. The same **point b** in figure 9 B yields 12.3 gallons oil per ton.

Point c in both figure 9 A and 9 B is on the line of 50 percent Humic, 50 percent Sapropelic. From the coordinate of **point c** in figure 9 A, it indicates that total organic matter is 20% and Uranium is 0.0036 %. The same **point c** in figure 9B yields 7.6 gallons oil per ton.

Point c/ in both figure 9 A and 9 B is on the line of 50 percent Humic, 50 percent Sapropelic. From the coordinate of **point c/** in figure 9 A, it indicates that total organic matter is 30% and Uranium is 0.0055 %. The same **point c/** in figure 9 B yields 11.6 gallons oil per ton.

From the above graphs mentioned in Figure 9 A and 9B we can infer as follows:

1. Uranium percent increases with increase of total organic matter.
2. Oil yield also increases with increase of total organic matter.
3. Uranium percent is high if Humic in percentage is more than Sapropelic in total organic matter.
4. Oil yield is high if Sapropelic in percentage is more than Humic in total organic matter.

From the above discussion, it can be said that uranium content from NGS log can evaluate the total organic matter of the source rock and from those yields of hydrocarbon and its potential.

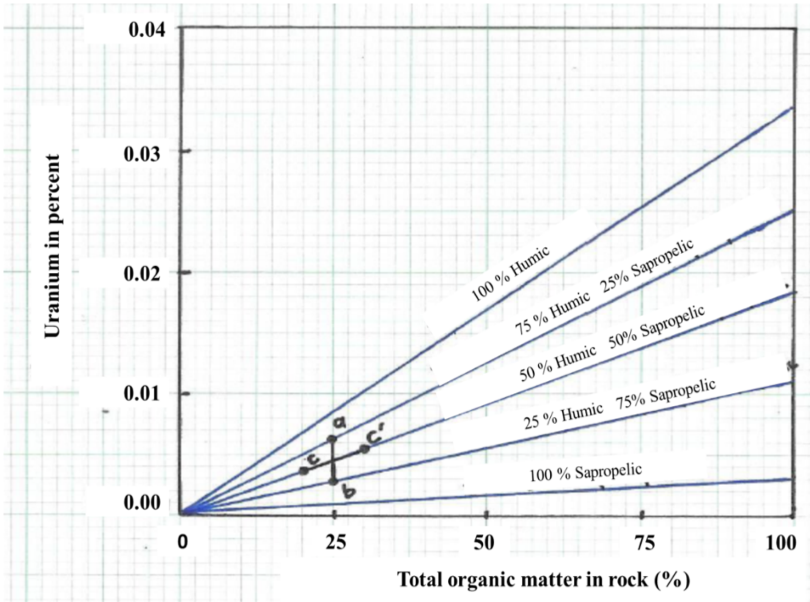

Figure 9 A: Uranium percent versus total organic matter of a black marine shale which contains organic matter in proportions of Humic and Sapropelic material (from Swanson,1960)

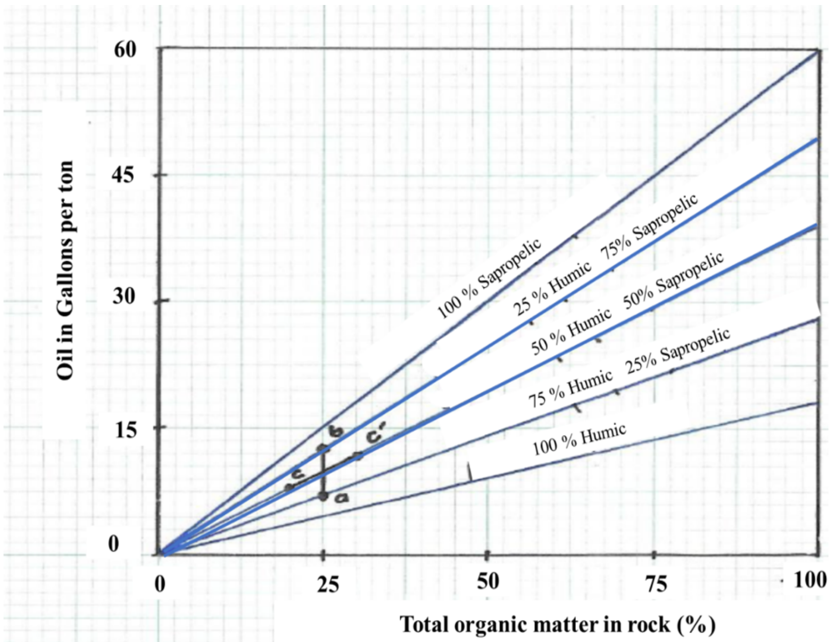

Figure 9 B: Oil yield versus total organic matter in percent of a black marine shale which contains organic matter in proportions of Humic and Sapropelic material (from Swanson 1960)

8. DISCUSSION AND CONCLUSIONS

Gamma ray high in geological bed does not mean that it is shale. The log data in Figure 5 shows that in Dolomite bed Uranium is high, Potassium is low. Uranium in dolomite bed is high due to presence of organic carbon or phosphatic minerals. Also, it is observed that Uranium is flat or nearly zero and potassium is very high in shale bed. Thus NGS is able to distinguish reservoir and non-reservoir rock.

NGS distinguishes between shale and potassium salts (Evaporites). Both of them contain potassium but in evaporites, potassium percentage are very high. Cross plots of bulk density (ρ_b) versus K%, Neutron porosity (Φ_n) versus K% and Sonic transit time (DT) versus K% are sufficient to identify the potassium salts (Figure 4a, 4b and 4c).

Log data of well Z of India is obtained as Induction log deep/Spontaneous Potential /Thorium/Potassium/ CGR/Total Gamma ray within certain interval. These petrophysical data are not able to find unconformity. But when we have plotted Th/K ratio in a particular track, it is observed that the ratio of Th/K is abruptly high below the depth of 3900 m which indicates that depth interval below 3900 m is a zone of Unconformity (Figure 8). Therefore, NGS plays an important role to identify the unconformity which is very cost effective as NGS tool is comparatively cheaper than Dip Meter tool such as Micro Resistivity Imager tool which shows sudden change of dip magnitude and dip azimuth of geological beds called Unconformity.

Core sample of source rock is obtained from black marine shale of one well. Calibration of core sample was carried out with uranium content and organic matter and from that hydrocarbon yield are obtained. It was found that oil yield is high if Sapropelic in percentage is more than Humic in total organic matter (Figure 9). This calibration of core sample can be used to find organic matter from uranium content obtained from NGS log and in turn oil yield of source rock.

Mineralogical identification within the rock is not obtained from conventional logging tools. But NGS plays a very important role for identify mineralogy of rocks. If the reservoir is sandstone, it can be understood from conventional tools but whether it is Feldspathic, Micaceous or quartzite that cannot be distinguished by logging tools except NGS. Th/K ratio obtained from NGS are used to identify lithology. As feldspar contains more potassium and very less thorium, so, the ratio of Th/K is very low indicating it is Feldspathic sandstone. In Micaceous sand, Potassium is low and thorium is comparatively high as a result Th/K ratio is high indicating that it is Micaceous sand (Figure 6).

Origin of Carbonate rock either it is pure chemical origin or organic, could not be found out from any logging tools except NGS. NGS tool has an application in sedimentology. Depositional environment of carbonate rock could be understood from uranium measurement. Free of uranium or very low percentage of uranium found in carbonate indicates oxidizing environment and therefore, carbonate is of pure chemical origin. If uranium found in carbonate is rich, it indicates deposition of carbonate in reducing environment and so carbonate is organic origin.

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REFERENCES

Clark, S.P., Peterman, Z.E. and Heir, K.S. (1966), Abundances of Uranium, Thorium and Potassium, Geological Society of America Memoirs, 97, 521-542.

Hassan, M., A. Hossin, and A. Combaz (1976), Fundamentals of differential gamma ray log interpretation technique, SPWLA (Society of Petrophysics and Well Log Analysis), Denver.

O. Serra., J. Baldwin., and J. Quirein (1980) Theory, Interpretation and practical application of Natural Gamma Ray Spectroscopy, SPWLA, 21st Annual Logging Symposium, Lafayette, Louisiana, July 1980.

Schlumberger (1982), Natural Gamma Ray Spectrometry: Essentials of N.G.S interpretation, Schlumberger Asia Services Limited (SASL) , 49 pages.

Swanson, V.E., 1960, Oil yield and uranium content of black shales, U.S. Geological Survey Professional paper 356-A, p. 1-44.