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In-situ delineation of uranium and thorium zones in boreholes using Spectral Gamma Ray Logging - A case study from Singhbhum Shear Zone, Jharkhand

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The paper presents a study on applying spectral gamma-ray logging of boreholes for uranium exploration in Singhbhum Shear Zone (SSZ), Jharkhand, India. It aims to demonstrate the effectiveness and reliability of spectral gamma-ray logging in delineating uranium and thorium bearing formations in subsurface environments. Field data collected from uranium exploration sites is analyzed and validated with laboratory measurements to demonstrate the utility of the spectral logging system. The findings showcase the potential of spectral gamma ray logging as a cost-effective and efficient technique for successfully delineating subsurface uranium and thorium zones in uranium exploration.

Keywords: Singhbhumshear zone, Spectral gamma-ray logging (SGRL), Uranium, Thorium, Spectrometry, eU_3O_8, ThO_2, $Ra(eU_3O_8)$ and K

1 Introduction

Radioactivity in rocks can be attributed to naturally occurring radioisotopes of uranium, thorium and potassium. In the uranium exploration program, the most common technique used for sub-surface identification of radioactive zones is based on gross gamma-ray logging[1]. Although it is a robust and fast method, it has an inherent assumption that the uranium present in the borehole is in a state of equilibrium with all the daughter elements in its decay chain and thorium is negligible. In any geological setup, the uranium series may be out of equilibrium with its daughters apart from the presence of thorium. Moreover, gross gamma-ray logging will not give any information about the presence of any radioisotope. Therefore, it is necessary to carry out gamma-ray spectrometric analysis of the core samples from the borehole to estimate the concentration of radioactive elements, e.g., eU_3O_8, ThO_2, $Ra(eU_3O_8)$ and K. Gamma-ray spectrometry of core samples involves several steps, e.g., sampling of core, splitting, crushing, powdering and final sample preparation involving coning and quartering[2].

These difficulties can be overcome by carrying out spectral gamma-ray logging (SGRL) of the boreholes. Jegannathan *et al.* have demonstrated the utility of SGR in Pakkanadu area of Tamil Nadu using NaI(Tl) detector[3]. CsI(Tl) detector provides a higher counting efficiency with a smaller detector size, counting time can be considerably reduced. SGR logging is based on discriminating energies of the gamma-rays. It identifies the uranium and thorium concentrated zones in the borehole *in-situ,* thereby reducing the number of samples that require either a radiometric or chemical analysis. In new exploration areas, non-coring boreholes [Down the Hole (DTH)] are drilled to establish the uranium potential. No cores are available in such cases; therefore, SGRL of boreholes is essential.

In the present study, SGRL is carried out in some boreholes of Singhbhum Shear Zone, Jharkhand. The results reflect that it is possible to discriminate between the uranium and thorium concentrated zones. The results obtained with SGRL are well correlated with the results of sample analysis using gamma-ray spectrometry analysis. This study aims to establish that SGRL technique can play an effective role in pacing up the uranium exploration program.

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2 Study Area

Singhbhum Shear Zone (SSZ), located primarily in the state of Jharkhand, is a prominent geological setup, located in the eastern part of India. It extends over nearly 180 km and is known for its complex geological history and significant mineral deposits, particularly uranium. It is characterized by a series of parallel to sub-parallel zones along which intense shearing and deformation have occurred.

The rocks within the SSZ consist mainly of granite gneisses, migmatites, schists, and meta volcanic rocks. These rocks have undergone extensive metamorphism and deformation, exhibiting distinctive textures and mineral compositions. SSZ is known as the major uranium province of India, which occurs primarily within meta sedimentary rocks such as quartzites, phyllites and associated granitic intrusions. Uranium mineralization in SSZ is thought to be due to hydrothermal processes, which have evolved during various stages of geological evolution[4]. These hydrothermal fluids, enriched in uranium and other elements, migrated through fractures and faults within the shear zone, precipitating uranium minerals in suitable host rocks. Uranium minerals in SSZ include uraninite (UO_2), pitchblende, coffinite, and brannerite. These minerals often occur as disseminations, vein fillings or within fracture zones. Extensive exploration for uranium in SSZ has led to the establishment of several working mines that supply uranium to India's Nuclear Power Programme. In addition, SSZ has vast potential to host many more uranium deposits.

3 Spectral Gamma Ray Logging (SGRL) in Uranium Prospecting

SGRL plays a vital role in uranium prospecting because it provides valuable information about the presence and distribution of uranium and thorium bearing formations in subsurface environments. It is a specialized geophysical method that utilizes gamma-ray spectroscopy to estimate the subsurface concentration of eU_3O_8, ThO_2, $Ra(eU_3O_8)$ and K based on the intensities of gamma-rays emitted by elements of the uranium, the thorium series and (^{40}K)[5]. These measurements aid in characterizing the geological formations being explored. By carrying out measurements at regular intervals along the depth of a borehole, spectral gamma-ray logging generates a continuous profile of gamma-ray emissions. This profile can be used to map the spatial distribution of uranium-bearing formations, aiding in delineating potential uranium deposits.

3.1 Instrumentation

The instrument used for the present study is IFG Corporation BSG-02, a fully digital Spectral Logging Probe designed for high-resolution spectral gamma-ray logging in boreholes. It is widely utilized in mineral exploration, environmental monitoring, and geological surveys, particularly for uranium prospecting and mapping. The probe identifies and quantifies uranium in subsurface formations by analyzing the gamma-ray energy spectrum. Additionally, it detects and measures other naturally occurring radioactive elements, such as thorium (Th-232) and potassium (K-40), offering valuable insights into the geological composition of the subsurface. The BSG-02 enables real-time data acquisition during borehole logging. Its compact and portable design makes it ideal for field application seven in challenging terrains. The probe samples natural gamma radiation in the energy range of 100 keV to 3 MeV in 512 channels, integrating the total spectrum every second and transmitting the data to the surface at this rate.

The detector is a 1"×3 " CsI(Tl) crystal. The temperature of the crystal detector is monitored and recorded during the borehole logging, which enables monitoring and correcting any shift in the spectrum caused by temperature changes.

The spectral gamma probe is designed for systems that include the BIN-04 digital data interface, 4 conductor logging cable and the data acquisition software. The probe is controlled by an on-board microprocessor that transmits the digital values (Spectrum) along the logging cable to the surface console (BIN-04) for the re-formatting and transferring to a microcomputer. The microcomputer and the acquisition software (GDAS) display and record the data in real time. The acquisition software allows up to 10 energy windows to be displayed and examined during logging. The data can be viewed in either graphic or numeric format. The **SPECTRA**, post processing software, displays and processes the recorded spectrum data. This software calibrates the gamma spectrum and computes to a maximum of10 energy windows. A schematic diagram of the spectral logging system comprising logging probe, winch and control PC is shown in Fig. 1.

3.2 Energy Range and Channel Windows

In spectral gamma-ray logging, the following isotopes were used to map the natural radio elements Potassium, Uranium, and Thorium

Potassium	^{40}K	1.46 MeV	Isotope	200 KeV window width	Channel-per-keV value of the logging system is 0.16
Uranium	^{214}Bi	1.76 MeV	Daughter of ^{238}U	200 KeV window width	
Thorium	^{208}Tl	2.62 MeV	Daughter of ^{232}Th	400 KeV window width	

Gamma rays corresponding to each element are counted in the corresponding energy windows. The energy windows are set to the default in the acquisition software. Typical spectrum acquired by the system is shown in Fig. 2. The width of the energy windows are 200 keV for 1.46 Mev, 200 KeV for 1.76 Mev and 400 KeV for 2.62 MeV respectively as shown in this figure.

3.3 Calibration

Calibration of spectral logging is important for obtaining faithful data[6]. Calibration was carried out in three Model Boreholes containing known uranium, thorium, and potassium values. Calibration estimated individual channel sensitivities for potassium, uranium, and thorium (S_k, S_u, and S_{th}) apart from the total channel sensitivity (S_{tot}). The stripping ratios α, β, γ, a (the contribution of high energy gammas of Th in U and K Channels, the contribution of U in K and Th channels) were also determined[7]. All measurements were taken with a minimum of 5-minute accumulation time in the active zone and 5 minutes in the barren zone. Stripping factors are defined as below:

Fig. 1 — Spectral Logging System

$$\alpha = \frac{\text{Net counts in Uranium channel due to Thorium Standard}}{\text{Net counts in Thorium channel due to Thorium standard}} = N_u^{th}/\,N_{th}^{th} \quad \ldots (1)$$

$$\beta = \frac{\text{Net counts in Potassium channel due to Thorium Standard}}{\text{Net counts in Thorium channel due to Thorium standard}} = N_k^{th}/\,N_{th}^{th} \quad \ldots (2)$$

$$\gamma = \frac{\text{Net counts in Potassium channel due to Uranium Standard}}{\text{Net counts in Uranium channel due to Uranium standard}} = N_k^{u}/\,N_{u}^{u} \quad \ldots (3)$$

$$a = \frac{\text{Net counts in Thorium channel due to Uranium Standard}}{\text{Net counts in Uranium channel due to Uranium standard}} = N_{th}^{u}/\,N_{u}^{u} \quad \ldots (4)$$

After subtracting the background counts in each channel from the counts obtained in the radioactive zones in three standard boreholes respectively, the net counts are obtained from each channel using stripping ratios. Sensitivity of each channel is also obtained as counts per second per ppm using the Model Borehole. On multiplying the net counts with sensitivity gives the concentration of K, U, and Th. The sensitivity factors and stripping ratios are shown in Table 1.

Table 1 — Window sensitivities and stripping ratios

S_k	0.2833	Counts/sec per % K
S_u	0.0657	Counts/sec per ppm U
S_{th}	0.0306	Counts/sec per ppm Th
α	1.1289	
β	1.3821	
γ	1.6923	
a	0.0379	

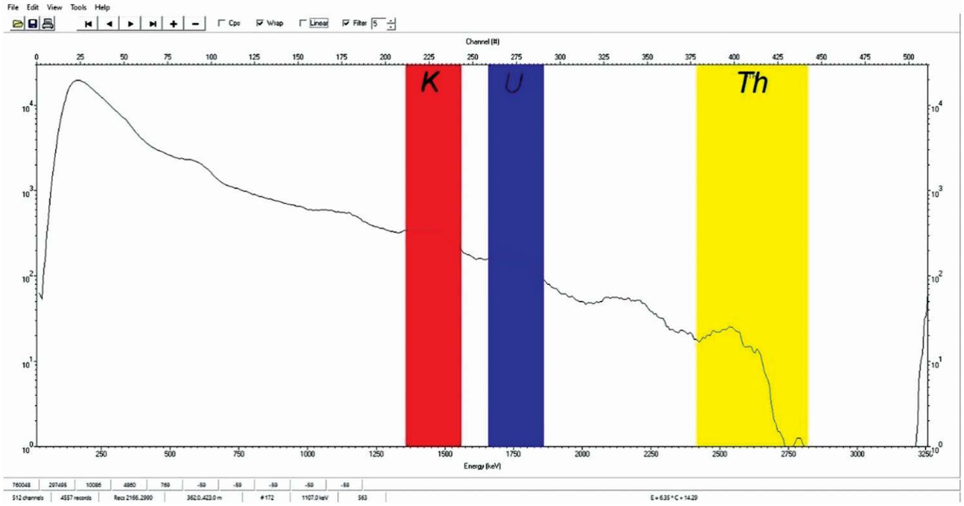

Fig. 2 — A typical Spectral logging spectrum (Log scale)

Width of the 662 keV peak of ^{137}Cs is checked periodically to ascertain any deterioration in the system. It is a regular practice to check for any deterioration in the system. The system must be re-calibrated, if any parameter is offset from the desired value.

3.4 Calculation of Concentration

With stripping ratios in hand, the following equations are used for estimation of concentrations of RaeU_3O_8, Th, and K:

$$Th_{ppm} = \{[N_{Th} - aN_U]/(1 - a\alpha)\}/S_{th} \quad \ldots (5)$$

$$U_{ppm} = \{[N_U - \alpha N_{Th}]/(1 - a\alpha)\}/S_u \quad \ldots (6)$$

$$K_{\%} = \{N_K - ((\gamma - \beta a)/(1 - a\alpha))N_U - ((\beta - \gamma\alpha)/(1 - a\alpha))N_{Th}\}/S_k \quad \ldots (7)$$

where N_U, N_{Th}, N_K are net counts in the U, Th, and K windows due to the respective radio nuclides. The system measures potassium values when the ore is at ppm level and sufficient counting time is given to reduce the error in the measurement. However, in the present study, the motive is to discriminate between U and Th zones with eU_3O_8 values > 100 ppm so the values of potassium concentration are not important.

3.5 Correction for Borehole Casing

In borehole logging, corrections are made for the presence of steel casing on both stripping ratios and sensitivities. This has been done by initially performing separate probe calibrations in standard boreholes for different casing thickness and in the absence of casing. The ratios or correction factors thus obtained are used to modify the counts obtained for the gamma energies of interest.

4 Methodology

Spectral logging data from five boreholes (SSZ/A, SSZ/B, SSZ/C, SSZ/D, SSZ/E) drilled in different exploration areas of Singhbhum Shear Zone is considered in the study. A borehole is first logged using a Gieger-Mueller (GM) detector-based logging system to identify the radioactive zones having eU_3O_8> 100 ppm, based on gross gamma counting. This step is crucial as it ensures that only radioactive zones of interest can be taken up for spectral logging instead of the entire borehole.

Spectral logging is carried out in the radioactive zones of interest at intervals of 20 cm. It is based on counting gamma-rays with known energies in respective energy channels. Uranium itself cannot be detected by gamma spectrometry. However, an indirect estimate of its concentration can be obtained by counting any gamma-energy emitted by its daughter elements. Gamma-rays of energy 1.76 MeV gamma emitted by ^{214}Bi (daughter of ^{238}U) is chosen for this purpose. Uranium estimation based on this energy is known as Ra(eU_3O_8). This estimation of Ra(eU_3O_8) based on gamma counting of 1.76 MeV emitted from ^{214}Bi gives the amount of actual U_3O_8 provided there is state of secular equilibrium in the uranium series. At every point, sufficient counting time is given to ensure that the error in the measurement is less than 10 % at 1 σ confidence level[8]. Error propagation is applied to arrive at the final error reported in the concentration values. The counts obtained in respective windows are corrected with stripping ratios and concentrations are estimated using Eqs.5-7.

5 Results

After logging the borehole, data is analyzed using SPECTRA software to check for any shift in the spectrum or malfunctioning. After necessary corrections, Ra(eU_3O_8) and ThO_2 values are calculated at each point of the radioactive zone. The values are tabulated in Tables 2, 3, 4, 5, and 6 for the five boreholes respectively. Potassium values are not listed since the zones of interest have eU_3O_8> 100 ppm, and the purpose of spectral logging in this study is to delineate uranium and thorium zones in the borehole. Data obtained from spectral logging reflects that the system can clearly distinguish between uranium and thorium concentrated zones.

Table 2 — Spectral logging data of borehole and spectrometric analysis data of core samples derived from the corresponding zone for borehole SSZ/A

Borehole	Spectral Logging Data			Radiometric Analysis Data of Core Samples			
	ZONE I			ZONE I			
SSZ/A	Depth	% Ra(eU_3O_8)	% ThO_2	Sl.No.	Sample Name	% Ra(eU_3O_8)	% ThO_2
	347.9	< 0.005	0.021	1	SSZ/A-1	<0.005	0.019
	348.1	< 0.005	0.024	2	SSZ/A-2	<0.005	0.039

(*Contd.*)

Table 2 — Spectral logging data of borehole and spectrometric analysis data of core samples derived from the corresponding zone for borehole SSZ/A (*Contd.*)

Borehole	Spectral Logging Data			Radiometric Analysis Data of Core Samples			
		ZONE I			ZONE I		
SSZ/A	Depth	% Ra(eU_3O_8)	% ThO_2	Sl. No.	Sample Name	% Ra(eU_3O_8)	% ThO_2
	348.3	< 0.005	0.013	3	SSZ/A-3	0.005	0.019
	348.5	< 0.005	0.020	4	SSZ/A-4	<0.005	0.025
	348.7	< 0.005	0.021	5	SSZ/A-5	<0.005	0.027
	348.9	0.006	0.023	6	SSZ/A-6	<0.005	0.022
	349.1	< 0.005	0.038	7	SSZ/A-7	<0.005	0.014
	349.3	0.006	0.019	8	SSZ/A-8	<0.005	0.034
	349.5	< 0.005	0.015	9	SSZ/A-9	<0.005	0.024
	349.7	< 0.005	0.014	10	SSZ/A-10	<0.005	0.032
	349.9	< 0.005	0.015	11	SSZ/A-11	<0.005	0.050
	350.1	< 0.005	0.016	12	SSZ/A-12	<0.005	0.033
	350.3	< 0.005	0.019	13	SSZ/A-13	<0.005	0.018
	350.5	< 0.005	0.012	14	SSZ/A-14	0.006	0.018
	350.7	< 0.005	0.016	15	SSZ/A-15	<0.005	0.022
	350.9	< 0.005	0.019	16	SSZ/A-16	<0.005	0.023
	351.1	< 0.005	0.012	17	SSZ/A-17	<0.005	0.025
	351.3	< 0.005	0.014	18	SSZ/A-18	<0.005	0.055
	351.5	< 0.005	0.015	19	SSZ/A-19	<0.005	0.025
	351.7	< 0.005	0.016	20	SSZ/A-20	<0.005	0.021
		ZONE II			ZONE II		
	382.7	0.006	0.015	21	SSZ/A-21	0.006	0.016
	382.9	0.028	< 0.005	22	SSZ/A-22	0.010	0.020
	383.1	0.047	< 0.005	23	SSZ/A-23	0.005	0.014
	383.3	0.053	< 0.005	24	SSZ/A-24	0.016	0.013
	383.5	0.010	< 0.005	25	SSZ/A-25	0.015	<0.005
	383.7	0.018	< 0.005	26	SSZ/A-26	0.026	<0.005
	383.9	0.042	< 0.005	27	SSZ/A-27	0.092	<0.005
	384.1	0.079	< 0.005	28	SSZ/A-28	0.092	0.005
	384.3	0.055	< 0.005	29	SSZ/A-29	0.037	<0.005
	384.5	0.032	< 0.005	30	SSZ/A-30	0.030	<0.005
	384.7	0.031	< 0.005	31	SSZ/A-31	0.036	<0.005
	384.9	0.022	< 0.005	32	SSZ/A-32	0.017	<0.005
	385.1	0.012	< 0.005	33	SSZ/A-33	0.032	<0.005
	385.3	0.011	< 0.005	34	SSZ/A-34	0.015	<0.005
	385.5	0.019	< 0.005	35	SSZ/A-35	0.013	<0.005
	385.7	0.035	< 0.005	36	SSZ/A-36	0.035	<0.005

Table 3 — Spectral logging data of borehole and spectrometric analysis data of core samples derived from the corresponding zone for borehole SSZ/B

Borehole	Spectral Logging Data			Radiometric Analysis Data of Core Samples			
		ZONE I			ZONE I		
	DEPTH (m)	% Ra(eU_3O_8)	% ThO_2	Sl. No.	Sample Name	% Ra(eU_3O_8)	% ThO_2
SSZ/B	317.6	< 0.005	0.030	1	SSZ/B-1	0.006	0.051
	317.8	0.016	0.045	2	SSZ/B-2	0.026	0.092
	318.0	0.012	0.097	3	SSZ/B-3	0.014	0.042
	318.2	0.022	0.083	4	SSZ/B-4	0.023	0.093
	318.4	0.020	0.039	5	SSZ/B-5	0.035	0.12
	318.6	0.012	0.018	6	SSZ/B-6	0.005	0.014
	318.8	0.006	0.044	7	SSZ/B-7	0.040	0.14
	319.0	0.012	0.025	8	SSZ/B-8	0.018	0.061
	319.2	0.008	0.029	9	SSZ/B-9	<0.005	0.033
	319.4	< 0.005	0.030				

Table 4 — Spectral logging data of borehole and spectrometric analysis data of core samples derived from the corresponding zone for borehole SSZ/C

Borehole	Spectral Logging Data			Radiometric Analysis Data of Core Samples			
	ZONE I			ZONE I			
	DEPTH (m)	% Ra(eU$_3$O$_8$)	% ThO$_2$	Sl. No.	Sample Name	% Ra(eU$_3$O$_8$)	% ThO$_2$
SSZ/C	452.3	0.013	< 0.005	1	SSZ/C-1	0.014	<0.005
	452.5	0.023	< 0.005	2	SSZ/C-2	0.030	<0.005
	452.7	0.029	< 0.005	3	SSZ/C-3	0.027	<0.005
	452.9	0.033	< 0.005	4	SSZ/C-4	0.020	<0.005
	453.1	0.018	< 0.005	5	SSZ/C-5	0.034	<0.005
	453.3	0.015	< 0.005	6	SSZ/C-6	0.017	<0.005
	453.5	0.011	< 0.005	7	SSZ/C-7	0.015	<0.005
	ZONE II			ZONE II			
	512.9	< 0.005	0.020	8	SSZ/C-8	<0.005	0.022
	513.1	< 0.005	0.026	9	SSZ/C-9	<0.005	0.025
	513.3	< 0.005	0.021	10	SSZ/C-10	<0.005	0.024
	513.5	< 0.005	0.027	11	SSZ/C-11	<0.005	0.032
	513.7	< 0.005	0.033	12	SSZ/C-12	<0.005	0.032
	513.9	< 0.005	0.030	13	SSZ/C-13	<0.005	0.019
	514.1	< 0.005	0.027	14	SSZ/C-14	<0.005	0.017
	514.3	< 0.005	0.017	15	SSZ/C-15	<0.005	0.022

Table 5 — Spectral logging data of borehole and spectrometric analysis data of core samples derived from the corresponding zone for borehole SSZ/D

Borehole	Spectral Logging Data			Radiometric Analysis Data of Core Samples			
	ZONE I			ZONE I			
	DEPTH (m)	% Ra(eU$_3$O$_8$)	% ThO$_2$	Sl. No.	Sample Name	% Ra(eU$_3$O$_8$)	% ThO$_2$
SSZ/D	539.2	0.014	< 0.005	1	SSZ/D-1	0.012	<0.005
	539.4	0.012	< 0.005	2	SSZ/D-2	0.010	<0.005
	539.6	0.011	< 0.005	3	SSZ/D-3	0.011	<0.005
	539.8	< 0.005	0.018	4	SSZ/D-4	<0.005	0.010
	540.0	0.012	< 0.005	5	SSZ/D-5	0.028	0.005
	540.2	0.013	< 0.005	6	SSZ/D-6	0.019	<0.005
	540.4	0.013	< 0.005	7	SSZ/D-7	0.020	<0.005
	540.6	0.023	< 0.005	8	SSZ/D-8	0.037	<0.005
	540.8	0.012	0.006	9	SSZ/D-9	0.032	0.005
	541.0	0.016	< 0.005	10	SSZ/D-10	0.019	0.006
	541.2	0.039	< 0.005				
	541.4	0.030	0.005				
	541.6	0.018	< 0.005				

Table 6 — Spectral logging data of borehole and spectrometric analysis data of core samples derived from the corresponding zone for borehole SSZ/E

Borehole	Spectral Logging Data			Radiometric Analysis Data of Core Samples			
	ZONE I			ZONE I			
	DEPTH (m)	% Ra(eU$_3$O$_8$)	% ThO$_2$	Sl. No.	Sample Name	% Ra(eU$_3$O$_8$)	% ThO$_2$
SSZ/E	604.9	0.010	< 0.005	1	SSZ/E-1	0.029	<0.005
	605.1	0.020	< 0.005	2	SSZ/E-2	0.018	<0.005
	605.3	0.013	< 0.005	3	SSZ/E-3	0.022	<0.005
	605.5	0.025	< 0.005	4	SSZ/E-4	0.016	<0.005
	605.7	0.012	< 0.005				
	605.9	0.010	< 0.005				

To confirm the values obtained in the spectral logging, borehole core samples derived from the corresponding radioactive zones, given in the Tables 2-6, were analyzed in the laboratory-based gamma-ray spectrometry system using a 5” × 4” NaI(Tl) detector coupled to a DSP unit. Results obtained are presented along with spectral logging data in the respective tables, and it can be said that the uranium and thorium values obtained in the two measurements are in agreement.

6 Conclusion

The spectral logging of different radioactive zones in the boreholes yields uranium and thorium content which is in qualitative agreement with the radiometric sample analysis. For example, consider Zone I and Zone II of the borehole SSZ/A. It is evident that Zone I has thorium mineralization with %ThO_2 values ranging from 0.012 % to 0.038 % whereas Zone II has uranium mineralization with % Ra(eU_3O_8) values ranging from 0.006 % to 0.079 %. Borehole core sample radiometric analysis data also shows that samples from Zone I have thorium content and those from Zone II have uranium content, which are in qualitative agreement with the values obtained in SGR logging of these zones respectively. The motive of the study is not to provide a point wise correlation since exact point-to-point depth match cannot be ensured between the logging and sample assay data. Sample assay results provide qualitative agreement between uranium and thorium values. Therefore, a spectral logging system can delineate uranium and thorium mineralization in the borehole.

The results are important from an exploration perspective as *in-situ* delineation of uranium and thorium concentrated zones will help reduce the core sample analysis load of the laboratory, thereby helping exploration of uranium resources in the country at a faster pace. In addition, for a new geological area to be taken up for uranium exploration, spectral gamma ray logging would be essential as it provides a quantitative data on uranium and thorium concentrated zones in the very initial stage. This would help to decide further exploration strategies.

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