Interpolation study on ambient gamma levels in parts of Khasi Hills, Meghalaya (India): Preliminary findings for U exploration

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This paper discusses an experimental approach to examine uranium exploration avenue over the geologically extended parts of Mahadek basin in Meghalaya, amid some of the environmental constraints. Study comprises periodic measurements of prevailing ambient gamma levels across 320 georeference points, in relation to the major litho units of Mahadek basin, covering 673 line km of Khasi Hills. Acquired sample data points were then analysed in geostatistical software (Surfer™) to develop analytical model of sample variogram having bearing on the uranium exploration in the area. Study findings have given encouraging surface indicators with mostly elevated gamma levels over the parts of West Khasi Hills. Delineated gamma anomalous zones are lithologically well correlated including to that of existing uranium occurrences in the basin. Identified anomalous zones over the parts of West Khasi Hills by this study work, are mainly associated with the Mahadek sandstone (Upper and Lower Mahadek) and Precambrian basement granites. Lower Mahadek sandstone is host rock for uranium mineralisation in the basin. Initial findings suggest with the closer spatial resolution (~1 km) of sample data points, the approach adopted by the study work holds promising application in locating potential uranium exploration targets especially to the extended and inaccessible parts of the basin.

1. Introduction

Mahadek basin of Meghalaya nearly extends over a stretch of 180 km from the Jaintia Hills in the east to the Garo Hills in the west. In the basin, systematic exploration of Upper Cretaceous Mahadek sediments have established country's two largest sandstone-type uranium deposits, viz., Domiasiat (Kaul and Varma 1990; Sunil Kumar *et al.* 1990) and Wakhyn (Sen *et al.* 2002) in the West Khasi

Hills district. Geological evidences (Srivastava *et al.* 2008) in the basin indicates large uranium reserves potential of medium to small ore pocket size (grade <0.10% U₃O₈) disposed at shallow depth. The favourability criteria of uranium occurrences to the extended areas in the basin have readily brought to light new locales of uranium mineralization namely Wakhyn, Lostoin, Wakhut and Umthougkut, etc. Together with the main deposit at Domiasiat and satellite deposits, the basin as on date, host one of

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the largest and richest grade sandstone-type uranium deposits in the country with 20,000 (plus) tonnes of proven ore reserve.

However, led by the prevailing environmental conditions, four decades of constant exploration activities in the basin could only explore about one third aerial extent of the basin area. In view of extended geological favourability also to the remaining part of the basin, there exist high uranium potential to the unexplored part of the basin. This unexplored part of the basin remains highly inaccessible due to number of factors such as thick Tertiary cover, typical prevailing tropical to sub-tropical climate (heavy rain falls), terrain difficulty, thick forest and poor logistics (roads and communication). Under these practical constraints, operational task often becomes most challenging and resource intensive. Apart from the proven uranium resources in the basin, significant amount of work has been undertaken in the basin to better understand the geological aspect of uranium hosting environment (Hamilton *et al.* 2009, 2010, 2012), abrupt discontinuity between the surface and sub-surface uranium mineralization (Kukreti *et al.* 2012) as well status of uranium migration across the exploratory block (Kukreti and Pramod Kumar 2013; Kukreti *et al.* 2015).

It is well established that the surrounding rock/soils medium exhibits considerable variation in ambient gamma levels (IAEA 1990) owing to different chemical and mineralogical composition of constituting rocks that contain varying concentrations of ^{40}K , ^{238}U and ^{232}Th primordial radio elements. Using ambient gamma level-based radiometric survey, one gets rapid and effective tool in assessing the potential uranium exploration targets and to guide the exploration activities. Amid environmental constraints observed during the field exploration operations over the major parts of Mahadek basin, an experimental (georeference based) measurement and analysis of ambient gamma levels in parts of Khasi Hills (with known uranium occurrences) is being taken up to understand spatial continuity of sample data points. With due consideration of regional geological factors, suitable interpolation of acquired sample data points (Davis 2002) now offers quick preliminary assessment (based on gamma levels) for uranium prospecting over the large and inaccessible areas in the basin.

Literature survey shows kriging based interpolation techniques as the most effective technique in several field applications including mineral exploration (Matthew Kay and Roussos Dimitrakopoulos 2000) as well as critical environmental studies (Wright *et al.* 2002; Abraham and Comrie 2004). Kriging offers several advantages in terms of making use of irregular-spaced sample data points, which is often the case during data acquisition

phase in the field. It provides the most predictable results over the large grid area together with good overview and easier to detect pattern.

2. Geological set-up and study area

Meghalaya plateau considered to be the north-eastern extension of the Precambrian peninsular shield comprises rocks from the oldest Precambrian gneissic complex to the recent alluvium formations (GSI 1974; Nandi 1980). The Precambrian gneissic complex (para/ortho gneisses and migmatites) and Shillong Group of rocks (mainly quartzites) are exposed in the central, eastern and northern parts of Meghalaya plateau (Acharya 1976). They are intruded by basic and ultrabasic intrusives and Neo-Proterozoic granite plutons, such as South Khasi batholith, Myllem granite, Kyr-dem granite, and Nongpoh granite (Ghosh *et al.* 1991). The Lower Gondwana rocks (pebble bed, sandstone and carbonaceous shale) are observed in West Garo Hills. The Sylhet trap (mainly basalt, rhyolites and acid tuffs) of Middle Jurassic age is exposed in a narrow E–W strip along the southern border of Khasi Hills (Baksi *et al.* 1987). The Cretaceous Mahadek sandstones and Tertiary sediments occupy southern part of the plateau and forms part of the Mahadek basin. Figure 1 shows detailed geological map of the study area under Mahadek basin.

Mahadek basin essentially stretch nearly 180 km length from the Jaintia Hills in the east to the Garo Hills in the west with 7–18 km width from south to north in Jaintia, East Khasi, West Khasi and Garo Hills districts. Fluvial Lower Mahadek arkosic sandstone (thickness 30–70 m) and marine Upper Mahadek purple sandstone (thickness 50–300 m) are exposed over an area of 500 km². The remaining 1300 km² of basin is overlain by younger Tertiary sediments (Langpar formation – calcareous sandstone/shale, Shella formation – alternations of sandstone and limestone, Baghmara formation – feldspathic sandstone, conglomerate and clay, etc.). The basin contains proven sandstone type uranium deposits (Kaul and Varma 1990; Sunil Kumar *et al.* 1990; Sen *et al.* 2002) in the West Khasi Hills district with uranium mineralization associated with the Lower Mahadek sandstone.

3. Materials and methods

3.1 Field measurements

Considering environmental and logistic constraints in major parts of Khasi Hills in Mahadek basin, onsite measurements of ambient gamma levels

Figure 1. Parts of Khasi Hills study area (shown by dotted block) together with detailed geological map of Mahadek basin, Meghalaya (India).

Figure 2. Georeference based field measurements over the study area (shown by blue dots) of ambient gamma levels in parts of Khasi Hills, Meghalaya (India).

were done in several phases covering 18 sectors with cumulative distance of 673 line km (figure 2). Pre-calibrated battery operated high sensitivity environmental radiation monitor type ER-705M (Nucleonix 2001) and GPS device (GARMIN

make, model GPS-V) were used for *in-situ* gamma field and site coordinate measurements. During field work, georeference points were recorded at about 2–3 line km periodic intervals using vehicle-borne milometer such that covering major land

Figure 3. Typical box and whisker plot of ambient gamma levels for the major litho units of Mahadek basin. Dot represents mean ambient gamma radioactivity level.

marks and lithological occurrences to the survey route. Thus generating 320 georeference points, at an average 2.1 line km intervals. *In-situ* gamma field was measured at 1 m above the ground height with approximately 3 min counting time, together with lithological occurrence types. Litho unit based reproducibility of measured gamma levels was ascertained by performing random checks on few georeference points. The acquired sample data points were first clustered and represented by box plots for the major litho units of Mahadek basin. Typical prevailing gamma levels for the major litho units of Mahadek basin is plotted in figure 3 together with relative non-terrestrial gamma component (mainly cosmic, atmospheric radon and scattered gamma). This non-terrestrial gamma component was measured over the freshwater body (150 feet water column) at the Umium (MSL 965 m) about 17 km outskirts of state capital Shillong, Meghalaya.

3.2 Study approach

A generalised linear estimate (Chilès and Delfiner 1999) of quantity Z at unknown location x_0 (say) can be mathematically expressed as:

$$Z_0^* = Z^*(x_0) = \sum_{i=1}^n \lambda_i Z(x_i) \quad (1)$$

where Z_0^* is the estimated value at location x_0 using data value $Z(x_i)$ measured at the sampling points i ($=1, 2, 3, \dots, n$) each having weightage factor λ_i such that:

$$\sum_{i=1}^n \lambda_i = 1. \quad (2)$$

Estimated value Z_0^* is differentiated from the true value Z_0 . Determination of weightage factor λ_i is

done experimentally by fitting variogram $\gamma(h)$ on the measured data values $Z(x_i)$ as a function of separation vector h (also called lag vector) using following equation.

$$\gamma(h) = \frac{1}{2N_h} \sum_{i=1}^{N_h} [Z(x_i + h) - Z(x_i)]^2 \quad (3)$$

where N_h is the number of data pairs for the specified separation vector h . The separation vector is denoted with certain direction and distance tolerance.

4. Data analysis

4.1 Sample variogram

Prior to the interpolation of sample data points over the study area, one need information on sample variogram using sample data points. To develop analytical model of sample variogram, variogram grid was first defined in geostatistical software SurferTM (v 11.0) for the acquired sample data points. Subsequently, acquired sample points were then filtered for duplicate/overlapped measurements in the field by defining X and Y direction filtering criteria, each of 1.1 km tolerances in SurferTM and replacing such field measurements with averaged value. A total of 114 duplicate data points were identified by the selected criteria (in analysing software) over 46 locations in the variogram grid and were replaced by equivalent average. Thus effectively giving $n = 252$ active data points. Statistical summary for the two datasets (raw and filtered) is presented in table 1. Post-filtering, active data points ($n = 252$) were then processed in SurferTM to compute sample variogram $\gamma(h)$ defined by equation (3) over all pair of observations N_h with specified lag vector (h). By default, SurferTM defines max lag distance as one third of diagonal extent of sample data points and computes as 43.41 km with 25 lag points (default). This gave an average lag vector (h) 1.74 km, other parameters of sample variogram and grid geometry are listed in table 2.

Thereafter, computed variogram with default lag vector (h) was modelled using mathematical function that best describe the spatial relationship of sample data points. After several iterations of optimisation of sample variance (in computed variogram) including varying lag vector 1.74 km (default) to 1.1 km, analytical shape of sample variogram model (figure 4) is best matched to the following theoretical model (Pannatier 1996).

$$\gamma(h) = c_0 + c \left[\frac{3h}{2a} - \frac{h^3}{2a^3} \right] \quad (4)$$

where c_0 , c and a refer to nugget, partial sill and range, respectively. Table 2(b) lists detailed

Table 1. Sample data points for variogram analysis.

Parameters	Unfiltered sample data points ($n = 320$)	Filtered sample data points ($n = 252$)	Remark
Average	136.2	133.9	Distribution of sample data points (either case) shows dominating contribution from gamma levels <231 nGy/ h. Filtering criteria for sample data points is defined as X and Y direction tolerance 1.1 km each and replacing duplicate/ overlapped data points for the said location with average value.
Median	121.9	120.7	
Min	60	60.9	
Max	389.3	389.3	
Variance	2633	2533.4	
Std. dev.	51.3	50.33	
95 percentile	230.6	223.8	

Table 2. Sample variogram model ($n=252$).

(a) Variogram grid geometry				(b) Variogram model		Remark
				Components	Parameters	
NN statistics		Lag parameters		Spherical	Scale =1020	Sill = 1770
Min	0.033 km	Max lag distance	43.41 km	Nugget	Range= 18.82 km	Nugget/Sill = 0.42
Max	3.44 km				Anisotropy ratio=1.2	NN – Nearest
Median	1.52 km	No. of lag points	25		Anisotropy angle= 60°	Neighbour distance.
Average	1.59 km				Direction= 10°	To the nested sample
Std. dev.	0.57 km	Lag interval (default)	1.74 km		Tolerance = 45°	variogram, partial sill is
		Lag interval (fitted)	1.1 km			referred by Surfer as scale.

parameters for the analytical model of fitted sample variogram in SurferTM.

4.2 Interpolations of experimental data points

Prior to the interpolation of sample data points, a qualifying check on analytical model of sample variogram was performed. This was done by running compatibility check on the acquired sample data points (figure 2) using analytical model of fitted variogram model, pre-defined data filtering criteria (table 1) and interpolation grid parameters listed under table 3(a) in SurferTM. Summary of variogram analytical model based predicted results are listed in table 3(b) and plotted on figure 5 for comparative analysis.

After ascertaining qualification of sample variogram (figure 4), defined interpolation grid presented in table 3(a) for kriging algorithm in SurferTM was retained to interpolate active sample data points ($n = 230$) over the study area. Default grid interval 1.12×1.12 km together with 100 (X direction) by 47 (Y direction) nodes grid geometry was used. This generated 47,000 node points for the coordinates range covered by the present field work. Interpolated gamma levels, at the grid points, were then plotted in SurferTM to generate detailed contour maps (figure 6).

Figure 4. Analytical model of sample variogram for the Khasi Hills field measurements. Number indicates total number of observation pairs associated with each bin in the sample variogram.

Table 3. *Compatibility check of sample variogram.*

(a) Interpolation grid geometry		(b) Statistical summary of measures			
		Parameter	Input sample data points	Predictated data points	
NN statistics					Remark
Min	0.90 km	Average ($n=230$)	134.38	134.13	Sample data points are filtered using pre-defined criteria in sample variogram analysis (table 1).
		Median	121	134.82	
Max	3.44 km	Min	66.80	84.60	
		Max	389.30	288.55	
Median	1.64 km	Variance	2468.32	965.62	Kriging minimises error (Std. dev. & RMD) while interpolating data points.
Average	1.76 km	Std. dev.	49.68	31.07	
		RMD	0.384	0.264	
Std. dev.	0.48 km	Skew	1.69	0.40	
		Kurto	4.56	-0.51

Figure 5. Comparison of variogram model predicted gamma levels to that of measured sample data points ($n = 230$) in parts of Khasi Hills, Meghalaya (India).

5. Interpretation and discussion

Mapping of ambient gamma levels in relation to the major litho units of Mahadek (figure 3) gives considerable overlap particularly to the Mahadek sandstone and basement granites. Therefore, while interpreting elevated gamma levels especially to the geological favourability areas for uranium exploration, must be considered.

Analytical model of sample variogram (figure 4) is a measure of spatial continuity of sample data points over the study area and shows reasonably good fit to that of theoretical model. High nugget and large fluctuation seen by the sample variogram (nested one) are physically observed during field measurements in the form of high nugget presence to the drawn and radiometrically analysed grab samples. Examined goodness-of-fit for the analytical model of sample variogram (figure 4) is well supported by several test measures undertaken and presented in table 3(b). Comparison of georeference

data points and their predictability by the analytical model of sample variogram (figure 5) shows good match (95%) within experimental errors, barring few high values (>231 nGy/h) sample data points (mainly basement granites in the area). This agreement between the two sets of data points, is well supported by the ANOVA test done at high degree of confidence (table 4).

Developed variogram model, used for the interpolation of sample data points over the parts of Khasi Hills gives good overview of radiometric signatures (figure 6) with elevated gamma levels towards the part of West Khasi Hills. Except for Shillong and its extension, mostly lower gamma levels are observed over the parts of East Khasi Hills. The reported lower gamma levels in parts of East Khasi Hills are much in relation to the major lithological occurrence (figure 1) in the basin and well correlated by the dominating exposure of Tertiary formation (Shella sandstone and limestone) and Sylhet Trap, both characterized with lower gamma levels (figure 3). To the Shillong and its surroundings, elevated gamma levels are mainly attributed to the Neo-Proterozoic granites and quartzites of Shillong Group of rocks having higher concentration of primordial radio elements (figure 3).

Manifested elevated gamma levels to the parts of West Khasi Hills are also lithologically well correlated on ground, since major rock exposure is attributed to the Mahadek sandstone (Upper and Lower Mahadek) and Precambrian basement granites both contributing high gamma levels (figure 3).

Presence of several high gamma anomalous zones (figure 6) identified by the study especially to the proven uranium resources in the basin, viz., Domiasiat (Kaul and Varma 1990; Sunil Kumar *et al.* 1990) and Wakhyn (Sen *et al.* 2002) confirms its application in identifying potential uranium exploration targets in the field. These identified anomalous zones are also well correlated

Figure 6. Interpolation of ambient gamma levels in parts of Khasi Hills, Meghalaya (India). Delineated anomalous gamma radioactivity zones (targets) are shown by yellow and red contours.

Table 4. ANOVA test for the sample variogram predicted data points.

	Sum of squares	df	Mean square	F
Between groups	6.96	1	6.96	0.004
Within groups	786371.3	458	1716.97	
Total	786378.2	459		

to the Lower Mahadek sandstone-host rock for uranium mineralisation in the basin. Elsewhere, high gamma anomalous zone namely around Nongstoin and to the north of Tiniang (figure 6) are mainly due to basement gneiss (figure 3) and not favourable to exploration work.

6. Conclusion

Preliminary findings on measurements of ambient gamma levels in relation to the major litho units of Mahadek basin and its interpolation in the basin were able to delineate existing uranium occurrence. The approach demonstrated by the study work can be adopted to explore uranium bearing potential over the extended and larger part of Mahadek basin having favourable geological considerations. Modelled sample variogram shows reasonably good fit to that of theoretical model (in view of good agreement between the sample data points *vis-à-vis* predicted one).

Presence of high nugget seen to the developed sample variogram model still desires closure sampling interval typically to the order of lag interval (~ 1 km) for detailed local characterisation and

exploration of new uranium avenue especially to the extended and inaccessible areas in the basin.

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