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Surface Radiogenic Heat Distribution in Obio-Akpor Area of Rivers State, Nigeria

Adegoke, J.A., Farai, I.P. and Oyekan, K.A.

Abstract
Radiogenic heat production rates of soil samples from some selected sites in Obio-Akpor area of Rivers state, Nigeria are presented. Activity concentration of naturally occurring radionuclides: ^{40}K, ^{238}U and ^{232}Th in samples were determined using a NaI(Tl) gamma-ray spectrometer. Radiogenic heat production rates calculated from activity concentrations ranged from 0.2 to 11.2 pW/kg for^{40}K, BDL to 178.2 pW/kg for ^{238}U, and BDL to 958.8 pW/kg for ^{232}Th. Total heat production varied from 102.1 to 1086.0 pW/kg. As much as 90% of total heat production is from ^{232}Th, while ^{40}K and ^{238}U contribute 1% and 9% respectively. Heat production is higher than that of a region in the south-western part of the country but lower than that from the northern part.

Key words: Radiogenic, heat, gamma-ray, spectrometer, activity concentration, soil.

Introduction

Radiogenic heat sources present in the continental earth crust contribute significantly to the total surface heat flow and temperature distribution in the crust [1]. The principal heat-producing isotopes are thorium-232 (^{232}Th), uranium-238 (^{238}U), potassium-40 (^{40}K), and uranium-235 (^{235}U) with respective half-lives of 14.0, 4.47, 1.28, and 0.70×10^9 years. Uranium-235 is about 0.72% of natural uranium while ^{238}U constitutes the remaining 99.28%. Heat production from ^{238}U can therefore, for practical purposes be taken as the heat production due to natural uranium [2]. Other natural radioactive isotopes can be ignored in the heat production processes because of one or a combination of their low disintegration energy, small natural abundances and very short half lives. Radiogenic heat production decreases with depth because the concentration of the heat-generating isotopes decreases with depth. The concentrations of uranium and thorium in rocks are generally in trace amounts measured in parts per million, while potassium is much more abundant, in the range of a few percent, of which a small but well-known fraction is the radioactive ^{40}K. [3]

Adegoke, J.A., Farai, I.P. and Oyekan, K.A.
Department of Physics, University of Ibadan, Nigeria
Email: adegokeja@yahoo.com

Detailed surface heat-flow data exist for many continental regions, particularly in the United States of America, Western Europe and the former USSR [3]. Unfortunately, data from Antarctica, South America, Australia, and most parts of Africa on heat production are quite sparse. Where unaffected by thermal transients associated with climatic, tectonicor groundwater activity, variations in surface heatflow can be attributed to variations of the abundance of crustal radiogenic sources. The global mean value of heat production in the continental crust is 65 ± 1.6 mWm^{-2} [3] of which about 30 mWm^{-2} is attributed to radiogenic heatproduction within the crust with the remainder being due to heat supplied to the lithosphere by convective processes in the deeper mantle [4]. As a result of the geographic distribution in the global heat-flowdataset, the natural range of surface heat flow and the relative contributions of crust and mantle sources are poorly understood [3]. As a result, there are empirical relations for heat flow and heat production in regions of the United States of America and Western Europe, we need such data in the different parts of Africa.

This work is one of the pioneering works in Nigeria aimed at generating radiogenic heat production data in order to beef up available data in the country. The heat production has been determined from the

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concentration of the primordial radionuclides in selected soil samples in the oil producing area of Niger delta [10].

Materials and Methods

The study area for this research work was Obio-Akpor area, Port Harcourt, the capital city of Rivers state, Nigeria. It lies within latitude 7^0 15' N and longitude 4^0 5 ' E. Rivers state is one of the oil producing states in Nigeria and is located in the southern part of the country. Obio-Akpor is heavily populated and it is a key industrial area in the oil producing region of Niger delta. The map of Obio-Akpor area showing the locations from which the soil samples were collected with their respective coordinates as indicated by Geographical Positioning System (GPS) are shown in Figure 1.

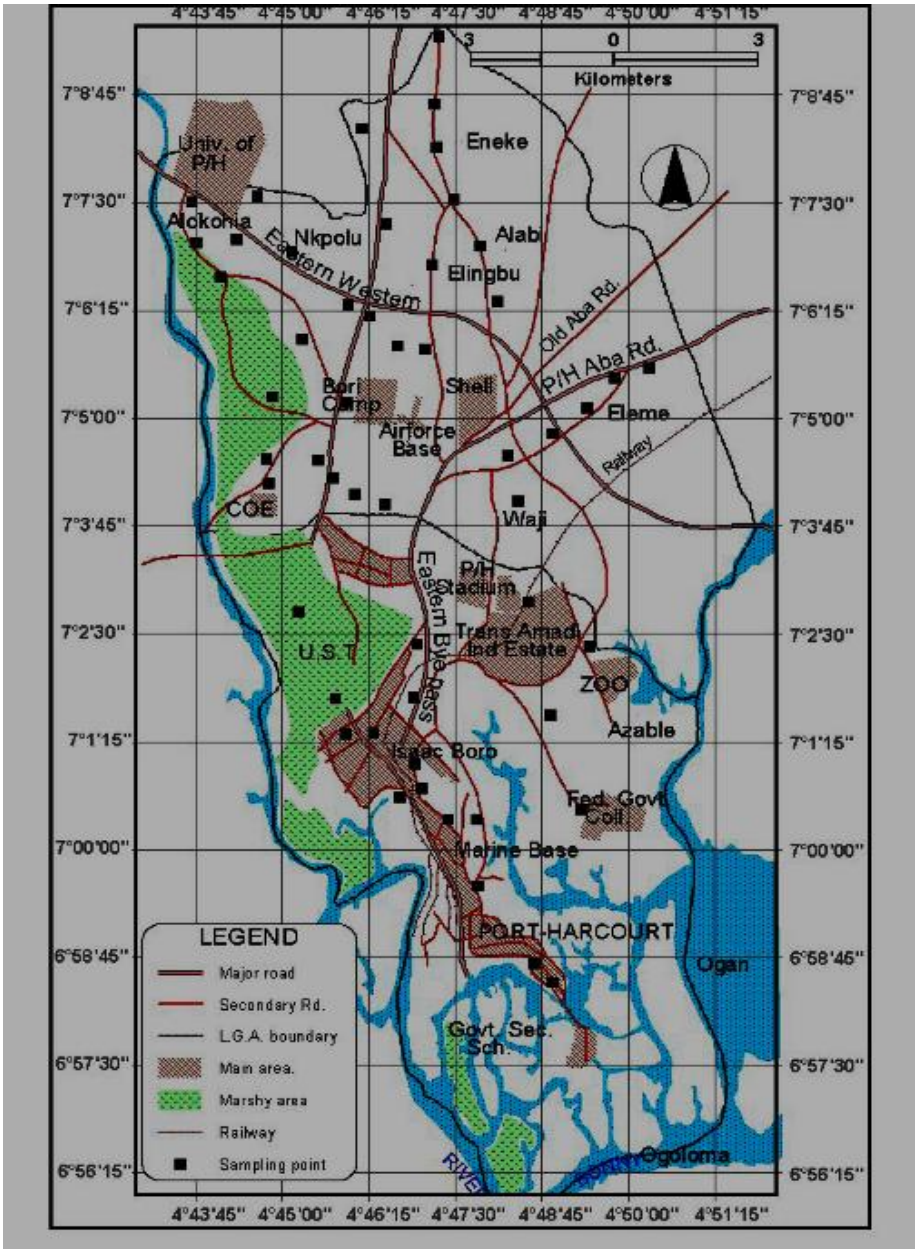

Fig. 1: Map of Obio-Akpor showing sampling locations.

Between 3 and 4 soil samples were collected at each of the 50 sites surveyed within Obio-Akpor area. All the samples collected from each site were thoroughly mixed to obtain the representative composite sample for the site. The samples were collected to depths of between 10 and 15cm below the earth surface. Each sample was packaged in a polythene bag and labelled. The samples were sun dried, pulverized, weighed and hermetically sealed in 100ml plastic containers which can sit with high geometry on the detector. They were left for a period of four weeks in order for the short-lived Rn gas in the uranium and thorium series to attain secular equilibrium before counting was carried out.

A NaI(Tl) scintillation detector of dimension 7.6 cm x 7.6 cm was used in this work due to its high gamma-ray detection efficiency. The energy resolution of the detector is about 8% at 0.662 MeV of ^{137}Cs. This value is good enough to distinguish the different gamma-ray energies of the radionuclides investigated. The assembly consists of a 6 cm thick cylindrical lead shield container in which the detector and the sample to be measured are enclosed. The NaI(Tl) scintillation detector crystal (model 802 series, Biron NaI), is coupled to a Canberra series 10 plus Multi-Channel Analyzer (MCA) through a preamplifier. The MCA has an analog-to-digital converter which is biased by an in-built high voltage power supply (HVPS). It is thus capable of calculating and storing the area under the photopeak lying within a predefined region of interest in the MCA's memory. The set-up therefore allows acquisition, storage, display and analysis of the data from the soil samples.

The efficiency quantitative calibration of the detector system was carried out using a standard reference soil sample prepared from Rocketdyne Laboratories, California USA and a traceable to a mixed standard gamma source (Ref. No. 48722-356) from Analytic Inc., Atlanta, GA, USA. The firm-ware algorithm of the MCA was used to calculate the concentration of each radioisotope in Bqkg^{-1} from the values of area under photopeak for each sample. The radionuclides ^{40}K, ^{238}U and ^{232}Th were detected and quantified using gamma energies 1.46, 1.76 and 2.62 MeV emitted by their respective progenies. Concentration in Bqkg^{-1} was then converted to concentration in part per million (ppm) as shown in Table 3. The values of concentration in ppm in Table 1 were used to calculate the radiogenic heat production rate Q_r (pWkg^{-1}) using the Rybach equation[6]:

$$Q_r = 95.2C_u + 25.6C_{Th} + 0.00348C_K$$

where, C_u,C_{Th}, and C_K are the concentrations (in ppm) of ^{235}U, ^{232}Th and ^{40}K in each sample respectively.

Table 1: Concentration of the Radionuclides in Bq/Kg and ppm in each Sample

Sample	Conc. of ^{40}K (Bq/kg)	Conc. of ^{40}K (ppm)	Conc. of ^{238}U(Bq/kg)	Conc. Of ^{238}U(ppm)	Conc. of ^{232}Th (Bq/kg)	Conc. of ^{232}Th (ppm)
1	36.0 ± 0.1	1190.72	3.7 ± 0.7	0.30	105.2 ± 0.1	25.81
2	69.43 ± 0.1	2294.52	22.6 ± 0.6	1.85	143.5 ± 0.1	35.22
3	59.2 ± 0.1	1955.45	22.9 ± 0.6	1.87	83.2 ± 0.1	20.43
4	7.8 ± 0.2	256.12	16.7 ± 0.6	1.37	0.5 ± 0.1	0.12
5	59.1 ± 0.1	1951.49	6.4 ± 0.7	0.52	61.3 ± 0.1	15.04
6	5.5 ± 0.1	181.43	15.1 ± 0.6	1.24	40.6 ± 0.1	9.97
7	25.9 ± 0.1	855.61	5.5 ± 0.7	0.45	64.1 ± 0.1	15.72
8	40.4 ± 0.1	1336.46	10.4 ± 0.7	0.85	101.1 ± 0.1	24.82
9	45.5 ± 0.1	1502.03	15.6 ± 0.6	1.27	124.8 ± 0.1	30.64
10	19.8 ± 0.1	654.35	BDL	BDL	139.0 ± 0.1	34.11
11	48.3 ± 0.1	1596.88	10.9 ± 0.6	0.89	108.5 ± 0.1	26.62
12	58.0 ± 0.1	1916.12	0.6 ± 0.8	0.05	68.9 ± 0.1	16.90
13	43.1 ± 0.1	1423.38	8.7 ± 0.7	0.71	125.6 ± 0.1	30.83
14	65.1 ± 0.1	2148.78	1.5 ± 0.8	0.12	52.5 ± 0.1	12.88
15	14.7 ± 0.1	484.81	BDL	BDL	64.6 ± 0.1	15.85
16	50.2 ± 0.1	1660.00	11.0 ± 0.6	0.90	130.1 ± 0.1	31.94
17	95.4 ± 0.1	3154.10	0.7 ± 0.8	0.06	30.5 ± 0.1	7.49
18	97.4 ± 0.1	3217.22	7.9 ± 0.7	0.65	47.9 ± 0.1	11.76
19	41.8 ± 0.1	1380.09	2.9 ± 0.7	0.24	112.5 ± 0.1	27.61
20	33.2 ± 0.1	1096.20	1.3 ± 0.8	0.11	152.6 ± 0.1	37.45
21	42.1 ± 0.1	1391.65	7.9 ± 0.7	0.65	82.5 ± 0.1	20.24
22	48.6 ± 0.1	1604.81	4.5 ± 0.7	0.34	87.3 ± 0.1	21.42
23	36.5 ± 0.1	1206.58	BDL	BDL	93.1 ± 0.1	22.84
24	1.6 ± 0.1	59.16	BDL	BDL	5.6 ± 0.1	1.36
25	66.5 ± 0.1	2196.04	1.1 ± 0.8	0.09	80.5 ± 0.1	19.75
26	25.1 ± 0.1	827.85	0.00 ± 0.00	BDL	42.6 ± 0.1	10.46
27	94.5 ± 0.1	3122.71	5.1 ± 0.7	0.42	61.3 ± 0.1	15.04
28	49.4 ± 0.1	1632.24	BDL	BDL	43.6 ± 0.1	10.71
29	26.3 ± 0.1	867.51	9.3 ± 0.7	0.76	145.3 ± 0.1	35.66
30	52.6 ± 0.1	1738.66	6.2 ± 0.7	0.51	60.0 ± 0.1	14.73
31	68.5 ± 0.1	2263.13	0.7 ± 0.8	0.06	84.5 ± 0.1	20.74
32	11.2 ± 0.1	370.47	5.8 ± 0.7	0.48	108.7 ± 0.1	26.68
33	74.3 ± 0.1	2456.13	5.8 ± 0.7	0.48	122.3 ± 0.1	30.02
34	30.8 ± 0.1	1017.22	12.7 ± 0.6	1.04	BDL	BDL
35	68.1 ± 0.1	2251.23	18.8 ± 0.6	1.54	127.1 ± 0.1	31.20
36	38.2 ± 0.1	1261.77	21.1 ± 0.6	1.72	2.5 ± 0.1	0.62
37	54.2 ± 0.1	1789.88	15.9 ± 0.6	1.30	35.8 ± 0.1	8.79
38	32.2 ± 0.1	1063.82	10.8 ± 0.6	0.88	140.5 ± 0.1	34.48
39	83.6 ± 0.1	2763.81	6.5 ± 0.7	0.53	48.4 ± 0.1	11.88
40	24.1 ± 0.1	796.46	BDL	BDL	87.5 ± 0.1	21.48
41	31.4 ± 0.1	1037.05	12.2 ± 0.6	1.00	132.7 ±0.1	32.56
42	44.3 ± 0.1	1462.71	4.9 ± 0.7	0.40	80.7 ± 0.1	19.81
43	57.5 ± 0.1	1900.26	BDL	BDL	23.0 ± 0.1	5.63
44	56.3 ± 0.1	1860.93	8.9 ± 0.7	0.73	58.3 ± 0.1	14.30
45	33.1 ± 0.1	1092.24	BDL	BDL	55.0 ± 0.1	13.50
46	72.5 ± 0.1	2396.97	4.5 ± 0.7	0.36	41.9 ± 0.1	10.28
47	85.2 ± 0.1	2815.03	5.0 ± 0.7	0.41	143.5 ± 0.1	35.22
48	66.7 ± 0.1	2203.97	1.2 ± 0.8	0.10	66.6 ± 0.1	16.34
49	71.1 ± 0.1	2349.71	7.1 ± 0.7	0.58	65.6 ± 0.1	16.09
50	26.7 ± 0.1	883.04	BDL	BDL	118.0 ± 0.1	28.97

*Below Detection Limit

Table 2: Radiogenic Heat Production Rate in each Soil Sample (pW/kg)

S/N	Coordinates		^{40}K (pW/kg)	^{238}U (pW/kg)	^{232}Th (pW/kg)	Total (pW/kg)
	Long. (^{o})	Lat.(^{o})				
1	4.79	7.16	4.1	28.5	660.9	693.5
2	4.79	7.14	8.0	176.3	901.7	1086.0
3	4.77	7.14	6.8	178.2	523.0	708.0
4	4.79	7.14	0.9	130.4	3.1	134.4
5	4.75	7.13	6.8	49.8	385.1	441.7
6	4.75	7.13	0.6	117.8	255.1	373.5
7	4.79	7.13	3.0	42.5	402.5	448.0
8	4.74	7.12	4.7	81.2	635.5	721.4
9	4.75	7.12	5.2	121.2	784.4	910.8
10	4.76	7.12	2.3	0.0	873.2	875.5
11	4.78	7.12	5.6	84.5	681.5	771.6
12	4.79	7.11	6.7	4.4	432.6	443.7
13	4.80	7.13	5.0	67.6	789.2	861.8
14	4.75	7.11	7.5	11.6	329.6	348.7
15	4.77	7.11	1.7	0.0	405.7	407.4
16	4.80	7.11	5.8	85.4	817.8	909.0
17	4.78	7.10	11.0	5.3	191.8	208.1
18	4.76	7.10	11.2	61.8	301.1	374.1
19	4.78	7.10	4.8	22.7	706.8	734.3
20	4.79	7.10	3.8	10.1	958.8	972.7
21	4.76	7.09	4.8	61.8	518.2	584.8
22	4.77	7.09	5.6	32.3	548.3	586.2
23	4.82	7.09	4.2	0.0	584.8	589.0
24	4.83	7.09	0.2	0.0	34.9	35.1
25	4.82	7.09	7.6	8.2	505.5	521.3
26	4.81	7.08	2.9	0.0	267.8	270.7
27	4.80	7.08	10.9	39.6	385.1	435.6
28	4.76	7.08	5.7	0.0	274.2	279.9
29	4.77	7.08	3.0	72.4	912.8	988.2
30	4.76	7.08	6.1	48.3	377.1	431.5
31	4.77	7.07	7.9	5.3	530.9	544.1
32	4.78	7.07	1.3	45.4	683.0	729.7
33	4.78	7.07	8.5	45.4	768.6	822.5
34	4.80	7.07	3.5	98.5	0.0	102.0
35	4.76	7.05	7.8	146.4	798.7	952.9
36	4.80	7.05	4.4	164.2	15.8	184.4
37	4.78	7.04	6.2	123.6	225.0	354.8
38	4.82	7.04	3.7	84.0	882.7	970.4
39	4.77	7.03	9.6	50.7	304.3	364.6
40	4.78	7.03	2.8	0.0	549.9	552.7
41	4.81	7.03	3.6	95.1	833.6	932.3
42	4.77	7.02	5.1	38.2	507.1	550.4
43	4.77	7.03	6.6	0.0	144.2	150.8
44	4.78	7.02	6.5	69.6	366.0	442.1
45	4.78	7.02	3.8	0.0	345.5	349.3
46	4.78	7.01	8.3	34.7	263.1	306.1
47	4.80	7.01	9.8	38.6	901.7	950.1
48	4.80	7.01	7.7	9.2	418.4	435.3
49	4.82	7.01	8.2	55.1	412.0	475.3
50	4.80	6.99	3.1	0.0	741.7	744.8
		Total	**274.9**	**2646.0**	**25140.1**	**28061.1**
		Mean	**5.5**	**52.9**	**502.8**	**561.2**

Table 3: Conversion Factors from Becquerel to Part per Million

Radionuclide	**K-40**	**U-238**	**Th-232**
$BqKg^{-1}$	0.030259	12.222222	4.074074
Ppm	1	1	1

Results and Discussions

The radiogenic heat production rate are presented in Table 2, showing ^{232}Th, as having the heat production rate ranging from BDL (Below Detection Limit) to 958.8 $pWkg^{-1}$, with a mean of 502.8 $pWkg^{-1}$, followed by ^{238}U values ranging from BDL to 178.2 $pWkg^{-1}$, with a mean of 52.9 $pWkg^{-1}$, and least heat production rate by ^{40}K, with values ranging from BDL to 11.2 $pWkg^{-1}$, with a mean of 5.5 $pWkg^{-}1$. This trend is observed to be similar to that obtained from a similar work carried out in the Benue trough in the Northern part of the country [7].

From Figure 2, it can be seen that the heat production rate is highest at location 2 with coordinates 4.79^{o}, 7.14^{o}. This can be explained from the high value of thorium at this location. Figure 3 shows that heat production rate due to Th-232 is highest at location 20, while those due to U-238 and K-40 are highest at locations 3 and 18 with coordinates 4.77^{o}, 7.14^{o} and 4.76^{o}, 7.10^{o} respectively.

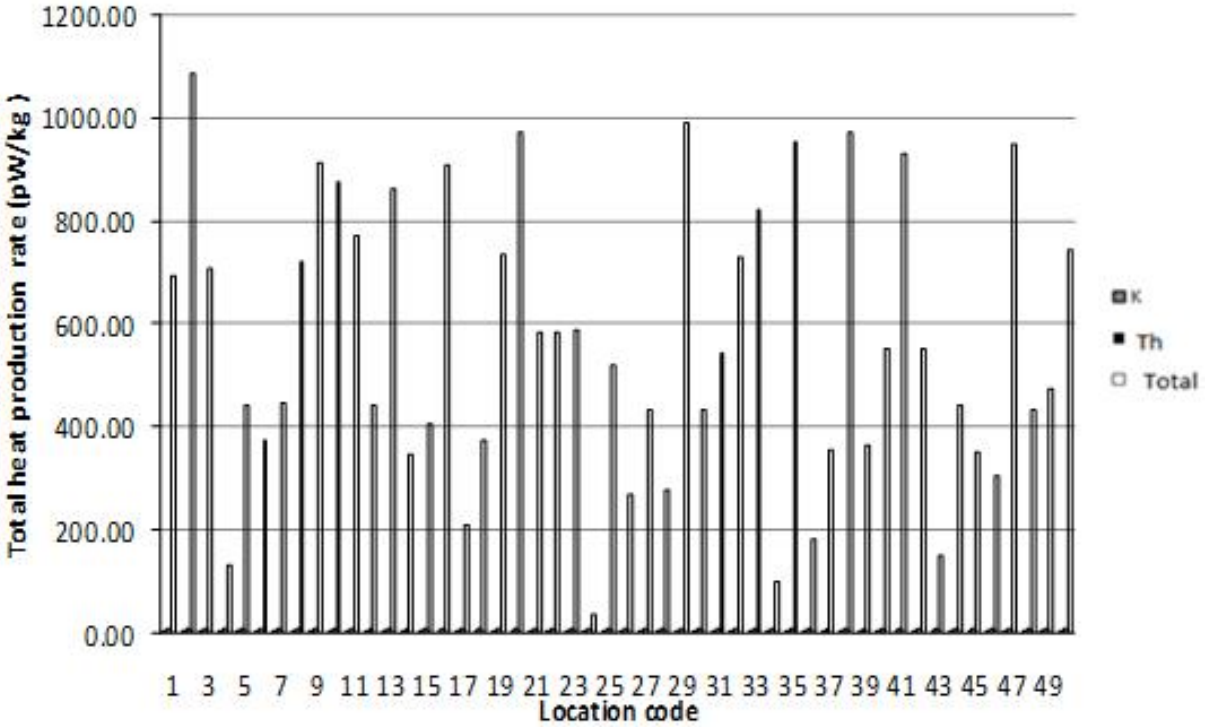

Fig. 2: Total heat production rate of radionuclides at each point.

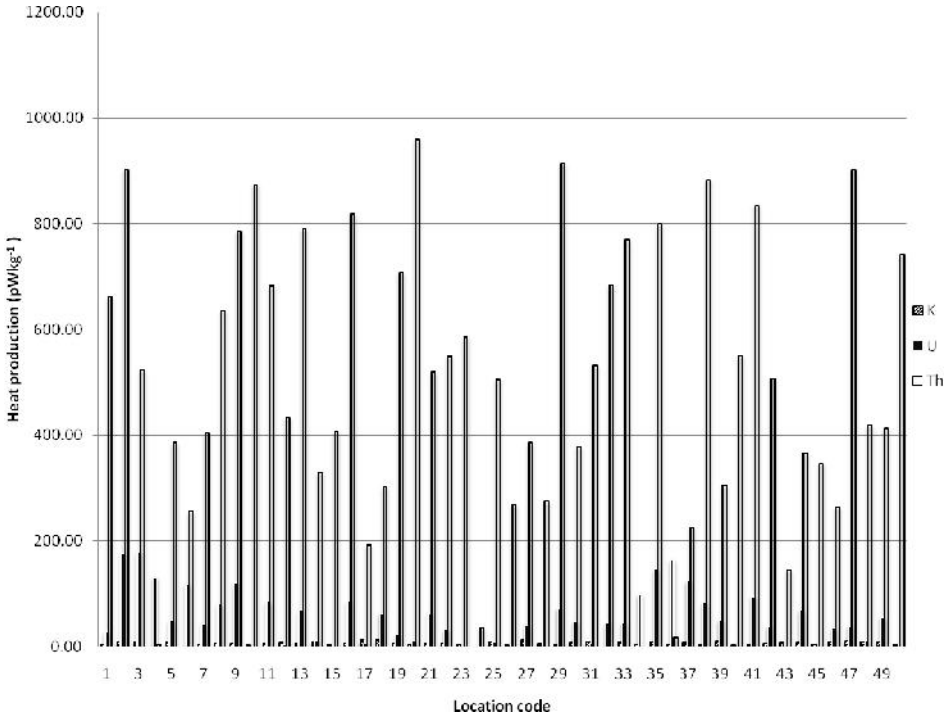

Fig. 3: Heat production rate of each radionuclide at each sampling point.

Total heat production rate for the sites ranged from 35.1 to 1086.0 $pWkg^{-1}$. The mean total heat production rate is 561.2 $pWkg^{-1}$ (Table 2) and 90% of the mean value is from Th-232 while U-238 and K-40 contribute 9% and 1% respectively. The results also show that the heat production rates for the samples from Obio-Akpor area are higher than those of the samples from Oyo and Osun States [8, 9] and lower than those of the Benue trough [7]. The surface distribution of total heat production rate across the study area is shown in Figure 4.

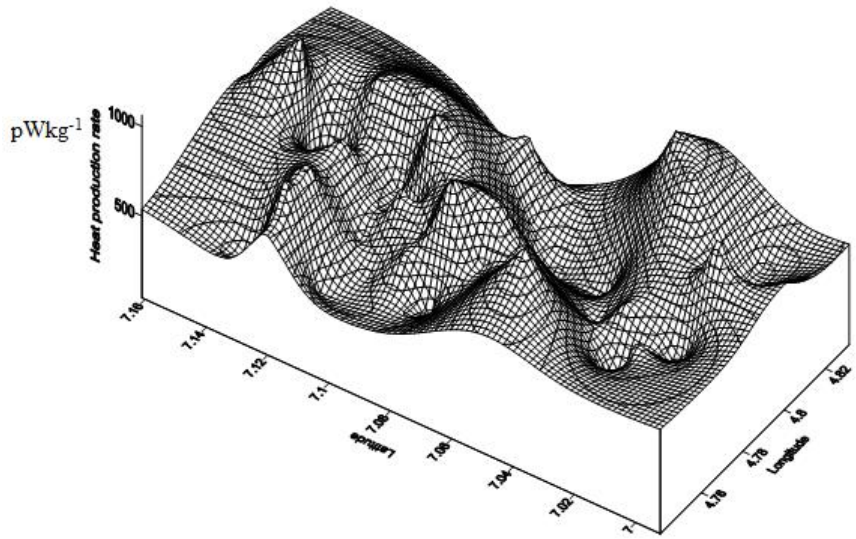

Fig. 4: A contour map of radiogenic heat production rate of the area.

Conclusion

Gamma-ray spectrometry method, using a NaI(Tl) scintillation detector was used to determine the elemental concentrations of the primordial radionuclides K-40, Th-232 and U-238 in soil samples from selected sites from Obio-Akpor area. Radiogenic heat production for each sample was calculated using the radioactivity concentrations of the radionuclides. Results show a wide variation in the concentrations of radionuclides and heat production rates. Heat produced by ^{232}Th is highest in all samples, while that of ^{40}K is lowest. The heat production rates for most of the sampling points are lower than those obtained from the Benue trough where heat production due to ^{232}Th is also the highest.

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