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Radiogenic Heat Production Due to Natural Radionuclides in the Sediments of Bonny River, Nigeria

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Authors' contributions

This work was carried out in collaboration between both authors. Author CPO designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Author AB managed the analyses of the study. Author AB managed the literature searches. Both authors read and approved the final manuscript.

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ABSTRACT

In this study, the analysis of sediment samples was carried out to determine the concentrations, distribution and the pattern of Radiogenic Heat Production of radioactive elements in sediment samples from Bonny River, Rivers State, Nigeria. Twenty sediment samples were collected at various sites of the River and the analysis of the sediment samples using a cylindrical NaI(Tl) detector reveals that the contents of the radioactive elements (^{238}U, ^{232}Th and ^{40}K) in the sediments fall below the WHO's critical values of contaminated sediment/soil. Field observations and sediment properties show that the sediments were derived from weathering of preexisting sedimentary bedrocks which constitute the geology of the area. The results also show that the contribution and rate of heat production of ^{40}K, ^{238}U and ^{232}Th in the samples vary significantly with geological locations, which ranged 0.0286 µW/m^3 to 2.5094 µW/m^3 with an average value of 0.6002±0.64 µW/m^3, with ^{232}Th as the major element which predominates in heat production for the Bonny River sediment of the study area, while ^{238}U and ^{40}K are trace elements. The radiogenic

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heat production elements (RHPE) contribution shows that all the points on the sites have the same pattern of radiogenic heat production contribution of the elements to the radiogenic heat production (RHP).

Keywords: Radiogenic; heat production; Bonny River; sediment.

1. INTRODUCTION

The thermal structure and evolution of continents depend strongly on the amount and distribution of radioactive heat sources in the crust [1]. Determining the contribution of crustal rocks beneath a superficial layer is a major challenge because heat production depends weakly on major element composition and physical properties such as seismic wave speed and density. Enriched granitic intrusive that lie at the current erosion level have a large impact on the surface heat flux but little influence on temperatures in the deep crust [2].

Analysis of global and regional data sets reveals the absence of a positive correlation between surface heat flow and crustal thickness, showing that the average crustal heat production is not constant [3]. Differences of heat flow between geological provinces are due in large part to changes of crustal structure and bulk composition. Collating values of the bulk crustal heat production in a few age intervals reveals a clear trend of decrease with increasing age [2]. This trend can be accounted for by radioactive decay, indicating that thermal conditions at the time of crustal stabilization have not changed significantly. For the average crustal thickness of 40 km, Moho temperatures are near solidus values at the time of stabilization, suggesting an intrinsic thermal control on the crustal thickness and heat production distribution. Crustal thickening by more than about 10 km above the mean value induces changes of gravitational potential energy that exceed the strength of the lithosphere [1,2].

Determining the temperature distribution within the lithosphere requires the knowledge of the radiogenic heat production (RHP) distribution within the crust and the lithospheric mantle [4]. RHP of crustal rocks varies considerably at different scales as a result of the petrogenetic processes responsible for their formation and therefore RHP depends on the considered lithology's [5]. The radiogenic decay of the unstable isotopes of uranium (^{238}U; ^{235}U), thorium (^{232}Th) and potassium (^{40}K) provides the largest internal source of heat [6,7]. During radioactive decay, mass is converted into energy. The energy emitted by decay processes, consisting of the kinetic energy of the emitted particles and the γ- radiation associated with the different decay processes is absorbed in the rocks and finally transformed into heat [8].

Radiometric surveys are of use in geological mapping as different rock types can be recognized from their distinctive radioactive signature [9]. The widespread occurrence of geothermal manifestations in Nigeria is significant because the wide applicability and relative area of exploitation of geothermal energy are of vital importance to an industrializing nation like Nigeria [1]. There are three known geothermal resource areas in Nigeria: the Ikogosi Warm Springs of Ekiti State, the Wikki Warm Springs of Bauchi State and the Rafin Rewa Warm Springs of Jos in Plateau State. A combination of measurement and analyzing radionuclides contributions to geothermal heat production would help in the accurate evaluation of suspect geothermal resource areas for future detailed investigations and possible exploitation [10].

In this study, measurement of activity concentration of Potassium (^{40}K), Uranium (^{238}U) and Thorium (^{232}Th) was done using Gamma-ray spectroscopy. The activity concentrations in $Bqkg^{-1}$ were converted to parts per million (PPM), which was used in the determination of radiogenic heat production of each of the elements and its distribution pattern.

2. MATERIALS AND METHODS

2.1 Study Area

Bonny Island is approximately 40 km South of Port Harcourt in the Rivers State of Nigeria and on the eastward side of the Cameroon Mountain. The Island lies on the E7°10' N4°27'with an estimated population of 270,000 [11] and plays host to multinational oil and gas companies such as Shell Petroleum Development Company (SPDC) Export terminal, Mobil Producing Unlimited, Chevron Nigeria Limited and Nigerian Liquefied Natural Gas Company (NLNG). Other cottage industries exist but on a small scale. These include bakeries, block molding, tile manufacturing as well as gas and welding industries [12]. The region produces a type of crude oil as Bonny light oil. Much of the oil extracted onshore in Rivers State is piped to Bonny for export. The Island has a relatively flat topography on an elevation of 3.05 atmospheric mean sea level with a total land area of 214.52m^2 [13] with about 70% of its size suffering from tidal flooding and land subsidence. The geology of the area comprises basically of alluvial sedimentary basin and basement complex. The substrata of the island consist mainly of fine sands, down to about 10m with occasional clay layers. Figure 1 shows the map of Bonny indicating sampling points. Economically, the main occupations of people on Bonny Island are farming, fishing and trading.

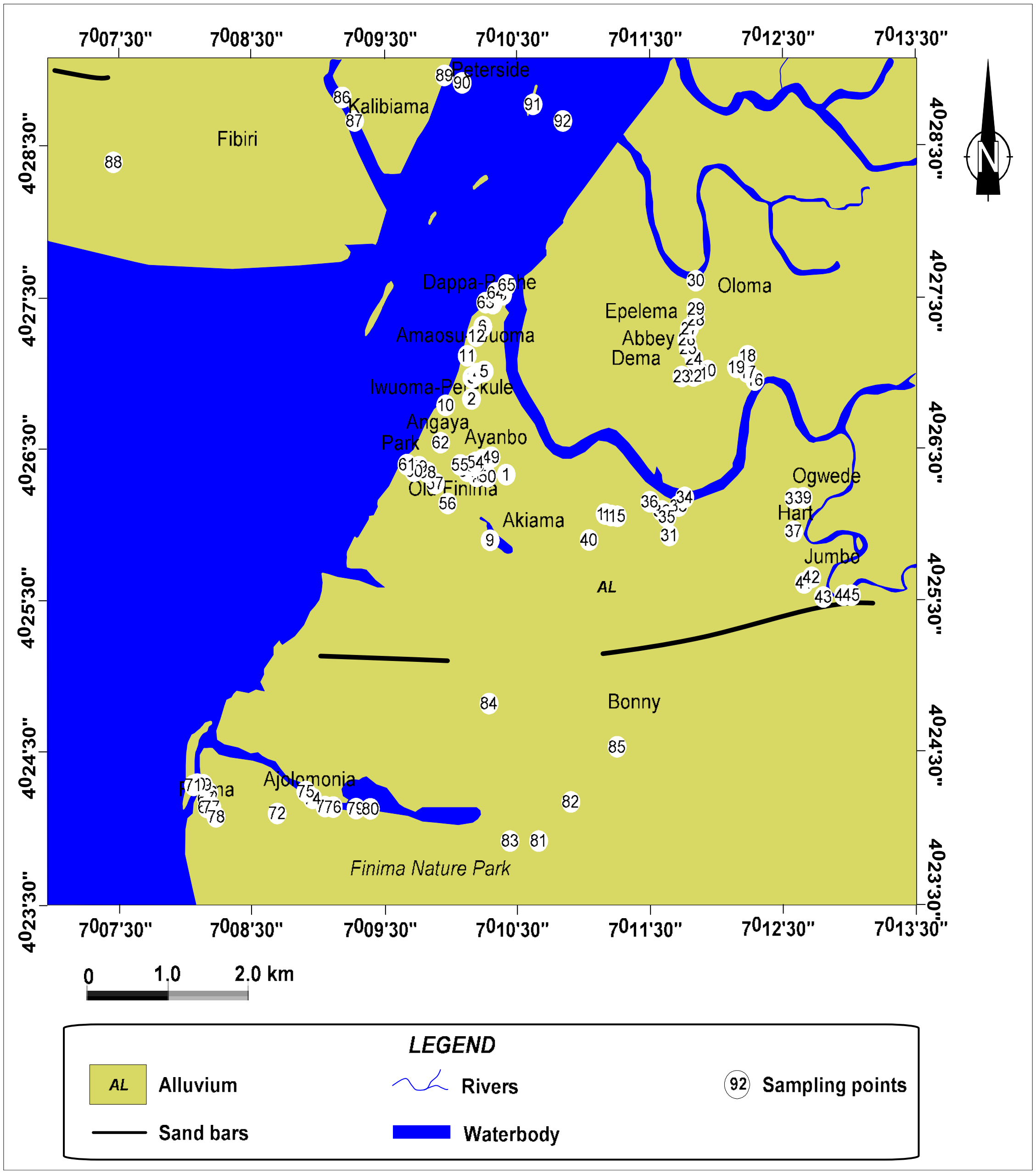

Fig. 1. Map of Bonny Island showing sampling points

Farming takes place on the dry land ridges within the galloping swamp forest. Fishing is a very important economic activity at Bonny Island. It has been estimated that fish may account for as much as 80% of protein consumption in such coastal areas of Nigeria. The catches are partly retained for consumption and partly sold at market.

2.2 Sample Collection and Analysis

20 samples of sediments were collected from the Bonny River. The location of the sampling points was taken by a Global Positioning System. The samples were placed in polyethylene bags and transported to the laboratory. The collected samples were taken to the laboratory, air dried to remove moisture, pulverized into a fine powder for the greater surface area using a mini mortar and pestle before homogenized by sieving with a 2mm sieve [14]. Dried samples weighted 0.5kg were measured, packed into a white cylindrical plastic PVC container, labelled appropriately, sealed and airtight with a paper tape. The containers were sealed and airtight to prevent the escape of gaseous ^{220}Rn and ^{222}Rn, incubated for about a month to bring the daughter radionuclide into secular radioactive equilibrium with their respective long-lived parents [15,16,17,18]. The activity concentration measurement was determined using a thallium activated Canberra vertical high purity 2″×2″ Sodium iodide (NaI(TI) detector connected to ORTEC 456 Digi base amplifier. The detector was connected to a computer program MAESTRO window that matched gamma energies to a library of possible isotopes. The detector was shielded by 15cm thick lead on all four sides and 10 cm thick on top. The energy resolution of 2.0 keV and relative efficiency of 33% at 1.33Mev was achieved in the system with the counting ε time of 10800 seconds. The detector limits of the sodium iodide detector used are 0.010, 0.027 and 0.006 Bqkg^{-1} for uranium, thorium and potassium respectively.

2.3 Radiogenic Elements and Radiogenic Heat Production (RHP)

The heat generated by long-lived isotopes has been an important heat source during most of Earth's history. In order to be a significant source of heat radioactive isotopes must have a half-life comparable to the age of the Earth, the energy of its decay must be fully converted to heat and isotopes must be sufficiently abundant. The main isotopes that fulfill these conditions are 238U, 235U, 232Th and 40K. The isotope 235U has a shorter half-life than 238U and release more energy in its decay [10]. In this work, an attempt had been made so as to determine the radioactivity heat produced by the naturally occurring radionuclides present in Bonny river sediments in all the different sites of the locations covered.

The total heat generation A of a rock (sediment) is the sum of the individual contributions Au, A_{Th} and A_k by uranium, thorium and potassium [19].

$$A = \rho * (C_U A_U' + C_{Th} A_{Th}' + C_K A_K') \quad (1)$$

Where ρ is sediment density A' and C is the heat generated per mass of element and concentration of an element in question in the sediment. Thus, if the density of the sediment is ρ and the concentrations in Uranium (C_U), thorium (C_{Th}) and potassium (C_K) are known, its radiogenic heat generation rate A can be determined using the values given [19].

$$A[\mu Wm^{-3}\} = 10^{-5}*\rho[kgm^{-3}]*(9.52*C_u[ppm] + 2.56*C_{Th}[ppm] + 3.48*C_k[\%]) \quad (2)$$

Where concentration are given in weight-ppm (i.e 10^{-6}kg/kg), weight-ppm and weight-% for uranium, thorium and potassium respectively. The density of the samples from Bonny River was calculated. The mass of each sediment was 0.2kg. The plastic container used for the package of the sediments and soil during measurement was cylindrical in shape and so the dimension of the volume was $\pi r^2 h$, the diameter was 6.5cm and the height was 9.00cm, therefore to calculate the density of the sediment samples [18].

$$\text{Density of samples} = \frac{Mass}{Volume} \quad (3)$$

$$\text{Density} = \frac{0.2}{\pi r^2 h}\left(kg / m^3)\right) \quad (4)$$

Equation 4 was used to generate the value of the density for each of the samples obtained. The concentration in ppm (parts per million) for ^{238}U and ^{232}Th and in % for ^{40}K of each of the twenty sites were used to calculate the radiogenic heat production [19].

3 RESULTS AND DISCUSSION

The photopeak counts obtained for each rock sample was converted to concentration in Bqkg^{-1} by using a standard conversion factor. Thereafter, the concentration of the radionuclides was converted from Bqkg^{-1} to ppm (part per million) as presented in Table 1. Radiogenic heat production was computed from the U, Th, K concentration using the formula (2) proposed by [19], and presented in Table 1. Considering the distribution of the radiogenic heat production elements (RHPE) contribution, it can be seen from the pattern of distribution shown in Table 1, that ^{232}Th is the major element which predominates in heat production while ^{238}U and ^{40}K are trace elements.

From the result obtained, the radiogenic heat production rate was estimated to range from 0.0286 µW/m^3 at Abalamabie (SEAB 1) to 2.5094 µW/m^3 at Hart/Long John(SEL) with a mean value of 0.6002±0.64 µW/m^3 this means that Bonny River sediments had shown radiogenic heat production with less than 1µW/m^3. The contribution to the radiogenic heat production rates of Bonny River was mostly from Thorium followed by Uranium then Potassium with a percentage contribution of 75.47%, 21.73% and 2.80% respectively (Table 1, Fig. 2). Although the high radioactive concentration of a particular radionuclide at a given location does not necessarily imply high contribution to radiogenic heat production rate [19]. Measurements of radiogenic heat in rocks of Southeastern Nigeria show relatively higher values, in the range of 3 to 65% as the contribution of radiogenic heat production to surface heat flow Joshua *et al*. [20]. Alabi et al. [21] noted that rock samples from Erin-Ijesha River are associated with high total heat production of between 8.21 and 235.82 pW kg^{-1}, which varies significantly with geological location.

Three groups of total Heat Production (HP) have been identified and designated as low (LHP), moderate (MHP) and high (HHP) Ehinola et al. [22]. The LHP sandstones include Bima Sandstone (BS), limestone of Dukul Formation (DF) and coal of Lamja Sandstone (LS) with total heat production of <750 pW kg^{-1}. Clay of BS, siltstone of Yolde Formation (YF), limestone of Sukuliye Formation (SF) and Numanhan Formation (NF) and sandstone of LS belong to MHP with total heat production of between 750 and 1500 pW kg^{-1}. Shale of YF, SF and NF with total heat production of >1500 pW kg^{-1} belong to HHP. Ray et al. [23] made *in situ* radioelement (K, U and Th) analysis and heat production estimates at 59 sites in the Kerala Khondalite Block (KKB) of the Southern Granulite Province (SGP) of India and obtained relatively high mean radiogenic heat production values for garnet-biotite gneiss, khondalite, leptynite and charnockite as 5.5, 2.7, 2.4 and 2.2 µW m^{-3}, respectively and 2.6, 3.4, 4.6 and 1.4 µW m^{-3}, for the granites, leucogranites, granitic gneisses and syenites, respectively.

Okeyode [24], reported the average RHP of Ogun River sediment, Nigeria to be 0.48 µWm^{-3}, Yehuwdah [25] reported that the heat production rate of Delta Basin, Nigeria ranged from 0.0000014 µ^{o}c m^{-2} to 0.004µ^{o}cm^{-2} with the mean value of 0.0006µ^{o}cm^{-2} and Osimobi [26] with a mean value of 0.95µWm^{-3}. All of their values total heat production was lower than that obtained in this work (Bonny River sediment).

Similar results of radiogenic heat generation have also been observed in some of the granites and gneisses of the Bundelkhand and Bastar terrains in Central India, using *in situ* gamma-ray spectrometry [27] (Menon et al. 2003). The findings of Ali and Orazulike [28], [20-22,24] show marked differences with the results of this study. This may be attributed to differences in methodology, variations in the local geology of the different study areas, lithological variations and differences in geologic history of the different areas of study. On the other hand, the low radiogenic heat generation obtained in this study agrees with the low mean heat generation values for amphibolites rocks of 0.358±0.118 µW m^{-3} and tonalite gneiss rocks of 0.802±0.039 µW m^{-3} at Site 1067 and for serpentinized peridotite rocks of 0.0108±0.0003 µW m^{-3} at Site 1068 obtained by gamma-ray spectrometry measurements on data collected at Bremen Germany, landward of ocean drilling sites 1067 and 1068 during an ocean drilling project (ODP) leg 173 [29].

The low values of calculated heat production, percentage heat generation and heat contribution to surface heat flow in the Niger Delta region indicate that for the Niger delta crust, radiogenic heat production is an insignificant source of earth interior heat. Hence, radiogenic heat, therefore, may not be a necessary parameter for inclusion in thermal models of the Niger Delta basin. This is at variance with the high values obtained for the Gulf of Mexico [30].

Table 1. Concentration of ^{238}U, ^{232}Th and ^{40}K and radiogenic heat production sediments

Location Site	Site code	Activity Concentrations			Heat Production ($pWkg^{-1}$)				A(μWm^{3})
		^{40}K (%)	^{238}U(PPM)	^{232}Th	^{40}K	^{238}U	^{232}Th	Total	
Hart	(SEL 1)	2.1516	3.9447	128.7988	7.4875	37.5537	329.725	374.7662	2.5094
Fibiri	SEF 2	1.4449	2.2336	57.4656	5.0283	21.2634	147.112	173.4037	1.1611
Akiama	SEAK 1	0.6417	2.0780	11.1111	2.2331	19.7825	28.44431	50.45995	0.3379
Ajolomonia	SEAJ 1	2.1825	3.5947	BDL	7.5951	34.2216	0.00	41.81662	0.2800
Iwuoma	SEOG 1	0.5722	2.5447	BDL	1.9912	24.2253	0.00	26.21653	0.1755
Ayanbo	SEAY 1	0.0740	1.3780	BDL	0.2577	13.1183	0.00	13.37601	0.0896
Epelema	SEE 1	0.3289	4.6836	9.9102	1.1446	44.5881	25.37002	71.1027	0.4761
Agaya	SEAG	0.2503	3.2836	14.9539	0.8711	31.2597	38.28204	68.67061	0.4598
Abalamabie	SEAB 1	0.5722	0.2943	1.9843	1.9912	-2.8017	5.079688	4.269273	0.0286
Park Com. 1	SEPC 1	0.7962	2.1169	44.4960	2.7707	20.1527	113.9096	136.833	0.9162
Oloma	SEO 1	1.5569	2.6225	9.9102	5.4180	24.9658	25.37002	55.75381	0.3733
Minima	SEM 1	1.5453	3.6725	BDL	5.3777	34.9620	0.00	40.33974	0.2701
Main Bonny Town	SEMB 1	0.5567	1.3002	2.2244	1.9375	12.3779	5.694546	20.0099	0.1340
Light House	SELH 1	0.7267	3.9447	93.4925	2.5288	37.5537	239.3408	279.4232	1.8710
Park Com.2	SEPC 2	1.7770	4.1781	BDL	6.1840	39.7750	0.00	45.95907	0.3077
Peterside	SEP 1	0.7576	0.7557	BDL	2.6363	7.1946	0.00	9.830897	0.0658
Kalabiama	SEK	0.7962	4.0614	BDL	2.7707	38.6643	0.00	41.43501	0.2774
Ayanbo 2	SEAY2	1.0317	4.0614	51.7013	3.5904	38.6643	132.3554	174.6101	1.1692
Dappa-Poshe	SEAD-P	1.7423	3.6725	20.9584	6.0631	34.9620	53.65351	94.67861	0.6340
New Finima	SEFM 2	0.6147	1.7669	19.8720	2.1391	16.8207	50.87243	69.83214	0.4676

BDL = below detectable limit

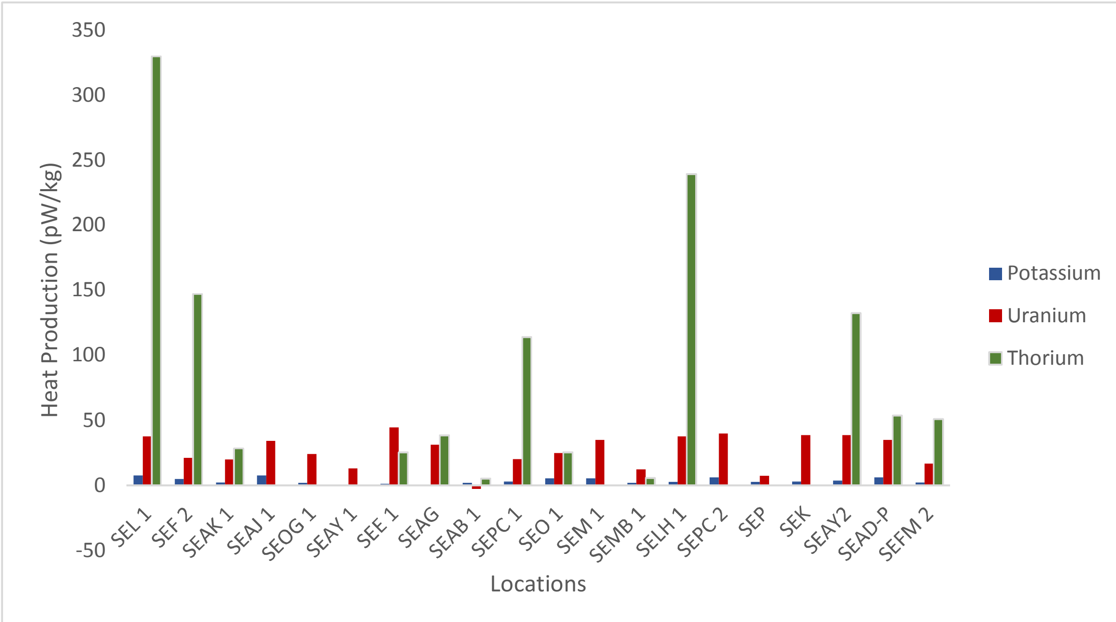

Fig. 2. Heat Production of different radionuclides

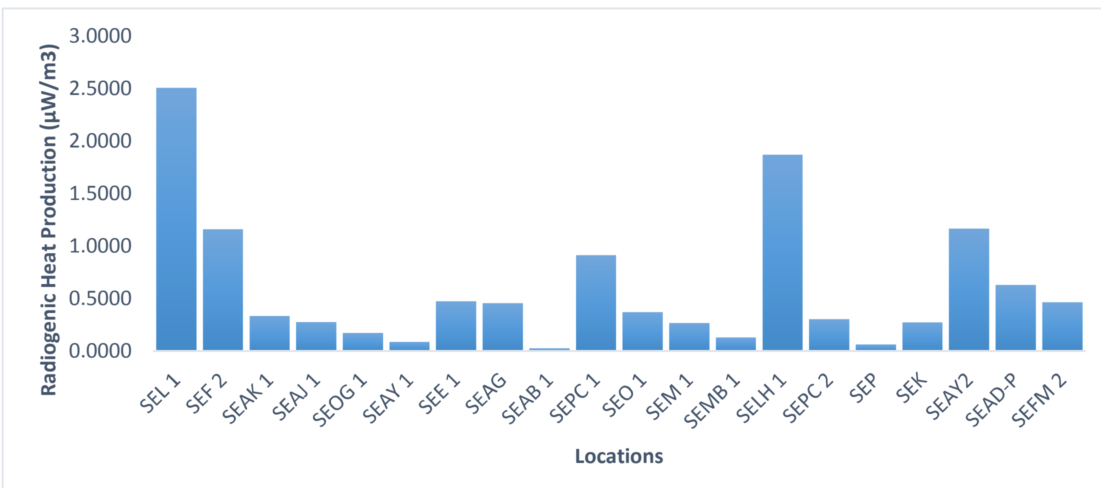

Fig. 3. Distribution of the radiogenic heat production rates from Bonny River

Fig. 2 is a bar graph showing a wide variation of heat generation of the three radionuclides while Fig. 3 reveals an irregular trend and distribution of total radiogenic heat generated with respect to their sampling areas. The observed wide variation in radiogenic heat produced from location to location might be due to localized differences in subsurface geology. Also, these values of a fraction of crustal heat budget or surface heat flow contributed by radioactive heat sources are considerably small when compared with the mean surface heat flow in continental areas of the Niger Delta [31]. This study was able to give an insight of the radiogenic heat production rate that contributed to the surface heat flow in Bonny River basin due to the radionuclide considered in the work.

4. CONCLUSION

It was observed from the result that radioactive elements are present in all the sediment samples and the heat production pattern of all the sites are the same. The SEL 1 and SELH had a high radiogenic heat production due to the effluents from gas the liquefied natural gas company emptying at the sites. There is the irregular contribution of these radionuclides (U, Th, and K) to the radiogenic heat production in the sediment as a result of their geological location.

Hence the model of radiogenic heat production of Rivers state of Nigeria has ^{232}Th as the major element, which predominates in heat production while ^{238}U and ^{40}K are trace elements. Due to the dearth of data on radiogenic heat generation studies in the area studied, we have been unable to carry out a comparative analysis of previous work that was situated in the basin. Therefore, the radiogenic heat generation properties determined for the Bonny area and presented in this study serve as baseline data and the basis for further research into the impact of radiogenic heat in the area. This study also provides new aspects for hydrocarbon and geothermal energy resource evaluation in the region.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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