

# Review of variability of radiogenic heat properties of some rock types as a basis for geothermal characterization in Nigeria

Sedara, S. O.\* and Asere, A. M.

Department of Physics and Electronics, Adekunle Ajasin University, Akungba-Akoko, Ondo State, Nigeria.

\*Corresponding author. Email: samuel.sedara@aau.edu.ng

Copyright © 2020 Sedara and Asere. This article remains permanently open access under the terms of the [Creative Commons Attribution License 4.0](https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Received 2nd June, 2020; Accepted 13th July, 2020

**ABSTRACT:** The southwestern part of Nigeria is one of the three known regions in Nigeria with geothermal prospect. It is characterized by distinctly different thermal state and surface thermal manifestations. Although a number of geophysical explorations have been undertaken, but studies on fundamental geothermal theory remain scarce, including a lack of high-quality heat flow determinations and thermal structure studies. Heat production and heat flow properties play a very critical role in the study of thermal structure in a region. In this report, heat production and heat flow data of rock samples from published studies from some localities in Nigeria was compiled. To optimize this data, the rock-type denominations from the original studies was classified. This was used to characterize the thermal structure of the areas for possible geothermal exploration and radiogenic heat production distribution for the different rock types in the region. This gave some useful guidelines to lithospheric thermal modeling. From the heat production data, there is a wide range in values with igneous rocks having a maximum  $11.17 \mu\text{Wm}^{-3}$  and the metamorphic rocks having  $131.37 \mu\text{Wm}^{-3}$  as maximum value. The metamorphic rocks have higher values than the igneous rocks while the heat flow compiled for the country area has a minimum of  $29 \text{mWm}^{-2}$  and a maximum of  $130 \text{mWm}^{-2}$  with a mean value of  $80 \text{mWm}^{-2}$ . The high heat flow observed from data of the southwest zones may suggest the existence of anomalous heat source body in crust due to the radiogenic heat of the solid crust. This work is also an appraisal to direct attention to the lack of thermal properties investigations in the southwestern part of Nigeria and the need to improve on the heat flow database of Nigeria. Hence some parts of the study areas could be further explored for geothermal energy using appropriate geophysical techniques.

**Keywords:** Heat flow, heat production, geophysical exploration, geothermal resources, thermal structure.

## INTRODUCTION

Geothermal energy is an environmentally friendly, renewable, and sustainable source of energy and is well positioned to play an important role in mitigating global climate change, increasing national energy security, and safeguarding public health (Harðarson, 2007). Geothermal energy is formed deep within the earth crust, and is exploited for electricity generation and other direct uses. The medium of this energy transfer is geothermal fluid. On the surface, these are manifested as hot grounds, fumaroles, geysers, mud-pools and hot springs (Clauser and Huenges, 1995). Therefore, in any geothermal studies, the rock thermal conductivity (TC) and heat

production constitutes vital parameters and is essential for the determination of the heat flow from the Earth's interior and is indispensable in any thermal modeling (Clauser, 2006). Also, the modeling of temperature distributions within the earth crust is critical to the characterization of geothermal reservoirs. The thermal conductivity and heat production of geological formations are of fundamental importance in understanding the thermal regime below the surface of the earth (Clauser, 2006). The huge unpredictability of thermal conductivity of rocks, predominantly within the upper crust has been recognized in some geothermal literature (Roy et al., 1981; Clauser and

Huenges, 1995; Clauser, 2006; Ray et al., 2007). Hence, investigations of the subsurface geothermal structure are very crucial to the understanding of geothermal activities and processes associated with active areas.

The exploitation of geothermal resources for energy is common practice in areas where geothermal gradients are high, such as tectonically active regions and in volcanic areas. As demand for sustainable energy increases, however, and the technology to harness it improves, geothermal resources in relatively quiet regions prove increasingly viable (Clauser and Huenges, 1995).

As a first step in any new heat flow and heat production studies, it is a good practice to collate data from previous works of researchers. However, locating all such data may not be simple. The compilations may include most published data available at this time but not all data are published and new data are always being collected. Not much has been done as regards the exploration and utilization of geothermal energy in Nigeria, though limited data are available due to the cost effect of acquiring well logging data. Though geothermal data are not restricted to heat flow measurements alone, other kinds of data are often sought such as the data compiled in this report such as radiogenic heat production, geothermal gradient and aeromagnetic data. Earlier studies relating to thermal modeling have been undertaken in Nigeria which has been limited to selected geophysical, geological and geochemical studies (Rogers et al., 1969; Loehnert 1985; Adegbuyi et al., 1996; Ajayi et al., 1996; Adegbuyi and Abimbola, 1997; Oladipo et al., 2005; Ojo et al., 2011; Joshua and Alabi, 2012; Abraham et al., 2014).

However, information about thermal conductivity of the different rock formations is practically non-existent primarily due to a lack of heat flow investigations especially in the southwest region. In recent years, however, interest in geothermal studies in the area have been propelled primarily because of the growing realization of the role of thermal evolution in understanding tectonics of the area and assessment of geothermal potential of the hot springs. Thermal models so far proposed for the area and other terrains in Nigeria are dependent on assumed values of thermal conductivity of the various rock types (Abraham et al., 2014; Olorunfemi et al., 2013). Nigeria's location within the continental crust and its low to moderate geothermal gradients (Abraham et al., 2014) have, until now, warranted little investigation into its geothermal properties.

This research report is an eye opener for the need to carry out in-depth investigations to acquire heat flow data from appropriate geophysical techniques and this will give a clearer understanding and proper thermal characterization of the southwest region.

### Heat flow studies

Heat flow values can be determined conventionally from deep boreholes (>150 m for shield area) by measuring thermal gradient in the boreholes and thermal conductivity

of rocks pertaining to the borehole lithologies by using Fourier's equation given in equation 1 (Beardmore and Cull, 2001):

$$\text{Heat flow, } q = \lambda * \frac{\partial T}{\partial Z} \quad (1)$$

where  $\lambda$ =Thermal conductivity and  $\frac{\partial T}{\partial Z}$ = Geothermal gradient.

Heat flow also can be determined from bottom hole temperature (BHT) but there are some indirect methods by which heat flow can be determined when no borehole is available, such as from aeromagnetic data. So, heat flow data around Nigeria was compiled to characterize the thermal structure of the subsurface. Conventional heat flow data in Nigeria is very less, it is available in the works of Brigaud and Lucazeau (1985) from the West Africa Shield (Nigeria, Ghana and Liberia) with values ranging between 30 to 40 mWm<sup>-2</sup> and Verheijen and Ajakaiye (1979) with average value of 38.5 mWm<sup>-2</sup> (Table 2). No borehole data or well logging data were available in the southwest. The heat flow estimation in southwest Nigeria has been through CPD estimation and assuming a constant Curie temperature and rock thermal conductivity value (Abraham et al., 2014). Hence most of heat flow data available around Nigeria were either acquired through aeromagnetic data or well logging. In absence of conventional heat flow data as well as thermal conductivity characterization of the rocks in the above area, it is difficult to arrive at the variations of reported heat flow from the actual heat flow of the regions. The heat flow data around Nigeria and heat flow values computed from this work from aeromagnetic data is presented in the Table 2 along with the methods applied.

### Radiogenic heat production studies of rocks

Radioactive decay of long-lived isotopes of potassium, uranium and thorium contributes to the bulk of the heat produced in the crust. Variation of abundance of these radioactive elements in rocks constituting the crustal column over a large region is reflected in the lateral variation of surface heat-flow. Most of the potassium is present in K-feldspar and micas, while uranium and thorium are largely present in the accessory minerals such as zircon, allanite, sphene, monazite, apatite etc. These minerals are more abundant in granitoid rocks, which therefore account for bulk of the heat production in the continental crust.

The radiogenic heat production of rock in the shallow crust is an important part of terrestrial heat flux as measured from the ground, and it is one of the important heat sources of the earth's inner heat. However, the heat difference may be great in different regions or geological conditions, and part of the heat is affected by factors such as the ability of the bedrock structure to carry on redistribution. Therefore, this important parameter should

be considered in order to faithfully simulate the formation temperature field. The radiogenic heat production of rock,  $A$  is the released energy in unit time from the disintegration of radionuclides contained in unit volume rock, and the measurement unit is  $\mu\text{W}/\text{m}^3$ . There are many radionuclides contained in rock, but only uranium (U), thorium (Th) and kalium (K) are relevant to terrestrial inner heat sources. Generally, the radiogenic heat production of rock is obtained by calculating the measured contents of U, Th and K in rock, and it can be calculated by seismic wave velocity for regions with no core sample holes. The space-time distribution of radionuclides has great influence on the terrestrial inner temperature field, and sometimes 30 to approximately 40% of ground heat flux density is generated by radionuclides. Therefore, radiogenic heat production is not an effective parameter for studying the physical characteristics of deep earth, such as the thermal status of the deep basin, and the thermal configuration of the lithosphere, but it is an important parameter for detailing the basin's geothermic history.

Though the southwestern Nigeria province has been suggested by earlier researchers to be a region of high heat-flow, although both heat-flow and heat production data are scanty compared to the data available from other regions. Heat production of the basement granitoids in this region has largely remained uncharacterized (cite reference in this paragraph).

The origin and distribution of naturally occurring radionuclides depend on the distribution of rocks from which they originate and the geological processes which concentrate them. By far, the biggest source of crustal heat is radioactive isotopic decay which, depending upon geographic location is estimated to generate up to 98%. Friction from plate motions, oxidation of sulphides and exothermic metamorphic and diagenetic processes make up the difference (Jessop, 1990). Other contributions, such as cosmic neutrino interaction with the earth mass (Hamza and Beck, 1972) and gravitational distortion (Beardsmore and Cull, 2001) are likely to be very small indeed. The decay of the unstable isotopes of uranium ( $^{238}\text{U}$  and, to a far lesser extent,  $^{235}\text{U}$ ), thorium ( $^{232}\text{Th}$ ) and potassium ( $^{40}\text{K}$ ) provide the largest internal source of crustal heat that is geologically significant today (Brown and Mussett, 1993). Using the heat production constant values, assumed or measured density ( $\rho$ ,  $\text{kg}/\text{m}^3$ ) and measured ppm concentrations of uranium ( $C_U$ ) and thorium ( $C_{Th}$ ), and wt.% concentration of potassium ( $C_K$ ), the heat production rate (HPR) has been determined thus:

$$HPR (\mu\text{W}/\text{m}^3) = 10^{-5}\rho (9.52C_U + 2.56C_{Th} + 3.48C_K) \quad (2)$$

(Rybach, 1988)

Radiogenic heat production values in the crust, in conjunction with heat flow density data, contribute to the knowledge of the structure of earth lithosphere (Taylor and McLennan, 1985; Beardsmore and Cull, 2001; Jaupart and Mareschal, 2003) and heat variation plays an important role in crustal processes (Bea et al., 2003; Sandiford and

McLaren, 2005). More practically, areas of high heat production are increasingly being identified as possible targets for hot dry rock geothermal resources. So radiogenic heat production calculated from a compiled dataset of previously published articles of over 100 rock samples of some parts of Nigeria was used for this research to characterize the thermal behavior of rocks from the heat flow and heat production data. This can be a basis for geothermal modeling studies.

## METHODOLOGY

### Geology and location of the study area

Generally, the southwest region of Nigeria is of basement complex (Figure 1). In general, Ekiti State is underlain by metamorphic rocks of the Precambrian basement complex, the great majority of which are very ancient in age. Thus, the study area is characterized by undulating land forms with the quartzite forming the highland and the river channels indicating valleys. The quartzite constitutes the residual hills covered with gently sloping sediment that post erosion threat to the environment (Oladipo et al., 2005; Ojo et al., 2011).

### Data collection and compilation

The data for this work was compiled from published and unpublished works of other researchers. This was done in order to evaluate the development of how natural radionuclide concentrations and heat flow of rocks vary with location. The compiled data analyses allowed for evaluating the mean behavior of the natural radionuclides distribution for each type of rocks and different locations and it also allowed evaluating the mean distribution along the locations. *In situ* analyses provide estimates representative of larger mass of rock in contrast to the laboratory analysis on much smaller samples. *In situ* gamma-ray spectrometric survey was carried out in some of the gneissic and granitic regions of Southwestern Nigeria and data from heat flow studies in some parts of Nigeria were also used in this research. Geothermal and heat flow distribution data was compiled from different locations in Nigeria from Curie Point Depth (CPD), temperature logging and thermal conductivity measurements. It will also serve as a concise access and update on the database of thermal property for the region.

## DATA DISCUSSION

### Radioelemental data and heat production estimates

The radioelemental concentrations and heat production values for the rocks are given in Table 1. These data indicated the following:

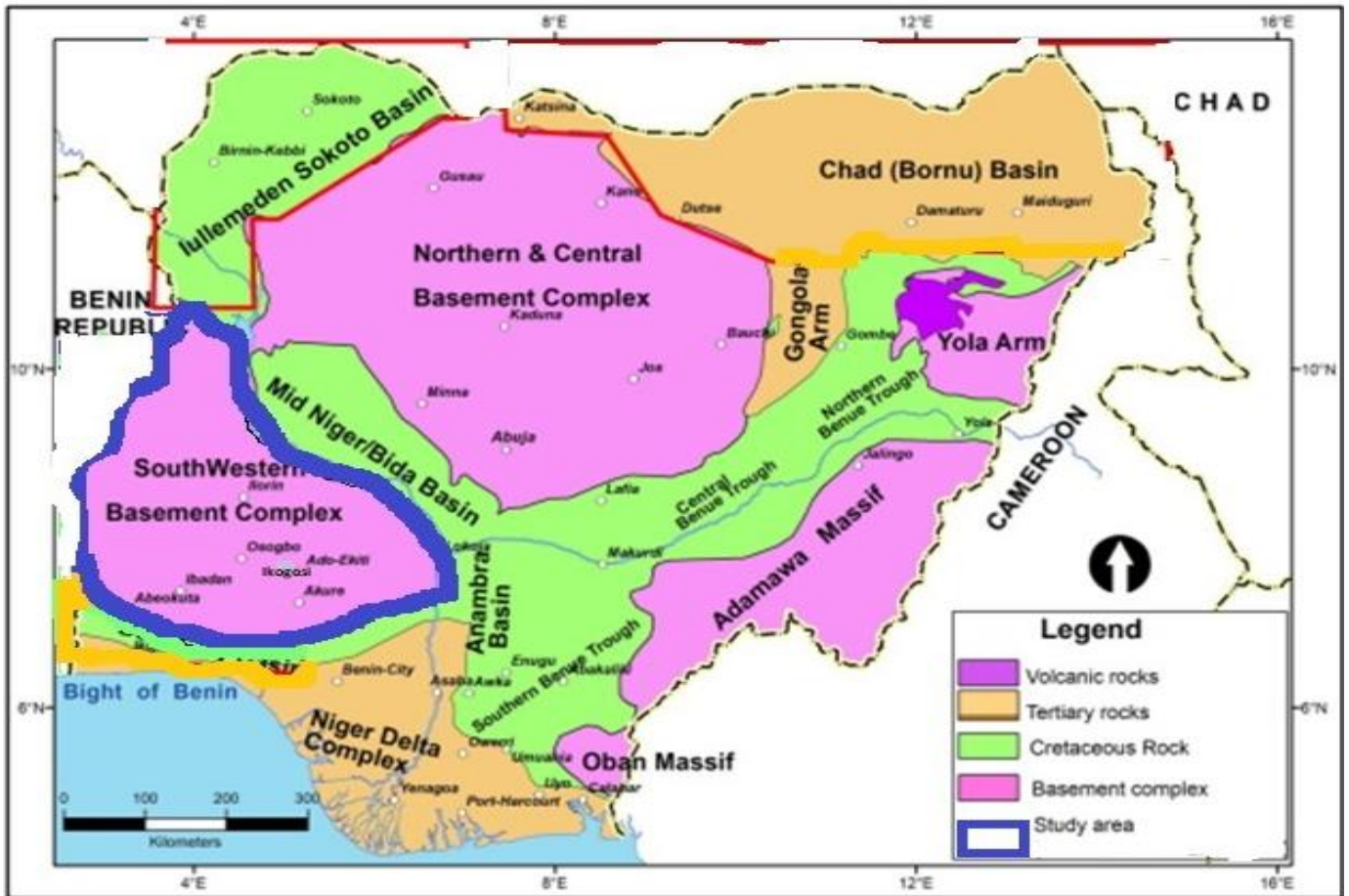


Figure 1. Geological Map of Nigeria (modified after Boboye et al., 2018). SW areas have been marked by blue tint.

1. The igneous group of the SW is distinctly moderate in K, U and Th abundances and account for low heat production which range between 0.04 to 11.17  $\mu\text{Wm}^{-3}$  (Faweya, 2008; Alabi et al., 2007; Joshua and Alabi, 2012; Sedara and Adelowo, 2015; Sedara et al., 2020).
2. The porphyritic and the medium-to-coarse grained varieties of Ekiti granite show a wide range of U and Th abundances, giving rise to a broad range of heat production. The mean heat production of these textural varieties, which are the most dominant rock type is 0.06 to 3.05  $\mu\text{Wm}^{-3}$ . The fine-grained granite, which is a minor phase, has a restricted range and lower heat production of 0.05 to 3.27  $\mu\text{Wm}^{-3}$ . This may have arisen because of a slightly lower content of U compared to that present in the porphyritic and coarse-to-medium grained variants (Oladunjoye et al., 2014; Okeyode and Akanni, 2009).
3. The distinct rise in the heat production of granitoids has been observed as evident from (1) and (2). However, such a rise in heat production is not evident. The granites have a mean heat production of 1.26  $\mu\text{Wm}^{-3}$  and the gneisses, 0.20  $\mu\text{Wm}^{-3}$ .
4. Among all the granites and gneisses rocks studied in the SW terrain, the migmatized gneisses are the most enriched in radioelements with an average of 46.7  $\text{mWm}^{-3}$  which accounts for the highest heat production. Also, the porphyritic granites which has an average heat production of 8.42  $\mu\text{Wm}^{-3}$  (Lapworth et al., 2018; Okeyode, 2012).
5. The pure granites/granitoid rocks of the southwest region examined appeared to be characterized by a high heat production compared to the granitoids and gneisses of the other terrain of the country (Figure 4).

#### Heat flow data compilation and estimates

Most of the heat flow studies in Nigeria were from the spectral analysis of aeromagnetic data and few from well logs. In general the heat flow from published research across Nigeria varies between 29 and 141  $\text{mWm}^{-2}$  (Anomohanran, 2004; Megwara et al., 2012; Nwankwo and Sunday, 2017; Nwankwo et al., 2009; Onuoha and Ekine, 1999; Ozoko and Ifediegwu, 2016; Avobovbo, 1978; Nwachukwu, 1976; Adetona et al., 2017; Ayuba and

**Table 1.** Compiled radioelement abundances and heat production for major rock types in Southwestern Nigeria.

Lithology	D	N	K%		U(ppm)		Th(ppm)		A( $\mu\text{Wm}^{-3}$ )		References
			Range	Mean	Range	Mean	Range	Mean	Range	Mean	
IG porphyritic granite	2.65	9	3.25-3.67	3.44	1.80-4.60	3.48	63.20-142.5	104.63	5.71-11.17	8.42	Oladunjoye et al., 2014
IG Pegmatite	2.65	2	3.30-4.53	3.92	1.50-8.00	4.75	4.00-10.10	4.75	1.50-2.64	2.07	
IG Granites	2.65	5	2.82-3.61	3.18	0.61-0.93	0.78	26.10-28.60	27.58	2.31-2.51	2.4	Okeyode and Akanni, 2009
IG pegmatite	2.65	5	0.34-0.69	0.46	0.01-0.02	0.02	0.01-0.03	0.02	0.04-0.07	0.05	Faweya, 2008
IG Aplites	2.65	5	0.41-1.32	0.88	0.02-0.025	0.02	0.003-0.079	0.03	0.044-0.13	0.09	
IG Pegmatite	2.65	1	2.48	-	0.5	-	0.15	-	0.37	0.37	Alabi et al., 2007
IG Granite	2.65	28	0.05-4.28	1.79	0.00-1.00	0.33	0.08-3.24	0.56	0.05-0.56	0.29	Joshua and Alabi, 2012
IG Granite	2.65	10	0.09-8.16	2.86	0.02-1.97	0.59	0.08-0.95	0.54	0.07-0.82	0.45	Sedara and Adelowo, 2015
IG Granites	2.65	27	0.59-2.39	1.48	0.70-7.60	3.17	6.70-24.30	13.4	0.97-3.27	1.88	Sedara, et al., 2020
MET Migmatitic gneiss	2.86	281	0.0012-6.67	1.74	0.97-224.00	11.6	4.39-922.00	65.6	0.59-131.37	46.74	Lapworth et al., 2018
MET charnockitic rock	2.86	6	0.33-1.17	0.81	0.01-0.33	0.01	0.01-0.07	0.03	0.04-0.22	0.1	
MET quartzite series	2.86	7	0.22-1.13	0.75	0.01-0.2	0.05	0.01-0.03	0.02	0.06-0.12	0.1	
MET Gneiss	2.86	18	0.06-3.87	0.68	0.04-0.81	0.23	0.08-0.95	0.41	0.06-0.51	0.16	
MET Quartzite	2.86	2	3.26-6.02	4.64	0.38-0.48	0.43	0.10-0.26	0.18	0.44-0.75	0.6	
MET Gneiss	2.86	2	1.70-1.85	1.77	0.04-0.08	0.06	0.52-0.59	0.56	0.22-0.25	0.24	
MET Schist	2.86	2	3.15-3.51	3.33	0.22-0.30	0.26	0.05-0.10	0.08	0.38-0.44	0.41	
MET Quartzite	2.86	1	6.02	-	0.15	-	0.5	-	0.68	0.68	
MET Mica-schist	2.86	1	0.85	-	0.81	-	0.24	-	0.33	0.33	
MET quartzites	2.86	22	0.01-2.81	1.33	0.06-7.60	2.42	1.70-20.60	8.27	0.22-3.05	1.42	Sedara et al., 2020
MET granite gneiss	2.86	9	1.23-1.95	1.61	0.46-1.67	0.94	1.59-5.67	2.51	0.44-1.03	0.61	Okeyode, 2012
MET biotite schist	2.86	6	1.48-1.87	1.66	0.87-1.29	1.05	2.04-2.88	2.38	0.55-0.72	0.63	
MET Quartzite	2.86	1	1.93		0.84		2.12		0.58	0.58	
MET granite gneiss	2.86	14	0.02-3.55	1.03	0.30-5.40	2.51	1.20-8.60	4.84	0.38-1.86	1.16	Sedara, et al., 2020
MET migmatite gneiss	2.86	14	0.10-1.75	0.67	0.10-2.50	1.59	1.60-13.80	4.38	0.51-1.89	0.83	
MET Quartzite	2.86	8	0.09-0.34	0.22	0.02-0.19	0.08	0.12-1.13	0.72	0.05-0.14	0.1	
MET schist	2.86	4	0.05-0.19	0.09	0.06-0.17	0.12	0.01-1.03	0.35	0.02-0.13	0.07	
MET granite gneiss	2.86	10	0.12-6.02	2.37	0.04-0.81	0.28	0.05-0.82	0.31	0.07-0.68	0.34	

Nur, 2018; Kasidi and Nur, 2013; Onyedim and Awoyemi, 2015; Emujakporue, 2017; Anakwuba et al., 2016).

The south western part of Nigeria lacks sufficient heat flow studies and therefore recommended for further investigation. The average heat flow in thermally normal continental regions is reported to be above 60  $\text{mWm}^{-2}$ . Heat flow values in excess of

80 to 100  $\text{mWm}^{-2}$  point to anomalous geothermal conditions. Anomalous high heat flow values have been observed in Ikogosi area ( $>100 \text{mWm}^{-2}$ ) (Emujakporue and Ekine, 2014; Odumodu and Mode, 2016; Nwobodo et al., 2018; Nwankwo et al., 2011; Ofor and Udensi, 2014) (Table 2). These data bring forth certain noticeable features about radioelemental distribution and heat production in

major rocks comprising the upper crust in some parts of southwest region of Nigeria. The metamorphic rocks have the highest density and heat production values (Figures 2 and 3).

This study indicates that the metamorphic group has higher concentrations of heavy minerals than the igneous samples. Thorium, Uranium and Potassium concentrations of granitic rocks are

**Table 2.** Compiled Heat flow data from some parts of Nigeria.

Location	Geothermal Gradient (°CKm <sup>-1</sup> )	Thermal Conductivity (Wm <sup>-1</sup> K <sup>-1</sup> )	Heat Flow (mWm <sup>-2</sup> )	Heat Production (μWm <sup>-3</sup> )	Methods	References
Delta Region	–	–	38.93-89.59	–	Oilwell	Anomohanran, 2004
Bida Basin	–	–	69.17-124.82	0.91-4.53	Oil Well	Megwara et al., 2012
Bida Basin	19.58-37.25	–	48.41-93.12	–	Cpd	Nwankwo and Sunday, 2017
Chad Basin	30-44	1.7-3.11 (av: 2.35)	63.6-105.6 (av: 80.6)	–	Oil Wells	Nwankwo et al., 2009
Anambra Basin	25-49	–	48-76	–	Oil Well	Onuoha and Ekine, 1999
Enugun	29-116	–	–	–	Boreholes	Ozoko and Ifediegwu, 2016
Eastern Niger Delta	13.46-33.66	–	–	–	Oil Well	Emujakporue and Ekine, 2014
Eastern Niger Delta	18-45	–	29-55 (av:42.5)	–	Oil Well	Odumodu and Mode, 2016
Chad Basin	25.5-56.75	–	63.8-141.8	–	CPD	Nwobodo et al., 2018
Nupe Basin	10.0-45	–	30-120	–	Oil Well	Nwankwo et al., 2011
Sokoto Basin	26.18-44.62	–	52.36-98.57	–	CPD	Ofor and Udensi, 2014
Benue Trough &Anambra Basin	25.2-38.9	–	64.4-97.3	–	CPD	Bello et al., 2017
Niger Delta Oil Field	17.3-24.33	–	38.06-56.39	–	Oil Well	Omokenu and Nwosu, 2016
Niger Delta 2	13-47	–	–	–	Oil Well	Kurowska and Schoeneich, 2010
Bornu Basin	11.0-59	–	–	–	Oil Well	Kurowska and Schoeneich, 2010
Sokoto Basin	9.0-76	–	–	–	Oil Well	Kurowska and Schoeneich, 2010
Bida Basin	20-25.0	–	–	–	Oil Well	Kurowska and Schoeneich, 2010
Anambra Basin	29.0-47	–	–	–	Oil Well	Avbovbo, 1978
Warri and Portharcourt	22.0-26	–	–	–	Oil Well	Avbovbo, 1978
Niger Delta Basin	13.0-18	–	–	–	Oil Well	Nwachukwu, 1976
Upper Anambra & Lower Benue Basin	32-80	–	46-98	–	Oil Well	Adetona et al., 2017
Nasarawa & Environs (NC Nig)	25-32	–	63-80	–	CPD	Ayuba and Nur, 2018
Jalingo and Environs (NE NIG)	21-23.0	–	53-61	–	CPD	Kasidi and Nur, 2013
Chad Basin 2	34-173	–	87-446	–	Oil Well	Onyedim and Awoyemi, 2015
Chad Basin 3	–	2-2.2 (av:2.3)	63.6-105.6	0.9-1.9 (av:0.96)	Oil Well	Emujakporue, 2017
Eastern Chad Basin	17.45-25.64	–	46-67.6	–	Oil Well	Anakwuba et al., 2016
Ririwai Complex (Granite Prov Northern Nigeria)	–	–	38.5	–	Boreholes	Verheijen and Ajakaiye, 1979
Ikogosi Warm Spring (SW Nig)	–	–	91.2	4.06	CPD	Abraham et al., 2014
Wikki Warm Spring (Bauchi)	54.11 av	–	135.28	–	CPD	Abraham et al., 2015
West Africa Shield (Nig, Ghana, Liberia)	–	–	30-40	–	Boreholes	Brigaud and Lucazeau, 1985
Chad Basin 3	–	–	–	0.17-1.90	Oil Well	Ali and Orazulike, 2010
Chad Basin 4	28.1-58.8	0.58-4.2	45-90	–	Oil Well	Kwaya et al., 2016
Worldwide Range (Precam Basement Complex)	–	–	37.6-87.8	–	–	Lee and Uyeda, 1965; Kappelmeyer and Haenl, 1974
Borno-Chad Basin	–	1.90-2.86	-	–	Oil Well Log	Dieokuma et al., 2013





does not necessarily imply high contribution to radiogenic heat production but the radionuclide involved.

So, we can say that the metamorphic group may have contributed highest to the heat production of rocks in the southwest region and as a result this is a signature to support geothermal studies and existence for exploration in the southwest region especially in areas with manifestations of hot springs. This will enhance the geothermal modeling of the area for future exploration.

### Heat flow and geothermal gradient data discussion

The result from the studies of the heat flow of Nigeria was divided along regional lines (northern and southern Nigeria) where we have Chad, Nupe, Nasarawa, Sokoto, Benue, Bornu basins representing the North and Anambra, Delta, Warri and Portharcourt, Enugun and Ikogosi representing the southern part. The heat flow values of the northern part vary from 30 to 141.8 mWm<sup>-2</sup> while that of the south varies from 29 to 130.4 mWm<sup>-2</sup> (Bello et al., 2017; Omokenu and Nwosu, 2016; Kurowska and Schoeneich, 2010; Verheijen and Ajakaiye, 1979; Abraham et al., 2014; Abraham et al., 2015; Brigaud and Lucazeau, 1985; Ali and Orazulike, 2010) (Table 2).

Also, the result from the study showed that the geothermal gradients of the northern part ranged between 9.0 and 173°C/km while the southern part varies between 13.46 to 116°C/km (Kwaya et al., 2016; Lee and Uyeda, 1965; Kappelmeyer and Haenl, 1974; Dieokuma et al., 2013; Pollack et al., 1993; Sharma, 2004; Jaupart and Mareschal, 2003; Sedara et al., 2020; Olorunfemi et al., 2013) (Table 2). This finding revealed that the geothermal gradient of the area lies within the range interval commonly encountered in tectonically inactive regions. The result is also an indication of an enormous energy potential which can be utilized for many purposes including electricity generation. It likewise further revealed that the heat flow and geothermal gradient of the study area decreases southward toward the ocean. This is an indication that fluid migration path is to the southern part of the country. This fact clearly indicates that the utilization of the energy potential of southern Nigeria especially the Ikogosi area will be optimal if geothermal plants are cited in the area for exploration. On the other hand, the fact that hydrocarbon migration path is to the south-south (Niger Delta) region of Nigeria and this can be a basis why more wells are expected in that area than the northern part.

### Conclusion

Heat flow data have been compiled from some parts of Nigeria, though some parts of the study area is devoid of thermal gradient, thermal conductivity and heat flow data. Also calculated heat production data from U, Th and K concentrations from rocks of Southwestern Nigeria was also compiled. Since there is no precise heat-flow data for

the southwest region so far (*in-situ* measurement or well log data), an attempt can be made to compute heat flow by using thermal conductivity values for the comparable rocks in the area using aeromagnetic data as was used in Ikogosi warm spring (IKGWS) area. The average heat flow and heat production value of IKGWS and other southwest region is 99.89 mWm<sup>-2</sup> and 1.3 μWm<sup>-3</sup> respectively.

In the study area, the rock types present are quartzite, quart-mica-schist, meta-sediments (amphibolite, phyllite), gneisses and granites. Thus, from thermal point of view, the area consists of heterogeneous rocks with large variability in thermal properties.

The data from radiometric survey can be broadly applied to sedimentological studies such as textural, mineralogical, provenance investigations, transport history and depositional environment studies for the sediments based on radionuclide activity concentrations of the radionuclides. The temperature distribution of the area could also be a potential source of electricity generation which will be cost effective compared to other energy sources will enable the various authorities to effectively monitor and exploit the geothermal energy of potential areas for the country.

This work is a review which attempted to show that the pattern of heat flow and heat production and geothermal gradient of the region and could be a basis for further research in geothermal energy exploit for Nigeria using suitable and appropriate geophysical techniques.

### CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

### REFERENCES

- Abraham, E. M., Lawal, K. M., Ekwe, A. C., Alile, O., Murana, K. A., & Lawal, A. A. (2014). Spectral analysis of aeromagnetic data for geothermal energy investigation of Ikogosi Warm Spring-Ekiti State, southwestern Nigeria. *Geothermal Energy*, 2, Article Number 6.
- Abraham, E. M., Obande, E. G., Chukwu, M., Chukwu, C. G., & Onwe, M. R. (2015). Estimating depth to the bottom of magnetic sources at Wikki Warm Spring region, northeastern Nigeria, using fractal distribution of sources approach. *Turkish Journal of Earth Sciences*, 24(5), 494-512.
- Adegbuyi, O., Abimbola, A. F. (1997). Energy resource potential of Ikogosi Warm Spring Area, Ekiti State, Southwestern Nigeria. *African Journal of Science*, 1(2), 111-117.
- Adegbuyi, O., Ajayi, O. S., & Odeyemi, I. B. (1996). Prospect of a hot-dry-rock (HDR) geothermal energy resource around the Ikogosi-Ekiti Warm Spring in Ondo State. *Nigeria Journal Renewable Energy*, 4(1), 58-64.
- Adetona, A. A., Salako, K. A., & Rafiu, A. A. (2017). Curie depth and geothermal gradient from spectral analysis of aeromagnetic data over Upper Anambra and Lower Benue Basin, Nigeria. *Nigerian Journal of Technological Research*, 12(2), 20-26.
- Ajayi, O. S., Adegbuyi, O., Farai, P., & Ajayi, I. R. (1996).

- Determination of natural radionuclides in rocks of the Ikogosi Ekiti warm spring area, Ekiti State, Nigeria. *Nigerian Journal of Science*, 30(2), 15-21.
- Alabi, O. O., Akinluyi, F. O., Ojo, M. O., & Adebo, B. A. (2007). Radiogenic heat production of rock from three rivers in Osun state of Nigeria. *Journal of Applied Science*, 7(12), 1661-1663.
- Ali, S., & Orazulike, D. M. (2010). Well logs-derived radiogenic heat production in the sediments of the Chad Basin, NE Nigeria. *Journal of Applied Science*, 10(10), 786-800.
- Anakwuba, E. K., Onwuemesi, A. G., Chinwuko, A. I., Onuba, L. N., (2011). The interpretation of aeromagnetic anomalies over Maiduguri-Dikwa depression, Chad Basin Nigeria: A structural view. *Archives of Applied Science Research*, 3(4), 499-508.
- Anomohanran, O. (2004). The use of third degree polynomial for accurate conversion of Seismic time to depth and vice versa. *Journal of the Nigerian Association of Mathematical Physics*, 8, 241-246.
- Avbovbo A. A., (1978). Geothermal gradients in the southern Nigerian basin. *Bulletin of Canadian Petroleum Geology*, 26(2), 268-274.
- Ayuba, R. A., & Nur, A. (2018). Determination of curie depth isotherm and geothermal studies over parts of Nasarawa and environs, North Central Nigeria. *International Journal of Energy and Environmental Science*, 3(4), 69-81.
- Bea, F., Montero, P., & Zinger, T. (2003). The nature, origin, and thermal influence of the granite source layer of Central Iberia. *The Journal of Geology*, 111(5), 579-595.
- Beardmore, G. R., & Cull, J. P. (2001). *Crustal heat flow: A guide to measurement and modelling*. Cambridge University Press, City.
- Bello, O. A., Özgür, N., & Çalışkan, T. A. (2017). Hydrogeological, hydrogeochemical and isotope geochemical features of Geothermal waters in Simav and environs, Western Anatolia, Turkey. *Procedia Earth and Planetary Science*, 17, 29-32.
- Boboye, O. A., Adeyemi, M. S., & Madukwe, H. Y. (2018). Lithostratigraphy and Inorganic Geochemical Studies of Cretaceous-Tertiary Lithofacies from Nigerian Three Inland Basin. *Open Journal of Geology*, 8(7), 711-736.
- Brigaud, F., & Lucazeau, F., (1985). Heat flow from the West African shield. *Geophysical Research Letters*, 12(9), 549-552.
- Brown, G. C., & Mussett, A. E. (1993). *The inaccessible earth: An integrated view to its structure and composition (2nd edition)*. Chapman & Hall, London.
- Clauser, C. (2006). Geothermal Energy. In: Heinloth, K. (Ed.), Landolt-Börnstein, Group VIII, Advanced Materials and Technologies. Energy Technologies, Sub volume: C Renewable Energies, Vol. 3. Springer Verlag, Heidelberg-Berlin. Pp. 480-595.
- Clauser, C., & Huenges, E. (1995). Thermal conductivity of rocks and minerals. In: Ahrens, T.J. (Ed.), *Rock Physics and Phase Relations — a Handbook of Physical Constants*. AGU Reference Shelf, 3, 105-126.
- Dieokuma, T., Gu, H. M., & Uko, E. D. (2013). Preliminary estimation of thermal conductivity in Bornu-Chad Basin, Nigeria. *European Scientific Journal*, 9(30), 300-309.
- Doveton, J. H., & Prenskey, S. E. (1992). Geological applications of wireline logs: A synopsis of developments and trends. *The Log Analyst*, 33(3), 286-303.
- Emujakporue, G. O. (2017). Subsurface temperature distribution from heat flow conduction equation in part of Chad Sedimentary Basin, Nigeria. *Egyptian Journal of Petroleum*, 26(2), 519-524.
- Emujakporue, G. O., & Ekine, A. S. (2014). Determination of geothermal gradient in the Eastern Niger Delta Sedimentary Basin from bottom hole temperatures. *Journal of Earth Sciences and Geotechnical Engineering*, 4(3), 109-114.
- Faweya, E. B. (2008). Radiogenic heat production in pebble from rocks in Ekiti State, Nigeria. *Jurnal Fizik Malaysia*. 29(1&2), 21-24.
- Hamza, V. M., & Beck, A. E. (1972). Terrestrial heat flow: The neutrino problem of vertical distance heat production in the east alps and a possible energy source in the core. *Nature*, 240, 343-344.
- Harðarson, B. S., (2007). Geothermal exploration and development of the Hengill high-temperature field (presentation). In: Georgsson, L. S., Holm, D. H., Simiyu, S. M., & Ofwona, C. (eds). *Short course II on surface exploration for geothermal resources*. UNU-GTP & KenGen, Naivasha, Kenya, UNU-GTP CD SC-05, 29p.
- Jaupart, C., & Mareschal, J. C (2003) Constraints on crustal heat production from heat flow data. In: *Treatise of geochemistry (3): The crust*. Rudnick, Elsevier. Pp. 65-84.
- Jessop, A. M. (1990). *Thermal Geophysics*. Elsevier, Amsterdam.
- Joshua, E. O., & Alabi, O.O. (2012). Pattern of radiogenic heat production in rock samples of Southwestern Nigeria. *Journal of Earth Sciences and Geotechnical Engineering*, 2(2), 25-38.
- Kappelmeyer, O., & Haenl, R. (1974). *Geothermics*. Borntraeger, Berlin, 238p.
- Kasidi, S., & Nur, A. (2012). Analysis of Aeromagnetic data over Mutum-biyu and environs, Northeastern Nigeria. *Research Journal of Engineering and Applied Science*, 2(1), 142-148.
- Kurowska, E., & Schoeneich, K. (2010). Geothermal exploration in Nigeria. *Proceedings of World Geothermal Congress*. Bali, Indonesia, 25-29 April 2010. Pp. 1-5
- Kwaya, M. Y., Kurowska, E., & Arabi, A. S. (2016). Geothermal Gradient and Heat Flow in the Nigeria Sector of the Chad Basin, Nigeria. *Computational Water, Energy, and Environmental Engineering*, 5(2), 70-78.
- Lapworth, D. J., Knights, K. V., Key, R. M., Johnson, C. C., Ayoade, E., Adekanmi, M. A., Arisekola, T. M., Okunlola, O.A., Backman, B., Eklund, M., Everett, P. A., Lister, R. T., Ridgway, J., Watts, M. J., Kemp, S. J., & Pitfield, P. E. J. (2012). Geochemical mapping using stream sediments in west-central Nigeria: Implications for environmental studies and mineral exploration in West Africa. *Applied Geochemistry*, 27(6), 1035-1052.
- Lee, W. H., & Uyeda, S. (1965). Review of heat flow data. *Terrestrial Heat Flow*, 8, 87-190.
- Loehnert, E. P. (1985). Hydrochemical and isotope data on Ikogosi warm spring, southwestern Nigeria. In *Geothermics, thermal-mineral waters and hydrogeology* (pp. 97-109). Theophrastus, Athens.
- Megwara, J. U., Udensi, E. E., Olasehinde, P. I., Daniyan, M. A., & Lawal, K. M. (2013). Geothermal and radioactive heat studies of parts of southern Bida basin, Nigeria and the surrounding basement rocks. *International Journal of Basic and Applied Sciences*, 2(1), 125-139.
- Nwachukwu, S. O. (1976). Approximate geothermal gradients in Niger Delta sedimentary basin. *AAPG Bulletin*, 60(7), 1073-1077.
- Nwankwo, L. I., & Sunday, A. J. (2017). Regional estimation of Curie-point depths and succeeding geothermal parameters from recently acquired high-resolution aeromagnetic data of the entire Bida Basin, north-central Nigeria. *Geothermal Energy Science*, 5(1), 1-9.
- Nwankwo, L. I., Olasehinde, P. I., & Akoshile, C. O. (2011). Heat

- flow anomalies from the spectral analysis of airborne magnetic data of Nupe Basin, Nigeria. *Asian Journal of Earth Sciences*, 4(1), 20-28.
- Nwankwo, N. C., Anthony, A. S., & Nwosu, L. I. (2009). Estimation of the heat flow variation in the Chad Basin Nigeria. *Journal of Applied Sciences and Environmental Management*, 13(1), 73-80.
- Nwobodo, A. N., Ezema, P. O., & Ugwu, G. Z. (2018). Determination of the curie point depth, geothermal gradient and heat flow of Guzabure and its environs, Chad Basin, Nigeria using Aeromagnetic data. *International Journal of Scientific and Engineering Research*, 9(3), 1876-1889.
- Odumodu, C. F. R., & Mode, A. W. (2016). Geothermal gradients and heat flow variations in parts of the eastern Niger delta, Nigeria. *Journal of the Geological Society of India*, 88, 107-118.
- Ofor, N. P., & Udensi, E. E. (2014). Determination of the heat flow in the Sokoto basin, Nigeria using spectral analysis of aeromagnetic data. *Journal of Natural Sciences Research*, 4(6), 83-93.
- Ojo, J. S., Olorunfemi, M. O., & Falebita, D. E. (2011). An appraisal of the geologic structure beneath the Ikogosi warm spring in south-western Nigeria using integrated surface geophysical methods. *Earth Sciences Research Journal*, 15(1), 27-34.
- Okeyode, I. C. (2012). Radiogenic heat production due to natural radionuclides in the sediments of Ogun River, Nigeria. *Journal of Environment and Earth Science*, 2(10), 196-207.
- Okeyode, I. C., & Akanni, A. O. (2009). Determination of some physical parameters of Olumo rock, Abeokuta Ogun-State, Nigeria. *Indian Journal of Science and Technology*, 2(7), 6-10.
- Oladipo, A. A., Oluyemi, E. A., Tubosun, I. A., Fasisi, M. K., & Ibitoye, F. I. (2005). Chemical examination of Ikogosi warm spring in south western Nigeria. *Journal of Applied Sciences*, 5(1), 75-79.
- Oladunjoye, M. A., Akinmosin, A., & Ekugum, U. K. (2014). Distribution of radioactive elements of some rocks in South-Western Nigeria. *RMZ-M&G*, 61, 231-240.
- Olorunfemi, M. O., Adepelumi, A. A., Falebita, D. E., & Alao, O. A. (2013). Crustal thermal regime of Ikogosi warm spring, Nigeria inferred from aeromagnetic data. *Arabian Journal of Geosciences*, 6(5), 1657-1667.
- Omokenu, E. G., & Nwosu, L. I. (2016). Statistical analysis of geothermal data of an oil field in parts of Niger Delta, Nigeria. *Current Research in Geoscience*, 6(2), 91-97.
- Onuoha, K. M., & Ekine, A. S. 2009. Subsurface temperature variations and heat flow in the Anambra Basin, Nigeria. *Journal of African Earth Sciences*, 28(3), 641-652.
- Onyedim, G., & Awoyemi, M. O. (2015). Geothermal and Hydrocarbon implications of Curie point depths determined from spectral analysis of high resolution aeromagnetic data over parts of Chad basin, Nigeria. *Proceedings in International Conference on Green Energy & Expo, September 21-23, 2015, Orlando, USA*.
- Ozoko, D. C., & Ifediegwu, S.I. (2016). Temperature characteristics of boreholes in Umulokpa and environs, Enugu State, Southeastern Nigeria. *International Journal of Innovative Science, Engineering and Technology*, 3(2), 386-391.
- Pollack, H. N., Hurter, S. J., & Johnson, J. R. (1993) Heat flow from the earth's interior: analysis of global data set, *Reviews of Geophysics*, 31:267-280.
- Ray, L., Bhattacharya, A., & Roy, S. (2007). Thermal conductivity of higher Himalayan crystallines from Garhwal Himalaya, India. *Tectonophysics*, 434(1-4), 71-79.
- Rogers, A. S., Imevbore, A. M. A., & Adegoke, O. S. (1969). Physical and chemical properties of Ikogosi Warm Spring, western Nigeria. *Nigeria Journal of Mining Geology*, 4, 1-2.
- Roy, R. F., Beck, A. E., Touloukian, Y. S. (1981). Thermophysical properties of rocks. In: Touloukian, Y.S., Judd, R.R., Roy, R.F. (Eds.). *Physical properties of rocks and minerals*. McGraw Hill, New York, Pp. 409-502.
- Rybach, L. (1988). Determination of heat production rate. In: *Handbook of terrestrial heat-flow density determination* (pp. 125-142). Kluwer Academic Publishers, Dordrecht.
- Sandiford, M., & McLaren, S. (2005). Thermo-mechanical Controls on Heat Production Distributions and the Long-term Evolution of the Continents. In: Brown, M., & Rushmer, T. (eds.) *Evolution and Differentiation of the Continental Crust* (pp. 67-92). Cambridge University Press, Cambridge.
- Sedara, S. O., & Adelowo, A. (2015). Assessment of radiogenic heat production in soil samples around Ife steel rolling mill site in Southwestern Nigeria. *International Journal of Innovation and Scientific Research*, 13(1), 249-256.
- Sedara, S. O., Ray, L., & Ojoawo, A. I. (2020). Thermal prospect of the rocks and heat flow estimates in the southwest Nigeria by indirect method: Possibility of geothermal prospect. *Unpublished article in press*.
- Sharma, P. V. (2004). *Environmental and engineering geophysics*. Cambridge University Press, Cambridge. Pp. 357-359.
- Taylor, S. R. and McLennan, S. M. (1985). *The Continental Crust: Its Composition and Evolution*, Blackwell, Oxford, p. 312.
- Verheijen, P. J. T., & Ajakaiye, D. E. (1979). Heat-flow measurements in the Ririwai ring complex, Nigeria. *Tectonophysics*, 54(1-2), T27-T32.