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Geophysical analysis of Thermo-Physical properties of rocks in Ikogosi field for geothermal energy prospect

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Keywords
Low enthalpy
Ikogosi
Heat flow
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Porosity

ABSTRACT

The thermal and physical properties of rock units from Ikogosi Warm Spring (IKGWS) in the Southwestern part of Nigeria were examined in order to characterize and explore its geothermal prospect and to provide an insight into the different thermal properties of rocks of the study area. A total of 40 rock samples made up of granite, quartzite and gneiss series were collected from the outcrops of the study area and analyzed for Thermal conductivity (TC), Radiogenic heat production (RHP), Heat flow (HF), Porosity, Density and surface spring temperature measurements. The RHP values for all samples varied from 1.8 to 3.5μWm^{-3} with an average value of 2.5μWm^{-3} and standard deviation (SD) of 0.4 while the heat flow values varied from 14 to 27mWm^{-2} with an average of 19mWm^{-2} and SD of 3.4. The TC values varied from 2.95 to 4.11 with a mean of 3.49mWK^{-1} with a SD of 0.4 while the porosity values varied from 0.21-1.15 % with a mean of 0.62% with SD of 0.39. The density values varied from 2.68 to 2.85gcm^{-3} with a mean of 2.76gcm^{-3} and SD of 0.067. The surface temperature of the spring varied from 32 to 45°C with a mean of 38.9°C. From these results the average RHP and HF values estimated from all samples was below the 4μWm^{-3} and 100mWm^{-2} recommended value of heat to be considered for economic importance. Thus, the IKGWS geothermal field cannot be explored for power generation but for other geothermal activities and may be classified as a low enthalpy geothermal system (<150°C).

1. INTRODUCTION

There have been so many researches in the Ikogosi warm spring (IKGWS) area in the attempt to understand the general structural pattern and their results pointed to the fact that IKGWS is situated along a trending faults and fractures (Ojo et al. 2011; Abraham et al., 2014). As a follow-up, some research work has also been done to investigate the prospect of geothermal energy exploration and their results indicated potential of the IKGWS for geothermal prospect based on the fact that fractures and faults acts as pathways for the thermal fluid to the subsurface (Abraham and Alile, 2019; Salawu et al., 2021; Sedara, 2020; Sedara and Alabi, 2021). Thus, in a follow up for these geothermal investigations within IKGWS, we have attempted to scale and classify the geothermal potential prospect of the area using combined thermal properties of rocks within the study area.

Geothermal energy is a reliable renewable energy source from within the earth and comparing with other renewable energies, it is fundamentally confined and location specific especially with regions of magmatic occurrences (Huenges and Ledru, 2011). However, the depletion and reduction of energy resources have become more widespread and therefore the necessity to consider and develop geothermal energy resource which has become is now becoming more generally recognized and accepted (Zhu et al., 2021). Several Earth processes are largely dependent on temperature variances within the Earth and estimating these temperatures variations and uncertainties are challenging without considering the evaluation of radiogenic heat production (McKenzie and Priestley, 2016; Liu and Currie, 2016).

Basically, the three main modes of heat energy transfer are conduction, convection, radiation but the radiation and convection are assumed to have a

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reasonably slight influence on geothermal energy transfer.

The understanding of the thermal and structural setting of an area involves precise information of radiogenic heat production, heat flow and thermal conductivity of all rock units of the area. A detailed data for all these properties are not only predictable for evaluating the thermal improvement of basement and sedimentary formations (Popov et al., 2016).

Therefore, this research paper mainly investigates the lithological units and their basic heat and physical properties that governed and contributed to the thermal processes. These processes are influenced by thermal conductivity, porosity, density, mineral composition, water content. All these play vital roles in many research fields like hydrothermal resources development, subsurface thermal energy; civil engineering and environmental and geotechnical engineering (Popov et al., 1999; Gao et al., 2015).

A characteristic instance of an area with great geothermal and geodynamic activities conveyed by surface spring manifestation is the Ikogosi warm spring area situated in the southwestern part of Nigeria (Abraham et al., 2014; Olorunfemi et al., 2013). Like some other geothermal regions, geothermal resources around IKGWS are expressed on the outward in the like hot springs which have been ascribed to the manifestation of many faulting systems in the area (Abraham et al., 2014; Adepelumi et al., 2008). The lithological units and their effect on the hot and cold spring manifestations around the IKGWS is yet to be well examined in line with geothermal potential of the area (Figure 1). Likewise, the heat source depth which may perhaps provide evidence for thermal configuration and geodynamic events of the area is not well defined despite the immense manifestation of geothermal resources on the surface (Ozgener and Kocer, 2004; Abubakar et al., 2017; Ozdemir and Palabiyik, 2019; Ozdemir et al., 2021).

The rocks analyzed were mainly from the different sections in the IKGWS area and a total of 40 samples were collected comprising of granite, gneiss and quartzite series. In particular, the samples were analyzed majorly for radiogenic heat production, water content, thermal conductivity, porosity and heat flow content to define the connection between all the properties and their link with geothermal prospect of the area.

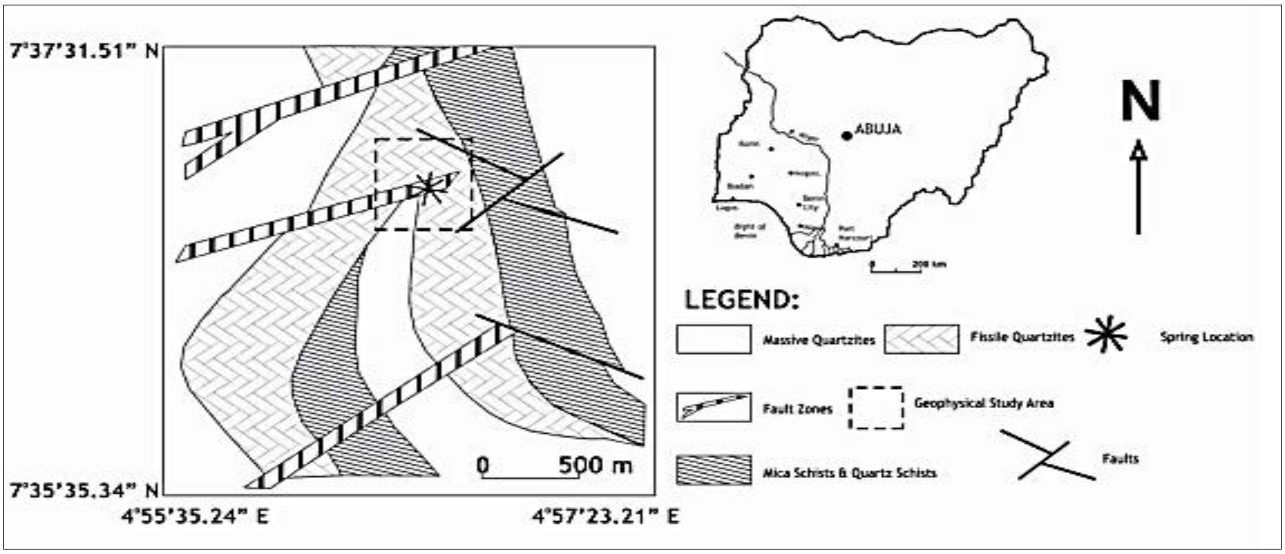

Figure 1. Map of Geology of Ikogosi warm spring area (modified after Adegbuyi et al., 1996)

2. MATERIALS AND METHODS

2.1. The Radiogenic Heat Measurements and Estimations

Radiations (alpha-α, beta-β and gamma-ɣ) from decay of radioactive elements contained in rock units around the study area are of particular interest. The radiations from the decay of radioelements of ^{232}Th, ^{40}K and ^{238}U contained in the outcrop of rock unit in parts per million (ppm) were measured from laboratory analysis of 30 rock samplings of the study area (Figure 2) from NaI Spectrometry. The concentrations of the radioelements (C_{Th}, C_U and C_K) and density, ρ) were measured in a research laboratory and the resulting concentrations were inserted in equation (1) of Birch, (1954) to estimate the radiogenic heat production (HP in μWm^{-3}):

$$HP=\rho*(0.026*C_{Th}+0.097*C_U+0.035*C_K) \quad (1)$$

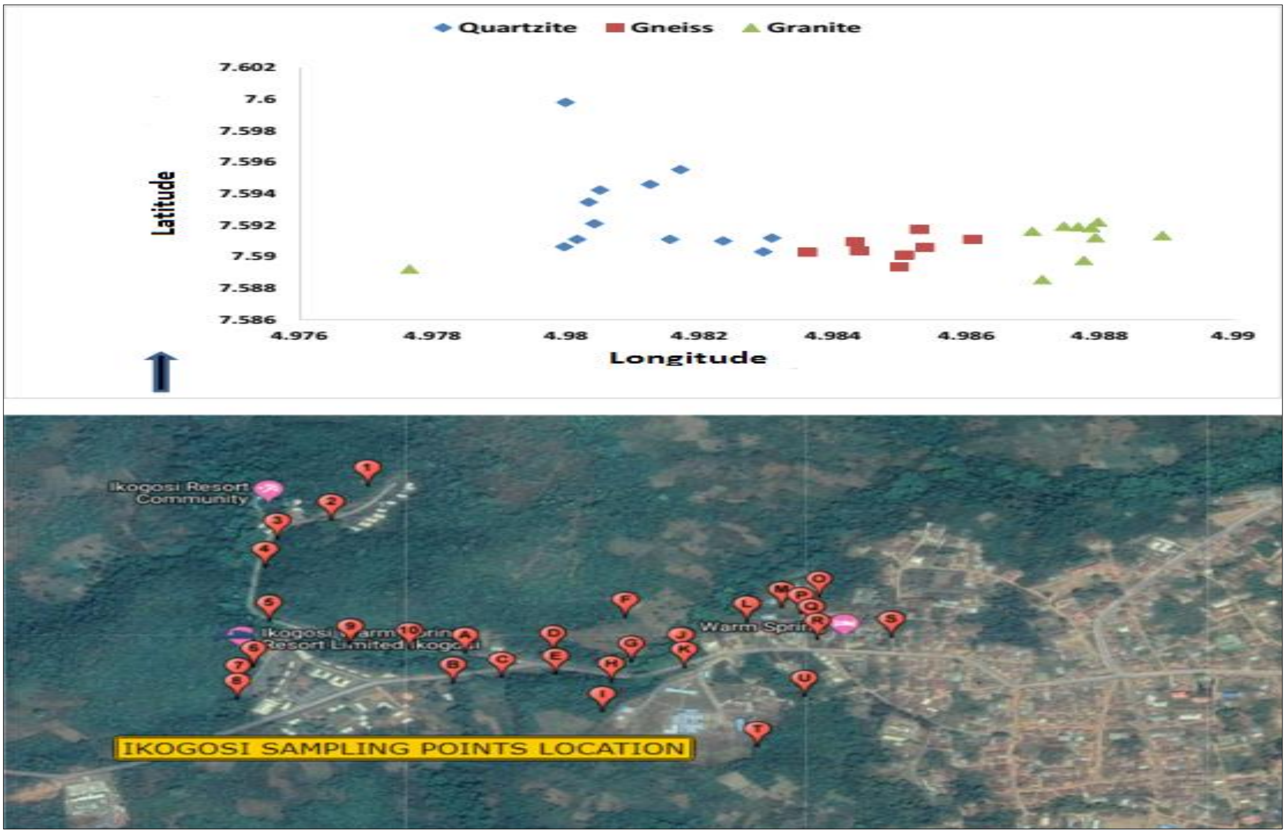

Figure 2. The sampling points and location of study area

2.2. The Thermal Conductivity Measurements and Estimations

There are two methods of measuring the thermal conductivity of materials which are direct (laboratory) and indirect (computational). The thermal conductivity of rock samples in this work was measured using Thermal conductivity meter. Before taking measurements, the thermal conductivity meter was standardized and calibrated using reference specimens. Ten rock samples comprising of three Quartzite, three Gneiss and four Granite series were broken from fresh outcrops of IKGWS. The samples were dressed, cut and refined into cylinder-shaped discs of diameter 25 mm and thickness between 10 and 25 mm which is dependent on rock sample variety and grain size.

The dressed rock discs are pulverized and refined till the thickness variant is less than 0.01 mm. Then the samples are placed inside the stack one after the other and readings were taken. Each measurement takes about 30-40 min to attain steady state condition. Readings (upper voltage V_U, lower voltage V_L, heat sink V_{HS} and reference voltage V_{REF}) are noted and recorded. Using the above readings and calibration, thermal conductivity values of the rocks are determined. To minimize loss of heat to the environs, the rock stack is sheathed and insulated and the entire system is bounded within a shielded case and measurements taken after the stack reaches in steady-state or equilibrium condition and finally the readings taken are inserted into a processing software to get the values of Thermal Conductivity of the respective rock samples.

2.3. Measurement of Density, Porosity and Surface Spring Temperature

The rock samples were weighed up in water and in air on established law of Archimedes principle. The rock sample density (ρ_{sample}) was gotten by the equation 2 by weightiness of the rock sample in air, water and density of water (W_{air}, W_{wate} and ρ_{water}).

$$\rho_{sample} = \frac{W_{air} * \rho_{water}}{W_{air} - W_{water}} \quad (2)$$

Also the porosity (V_p) is divided by volume of rock (V_r) (solid + space or holes) given by equation 3:

$$Porosity = \frac{Volume\ of\ voids(V_P)}{Total\ volume(V_r)} * 100\% \quad (3)$$

The cylinder-shaped disc containing the rock samples are oven dried and the measurements of the dry rock samples (W_{dry}) taken. The samples are placed inside a desiccator to take away the air from the rock pores and later saturated with tap water under vacuum for almost 20 hours to permit water into the pores and then the water-saturated rock sample weight (W_{sat}) is measured. The porosity can be expressed as equation 4:

$$Porosity = \frac{W_{sat} * W_{dry}}{\pi * R * R * H} * 100 \quad (4)$$

Where: R=radius of the rock sample disc, H=thickness of the rock sample disc.

The values of density and porosity of the rock samples are tabulated in next section.

2.4. Heat Flow Estimations

Two unconventional computational methods (Turcotte and Schubert, 2002; Beardsmore and Cull, 2001; Faweya, 2008; Sedara, 2020) was used to get the values of heat flow for the rock samples given in equations (5) and (6) as:

$$H_f = \frac{H_{RT}(Mm + Cr)}{S} \quad (5)$$

$$H_f = \frac{\partial T}{\partial x} \lambda \quad (6)$$

Where: H_f=heat flow in (mWm^{-2}), H_{RT}= total heat production from radioactive decay in the rock, Mm + Cr= the mass of mantle plus crust given as ≈ 4 × 10^{24} kg, S= total surface area of the earth given as ≈ 5.1 × 10^{14} m^2, $\frac{\partial T}{\partial x}$=Temperature gradient, λ=Thermal conductivity.

The reason why this is done is because direct measurements of heat flow are very less in basement complex terrains of Nigeria. The only existing records of heat flow is found in the results of Brigaud et al., (1985) of the Western part of Africa Shield of Ghana, Liberia, and Nigeria with values fluctuating between 30 and 40 mWm^{-2} and also results from Verheijen and Ajakaiye, (1979) with mean value of 38.5 mWm^{-2}. There have been no bottom hole or borehole data in the southwestern part of Nigeria. The estimation of heat flow in Southwestern part of Nigeria has been through Curie Point Depth (CPD) estimation from aeromagnetic data which assumed constant values of Curie temperature and Thermal conductivity. The heat flow gotten from equation 5 was use to get the temperature gradient for the rock samples using the measured TC values of each rock samples from equation 6. But going by the approach applied in this work, the heat flow data estimated for IKGWS varied from 14 to 27 mWm^{-2} with mean value of 19 mWm^{-2}.

3. RESULTS and DISCUSSION

3.1. Deductions from Measured Parameters

The granitic rocks have the highest heat production while the gneiss and quartzite samples are characterized by variable abundances in K and Th. Uranium, however is almost at the same level in rocks in the area. K content ranged from 1.65 to 5.70 % with average of 3.24 %. Th content is highly variable from as low 9.4 to 25.20 ppm while U content varied from 1.07 to 3.75 ppm with an average of 2.31 ppm. Th concentration has large variability compared to U and K respectively (Table 1). The values of the heat production varied from 1.8 to 3.5 μWm^{-3} with an average of 2.5 μWm^{-3}. The plots show that HP values correlates well with Th abundances for most of the samples whereas no such prominent correlation are observed with K and U (Figure 3). The granite (IKGL3) samples has larger amount of K, U, and Th concentrations than the two other samples and it produces the largest amount of heat production. The present study is limited on data around IKGWS but detailed study in the Southwestern part of Nigeria is needed to characterize radio elemental and heat production for the whole region which will be useful for constraining thermal structure of the region. This study also showed that the various thermal properties vary from the different samples from the different points of the study area (Figure 4).

For the individual rock contribution, the quartzite heat flow value is the highest which varies from 14-27 mWm^{-2} with a mean value of 18 mWm^{-2}. The heat flow values for gneiss varies from 16-23 mWm^{-2} with a mean value of 20 mWm^{-2} while for granites, the heat flow varies from 17-25 mWm^{-2} with a mean of 21 mWm^{-2}. The Uranium contribution to the heat production of the area is higher in the quartzite series compared to other rock series likewise, for the heat flow (Figure 8 and 9).

However, the study area and its environs is assumed to be tectonically stable so the interference of magma to the subsurface such that it will cause earthquake is limited. The high heat flow in many geothermal provinces is based on induced magmatic and tectonic activities (Espinosa-Cardeña, and Campos-Enriquez, 2008). Also, the existence of active lineaments may as well be liable for the surface expressions of hot and cold springs in IKGWS area. The density and porosity values of ten rock samples have been given and summarized in Table 2. The three rock series showed slight difference in density (narrow range with): Quartzite range between 2.79 to 2.85 gcm^{-3} with an average of 2.81 ±0.03gcm^{-3}. Gneiss range from 2.68 to 2.85 gcm-3 with an average value of 2.76 ± 0.09 gcm^{-3}. Granite series varies from 2.67 to 2.72 gcm^{-3} with a mean density of 2.7±0.03 gcm^{-3} as shown in Figure 5 even when compared with granitoids of the other countries (Chopra et al., 2020; Ozdemir et al., 2021).

Table 1. Radiogenic heat production (RHP) estimation results for the rock types in IKGWS

Latitude	Longitude	Lithology			K%	U(ppm)	Th(ppm)	A (μWm^{-3})	HF (mWm^{-2})
7.595528	4.981714	Quartzite (IKGL1)	QUI	N=12	5.7	1.38	11.2	2.79	22
7.594592	4.981263		QUII		4.06	1.42	9.65	2.19	17
7.59423	4.980512		QUIII		2.71	1.79	15.1	2.39	19
7.593465	4.980341		QUIV		2.66	1.14	10.22	1.84	14
7.592103	4.980427		QUV		5.01	2.02	19.51	3.48	27
7.591104	4.980169		QUVI		2.32	2.11	15.44	2.34	18
7.590636	4.979976		QUVII		2.35	1.74	20.02	2.78	22
7.599806	4.979997		QUVIII		2.24	3.01	15.11	2.35	18
7.591104	4.981564		QUIX		1.65	1.07	12.23	1.76	14
7.590997	4.982358		QUX		3.02	2.77	9.4	1.98	16
7.591189	4.983087		QUXI		1.78	2.86	14.02	2.1	16
7.590317	4.982959		QUXII		2.08	3.12	11.49	1.95	15
				Min	1.65	1.07	9.4	1.76	14
				Max	5.7	3.12	20.02	3.48	27
				average	2.97	2.04	13.62	2.33	18
				SD	1.29	0.74	3.58	0.49	4
7.590295	4.983624	Gneiss (IKGL2)	GNI	N=8	2.14	1.5	20.11	2.71	21
7.590955	4.984332		GNII		2.75	2.55	16.21	2.57	20
7.59038	4.984396		GNIII		1.93	1.66	14.27	2.08	16
7.591742	4.985297		GNIV		5.41	3.46	10.02	2.75	22
7.590593	4.985383		GNV		3.31	1.23	19.04	2.91	23
7.590104	4.985083		GNVI		3.01	2.04	17.04	2.68	21
7.589359	4.984997		GNVII		2.87	3.04	11.66	2.18	17
7.591104	4.986091		GNVIII		2.81	3.68	10.24	2.07	16
				Min	1.93	1.23	10.02	2.07	16
				Max	5.41	3.68	20.11	2.91	23
				average	3.03	2.4	14.82	2.49	20
				SD	1.06	0.93	3.91	0.33	3
7.591614	4.986993	Granites (IKGL3)	GRI	N=10	2.21	2.56	16.82	2.3	18
7.591933	4.987465		GRII		3.87	2.61	14.2	2.48	19
7.59221	4.98798		GRIII		4.64	2.11	20.11	3.19	25
7.591891	4.987679		GRIV		2.81	1.87	25.2	3.18	25
7.591848	4.987872		GRV		3.32	3.23	22.11	3.12	24
7.59121	4.987937		GRVI		4.04	3.75	10.21	2.23	17
7.591338	4.988945		GRVII		5.05	2.68	11.71	2.56	20
7.588551	4.987143		GRVIII		3.46	2.78	16.67	2.62	21
7.589764	4.987765		GRIX		2.82	2.61	18.52	2.61	20
7.589211	4.977659		GRX		5.3	1.62	12.44	2.61	20
				Min	2.21	1.62	10.21	2.23	17
				Max	5.3	3.75	25.2	3.19	25
				average	3.75	2.58	16.8	2.69	21
				SD	1.02	0.62	4.81	0.35	3

The porosity of the three rock series showed that: Quartzite range between 0.91 to 1.15 % with a mean value of 1.05±0.11 %. Gneiss series have a range between 0.21 to 0.35% with an average value 0.27 ±0.07 %. Granites porosity varied from 0.25 to 0.5% with mean of 0.38 ±0.13%. Here the porosity values of the granite and gneiss series is very low compared to the quartzite porosity values (Figure 5 and 6).

The thermal conductivity values for the three rock series showed a wide range. The TC for: Quartzite ranged between 3.22 and 4.11 $Wm^{-1}K^{-1}$ with mean value of 3.81±0.4 $Wm^{-1}K^{-1}$. Gneiss ranged from 2.95 to 3.65 $Wm^{-1}K^{-1}$ with mean value of 3.21±0.38 $Wm^{-1}K^{-1}$. Granite series ranged between 2.98 to 3.62 $Wm^{-1}K^{-1}$ with mean value of 3.34±0.33 $Wm^{-1}K^{-1}$. Hence Gneiss and Quartzite had higher values than the Granite series (Figure 6 and 7).

In absence of conventional heat flow data, it is difficult to reach a conclusion on the variations of reported heat flow from the actual heat flow of the regions. But in this work, I have determined the thermal conductivity and some other thermal and physical properties of the area in order to characterize the rocks and their influence for geothermal energy prospect in the area.

Table 2. Thermal Conductivity, Density and Porosity values from IKGWS rock samples

	Quartzite			Gneiss				Granite		
	IKGL1	**IKGL1**	**IKGL1**	**IKGL1**	**IKGL2**	**IKGL2**	**IKGL2**	**IKGL3**	**IKGL3**	**IKGL3**
Thermal Conductivity	3.22	3.89	4.02	4.11	3.65	3.04	2.95	2.98	3.42	3.62
Porosity	1.12	1.15	1.01	0.91	0.35	0.21	0.25	0.4	0.5	0.25
Density	2.8	2.81	2.85	2.79	2.68	2.85	2.75	2.7	2.67	2.72

Rock Type	**N**	**Thermal Conductivity Wm^{-1}K^{-1}**			**Density gcm^{-1}**			**Porosity %**		
		Range	Average	SD	Range	Average	SD	Range	Average	SD
Quartzite	4	3.22-4.11	3.81	0.4	2.79-2.85	2.81	0.03	0.91-1.15	1.05	0.11
Gneiss	3	2.95-3.65	3.21	0.38	2.68-2.85	2.76	0.09	0.21-0.35	0.27	0.07
Granite	3	2.98-3.62	3.34	0.33	2.67-2.72	2.7	0.03	0.25-0.5	0.38	0.13

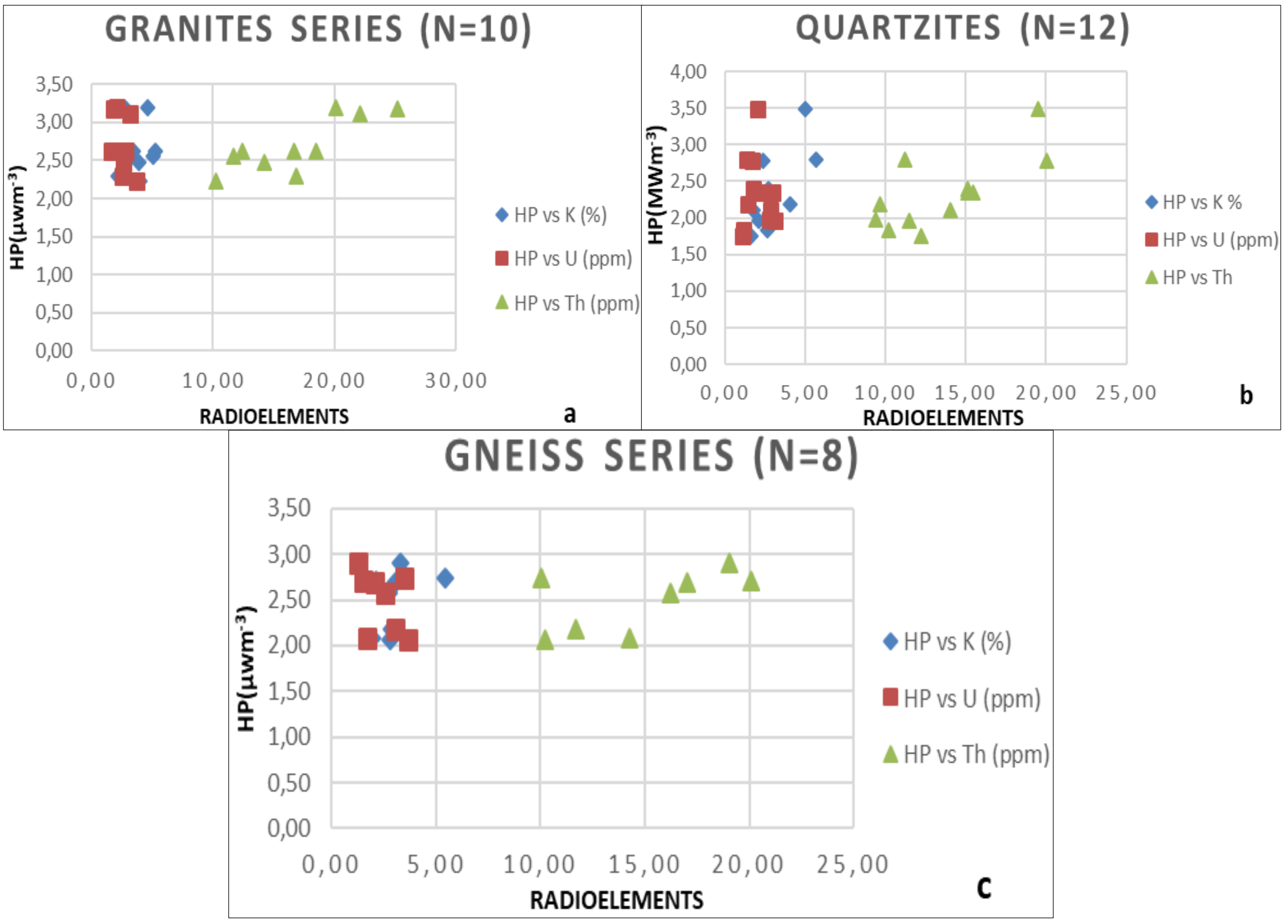

Figure 3. Heat Production vs radioelements distribution in a: Granite series; b: Quartzite series; c: Gneiss series of IKGWS

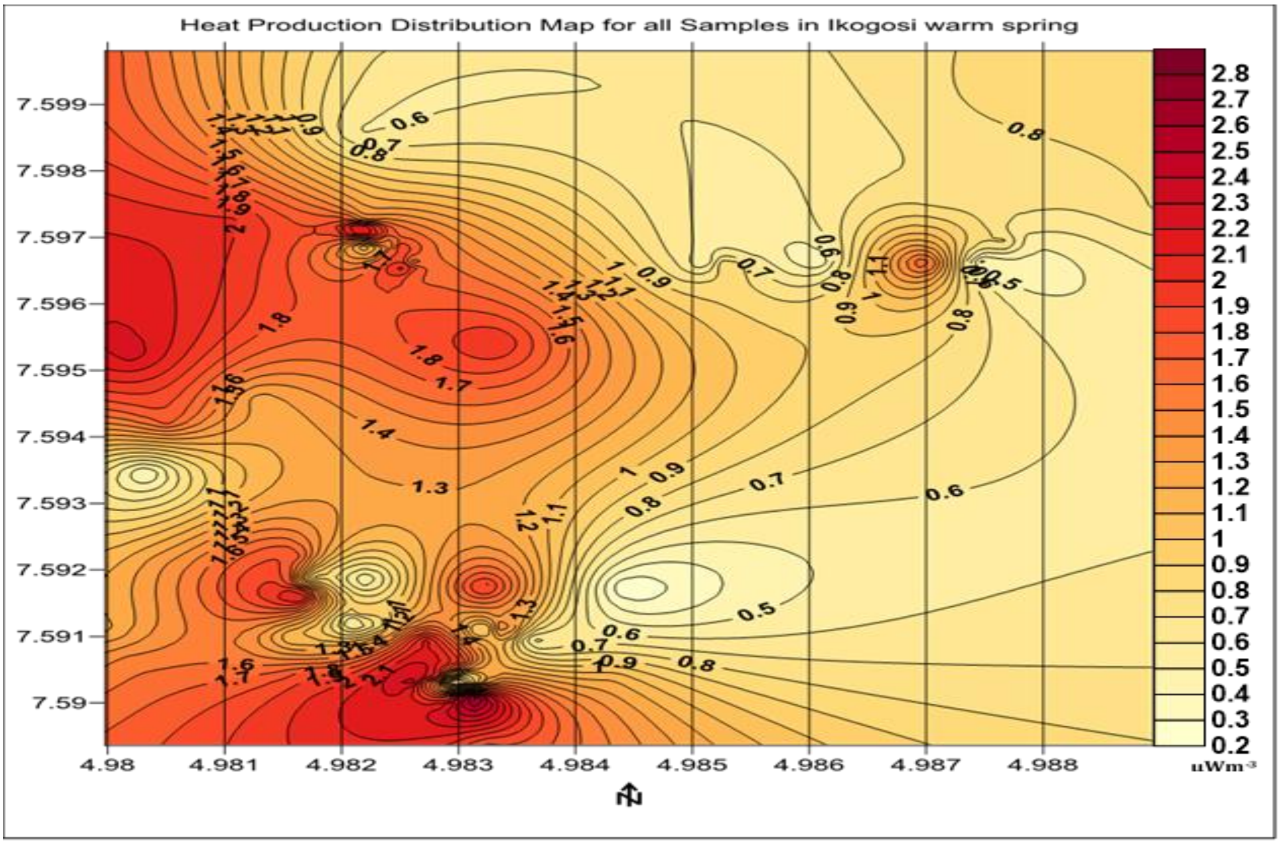

Figure 4. Radiogenic Heat Production Distribution Contour map for all samples in IKGWS

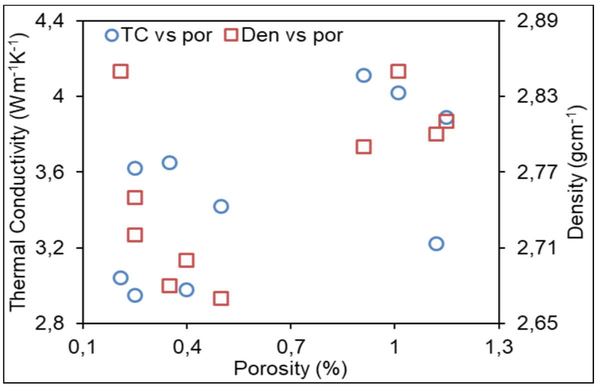

Figure 5. Distribution plot of Thermal conductivity, porosity and Density of all rocks

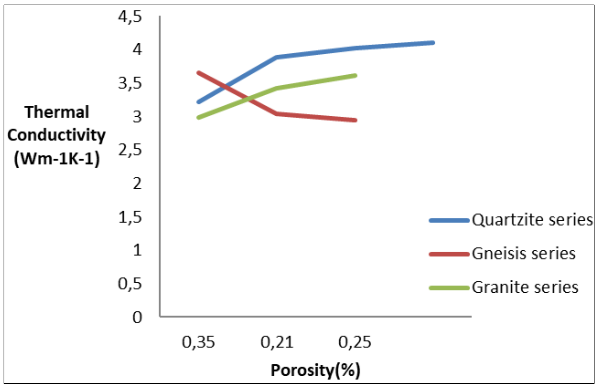

Figure 7. Distribution of each rock series from Thermal conductivity and Porosity

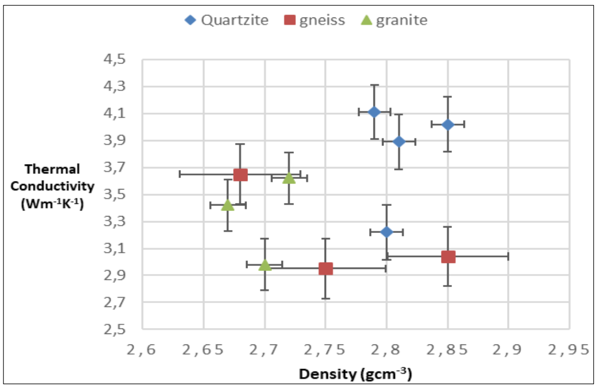

Figure 6. Bivariate plot showing Mean Thermal conductivity and Density of all rocks with SE

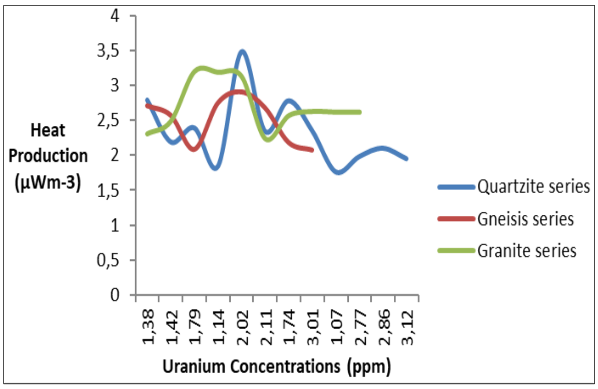

Figure 8. Contribution of Uranium concentration to RHP of each rock series

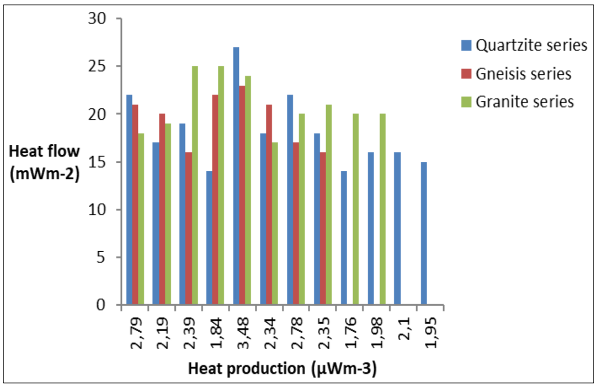

Figure 9. Heat flow and RHP distribution of each rock series

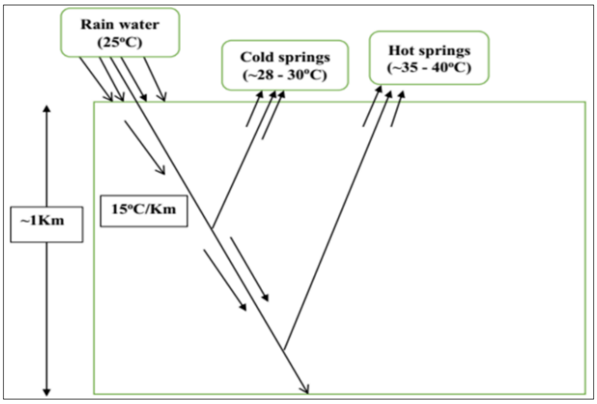

Figure 10. Typical activities of hydrothermal model of IKGWS

Meanwhile there is no defined data for heat flow in the southwestern part of Nigeria so I computed heat flow by using the measured thermal conductivity of comparable rocks in IKGWS area and compared the average heat flow and heat production values of IKGWS (27 mWm^{-2} and 3.3 μWm^{-3} respectively) with other geothermal potential regions of the world like Tattapani, India which is of the order of 290± 50 mWm^{-2} (Shanker et al., 1987, 1991; Ozdemir et al., 2017; Ozdemir and Palabiyik, 2019). The deviation in value is obvious which makes the IKGWS area far less in potential for geothermal energy exploration. The maximum heat flow computed in the crustal areas of the Indian shield is in the order of 75 ± 15 mWm^{-2}. Therefore, it is proven that the Tattapani geothermal variance and anomaly is a very robust one and could be higher than it appears at the moment. However, we cannot conclude that the IKGWS area is strong for geothermal anomalies since there have been no comprehensive research that can ascertain and characterize its geothermal potential perfectly. So, well logging or Borehole techniques, Magnetotellurics (MT) should be carried out and more rocks samples analyzed within the region.

If the water is not juvenile but meteoritic then the observed temperature can be obtained by the following procedure. If surface temperature is between 20-30 °C and rainwater/surface water go to the subsurface up to 1 km with normal gradient (~15 mK/m), then temperature attained by water will be between 35 to 45 °C. When this water comes up through some fault/fracture, it can provide a temperature of ~30-40 °C. When the water comes up by some fracture after going few hundred meters then temperature will be lower than the temperature above. The temperature will depend on the depth of penetration of the water in the sub-surface (Figure 10).

4. CONCLUSIONS

The radiometric survey showed the distribution of radio-nuclides and heat production in rocks. The radiogenic heat production study revealed that the contribution of heat from the different rock samples is dependent on the type of rocks (results from the radioactive decay of U238, Th232, and K40). The quartzite series contributes the highest followed by the granites and gneiss series. Since most of these rock samples were collected from surface outcrops, there is an uncertainty about the concentration of the radioactive elements with depth. The heat production value varied between 0.21 and 3.3 μWm^{-3}. The thermal conductivity results also indicated varied widely from 2.41 to 5.07 $Wm^{-1}K^{-1}$ which implies a heterogeneous characteristic of the subsurface. This thermal conductivity of rocks is basically controlled by chemical composition of the rocks samples. The distribution of temperature within the earth is mainly controlled by the thermal conductivity and heat production of the geological material. The heat flow value estimated for IKGWS is 27 mWm^{-2}. This falls within the range of the regional value of 30-40 mWm^{-2} but the best method to arrive at a good value is through well logging of the area. This possibly could have affected the value for the heat production which is moderately low compared with regional heat production of Nigeria which varied between 4.0 and 4.8 $\mu W/m^3$. Therefore, from the approach of thermal assessment, the region is made of diverse rocks with huge inconsistency in thermal properties.

Clearly, no comprehensive deductions can be made from limited measurements as done in this work so it is essential to get more data from other geophysical techniques like well logging in IKGWS area to get a precise geothermal prospective assessment of the area. This will also give a perfect indication to the mechanism of heat flow and geothermal potential in the area.

Author Contributions

Samuel Sedara: Conceptualization, Methodology, Software, Data curation, Writing- Reviewing and Editing.

Conflicts of Interest

The authors declare no conflict of interest.

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