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Assaying the Geothermal Energy Resource Potential of Gombe State in North-Eastern, Nigeria from Aeromagnetic Survey

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Abstract
A geothermal investigation of the whole of Gombe State in northeastern Nigeria has been done from a 2D spectral analysis of recently acquired high resolution aeromagnetic data as a means to elucidate likely concealed geothermal reservoirs in the state. The aeromagnetic data were divided into 20 overlapping blocks of 180 x 180 Km and each block analysed to estimate the Curie-point depths and ensuing geothermal gradient and heat flow isotherms. The results revealed Curie-point depths ranging from 20.03 to 29.83 Km with an average of 24.92 Km while geothermal gradients range between 19.44 and 28.69 ^{o}C/Km with an average of 23.60 ^{o}C/Km and an average value of 58.69 mW/m^2 (i.e. 48.61 – 72.39 mW/m^2) for heat flow. The results demonstrate that the entire State is dominated with thick crustal layer (above 15 Km) and heat flow that is less than both the global average of 87 mW/m^2 and accepted value of 80 - 100 mW/m^2 for anomalous geothermal conditions. Therefore, this study deduces that Gombe State may not have traces of anomalous geothermal settings, having shown no zone of considerable crustal attenuation and elevated heat flow. Even so, the study contributes to understanding of the thermal state of the lithosphere and regional heat flow variations of the geological formation housing the state.

Keywords: Heat-flow, Curie-depth, Aeromagnetic Exploration, Geothermal Exploration, Renewable Energy, Nigeria

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Introduction

The rising cost and demand for energy, coupled with the global Net Zero agenda to mitigate climate change through considerable carbon emissions reduction, have fast-tracked the search for and the development of renewable energy resources, including geothermal energy. Geothermal energy is the natural heat from Earth's interior that is produced as hydrothermal reservoir when rising hot water and steam beneath the ground surface is trapped in permeable and porous rocks under a layer of impermeable rock (Dickson and Fanelli, 2004). This heat energy provides a clean resource that can be used to generate electricity, produce preheated water or create low pressure steam system for heating of buildings and baths, growing of plants in greenhouses, and/or develop tourist sites (Batini, 2005). Exploration and exploitation of geothermal heat can therefore provide opportunities to increase energy options (direct and in-direct) and decrease greenhouse gases (AGU, 2015).

One of the many means of geothermal exploration is magnetic surveying, which can be carried out on land (ground magnetics), at sea (marine magnetics), in the air (aeromagnetics), and from outer space (satellite magnetics). Nevertheless, airborne surveys are often chosen for large area explorations because they permit faster and usually cheaper coverage of inaccessible areas (Thebault *et al*., 2010). The data obtained from such magnetic surveys can be analysed to estimate the depth to magnetic basements (Finn and Ravat, 2004; Ravat *et al.*, 2007, Bansal *et al*., 2011, Nwankwo and Shehu, 2015, etc.), which is also considered as an index of the Curie-point depth (Bansal *et al*., 2011).

Crustal rocks lose their magnetization at the Curie-point temperature (CPT) - a theoretical surface in the crust with a temperature of about 580 ºC (Hsieh *et al*., 2014). At CPT, ferromagnetic minerals lose their ferromagnetic properties and the thermal agitation causes the spontaneous alignment of the various domains to be destroyed or randomized so that the ferromagnetic minerals become paramagnetic (Langel and Hinze, 1998; Hsieh *et al.*, 2014). Thus, the CPT isotherm corresponds to the surface of crustal magnetic basement (Bansal *et al*., 2011). Consequently, the ability to estimate the depth to magnetic basement is also an ability to evaluate the Curie-point depth, which is then transformed into geothermal gradients and subsurface heat flow using Fourier's heat conduction equation (Tanaka *et al*., 1999). Estimation of Curie-point depth isotherm is typically used to examine crustal thermal structure, which defines deformation types and zones, brittle depths and/or regional heat flow variations (Kasidi, 2019). Quantitatively, Curie-point depths shallower than 15 Km are construed as areas of volcanic and geothermal fields, between 15 and 25 Km for island arcs and ridges, and deeper than 20 Km for plateau and trench phenomena (Tanaka *et al*., 1999).

In this work, therefore, a 2D radially-averaged power spectral analysis of recently acquired high resolution aeromagnetic data was carried out to estimate the Curie-point depths and resulting geothermal gradients and heat flow anomalies of the whole of Gombe State in northeastern Nigeria. This is in order to elucidate likely concealed geothermal reservoirs in the state.

Review of Literature

The last decade has witnessed a greater than before number of geoscientists investigating the geothermal landscape of Nigeria. Most of these researchers have computed Curie-point depths and ensuing geothermal parameters of different parts of the country from the analysis of aeromagnetic data (Nwankwo and Shehu, 2015; Lawal and Nwankwo, 2017; Nwankwo and Sunday, 2017; Chukwu *et al*., 2018; Abdulwahab *et al*., 2019; Kasidi, 2019; Odidi *et al*., 2020; Dopamu *et al*, 2021; etc.).

Nwankwo and Shehu (2015) studied the magnetic anomaly of the entire Sokoto basin and reported Curie-point depth values varying between 11.3 and 27.83 Km with a mean value of 18.57 Km, and heat flow values ranging between 52.11 and 130.28 mW/m^2 with a mean value of 84.97 mW/m^2. They also reported that areas with anomalous high heat flow (above 100 mW/m^2) exist in the basin and recommended detailed geothermal exploration. The Nigerian sector of the Chad Basin was also studied by Lawal and Nwankwo (2017) and reported Curie-point depth, geothermal gradient and heat flow values range between 18.18 and 43.64 Km, 13.29 and 31.29 ºC/Km, and 33.23 and 79.76 mW/m^2 respectively. The entire Bida basin was likewise computed by Nwankwo and Sunday (2017) and estimated Curie-point depth values of 15.57 - 29.62 Km with a mean value of 21.65 Km, and heat flow varying between 48.41 and 93.12 mW/m^2 with a mean value of 68.80 mW/m^2. In the Niger Delta basin, aeromagnetic fields were also examined for geothermal studies and values ranging from 7.46 to 24.86 Km, and 34.19 to 84.40 mW/m^2 for Curie-point depths and heat flow respectively were reported by Chukwu *et al*. (2018).

A more recent investigation is by Kasidi (2019) who worked on the Lamurde area of Adamawa State and reported that the Curie-point depth in the area varies between 9.62 and 10.92 Km with an average of 10.45 Km, and heat flow values between 150.73 and 132.78 mW/m^2 with an average of 139.12 mW/m^2. Areas of anomalous geothermal conditions were mapped, having observed heat flows that are more than 100 mW/m^2. This result may not be farfetched because of the existence of Lamurde hot spring (locally called Ruwan Zafi) in the area. Another work is by Abdulwahab *et al* (2019) that studied Kaltungo, Guyok, Lau and Dong quadrangle and reported values ranging from 12.43 to 33.91 Km, 17.10 to 46.66 $^oC/Km$, and 42.75 to 116.65 mW/m^2 for Curie-point depth, geothermal gradient and heat flow respectively. A similar work done in central parts of Benue Trough by Odidi *et al.* (2020) revealed Curie-point depth values ranging from 7.63 to 34.52 Km, with a mean value of 14.79 km, geothermal gradient ranging from 16.80 to 75.97 $^oC/Km$, with mean value of 45.70 $^oC/Km$ and heat flow values ranging from 42.01 to 189.94 mW/m^2 with a mean value of 114.26 mW/m^2. Most recently, Dopamu *et al.* (2021) reported that values from 12.5 to 38.3 $^oC/Km$ with a mean value of 26.0 $^oC/Km$ were obtained while assessing the Curie-point depths of the entire Benue Trough. They also reported values ranging from 15.0 to 45.3 Km with a mean depth of 23.2 Km, and 31.2 to 95.8 mW/m^2 with a mean value of 65.1 mW/m^2 for Curie-point depth and heat flow respectively. Their analyses suggested 5 zones of unusual heat flow that need further investigations.

Location and Geology of the Study Area

The study area is the whole of Gombe State bounded by latitudes 9.5^{o}N and 11.5^{o}N and longitudes 10.5^{o}E and 12^{o}E (Figure 1). The area is geologically located within the Gongola sub-basin of upper region of the cretaceous sedimentary Benue Trough. The entire Benue Trough is divided into lower (southern), middle (central) and upper (northern) parts, with the upper portion again sub-divided into three sub-basins: Lau, Gongola and Yola. The Gongola sub-basin, housing the study area, is a north-south trending arm with varying sequence of stratigraphy (Figure 2, 3).

The stratigraphic sequence indicates that sedimentation process was activated with the deposition of the continental Bima Sandstone that unconformably overlies the Precambrian Basement Complex (Obaje, 2009). The Bima Sandstone consists of feldspathic sandstones and clays which pass upwards into medium to coarse grained sandstones with less feldspar. The Bima Sandstone is overlain by Yolde Formation, which consists of a sequence of sandstones and shales. On top of Yolde Formation is Pindiga Formation that is mainly marine shale facies with limestones at the base. Pindiga formation, which is presumed to be deposited during the early – late Turonian and Coniacian times, is overlain by the Gombe Formation. Gombe Formation is made up of three major lithofacies: alternating beds of silty shales and fine-medium grained sandstones with ironstone intercalations; overlain by medium grained quartz arenite with occasional and iron oxide cement; and brick-red coloured, fine - medium grained sandstones, with tabular cross-bedding highlighted by layers and streaks of pure white sandstones. The most recent formation in the Gongola sub-basin is the Kerri-Kerri Formation, which a gently dipping continental conglomerates, sandstones, siltstones and clays that overstep into the Gombe Formation.

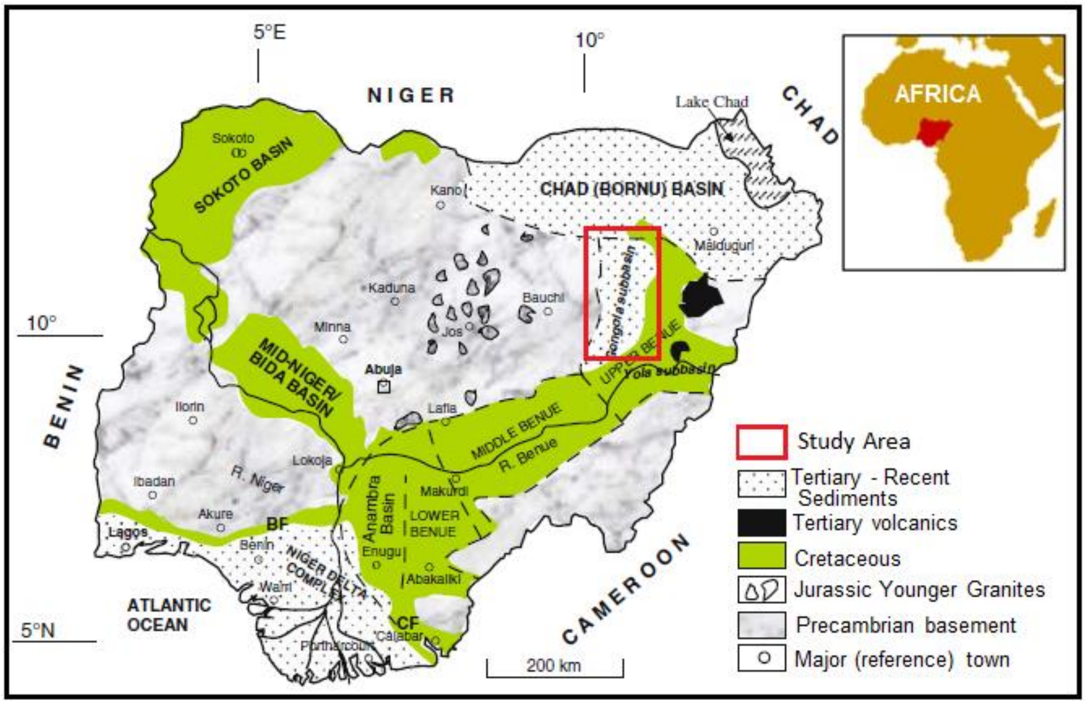

Figure 1: Geological Map of Nigeria showing the study area

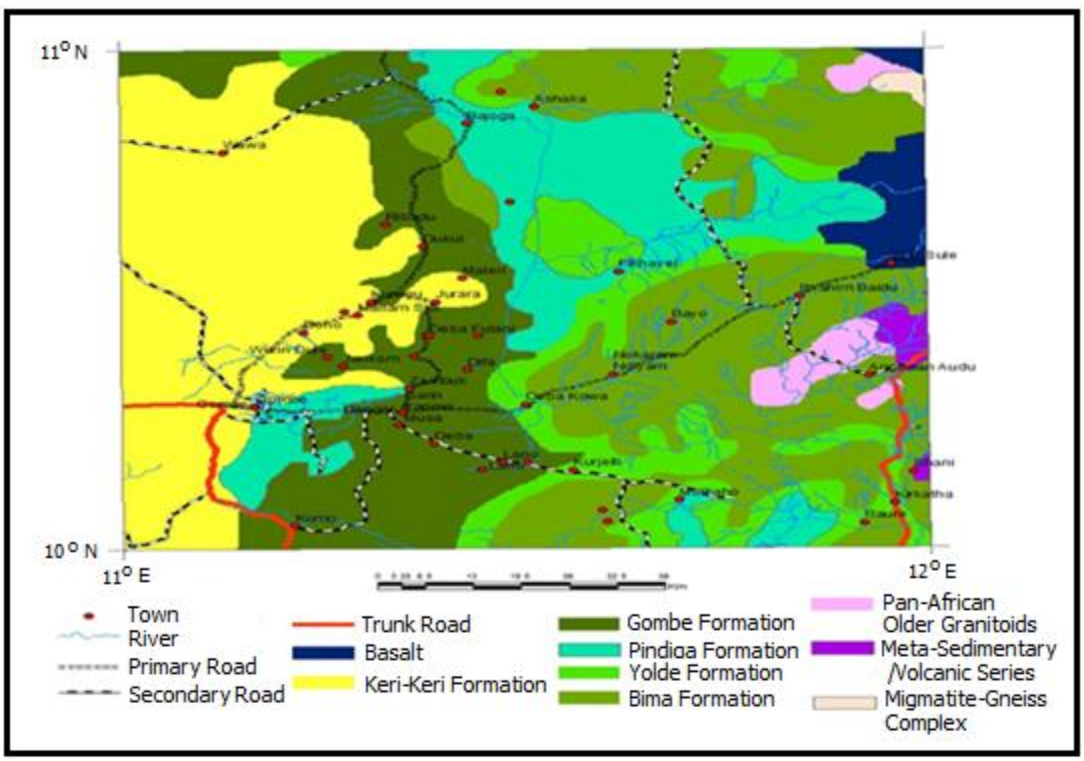

Figure 2: Geological map of the study area

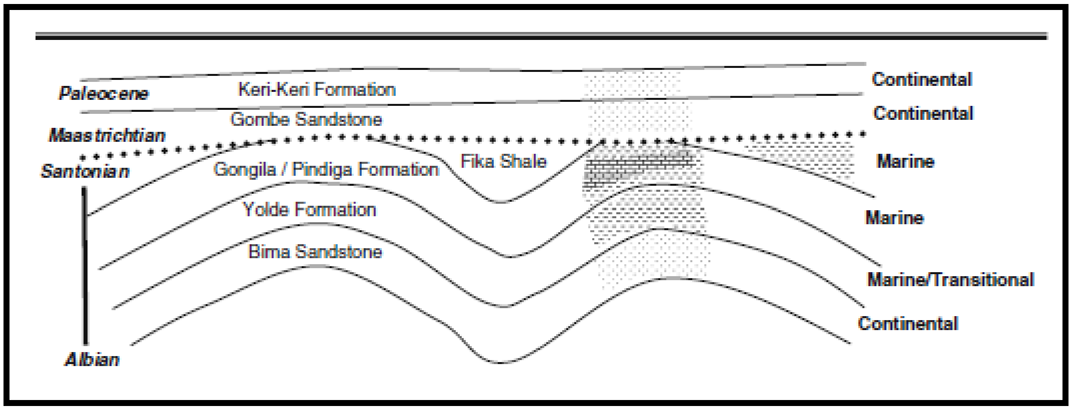

Figure 3: Stratigraphic sequence of Gongola Sub-basin (After Obaje, 2009)

Materials and Method

High-resolution aeromagnetic maps, extending the study area on opposite sides by half-degree, were utilized as the primary data in this work. The data were acquired via fixed-wing aircraft with attached 3x Scintrex CS3 Cesium vapour magnetometers between 2007 and 2009 by Fugro Airborne Survey Limited for the Nigerian Geological Survey Agency (NGSA). The aircraft were flown at mean terrain clearance of 80 m, 500 m line spacing, and nominal tie-line spacing of 2 km. The flight line and tie-line trends were 135 and 45 degrees respectively. Several pre-processing filtering techniques were applied on the acquired raw data by Fugro before being published as maps; these include regional correction based on the International Geomagnetic Reference Field and the subtraction of a constant value of 33,000 nT. These maps were then merged into a composite Total Magnetic Field Intensity map covering the study area and next divided into twenty (20) overlapping square blocks of length 180 km each, after reduction to the equator filter was applied.

Each of the blocks was further analysed using power spectral centroid codes developed in Matlab environment. The underlying technique is based on the examination of the shape of isolated magnetic anomalies, the study of the statistical properties of magnetic ensembles, and the evaluation of centroid part of the magnetic ensemble (Spector and Grant, 1970; Bhattacharyya and Leu, 1977; Blakely, 1995; Tanaka *et al.*, 1999; Okubo *et al.*, 1985; Nwankwo and Shehu, 2015; Nwankwo and Sunday, 2017).

The averaged power spectrum of each block's magnetic anomaly is expressed as:

$$\phi(|k|) = Ae^{-2|k|Z_t}(1-e^{-2|k|(Z_b-Z_t)})^2, \quad (1)$$

where k is the wavenumber (2π/km), A is a constant, and Z_b and Z_t are depths to bottom and top of magnetic layer respectively. Z_t is obtained from the slope of high wavenumber portion of the power spectrum:

$$\ln(\phi(k)^{1/2}) = A - |k|Z_t, \quad (2)$$

A centroid depth, Z_o, of magnetic sources is also calculated from the low wavenumber portion of the wavenumber-scaled power spectrum:

$$\ln(\phi(k)^{1/2}/k) = B - |k|Z_o, \quad (3)$$

Next, Z_b, which is also interpreted as Curie-point depth, is then computed:

$$Z_b = 2Z_o - Z_t, \quad (4)$$

Finally, geothermal gradient (*GT*) and heat flow (*HF*) are estimated:

$$GT = \left(\frac{\theta_c}{Z_b}\right), \quad (5)$$

$$HF = -\sigma\left(\frac{\theta_c}{Z_b}\right), \quad (6)$$

where θ_c and σ are Curie-point temperature (580 ºC) and thermal conductivity (2.5 Wm^{-1} $^oC^{-1}$) respectively (Huang *et al.*, 2008; Trifonova *et al.*, 2009).

Results

The estimated results for each of the 20 overlapping blocks are presented in Table 1. The table reveals that the Curie-point depth varies from 20.03 to 29.83 Km with an average of 24.92 Km, the geothermal gradient varies between 19.44 and 28.69 ºC/Km with an average of 23.60 ºC/Km, and heat flow varying between 48.61 – 72.39 mW/m^2 with an average of 58.69 mW/m^2. Subsequent isotherm map of each geothermal parameter for the study area is also plotted and presented in Figure 4.

Table 1: Estimated Curie-point depths, geothermal gradients and heat flow values.

Block	*Long. ºE	*Lat. ºN	Curie-Point Depth (Km)	Geothermal Gradient (ºC/Km)	Heat Flow (mW/m^2)
1	10.50	11.50	23.01	25.21	63.02
2	10.50	11.00	24.06	24.11	60.27
3	10.50	10.50	24.50	23.67	59.18
4	10.50	10.00	20.07	28.90	72.25
5	10.50	9.50	20.03	28.96	72.39
6	11.00	11.50	23.51	24.67	61.68
7	11.00	11.00	25.20	23.02	57.53
8	11.00	10.50	27.06	21.43	53.58
9	11.00	10.00	22.39	25.90	64.76
10	11.00	9.50	21.41	27.09	67.72
11	11.50	11.50	25.50	22.75	56.86
12	11.50	11.00	25.62	22.64	56.60
13	11.50	10.50	28.10	20.64	51.60
14	11.50	10.00	29.83	19.44	48.61
15	11.50	9.50	27.38	21.18	52.96
16	12.00	11.50	21.06	27.54	68.85
17	12.00	11.00	26.00	22.31	55.77
18	12.00	10.50	29.50	19.66	49.15
19	12.00	10.00	26.84	21.61	54.02
20	12.00	9.50	27.29	21.25	53.13
	Mean		24.92	23.60	58.69

* Coordinates show the centre of each square block

Discussion

The Curie-point depth map (Figure 4a) demonstrates that the entire Gombe State is dominated by a deep crustal layer (20 to 30 Km). The crustal structure trends generally with a radially decreasing thickness in the western direction and the shallowest portion (about 20 Km) occur at the SW zone. Different Curie-point depth values are associated with different geological environments, such that volcanic, tectonic and associated geodynamic and geothermal environments have Curie-point depth shallower than 15 Km, while Curie-point depth ranging from 15 to 25 Km results from island arcs and ridges, and Curie-point depth deeper than 20 Km is connected with plateaus and trenches (Tanaka *et al*., 1999; Salk *et al*., 2005). Consequently, the study area may not be associated with tectonic or geothermal activities. Expectedly, the geothermal gradient map (Figure 4b) and heat flow map (Figure 4c) exhibit an inverse relationship with the Curie-point depth and the SW zone having the highest but moderate geothermal gradient (about 28 ºC/Km) and heat flow (about 70 mW/m^2).

Nevertheless, the moderate heat flow anomaly observed for the SW zone is in no way near the global average global heat flow value. Recent chronicles indicate that the global heat flow, derived from 38,347 direct

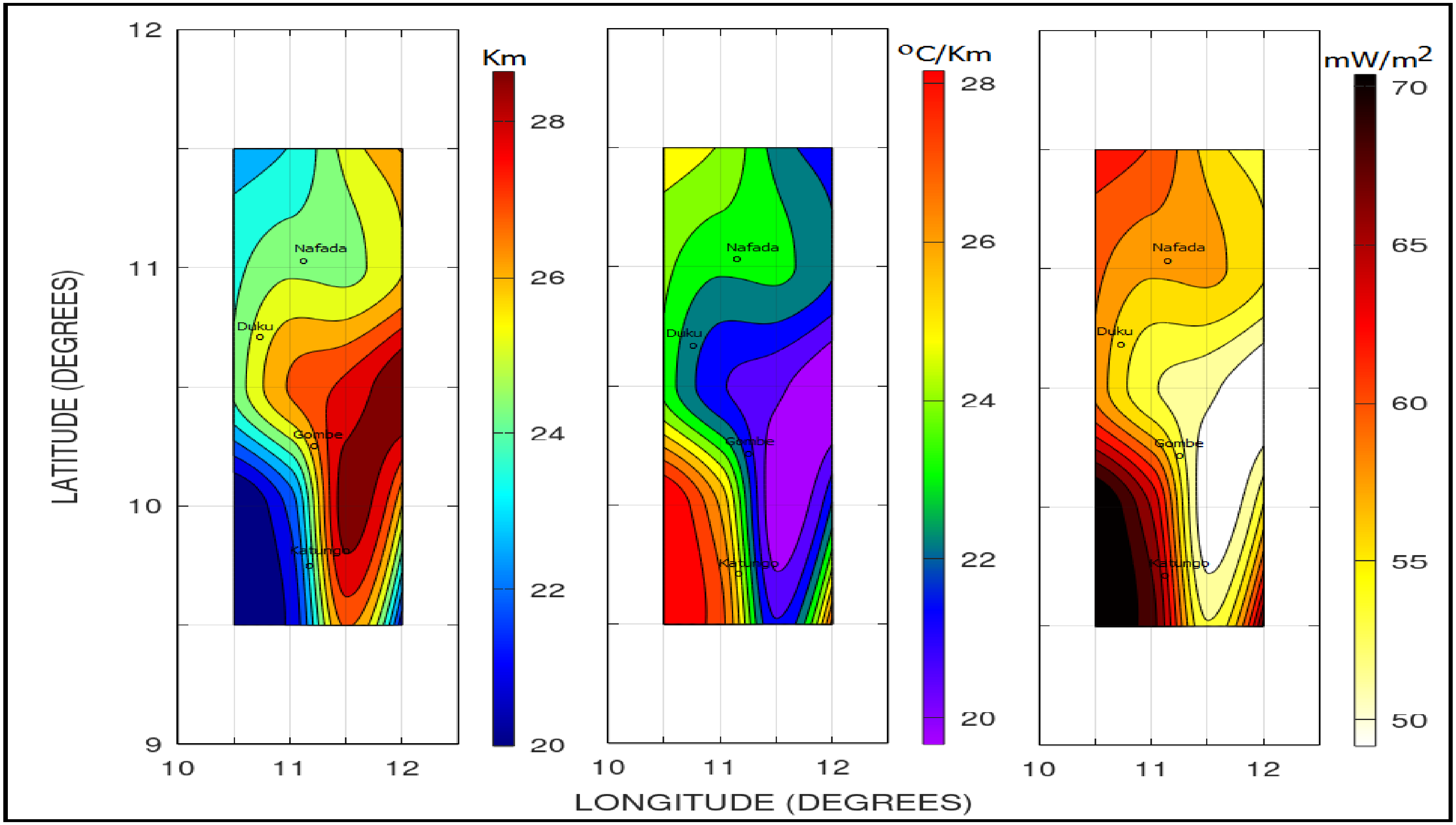

Figure 4: (a) Curie-point depth (b) Geothermal Gradient, and (c) Heat Flow isotherm of the study area

temperature measurement points, varies from 23.0 to 132.6 mWm^{-2} with an average of 87 mW/m^2 (Davies and Davies, 2010).

Neither is the heat flow anomaly in the entire State near the heat flow condition for anomalous geothermal signatures. Heat flow values ranging from 80 to 100 mW/m^2 and above indicate anomalous geothermal conditions (Jessop *et al*., 1976).

Generally, the pattern of the moderate heat flow observed in this study is neither governed by shallow crustal and lithospheric processes nor young heat losing rocks in the subsurface. Therefore, this study deduces that Gombe State may not contain areas of anomalous geothermal conditions for substantive geothermal energy exploration, having shown no zone of considerable crustal attenuation and elevated heat flow. On the other hand, this study is expected to contribute meaningfully to the quantitative evaluation of the geo-processes, rheology and understanding of the thermal state of the lithosphere and regional heat flow variations of the geological formation (i.e. Gongola sub-basin) housing Gombe state.

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