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A Short Review on The Application of Potential Field Methods for Geothermal Energy Exploration

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Abstract

There is quite a long history in Nigeria of Geothermal energy exploration. Geothermal energy resources are available in every part of Nigeria beneath the subsurface. The resources, however, vary in concentration in all the geological parts of the country. This paper reviewed the prospects of geothermal energy exploration by using the potential field (magnetic and gravity) technique for the exploration activities. The potential field data is capable to provide information on the subsurface structures after some filtering techniques (in case of magnetic) or data corrections (in case of gravity) have been applied to the raw field data. The processed data is capable to scan the lateral and vertical extent of anomalous zones beneath the surface. Geothermal energy, if properly exploited would contribute to the generation of clean energy in Nigeria for domestic and industrial purpose.

Keywords: *Gravity Method, Magnetic Method, Geothermal Energy, Exploration Geophysics, Clean Energy, Renewable Energy*

1. Introduction

In the event of an ever-increasing pollution of the environment and the fast-waning resources of the economy of the nations in Nigeria, it is very important to explore and establish alternative cleaner and more sustainable sources of energy for the satisfaction of human energy needs in Nigeria (Adagunodo et al. 2023; Aiyenero et al. 2023). The recognized natural resource of power generation which supplies the major portion of the total energy in the world at large is from the hydro, wind, oil and gas power generation. However, the exploitation of crude oil resources can no longer keep up with the pace of the ever-increasing rates of energy consumption in the world at large (Chandrasekharam, 2005; Prajapati et al. 2022). Also, the contributions of hydrocarbon waste to environmental hazards cannot be underestimated. The availability of the hot water steam and natural hot water spring can be utilized for the power generation and other heating purposes in so many regions of the globe at large including Nigeria (Abraham et al. 2014). The incessant increase in fuel prices (as a result of fuel subsidy's removal) has brought about an increasing interest to looking for an alternative natural source of energy like geothermal energy generation. Quite number of researches on geothermal prospecting has been done in Nigeria, it is worrisome that few projects have been executed till date (Okolie et al. 2019).

Geothermal energy can be described as the energy that determines the temperature of any matter of what is generated, at the same time store in the earth. Geothermal energy that is originated from the formation of the earth's crust constitute about 20%, while the rest which originated from the radioactive decay of the mineral contents embedded in the earth constitute the remaining 80% (Abdullahi, 2014). Geothermal resources are available in almost every part of Nigeria beneath the subsurface, even though they can vary in their concentrations from one geological domain to the other (Adagunodo et al. 2019a, 2019b, 2019c). The Geothermal gradient is the temperature difference between the core of the planet and the surface that drives continuously the conduction of the thermal energy from the earth's core to the surface in the form of heat. The Curie depth point is the point at which the magnetic mineral that is dominant in the crust losses the ferromagnetic properties due to an increase in temperature. The geothermal energy is renewable, environmentally friendly source of energy that is based on the internal heat from the earth. Geothermal energy can be in association with the volcanic activities of the earth crust, permeability of the sedimentary layers at a great depth or even the hot part of the crust at the active tectonic depth. For many years, people have been utilizing the source of energy from geothermal spring for cooking, washing or for large scale direct usage and even for generating electricity. More than about 50 countries are now utilizing geothermal energy worldwide (Prajapati et al. 2022).

Volcanic activities have been linked to the geothermal energy resource in Nigeria. The northern parts of the country (such as the Cretaceous Benue Trough, Borno Basin, Chad Basin and Sokoto Basin) have shown higher geothermal prospectivity than the south. The overpressured thick sediments in south are presumed to aid the heat flow as a result of the anomalously high temperature gradients of the sedimentary strata overlying the deep-seated bedrock (Abraham et al. 2014). The study of the subsurface heat flow in the Nupe Basin by Nwankwo et al (2009a) and (2009b) showed some geothermal potential in the region with the geothermal gradient ranging from 10 - 45^0CKm^{-1}, and the heat flow ranging from 30 - 120 mWm^{-2}. Aeromagnetic investigation from Ikogosi warm spring revealed that the environment is characterized by shallow Curie point depth or basal depth of 15.1 km and high heat flow of 91.2 mWm^{-2}, respectively (Abraham et al. 2014). Aeromagnetic investigation of some notable parts in SW Nigeria revealed a subsurface average geothermal gradient of 42.5 °Ckm^{-1} and average (shallow) Curie point depth of 8.5 km, with the mean heat flow of 55 mWm^{-2} (Ayuba et al. 2019). The promising prospects for geothermal in their study are within Osogbo and Ogbomoso axis, with latitude 7.8 to 8.2° north and longitude 4.2 to 4.6° east. Within Osogbo-Ogbomoso axis, a maximum heat flow, maximum geothermal gradient and lowest Curie point depth of 190 mWm^{-2}, 75 °Ckm^{-1} and 5.5 km were obtained.

The geothermal prospectivity study of some parts of the Central and the North-Eastern Nigeria, shich coincides with the Benue Trough, Gongola Basin, Yola Basin, Younger granites in the Jos Plateau, crytalline basement terrain in the Northern Nigeria and some parts of Bauchi and Nasarawa states using aeromagnetic data revealed that the subsurface is endowed with the geothermal features of 7.6 to 34.5 km for the Curie point depth, 16.8 to 76.0 °Ckm^{-1} for geothermal gradient and 42.0 to 189.9 mWm^{-2} for the subsurface heat flow, respectively (Odidi et al. 2020). The mean geothermal prospectivity of the zone for the Curie point depth, geothermal gradient and the subsurface heat flow are 14.8 km, 45.7 °Ckm^{-1} and 114.3 mWm^{-2}, respectively. The geothermal energy investigation of some parts of the Niger Delta Basin using the potential field theory showed the geothermal gradient and the heat flow as 2.25 °Ckm^{-1} and 52.6 mWm^{-2}, respectively. The obtained value for the heat flow in the Niger Delta was below the geothermal energy potential standard of 100 mWm^{-2} (Chukwu et al. 2018). The study concluded that it may not be logical to explore the Niger Delta basin for geothermal energy.

Integration of aeromagnetic and aerogravity data in the southeastern part of Nigeria showed that the Curie point depth, crustal thickness and the geologic features of the environment are in support of the geothermal energy resource (Abraham et al. 2019). A range of 9.8 to 19.3 km was obtained as the Curie point depth, 26.5 to 35.8 km was obtained as the crustal thickness (depth to Moho), 29.0 to 45.0 °Ckm^{-1} as the geothermal gradient and 52.2 to 101.5 mWm^{-2}, being the subsurface heat flow of the SE Nigeria. The potential field investigation over Dahomey Basin in the SW Nigeria revealed that the Curie point depth, heat flow and geothermal gradient varied from 11.0 to 27.0 km, 53.0 to 130.0 mWm^{-2} and 21.0 to 52.0 °Ckm^{-1}, respectively (Oladele et al. 2022). The geo-resistivity results of the Dahomey Basin showed that the thermal aquifer (that is, a sandy zone with resistivity values varying from 1 to 20 Ωm) is vertically housed between 155 and 210 m within the crust. It was revealed that Dahomey Basin is thermally unstable, with a massive prospectivity for geothermal energy resource (Oladele et al. 2022). Other applications of the potential field data could be found in Joel et al. (2019), (2020), Oladejo et al. (2019) and (2020). Notable locations of hot springs or geysers in Nigeria are presented in Table 1. The prospective surface geothermal energy resource locations in Nigeria are also revealed in Fig.1.

Table 1: Hot spring locations in Nigeria (Adapted from Okolie et al. 2019)

Location	State	Location	State
Essie	Kwara	Bauchi	Bauchi
Madalla	Abuja	Enugu	Enugu
Ijebu-Ode	Ogun	Idanre	Ondo
Akampa	Cross River	Abaji	Abuja
Minna	Niger	Jalingo	Taraba
Lokoja	Kogi	Ijebu-Jesa	Osun
Jos	Plateau	Ikogosi	Ekiti

Kwali	Abuja	Ile-Ife	Osun
Onitsha	Anambra	Gurara	Bauchi
Obudu	Cross River	Kabba	Kogi

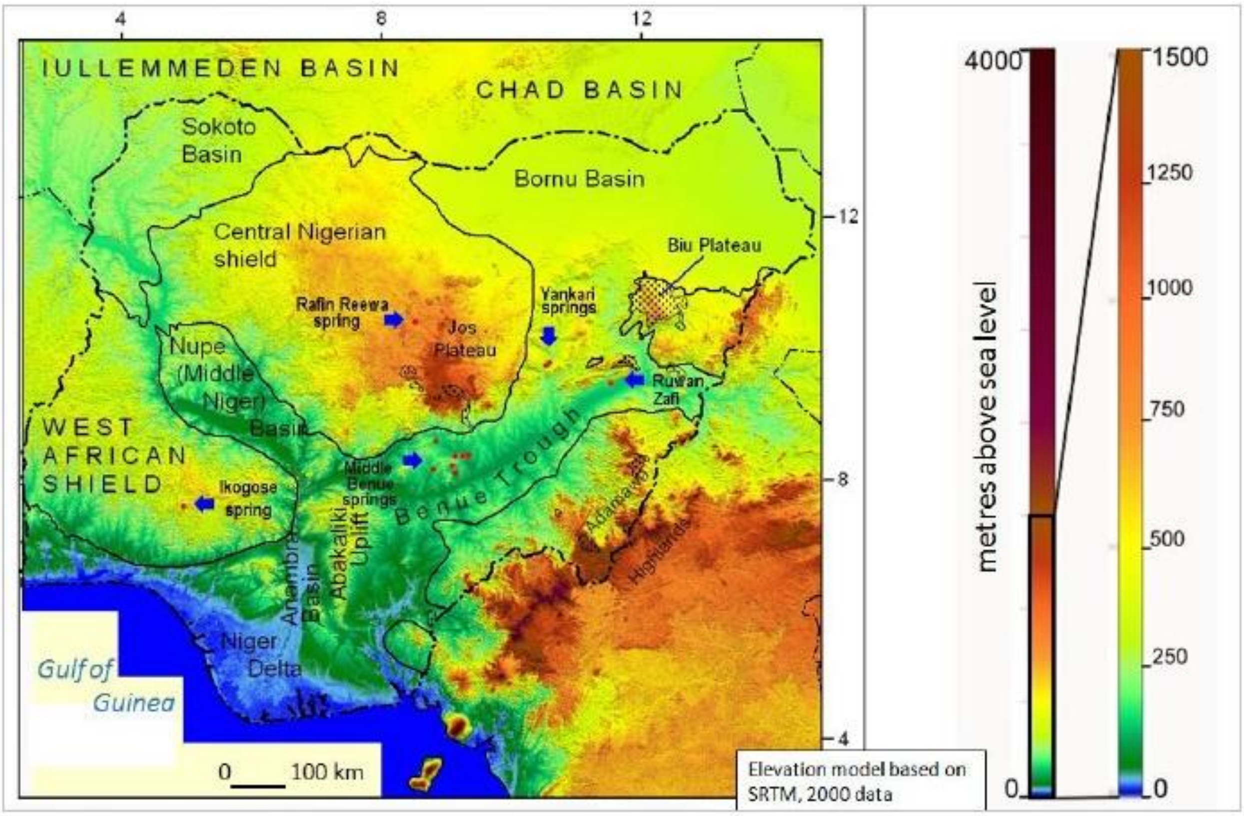

Fig.1: Topgraphic and geothermal disrtibutions in Nigeria reaving some notable thermal springs

Nigerian Geological Settings: Overview

In general, Africa is predominantly composed of sediments and/or weathered rocks, known as Cratons, liying above the basement complex rocks. The Cratons are composed of granitic families, various types of gneiss and low-grade greenstone belts. The tectonic and geologic settings of Africa have been discussed by Adagunodo et al. (2018a). The Nigerian geology is characterized by the re-grouped basement rocks of West Africa (Adagunodo et al. 2018b), where the proportions of basement rocks and sedimentary basins are almost the same, with varying ages and deposition histories. Other minor formation in Jos and its environs include the volcanics, which are composed of the younger granites. The hydrogeology of the Nigerian terrain has been classified into basement rocks, volcanics, consolidated and unconsolidated sediments (Sunmonu et al. 2012).

The basement rocks are majorly made up of crystalline and metamorphic rocks that have been challenged with various tectonic deformations over long geological era (> 550 Ma). The basement rocks are composed of migmatite-gneissic-quartzite complex, schist belts, granitoid pluton (from older granites). In the western region of the country, the basement lithologies include the migmatite gneiss, granite, amphibolite, pegmatite, quartzite, biotite, muscovite and talk-tremolite. The basement rocks are intrusions to schistose in some environs, while they are found as intrusions to older granites in other domains (Abraham et al. 2014). The tectonic deformations of the basement rocks in Nigeria have resulted to series of fracture networks being discussed by some geoscientists (Eze et al. 2011; Oladejo et al. 2020).

The alluvial deposits are found along the river channels. The sedimentary basins' sediments overlie the basement complex rocks at varying thickness and depths. Most common sedimentary rocks in Nigeria include sandstones (cross bedded and poorly sorted ones), gravels, and arkosic (Kwaya and Kuriwska, 2018). These rocks are of Cretaceous and Tertiary ages. The notable sedimentary basins in Nigeria are: The Anambra Basin, the Benue Trough (Lower, Middle and Upper zones), the Bida-Nupe (or mid-Niger) Basin, the Chad Basin, the Dahomey Basin, the Niger Delta Basin and the Sokoto Basin. The geological settings across Nigeria are shown in Fig. 2.

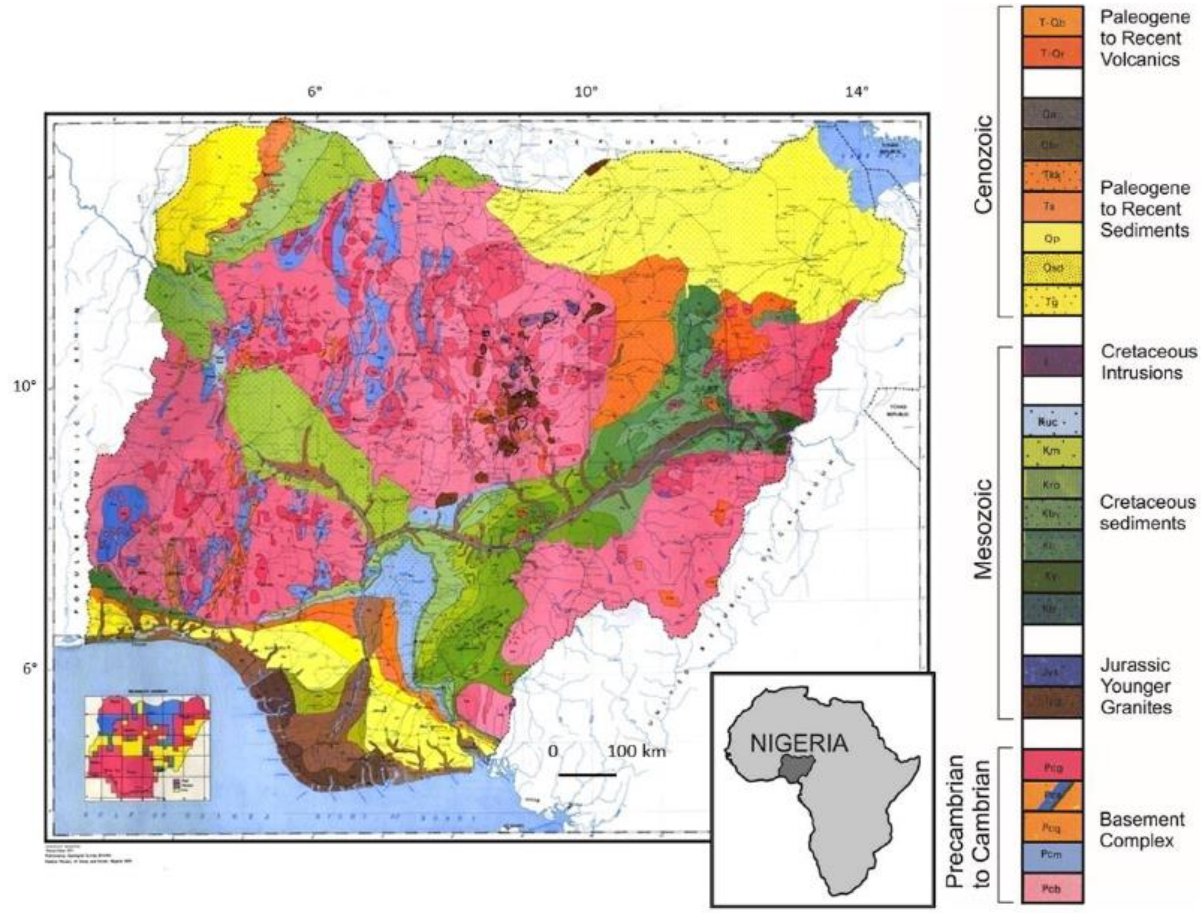

Fig. 2: Geological provinces in Nigeria (Adapted from Kwaya and Kurowska, 2018)

Magnetic and Gravity Methods for Geothermal Exploration

Geophysical studies can provide non-destructive method which can be used to obtain the information of the earth condition or any possible problem in the subsurface. Geophysical survey had in several ways provided much information on engineering and environmental application such as soil stratification, water table or slip planes. To locate a geothermal area on the land, it is important to explore for the areas which have the surface features with the boiling pools and fumaroles. In a similar manner, the most probable evidence for geothermal source of heat on the ocean floor is the hydrothermal venting. On the land surface, these features can easily be discovered by direct observation and a simple geologic reconnaissance, but for ocean exploration, direct observation of the vents will require towed cameras and submersibles and getting to the vent sites will requires a large worthy ocean ship.

Magnetic and gravity methods are presenting the most economically geophysical data techniques for obtaining a model that is acceptable for the geothermal system of analysis (Moghaddam et al. 2016). Aeromagnetic and gravity methods can reduce the ambiguity that may arise with the complementation of each other (Hospers, 1965), because each geophysical method relies on its strength and its weakness that depend on the area of target in their survey. The analysis of the aeromagnetic data can be used in production of a contour Curie point depth map. The representation of the map will be correlated to a significant higher dimension extent of various indicators of known geothermal activities in the region that is undergoing consideration (Bansal et al., 2011). The combination of magnetic and gravity methods is very essential towards presenting enhanced geothermal structures around any given study area. At varying strata and depths, the magnetic method is capable to map different rock properties and magnetic susceptibilities, while gravity method has the ability to map the near-surface rock densities. In geothermal exploration, the magnetic measurement is generally aimed to estimate the depth, track the individual buried faults, to map the near-surface dykes and to locate any hidden intrusive bodies. It can equally help to locate regions with low magnetization as a result of the thermal activity (Georgsson, 2009). The patterns at which the range of depth of magnetic sources could be determined are categorized into the shape of isolating magnetic anomalies and the statistical characteristics of the pattern of the magnetic anomalies. In the transformation of spatial data into frequency domain, magnetic sources could synergize between the spectrums of the magnetic-source depths and magnetic anomalies (Obande et al., 2014, Chukwu et al. 2018).

Magnetic Survey

Magnetic survey is very useful for many purposes: it can be used to estimate the thickness and size of rock formations, age relationships between crustal areas, estimate sizes and thicknesses of rock formations, and to find tectonic/structural trends as well as unusual magnetic properties that can be linked to other geologic features (Jónsson et al. 1991). However, it is important to obtain a useful detailed model for the magnetic survey of the geothermal exploration before it can be utilized (Georgsson, 2009). An enhanced subsurface mapping of the geothermal reservoir can be of great help in this regard. With identification of geothermal reservoirs, it can be easy to delineate regions with favourable heat flow for geothermal energy. The Magnetic survey has the usefulness by revealing the depth at which a Curie isotherm temperature of about 580°C can be achieved in the subsurface (Bouligand et al., 2009). In the shallow water, which is closer to the shore, the magnetic survey measurement can be conducted from the boats around the surface which is relatively very inexpensive and easy. For data analysis of the magnetic survey, the procedures laid by Okubo et al. (1985), Tanaka et al. (1999), Oladejo et al. (2020) Oladele et al. (2022) and Oni et al. (2023) can be followed. The magnetic source's top bound (Z_t) and centroid (Z_0) can be estimated from the spectrums of the potential field anomalies and then utilize to estimate the depth of basal point of the magnetic source, Z_0.

There are basic assumptions given as follows:

i. The layers extend in lateral horizons infinitely;

ii. The vertical distance to the top of magnetic sources is small when compared to the lateral distance of the magnetic body; and

iii. The magnetization M(x,y) is a random function of x and y and the power density spectra of the total field anomaly, $\emptyset_{\Delta T}$. The $\emptyset_{\Delta T}$ is given by Eq. (1).

$$\emptyset_{\Delta T}\,(K_{x,}K_{y,}) = \emptyset_M\,(K_{x,}K_{y,}) \times F\,(K_{x,}K_{y,}) \tag{1}$$

$$F\,(K_{x,}K_{y,}) = 4\pi^2 C_M^2 |\emptyset_M|^2 |\emptyset_F|^2 e^{-2KZ_t}(1 - e)^2 \tag{2}$$

where $\emptyset_M$ is the power-density spectra of the magnetization and C_M is the proportionality constant, but $\emptyset_M$ and $\emptyset_f$ are the factors for the magnetizing direction and geomagnetic field direction respectively.

If the M(x,y) is uncorrected and random completely, the $\emptyset_M\,(K_{x,}K_{y,})$ is a constant.

Therefore, the radial average of $\emptyset_{M\Delta T}$ is given by

$$\emptyset_{\Delta T}\,(|K|) = A\ e^{-2KZ_t}(1 - e^{|-K(Z_b\ -\ Z_t)|})^2 \tag{3}$$

where A is a constant.

Any wavelength < twice layer's thickness, Eq. (3) becomes:

$$\text{Ln}\,[\,\emptyset_{\Delta T}\,|(K)|^{\frac{1}{2}}\,] = \ln B - \ln |K| Z_t \tag{4}$$

where B is a constant. By using the slope of the Power spectrum, we can estimate the top bound of the magnetic source.

We can re-write Eq. (3) as follows

$$\emptyset_{\Delta T}\,|(K)|^{\frac{1}{2}} = C\,e^{-KZ_t - Zo}\ (\,e^{-K(K(Z_t - Zo)} - \ e^{-K(Z_t - Zo)} \tag{5}$$

where the value of C is a constant

At a long wavelength, Eq. (5) now becomes

$$\emptyset_{\Delta T}\,(|K|)^{\frac{1}{2}} = Ce^{-KZo}\ (\,e^{-K(-d)} - e^{-K(-d)}) \sim C\,e^{-KZo}2|K|d \tag{6}$$

where 2d denotes the magnetic source's thickness.

From Eq. (6), we can then take the logarithms of both sides as follows

$$\ln\{\,[\,\emptyset_{\Delta T}\,|(K)|^{\frac{1}{2}}/\,|K|]\,\} = \ln D - |K| Z_0 \tag{7}$$

where D is a constant. We summarize Eq. (4) and Eq. (7) as

$$\text{Ln}\,[\,P(K)^{\frac{1}{2}}] = \ln B - |K| Z_t \tag{8}$$

$$\text{Ln}\left[\frac{P(K)^{\frac{1}{2}}}{|K|}\right] = \ln D - |K|Z_0 \quad (9)$$

where $\emptyset_{\Delta T}\ (|K|)^{\frac{1}{2}}$ can be written as $P(K)^{\frac{1}{2}}$

The magnetic bodies' top and bottom (centroid) can be estimated through fitting of a straight line over a high and low wave number of the radially averaged spectrum of $\ln[P(K)^{\frac{1}{2}}]$ and $\ln[\frac{P(K)^{\frac{1}{2}}}{|K|}]$ from Eq. (8) and Eq. (9), respectively. As the frequency unit is in cycles per kilometre. The spectrum is divided by (4π). The depth to the base of the magnetic source (known as basal depth) is given by:

$$Z_b = 2Z_0 - Z_t \quad (10)$$

The Curie point depth is the presumed estimation of basal depth.

Conductive Heat Flow

For conductive heat flow conveyance, the fundamental relation that can be considered is the Fourier law (Tanaka et al., 1999). In 1D occurrence, the vertical direction is assumed for the temperature variation and the constant temperature gradient $\frac{dT}{dZ}$.

Fourier law for heat flow is of the form given by:

$$q = K\frac{dT}{dZ} \quad (11)$$

where K is the coefficient of thermal conductivity and q is the heat flux.

The Curie temperature (t) is defined as:

$$t = \left(\frac{\partial T}{\partial Z}\right) Z_b \quad (12)$$

where Z_b is the Curie point depth, in as much as there is no heat source or sink existing between the Curie point depth and the Earth's surface.

The surface temperature is given as 0°C, while $\frac{dT}{dZ}$ is a constant.

At any depth, the heat flow is conversely directed to the thermal isotherm (Tanaka et al., 1999). For magnetic computation, we can easily calculate for the geothermal gradient and the heat flow based on the Curie point depth estimation from Eq. (11) and Eq. (12).

Gravity Survey

Gravity survey is valuable in the conventional geothermal system exploration because it can be very useful to identify the subsurface anomalies that are in connection with the deep magmatic and granitic bodies, which includes the zones of fault and altered structures, indicating the geothermal activities. The density contrast of such zones with unchanged rock surrounding's fault structures, which provides preferential pathways by the subsurface for circulating geothermal fluids and the structures of the faults are concealed by the sedimentary cap rock in succession (Kohrn et al., 2011). The gravity method has proved to be victorious in the discovery of the hidden geothermal systems. Gravity method had proved to be a possible method of achieving results practically for the geothermal exploration that involves the delineation of fracture and fault zones, which have similarities with the geothermal reservoirs. It is also connected into probing of basement configuration basement and intrusive magma bodies in relation to the heat source (that is, geothermal energy) (Moghaddam et al. 2016; Narittomi, 2017). The edge detection filters can be used in gravity method to determine the following: normalised horizontal tilt derivative (NHTD) and tilt derivative (TD). The enhancement of edges for the sources are universal tools for interpreting the potential field data and some of the balance edge detection filters that existed before now can only makes use of the features that gives the maximum value as the vertical derivatives amount to zero, hence it cannot give spurious edges, but brings out an accurate result thereby suppressing the noise, as when compared to the edge detection filters (Li et al., 2014). The procedures reported by Yusuf et al. (2021) can be adopted for the analysis of gravity data.

Total horizontal derivative (THD) is capable to give maximum sudden changes in the density of the grids (Nishijimaa and Naritomi, 2017).

$$\text{THD} = \sqrt{\left(\frac{\partial g}{\partial x}\right)^2 + \left(\frac{\partial g}{\partial y}\right)^2} \quad (13)$$

where the $(\frac{\partial g}{\partial x})^2$ and $(\frac{\partial g}{\partial x})^2$ are directional derivatives for gravity anomaly in respect of x and y directions.

The THD's advantage is that it is less susceptible to the noise and the edges of the deep and shallow structures can be clearly re-organized.

The NHTD is given by:

$$\text{NHTD} = Tan^{-1}\left(\frac{\sqrt{\left(\frac{\partial g}{\partial x}\right)^2 + \left(\frac{\partial g}{\partial y}\right)^2}}{P \ + \left|\frac{\partial g}{\partial z}\right|}\right) \quad (14)$$

where P is a positive constant value that can be determined by the interpreter. Generally, the value of P is approximately resulted to the 1/10th or 1/20th of the THD_{Max}. The estimated value of the crustal thickness from the gravity data when we assume a single density contrast within a crustal and the base can be expressed as:

$$H = 29.98 \ - \ 0.075\nabla g \quad (15)$$

where H is the thickness of the crustal in kilometres and ∇g is the gravity anomaly values in mGal.

Geothermal Energy Exploration: Case Histories

In addition to the geothermal exploration potential of each region in Nigeria that has been highlighted in the Introduction, few records from sedimentary terrain and surface manifestation of geothermal energy from some thermal springs in Nigeria will be discussed. A Nigerian Chad Basin, which is about 1/10th of the whole Chad, has an overall sediment thickness of ≈ 10 km (Avbovbo, 1986). The average aeromagnetic data interpretation revealed that the geothermal gradient from the Chad Basin varied from 3.00 to 6.44 °C/100 m, the thermal conductivity varied from 0.58 to 4.21 WmK^{-1}, while the heat flow ranged from 45 to 90 mWm^{-2}, respectively (Kwaya et al. 2016). Meanwhile, the gravity data interpretation showed that the geothermal reservoirs in the Chad Basin are housed within the depth varying from 23 to 26 km (Kwaya and Kurowska, 2018). The geothermal anomalies in the basin are as a result of the thinned crust resting above the fault-confined graben and horst networks from the tectonic activities. In addition, the main source of heat (and thermal energy) in the Chad Basin is presumed to originate from the upper mantle (Ikpokonte, 2009).

The aeromagnetic interpretation from the Sokoto Basin revealed that the mean geothermal gradient of the basin varied from 20.84 to 52.11 $°Ckm^{-1}$, while the heat flow varied from 52.11 to 130.28 mWm^{-2} (Nwankwo and Shehu 2015). The estimated geothermal gradients from temperature data across 50+ boreholes in the Sokoto Basin varied from 3.24 to 16 .00 °C/100 m. The geothermal potential of the Niger Delta Basin is generally low from literature. Subsurface heat flow varying from 20 to 30 mWm^{-2} was obtained from the central Delta, while the heat flow ranging from 40 to 55 mWm^{-2} was obtained from the southern and northern parts of the Niger Delta Basin (Avbovbo 1978; Idara 2009). There have been connections between the Curie point depth and heat flow or temperature gradient from literature. Generally, shallow Curie point depth is associated with high temperature gradient and high heat flow.

Geothermal potential (under surface activities) from thermal springs in Nigeria is also feasible. Rafin Rewa warm spring in the north originated from weathered migmatites of the Precambrian basement rocks. The spring flows from an approximate depth of 700 m below the earth surface. It is believed to be the only juvenile water in Nigeria (Garba et al. 2012). Other notable springs in Nigeria are Ikogosi warm spring in Ekiti state and the Wikki warm spring in Yankari, Bauchi state. Some thermal springs from the Benue Trough are Awe, Akiri, Ribi, Keana, Azara and Assakio (Bako 2010). The temperature of Rafin Rewa spring is about 42.2 °C, Akiri spring is 53.5 °C, while the Ruwan Zafi spring is ≈ 54.0 °C. Results from the Benue Trough showed some promising zones for development of geothermal systems (Nghargbu et al. 2017). The geothermal prospect of the Benue Trough could corroborate the promising zones that were mapped by Oladele et al (2022) in Dahomey Basin for development of geothermal energy in Nigeria.

Some challenging issues to the development of geothermal energy in Nigeria include: constraints in indigenous technological capacity and human resources; limited sponsorship on geophysics researches being tailored towards geothermal exploration and identification of geothermal reservoirs for drilling; ignorance about hydrogeological diversities (such as porosity, permeability, lithology and so on) of various geological settings in Nigeria; current security challenges in the country; time and high-cost of geophysical fieldwork required to acquire data for geothermal exploration. It is believed that areas with geothermal gradients > 5 °C/100 m (such as Benue Trough, Chad, Sokoto, Dahomey Basins as well as some notable zones in the basement complex) could be utilized for geothermal energy (Kwaya and Kurowska 2018). The identified geothermal reservoirs will boost the Nigerian energy mix if the government and other concerned agencies could look into the installation of geothermal binary power generation system for the production of electricity, since there is no active volcanic domain in Nigeria that could be adopted for other applications of geothermal energy other than electricity.

4. Conclusion

The paper reviewed the prospects of geothermal energy in Nigeria. There is almost an availability of geothermal resources in virtually every part of Nigerian's subsurface, although the geological compositions being responsible for geothermal energy may vary from one province to the other. A combination of gravity and magnetic data can be used to model the subsurface structures for geothermal reservoirs; the analysis of the results can be utilized to build sustainable geothermal energy systems across the country. The rift-induced magma is the main process that controls the subsurface heat flow. A high heat flow is as a result of an active magmatism. The heat within the crust could originate from the magma being transported from the earth's interior through convection as a result of thinning and bowing of the crust. The maximum power generated in Nigeria in the year 2023, which is expected to meet the need of 200 million + people is 4, 962.7 MW. It is imperative to state that Nigeria needs an alternative (renewable) energy source urgently, to augment the power generation from hydro and gas-fired thermal power plants. Since this review has highlighted some regions that could be exploited for geothermal energy, priority should be given to the production of electricity through the geothermal energy and other renewable energy resources for the sustainable development of Nigeria.

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