ASSESSMENT OF GEOTHERMAL PROSPECTIVE AREA USING INTEGRATED MULTI-SPATIAL DATA ANALYSIS AT NORTHEASTERN NIGERIA

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by

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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
CPD	Curie point depth
CR	Consistency Ratio
DEM	Digital Elevation Model
ENVI	Environment for Visualizing Images
eTh	Equivalent Thorium
eU	Equivalent Uranium
GIS	Geographic Information System
IGRF	International Geomagnetic Reference Field
IGSN	International Gravity Standardisation Net
KUST	Kano University of Science and Technology
MCE	Multi Criteria Evaluation
MW	Mega Watts
NE	North East
NGSA	Nigerian Geological Survey Agency
NW	North West
N-S	North -South
OLI	Operational Land Imager
% K	Percentage Potassium
RHP	Radiogenic Heat Production
R-R-F	Rift-Rift-Faults
RTE	Reduced to Equator
SE	South East
SRTM	Shuttle Radar Topography Mission
SW	South West

TMI	Total Magnetic Intensity
TOC	Total Organic Content
UAV	Unmanned aerial vehicle
USM	Universiti Sains Malaysia
WO	Weighted Overlay
Wt	Class Weight Value

LIST OF SYMBOLS

C_k	Potassium concentration
C_{Th}	Thorium Concentration
C_u	Uranium Concentration
°C	Degree Celsius
d_{ii}	The ratio of the Significance of *i* to *j*.
°	Degrees
´	Minutes
M^3	Cubic-metre
m	Metre
n	A Judgment Matrix Order
μ	Micro
ρ	Rock Density
´´	Seconds
∑	Summation
λ	eigenvalue of A
Ө	Temperature
δ	Differentials
δt	Changes in temperature
δT/δH	Total Horizontal Gradient
X_{ij}	The Standardized Pixel Value
X*j*	Pixel Value on Position *j*
δx	Changes along X-direction
δy	Changes along Y-direction
Z_o	Depth to the Central Part of the Magnetic Sources
Z_b	Depth to the Bottom of Magnetic Sources

Z_t	Depth to the Top of the Magnetic Sources

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PENILAIAN KAWASAN PROSPEKTIF GEOTERMA MENGGUNAKAN ANALISIS DATA PELBAGAI RUANG BERSEPADU DI TIMUR LAUT NIGERIA

ABSTRAK

Pemetaan ruang bagi zon prospektif geoterma ialah alat penting yang digunakan dalam penerokaan awal bentuk tenaga boleh diperbaharui di dunia. Kajian terdahulu telah mengabaikan peranan sumber haba radiogenik dalam pembinaan model peta potensi geoterma mereka. Oleh itu, ia meninggalkan jurang kajian yang tidak lengkap, di mana aspek penting haba bumi diabaikan.Oleh itu, kajian ini menggunakan haba radiogenik bersama-sama parameter lain dalam pemetaan dan analisis kawasan potensi geoterma berubah menggunakan pendekatan penilaian kriteria berbilang berasaskan GIS. Kajian ini merupakan kajian geoterma pertama yang menganggap haba radiogenik bersama dengan parameter lain untuk analisis potensi lokasi geologi yang agak tidak diketahui. Objektif kajian termasuk; pengenalpastian potensi geoterma serantau di kawasan ini melalui pemprosesan data ruang yang berkaitan untuk mendapatkan lapisan geoterma untuk penyiasatan awal, penjanaan/analisis tahap sub-kemungkinan lapisan tematik yang berbeza untuk analisis lapisan individu, dan Ketiga, menyepadukan peta sub-kemungkinan berbeza ke dalam peta komposit tunggal menggunakan teknik tindanan berwajaran berasaskan GIS untuk analisis komprehensif. Pelbagai set data model aeromagnet, aerograviti, aeroradiometrik, model ketinggian digital topografi radar ulang-alik (SRTM-DEM), peta litologi dan data pengimejan darat (OLI) operasi Landsat-8 telah diproses. Oleh itu, sebanyak lima (5) lapisan bukti; Pengeluaran haba radiogenik (RHP), kecerunan suhu, garisan bersepadu, graviti sisa dan peta geologi telah dihasilkan. Lapisan tersebut telah disepadukan ke dalam peta kelebihan geoterma.

Kedalaman titik curie (CPD) yang dianalisis menunjukkan nilai minimum, maksimum dan purata masing-masing 8.18 km, 31.48 km dan 13.0 km. Nilai kecerunan suhu minimum, maksimum dan purata yang diperoleh ialah 18.42 °C/km, 70.91 °C/km dan 50.2 °C/km. Begitu juga, nilai minimum, maksimum dan purata pengeluaran haba radiogenik (RHP) berikut yang direkodkan di kawasan tersebut ialah masing-masing; 1.4 µW / m^3, 2.3 µW / m^3, dan 1.76 µW / m^3. Dapatan kajian menunjukkan empat (4) tahap potensi yang merangkumi; kategori rendah, sederhana, tinggi dan sangat tinggi. Kriteria unik yang digunakan dalam pemetaan kawasan berpotensi lebih tinggi ialah; anomali graviti tinggi (batu granit/gunung berapi padat), nilai RHP yang tinggi (pengayaan radioaktif), kecerunan suhu tinggi, (CPD cetek), litologi yang memuaskan (Batuan gunung berapi/granit), dan zon garisan struktur yang sangat padat. Kawasan "prospek geoterma yang berpotensi" ditemui berhampiran; barat Darazo, Nafada, Bajoga, Wuyo, Tula, dan barat bandar Alkaleri.

ASSESSMENT OF GEOTHERMAL PROSPECTIVE AREA USING INTEGRATED MULTI-SPATIAL DATA ANALYSIS AT NORTHEASTERN NIGERIA

ABSTRACT

Spatial mapping of prospective geothermal zones is an important apparatus used in an initial exploration of renewable form of energy in the World. Previous studies have ignored the role of radiogenic heat sources in the construction of the models of their geothermal potential maps. Hence, left an incomplete study gap, where a vital aspect of earth's heat is ignored. Therefore, the present study employed the radiogenic heat together with other parameters in mapping and analysis of areas of variable geothermal potentials using the GIS-based multicriteria evaluation approach. This study is the first geothermal study that accounted for the radiogenic heat in conjunction with other parameters for analysis of potential of this relatively not known geological location. The objectives of the study include; an; identification of the regional geothermal potential of this area through processing of relevant spatial data in order to derived the geothermal layers for preliminary investigation, generation/analysis of sub-prospectivity levels of the different thematic layers for individual layer analysis, and Thirdly, integrating the different sub-prospectivity maps into a single composite map using a GIS-based weighted overlay technique for comprehensive analysis. The various data sets of aeromagnetic, aerogravity, aeroradiometric, shuttle radar topography digital elevation model (SRTM-DEM), lithological map, and Landsat-8 operational land imager (OLI) data were, processed. Hence, a total of five (5) evidence layers of; radiogenic heat production (RHP), temperature gradients, integrated lineaments, residual gravity and geology map were produced. The layers were integrated into a

geothermal favourability map. The analysed Curie point depth (CPD) shows the minimum, maximum, and the average values of 8.18 km, 31.48 km, and 13.0 km, respectively. The minimum, maximum and average temperature gradients values obtained are 18.42 °C/km, 70.91 °C/km, and 50.2 °C/km. Similarly, the following minimum, maximum and average values of radiogenic heat productions (RHP) recorded in the area are; 1.4 $\mu W/m^3$, 2.3 $\mu W/m^3$, and 1.76 $\mu W/m^3$, respectively. The research finding shows four (4) levels of potentials that include; low, moderate, high, and very high categories. The unique criteria used in mapping the regions of higher potentials are; high gravity anomaly (dense granitic/volcanic rocks), high RHP values (radioactive enrichments), high temperature gradients, (shallow CPD), favourable lithologies (volcanic/granitic rocks), and a very dense structural lineaments zones. Regions of "promising geothermal prospects" are found near; west of Darazo, Nafada, Bajoga, Wuyo, Tula, and west of Alkaleri town.

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Geothermal energy is among the few significant processes through which sustainable energy derive can be achieved globally. Moreover, the use of geothermal energy to meet power supply and other energy demands cleanly and efficiently has been gaining ground among geoscientists, decision-makers, governments, and authorities globally (Mohamed et al., 2015; Abdel Zaher et al., 2017; & Abdel Zaher et al., 2018). Considering the climate change and other environmental issues affecting the world today, it is very apparent that the easiest and the best way to provide an alternative to the fast depleting fossil fuels (hydrocarbon) means of energy generation is to explore and exploit geothermal energy sources (Anderson & Rezaie, 2019; Calvin et al., 2015). The exploration for a geothermal resource is being performed conventionally in several phases or stages: preliminary phase (reconnaissance stage), pre-feasibility stage, and detailed survey stage (Procesi et al., 2015). In each stage, favourable geothermal areas are accorded more attention while discarding the less important areas (Noorollahi et al., 2008). Furthermore, during the preliminary stage, an analysis of multiple data sets includes surface, sub-surface data sets like magnetic, gravity, lithology, hot springs, hydrothermal alterations, and remote sensing data, is highly needed (Procesi et al., 2015). Currently, the major method for predicting areas of favourable occurrence of geothermal energy resources is the Geographic information system (GIS) based multi-criteria evaluation (MCE) method (Abdel Zaher et al., 2018; Meng et al., 2021). This method employed the use of multiple different data that are geothermally related. The data are assigned weight and subsequently aggregated (summed up) to generate the most favourable areas for further detailed investigation (Brahim et al., 2020; Meng et al., 2021).

Multi-criteria evaluation (MCE) is a significant instrument applied in resolving decision-making issues employing multiple-input data synthesis (Mostafaeipour et al., 2020). The focal objective of applying the MCE procedure is to analyse the carefully chosen possibilities based on several thematic layers. Consequently, the application of MCE in a GIS environment assisted in the categorization, reorganization, and analysis of existing data regarding the choice possibility for effective planning. The analytic hierarchy process (AHP) is a multiple criteria judgement technique that can facilitate a decision from a decision-maker, especially when challenged by several, multifaceted, inconsistent, and subjective layers (Mostafaeipour et al., 2020). Furthermore, the Multicriteria evaluation (MCE) applied for the current research has many advantages that comprise of; processing and handling of wide-ranging information that covers a huge expanse of land, examination of existing and future geothermal fields, and accomplishing a better plan in addition to accurate result through compressing the target zone.

A greater percentage of Nigeria's energy source comes from the hydrocarbon sources known as the fossil fuel (hydrocarbon) method. As of the year 2015, Nigeria generates energy that is estimated to be around 4000 Megawatts (MW). This amount is far below a corresponding demand by the population of about 170 million (Abraham & Nkitnam, 2017). Hence, the inadequacy of the amount of energy generated, coupled with the environmental problems caused by hydrocarbon exploitation, and demands a better approach to energy generation that is renewable and environmentally friendly.

Hence, the absence of any comprehensive (integrated) geoscientific study towards a preliminary geothermal investigation of the current location despite some surface manifestation around the area serves as a major motivator for this study.

1.2 Problem Statement

For an efficient investigation for an area of unknown geothermal potential, a need for a regional prospectivity map that can reveal the variation in the level of geothermal occurrences is highly essential. The development of a regional geothermal prospectivity map can be achieved via a number of specific road maps (objectives) that include; processing of sets of geophysical, geological, and remote sensing data in order to derive the needed relevant geothermal criteria for preliminary analysis. Secondly, the individual thematic layers derived from the First objective can be analysed on a separate impact assessment basis. Thirdly, the integration of the various sub-prospective regions analysed from the different thematic layers can then be effectively integrated on a GIS-platform for further comprehensive analysis. The above road maps (objectives) can be adopted in order to have a better analysis and construction of a regional geothermal prospectivity model (map) for the area and other similar location in the globe. The Prospectivity of an area is a measure of spatial intersection among certain specific features that influences geothermal occurrences (Wibowo, 2006). Therefore, an area of high prospectivity is considered to have a better intersection between a set of geothermal influencing layer maps and vice – visa.

Previous geothermal energy investigation studies in Nigeria has been largely confined to the discrete usage of either geological indicators or geophysical information on a small scale, covering areas near (surrounding) surface geothermal pointers for example; Ikogosi warm springs, Wikki warm springs, Akiri warm springs, Rafin Rewa warm spring, Ruwan Zafi Hot springs, Keana-Awe thermal springs, Kerang volcanic flows among others (Kurowska & Schoeneich, 2010; Kasidi & Nur, 2013; Obande et al., 2014, Abraham & Nkitnam, 2017). However, the present study involves integrating and analysing multiple input data sources to reveal the prospective geothermal areas on a regional scale, which could serve as all-encompassing and preliminary information upon which detailed geothermal prospecting can be conducted in the research area for possible future exploitation of the energy.

Numerous useful data available for usage at both public and non-public domains were used in the exploration for areas of geothermal prospectivity at a regional scale. These data include airborne magnetic, gravity, radiometric, geological maps, digital elevation model (DEM), and Landsat -8 Operational land imager (OLI) data. These multiple data could be integrated to create a regional scale geothermal favourability model for the study site. Previously, no attempt was made to analyse and integrate multiple geoscientific data for usage as a tool to perform preliminary and regional extent geothermal exploration of this part of Northeastern Nigeria, despite the existence of several surface pointers such as the warm/hot springs, mud volcanoes, and volcanic plugs etc. Therefore, the present research aims to evaluate the method and analyse the spatial relation between the multiple geoscientific data set to produce a geothermal suitability (favourability) map using the GIS-based multiple data analysis method.

1.3 Scope of the Study

The current research is limited to the use of multiple data such as; geophysical data (Gravity, magnetic), radiometric, geological, and satellite data (DEM, and Landsat-8 data) to generate thematic map layers such as; temperature gradients, radiometric heat production map (RHP), residual gravity anomaly map, lithology map, and structural lineaments density to integrate and analyse them into a regional-scale geothermal prospectivity map of the present study site using a GIS-based technique.

1.4 Objectives of the Research

The objectives of the research are;

i. To identify the regional geothermal potential of the area from the processed sets of spatial data (magnetic, gravity, radiometric, geological, and remote sensing data), with the purpose of obtaining the different thematic layers for preliminary geothermal evaluation.

ii. To generate sub-prospectivity maps from the different regional geothermal thematic layers for individual thematic layer analysis.

iii. To integrate the different sub-prospectivity maps with the purpose of mapping and analysing areas of diverse prospectivity on a regional scale using the GIS-based weighted overlay technique.

1.5 Significance/Novelty of the Study

The novelty of this study lies in the fact that it is the first-ever GIS-based multiple data integration attempt involving the use of the radiogenic heat contribution along with other input parameters (As indicated in the research work flow shown in Fig. 3.1) to create/unveil a regional scale geothermal prospectivity map. This is because, previous prospectivity models have not been involving radiogenic heat sources among its evaluation criteria. Therefore those models are deficient, because a significant aspect of earth’s heat contribution was not recognised in the construction of those geothermal potential evaluation models. Therefore, those models were considered not too reliable. Moreover, a geothermal prospecting study that tries to give more reliable information is highly needed, as it helps stakeholders predict much more accurately where geothermal heat can be explored. Studies by Gaafar & Aboelkhair, 2014; Joshua & Alabi, 2012; McCay et al., 2014; Maden, 2015; and Salem et al. (2005) highlighted the significance of radiogenic heat to geothermal occurrences.

Another significance of this research is to reveal the previously non-available regional geothermal favourability view of the area of focus (Northeastern Nigeria) using multiple-input data as presented, and processed in the research work flow pattern indicated in chapter 3 (Fig.3.1). The partial impact (sub-prospectivity analysis) of these thematic layers on the possible incidences of geothermal energy potentials can be evaluated. The surface geological indicators such as hot springs, mud pools, volcanic caps etc. are indicators of possibility of getting better prospect when relevant data were collected and analysed using GIS-platforms as shown in the work flow pattern presented in this study.

This study is significant and novel because previously, the only attempt made to understand some of the geothermal potentials of this area involved only the separate use of either magnetic data to calculate Curie point depth (CPD) around the vicinity of some of the surface indicators, which helped in revealing areas of shallower CPD, which in turn correlates with regions of high geothermal gradients (Elbarbary et al., 2018; Tanaka et al., 1999; Okubo et al., 1985) or the use of surface geological indicators to predicts areas of possible occurrences (Kurowska & Schoeneich, 2010). The separate use of these parameters to evaluate and draw a reasonable conclusion on the appropriate sites for further investigation of the geothermal potential of an area is logically and scientifically not sound without integrating all the possible parameters that could have influence the occurrence of a geothermal energy field in an area (Malczewski, 2006;

Wibowo, 2006). The reason is that several parameters tend to have a partial impact on the possible occurrence of a geothermal resource. Therefore their integration in a logical manner tends to give a better view of the appropriate locations to concentrate on for future research (Malczewski, 2006; Yalcin & Kilic, 2017; Abuzied et al., 2020; Meng et al., 2021) . Hence, the previous studies conducted on this locality and other parts of the world left a research gap of not using better approach interms of selection criteria, the right and all-encompassing prospectivity models that needs to be filled by embarking on this kind of study following the criteria and flow pattern indicated here.

Finally, this study is very significant and novel in the sense that it is the first attempt made in the whole of Northeastern Nigerian territory to incorporate multiple geo-scientific data on a broader scale to provide the regional view of the geothermal energy resources of this area which could serve as a preliminary stage for geothermal (renewable) energy exploration drive of the government of Nigeria. It is also the first study to select and integrate radiogenic sourced heat and other geothermal influencing parameters to construct a regional and a preliminary geothermal prospectivity map of in a GIS platform.

1.6 Limitation of the Study/research

The present study is limited to the use of geophysical (gravity, magnetic, and radiometric), and remote sensing data (DEM, Landsat-08) in the analysis and prediction of the prospectivity of this area on a GIS platform. However, other environmental suitability factors were not considered in the analysis and creation of the prospectivity model generated for this area. This will translate to higher environmental risk. The environmental factors such as; topography, vegetation cover, Land-use cover, surface drainages networks, etc. are very critical in the search, and analysis of better sites for geothermal exploitation (Noorollahi, et al., 2008). Hence, the non-inclusion of these factors means increasing the risk of well siting due to environmental issues. Therefore, the next phase (stage of this study) should consider the use of the environmental factors in its analysis. This will therefore ensure better areas for more reliable, low risk, and accurate siting of well is conducted.

1.7 Thesis Framework

The present thesis is arranged or prepared into several chapters that include Chapter one (Introduction). This chapter gives the general overview (background) of the research topic, highlighting the problems at hand, the scope of the research, the significance and novelty of the study, and the objectives of the study. The second segment of this thesis is referred to as Chapter two (Literature review). This chapter presents an overview of the previous research works done on the research topic and the chosen or selected study area (Northeastern Nigeria). Furthermore, a review of the regional geological setup of the study area is also presented here. It also highlights an area of research interest that was not previously filled (conducted). The next chapter to be presented after the literature review is Chapter three (3), which is a chapter that tries to explain the materials and the methodology followed in the conduct of the present research.

Following chapter three (3) in the thesis is Chapter four (4). This chapter is named “Results and Discussion” because it is where the final results of the geothermal prospectivity mapping exercise will be presented and discussed simultaneously. The results will be presented in the form of maps, tables, figures, and charts.

Finally, the summary of the entire findings of the research is presented in Chapter 5. Then, conclusions and recommendations are drawn from the research findings and presented in this same Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Geothermal Systems

Geothermal energy resources is the thermal energy found inside the earth's sub surface’s deeper (interior) parts (Wibowo, 2006). The term geothermal is used to indicate systems where the earth's heat content is adequately concentrated to a form referred to as an energy resource (Rybach & Muffler, 1981). Geothermal anomalies are indicated by the localization of thermal energy in a certain geothermal system in a particular location relative to the other adjacent location (Wibowo, 2006). The formation of a geothermal anomaly depends on some geologic, hydrologic factors and the concept of heat transfer (through conduction, convection, and radiation). On a general note, heat transfer through the upward movement of magma from the deeper portions of the earth’s crust results to the formation of geothermal anomalies. It has been observed that high temperature geothermal fields are often associated with younger volcanic plugs (Wibowo, 2006). Therefore, it is very obvious that the heat energy source is related to igneous intrusive usually formed from a magma chamber beneath.

2.2 Geology, Tectonic Set-up, and relationship to geothermal occurrences

Gongola basin is a segment of the Upper Benue trough, which constitutes portion of the continental Benue basin of Nigeria. It trends in a N-S pattern occupying a total of surface area of 15000 km^2. Adjoining the basin to the west are the outcrops of crystalline basements rocks. Additionally, the eastern parts are characterised by outcropping older granitic and volcanic lithologies commonly termed the “Gubrunde horst” and “Biu and Lunguda” basalts.

The lithologies occupying the western portions include; the Migmatites- gneiss, Banded-gneiss, biotite-hornblende granites, charnokytes and Ignimbrites. The next lithologic exposures occurring at the eastern portions of the research area are: basaltic plugs and porphyritic granite. The pre-existing outcropping rocks were pierced by the intruding granites and their related rock types throughout the period of occurrence of the foremost Pan-African thermo-tectonic activity (Abdullahi et al., 2019)

The sediments accommodation in the entire Benue trough occurred during the Albian - Tertiary history of the earth **(**Fig. 2.1, Obaje, 2009, Shettima et al., 2016). The oldest lithology deposited in the Gongola basin is the Braided/lacustrine/Alluvial fan - Bima Sandstones Formation. It encompasses sandstones, shale, mudstones and clays. The Bima Formation was overlain by the Barrier Island/deltaic Yolde Formation during upper Albian to Cenomanian times. It is characterised by the presence of cross-bedded sandstone, shale, and claystones. It is a transformation interphase during which a transformation from continental to marine set-up occurred.

The ultimate change from the continental to marine setting resulted to the emplacement of a fully marine (offshore/estuarine) rock entity recognised as the Pindiga Formation (Shettima et al., 2016). The emplacement of the Pindiga Formation started from late Cenomanian to mid-Santonian times (Shettima et al., 2016). The Pindiga Formation comprises black shale, siltstone and sandstone. A major tectonic event known as Santonian orogeny took place throughout the Santonian period; this event impacted on the whole of the Benue trough. The Santonian event resulted to the numerous structural folds and uplifts found in the sediments existing before its existence

(Giraud & Bosworth, 1997). The sediments' deformations during the Santonian times were due to the re-arrangement of the global tectonic plates (Giraud & Bosworth, 1997). The sediments emplacement continued after Santonian events in the entire Benue trough (Gongola basin inclusive). The process caused the emplacement of the fluvial Gombe Formation during the Campanian – Maastrichtian times (Shettima et al., 2016). The Gombe Formation encompasses sandstones, ironstones, siltstones, coal, and mudstones (Shettima et al., 2016). Overlying the Gombe Formation in the tertiary period is the fluvial/lacustrine Keri-Keri Formation, which comprises sandstones, shale, and clays. The tertiary Keri-Keri Formation was deposited in continental set-up (Shettima et al., 2016).

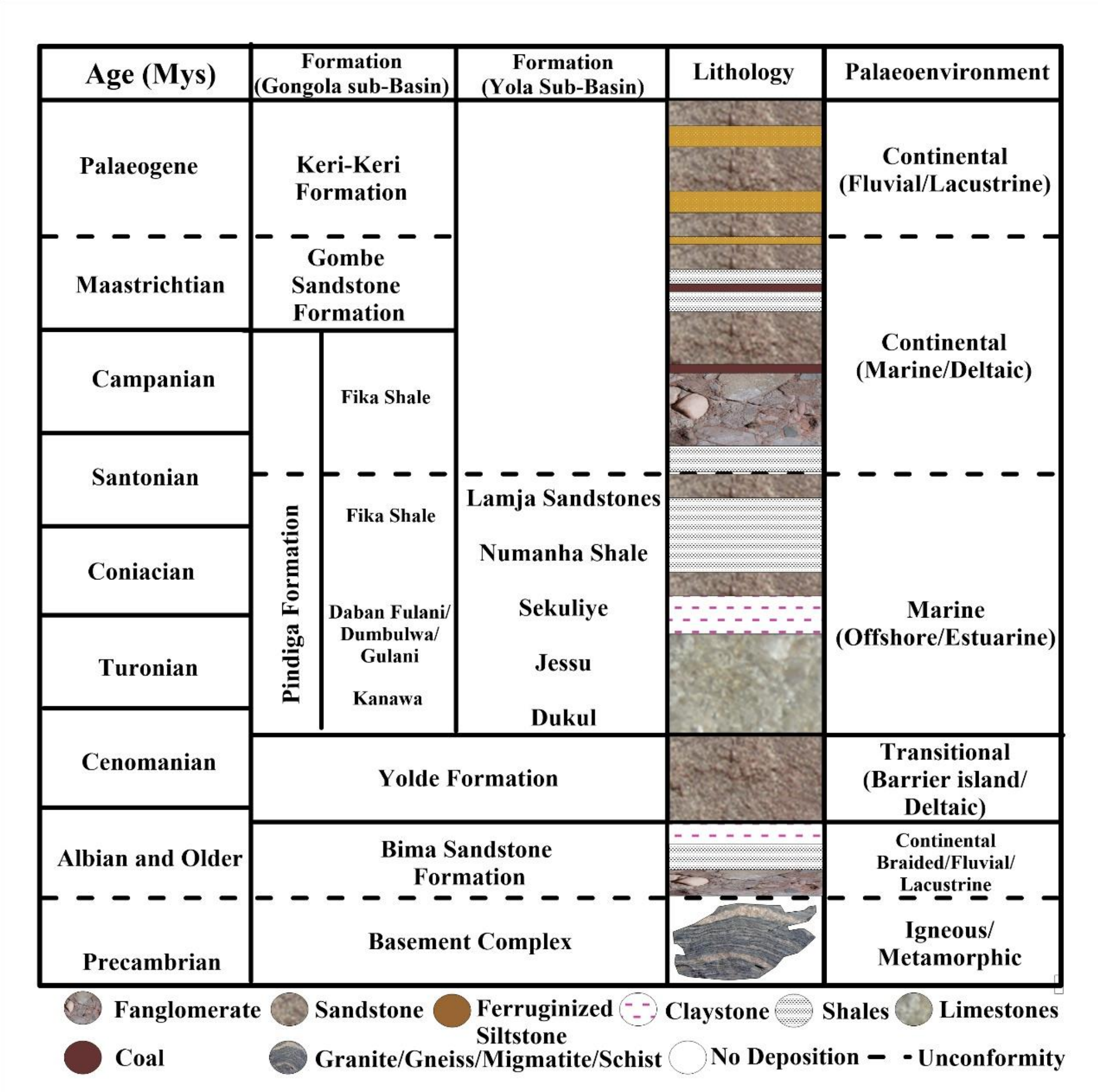

Figure 2.1 Stratigraphic succession of the Gongola basin (modified after Shettima et al., 2016).

The formation process of the whole of Benue trough has been debated in the past by several geoscientists. There were two models put forward to explain the mechanism of formation of this giant tectonic structure referred to as Benue trough. These are; the "rift system model" and the "pull-apart basin model" (Giraud & Maurin, 1992). There were several models suggested to explain the formation mechanism of Benue trough under the "rift system model". The rift system model explained the formation mechanism through the direct impact of the separation of African continental plates from the South American plate. This process produced the present-day Atlantic Ocean. The rift system model explained the presence of a triple junction beneath the present Niger-delta, which began to spread (open) apart in all three of its arms until one of the arms fail at certain times in the earth history. It led to the formation of what is considered as Benue trough (rift basin). This model was supported by Cratchley et al. (1984) using geological and gravity evidence. Nevertheless, Burke et al. (1971) suggested an Rift-Rift-Fault (R-R-F) type triple junction slightly beneath the current location of the Niger-delta basin as the formation mechanism of this giant's tectonic structure. Hence, Olade (1975) considered the trough to have been formed as aulogen from one of the three arms that fail during R-R-F spreading.

The second formation mechanism model was proposed by Giraud & Maurin (1992). They proposed the "Pull-apart system" in which wrenching is considered the principal tectonic driver that resulted in the formation of the Benue basin. The model was developed using geological and geophysical research data that indicates trans-current faults as the major structures rather than the normal faults attributed to the rift system model as presented by the former rift system model.

Geological and structural distribution in an area has some considerable degree of impact on the occurrences of a geothermal energy (Wibowo, 2006). Geothermal heat is being conveyed from the interior of the earth (geothermal reservoir) to the surface through faults and fractures found on the rocks. The hot molten fluid (magma) carries geothermal heat to the surface and formed either basic, felsic or intermediate rock. Hence, the younger volcanic, granitic rocks serves as a recent indicators of geothermal occurrences (Siler et al., 2019). They also have the greatest degree of influence among the various rock types available. Therefore, rocks distribution help in preliminary mapping of areas of better geothermal energy prospects.

Global geothermal occurrences shows great link to the tectonic structural regions (Wibowo, 2006). Studies such as Omenda, 2011; Siler et al., 2019), shows the distribution of numerous existing geothermal fields near both local and regional tectonic structures such as rift, (e.g. East African rift system, Benue rift, etc), and Trenches (E.g. Aleutian trench, Java trench, Philippines trenches etc.) in their respective areas of focus.

The distribution and interconnectivity of structural joints and faults serves as an avenue through which hot geothermal fluid get transferred to the earth surface forming surface manifestation such as volcanic plugs, hot springs etc. (Omenda, 2011; Philipp et al., 2007; Siler et al., 2019). The greater the density and interconnectivity of faults, Joints, and fractures, the higher the chances of allowing the transfer of geothermal fluid.

Hence, the present study location being a rift structural zone, is therefore found to be characterized by the presence of numerous volcanic rocks, and a number of hot/warm springs that tends to aligned themselves with the major regional tectonic trend of this area. This implies that the geothermal indicators are being influenced by the presence of these mega tectonic structures.

2.3 Previous Exploration Attempts

Identifying/mapping better geothermal prospects is the first and critical activity being carried out during the preliminary aspects (first stage) of geothermal energy investigation. This stage is among the very complex and strenuous parts of the investigation that is often being conducted gradually and logically (Yalcin & Kilic, 2017). Thus, having an effective decision on the areas of high geothermal potential in an area requires the use of different data types in an integrated form (Yalcin & Kilic, 2017). Therefore, while performing this kind of integration, errors coming from humans is almost inevitable. As such, to reduce these errors to the minimum, GIS-based multiple data layers, integration methods are used (Noorollahi et al., 2008, Yalcin & Kilic, 2017).

Several authors have deployed multi-criteria evaluation (MCE) in several locations in different sites for evaluating different items such environmental studies, etc. The methods were used to help decision-makers have a better decision concerning the choice of best locations for continuing with the detailed investigation for geothermal energy resources. These include; Coolbaugh et al. (2007), who used remote sensing data (ASTER Infrared images) around Brady's hot springs in Nevada, USA to deduced the subsurface geothermal heat contribution of its study area from the interpreted ASTER images. However, this study fails to incorporate other geothermal influencing information such as heat from radiogenic sources, structural distributions of the area, Curie point depth (CPD) values, temperature gradients values, lithological data, among other sources, as an input parameter to evaluate the geothermal potential of its study area effectively. Therefore, they excluded important components of geothermal energy evaluation.

Noorollahi et al. (2008) also used the GIS integration method for geothermal investigation and well siting around Sabalan geothermal field of NW of Iran. They used geological, geochemical and geophysical data in their study and selected appropriate locations for geothermal well siting. Moreover, Yousefi et al. (2010) constructed a geothermal resources map of Iran using geological, geochemical and geophysical data to map promising zones for geothermal resources investigation of Iran. This study generated a geothermal energy model of Iran, which helped in giving the first set of information needed for effective geothermal energy exploration. Both studies by

Noorollahi et al. (2008), and Yousefi et al. (2010) fails to include RHP data in their prospectivity model.

Abdel Zaher et al. (2019) employed 2 parameters of aeromagnetic and aerogravity data to calculate the CPD values, which consequently facilitated the understanding of the geothermal potentials of Frafra Oasis, in the Western Desert of Egypt. The study further revealed the regions with favourable and unfavourable potentials for geothermal occurrences based on the criteria of high heat flow, shallow depth to basement identified from gravity inversion and shallow CPD gotten from magnetic data. It however fails to incorporate the impact of radiogenic heat in the evaluation of its geothermal potentials. Additionally, Abdel Zaher et al. (2011a) applied gravity and magnetotellurics means to comprehend the source of the Hammam Faraun hot spring that is near the Egyptian Sinai Peninsula. The study enabled mapping of the structural features close to the Hamman Faraun hot spring in the Egyptian Sinai Peninsula. However, the study is disadvantaged by the use of non-sufficient evaluating parameters, and the few parameters used were not integrated into a more meaningful prospectivity model. Furthermore, Abdel Zaher et al. (2011b) did a regional evaluation of the geothermal energy of the Gulf of Suez, Egypt via temperature records from many oil-wells distributed in the area, this is in addition to gravity and aeromagnetic data to examine the sub-surface structural pattern and how connected it is to the shallow geothermal pointers, e.g. hot springs, etc. The study is limited to mapping of structures of geothermal influence only, thereby excluding other important evaluation parameters such as; CPD, RHP, etc. this reduces the reliability of the result obtain, because, the higher the number of the evaluation criteria, the greater the chances of accurately being able to map a geothermal potential region. Abdel Zaher et al. (2017) employed magnetic and gravity measurements to perform a geothermal evaluation of the Siwa

Oasis province located in the Western Desert of Egypt. The study applied the spectral process in computing the CPD, heat flow, and geothermal gradients data over the Siwa Oasis area to reveal the geothermal potential predictions of its case study site. This study however, did not used the effective GIS-based Multicriteria integration technique. This could lead to non-effective integration of digital thematic layers, and subsequently lead to faulty and non-reliable results. Abdel Zaher et al. (2018) employed geophysical, geological, and well data to construct a geothermal favourability map of Egypt using the GIS integration process. The study showed regions with very low, low, moderate, high, and very high geothermal potentials based on high crustal heat flow, shallow CPD anomalies, and proximity to structural faults distributions. It however, did not account for the heat sources from radiogenic sources in the construction of the model of its potentials maps.

Calvin et al. (2015) determined the geothermal-related minerals in Nevada using remote sensing data and mapped areas of occurrence of geothermal minerals there. This research focused on the mapping of areas of geothermal minerals occurrences only, it was silent on the general prospectivity of its area interms of production of composite prospectivity map. Nishar et al. (2016) used a thermal infrared imaging method to study the geothermal environments of Wairakei - Tauhara areas of New Zealand (NZ). The research established unmanned aerial vehicle (UAV) as an innovative form of geothermal energy investigation. Additional geothermal investigation conducted on the fish-lake valley found in Nevada, USA, using remote sensing measurements was performed by Littlefield & Calvin (2014). The study only focussed on remote sensing as the main evaluation criteria, and ignore other parameters such as RHP, CPD, temperature gradients etc. John et al. (2008) performed a potential geothermal mapping of West Java, Indonesia, using an integration of several spatial data available in the public domain. The study was also able to generate the first regional geothermal prospectivity model of Indonesia. Furthermore, Moghaddam et al. (2013) carried out a spatial integration and multi-criteria analysis in a regional-geothermal favourability mapping using Fry-analysis and weight of evidence technique. The study created a favourability map through spatial synthesis of input evidence data using Boolean index overlay and Fuzzy prediction modelling. It however ignored the role of RHP in the evaluation process.

Isa et al. (2011a) performed a 2-dimensional estimates of a temperature occurrences via a method of finite differences along the Aceh, geothermal zones of Indonesia. The study was able to show the distribution of heat in 2-D, and correct the model information through the temperature monitoring technique. The study further showed a predicted geothermal temperature of 180°C and a corresponding reservoir depth of greater than 550m. Moreover, Isa et al. (2011b) used a very low frequency (VLF) technique to examine the response of electromagnetic (EM) field in a Sabang geothermal zone of Indonesia. The study tried to observe the response of EM regarding the position, shape and depth of occurrence of the hydrothermal fields. A greatest anomalies occurring at intervals of 400-600m, and a depth of 10-14m were found.

Also, Tampubolon et al., (2016) carried out a geothermal resources identification of Dolok Marawa using GIS, and remote sensing method. The study used a computed Land Surface Temperature (LST) to map the geothermal resources of the area. It further showed a greatest LST value that points to the zones of geothermal significance.

Also, another section of those who work on the area concentrated more on the use of different data sources; that involve magnetic data to establish the basin configuration as well as thickness of the sediments infilling the different parts of the upper Benue trough and other sedimentary basins of the country using either; source parameter imaging, spectral analysis, as well as Euler deconvolution methods, these include; Maxwell et al. (2012), Alagbe & Sunmonu, (2014), Salako (2014), Anakwuba, & Chinwuko (2015), Abraham et al., (2015) and Aliyu et al. (2018).

However, a minor section of scholars operated with aeromagnetic and radiometric data with the single goal of appraising the geothermal potentials of particular parts of Nigeria (excluding the present area of interest). These include Olorunsola & Aigbogun, (2017) work who used aeromagnetic and radiometric data to study the Anambra basin of Nigeria. Others are Olorunsola & Chukwu (2018), who also used aeromagnetic data to evaluate the heat flow pattern of the Bida basin of Nigeria. These studies however, fails to integrate the few data generated into a more reliable prospectivity map for optimum geothermal energy evaluation. Similarly, Nwankwo & Sunday (2017) performed a CPD and geothermal computations of the same Bida Basin by means of aeromagnetic data and disclosed locations with high geothermal potentials in the basin. In an additional geothermal investigation conducted in a nearby area known as the lower Benue trough, Ayuba & Nur (2018), Kasidi & Nur (2012) conducted studies on geothermal and Curie- depth isotherm determination over parts of Nassarawa and environs, North-central Nigeria, and they delineated areas of higher geothermal potentials within the area. Most of these studies did not use sufficient criteria for geothermal layers, the effective GIS-based multiple data integration approach, and did not use conventional geothermal resources assessment methods. No geothermal prospectivity map was generated by these studies. Hence the composite effect of the evaluation parameters were not computed for better and reliable prediction.

2.4 Chapter Summary/Concluding Remark

A summarised view of the previous studies that employed GIS-based multiple data integration in the study of geothermal occurrences or potentials of different parts of the globe shows the application of the GIS-based multiple data integration and analysis for establishing the level of prospectivity of several parts of the world. It is exemplified by the numerous published geothermal studies carried out. Now, after careful study of the role of radiometric heat in the geothermal energy contribution for an area as revealed by the findings of studies by (McCay et al., 2014; Gaafar & Aboelkhair, 2014; Joshua & Alabi, 2012; Maden et al., 2015; Salem et al., 2005) among others, the present study incorporated the radiogenically produced heat values as an important layer along with other data types such as temperature gradients (derived from magnetic data), structural information (derived from DEM, magnetic, and Landsat data), gravity, and lithology data to appraise the geothermal potential of this area in a GIS-based integration platform.

A synopsis of the various studies carried out both on different parts of the world and locally on different parts of Benue trough of Nigeria was formed (Figures 2.1). It shows that most of the work on Benue trough of Nigeria concentrated on using one or maximum of two parameters in assessing geothermal potential of these geological terrains. Furthermore, on a global scale, single and multiple data were used in the analysis of the geothermal potentials of several areas, but none of the GIS based multiple evaluation studies incorporated the radiogenic heat component of the geothermal energy contributions. However, the significance of radiogenic heat contribution in geothermal occurrences were highlighted by numerous authors such as; McCay et al., 2014; Gaafar & Aboelkhair, 2014; Joshua & Alabi, 2012; Maden et al., 2015; Salem et al., 2005 and so on.

Despite the manifestation of surface indicators of geothermal occurrences, no serious attention was given to studying the country's geothermal energy resources, especially the present area of focus using conventional methods that include regional integration of multiple geothermal influencing layers, feasibility and a detailed study. Most of the available studies conducted in this regard only manage to use magnetic data to compute depth to basements, CPDs, and deduced areas of better prospect or the use of temperature measurements from oil exploration wells that are localised to only a few locations (such as in Bornu basin) and deduced geothermal gradients values of those geological terrains. These include; studies by Obande et al. (2014), who use a lesser resolution aeromagnetic data and applied spectral analysis approach to deduced the CPD, values of range 6 km to 12 km around the vicinity of the Wikki warm spring. The study was able to compute the average heat flow of 170 mW/m^2, and the average geothermal gradients value of 68 $^{\circ}$C/km. The study however, fails to integrate other relevant geothermal parameters such as RHP, geology, and structures among others into a composite potential map. This makes the results obtain less reliable, as more data are needed to be use in the evaluation, and the production of a regional prospectivity map. Because, the map is highly essential in any reasonable and comprehensive geothermal potential mapping (Abdel Zaher et al., 2018; Elbarbary et al., 2018; Meng et al., 2021; Wibowo, 2006). Moreover, Mono et al. (2018) evaluated the geothermal prospect of the nearby Cameroonian terrain using spectral method. Similarly, this study focussed only on 2 parameters of heat flow, and geothermal gradients. It did not also integrate the two results into a single prospectivity model using any available platform (GIS, etc.) for better assessment of their composite geothermal effect. Additionally, Kurowska & Schoeneich (2010) used bottom hole temperature measurements to deduce a temperature gradients estimates whose values ranges from 11°C/km to 59°C/km. This study relied only on one parameter (temperature gradients measurements) to draw a conclusion on geothermal prospect of this terrain. (Nwankwo & Ekine, 2009) also used bottom-hole temperature measurements from the adjacent Chad basin and disclose a temperature gradients values of range 30 $^{\circ}$C/km to 40 $^{\circ}$C/km, with an average of 34°C/km. The study also concluded on account of an evaluation of a single parameter of temperature gradients, which is against the general conventional practice of multiple data integration for a more reliable prediction of regions of geothermal occurrences (Wibowo, 2006).

Bolarinwa & Bute 2016; Bute, 2013, 2017; Haruna et al., 2012; Suh and Dada, 1998; Suh et al., 1998) used geological, petrological, and geochemical approach to indicate uranium enrichment areas, and sources, and origin within the northeastern geological terrain of Nigeria. The study was silent on the computation of radiogenic heat production (RHP) of the area, which is a vital component of the earth's heat production (McCay et al, 2014; Salem et al., 2005). Hence, the need for its computation in the present study. Nevertheless, the present research work employed an integrated approach using magnetic, radiometric as well as remote sensing data using GIS-based multi-criteria evaluation techniques to generate a comprehensive geothermal prospectivity map of the study area, which is a first attempt to give a regional and preliminary view of the prospectiveness of this area. It is also the first study to integrate radiogenic heat sources along with other possible geothermal evidence layers and construct a potential geothermal map in a GIS-based platform as shown in the work flow pattern (Fig.3.3). This study was able to fill the gap of non-availability of any geothermal prospectivity model where RHP was included among the evaluation parameters. This will help in comprehensive evaluation of the prospectivity of the area since a major contributing factor (RHP) is now added in the model produced. Therefore, this study tries to fill the incomplete study gap left by some of the previous studies as well as the production of prospectivity models that did not took into account the radiogenic contribution as demonstrated in previous geothermal studies practiced in other parts of the world (Table 2.1). Table 2.1 is a summarised form of the previous studies done on the topic as applied to the present and other localities in the globe.