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ASSESSMENT OF GEOTHERMAL RESOURCES IN THE NIGERIAN SECTOR OF THE CHAD BASIN, NE-NIGERIA

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ABSTRACT

Nigeria, with a population of over 200 million people, has been a slave to the energy conundrum. The need for alternative and cleaner energy sources is imperative to ensure Nigeria´s energy growth and energy mix (fossil fuel and renewables). The Nigerian sector of the Chad Basin has been the location of intense petroleum exploration in the 1980s and early 1990s with 23 oil wells drilled and oil and gas found in some of them. These wells can also shed light on the presence of exploitable geothermal resources in the basin. Temperature logs from 22 wells were analysed to determine the geothermal gradient in the area and wells in anomalous areas were selected for further studies. Reservoir temperatures below 120°C are suitable for direct use, including space-heating, while temperatures above 120°C can be utilized for electricity generation. The Bima sandstone was identified as a potential reservoir and wells with temperatures above 120°C at the top of the Bima sandstone were selected. Five wells, that is Ga1, Kn1, Kr1, Wd1 and Kt1 met these criteria with temperatures in the range of 120-152°C. These wells are within the sub-basinal structure in the southern part of the basin. A conceptual model of the resource showed that a geothermal system exists with the sandstone layers of the Bima providing the best geothermal reservoir conditions in the area. Monte Carlo volumetric assessment was performed indicating a P90 result of 285 MWe (90% likelihood that this can be achieved). Sustainable utilization of the geothermal resource in the area will depend on further investigation, and how well the reservoir is understood. The reservoir management, particularly the re-injection planning as well as the exploitation technology play an important role. The best mode of production is to adopt a step-wise increase in production for sustainable utilization.

1. INTRODUCTION

Energy remains a major driving force for the economic growth of any country and associated energy commodities promote economic development through increase in productivity and income, as well as creation of employment (Rapu et al., 2015). Ironically, energy, particularly electrical power, has been the bane of economic growth in Nigeria. This necessitated the creation of a National Energy Policy in 2003 (Energy Commission of Nigeria, 2003) which has the following cardinal objectives in the long, medium and short term:

- Identifying emerging renewable energy technologies both national and international;
- Identifying and quantifying the national resource base for each renewable energy resource;
- Establishing focal points for research and development for identified viable emerging technologies/resources within existing institutions;
- Assessing the potentials of emerging technologies and prioritizing them according to national energy needs.

The earth can be likened to a large heat engine where a huge amount of heat is continuously transported from its core, mantle and lower crust to the surface by thermal convection and conduction. This heat acts as a driving force of most large-scale geologic processes that occur on the surface of the earth. Also, part of the heat that is conducted through the earth's crust is used to drive the chemical reactions which transform organic matter contained in sedimentary rocks into petroleum and where there is a significant heat density anomaly, there is also a huge prospect for geothermal development. Geothermal resources can be harnessed from abandoned oil wells using heat exchangers, saving drilling cost and addressing the safety aspects of abandoned oil wells (Cheng et al., 2013; Bu et al., 2012). In addition, geothermal resources stored in hydrocarbon reservoirs can present a great potential, not only because geothermal energy exists in oil and gas reservoirs but oilfields also have enormous advantages to develop geothermal energy (Wang et al., 2018). Nigeria shows significant geothermal potentials, especially within the Benue Trough, the Nigerian sector of the Chad Basin and the Niger Delta.

Geothermal technology and reservoir engineering owe their developments to the theory of groundwater flow and petroleum reservoir engineering. However, geothermal reservoirs are considered to be more complex than groundwater systems or petroleum reservoirs (Axelsson, 2012). Petroliferous basins can also be rich in medium- to low-enthalpy geothermal resources. For instance, power generation pilot tests are being carried out in the Huabei oilfield in China (Wang et al., 2016). Despite the limiting factors for full utilization of low-enthalpy geothermal systems, the presence of a workable geothermal system in the Nigerian sector of the Chad Basin will add value to petroleum exploration in the area, generate electricity, develop space cooling, encourage food (fish) drying, reduce carbon footprint and other negative environmental impacts in the field, just to mention some benefits.

The Nigerian sector of the Chad Basin (Figure 1) (also referred to as the Bornu Basin) has been explored

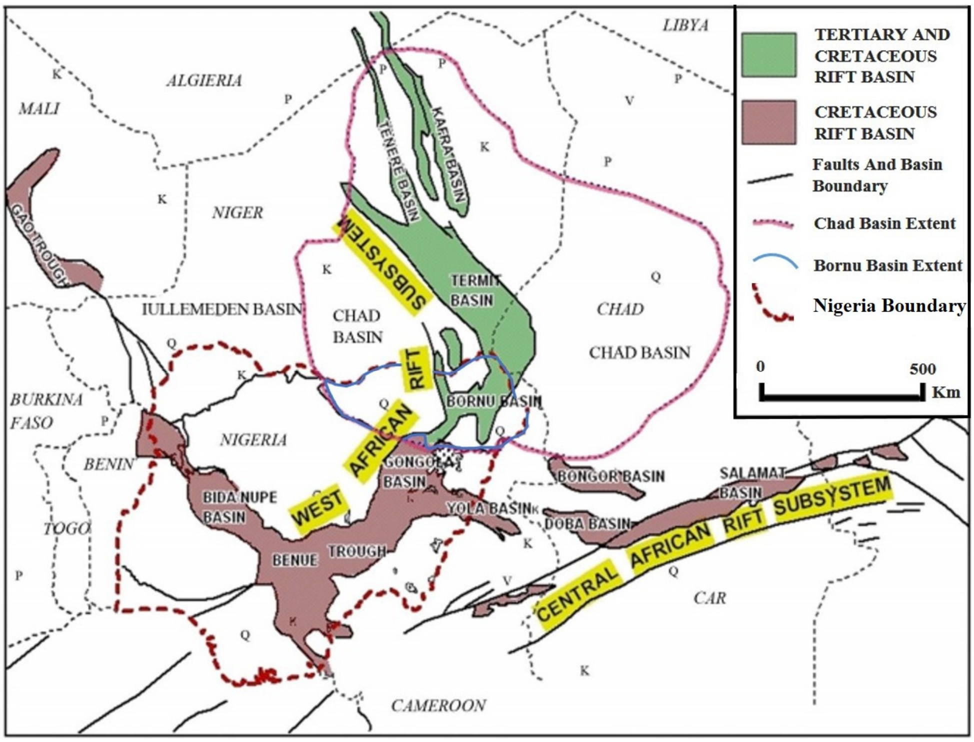

FIGURE 1: Location of Nigerian sector of the Chad Basin (Borno Basin) within the West African rift system (after Genik, 1992).

for petroleum resources since the 1980s which was occasioned by the presence of oil in the concomitant Termit Basin in Niger and resulted in the drilling of 21 exploration wells. Various scholars have used data from the well logs to deduce various geothermal parameters such as temperature gradient, heat flow, sediment distribution, structural styles, basement architecture and fluid movement. This study is aimed at attempting to estimate the heat in place (thermal) and electricity generation potential of the area by simulating the results from earlier work, developing a conceptual model for the geothermal resources in the area and applying static modelling (volumetric analysis) to make a first estimate of the likely capacity of geothermal resources in the area.

2. THE NIGERIAN SECTOR OF THE CHAD BASIN

2.1 Regional tectonic setting

The Nigerian sector of the Chad Basin accounts for about 10% of the Chad Basin which cuts through 5 countries; Nigeria, Chad, Niger, Cameroun and the Central African Republic, covering a total area of about 2.335 million km^2 (Obaje et al., 2004; Obaje, 2009). The Chad Basin is genetically associated with the Early Cretaceous opening of the South Atlantic resulting in the separation of the African and South American plates and creating a rift-rift-rift (RRR) triple junction (Burke et al., 1971). This was followed by episodes of crustal extension, compression, transcurrent faulting and strike-slip faulting, which resulted in formation of sub-basinal structures and pull-apart basins within the Central West African Rift system (Fairhead, 1988; Benkhelil, 1989; Guiraud and Maurin, 1992; Abubakar et al., 2014). Figure 1 shows the relative position of the Nigerian sector of the Chad Basin within the West African Rift System (WARS). These basins continued to evolve due to thermal sag until the Santonian when it was ended by a regional compressive event which resulted in the deformation of the sedimentary sequences in the rift (Genik, 1992; Wilson and Guiraud, 1992). Genik (1992; 1993) presented the major phases of tectonic evolution of the Chad Basin:

i. *Pan-African crustal consolidation (750-550 Ma)*
This phase produced major basement lineaments and faults following the same trends as subsequent cretaceous to tertiary rifts. For the Borno Basin, the dominant trend was NE-SW (Ajakaiye et al., 1986; Avbovbo et al., 1986; Benkhelil, 1989).

ii. *Early rift stage (130-98 Ma)*
During the Early Cretaceous opening of the Benue Trough extending to the Chad Basin, strike slip movements of wrench faults which originated from South America to Nigeria in response to the separation of the two continents contributed to the development of the Chad Basin and resulted in the trans-tensional opening of the Benue Trough and the Chad Basin (Fairhead, 1988; Benkhelil, 1989; Genik, 1992; 1993). The rifts across middle Africa became fully developed at about 108 Ma and were filled entirely with continental sediments (Genik, 1992).

iii. *Late rift stage (98-75 Ma)*
This period was dominated by Late Cretaceous shortening coincident with eustatic sea level rise and deposition of marine sediments due to epicontinental transgressions from the Tethys and the South Atlantic into the basin through Mali and Algeria from the north and through the Benue Trough from the south, respectively (Allix et al., 1981; Benkhelil and Robineau, 1983). The period was also associated with reduced rifting and regional tectonism which resulted in a mainly trans-pressional, tectonic pulse at around 85 Ma, causing folding and basin inversion in the Benue, Yola and Bornu Basins (Avbovbo et al., 1986; Genik, 1992; Guiraud, 1993).

iv. *Post rift stage (66-0 Ma)*
In this period the area was not subjected to significant tectonic activity and no faulting or appreciable folding is observed in the Tertiary to Quaternary strata which dip gently to the north and northeast towards the Chad Basin (Obaje, 2009).

Structural features in the area include diverse extensional, trans-tensional and trans-pressional structures (Genik, 1992). Fault structures in the Bornu Basin are basement related, producing horst and grabens with movement along basement faults translated into high-angle faults in the overlying sediments. Fold related structures are folded sediments with low fold frequency, increasing fold amplitude basin-ward and spatially restricted in the south-eastern part of the basin (Avbovbo et al., 1986). Many of the faults in the Bornu Basin terminate below the Cretaceous-Tertiary boundary unconformity while fold axes extend over long distances, with most of them without effective strike closure. The major fold features in the area are the Dumbulwa anticline and Mutwe syncline which trend NW-SE (Avbovbo et al., 1986; Obaje, 2009).

2.2 Geology and stratigraphy

The intra-continental Bornu basin lies between latitudes 11°N and 14°N and longitudes 9°E and 14°E, (Figure 2). The Bornu basin is underlain by Precambrian to Lower Palaeozoic migmatites and granite overlain by the Aptian-Cenomanian Bima sandstone, made up mainly of sandstones with intercalation of shales (Carter et al., 1963; Avbovbo et al., 1986). Gongila formation, made up of calcareous shales and limestones deposited in shallow marine environment, lies above the Bima sandstone and is overlain by the gypsiferous marine shales and limestones of the Fika shale formation. The sandstones, siltstones and clay beds of Gombe sandstones overlie Fika shales and are overlain by the Kerri-Kerri formation and Chad formation (Carter et al., 1963; Avbovbo et al., 1986, Olugbemiro et al., 1997; Obaje, 2009; Zarma and Tukur, 2015). Figure 3 shows the stratigraphic succession of the Nigerian sector of the Chad Basin.

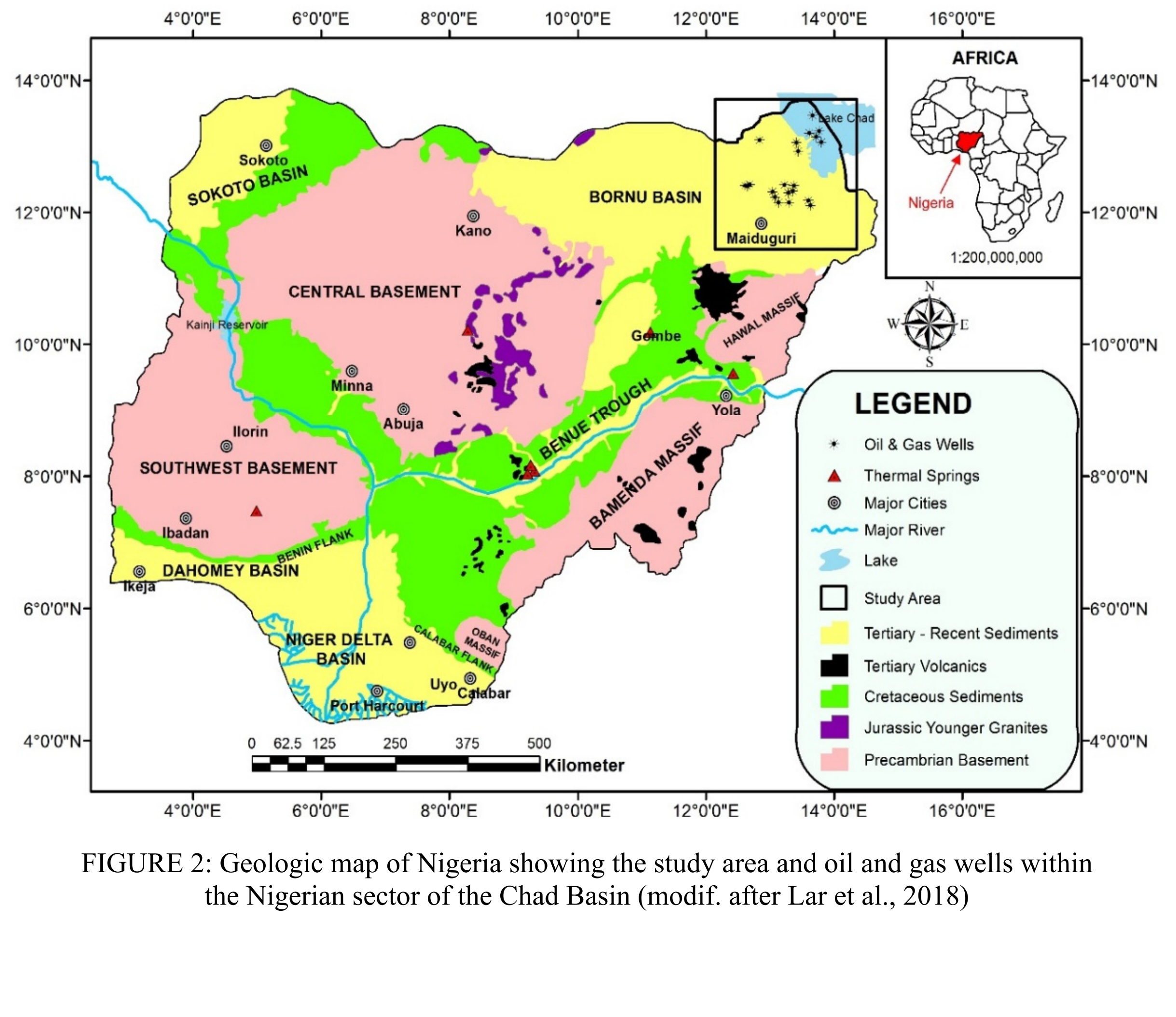

FIGURE 2: Geologic map of Nigeria showing the study area and oil and gas wells within the Nigerian sector of the Chad Basin (modif. after Lar et al., 2018)

2.2.1 The Bima sandstones

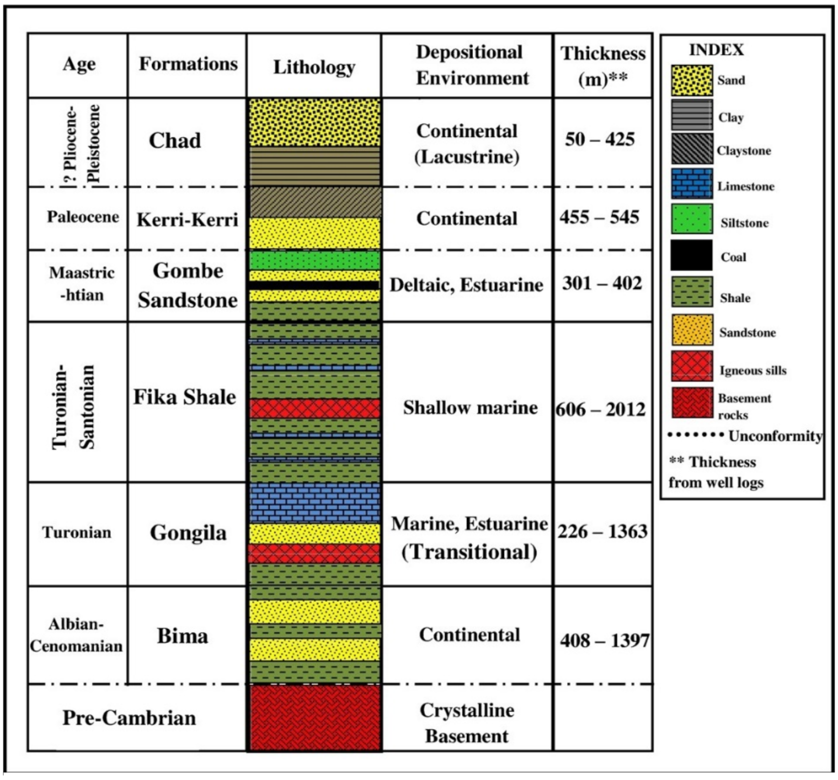

FIGURE 3: Stratigraphic succession in the Nigerian sector of the Chad Basin (adapted from Adegoke et al., 2014)

Sedimentation in the Chad Basin is believed to have begun during the Albian with the continental Bima sandstones which is made up of sparsely-fossiliferous, poorly-sorted, medium- to coarse-grained, feldspathic sandstone, laying unconfirmable on basement rock (Carter et al., 1963). The thickness of the Bima sandstone in the basin has been reported to be up to 2,000 m from seismic section analysis (Avbovbo et al., 1986) while Carter et al. (1986) reported an average of 3050 m. According to Adegoke et al. (2014), the thickness is in the range of 408-1,397 m and Olabode et al. (2015) reported over 1500 m for the Bima sandstone based on well log data. The sandstone layers in the Bima are the location of the reservoir for both oil and water.

2.2.2 Gongila formation

Overlying the Bima sandstone is the Late Cenomanian to Early Turonian Gongila formation made up of alternating calcareous shale and sandstone with interbeds of limestone (Olugbemiro et al., 1997; Isyaku et al., 2016). Olabode et al. (2015) reported the presence of Yolde between the Bima and Gongila formation in some areas. The Gongila formation has an average thickness of 420 m (Carter et al. 1963) and seismic thickness of up to 800 m (Avbovbo et al., 1986). A thickness range of 226-1,363 m has been reported by Adegoke et al. (2014).

2.2.3 Fika shales

The marine transgression in the Albian resulted in the deposition of the bluish-black, ammonite-rich, open-marine Fika shales up to the Senonian with seismic sediment thickness of 900 m and average thickness of 430 m (Carter et al., 1963; Avbovbo et al., 1986). Adegoke et al. (2015) reported a thickness range of 606-2,012 m.

2.2.4 Gombe sandstones

The Maastrichtian Gombe formation was deposited in an estuarine/deltaic environment and consists of sandstones, siltstones, clay, ironstones and coal measuring 430 m on average with a seismic thickness of up to 1,000 m (Carter et al., 1963; Avbovbo et al., 1986; Olugbemiro et al., 1997). According to Adegoke et al. (2014), the thickness is 301-402 m.

2.2.5 Kerri-Kerri formation

A late Maastrichtian extensional deformation in the Chad Basin lasted until the end of the Cretaceous and resulted in the reconstruction of the basin into a NW-SE elongated graben system. This created space for subsequent deposition of the Tertiary Kerri-Kerri formation (made up of iron rich sandstones and clay with rich lateritic cover) unconformably on Gombe sandstones (Carter et al. 1963; Avbovbo et al., 1986). An average thickness of 130 m was reported by Carter et al. (1963) and a thickness range of 455-545 m has been reported by Adegoke et al. (2014).

2.2.6 Chad formation

The Quaternary Chad formation is the topmost layer in the sedimentary basin and is made up of fine- to coarse-grained sands, siltstones, diatomites, clays and blue-grey shales (Okosun, 1995; Adekoya et al., 2014). Carter et al. (1963) stated the average thickness of the Chad formation to be 400 m while Avbovbo et al. (1986) used seismic data to estimate a joint average thickness of both the Kerri-Kerri formation and the Chad formation to be up to 800 m. Adegoke et al. (2014) found a thickness range of 50-425 m using well log data.

2.2.7 Cenozoic igneous rocks

The Cenozoic magmatism is important because of the role it can play on the possible heat generation in the Chad Basin. Many occurrences of Tertiary-Quaternary magmatism have been observed within West and Central Africa and there has been a rejuvenation of tectono-magmatic activities in several of the Cretaceous basins during the Neogene (Wilson and Guiraud, 1992). Though the location of volcanism may have been controlled by pre-existing basement fractures and lineaments, the cause of the Tertiary-Quaternary magmatism in West and Central Africa is not fully understood (Wilson and Guiraud, 1992; Suleiman et al., 2017). However, evidence has been presented for the occurrence of igneous intrusions in the Benue trough and Bornu basin by Avbovbo et al. (1986), Benkhelil (1989), Genik (1992) and Suleiman et al. (2017).

Suleiman et al. (2017) confirmed the presence of igneous intrusions with the recovery of dolerite cuttings from 4 wells in the area and also mapped the intrusions in the area. Mapping of the intrusion showed that:

i. Most of the intrusions occur below the Cenozoic unconformity, particularly in the Bima sandstones, Gongila formation and Fika shales.
ii. In very rare occasions, the intrusions cut across the Cenozoic unconformity and extend upwards into the overlying Kerri-Kerri formation.
iii. The intrusions appear as strata-concordant or strata-discordant and laterally discontinuous (maximum of about 14 km).
iv. Three major geometrical styles of the igneous bodies were established:
    - Saucer shaped sills;
    - Strata-concordant sills;
    - Volcanic cones.

2.3 Hydrogeology

The aquifer system in the Chad Basin has been studied by many scholars, notably the first 600-700 m of the Quaternary Chad and Tertiary Kerri-Kerri formation contain three zones of aquifers. Barber and Jones (1960) were first to establish three water-bearing zones in the Chad formation of the Maiduguri area using data from 231 boreholes (Figure 4). The lower zone aquifer is made up of alternating sand and clayey sand of 89 m thickness with individual, fine- to coarse-grained sand units of up to 14 m thickness (Barber, 1965). The 25 m thick middle zone consists of three sandy units which are fine to very-coarse grained, poorly graded and mostly uncemented. The sandy units have a maximum thickness of about 8 m. The upper zone is made of interbedded sands and clay (Edmunds et al., 1999).

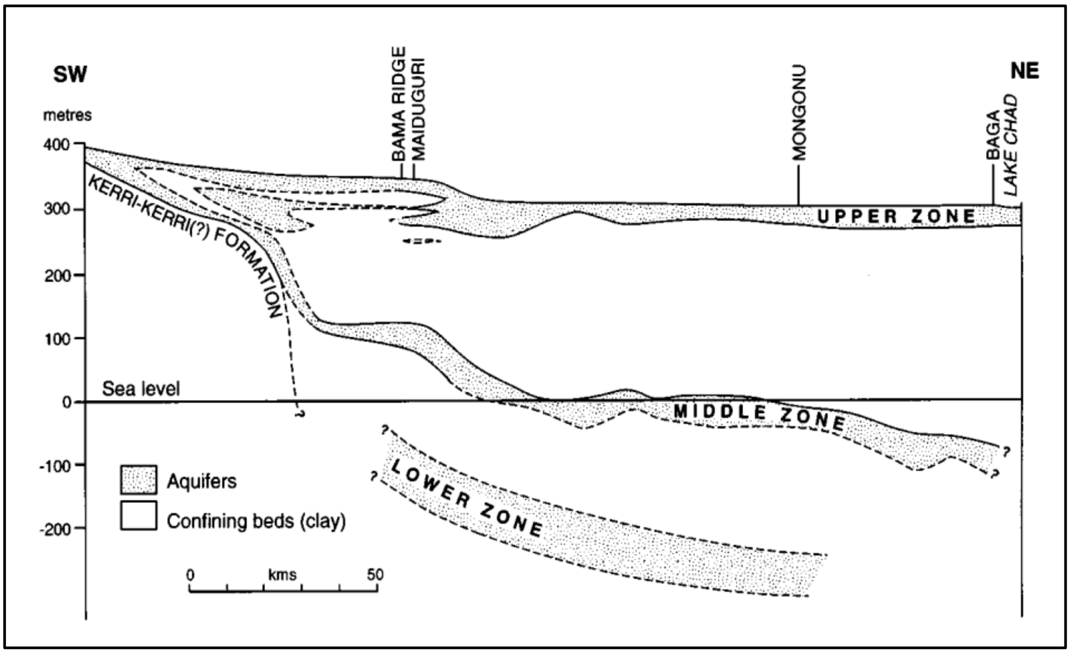

FIGURE 4: Geologic cross-section through the Chad Basin aquifer (Barber 1965)

Most of the water used for human purposes comes from this Quaternary phreatic aquifer which has a continuous water table in the extensive reservoir covering an area of about 500,000 km^2 (Eberschweiler, 1993; Lopez et al., 2016). Two piezometric depressions within the Quaternary aquifer (Nigerian sector of the Chad Basin), Kadzell and Bornu depressions were reported to cover an area of 4,400 km^2 and 16,500 km^2 with a piezometric level of 50 and 60 m below ground level, respectively (Lopez et al., 2016). Figure 5 shows the Kadzell and Bornu depressions in the Northern sector of the Chad Basin and the direction of water flow.

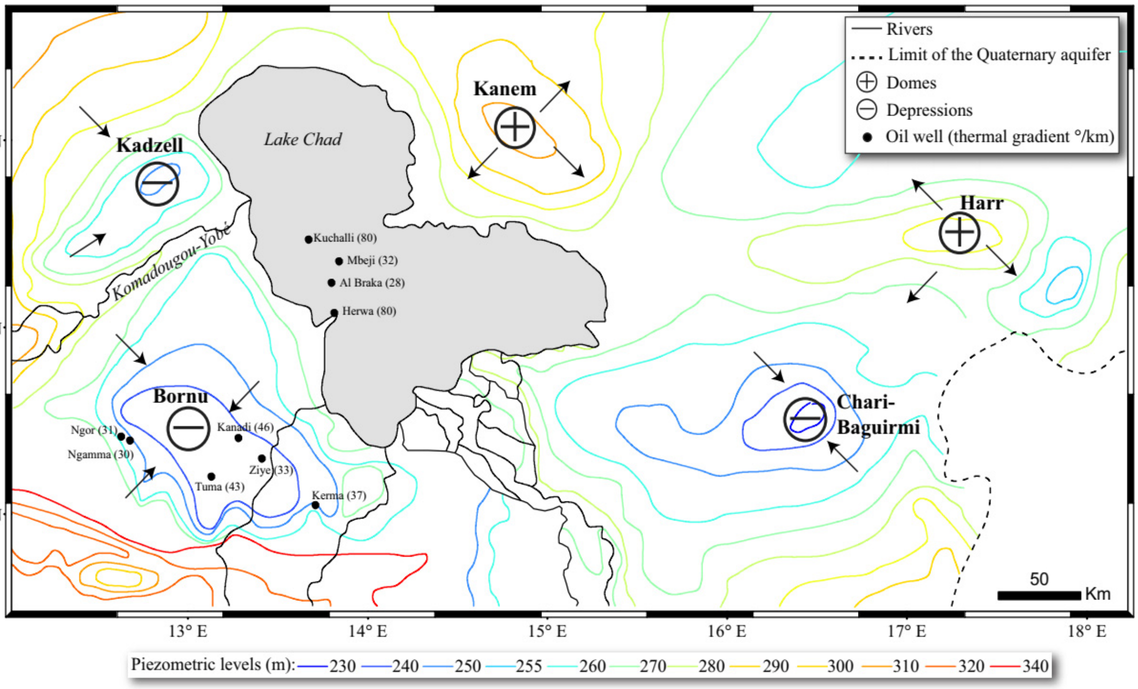

FIGURE 5: Piezometric map of the Quaternary phreatic aquifer (QPA) showing the Kadzell and Bornu depressions, water flow direction (arrows) and oil well locations from Nwankwo and Ekine (2010) in the Nigerian sector of the Chad Basin (adapted from Lopez et al., 2016)

There is paucity of information about the hydrodynamics within the Cretaceous sequences in the Nigerian sector of the Chad Basin. However, Bima sandstones display suitable porosity and permeability to be good aquifers but lack the vertical link with overlying aquifers that could enhance recharge. Data from a seismic survey at oceanic margins show that overpressured clay layers develop giant polygonal fractures when subjected to horizontal tensile stresses of a few bars and Lopez et al. (2016) discovered such structures in the Bornu basin.

2.4 Recent geothermal studies

Numerous scholars have investigated the geothermal potential of the area directly or indirectly. Most of the works are confined to the determination of the geothermal gradient and heat flow in the area. Table 1 shows the summary of results obtained by various scholars in the Nigerian sector of the Chad Basin.

TABLE 1: Geothermal gradient and heat flow results from recent geothermal studies in the area

S/N	Authors	Geothermal gradient (°C/100 m)		Heat flow ($W \times 10^{-3}/m^2$)
		Range	Average	
1	Miller et al., 1968	NA	3.2	NA
2	Askira and Schoeneich, 1987	3.00 – 6.44	NA	NA
3	Kwaya et al, 2016	2.81 – 5.88	3.71	45 – 90
4	Nwazeapu, 1990	2.16 – 5.26	NA	NA
5	Nwankwo et al., 2009; Nwankwo and Ekine, 2009	3.00 – 4.40	3.4	63.6 - 105.5
6	Olugbemiro and Ligous, 1999	2.8 – 4.2	NA	NA
7	Umar, 1999	NA	3.31	NA

NA = Not Available

3. WELL DATA AND RESERVOIR CONDITION

3.1 Temperature logs and geothermal gradient

Twenty-three (23) oil exploration wells have been drilled in the Nigerian sector of the Chad Basin and the bottom hole temperatures (BHT) from 22 of these wells as well as the temperatures at their well tops were used for this study. Measured BHT does not reflect the static or true temperature of the formation at which the measurement was taken because this is usually done a few hours to tens of hours after stopping circulation of drilling fluid in the borehole. The drilling fluid convects heat within the hole, creating untrue static formation temperature for which corrections have to be made. The BHT correction method of Waples et al. (2004) and ZetaWare (2006) was applied for BHT correction in this study. The corrected subsurface temperature (in °C) is given by:

$$T_t = T_s + f(T_m - T_s) - 0.001391(Z - 4498) \quad (1)$$

where T_t = True temperature (°C);
T_s = Surface temperature (°C);
T_m= Measured downhole temperature (°C);
f = Correction factor (a function of time since end of fluid circulation);
Z = Depth (m).

The corrected BHT was used to determine the geothermal gradient in the area, using:

$$G = \frac{T_t - T_S}{Z} * 100 \quad (2)$$

where G = Geothermal gradient (°C/100 m);
T_t= Corrected bottom hole temperature (°C);
T_S= Surface temperature in the well (°C);
Z = Depth of measurement (m).

Table 2 shows the geothermal gradients obtained in this study and those of earlier studies in the area (see Figure 2). The values obtained show a correlation between the present study and earlier results and Figure 6 shows the geothermal gradient in this study. The geothermal gradient ranges from 3.0 to 5.5°C/100 m with anomalously high values in the central and southern part of the study area which are 5.5°C/100 m in both Kasade-1 (Ks1) and SA-1 (Sa1). However, the BHT temperatures in both of these wells were measured at relatively shallow depths, 1,217 and 609 m, respectively.

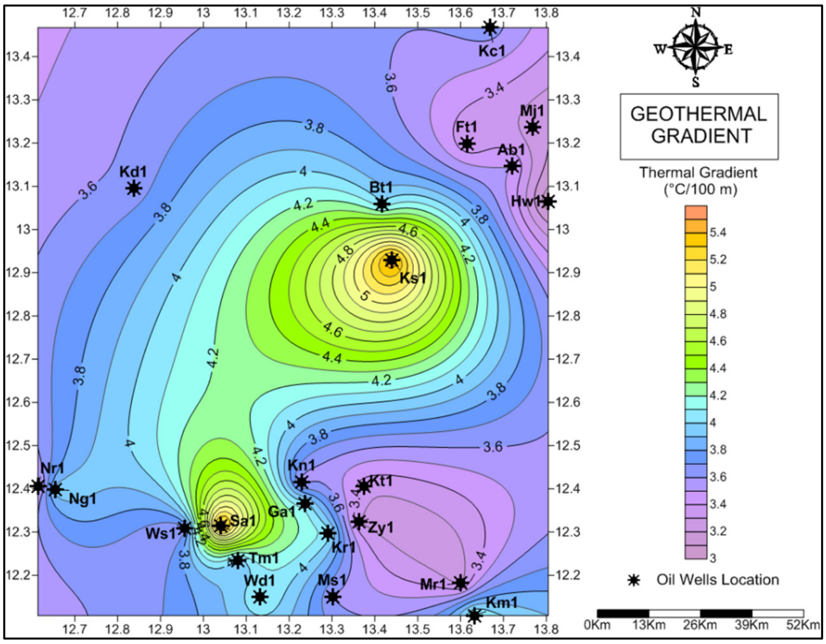

FIGURE 6: Geothermal gradient with respect to bottom hole temperature (BHT) in the Nigerian sector of the Chad Basin

TABLE 2: The geothermal gradient obtained from the present study and other recent studies in the Nigerian sector of the Chad Basin (geothermal gradient in °C/100 m)

Wells	Well ID	Nwankwo and Ekine (2009)	Kwaya et al. (2016)	This study
Al-Barka-1	Ab1	3.3	3.32	3.5
Bulte-1	Bt1	3.4	3.47	4.0
Faltu-1	Ft1	3.1	3.01	3.3
Gaibu	Ga1	NA	NA	4.1
Herwa-1	Hw1	3.5	3.09	3.0
Kadaru-1	Kd1	3.2	NA	3.6
Kanadi-1	Kn1	3.8	5.02	3.6
Kasade-1	Ks1	4.4	4.59	5.5
Kemar-1	Km1	3.7	5.88	4.2
Kinasar-1	Kr1	3.6	3.61	4.1
Krumta-1	Kt1	3.4	3.08	3.4
Kuchalli-1	Kc1	3.1	3.24	3.7
Masu-1	Ms1	3.5	3.67	3.6
Mbeji-1	Mj1	4	3.07	3.2
Murshe-1	Mr1	3	2.99	3.3
NgammaE-1	Ng1	3.6	4.29	4.0
Ngor N-1	Nr1	3.1	NA	3.4
SA-1	Sa1	3.3	4.71	5.5
Tuma-1	Tm1	3.4	3.14	3.9
Wadi-1	Wd1	3.2	3.74	4.1
Wushe	Ws1	NA	3.34	3.6
Ziye-1	Zy1	3	3.28	3.3

NA = Not Available

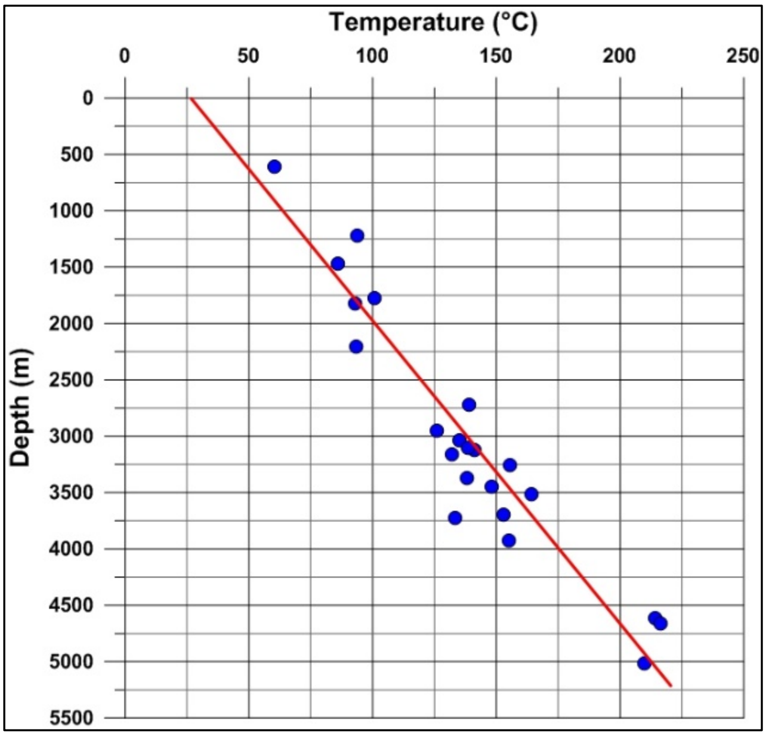

FIGURE 7: Depth against bottom hole temperature (BHT) showing the regional trend of geothermal gradient in the Nigerian sector of the Chad Basin.

Depth against BHT was also plotted to analyse the trend of the temperature profile and the regional gradient in the area (Figure 7). The plots showed an average linear trend signifying the conductive nature of temperature variation in the area, typical for sedimentary basins. A regional geothermal gradient of 3.8°C/100 m was observed which is higher than the global average of 3.0°C/100 m for sedimentary basins (Saemundsson et al., 2009), making it suitable for geothermal exploitation.

3.2 Reservoir properties

The geothermal gradient alone was not sufficient to determine the most suitable area for estimating geothermal resources in the area. The Bima sandstone in the area is made up of continental sands and shales and presents the best target for a potential geothermal reservoir in the area due to depth and range of temperature. Generally, aquifers with fluid temperatures of less than 120°C can be utilised for direct use and space heating while temperature above 120°C is suitable for electricity generation (Tulinius et al., 2010). Maps of temperature and depth at the top of the Bima sandstones (Figure 8 and 9) together with the geothermal gradient to the top of Bima (Figure 10) were plotted, not including SA-1 and used to identify the wells that are best suited for geothermal exploitation purposes. Kadaru-1 (Kd1) and Tuma-1 (Tm1) show very high temperature at the top of Bima but also have the Bima sandstones at relatively great depth of over 5 and 3.5 km, respectively. The temperature gradients in Kasade-1 (Ks1) and SA-1 (Sa1) (Figure 6, Table 2) look promising but BHTs of 94.0°C (1,217 m) and 60.4°C (609 m) are not encouraging for geothermal utilization.

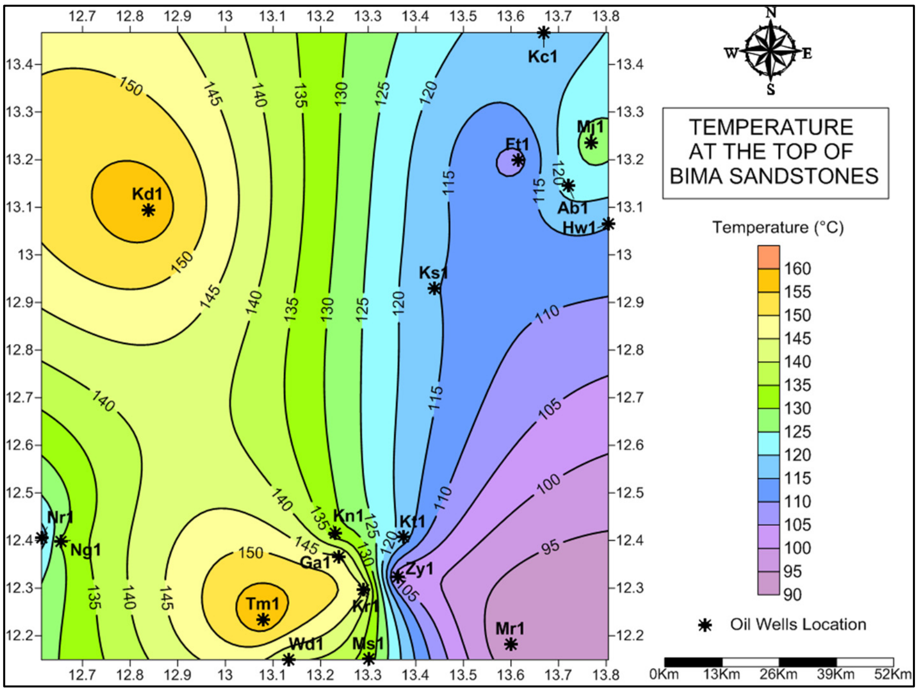

FIGURE 8: Temperature at top of the Bima sandstones in the Nigerian sector of the Chad Basin.

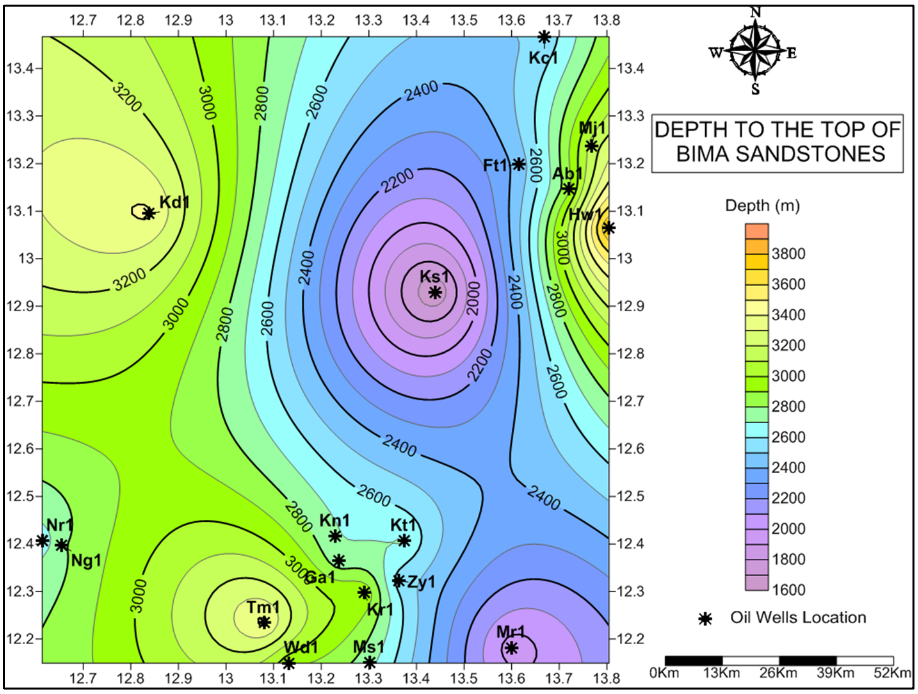

FIGURE 9: Depth to the top of the Bima sandstones in the Nigerian sector of the Chad Basin

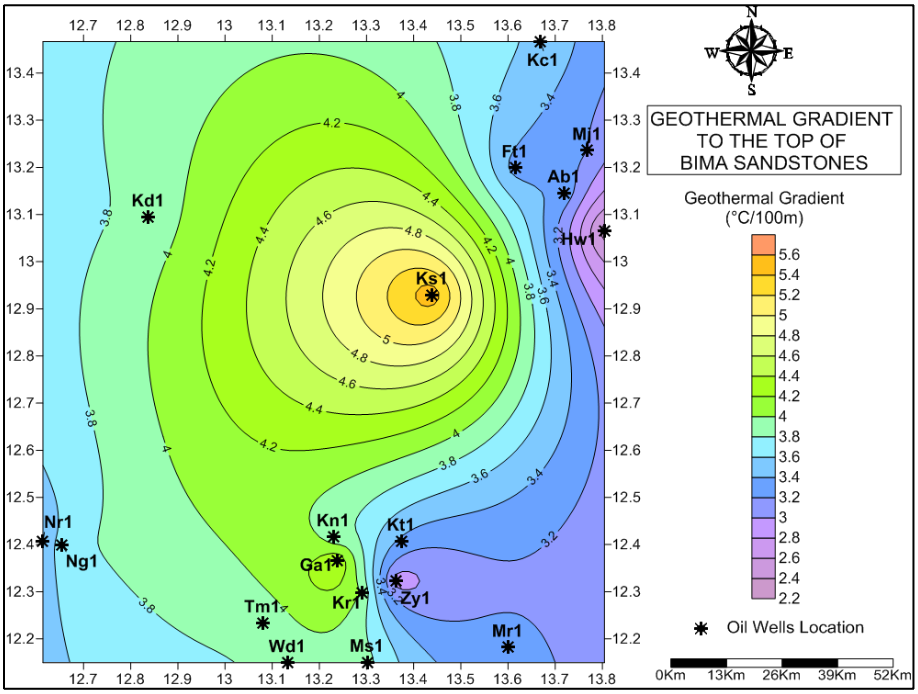

FIGURE 10: Geothermal gradient to the top of the Bima sandstones in the Nigerian sector of the Chad Basin

The results were further refined by plotting depth versus temperature at the top of the Bima sandstones and applying a cut-off temperature and depth of 120°C and 3 km, respectively (Figure 11). Thicknesses of the Bima sandstone layers in the promising wells are shown in Figure 12. Five wells fell within the productive zone; Gaibu-1 (Ga1), Kanadi-1 (Kn1), Ngamma E-1 (Ng1), Wadi-1 (Wd1) and Kinasar-1 (Kr1). They all lie within a structural sub-basin in the southern part of the study area, except for Ngamma E-1 (Ng1) which is located further west (towards the western margin). Kasade-1 (Ks1) has a relatively high potential due to its high geothermal gradient and a temperature of 115°C at a depth of less than 1,700 m. If the well is drilled further, there is a very high probability that high temperatures

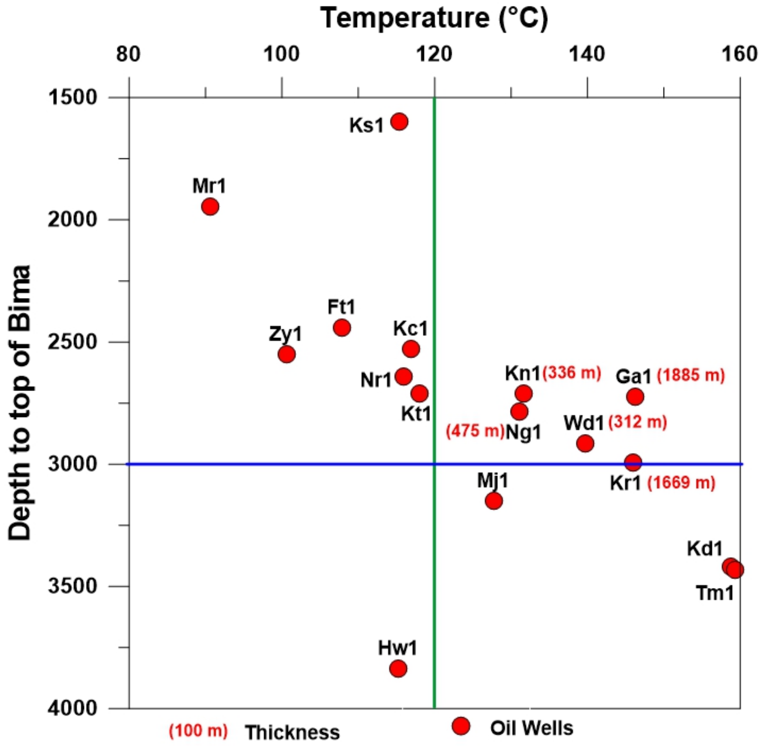

FIGURE 11: Depth against temperature at the top of the Bima sandstones in the Nigerian sector of the Chad Basin

will be observed at shallower depth than in all the other wells. Kuchalli-1 (Kc1), Ngor N-1 (Nr1) and Krumta-1 (Kt1) are close to the 120°C boundary (Figure 11) and could fall within the temperature target in spite of shallow depths. Some of the wells did not reach the Bima and were omitted from the analysis.

Bima in the study area is made of sandstone and shales but only sandstones are of importance for the geothermal resource assessment. Therefore, wireline logs were used to identify sandstone layers within the target zones of Bima in the selected wells and their thicknesses and temperature at the top of the layers were recorded (Table 3).

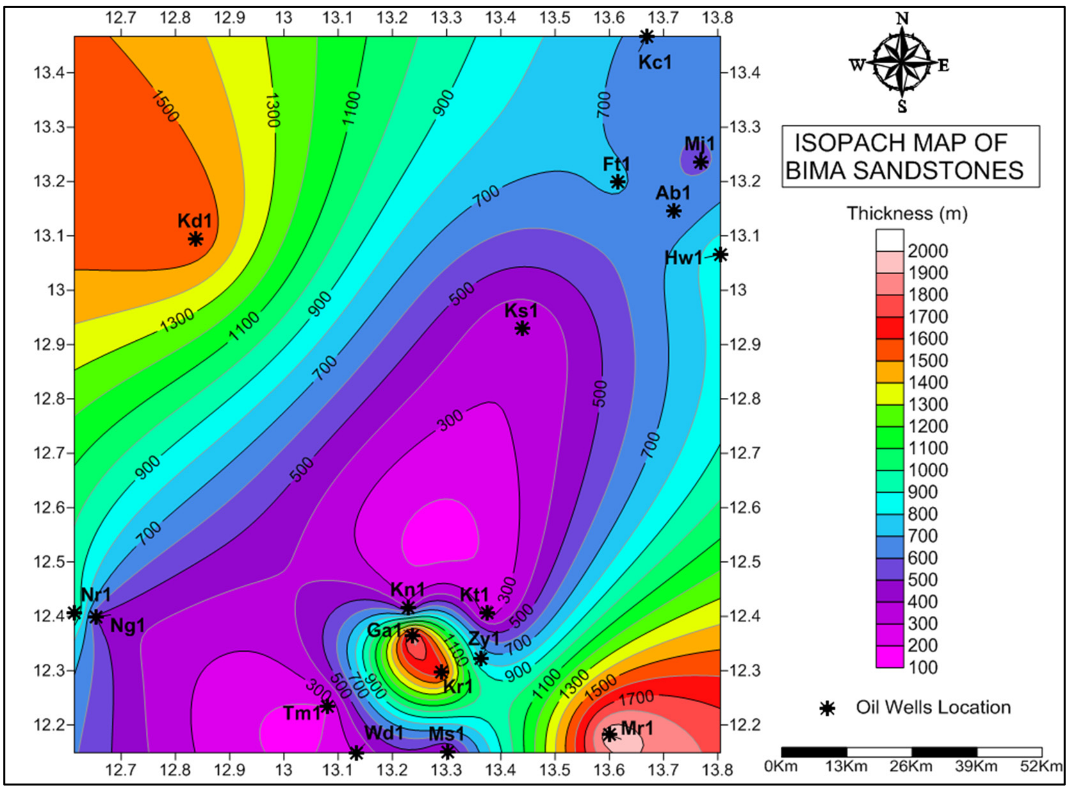

FIGURE 12: Thickness of the Bima sandstones in the Nigerian sector of the Chad Basin

TABLE 3: Depth, thickness and temperature at top of reservoir layer

Wells	Well ID	Depth to top of Bima (m)	Depth to top of reservoir layer (m)	Thickness (m)	Temperature (°C)
Gaibu-1	Ga1	2,725	2,900	290	152
Kanadi-1	Kn1	2,712	2,800	248	133
Kinasar-1	Kr1	2,994	3,166	204	152
Ngamma E-1	Ng1	2,785	2,785	475	134
Wadi-1	Wd1	2,915	2,915	312	140
Krumta-1	Kt1	2,710	2,760	190	120

The following was determined based on the results:

i. Four wells (Gaibu-1, Kanadi-1, Kinasar-1, and Wadi-1) were automatically selected.
ii. Ngamma E-1 was discarded because of its location, it did not lie within the sub-basinal structure hosting the other wells.
iii. Krumta-1 was found to be relatively close to Gaibu-1, Kanadi-1, and Kinasar-1 with the reservoir sand layer at 2,760 m and a temperature of 120°C and subsequently selected.

Based on the results obtained, the sub-basinal structure in the southern part of the study area, hosting Kanadi-1 (Kn1), Gaibu-1 (Ga1), Krumta-1 (Kt1), Kinasar-1 (Kr1) and Wadi-1 (Wd1), was delineated as the most prospective area for further geothermal exploration (Figure 13).

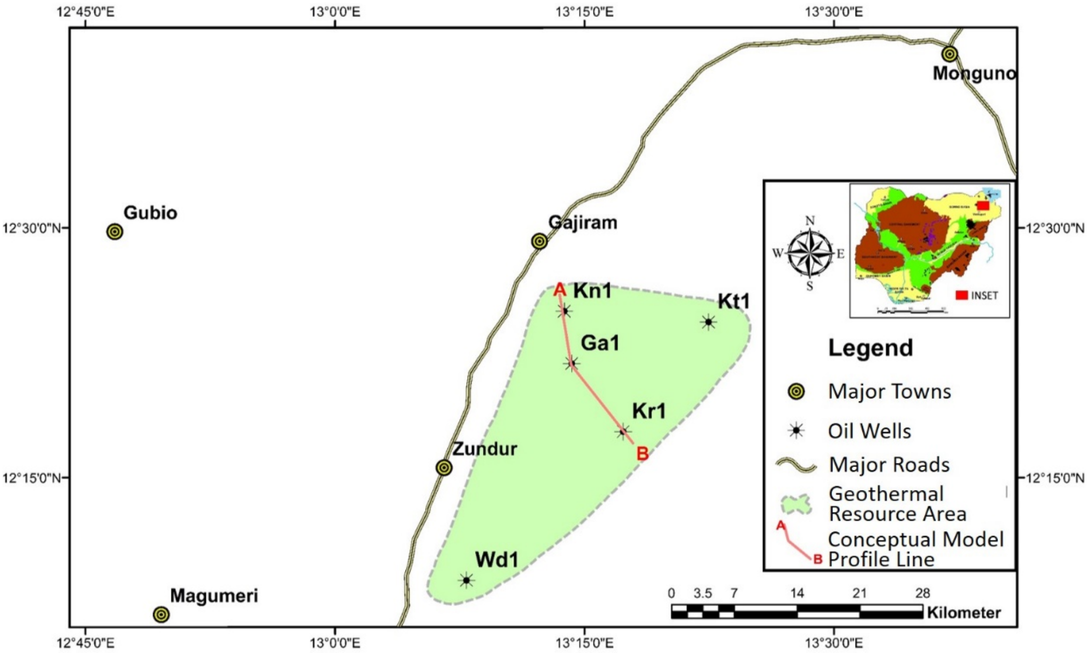

FIGURE 13: Prospective geothermal resource area in the Nigerian sector of the Chad Basin

3.3 Conceptual model

The conceptual model of the prospective geothermal resource area was developed using the results obtained in this study from wireline logs and temperature data as well as available literature of the area (sedimentary distribution, seismic sections, depth to basement, etc.). A cross-section from A to B in Figure 13 was used to develop the conceptual model shown in Figure 14. The well paths of Kn1, Ga1 and Kr1, which are all vertical wells, are projected onto the cross-section.

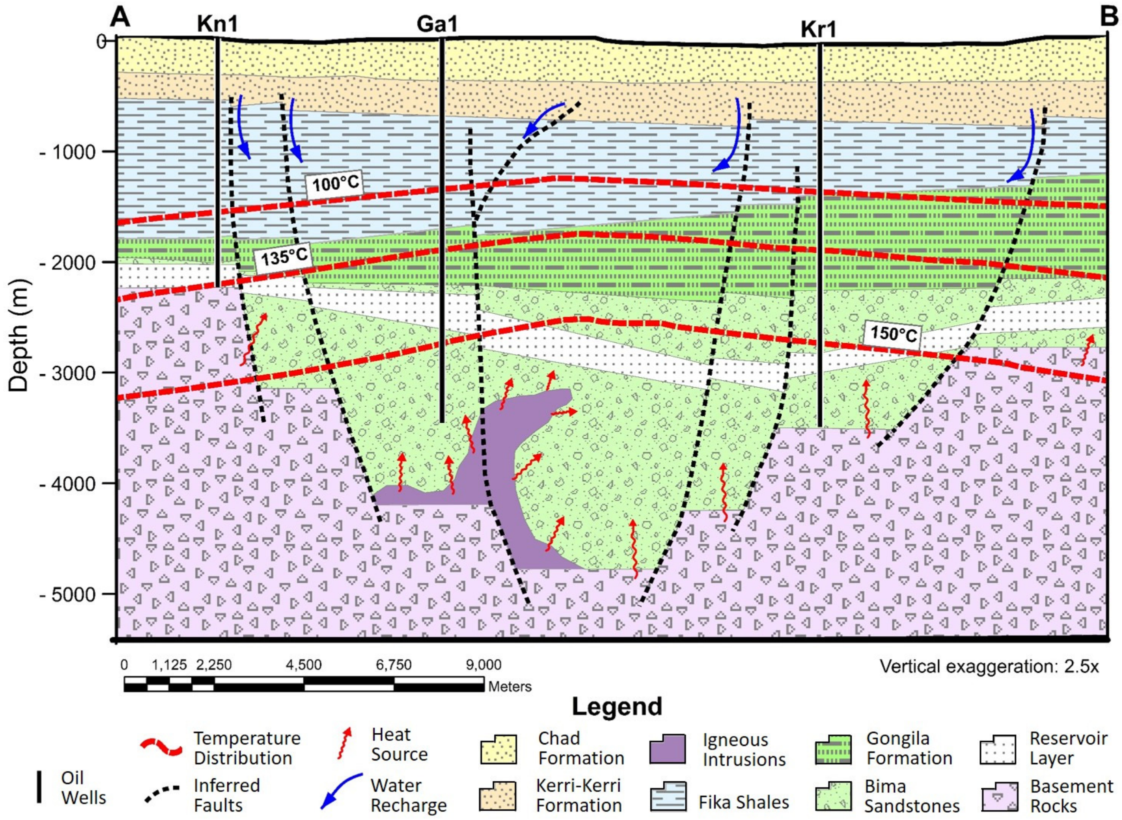

FIGURE 14: Conceptual model of the prospective geothermal resource area in the Nigerian sector of the Chad Basin.

The following can be stated:

Heat source. In the rifted basement, thinning of the crust occurs which leads to heating of the overlying rocks via conduction and is typical for sedimentary basins. The Tertiary-Quaternary igneous intrusions in the area also add to the thermal gradient and may be responsible for local anomalies when they rise to shallower depths.

Reservoir. The identified geothermal reservoir in the area is the Bima sandstones with the productive zone being the sandstone layers at around 3,000 m depth. The productive zone, made of horizontal and confined sandstones, is found from depths of 2,760 to 3,370 m. Temperature distribution in the productive zone ranges from 120 to 177°C.

Cap rock. The cap rock in the area are the shales found above the reservoir which are the shales of Gongila formation.

Structures and recharge. The structures in the area are mainly Cretaceous and may have been reactivated over time. The significant structures are the faults and fractures or connections of faults and fractures which run deep into the reservoir. These permeable structural boundaries also act as the conduit for recharge. The recharge is meteoric water that seeps from the Quaternary Chad and Kerri-Kerri formations into fractures and faults to the reservoir.

The conceptual model affirms the presence of an exploitable geothermal resource in the study area covering about 650 km^2, northeast of the capital city of Borno state, Maiduguri.

4. VOLUMETRIC RESOURCE ASSESSMENT

4.1 Theoretical background

The origin of volumetric resource assessment can be traced to the United States Geological Survey (USGS) in the 1970s when it was used to assess geothermal resources in several fields in the USA (Takashi and Yoshida, 2018). The volumetric resource assessment method involves estimating the total energy content in a geothermal system and how much of that can be extracted over a given time span, based on the volume and temperature of the reservoir. It is usually employed when the data available is sparse and more detailed modelling (e.g. lumped-parameter or numerical modelling) cannot be done. However, it does not consider the dynamic response of the reservoir and its geometry. Such responses are, e.g., pressure change, recharge, permeability, etc. This accounts for the uncertainty in many of the parameters used in volumetric calculations. The volumetric method is usually a first stage assessment method for geothermal resource assessment.

The Monte Carlo method is usually applied to volumetric calculations to take into account the overall uncertainty in the results obtained. Probability distributions, P90, P50 and P10, for 90%, 50% and 10% probability of a given outcome, respectively, are assigned to different parameters of the governing equations (Tulinius, 2019). The governing equations for total energy E in a geothermal system are given by:

$$E_{res} = E_{rock} + E_{fluid} \tag{3}$$

$$E_{rock} = V(1-\emptyset)\rho_{rock} \times C_{rock} \times (T_{res} - T_{reference}) \tag{4}$$

$$E_{fluid} = V\emptyset\rho_{fluid} \times C_{fluid} \times (T_{res} - T_{reference}) \tag{5}$$

or

$$E_{fluid} = V\emptyset\rho_{fluid} \times (h_{res} - h_{reference}) \tag{6}$$

where E_{res} = Total energy in the reservoir (J);
E_{rock} = Energy in the reservoir rock (J);
E_{fluid} = Energy in the reservoir fliud (J);
T_{res} = Reservoir temperature (°C);
$T_{reference}$ = Reference temperature (°C);
V = Reservoir volume studied (m^3);
$\emptyset$ = Porosity (fraction);
C = Heat capacity (J/kg°C);
ρ = Density (kg/m^3); and
h = Enthalpy (J/kg).

Total recoverable thermal energy $E_{recoverable}$ is given by:

$$E_{recoverable} = A \times R \times E_{res} \tag{7}$$

where A = Accessibility; and
R = Recovery factor.

Therefore, thermal power $P_{thermal}$, the electrical energy capacity E_e and power capacity P_e can be determined using:

$$P_{thermal} = \frac{E_{recoverable}}{\Delta t} \tag{8}$$

$$E_e = \eta_e \times E_{recoverable} \quad \text{(above reference temperature)} \tag{9}$$

$$P_e = \frac{E_e}{\Delta t} \tag{10}$$

where $P_{thermal}$ = Thermal power (W);
P_e = Power capacity (W);
E_e = Electrical energy capacity (Wh);
η_e = Efficiency of the power plant (%); and
Δt = Utilization time period (years).

4.2 Monte Carlo volumetric calculations

The Monte Carlo Software developed at ÍSOR (Iceland GeoSurvey) was used for the volumetric calculations. Input parameters used for the calculations are given below:

Area: The reservoir Bima sandstones are found within the sub-structural basin where Kanadi-1, Gaibu-1, Kinasar-1, Wadi-1 and Kruma-1 wells are sited and covers an area of 650 km^2. Values of 450, 800 and 650 km^2 were used for the pessimistic, optimistic and most likely area estimations.

Thickness: The thickness of the reservoir layer ranges from 170-290 m. Therefore, values of 170, 290 and 230 m were used for the pessimistic, optimistic and most likely thickness, respectively.

Reservoir temperature: The temperature value considered for the minimum temperature is the minimum temperature at the surface of the reservoir layer (120°C) and the maximum temperature is the temperature at the bottom of the reservoir layer (177°C). Therefore, values of 120, 177 and 149°C were used for the pessimistic, optimistic and most likely values, respectively.

Porosity: Based on the compaction curve of Limberger et al. (2018) for sand sediments, at depth of 3 km, the porosity is approximately 0.14. Therefore, values of 0.10 (pessimistic), 0.18 (optimistic) and 0.14 (most likely) were used.

Specific heat capacity of rock: Based on the Engineering Toolbox (2019a), specific heat capacity of sandstone is about 830 J/kg°C. For this study the following values were used; 800 (pessimistic), 880 (optimistic) and 830 J/kg°C (most likely).

Density of rock: Based on the Engineering Toolbox (2019b), sandstones have a density ranging from 2,100 to 2,400 kg/m^3. Therefore, values of 2,100, 2,400 and 2,250 kg/m^3 were used for pessimistic, optimistic and most likely density, respectively.

Specific heat capacity of water: This will be calculated by the volumetric software based on the input temperature of the reservoir.

Density of water: This will be calculated by the volumetric software based on the input temperature of the reservoir.

Recovery factor: Recovery factor values of 5% (pessimistic), 20% (optimistic) and 12.5% (most likely) were used (Gudni Axelsson, ÍSOR, pers. comm., 20th September, 2019).

Cut-off temperature: A cut-off temperature of 70°C was used, assuming a binary power generation mode for the geothermal resource.

Efficiency: Estimated efficiency values of 11%, 16% and 13.5% were used for pessimistic, optimistic and most likely values, respectively (Helga Tulinius, ÍSOR, pers. comm., 24th September, 2019).

Load factor: An estimated load factor of 95% was used.

An energy utilization period of 30 years was used for the simulation, which was done with 1,000,000 Monte Carlo runs. Figure 15 shows the input values and parameters used for the volumetric calculation.

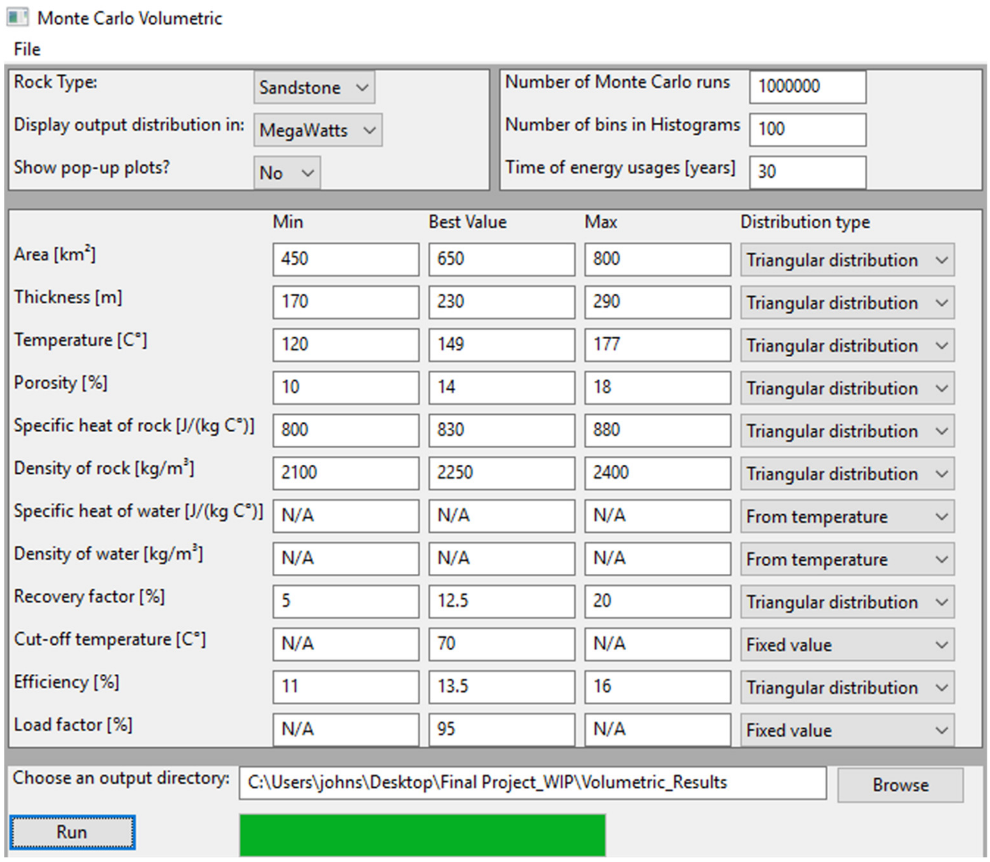

FIGURE 15: Input parameters for Monte Carlo volumetric assessment of the geothermal reservoir in the Nigerian sector of the Chad Basin

4.3 Results

Results for the Monte Carlo volumetric calculations are shown in Figures 16, 17 and 18. Figure 16 shows the probability distribution of the assessment presented as a function of normalized probability density (1/MWe) against power (MWe). Figure 17 shows a function of the percentage cumulative distribution (%) against power (MWe). Figure 18 shows the percentage sensitivity of the results obtained to the main calculation parameters.

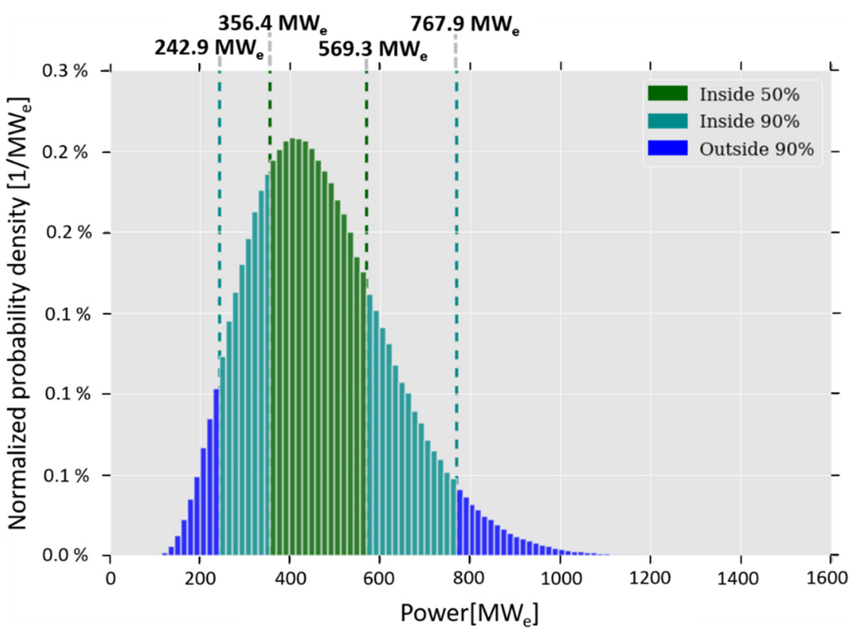

FIGURE 16: Probability distribution for Monte Carlo volumetric assessment of the geothermal reservoir in the Nigerian sector of the Chad Basin

The results show that the volumetric assessment

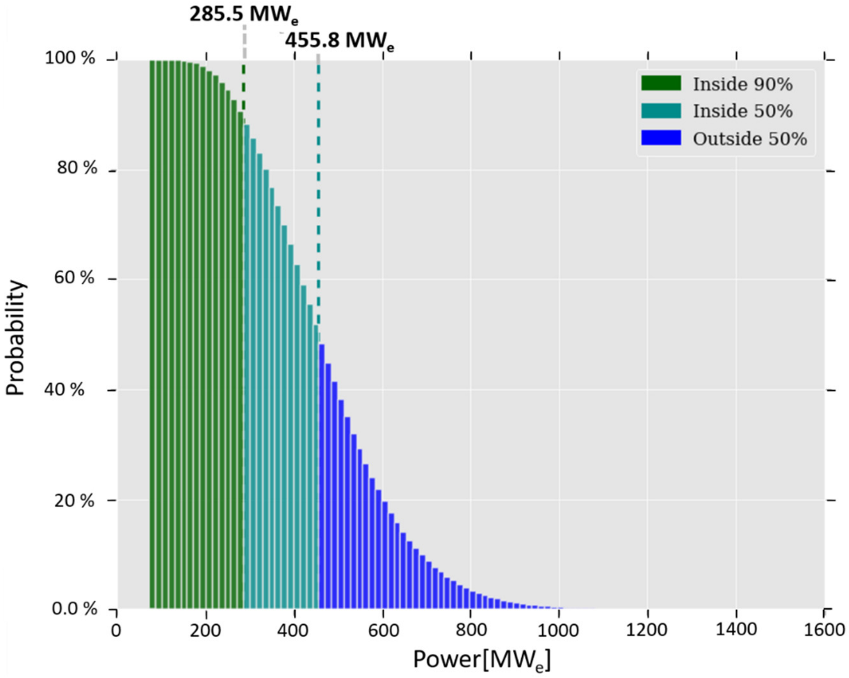

FIGURE 17: Cumulative probability distribution for Monte Carlo volumetric assessment of the geothermal reservoir in the Nigerian sector of the Chad Basin

calculations were most sensitive to the recovery factor, temperature, area, thickness and efficiency. The most likely power generation capacity is 406 MWe while the optimistic and pessimistic values are 1,492 and 73 MWe, respectively. The results show a mean of 467 MWe, median of 449 MWe, standard deviation of 159 MWe and skewness of 0.7 MWe^2. The possible electrical power potential, based on P90 and P10, range from 285 to 682 MWe. Table 4 shows the summary of the results obtained from Monte Carlo volumetric assessment.

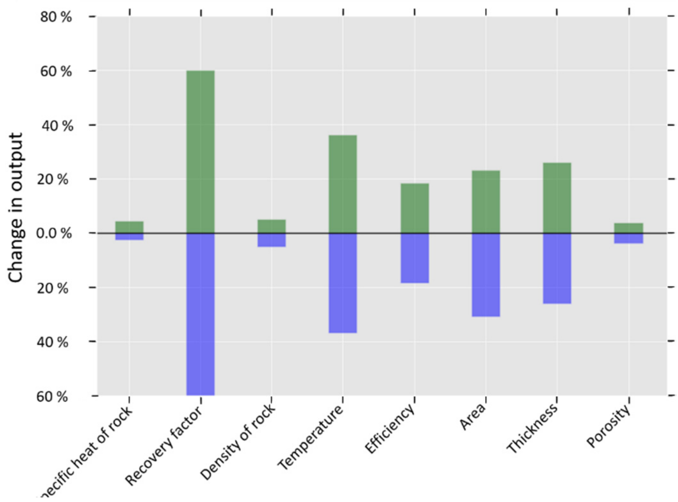

FIGURE 18: Sensitivity of the volumetric assessment results to the input parameters

TABLE 4: Results of the Monte Carlo volumetric assessment showing the cumulative probability thresholds and other statistical parameters

P90	285	MWe
P50	455	MWe
P10	682	MWe
Most likely	406	MWe
Highest value	1,491	MWe
Lowest value	72	MWe
Mean	467	MWe
Median	449	MWe
Standard deviation	159	MWe
Skewness	0.7	MWe^2

5. DISCUSSION

The results show P90, P50 and P10 values of 285, 455 and 682 MWe, respectively. The P90 value, 285 MWe, represents a more conservative estimate of the electrical power capacity of the resource area because it has a higher degree of confidence with about 90% probability of success given the information available. The P10 value, 628 MWe, represents a 10% probability which means very low confidence while the P50 represents the modal value of the distribution. With further exploration, the values of P90 may increase or decrease, depending on the outcome of the exploration. The temperature distribution in the reservoir and values obtained from the volumetric assessment support the utilization of the resource for power generation using a binary plant (Organic Ranking Cycle or Kalina Cycle). Binary plants use secondary working fluids with low boiling point and high vapour pressure at low temperature. The pressure produced is used to drive the turbine after which the fluid is cooled and condensed and the cycle continues.

There is, however, the need for adequate management of the resource to make its use sustainable. With exploitation of a geothermal reservoir, pressure change will be experienced due to mass extraction. This will lead to decline in production from the field with time, if not managed well. The long term response to geothermal utilization in a field is controlled by the size and energy content, permeability structures, boundary conditions and re-injection management (Axelsson, 2016). Sedimentary geothermal systems are mainly closed systems (Gudni Axelsson, ÍSOR, pers. comm., 14th October, 2019), therefore, re-injection management is required in the study area and it may need to be up to 100% re-injection. This will serve the purpose of protecting the environment from surface discharge of mineralized water, augmenting natural recharge and stabilizing the reservoir.

Utilization of geothermal resources in sedimentary basins is not new and has been practised in many countries; notably China, Germany, Hungary and France. Most of them have been utilized for direct use of geothermal but a few have been used for power generation. The resource management in these countries will give useful information on how to manage the resource in Nigeria. For instance, re-injection in a sandstone reservoir is challenging and can cause reduction of permeability over time. Seibt (2003) worked on the re-injection of thermal waters into sandstone reservoirs in the North German basin and identified the following challenges to permeability (clogging):

- Weathering and rearrangement of rock particles due to high flow rates (injection and production);
- Introduction of oxygen into the reinjection loop which reacts with iron to precipitate oxides of iron;
- Corrosion in installations due to reaction with acidic fluid, aggressive ions (e.g. Cl-) and gases (e.g. CO_2); and
- Bacterial activities which result in transformation of sulphides to sulphide precipitates.

He also proffered measures to mitigate this clogging and loss of permeability, among which are:

- Controlling the re-injection flow rates to suit the hydraulic regime in the system;
- Adequately filtering the geothermal fluid on the surface to prevent precipitation and re-introduction of traces of oil;
- Adding appropriate chemical inhibitors to prevent corrosion or precipitation; and
- Making sure the reinjection loop is sealed to prevent oxygen influx.

The Nigerian sector of the Chad Basin can be a viable geothermal resource area going by experiences in other basins where both producing and abandoned oil wells have been utilized for power generation. Gulyas et al. (2018) gave an account of the geothermal potential of the global oil industry: water production in mature oil fields is 10-20 times more than oil production; some of this water is produced at temperatures greater than 100°C; the Brent and Ninian petroleum fields produced 10 and 31 MWe, respectively; and the power generation capacity of produced water in the North Sea petroleum field is estimated at 250 MWe. The Huabei oil field in China produces about 400 kWe of electricity from abandoned oil wells. In the case of abandoned oil wells, heat exchangers (double-pipe heat exchanger, coaxial wellbore heat exchanger, etc.) are used to mine heat from the well using the binary system. Bu et al. (2012) reported that power production from abandoned oil wells depends largely on fluid flow rate and geothermal gradient. He estimated 53.7 kWe for a single well with a geothermal gradient of 45°C/km and outlet temperature of 130°C. However, the power production is also heavily reliant on the type and quality of the turbine used. With advancement in technology, more efficient binary turbines will be made and temperatures that are not good for geothermal power production today can be suitable in the near future.

For the geothermal resources in the study area to be used in a sustainable manner, it might be necessary to adopt step-wise increase in production (Axelsson, 2010). In addition to sustainable management of the resource, keeping in mind that no two geothermal fields are the same, the key to success in exploitation is perfect understanding of the reservoir conditions and selection of the best exploitation technology.

6. CONCLUSIONS AND RECOMMENDATIONS

Nigeria, with a population of over 200 million people, requires power to drive the economy because no nation can achieve development without meeting her power needs. Therefore, the need for exploring the various potentials for power generation in the country cannot be over-emphasized. One of the means through which clean renewable energy can be provided in Nigeria is by harnessing its geothermal potentials and the Nigerian sector of the Chad Basin possesses a significant capacity for geothermal power production.

Based on the available information from drilling (such as geophysical well logs) and deduced geological sections in oil wells in the area as well as distinct temperature measurements in the wells, the prospective reservoir in the area was identified as the sandstone layers within the Bima sandstones. Temperature distributions within the reservoir range between 120 and 177°C. A geothermal resource area was demarcated and found to be located within a sub-basinal structure at the southern part of the study area, containing wells Kn1, Ga1, Kr1, Kt1 and Wd1. The conceptual model for the resource area was based on the interplay of the major elements of a geothermal system and Monte Carlo volumetric assessment was done to estimate the possible electrical power potential of the area. Values based on P90 and P10 distribution show potential electrical power generation ranging from 285 to 682 MWe. Therefore, a conservative estimation of the electricity capacity in the prospective geothermal resource area is 285 MWe with a 90% probability of success.

This study is just the first estimate of the possible electrical power potential in the study area and depends largely on well data that was acquired for oil and gas exploration purposes. These wells are also far apart and may not give reliable information on the area between the wells. For further geothermal studies in the area, the following is recommended:

1. Surface electromagnetic sounding, such as MT and TEM surveys, as well as magnetics and gravity measurements to better image the subsurface and update the conceptual model;
2. Activation of selected wells and performing wireline logs in the oil wells, with emphasis on continuous temperature, pressure and spinner logs;
3. Examining core samples for temperature alteration minerals of the selected wells; and
4. Running of well tests to better estimate the reservoir conditions of selected wells.

Also, the Federal Government of Nigeria must have a pivotal role to play in the success of geothermal energy in Nigeria by:

1. Enacting policies which will further encourage renewable energy development, especially geothermal, for example through making the petroleum multinationals (Chevron, Shell, etc.), Nigerian National Petroleum Corporation (NNPC) and the Petroleum Trust Development Fund (PTDF) to invest in geothermal exploration and development, in their various capacities;
2. Empowering government institutions dealing with geothermal development (e.g. NCPRD ECN) to enable them to conduct quality exploration of geothermal resources, because geothermal exploration and development has huge upfront cost but good returns in the long run; and
3. Instituting a renewable energy scholarship scheme to encourage renewable energy research and development, particularly in geothermal energy.

With increased attention on the geothermal potential in the study area and implementation of the aforementioned recommendations, better reservoir models (lumped-parameter and numerical models) can be developed to maximise the output of the field and manage it sustainably after a significant period of utilization. Also, through that Nigeria would have made a huge statement in its drive to achieve the United Nations Sustainable Development Goals, particularly Goals 7, 11 and 13.

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