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Geothermal Well Exploration in Nigeria Using Remote Sensing and Modified Thermal Equations

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Abstract

Based on the preliminary evidence of volcanoes, hot springs, and Geysers in parts of Nigeria, it is proposed that deep geothermal wells can be found in Nigeria. This research uses thermal anomalies zones to identify types of geothermal wells in Nigeria, i.e., using remote sensing and modified thermal equations. The remote sensing dataset includes the ground heat flux (GHF) dataset from Modern-Era Retrospective analysis for Research and Applications (MERRA) of 28 years; sediment thickness dataset from EarthData; and surface geology from LANDSAT. The thermal transport model was used to narrow potential locations across Nigeria using the ground heat flux and sediment thickness, while the surface geology was used to confirm the deep geothermal zones. Four GHF patterns were discovered in Nigeria. The research shows that the deep geothermal wells might be located in Plateau, Bauchi, Gombe, Taraba, Ekiti, Kogi, Benue, Nassarawa, and Taraba. Also, the medium-depth geothermal wells may be located in Sokoto, Zamfara, Kastina, Kwara, Oyo, and Jigawa States. It was revealed that the southern parts of Nigeria have lots of shallow geothermal wells. The deep geothermal wells can be found in the Chad Basin and Benue trough, while the medium-depth geothermal wells can be found in the Sokoto basin, Bida basin, and parts of the lower Benue trough. It is recommended that further ground trotting exploration be carried out in the identified geographical locations.

Keywords: *Ground heat flux; geothermal; energy; alternative energy.*

1. Introduction

Based on the preliminary evidence of volcanoes, hot springs, and Geysers in parts of Nigeria, it is logical to agree with the International Geothermal Association report on geothermal energy potential in Nigeria [1]. There are about ten warm springs in Nigeria, including Rafin Rewa Warm Spring, Ikogosi Warm Spring, Lamurde Hot Spring, Keane-Awe Thermal Springs, Akiri Warm Spring, Nike warm spring, Kerang warm spring, Ngeji warm spring, and Wikki Warm Spring. Also, there is a volcanic site in Plateau. Most of the warm spring and volcanic sites are located in the Cretaceous Benue Trough in the northern part of Nigeria [2]. In the southern parts, it has been postulated that the overpressured thick sediment strata are characterized by anomalous temperature gradients, which have influenced heat flow [3]. Detection of anomalous thermal zones to predict potential geothermal energy sites has been adopted in various studies [4]. Since the pioneering research on geothermal energy exploration using remote sensing to detect temperature anomalies [5], many research has followed the same route. The typical challenge in most studies using remote sensing to determine the temperature anomalies is the duplication of false sites due to prevailing climate change. This research seeks to adopt various techniques to streamline the false hot areas to reduce the high cost of unfruitful field exploration.

The geology of geothermal well is as confusing as exploring hydrocarbon deposition in some geographical regions. Geothermal wells found in Madrid between 1985-1990, show that it is usually a dependable reservoir in tertiary clastic host rocks at 1500-2000 m depths [6]. However, it was found that the ultra-deep geothermal horizons are within 3500-5000 m depth. At this point, the source and condensing temperatures are well above 160 oC and 65 oC, respectively. Significant pointers to the geothermal well discovery may occur synonymous with hydrocarbon exploration. For example, the sedimentary basin is usually the first geological pointer to hydrocarbon reservoirs in hydrocarbon exploration. Likewise, the significant geological features in geothermal well detection are synonymous with warm springs' geological features [7,8]. Shallow and medium depth geothermal wells are most times characterized by hydrothermal wells. The main geothermal well is located in the deep and ultra-deep seated geothermal environment. The popular technique for detecting geothermal wells is considering regions near active tectonic plate boundaries where volcanic activity has occurred, such as in Iceland, New Zealand, and the Philippines [9].

The geology of Nigeria is significant, and there are high prospects of discovering geothermal energy sources. Currently, the energy demands in Nigeria have risen high [10]. The primary sources of power (i.e., gas stations and hydroelectricity) in Nigeria may not be sufficient. The proposal for the nation to have main sources of energy across the geopolitical zones (Figure 1) would help reduce the high cost of transferring energy from one region to another. The geothermal energy source exploration is very important in the national energy drive because of the enormous energy

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accruable. Geothermal energy source (GES) exploration is very expensive using conventional techniques. Most conventional techniques are plagued with fundamental theoretical flaws [11]. These technical flaws have led to the frequent modification of its techniques when applied to various geological terrains.

The design, model, and optimization of ground heat exchangers depends on the undisturbed ground temperature (UGT), which is directly proportional to the subsurface layer's ground temperatures, which depend on the location's geology. Scientists believe that the thickness of the subsurface layer plays a vital role [12]. However, the geology and the components of the subsurface layer are vital for the thermal conservation and diffusivity of the ground. Over certain earth locations, the thermal inertia of the ground ensures the amplitude of changes in the ground temperature decreases with an increasing depth [13]. Several models have proved the relation between longwave and geothermal parameters. Some scientists have correlated UGT with meteorological parameters [14-15] and detailed models to show the advantage and disadvantages of UGT. Ultimately, the UGC is applied to projected to be essential for space heating via the use of heat pump systems (such as the ground-coupled heat pump systems (GCHPs)) to extract heat from the geothermal energy [16].

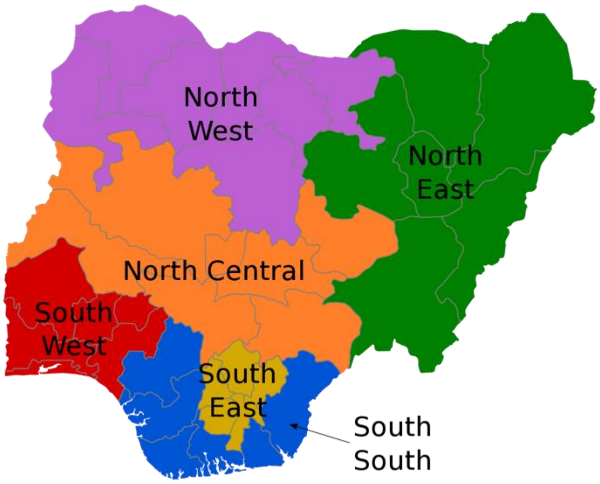


Figure 1. The geopolitical regions of Nigeria.

This study combines remote sensing and mathematical techniques for discovering geothermal wells and ground heat catchments. The limitation of this work is that the lithology is almost assumed to be equal over the same geological basin. The application of this work may be extended to the agricultural sector and planning for ground source heat pump systems.

2. Methodology

The different geology of Nigeria is presented in Figure 2. It has been discovered that the warm springs are located along the cretaceous rock (Figure 2). In this research, the satellite remote sensing technique was adopted. The satellite remote sensing technique (SRST) has shown high prospects for determining the geological features, hydrocarbon deposit, seepage, geothermal heat flux, ground heat flux, latent heat flux, etc. In this research, the ground heat flux was examined. Ground heat flux is an important component of the energy balance at the land surface, particularly over the relatively dry land surface and over a daily time scale. It is a reliable parameter that accounts for how the earth gives off and absorbs heat. The dataset was obtained from the NASA MERRA. The ground heat flux dataset for 1990-2017 was used for this study. Modified thermal equations were used to estimate geothermal temperatures in suspected GES in Nigeria.

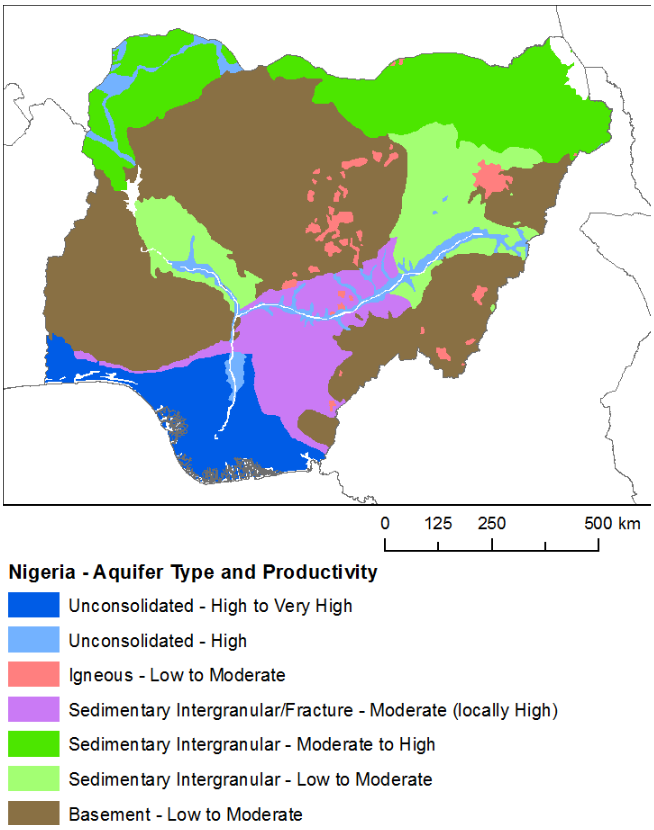


Figure 2. The geology of Nigeria.

The geothermal energy well stores heat in two major forms. The earth's surface acts as a very large collector of solar energy, where the energy radiated from the sun is stored below the earth's surface. Secondly, there is heat transferred from the belly of the earth's crust to the earth's surface. Therefore, one of the appropriate techniques to understand the heat variations in the aforementioned heat sources is the use of ground heat flux.
The power generation from this type of enhanced geothermal system is given as [17]:

$$E_w = \phi\left[\frac{h_w(\rho_i,\theta_i)}{v_w(\theta_i)} - \frac{h_w(\rho_f,\theta_f)}{v_w(\theta_f)}\right] = \left[\frac{h_{wi}}{v_{wi}} - \frac{h_{wf}}{v_{wf}}\right] \quad (1)$$

where h is the liquid enthalpy, i is the initial term, f is the final term, v is the liquid specific volume, p is reservoir pressures, ϕ is the porosity. The ground heat flux will give insight into the different enthalpy. Hence, the mathematical formula of ground heat flux is given as [18]:

$$H_G = -k\frac{\partial T}{\partial z} = \frac{\rho c \kappa A}{DRe\{1+i\}\exp(i\omega t)} = \rho c(\kappa\omega)^{0.5} A\cos(\omega t + \tfrac{\pi}{4}) \quad (2)$$

where T is the temperature of the ground (∘C); k is thermal diffusivity of the ground (m^2/s), z is the position coordinate, t is the time, ρ is the density of the medium, A is the amplitude of daily average temperature of the ground surface, ω is the frequency of temperature fluctuations.

The ground heat flux clearly shows the heat transfer and temperature distribution depends on the geological features (which includes rock conductivities). The conductivity is a composite rock (with grains arranged in parallel orientation (equation 3) and layered sequence perpendicular (equation 4) to the direction of heat flow) is given by [19]

$$K_p = n_1 K_1 + n_2 K_2 + n_3 K_3 + \cdots .... \quad (3)$$

$$\frac{1}{K_s} = \frac{n_1}{K_1} + \frac{n_2}{K_2} + \frac{n_3}{K_3} + \cdots ..... \quad (4)$$

Where K_p is the bulk parallel rock conductivity, n is the fractional volumes of mineral phases and K is the conductivities of minerals.

Hence, the sum of bulk series and parallel conductivities is given as [19]:

$$K_{ps} = \frac{1}{2}\left(K_p + K_s\right) \quad (5)$$

The modified geothermal temperature T(z) can be estimated under steady-state conditions as [20]:

$$T(z) = T_s + \frac{q_s}{k} z - \frac{\rho A}{2k} z^2 \quad (6)$$

where q_s is the ground heat flux, Ts is the surface temperature, A is the radioactive heat production, z is the depth, ρ density of medium and k is the thermal conductivity (3.138 $Wm^{-1o}C^{-1}$).

3. Results and Discussion

Figure 3a shows that high ground heat flux is observed in the northern region of Nigeria. However, a significant amount of ground heat flux was domiciled in the cretaceous rocks with possible extension into the neighboring Precambrian basement. This discovery may prove that the ground heat flux was more from within the earth's crust than the heat trapped by solar energy. Also, the warm spring locations were found to have high ground heat flux. Figure 3b shows a reversed ground heat flux pattern where southern Nigeria is found to have higher heat flux than northern Nigeria. This image shows the earth's crust ground heat signatures.

Figure 3c shows that the ground heat flux is diffuse with time from the region of higher ground heat flux signatures to regions of lower ground heat flux. It is noted that the geological cross-sectional profile of Nigeria allows for heat transfer with high convenience. Figure 3d showed a combination of the two sources of ground heat flux (GHF). Like Figure 3a, a significant amount of ground heat flux was found to be domiciled in the cretaceous rocks with possible extension into the neighboring Precambrian basement. Like Figure 3b, the GHF diffuses from the northern belt to the southern belt (Figure 3e). The GHF trend was found to repeat in Figures 3f -3i. Figures 3j and 3k had the same GHF trend but different patterns. The area of coverage was central Nigeria, which is mainly cretaceous. This result is the second GHF pattern in Nigeria. The GHF diffusion had the same pattern (Figure 3i). Figures 3l-3p had different GHF patterns that suggest sustained storage of solar energy. However, it is observed that the pattern is mainly in northern Nigeria. This result is the third GHF pattern in Nigeria. Figure 3q reveals the GHF diffusion towards the southern parts, while Figure 3r shows the higher GHF in the south. The geological possibility of this unique GHF pattern can be traced to the geological cross-section between Lagos and Port Harcourt (Figure 4) [21]. The profile is mainly Cenozoic, upper cretaceous, and lower cretaceous. This profile converges between Ondo and Delta states (Figure 1). Figures 3s-3x show the fourth GHF pattern where the GHF diffusion pattern is from south to northern Nigeria. Figures 3y-3ab show that the GHF activities are mainly in the central part of Nigeria. The central part includes Ekiti, Kogi, Benue, Nassarawa, and Taraba (Figure 1). Three of the identified warm spring lies in the Benue trough.

Therefore, with the GHF analysis of Nigeria, the first type of deep geothermal wells may be located in the following states, i.e., Plateau, Bauchi, Gombe, and Taraba. The second type of deep geothermal wells may be located in the following states i.e., Ekiti, Kogi, Benue, Nassarawa, and Taraba. Shallow geothermal wells mainly characterize the southern parts of Nigeria. Medium depth geothermal wells may be located in Sokoto, Zamfara, Kastina, Kwara, Oyo, and Jigawa.

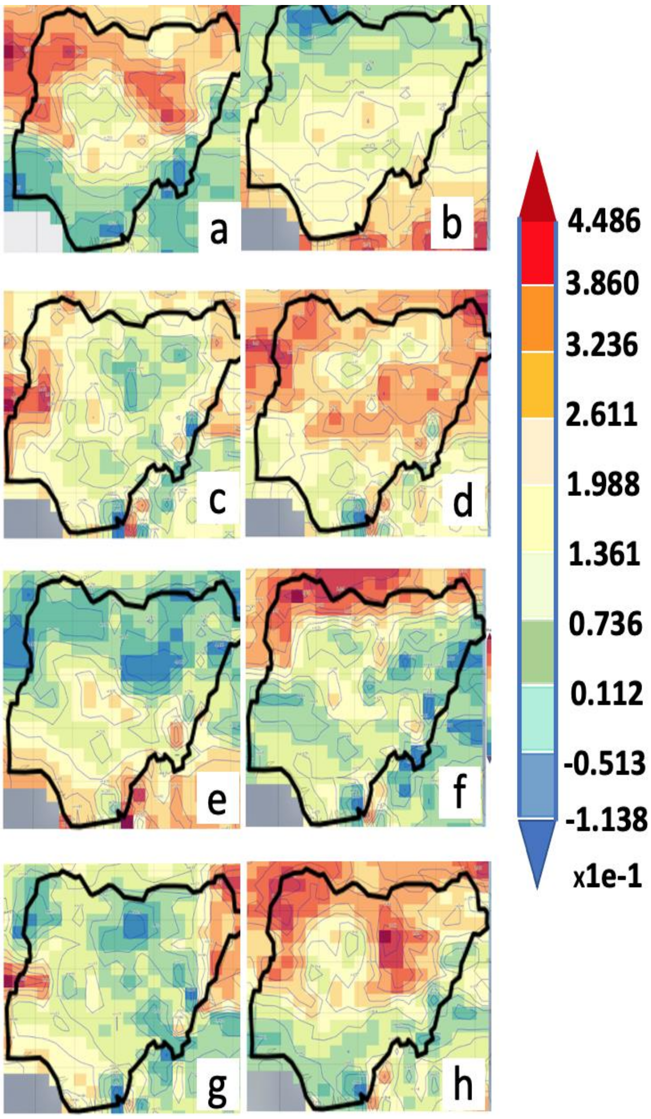
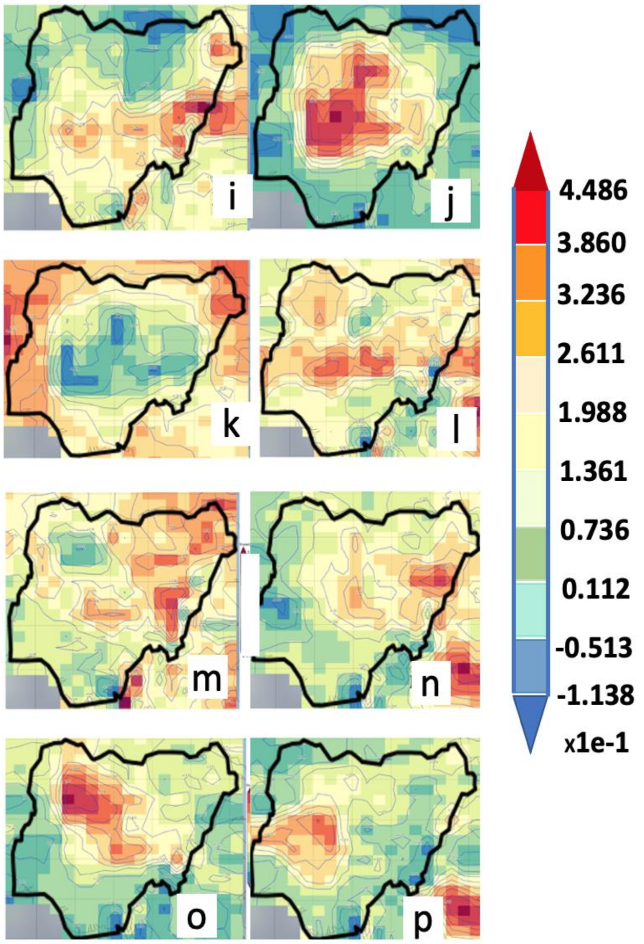
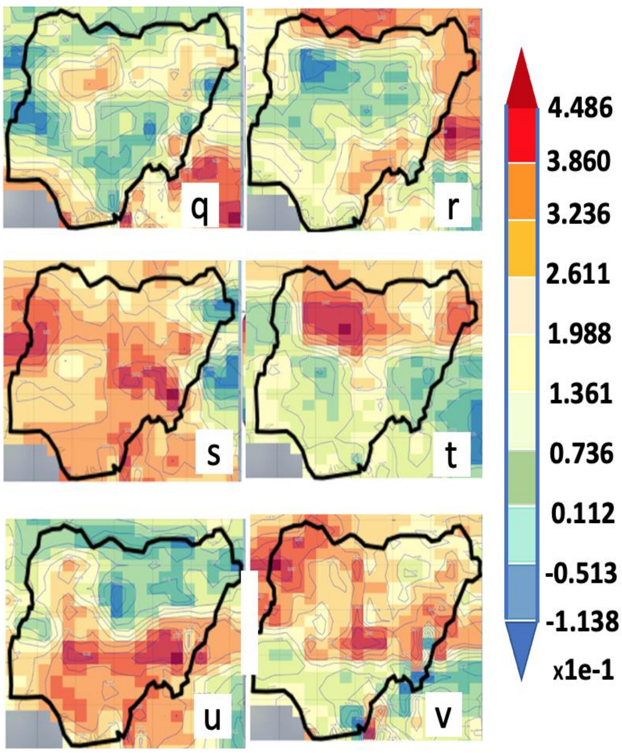
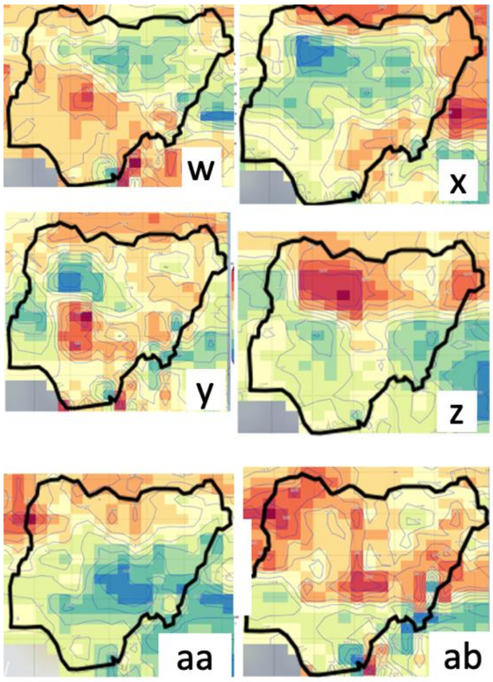


Figure 3. Ground heat flux analysis over Nigeria (1990-2017).







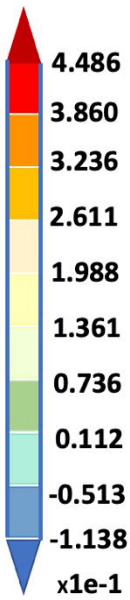


Figure 3. Ground heat flux analysis over Nigeria (1990-2017) (continue).

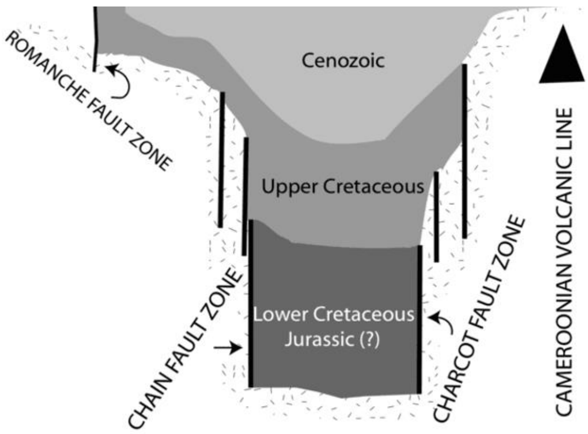


Figure 4. Geological cross-section of the lower south of Nigeria [21].

The geology of Nigeria is made up of four groups i.e., basement complex (Migmatite-Gneiss, schist belts, and pan-African Granitoids), Younger Granites (complexes of Triassic), sedimentary rocks and Tertiary volcanic rocks [22]. In most parts, the Schist belts are in-folded into the older Migmatite-Gneiss Complex in the southwestern part of Nigeria. Though, a small extension of the schist belts can be found in the southeastern part of Nigeria [23]. Also, schist belts of Nigeria are best developed in the northwest and southwestern portions of the country [24]. Hence, the connection of Ekiti and Ogun state in the league of geothermal wells in Nigeria. The Ogun geological profile includes porphyroblastic (Augen) gneiss, hornblende-biotite gneiss, banded gneiss and quartz schist [25]. Zamfara state has quartz-grain, very coarse-grained and fine-grained granitic rocks [26]. Sokoto state, which sits on the Sokoto basin (Figure 5), is characterized by: the Gundumi formation in the Lower Cretaceous; limestone in Kalambaina formation; clay beds in the Dange formation; fine gray sand of the Wurno formation; dark gray clay of the Taloka formations; and clay shale of the Dukamaje formation [27]. The Gundam formation has sedimentary rocks.

Generally, the Cretaceous and Tertiary formations in the Sokoto Basin are northeasterly and dip about 20 feet per mile to the northwest [27]. Bauchi and Jigawa states sit on the Chad basin (Figure 5). It is comprised of: shale and sandstone in the Bima formation; sandstones and bluish-black shale (calcareous) in the Gongila formation; Cretaceous sediments in the Kerri-Kerri formation [28]. The composition of the Kerri-Kerri formation includes coarse-grained sandstones, clayey grits, siltstones and clay stones. The Gombe sandstone is mainly folded at the end of the Cretaceous [29]. The geological of Kogi state is made up of migmatite and mica schist, granitic suite (i.e. fine- medium-grained granite, granodiorite and porphyritic granite) [28].

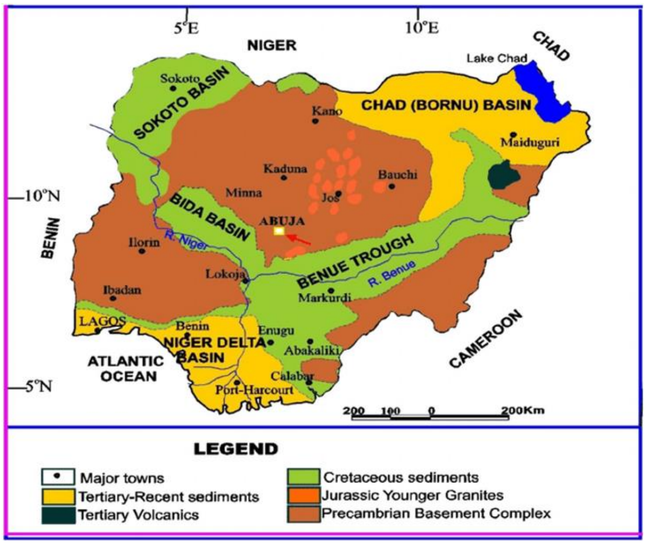


Figure 5. The basins and trough in Nigeria [30].

The rock formation in Kwara includes migmatitic gneiss, quartzite, quartz-mica schist, talc-tremolite schist, porphyroblastic granite, porphyritic granite, coarse-grained alkali granite, medium-grained granodiorite, medium-grained alkali granite, alkali syenite, pegmatite/aplite and vein quartz [21, 31]. Taraba and Benue state sits on the Benue Trough. It is characterized by: volcanic rocks (basalts suite, olivine basalt, and trachyte basalt); shallow subsurface structures (faults and dykes); and basaltic intrusions [32]. These formations support locations in the Benue trough (such as Benue and Taraba States) as places of potential deep geothermal wells. Via the connection in the Gongola sub-basin and the Benue trough (Figure 5), it is easy to understand the inclusion of Gombe state as a place of potential deep geothermal wells. Plateau state is reported to have rock formations such as alkaline feldspar granites, rhyolites, vom microgranite, biotite suite, shen hornblende – fayalite granite, minor gabbros and syenites [33, 34]. More so, this results from sub-volcanic intrusive complexes of ring dykes and related annular and cylindrical intrusions [35]. The basement complex in Nassarawa State has the following rock formations: Pelitic schist - amphibolite, granodiorite gneiss, plagioclase feldspar, quartz, muscovite, biotite, lepidolite and tourmaline [36].

The analysis of the geothermal temperature across the geological basins over Nigeria was calculated as presented in Figure 6. The sediment thickness was adopted in place of depth.

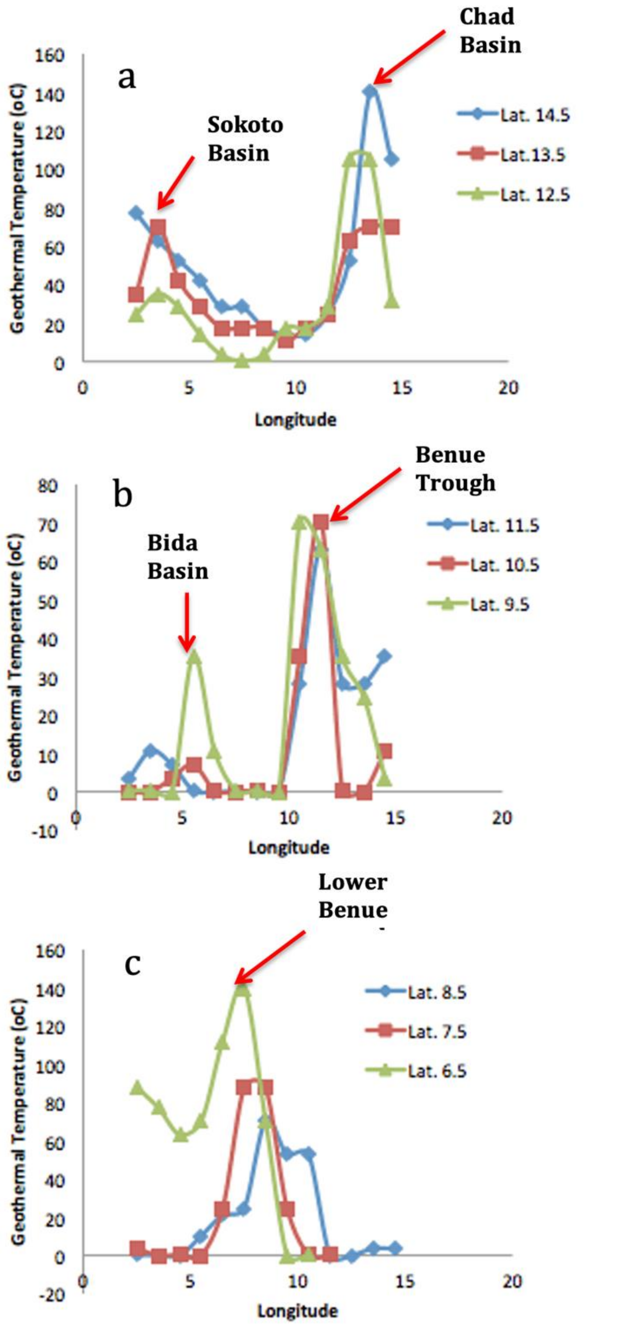


Figure 6. Analysis of geothermal temperature in Nigerian basin (a) Sokoto basin, (b) Bida basin, (c) Lower basin.

The sediment thicknesses over the Nigerian basin were obtained from the Marine Geoscience Data System. It is salient to note that the sediment thickness can be used to find the minimum geothermal temperature, not the exact temperature. This result is because the conductivities of the rock formations over the location are quite important to estimate the exact geothermal energies. In this calculation, q_s = 1.674, Ts =26.8°C, A =0.28, ρ =0.68 kg/m^3 and k = 1.24 Wm^{-1o}C^{-1}. Figure 6a affirmed that States in the Chad and Sokoto basins would have a geothermal well. However, States in the Chad basins are likely to have deep geothermal wells, while States in the Sokoto basin may have medium-depth geothermal wells. These results agree with the remote sensing results presented above. Figure 6b affirmed that States in the upper Benue trough and Bida basin would have geothermal wells. While Bida is likely to have medium-depth geothermal wells, the upper Benue trough would certainly have deep geothermal wells. These results agree with the remote sensing results presented above. Figure 6c affirmed that States in the Lower Benue trough would likely have deep and medium-depth geothermal wells. These results agree with the remote sensing results presented above.

4. Landsat imagery of surface geology

Ground temperature at a depth of 2 meters can be used to delineate relatively hot areas or thermally anomalous zones related to subsurface geothermal features [37]. Likewise, the Landsat imageries can be used to determine the hot areas or thermally anomalous zones as they are useful techniques in geology for interpretation of hydrothermal alteration, lithological discrimination, and tectonic setting [38-39]. The imagery was an integration of Landsat 7 (ETM +) and 8 (OLI) outcomes with an accuracy of 95%. The satellite images were obtained from the United States Geological Survey (USGS). Typically, Landsat 8 has 11 image bands taken 250 scenes a day, whereas Landsat 7 only has 8 image bands.

Five locations were considered out of the nine highlighted locations from the previous sections. Figure 7 is the LANDSAT imagery in parts of Gombe. The objective of this section was to determine the thermally anomalous zones related to subsurface geothermal features from the LANDSAT image slicing, as presented in Figures 7-11. In Gombe State, the red arrows identified the thermally anomalous zone at the northeast section of the map. Different authors postulate the various features of the thermally anomalous zones. Garibaldi et al. [40,41] proposed that the thermally anomalous zones lie along the fault and permeable zones. Mao and Li [42] proposed that the thermally anomalous zones lie along the uplift zones.

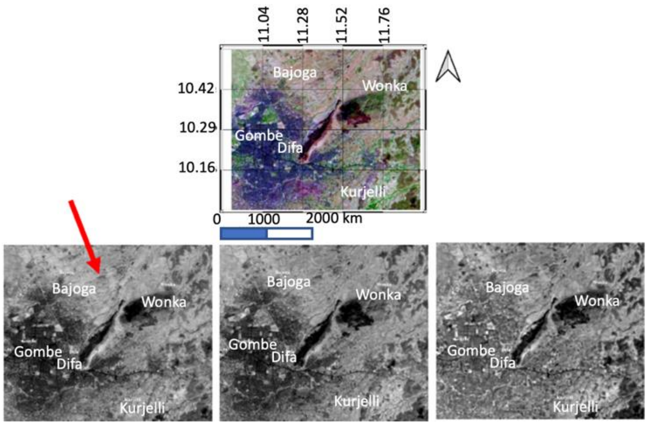


Figure 7. Slice of LANDSAT imagery in Gombe

In addition to the above, the determination of thermally anomalous zones in this section identifies isolated fault zones. Few of the isolated fault zone close to the uplift zone close to the uplift zone was identified as the potential thermally anomalous zones related to subsurface geothermal features. For example, the isolated fault zone was used to determine the thermally anomalous zone in Gombe, Bauchi, and Benue as presented in Figures 7-9.

The isolated fault zones close to uplift zones were used to identify the thermally anomalous zone in Ikogosi (Figure 11). This method was used to identify potential deep geothermal wells close to Pankshin in Plateau State. Figure 10 shows that the location has no significant thermally anomalous zone. In other words, a location may have potential mineral deposits but not have features of geothermal wells. Hence, this section has corroborated the findings highlighted in the previous sections.

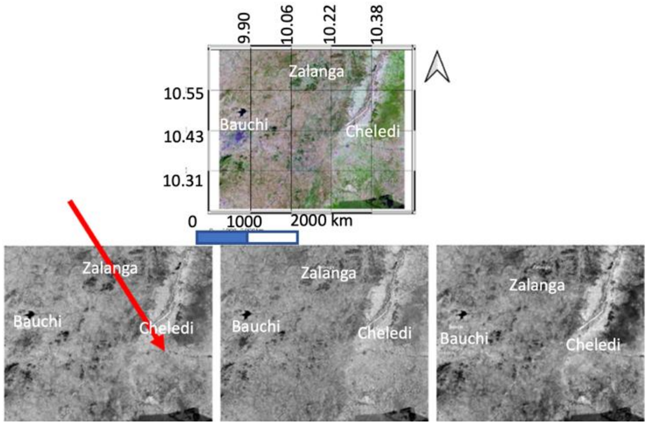


Figure 8. Slice of LANDSAT imagery in Bauchi

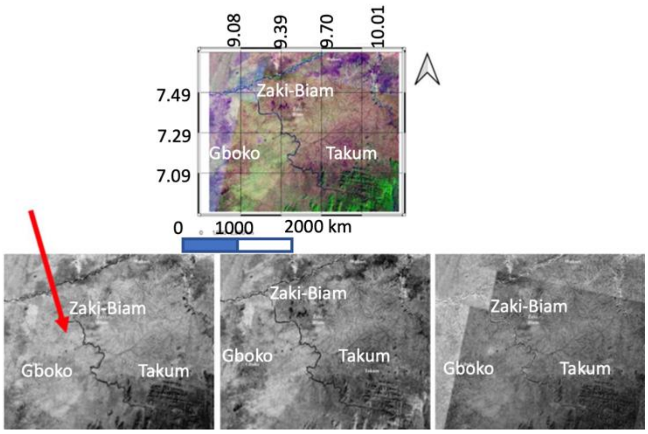


Figure 9. Slice of LANDSAT imagery in Benue

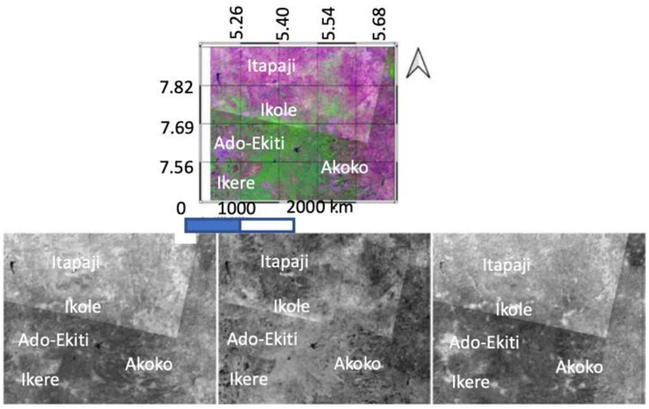


Figure 10. Slice of LANDSAT imagery in Ekiti

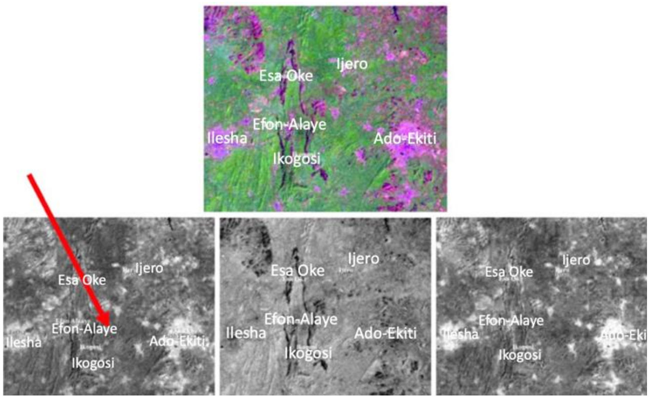


Figure 11. Slice of LANDSAT imagery in Ikogosi

In summary, the twenty-eight years ground heat flux dataset from the MERRA gave insight into surface thermal variability, which is not dependent on the thickness of the subsurface layer alone, but on the near-surface geology of the location. The thicknesses of the sediments in each location were obtained from the NASA satellite. The model was used for geothermal temperature expected at the sediment thicknesses along several transverses of the study location. This procedure helped classify prospective shallow, medium, and deep geothermal across the study location. The LANDSAT imagery was used to differentiate between medium and deep geothermal wells over the study location. The results from the study corroborate existing aeromagnetic over selected locations in the study area, such as Ikogosi [43], Sokoto Basin [44], and Wikki [45].

5. Conclusion

The research has revealed that the shallow, medium-depth and deep geothermal wells can be obtained in various locations in Nigeria. The deep geothermal wells may be located in Plateau, Bauchi, Gombe, Taraba, Ekiti, Kogi, Benue, Nassarawa and Taraba using remote sensing. It was revealed that the southern parts of Nigeria have lots of shallow geothermal wells. The remote sensing results also showed that the medium depth geothermal wells might be located in Sokoto, Zamfara, Kastina, Kwara, Oyo, and Jigawa States. Using the modified thermal equations, it was observed that deep geothermal wells could be found in the Chad Basin and Benue trough, while the medium-depth geothermal wells can be found in Sokoto basin, Bida basin and parts of the lower Benue trough. These results agree with the remote sensing results. It is recommended that further ground trotting exploration be carried out in the identified geographical locations.

Acknowledgements:
The author appreciates NASA for the satellite imagery and the Marine Geoscience Data System for the dataset.

Nomenclature

h	*liquid enthalpy,*
i	*initial term,*
f	*final term,*
v	*liquid specific volume,*
p	*reservoir pressures,*
ϕ	*porosity.*
T	*temperature of the ground (◦C)*
k	*thermal diffusivity of the ground (m^2/s)*
z	*position coordinate*
t	*time*
ρ	*density of the medium*
A	*amplitude of daily average temperature of the ground surface*
ω	*frequency of temperature fluctuations*
K_p	*bulk parallel rock conductivity*
n	*fractional volumes of mineral phases*
K	*conductivities of minerals*
$T(z)$	*modified geothermal temperature*
q_s	*ground heat flux*
Ts	*surface temperature*
A	*radioactive heat production*
z	*depth*
ρ	*density of medium*
k	*thermal conductivity (3.138 $Wm^{-1o}C^{-1}$)*

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