SCIENCE FORUM (JOURNAL OF PURE AND APPLIED SCIENCES) 22 (2022) 541 – 549

http://dx.doi.org/10.5455/sf.XXXXX

Science Forum (Journal of Pure and Applied Sciences)

journal homepage: www.atbuscienceforum.com

2D magnetotelluric inversion of basement complex rocks of Tangur for groundwater exploration, North Central Nigeria

Solomon Nehemiah Yusuf*, Isaac Godwin Wamtas, Lucky Osaro Imagbe, Ovye Musah Yohanna

Department of Geology, University of Jos, Jos, Nigeria

ABSTRACT

2D magnetotelluric surveying is becoming common in Nigeria for groundwater exploration because the equipment is cheaper compared to other geophysical tools and also very easy to use in terms of field application. The results are presented in 2D inversions, making it relatively easy to be interpreted in terms of electrical distribution and variations within the subsurface. Ten profiles of magnetotelluric data were conducted in Tangur and Environs, which is basically a basement terrain, with the aim of delineating areas for groundwater exploration. Tangur falls under the Sha-Kaleri complex whose geology includes granite Gneiss, biotite granite, basalt, and diorite dike. The geological structures include fractures, mafic-rich mineral dikes, and mafic enclaves. The profile results show that the study area has good groundwater potentials. The resistivity values of potential areas for groundwater exploration in Tangur from 2D magnetotelluric profiles are 115–215, 130–205, 123–245, 35–125, 90–240, and 155–245 Ωm, while the depths for drilling of boreholes are recommended to be 60–80, 0–80, 60–80, 180–200, and 180–200 m, respectively; these are based on the location of the profiles.

ARTICLE INFO

Article history:
Received 12 February 2022
Received in revised form 15 February 2022
Accepted 16 February 2022
Published 31 December 2022
Available online 31 December 2022

KEYWORDS

ADMT
2D Inversion
Groundwater
Magnetotelluric
Borehole and basement

1. Introduction

The study area is located in the Sha-Kaleri complex which is a part of the Jos Plateau Younger Granite province. This is characterized by high and low terrains (Daspan et al., 2007) and is unconformably underlain by the Precambrian basement complex. The basement complex here is made up of rock groups such as migmatite–gneiss complex, the schist belts, and the older granite, with some areas having volcanic rocks (Fatoye and Gideon, 2013).

Groundwater is one of the reliable sources of drinking water in Africa and most parts of the world, especially in areas with restricted or contaminated surface water sources (Issah et al., 2018). For any developmental activity, both surface and groundwater sources are the main components, depending on their quality and availability. In an area where surface water is not feasible for the desired activity, groundwater is the second alternative, if it has the anticipated amount and quality. During the dry season, Tangur and the surrounding communities have little or no surface water supply. The main goal of this study is to investigate probable groundwater zones in the community using the magnetotelluric method to improve supply.

The magnetotelluric method is selected for this study because of its ability to probe deep geologic structures and variations with respect to groundwater exploration. The magnetotelluric method has been used to study the deep aquifer system in Senegal to

*** Corresponding author** Solomon Nehemiah Yusuf yusufso@unijos.edu.ng Department of Geology, University of Jos, Jos, Nigeria.

understand the geometry of aquifers (Giroux et al., 1997). In recent years, 2D/3D inversion has been widely use to interpret the results of magnetotelluric soundings, in both shallow subsurface explorations and the crust and upper mantle studies (Slezak et al., 2019). Magnetotelluric is a very useful tool in imaging resistivity distribution of both shallow and deep geology of the subsurface (Alvarado, 2011).

Several magnetotellurics are developed around the world to study hydrothermal fluid, clays, and magnetic conduits (Ingham et al., 2009; Matsushima et al., 2001; Müller and Haak, 2004). Various researchers have also employed magnetotellurics for mineral and groundwater exploration (Bernard et al., 1990; Chave and Jones, 2012). Magnetotelluric has been successfully used in Obrzycho, Poland, to study the deep Cenozoic graben structure (Cygal et al., 2021).

2. Location of the Study Area

Tangur is a village in Bokkos local government area of Plateau State in North Central Nigeria and lies between Lat. N09°14'0"–N09°17'0" and Long. E09°0'0"–E09°4'0". It is bordered to the north by Bokkos central, Mushere to the south, Mbar to the west, and Mangu local government to the east and has a population of about 736,113 (2006 census). Villages such as Ngoksar, Lalem, and part of Mom lack potable water supply during the dry season.

The drainage system over the area and most of the crystalline environment is usually marked with the increase in many smaller river channels and streams (Moses et al., 2016). Some of the rivers found in Tangur area include rivers Mbah, Cheref, and Ramok, with other smaller streams around Matelem, Ngapur, Manau, Ngoksar, and Manduk. All the springs water discovered were found oozing out from the river channels and the streams. The drainage pattern of the study area is the dendritic drainage pattern.

3. Brief Geology of the Study Area

The most common rock type in the research region is granite gneiss, which is a metamorphic rock generated by the regional metamorphism of granite and contains biotite, mica, feldspar, quartz, hornblende, and muscovite. They revealed distinct foliation (bands of feldspar) in the area as shown in Figure 2. Pockets of biotite granite occurred in some parts of the study area such as Jwakring, part of Pyakmalu, Mom, and part of Ngapur. The biotite–granite is an igneous (plutonic) rock which is Proterozoic in age (Barr et al., 2003) with a gray to white color that has medium-grained sizes.

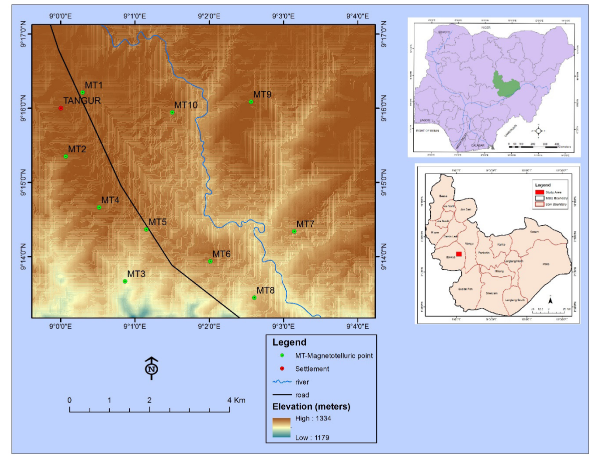

Figure 1. Location map of Tangur (National Center for Remote Sensing, Jos, Nigeria, 2021).

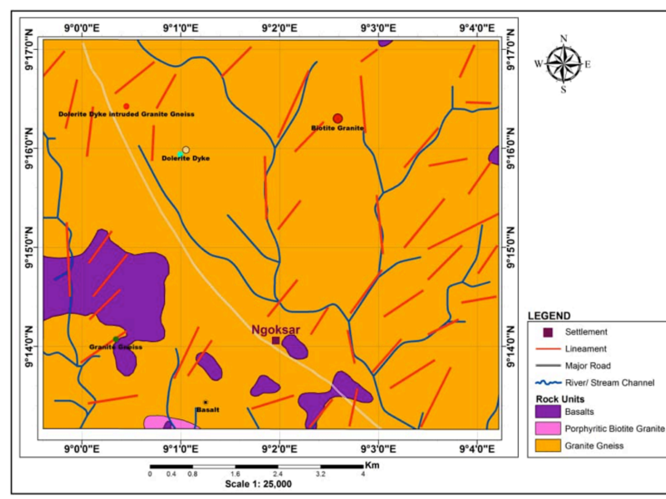

Figure 2. Geology of Tangur.

The mineralogical compositions of the biotite–granite include quartz, potassium feldspar, biotite, epidote, muscovite, and hornblende. Large outcrop of basaltic rocks occurred in the western part of Ngoksar with smaller outcrops aligning in the SE–NW direction, with few outcrops mapped at the edge of the study area. Scattered outcrops were also mapped in some parts of Ngapur, Lut-manau, and Kwantu-Manduk. The basaltic rock is an extrusive igneous rock with dark gray color fine-grained sizes, formed as a result of rapid cooling of low viscous lava that is rich in magnesium and iron that are exposed near the surface of the earth.

4. Structural Trend in Tangur and Environs

The Pan-African trend was overprinted by the Hercynian orogeny which imposed a more north-easterly regime on the Paleozoic and older rocks (Don and Daniel, 2016). One of the structural features left following the Pan-African orogeny was an elongate arch extending NW–SE from Tibisti mountains to the vicinity of Tripoli and evidence of arch is to be found in the separation of the Kufrah and Murzug basin, in the Qarqaf arch, and the area west of the Hun Graben which separates the Ghadamis basin from the Zazam depression (Don and Daniel, 2016).

The deformation or tectonic structures found within the study area include fractures; these structures gave room for the intrusion of veins and dykes; the structural trends were measured in the field during geological mapping, as shown in the rose plot in Figure 3. The joints and fracture pattern of the rocks in the study area show dominant trends of NW–SE and N–S, respectively. These trends conform to the general structural trends found within the basement complex rocks of Nigeria (Oyinloye, 2011).

The structures influenced the weathering pattern of the rocks within the study location, i.e., the mafic enclaves and dolerite dike weathered easily, which gives room for fluid storage. The quartz veins and dolerite dikes also trend in NW–SE and N–S direction, which suggests that they are epigenetic with the host rocks (Boyle, 1987). The geological structure such as joints and fractures control the movement and storage of groundwater in crystalline rocks. Hence, in terms of groundwater exploration, drilling at these points will produce good yield.

5. Materials and Methods

The magnetotelluric method allows the determination of an electric conductivity earth model from the measurements of natural variations of the surface electric (E) and magnetic field (H) over a wide frequency range (Vozoff, 1972). The magnetotelluric field that moves through the earth is dependent on the resistivity of the geologic materials and frequency of the equipment (Agyemang, 2020). Detailed explanation on magnetotelluric technique is found in Vozoff (1972), Kaufman and Keller (1981), and Berdichevsky et al. (1984). The inversion was carried out using Bostic's (1977) method, with the inversion generated and represented as continues resistivity progression versus depth. The instrument used is ADMT 600S-X; it is considered cheap but it has proven useful and effective in delineating the natural magnetotelluric field within the earth for mineral and groundwater study. ADMT 600S-X geophysical instrument comprises two electrodes, connecting cable and main frame with touch screen.

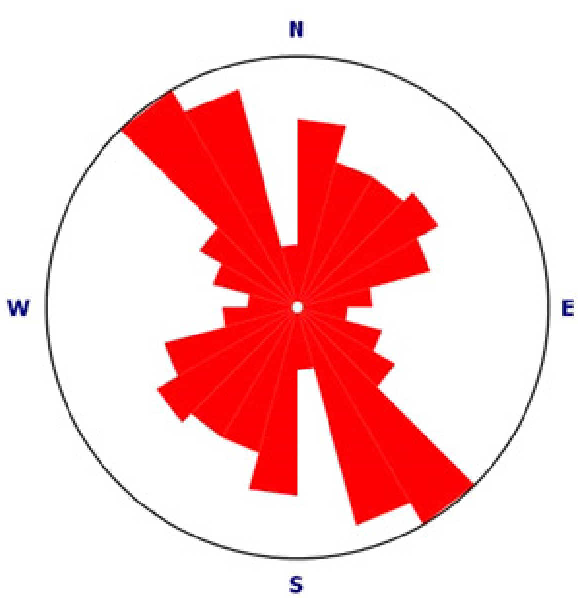

Figure 3. Rose plot of Tangur and Environs.

The Maxwell equation, as described in Equations (1)–(8), governs ground electromagnetic waves in the earth and soil. If we assume that the majority of subsurface geologic formations are nonmagnetic and uniformly conductive macroscopically, with no charge accumulation, the Maxwell equation can be simplified as follows:

$$\nabla^2 H + k^2 H = 0 \quad (1)$$

$$\nabla^2 E + k^2 E = 0 \quad (2)$$

where k is called the wave number (or propagation coefficient)

$$k = [\omega^2 \mu\varepsilon - \mathrm{i}\omega\mu\sigma]^{1/2} \quad (3)$$

Considering that the propagation coefficient k is a complex number, let $k = b + i\,a$

where "a" is called the phase coefficient and b is called the absorption coefficient.

In the electromagnetic frequency range measured by the ADMT series of natural electric field geophysical instruments (0.1 Hz to 5 kHz), the displacement current can usually be ignored, and k is further simplified as follows:

$$k = -\mathrm{i}\omega\mu\sigma \quad (4)$$

5.1. Wave group resistance and resistivity

A magnetic field with a change in the Helmholtz equation induces a changing electric field, and the magneto electric relationship as follows:

$$\frac{E}{H} = -\frac{\mathrm{i}\omega\rho}{k} \quad (5)$$

The surface impedance Z is defined as the ratio of the surface electric field and the horizontal component of the magnetic field. In the case of uniform earth, this impedance is independent of the polarization of the incident field and is related to the earth resistivity and the frequency of the electromagnetic field as follows:

$$Z = \frac{E}{H} = \sqrt{i\omega\mu\rho}^{\ i\pi/4} \qquad (6)$$

Equation (5) can be used to determine the resistivity of the earth as follows:

$$\rho = \frac{1}{5f}\left|\frac{E}{H}\right|^2 \qquad (7)$$

5.2. Skin depth

In nonmagnetic media, the skin depth formula is as follows:

$$\delta \approx 503\sqrt{\frac{\rho}{f}} \qquad (8)$$

It can be seen from the above equation that the penetration depth of electromagnetic waves is related to frequency and resistivity. The frequency is certain; the higher the resistivity, the greater the penetration depth, and the higher the resistivity, and the lower the frequency, the greater the penetration depth. Through multichannel simultaneous input measurement, large data with high-density measurements can be obtained, which breaks through the depth's limitation of traditional high-density electrical method and enables the maximum exploration depth. Two methods are involved in carrying out the measurement of the subsurface using this equipment and these are given below.

5.2.1. Method 1: Electrode measurement

The measuring points are at the midpoint of the MN electrode as shown in Figure 4.

5.2.2. Method 2: Wireless probe measurement

The measurement point of the wireless probe is at the midpoint of the wireless probe when the probe is continuously moved at 2-m intervals, as shown in Figure 5.

6. Results

The aim of the magnetotelluric survey is to ascertain the resistivity distribution of the surrounding rock materials to delineate potential groundwater sources. Low frequencies are generated and supplied into the sub-surface, and the resulting potential differences were measured and the data obtained are processed and presented as resistivity pseudosections (Teoh et al., 2018).

The results of all the magnetotelluric profiles conducted are presented as 2D images; Y-axis represents the depth and X-axis represents the distance on ground. The data were interpreted by comparing the geology of the area with electrical resistivity of earth materials. The color bar indicates the range of electrical resistivity values in the unit of ohm-meters; the color legend scale is logarithmic and consistent with contour intervals. Cool colors (i.e., blue) represent areas of low resistivity values, warm colors (i.e., red) represent areas of high resistivity values (Arjwech et al., 2020). The green, blue,

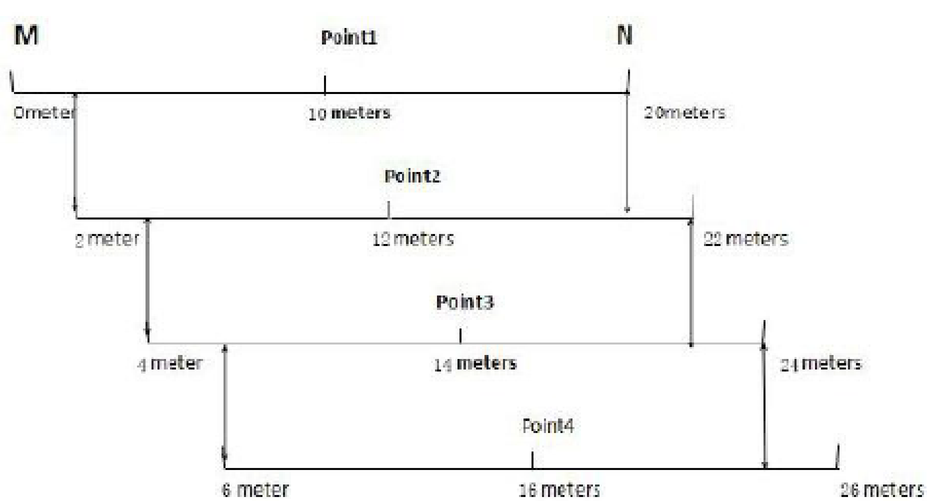

Figure 4. Electrode measurement (AIDU, 2020).

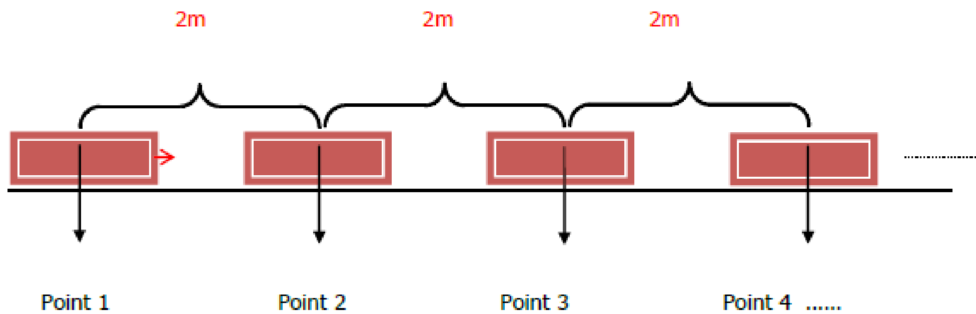

Figure 5. Wireless probe measurement (AIDU, 2020).

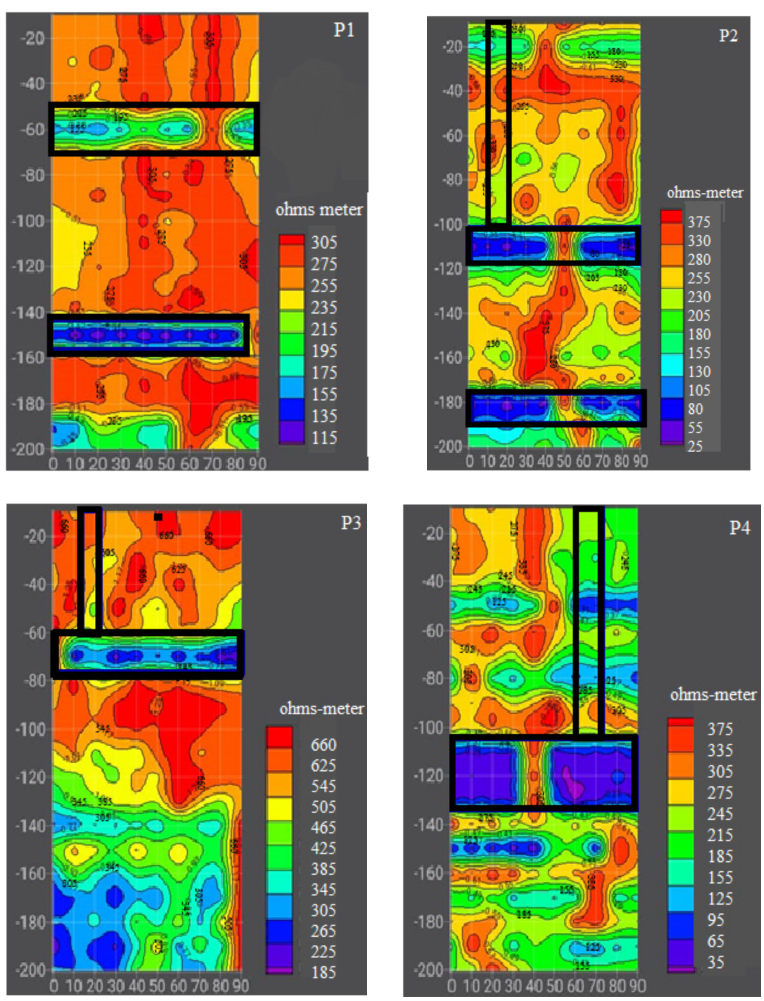

Figure 6. Magnetotelluric profiles P1, P2, P3, and P4.

and purple colors reveal lower resistivity areas that are conductive, and most of its resistivity values are <200 Ωm; light green to yellow color shows slightly weathered geologic materials and red color shows fresh basement.

In Figure 6, P1 shows the conductive layer from 55 to 65 m with a thin resistive fresh basement at point 70, with the values of 305 Ωm; the thick low resistive geologic materials at 140–160 m, with resistivity of 115 Ωm; and wide range of highly conductive materials were also delineated from 180 to 200 m, with resistivity of 195 Ωm. P2 shows thick conductive geologic materials at 0–30 m with resistivity of 180 Ωm which also has a thin layer of high resistive fresh basement at point 30 on the *X*-axis with resistivity of 375 Ωm. A depth of 100–120 m shows highly conductive geologic

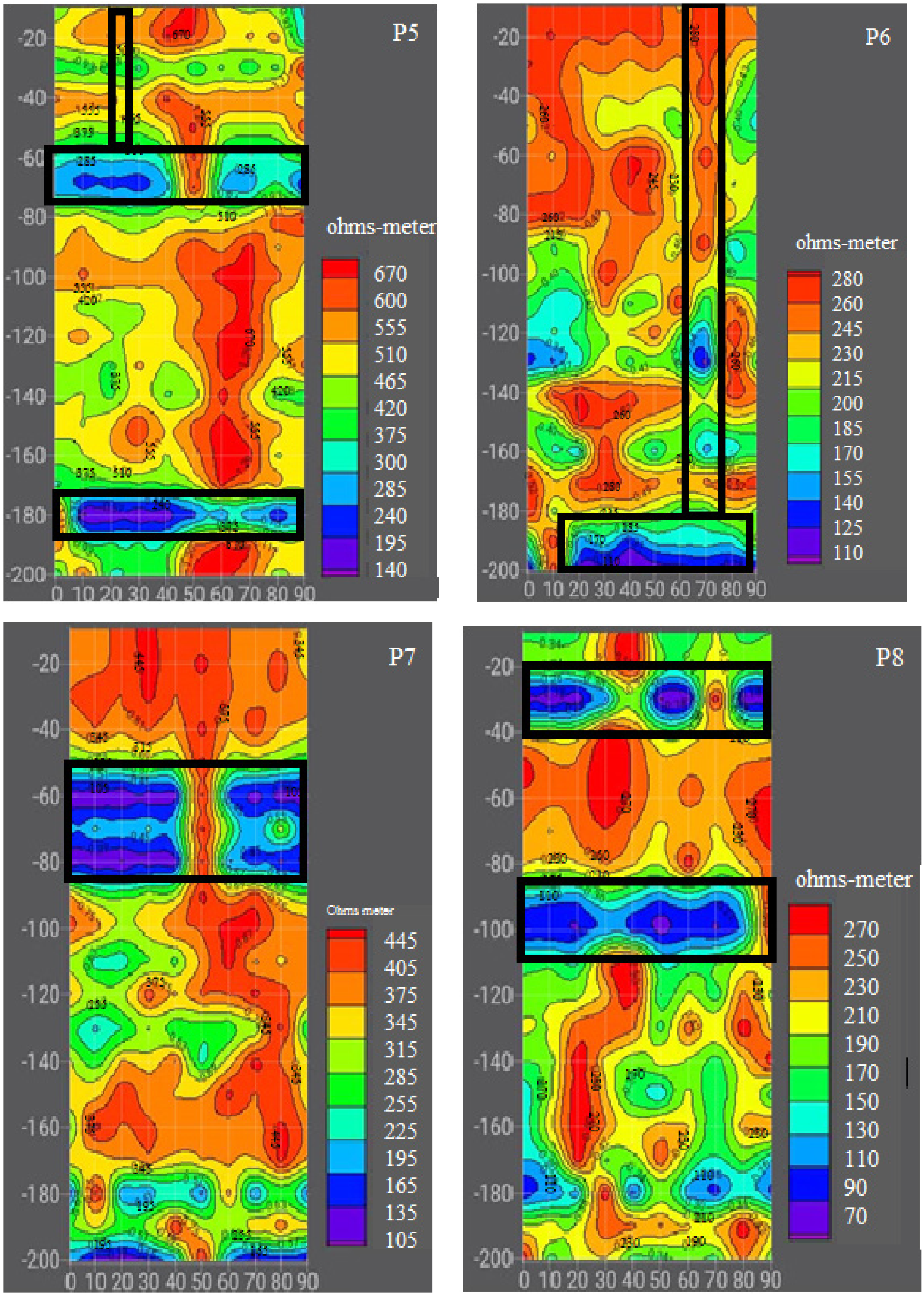

Figure 7. Magnetotelluric profiles P5, P6, P7, and P8.

formation with thin zones of high resistive material at 50, with resistivity of 375 Ωm. The profile also revealed another thick zone of low resistive geologic materials at a depth of 180–200 m, with resistivity of 55 Ωm. P3 shows conductive geologic materials at a depth of 60–80 m having 265 Ωm resistivity values.

The magnetotelluric profile P4 shows a narrow weathered zone with 155 Ωm from the depth of 40–60 and 0–85 m (185 Ωm) as indicated by the green colors. The thick zone of conductive geologic material at 100–140 m having resistivity of 65 Ωm suggest good groundwater source on this profile with pockets of

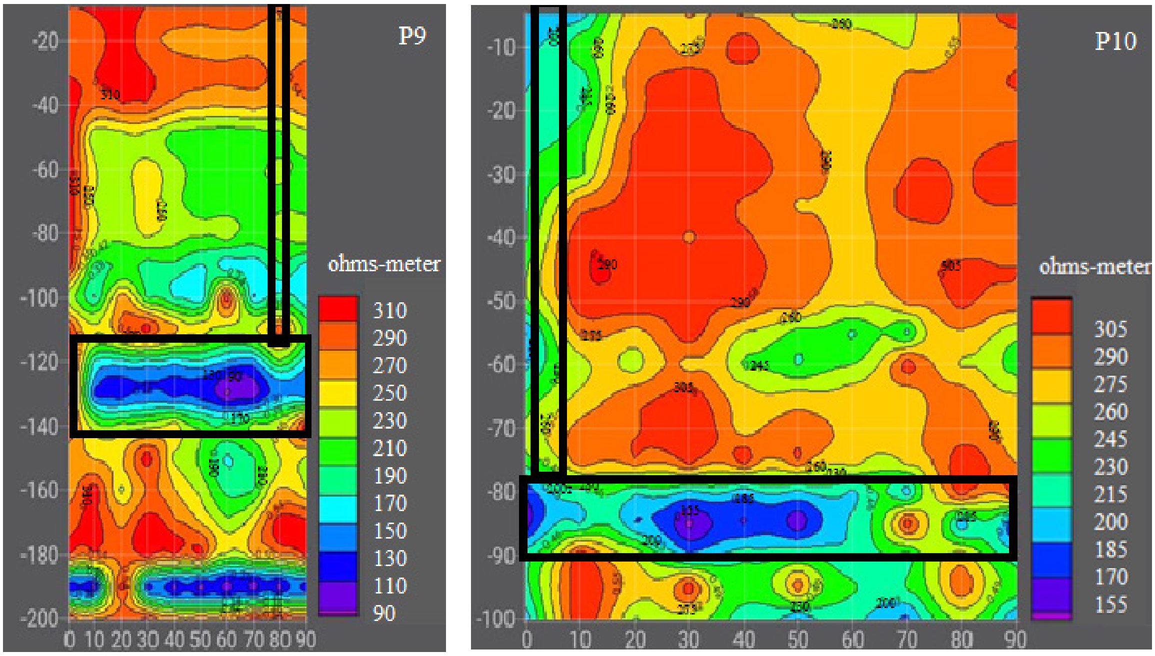

Figure 8. Magnetotelluric profiles P9 and P10.

narrow weathered granite are also seen at the bottom of the profile.

The profile shown in Figure 7 (P5) is characterized by conductive layers from 60 to 80 m with resistivity of 24 Ωm having thin layer of high resistive geologic materials at point 50 with 600 Ωm suggesting fresh basement; also, at the depth of 165–195 m it revealed conductive zones with patches of low resistive geologic materials of 195 Ωm. P6 shows low resistivity of 125 Ωm and high conductive geologic materials at 180–200 m with high resistive materials which outcrop on the surface and is indicated from 0 to 85 m with resistivity of 280 Ωm which could be fresh basement.

Profile P7 is characterized by wide and thick resistive rocks of 445 Ωm that is outcrop, followed by conductive material at the depth of 50–80 m with 105 Ωm resistivity value. The profile also displayed patches of conductive geologic materials at the depth of 100–145 m of 255 Ωm. Profile P8 shows a thick overburden from 0 to 20 m with resistivity value of 150 Ωm, followed by conductive geologic materials from 20 to 40 and 80 to 110 m with resistivity of 70–190 Ωm and a lot of patches of conductive materials at the bottom of the profile.

Figure 8 shows that P9 has a wide range of high resistivity of 310 Ωm, suggesting fresh granitic rocks. Weathered geologic materials were delineated from 40 to 110 m of 150 Ωm with a zone of highly conductive zone from 120 to 140 and 180 to 200 m with resistivity values of 70–185 Ωm. Profile P10 is characterized by highly resistive geologic materials from 0 to 78 m of 305 Ωm, which is followed by a weathered zone from 80 to 90 m of 155 Ωm.

7. Discussion

The dominant rock types in Tangur and Environs are granite gneiss, biotite granite with pockets of basaltic rocks, and dolerites occurring as dikes. The structural trends are dominant in the NW–SE direction which is a result of the Pan-African orogeny that resulted from the separation of the Kufrah and Murzug basin in the Qarqaf arch and the area west of the Hun Graben which separates the Ghadamis basin from the Zazam depression which resulted in an elongated arch extending NW–SE from Tibisti mountain to the vicinity of the Tripoli (Don and Daniel, 2016). The geologic structures include fractures, joints, dikes and patches of mafic enclaves. Fractures and joints are said to host and allow fluid movement dolerite, and mafic enclaves when weathered will create openings for fluid accumulation and movement. The result of magnetotelluric indicated by colored legend with blue to green colors indicates areas with lower resistivity values, light green to yellow indicates slightly weathered basement, and red colors indicate fresh basement (Loke, 2004).

The study area is characterized by resistive rocks that outcrops all over Tangur and Environs with resistivity ranging from 270 to 660 Ωm, suggesting that biotite granite is not exposed to secondary tectonic activities. Horizontal zones of conductive geologic materials with patches of low resistive formation were delineated and are referred to be potential points or areas for groundwater exploration.

The resistivity of potential areas in P1 range from 115 to 215 Ωm; P2 shows thick overburden weathered granite from 0 to 35 m, with 130–205 Ωm; weathered materials are known to enhance groundwater recharge in boreholes. Outcrop of biotite granite were delineated in profile P3 with resistivity values of 545–660 Ωm, followed by weathered/fractured basement located from 60 to 80 m, suggesting good area for groundwater exploration. Green color represents the possible weathering which occurs from 0 to 80 m in profile P4 with resistivity values of 123–245 Ωm with very low resistivity values of 35–125 Ωm located from 100 to 135 m.

The results of all the profiles shows clearly the advantage of low frequency equipment over current based in delineating deep groundwater sources in basement terrain. Profile P5 delineated potential groundwater area at 60–80 and 180–200 m with resistivity values ranging from 140 to 465 Ωm, while profile P6 shows deep groundwater sources at 180–200 m with resistivity of 110–200 Ωm agreeing with Okrah et al., (2012) study that resistivity greater than 800 Ωm in granitic environment can result to failed boreholes. P6 and P7 are characterized by areas with thick resistive overburden which are granite gneiss outcrop making groundwater drilling difficult, and if not carefully done will result in abortive boreholes (Yusuf et al., 2021). Profiles P9 and P10 revealed fresh granite gneiss out crop, followed by possible weathered/fractured basement with resistivity ranging from 90 to 240 and 155 to 245 Ωm.

8. Conclusion

Magnetotelluric equipment (ADMT 600S-X equipment) are relatively new in Nigeria; however, they are becoming increasingly common due to low cost and ease of field application. The magnetotelluric survey has proven useful in delineating deep-seated groundwater sources in the basement terrain in Tangur and Environs. The results of the surveys are positive for groundwater exploration, especially in rural areas where there are no or less interferences. This equipment is prone to interferences if used close to power lines and communication masks. Caution must be taken to achieve the desired result.

9. Acknowledgments

The authors are grateful to Department of Geology, University of Jos, for permission to use the ADMT 600S-X equipment, and also to our anonymous reviewers, the authors are grateful for the time taken out to review this paper.

References

Agyemang VO. Application of magneto-telluric geophysical technique in delineation of zones of high groundwater potential for borehole drilling in five communities in the Agona East District, Ghana. Appl Water Sci 2020; 10:1–6.

AIDU. ADMT 600S-X Manuel. 2020.

Alvarado DD. Magnetotelluric study of the Western Cordillera (Northern Chile), with a focus on Lascar volcano. Dissertation zur Erlangung des Doktorgrades, Naturwissenschaften am Fachbereich Geowissenschaften, Freien Universität Berlin, Berlin, Germany, 2011, 133 p.

Arjwech R, Sriwangpon P, Somchat K, Pondthai P, Everett M. Electrical resistivity tomography (ERT) data for clay mineral mapping. Data Brief 2020; 30:105494.

Barr S, White C, Miller B. Age and geochemistry of late Neoproterozoic and Early Cambrian igneous rocks in southern New Brunswick: similarities and contrasts. Atlantic Geol 2003; 39(1):55–73.

Berdichevsky MN, Zhdanov MS, Pyankova T. Advanced theory of deep geomagnetic sounding. Elsevier, Amsterdam, Netherlands, 1984, p 408.

Bernard J, Vachette C, Valla P. Deep groundwater survey with audiomagnetotelluric soundings. In SEG, 60th Annual International Exposition and Meeting, San Francisco, CA, Vol. 60, 1990, pp 528–31.

Bostick FX. A simple almost exact method of magnetotelluric analysis. In Workshop on Electrical Methods in Geothermal Exploration, US Geological Survey, Salt Lake City, UT, 1977, pp 174–83.

Boyle RW. Origin of epigenetic gold deposits—secretion theories. In: Gold, Springer, Boston, MA, pp 6–14, 1987; doi:10.1007/978-1-4613-1969

Chave A, Jones A. The magnetotelluric method, theory and practice. Cambridge University Press, Cambridge, UK, 2012.

Cygal A, Stefaniuk M, Kret A. Integrated magnetotelluric and seismic investigation of Cenozoic graben structure near Obrzycko, Poland. Acta Geophys 2021; 69:711–23.

Daspan RI, Yakubu JA, Lar UA. Geochemical characteristics of Gabroic intrusive bodies in the Sha- Kaleri Younger Granite complex, central Nigeria. Continental J Earth Sci 2007; 2:7–13.

Don H, Daniel CL. Structure, Pan Africa Orogeny. In: Petroleum geology of Libya, 2nd edition, Elsevier, Netherlands, p 227, 2016.

Fatoye FB, Gideon YB. Geology and mineral resources of the lower Benue Trough, Nigeria. Adv Appl Sci Res 2013; 4(6):21–8.

Giroux B, Chouteau M, Descloîtres M, Ritz M. Use of the magnetotelluric method in the study of the deep Maestrichtian aquifer in Senegal. J Appl Geophys 1997; 38:77–96.

Ingham MR, Bibby HM, Heise W, Jones KA, Cairns P, Dravitzki S, et al. A magnetotelluric study of Mount Ruapehu volcano, New Zealand. Geophys J Int 2009; 179:887–904.

Issah MM, Aning AA, Noye RM, Mainoo PA. Prospecting for groundwater using the continuous vertical electrical sounding method. Eur Sci J 2018; 14:67–85; doi:10.19044/esj.2018.v14n3p67

Kaufman AA, Keller GV. The magnetotelluric sounding method. In: Methods in geochemistry and geophysics, Elsevier, New York, NY, Vol. 15, p 595, 1981.

Loke MH. Tutorial: 2-D and 3-D electrical imaging surveys. Geotomo Software, Res2dinv 3.5 Software. 2004.

Matsushima N, Oshima H, Ogawa Y, Takakura S, Satoh H, Utsugi M, et al. Magma prospecting in Usu volcan, Hokkaido, Japan, using magnetotelluric soundings. J Volcanol Geothermal Res 2001; 109:263–77.

Moses AD, Unuevho CI, Oke SA, Okujagu DC. Structural and lithological reconnaissance studies of North Central Nigeria using Landsat Enhanced Thematic Mapper Plus and Shuttle Radar Topography Mission satellite imageries. Int J Sci Technol Res 2016; 5(12):133–9.

Müller A, Haak V. 3-D modeling of the deep electrical conductivity of Merapi volcano (Central Java): integrating magnetotellurics, induction vectors and the effects of steep topography. J Volcanol Geoth Res 2004; 138(3–4):205–22.

National Center for Remote Sensing, Jos, Nigeria (2021)

Okrah C, Danuor SK, Dapaah-Siakwan S. Groundwater exploration in granitic rock formation of Komenda/Edina/Eguafo/Abirem district using integrated geophysical techniques. J Ghana Sci Assoc 2012; 14(2):56–72.

Oyinloye AO. Geology and geotectonic setting of the basement complex rocks in South western Nigeria: implications on provenance and evolution. In: Earth and Environmental Sciences, 2011, pp 1–23; doi:10.5772/26990

Slezak K, Jozwiak W, Nowozynski K, Orynski S, Brasse H. 3-D studies of MT data in the Central Polish Basin: influence of inversion parameters, model space and transfer function selection. J Appl Geophys 2019; 161:26–36.

Teoh YJ, Bruka MA, Idris NM, Ismail NA, Muztaza NM. Subsurface investigation using 2D resistivity and ground penetration radar at Teluk Kumbar, Penang. J Phys Conf Ser 2018; 995:1–14; doi:10.1088/172

Vozoff K. The magnetotelluric method in the exploration of sedimentary basins. Geophysics 1972; 37:98–141.