Groundwater exploration by magnetotelluric method within the birimian rocks of mankessim, Ghana

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Received: 10 February 2021 / Accepted: 21 January 2022 / Published online: 7 February 2022
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Abstract

The Magnetotelluric (MT) geophysical method has successfully been applied in groundwater exploration within the Birimian rocks of Mankessim. The technique has provided information on the rocks and structural relationships within the investigative depth of up to 300 m for hydrogeological purposes. The method provides information on the aquiferous zone and the general depth of burial. The study revealed that the resistivity of the subsurface materials within the study area ranges from 0.1 Ωm to 4.0 Ωm . The study shows that the groundwater occurrence in the area is mainly controlled by fractured and weathered zones. It is highly possible to encounter groundwater at the saprock zone. This zone is fractured and weathered zones sandwiched by the overburden and the bedrock. The static water level of the study area is about 25 m. This shallow depth makes the groundwater resource prone to contamination through anthropogenic activities such as the application of agrochemicals and the use of pit latrine which are common practices in the study area. The MT method is effective in the exploration of groundwater within the sedimentary environment.

Keywords Magnetotelluric · Birimian rocks · Ghana · Groundwater · Exploration

Introduction

The increasing population growth, advances in technology in agriculture, mining, road construction, etc. are continuously increasing the water demand. This calls for effective groundwater resource development of which groundwater exploration and characterization play major roles. Therefore, there is the need for the invention and application of new geophysical techniques. In the last two decades, there has been great advancement in the application of geophysical tools in groundwater exploration. The geophysical method that has gained much popularity is the resistivity method which measures the resistivity of the ground and it is very useful in studying pore fluid salinity and effective porosity (Archie 1942). Even though the Electrical Geophysical Methods are commonly used in groundwater investigations, the current study aimed to apply the Magnetotelluric (MT) method in the searching for suitable points for drilling prolific boreholes for community water supply. This method

was chosen because the Electrical Tomography cannot achieve deeper targets and the Electrical Vertical Sounding cannot ensure complete and dense space coverage but the Magnetotelluric method can be used for great depths of investigation, good space sampling, as well as differentiate between salt-saturated water and freshwater layers. The use of this method in groundwater studies and other geoscience investigation is common globally as they are well documented in the literature (Tinlin et al. 1988; Brasse 1989; Bernard et al. 1990; Bartel 1991; Chouteau et al. 1994; Nichols et al. 1994; Bourgeois et al. 1994; Dennis et al. 2011; Chave and Jones 2012; Nittinger and Becken 2016; Amjadi et al. 2020; Muttaqien and Nurjaman 2021). MT is a passive induction-based electromagnetic method that uses the naturally occurring electromagnetic field in detecting resistivity variations within the earth's materials (Simpson and Bahr 2005). Archie's law shows the relationship between the porosity of rock materials and their electric conductivity which is very helpful in the application of MT in groundwater exploration especially in areas where groundwater occurrence depends on fractures and weathering (Archie 1942). The short periodic signal originates from global lightning activity, while the long periodic signal is produced from the fluctuations in the intensity of the solar wind. The released

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electromagnetic energy in discharge propagates over a large distance with slight attenuation in a wave-guide between the ionosphere and Earth's surface. When the energy travels through a far distance from the source it is a plane wave with a frequency range of about 10^{-5} – 10^5 Hz. According to Telford et al. (1990), the MT fields are capable of inducing telluric currents in the subsurface after penetrating through the earth's surface. This study aimed to assess the potential of the 2D MT method for the detection of fractures and weathered zones serving as groundwater reservoirs within the Birimian rocks in the study area.

Study area

The study area is located between latitudes $05^{\circ}15'45.108$ N & $05^{\circ}15'40.248$ N and longitudes $0^{\circ}58'46.488$ W & $0^{\circ}58'59.880$ W and geology is predominantly the Middle Precambrian Birimian and Tarkwaian Formations (Fig. 1). The Birimian formation contains metamorphosed volcanic and sedimentary rocks which have been folded, metamorphosed under the greenschist-facies condition, and invaded by granitoids during the Eburnean (Junner 1935; Kesse 1985; Leube et al. 1990). The structures such as folds, foliations, faults, and joints of the Birimian formation enhance the permeability for groundwater storage, and transmission in the rocks Junner (1935). The contact zone between the Birimian rocks and the intruded granitoids are highly sheared and show foliations oriented North–South. Quartz and pegmatite veins aligned parallel to the plane of shearing. The Birimian formation is made of isoclinally folded, steeply dipping, alternating phyllites, schistose greywackes, sheared conglomerates, slates, and argillaceous beds with some tuffaceous schist and lava. The

Dixcove granite (G2) consists of soda-rich hornblende, biotite granite, or granodiorites which grade into quartz diorite and hornblende diorite and are commonly tonalitic in composition intrudes into the Birimian metavolcanic. Rocks in the study area include greywackes, phyllites, slates, schists, tuffs, conglomerate, mudstone, siltstones, granite, and sandstones. Hence, common minerals in the area include orthoclase, plagioclase, quartz, biotite, muscovite, amphibole, hornblende, calcite, silica, and chlorite. The Eburnean granitoids contain well foliated magmatic, potash-rich rocks and come in the form of muscovite–biotite granite, granodiorites, porphyroblastic biotite gneiss, aplites, and pegmatites some of which are medium-grained (Kesse 1985; Leube et al. 1990). The Granitoids are characterized by the presence of many enclaves of schists and gneisses, which are generally associated with Birimian meta-sedimentary rocks and their internal structures, are always concordant with those of their host rocks (Taylor et al. 1992). The Tarkwaian Group contains different kinds of sandstones, conglomerates, argillites, and it is subdivided into four major units, which are, from the base to the top: the Kawere Group; the Banket Series; the Tarkwa Phyllite; and the Huni Sandstone (Griffis et al. 2002). The hydraulic properties of the Birimian and Tarkwaian Formations are enhanced by the extensive weathering, availability of quartz vein, and presence of buried river channel (Dickson and Benneh 1995; Kortatsi 1994; CSIR-WRI Database; 2007).

Fig. 1 Geological map of the study area (Modified after GSD 2009)

Magnetotelluric data acquisition and processing

Terrain assessment was done to select suitable points for the geophysical survey data collection. The static water level of the available hand-dug well was measured to be 25 m. Three profile lines of length 50 m, 50 m, and 100 m for profiles A, B, C, respectively, were selected at interline space of 25 m (Fig. 1). Data were taken at MT soundings stations along the profile lines at 5 m intervals using the GMS-06 Metronix Inc multichannel geophysical measurement system. The collected field data were processed and inverted using Mapros and ZondMT2D softwares to obtain the Edi file and subsurface resistivity model, respectively, at a frequency range of 32–288 Hz. The Fast Fourier Transform technique was applied to transform the MT time series data into apparent resistivity and phase-amplitude after noises on E and H time series were removed. Data of field coherencies greater than 0.7 and apparent resistivity that showed errors less than 10% were used for the investigation. Generation of the 2D resistivity subsurface structures from the Edi files was done using ZondMT2D software, and the output of the inversion is the profile earth subsurface structure which displays the resistivity model (ρ) (Ωm) as depth function Z (m) as seen in Fig. 2A, B, C.

Results and discussion

The 2D MT model reveals a conductive nature of the study area with varying resistivity values of 0.1–4.0 Ωm across the three profiles. The three traverses (A, B, C) showed the lowest resistivity values at depths 170–190 m & 260 m-below, 20–120 m & 160 m-below, and 20–120 m & 140 m-below, respectively. In general, the low resistivity nature of the subsurface materials can be explained with various subsurface mechanisms, such as the presence of fluids within interconnected pore spaces (Hyndman and Shearer 1989); fluids in high permeability zones associated with faults; and conductive mineral phases of interconnected graphite, sulfides, or oxides (Glover and Vine 1992; Pommier 2014). For example, the plagioclase in the Birimian rocks may have altered to clay minerals like illite, smectite, etc., and/or the developed primary/secondary porosity and permeability may have increased the conductivity anomaly due to the increased interconnected pore space in the bulk rock (Schill et al. 2010). According to Okrah et al. (2012), the Birimian formation contains laterite, clay, sandy-clay, and bedrocks which are made of either partly weathered or fresh phyllite and granite (Table 1). The presence of the clay material may account

for the general low resistivity of the subsurface materials within the study area. However, the areas of lowest resistivity values on the three profiles are located at a particular point of the study area at depths of 170–190 m & 260 m-below, 20–120 m & 160 m-below, and 20–120 m & 140 m-below, for profile A, B, and C, respectively. The point of lowest resistivity is the end of profile A around where profiles B and C began (Fig. 1). Hence, a localization of a conductive anomaly on a fractured zone could be established. Okrah et al. (2012) observed that both the Vertical Electric Sounding method and the bore-hole logs revealed the same aquiferous horizons within the range of 17.0–39.0 m (Table 2). This occurrence is common within the Birimian as the structural features such as faults, folds, foliations, and joints enhance the permeability for groundwater, storage, and transmission in the rocks (Junner 1935). Also, the observation of the lowest resistivity value at a particular locality from 20 to 300 m deep revealed the presence of possible contact zones between the Birimian rocks and granitoids which also promote the occurrence of groundwater within the Birimian (Abouchami 1990). The mode of groundwater occurrence is also linked with the nature and thickness of the decomposed zone, rock fracture, joints, quartz veins, and pegmatites (Yidana et al. 2014). Most of the quartz veins and pegmatites are fractured and to some extent brecciated as a result of brittle deformation as a consequence of Proterozoic Eburnean orogenic activities that affected them (Kesse 1985). The aquiferous zone of the Birimian rocks is the lower part of the saprolite and the upper part of the saprock which usually complement each other in terms of permeability and storage (Junner 1935; Dapaah-Siakwan and Gyau-Boakye 2000; Carrier et al. 2008). Coffey (2007) noted that the aquifers of the Birimian formation have limited areal extent, low storage capacities, an average transmissivity of 2.98 m^2/d , static water level range of 1.7–23.3 m with a mean of 9.16 m, while the observed static water level of available hand-dug well in this study was 25 m which agrees with the observation made by WRI (1990).

Conclusion

The Magnetotelluric (MT) geophysical method has successfully been applied in groundwater exploration within the Birimian rocks of Mankessim. The technique has provided information on the rocks and structural relationships within the investigative depth of up to 300 m for hydrogeological purposes. The method provides information on the aquiferous zone and the general depth of burial. The study revealed that the resistivity of the subsurface materials within the study area ranges from 0.1 Ωm to 4.0 Ωm . The study shows that the

Fig. 2 2D-Apparent Geo-Electrical Resistivity Pseudo-sections of the surface at the study area underlain by the Birimian rocks (A, B, C)

Table 1 Correlating lithology deduced from geophysics with the drilling results (Okrah et al. 2012)

Drilling log		Geophysics		
Lithology	Thickness (m)	Resistivity (Ω m)	Thickness	layer
Sandy-clay and gravel	0–2	147.7	2.7	1
Sandy-clay	2–10			2
Sandy-clay and gravel	10–18	286.8	15.9	3
Rusty weathered phyllite	18–38	57.7		
Weathered granite	27–33	–	–	–
Fresh granite	33–51			

Table 2 Comparison between drilling and geophysical results (Okrah et al. 2012)

Community	VES Point	Aquifer horizon (m)	
		Geophysical interpretation (estimated)	Borehole drilling
Buabinso	B30	40.0–50.0	25.0–36.0
Buabinso	C100	20.0–40.0	32.0–39.0
Congo No.1	B80	15.0–40.0	17.0–23.0
Zion No.1	A40	40.0–60.0	31.0–40.0
Achiase	B100	10.4–extended	20.0–38.0

groundwater occurrence in the area is mainly controlled by fractured and weathered zones. It is highly possible to encounter groundwater at the saprock zone. This zone is fractured and weathered zones sandwiched by the overburden and the bedrock. The static water level of the study area is about 25 m. This shallow depth makes the groundwater resource prone to contamination through anthropogenic activities such as the application of agrochemicals and the use of pit latrine which are common practices in the study area. The MT method is effective in the exploration of groundwater within the sedimentary environment. The method is effective and relatively cheaper in investigating great depths with dense space sampling as compared to deep electrical sounding even though it is very sensitive to the surface and urban noises due to the level of urbanization of the study area.

Funding This study was funded by the author.

Declarations

Conflict of interest The author declares that he has no conflict of interest.

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