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ORIGINAL PAPER-EXPLORATION GEOPHYSICS

Geologic mapping and basement–sediment contact delineation along Profile X, Igarra–Auchi area, Southern Nigeria using ground magnetic and electromagnetic methods

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Abstract

Outcrop mapping as well as electromagnetic and ground magnetic surveys was carried out within Auchi and Igarra localities in order to attempt an interpretation of the geology of the areas and to delineate the boundary between basement and sedimentary terrains. Geologic mapping was done by collecting samples of outcrops at five different locations within the areas. Three lithofacies were identified within Auchi area and they are the basal shale unit, tabular cross-bedded sandstone unit and ferruginized sandstone unit. The pebbly shale is greyish black in colour; the cross-bedded sandstone unit is greyish white, coarse-grained at the base and finer at the top with pockets of clay, while the ferruginized sandstone is dark red. Rocks of the Precambrian basement complex underlie Igarra area. The area is underlain by metasediments that have been intruded by igneous rocks. Results show the presence of three major groups of igneous and metamorphic rocks within the area, and they are the migmatite–gneiss complex, metasediments and porphyritic granites. The electromagnetic and ground magnetic data acquired along Profile X located along Auchi–Igarra–Ibillo road were processed using Microsoft Excel Software and the resulting plots delineated areas with lower electrical conductivities and higher magnetic susceptibilities, as well as areas with higher electrical conductivities and lower magnetic susceptibilities. The areas with lower electrical conductivities and higher magnetic susceptibilities are interpreted to be underlain by basement rocks, while the areas with higher electrical conductivities and lower magnetic susceptibilities are underlain by sedimentary rocks. The plots also delineated the most likely basement–sedimentary boundary in the area.

Keywords Geologic mapping · Basement–sediment boundary · Electromagnetic method · Electrical conductivity · Magnetic susceptibility

Introduction

The Auchi/Igarra area of Edo State situated within the southern region of Nigeria is an area that is geologically significant. Its geologic significance stems from the fact that Auchi lies within the western part of Anambra Basin which is located in the Lower Benue Trough and as such is underlain by rocks of purely sedimentary origin, while Igarra area is an area underlain by rocks of the Precambrian basement, the area consists of metasediments intruded by Pan-African igneous rocks (Egbuniwe and Ocan 2009).

Several authors including Umeji and Nwajide (2007), Adekoya et al. (2011) have studied the sediments of Auchi area using methods like geologic mapping, textural and mineralogical characterization and diagenetic studies among others. The makeup, structural elements and nature of the

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Precambrian basement rocks underlying Igarra area have also been studied by authors including Egbuniwe and Ocan (2009), Odeyemi and Rahaman (1992) and Oluseyi (2006). None of these authors was, however, able to delineate and establish the approximate contact or boundary between the basement terrain of Igarra area and the sedimentary environment of Auchi area.

The methods of investigation in this study involved field geologic mapping, electromagnetic survey using the very low-frequency (VLF) method and ground magnetic survey. Field geologic mapping is a method which entails studying rocks and geologic structures where they are best exposed and most easily interpreted. Electromagnetic method, on the other hand, is a geophysical survey technique that applies the principle of electromagnetic induction to measure the electrical conductivity of the subsurface (Kearey et al. 2002). The magnetic method is a geophysical survey technique which is used to investigate subsurface geology based on anomalies in the Earth's magnetic field originating from the magnetic properties of the underlying rocks (Kearey et al. 2002). The electromagnetic method and the magnetic method are the most important and commonly used technique for studying the electrical conductivity and magnetic susceptibility of underlying rocks. Field geologic mapping of outcrops in this area will validate the fact that Auchi area is underlain by rocks of purely sedimentary origin and Igarra area is underlain by rocks of the Precambrian basement. Delineating the boundary between these geologic terrains by studying the electrical and magnetic properties of the underlying materials will enable solid mineral miners and

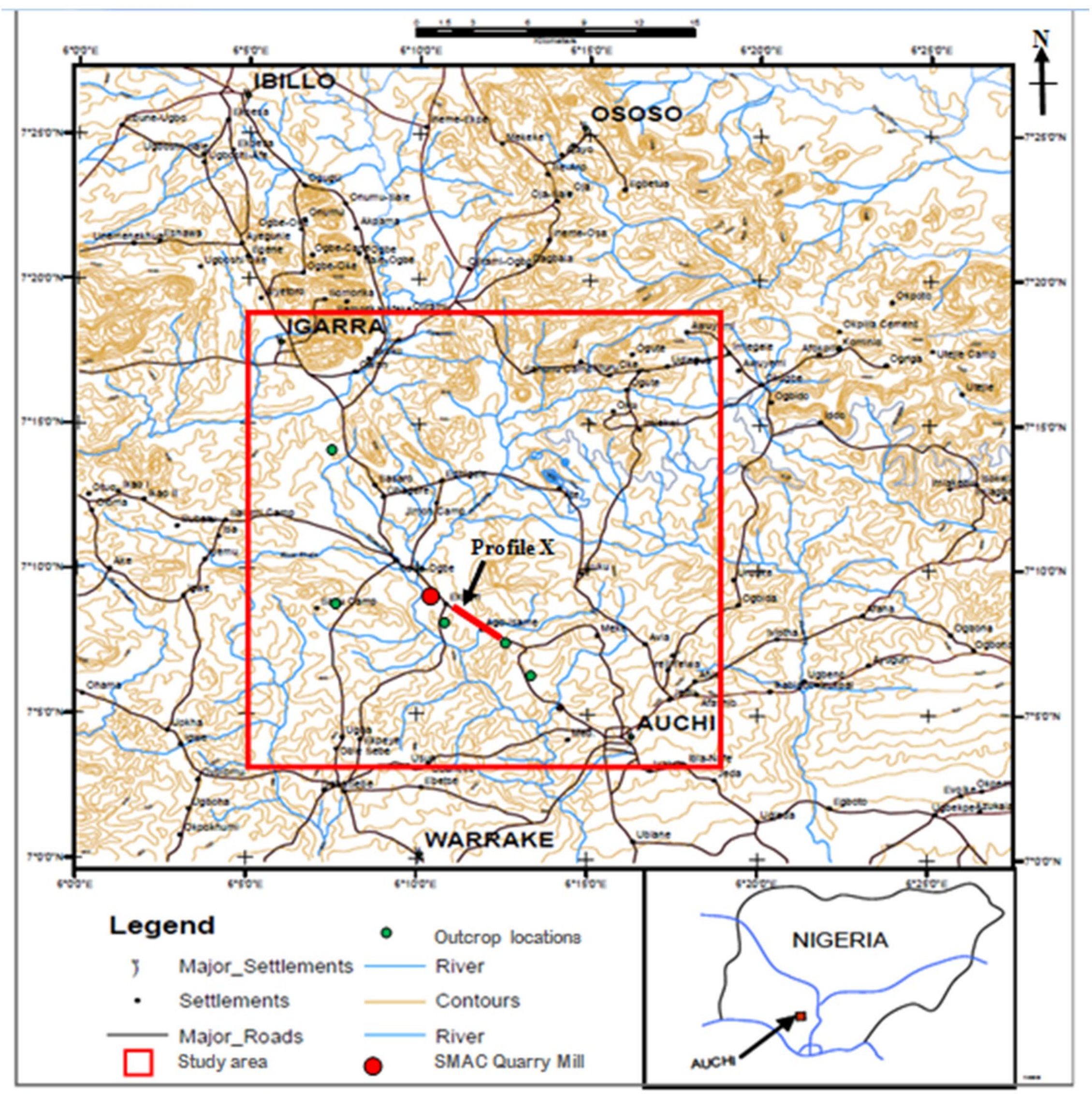

Fig. 1 Location map showing the study area, including outcrop locations and profile X (Modified from Authors' extract of Auchi and environs (2012))

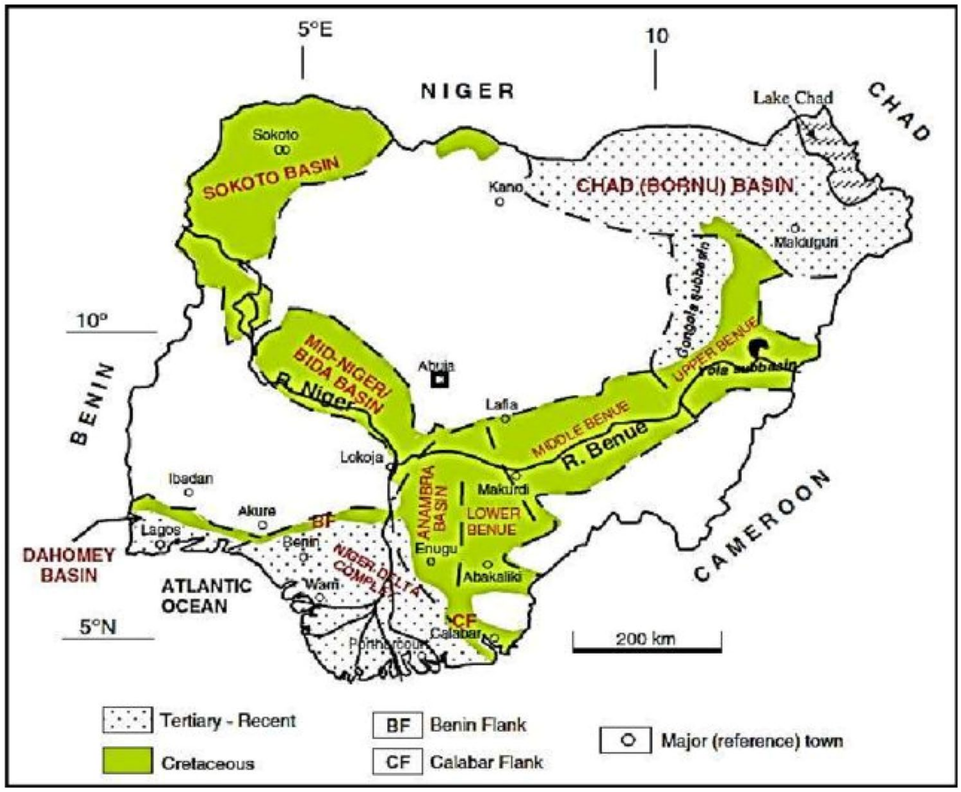

Fig.2 Sedimentary basins of Nigeria (after Obaje 2009)

geologists involved in quarrying activities within Igarra area to have a good knowledge of the termination point of basement environment in the area. Knowledge of the boundary between these two terrains will also serve as a guide for drilling activities within these environments.

This work therefore presents a detailed account of the electrical conductivities and magnetic susceptibilities of the rocks underlying Auchi and Igarra areas leading to a better delineation of the boundary between the sedimentary and basement environments.

Geology of the area

Auchi and Igarra area, situated in Edo State Southern Nigeria, lies within latitude 7°04′00″N and Longitude 6°16′00″E. Figure 1 shows the location map of the study area.

Auchi

Auchi area is located within the western portion of Anambra Basin. The shape of this basin is nearly triangular as shown in Fig. 3 and covers an area of about 3000 km^2 with a sedimentary pile of approximate thickness of 9 km (Olubayo 2016; Iheanacho 2016). This basin is situated west of the lower Benue Trough as shown in Fig. 2 and according to Obaje (2009); it forms part of the Lower Benue Trough that contains sediments of Campanian–Maastrichtian to Eocene ages. Three lithofacies belonging to two different lithostratigraphic units are recognized in Auchi area, namely shale unit overlain by cross-bedded, burrowed sandstone which is then overlain by ferruginized sandstone (Adekoya et al. 2011). The shale unit is said to likely belong to Mamu Formation while the sandstone units are most likely the extension of Ajali Formation (Geologic map of Nigeria, GSN 1994). The depositional environment of the shale is believed to be shallow marine while that of the sandstone units is fluvio-deltaic (Nwajide 1990). According to Ilegieuno et al. 2020, the sediments of Auchi area are fine- to coarse-grained and also poorly to moderately sorted.

Figure 2 shows the sedimentary basins of Nigeria after Obaje (2009), Fig. 3 shows the geologic map of Anambra Basin indicating the extension of Ajali sandstone within Auchi environs while Fig. 4 shows the stratigraphy and likely depositional environment of Anambra Basin modified from Tijani et al. (2010).

Igarra

Precambrian basement rocks, mainly metasediments intruded by igneous rocks of mostly pan-African age, underlie the entire Igarra area (Egbuniwe and Ocan 2009). According to Egbuniwe and Ocan (2009), this area is characterized by structural complexity due mainly to the different

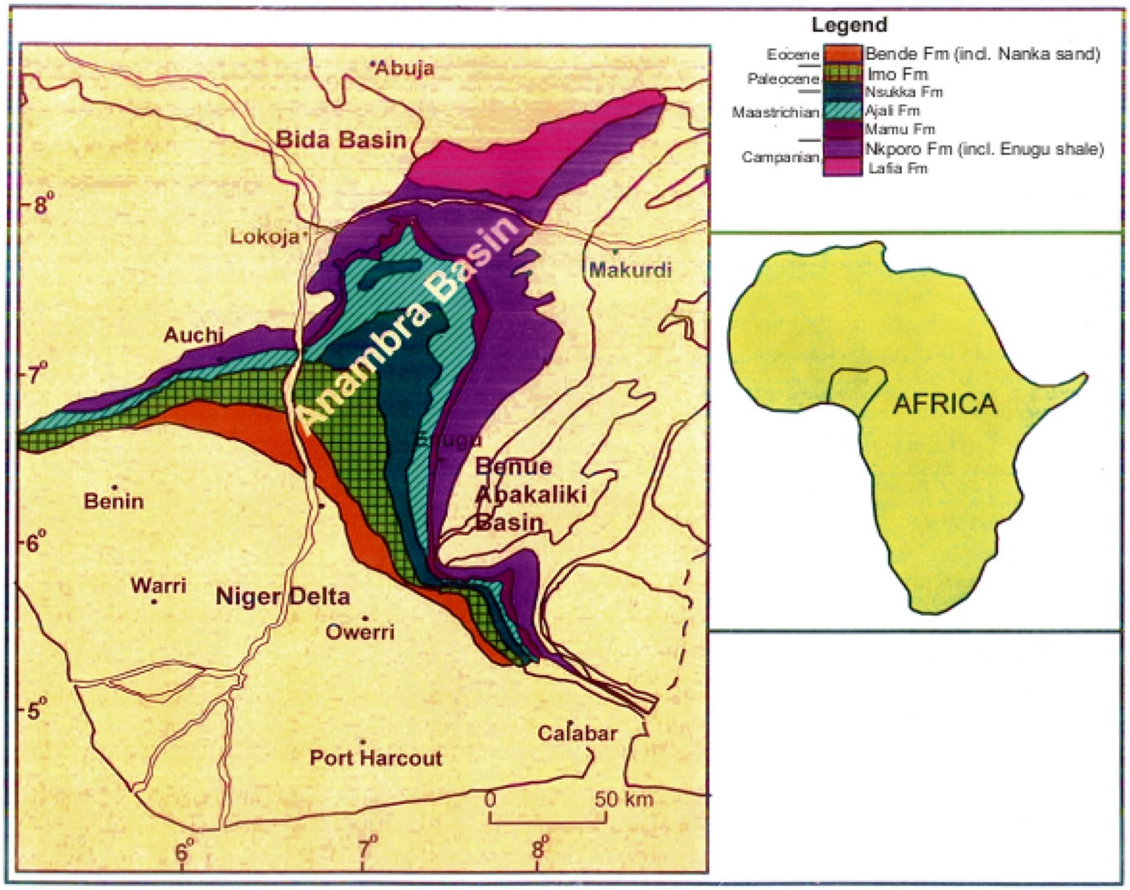

Fig.3 Geologic map of Anambra Basin showing the extension of Ajali sandstone within Auchi environs (Drawn from Geologic map of Nigeria, GSN 1994)

deformation components, including translation, rotation and strain, which produced structures during the Pan-African orogeny.

Underlying this area are metamorphic and igneous rocks classified into three major groups by Odeyemi and Rahaman (1992), namely the migmatite–gneiss complex, a sequence of upper Proterozoic metasediments and syn-to late-tectonic porphyritic granites shown in Fig. 5.

Granodiorites and syenites also exist in this area (Odeyemi and Rahaman 1992). From extensive study of the rocks of Igarra area, Odeyemi and Rahaman (1992) reported the existence of a discordance in structure between the older migmatite and both metasediment and older granite. This was due to the fact that most structural elements including folds and lineaments existing in this area have a common central axis with a dominant axis trending NW–SE in the metasediments and the older granites while the major structural element in the older migmatite trends E–W. This implies that there is no uniformity in the trend of structural elements in the rocks of this area. Marble, calc-gneiss, metaconglomerate, granites, pure quartz and kaolin occur in large quantities at different localities within Igarra area Oluseyi (2006). Figure 6 shows the geologic map of Igarra area after Anifowose et al. (2006).

Materials and methods

Field geologic mapping

The field geologic mapping covered a total of five localities within Auchi and Igarra areas from where samples were taken and examined. The materials used for this study include the Brunton Compass used to determine the direction of dip and strike of beds, sledge hammer to pick rock samples where they outcrop, hand lens to ascertain whether there are minerals within the rock, camera used for photographs and a small field knife for scratching the rock. At

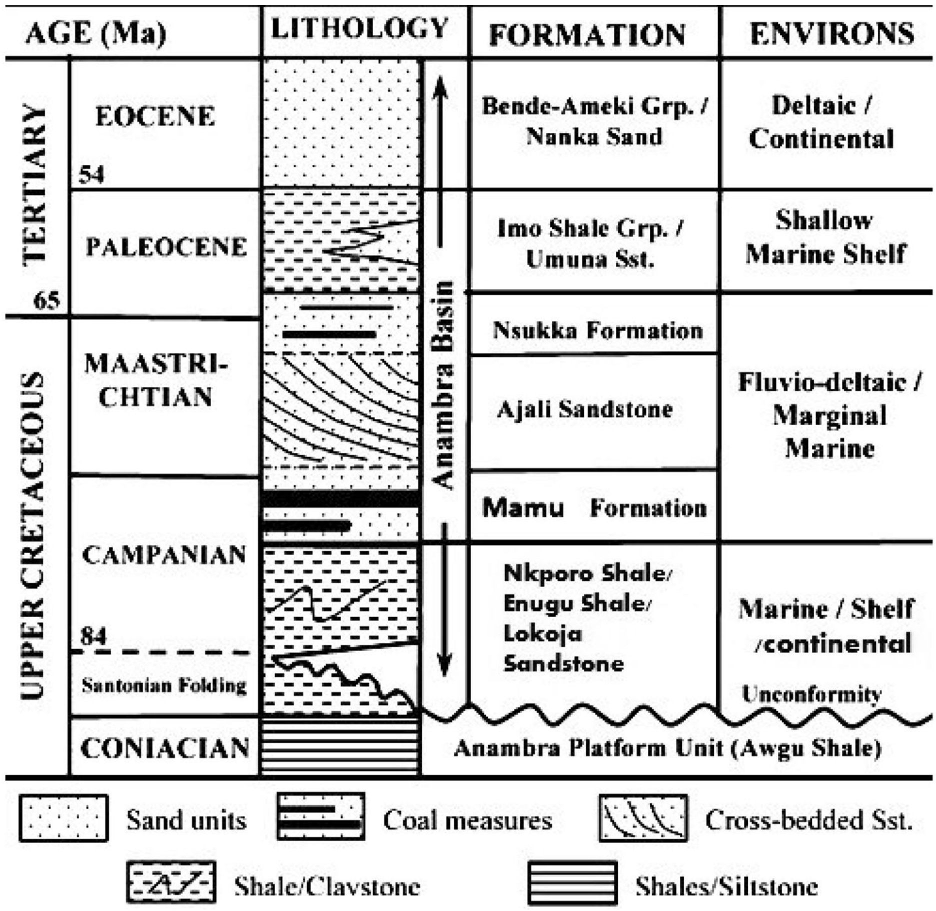

Fig. 4 Stratigraphy and likely depositional environment of Anambra Basin (Modified from Tijani et al. 2010)

(a) (b) (c)

Fig. 5 Sections of **a** porphyritic granite, **b** migmatite–gneiss and **c** quartzite (metasediment)

every location, the name of the locality, the geographical coordinates, the strike and dip of the beds at outcrop as well as the physical characteristics of the sediments visible at outcrop were determined and recorded. The field observations of outcrops at 5 different locations within Auchi and Igarra are provided in Table 1.

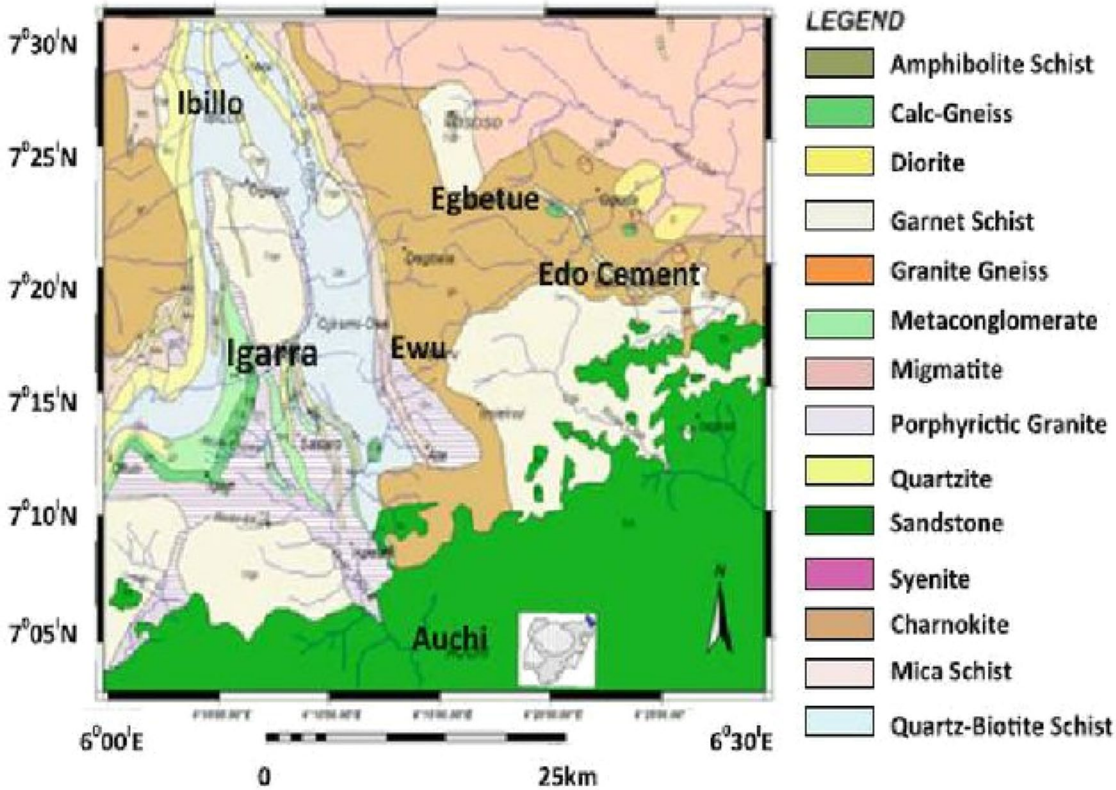

Fig.6 Geologic map of Igarra area (after Anifowose et al. 2006)

Electromagnetic surveying

In carrying out the electromagnetic survey along the profile of interest (profile X shown in Fig. 1), the very low-frequency (VLF) method of electromagnetic surveying which involves a stationary source and a moving receiver was employed. The name of the equipment used as receiver is the ABEM WADI EM receiver. The equipment has an antenna unit which contains horizontal and vertical bars. These bars contain the transmitting and the receiving coils. The horizontal bar measured horizontal variations while the vertical bar measured vertical variations in the subsurface. The power supply unit was used to power the antenna and the receiver, while the receiver unit received the resultant field. The starting point of the survey was at about 120 m from SMAC Quarry Mills, along Auchi–Igarra–Ibillo road, Ikpeshi–Igarra, Akoko–Edo LGA and was run toward Auchi. A total of 155 data points was covered, and data were collected every 20 m along the profile. At every data point, the raw real (%), the filtered real (%), the raw imaginary (%) and the filtered imaginary (%) values were read and recorded.

The VLF electromagnetic data consists of two separate components: the raw real otherwise called the in-phase data and the raw imaginary otherwise known as the quadrature data. These carry very important complex information about the geology of the subsurface of that environment. Because of the complexity of the information, it cannot be seamlessly related to the body causing the anomaly. In addition, these data carry high noise. To correct for these, filtering operators are applied, among other things, to reduce the nonlinear and harmonic noise, to transform the raw real into current density and to adequately position the amplitude of the anomalous body over its source. Hence, the filtered real and filtered imaginary data are respectively the raw real and raw imaginary data which have undergone filtering to correct the defects mentioned above. Microsoft Excel software was used to plot the survey data. The acquired survey data are shown in Table 2.

Table 1 Field observations of outcrops at 5 different locations within Auchi and Igarra

Location	Town	Coordinates	Outcrop	Strike and dip of beds	Description	Likely Formation
1	Ekpesa (Auchi–Ibillo road)	7°6′1″N, 6°14′20″E	Sandstone underlain by shale	N35°W, N10°E	Greyish black pebbly Shale alternated with ferruginized sandstone which shows a coarsening upward sequence	Ajali formation underlain by Mamu Shale
2	Ipeme (Bawa Hill)	7°7′12″N, 6°13′0″E	Sandstone	N120°W, N10°E	Cross-bedded Sandstone with ripple marks, coarse-grained at the base and finer at the top with pockets of clay. The cross-beds are planar or tabular in shape. The sandstone is greyish white with brown stains. The beds have a thickness of approximately 1.2 m	Ajali Formation
3	Ikpeshi (Auchi–Ibillo road)	7°7′59″N, 6°11′44″E	Quartzite	N320°W, 55°W (Tilt)	The Quartzite is brown in colour, shiny and shows evidence of shearing (faulting) which indicates mylonitization. The shiny nature may indicate the presence of mica. It also has veins with quartz. The Quartzitehas been tilted	Basement Complex (metamorphic)
4	AkokoIgarra Location 1	7°9′50″N, 6°7′16″E	Older granite	N/A	Foliated, medium- to coarse-grained, porphyritic biotite granite, greyish black in colour	Basement Complex
5	AkokoIgarra Location 2	7°14′44″N, 6°6′18″E	Granitic gneiss	N/A	Dark grey, feldspathic, biotite granite gneiss, invaded by pegmatitic materials (muscovite). Metasomatism was evident in the location due to metamorphic reaction. There is also the presence of augengneiss which is as a result of tectonism. The gneiss are banded	Basement complex

Table 2 Electromagnetic survey data acquired along Profile X, Auchi–Igarra–Ibillo road

Electromagnetic survey data					
Location: Along Auchi–Igarra–Ibillo express way					
Starting point: 120 m from SMAC Quarry Mills, Ekpeshi Igarra, Akoko-Edo LGA, Edo State (moving toward Auchi from Igarra)					
Station (m)	Raw real (%)	Filtered real (%)	Raw imaginary (%)	Filtered imaginary (%)	Remark
0	0	1	17.5	0.9	Basement
20	1.5	−0.2	13.5	−0.6	Basement
40	−2.1	−0.3	18.9	−1.3	Basement
60	2.4	−0.3	20.9	2.5	Basement
80	−4.1	2	8.6	1	Basement
100	6.7	4.6	16.8	−1.7	Basement
120	−0.8	−3	15.2	−0.2	Basement
140	−1.2	−2.3	19.7	0.7	Basement
160	−2.2	−1	9.7	−0.5	Basement
180	0.5	1	19.8	−3.6	Basement
200	−0.1	1.3	21.8	−1	Basement
220	2.5	−2.2	24.1	1.7	Basement
240	−4.3	−4.2	14.6	2.4	Basement
260	−0.8	0.8	13.8	−1.9	Basement
280	−0.1	4.4	22.8	−1.4	Basement
300	4	6.6	19.9	1.1	Basement
320	3.7	1.9	18.3	1	Basement
340	0.7	−4.5	13.9	−0.9	Basement
360	−5.4	−2.9	22.1	−1.7	Basement
380	0.8	1.5	20.6	0.3	Basement
400	1	−2.1	19.2	−1	Basement
420	−2.6	−2.7	22.8	−0.8	Basement
440	0.1	−2.6	21.4	−0.2	Basement
460	−3.5	−1.6	23.9	1.5	Basement
480	1.3	1.5	17	3.2	Basement
500	−0.4	2.5	12	−0.2	Basement
520	2	5.8	18.4	−2.5	Basement
540	4.6	3.2	22.4	−0.6	Basement
560	−1.2	2.6	20	1.4	Basement
580	4.5	1.1	18.2	3	Basement
600	−2.3	−4.5	8.6	0.8	Basement
620	−2.3	−1.9	16.4	−1.6	Basement
640	−0.6	−0.8	16.5	0.3	Basement
660	−0.5	−0.4	13.9	−1.6	Basement
680	−0.2	0.5	19.8	−1.9	Basement
700	1.1	0.5	20.4	−0.3	Basement
720	−1.8	3.9	19.5	−0.4	Basement
740	5.9	2.1	20.5	0.8	Basement
760	−1.5	−5.9	20.8	3.4	Basement
780	−5.4	−5.9	4.1	−1.1	Basement
800	4.2	−25.3	28.7	0.6	Basement
820	−28.5	−26.9	6.3	6.4	Basement
840	−8.3	13.4	3.5	−3.1	Basement
860	16.4	17.6	14.4	−4.6	Basement

Table 2 (continued)

Electromagnetic survey data					
Location: Along Auchi–Igarra–Ibillo express way					
Starting point: 120 m from SMAC Quarry Mills, Ekpeshi Igarra, Akoko-Edo LGA, Edo State (moving toward Auchi from Igarra)					
Station (m)	Raw real (%)	Filtered real (%)	Raw imaginary (%)	Filtered imaginary (%)	Remark
880	4.4	9.3	21.8	− 3.4	Basement
900	8.3	2.4	21.2	− 1.2	Basement
920	0.9	− 25.8	27.7	5.2	Basement
940	− 24.5	− 30.3	2.2	5.5	Basement
960	− 12.2	− 9.7	9.7	1.9	Basement
980	− 2.3	− 3	7.8	9.7	Basement
1000	− 3.1	6.2	− 23.8	1.7	Basement
1020	9.1	10.5	2.2	− 5.1	Basement
1040	1.9	5.1	0.1	1.8	Basement
1060	6.1	1.6	− 3.9	0.7	Basement
1080	− 5.4	4.1	− 6.4	0.1	Basement
1100	8	10.4	− 3.6	− 1.4	Basement
1120	4.2	− 0.1	− 1.1	− 0.9	Basement
1140	− 2	− 3.9	− 0.8	0.2	Basement
1160	− 1.3	− 6.1	− 3.2	0.1	Basement
1180	− 5.2	− 10.1	− 2.2	− 0.8	Basement
1200	− 3.3	− 14.6	− 0.5	1.3	Basement
1220	− 2.1	− 11.5	− 0.6	7.3	Basement
1240	− 1	− 1.1	− 25	5.6	Basement
1260	− 3.5	5.1	− 20	− 2	Basement
1280	8.1	9.5	− 12.6	− 0.4	Basement
1300	2.8	2.6	− 15.9	0.8	Basement
1320	2.2	− 1.3	− 16.9	1	Basement
1340	− 3.6	− 1.9	− 19.7	0.9	Basement
1360	0.9	− 0.4	− 19	1.8	Basement
1380	− 0.6	− 2.2	− 19.2	5.3	Basement
1400	− 4.2	5.8	− 44.1	− 2.9	Basement
1420	11	3	− 4.5	− 3.6	Basement
1440	− 7.2	0.2	− 31.2	1.2	Basement
1460	5	12.9	− 14.4	− 5.7	Basement
1480	9.2	0.5	− 10.1	5.3	Basement
1500	− 4.5	− 9.7	− 27.4	7.6	Basement
1520	− 5.8	− 2.9	− 41.8	− 2.1	Basement
1540	− 0.6	2.7	− 22.3	− 11.1	Basement
1560	4.4	− 2.5	− 2.7	− 5.9	Basement
1580	− 5.9	− 3.6	2.1	6.6	Basement
1600	0.5	0.7	− 35	5.3	Basement
1620	2.9	− 0.4	− 15.4	− 1.3	Basement
1640	− 14.8	3.1	− 30.3	− 4.2	Basement
1660	17.2	5	− 0.8	− 7.7	Basement
1680	− 8.2	− 13.5	− 2.8	4.3	Basement
1700	− 4.5	− 4.5	− 19.1	4.7	Basement
1720	− 2.4	− 4.4	− 16.8	6.4	Basement
1740	− 2.8	− 2	− 39.1	0.3	Basement

Table 2 (continued)

Electromagnetic survey data					
Location: Along Auchi–Igarra–Ibillo express way					
Starting point: 120 m from SMAC Quarry Mills, Ekpeshi Igarra, Akoko-Edo LGA, Edo State (moving toward Auchi from Igarra)					
Station (m)	Raw real (%)	Filtered real (%)	Raw imaginary (%)	Filtered imaginary (%)	Remark
1760	−0.7	2.8	−21.6	−11.7	Basement
1780	4.4	−1.1	4.1	−3.7	Basement
1800	−5.1	−1.6	−6.9	6.5	Basement
1820	1.8	7.5	−24.6	4.2	Basement
1840	4	9.5	−25.3	−3.2	Basement
1860	6.6	7.4	−8.9	−3.8	Basement
1880	2.2	3.4	−9.9	−8.1	Basement
1900	0.4	3.7	−13.7	−1.4	Basement
1920	5.4	−4.1	−7.5	−1.5	Basement
1940	−8.6	−6.9	−10.4	−2.1	Basement
1960	−0.7	2.7	−1	−1.6	Basement
1980	3.1	−0.2	−5.9	0.7	Basement
2000	−4	3.1	−6.1	−1.8	Suspected termination of basement
2020	7.3	4.8	−1.5	−1.7	Suspected boundary
2040	−2.1	−0.7	1.4	1.2	Suspected boundary
2060	2.8	−0.6	−6.3	2.4	Suspected boundary
2080	−4	0.3	−6.6	0.6	Suspected boundary
2100	2	8.2	−10.2	−2.2	Suspected boundary
2120	7.2	2	4.2	−0.3	Suspected beginning of sedimentary
2140	−3.3	−5.3	−9	3	Sedimentary
2160	0.1	−3.1	−7.7	−1.2	Sedimentary
2180	−10.5	19	−8.2	−4.6	Sedimentary
2200	26.5	26.3	6.6	−6.2	Sedimentary
2220	8.7	−10.6	13.6	−0.6	Sedimentary
2240	−12.8	−19.7	1.4	2.8	Sedimentary
2260	−3.5	−16.4	0.6	0.4	Sedimentary
2280	−12.6	−7.4	1.8	0.5	Sedimentary
2300	0.3	11.1	0.9	0.1	Sedimentary
2320	8.9	16.6	1	−0.3	Sedimentary
2340	8	18.2	1.9	−0.2	Sedimentary
2360	13.1	12.4	1.3	−0.2	Sedimentary
2380	2.2	−0.1	2.6	−0.6	Sedimentary
2400	2.2	−16.8	1	−1.6	Sedimentary
2420	−13.9	−27.4	10.2	0.6	Sedimentary
2440	−26	16.2	−2.8	0.6	Sedimentary
2460	34.8	25.8	6.2	−2.5	Sedimentary
2480	5.5	−32.1	7.3	1	Sedimentary
2500	−32.5	−27.1	3.1	0.7	Sedimentary
2520	−2.4	−4.7	2.4	−0.8	Sedimentary
2540	−9.8	6	7	0.7	Sedimentary
2560	3.8	34.2	3.5	4.2	Sedimentary
2580	28.9	21.6	−7.5	2.6	Sedimentary
2600	−2.7	10.6	−5.5	−1.4	Sedimentary
2620	14.7	8.1	−1.3	−3	Sedimentary

Table 2 (continued)

Electromagnetic survey data					
Location: Along Auchi–Igarra–Ibillo express way					
Starting point: 120 m from SMAC Quarry Mills, Ekpeshi Igarra, Akoko-Edo LGA, Edo State (moving toward Auchi from Igarra)					
Station (m)	Raw real (%)	Filtered real (%)	Raw imaginary (%)	Filtered imaginary (%)	Remark
2640	3.8	−37.1	3.6	−3.7	Sedimentary
2660	−38.6	−28.5	8.8	−1.8	Sedimentary
2680	−7.6	31.8	8.8	1.7	Sedimentary
2700	33.3	30.8	2.4	3.1	Sedimentary
2720	8.4	2.6	−2.3	1.3	Sedimentary
2740	−2.6	4.1	0.5	1.4	Sedimentary
2760	10.3	−19.7	−3.1	2.1	Sedimentary
2780	−24	−41.1	−10.3	−2	Sedimentary
2800	−24.4	−12.9	7.5	−1.2	Sedimentary
2820	7	−10.9	−11.3	−3.6	Sedimentary
2840	−18.2	−14.3	18.1	−5.3	Sedimentary
2860	0.8	−0.5	7.3	1.2	Sedimentary
2880	−3.8	5.9	9.3	−1.2	Sedimentary
2900	0.7	41.6	15.2	9.9	Sedimentary
2920	40.2	43.4	−14.6	16.3	Sedimentary
2940	11.7	12.5	−39.4	6	Sedimentary
2960	9.5	0.9	−28.5	−1	Sedimentary
2980	−7.1	−7.8	−24.8	−1.3	Sedimentary
3000	−3.8	2.6	−31.7	−8.5	Sedimentary
3020	5.6	0	6.1	−1.4	Sedimentary
3040	−3.5	−6	−27.1	7.6	Sedimentary
3060	−3.4	0.4	−25.1	−0.4	Sedimentary
3080	3.9	−0.6	−24.6	1.3	Sedimentary
3100	−3.1	−3	−24.4	−0.3	Sedimentary

Magnetic surveying

In carrying out the magnetic survey along the same profile X, a set of field equipment which includes the magnetometer and the sensor unit was employed. As in electromagnetic survey, the starting point of the ground magnetic survey was at about 120 m from SMAC Quarry Mills, along Auchi–Igarra–Ibillo road, Ikpeshi–Igarra, Akoko–Edo LGA and was run toward Auchi. A total of 44 data points was covered, and data were collected every 50 m for the first 1 km and every 100 m for the remaining 2.3 km along the profile. At every data point, the peak value (μT) was read and recorded twice, and the field value (μT) was also read and recorded twice. Their average values were later calculated. This was done to reduce errors in the readings. Also, the time at which data were acquired at every location was read and recorded.

Microsoft Excel software was used to plot the survey data. The acquired survey data are shown in Table 3.

Results

The results of the geologic field investigations of outcrops carried out at five different locations within Auchi and Igarra areas are presented below.

Table 3 Ground magnetic survey data acquired along Profile X, Auchi–Igarra–Ibillo road

Distance (m)	Peak 1 and 2 (μT)	Average peak (μT)	Variation in peak (μT)	Field 1 and 2 (μT)	Average field (μT)	Variation in field (μT)	Time (hours)
0	25.585, 22.008	23.797	0.000	21.550, 21.639	21.595	0.000	14:31
50	16.601, 18.200	17.401	−6.396	16.343, 15.007	15.675	−5.920	14:35
100	16.066, 15.977	16.022	−1.379	15.781, 15.821	15.801	0.126	14:42
150	14.177, 13.764	13.971	−2.051	13.848, 13.736	13.792	−2.009	14:44
200	15.158, 14.738	14.948	0.977	14.583, 14.681	14.632	0.840	14:46
250	17.236, 17.214	17.225	2.277	17.214, 17.20	17.212	2.580	14:49
300	18.431, 17.815	18.123	0.898	17.544, 17.581	17.563	0.351	14:53
350	15.721, 15.988	15.855	−2.268	15.753, 15.335	15.544	−2.019	14:56
400	15.175, 15.114	15.145	−0.71	14.758, 15.006	14.882	−0.662	14:58
450	15.466, 15.290	15.378	0.233	15.221, 15.281	15.251	0.369	15:00
500	14.496, 14.496	14.496	−0.882	14.011, 14.011	14.011	−1.240	15:03
550	15.958, 15.958	15.958	1.462	15.951, 15.951	15.951	1.940	15:05
600	16.931, 16.738	16.835	0.877	16.669, 16.624	16.647	0.696	15:08
650	16.370, 16.414	16.392	−0.443	16.222, 16.211	16.217	−0.430	15:09
700	17.480, 18.480	17.98	1.588	18.358, 17.840	18.099	1.882	15:12
750	15.106, 15.131	15.119	−2.861	15.054, 14.880	14.967	−3.132	15:14
800	15.495, 15.380	15.438	0.319	14.988, 15.347	15.168	0.201	15:16
850	14.513, 14.193	14.353	−1.085	14.162, 14.173	14.168	−1.000	15:18
900	14.899, 14.953	14.926	0.573	14.776, 14.788	14.782	0.614	15:19:00
950	15.500, 15.381	15.441	0.515	15.310, 15.351	15.331	0.549	15:22
1000	16.616, 16.597	16.607	1.166	16.600, 16.588	16.594	1.263	15:24
1100	15.000, 14.613	14.807	−1.8	14.259, 14.155	14.207	−2.387	15:43
1200	11.781, 11.789	11.785	−3.022	11.750, 11.779	11.765	−2.442	15:46
1300	13.571, 14.741	14.156	2.371	13.481, 13.500	13.491	1.726	15:49
1400	11.795, 11.658	11.727	−2.429	11.765, 11.622	11.694	−1.797	15:52
1500	13.667, 13.662	13.665	1.938	13.640, 13.648	13.644	1.950	15:54
1600	13.325, 13.282	13.304	−0.361	13.268, 13.263	13.266	−0.378	15:57
1700	14.171, 13.358	13.765	0.461	14.331, 13.341	13.836	0.570	16:00
1800	13.324, 13.342	13.333	−0.432	13.313, 13.335	13.324	−0.512	16:03
1900	13.609, 13.563	13.586	0.253	13.534, 13.552	13.543	0.219	16:06
2000	14.566, 14.441	14.504	0.918	14.432, 14.437	14.435	0.892	16:09
2100	15.497, 14.750	15.124	0.62	15.280, 14.720	15	0.565	16:13
2200	12.495, 12.468	12.482	−2.642	12.397, 12.349	12.373	−2.627	16:16
2300	9.077, 9.278	9.178	−3.304	8.847, 8.925	8.886	−3.487	16:19
2400	10.419, 10.249	10.334	1.156	10.142, 10.216	10.179	1.293	16:23
2500	11.677, 11.676	11.677	1.343	11.560, 11.616	11.588	1.409	16:27
2600	13.097, 13.270	13.184	1.507	13.018, 13.030	13.024	1.436	16:31
2700	13.745, 13.478	13.612	0.428	13.685, 13.427	13.556	0.532	16:35
2800	13.717, 13.702	13.71	0.098	13.680, 13.618	13.694	0.093	16:38
2900	14.641, 14.641	14.641	0.931	14.270, 13.200	13.735	0.086	16:41
3000	15.561, 15.111	15.336	0.695	15.007, 14.657	14.832	1.097	16:44
3100	15.081, 14.335	14.708	−0.628	14.244, 14.257	14.251	−0.581	16:47
3200	10.043, 10.137	10.09	−4.618	9.886, 9.700	9.793	−4.458	16:51
3300	8.580, 4.556	6.568	−3.522	4.419, 4.256	4.338	−5.455	16:54

Fig.7 Vertical section of tabular, cross-bedded, fine-to-medium-grained sandstone facie observed at location 2

Fig.8 A section of the quartzite observed at location 3

Location 1 (Ekpesa, Auchi): At this location, an outcrop of ferruginized sandstone underlain by greyish black pebbly shale was seen. This shows a coarsening upward sequence.

Location 2 (Ipeme, Auchi): This location has an exposure of tabular cross-bedded, greyish white sandstone with ripple marks, coarse-grained at the base and finer at the top with pockets of clay. This outcrop shows a fining upward sequence (Fig. 7).

Location 3 (Ikpeshi–Igarra): Here, an outcrop of light brown, shiny quartzite was observed. By visualization, the quartzite shows evidence of shearing (faulting) which indicates mylonitization. The shiny nature may indicate the presence of mica. It also has veins with quartz. The quartzite has been tilted (Fig. 8).

Location 4 (Akoko–Igarra 1) This location is at Akoko–Igarra and it is an older granite complex. The biotite granites are foliated, medium-to-coarse-grained, porphyritic and greyish black in colour. They have areas of jointing which helps to determine their direction of weakness (Fig. 9).

Location 5 (Akoko–Igarra 2): This location has an exposure of granite gneiss. This granitic gneiss is dark grey in colour, feldspathic and invaded by pegmatitic materials (muscovite). Metasomatism was evident in the location due to metamorphic reaction. There is also the presence of augengneiss which is as a result of tectonism. The gneiss is specially banded (Figs. 10, 11).

Electromagnetic survey

The data in Table 2 were obtained from the electromagnetic survey carried out along profile X within the study area.

The above data were plotted using Microsoft Excel software. The filtered real (%) and raw real (%) were plotted against distance (metres) on the same graph (Fig. 12); the raw real (%) was plotted against distance (Fig. 13); and finally, the filtered real (%) was also plotted against distance (Fig. 14).

Magnetic survey

The data in Table 3 were obtained from the ground magnetic survey carried out along profile X within the study area.

The above data were also plotted using Microsoft Excel software. The variation in peak measured in MicroTesla (μT) was plotted against distance (metres); the variation in field (μT) was plotted against distance (metres), and finally, the variations in peak and field (μT) were plotted against distance (m) on the same graph. The plots are shown in Figs.15, 16 and 17 respectively.

(a) (b)

Fig. 9 Sections of the foliated, porphyritic biotite granites observed at **a** first Akoko-Igarra location, outcrop 1, **b** first Akoko-Igarra location, outcrop 2. Both constitute location 4

(a) (b)

Fig. 10 Sections of the **a** banded gneiss observed at second Akoko-Igarra location, outcrop 1, **b** dark grey, feldspathic, biotite granite gneiss observed at second Akoko–Igarra location, outcrop 2. Both constitute location 5

Discussion

From the field observations, three different lithofacies belonging to two lithostratigraphic units were observed within Auchi area studied (locations 1 and 2). These are: shale unit, cross-bedded sandstone unit and ferruginized sandstone unit. The shale unit is overlain by the cross-bedded sandstone and the ferruginized sandstone units which are in agreement with previous studies carried out in the area. The outcrops observed within Igarra area are rocks of the Precambrian basement complex, a metasedimentary suite which has been intruded by igneous rocks of mostly Pan-African age.

From the results of the electromagnetic survey carried out, it can be seen that from a distance of 0 m (starting point) to a distance of about 2000 m, the conductivity was much lower when compared to the conductivity from a distance of about 2120 m up to 3000 m. This shows that the rocks underlying the area between 0 m to about 2000 m have lower electrical conductivities when compared to the rocks underlying the area between about 2120 m up to 3000 m. From theoretical knowledge, basement rocks have very low electrical conductivities because of their lack of porosity, saturation and possibly salinity, while sedimentary rocks have higher conductivities because of these properties.

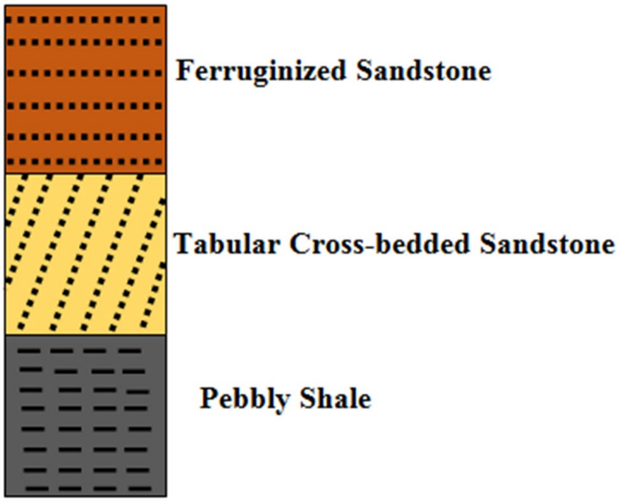

Fig. 11 Observed lithofacie units of Auchi area

Hence, since the study profile is underlain by basement terrain on one section and sedimentary terrain on the other, it can be deduced from the plots that the distance between 0 m to about 2000 m is underlain by basement rocks because of their lower electrical conductivity values, while the area between a distance of about 2120 m up to 3000 m is underlain by sedimentary rocks because of their higher electrical conductivity values. Also, the area between a distance of 2000 and 2120 m (about 120 m) can be said to be the transition zone and boundary between basement and sedimentary environments.

From the results of the ground magnetic survey carried out, variations in magnetic susceptibility are higher from a distance of 0 m to a distance of about 1900 m than from a distance of about 2100 m up to 3000 m. Considering the linear variation in peak (μT) and the linear variation in field (μT) in the plots, it can be seen that the average magnetic susceptibility decreased when moving from a distance of 0 m up to a distance of 3000 m. The magnetic susceptibility of most rocks is directly proportional to their content of ferromagnetic minerals like magnetite, ilmenite, pyrrhotite and franklinite (Kearey et al. 2002). Basement rocks contain more of these magnetic minerals than sedimentary rocks.

It can be deduced from the plots that the distance between 0 m to about 1900 m is underlain by basement rocks because of their higher magnetic susceptibility values, while the area between a distance of about 2100 m up to 3000 m is underlain by sedimentary rocks because of their lower magnetic susceptibility values. The area between a distance of 1900 m to 2100 m (about 200 m) can be said to be the transition zone and boundary between basement terrain and sedimentary terrain. These are in agreement with the information obtained from the electromagnetic survey analysed above.

A schematic model of the basement–sedimentary geometry along profile X is shown in Fig. 18.

Conclusion

The field geologic investigation of some outcrops within Auchi and Igarra area of Edo State, Southern Nigeria, was carried out. Also, an electromagnetic and ground magnetic survey was carried out along profile X within Auchi–Igarra area. From the results of these geologic and geophysical investigations carried out, it can be concluded that the sediments of Auchi areas studied (locations 1 and 2) are made up of three major lithofacies: the basal shale unit, the tabular cross-bedded sandstone unit and the ferruginized sandstone unit. The shale unit is overlain by the

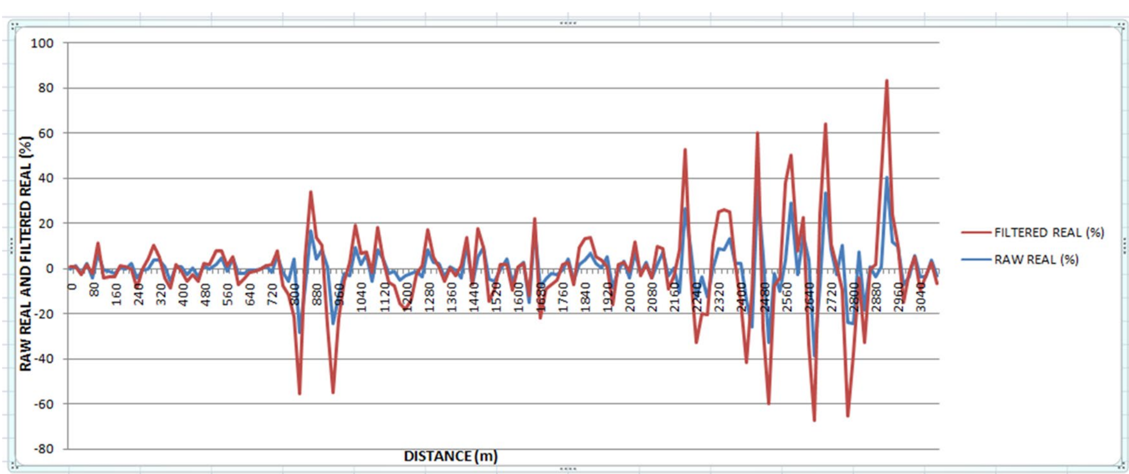

Fig. 12 Plot of raw real (%) and filtered real (%) against distance (metres)

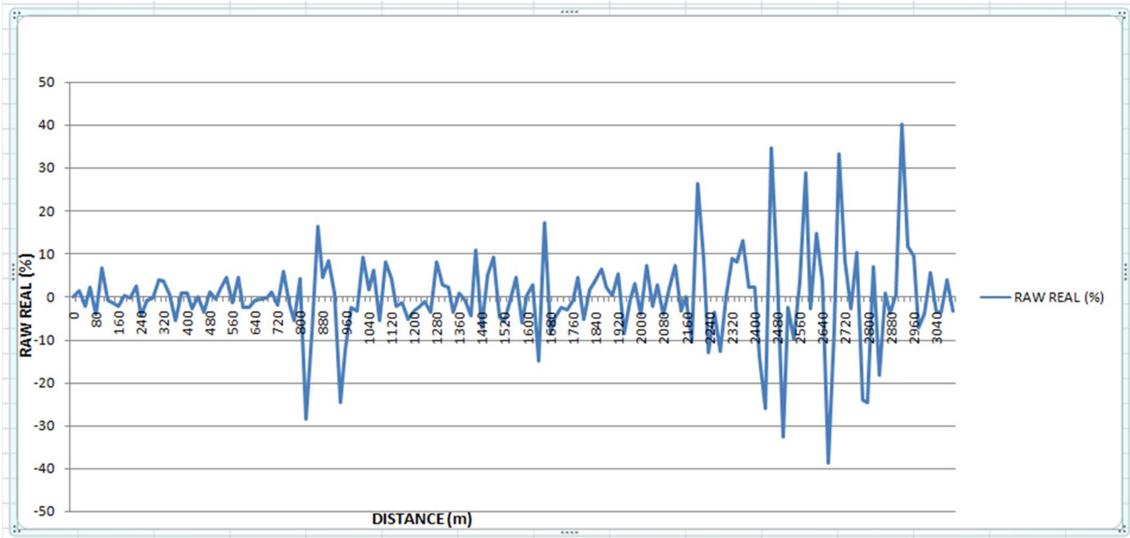

Fig.13 Plot of raw real (%) against distance (metres)

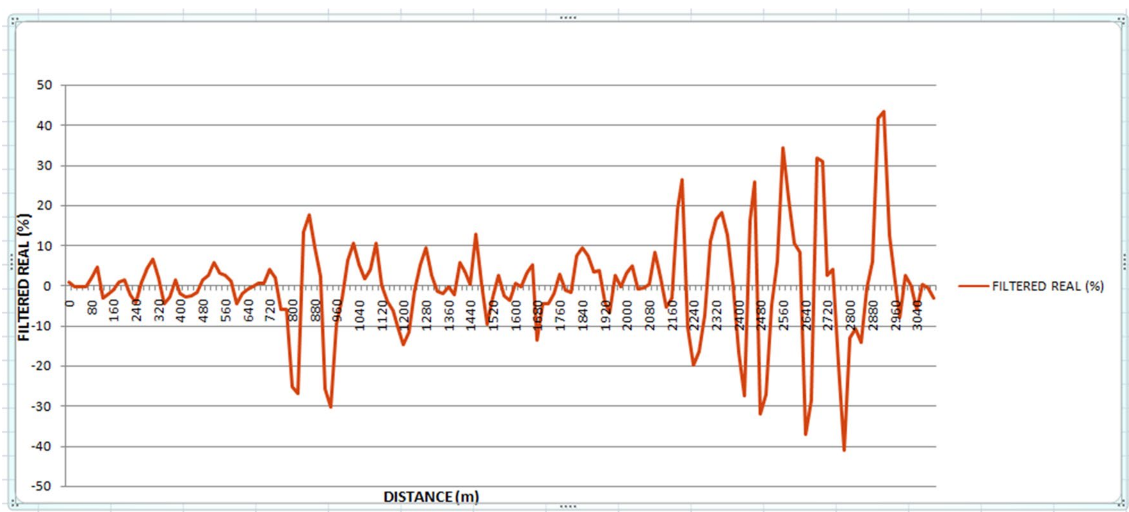

Fig.14 Plot of filtered real (%) against distance (metres)

cross-bedded sandstone and the ferruginized sandstone units which are in agreement with previous studies carried out in the area.

Rocks of the Precambrian basement complex underlie Igarra area. The area is underlain by metasediments that have been intruded by igneous rocks. Results show the presence of three major groups of igneous and metamorphic rocks within the area and they are the migmatite–gneiss group, metasediments and porphyritic granites.

From the two geophysical surveys carried out, the boundary between basement terrain and sedimentary terrain in this area lies at approximately between a distance of 2000 and 2120 m from SMAC Quarry Mills, along Auchi–Igarra–Ibillo road, Ikpeshi–Igarra, Akoko-Edo Local Government Area, Edo State, Southern Nigeria (moving toward Auchi from Igarra).

From the entire investigations carried out, it is recommended that more outcrop locations should be accessed and investigated within the study area. This might give additional information about the geology of the area. In future, data or sampling points on the acquisition profile should be

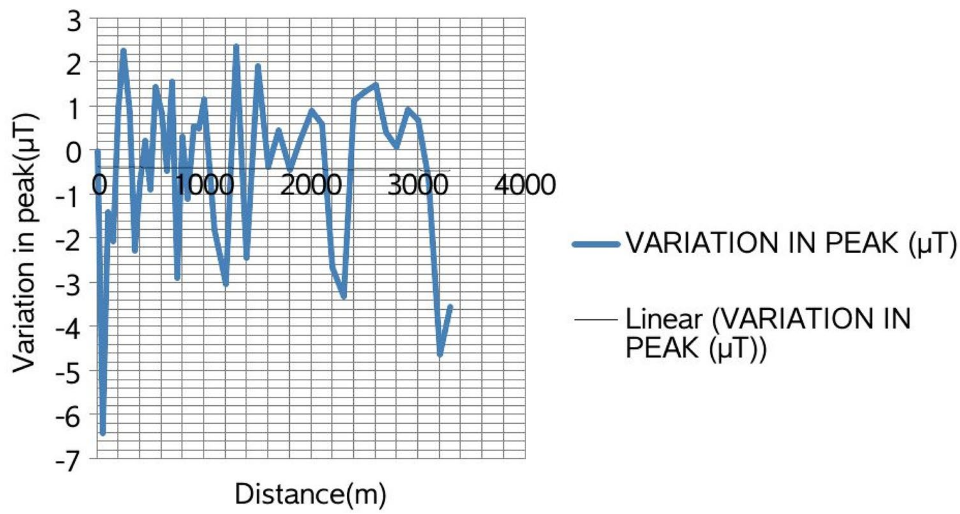

Fig.15 Plot of variation in peak (μT) against distance (metres)

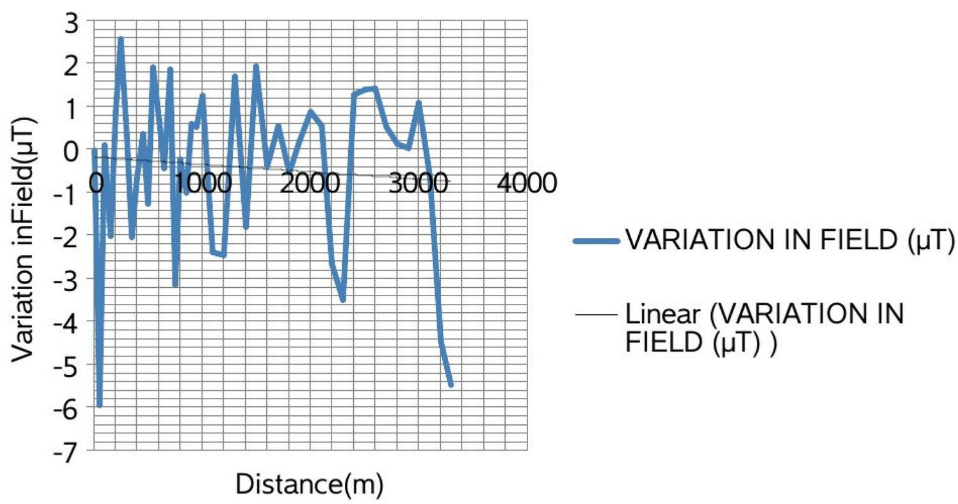

Fig.16 Plot of variation in field (μT) against distance (metres)

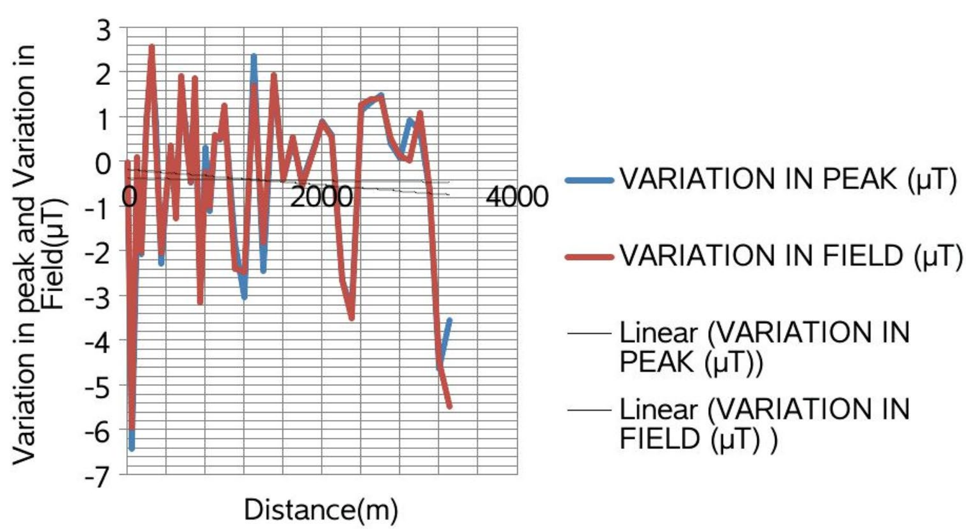

Fig.17 Plots of variation in peak (μT) and variation in field (μT) against distance (metres)

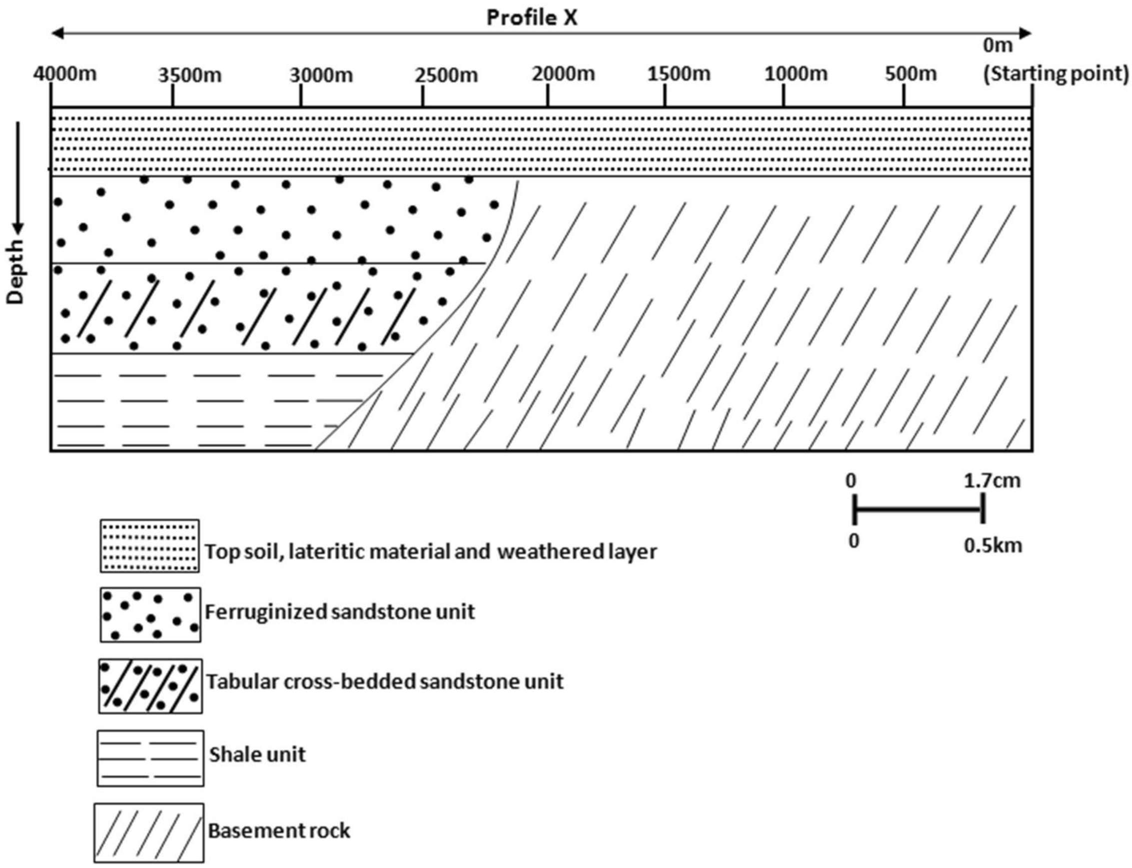

Fig.18 Schematic model of the basement–sedimentary geometry along profile X

established at a much closer interval, particularly for the magnetic survey, in order to obtain a far better subsurface electrical conductivity and magnetic susceptibility information about the area.

It is also suggested that electrical resistivity method should be carried out around the suggested boundary between basement and sedimentary terrains to validate the results of the geophysical surveys utilized in this study.

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Declarations

Conflict of interest There are no competing interests to declare.

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