Near - surface characterization of sediments of the Sokoto group exposed around Wamakko area, Northwestern Nigeria: an integrated approach

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ABSTRACT
An integrated approach involving sedimentological and geophysical studies was carried out to characterize the surface and subsurface geology of part of the southwestern Iullemmeden basin (Sokoto Basin, North-western Nigeria). The Kalambaina Formation (limestone) of the Sokoto Group is being investigated. The general objective of this study was to optimize lateral and vertical resolution amidst the subsurface lithological heterogeneity and that informed the choice of integrating sedimentology and geophysics (involving Vertical Electrical Sounding – VES and Electrical Resistivity Tomography – ERT). Surface geological mapping complemented by geophysical (4 VES and 2 ERT) surveys were carried out. Data integration involved geological (outcrop stratigraphic data), geophysics and data from down-hole core descriptions within the area of investigation. Results of 1D resistivity (VES) yielded QH and QHC curve types with OH being predominant. Based on their contrasting resistivities, four-layer geoelectric sections was erected using VES data (ironstone topsoil, limestone, shale and clay/sandy clay layers). From the ERT modelling, four lithologic sections were also identified. These lithologic discriminations correlated well with few borehole data within the study area. With integration of geophysics with stratigraphic data, a subsurface facies distribution model (fence diagram) was developed having a high vertical and lateral resolution. This study revealed that during reconnaissance mapping, with integrated approach using resistivity and sedimentological data, accurate subsurface imaging could be achieved, at a reduced exploration cost, even in areas of abrupt facies changes (lithological heterogeneities).

Introduction
This study is an attempt to better understand the distribution of limestone in the near subsurface using geophysical prospecting (electrical resistivity) and sedimentological studies. The study is restricted to the Sokoto Group which represents deposits of an epeiric sea that incised into the Nigerian sector of the Iullemmeden Basin during the Paleogene. The topography of the area bordered by the basin is gently undulating with elevation between 260 and 400 m above sea level. The most striking topographic feature of the basin is the Dange Scarp (NNE – SSW structure) from which major rivers take their source (Nwajide, 2013; Obaje, 2009). The Sokoto basin is known to possess deposits of industrial and agricultural significance, some of which have been studied appreciably and others only mentioned. Major works carried out in the Nigerian sector of the basin have been on the geology and biostratigraphy (Kogbe, 1976, 1976, 1989; Nwajide, 2013; Obaje, 2009; Obioso et al., 1998; Okosun, 1999; Petters, 1979; Raeburn & Tattam, 1930; Reyment, 1965; Wright et al., 1985). Despite current operations of the Cement Company Northern Nigeria (CCNN) on the Kalambaina Formation, it is necessary to study the subsurface distribution to properly guide future expansion programs. Outcrops in the area under investigation are not well exposed and the materials of interest (limestone) do not occur at the surface especially in the areas designated for future development. Geophysical prospecting is known to provide information about subsurface variations in earth material (rocks) characteristics, depth to geoelectrical basement (thickness) and aquifer delineation (Olayinka & Olorunfemi, 1992). This is achievable by careful selection of the geophysical approach that best enhances a clear contrast between the object of interest and its surrounding materials. This study focuses on the integration of geological mapping (sedimentological) and geophysics (electrical resistivity), to characterize near – surface sediments (limestone deposit) around Wamakko area where these rocks sparsely outcrop (Figure 1).

Regional geology and stratigraphic setting
The Iullemmeden Basin is a circular intra-cratonic basin in the south-central Saharan region of Africa, covering an extent of about 700,000 km². It stretches across parts of Mali, Niger republic, Benin Republic and...
north-western Nigeria. To the far north, it is bordered by the Adar des Iforas, Hoggar mountains and the Air ranges towards the east, and the basement rocks of the Benin – Nigeria axis to the south (Petters, 1991). Two notable sedimentary basins in this south Saharan region to the left and right of the Iullemmeden basin are the Taoudeni and the Chad basin respectively. At the onset of the 20th century, Falconer (1911) described the geology and geography of the Nigerian sector of the Iullemmeden basin referred to as the Sokoto Basin. Other notable studies carried out in this basin are those of Petters (1978, 1979), Kogbe (1989), and Kogbe and Sowummi (1975), Odunfa (1988); Odibo (1988); Offodile (2002); Ibeh et al. (2007), Obaje et al. (2013), among others. Nwajide (2013) noted that the basin originated probably by rapid subsidence in the late Jurassic (ca. 140 Ma) from its central portion and this was accompanied by slow phase in the early Cretaceous – Turonian and then faster again from about 80 Ma. Stratigraphic evolution in the basin dates back to late Jurassic – earliest Cretaceous.

Deposition was continuous only from Upper Cretaceous to the lower part of the Paleogene with marine and estuarine conditions prevailing leaving mainly shale, mudstone and limestone as products. The “Continental Intercalaire” of Wright et al. (1985) represents the basal sediments of the basin are chiefly continental whereas during the Maastrichtian – Palaeocene sedimentation was a result of two transgressive-regressive episodes ushered by the advancement and retreats of the Tethys sea (Petters, 1979). Figure 2 presents the lithostratigraphic subdivision of the sedimentary packages in the Iullemmeden basin, emphasizing the terminologies used in its occurrence within the Sokoto basin, northwest Nigeria. Notably four unconformity bounded sequences are known in the entire basin and can be mapped in the Nigerian sector of the basin. A brief description of the lithological package is given below, detailed accounts of the lithologic characteristics are available in published literatures (Kogbe, 1976; Nwajide, 2013; Obaje, 2009; Petters, 1979). The first and the oldest formations are the non-marine, pre-Maastrichtian Gundumi and Illo Formations which are believed to be lateral equivalents and overlie the basement towards the northeast and southwest of the basin respectively in the Nigerian sector. The beds are continental in origin and devoid of body fossils

Figure 1. Regional geological map of Sokoto Basin (source: United States Dept of Interior Geological survey).
except for some fossil-wood (Kogbe, 1973). The Gundumi Formation consists of clay, grits, sandstone, and pebbles that are lacustrine and fluviatile in origin, while its lateral equivalent, the Illo Formation, consists essentially of cross-bedded pebbly grits, sandstone and pisolithic clay that known to be rich in bauxite. The Gundumi is overlain only by the Rima Group of Maastrichtian age while the Illo Formation is unconformably overlain successively from east to west by Rima Group, Sokoto Group and Gwandu Formation (Kogbe, 1973).

The Rima Group is made up of the Taloka, Dukamaje and Wurno Formations. The Taloka Formation, which is the oldest of the three, consists of white, fine-friable sandstone and poorly consolidated reddish-purple to brown clayey siltstones and some carbonaceous mudstone. The Dukamaje Formation consists predominantly of fossiliferous gypsiferous shale with some marl – mudstone intercalations (Obaje, 2009) and characteristic bone bed towards the base (Petters, 1979); while the youngest, Wurno Formation, has close similarity in its lithologic affinities with the Taloka Formation (Kogbe, 1973; Obaje, 2009). It consists of pale, friable, fine-grain sandstone, siltstone and intercalated mudstones.

Unconformably overlying the Rima Group is the Sokoto Group which is almost entirely marine in origin. This Palaeocene deposits have three main formations viz; Dange, Kalambaina and Gamba Formations. The Dange Formation consists of indurated bluish-grey shale, interbedded with thin beds of limestone/marl units, while the Kalambaina Formation which overlies the Dange Formation is made up of white, highly fossiliferous limestone and few marl interbeds. The Gamba Formation consists of yellowish to brown, slightly fossiliferous “paper” shale. The limestone deposit of the Kalambaina formation is the interest of this investigation.

The Eocene continental Gwandu Formation is the fourth phase sedimentary deposit in the Sokoto Basin. It outcrops in the north-western and Southern part of the Basin and consists of indurated, interbedded, thick grey mudstone, quartz and lignite. The Gwandu Formation is overlain by the younger deposit, Alluvium, which mostly occurs along the River Sokoto and its tributaries. Sediments of the Sokoto Group is the focus of this study.

The area of interest is located between latitudes 13° 3’ 15” and 13° 4’ 00” N and longitudes 5° 10’ 00” and 5° 10’ 30” E (Figure 3). The topography of the area is
gently undulating to almost flat-lying, with elevation ranging from 261 to 264 meters above sea level and minor occurrence of outliers in some places principally consisting of ironstones. The soil profile shows the high resistant laterites/ironstone crust.

**Methodology**

This study carried out in north-western Nigeria, involves the integration of geological (sedimentology) and geophysical mapping of a part of the Sokoto Group in close proximity to the quarry site of Cement Company Northern Nigeria. Geological field studies, including stratigraphic logging were carried out and correlated with data from eight available boreholes (core) described for the area. The composite stratigraphic profile (Figure 4(a-c)) erected from field observations summarizes the lithological characteristics of the area. Predominantly, the exposure consists of ferruginized – lateritic ironstones cap, with limestones and shales belonging to the Kalambaina Formation and the Gamba Shales respectively. The shale characteristically thins out towards the east where the ironstone is seen to overlie the limestone in places (Figure 4(d)). This shale unit that overlies the limestone is part of the Gamba Formation while the

![Figure 3. Map of the study area showing the profile lines for Wenner and VES arrays.](image)

![Figure 4. (a) Composite Lithologic description of the exposed section within the study area. (b) Photograph of outcrop exposed at Sokoto Cement Quarry (Lat 13°2'50.30", Lon 5°10'28.15'). (c) Photograph of outcrop exposed along the Quarry face (Lat 13°2'42.22", Lon 5°10'23.72'). (d) Photograph of outcrop exposure along Kalambaina Village (Lat 13°03'45.11", Lon 5°10'26.75').](image)
one underlying the Limestone, not exposed in this study area, is the shales of the Dange Formation. Geophysical studies were also carried out using Vertical Electrical Sounding (VES) and Electrical Resistivity Tomography – ERT to further delineate the near subsurface characteristics of sections within the study area where no outcrop exposure was available. This was necessary because of the continued success in the application of electrical resistivity for characterization of near-surface materials including groundwater, geotechnical site characterization, lithological characterization, etc (Adegbola et al., 2010; Adelekan et al., 2017; Bersezio et al., 2007; Kumar et al., 2014; Olasehinde et al., 2015; Oyedele et al., 2011).

The geophysical survey consists of VES and 2D geoelectrical resistivity. Survey design took into account the capabilities of the data acquisition system, heterogeneity of the subsurface electrical conductivity and the required resolution. Manual data measurement was adopted using an Allied Omega Terrameter for both the resistivity soundings and the 2D geoelectrical resistivity measurements. The survey was designed such that the VES and traverses cover the entire area of interest. It was conducted at the peak of dry season, and the lack of moisture was potential source of reading error, but was overcome by pouring some water on the ground before fastening the electrodes. A total of six VESs were conducted within the area with the aim of delineating the subsurface lithostratigraphy of the area. Schlumberger array with maximum half current electrode separation (AB/2) ranging from 1.5 m to 95 m was used for data measurements of the resistivity soundings. The choice of array was dependent on the geological structures to be delineated, heterogeneities of the subsurface, sensitivity of the resistivity meter, the background noise level and electromagnetic coupling. Other factors considered are the sensitivity of the array to vertical and lateral variations in the resistivity of the subsurface, its depth of investigation, and the horizontal data coverage and signal strength of the array. The 2D geoelectrical resistivity was conducted along two traverses (see Figure 3) along the North-West–South-East and Southwest–Northeast directions of the study area; due to proximity of company and its activities, Wenner array was used for the data measurements. Wenner array is preferred for surveys in a noisy site because of its high signal strength. Each of the traverses was 180 m in length due to space limitation; the electrode separation used for the measurements ranges from 10.0 to 60.0 m in an interval of 10.0 m. To ensure data quality, the electrode positions were clearly marked and pegged before the commencement of the data measurements for each traverse as well as the resistivity soundings. This ensured that electrode positioning error commonly associated with manual multi-electrode data measurements was minimized. Good connectivity between the electrodes and the connecting cables was ensured, while maintaining effective contact between the ground and the electrodes. The injected current was automatically selected from a minimum of 1.0 mA to a maximum of 200.0 mA by the resistivity meter based on the subsurface conductivity. Electrical Resistivity Tomography (ERT), that uses electrical imaging surveys to map subsurface areas thought to be characterized by complex geology was also carried out according to the method of Griffiths and Barker (1993) to complement the data generated from the VES.

Borehole core data for three holes were made available and used for sedimentological description, this was complemented with outcrop data and used for integration with resistivity data for subsurface lithology characterization.

**Data processing**

The apparent resistivity data generated from the soundings were plotted against AB/2 on bi-logarithmic sheets. The field curves were then curve-matched with Schlumberger master curves to obtain estimate of the resistivity and thickness of the delineated layers. The estimated geoelectric parameters were then used as initial models for computer iteration on Win-Resist program to obtain model geoelectric parameters for the delineated layers.

Similarly, the 2D apparent resistivity data sets for each traverse were inverted using RES2DINV inversion code as outlined by Loke and Barker (1996). The RES2DINV program uses non-linear optimization technique that automatically determines the inverse model of the 2D resistivity distribution of the subsurface for the apparent resistivity (Griffiths & Barker, 1993; Loke & Barker, 1996).

The program subdivides the subsurface into a number of rectangular blocks based on the spread and density of the observed data as well as the survey parameters (electrode configuration, electrode spacings and positions, and data level). Least squares inversion technique with standard least-squares constraint (L2-norm), which minimizes the square of the difference between the observed and the computed apparent resistivity values, was used for the inversion.

**Results and discussion**

The interpreted result for the VES survey is presented in Table 1. After converting resistance to resistivity by multiplying with appropriate geometrical factors for the Schlumberger array, the VES data were plotted on log-log graphs with apparent resistivity and half electrode separation (AB/2) values on the ordinate and abscissa respectively (Figures 5–8). Geoelectric
Table 1. Interpreted results for all VES locations/points.

| VES no. | Layer | Resistivity (Ωm) | Depth (m) | Curve type | Inferred lithology |
|---------|-------|------------------|-----------|------------|-------------------|
| 1       | 1     | 608.2            | 1.80      | QH         | Ironstone         |
|         | 2     | 100.7            | 0.8       |            | Ironstone/Limestone |
|         | 3     | 26.0             | 10.8      |            | Limestone         |
|         | 4     | 13.1             | ??        |            | Shale             |
| 3       | 1     | 1387.0           | 2.3       | QH         | Ironstone         |
|         | 2     | 172.4            | 12.5      |            | Limestone         |
|         | 3     | 13.7             | 27.4      |            | Shale             |
|         | 4     | 69.1             | ??        |            | Sandy clay        |
| 6       | 1     | 1386.0           | 2.5       | QH         | Ironstone         |
|         | 2     | 137.3            | 14.0      |            | Limestone         |
|         | 3     | 12.7             | 30.4      |            | Shale             |
|         | 4     | 91.4             | ??        |            | Sandy clay        |
| 7       | 1     | 1374.1           | 2.0       | QHQ        | Ironstone         |
|         | 2     | 237.4            | 13.10     |            | Limestone         |
|         | 3     | 37.6             | 18.9      |            | Shale             |
|         | 4     | 38.8             | ??        |            | Clay/Sandy clay   |
| 8       | 1     | 473.4            | 2.2       | QH         | Topsoil/Ironstone |
|         | 2     | 109.5            | 3.1       |            | Ironstone         |
|         | 3     | 94.1             | 7.8       |            | Limestone         |
|         | 4     | 23.3             | ??        |            | Shale/Clay        |

Figure 5. Typical curve for VES station 1.

Figure 6. Typical curve for VES 7.
Figure 7. Typical curve for VES station 8.

Figure 8. Typical curve for VES station VES 3.

Figure 9. Geoelectric sections of VES 1–3.
sections were constructed to visualize the subsurface distribution of the various lithologic units along W–E (geologic strike) directions using GeoGraphic 2012 software and the results obtained are shown in Figure 9. Superimposed upon the geoelectric sections are borehole description data that effectively assisted in the correlation of borehole and geologic data. 1D resistivity model curves of the study area for VES 1, 3, 4 and 5 are presented (Figures 5–8).

The computer-iterated curves showed a smooth geometry of four layers, characteristic of a typical sedimentary terrain. The curve types identified within the study area include QH, and OHQ, type with the QH as the predominant curve type. Four VES data (Table 1) presented reveal a maximum of four geo-electric layers which is composed of topsoil/ironstone, Limestone, Shale and Clay/sandy-clay intervals.

This interpretation was achieved by combining the resistivity and conductivity values with those of established ranges for rocks, soils and water as presented in Table 2 and comparing also with the litho-logs from the study area. The topsoil typically has a relatively high resistivity between the range 1387.0 and 473.4 \( \Omega \text{m} \) and thickness range of 0.0–2.5 m. The high resistivity values of the topsoil are attributed to the hard nature of ironstone deposits in the study area. The second layer has resistivity and thickness values ranging from 26.0 to 172.4 \( \Omega \text{m} \), and 2.0–14.0 m respectively and was inferred to be Limestone. The third layer has resistivity range of 12.7 \( \Omega \text{m} \) to 13.1 \( \Omega \text{m} \), was inferred to be Shale, while the fourth layer resistivities ranged from 23.3 to 91.4 \( \Omega \text{m} \) and sandy clay was inferred.

The 2D Wenner resistance data was converted to resistivity by multiplying it with the appropriate geometrical factors of \( 2\pi a \), where “a” represents the spacing. The appropriate resistivity values for the 2D data set were inverted for true subsurface resistivity using RES2DINV inversion software and the resulting estimated models presented and interpreted accordingly (Figure 10(a,b)). The ERT surveys were interpreted by integrating the resistivity and conductivity values of rocks, soils and water as shown in Table 2 with the described lithology (outcrop and drill-hole data) across the study area. In survey 1 (DHS3 ERT), the model

| Material                        | Resistivity (\( \Omega \text{m} \)) | Conductivity (\( \Omega \text{m}^{-1} \)) |
|---------------------------------|-------------------------------------|------------------------------------------|
| Igneous and metamorphic rocks   |                                     |                                          |
| Granite                         | \( 5 \times 10^2 - 10^6 \)          | \( 10^{-2} - 2 \times 10^{-4} \)         |
| Basalt                          | \( 10^2 - 10^5 \)                   | \( 10^{-6} - 10^{-5} \)                  |
| Slate                           | \( 6 \times 10^2 - 4 \times 10^7 \) | \( 2.5 \times 10^{-6} - 1.7 \times 10^{-3} \) |
| Marble                          | \( 10^2 - 2.5 \times 10^4 \)       | \( 4 \times 10^{-2} - 10^{-3} \)        |
| Quartzite                       | \( 10^2 - 2 \times 10^8 \)         | \( 5 \times 10^{-5} - 10^{-4} \)        |
| Hornfels                        | \( 8 \times 10^2 - 6 \times 10^7 \) | \( 1.7 \times 10^{-4} - 1.3 \times 10^{-3} \) |
| Sedimentary rocks               |                                     |                                          |
| Sandstone                       | \( 8 - 4 \times 10^3 \)             | \( 2.5 \times 10^{-5} - 0.125 \)        |
| Shale                           | \( 20 - 2 \times 10^3 \)            | \( 5 \times 10^{-4} - 0.05 \)           |
| Marl                            | \( 3 - 7 \)                         | \( 1.4 \times 10^{-6} - 0.3 \)          |
| Limestone                       | \( 50 - 4 \times 10^2 \)            | \( 2.5 \times 10^{-4} - 0.02 \)         |
| Soils and water                 |                                     |                                          |
| Clay                            | \( 1 - 100 \)                       | \( 0.01 - 1 \)                           |
| Alluvium                        | \( 10 - 600 \)                      | \( 1.25 \times 10^{-3} - 0.1 \)         |
| Groundwater (fresh)             | \( 10 - 100 \)                      | \( 0.01 - 0.1 \)                         |
| Sea water                       | \( 0.15 \)                          | \( 6.7 \)                                |

Figure 10. Wenner array Pseudo-sections (a) DHS3 and (b) DHS8.
resistivity inversion revealed four (4) major geoelectrical layers. The four geoelectrical layers have resistivity range > 72.0 Ωm (Ironstone), 24.1 – 72.3 Ωm (Limestone), 4.66–20.6 Ωm (Shale unit) and < 5.0 Ωm (Clay unit). In the second survey (DHS8 ERT), five (5) geoelectrical layers were identified. These include the topsoil interpreted to be ironstone with resistivity greater than 70 Ωm and with depth range of 2 m down to 10 m though thinning out westwards (West – East direction of the survey). The topsoil overlies another layer interpreted to be ironstone-limestone intercalations suggesting that the limestone boundary is gradational. The second geoelectrical layer has the thickness of about 6–7 m with resistivity range 50.3–70 Ωm. The third geoelectrical unit is a limestone with thickness ranging from 12 m to 26 m and resistivity values ranging from 23.5 to 50.3 Ωm. Shale and Clay units form the fourth and fifth layers with resistivity values range 7.0–18.0 Ωm and 0–7.49 Ωm respectively.

**Stratigraphic correlation**

Within the area of interest, eight (8) exploratory well had been drilled. For the purpose of this study, information from three (3) well were used in modelling the VES and ERT data, while all others were integrated in stratigraphic analysis (correlation). Information from the boreholes (H-1, H-3 and H-8) previously drilled close to the quarry were integrated with some selected VES locations and in between the wenner profiles; and their interpretations revealed that the stratigraphic succession within the area was sandy clay, shale, limestone and ironstone from the base to the top. The description of borehole data from H-1, H-3 and H-8 are as presented in Figures 11–13. The Sokoto Group, within which this study is undertaken, constitutes a narrow stratigraphic succession that is unevenly distributed in terms of their sediment thickness, about 37 km in the north and up to 280 km towards the southern part of the basin. For this reason, information about the precise location and distribution of the limestone deposit is important.

![Figure 11. Lithology description for borehole H-1.](image-url)
Within the area investigated, indicative features and characteristics of ironstone, shale, limestone and clay/sandy clay were observed in all the methods adopted. The ironstone, which forms the topsoil material averaged about 5.10 m deep. The resistivities revealed patches of very high readings; and pockets of medium resistivity readings (both with VES and Wenner surveys). The high resistivity values may have resulted from some massive rocky boulders common in the area forming minor scarps and characterized by medium resistivity of unconsolidated clayey laterites/mudstone. Underlying the ironstone is a limestone unit as observed in the borehole data and geophysics model. But 100 m north of borehole H-3 and 500 m southwest of borehole H-8 of the area, geologic mapping carried out revealed shale unit immediately after the top ironstone (Figure 4(a-d)). This lithostrata (shale) is about 0.50–5.00 m thick. According to Kogbe (1973), Obaje (2009), and Nwajide (2013), the shale unit is referred to as Gamba Formation. This Formation is not uniformly distributed throughout the area based on information from borehole drilling campaign in the area. This character may be attributed to pinching-out of this unit laterally or it may have experienced rapid erosional activity shortly after deposition during the regression of the Trans-Saharan sea. Kogbe (1976) thought that it may have been due to gradual desolution and weathering of the already “folded” formation. Therefore, the overlying shale unit is gradually being removed by solution of the underlying limestone unit and slumping of the overlying ironstone. Surface mapping revealed some gradational contact between the shale unit and ironstone, but the drilled boreholes showed sharp contact between the ironstone and the underlying limestone at their drilled positions. This was also interpreted from the shallow geophysical surveys in the area. The light grey, whitish grey, chalky limestone unit encountered in all the drilled holes varies slightly from 11.2 m to 15.70 m in thickness (Figures 11-13) and at the mapped areas, the bottom of the unit was not exposed (see Figure 4(b-d)). It showed gradational contact with the underlying shale unit but sharp contact with the overlying ironstone. This shale layer is

![Figure 12. Lithology description for borehole H-3.](image-url)
Figure 13. Lithology description for borehole H-8.

Figure 14. Fence diagram showing the distribution of the different formation in the area.
characterized by yellowish to brownish colour in its exposed surfaces and has few fossil (Figure 4(b-d)). The underlying Kalambarina limestone unit is overlain by ironstones in most places (Kogbe, 1973). This succession is not observable in outcrop exposures. A stratigraphic fence diagram was prepared using information from all the drill holes available within the area of interest and integrated with the ERT to model the subsurface and determine the distribution of the geobody (limestone) of interest (Figure 14). Directly underlying the Kalambarina limestone is a shale Formation known as the Dange Formation. The shale is grey to dark grey in colour while the slightly weathered portion becomes yellowish in colour. It exhibits high fissility and contains abundant phosphate nodules. It is gypsumiferous towards the base and generally constitutes the basal formation of the Sokoto Group. Unconformably underlying the Dange Formation is the Wurno Formation (the youngest formation of the Rima Group). As revealed from this study, the subsurface lithological characterization and lateral extent of part of the Sokoto Group is divisible into four-layer sections. The significance of ERT techniques integrated with a good control on the sedimentologically described core data available at point locations has proven to be very useful in the delineation of the geobody of interest, in this case, the limestone unit (11.2–15.7 m).

Using the subsurface stratigraphic model developed for the area, sections with varying thickness and especially towards the NE and central portion of the investigated area were identified (Figure 14). Also, the overburden thickness was observed to be not more than 5.1 m across the study area and this, in itself, shows how the integration of ERT studies will largely reduce exploration cost in the reduction of overall number of exploratory boreholes to be drilled if properly deployed.

Conclusions
Surface geological mapping enhanced through the integration of shallow subsurface geophysical mapping largely facilitated the delineation of the geometry of limestone resource within the area investigated. Such an integrated approach is highly recommended especially in areas with limited subsurface/borehole data and where a high degree of exploration accuracy is anticipated. Although the availability drill holes and/or core data may provide exact down-hole lithologic information of any particular location, this information is largely limited due to its 1D nature. Another consideration is from the budgetary point of view during project management stages. Heterogeneity of geological/earth materials is a major challenge during exploration and must be catered for. Future development of mining areas will find subsurface lithological analysis very important to the developmental plans. This has made this study of utmost significance, and when compared to complementary approaches, this approach seems to be the most suited, accurate and less expensive. It is therefore recommended in areas deficient in exposed rocks (outcrops) and subsurface information.

Acknowledgments
We acknowledge the management of MECON Geology and Engineering Services Ltd for providing the Borehole data and permitting its use in this study. Also, we thankfully acknowledge all the authors whose works were referenced to validate our thoughts in this study.

Disclosure statement
No potential conflict of interest was reported by the authors.

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