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GEOELECTRICAL AND GEOCHEMICAL INSIGHTS INTO EXPLORATION POTENTIALS OF KAOLINITIC CLAY DEPOSITS IN OBUDU MASSIF, SOUTH EASTERN NIGERIA

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ABSTRACT

Combining various techniques in delineating mineral deposits increases the chance of practical discovery and characterization of potential mineralization zones. Choosing a suitable dataset is a key factor for a detailed geophysical and geochemical mineralization mapping. geophysical and geochemical techniques have proven their effectiveness as tools for reliable mineral mapping. In this study, twenty (20) Vertical Electrical Sounding (VES) stations were observed with maximum AB/2 of 300m and 5 transects electrical resistivity tomography traverses were conducted along selected profiles. The geoelectrical results revealed four to six electro-lithostratigraphic units. The electro-lithostratigraphic unit with resistivity varying between 10 Ωm and 90 Ωm were identified as kaolinite-rich zones. Samples of kaolinite collected were subjected to laboratory analyses ensuring their compliance with industrial standards. X-ray Diffraction (XRD) confirmed the presence of kaolinite as the dominant mineral, along with trace amounts of quartz and feldspar. X-ray fluorescence (XRF) revealed high concentrations of aluminum (Al_2O_3) 73. 5% and silicon (SiO_2) 25.6% respectively. The low content of iron oxide (Fe_2O_3) 0,8% and titanium dioxide (TiO_2) 0.1% observed established the purity of the kaolinite. Scanning Electron Microscope (SEM) revealed well-formed kaolinite crystals with hexagonal platelets while the particle size distribution with the majority of particles being <2µm. The specific gravity (SG) test revealed an average 2.92kg on average and further support the high-quality index of the deposit. The findings revealed that the kaolinite deposits in Obudu Massif, Southeastern Nigeria possess the requisite quality and quantity for commercial exploitation. The geoelectrical resistivity method proved to be an effective tool for mapping and evaluating the deposits, offering a cost-efficient approach for preliminary exploration. This study provides a framework for future geoelectrical assessments of mineral deposits and underscores the potential economic benefits of developing kaolinite resources in the region.

KEYWORDS: Kaolinite deposits, exploration potential, Subsurface Characteristics, Industrial applications, Obudu Massif.

INTRODUCTION

The application of geoelectrical and geochemical datasets in the explorations of minerals has been widely employed (Egba, 2011 and 2013; Atanda *et al*., 2012; Ekwueme, 2013, Ogundana et al., 2015; Ulem et al., 2022).

The fundamental significant in these assessments is the ability of geoelectrical and geochemical datasets to delineate altered aluminium silicate in an anhydrous state, mainly found in feldspar bearing rocks like granite, that had been subjected to hydrothermal alteration processess (Geological Survey of Ethiopia, 2011).

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These zones may perhaps be notable according to the detected minerals that mostly manifest exceptional resistivity and geochemical signatures. The assessment and characterization of kaolinite deposits are essential for determining their suitability for various industrial applications, ensuring efficient resource utilization and sustainable economic development. Kaolinite, is a clay mineral with a wide array of industrial applications and it is a vital raw material in several sectors including ceramics, paper, paint, and pharmaceuticals. It is also, one of the most extensively distributed clays mineral resources in the world. The increasing demand for high-quality kaolinite necessitates the identification and evaluation of new deposits (Ekwueme, 1991; Badmus and Olatinsu, 2009; Atanda *et al*., 2012; Ekwueme, 2013; Akinyemi *et al*., 2014; Akinola and Obasi, 2014; Ogundana et al., 2015 Ulem et al., 2022). In Nigeria, specifically, the Obudu Massif, southeastern Nigeria, kaolinitic clays plays a significant economic potential due to their abundance and quality. Nevertheless, notwithstanding the economic importance of kaolinitic clays, understanding their lateral and depth extent, composition, and quality involves in-depth geophysical and geochemical studies that are often underexplored in many parts of Nigeria including Obudu Massif. Geoelectrical resistivity surveys have become a widely adopted method for subsurface exploration due to their non-invasive nature and ability to provide detailed information about the geological structures. Numerous studies have demonstrated the efficacy of this technique in identifying and characterizing mineral deposits, groundwater resources, and other subsurface features. Geoelectrical resistivity method involving vertical electrical sounding (VES) and Electrical resistivity tomography ERT) techniques have been successfully employed to map subsurface lithologies and delineate mineral deposits in various regions of Nigeria (Ekosse, 2010; Chima et al., 2018; Dewi1, et al., 2018; Adewole et al., 2020; Aliu et al., 2021 and Ulem et al., 2022). Similarly, geochemical analysis is crucial in evaluating kaolinite clay quality and suitability for various industrial applications. Geochemical techniques such as X-ray Diffraction (XRD), X-ray fluorescence (XRF) and Scanning Electron Microscope (SEM) are used to analyze major and trace elements, providing insights into the mineralogical composition and degree of alteration. Previous studies on kaolinitic clays in Nigerian have generally shown variable concentrations of silicon (SiO_2) and aluminum (Al_2O_3) usually reflecting the purity and potential industrial applications.

However, the interaction between geoelectrical properties and geochemical characteristics in assessing clay quality has not been fully explored in the Obudu Massif, where clay deposits remain under-characterized (Adewole et al., 2020; Aliu et al., 2021 and Ulem et al., 2022). These studies highlight the importance of integrating geoelectrical resistivity data with geochemical information to enhance the accuracy of subsurface characterization. In Nigeria, several scholars (E.g., Akinniyi et al., 2019; Olaonipekun et al., 2020; Aliu et al., 2021; Badmus, 2009; Badmus and Olatinsu, 2009; Egba, 2011; Atanda *et al*., 2012; Egba, 2013; Akinyemi *et al*., 2014; Akinola et al., 2014; Ogundana et al., 2015 & Ulem et al., 2022), have investigated the occurrences and properties of kaolinite deposits in different parts of the country. These studies have provided valuable insights into the mineralogical, geochemical, and physical characteristics of kaolinite, emphasizing its potential for various industrial uses. Despite the extensive research on kaolinite deposits and the application of geoelectrical resistivity and geochemical methods for subsurface exploration, there is a notable gap in the specific assessment and characterization of kaolinite deposits particularly in the Obudu Massif using geoelectrical resistivity and geochemical techniques. Previous studies have largely focused on other regions of Nigeria, leaving the kaolinite deposits in the Obudu Massif underexplored and uncharacterized. This may be attributed to inadequate technical information on their geology, compositional features and suitability for industrial applications (Premium Times. Nigeria, 2020). Therefore, Technical and scientific data on these kaolinitic deposits in both private sectors and government agencies have remained unrevealing. This state of affairs or information gap has continued to dampen both government and private investors interest in Obudu Massif kaolinitic deposits whereas, artisanal mining is incessant with attendant loss of revenue by government. Addressing this gap, it is crucial for unlocking the economic potential of kaolinite deposits in Obudu Massif and providing a scientific basis for sustainable resource management. Consequently, employing geoelectrical and geochemical techniques, this study will also contribute to the sustainable exploitation of kaolinite resources in the region, supporting local industries and fostering economic development.

Study area description

The Obudu Massif is located in Southeastern Nigeria, within the Cross River State. Geologically, the area is characterized by its rugged terrain, with elevations reaching up to 1,700 meters above sea level, making it one of the highest points in Southeastern Nigeria. The Obudu Massif is accessible via road from major cities such as Calabar and Enugu, making it a significant geographic and economic landmark in the region (Barne, 1981; Orajaka, 1964; Umeji, 1988; Ekwueme, 1991; Ukaegbu, and Ekwueme, 2005. Ushie and Anike, 2010;). Specifically, the study area (Fig. 1), falls within the southwestern part of Obudu in the southeastern Nigerian Precambrian basement complex, approximately delimited between latitudes $6^0$10' 25.5''N and 6^0 40' 15.5''N and longitudes 9^0 02' 10''E and 9^0 10' 0''E with an average elevation of 198 m above mean sea level covering an area of about 5000 m^2 (Ephraim et al., 2015).

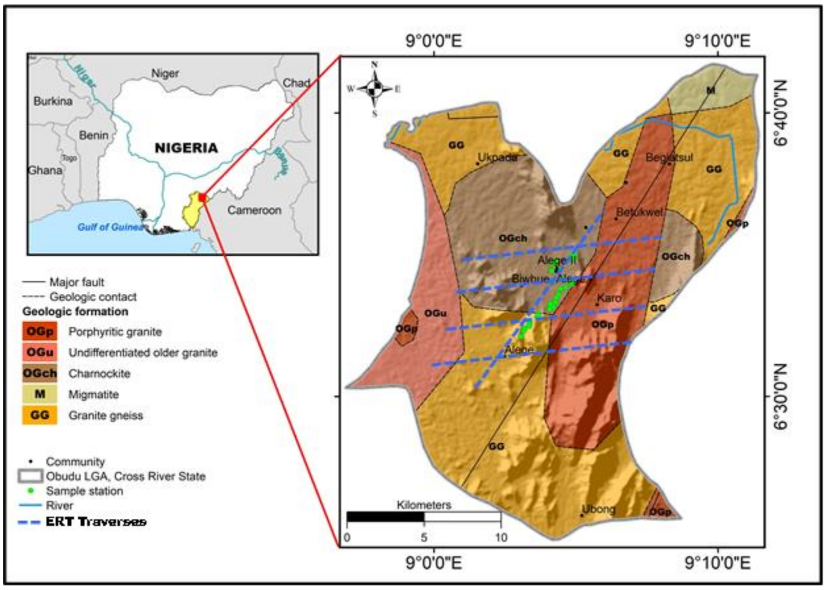

Fig. 1: Geology map of the study area showing VES stations and ERT traverses

Methods / Techniques

The geoelectrical resistivity assessment employed IGIS signal stacking resistivity meter model SSR-MP-ATS with good signal enhancement microprocessor-built data acquisition procedure. The SSR-MP-ATS model resistivity meter takes 16 cycles for data averaging with accuracy of $\pm$1 % and can penetrate up to the depths of 600 m under favourable geologic conditions. Field data acquisition was conducted using two standard electrical resistivity procedures involving vertical electrical sounding (VES) and electrical resistivity tomography (ERT) techniques.

The one-dimensional electrical resistivity data acquisition was performed in the sounding mode implementing the Schlumberger electrode configuration. In the geoelectrical resistivity technique involving vertical electrical sounding (VES), 30 stations were occupied and evenly distributed across the study area. Some vertical electrical sounding stations were observed close to boreholes construction sites and hand dug well locations that constrained resistivity measurements employing lithologic information from boreholes. The current electrode spacing, AB (transmitting line) ranges from 200 to 600m and the corresponding potential electrode spacing, MN (receiving line) varied between 0.5m to 20 m. The 1D data acquisition using the vertical electrical sounding technique was implemented by collinearly placing all the four metal stakes (electrodes) with respect to their common mid-point. After each successive measurement, the distance of the transmitting electrode is progressively increased from the centre. The observed one-dimensional apparent resistances at each station were converted into apparent resistivity values by applying equation 1.

$$\rho_{as} = \frac{\pi R a^2}{b} \quad (1)$$

Half current electrode separation a = AB/2 and the distance between the current electrodes, b = MN/2. The apparent resistance R, is derived from Ohm's law and it is given by equation 2.

$$R = \frac{V}{I} \quad (2)$$

Therefore, the quantity $\frac{\pi a^2}{b}$ is called the geometric factor G, which is depends on the procedure adopted.

The fraction of the total current penetrating the subsurface at depth Z and distance d, separating the current electrodes is given by equation 3 (Burger, 1992).

$$I_f = 2\pi tan^{-1}\left[\frac{2Z}{d}\right] \quad 3$$

Where, I_f = fraction of current penetrating the ground
d = distance between the current electrodes
Z = depth of current penetration

Two-dimensional electrical resistivity tomography (ERT) data were observed along twenty traverses in the profiling mode employing the Wenner electrode configuration to generate high resolution subsurface tomograms. The two-dimensional electrical resistivity tomography derived images display the spatial resistivity distribution of the subsurface. Ten parallel traverses were occupied in the NE-SE trending direction while the remaining ten traverses were occupied diagonally in the NW-SW directions. A constant inter-profile spacing of 50 m and inter-electrode spacing of 5 m was maintained. The spread length for the survey profiles ranges from 120 m to 200 m and were evenly distributed to ensure optimum coverage of the subsurface geological structures within the study area. The standard four electrodes (two current and two potential) system were used for the two-dimensional resistivity measurements. The subsurface responses to geological structures were estimated as apparent resistivity (ρ_a) by multiplying observed apparent resistances with the geometric factor for the Wenner electrode configuration equation 5.

$$\rho_{aw} = 2\pi aR \quad 5$$

$$R = \frac{\Delta V}{I}$$

Where, R = measured apparent resistance
I = injected current
ΔV = measured voltage between the potential electrodes

Fig. 2: Kaolinite sample collected from borehole construction sites for geochemical analysis

Results/Discussion

Several outcrops of kaolinite deposits were revealed from geological mapping, primarily located in the southwestern parts of the Obudu Massif. A total of 10 kaolinite samples were collected from various locations identified during mapping, hand dug wells and boreholes construction sites. The geoelectrical resistivity survey conducted across various sites in Obudu Massif, Southeastern Nigeria provided significant insights into the subsurface distribution and quality of kaolinite deposits. Findings from the resistivity measurements revealed 5 – 6 electro-stratigraphic distinct layers/units comprising of lateritic topsoil (sandy/clay to clay/sand intercalations), kaolinitic clay, weathered granitic rocks, fractured granitic rocks and fresh basement. The dominant layer with low to moderate resistivity values (typically between 10 – 90 Ωm), is indicative of clay-rich formations. These layers were identified at varying depths across the surveyed sites, confirming the presence of kaolinite deposits.

The characteristic modelled 1D derived apparent resistivity curves (Fig. 3) of the subsurface resistivity distribution obtained within the study area, are displayed as inverse apparent resistivity curves. The root mean square (rms) error of the inverse models mostly ranges from 2.2 % – 4.2 % on minimum iterations across the study area. The 1D modelled apparent resistivity curves (Fig. 3), indicate the presence of low resistivity zones ranging from 20 - 90 Ωm associated with kaolinite deposits, typically found at depth ranging from 5 - 40 m with average thickness of 35.5 m. The dominant curve types revealed in the study area are mostly H, HK and HKH, characterized by low resistivity, moderate resistivity and high resistivity geoelectric layers. The curves type reflects the resistivity variation and distribution with depth in the study area. The summarized primary geoelectric parameters obtained from the modelled 1D derived inverted apparent resistivity curves are presented in Table 1.

The top layer observed from 2-D electro-stratigraphic cross-section (Fig. 4) is predominantly lateritic to sandy-clay characterized by low to moderate resistivity that ranged from ~132 Ωm to ~606 Ωm with varying thickness ranging from ~1.0 m to ~10.0 m. The depth to the top of the kaolinite layer ranged from 2 – 10m in some locations, while the thickness of the kaolinite-bearing strata varied from 5 – 40 corresponding to the thickness observed along road cuttings and litho-logs. Lithologic data obtained from borehole drilling sites and hand dug wells indicates that kaolinite bearing layer is predominantly characterized by chalky to white silty clay. The spatial resistivity distribution demonstrated a heterogeneous kaolinite deposit, with some areas displaying more substantial and continuous kaolinite layers than others. The utmost significant deposits were found in regions with low resistivity anomalous zones, suggesting higher clay content. The lateral extent of the kaolinite deposits was delineated, revealing areas with potential for large-scale mining (Fig. 4). These zones exhibited extensive low-resistivity signatures, indicating substantial kaolinite reserves (Fig. 4). Correlating the resistivity data with Lithologic data obtained from borehole drilling sites, hand dug wells, and standard resistivity values and laboratory analyses, it was observed that regions with moderate resistivity values corresponded to high-quality kaolinite with negligible impurities. In contrast, very low resistivity values often indicated higher moisture content and potential contamination with other clay minerals. Complementary geochemical and mineralogical analyses of the borehole samples provided detailed information on the composition and quality of the kaolinite deposits.

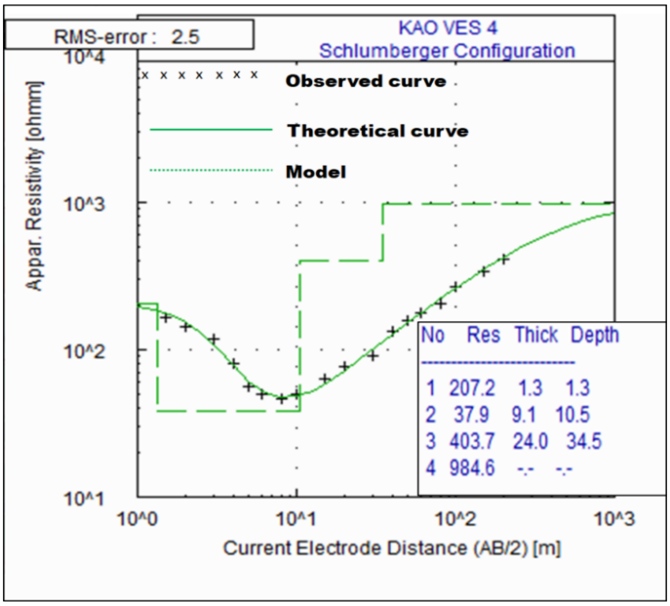

Fig. 3: Typical 1D inverted VES curve

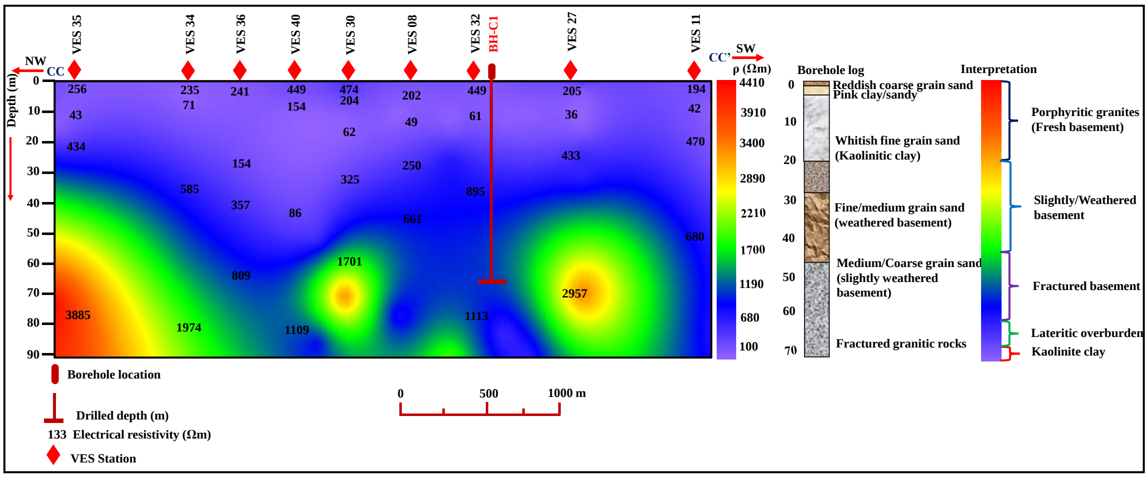

Fig. 4: Typical 2D derived electro-stratigraphic cross section

The 5 transects electrical resistivity tomography ERT conducted along 5 selected traverses were used to generate 2D derived tomograms. The 2D derived tomograms (Fig. 5a), revealed clearly the delineation of kaolinite-rich zones with resistivity ranging from 30 - 70 Ωm along the profile at varying depths ranging from ~2 m to ~15 m corroborating the findings of 1D derived apparent resistivity curves and 2D derived electro-stratigraphic cross sections. Artisanal mine pit was observed along the profile between stations 50m and 105m.

TABLE 1: Summary of primary geoelectric parameters

S/N	No. of layers	VES No.	Estimated electrical resistivity of the primary geoelectric layers (Ωm)					Estimated thickness of the primary geoelectric layers (m)				Estimated depth top to bottom of the observed geoelectric layers (m)				Estimated thickness of kaolin clay (m)
			ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	h_1	h_2	h_3	h_4	D_1	D_2	D_3	D_4	h_k
1.	4	NE-A01	146.9	38.6	74.7	1493.2	-	1.6	6.5	7.6		1.6	6.5	8.1	15.7	6.5
2.	4	NE-A02	198.2	65.9	247.1	1280.4		1.7	9.7	34.2		1.7	11.4	45.6	-	9.7
3.	3	SE-B03	470.9	52.6	2625.2	-	-	1.1	12.5	-	-	1.1	13.6	-	-	13.6
4.	4	SE-B04	456.9	66.4	519.7	1737.4		1.0	13.7	20.9		1.0	14.7	34.6	-	14.7
5.	5	NE-A05	183.3	51.1	627.9	1365.1	5600.4	2.0	10.6	20.0	33.5	2.0	12.6	32.6	66.1	10.6
6.	5	NE-A06	339.2	58.7	598.3	1206.1	2109.2	1.0	8.7	27.7	39.0	1.0	9.7	39.4	78.4	8.7
7.	4	NE-A07	148.5	42.4	461.8	650.0	-	1.1	10.7	21.2	-	1.1	11.8	33.0	-	10.7
8.	4	SE-B08	171.0	45.1	252.2	678.8	-	1.5	9.8	28.6	-	1.5	11.3	39.9	-	9.8
9.	4	SE-B09	264.6	71.8	439.5	868.7	-	2.0	13.0	26.9	-	2.0	14.0	40.9	-	13.0
10.	4	NE-A10	480.2	76.5	325.4	465.4	-	1.7	16.0	30.5	-	1.7	18.6	49.1	-	16.0
11.	5	NE-A11	502.3	74.8	185.7	888.6	1031.2	1.2	6.8	23.7	34.2	1.2	7.0	30.7	64.9	6.8
12.	5	SE-B12	606.1	81.0	152.3	1400.3	3865.3	1.6	10.0	16.1	30.5	1.6	11.6	27.7	58.2	10.0
13.	4	NW-C13	256.9	60.5	507.3	791.9	-	2.9	11.4	21.1	-	2.9	14.3	35.4	-	11.4
14.	4	NW-C14	441.2	79.8	458.2	653.1	-	1.1	14.0	60.4	-	1.1	15.1	75.5	-	14.0
15.	4	NW-C15	234.8	68.3	300.4	510.2	-	1.1	11.7	28.5	-	1.1	12.8	41.3	-	11.7
16.	4	NE-A16	263.8	63.6	146.4	638.9	-	6.8	17.7	41.4	-	6.8	24.5	65.9	-	17.7
17.	4	NW-C17	440.4	104.4	333.7	1023.6	-	2.2	39.3	51.0	-	2.2	41.5	92.5	-	25.3
18.	4	NE-A18	293.8	63.2	216.2	561.3	-	2.3	22.2	35.8	-	2.3	24.5	60.3	-	22.2
19	4	NW-C19	361.0	55.9	324.9	1002.0	-	1.6	12.2	24.1	-	1.6	13.8	37.9	-	12.2
20.	4	SE-B20	225.0	68.4	323.3	468.1	-	5.0	28.0	50.2	-	5.0	33.0	56.2	-	28.0

The 2D derived tomograms (Fig. 5b) generated from tomographic inversion procedure were used to create electro-lithostratigraphic cross section that represents the true subsurface geologic model. The electro-lithostratigraphic cross section (Fig. 5b) revealed 4 - 5 lithostratigraphic units with fine well graded sand (alluvium), kaolinite clay, saprolite clay, weathered granite and fresh basement. The electro-lithostratigraphic sequence also revealed the lateral and vertical subsurface resistivity distribution of the various lithologies penetrated. The primary geoelectric parameters such as kaolinite resistivity, kaolinite thickness and overburden thickness were deployed into Golden Surfer software version 19 to generate iso-maps. The kaolinite Iso-resistivity contour map (Fig. 6), revealed low to high resistivity from the northwestern part towards the southeastern parts of the study area.

The chemical composition of kaolinite samples exhibited high levels of alumina (Al_2O_3) 73. 5% and silica (SiO_2) 25.6% respectively. The low content of iron oxide (Fe_2O_3) 0.8% and titanium dioxide (TiO_2) 0.1% established the purity of the kaolinite, which is vital for its prospective industrial applications. Mineralogical characteristics obtained from X-ray diffraction (XRD) investigation validates the dominance of kaolinite in the samples, with minor amounts of quartz and illite. The crystallinity index of the kaolinite was high, indicating well-ordered kaolinite structures suitable for high-end industrial applications. Scanning electron microscopy (SEM) revealed well-formed kaolinite crystals with hexagonal platelets, further supporting the high quality of the deposits.

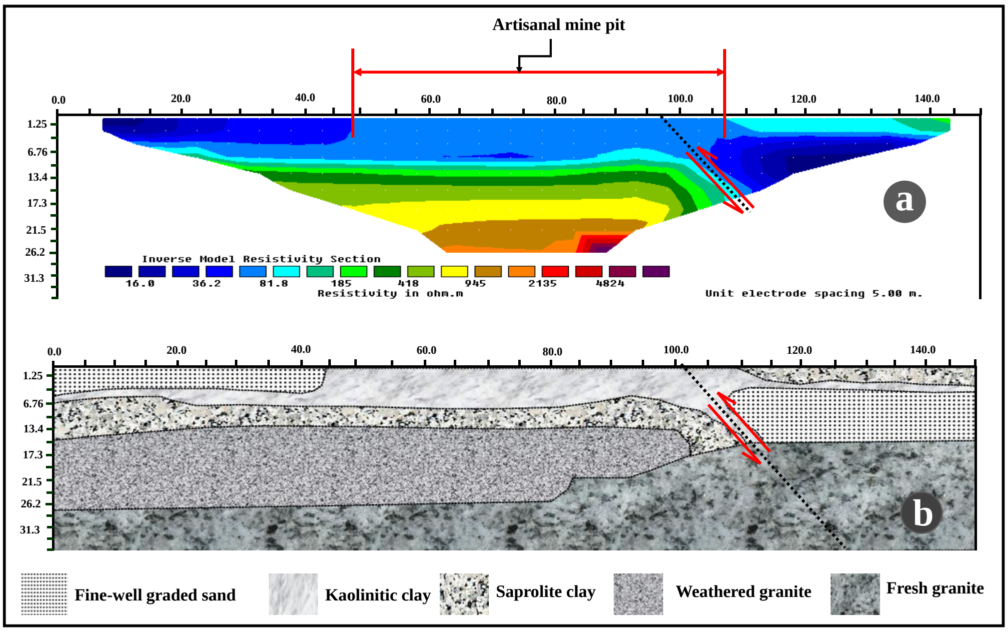

Fig. 5: (a) 2D derived inverted Tomogram (b) 2D derived electro-lithostratigraphic model

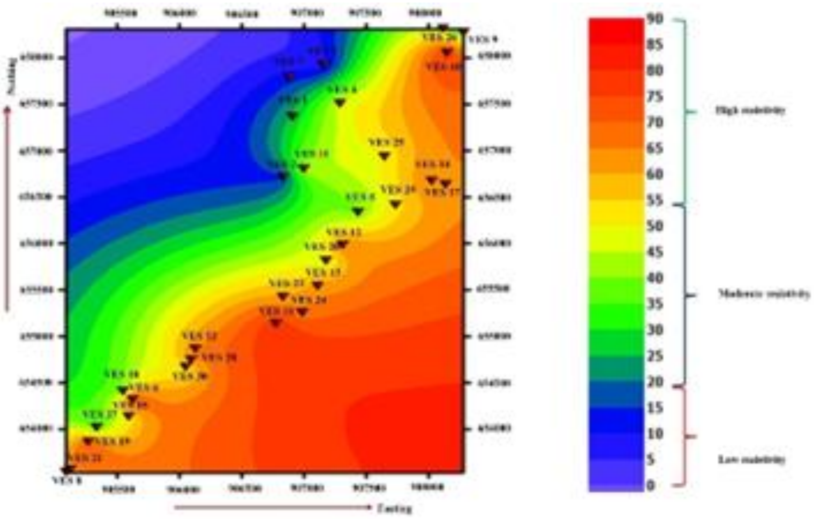

Fig. 6: Iso-resistivity contour map for kaolinite resistivity

The physical Properties indicating the particle size distribution analysis displayed that the kaolinite had a fine-grained texture, with the majority of particles being less than two micrometers (<2µm) in size. This fine particle size is advantageous for applications in the ceramics and paper industries, where smooth texture and high surface area are desirable. The findings of geoelectrical resistivity evaluation and laboratory investigations show that the kaolinite deposits in Obudu Massif, southeastern Nigeria are of high quality and suitable for various industrial applications. The results of geological mapping, geophysical inversion revealed a strong correlation between low resistivity signatures and kaolinite-rich zones and validated the geochemical results. Statistically, these trends and patterns confirmed the consistency of resistivity measurements and the spatial distribution of kaolinite-rich zones within the study area.

CONCLUSIONS / RECOMMENDATIONS

The present study integrated geoelectrical resistivity and geochemical datasets to interpret the hydrothermal alteration zones associated with kaolinization in the study area, underscoring the efficacy of combined geoelectrical and geochemical datasets. The two datasets are suitable for comprehensive delineation of altered aluminium silicate in an anhydrous state, mainly found in feldspar bearing rocks like granite, that are attributed to hydrothermal alteration processess.

The geoelectrical resistivity survey successfully delineated the depth and lateral extent of the kaolinitic clay zone while the geochemical data characterizes the kaolinitic clay zone to be of substantial high-quality. Laboratory analysis validates the high quality of the kaolinitic clay and its suitability for various industrial applications. The integrated technique using geological, geophysical and geochemical datasets provided a comprehensive understanding of the distribution, composition, and industrial suitability of the kaolinite deposit. Therefore, the present study unravels the hydrothermal alteration patterns dominated mainly by aluminum (Al_2O_3) 73. 5%, silicon (SiO_2) 25.6% respectively and low content of iron oxide (Fe_2O_3) 0.8% and titanium dioxide (TiO_2) 0.1% which established the minerals associated with kaolinization. These findings support the prospect of identifying genuine alterations zones associated with kaolinization and the potential for large-scale and sustainable mining of kaolinite resources, contributing to the regional economy and meeting the demands of various industrial sectors. Future work should focus on detailed feasibility studies and the development of environmentally friendly mining and processing techniques to maximize the benefits of these valuable resources.

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