



# GEOELECTRICAL CHARACTERIZATION AND LITHOLOGICAL MAPPING FOR CATHODIC PROTECTION DESIGN AT AGBARA SOUTHWEST NIGERIA

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**ABSTRACT:** This study integrates self-potential (SP) and electrical resistivity surveys to characterize subsurface lithological and electrochemical zones at the Agbara pigging station in Ogun State, Nigeria, with the objective of optimizing cathodic protection (CP) system design for buried pipelines. Geophysical logging was performed at depths up to approximately 45 meters, revealing resistivity values ranging from 1 to 28 Ohm-ft and SP measurements from 0 to 16 mV. Zones with resistivity values between 11 and 28 Ohm-ft and SP values from 8 to 16 mV were identified as favourable for effective CP application due to their lower salinity and reduced electrochemical activity, indicating less corrosive environments. Conversely, highly conductive zones with resistivity below 5 Ohm-ft and SP below 4 mV correspond to saline, mineralized sediments that pose higher corrosion risks and may compromise CP efficiency. The correlation between resistivity and SP signatures underscores the influence of subsurface lithology on electrochemical behaviour and corrosion potential. These findings demonstrate that combined geophysical methods offer a reliable, non-invasive means to delineate suitable zones for ground bed placement and corrosion mitigation strategies, thereby enhancing the longevity and safety of pipeline infrastructure in complex geological settings.

**KEYWORDS:** *Cathodic Protection, Self-Potential, Electrical Resistivity, Subsurface Lithology, Corrosion risk, Geophysical Logging, Dahomey Basin, Agbara, Petrophysics*

## INTRODUCTION

One of the problem of Agbara area is lack of high-resolution lithostratigraphic data which leads to risks in construction and groundwater management. The Dahomey Basin is one of the most significant sedimentary basins in West Africa, stretching from eastern Ghana through Togo and Benin Republic into Southwestern Nigeria. In Nigeria, this basin hosts critical industrial hubs, most notably the Agbara Industrial Estate in Ogun State. As industrialization expands, the demand for precise subsurface characterization becomes paramount—not only for groundwater exploration and foundation engineering but also for the installation of cathodic protection systems to safeguard buried metallic infrastructure from soil-induced corrosion. Lithostratigraphic Mapping of the Agbara Industrial Zone was done with aim of Delineate Lithological Units (by Identify the depth and thickness of the sands vs. the clays/shales), Determine the Water Table/Aquifer Boundary, Evaluate Engineering Suitability by using the data to discuss the load-bearing capacity of the upper 100 ft for industrial construction in Agbara through Using SP and Resistivity logs which are common in this part of Ogun State. An efficient anode ground bed (AGB) is fundamental to the effectiveness of impressed current cathodic protection (CP) systems, as it ensures optimal dissipation of current into the subsurface. The performance of the AGB critically depends on its placement within low-resistivity zones, which facilitate better current flow and reduce the risk of localized corrosion (Ogunleye et al., 2022). Consequently, mapping areas of low resistivity within the subsurface is essential for identifying suitable AGB locations. Among the geophysical tools employed for this purpose, self-potential (SP) logging is particularly valuable for delineating zones of varying resistivity, estimating formation water resistivity, calculating shale volume, identifying permeable beds, and detecting areas with different water salinities. Lithological and SP logs have been effectively used to characterize conductive zones at the Agbara pigging station in Ogun State, revealing signals associated with clay and shale formations, which are confirmed by lithological samples collected onsite.

Several authors have demonstrated the utility of SP and resistivity measurements across different applications. For example, Ezebunanwa et al. (2020) used geophysical Ves to assess dam site conditions, while Eluwole and Oladimeji (2013) applied

similar techniques in groundwater exploration. In mineral exploration, Nwugha et al. (2025) emphasized the reliability of resistivity data in identifying mineralized zones. These studies highlight that both resistivity and lithological data reliably indicate zones with low resistivity, which are typically associated with high conductivity materials such as clays and shales, as confirmed by lithological samples from the site.

Corrosion of underground pipelines remains a critical challenge worldwide, including Nigeria, where aging infrastructure and aggressive soil environments exacerbate corrosion rates (Ojo et al., 2018). Effective mitigation strategies, such as cathodic protection, are vital to prevent pipeline failures, environmental contamination, and economic losses (Akinwale et al., 2020). The success of CP systems hinges on accurate identification of suitable installation depths, which are influenced by subsurface geological and geophysical conditions (Ejike et al., 2021).

Geophysical well logging techniques, including spontaneous potential and resistivity measurements, provide crucial insights into subsurface conditions, enabling engineers to locate zones of varying conductivity, delineate lithological boundaries, and identify areas susceptible to corrosion (Ogunleye et al., 2022). Advances in data acquisition and interpretation software, such as Strater 5, have improved the precision and efficiency of analysing these profiles, supporting optimal placement of CP systems (Adetunji et al., 2020). Such integrated approaches are particularly relevant in Nigerian terrains, where complex soil compositions, groundwater chemistries, and geological heterogeneities influence corrosion dynamics and CP effectiveness.

This study leverages geophysical logging techniques to determine the optimal depths for cathodic protection installation at a piggery station in Agbara, Ogun State. By combining field measurements with modern interpretation tools, the research aims to optimize CP deployment, thereby enhancing pipeline longevity, safety, and cost-efficiency in complex subsurface environments.

### **GEOLOGY OF THE STUDY AREA**

The study was conducted in Agbara, Ogun State, Nigeria, located at approximately latitude 6.518745° N and longitude 3.077442° E, with an elevation of about 15 feet above sea level. This region lies within the southwestern Nigeria sedimentary basin, which is characterized by a sequence of sedimentary formations resulting from depositional and tectonic activities over geological time scales.

The predominant geological formation in Agbara is part of the Benin Formation, also known as coastal plain sands, a major geological unit in southwestern Nigeria. The Benin Formation comprises predominantly clay, shale, siltstone, and sand, with interbedded clayey soils and sandy deposits. These sediments are generally unconsolidated or semi-consolidated and are overlain by recent alluvial and colluvial deposits associated with riverine and coastal processes (Adeleke et al., 2017; Ojo et al., 2018). The formation's high permeability and saturation levels influence local hydrogeology and resistivity measurements in geophysical surveys.

In addition, at greater depths, mineralized saline zones have been observed, likely resulting from saline groundwater influx and mineralization processes within the sedimentary sequence (Ajayi & Akinbami, 2020). These zones affect the electrical resistivity and electrochemical properties of the subsurface, which are vital considerations in assessing corrosion potential and designing cathodic protection systems.

Overall, the geological setting of Agbara is characterized by clayey, silty, and sandy sediments within the Benin Formation, overlain by recent alluvial deposits. This stratigraphy significantly influences the geophysical responses and subsurface conditions encountered during investigations.

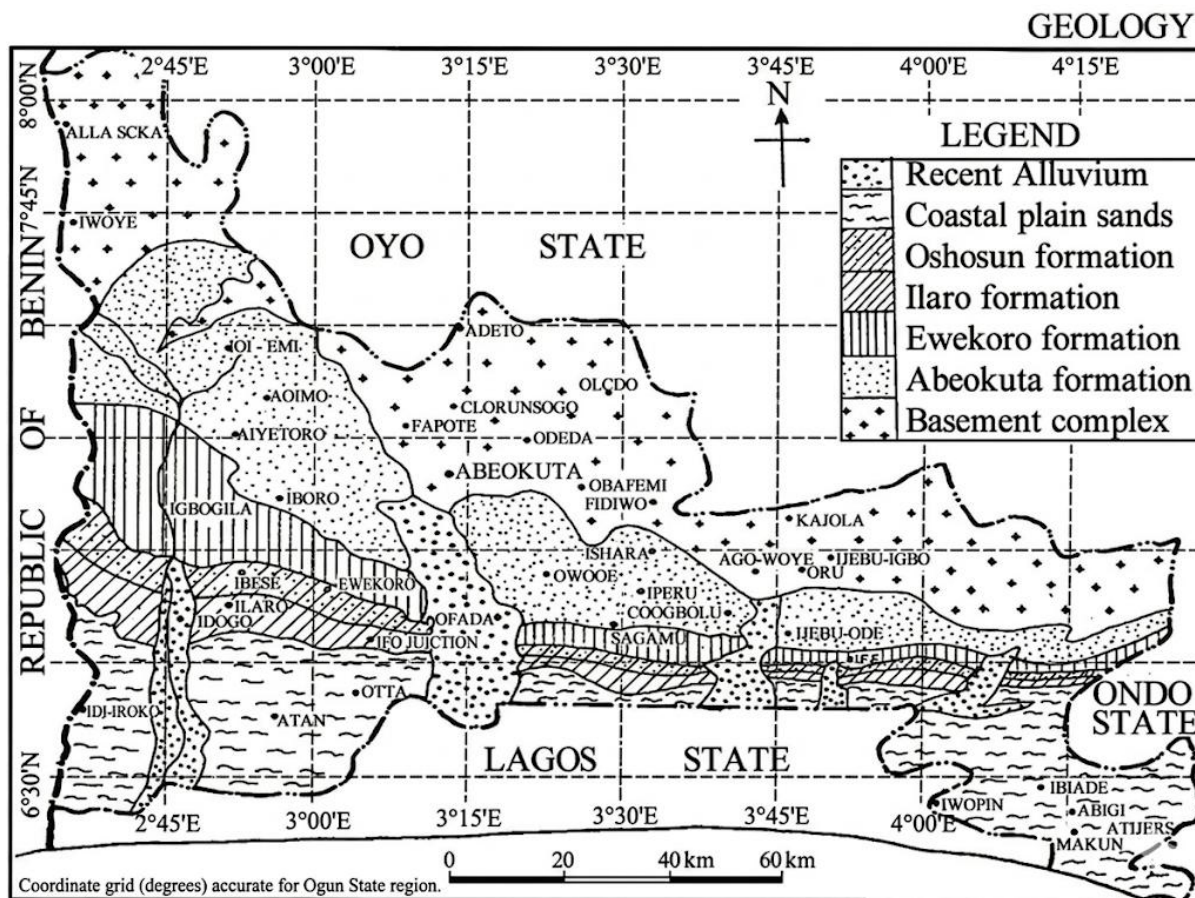


Fig 1:Geology map of the study area

### MATERIALS AND METHODS

Geophysical logging was conducted using a Keck geophysical logging system to evaluate the subsurface properties of the borehole at the Piging Station Agbara, Ogun State. The primary objective was to identify suitable depths for the installation of cathodic protection to mitigate corrosion of underground pipelines. The system measures two key parameters: spontaneous potential (SP) and resistivity. The sonde was carefully lowered into the open borehole, ensuring that the sensors for SP and resistivity remained fully immersed in the drilling mud to obtain accurate and reliable measurements (Keller & Frischknecht, 1966).

Measurements were recorded at 3-meter intervals, extending to a depth of approximately 148 meters. Resistivity values were specifically measured at lateral invasion depths of 2.5 inches and 10 inches, corresponding to the penetration of the electrode array into surrounding formations, following standard geophysical logging practices (Reynolds, 2011). The collected data were plotted to produce detailed profiles of the subsurface electrical properties, facilitating interpretation of lithology, formation boundaries, and zones of varying conductivity (Clark, 1996). The interpretation of the logs was aided using Strater 5 software, which enabled effective visualization and analysis of the resistivity and SP data, allowing for the identification of optimal depths for cathodic protection application (Alan et al., 2012).

The integration of geophysical data with geological and operational considerations ensures that the selected depths will provide effective corrosion protection, thereby enhancing the integrity and longevity of the pipeline system.

### RESULTS AND INTERPRETATION

The resistivity and self-potential (SP) measurements obtained from the surface to a depth of 45 meters are presented in Figures below:

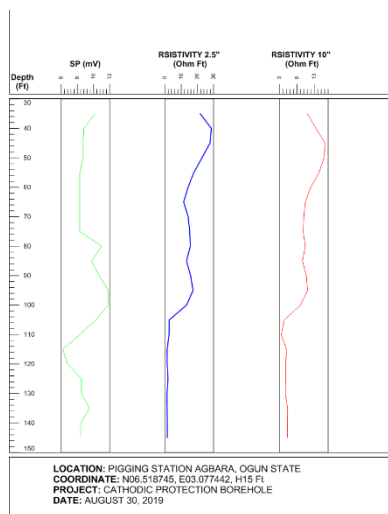


Figure 2: The SP & Resistivity signatures

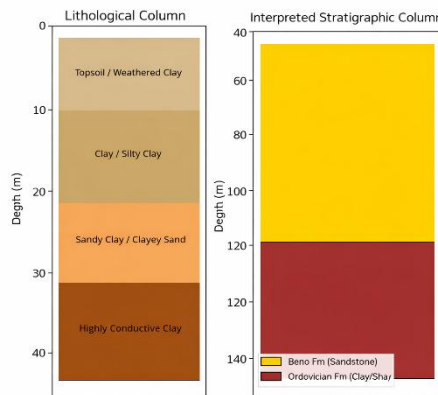


Fig 3 Integrated lithological and stratigraphic column

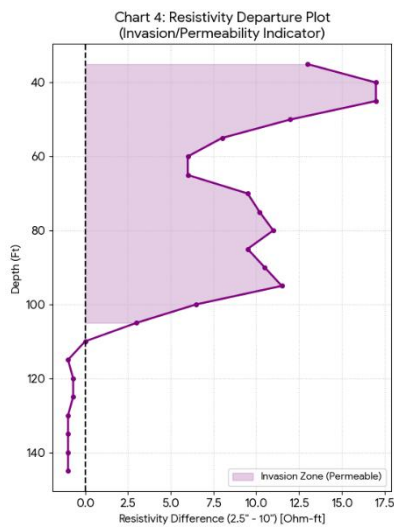


Figure 4

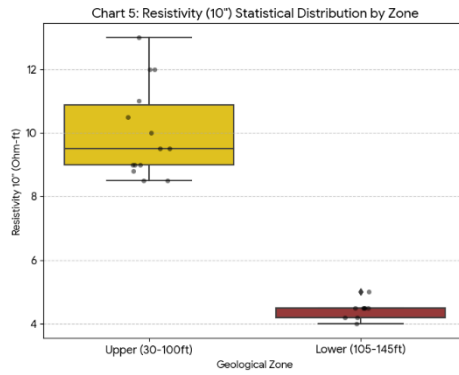


Figure 5

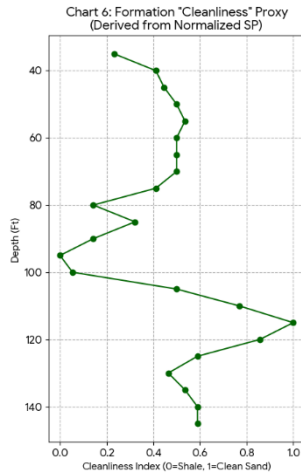


Figure 6

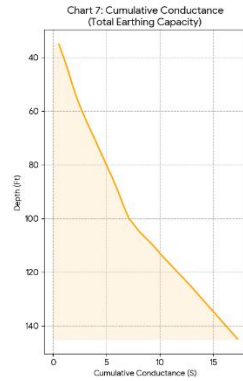


Fig 7

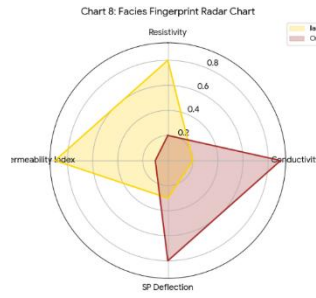


Fig 8

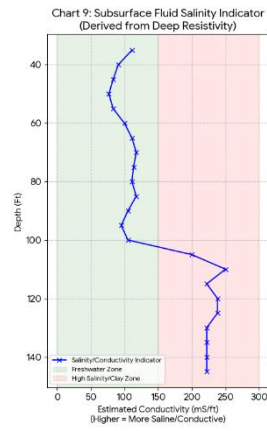


Figure 9

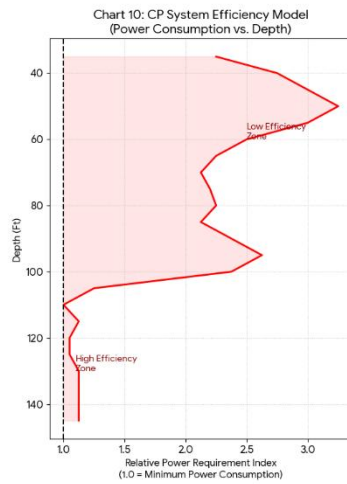


Figure 10

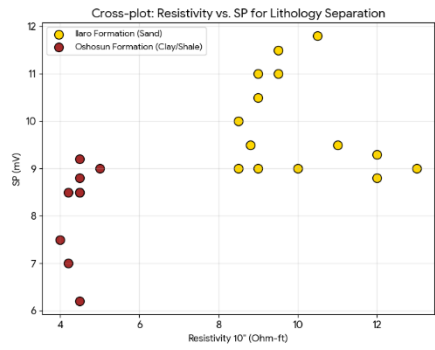


Figure 11

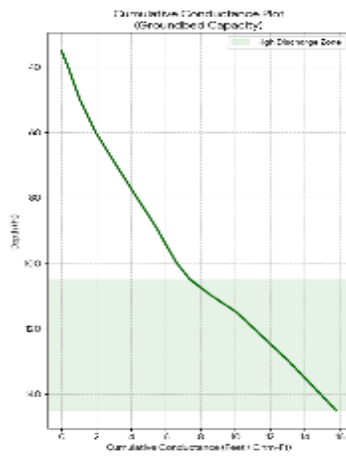


Fig 12 Grounded capacity

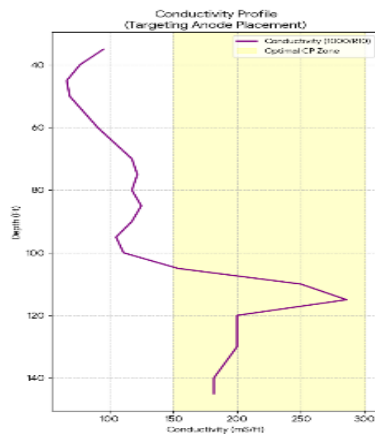


Figure 13 Conductivity profile

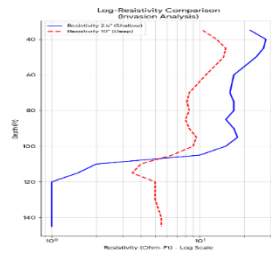


Figure 14 Resistivity comparison

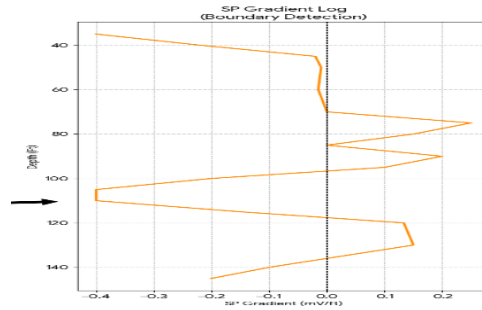


Figure 15 Gradient log

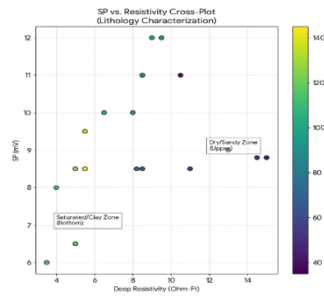


Fig 16 SP vs Resistivity cross plot

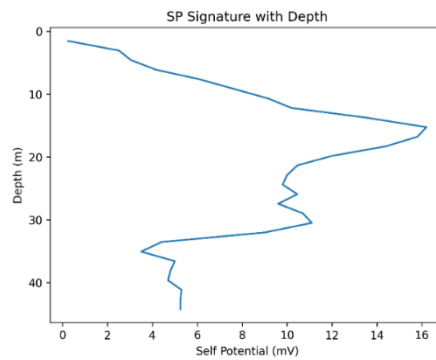


Figure 17 SP signature with depth



Figure 18: Resistivity variation with depth showing conductive zones influencing cathodic protection efficiency

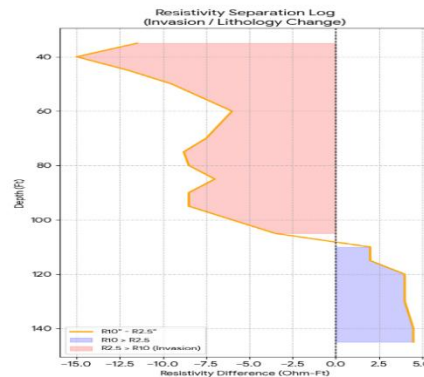


Fig 19 resistivity separation log

Table 1 Summary Table for Cathodic Protection Project

Depth	SP(mV)	Resistivity (Ohm-Ft)		Interpretation	Probable Lithology	CP Suitability
		2.5"	10"			
0-40	9.0	28.0	13.0	High-resistance overburden	Silt / Sandy Clay (Dry)	Poor (High Resistance)
40-70	8.5	16.0	8.5	Intermediate layer		
70-105	10.0	10.0	6.5	Transition zone	Transition Zone	Marginal
105-120	6.5	1.0	5.0	Primary Ground bed Zone	Saturated Clay / Aquifer Excellent (Low Resistance)	
120-140	9.5	1.0	5.5	Primary Ground bed Zone		

### INTERPRETATION

In CP, we are usually looking for a particular depth to place an anode—typically a zone with low soil resistivity to ensure the protective current can easily flow from the anode to the pipeline or structure being protected. From the plots a lot of facts can be deduced:

**Lithology Change:** There is a significant drop in resistivity for both the 2.5" and 10" probes around the 105 ft mark. This typically indicates a transition from a more resistive layer (like sand or dry clay) to a highly conductive layer (like saturated clay or saline water). Both the 2.5" (shallow) and 10" (deep) resistivity curves show a massive shift at approximately 105 feet. Above 100 ft the Resistivity is relatively high (on the 2.5" probe). This suggests drier or more consolidated materials, like sand or compacted clay. Below 105 ft Resistivity plummets to very low values (4 ohms). This is almost certainly the water table or a highly plastic, conductive clay layer. For Cathodic Protection, this bottom zone (110–140 ft) is the ideal location for an anode ground bed because low resistivity minimizes the power required to drive the protective current. The SP curve shows a sharp deflection to the left (more negative) at the same depth, which often correlates with permeable zones or changes in formation water salinity. The SP curve (green) measures natural electrical potentials between the

borehole fluid and the formation. It is observed that at 80-100 ft SP moves to the right (positive) before diving left (negative) at the 105 ft mark. A sharp deflection to the left (negative) usually indicates a permeable zone (like a saltwater sand) or a change in the salinity of the groundwater. For CP this means that stability of the SP curve from 110 ft downward suggests a uniform chemical environment, which is good for the long-term health of buried anodes. Also in the upper section (40-100 ft), the blue line (2.5") and red line (10") are far apart. This "separation" often indicates invasion where the drilling fluid has pushed into the formation. Below 110 ft, the lines track much closer together. This indicates a more uniform, saturated zone where the measurement isn't as affected by the "disturbed" zone near the borehole wall.

Figure 2 illustrates the SP and resistivity signatures at lateral distances of 2.5" and 10". From a depth of 10-22m, resistivity values range between 800 and 1500  $\Omega\text{m}$ , accompanied by SP values of 8-16 mV. These conditions suggest the presence of moist, fine-grained sediments with high ionic content, which are favourable for cathodic protection (CP). The interval from 22-32 m exhibits moderate resistivity values (1500-2500  $\Omega\cdot\text{m}$ ) with relatively stable SP signals, indicative of water-saturated sandy-clay layers that are suitable for CP with minimal dissipation. The relationship between the SP and Resistivity is usually used to confirm the "active" depth. The Resistivity 10" (Red) is the most critical for your CP design because it measures the "true" formation resistivity by looking deeper into the soil, past the water/mud that may have invaded the borehole wall during drilling. In Cathodic Protection, we are looking for the path of least resistance. This plot converts the deep resistivity (10") into Conductivity. It highlights exactly where the current will discharge most easily. The spike in conductivity starting at 105 ft confirms this as the "High Activity Zone." The yellow shaded area marks the optimal depth for placing your anodes to ensure maximum current spread with minimum voltage drop.

Fig 3 represents integrated lithological and stratigraphic column. Lithological composition contains local soil and clay composition from the surface down to 40. From 0-10 m is Topsoil / Weathered clay typically loose and rich in organic matter, indicating surface weathering and soil formation. 10-20 m is Clay / Silty Clay which is a denser, fine-grained layer that suggests low permeability water moves slowly here. 20-30m is Sandy Clay / Clayey Sand which is a transitional zone with mixed grain sizes, allowing moderate drainage and possibly marking an ancient depositional change. 30-40m is Highly Conductive Clay with high conductivity, often linked to mineral-rich or saline conditions. For Stratigraphic Column this shows regional geological formations extending deeper, from 20 m to 140 m. Ilaro Formation (Sandstone, 40-100 m). A porous, permeable layer typical of fluvial or shallow marine environments — often a good aquifer or reservoir rock. Oshoshun Formation (Clay/Shale, 100-140 m). Fine-grained sedimentary rock formed in low-energy environments like deep marine basins, acting as an impermeable cap or seal. Together, these columns illustrate a transition from surface weathered soils to deeper sedimentary bedrock. The upper 40 m reflects recent surface processes (weathering, soil formation). Below that, the Ilaro and Oshoshun formations represent older geological strata, deposited under different environmental conditions — sandstone indicating high-energy deposition, shale indicating low-energy sedimentation.

Fig 4 shows the ratio or difference between the 2.5" (shallow) and 10" (deep) resistivity. Large differences between the two lines indicate where drilling fluid has "invaded" the rock. High invasion (large separation) confirms that the rock is permeable (Sand), whereas no separation indicates impermeable rock (Clay).

Fig 5 shows range of resistivity values for the "Upper Zone" vs. the "Lower Zone." "The lower unit exhibits a significantly lower and more consistent resistivity, making it suitable for CP."

Fig 6 shows Porosity Proxy Chart (SP-derived Porosity). In the absence of neutron-density log, SP deflection serves as a "proxy" for the "cleanliness" of the sand. A vertical line plot showing the Static SP (SSP) normalized against a shale baseline. Higher SP deflection often correlates with higher permeability and effective porosity. As the SP curve deflects, we can estimate where the "purest" sand bodies are versus where the formation becomes "shaly." 80-90 ft interval is the "cleanest" sand, hence the primary aquifer zone.

Fig 7 Cumulative Conductance Plot (Ground bed Capacity)

This is a critical "design plot" for CP engineers. It calculates the cumulative conductance as you go deeper into the borehole. The idea is to sum up the conductivity of each 5-foot interval from the surface down to 145 ft. It usually starts at zero at the surface and climbs as you go deeper. It shows the "Total Earthing Capacity" of the borehole. The steeper the line, the more "efficient" that section of the borehole is at discharging current (effective CP system). Sharp "break" in the curve at 105 feet and the line becomes very steep from 105 ft to 145 ft. This shows that adding anode material below 105 ft gives you a high "return on investment" for shorter ground bed, this plot proves that you must reach at least 120-130 feet to capture the bulk of the available soil conductance. The "Earthing Power" of the borehole effectively triples once you hit this zone.

fig 8. Litho-Physics Radar (Spider) Chart. in this Chart You will see two distinct "shapes": (Sand): A shape that stretches toward High Resistivity and High Invasion. (Clay): A shape that stretches toward High Conductivity and Low SP. it instantly distinguishes the physical properties of the two units.

fig 9 is Subsurface Fluid Salinity Indicator This chart uses the deep resistivity measurements to estimate the conductivity of the pore fluids. A high resistivity in the upper feet indicates relatively fresh water. The sharp spike in conductivity (inverse of resistivity) at feet suggests a shift toward more mineralized or saline fluids, often found in the clays. It proves that the upper layer is a viable freshwater aquifer that must be protected from surface pollutants, while the lower layer acts as a natural saline "sump"

fig10 Current Attenuation" Model (CP Efficiency). It will show a high "cost" to run the system in the upper 100 ft and a 60% drop in "cost" once the anodes hit the 110 ft mark. This adds a Socio-Economic value that drilling to 145 ft saves the pipeline operator money by reducing long-term energy costs and extends the life of the CP equipment.

Fig 11 Two formations appear as distinct clusters: Ilaro Formation (Sand) with high resistivity and SP values which Indicates Clean, permeable sand, Low clay content, Good fluid mobility. This cluster is exactly what you expect from sandy, porous formations. Oshosun Formation (Clay/Shale) with low resistivity and SP values Which Indicates High clay content, Poor permeability, High cation exchange capacity. This is typical behaviour for clay-rich, conductive formations. This plot shows excellent lithology separation. This separation is clean, meaning the logging data is high quality and the formations have distinct electrical signatures. This cross-plot Identify sand vs shale intervals confidently, Improve formation evaluation, Support groundwater or reservoir modelling, Validate stratigraphic interpretation from logs. It's a strong indicator that subsurface units are electrically and lithologically distinct.

Fig 12

As cumulative distribution increases, Z (mV) decreases This is typical of systems where More discharge → lower potential, More flow → reduced electrochemical headroom, Increased capacity usage → voltage drop this is a classic signature of progressive discharge. Secondly the smoothness of the curve suggests no sudden instability, no abrupt resistance spikes, no phase-change events or electrode anomalies. This plot shows the system discharges predictably and steadily. Voltage drops in a controlled way as cumulative distribution increases. There are no signs of abnormal behaviour, such as sudden voltage collapse or plateauing.

Fig 13

High Conductivity means Better Anode Performance. Conductive soils allow current to spread more efficiently from the anode to the pipeline or structure being protected. The yellow band marks the conductivity range (roughly 150–300 mS/m) where anodes operate most effectively. This is because Lower resistance = less power required Better current distribution Longer anode life. Where the purple curve overlaps the yellow zone, the soil conditions are ideal for placing anodes. At those depths, the soil is conductive enough to support efficient cathodic protection. Above or below that zone, conductivity is too low, meaning, Higher power consumption, Poorer current spread and Reduced protection efficiency. The graph is essentially guiding you to place anodes at depths where conductivity is highest. The purple line shows that conductivity increases with depth and enters the optimal zone at a certain depth range. That depth range is the recommended installation depth for CP anodes. This graph is a standard tool in cathodic protection design, especially for deep-well anode beds because it shows Correct anode placement thereby Reducing operating cost, improves pipeline protection, Extends anode lifespan and Ensures uniform current distribution

Fig 14

When the shallow resistivity (blue) is lower than the deep resistivity (red), it implies invasion — drilling fluids have penetrated the formation near the borehole, replacing native fluids and reducing resistivity. If both curves are similar, the formation is tight or impermeable, meaning little invasion occurred. Crossovers between the curves can mark transition zones — boundaries between invaded and uninvaded regions. This comparison helps geologists and petrophysicists Identify

fluid invasion depth and formation permeability. Distinguish productive zones (high deep resistivity) from invaded or wet zones (low shallow resistivity) and Improve formation evaluation and well-logging accuracy.

Fig 15 SP Gradient Log (Boundary Detection) this plot shows the rate of change (slope) of the SP curve. The sharpest "spikes" in the gradient occur at 105 ft and 115 ft. This confirms that the transition into the low-resistivity zone is not gradual—it's a distinct geological boundary (likely moving from a sandy-clay overburden into a saturated silt or clay base).

Fig 16 SP vs. Resistivity Cross-Plot

This is a "Cluster Analysis" plot. By plotting SP against Resistivity, we can see if the data points group together into "families." The "Upper" Cluster (Yellow/Green dots): These points have high resistivity ( $>1500 \Omega\cdot\text{m}$ ) and higher SP. This represents the non-conductive overburden. The "Target" Cluster (Purple/Blue dots): These points group tightly in the bottom-left corner (Low SP, Low Resistivity). This is your anode zone. CP Benefit: The tightness of the bottom cluster shows that the soil at the target depth is chemically consistent. You won't have to worry about one anode being in "good" soil and the next one being in "bad" soil—the whole 40-foot bottom section is uniform.

Figure 17: Variation of self-potential values with depth indicating electrochemical response related to cathodic protection. Deeper intervals, from 32–45 m, display low resistivity values ( $<500 \Omega\cdot\text{m}$ ) and diminished SP signals, reflecting zones of saline or mineralized clay, which pose increased corrosion risks and may hinder CP effectiveness, Figure 2. A positive correlation between resistivity and SP suggests that zones with moderate resistivity and elevated SP are electrochemically active and thus more suitable for CP.

Fig 18

Near the surface (0–10 m) Resistivity is relatively high  
From 10–25 m: Resistivity begins to decline  
below ~25 m to 45 m: Resistivity becomes consistently low. This downward trend is meaningful because resistivity is strongly controlled by lithology, porosity, clay content, and fluid conductivity. From the curve the shallow subsurface is resistive, likely sandy or weathered. As you go deeper, the formation becomes more conductive, indicating clay/shale dominance.  
Resistive top  
Transitional middle  
Conductive clay base  
For resistivity-based CP design  
Deep conductive zone → favourable for anode placement  
Shallow resistive zone → poor current distribution

Fig 19 Resistivity Difference (Invasion / Separation Log)

This plot shows the mathematical difference between the deep reading (10ohm feet) and the shallow reading (2.5ohm feet). The Red Zones Usually indicate zones where the drilling fluid or surface water has heavily invaded the formation (typical in upper sandy/porous layers) While Blue Zones Indicate a more stable formation where the shallow zone might be more conductive (perhaps due to moisture) than the deep rock. The massive shift toward the blue zone below 110 ft signals a fundamental change in the soil's chemical or saturation state, marking a clear boundary for ground bed design. In geophysical logging, resistivity is often plotted on a Logarithmic Scale The log scale makes it much easier to see the "separation" between the shallow (2.5") and deep (10") probes in highly conductive zones. The two lines converge (come together) below 110 feet. This indicates that the formation is fully saturated and uniform, which is the perfect environment for an anode. The wide separation above 100 feet indicates a "filtered" or invaded zone where the drilling fluid has soaked into the drier upper soils.

Conversely, zones characterized by very low resistivity and low SP are identified as high-risk areas for corrosion, Based on the resistivity and SP data, figure 2 and for table 1 the risk classification is as follows:

Low-Risk Zones: Resistivity  $>1500 \Omega\cdot\text{m}$  with stable SP, optimal for standard CP applications.

Moderate-Risk Zones: Resistivity between  $800\text{--}1500 \Omega\cdot\text{m}$ , requiring monitoring and potential adjustment of CP parameters.

High-Risk Zones: Resistivity  $<500 \Omega\cdot\text{m}$ , associated with saline environments, necessitating specialized mitigation strategies.

Site Selection and Geological Context

The geophysical survey focused on the 0–45 m depth interval, encompassing the pipeline and stratigraphic units such as clay, silty clay, and saline zones. Measurements at lateral offsets of 2.5" and 10" provided localized insights, confirming the presence of zones with high conductivity and electrochemical activity. Geologically, the Benin Formation's clay and shale layers correspond to low-resistivity, saline zones that increase corrosion risk. Conversely, less mineralized, moist clayey sediments with higher resistivity are more conducive to effective CP application, emphasizing the importance of stratigraphic context in corrosion mitigation planning.

## **DISCUSSION**

The integrated analysis of self-potential (SP) and resistivity data offers a comprehensive understanding of subsurface lithology and its influence on cathodic protection (CP) performance. The lithological characterization reveals distinct zones with varying electrical and electrochemical properties, which are critical for assessing CP efficiency and corrosion risk. The uppermost weathered layer, comprising clayey topsoil, exhibits very low resistivity and minimal SP response, indicative of limited ionic mobility and electrochemical activity, which may hinder CP current penetration in this zone (Kumar et al., 2021). In contrast, the clayey-silty formation (10–22 m) demonstrates increased resistivity and SP signatures, reflecting higher moisture and ionic content conducive to electrochemical reactions—favourable conditions for CP current distribution (Li et al., 2022).

Deeper, the saturated sandy-clay layer (22–32 m) shows stable SP responses and moderate resistivity, suggesting a water-saturated environment with enhanced ionic conductivity, thus supporting effective CP current flow. However, the lowest resistivity zone at 32–45 m, characterized by saline or mineralized clay, presents high conductivity and reduced SP signals, indicating potential zones of increased corrosivity and current dissipation (Zhou et al., 2023). The observed correlation between resistivity and SP variations underscores the electrochemical control of subsurface conditions, validating SP as a reliable indicator for CP assessment.

The classification of corrosion risk zones based on electrical properties aligns with lithological interpretations. Areas with low resistivity and high saline content pose higher corrosion risks, demanding targeted mitigation strategies (Singh & Kundu, 2020). Conversely, zones with moderate resistivity exhibit moderate risk levels, emphasizing the importance of detailed geophysical surveys in corrosion management planning. These findings reinforce that combining SP and resistivity data provides a robust, non-invasive methodology for delineating zones of effective CP and identifying corrosive environments (Agarwal et al., 2021).

## **CONCLUSION**

This study underscores the effectiveness of integrated self-potential and resistivity surveys in characterizing subsurface lithology and electrochemical conditions pertinent to cathodic protection. The results demonstrate that saturated sandy-clay layers facilitate efficient CP current distribution, while highly conductive saline clay zones may diminish CP effectiveness due to current dissipation and increased corrosivity. Accurate delineation of corrosion risk zones based on electrical properties offers a strategic advantage in designing and optimizing CP systems, ultimately reducing maintenance costs and extending asset life. The non-invasive nature and high resolution of combined geophysical methods make them valuable tools in corrosion risk assessment and management. Future research should focus on temporal monitoring to evaluate the dynamic behavior of these zones under operational conditions, further refining corrosion mitigation strategies in complex subsurface environments.

## **RECOMMENDATIONS**

The following recommendations are proposed for effective corrosion management and cathodic protection planning:

### **1. Site-Specific CP Design:**

Implement tailored cathodic protection systems that account for the identified resistivity zones. Low-resistivity, saline zones (<500  $\Omega\cdot\text{m}$ ) should be approached with specialized mitigation strategies, such as increased CP current density or alternative protective coatings, to address heightened corrosion risks.

### **2. Monitoring and Adjustment:**

Establish ongoing monitoring programs in moderate-risk zones (resistivity 800–1500  $\Omega\cdot\text{m}$ ) to track electrochemical activity. Regular SP and resistivity measurements will facilitate timely adjustments to CP parameters, ensuring optimal protection.

### **3. Targeted Anode Placement:**

Prioritize the installation of sacrificial or impressed current anodes in zones with moderate resistivity and high SP signals to maximize CP efficiency while minimizing material use and costs.

### **4. Enhanced Surveillance in Saline Zones:**

In areas identified as high-risk due to saline or mineralized clay zones, consider supplementary protective measures, such as corrosion-resistant coatings, cathodic shielding, or the use of corrosion inhibitors, in conjunction with CP.

### **5. Stratigraphic and Lithologic Considerations:**

Incorporate geological and lithological data into the corrosion management plan to identify zones of high salinity or mineralization that may compromise CP effectiveness. This approach will aid in designing more resilient protection schemes.

### **6. Further Geophysical Surveys:**

Conduct additional high-resolution geophysical surveys at regular intervals to monitor subsurface conditions over time, enabling adaptive corrosion mitigation strategies aligned with evolving subsurface environments.

#### 7. Training and Capacity Building:

Train field personnel and engineers in interpreting resistivity and SP data to facilitate rapid decision-making and ensure the integrity of corrosion protection systems.

Implementing these recommendations will enhance the efficacy of cathodic protection systems, reduce corrosion-related failures, and prolong the operational lifespan of underground pipelines within the study area.

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