EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2026, 27(3), 91–110
https://doi.org/10.12912/27197050/217631
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Received: 2026.01.12
Accepted: 2026.02.16
Published: 2026.03.01

Investigation of the hydrogeophysical and geological characterization of the Dakhla, Bir Gandouz and Guerguerate regions, southern Morocco

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ABSTRACT

This study aims to improve the geological and hydrogeophysical knowledge of the Dakhla, Bir Gandouz and Guerguerate regions in southern Morocco. These areas, characterized by arid to hyper-arid climates and strong environmental constraints, remain largely unexplored, with limited detailed geological, hydrogeological, and geophysical information. The main objectives are to characterize subsurface lithological structures, delineate aquifer horizons, and identify zones potentially affected by seawater intrusion and groundwater salinization in this coastal arid environment. A comprehensive approach combining field geological observations and geophysical investigations was employed. Electrical resistivity tomography (ERT) profiles and vertical electrical soundings (VES) were conducted to investigate subsurface structures. The data were processed and interpreted using the two-dimensional inversion method, enabling the construction of geo-electrical models correlated with surface geological information. Core drilling is planned to validate and calibrate geophysical interpretations, enhancing the reliability of the results. The results reveal high-resistivity limachellic limestone formations at the surface, intermediate-resistivity sandy layers corresponding to productive aquifer horizons, and low-resistivity conductive layers associated with marls and clays saturated with saline water. Geo-electrical sections indicate a general east-to-west dip of formations, with resistivity contrasts controlled by sediment texture and water content. These findings provide new insights into the functioning of coastal aquifers in southern Morocco, specifying aquifer properties, depth, and the geological layers that compose them. Limitations include the spatial density of geophysical measurements and difficult access due to climatic constraints. Nevertheless, the study offers a solid scientific basis for groundwater exploration, sustainable management, and protection of water resources in the region.

Keywords: hydrogeological, lithological, resistivity tomography, conductivity, electrical resistivity tomography.

INTRODUCTION

Hydrogeological and hydrogeophysical cartography is an essential tool for comprehending the subsurface and rationally managing natural resources, particularly in dry and semi-arid environments. This cartography provides a complete overview of the lithological, structural, and hydrogeological characteristics of a territory, information that is essential for land use and development projects (Mostafa et al., 2025; El Kenawy, 2024; Adiat et al., 2024). Wide-scale geological cartography often presents difficulties, especially in complex areas (areas of fracturing, folding, or cavities) or in regions where outcrops are rare. Hydrophysical studies are an essential complement in these contexts, providing a more complete picture of the subsurface (Wu et al., 2021; Laghzali et al., 2025).

Over the past couple of decades, the role of applied geophysics in underground prospecting methods has become increasingly important. It can provide accurate information about underground structures and formations that cannot be revealed by surface observation, and it does so in a non-destructive manner. Techniques such as electrical resistivity tomography (ERT), vertical electrical sounding (VES), and electrical profiling can be used to indirectly characterize the nature and physical properties of geological formations (Tripathi, 2025; Balasco et al., 2022; Obasi et al., 2022). These indirect measurements need to be calibrated using known geological or hydrogeological data (drill holes, outcrops, logs, etc.) to refine interpretations. Each geophysical method explores a defined volume of soil sample referred to as the investigation volume, the size of which depends on the technique and measurement parameters (Romero-Ruiz et al., 2018; Robinson et al., 2008).

Overall, interpreting the results is based on creating two-dimensional electrical profiles and cross-sections that show the spatial distribution of resistivities. These representations highlight lithological variations, tectonic structures, and potential aquifers. A hydrogeophysical study generally involves several key stages. It begins with a preliminary geological analysis to identify targets to be studied using appropriate geophysical methods, in order to better understand the geological context and define the objectives of the investigation. On this basis, the most appropriate exploration method is chosen and interpretation hypotheses are established. The work continues with the acquisition of geophysical data in the field, followed by its processing and analysis. The results are then interpreted taking into account the proposed geological models and correlated with direct information from drilling or field observations in order to improve the reliability of the interpretation. Finally, the geological and hydrogeophysical maps produced incorporate essential parameters such as lithological and structural data, hydrogeological conditions, and the geomorphological characteristics of the environment under study.

Geological and hydrogeophysical studies contribute to a better understanding of the subsurface and provide an essential basis for sustainable development and sustainable water resource management (Attwa et al., 2021; Kant and Wrat, 2025).

The geophysical techniques used have diversified considerably and are now indispensable in geology and hydrogeophysics for characterizing the subsurface. Three main approaches are generally used: directly, indirect and cartographic, enabling geological structures to be identified and modeled in two and three dimensions. The integration and processing of geophysical data help improve the accuracy of geological and hydrogeophysical maps. However, the correlation between geophysical parameters, such as resistivity, and geological properties requires rigorous calibration. Finally, the fusion of data from multiple sources provides a more reliable and comprehensive interpretation of subsurface structures and formations.

PRESENTATION OF THE STUDY AREA

Geographical location

The three areas studied the Dakhla-PK40-Port Atlantique region, Bir Gandouz-Lamhiriz, and El Guerguarate, are located in the Oued Ed Dahab-Lagouira region in southern Morocco. The western part of this region consists of a vast plateau (Hamada) with little relief, interrupted locally by depressions (Graeres, Sebkhats) and consolidated or active dune formations oriented generally NNE-SSW. The eastern part, which is more rugged, has altitudes that can exceed 500 m (Laurance et al., 2011; Elsen et al., 2018).

This area constitutes the southern tip of the Laâyoune-Tarfaya-Dakhla-Lagouira (LTDL) basin. The climate is hyperarid, characterized by very low rainfall (20 to 100 mm/year) and high interannual variability. Rainfall, which is rare and irregular, occurs mainly in late summer/early fall and winter, often in the form of short, violent, stormy episodes that cause local flooding (McEwen, 2006; McEwen, 2006). The oceanic influence is limited to the coastal strip, while the interior of the country has pronounced desert conditions (Figure 1).

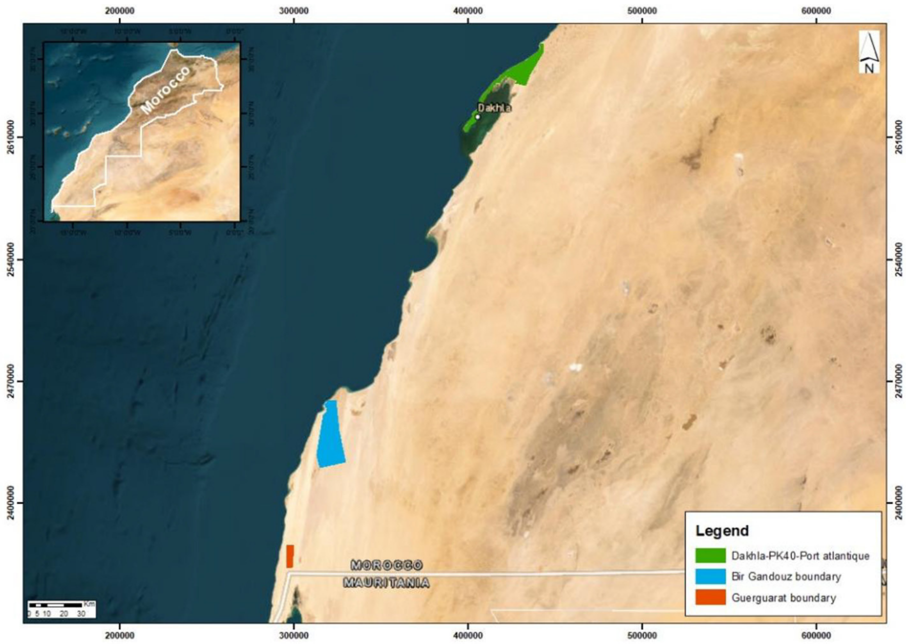


Figure 1. Map showing the location of the study areas: Dakhla, Bir Guendouz and Guerguarate

GEOLOGICAL BACKGROUND

The study areas mainly belong to the Tarfaya-Laayoune-Dakhla Mesozoic basin, formed by small basins running parallel to the coast, while the southeastern part corresponds to the Oulad Dlim domain, attached to the Réguibate ridge. The coastal zone features entablatures and tabular reliefs, while the interior is marked by depressions (sebkhas) and NE-SW oriented dune ridges (Coasts et al., 2018)

The southeastern bedrock is composed of granito-migmatites from the Oum Lbayna suite, affected by several tectonic phases (Archean, Eburnean, Panafrican, and Hercynian) that generated millimeter- to kilometer-scale folds and complex structures such as mantled gneiss domes. Neoproterozoic deposits are associated with an NNE-SSW graben basin, covered in the north by Cretaceous and Eocene formations (Strugale and Cartwright, 2022; Strugale and Cartwright, 2022; Azizi and Chihi, 2021).

The coastal formations include the Eocene (marls, chalks, clays, and flintstones), the Miocene (sandy marls, lumachelles, quartzites), and the Moghrébien (lumachelles with Pectinidae and shell limestone sandstones), often in discordance with the earlier formations. Mesozoic-Cenozoic brittle tectonics are characterized by NE-SW main faults and ENE-WSW secondary faults, which controlled regional evolution (Jiang et al., 2016). The Quaternary is marked by Pliocene-Quaternary deposits and consolidated dunes (Aguerguer), whose chronology includes several phases of uplift, dune deposition, consolidation, and desertification. The Moghrébien represents a late marine transgressive episode, attributed to the Pleistocene, followed by the Maarifien and Anfatien marine Quaternary levels. These sequences reflect the geodynamic evolution of the Saharan coastal platform, marked by alternating episodes of extension, marine transgression, and aridity (Rad et al., 2012; Newell et al., 2015) (Figure 2, 3).

HYDROGEOLOGICAL FRAMEWORK

The study area comprises two main hydrogeological domains: the crystalline basement and the Laâyoune-Dakhla sedimentary basin (Mizeb et al., 2022; Afquir et al., 2024; Afquir et al., 2024).

Crystalline bedrock, where there are no extensive aquifers. Groundwater flow occurs mainly along fractures and riverbeds, with local and discontinuous aquifers linked to highly fractured areas. Groundwater resources are

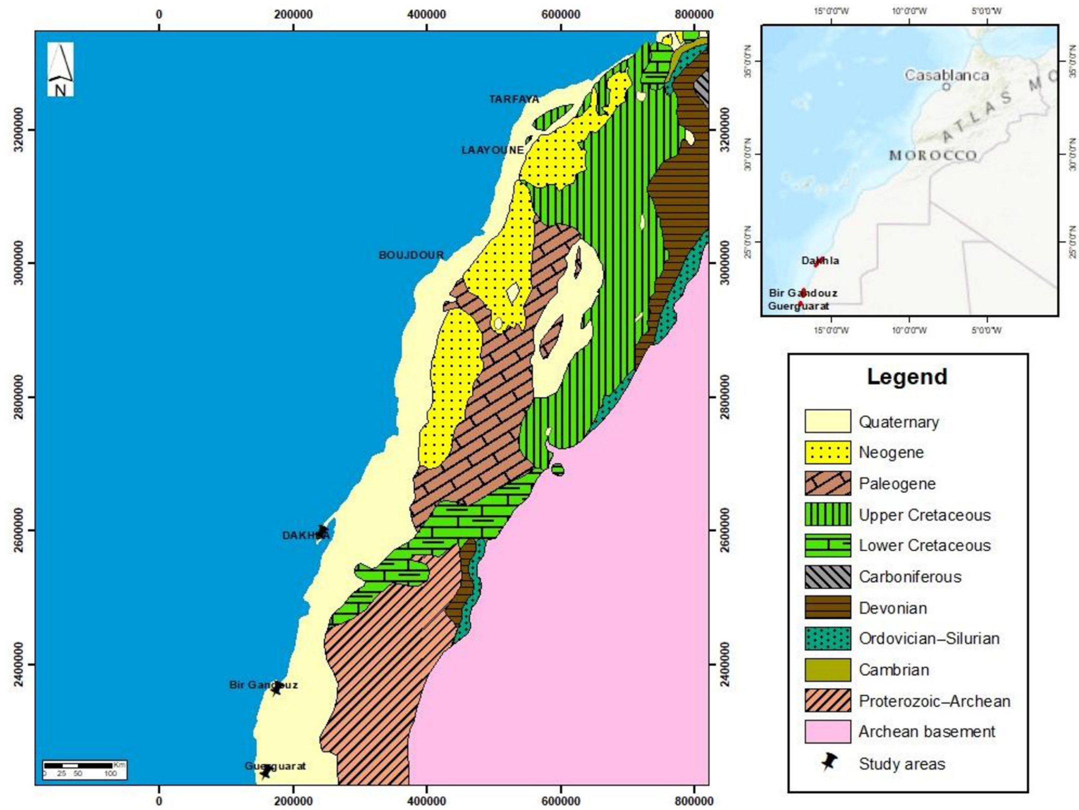


Figure 2. Schematic geological map of the study area

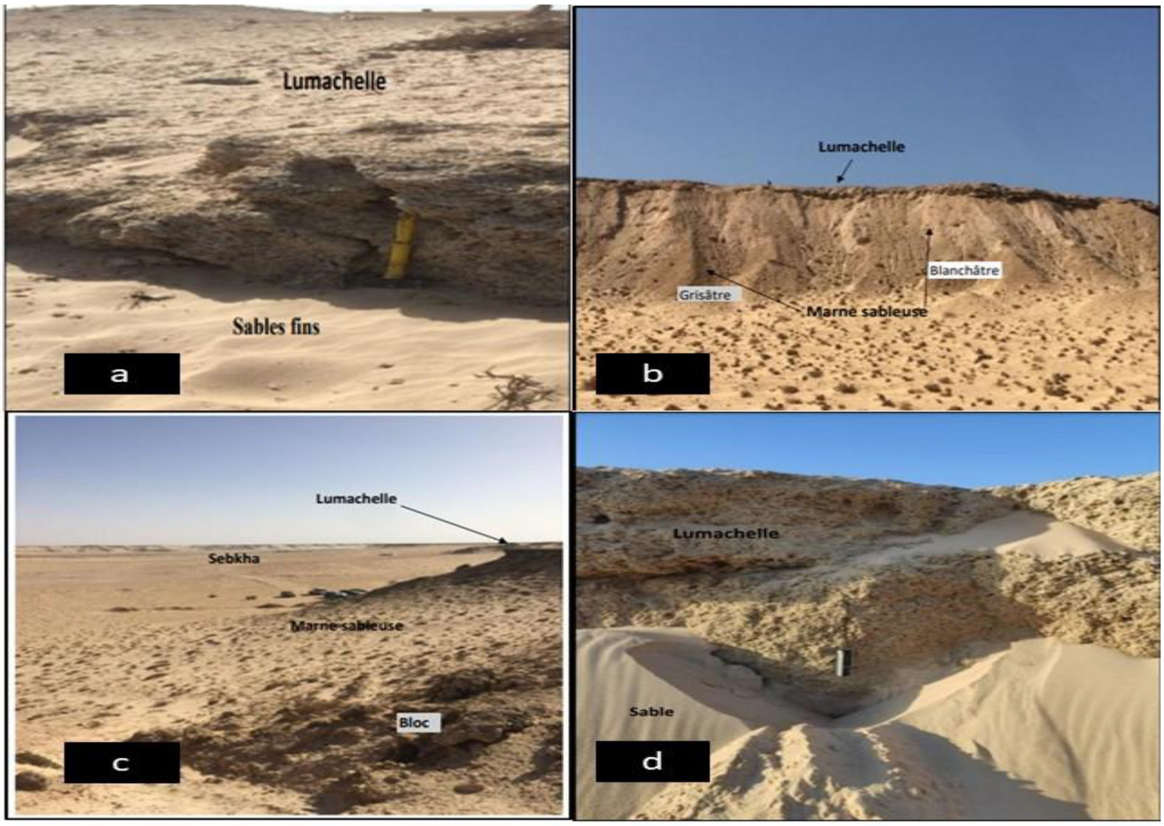


Figure 3. Selected geological features of the Dakhla region: (a) Lumachelle overlying fine sands; (b) Lumachelle associated with sandy marl; (c) Marine sebkha deposits interbedded with sandy marls; (d) Aeolian sand deposits overlain by lumachelle

limited to shallow wells, which generally have low flow rates and often poor water quality.

The sedimentary basin contains important aquifers, both shallow and deep, of varying quality. Several aquifer levels can be distinguished. The Pliocene-Quaternary formations correspond to small, shallow, slightly saline aquifers, which are exploited locally for drinking water and livestock watering.

The Continental Terminal (Miocene-Pliocene) forms a multi-layer system comprising unconfined and confined aquifers, exploited at depths of between 50 and 100 m, with flow rates varying from 1 to 10 l/s and good to average water quality.

The Paleogene (Paleocene-Eocene) represents a deep aquifer developed in sands and sandy marls, tapped between 150 and 300 m, with flow rates of 5 to 40 l/s and sometimes presenting artesian wells. Finally, the Lower Cretaceous represents the most extensive and productive aquifer, consisting of sands and sandy clays, located at depths between 100 and 500 m, with flow rates of 3 to 14.6 l/s, salinity varying from 2.5 to 19 g/l and, in some cases, high-pressure artesian wells

The sedimentary basin's aquifers provide a considerable reserve of groundwater, which is exploited according to depth, lithology, and water quality, providing an essential resource for domestic and agricultural use. (Figure 4)

METHODOLOGICAL APPROACH

The investigation program conducted in the Dakhla, Bir Gandouz, and El Guerguerate regions aims to develop a methodology adapted to the geological and hydrogeophysical mapping of aquifer systems. The approach is based on a multidisciplinary framework combining field geology, hydrogeology, and electrical geophysics. It is structured into two successive and complementary phases, each defined by specific objectives, procedures, and selection criteria.

Geological and hydrogeological investigation

A comprehensive study was conducted to characterize the geological and hydrogeological setting of the study area. It began with detailed field geological mapping aimed at identifying lithology, stratigraphy, structural features such as faults, fractures and bedding attitudes, as well as the degree of weathering of the outcropping formations. At the same time, existing data including geological maps, borehole logs, lithological descriptions and available hydrogeological information, notably piezometric levels, spring locations and pumping data, were compiled and integrated into a georeferenced database. The analysis of these data made it possible to identify potential aquifer units, recharge zones, structural

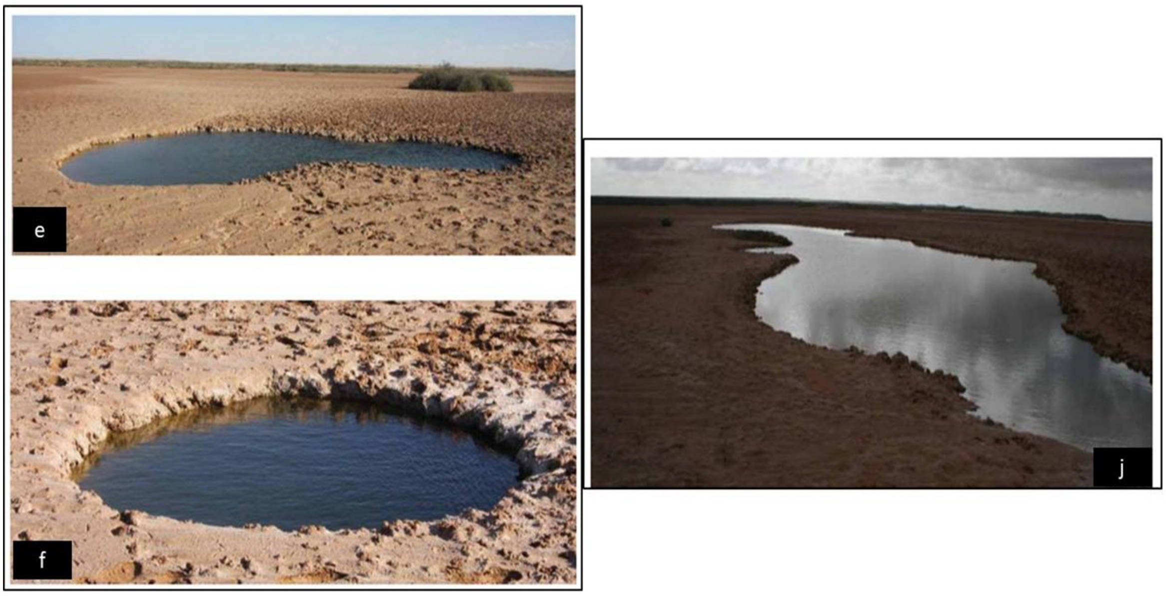


Figure 4. Karst-related water cavities in the Saharan zone of Morocco: (e) shallow water-filled karst depression; (f) circular collapse cavity partially filled with groundwater; (j) water-filled karst cavity developed in an arid environment.

controls on groundwater flow and areas likely to be affected by saline or marine intrusion.

The selection of geophysical methods was based on the expected physical contrasts between lithologies and fluids, the required depth of investigation, the structural complexity of the site, favorable field conditions and the objectives of the study, particularly aquifer delineation, detection of geological discontinuities and identification of marine intrusion. In this context, electrical resistivity methods were selected due to their high sensitivity to variations in lithology, porosity, fracturing and salinity, whereas seismic and magnetic methods were excluded because of their technical limitations and their inadequacy for the hydrogeological objectives. This preliminary phase allowed the establishment of a conceptual hydrogeological model and the appropriate definition of the choice and layout of the geophysical profiles.

Geophysical phase: Electrical resistivity investigations

The primary objective of this study is to characterize the subsurface resistivity distribution in order to delineate aquifer units, identify major geological structures, and assess hydrogeological conditions, with particular emphasis on distinguishing freshwater zones from areas affected by saline intrusion. To achieve this objective, vertical electrical soundings were conducted to analyze vertical resistivity variations and to estimate the thickness and electrical properties of the different subsurface layers by progressively increasing electrode spacing to investigate greater depths. In addition, two dimensional Electrical Resistivity Tomography profiles were acquired along selected transects to image both lateral and vertical resistivity variations with high spatial resolution. This integrated approach enables the identification of geological discontinuities such as faults and lateral facies changes, as well as the delineation of zones potentially impacted by saline intrusion.

Data processing and interpretation

Apparent resistivity data were processed and inverted using the least-squares inversion algorithm of Loke and Barker (1996) to generate two-dimensional resistivity models representative of the subsurface structure. The inverted sections were interpreted in an integrated manner with the results of Vertical Electrical Soundings and correlated with available geological and borehole data to ensure a coherent interpretation.

The hydrogeological analysis focused on identifying lithological contrasts and stratigraphic boundaries, assessing the degree of fracturing and porosity of the formations, estimating their saturation state, characterizing the geometry and lateral extent of aquifers, and highlighting faults and structural controls on groundwater flow. Special attention was given to detecting and delineating areas affected by saline or marine intrusion.

Validation and integration

To validate the geophysical interpretations, the resistivity models were systematically compared with existing borehole logs and reconnaissance drillings. This comparison ensured consistency between the geophysical results, lithological observations, and actual hydrogeological conditions. Results: This integrated approach enabled (1) the characterization of geological formations, (2) the delineation of aquifer geometries, and (3) an improved understanding of the hydrogeological functioning of the Dakhla, Bir Gandouz, and El Guerguerate regions.

Principle of the electrical prospecting method

The electrical prospecting method is based on injecting an electrical current into the ground using two current electrodes (C1 and C2) and measuring the potential difference between two receiving electrodes (P1 and P2). Ohm's law is applied to calculate the apparent resistivity of the subsoil, a quantity that depends on the nature and structure of the terrain.

The apparent resistivity (ρa) differs from the actual resistivity when the ground is heterogeneous. A geometric factor (K), linked to the configuration of the electrodes (Wenner, Schlumberger, etc.), allows this relationship to be expressed in the form:

$$\rho = \frac{K \times V}{I} \qquad (1)$$

The electrical investigations in this study were conducted using the most commonly employed instruments, namely the Wenner and Schlumberger devices.

Wenner device

The Wenner device is particularly suitable for resistivity measurements and for studying vertical layer variations. The depth of investigation depends on the spacing between electrodes, allowing detailed characterization of subsurface stratigraphy.

Schlumberger device

The Schlumberger device is more practical for field surveys, as only the two potential electrodes need to be moved. This reduces setup time while providing reliable resistivity measurements for both shallow and moderately deep layers.

Electrical prospecting was implemented using three main methods:

Electrical profiling

In this method, a quadrupole array is moved along a profile to map lateral resistivity variations. This allows the identification of geological contacts and vertical discontinuities within the subsurface.

Vertical electrical sounding (VES)

VES involves progressively increasing the spacing between electrodes to investigate deeper subsurface layers. The results are typically presented as bilogarithmic curves, from which the resistivity and thickness of different layers can be estimated using theoretical models. Interpretation of VES data is guided by two fundamental principles: the principle of suppression, which explains why thin layers may not appear on the curves, and the principle of equivalence, whereby different combinations of resistivity and thickness can produce the same response. This method thus allows a reliable characterization of subsurface stratigraphy, providing essential information on aquifer thickness, composition, and potential zones of salinization or seawater intrusion (Figure 5).

The electrical resistivity tomography (ERT) method, which provides a 2D or 3D image of the actual resistivity of the soil. This method involves acquiring a large number of measurements according to a predefined sequence, then applying digital inversion [26] to reconstruct the actual distribution of resistivities.

It offers better spatial resolution and allows geological and hydrogeological structures to be visualized with precision (Figure 6).

The Wenner devices are known for their stability, while the Dipole–Dipole and Pole–Dipole devices offer excellent lateral resolution.

Geophysical profiles were established in the various study areas in order to:

- improve geological reconnaissance in little-known areas,
- geophysically characterize certain facies of the stratigraphic series
- detect and delineate marine intrusion. In this study, electrical tomography sections, obtained by inversion using the least squares method, were interpreted in conjunction with VES (Loke and Barker, 1996)., which were themselves correlated with dated reconnaissance soundings. This approach aims to represent the geometry of lithological levels in 2D and to identify structures such as undulations and faults. The geophysical database developed includes 18 VES (AB = 1000 m) providing E–W oriented geoelectric sections, as well as 40 electrical tomography sections carried out over three areas: Dakhla, Bir Gandouz, and El Guergarate (Table 1, Figure 7).

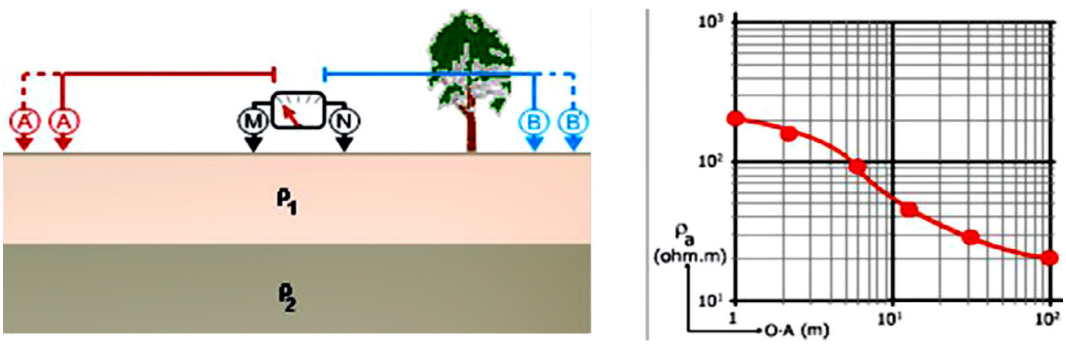


Figure 5. Presentation of electrical survey results as a bilogarithmic diagram

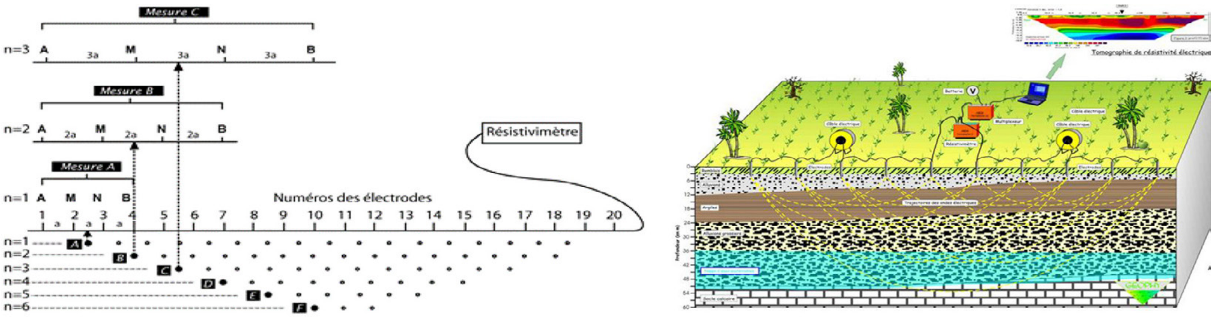


Figure 6. Geophysical methodology for electrical resistivity surveys: schematic representation of the resistivity measurement principle, instrumentation and measurement sequence for pseudosection acquisition using the Wenner α array (after Barker, 1979), and field equipment at the study site

Table 1. Distribution of vertical electrical soundings by sector

Sector	Number of VES	Number of ERT
Dakhla	16	6
Bir Gandouz	6	4
El Guergarate	4	4

Note: VES – vertical electrical sounding, ERT – electrical resistivity tomography (2D).

Electrical surveys were conducted to determine the resistivity scale of geological formations, ensure geoelectric-geological calibration, and delineate marine intrusion. Due to the limited range of electrical tomography profiles, the analysis focused on locating the freshwater/saltwater boundary. Saltwater intrusion, resulting from a hydrodynamic imbalance linked to a deficit in natural inflows and overexploitation of aquifers (Najine et al., 2006). The use of the AMNB method, applied along parallel profiles, enabled the development of resistivity maps facilitating the detection of conductive zones and the optimization of the location of additional boreholes.

The equipment used includes several units specially designed for subsurface exploration and adapted to geological and geotechnical studies. It allows for the characterization of deep formations and the detection of structural anomalies. Data acquisition is automated via a microprocessor that corrects for spontaneous polarization, improves the signal-to-noise ratio, and controls the quality of measurements. The package includes a resistivity meter with a multi-electrode device (32 electrodes, 5 m spacing), a switch, conductive cables, a processing computer, a water level probe, a GPS, and a power supply system. The Wenner configuration was chosen to optimize resolution (Kermorvant, 1984).

Geoelectrical data processing and interpretation

Electrical sounding data were processed and interpreted using the software IPI2WIN and RES-2DINV. VES data were inverted with IPI2WIN to obtain one-dimensional geoelectrical models, providing estimates of layer resistivities and thicknesses. Two-dimensional ERT data were processed with RES2DINV using a least-squares inversion algorithm to generate true resistivity sections highlighting vertical and lateral subsurface variations.

The resulting VES and ERT models were correlated with geological mapping and available borehole data. Resistivity values were assigned to specific geological formations based on their lithological characteristics and saturation conditions, allowing the construction of geoelectrical profiles and the interpretation of subsurface stratigraphy and aquifer geometry within the study area.

RESULTS AND DISCUSSION

The geoelectric data were converted into pseudo-sections, then inverted using the Loke and Barker algorithm (1996) to obtain 2D models of subsurface resistivity. Analysis of the iso-resistivity sections made it possible to identify physical contrasts between formations and to establish lateral correlations across the study area, linking variations in resistivity to the lithologies encountered. The inversion was carried out iteratively using dedicated software, integrating geological constraints and reconnaissance survey

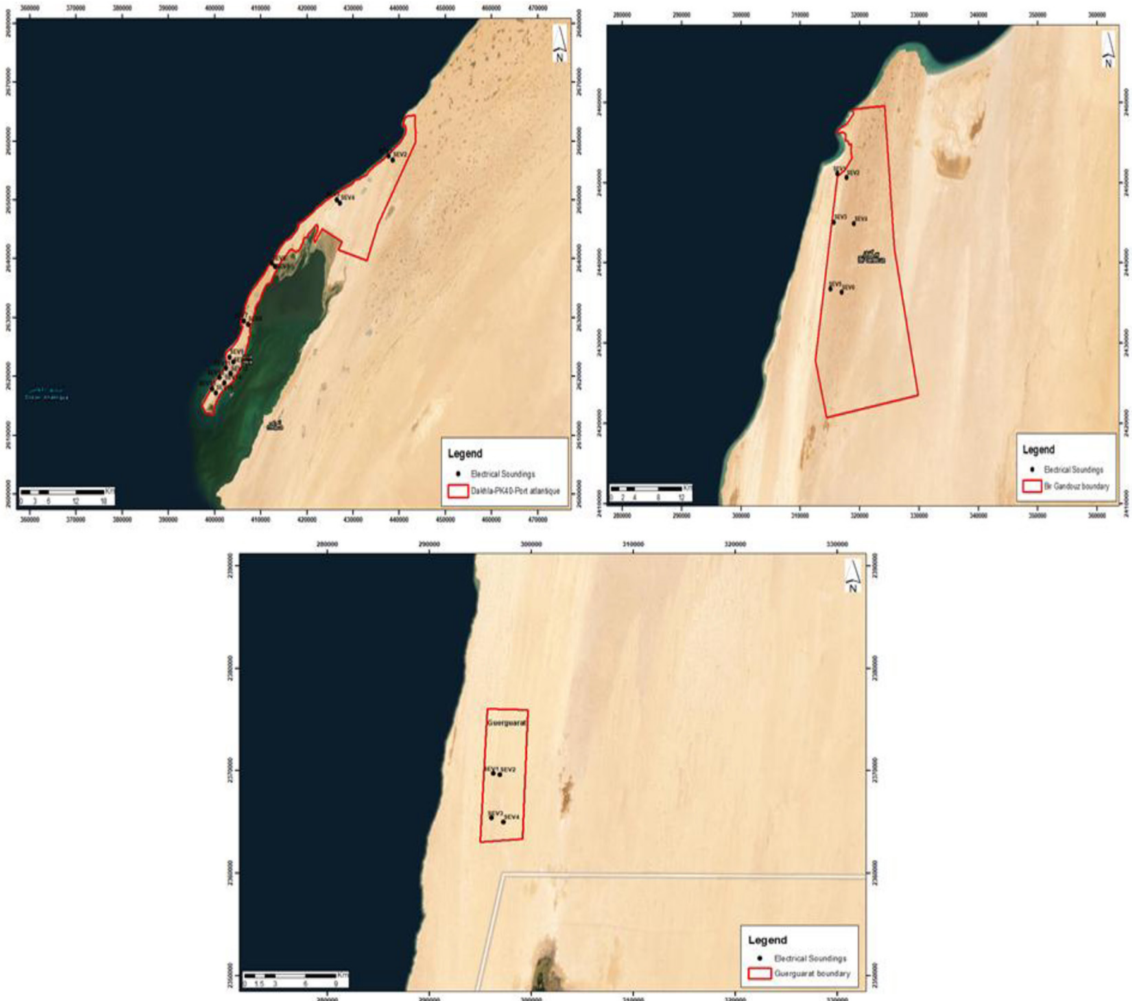


Figure 7. Spatial distribution of VES and 2D electrical resistivity tomography surveys

data to calibrate and validate the models. The sections obtained highlight changes in thickness and resistivity, the continuity or discontinuity of horizons, and provide details on the thickness of surface formations and the lateral distribution of facies (Ouzerbane et al., 2021).

Analysis of the results obtained enabled detailed geological mapping for each area. The data collected was added to the final map after validation in the field or based on mechanical surveys.

The geophysical study shows that the outcropping terrain on the Dakhla Peninsula is mainly of Pliocene-Quaternary age and consists of Lumachellic limestone and sand.

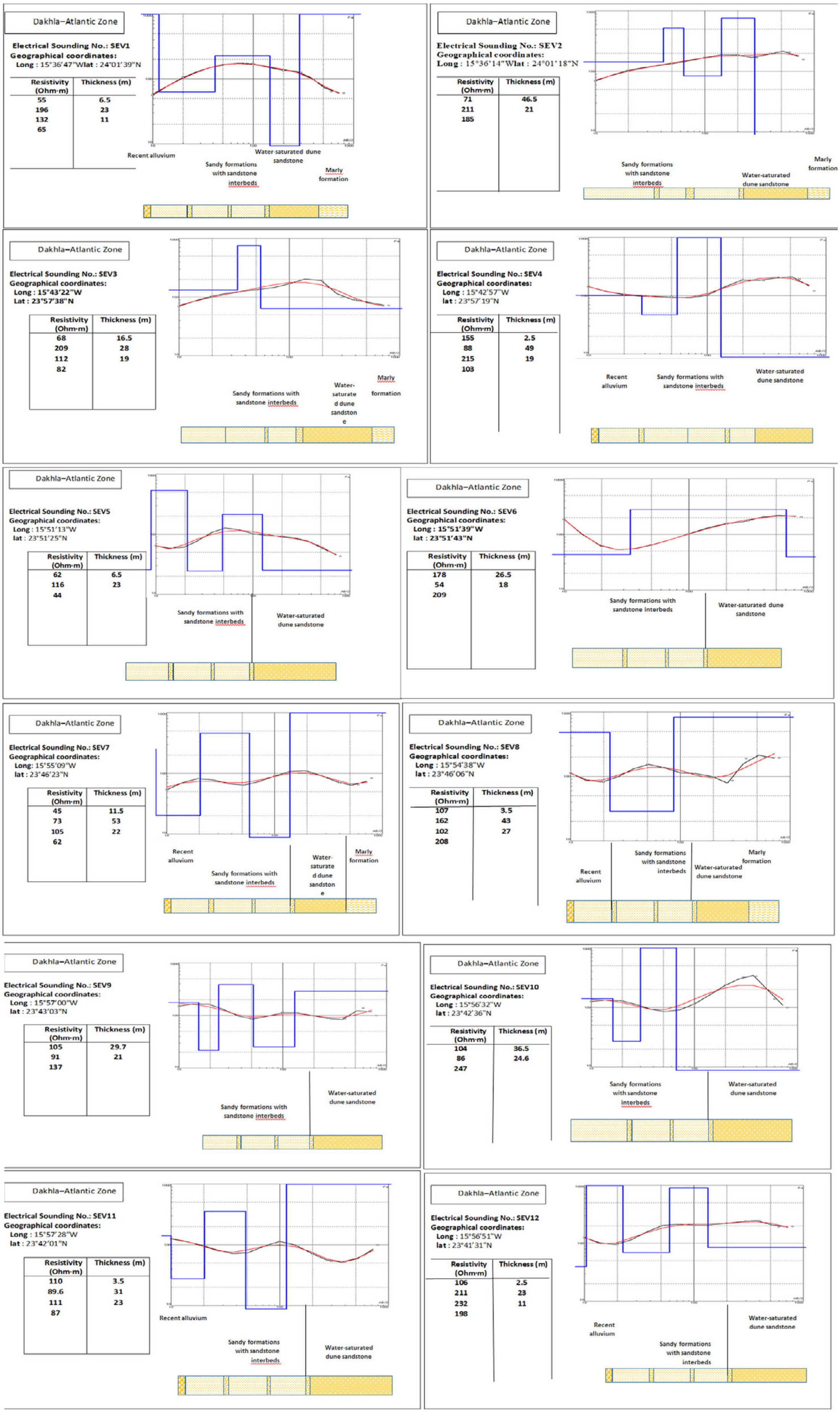
Further east, the Lower Cretaceous outcrops in the form of red sand and clay on metamorphic and eruptive terrain of Paleozoic and Precambrian age.

The Upper Cretaceous is either eroded or continental in appearance and becomes difficult to distinguish from the Lower Cretaceous.

Drilling carried out on the Dakhla Peninsula has revealed the existence of an artesian Paleogene aquifer (Figure 8).

The Lower Cretaceous aquifer, which is not captured on the Dakhla Peninsula, is believed to be a fossil aquifer that was recharged several thousand years ago and may correspond to conditions that were wetter and colder than those of today. The recharge zone of the Lower Cretaceous aquifer is located to the east, in contact with the Archean basement.

The sections also show a general dip of the geological formations from east to west towards Dakhla. The fine to medium sands of the Paleogene are well mapped and delineated. The flint sands at the base of the Paleogene and the whitish sands at the top of the Lower Cretaceous are not reached at the depth probed by the electrical tomography technique (Afquir et al., 2024). The Lower Cretaceous is clayey from a depth of 560 m, with a thickness of 950 m, and


Dakhla–Atlantic Zone
Electrical Sounding No.: SEV1
Geographical coordinates:
Long : 15°36'47"Wlat : 24°01'39"N
Resistivity (Ohm·m) | Thickness (m)
55 | 6.5
196 | 23
132 | 11
65
Recent alluvium
Sandy formations with sandstone interbeds
Water-saturated dune sandstone
Marly formation
Dakhla–Atlantic Zone
Electrical Sounding No.: SEV2
Geographical coordinates:
Long : 15°36'14"Wlat : 24°01'18"N
Resistivity (Ohm·m) | Thickness (m)
71 | 46.5
211 | 21
185
Sandy formations with sandstone interbeds
Water-saturated dune sandstone
Marly formation
Dakhla–Atlantic Zone
Electrical Sounding No.: SEV3
Geographical coordinates:
Long : 15°43'22"W
Lat : 23°57'38"N
Resistivity (Ohm·m) | Thickness (m)
68 | 16.5
209 | 28
112 | 19
82
Sandy formations with sandstone interbeds
Water-saturated dune sandstone
Marly formation
Dakhla–Atlantic Zone
Electrical Sounding No.: SEV4
Geographical coordinates:
Long : 15°42'57"W
lat : 23°57'19"N
Resistivity (Ohm·m) | Thickness (m)
155 | 2.5
88 | 49
215 | 19
103
Recent alluvium
Sandy formations with sandstone interbeds
Water-saturated dune sandstone
Dakhla–Atlantic Zone
Electrical Sounding No.: SEV5
Geographical coordinates:
Long : 15°51'13"W
lat : 23°51'25"N
Resistivity (Ohm·m) | Thickness (m)
62 | 6.5
116 | 23
44
Sandy formations with sandstone interbeds
Water-saturated dune sandstone
Dakhla–Atlantic Zone
Electrical Sounding No.: SEV6
Geographical coordinates:
Long : 15°51'39"W
lat : 23°51'43"N
Resistivity (Ohm·m) | Thickness (m)
178 | 26.5
54 | 18
209
Sandy formations with sandstone interbeds
Water-saturated dune sandstone
Dakhla–Atlantic Zone
Electrical Sounding No.: SEV7
Geographical coordinates:
Long : 15°55'09"W
lat : 23°46'23"N
Resistivity (Ohm·m) | Thickness (m)
45 | 11.5
73 | 53
105 | 22
62
Recent alluvium
Sandy formations with sandstone interbeds
Water-saturated dune sandstone
Marly formation
Dakhla–Atlantic Zone
Electrical Sounding No.: SEV8
Geographical coordinates:
Long : 15°54'38"W
lat : 23°46'06"N
Resistivity (Ohm·m) | Thickness (m)
107 | 3.5
162 | 43
102 | 27
208
Recent alluvium
Sandy formations with sandstone interbeds
Water-saturated dune sandstone
Marly formation
Dakhla–Atlantic Zone
Electrical Sounding No.: SEV9
Geographical coordinates:
Long : 15°57'00"W
lat : 23°43'03"N
Resistivity (Ohm·m) | Thickness (m)
105 | 29.7
91 | 21
137
Sandy formations with sandstone interbeds
Water-saturated dune sandstone
Dakhla–Atlantic Zone
Electrical Sounding No.: SEV10
Geographical coordinates:
Long : 15°56'32"W
lat : 23°42'36"N
Resistivity (Ohm·m) | Thickness (m)
104 | 36.5
86 | 24.6
247
Sandy formations with sandstone interbeds
Water-saturated dune sandstone
Dakhla–Atlantic Zone
Electrical Sounding No.: SEV11
Geographical coordinates:
Long : 15°57'28"W
lat : 23°42'01"N
Resistivity (Ohm·m) | Thickness (m)
110 | 3.5
89.6 | 31
111 | 23
87
Recent alluvium
Sandy formations with sandstone interbeds
Water-saturated dune sandstone
Dakhla–Atlantic Zone
Electrical Sounding No.: SEV12
Geographical coordinates:
Long : 15°56'51"W
lat : 23°41'31"N
Resistivity (Ohm·m) | Thickness (m)
106 | 2.5
211 | 23
232 | 11
198
Recent alluvium
Sandy formations with sandstone interbeds
Water-saturated dune sandstone

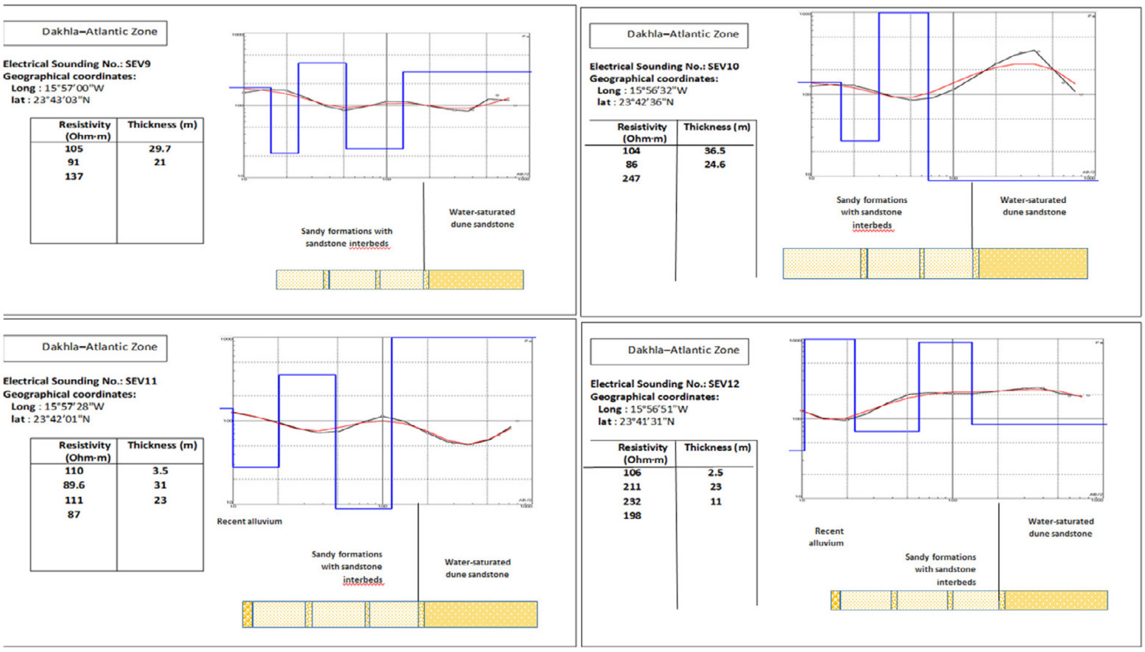


Figure 8. Geoelectrical curves from the electrical sounding in the Dakhla region

rests on a Precambrian substrate at the Imlili No. 35/125 borehole

The Paleogene is characterized by an abundance of flint in the various sand, clay, and marl formations, reflecting a climate typical of the Paleogene. The results of geophysical prospecting have shown generally resistant levels

- lumachelles,
- sands,
- sandstones.

These levels form potential aquifer reservoirs (R1, R2, R3) and conductive levels (marls, clays, etc. (C0, C1, C2)).

In the Dakhla region, the roof of the Paleogene and the roof of the basal part of the Paleogene and the top of the Lower Cretaceous dip towards the northwest and thicken significantly. The roof of the Paleogene is thought to be very deep in the Dakhla Peninsula, while the roof of the basal part of the Paleogene and the top of the Lower Cretaceous is between 650 and 700 m deep, according to some studies.

In the southern part of the Dakhla region, examination of all the results obtained reveals significant variations in the electrical resistivity of the subsoil, indicating its heterogeneity. Schematically (Baqloul et al., 2021). The area covered by the geophysical surveys is formed by five (5) geo-electrical levels corresponding to five (5) major lithological units:

- A highly conductive level with resistivity below 50 Ohm.m corresponding to Quaternary alluvium or marl or clay with sandy intercalations.
- A resistant level with resistivity exceeding 250 Ohm.m corresponding to the lumachellic level. This observation is justified by the electrical calibration surveys carried out southeast of the city of Dakhla.

A less resistant level with resistivity between 50 and 120 Ohm.m corresponding to sandy formations

A resistant sandstone bench well represented on the eastern and southeastern profiles of Dakhla, with resistivity exceeding 400 Ohm.m.

The subsurface resistivity model obtained along the "North" line profiles shows a large resistant zone at the northernmost end of the section, separated from another more conductive zone located to the south. Given the location of these profiles, it is clear that the resistive R1 observed on the surface at the northern end of the profile corresponds to the lumachelle level. This resistive zone is separated from a more conductive block located to the south and shows two clearly distinct levels:

The superficial conductor C1 located in the middle and south of the profile would represent the alluvial mass that thickens in the center of the valley (result confirmed by the two electrical calibration surveys SE2 and SE 3)

Conductor C2 corresponds to the mass of saturated sand. This behaves like a stack of sand beds with some marl-clay intercalations.

In the sections, we also note the presence of a dislocated lumachellic resistive layer forming the roof of the series, which appears at varying depths and has a tabular shape.

The resistivity sections obtained in the south show two resistive masses of unequal size separated by a conductive zone C1, which corresponds to the layer of water-soaked sand or sandstone. As with the previous line, the two resistive masses would represent the lumachellic limestone bank. However, at this line (Mohammed et al., 2022), the lower sandstone bar appears to extend further eastward. It continues at depth to the west, where it stops abruptly. This suggests an extension of the sedimentary formations to the west (Figure 9).

In the Bire Gandouz region, we find the stratigraphic succession predicted by local geology. Thus, in addition to the surface resistive layer (R1), which should correspond to a layer of lumachellic limestone, we find the three lithological units outlined in sections BG1 to BG20, namely sands with some sandstone passages (resistive R2), the aquifer layer formed of water-soaked sands (Conductive C2) and the lower sandstone bench (Resistive R3).

In accordance with the surface geology, the lower sandstone bar is continuous to the east across all profiles. A relative decrease in resistivity at this location could correspond to the presence of salt water in the sandstone-sand aquifer (Figure 10).

In the El Gargarate region, the sections mainly highlight the three geological entities mentioned above. Indeed, the resistivity model obtained shows a deep resistive layer (R3) that would represent the continuity of the sandstone banks. This is overlain by a less resistant formation that would represent the upper sandy layer.

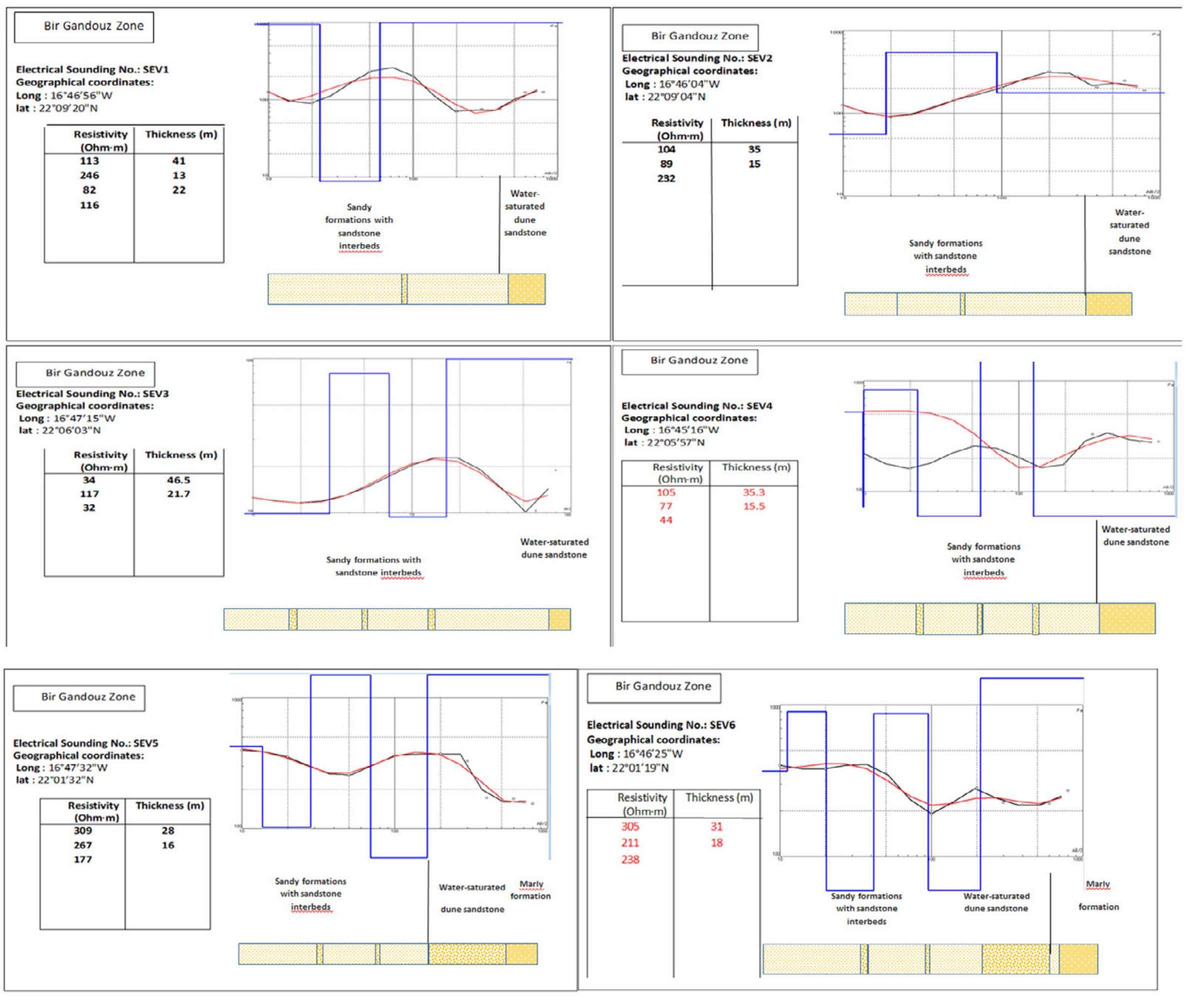


Figure 9. Geoelectrical curves from the electrical sounding in the Bir Gandouz region

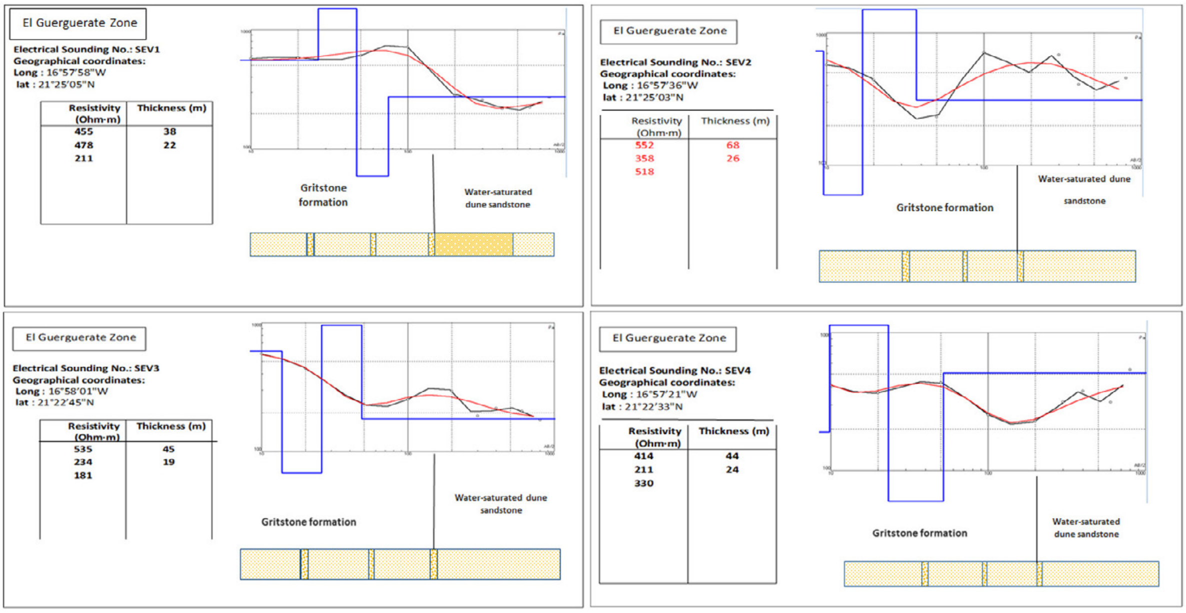


Figure 10. Geoelectrical sounding curves for the El Guerguerate region

The ten sections are complementary. Combining the resistivity models from these sections provides an overview of the variation in resistivity in the NE-SW direction across the area covered by the measurements. It should be noted that these profiles were placed at predefined sites in order to better clarify the structure of the deep subsurface at this location. Given the strong contrast in resistivity between the sandstones, lumachelles, and sands, the identification of such structures was very clear.

Ultimately, analysis of the results leads to zoning of the study area, i.e., the determination of vertical sections (2D ERT), electrical profiles (electrical drag), or electrical surveys (Vertical electrical sounding). All of these zoning techniques made it possible to represent significant variations in the physical properties of the different lithologies. The interpretation of the geophysical survey was correlated upstream with the results of the preliminary study phase and downstream with the results of the surveys, which were more judiciously implemented where the geophysical measurements indicated a significant change in the physical properties of the soil (Chalikakis, 2006).

Based on the qualitative and quantitative interpretation of data from the geophysical survey, particularly electrical surveys, it was possible to map approximately the boundary of marine intrusion into the aquifer on the three maps.

Interpreting the electrical survey data appears to be difficult due to confusion between the resistivities of formations saturated with salt water and those of marly to clayey marly formations, and even between different resistivities that may have the same origin (sandy formations have different resistivities ranging from 120 to 150 Ohm.m). Analysis of the apparent resistivity profiles shows that there are two levels, the first to the west with low resistivities and another at depth with high resistivities.

The high resistance values recorded in the vertical electrical soundings (VES 2, 4, 6, 8, and 10) are explained by the presence of highly resistant dune formations, and those in (VES 1, 3, 5, 7, and 9) is due to coarse alluvial formations on the surface and water-soaked sandy formations. The low values recorded indicate contamination of the aquifer.

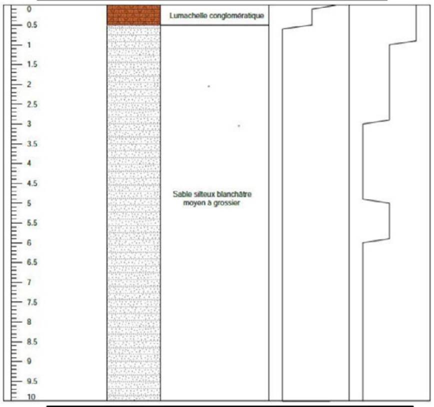
Results of electrical tomography profiles of the Dakhla area

The geoelectric study carried out in the Dakhla region, using six electrical resistivity tomography sections (DK1–DK6), made it possible to characterize the lithological structure of the subsoil by distinguishing several horizons with contrasting resistivities.

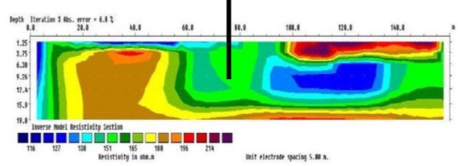
Northern Dakhla section

Geoelectric sections reveal the presence of a thin (≤3 m) resistant surface layer (R1), corresponding to discontinuous lumachellic formations with resistivity between 150 and 250

CORE DRILLING SURVEY No. 1

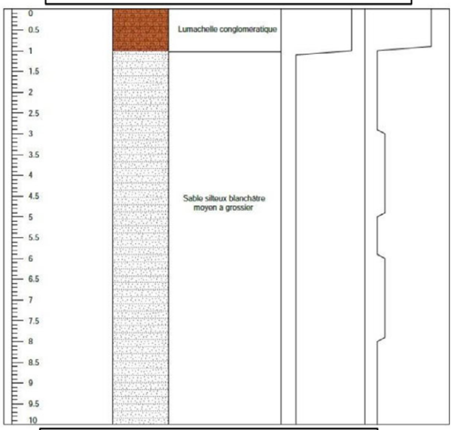


DK 1

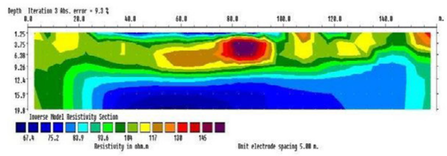


The resistivity section does indeed show the presence of a thin layer of conglomeratic lumachelle crust, no more than 1.5 m thick. It is clear that this crust is dislocated and forms a discontinuous layer overlying a less conductive layer attributed to silty, sometimes marly sands intersected by a highly conductive layer corresponding to highly localized conductive marly-silty deposits. Below this layer is a very resistant sandstone bank extending deep underground.

CORE DRILLING SURVEY No. 2

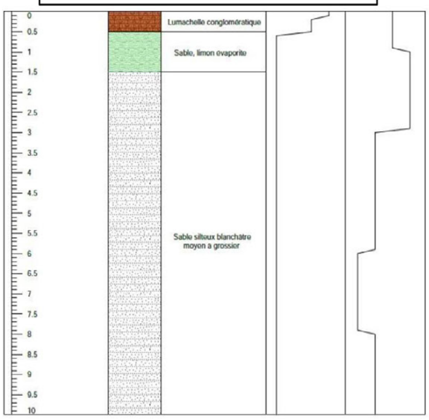


DK2

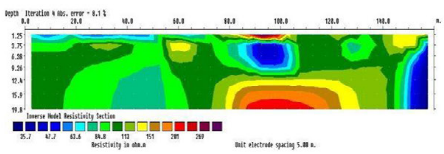


In this typical section, we find the stratigraphic sequence predicted by local geology. Thus, in addition to the surface resistance (R1), which should correspond to a layer of lumachellic limestone in the form of dislocated fragments, we find a thick sandy horizon. This level has variable resistivity due to varying levels of silt and marl content. The conductive level identified at the surface corresponds to a sandy level with a relatively high water content.

CORE DRILLING NO. 3

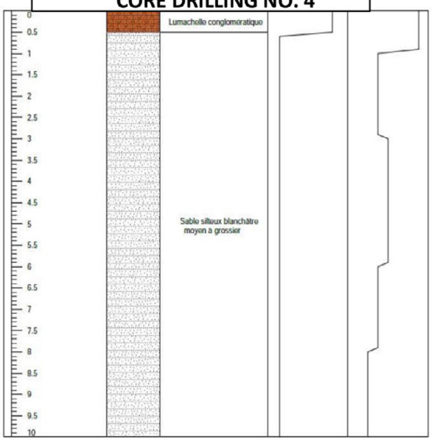


DK3

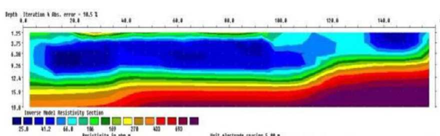


This section shows the presence of resistant bodies of various sizes attributed to lumachellic limestones cut by the dominant sandy facies. The lithological units outlined in the previous sections are found here, namely sands with some marly passages and whitish sands.

CORE DRILLING NO. 4

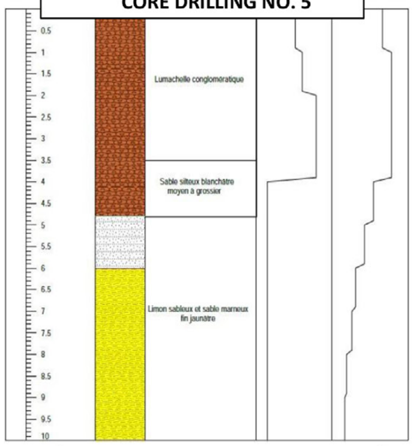


DK4

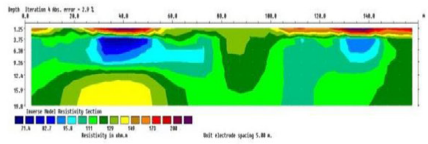


In this region, the sections mainly highlight the two main geological entities. Indeed, the resistivity model obtained shows a surface resistivity not exceeding 50 cm, represented by a thin, discontinuous conglomerate layer. Below this crust, there is a sandy horizon extending to a depth of more than 10 m. The significant variations in resistivity observed at the sandy horizon are mainly due to the water content at depth.

CORE DRILLING NO. 5

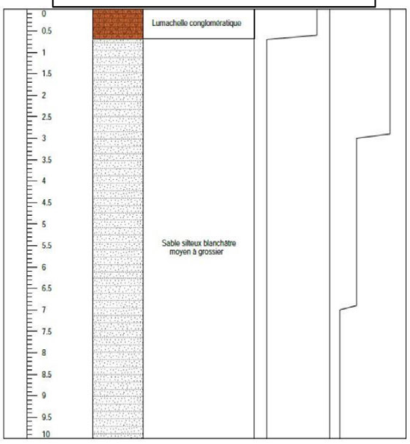


DK5

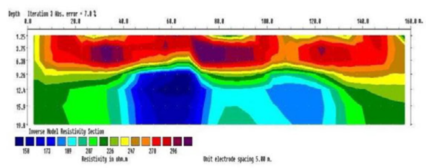


This section contains the three lithological units characteristic of the southern Dakhla area, with a first layer of conglomeratic lumachelle varying in thickness between 1.5 and 3.5 m. The discontinuous and dislocated nature of this section is clearly confirmed. Sandy deposits have also been observed on the surface and extend to depths of 7 m below this first level composed of sandy silt and yellowish marly sand. This complex has variable resistivity depending on the silt and interstitial water content.

CORE DRILLING NO. 6

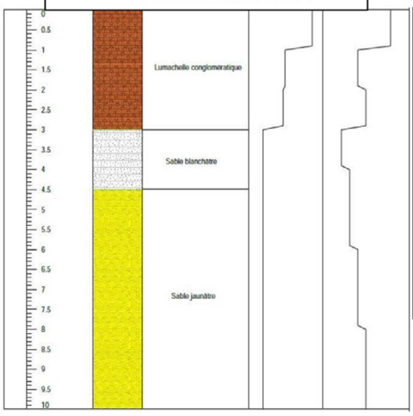


DK6

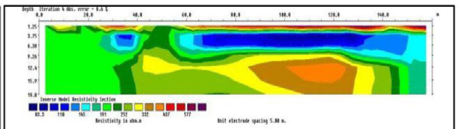


Near core sample No. 6, the electrical tomography section mainly highlights the two main geological entities. The resistivity model obtained shows a dominant resistive feature (R2) that would represent the continuity of the sandy banks. This is overlain by a more resistant formation that would represent the conglomeratic lumachelle crust, which is more or less continuous at the surface but varies in thickness.

CORE DRILLING NO. 7

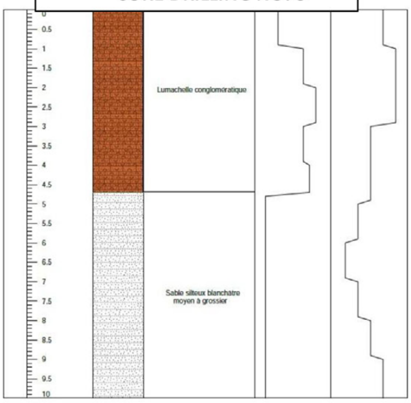


BG 1

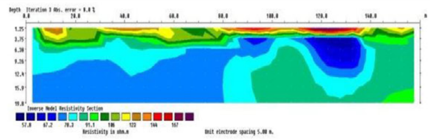


This section contains the three lithological units shown in most sections, namely conglomeratic lumachelles forming a distinctly discontinuous crust on the surface with a thickness not exceeding 3 m, sands with some marly-silty passages (resistivity R2), and the dominant horizon consisting mainly of yellowish sands reaching depths exceeding 10 m.

CORE DRILLING NO. 8

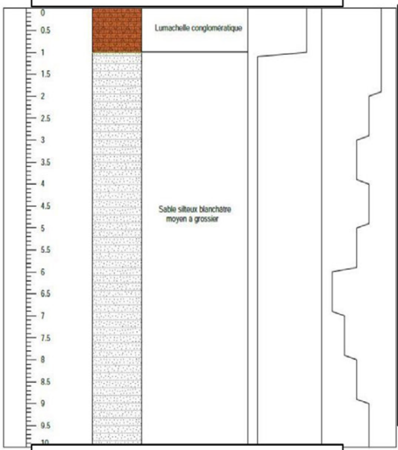


BG 2

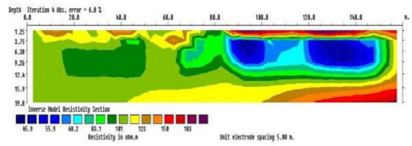


This section contains the three lithological units characteristic of the southern Dakhla area, with a first layer of conglomeratic lumachelle varying in thickness between 1.5 and 3.5 m. The discontinuous and dislocated nature of this section is clearly confirmed. Sandy deposits have also been observed on the surface and extend to depths of 7 m below this first level composed of sandy silt and yellowish marly sand. This complex has variable resistivity depending on the silt and interstitial water content.

CORE DRILLING NO. 9

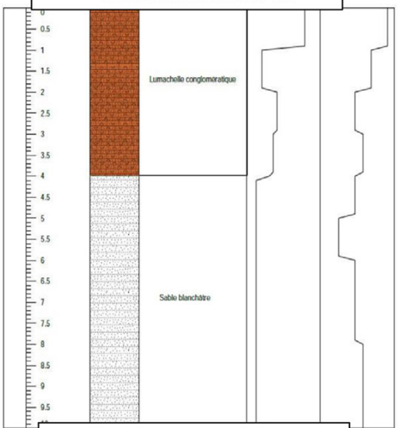


BG3

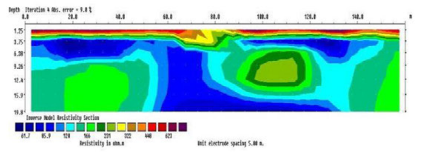


In the southeastern region of Dakhla, the sections clearly highlight the two main geological entities. Indeed, the resistivity model obtained shows a surface resistivity (R1) attributed to conglomeratic lumachelles with a thickness varying between 1 and 3.5 m. This is overlain by a less resistant formation consisting mainly of medium to coarse whitish silty sands extending to depths of up to 10 m. The variations in resistivity observed in the sandy layer are related to the varying content of marl, silt, and imbibition water.

CORE DRILLING NO. 10

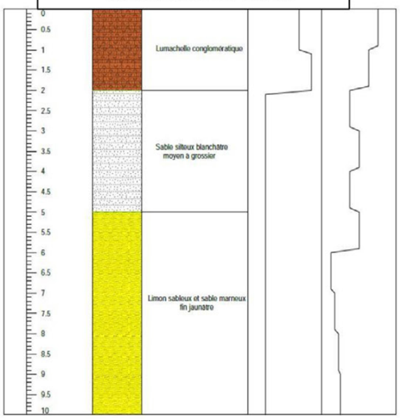


BG4

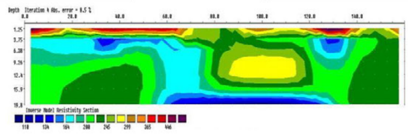


This section contains the three lithological units characteristic of the southern Dakhla area, with a first layer of conglomeratic lumachelle varying in thickness between 1.5 and 4.5 m. The discontinuous and dislocated nature of this section is clearly confirmed. Sandy deposits have also been observed on the surface and extend to depths of 7 m below this first level composed of sandy silt and yellowish marly sand. This complex has variable resistivity depending on the silt and interstitial water content.

CORE DRILLING NO 11

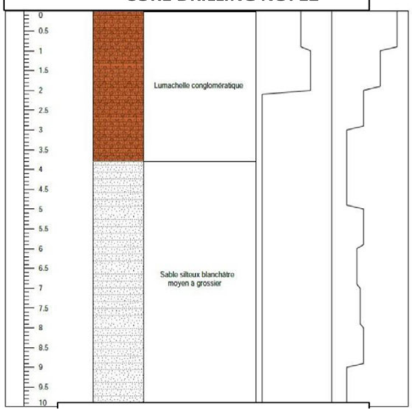


EG 1

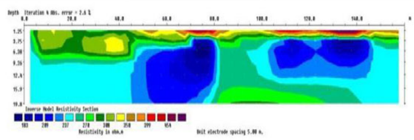


In general, the results of geophysical prospecting showed the presence of three lithological levels represented by: -lumachelles in the form of dislocated and discontinuous tabular plates forming the roof of the series (R1). These lumachelles most often appear in the form of very compact conglomerates with medium to coarse elements; -medium to coarse whitish silty sands, transitioning in places to silty sands with evaporites (R 2); - silty sands and marly sands, transitioning in places to yellowish sands (C1).

CORE DRILLING NO. 12



EG2



Two electrical levels were observed on the electrical section. The first was a thin, superficially resistant layer with limited lateral extension. This was a conglomeratic lumachelle crust interspersed with more conductive sandy layers, particularly in the west and center of the section. This resistant level overlies the dominant facies, which consists mainly of whitish silty sands characteristic of the regional geology of the Dakhla Peninsula. Marly-silty layers are omnipresent and most .often occur as ovoid bodies extending to depth

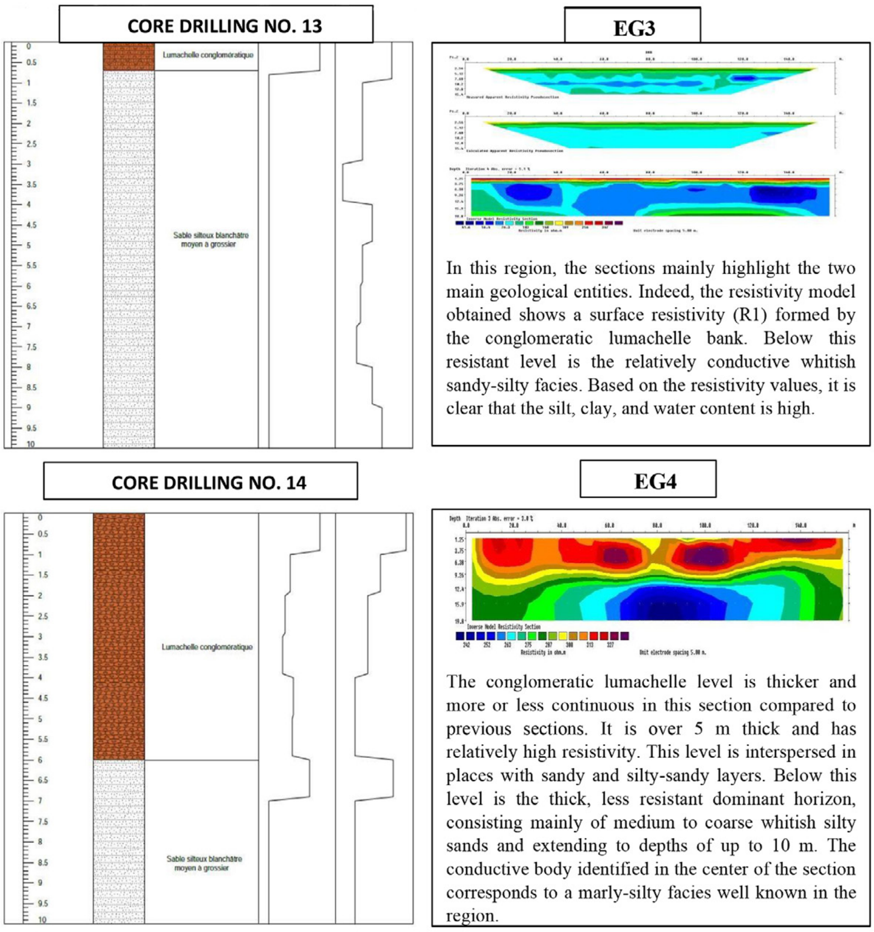


Figure 11. Interpretation of cored borehole data using 2D electrical resistivity tomography profiles

Ω•m. This layer rests on a more conductive horizon (R2), formed of silty to loamy sands locally enriched with evaporites. At depth, an even more conductive horizon (C1), attributed to loamy and marly sands, has a resistivity of less than 60 Ω•m.

All of the profiles reveal three main lithological units:

- R1: discontinuous, compact, conglomeratic tabular lumachelles;
- R2: silty to loamy sands with evaporitic passages;
- C1/C2: yellowish sands and marls with high conductivity, locally interbedded in the northern and eastern sectors of Dakhla.

Southern part of Dakhla

Analysis of the geoelectric profiles of southern Dakhla reveals greater heterogeneity in the subsoil, represented by five main units:

- C0: highly conductive level (<50 Ω•m) corresponding to Quaternary alluvium or clayey marl with sandy intercalations;
- R1: resistant lumachellic level (>250 Ω•m) confirmed by calibration surveys;
- R2: medium sandy formation (50–120 Ω•m);
- R3: very resistant sandstone bank (>400 Ω•m) present mainly in the eastern and southeastern profiles.

Interpretations indicate that the outcropping terrain of the Dakhla Peninsula is Pliocene-Quaternary in age, dominated by lumachellic limestones and sands. Geoelectric sections show a general dip of the formations from east to west. The deep horizons of the Lower Cretaceous and Paleogene were not reached by the survey due to the limited length of the profiles. However, data from the Imlili borehole (No. 35/125) confirm the deep lithological succession, with clayey Lower Cretaceous resting on a Precambrian substrate.

Spatial variations in resistivity are mainly related to grain size, lithological nature (proportion of silt, clay, and mud) and water content. Correlations between electrical data, mechanical surveys, and geological field observations have made it possible to refine the geoelectric model and improve the mapping of surface and sub-surface formations in the Dakhla region (Figure 11).

Bir Gandouz region

The electrical resistivity tomography profiles (BG1–BG4) carried out in the Bir Gandouz region confirm the stratigraphic sequence expected based on surface geological observations. Three main lithological units were identified:
- R1: a resistant surface horizon, corresponding to lumachellic limestones;
- R2: a sandy level with sandstone passages, of moderate resistivity (120–150 Ω•m);
- C2: a conductive horizon corresponding to the aquifer formed of water-soaked sands, resting on a resistant lower sandstone bench (R3).

The continuity of the lower sandstone bench towards the east is clearly marked across all profiles, while a local decrease in resistivity suggests the presence of salt water within the sandstone-sand aquifer. Interpretation becomes more complex near the coastline due to the similarity in resistivity values between formations saturated with salt water and marly or clayey-marly levels. Overall, two areas can be distinguished: a shallow level with low resistivity to the west and a deeper level with higher resistivity, reflecting the lateral variation in sedimentary facies. El Gargarate region (Ouzerbane et al., 2022).

In the El Gargarate region, geoelectric (GE) results reveal two main units. The first, represented by a dominant resistive level (R2), corresponds to the lateral continuity of sandy banks. It is overlain by a less resistive formation attributed to surface sands. The ten sections acquired show remarkable lithological and structural consistency, allowing reconstruction of spatial resistivity variation in a NE-SW direction (Étienne, 2005).

The strong contrast in resistivity between sandstones, lumachelles, and sands has made it easier to identify the main structures of the subsoil. In-depth analysis of 2D electrical resistivity tomography (ERT) models reveals two dominant geological entities in the southeastern part of Dakhla: a resistant surface layer (R1) formed of conglomeratic lumachelles with a thickness of 1 to 3.5 m; a less resistant underlying formation consisting of medium to coarse whitish silty sands (Najine et al., 2005), reaching a depth of approximately 10 m. The lateral variations in resistivity observed in these sandy formations reflect changes in the content of marl, silt, and water saturation, reflecting textural heterogeneity and local hydrogeological dynamics (Abdelfadel et al., 2025).

CONCLUSIONS

This research highlights the effectiveness of an interdisciplinary geological and hydrogeophysical study to characterize underground structures and aquifer systems in arid and hyperarid environments in southern Morocco (Dakhla, Bir Gandouz, and El Guerguerate). The combined use of electrical resistivity tomography, vertical electrical soundings, and geological field observations has enabled better identification of lithological and hydrostratigraphic units. Geoelectric models reveal a marked organization of formations, with resistive limestones, aquiferous sands and sandstones, and conductive marl-clay levels often associated with salt water. The general east-west dip towards the Atlantic controls the geometry and continuity of the aquifers. In Dakhla, several shallow, intermediate, and deep aquifer levels have been identified, with clear evidence of marine intrusion. Similar results at Bir Gandouz and El Guerguerate confirm the regional continuity of the formations and the local salinization of groundwater. The integration of geophysical and geological data improved the reliability of interpretations despite some resistivity ambiguities. This approach provides a robust framework for sustainable water resource management in the arid coastal basins of southern Morocco.

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