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Geophysical and geological contribution to determining the neritic limestone aquifer structure of Hammam Bradaa – El Fedjoudj (Seybouse medium), Northeastern Algeria

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Abstract

Purpose. The neritic aquifer that extends between Hammam Bradaa and El Fedjoudj, despite its faulted and in places karstified structure, due toits capacity and lateral extension represent a strategic resource for the region. Its waters are used for drinking water supply in the neighboring towns: Heliopolis, Guelaat Bousbaa, Nechmaya and El Fedjoudj, as well as in part of the Annaba wilaya. These neritic limestones outcrop at Djebel Debagh and Bouzitoune.

Methods. In order to better study the potential of this aquifer, it is essential to identify its geometry and structure by analyzing the geological data, mechanical drilling data and geophysical data analysis through an electrical survey campaign.

Findings. The main results indicate that the study area has identified two important aquifer formations: a formation in the Mio-Plio-Quaternary alluvium consisting of clays, marls, gravel and sand; the second is a deep carbonate aquifer composed of fissured and karstified neritic limestone of the Cretaceous age of variable depth ranging within 50 and 350 m.

Originality. The originality of the study is in the fact that the studied area is characterized by the presence of thick, fractured and karstified carbonate formations, which are intensively tectonized and have significant aquifer potential.

Practical implications. The correlation of geological data with geophysical data made it possible to conclude that the studied area is a sedimentary basin bounded by faults predominantly oriented to the south-west and north-east, forming a highly fractured unit consisting of horsts and grabens. The significant water potential reservoir is formed essentially by carbonate geological formations, highly fractured with the presence of karst forms represented by resistant horizons.

Keywords: *Hammam Bradaa, geometry, electrical prospecting, neritic limestone*

1. Introduction

The study area is one of the outer areas of the Alpine Chainof the north-eastern Algeria. It is located northeast of Guelma, Algeria. The analysis of works and geological studies [1]-[5] carried out in the region, as well as logs of stratigraphic data from mechanical boreholes laid in this region, the deepest of which reaches 580 m in depth, make it possible to visualize different stratigraphic series. The main outcrops encountered in the study area are characterized by formations from Triassic to the Quaternary age [6], thus presenting a very diverse lithology which mainly includes: alluvium, marl, clay, flysch and, above all, fissured and karstified limestones.

The method of electrical prospecting makes it possible to quantify the effect produced by an electric current crossing the subsoil [7]. In this study, we relied on the geophysical campaign results of the electric method using the Schlumberger device [8]. Two geophysical campaigns using vertical electric sounding were carried out by the National Company of Geophysics E.N.A.G.E.O (1993-1994) and the Hydrosol Design Office(2014) in the Heliopolis region, as a result of which 38 VES (Hydrosol) on line AB = 2500 m and 40 VES (E.N.A.G.E.O) on line AB = 1000 m, AB = 2000 m and AB = 5000 m.

Vertical electric sounding (VES) is a geophysical survey method that is well adapted to hydrogeology and aims to be quantitative in determining aquifers [9].

1.1. Presentation of the study area

The study area is part of the middle Seybouse, located in the northeast of Algeria [10]. It represents the northern shore of the collapse basin of the Guelma plain, 3 km north of the communal capital of Heliopolis between longitude 7°22′00″E, 7°29′00″E and latitude 36°24′30″N, 36°35′00 N. It is bounded in the north by the Djebel Bousbaa mountains, by Oued Seybouse in the south, by Djebel Debagh in the west and by Djebel Guigba in the east.

1.2. Geological and hydrogeological setting

The study region is part of the outerzones of the Maghreb chain of northeastern Algeria [11]. It is a collapsed sub-basin characterized by a filling of the Mio-Plio-Quaternary formations such as clay, gypsum marl, and heterogeneous allu-

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vium in the form of a terrace. Structurally, the Guelma region includes the neritic area of Djebel Debagh and Heliopolis in the south (Fig. 1).

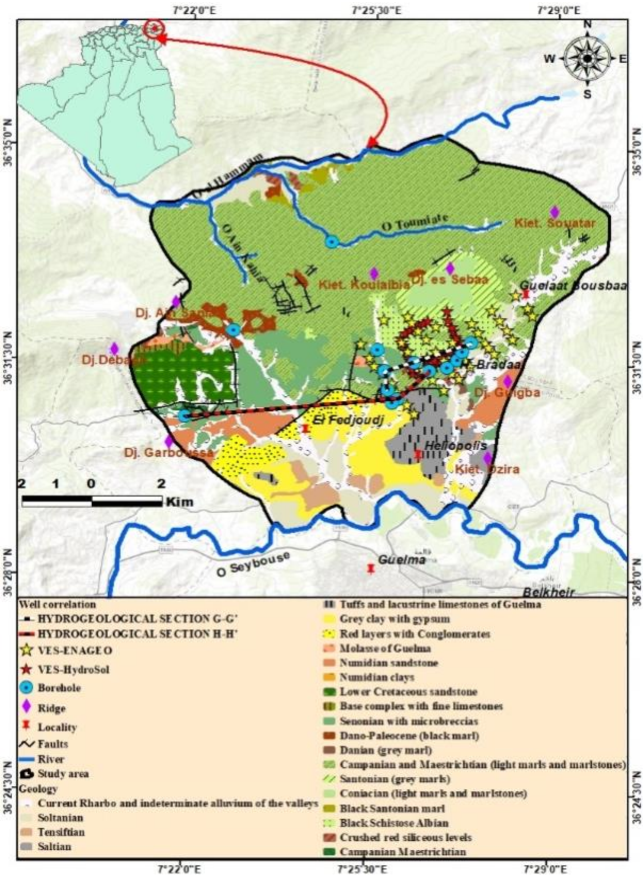

Figure 1. Geological and situation map of the study area (Villa, 1980)

This is a Cretaceous carbonate facies, the aquifer of which is associated with karstified Maastrichtian-Campanian limestones. These formations belong to the intensely cracked and karstified carbonate type, are composed of several thrust sheets and subjected to large tectonic stacks of sheets [12]. Thus, they form a favorable environment for groundwater circulation.

From the hydrogeological point of view, this geological configuration is reflected at the hydrogeological level by the presence of two types of aquifers. Firstly, a superficial alluvial aquifer of lesser importance, because of its limited extent by a Mio- Pio-Quaternary horizon with a depth within 5-15 m [13]. Secondly, a significant deep aquifer characterized by fissured and karstified limestone formations in a neritic limestone stratigraphic unit which occurs at a depth of 50 and 350 m. The exact limits of this formation are unknown, because it is covered by Tellian and Ultra Tellian sheets. The neritic limestone outcrops, which are part of the north-eastern group of neritic series, are isolated and of varying sizes. To delineate these formations, two hydrogeological sections were drawn based on the available data: one at the level of Mechtat Bouzitoune and the other along the El-Fedjoudj-Hammam Bradaa axis. In the Hammam Oulad Ali region, these carbonate formations are represented by a few tens of meters of biodetrital or micritic Upper Senonian limestone, similar to that of Douar Bouzitoune (Heliopolis). These formations plunge deep to the east under the thrust sheets to appear first in the Bouzitoune region and then in a small window near the Roman spring.

In the Bouzitoune region, the hydrogeological section GG′, created by six boreholes drilled along the southeast-northwest axis (Fig. 2), made it possible to delimit the neritic carbonate formations at a depth of 198 m. The El Fedjoudj II borehole, 220 m deep, has produced 73 l/s with a static level of 57 m [14]. Pumping in the El Fedjoudj II borehole with a static level of 57 m and a depth of 220 m at a flow rate of 73 l/s has led to the drying of the Hammam spring thermal waters [15]. This indicates the low potential in this part of the aquifer. From Djebel Debagh to Hammam Bradaa, the implementation of El Fedjoudj II, Bouzitoune and Hammam Bradaa boreholes, made it possible to assume the continuity of carbonaceous neritic formations in the same direction (Fig. 2).

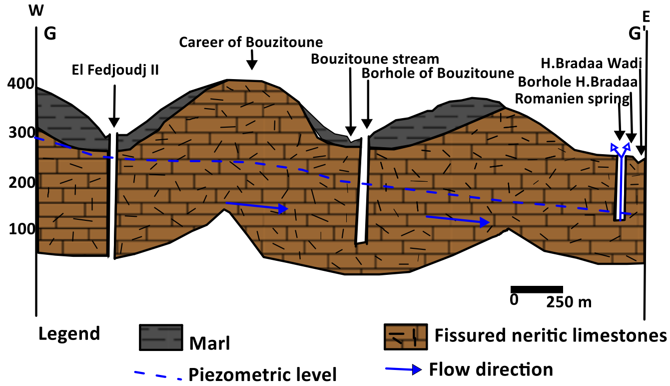

Figure 2. Hydrogeological section (GG') in the study area (Saaidia & Chaab, 2002, modified)

Indeed, to the south and north of this axis, translated by the HH′ hydrogeological section in the Bouzitoune region (Fig. 3), the top of the neritic limestones is 500 m [16] (borehole of Maachou and Bouzitoune II), while in the central part the limestones are found at a depth of 98 m (Bouzitoune I drilling case). The continuity of these formations constitutes the Hammam Bradaa aquifer.

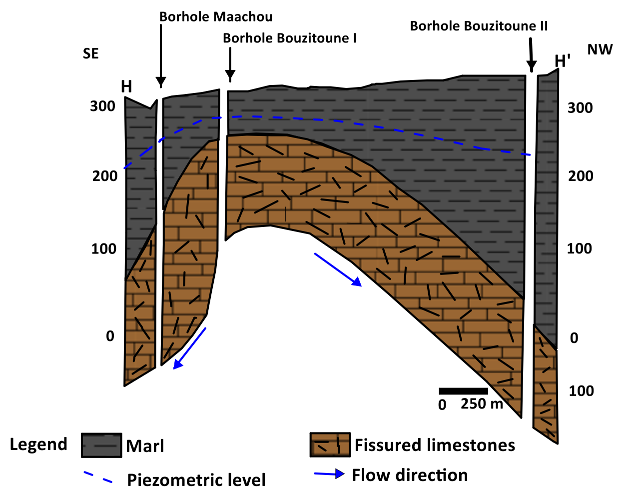

Figure 3. Hydrogeological section (HH') in the study area (Saaidia & Chaab, 2002, modified)

2. Materials and methods

The electrical resistivity method implemented during this study is a classic method for prospecting potential aquifers [17]. Our work consists in interpreting the VES raw data, which allow us to conduct geoelectric sections and have an idea on the extension and formation of neritic limestones.

To achieve our objective, the conclusions of geophysical study by the electrical method, as well as geological documents (maps, stratigraphic logs of existing boreholes in the study area and established geological sections) are used.

The principle of electrical prospecting based on Ohm's law, measurements of apparent resistivity from the earth's surface, and the geoelectrical characteristic of deep layers allowed to determine the lithological nature of deep layers by interpreting the curves of the vertical electrical soundings [18]. Electrical sounding is an investigation method for quantitative determination of variations in the electrical resistivity of subsoil formations as a function of depth.

This method of prospecting by vertical electric sounding (VES) consists in sending into the subsoil, via emission electrodes A and B, a direct electric current *I*, which measures the potential difference ΔV produced between two reception electrodes *M* and *N*. The apparent resistivity (ρa) is obtained by applying the following Formula:

$$\rho a = K \cdot \left(\frac{\Delta V}{I} \right), \tag{1}$$

where:

K – geometric coefficient depending on the position of *AMNB* electrodes for the Schlumberger device using the Formula:

$$K = \pi \cdot \left(\frac{AMAN}{MN} \right). \tag{2}$$

The vertical electrical sounding made it possible to estimate the apparent resistivity value according to the length *AB*; for this, a vertical electrical sounding sheet will be completed using a Shlumberger quadrupole device (Fig. 4).

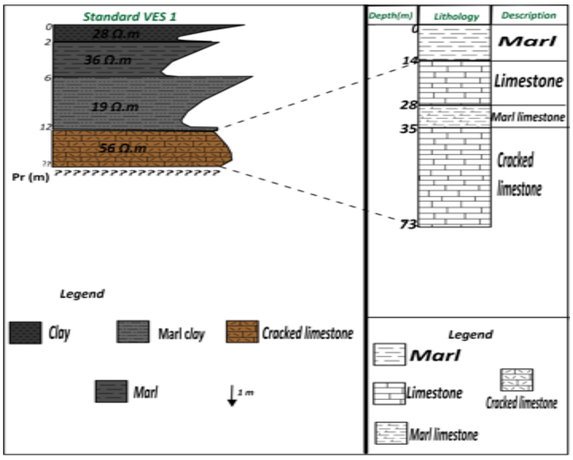

Figure 4. Results of the VES calibration and correlated with HB1 borehole data

During this electrical campaign, 78 vertical electrical soundings were carried out and interpreted. The depth of investigation of this device varies from 100 to 250 m, from 200 to 500 m and from 500 to 1250 m [19]. The potential difference ΔV and apparent resistivity measurements were carried out using the Iris Instruments type resistivity meter, and current was sent to the ground using an internal 600 W *AC*/*DC* converter powered by an external 12 V battery. Standard soundings were carried out to determine the resistivity scale and distributed over 2 geoelectric sections, one of which is oriented to the northwest and southeast; and the other is oriented to the northeast and southwest.

The various measurements of the physical resistivity parameter taken in the field are interpreted using the IPI2WIN software in the form of logarithmic curves reflecting the variation in apparent resistivity (ρa) as a function of the length *AB*/2 [20].

3. Results and discussion

3.1. Calibration of electrical soundings

A certain number of calibrations of electrical soundings have been carried out on the sites of existing mechanical boreholes in the field [21]. The simple correlation of the lithological section provided by the borehole and the curve of the vertical electrical sounding carried out in the vicinity of the borehole makes it easy to assign the electrical layers detected by the VES to the geological layers of the mechanical borehole.

The average values of resistivity of geological formations can be deduced by conducting several standard soundings [22]. We present below some calibration soundings.

3.2. Interpretation of vertical electrical soundings

A calibration electrical sounding *AB* = 1000 m was carried out next to a 90 m deep borehole in the Hammam Bradaa region at the following coordinates: *X* = 36145.00 m, *Y* = 4042889.00 m.

3.2.1. Calibration sounding of HB1 quarry borehole

The lithology of the terrain according to the borehole log data [23] indicates that the formations are as follows:

– 0.00 – 14.00 m: red vegetal soil with predominantly marly base and with light gray limestone level passage at the base;

– 14.00 – 28.00 m: very resistant and abrasive white limestones of dark gray color;

– 28.00 – 35.00 m: area of alternating gray marl and limestone;

– 35.00 – 73.00 m: very hard black limestone, heavily cracked with total loss of mud at a depth of 40 m.

Geoelectric curve model for VES HB1.

The interpretation of the HB1 electrical sounding shows (Fig. 4):

– a layer is 2 m thick, with a resistivity of 28 Ω-m, associated with clays;

– the second layer is 6 m thick and has a resistivity of 36 Ω-m, associated with marls;

– the third layer is 12 m thick and has a resistivity of 19 Ω-m, associated with marly clays.

The section is completed with a resistant substratum of 56 Ω-m, combined with cracked limestone.

It is important to note that the correlation with the borehole data from the HB1 quarry is almost perfect.

3.2.2. Bouzitoune borehole calibration sounding

A calibration sounding electrical line *AB* = 2000 m was conducted next to a borehole with a depth of 240 m in the Bouzitoune region at the following coordinates: *X* = 359725.00 m, *Y* = 4041969.00 m.

The examination of the earth lithology [24], according to the drilling log sheet (DHW Guelma 2020) can be summarized as follows (Fig. 5):

– 0.00 – 100.00 m: gray marls;

– 100.00 – 132.00 m: dense limestone, resistant light gray;

– 132.00 – 240.00 m: friable gray limestone, easily crushed by a tool: cracked zone, the presence of total losses of benthonic mud.

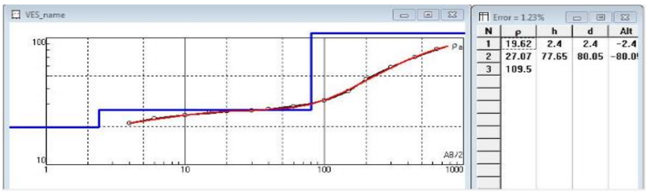

Figure 5. Geoelectric curve model for VES Bouzitoune

The interpretation of the standard electrical sounding of the Bouzitoune borehole distinguishes the following two layers (Fig. 6):

– the first conductive layer with an average resistivity of 23.34 Ω-m and a thickness of 80.00 m;

– the second conductive layer with a resistivity of 109.00 Ω-m.

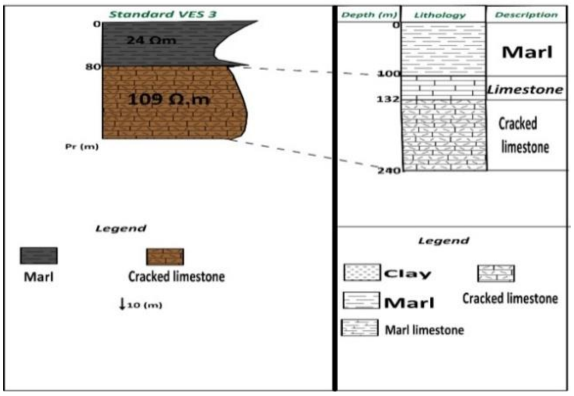

Figure 6. Results of the VES calibration and correlated with the Bouzitoune borehole data

These two formations correspond to the gray marl and cracked limestone, respectively, described in the Bouzitoune borehole log.

3.2.3. Calibration sounding of HB3 Maachou borehole

A calibration sounding electrical line $AB = 5000$ m was conducted next to a borehole with a depth of 410 m in the Hammam Bradaa region at the following coordinates: $X = 359367.00$ m, $Y = 4042801.00$ m (Fig. 7).

The borehole data sheet [25] presents the following formations:

– 0.00 – 10.00 m: topsoil, black clay;

– 10.00 – 200.00 m: laminated black marls;

– 200.00 – 270.00 m: gray plastic marls with limestone debris;

– 270.00 – 360.00 m: gray marls with crossing light gray limestone and presence of white calcite filaments;

– 360.00 – 400 m: very resistant and abrasive black limestone with total loss of mud at 399.00 m.

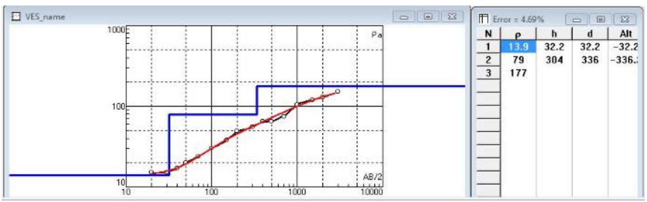

Figure 7. Geoelectric curve model for VES HB3

The interpretation of the HB3 electrical sounding shows:

– the first superficial layer with a thickness of 32.00 m and a resistivity of 13.90 Ω-m, associated with clays;

– the second layer with a thickness of 304.00 m and a resistivity of 79.00 Ω-m, associated with limestone formations with marly passages;

– the section ends with a resistant formation of 177.00 Ω-m, which corresponds to cracked limestone.

It should be noted that the correlation with the borehole data was not perfect, especially at the level of the second layer, where VES indicates a marl thickness of 304 m, which is significantly less than that given by the borehole log of 350 m (Fig. 8).

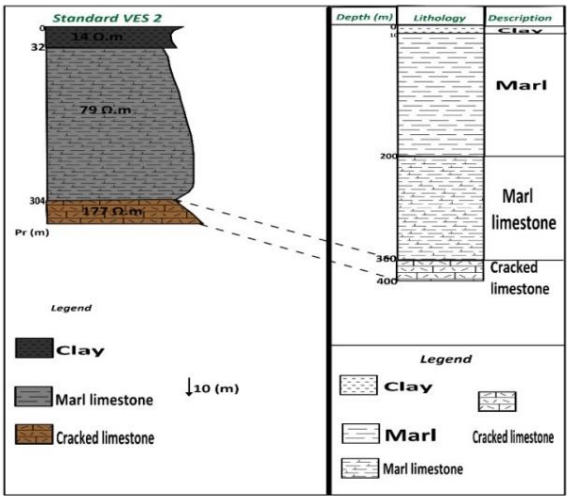

Figure 8. Results of the VES calibration and correlated with the HB3 borehole data

The study of these standard electrical soundings enabled us to develop a resistivity scale presented in the following Table 1.

Table 1. Resistivity scale of various geological formations

Formations	Resistivity (Ω-m)
Gray marl, marl clay	19-36
Resistant limestone	190
Cracked limestone	46-56
Clay	13-16

According to the resistivity scale, it can be said that dense limestones are distinguished by their high resistivity values exceeding 190 Ω-m. On the other hand, fissured limestones have a resistivity in the range of 56 Ω-m. The resistivity contrasts are sufficient to distinguish marks with a resistivity of 19-36 Ω-m from clays with a resistivity of 13-16 Ω-m.

3.3. Geoelectric sections

The geoelectric sections that allow to reveal the geometry of the electric horizons of various resistivities and follow horizontal extension [25] were developed from two geoelectric sections and using the VES interpretation results (Fig. 9).

The first geoelectric section identified according to VES No. 1 to VES No. 24 profile at the level of Hammam Bradaa is oriented to the northeast and southwest. It contains a long series of limestone affected by a series of faults and composed of a thick marly layer. In the southwest, at the level of VES 16, 23, 24, limestones on the surfaces sharply reach a depth of 400 to 500 m, at the level of VES 14 and 15, and vary from 200 to 400 m in depth at the level of VES 1, 10, 11, 12 and 13 (Fig. 10). The second geoelectric section was determined according to the VES 1 to VES 9 profile, oriented to the northwest-southeast.

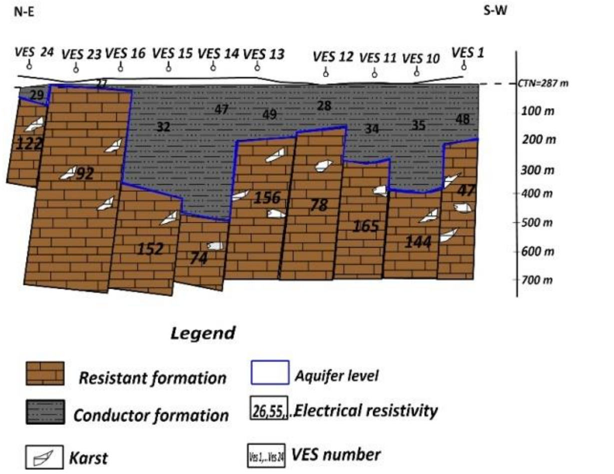

Figure 9. Geoelectric section AA'

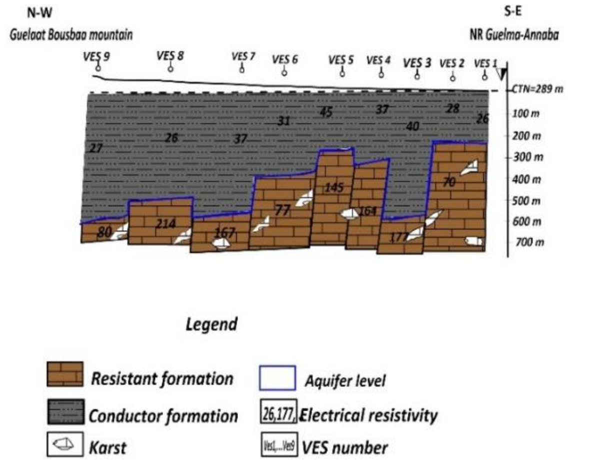

Figure 10. Geoelectric section BB'

It contains a long series of limestone affected by a series of faults and composed of a thick marly layer. The limestones gradually subside from the southeast to the northwest, reaching depths of more than 500 m at the level of VES 7, 8 and 9.

It can be concluded that these geoelectric sections show:

– a very large lateral extension of the neritic Constantine limestones;

– a very significant limestone thickness, which can reach up to 800 m;

– a structure affected by a series of faults showing limestone in the form of Horst and Graben;

– a variable depth of the aquifer top;

– very thick marly layer, especially in the northwest, overlying limestone.

3.4. Tectonics of the study area

The tectonic map of the study area was compiled based on the results of all geoelectrical sections developed taking into account the location of the faults marked on the sections [26]. On this tectonic map (Fig. 11), a system of predominantly southwestern-northeastern trending faults is distinguished.

These faults seem to link the most important transverse faults in alluvial deposits. On the other hand, we can report the presence of small faults in the northwestern part of the survey area of the same northeastern, southwestern orientation. These faults crossing the area draw attention to the hydrogeological relationships that exist between them and the aquifer zones.

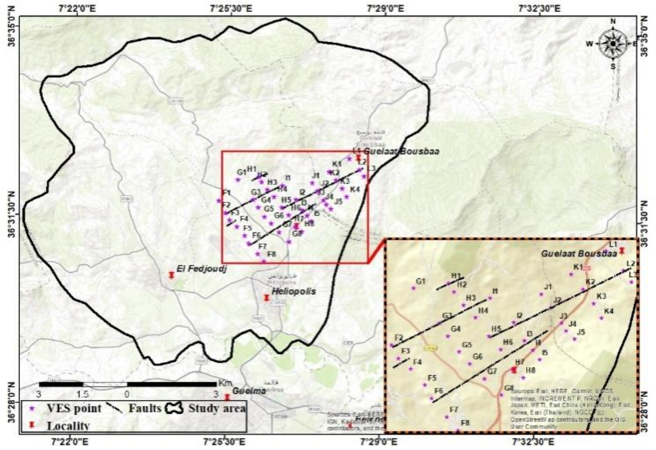

Figure 11. Tectonics map of the study area according to the VES data

3.5. Resistivity maps

Based on the *AB* injection lines used in the geophysical campaign, several resistivity maps have been compiled: *AB* 400 m, *AB* 1000 m and *AB* 2500 m, which corresponds to average depths of 40, 100 and 250 m (Fig. 12).

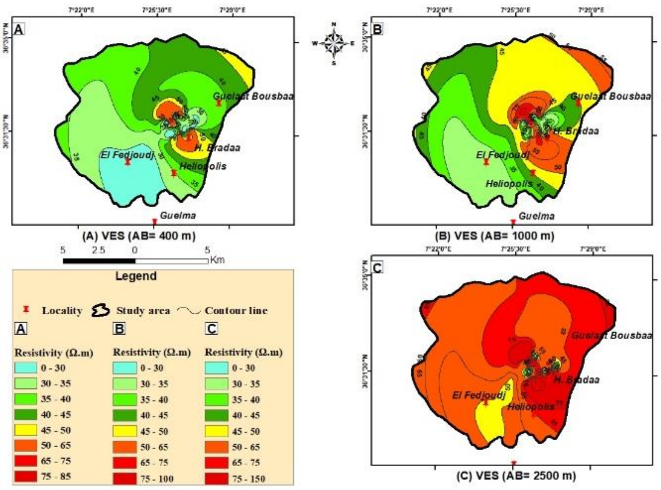

Figure 12. Resistivity map according to different AB lengths in the Heliopolis region

The resistivity map *AB* = 400 m, whose depth of investigation is between 40 and 100 m, i.e. (*AB*/10 and *AB*/4), shows apparent resistivity values equal to or greater than 70.00 Ω-m, forming a section to the south and southeast in the region of Heliopolis, Hammam Bradaa. This resistivity layer corresponds to the fissured limestones of the Cretaceous age. Furthermore, the lowest values (close to 22 Ω-m) correspond to the Mio-Plio-Quaternary formations (clay and marl) at the Guelaat Bousba level (Fig. 12a).

According to the map drawn by the line *AB* = 1000 m (Fig. 12b), it shows the distribution of resistivity ranges similar to *AB* = 400 m. These are resistant neritic limestones of the Cretaceous period, which are manifested in the northeastern part of the study area with an average resistivity of about 60 Ω-m. The rest of the area is occupied by a more or less conductive formation, characterizing the Mio-Plio-Quaternary formations, with a resistivity equal to 20 Ω-m.

For formations located at a depth from 250 to 625 m, the compiled map (Fig. 12c) shows that the apparent resistivity values are about 155 Ω-m, characterizing the fissured limestone Cretaceous formations in the southern and eastern part. Furthermore, the lowest values, ranging from 25 Ω-m, correspond to the Mio-Plio-Quaternary formations (clay and marl).

3.6. Top depth of the aquifer

The combination of geophysical information, drilling logs and the geological map of Guelma made it possible to compile a map of top depth of the Cretaceous limestones (Fig. 13).

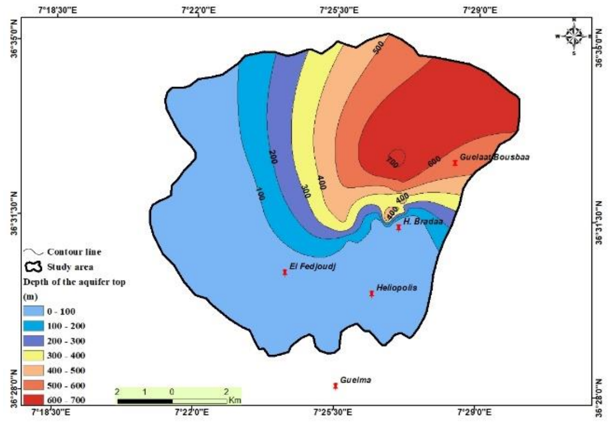

Figure 13. Top depth of the neritic limestone aquifer of Hammam Bradaa-El Fedjoudj

Based on the map analysis, the top depth clearly shows the neritic limestones of the Heliopolis – El Fedjoudj region in the Guelma wilaya.

According to this top depth map, these limestones outcrop in the southwestern part of the study area and gradually dip to the east and northeast, reaching 500 m depth of the El Fedjoudj pass under a significant Mio-Plio-Quaternary cover.

3.7. Transverse resistance

To study the potential of the deep aquifer, we have compiled a map of the transverse resistance. This map shows the variability of the resistivity of the wet layer as a function of its thickness. From this map (Fig. 14), we notice in the eastern part, a large transverse resistance (22000 Ω-m) which shows good hydrogeological characteristics.

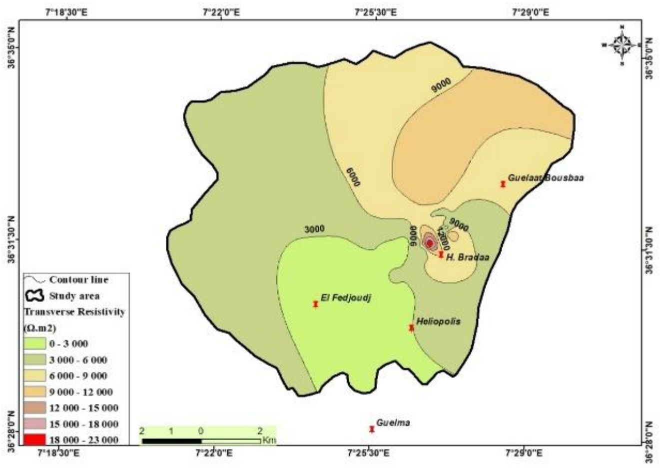

Figure 14. Transverse resistance map

It is noted that the low transverse resistance values appear in the southwestern region with average resistivity values (< 11000 Ω-m), reflecting the presence of a formation with bad hydrogeological characteristics.

4. Conclusions

The combination of data from the geophysical survey and geological data provided information on the geometry and constitution of the neritic aquifer. It consists of cracked limestone with an average thickness of 300 m from Hammam Bradaa and Bouzitoune to Guelaat Bousbaa. This carbonate formation is an important underground water table affected by a network of southwest and northeast oriented faults forming horsts and grabens that contribute to the karstification of aquifer formations.

The neritic and Senonian limestones of Heliopolis are of great interest as an aquifer, given the extension and thickness of the carbonate formations and, above all, the flow rate withdrawn. The general flow runs from west to east, from the eastern peak of Djebel Debagh to Hammam Bradaa, where the Roman spring emerged due to limestone outcrops.

From the hydrogeological and geoelectric cross sections, we have found a clear correlation between the hydrogeological cross sections and the geoelectric cross sections, whose average depth of the limestone is between 30 and 325 m. The average depth of the limestone roof is located approximately from 10 to 350 m, reflecting the irregular morphology of the neritic limestone formations of the study region and the favorable consequences on the possible identification of potential aquifers in the region.

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Геофізичні та геологічні внески у визначення структури водоносного горизонту неритового вапняку Хаммам Брадаа – Ель Феджудж (середній Сейбуз), Північно-Східний Алжир

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Мета. Геофізичні та геологічні дослідження особливостей і структури водоносного горизонту неритового вапняку Хаммам Брадаа – Ель Феджудж у північно-східному Алжирі, що за своєю потужністю та поперечним простяганням є стратегічним ресурсом для регіону та використовується для водопостачання питної води.

Методика. Для досягнення поставленої мети використовуються висновки геофізичних досліджень електричним методом, а також геологічні документи (карти, стратиграфічні карти існуючих свердловин на виїзній території та встановлені геологічні розрізи). Під час цієї електрокампанії було проведено та інтерпретовано 78 вертикальних електричних зондувань.

Результати. Основні результати показують, що в районі дослідження були виявлені дві важливі формації водоносного горизонту: формація в Міо-Пліо-четвертинному алювії, що складається з глин, мергелів, гравію та піску; друга формація – це глибинний карбонатний водоносний горизонт, складений тріщинуватими і закарстованими неритовими вапняками крейдяного періоду змінної глибини від 50 до 350 м.

Наукова новизна. Оригінальність дослідження полягає в тому, що досліджувана територія характеризується наявністю потужних, тріщинуватих і закарстованих карбонатних утворень, які інтенсивно тектонізовані та мають значний водоносний потенціал.

Практична значимість. Співвідношення геологічних даних з геофізичними дозволило зробити висновок, що досліджувана територія є осадовим басейном, обмеженим розломами, спрямованими переважно на південний захід і північний схід, утворюючи сильно тріщинувату товщу, що складається з горстів і грабенів. Значний водопотенційний резервуар сформований в основному карбонатними геологічними формаціями, сильно тріщинуватими, з наявністю карстових форм, представлених стійкими горизонтами.

Ключові слова: *Хаммам Брадаа, геометричні параметри, електророзвідка, неритовий вапняк, водоносний горизонт*