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GEOELECTRICAL SURVEY TO DELINEATE THE EXTENSION OF THE WATER BEARING FORMATIONS IN WADI GHARANDAL, SOUTHWEST SINAI, EGYPT

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مسح جيوكهربى لتحديد امتداد الطبقات الحاملة للمياه في وادى غرندل بجنوب غرب سيناء، مصر

الخلاصة: على مدى العقود الأخيرة جذب الموقع الاستراتيجى لشبه جزيرة سيناء انتباه المسئولين لوضع خطة للتنمية المستدامة للمنطقة، ولما كان وجود المياه بهذه المنطقة من أهم عناصر التنمية فقد كان لنا إجراء دراسة جيوكهربية بهدف تحديد أماكن تواجد المياه الجوفية في وادى غرندل وروافده لمساحة نحو ٨٧٠ كيلومتراً مربعاً بالناحية الشرقية لخليج السويس. وقد تم خلال هذه الدراسة إجراء ٣٥ جسة كهربية عمودية باستخدام نظام شلمبرجير للأقطاب الرباعية وبمسافة قصوى بين الأقطاب ما بين ٤٠٠ متر إلى ٤٠٠٠ متر.

وقد أوضحت نتائج الدراسة مدعمة بالمعلومات الجيولوجية والهيدروجيولوجية المتوافرة بالمنطقة بالإضافة إلى المعلومات الواردة من الآبار المحفورة هناك ومن خلال ٧ قطاعات جبوكهربية وجود ١١ طبقة جيوكهربية الأقدم منها أمكن التعرف عليه على عمق قليل فى (المصب) نتيجة لوجود عدد من الصدوع وكذلك بالنسبة لميل الطبقات.

كما توصلت الدراسة إلى أن الطبقات الحاملة للمياه هى خمس طبقات تم تعريفها ووصفها وتحديد أعماقها وامتدادها وكذا وصف الصدوع الموجودة وتأثير كل صدع على وجود المياه الجوفية بالمنطقة التى تناولتها الدراسة.

ABSTRACT: *In the last decades, the strategic situation of Sinai attracted the government to set a national plan for its sustainable development. Since water is an important factor of this development, this study was carried out with the aim of defining the groundwater occurrences along Wadi Gharandal and its tributaries. The area lies in the eastern side of the Gulf of Suez covering about 870 km^2. It extends between Latitudes 29º 11' N & 29º 25' N. and Longitudes 32º 52' 20" E & 33º 27' 20" E .*

Geoelectrical study was carried out by conducting 35 Vertical Electrical Soundings (VES) along the main channel of Wadi Gharandal and its tributaries. This study revealed that the subsurface succession consists of 11 geoelectrical units equivalent to a succession extending from the Lower Cretaceous to the Quaternary. Some of these units are considered as water bearing formations. The subsurface succession is found to be affected by a number of normal step faults throwing towards the Gulf of Suez (East). These faults play an important role in the groundwater occurrences along Wadi Gharandal.

INTRODUCTION

The strategic situation of Sinai made it an urgent national target for the sustainable development. One of the important factors in such development is the exploration and the management of groundwater. Consequently, Wadi Gharandal, which is considered as one of the main wadis in Southwest Sinai was chosen for the present study.

The study area lies in the eastern side of the Gulf of Suez between Latitudes 29º 11' & 29º 25' N and Longitudes 32º 52' 20" & 33º 27' 20" E (Fig.1). It covers an area of about 870 km^2.

GENERAL GEOMORPHOLOGY AND GEOLOGY

Hammad (1980) divided Sinai into seven geomorphological units. These are; southern elevated mountainous district, central plateaux district (El-Tih and El-Egma), hilly district, north and northwest coastal plain district, marshy and sabkhas district, alluvial coastal plains district and lakes. The investigated area is part of the central plateau's district and the alluvial coastal plains district.

Stratigraphically, the study area is covered by exposed rock units varying from Lower Cretaceous to Quaternary, where most of these rock units are considered as water bearing formations.

According to Shata (1956), Sadek (1959), Said (1962, 1990), Youssef (1969), Abd El Gawad (1970), Robson (1971), El Shazly et al. (1974), and Garfunkel and Bartov (1977), the major structures of the investigated area are dominated by normal and step faults. Generally, the downthrow of the faults ranges between few centimeters to several hundreds of meters. These faults may be related to synthetic or antithetic types. The synthetic type comprises all faults which are parallel to the Red Sea Graben, whereas the antithetic type is represented by the faults which are parallel to the Gulf of Suez and Gulf of Aqaba.

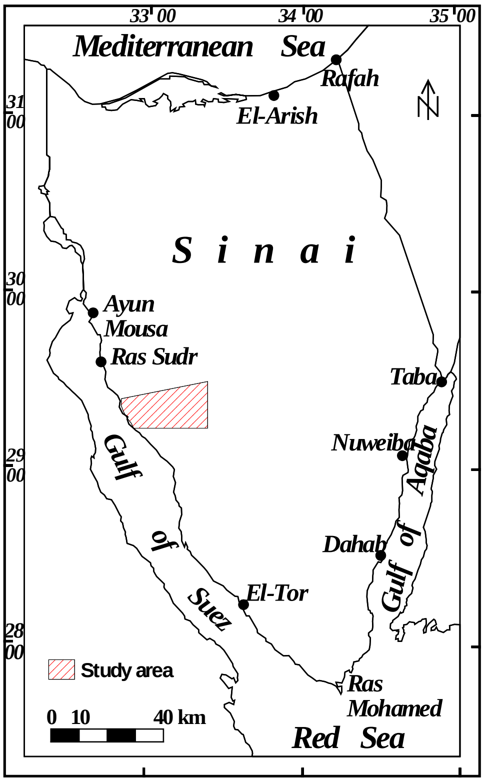


Fig. (1) : Location map of the study area

DATA ACQUISITION AND ANALYSIS

1. Data Acquisition:

The investigated area has a surface covered by wadi fill deposits forming terraces in some parts of the main channel of wadi Gharandal and its tributaries. The width of the main channel ranges between few meters in the upstream to about 700m in the downstream, so, it is difficult to carry out a regular grid pattern of the electrical soundings. However, a reasonable coverage of the area was reached by conducting 35 Vertical Electrical Soundings (Fig.2). The distribution of these soundings is as follows: 27 soundings along the main channel and the delta and 8 in the tributaries (3 in Wadi Al-Salfa, 3 in Wadi Al-Ghelan and 2 in Wadi Wata).

The Schlumberger array was used in the field work, where the current electrode half spacing (AB/2) starts from 1meter and increases successively to reach 200m in the delta and 2000m in the rest of the area. The field measurements were carried out using the earth resistivity meters TERRAMETER SAS 300 and SAS 4000, which enable measuring the resistance "R" with high efficiency.

2. Data Analysis:

The field curves of the electrical sounding measurements were quantitatively interpreted to provide the geoelectrical parameters, i.e., the true resistivities and the corresponding thicknesses of the encountered geoelectrical layer at each sounding station. These parameters help in the construction of the geoelectrical cross sections and maps to delineate the subsurface geologic succession, structures and the groundwater occurrences.

The quantitative interpretation was proceeded using the computer program "RESIST" (Van Der Velpen, 1988) for non- automatic iteration method in which the measured field data are compared with data calculated from an assumed model. The initial models were constructed depending on the available data from two drilled wells in the investigated area and the geologic map (G.S.E., 1994).

RESULTS AND DISCUSSION

The interpreted resistivities and thicknesses of the soundings were compared with the available geological and hydrogeological data to assign these resistivities to geoelectrical layers. With the help of the drilled wells and the geologic map, these geoelectrical layers were grouped as geoelectrical units to be equivalent to the geological formations. The lateral and vertical distribution of the geoelectrical succession, subsurface geologic structures and groundwater occurrence were clarified through the construction of 7 geoelectrical cross sections along the main channel of Wadi Gharandal and its tributaries (Figs.3-9).

1. Geoelectrical succession

The geoelectrical succession along Wadi Gharandal as well as its tributaries and delta consists of 11 geoelectrical units distributed along the subsurface, where the old formations were detected at shallow depths at the upstream (east) and go deeper towards the downstream (west) due to the effect of dip and step faulting. The resistivities, thicknesses and lithology of these units are shown in Table 1.

The description of the geoelectrical units from top to bottom is as follows:

Geoelectrical unit "A":

It includes two geoelectrical layers. The first, "$\mathbf{A_1}$" consists of a group of thin layers forming dry wadi fill deposits of boulders, gravels sand, clay and silt. The resistivity and the thickness of each layer has been used for determining a reasonable integral electrical parameter (average transverse resistivity) which gives a unique expression for the resistivities of the geoelectrical layer "$\mathbf{A_1}$" at each VES station. The average transverse resistivity ($\boldsymbol{\rho_t}$) has been calculated as follows :

$$\rho_t = \sum \rho_i * h_i \,/\, \sum h_i$$

where (ρ_t) is the average transverse resistivity of a column of n layers, (ρ_i) and (h_i) are the resistivity and thickness of each layer.

The average transverse resistivity (ρ_t) of geoelectrical layer "A_1" was found to range between 1 ohm-m and 7659 ohm-m (Table 1) with a median

Table 1: Resistivities, thicknesses and lithology of the geoelectrical units

Layer	**Resistiviy (ohm-m)**		**Thickness (meter)**		**Formation**	**Lithology**
	Minimum	**Maximum**	**Minimum**	**Maximum**		
A_1	1	7659	0.3	31	**Quaternary**	***Wadi fills***
A_2	11	166	2.2	20		***Wadi fills***
B_1	167		40.4		**Lower Miocene (Rudeis)**	***Sand and Arg. Limestone***
B_2	1	11	3	9		***Clay***
C_1	2	1247	0.3	19	**Lower Miocene (Nukhul)**	***Calc. sand, sandstone, conglomerate and shale***
C_2	2	107	3	45		
C_3	0.4	4	-----------	------------		
D	26	28	9.2	11)	**Oligocene (Abu Zenima)**	***Sandstone and siliceous conglomerate***
E_1	2	7	11	30	**Upper Eocene (Tanka)**	***Shaly Limestone and Gyps. Shale***
E_2	23	66	19	36		
F_1	98	160	23	47	**Lower-Middle Eocene (Darat)**	***Limestone, marl and, shale***
F_2	17	96	21	52		
G_1	60)	2976	35	156	**Lower Eocene (Minia)**	***Cherty limestone***
G_2	130	2471	------------	------------	**L.E (Thebes)**	***Limestone and chert***
H_1	2	14	22	35	**Sant.-Coniacian (Matulla)**	***Shale***
H_2	23	51	31	47		***Limestone, marl and sandy shale***
I_1	361	2163	9	13	**Turonian (Wata)**	***Massive limestone and dolomite***
I_2	70	112	11.3	41		***Marl and limestone***
J_1	5	60	15	50	**Cenomanian Galala (Raha)**	***Calcareous shale***
J_2	53	189	23.1	41		***Limestone and marly limestone***
J_3	7	49	28.1	82		***Calcareous shale***
J_4	308	15217	20	85.5		***Limeston and marly limestone***
J_5	22	113)	39.7	65		***Calcareous shale***
K_1	192	1386	0.3	31	**Lower Cretaceous (Malha Nubia Sandstone)**	***Sandstone, clay and siliceous sandstone***
K_2	47	195	65.6	83.2		
K_3	129	376	-----------	-----------		

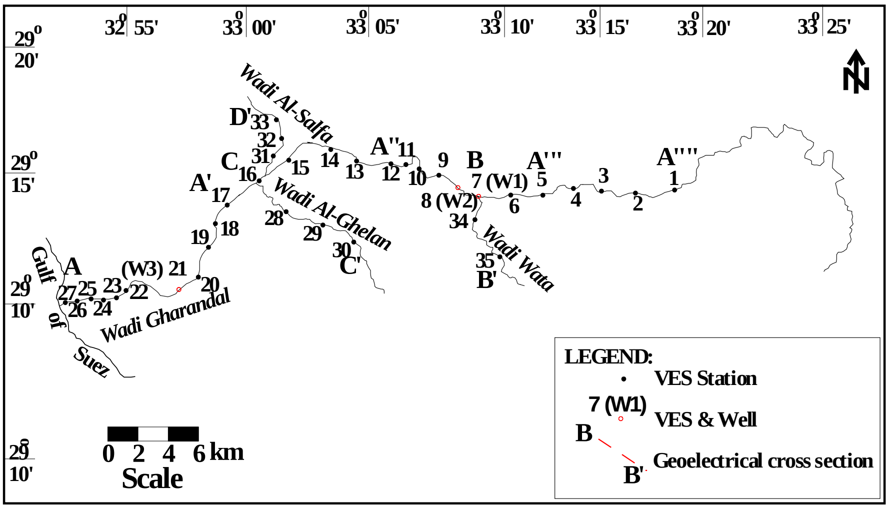


Fig. (2): Location map of geoelectrical soundings stations, wells and geoelectrical cross sections along Wadi Gharandal and its tributaries

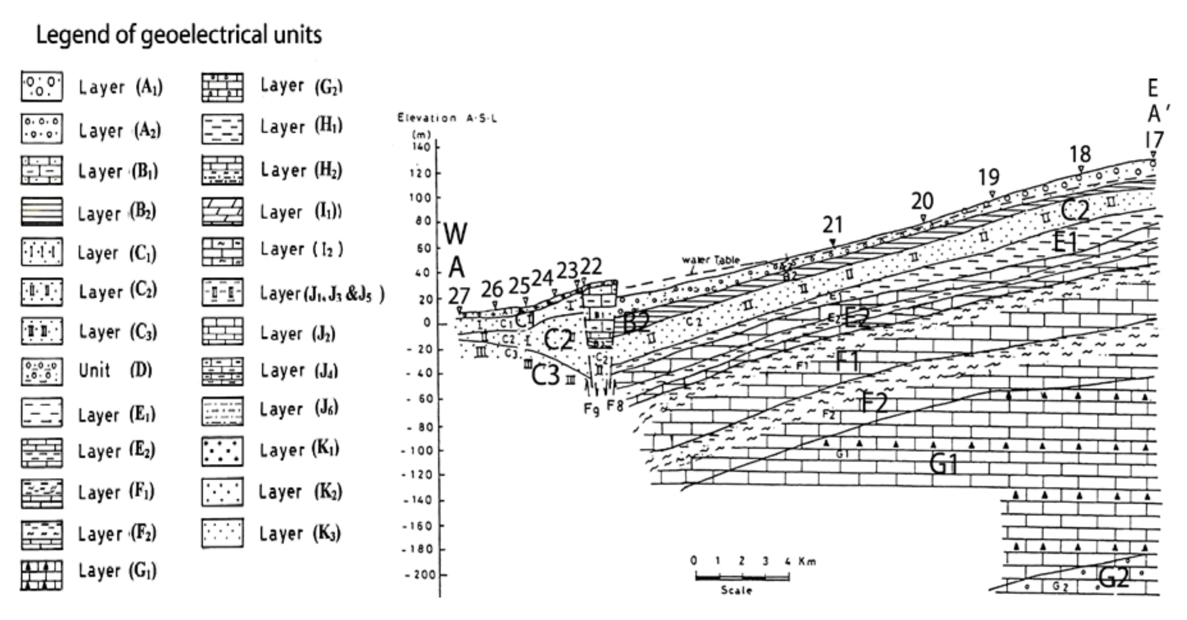


Fig. (3) : Geoelectrical cross section A-A' along the main channel of Wadi Gharandal

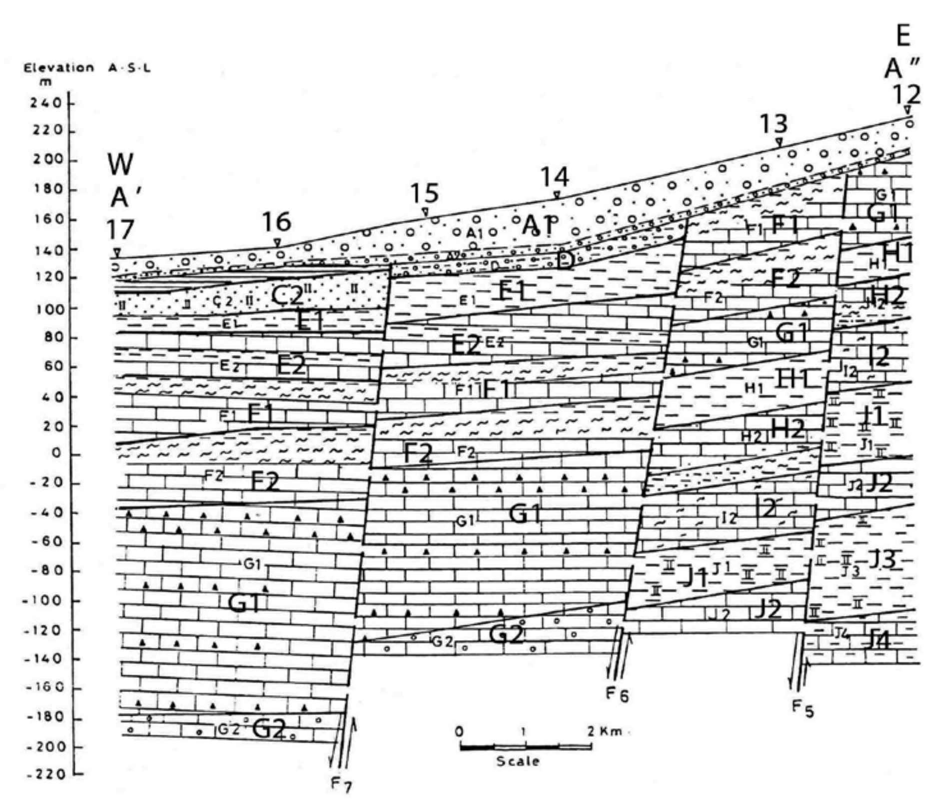


Fig. (4) : Geoelectrical cross sections A'-A" along the main channel of Wadi Gharandal

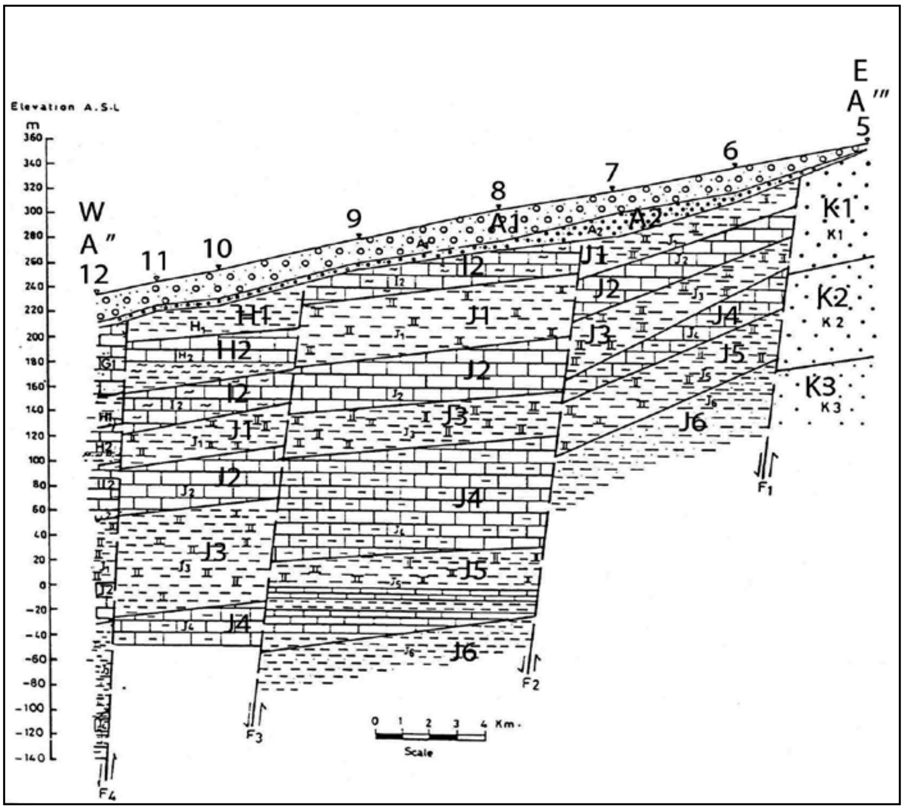


Fig. (5) : Geoelectrical cross section A'' – A''' along the main channel of Wadi Gharandal

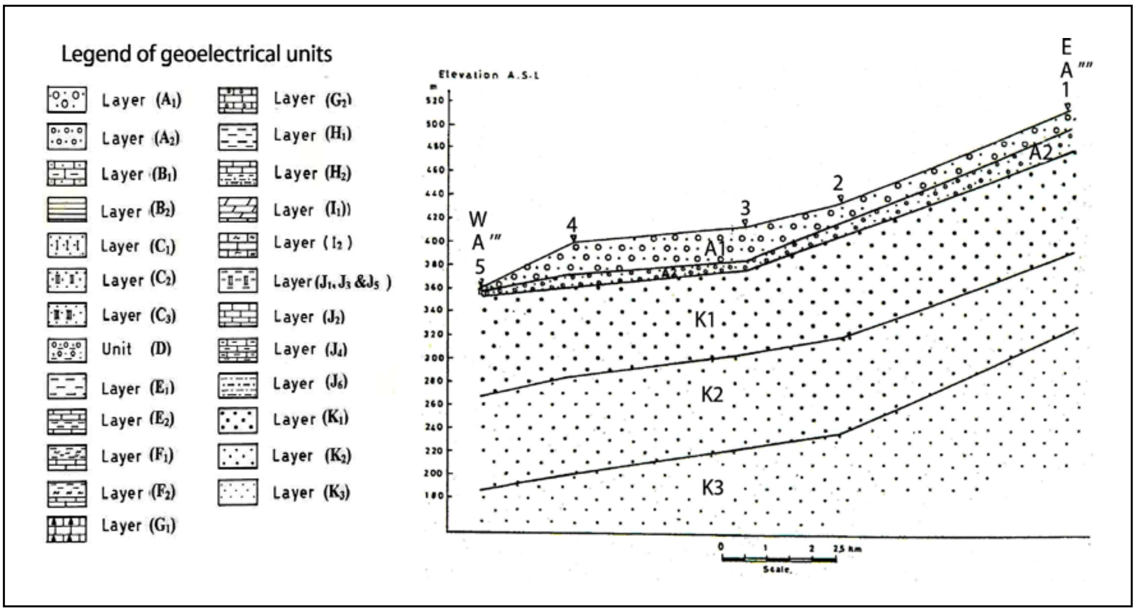


Fig. (6) : Geoelectrical cross section A''' – A'''' along the main channel of Wadi Gharandal

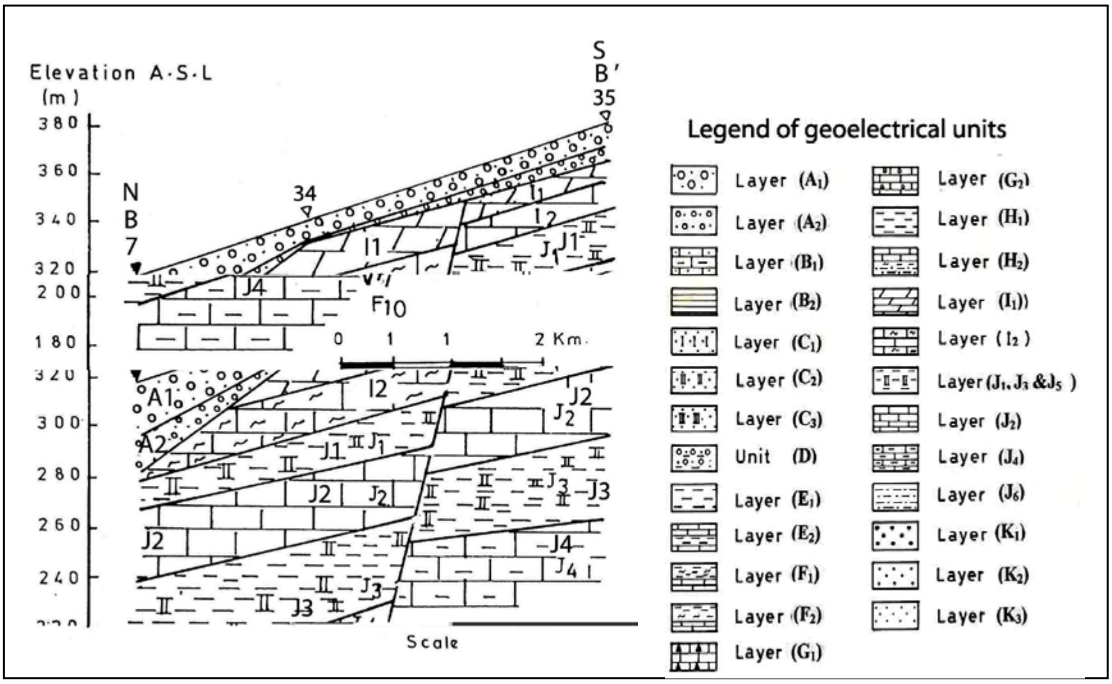
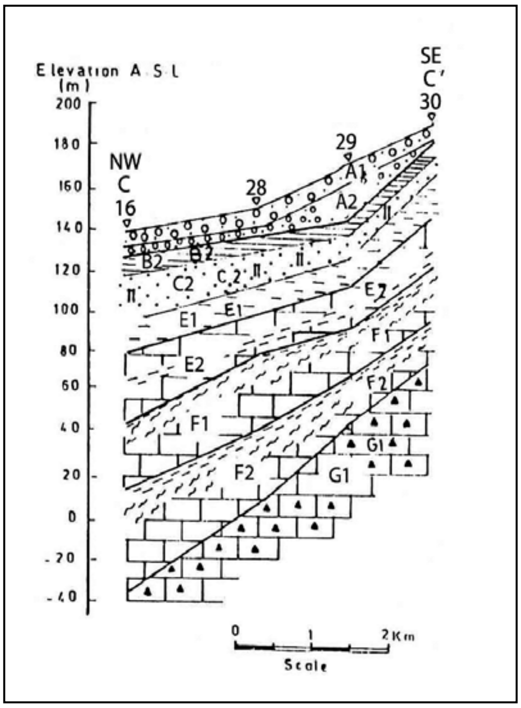


Fig. (7): Geoelectrical cross section B-B' along Wadi Wata



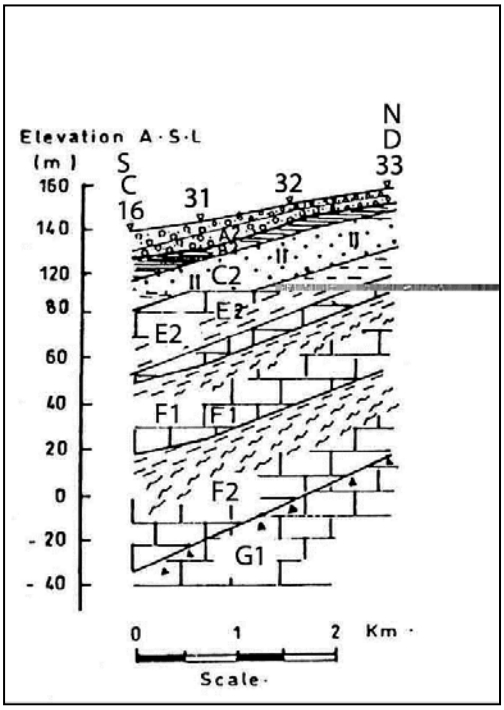


Fig. (8): Geoelectrical cross section C-C'
along Wadi Al-Ghelan

Fig. (9): Geoelectrical cross section C-D
along Wadi Al-Salfa

resistivity value of 1473 ohm-m. The low resistivity values at some sounding stations in the delta of Wadi Gharandal are attributed to the presence of sabkha. The minimum thickness of this layer is 0.3 m and the maximum thickness is 31.4 m with general westward decrease (downstream).

The second geoelectrical layer **“A_2”** consists of the same lithology of the first geoelectrical layer **“A_1”**, but it represents one of the main aquifers in the investigated area. This was confirmed by the data of nearby hand dug wells at some sounding stations. It shows a small range of resistivity values as compared with the upper one. Its resistivity varies from 11 ohm-m to 166 ohm-m. Generally, the resistivity of this layer decreases westwards (downstream). This may be attributed to the increase of the water salinity westwards as recorded from some wells, i.e., the salinity in the east at the hand dug well beside VES No.6 is 530 ppm, while it is 3000 ppm in the west at the hand dug well beside VES No. 21. The thickness of this layer ranges between 2.2 m and 20.1 m and decreases westwards (downstream).

Geoelectrical unit “ B ”:

This unit consists of two geoelectrical layers. Geologically, it is equivalent to Lower Miocene (Rudeis Formation). The upper layer “B_1“ appears only in the delta at VES No. 22, where this formation outcrops at the contact between the main channel and the delta. The second “***B2***“ was recorded in the main channel and its tributaries. The Miocene grits is the geological equivalent for layer “B_1”, where it consists of sandy limestone and hard clayey limestone. This layer consists of a group of small layers having average transverse resistivity value of 166.7 ohm-m. The thickness of this layer is 40.4 m. The second geoelectrical layer “B_2” was recorded between VES No. 16 in the east and VES No. 22 in the west along the main channel and at the sounding stations of wadi Al-Salfa and wadi Al-Ghelan (Figs. 3-8). Geologically, this geoelectrical layer is equivalent to Lower Miocene clays of the Rudeis Formation, which forms the base of Miocene. It exhibits low resistivity values as compared to the upper one, where it ranges between 1ohm.m and 11 ohm-m with a median resistivity value of 5 ohm-m. The recorded thickness of this layer ranges between 3m and 9m.

Geoelectrical unit “C”:

Geologically, this unit is equivalent to Lower Miocene (Nukhul Formation) which consists of calcareous sand, sandstone, conglomerates and minor shale as indicated from the cutting samples of the recently drilled well No. 3 beside VES No. 21. According to its lithology and resistivity, it can be classified into three geoelectrical layers (“C_1”, “C_2” and “C_3”).

The upper layer “C_1” consists of a number of thin layers, with average transverse resistivity values ranging between 2 ohm-m and 1247 ohm-m with median resistivity value of 253 ohm-m. The low resistivity values of this layer are attributed to the presence of sabkha at these locations, while the high resistivity values at the other stations are attributed to the dry nature of this layer. The thickness of this layer varies from 0.3m to 19m. (at VES No.7 beside well No.1).

The second geoelectrical layer “C_2” extends from VES No. 16 in the east to VES No. 22 in the west along the main channel in addition to all the stations of Wadi Al-Salfa, Wadi Al-Ghelan and the delta. Its resistivity varies from 2 ohm-m to 107 ohm-m. The thickness of this layer varies from 3m to 45.2m (well No.3).

The third geoelectrical layer “C_3” consists of sand and sandstone of Nukhul Formation and was detected only at the sounding stations of the delta. Its resistivity ranges between 0.4 ohm-m and 4 ohm-m with a median resistivity value of 1.2 ohm-m. The low resistivity values of this layer are attributed to the presence of highly saline water.

Geoelectrical unit “D ”:

This geoelectrical unit corresponds to Oligocene Tayiba red beds (Abu Zenima Formation), which consists of sandstone, siltstone, occasionally mudstone and conglomerate. It is present only at VES numbers “ 14” and “15” along the area of study. It attains resistivity values of 26 and 28 ohm-m (Table 1). The thickness of this layer ranges between 9.2m and 10.6 m..

Geoelectrical unit “ E”:

This geoelectrical unit comprises 2 geoelectrical layers (E_1 and E_2). Geologically, it is equivalent to Tanka Formation of the Upper Eocene which is composed of argillaceous limestone and gypseferous shale intercalation. It has been recorded at 14 sounding stations, where it is overlain by unit “***D***” at VES Nos. 14 and 15 and by geoelectrical layer “C_3” at the other stations. It extends from VES No. 21 in the west to VES No. 14 in the east along the main channel and at all the stations of Wadi Al-Salfa and Wadi Al-Ghelan. The resistivity of the first layer “E_1” ranges between 2 ohm-m and 7 ohm-m with a median resistivity value of 4.4 ohm-m. The low resistivity values of this layer may be attributed to the presence of gypseferous shale of Tanka Formation. Its minimum thickness is 11.3 m, while its maximum thickness is 30 m.

The second geoelectrical layer “E_2” has resistivity values ranging between 23 ohm-m and 66 ohm-m with a median resistivity value of 43 ohm-m. The recorded resistivity values of this layer reflect, to a great extent its lithological nature. The low resistivity values (less than 30 ohm-m) are attributed to the increase of the shale ratio, whereas the high resistivity values (>30 ohm-m) are attributed to the increase of limestone. Its thickness varies from 19m to 35.6 m.

Geoelectrical unit “F”:

This unit comprises two geoelectrical layers (***F1*** and ***F2***) corresponding to Darat Formation of Lower-Middle Eocene (limestone, marls and shale).

The upper geoelectrical layer “**F_1**” extends along the main channel from VES No. 21 in the west to VES No. 13 in the east and also along the sounding stations of Wadi Al-Salfa and Wadi Al-Ghelan. Its resistivity ranges between 98 ohm-m and 160 ohm-m with a median resistivity value of 123 ohm-m. The relative high resistivity values (98-160 ohm-m) of this layer, may be attributed to the increase of limestone ratio over that of marl and shale. The minimum thickness of this layer is 22.7 m, whereas the maximum thickness is 46.9m.

The second geoelectrical layer “**F_2**” has the same extension of the upper one, but exhibits low resistivity values, which may be due to the increase of shale and marl ratio over that of limestone. The minimum recorded resistivity value is 17 ohm-m, while the maximum resistivity value is 96 ohm-m with a median resistivity value of 60 ohm-m. Its thickness varies from 21.3 m to 52.1m.

Geoelectrical unit “G”:

The geoelectrical unit “***G***“ is equivalent to the Lower Eocene limestone and includes two geoelectrical layers. The upper layer “**G_1**“, corresponds to Minia Formation (limestone, chalky in its upper part), whereas the lower one “***G2***” is equivalent to Wasit (Thebes) Formation, which consists of hard limestone with bands and concretions of chert (G.S.E, 1994).

The first appearance of the upper geoelectrical layer “**G_1**” is at VES No.12 and extends westwards along the main channel. It is also recorded at the sounding stations of Wadi Al-Salfa and Wadi Al-Ghelan. It has resistivity values ranging between 60 ohm-m and 2976 ohm-m with a median resistivity value of 549 ohm-m. Its thickness ranges between 35.3 m and 155.7 m with a general increase westwards.

The lower geoelectrical layer “**G_2**“ consists of limestone with chert bands. It has high resistivity values as compared to that of the upper one, where it ranges between 130 ohm-m and 2471 ohm-m. The lower surface of this layer was not defined.

Geoelectrical unit “H”:

This geoelectrical unit is equivalent to the Matulla Formation of Santonian- Coniacian, which is composed of sandy shale with phosphatic marl and limestone intercalation with dominant shale at the top. This unit is differentiated into two geoelectrical layers (**H_1** and **H_2**). The upper geoelectrical layer “**H_1**” has resistivity values between 2 ohm-m and 14 ohm-m. This layer corresponds to the upper layer of the Matulla Formation (shale). The minimum thickness of this layer is 22 m , whereas the maximum thickness is 34.7 m.

The lower geoelectrical layer “**H_2**“ corresponds to the lower part of the Matulla Formation, which consists of limestone, marl and sandy shale. Its resistivity ranges between 23 ohm-m and 51 ohm-m and has a thickness of 30.8 - 46.9 m.

Geoelectrical unit “I”:

It overlies the geoelectrical unit “***H***” including two geoelectrical layers (**I_1** and **I_2**). Geologically, it is equivalent to Wata Formation, which is made up of massive limestone and dolomite with minor marl and shale. The upper geoelectrical layer “**I_1**” exhibits resistivity values ranging between 561 ohm-m and 2163 ohm-m. The high resistivity values confirm the surface exposure of this layer (massive limestone and dolomite), where it is exploited in this location through mining processes. Its thickness is 8.8-30m .

The second geoelectrical layer “**I_2**” has lower resistivity values with respect to the upper layer, where it ranges between 70 ohm-m and 112 ohm-m. Its thickness varies from 11.3m to 40.6 m, with a general increase westwards.

Geoelectrical unit “J”:

This unit is equivalent to Galala (Raha) Formation of Cenomanian age. According to the exhibited resistivity values and their correlation with the lithological data of the drilled wells Nos.1 and 2 beside VES Nos.7 and 8 consequently, this unit can be differentiated into 3 calcareous shale layers (“**J_1**”, “**J_3**” and “**J_5**”) alternating with 2 limestone and marly limestone layers (“**J_2**” and “**J_4**”), respectively, in addition to a sandy shale layer at the bottom (“**J_6**”).

The geoelectrical layers **“J_1”, “J_3”** and **“J_5”** are made up of the same lithology (calcareous shale) but with different ratios of the calcareous fraction. They have resistivity ranges of 5-60 ohm-m, 7-49 ohm-m and 22-113 ohm-m, respectively. On the other hand they are 15.3-50.44m, 28.4-82.2m and 39.7-65m thick, respectively.

The other two geoelectrical layers **“J_2”** (53-189 ohm-m and 23.1-42.3m thick) and **“J_4”** (308-15217 ohm-m and 20-85.5m thick) consist of limestone and marly limestone, while the last geoelectrical layer **“J_6”** (7-20 ohm-m) consists of sandy shale with undetected base.

Geoelectric unit “K”:

This unit is equivalent to the oldest formation in the geoelectrical succession (Nubian sandstone “Malha Formation” of Lower Cretaceous) and was detected only at the extreme eastern portion of the main channel of Wadi Gharandal (upstream). According to the resistivity values, this unit can be differentiated into three geoelectrical layers (“**K_1**”, “**K_2**” and “**K_3**”). The resistivity ranges of these geoelectrical layers are: 192-1386 ohm-m, 47-195 ohm-m and 129-376 ohm-m, respectively. The thickness ranges of the geoelectrical layers “**K_1**” and “**K_2**” are: 75.1-89.7m 65.6-83.2 m respectively, while the base of the third geoelectrical layer ”**K_3**” was not detected.

2. Groundwater occurrence

Based on the available data of the drilled wells Nos. 1, 2 and 3 (Fig.2) and the resistivity values of the aforementioned geoelectrical units, groundwater occurs in different types of lithological compositions and is present under unconfined or confined conditions. These aquifers can be discussed as follows (from top to bottom):

Quaternary aquifer is represented by the geoelectrical layer "A_2", which consists of wadi deposits. This aquifer occurs under unconfined condition and is considered as the main aquifer in the investigated area. The maximum depth to water table is 31.3m, while the water reaches the ground surface at the western part of the main channel between VES No. 21 and VES No. 22. Its thickness ranges between 2.2 m and 20.1m (at VES No.7 beside drilled well No.1). The water salinity of this aquifer increases westwards (downstream), where the measured salinity at a hand dug well beside VES No. 6 in the east (upstream) is 530 ppm and increases westwards (downstream) to reach 3000 ppm at a hand dug well beside VES No.21.

Lower Miocene aquifer corresponds to the geoelectrical layer "C_2" of Nukhul Formation, which consists of calcareous sand, sandstone, shale, marl and conglomerate interbeds. The water in this layer occurs under confined condition in the main channel as well as the tributaries and under unconfined condition in the delta.

1. ***Oligocene aquifer*** is represented by the geoelectrical unit "***D***" (Taiyba Formation) and consists of sandstone, siltstone, occasionally mudstone and conglomerates.
2. ***Calcareous aquifer*** is made up of the Eocene and Upper Cretaceous sediments, including 5 water bearing formations represented by the geoelectrical layers F_1, F_2, G_1, I_2 and J_2. The thickness of these layers increases generally westwards, in the same direction of the throw of the step faults.
3. ***Nubia sandstone aquifer*** is the last water bearing and is represented by the Lower Cretaceous Malha Formation in the eastern portion of the study area where two water bearing layers were detected. These two water bearing layers are represented by the geoelectrical layers "K_2" and "K_3". They are connected and lie beneath an upper confining bed of high resistivity (sandstone "K_1"). The thickness of the upper water bearing layer "K_2" increases westwards from 65.6 m to 83.2 m.

3. Geological structure and its impact on groundwater occurrence

It is clear from the constructed cross-sections that the study area is affected by 10 normal and step faults along the main channel (F1-F9) and Wadi Wata (F10) as seen on cross-sections A-A`, A'-A", A'-A"', A"'-A"" and B-B' (Figs.3-7). The downthrows of (F1- F8) are towards the downstream (westward), while that of "F9" is towards the east.

These faults play an immense role in the occurrence of the groundwater in the investigated area. The effect of these faults on the groundwater occurrence can be discussed as follows:

1. The normal fault "F1", uplifted the sandstone of Malha Formation (unit ***K***) against the shale and limestone confining beds (layers "J_4" and "J_5") of Raha (Galala) Formation at its downthrown side at the west, Consequently, these impervious layers prevent the movement of the groundwater towards the west (see cross section, Figs.3-8).

2. The faults (F_2-F_8) with their throw westwards (downstream), brought the older formations deeper below the younger ones, with an increase in their thickness in the same direction.

3. Some of the faults led to a partial communication between the water bearing formations.

4. The water pond found at the downstream of Wadi Gharandal between VES No. 21 and VES No. 22, occurs due to the action of the normal fault "F8" which led to the presence of the saturated wadi fill layer "A_2" in the upthrown side against sandy limestone and hard clayey limestone layer of unit "***B***" in the downthrown side. Therefore it acts as a wall against the wadi fill aquifer (layer "A_2") and forced the water to flow on the surface instead of further moving westwards in the delta.

Recommendations

From the above mentioned geoelectrical study, it is recommended that:

1. A hand dug well tapping the saturated wadi fill deposits (geoelectrical layer A_2) is recommended at VES No. 29 in Wadi Al Ghelan where it exhibits high resistivity (142.5 ohm-m), which in turn reflects brackish water and has a suitable saturated thickness (17.9 m).

2. Drill wells penetrating the Lower Miocene Nukhul Formation (which corresponds to geoelectrical layer "C_2") at VES stations Nos. 16 and 18 in the main channel and at VES Nos. 23, 24 and 25 in the delta.

3. Drill wells penetrating the Eocene water bearing layers at the VES stations of low resistivity values (probable presence of fractured limestone) corresponding layer "F_1" at VES Nos. 14, 15 and 19 and layer "G_2" at stations Nos. 12 and 19.

4. Drill well penetrating the Nubia sandstone of Lower Cretaceous (Malha Formation) at VES No. 5, where a suitable thickness of expected brackish water exists (geoelectrical layers K_2 and K_3).

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