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The Application of Geoelectrical Vertical Soundings in Delineating the Hydrostratigraphy of the Southern Red Sea Coastal Area, Saudi Arabia

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ABSTRACT. Because of the presence of detectable and significant contrasts in the physical properties of the subsurface lithological units in the southern Red Sea coastal areas (Wadi Damad and Wadi Sabya), an integrated application could be made of the results of electrical resistivity method and the data gathered from lithological well descriptions and the geophysical well logs to delineate the hydrostratigraphy and assess the salinity of groundwater with respect to the distance from the southern Red Sea coast.

The survey comprised 25 vertical electrical soundings (VES) distributed along two profiles. The Schlumberger configuration was used with a maximum half current-electrode spacing of 500 m and the density of data 7 measurements per decade.

The electric resistivity survey showed that it is possible to detect freshwater zones of medium resistivity (20 to 70 Ohm-m) beneath strata with very low resistivity (< 7 Ohm-m) at depths of greater than 60 m. The highest groundwater potential is found mainly in the upstream of Wadi Damad where the weathered bedrock is clearly identified and is overlain by Wadi alluvium which contains a lower clay content than found farther downstream.

The conclusions reached from this study indicate that the cause of lower electric resistivities in the coastal areas is probably due to seawater-saturated sediments, whereas farther inland the cause may be related to clay layers saturated with more saline irrigation water.

Introduction

The study area is located in the southwestern part of the Arabian Peninsula, near the southern Red Sea coast. It lies between latitudes 17º00′ N and 17º30′ N and longitudes 42º30′ E and 43º15′ E. It consists of two major catchments, Wadi Damad and Wadi Sabya.

The first published geologic map of the area was produced as part of the 1:500,000-scale reconnaissance map of the Asir region by Brown and Jackson (1959). A description of the Phanerozoic geology was published by Gillmann (1968). Coleman *et al.* (1972) described the Tertiary layered gabbro and a dike swarm at the eastern margin of the coastal plain. Gravity and seismic refraction data indicate that the area is underlain by crust of average continental thickness and density (Blank *et al.*, 1986). Germanconsult (1978) carried a detailed electrical resistivity study for groundwater investigation in the southern Red Sea region.

Recently, RGME (1994) made a detailed and comprehensive hydrogeological survey including chemical tests to assess water resources potential in Wadi Damad and Wadi Sabya.

The objectives of this paper are to integrate the results of VES soundings with subsurface lithological and geophysical logs, to delineate the geometry of the water-bearing layers and roughly estimate the salinity extent with respect to distance from the Red Sea coast. Information on lithology, water quality and typical resistivity values will help to estimate the geologic and hydrogeologic nature of buried materials and the geometry of subsurface geoelectric units.

Geologic & Hydrogeologic Setting

The study area comprises two major Wadi catchments, Damad and Sabya. These catchments are bounded by the Red Sea to the west and the mountainous region to the east. The two Wadis run in parallel from northeast to southwest.

In a traverse from west to east, the following units are encountered (RGME 1994): the Sabkhah unit (200-300 m), a broad zone of Quaternary alluvial deposits (30-35 km), Quaternary basalts, then a narrow zone of Tertiary igneous rocks with Ordovician sandstones which are exposed by faulting. Farther to the east, the Precambrian basement complex forms the elevated mountains (Fig. 1).

The geology of the area is the product of three major periods. These periods encompass late Proterozoic rocks of the Arabian Shield, remnants of sedimentary rocks deposited on the Shield between the Cambrian and early Tertiary times, and igneous and sedimentary rocks deposited in the Red Sea basin between the middle Tertiary and the present (Blank *et al.*, 1986). Structurally, the area is composed of two distinct units: the Precambrian elevated mountains and the Quaternary sediments in the plains. Major structural movements during the Precambrian caused a series of parallel thrust faults which are closely spaced with a broad symmetrical synclinorium which was followed by antithetic (Blank *et al.*, 1986).

Sogreah (1970) divided the groundwater in the study area into three types: freshwater from the alluvial sediments in the Wadis, saltwater from the alluvial sediments close to the Red Sea, and saltwater from Bayd formation. Germanconsult (1978) suggests that the saline groundwater underlies the coastal trip for about 8 km wide parallel to the Red Sea coastline and the inland salinity may be associated with thermal brines ascending along the abundant NW-SE trending fault zones parallel to the Red Sea trough.

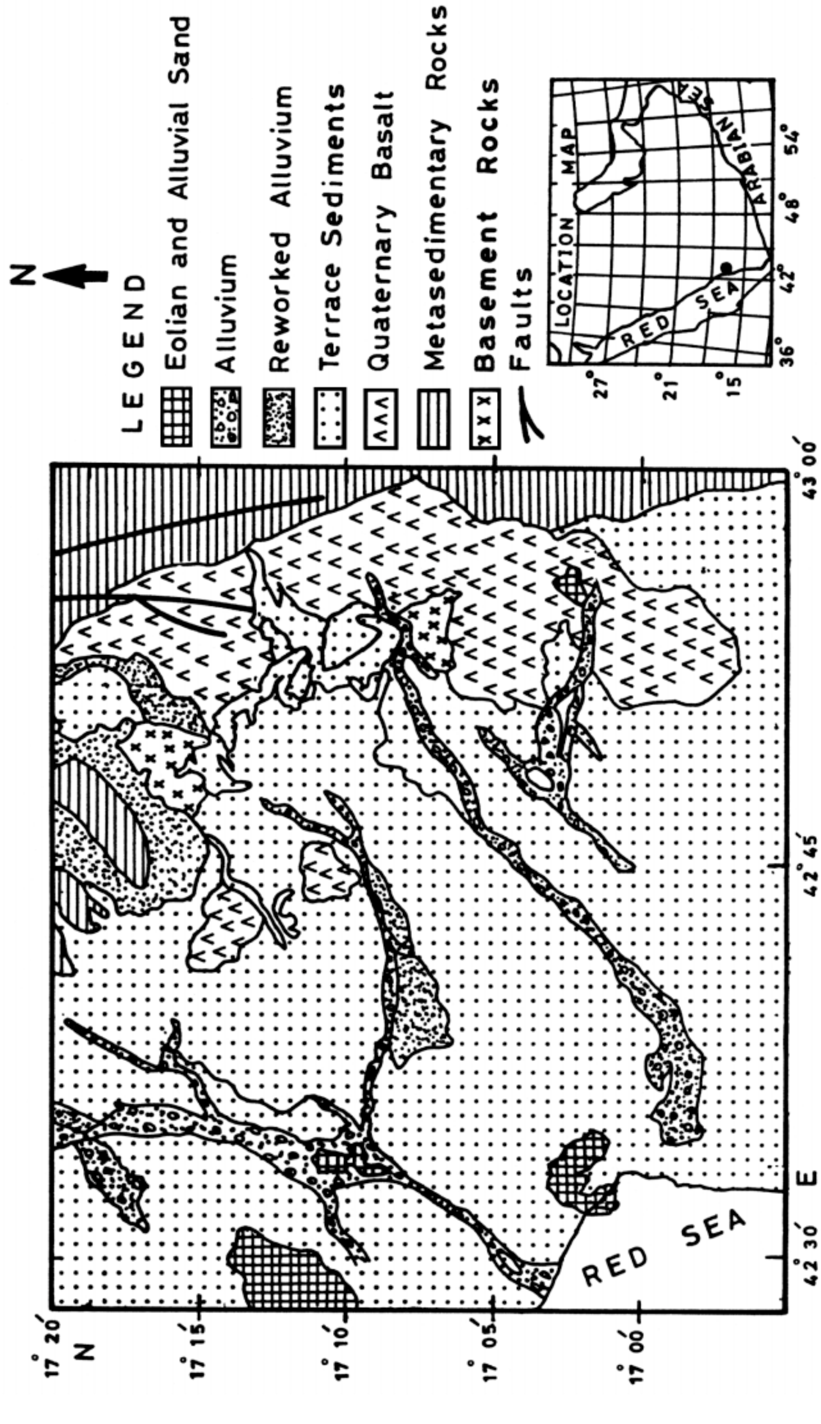

FIG. 1. Modified geological map of the coastal area of the southern Red Sea, Wadi Baysh quadrangle, Saudi Arabia (Fairer, 1985).

Chemical and biological analysis of the water quality showed significant contrasts in suitability. The downstream areas showed relatively medium to poor quality of water. The water quality in the bedrock was very saline in the interwadi area between Quassi and Damad (RGME 1994).

Data Analysis and Results

In order to delienate the geometry of the aquifer and to determine the subsurface geological and hydrological conditions, the resistivity method was carried out applying Schlumberger electrode-spacing arrangement to create vertical electrical soundings (VES). The object of VES is to deduce the variation of resistivity with depth and correlate it with the geological information in order to infer the depths and resistivities of the layers present.

A total of 25 VES were conducted in the study area (Fig. 2) and distributed according to the following scheme:

1. Thirteen in Wadi Damad (D1 - D13) and five in Wadi Sabya (S1 - S5).
2. Four at the downstream of Wadi Sabya (RS1 - RS4) and three at the downstream of Wadi Damad (RS5 - RS7), near the Red Sea coast.

An ABEM-SAS 300 C Terrameter was used to carry out the measurements. The maximum half current-electrode spacing (AB/2) reached 500 m and the measurements were made at the rate of about 7 readings per decade at AB/2 values reaching 1.5, 3, 4, 5, 7, 9, 10, 15, 30, 40, 50, 70, 90, 100, 150, 300, 400, and 500 m.

A large AB/2 values, some sounding curves indicated noise interferences. This could be due to the low power of the ABEM instrument, which can not provide sufficient signal strength to exceed the required signal to noise ratio. The field data were re-examined as individual soundings and unacceptable errors in the apparent resistivity curves have been removed during processing.

All soundings curves were processed and interpreted using an automatic interpretation computer program (Zohdy 1989). This program produced layered models, detailing the depth, thickness and bulk resistivity of each of the layers. The resistivity values and the sampling intervals were used automatically to create the first approximation of the corresponding multilayer model. Hence, this model has been modified in layer thicknesses and resistivities through a number of iterations until the best-fit between the calculated and the apparent resistivity curves is reached.

As mentioned earlier, 25 VES were conducted in the study area. These were suitably distributed and the data were used to prepare two resistivity contour sections in Wadi Damad and Wadi Sabya (Figs. 3 and 5, respectively) approximately oriented ENE-WSW (N 60º - 75º E).

Resistivity Cross-section along the Axis of Wadi Sabya to near the Red Sea Coast

Nine soundings were conducted in the Wadi Sabya-Red Sea coast area, extending from the confluence of Wadis Sabya and Quassi in the northeast to Al-Sabkhah in the

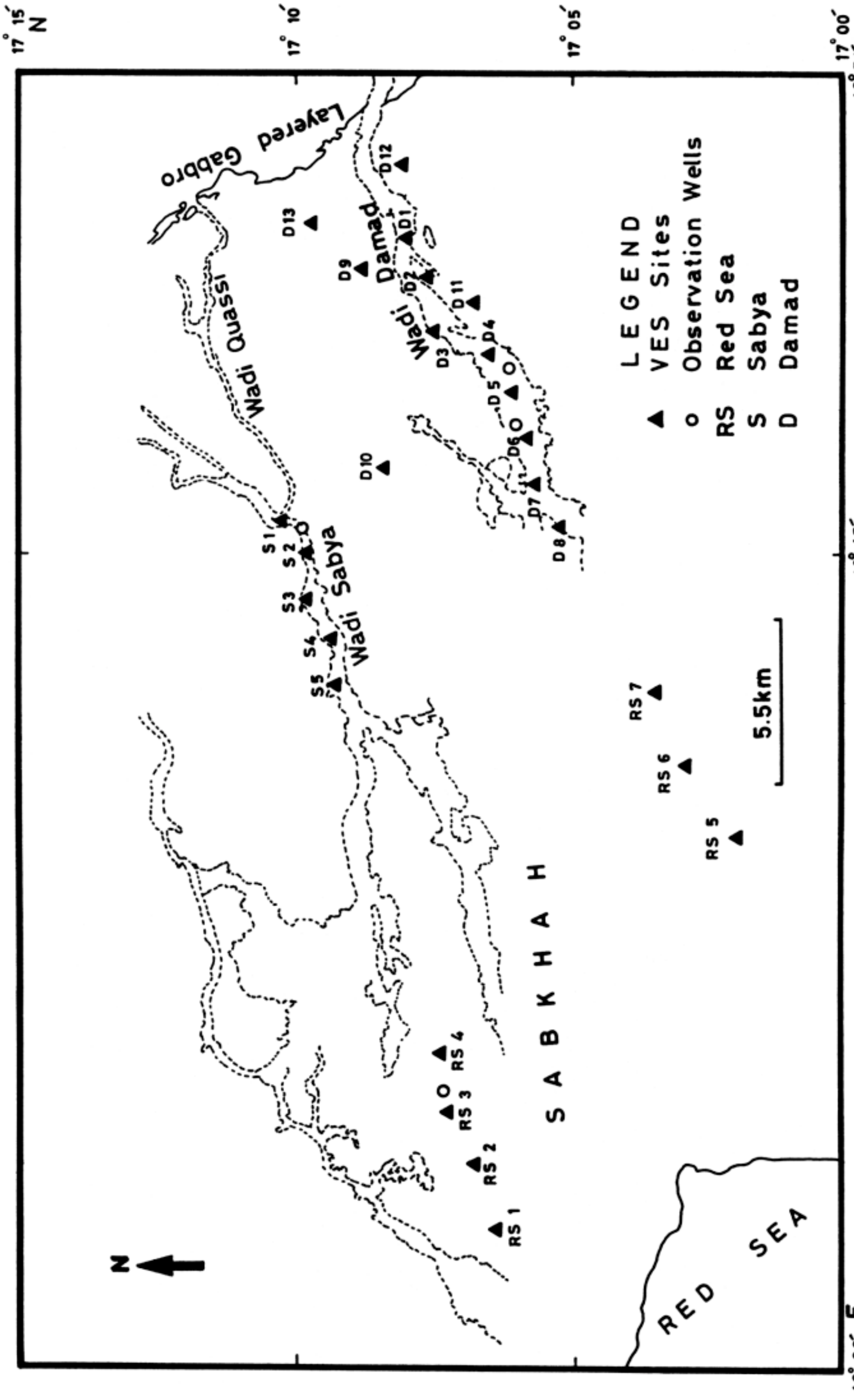

FIG. 2. Location map showing vertical electrical soundings (VES) and borehole sites along Wadis Sabya and Damad.

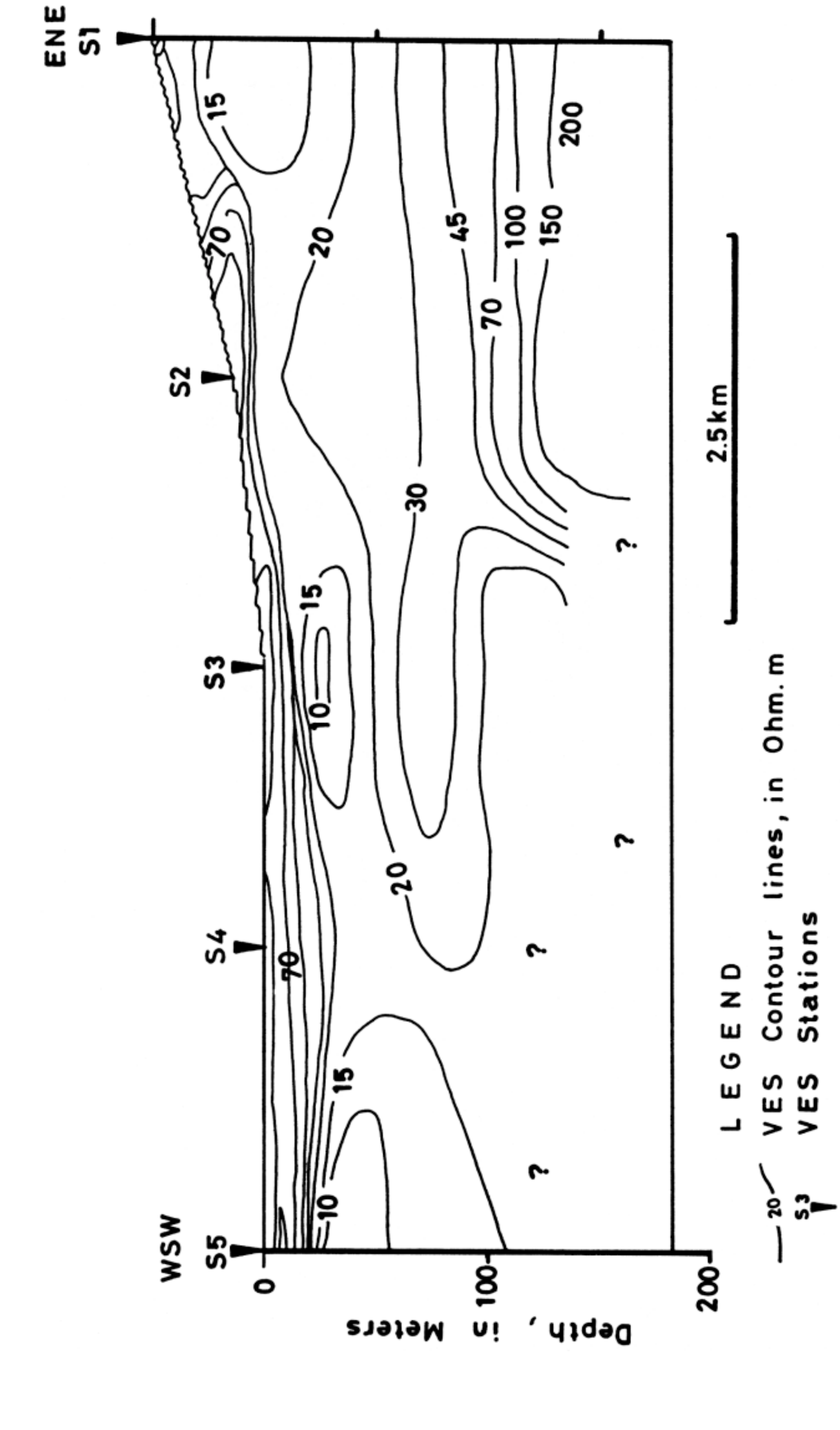

FIG. 3. Northeast-southwest vertical electrical resistivity contour section in Wadi Sabya.

southwest (S1 through S5 to RS1 through RS4) with a total length of about 30 km. The length of the contour section (Fig. 3) is approximately 8 km and extends only from S1 to S5.

In the ENE side of the section, beneath sounding S1 to S2, the resistivity in the upper 6 m ranges from 70 to 150 Ohm-m. This layer extends just to the east of sounding S4 and probably represents dry alluvial sediments.

The resistivity contour section of Fig. 3 reveals the range of extension of a medium-resistivity layer (20 to 70 Ohm-m) at a depth range from 6 too18 m, which is interpreted to represent sandy layers saturated with freshwater. This interpretation is supported by lithological data from the well 3 (W3) , which is located approximately between the soundings S1 and S2 (Fig. 4). Lithologic logs collected at a depth of 15 m below the ground surface are mostly sand intermixed with gravel. Chemical analysis of the groundwater samples of this well was found to contain chloride concentrations attaining 133 mg/l, total dissolved solids (TDS) of 435 mg/l, and electrical conductivity of 70 mhos/m. The freshwater zone extends from4 m below the surface to a depth of 66 m.

Between 18 and 85 m depth the surface, the resistivity ranges from 7 to 20 Ohm-m. Such resistivities could be indicative of the presence of clay layers. This interpretation is supported by the drilling results and the samples collected at depths varying from 15 to 40 m, which are predominantly sandy clay.

From a depth of about 85 to 147 m the resistivity values ranging from 20 to 70 Ohm-m indicate sandy layers saturated with freshwater. Germanconsult (1978) estimated the maximum thickness of the freshwater body in Wadi Sabya to be more than 100 m.

To the west of sounding S2, beneath soundings S3, S4 and S5 (Fig. 3), moderate resistivity values characterize the upper 15 to 20 m of dry alluvium (beneath S3) and a sandy layer saturated with freshwater (beneath S4 and S5).

At a depth interval from 20 to 87 m, there is a layer of very low resistivity (< 7 Ohm-m) whose thickness increases toward the southwest from about 40 m beneath sounding S4 to about 130 m beneath RS1 near the Red Sea coast (Fig. 4). This layer mostly contains porous sediments saturated with increasingly saline water as the coastline is approached.

Near the Red Sea coast, the profile extends from RS4 to the Sabkhah (RS1). Beneath soundings RS1, RS2, RS3 and RS4, the resistivity in the upper 10 m indicates medium resistivity values (20 to 70 Ohm-m) underlain by a thick clay layer of very low resistivity saturated with saline water. This interpretation is supported by the data gained from the well 4 (W4) which is located between RS3 and RS4. The water in the well is rather saline with an electrical conductivity of 338 mhos/m and a TDS concentration of 1840 mg/l.

Resistivity Cross-section along the Axis of Wadi Damad to near the Red Sea Coast

The resistivity contour section along the axis of Wadi Damad-Red Sea extends from sounding D12 in the ENE to RS5 in the Sabkhah in WSW (Fig. 2). The length of the en-

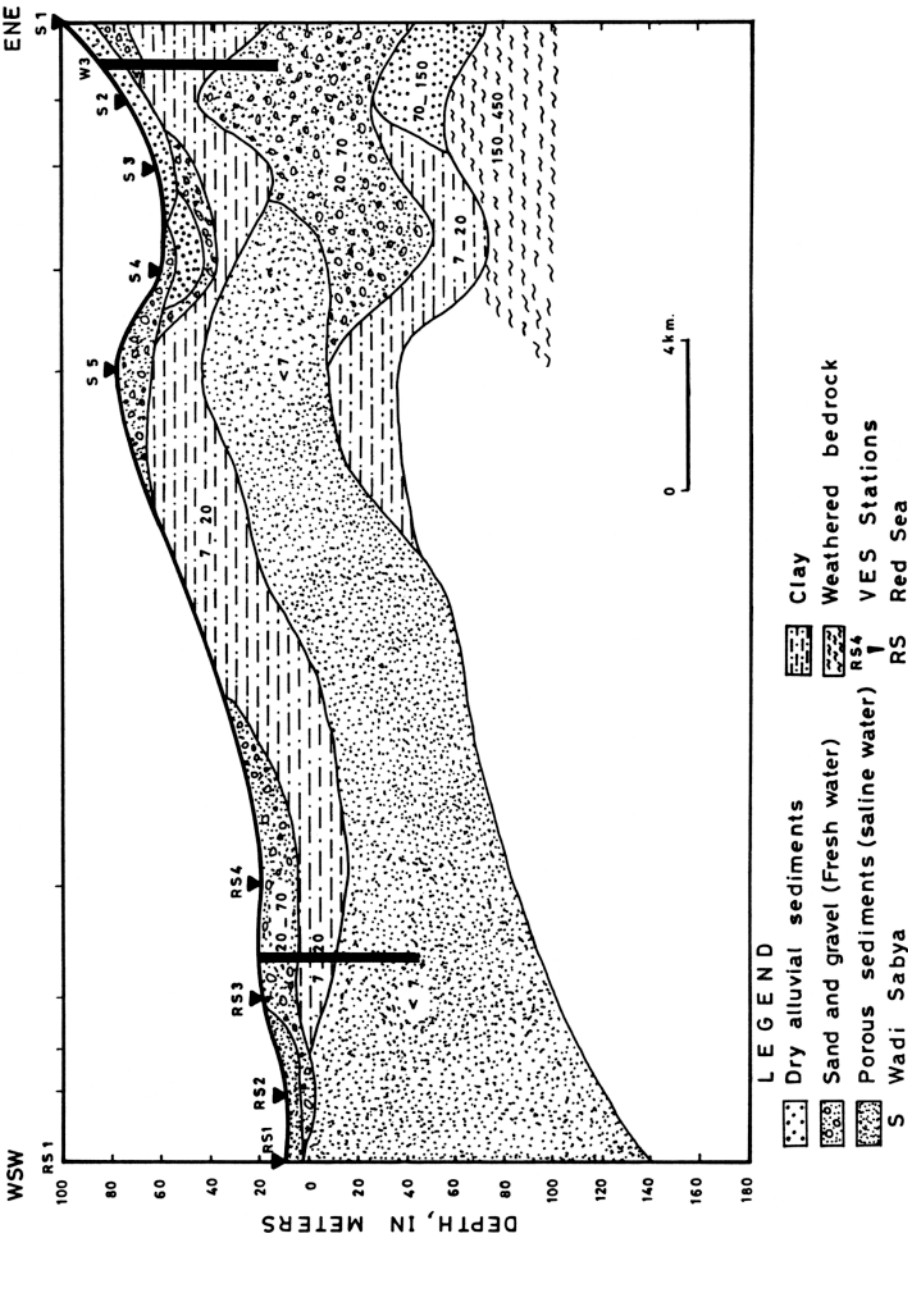

FIG. 4. Interpreted lithological cross-section along the axis of Wadi Sabya to near the Red Sea coast (ENE-WSW).

tire profile is approximately 30 km. The length of the resistivity contour sections along Wadi Damad which connects D1 and D8 is 13 km (Fig. 5.1) and 9.2 km from D5 to D13 (Fig. 5.2). To near the Red Sea coast, the length of the resistivity contour section which pass by RS 5, RS 6 and RS 7 is 5.4 km (Fig. 5.3).

On this section, the soundings in the upstream part of Wadi Damad (D1, D2, D11, and D4) show moderately high resistivity values (150-300 Ohm-m) down to a depth of 10 m. This layer is interpreted to represent very dry alluvial sediments intermixed with consolidated sediments. From a depth of about 20 to 40 m, the resistivity values are medium (20-70 Ohm-m) and are interpreted to represent a sand layer saturated with freshwater of good quality. The thickness of the potentially-freshwater zone diminishes between D1 and D8.

West of D4, a low resistivity clay layer (7 to 20 Ohm-m) is located beneath the aforementioned sandy layer. Freshwater saturated sediments are interpreted to be located beneath the low resistivity layer.

The resistivity interpretation is substantiated by the data from well 1 (W1) between D4 and D5 and Well 2 (W2) between D5 and D6, which show that the alluvium is composed predominantly of sand and silt in the upper 40 m (Fig. 6). Lithological logs indicate that weathered bedrocks are met with at depths greater than 63 m in W1 and 58.5 m in W2. Analyses of groundwater samples indicate that the concentrations of the chloride and TDS are 98 and 754 mg/l, respectively, well 1 (W1) and 70 and 759 mg/l, respectively, in well 2 (W2). At depths greater than 70 m the resistivity increases to greater than 450 Ohm-m, particularly beneath the soundings D1, D2, and D11. This layer is interpreted to represent the upper part of the basement complex.

In the central part of the profile, beneath the soundings D7 and D8, the resistivity at a depth ranging between 30 and 80 m, a very low resistivity layer (< 7 Ohm-m) is indicated. This layer increases gradually in thickness toward the WSW to reach 60 m thick beneath RS5 (Fig. 6). This continuous layer is interpreted to represent porous sediments saturated with increasingly saline water in westerly direction. This increase in salinity is supported by the overall distribution of groundwater quality analysis in field and laboratory tests.

Discussion & Implication

In the surveyed area, the electrical resistivity of surficial sediments depends primarily on the amount and the salinity of the water present. The higher the salinity of the saturating fluids, the lower the resistivity. An unsaturated clay has low resistivity because of the ability of clay minerals to conduct the electricity electronically (Zohdy *et al.*, 1974).

The general features of the interpreted resistivities in Figs. 3, 4, 5.1, 5.2, 5.3, and 6 ranged from very low (< 7 Ohm-m) for seawater-saturated sediments near the coast, to high (450 Ohm-m) for dry and consolidated sediments. On the basis of typical resistivities of materials in similar geologic environments, the resistivity ranges can be described in terms of lithology and chemical analysis of groundwater samples as follows:

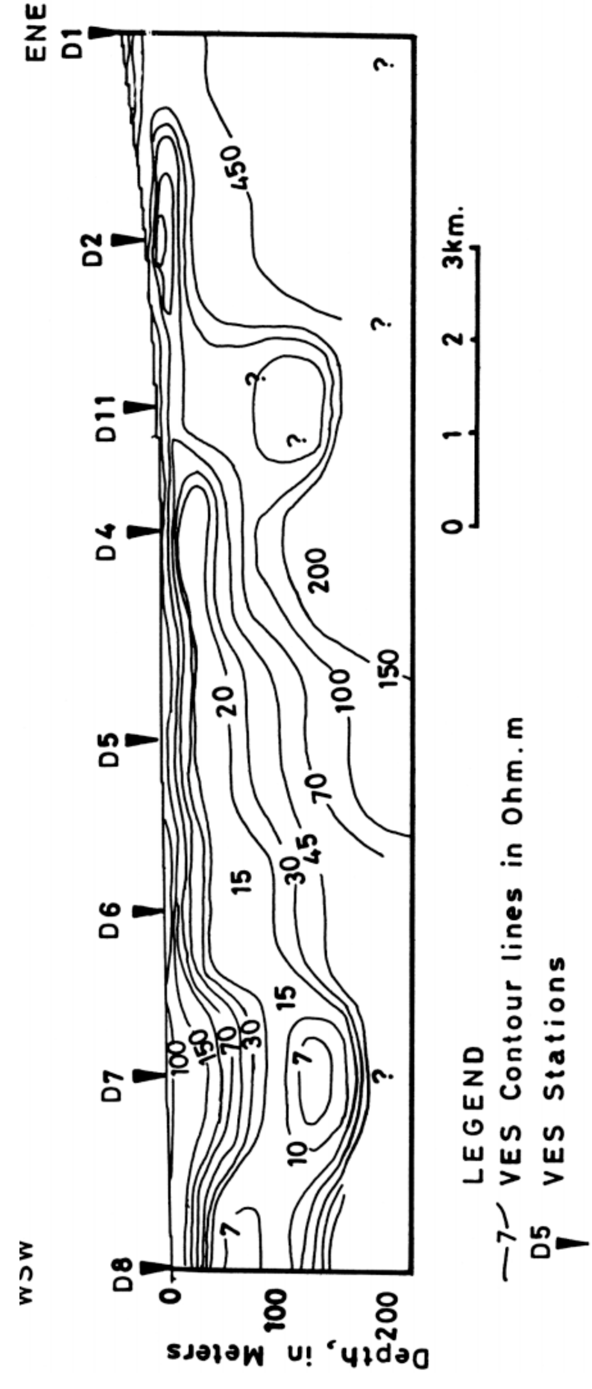

FIG. 5.1. Northeast-southwest vertical electrical resistivity contour section in Wadi Damad connects the soundings between D1 to D8.

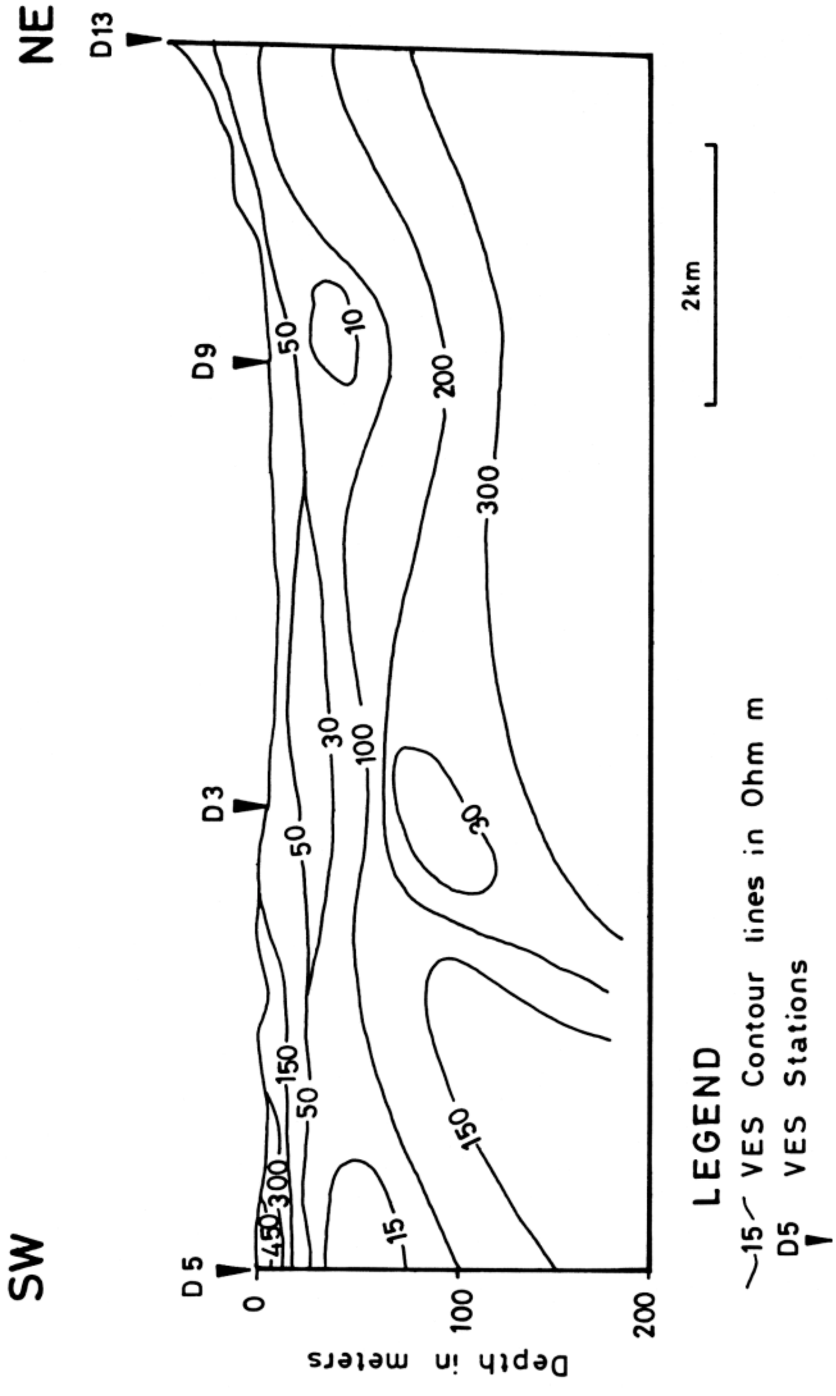

FIG. 5.2. Northeast-southwest vertical electrical resistivity contour section in Wadi Damad connects the soundings between D5 and D13.

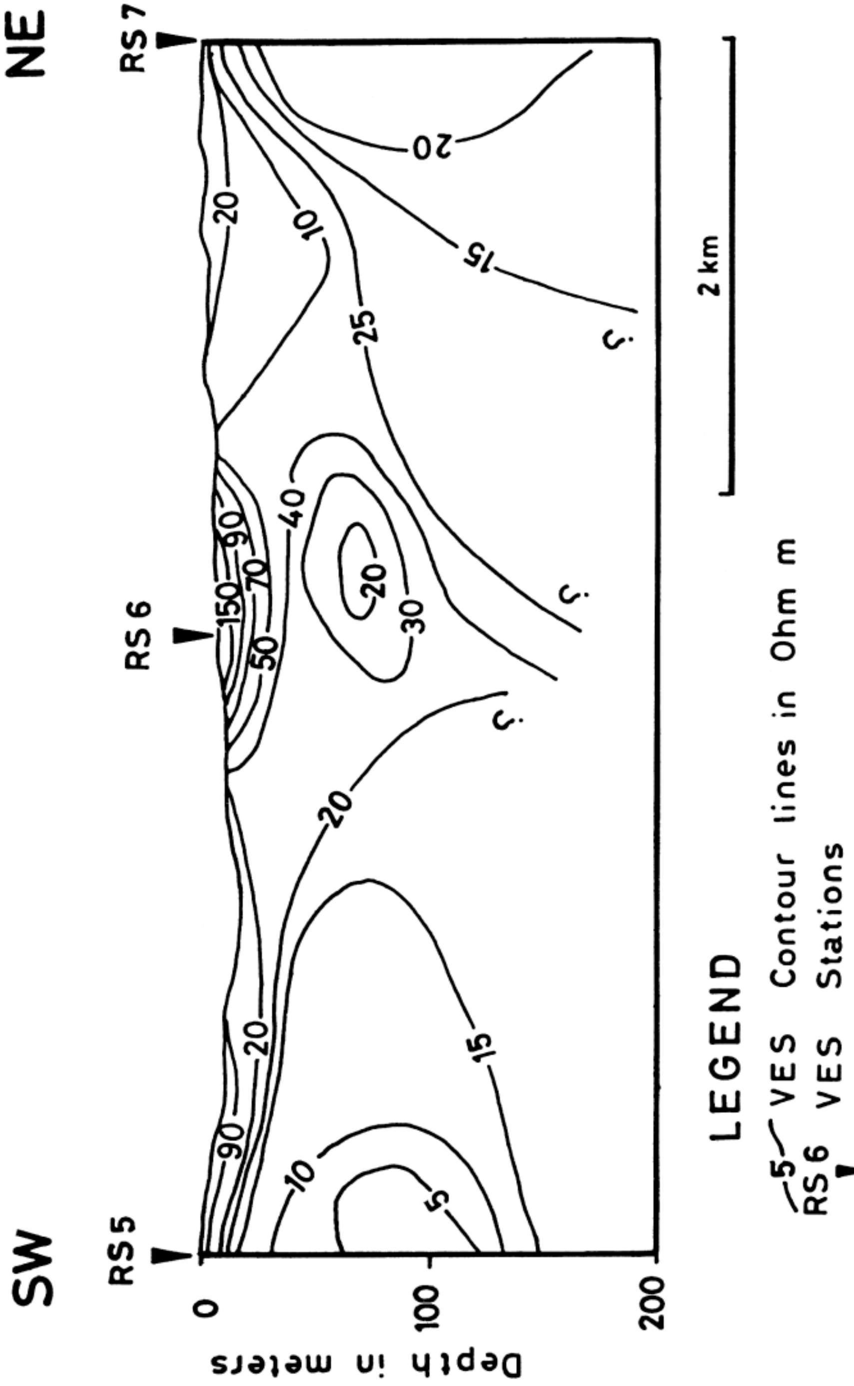

FIG. 5.3. Northeast-southwest vertical electrical resistivity contour section near the Red Sea coast connects the soundings RS5, RS6 and RS7.

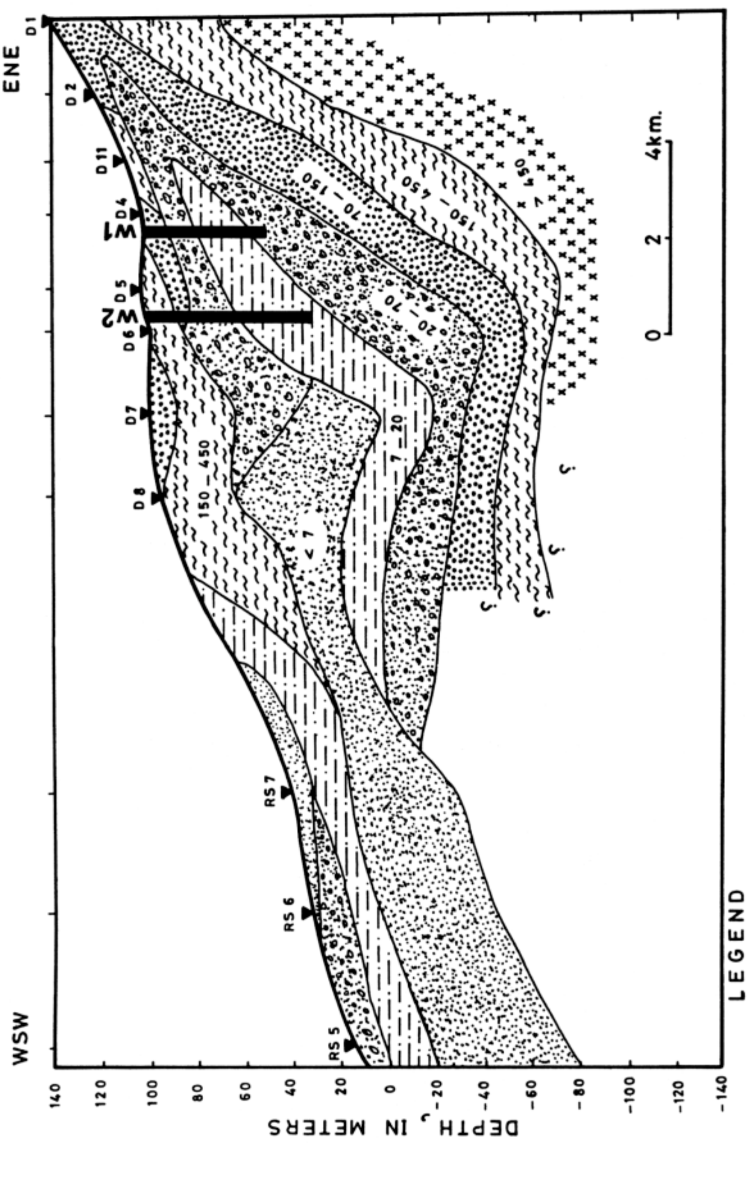

FIG. 6. Interpreted lithological cross-section along the axis of Wadi Damad to near the Red Sea coast (ENE-WSW).

1. The lowest resistivity layers (less than 7 Ohm-m) may indicate porous sediments saturated with saline water near coastal areas.

2. Layers with moderately low resistivities (7 to 20 Ohm-m) may represent clay, sandy sediments rich in clay, or possibly sand and gravel sediments saturated with poor quality of water.

3. Layers with medium resistivities (20 to 70 Ohm-m) probably represent silty sand saturated with freshwater.

4. Layers with resistivities (70 to 150 Ohm-m) probably represent weathered bedrock intermixed with saturated sediments.

5. Layers with high resistivities (150 to 450 Ohm-m) may represent dry and consolidated sediments or unfractured bedrock.

6. The highest resistivity layers (> 450 Ohm-m) may represent basement rocks (gabbro and diorite).

The lithological and geophysical logs of water wells (W1, W2, and W3) were correlated with the nearest interpreted resistivity sounding data (Figs. 4 and 6). The correlation between soundings D5, D6 and Well 2 is quite good. This well was drilled to a depth of 66 m (Fig. 7). The water table was encountered at 4 m from the ground surface and the lithology varied from sands with gravels to silts. The lower most layers from 36 m to 41 m consist of silty sands. The possibility for gravel and sand was also indicated beneath soundings D5 and D6.

Sogreah (1970) carried out 53 electrical soundings in Wadi Baysh (20 km north of Wadi Sabya) as well as Wadi Sabya. Their VES cross-sections revealed that beneath Wadi Sabya, the upper 50 m below the ground surface consists of alluvium which indicates moderately low resistivity (20 Ohm-m). This layer is underlain by the Bayd Formation of lahar boulders of basalt and gabbro which extend to greater depths and has a low resistivity (< 10 Ohm-m).

Germanconsult (1978) suggested that saline groundwater underlies the coastal strip for about 8 km wide running parallel to the Red Sea coastline and the inland salinity could be associated with thermal brines ascending along the abundant NW-SE trending fault zones.

Generally, on a Schlumberger sounding curve, a highly resistive basement is shown by a straight line that rises at an angle of 45 degrees (S-line). However, Zohdy *et al.* (1993) suggest that such a straight line does not necessarily indicate the detection of a very highly resistive basement rock, it merely indicates the presence of a thick layer with a resistivity which is 20 times greater than the resistivity of the overlying layer. To check the validity of this idea, two VES locations near the Red Sea coast (RS1 and RS2) were investigated the terminal branch rises at an angle of 45 degrees and the resistivity of the overlying material at these soundings is very low compared to the lower ones. Here, it was found that the rising branch does not necessarily indicate the detection of basement rocks, which confirms the idea of Zohdy *et al.* (1993).

On the other hand, at locations near the upstream areas of Wadis Damad and Sabya (D4, D5, D6, S1, S2, and S3), the rising branch at nearly 45 degrees indicates the ex-

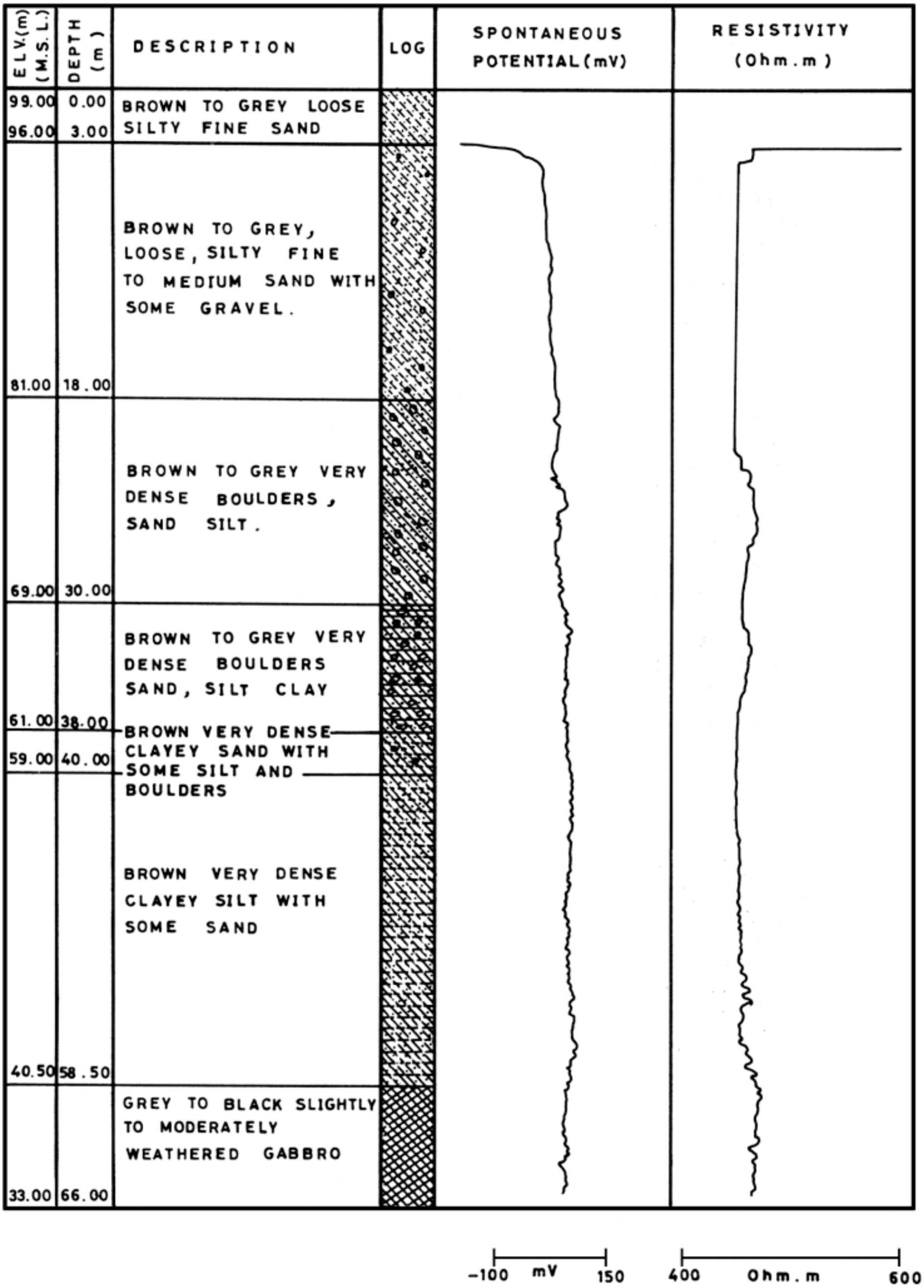

FIG. 7. Lithological and geophysical logs of the water well 2 (W2) in Wadi Damad.

istence of the high resistivity layer (weathered bedrock) at increasingly greater depths in a westerly direction.

The resistivity contour sections (Figs. 3, 5.1, 5.2, and 5.3) revealed that the low resistivities generally correspond to alluvial materials intruded by saline water or intermixed with clay. This has been proved by high electrical conductivity values, especially between Wadi Damad and Quassi. RGME (1994) estimated the average electrical conductivity for the whole area to reach 203 mhos/m and the majority of the wells have TDS values ranging between 1000-2000 mg/l increasing towards the coastal areas.

This study shows that the high chloride concentration estimated from wells in the downstream section of Wadi Damad, about 5 km from the coast, could be attributed to the presence of seawater or to the downward leakage of irrigation return water. The absence of subsurface lithological stratification in Wadi Damad and Sabya near the coast could be due to the fact that the resistivities of clays and sands are in the same low order since they contain saltwater of high chloride concentration.

Conclusions

Significant and detectable contrasts in the resistivity values of the lithological units enabled the application of electrical resistivity method using Schlumberger soundings in Wadis Sabya and Damad. This method provided useful information in identifying good locations for drilling, investigating the subsurface lithology, and delineating salinity conditions. The data obtained are not enough for estimating water salinity or aquifer thickness precisely.

In the depth range from 1 to 10 m, the resistivity data showed the prevalence of moderately high resistivity layers in the varying from 70 to 150 Ohm-m in the ENE and low resistivity layers varying from 7 to 20 Ohm-m in the WSW (near the coast) of both Wadi Damad and Wadi Sabya. Near the coast, the cause of these low resistivities is probably due to seawater-saturated sediments, whereas farther inland the cause may be related to clay layers saturated with more saline irrigation water. Due to later invasions from inland wells at intermediate depths, the resistivities were found the lowest in the southwest and became higher with increasing depth.

The geoelectric cross sections indicate the possibility of detection freshwater zones of medium resistivity (20 to 70 Ohm-m) beneath layers with very low resistivity (< 7 Ohm-m) at depth greater than 60 m beneath D4, D5, D6, D7, D8, S1, S2, S3 and S4.

Generally speaking, the results of the electrical resistivity survey indicate that the highest groundwater potential is found mainly in the upstream of Wadi Damad where the weathered bedrock is clearly identified and is overlain by Wadi alluvium which contains a lower clay content than found farther downstream. The absence of interpreted subsurface lithological stratification in both Wadi Damad and Wadi Sabya near the coast could be due to the fact that the resistivities of clays are very similar to those of sands saturated with saline waters, since they contain saltwater of high chloride concentration.

In order to investigate whether the increased salinity in the inland wells is caused by lateral invasion of seawater or by downward leakage of saline water from near-surface cultivated formations through some wells, additional geophysical studies (VES investigations and horizontal electrical profiling) and groundwater sampling at different depths are required.

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استخدام السّبر الكهربي الرأسي لرسم التراصف الطباقي المائي في المنطقة الساحلية جنوب البحر الأحمر ، المملكة العربية السعودية

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المستخلص . نظراً لوجود التباينات ذات الدلالة في الخواص الفيزيائية للوحدات الصخرية تحت السطحية في المناطق الساحلية في جنوب البحر الأحمر (وادي ضمد ووادي صبيا) ، أمكن إجراء تطبيق متكامل لنتائج طريقة المقاومية الكهربية مع معطيات أوصاف الوحدات الصخرية الكائنة بالآبار وتسجيلات السّبر الجيوفيزيائي البئري وذلك بهدف رسم الطبقات الحاملة للمياه وتقدير درجة ملوحة المياه الجوفية على ضوء بعدها عن الشاطيء الجنوبي للبحر الأحمر .

تضمن المسح إجراء ٢٥ سبر عمق كهربي عمودي موزعة على جانبيتين . وتم استخدام توزيع شلمبرجير ، حيث بلغ نصف أقصى مباعدة بين مسبري التيار الكهربي ٥٠٠ متراً ، وكثافة البيانات ٧ قياسات في الدورة العشرية الواحدة .

أوضحت نتائج مساحة المقاومية الكهربية إمكانية الكشف عن نطاقات للمياه العذبة ذات المقاومية المتوسطة (٢٠-٧٠ أوم-م) واقعة تحت طبقات ذات مقاومية منخفضة جداً (أقل من ٧ أوم-م) على أعماق تزيد عن ٦٠ م من سطح الأرض . لقد تم اكتشاف أعلى نطاق حامل للمياه الجوفية بالقرب من منبع وادي ضمد ، حيث ظهرت صخور القاعدة المجواة بوضوح تعلوها رواسب الأودية التي تشتمل على محتوى أدنى من الطفل عما هو كائن عند مصب الوادي .

دلت الاستنتاجات المستقاة من هذه الدراسة أن سبب المقاومية الكهربية المنخفضة في المنطقة الساحلية يعود إلى وجود الرواسب المشبعة بمياه البحر المالحة ، بينما يرجع سبب المقاومية المنخفضة على اليابسة بعيداً عن الشاطي إلى وجود طبقات من الطفل مشبعة بمياه الري الأعلى ملوحة .