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Application of vertical electrical sounding for Groundwater Exploration of Al-Sarrar area, east of Sana'a Governorate, Yemen

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Abstract

Vertical Electrical Sounding (VES) method is one of many methods in geophysics that was conducted in this research at Al-Sarrar, Al-Sharfa region, Bani Hashaysh District, Sana'a Governorate, Yemen. The aim of this research is to investigate and locate the depth of groundwater layer (aquifer). Data acquisition of VES was carried out using SYSCAL R2 and WDJD-4 Resistivity & IP Instrument with Schlumburger configuration of electrode. There are nine VES point in this research with various length of cable ranging from 500 m up to 1000 m. From nine VES point shown two different of resistivity value range. Very low resistivity value with range 10 Ω.m to 169 Ω.m represents alluvium sediment (Quaternary Deposit), meanwhile, another resistivity value ranging from 3 Ω.m to 4899 represents basalt (Tertiary Volcanic). Through the vertical electrical resistivity data and boreholes available around the study area, we found that groundwater reservoirs are located in volcanic rocks, but they are filled with many geological structures, such as faults, which led to the occurrence of brock-down within them. The second type of reservoirs was inside the sandstones of the Tawila Group, which are more abundant as we head west of the study area. Therefore, volcanic rocks can be considered a harvest area as they are full of geological structures.

Keywords: Al-sarrar, Vertical Electrical Sounding (VES), Schlumburger and Groundwater.

Introduction

One of the most vital resources in the planet, water is necessary for the existence of both plants and animals. Water exists on both the surface and beneath the earth, and it is essential to the preservation of life, health, and social order. Groundwater is the term used to describe subsurface water, whereas surface water includes things like lakes, rivers, and the ocean. Even if there is a lot of water on the surface of the earth, the quest for groundwater becomes essential and never ends. Governments and societies in basement complex areas have always placed a high priority on the availability of high-quality water resources. Even in regions with more frequent rainfall, the issue of getting an adequate supply of high-quality water is generally getting worse due to population growth and industrialization. These make surface water unreliable all year round, so it's necessary to find alternate sources to complement surface water (Alisiobi & Ako, 2012).

Utilizing electrical resistivity survey has become commonplace in groundwater research and has proven beneficial in examining the underlying layer's geology. Based on variations in the resistivity of rocks and soils of less than two and seismic velocities that typically do not fluctuate by more than a factor of ten, the resistivity method becomes a versatile geophysical approach (Olasehinde & Bayewu, 2011). The goal of vertical electrical sounding is to determine the layer of a potential well or yield by estimating the resistivity variation with depth below a particular spot and correlating it with the geological data that is already available. The pore-spaces between the particles that permit current to pass through them determine a surface's electrical resistance. Thus, compared to a clay layer with a tighter pore space between its particles, layers with vast pore spaces, such sand and sand stones, will have a higher resistivity value. The varied lithology and layer thicknesses that are present are determined by processing and analyzing the subsurface resistivity's behavior when electric current is introduced into it. Information about the various layers' components can be used to infer whether groundwater is present in a given place.

The survey aims to determine the possibility of the presence of groundwater in the region to drill boreholes to serve the water needs of inhabitants of the area, and to find out the reason behind the failure of failed water boreholes drilled in the area.

Location and Elevation of Study Area

The study area is located in Al-Sarrar, Al-Sharfa region, Bani Hashaysh District, Sana'a Governorate within latitudes of 15˚27ˈ30"- 15˚30ˈ00"N and longitudes of 44˚30ˈ00" - 44˚32ˈ30"E. It is located about 48 km east of Sana'a Governorate and covers an area of 5km^2. It is located on a mountainous plateau of volcanic rocks, intersected by many valleys such as Wadi Sarrar, Wadi Al-Hais and, Al-Qasair channel. The area is characterized by high terrain, with a height ranging between 2500 m, at the top of the mountain range in the south of the area, up to 2400 m in the valleys and agricultural plains located to the west of the area **(Figure 1)**.

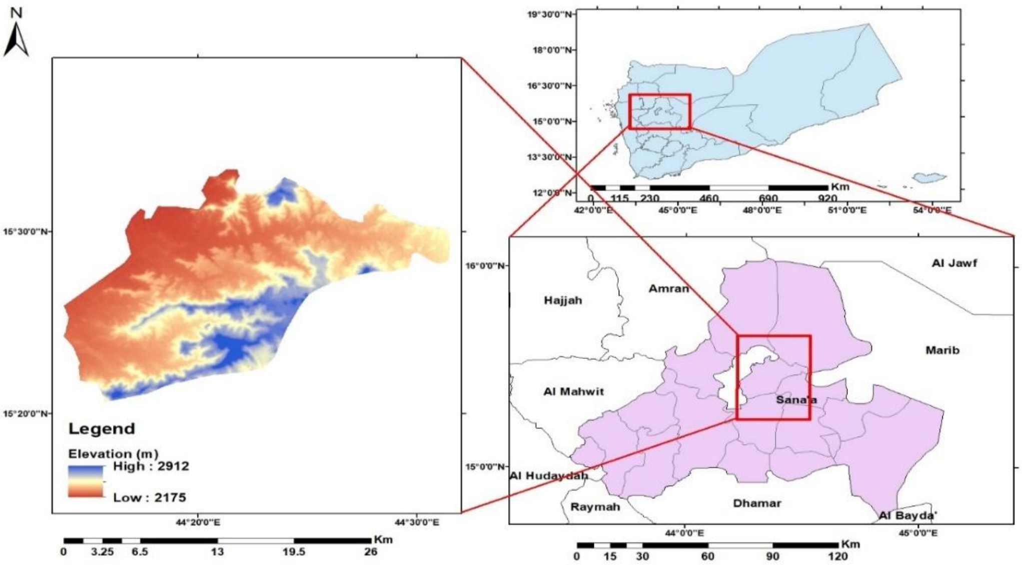

Figure 1: Shows location and elevation of the study area.

Geological and hydrogeological Setting

The geology of the study area consists mainly of layers and rock successions from the oldest to the youngest as in **Figure 2**:

- **Amran Group (Middle to Upper Jurassic):**

Amran Group comprises limestone and Dolomite. It covers 15% of the outcrops in the North of the basin. The Amran limestone is generally considered to be a poor aquifer although supplies can be obtained from the zones of secondary permeability. This group is spread in the Nihm district, north of the study area.

- **Tawilah Group (Cretaceous):**

Comprises a series of continental cross-bedded sandstones generally medium to coarse-grained with interbedded mudstones, siltstones, and occasional silty sandstones. The

Cretaceous Sandstones crop out over about 15% of the basin area in the north and north-east parts of the Basin. It is thought to reach a thickness of 400-850m. The Cretaceous sandstone forms the main aquifer in the region. It has low regional permeability but locally higher permeability is found in weathered and fractured zones. The sandstone is confined under several hundred meters of Tertiary volcanic in the south of the basin. The outcrops of these rocks are located to the west of the study area in Wadi Al-Sir and Wadi Rajam and are characterized by their saturation with groundwater.

- **Tertiary Volcanic:**

These rocks outcrop over some 35% of the Sana'a basin area. They form high plateaus to the South, West, and East of the Sana'a basin and underlie the Quaternary deposits in the South of the basin. It includes basalt dense homogenous basalt flow with columnar jointing, basalts, tuffs, and pyroclastic interbedded with fluvial-lacustrine deposits, comprising mixed basalt flows and rhyolite lavas. The total thickness is variable; reaching an estimation of groundwater contamination. It can be defined as the possibility of percolation and diffusion of contaminants from the ground surface into the groundwater system. The study area and its surroundings consist of these rocks.

- **Quaternary Volcanic:**

Volcanic activity continued into the Quaternary forming a plateau of extensive basalt cones in the North West of the basin interlayered with tuffs and alluvial sediments. The Quaternary basalts have a total thickness of about 100-300m and cover about 20 % of the area of the basin. The Quaternary basalts are highly permeable due to fracturing and the presence of clastic deposits between flows, where the formation is saturated. It provides an unconfined aquifer.

- **Quaternary Deposit:**

Consists of agricultural clay and sandy soil mixed with rocky pieces and spread along agricultural valleys and agricultural terraces scattered in the study area and beyond.

There have been just a few studies based on seismic and drilling data that examine the Sana'a Basin's structural makeup in detail. The basin is close to more intricate structural tendencies that are currently undergoing very active marine floor spreading (in the Red Sea to the west, the Gulf of Aden to the south, two other active boundaries such as the Zagrous thrust to the east and in the north the Dead Sea strike-slip fault). These borders represent the main tectonic trends and the most significant structural components that governed the Assyrian period, during which the NW-SE trend created a deep depression. Different tectonic trends of compressional and extensional regimes are present in the Sana'a Basin, see (**Figure2**), (HYDROSULT, 2007).

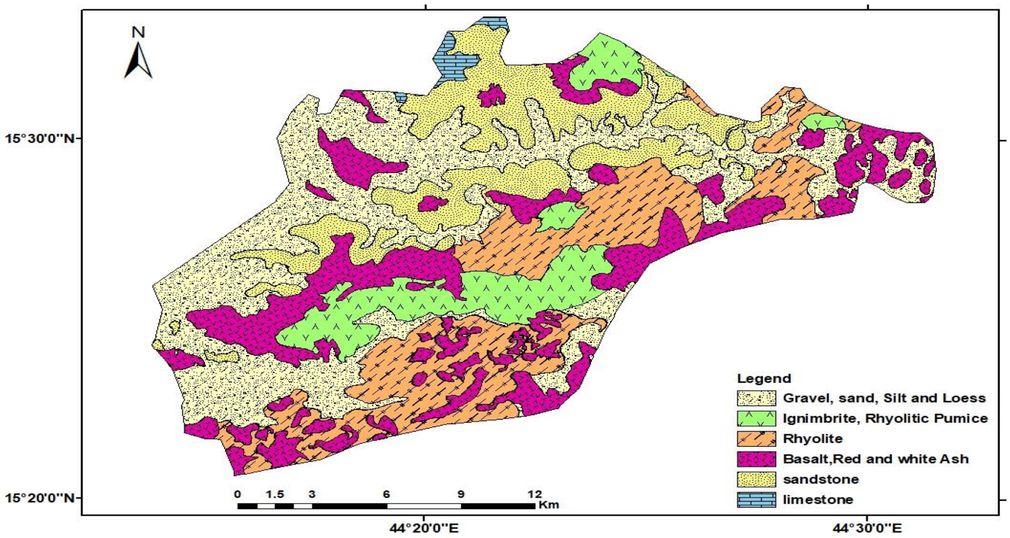

Figure 2: Geological map of the study area, (AL-Sururi, 2022).

Methodology

Vertical Electrical Sounding (VES) is a method that involves an electrical resistivity survey. An electrical resistivity survey measures the potential between two electrodes while transmitting a direct current between another two electrodes. The penetration of current is parallel with the distance between electrodes. The various spacing between electrodes will lead to information on resistivity stratification VES survey was carried out using SYSCAL R2 and WDJD-4 Resistivity & IP Instrument Quotation that consists of electrodes, 4cables, battery, and Global Positioning System device (GPS). Four electrodes are arranged in a straight line with various electrode spacing. The fieldwork of VES was carried out by using the Schlumberger configuration. The total number of VES points is (9), and includes three profiles (A–B), (C – D), and (E – F), which are trended parallel to the strike of layers, as shown in (**Figure3)**. The maximum distance between the current electrodes is (1000m) or (AB/2 = 500m), and the maximum distance between potential electrodes is (100m) or (MN/2 =50m). Includes three profiles (A–B), (C –D), and (E – F), which are trended parallel to the strike of layers.

After completing the vertical electrical sounding surveys VES in any field work, the results of the apparent resistivity values are plotted on log-log paper to form apparent field curves, this curve will show many distortions in the shapes.

During measurements, the monitor allows you to see the resistivity's standard deviation (a noise indication). Therefore, most distortions in the field curves in the studied area are caused by lateral in homogeneities and geological structures in the ground. Measurements (ρa) are required for the interpretation of VES points. Therefore, we must remove the distortions from apparent resistivity field curves through the processing of smoothing, which is represented as the first step in interpretation. However, the distortion phenomena that appear on the field curves are cups, scattering (ρa) values, discontinuity, and sharp maximum (Zohdy, 1974).

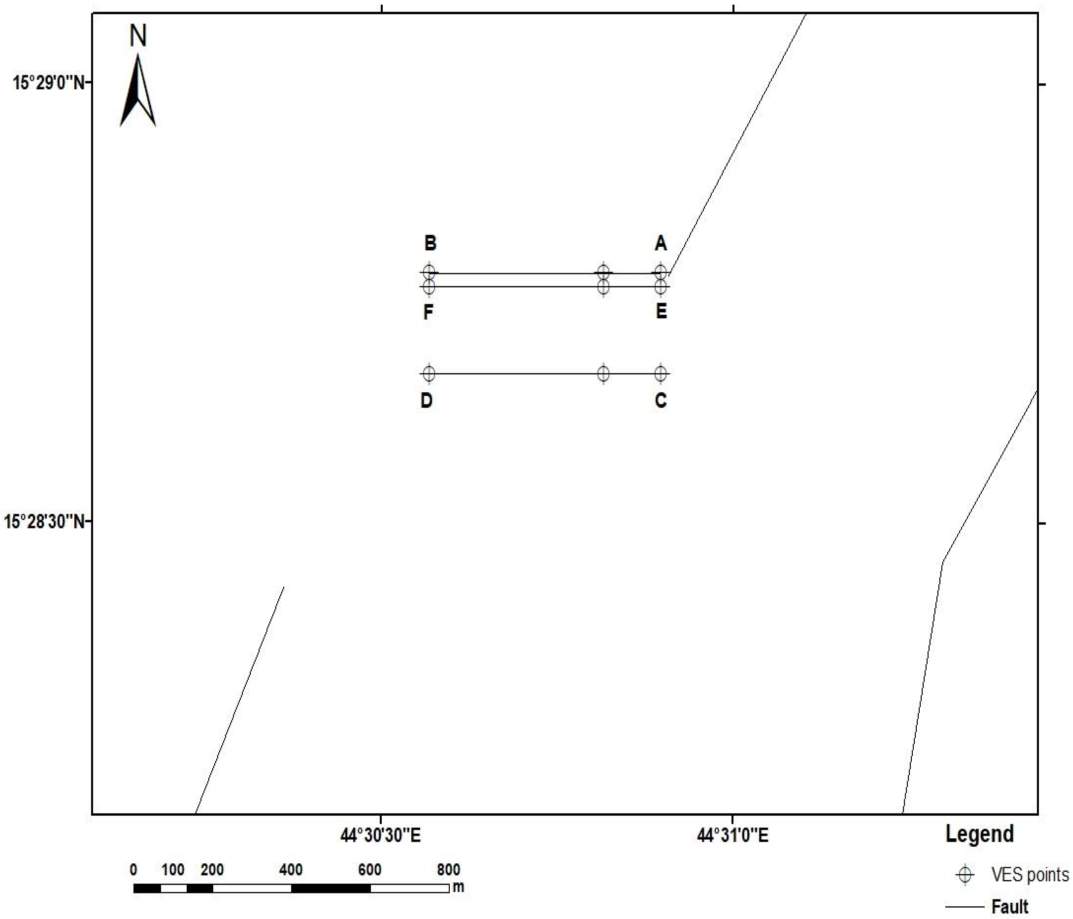

Figure 3: Shows the location of VES points.

The IPI2win is the most frequently software used for qualitative and quantitative interpretation, according to the majority of research that has been conducted in recent years. This program is made to evaluate data curves from induced polarization and one-dimensional vertical electrical sounding (VES) along a single profile. IPI2win's unique ability to focus on the geological outcome sets it apart from other well-known automated inversion tools (Bobachev, 2002). Regarding qualitative interpretation, that software is made to display the VES interpretation measurements as a fictitious cross-section.

Results and Discussion

The first stage in interpreting VES data is the smoothing procedure, which includes processing the displacement of field curve branches and reducing distortions.

Two methods of interpretation are used to interpret the vertical electrical survey measurements: qualitative interpretation and quantitative interpretation. The qualitative interpretation method includes primary evaluation of the resistivity values using a variety of techniques, such as:

A - Study of the Different VES Curve Types.

B - Pseudo-cross section with apparent resistance.

The second way, known as quantitative interpretation, uses two methods to determine the resistivities and thicknesses of electrical horizons for VES field curves. The first method involves manually matching curves, and the second method involves computer algorithms. Both methods are frequently combined. To get a more accurate geologic picture of the subsurface, the findings of interpretation must be combined with geological and hydrogeological data from maps.

In the present study, divides the field curves into groups based on their kinds, where the type (shape) may indicate vertical changes in the apparent resistivity distribution of the subsurface in the survey region. The field curves are distributed throughout the geological map in this method. Because of this, this method of interpretation provides basic information about the number of electrical horizons for each curve, where it is possible to observe changes in electrical properties by comparing the resistivity values for each horizon with one another at inflection points in the field curve (Griffith and King, 1981). However, the study area's field curves were divided into the following categories:

- **Group (AHK):**

This type is shown in VES-4, VES-7, and VES-9, as shown in (**Figure 4**). It consists of five electrical horizons, which start with the thin Alluvial sediments layer then the second horizon is the massive Basalt layer (Tertiary Yemen Volcanic) represents highest resistivity values. The Third horizon is Basalt with fractures layer (Tertiary Yemen Volcanic rift) representing the partial saturation zone which is characterized by a low resistivity value. Therefore, the fourth horizon is characterized by a high resistivity value and represents massive Basalt (Tertiary Yemen Volcanic), while the fifth horizon is Pyroclastic or Basalt with fracture layer (Tertiary Yemen Volcanic rift).

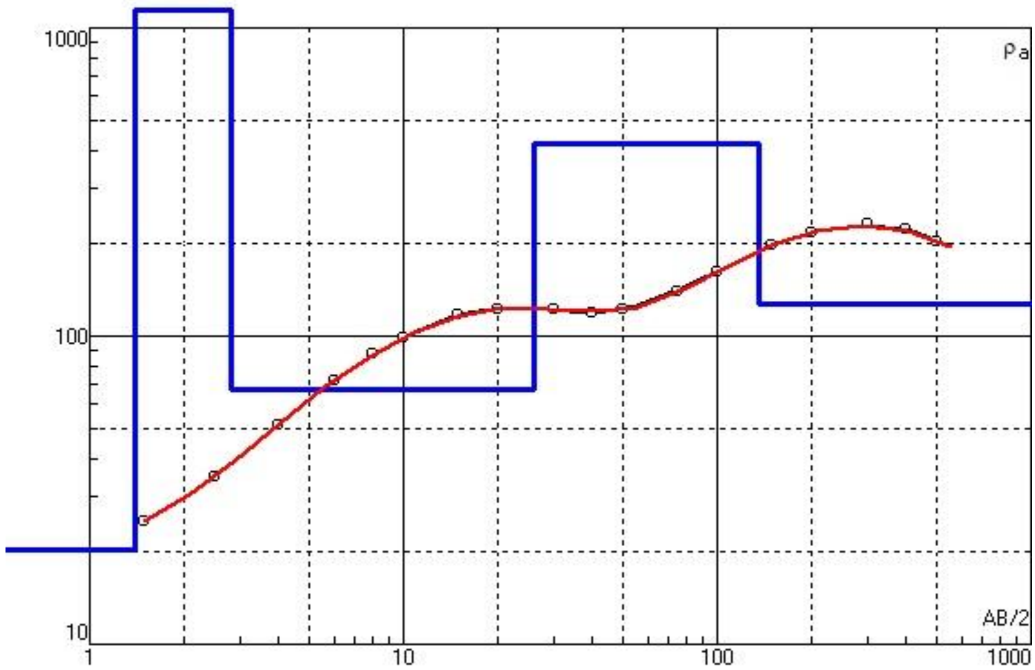

Figure 4: Shows (AHK) type of (VES-7).

- **Group (HK):**

This type is shown in VES-5, and VES-6, as shown in (**Figure 5**). It consists of four electrical horizons, which start with the thin Alluvial sediments layer, then the second horizon is Basalt with fracture layer (Tertiary Yemen Volcanic rift) maybe the presence of the partial saturation zone because represents low resistivity values, while the third horizon is massive Basalt (Tertiary Yemen Volcanic) characterized by the highest resistivity value, but in VES-5 the second, and the third horizons are Basalt with fracture layer(Tertiary Yemen Volcanic rift) maybe the presence of the partial saturation zone because represents low resistivity values. Therefore, in VES-6 the fourth horizon is characterized by the lowest resistivity value and represents Pyroclastic or Basalt with fracture layer (Tertiary Yemen Volcanic rift), while in VES-5 the fourth horizon is characterized by the highest resistivity value and represents the massive Basalt (Tertiary Yemen Volcanic), but the fifth horizon is characterized by the lowest resistivity value and represents the Pyroclastic or Basalt with fracture layer (Tertiary Yemen Volcanic rift).

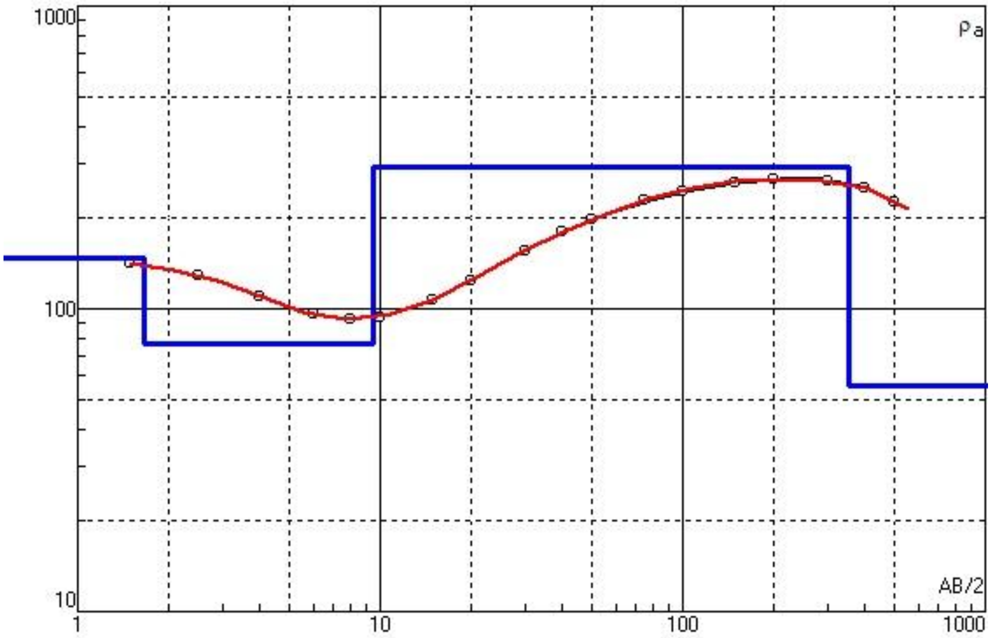

Figure 5: Shows (HK) type of (VES-6).

- **Group (HAK):**

It is represented by the sixth electrical horizon as shown in (**Figure 6**). The thin surface of the dry Alluvial sediments layer has relatively high resistivity values compared with the second horizon Basalt with fracture layer (Tertiary Yemen Volcanic rift) which represents low resistivity values and maybe the presence of the partial saturation zone. The third electrical horizon is of relatively high resistivity value compared with the second horizon, although it is located below the water table indicating the presence of lithological changes in the Tertiary Yemen Volcanic rocks in VES-1, VES-2, and VES-3. The fourth electrical horizon is of relatively high resistivity value compared with the third horizon and represents the Basalt with fracture layer (Tertiary Yemen Volcanic rift). Therefore, the fifth horizon is characterized by the lowest resistivity value and represents the Basalt with fracture layer (Tertiary Yemen Volcanic rift) maybe the presence of the partial saturation zone, while the sixth horizons massive Basalt (Tertiary Yemen Volcanic), and characterized by the highest resistivity value.

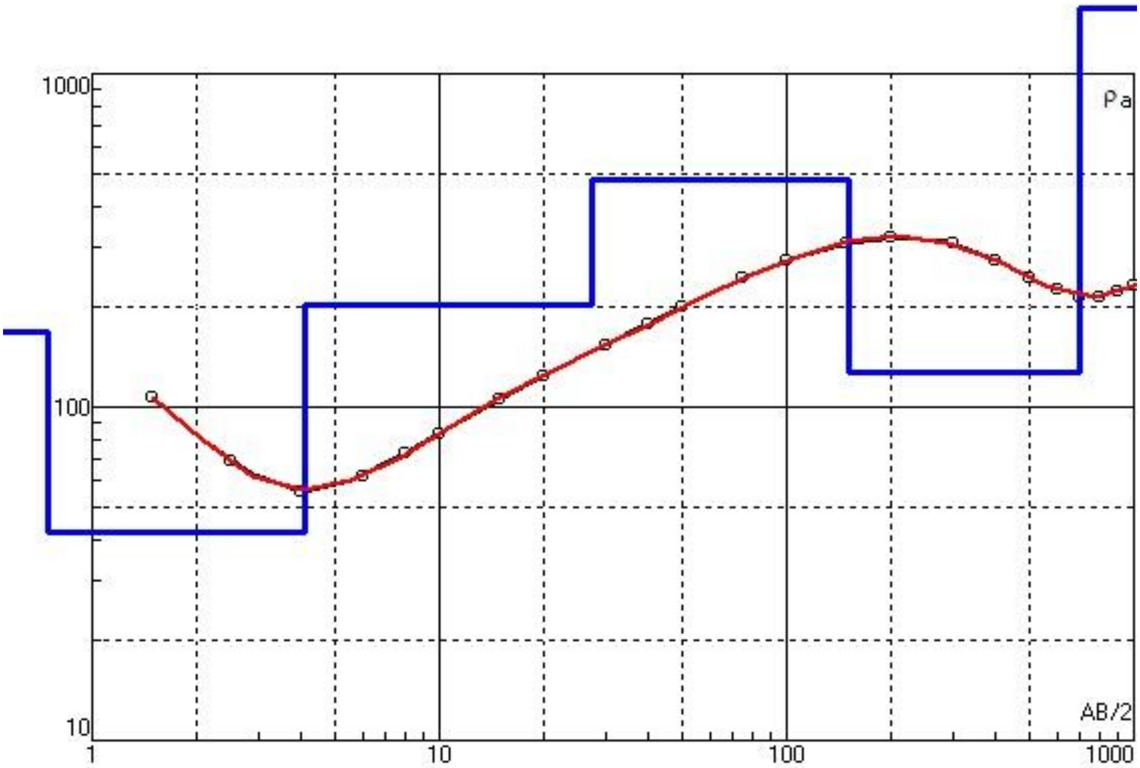

Figure 6: Shows (HAK) type of (VES-1).

- **Group (AAHK):**

This type is shown in VES-8, as shown in (**Figure 7**). It consists of six electrical horizons, which started with the thin Alluvial sediments layer, then the second horizon, the third horizon, and the fourth horizon are Basalt with fracture layer (Tertiary Yemen Volcanic rift), but the fourth horizon maybe the presence of the partial saturation zone because represents low resistivity values. The fifth horizon is massive Basalt (Tertiary Yemen Volcanic) and characterized by the highest resistivity value, while the sixth horizon is Pyroclastic or Basalt with fracture layer (Tertiary Yemen Volcanic rift).

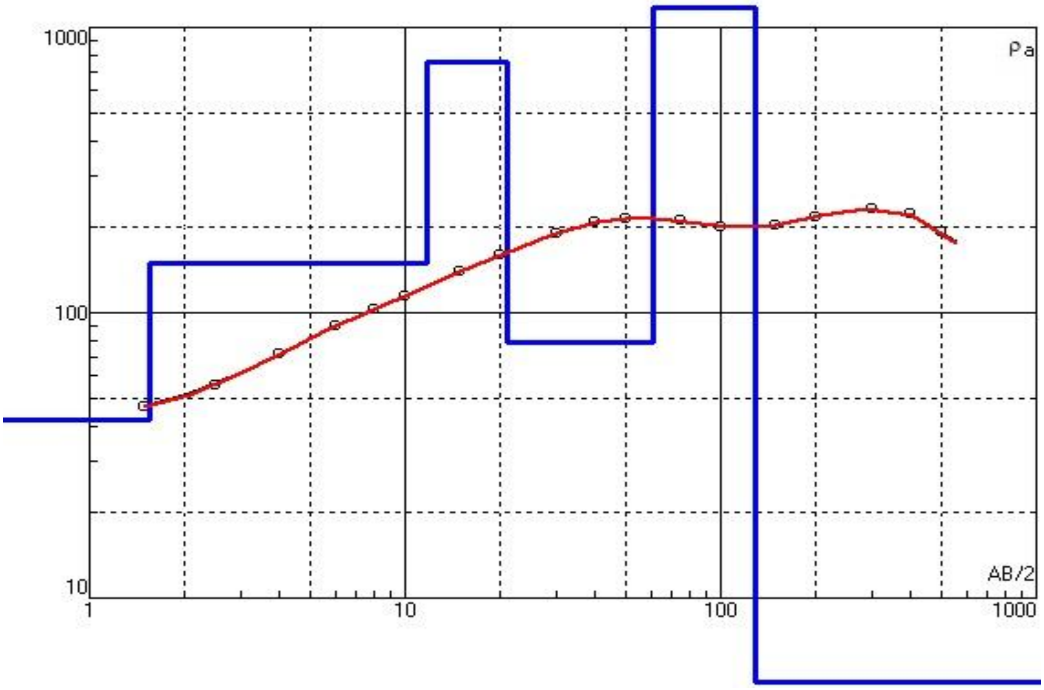

Figure 7: Shows (AAHK) type of (VES-8).

Pseudo Cross-Section

One of the various methods employed in qualitative interpretation is the apparent resistivity section or pseudo-cross-section, which provides the first insight into how the apparent resistivity values vary as the half-current electrode separations increase (AB/2). This data is represented as a two-dimensional image, with the horizontal dimension (x-axis) representing the locations of the vertical electrical sounding (VES) points and the vertical dimension (y-axis) representing the half-current electrode separation (AB/2), which is typically drawn on a linear scale rather than a logarithmic scale to minimize the impact of near-surface layers. However, both (AB/2) and their VES location on the surface will affect the apparent resistivity values. The (A – B) apparent resistivity section is passed along the VES points (1,2,3), as shown in (**Figure 8**). As for (C –D) apparent resistivity section, which passes along the VES points (4,5,6), as shown in (**Figure 9**). With respect to the (E –F) apparent resistivity section, which passes along the VES points (7, 8, 9), as shown in (**Figure 10**). The gradual increase in apparent resistance values under the sites, which reflects the presence of groundwater in the upper part of this section, followed by the gradual increase in apparent resistance values in a different manner, indicates the presence of geological structures in these layers, such as faults or because of the overlap between igneous and sedimentary rocks, in these layers.

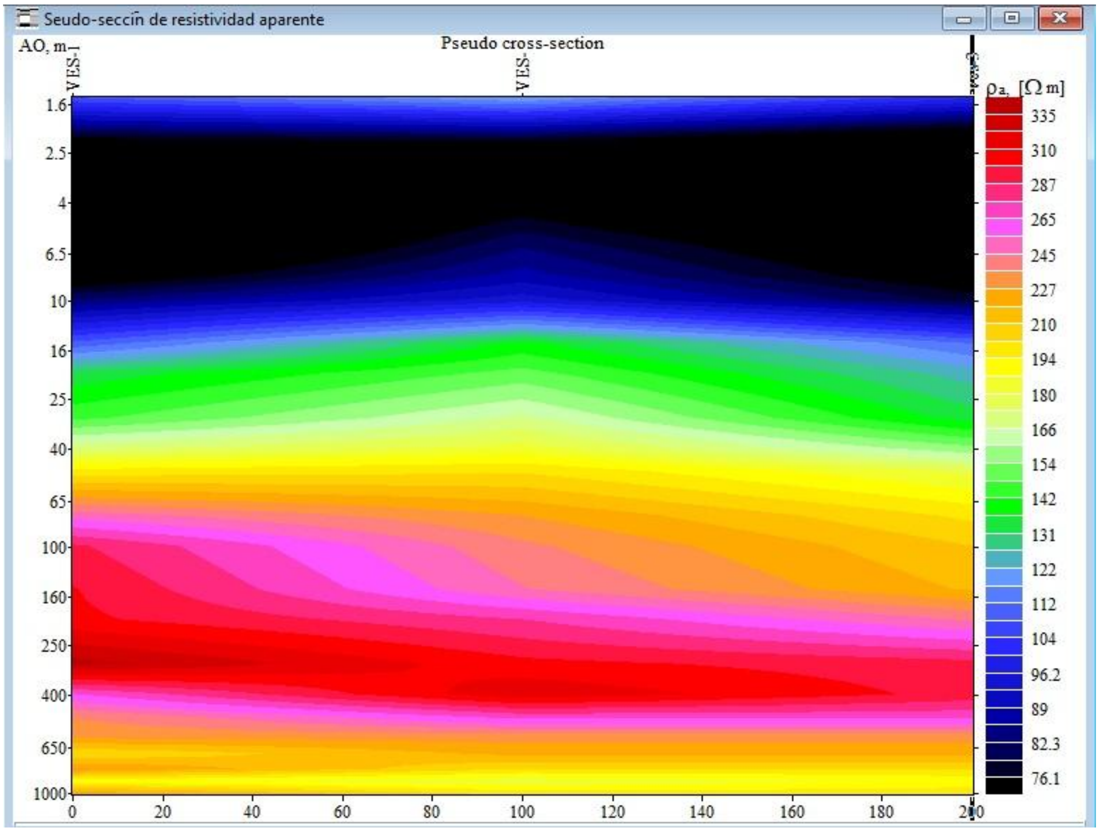

Figure 8: The Pseudo cross-section along the (A – B) profile.

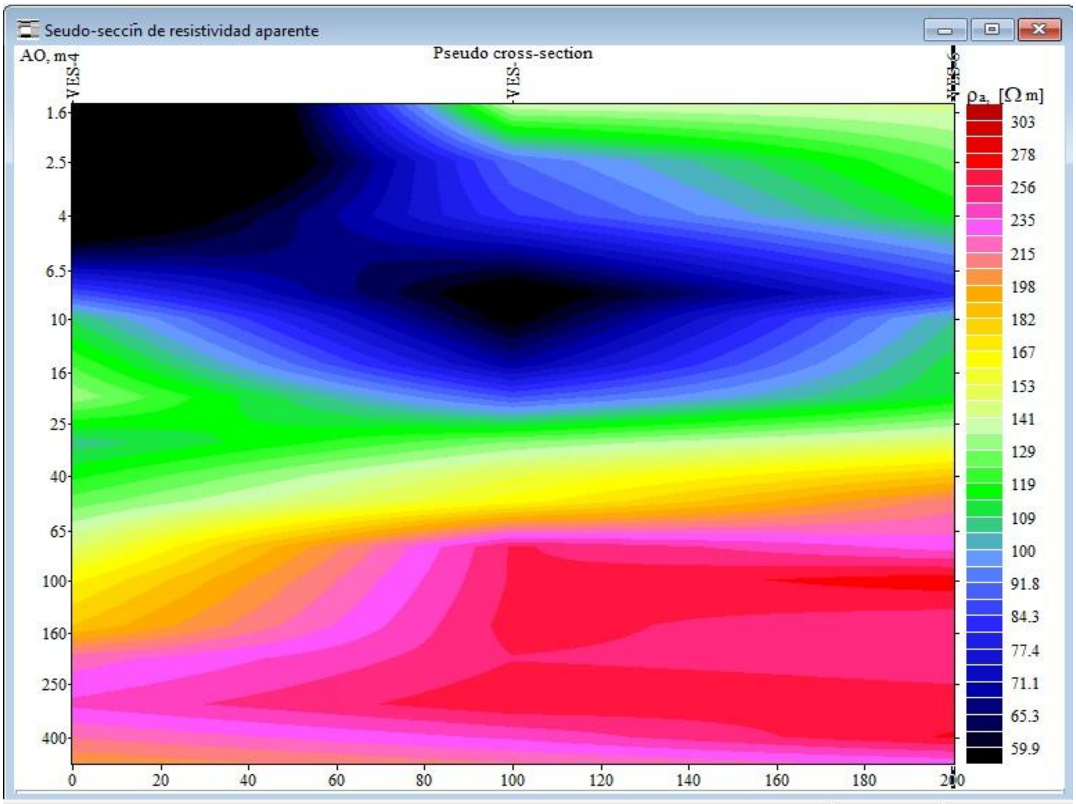

Figure 9: The Pseudo cross-section along the (B – C) profile.

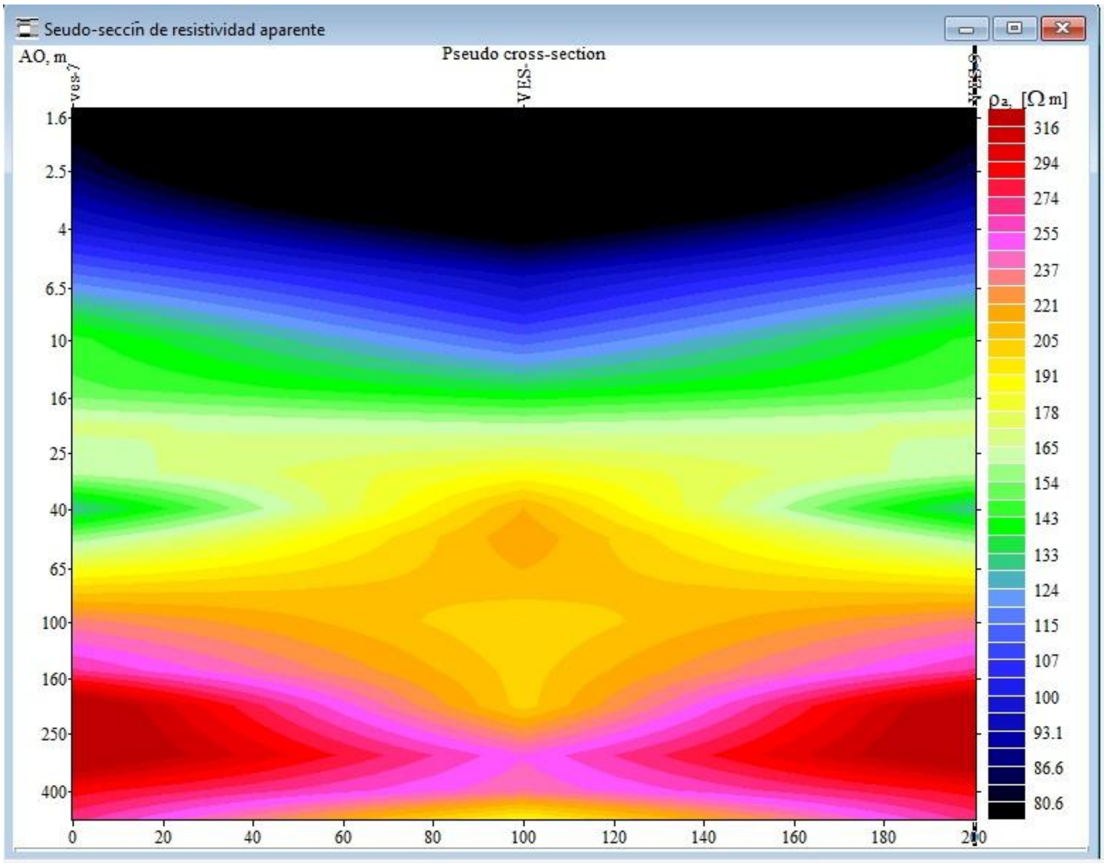

Figure 10: The Pseudo cross-section along the (E– F) profile.

Quantitative Interpretation

The apparent resistivity field curves have been used to quantitatively evaluate VES data in order to calculate the resistivity and thicknesses with depths of various electrical horizons. Although there are other strategies utilized in the quantitative interpretation are IPI2win frequently employed. The IPI2win is the most frequently software used for qualitative and quantitative interpretation, according to the majority of research that has been conducted in recent years. This program is made to evaluate data curves from induced polarization and one-dimensional vertical electrical sounding (VES) along a single profile. IPI2win's unique ability to focus on the geological outcome sets it apart from other well-known automated inversion tools (Bobachev, 2002). Regarding qualitative interpretation, that software is made to display the VES interpretation measurements as a fictitious cross-section.

The principle of equivalence, which allows for changes in the thicknesses and resistivity values for each layer of the field curve within certain bounds without changing the field curve shape, can be used to check (Bobachev, 2002) and improve the interpretation results for some field curves so that they agree with layer boundaries of the lithological sections from wells. Because they are closer to the manual interpretation results with the fewest percent of deviations, the interpretation results of the VES modeling approach are employed in the construction of the geoelectrical section. The outcomes VES modeling approaches' interpretation are shown in the following **(Table 1)**, While **Figures (11, 12, and 13)** show the geoelectrical Sections, which show us the geological situation of the subsurface layers and structures.

Table 1: The results of the VES interpretation.

VES NO.	1	2	3	4	5	6	7	8	9
Curve type	HAK	HAK	HAK	AHK	HK	HK	AHK	AAHK	AHK
P_1	168.2	166.8	127.8	10.9	160.5	148	20.15	42.3	74.73
P_2	42.24	42.47	14.41	1795	74.15	76.35	1137	150	237.2
P_3	202.3	204.4	199.8	62.51	23.53	292	66.81	760	86.31
P_4	480.7	493.7	401.6	527.8	841.6	55.91	420.1	78.4	921.7
P_5	127.5	132.4	8.916	169.5	196.3	-	127.4	1180	111.3
P_6	4899	2195	-	-	-	-	-	2.28	-
h_1	0.75	0.75	0.9	0.9	0.9	1.659	1.399	1.55	2.379
h_2	3.33	3.369	1	1	2.75	7.778	1.41	10.2	8.03
h_3	23.47	24.43	59.5	16.71	3.75	344.7	23.12	9.47	22.55
h_4	123	115.6	441.4	51.22	26.41	-	110.2	40.17	87.75
h_5	543	543.9	-	-	-	-	-	66.9	-

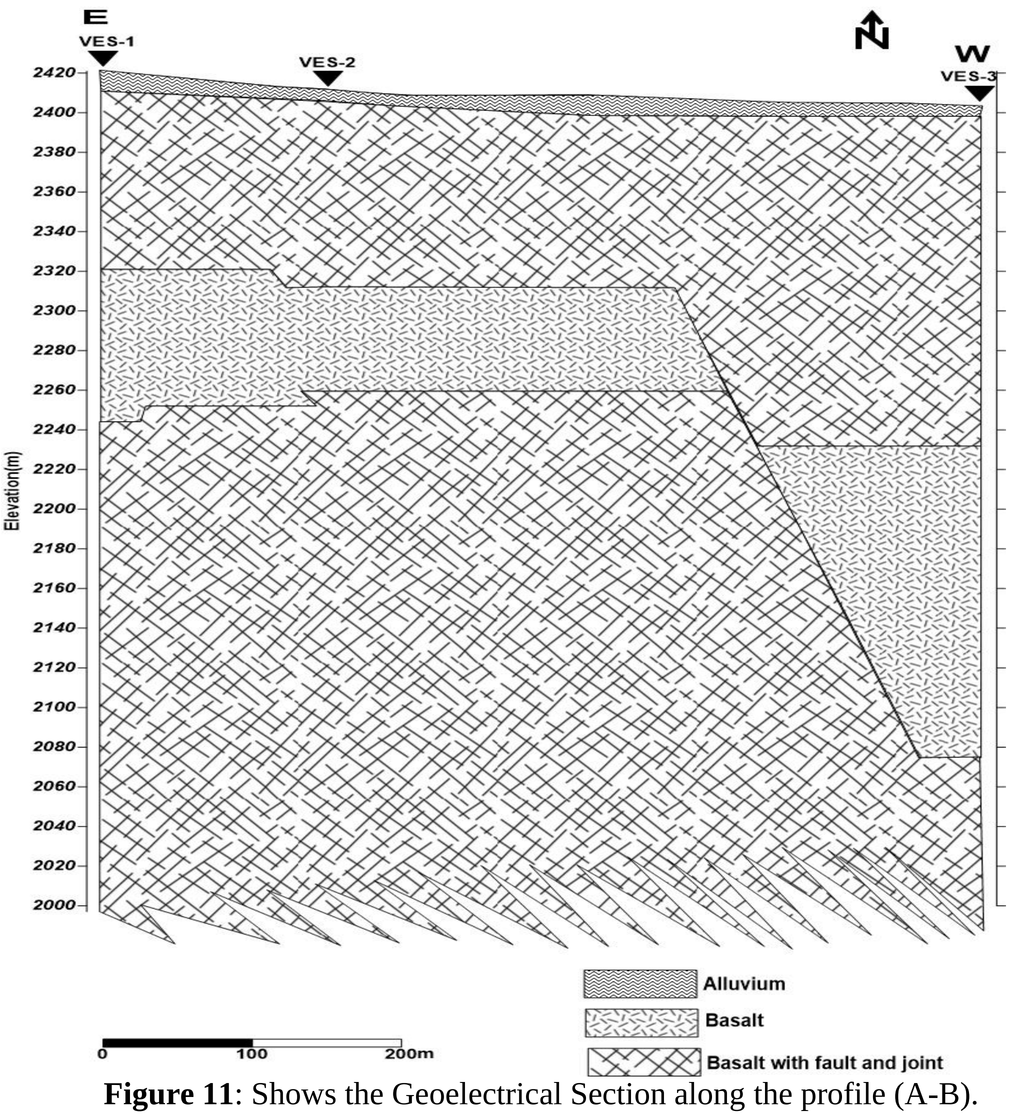

Figure 11: Shows the Geoelectrical Section along the profile (A-B).

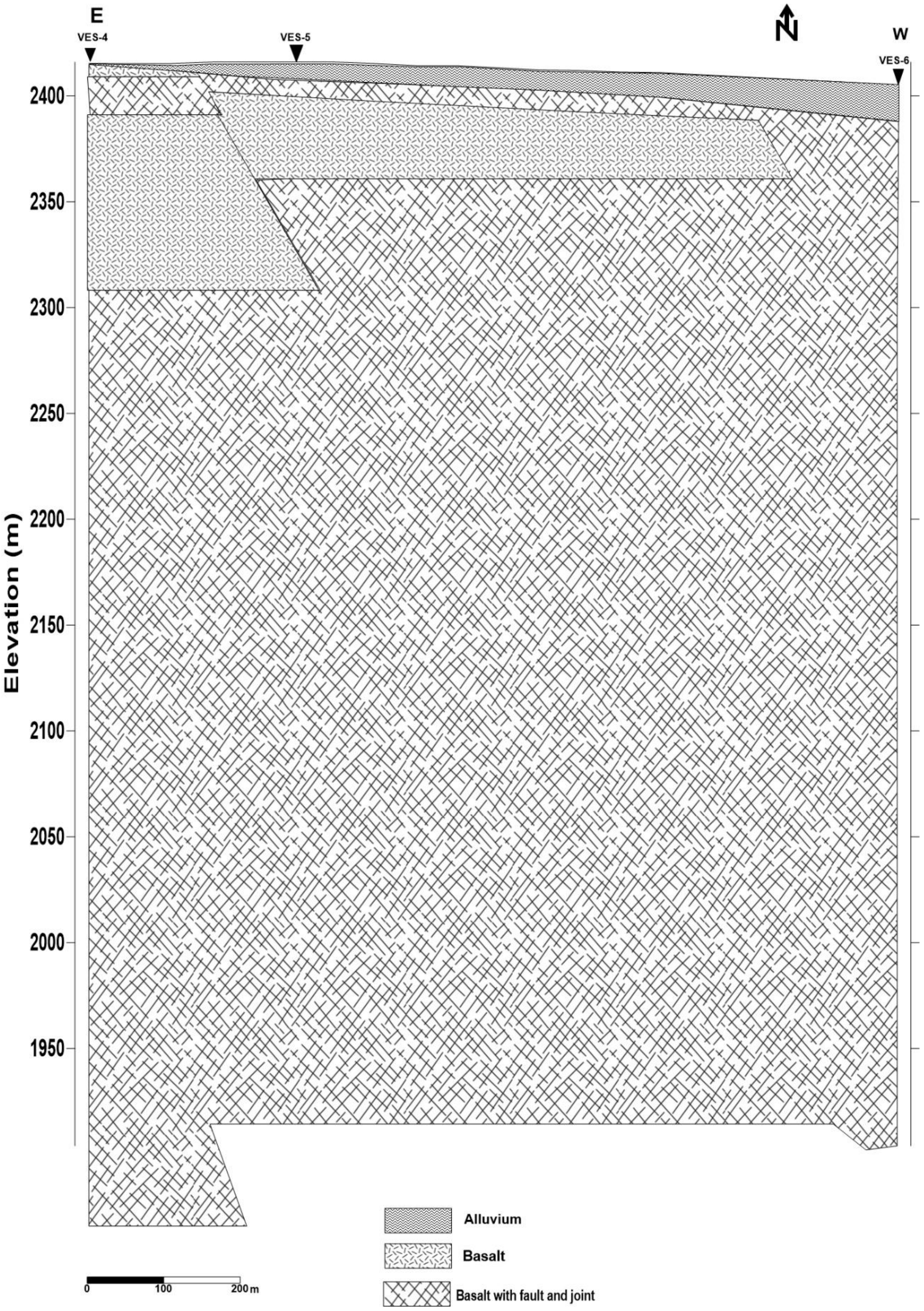

Figure 12: Shows the Geoelectrical Section along the profile (C-D).

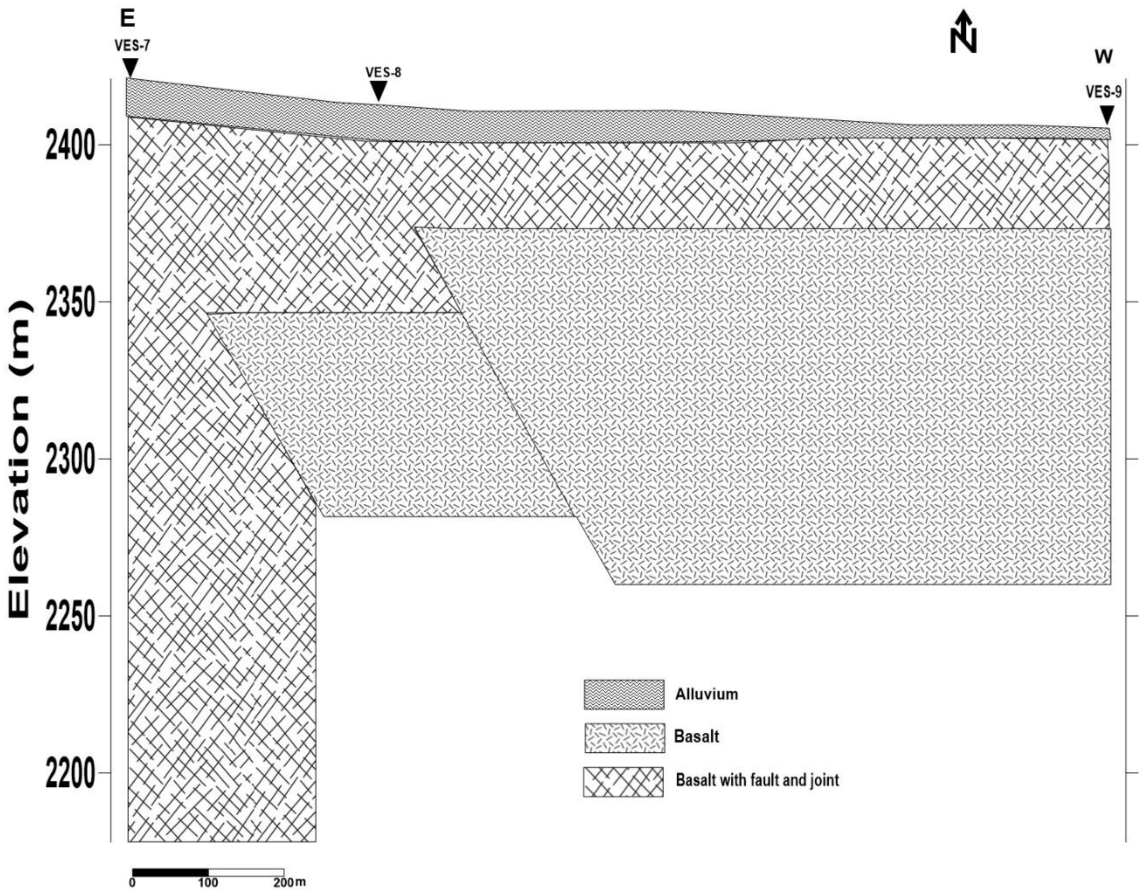

Figure 13: Shows the Geoelectrical Section along the profile (E-F).

Through the previous figures, it has been shown to us that the geology, in general, has been Alluvial sediment whose thickness does not exceed 20 meters in addition to the deformation basalt rocks or that are full of faults and joints, which arrive the depths of 250-350 meters, while the massive basalt rocks are very small in thickness, between 40 to 60 meters. As for the tectonic situation, it shows us that the general direction of the faults affecting the study area is NE-SW.

Boreholes data

In the study area, several boreholes have been dug; some of them are manual and have dried up, while others still contain some water **(Figure 14)**. There is also one deep well existence. The geology of each borehole was identified using the information about the boreholes that were gathered through photographing the boreholes with the (***M2 Borehole Inspection Camera*** instrument (from China), **(Figure 15)**. Alluvial sediment and basalt that have a significant proportion of fractures brought on by faults and joints situated in this area at various depths. Through the information obtained, it was found that most brock-down occur between a depth of 50-150 meters and between 250-350 meters. At depths of 50-150 meters, the reason is due to the existence of a very large number of faults and joints. As for the depth of 250-350 meters, it is because of the faults, in addition to that, it represents an area of Contact between the volcanoes of the Tertiary period and the Tawilah group. What was obtained from the boreholes and our geophysical studies were compared, and it was found that the results of the interpretation show the same geology, as well as the existence of deformation in the basalt rocks caused by faults and joints. For these reasons, the owners of the area did not drill many wells, due to a large number of brock-down inside the boreholes. The procedure for correlating the boreholes is shown in **(Figure 16)**.

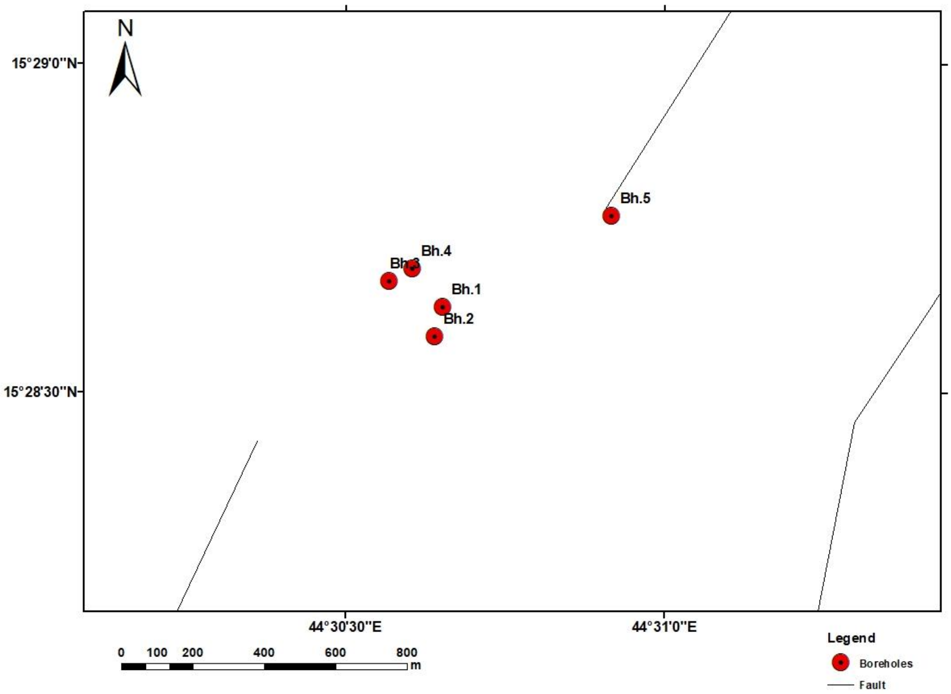

Figure 14: Shows location of boreholes.

Figure 15: M2 Borehole Inspection Camera.

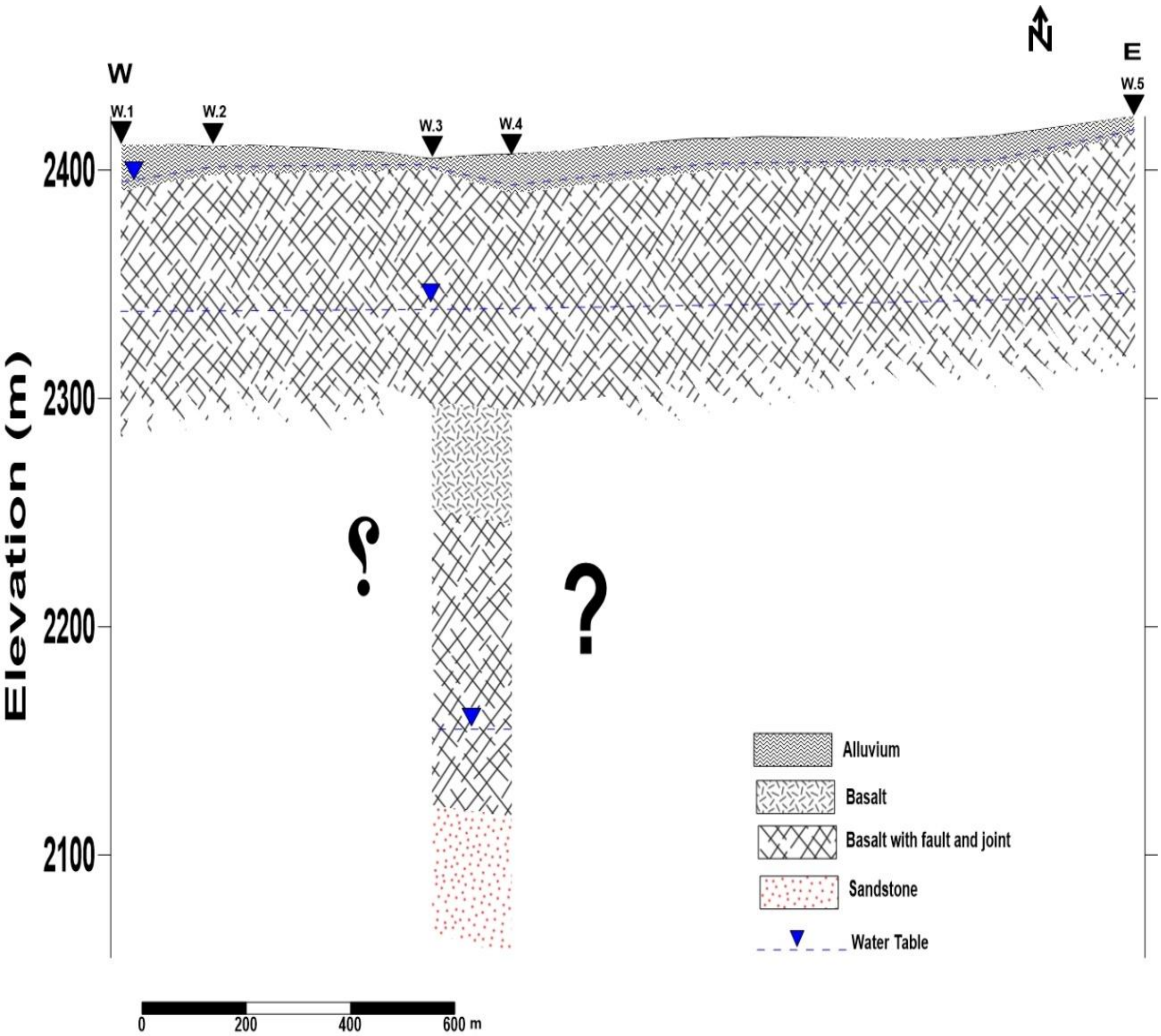

Figure 16: The correlation between the boreholes that were drilled at the study area.

After comparing the geology of the available wells, the geoelectrical findings indicated that we had a sandstone rock of the Tawilah Group at the depths greater than 350 meters. This indicates that as we head to West of the study area, the presence of sandstone rocks of the Tawilah Group, which is considered the main reservoir of the Sana'a Basin.

Conclusion

To explore and extract subsurface groundwater contained in possible aquifer formations in the research region, the geophysical method vertical electrical sounding has been applied efficiently and effectively. Data from vertical electrical sounding demonstrate contrast resistivity at each depth point. The lithology consists of volcanic rocks such as basalt and alluvium sediment. The top layer of alluvium sediment has resistivity ranging from 10 Ω.m to 169 Ω.m with thickness varies from 0.75 – 2.4 m followed by basalt resistivity ranging from 3 Ω.m to 4899 Ω.m with an average thickness is 1 – 693.5 m. Lithology distribution can be identified in the form of volcanic of measured resistivity values. Basalt correlation is carried out by resistivity value that has the same pattern as other point measurements. Other rock correlations show basalt as the potential aquifer also confirmed by geological and hydrogeology data. The Pseudo Cross section indicates the same resistivity change from massive basalt to basalt with fractures .So, after making geoelectrical sections of the vertical electrical data and comparing them to the wells, we found that the study area is considered a harvesting area because all the boreholes drilled in it are brock-down due to the faults affecting the area, and that the Tawilah sandstone rocks are present as we move west of the study area, which represent the main reservoirs in the surrounding areas to the west and the Sana'a Basin. This condition is supported by a basalt rock with fractures that it become rock porosity to allow groundwater to pass through and become more conductive. However, we do not recommend digging a well in this area because the basalt rocks are very susceptible to fractures, which may lead to the breakdown of the wall of the well. However, it is recommended to dig a well with a depth exceeding 700 meters to reach the sandstone rocks of the Tawilah group move west of the study area, as it represents the main reservoir for the areas adjacent to the study area.

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