International Journal of Water Resources and Arid Environments 3(2): 137-153, 2014
ISSN 2079-7079


# Fractures Density Mapping Using DC Resistivity and its Effects on Water Accumulation in Tirʿah and Ad Darʿah Areas, Wadi Alʿays Quadrangle, Saudi Arabia

*Abdallah Ibrahim Ammar*

Research Institute for Groundwater,
National Water Research Center, Cairo, Egypt

**Abstract:** Thirty Five vertical electrical sounding survey and correlation with hand-dug wells was carried out in the Tirʿah and Ad Darʿah areas, for detecting and estimating the density of fractures and its effects on groundwater accumulation in basement rocks. These VESs were interpreted and subsurface layers ranging from five to six geoelectric units were delineated. The general recorded lithologies were the wadi deposits, weathered basement and the fresh basement rocks. The weathered and fractured basement rocks in Tirʿah area and fractured basement rocks in Ad Darʿah area were considered the main aquifers. The true resistivity values of these rocks defined the fractures density and water content of the weathered rocks were as higher than in the fractured rocks. The true resistivity maps reflected that, the parts of very low to low resistivity values of the weathered rocks in Tirʿah area are suggest more groundwater accumulations, while the values of fractured rocks in the northwest parts depict an area rich in groundwater. In Ad Darʿah area, the central parts are expected more fractured and of intermediate water content. The hydrogeological properties of these rocks were predicted and differentiated from these values. The thickness maps of these rocks revealed the high fractures density and high water amounts of the small thickness were more effective for current penetration than the large thickness. The depth to groundwater was generally shallow and its accumulation and flow direction were expected in the areas of low resistivity and high fractures density. The zonings of resistivities of the weathered, fractured and hard rocks are classified to low, medium and high values, respectively. Overlap of the resistivity ranges for the saturated rocks was observed in some locations. Furthermore, the calculated porosity and fractures density referred to the average values of the weathered rocks in Tirʿah area was found to be 4.57% and 3.32/m, for the fractured rocks, 3.3% and 2.38/m in Tirʿah area and 2.45% and 8.03/m in Ad Darʿah area. These results confirmed that, the weathered rocks have the best good physical properties followed by the fractured rocks in Tirʿah area, then in Ad Darʿah area. Consequently, this study which summarized the hydrogeological properties of the delineated aquifers are expected better in Tirʿah area than in Ad Darʿah area. Also, from the statistical analysis between the formation factor, porosity and fractures of density, it was occurred that the evidence between them was strong in case of saturated weathered rocks but in case of saturated fractured rocks it was weak. Deriving from this study, the resistivity values must be carefully used mapping groundwater aquifers and fractures density.

**Key words:** VESs · Basement Rocks · Fractures Density · Water accumulation · Wadi AlʿAys · KSA

## INTRODUCTION

The Wadi AlʿAys quadrangle is bounded by latitude 25° 00″ and 26° 00″ N and longitude 37°30″ and 39°00″ E and occupies 16360km$^2$ surface area in the northwestern part of the Arabian Shield (Fig. 1A). It consists of deeply dissected mountainous country, in which the altitudes range from about 200 to 1600 m. The main ridge extends from Jabal Jufat Haja in the southwest, through Jabal Sharah, to Jabal Hammat Al Ambajah, where it is breached by Wadi Al Hamad and then continues through Jabal juwam to the northwestern corner of the quadrangle. Drainage is dominated by Wadi Al Hamad, which crosses the quadrangle from the southeast to northwest,

**Corresponding Author:** Abdallah Ibrahim Ammar, Research Institute for Groundwater, National Water Research Center, Cairo, Egypt.

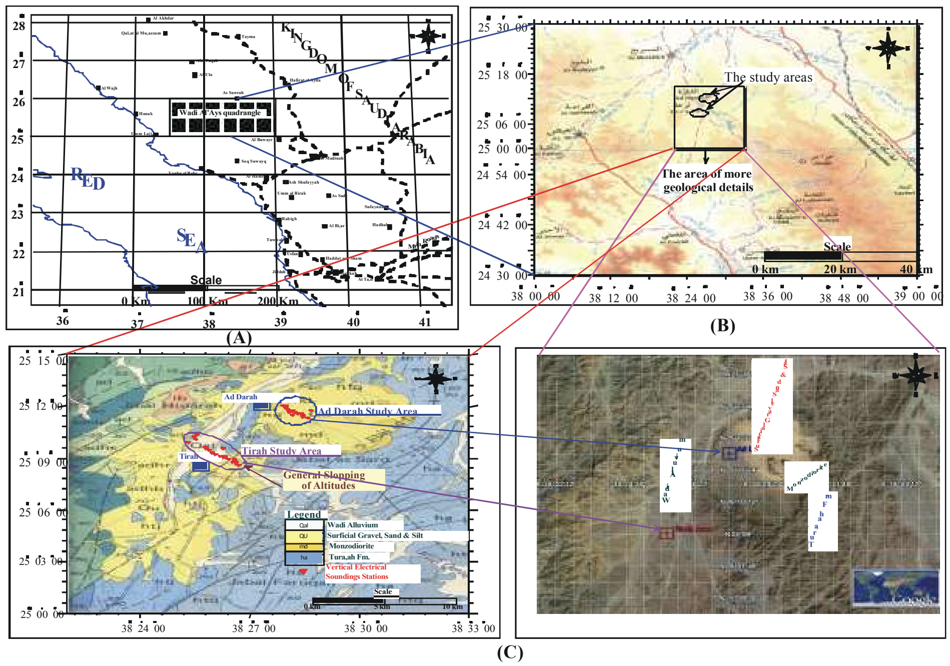



Fig. 1: Location map of the wadi Al'Ays quadrangle (Small Grid) (A), of the Tir'ah and Ad Dar'ah study areas including limits of the area of more geological details (B), and the general geologic map involving the two study areas and VESes locations (C).

descending in altitude from about 500 to about 200 m. It is joined by the important tributaries of Wadi Al Jizl from the north, Wadi Khaybar from the northeast, Wadi Tir'ah, Wadi Al'Ays and Wadi Marmiyah from the south and by Wadi Amudan from the northwest.

The climate is arid, with only occasional rainfall brought by the prevalent northwesterly winds mainly in December. The winter diurnal temperature range is 10°C-15°C, in the summer from June to September, temperature reaches daytime maxima of more than 40°C. The Tir'ah and Ad Dar'ah are the study areas included in quadrangle shown in Figure 1B.

Various researches in the past have used the resistivity techniques, acoustic televiewers and core samples to map fracture densities. For example, Lukes *et al.* [1] studied the determination of the degree to which the very compacted granite is fractured and the hydraulic conductivity of the fracture system at Czech Republic by using the combination of neutron log, electrical resistivity logs, density log, fluid-resistivity log and acoustic log to test the function of the fracture system. Fractures were identified using the acoustic televiewer and the inspection of the core samples. They reported the density of the fractures varying with depth and it was 3 fractures per meter near the surface and dropped to 0.9 fractures per meter at the depth of 80m. Between depths 80 and 300m, the density increased with depth to the maximum of 8.8 fractures per meter. The weathered zone to a depth of 25m had a hydraulic conductivity of $2x10^{-6}$m/s. The zone of opened fractures reached to a depth of 95m with hydraulic conductivity varied from $2x10^{-9}$ to $2x10^{-7}$ m/s. Also, he reported that the granite rocks below 95m have a dense network of fractures; however, the fractures were closed, so that the hydraulic conductivity was very low with values ranging from $2x10^{-12}$ to $4x10^{-9}$ m/s

Generally, Water availability in the Arabian Peninsula is governed by rainfall distribution, which is related in turn to topographic and geologic features. The main topographic features are the western, southwestern and southeastern mountain ridges, as well as the central plateau of the peninsula, which bring orographic rain. Surface runoff is more abundant in these regions than in the rest of the peninsula.

The other major features that influence the availability of groundwater resources are the peninsula's igneous and metamorphic basement rocks known as the *Arabian Shield* and the sequences of sedimentary layers known as the *Arabian Shelf*. The shield consists of an outcrop of hard rocks that begins in the western part of Saudi Arabia and extends from the Gulf of Aqaba to the Gulf of Aden. The shield has limited groundwater stores in the alluvial deposits of wadi channels and geological joints and fracture zones [2].

**Geology of Wadi Al'ays Quadrangle:** The Precambrian volcanic and sedimentary rocks of Wadi Al'Ays quadrangle are divided into three groups, the oldest of which is the Farri group. The lower half of the group consists of apparently sub-aqueous silicic volcanic rocks; the upper half begins with silicic andesitic and basaltic volcanic rocks intermixed with sedimentary rocks, some of which were of shallow-water origin and ends with thick pillow basalt.

Deposition of the succeeding Al'Ays group, that comprises a thick series of largely sedimentary rocks in the west and predominantly volcanic rocks in the east. Deposition of the Hadiyah Group that includes the Siqam Formation, consists mainly of basaltic to andesitic volcanic rocks, the Tir'ah Formation consists of distal submarine fan and trough-floor deposits and the Aghrad Formation comprises an alluvial fan conglomerate sequence overlain by thick sheet of sandstone deposits.

Unconsolidated deposits, ranging from silt to boulders, occur throughout the area. From near Jabal Al Jaziyah to the north of the quadrangle, the central part of the trough floor is occupied by wadi sand and silt, hummocky and channeled, through which the main water courses pass. The pediment slopes at the sides of the trough and at the southeast are occupied mainly by gravelly to sandy braided stream deposits. Rejuvenation of drainage in the upper parts of the pediment slopes by late minor uplift, probably apart of continuing movement related to the opening of the Red Sea, had resulted in the formation of Terraces in places.

Wadi alluvium and broad lateral braided stream deposits occur in the major wadis with feldspathic sand, being well developed in the area occupied by Jabal Ad Dar'ah monzodiorite (Fig. 1C). Windblown sand occurs mainly on the eastern side of the Jizl trough, deposited where the prevailing north-westerly wind, carrying alluvium from the trough floor and strikes the mountains to its northeast. A small area of windblown sand also occurs in the extreme southwest of Wadi Al'Ays quadrangle [3].

## Geoelectric Surveying

**Field Measurements:** Thirty-five (35) vertical electrical soundings (VESs) data were acquired using Schlumberger array in the selected area of study using maximum electrode spacing [AB/2] of 200m using CAMPUS OHMEGA (Ω) instrument. Through this study, four and three geoelectric cross sections are constructed in Tir'ah and Ad Dar'ah study areas (Fig. 2), respectively. Also, lithologic logging of some of the well encountered was carried out for correlation purposes with the VES data.

**Quantitative Interpretation of the Field Data:** Generally, the quantitative interpretation of the field data means the determination of the thicknesses and true resistivities of the individual layers. From the interpretation, it can detect the lithologies encountered within these layers in the vicinity of the analyzed VESs and between them by horizontal and vertical correlation of these VESs. This may reflect the vertical and lateral changes in the rock constitution of the shallow section penetrated by the electric current. The determination of the true resistivities of the different subsurface layers can give good information about fractures and their density and groundwater accumulation, as well as their properties.

The quantitative interpretation of the geoelectric data obtained for the present study in the two areas includes the followings:

A- Interpretation of the vertical electrical sounding curves depends on Zohdy's technique [4] and Rinvert's software [5], that was executed after the preliminary interpretation carried out according to Zohdy's technique in order to obtain the best picture of the true resistivities, which would assist in predicting the physical and hydrogeological properties of the recorded layers with depths. The results of VESs interpretation in Tir'ah area (such as Fig. 3) revealed that the number of the subsurface layers being varies from five, where the second layer is missed, to six layers, while in Ad Dar'ah area, they are generally five, because of missing of the third layer instead of the second one (such as Fig. 4). Generally, from this interpretation and geological data, the reported lithologies of the recorded geoelectric layers ranges from alluvium (Wadi alluvium) to alluvial (gravel, sand and silt) deposits in the first and second layers (Quaternary age), while the layers from third to sixth are made up of basement rocks (Precambrian age). Accordingly, the estimated true resistivities of these layers reflect the following:

- The alluvium and alluvial deposits of the first and second layers are dry to wet at the two areas.
- The weathered rocks (highly fractured) of the third and fourth layers are wet (moisturized) to fully saturated in Tir'ah area and dry to wet in Ad Dar'ah area.
- The fractured rocks (low to moderately fractured) of the fifth layer are saturated in Tir'ah area to low saturated in Ad Dar'ah area.
- The rocks of the sixth layer at the two areas are compacted.

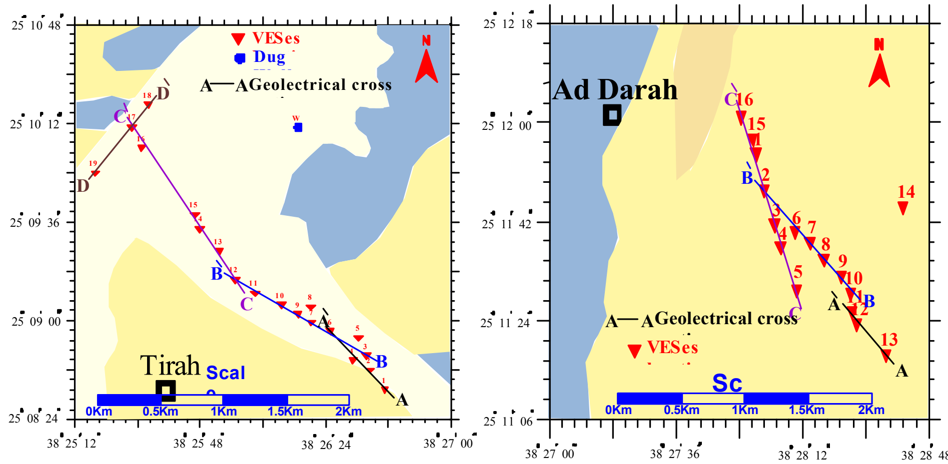



Fig. 2: Vertical Electrical Soundings (VESes) and geoelectric cross sections distribution map in Tir'ah (left) and Ad Dar'ah (right) study areas.

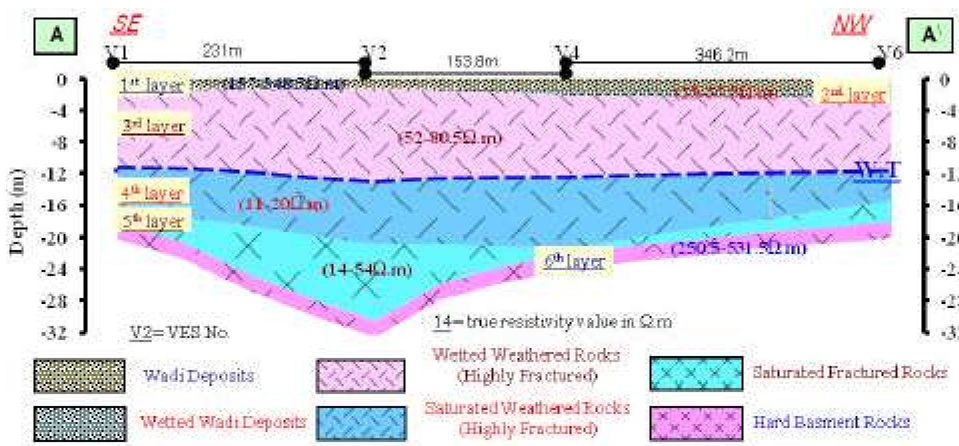



Fig. 3: Geoelectric cross section A-A\ in Tir'ah study area.

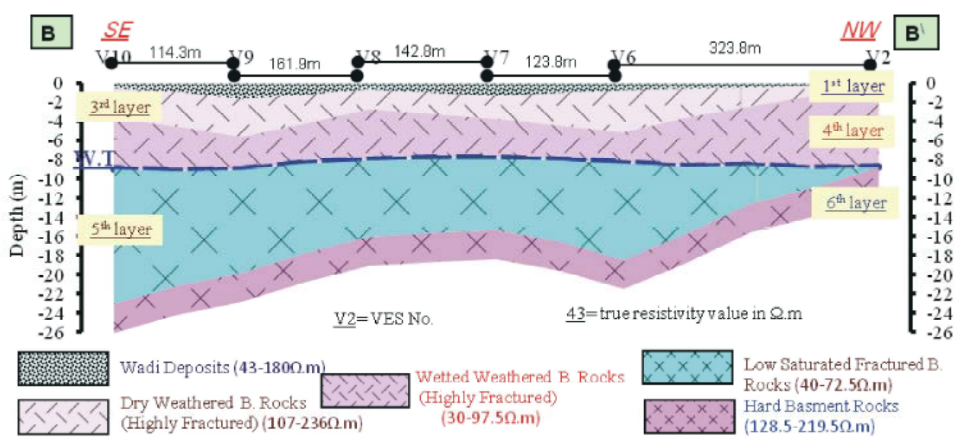



Fig. 4: Geoelectric cross section B-B\ in Ad Dar'ah study area.

**Geoelectric Outputs**

**Geoelectric Cross Sections:** The VESs and cross sections distributed along Tir'ah area (Fig. 2) have be taken from the southeast-to the northwest direction. The VESs were measured in the locations of Wadi deposits (Fig. 1C). On these cross sections (such as Fig. 3), the fourth and fifth layers are the predicted water-bearing layers at this area.

Table 1: True resistivity values of the saturated weathered and fractured layers and their average in Tir̀ah study area

| True Resistivity Value ($\rho_t$) | For Saturated Weathered Layer | For Saturated Fractured Layer |
|---|---|---|
| Maximum $\rho_t$ | 27.5Ohm.m | 72.5Ohm.m |
| Minimum $\rho_t$ | 7.5Ohm.m | 14Ohm.m |
| Average $\rho_t$ | 17.5Ohm.m | 43.3Ohm.m |

Table 2: True resistivity values of the saturated and semi-saturated fractured layer and their average in Ad Dar̀ah study area

| True Resistivity Value ($\rho_t$) | For Saturated to Semi-Saturated Fractured Layer |
|---|---|
| Maximum $\rho_t$ | 76Ohm.m |
| Minimum $\rho_t$ | 38Ohm.m |
| Average $\rho_t$ | 57Ohm.m |

The first geoelectric layer is characterized by high to very high 92.5-445 (Ohm.m) resistivity values, but the second layer is distinguished by intermediate to high 25-164 (Ohm.m) resistivity values. The interpreted resistivity values classified the basement sequence to four geoelectric layers, the third, fourth, fifth and sixth, followed the Quaternary deposits. The low to high 15-131 (Ohm.m), very low to low 7.5-21.5 (Ohm.m), low to medium 14-72.5 (Ohm.m) and very high >205 (Ohm.m) resistivity values are the ranged values of these layers, respectively. These values indicated to these layers are composed of possibly mottled weathered rocks (fully fractured), saturated weathered rocks (fully fractured), saturated fractured rocks and compacted rocks, respectively.

The true resistivity values of the weathered and fractured rocks were compared with each other (Table 1) for revealing the expected effect of fractures density and their saturation on the conductivity. This comparison indicated low value for the saturated weathered layer 7.5 (Ohm.m), while the low value 14 (Ohm.m) was interpreted to be saturated fractured layer. The high estimated values of the weathered and fractured rocks were 27.5 (Ohm.m) and 72.5 (Ohm.m), respectively. The calculated average of these values was 17.5 (Ohm.m) and 43.3 (Ohm.m) for the weathered and fractured rocks, respectively. The previous comparison concluded that, there is differentiation in the low, high and average values of these rocks and some overlapping between them (Fig. 11). This differentiation and overlapping gave a guide to the ability for separating between these rocks and expecting their hydrogeological

Ad Dar̀ah area, which is the second study area at Wadi Al̀Ays, is located in the northeastern side of Tir̀ah area (Fig. 1B). Sixteen VESs were measured, distributed along the area (Fig. 2) and directed southeast-northwest. The area is characterized by alluvial deposits and bounded by Monzodiorite, then Tir̀ah Formation (Figs. 1C and 2).

The interpretation of these VESs involved the construction of three geoelectric cross sections (such as Fig. 4). These cross sections showed the six recorded geoelectric layers. In comparison with the recorded layers in Tir̀ah area, it is revealed that the same geoelectrical layers as with Ad Dar̀ah area was obtained with slight differences in the subsurface geomorphology only. This comparison reflected that, the first and second layers are the same recorded layers in Tir̀ah area and sometimes the second layer is not recorded in the two areas at some locations. The third layer in Tir̀ah area is the third detected layer in Ad Dar̀ah area, but it is dry and recorded only in the B-B cross section (Fig. 4). The fourth layer in Tir̀ah area is the same recorded layer in Ad Dar̀ah area, but it is wetted. The fractured basement rocks are the recorded constituents of the fifth layer in the two areas. These rocks are highly saturated in Tir̀ah area and low to medium saturated in Ad Dar̀ah area. The hard basement layer is recorded in the two areas and considered the six geoelectric layer (Figs. 3 and 4). Also, this comparison attained that, the groundwater in Tir̀ah area is expected in the weathered and fractured layers, but in Ad Dar̀ah area is contained in the fractured layer and its content is expected to be higher in Tir̀ah area and lower to intermediate in Ad Dar̀ah area.

The true resistivity values of the fractured layer, which is the shared water-bearing layer, in the two areas were compared and summarized the minimum values of this layer were 14 (Ohm.m) and 38 (Ohm.m) in Tir̀ah and Ad Dar̀ah area, respectively. The maximum values were 72.5 (Ohm.m) in Tir̀ah area and 76 (Ohm.m) in Ad Dar̀ah area. The average of these values were 42 (Ohm.m) and 60 (Ohm.m) in the two areas, respectively (Tables 1 and 2). This comparison assisted in predicting the density of fractures and water content in Tir̀ah area are expected more abundant than in Ad Dar̀ah area.

## True Resistivity and Thickness Maps of the Saturated Weathered and Fractured Layers

**True Resistivity Maps:** Generally, the true resistivity values of the weathered and fractured rocks were mapped for understanding their physical properties and for predicting the intensity of fracturing in rocks and the areas of more fracturing and groundwater accumulation. The distribution of these values of the weathered rocks across Tir̀ah area (Fig. 5) suggest the differentiation in their values from very low in the southeastern parts to low in the northwestern parts. The parts having very low to low resistivity values <27 (Ohm.m), through the diagonal cross parts (Fig. 5) possibly suggest the probability for

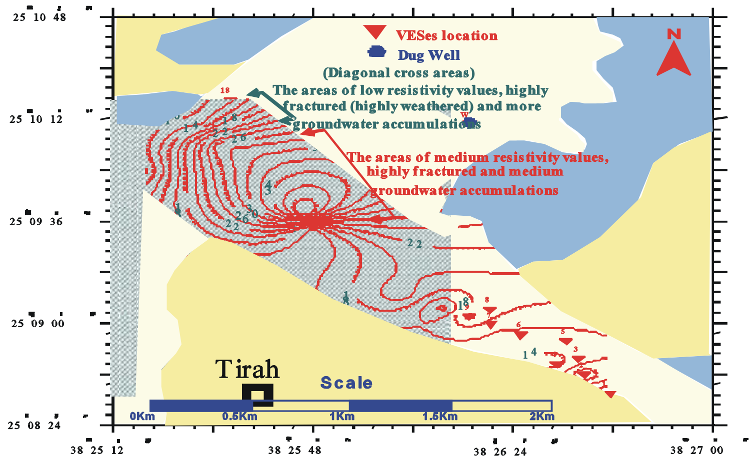



Fig. 5: True resistivity distribution map of the saturated weathered layer along Tir'ah study area.

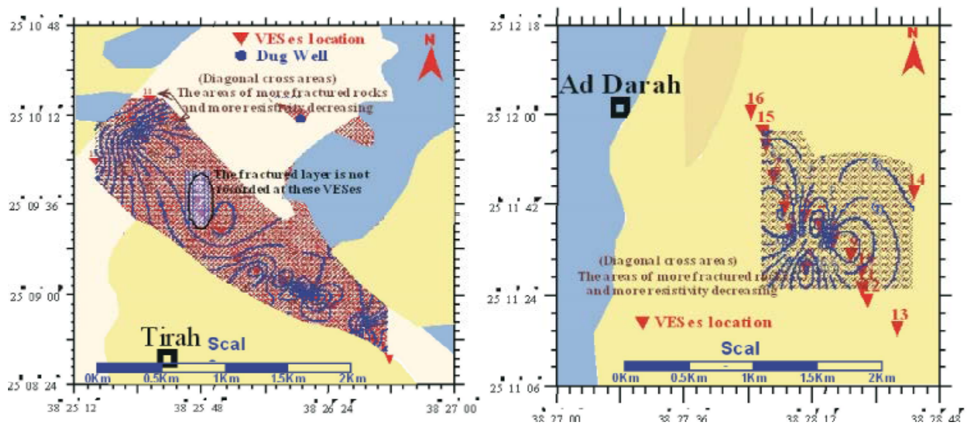



Fig. 6: True resistivity distribution map of the saturated fractured layer along Tir'ah (left) and Ad Dar'ah (right) study areas.

increase of fracture intensity and fractures density and therefore increasing in the water accumulation. The parts of intermediate values >27 (Ohm.m), between VESs 15 and 16, may be referred to the relative decreasing in fractures density and water saturation percentage. Therefore, these rocks at these areas are sloped to the fractured rocks.

The true resistivity map of the fractured rocks, displayed different parts and characterized by values less than 44 (Ohm.m) and more than 44 Ohm.m (<72.5 Ohm.m). The values less than 44 (Ohm.m) of the diagonal cross areas (Fig. 6), considered these parts of more fractured and more water content. The large part from this area was recorded in the northwest.

On these maps, the general decrease of these values is from the southeast to the northwest. Because of depending the electrical current penetrating the considered section on the density of pore system (fractures) and its saturation percentages, it can be concluded that the fracturing intensity and fractures density and their saturation are increased from the southeast to northwest. Consequently, the groundwater is expected more accumulated and its flow direction at the same direction along the area.

The true resistivity distribution map of the fractured layer in Ad Darʿah area (Fig. 6) displayed a conductive axis at the central part of the area in the northeast-southwest direction. This axis is characterized by less resistivity values ranged from 38 (Ohm.m) to 56 (Ohm.m), but the other resistivity values are more than 56 (Ohm.m). These values classified this layer into two parts; the first part, which recorded at the center of the area, is more fractured and it may include intermediate contents of groundwater. The second part, which includes the other locations, is predicted to be less fractured and of low groundwater content. At the end, these values predicted that, the amounts of groundwater at this layer are low to medium and less than the amounts of water implied within the same layer at Tirʾah area.

**Thickness Maps:** The thickness maps of the saturated rocks were constructed for delineating the horizontal and vertical variation in the thickness and determining the effect of aquifer thickness on rock resistivities (Figs. 7 and 8). The thickness map of the weathered layer (Fig. 7) summarizes some recorded parts characterized by large thickness, along diagonal cross parts. These thicknesses are comparable to the parts of low resistivity values (Fig. 5) and considered more efficient in lowering their resistivity.

The thickness map of the fractured rocks in Tir̔ah area (Fig. 8) reflected a considerable thickness at the diagonal cross parts. These parts are comparable to the recorded areas of low resistivity (Fig. 6) and expected more fractured and water content.

The thickness maps of the fractured rocks in Ad Dar̔ah area (Fig. 8) revealed that the thickness increases in some parts and decrease in the other parts as well as its missing in some other parts. On this map, the parts of increasing thickness (>11m) are the diagonal cross parts, while the parts of decreasing thickness (<11m) are the middle parts of the area, but it is not recorded under VESs 2, 12 and 13. However, the parts of less thickness are corresponding to the parts of low resistivity (Fig. 6). This refers to the penetration of electric current that might have influenced the density of fractures and the increase of water amounts, while the parts of large thickness are corresponding to the parts of high resistivity (Fig. 6) except in some parts.

**Depth to Groundwater Maps:** These maps were constructed (Fig. 9) to delineate the configuration of groundwater depths along the area for determining their expected flow direction and its relation with the general sloping of area altitudes and groundwater accumulation. The distribution of these depths in Tir̔ah area showed that, the depth to water in the southeastern part was 13m, while in the northwestern part was 6.5m. These values referred to the groundwater are expected to accumulate in the northwest than the southeast; while the general flow direction of groundwater is expected to be the northwest. Also, because of the general sloping of the area, the observed altitudes from the southeast to the northwest (Figs. 1C and 11), thus, the groundwater is expected to accumulate more in the northwest part.

In Ad Dar̔ah area, the depth to water range from 7.5m to 10.5m (Fig. 9). The shallow depths are recorded in VESs 3, 4, 6, 7 and 8, through the diagonal cross parts. These parts are comparable to the parts of low resistivities (Fig. 6) and the parts of large thickness (Fig. 8). Suggest high fractures density. Consequently, the main conditions for accumulating water, at the diagonal cross parts, are due to the condensation of fractures along these parts.

**Zoning of the True Resistivity Values of the Dry and Saturated Basement Rocks:** According to the true resistivity values of the recorded basement rocks, either the weathered or the fractured or the hard rocks at the two study areas, the zonings of these rocks for understanding their electrical and hydrogeological properties was carried out. These areas are classified to high zoning, medium zoning and low zoning. The high zoning characterizes the hard rocks, which have high electrical impedance and therefore they are compacted. The medium zoning characterizes the fractured rocks, which have medium electrical impedance and therefore they are fractured and have medium water content. The low zoning area characterizes the weathered rocks that have low electrical impedance and consequently they are highly fractured and have high water content (Fig. 10).

Generally, these zonings referred to the hard rocks at the two study areas have the same zoning and also the saturated fractured rocks, while the saturated weathered rocks in Tir̔ah area have different zoning that lies beneath the zonings of hard and fractured basement rocks (Fig. 10). These levels referred to that having fresh hard rocks in Tir̔ah area are relatively higher than in Ad Dar̔ah area, while the zoning of the fractured rocks in the two areas is relatively at the same level. The previous conclusions indicated that, the fracture density and groundwater amounts in Tir̔ah area are higher than in Ad Dar̔ah area.

**True Resistivity Ranges of the Saturated Weathered and Fractured Basment Rocks:** Generally speaking, hard rocks are bad conductors of electricity, but many geological processes and/or weathered rocks and significantly have lower resistivity values. For instance, dissolution, faulting, shearing, columnar jointing, weathering and hydrothermal alteration usually increase the rock porosity and fluid permeability and hence lower resistivity. In contrast to the above processes, precipitation of calcium carbonate or silica reduces porosity and hence increases resistivity. Hardening of rock by compaction and/or metamorphism will reduce porosity and permeability and hence increase resistivity [6].

Resistivity is, therefore, an extremely variable parameter, not only from formation to formation, but even within a particular formation. There is no general correlation of lithology with resistivity. Nevertheless,

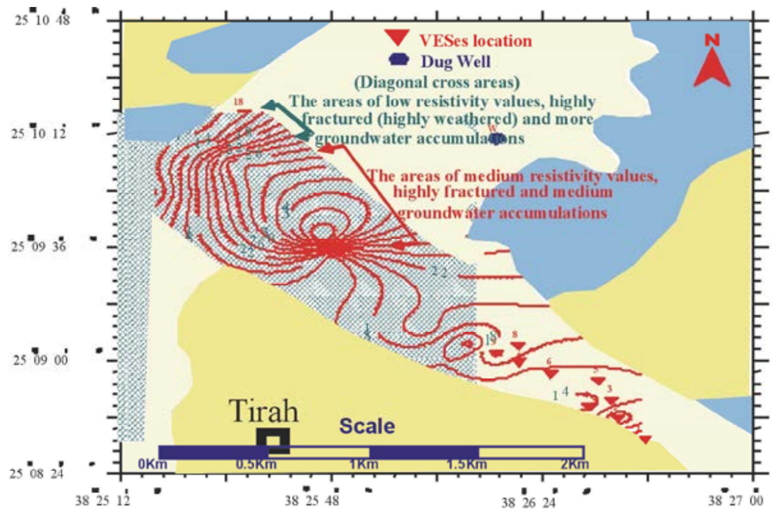



Fig. 7: Thickness distribution map of the saturated weathered layer along Tir'ah study area.

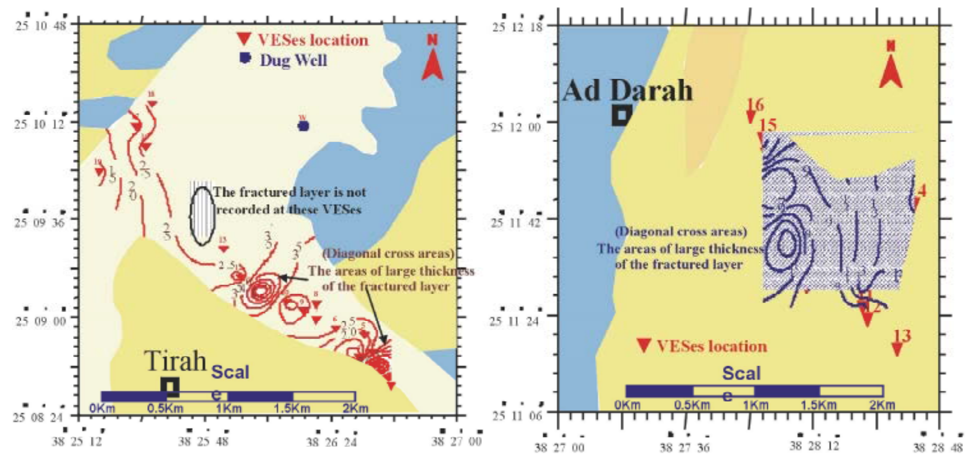



Fig. 8: Thickness distribution map of the saturated fractured layer along Tir'ah (left) and Ad Dar'ah (right) study areas.

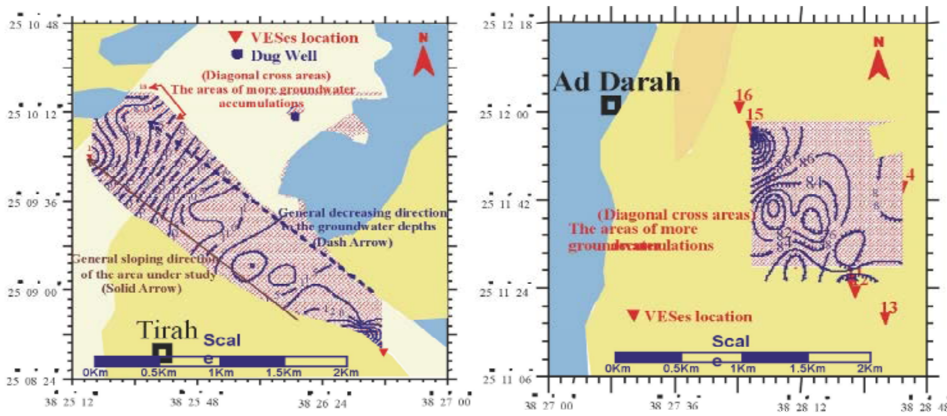



Fig. 9: Depth to groundwater distribution map along Tir'ah (left) and Ad Dar'ah (right) study areas.

a broad classification is possible according to which clays, shales, sands and gravel, compact sandstones and limestones and unaltered crystalline rocks stand in order to increase resistivity [6].

Figure (11) shows the approximate resistivity ranges of saturated weathered and fractured rocks in Tir'ah and Ad Dar'ah areas. From this figure, it is evident that there is overlap between the resistivity values of the weathered

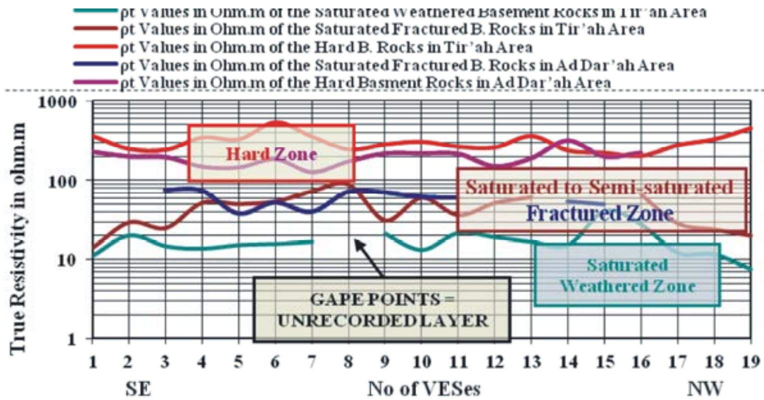



Fig. 10: True resistivity values zonations of the basement rocks in the two study areas.

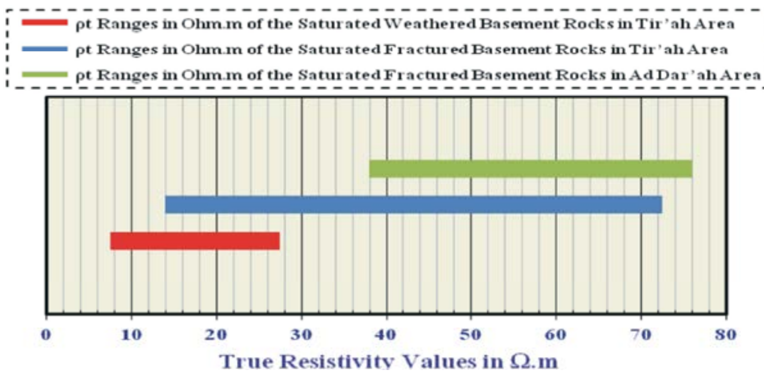



Fig. 11: Ranges of interpreted electrical resistivity of the weathered and fractured rocks in Tir'ah and Ad Dar'ah study areas.

and fractured rocks in Tir'ah area. This is because the resistivity ranges of the weathered rocks are between 7.5 (Ohm.m) and 27.5Ohm.m and of the fractured rocks are between 14 (Ohm.m) and 72.5 (Ohm.m). This overlapping refers to the assumption that, the two rocks are shared in some physical properties in some locations. While the resistivity ranges of the fractured rocks in Ad Dar'ah area are between 38 (Ohm.m) and 76 (Ohm.m). The general resistivity ranges of the fractured rocks in the two areas are between 14 (Ohm.m) and 76 (Ohm.m). These ranges confirms that, these rocks in some locations at Tir'ah area may include the same physical properties in Ad Dar'ah area such as their fracture density and water saturation, whereas the most locations in Tir'ah area are highly fractured and abundant in water content.

**Calculating the Expected Porosity and Fractures Density of the Saturated Weathered and Fractured Rocks:** Generally, the secondary porosity includes vuggy porosity that acquired as a result of dissolution, fracture porosity and intergranular produced due to weathering. These secondary porosities are developed after the processes of deposition, compaction and sedimentation. Unweathered igneous and metamorphic rocks rarely have water potential, because their primary porosity is very low. These rocks cannot form aquifers unless they are highly weathered or fractured. Weathered rocks are often good aquifers, provided they have low clay content [7].

**Quantity and Nature Distribution of the Electrolyte:** Ohm's law stated that, the resistance of a conductor is directly proportional to its length and inversely proportional to its cross-section.

$$\text{Resistance in Ohms} = \rho \frac{L}{S} \qquad (1)$$

where: ρ is the resistivity of the conductor.

In rocks, it is most often observed that water generally acts as a conductor. The more abundant the water, the wider the cross-section of the conductor; the quantity of water depends on porosity and saturation. On the other hand, the length of the conductor is proportionality reduced when the concentrations between pores are direct. From the foregoing, it is clear that the electrical resistivity of a rock essentially depends on its water content, the quality of this water, as well as the nature of its distribution [7].

These factors were taken into account in an extremely important experimental law established for saturated media.

**Archie's Law:** For a rock saturated with water, Archie established an experimental relationship linking the resistivity of the rock, porosity, the nature of distribution and the resistivity of the electrolyte:

$$\rho\text{rock}=\rho_{\text{W}}\alpha\varphi^{-m} \quad (2)$$

*where:* $\rho_{rock}$ *is the bulk resistivity of the rock in Ohm.m;*

- $\rho_w$ *is the resistivity of the formation water in Ohm.m;*
- $\varphi$ *is the porosity in %;*
- *m is the cementation factor, fairly constant for a given rock and in-dependent of the fluid, 'm' characterizes the distance travelled by the electric current; this is the equivalent of what we often call tortuosity. It depends on the shape of the pores and the interconnections between them; it generally varies between 1.3 and 2.2;*
- *a is the a factor which depends on the lithology and varies between 0.6 and 2 [7].*

Generally, the parameters in the above equation characterizing the texture of the rock are known as the formation factor (F):

$$F = a\varphi^{-m} \quad (3)$$

Archie's expression for a saturated rock then becomes:

$$\rho_{rock} = F\rho_w \quad (4)$$

The following relationship is generally accepted for carbonates and formations that are well cemented and consolidated:

$$F = 1\varphi^{-2} \quad (5)$$

Generally, the increase in permeability, also increases the formation factor [7].

According to the longitudinal conductance (Siemens), which is meaning the product of average conductivity and thickness of a layer:

$$\text{Longitudinal conductance} = \frac{h}{\rho_t} \quad (6)$$

By applying and considering the low interpreted resistivity values which suggest that an existing relation between density of fractures and resistivity thus, we derived an equation relating Min. $\rho_t$, h and $\rho_t$, (adding the Min. $\rho_t$ by multiplication in the last equation 6) that was used to calculate the expected density of fractures as shown as follow:

$$\text{Density of fractures} = \text{Min. } \rho_t \frac{h}{\rho_t} \quad (7)$$

By applying the equations numbers 4, 5 and 7, the formation factor (F), porosity (φ%) and density of fractures per meter to the saturated weathered and fractured basement rocks in the two areas were estimated (Tables 3, 4 and 5).

Tables 3 to 6 showed that the minimum calculated value of the formation factor of the weathered rocks in Tir'ah area as 3.52 and the maximum value as 6.88. The minimum and maximum calculated values of the porosity are 3.81% and 5.33%, respectively. While the calculated densities of fractures are 1.74/m as a minimum value and 4.89/m as a maximum value (Table 3).

The minimum calculated values of the formation factor, porosity and density of fractures of the fractured rocks in Tir'ah area are 4.48, 1.88% and 0.16/m, while the maximum values are 28.32, 4.72% and 4.6/m, respectively. Also, in Ad Dar'ah area, the minimum values are 12.16, 2.03% and 4.19/m and the maximum values are 24.32, 2.87% and 11.86/m, respectively (Tables 4 and 5). The maximum value of the fractures density (11.86/m), which calculated in Ad Dar'ah area, is expected, because these rocks are more fractured, but they have low to medium water contents.

For the various rock types encountered in the investigated area, the summary of the results obtained for the formation factors, porosity and fracture densities are shown in Table 6:

Our findings suggest that generally, the weathered rocks in Tir'ah area have good physical properties than the fractured rocks in the same area and in the Ad Dar'ah area. Consequently, we deduce that the hydrogeological properties of the mapped aquifers in Tir'ah area are better than in Ad Dar'ah area.

**The Relation Between Formation Factor and Porosity:** Generally, the porosity increasing with decreasing the formation factor according to Archie's formula as

Table 3: The calculated expected porosities and densities of fractures of the saturated weathered basement rocks in Tir'ah study area.

| No of VESes | $\rho_t$ Values in Ω.m of the Saturated Weathered B.R. in Tir'ah Area | Thickness (h) in m | $\rho_W$ in Ω.m | $F=\rho_t/\rho_W$ | $(\varphi)^2=1/F$ | (φ)% | Density of Fractures = Min.$\rho_t$*($h/\rho_t$) |
|---|---|---|---|---|---|---|---|
| 1 | 11 | 5.5 | 3.125 | 3.52 | 0.28 | 5.33 | 3.75 |
| 2 | 20 | 7.6 | 3.125 | 6.4 | 0.16 | 3.95 | 2.85 |
| 3 | 14.5 | 7.8 | 3.125 | 4.64 | 0.22 | 4.64 | 4.03 |
| 4 | 13.5 | 8.8 | 3.125 | 4.32 | 0.23 | 4.81 | 4.89 |
| 5 | 15 | 4.6 | 3.125 | 4.8 | 0.21 | 4.56 | 2.30 |
| 6 | 15.5 | 3.6 | 3.125 | 4.96 | 0.20 | 4.49 | 1.74 |
| 7 | 16.5 | 5 | 3.125 | 5.28 | 0.19 | 4.35 | 2.27 |
| 8 | | | The Weathered Rocks is not recorded | | | | |
| 9 | 21 | 6.4 | 3.125 | 6.72 | 0.15 | 3.86 | 2.29 |
| 10 | 13 | 6.7 | 3.125 | 4.16 | 0.24 | 4.90 | 3.87 |
| 11 | 21.5 | 6.6 | 3.125 | 6.88 | 0.15 | 3.81 | 2.30 |
| 12 | 19 | 10.8 | 3.125 | 6.08 | 0.16 | 4.06 | 4.26 |
| 13 | 16.5 | 9.4 | 3.125 | 5.28 | 0.19 | 4.35 | 4.27 |
| 14 | 15 | 8.9 | 3.125 | 4.8 | 0.21 | 4.56 | 4.45 |
| 15 | 40.5 | 10.7 | 3.125 | 12.96 | 0.08 | 2.78 | 1.98 |
| 16 | 27.5 | 10.4 | 3.125 | 8.8 | 0.11 | 3.37 | 2.84 |
| 17 | 12 | 7.5 | 3.125 | 3.84 | 0.26 | 5.10 | 4.69 |
| 18 | 11.5 | 7.8 | 3.125 | 3.68 | 0.27 | 5.21 | 5.09 |
| 19 | 7.5 | 8 | 3.125 | 2.4 | 0.42 | 6.45 | 8.00 |

Table 4: The calculated porosities and densities of fractures of the saturated fractured basement rocks in Tir'ah study area

| No of VESes | ρt Values in Ω.m of the Saturated Fractured B.R. in Tir'ah Area | Thickness (h) in m | $\rho_W$ inOhm.m | $F=\rho_t/\rho_W$ | $(\varphi)^2=1/F$ | (φ)% | Density of Fractures = Min.$\rho_t$*($h/\rho_t$) |
|---|---|---|---|---|---|---|---|
| 1 | 14 | 1.3 | 3.125 | 4.48 | 0.223 | 4.72 | 1.30 |
| 2 | 29.5 | 9.7 | 3.125 | 9.44 | 0.106 | 3.25 | 4.60 |
| 3 | 25 | 2.9 | 3.125 | 8 | 0.125 | 3.54 | 1.62 |
| 4 | 52 | 0.6 | 3.125 | 16.64 | 0.060 | 2.45 | 0.16 |
| 5 | 50 | 1.8 | 3.125 | 16 | 0.063 | 2.50 | 0.50 |
| 6 | 54 | 2.6 | 3.125 | 17.28 | 0.058 | 2.41 | 0.67 |
| 7 | 72.5 | 3.6 | 3.125 | 23.2 | 0.043 | 2.08 | 0.70 |
| 8 | 88.5 | 14.3 | 3.125 | 28.32 | 0.035 | 1.88 | 2.26 |
| 9 | 31 | 2.2 | 3.125 | 9.92 | 0.101 | 3.18 | 0.99 |
| 10 | 60 | 1.7 | 3.125 | 19.2 | 0.052 | 2.28 | 0.40 |
| 11 | 36 | 6.5 | 3.125 | 11.52 | 0.087 | 2.95 | 2.53 |
| 12 | 51.5 | 1.7 | 3.125 | 16.48 | 0.061 | 2.46 | 0.46 |
| 13 | 61 | 3.3 | 3.125 | 19.52 | 0.051 | 2.26 | 0.76 |
| 14 | | The Fractured Rocks is not recorded | | | | | |
| 15 | | The Fractured Rocks is not recorded | | | | | |
| 16 | 66 | 2.8 | 3.125 | 21.12 | 0.047 | 2.18 | 0.59 |
| 17 | 28.5 | 1.8 | 3.125 | 9.12 | 0.110 | 3.31 | 0.88 |
| 18 | 24 | 2.7 | 3.125 | 7.68 | 0.130 | 3.61 | 1.58 |
| 19 | 20 | 0.8 | 3.125 | 6.4 | 0.156 | 3.95 | 0.56 |

appeared on Figure 12. The statistical analysis between the calculated formation factor and porosity values of the saturated weathered and fractured basement layers in the two studied areas and the deduction of the relationship between these two variables were carried out by MINITAB statistical software package. This package was used for fitting the data to obtain an optimal estimation of the model's parameters. The outputs of this program were included the descriptive statistics, parameter estimation, statistical hypothesis testing and the basic linear regression which consists of linear regression, analysis of variance (ANOVA) table and model fit validation. Then by applying the previous statistical concepts, the relationship between two variables will be deduced

Table 5: The calculated porosities and densities of fractures of the saturated fractured basement rocks in Ad Dar'ah study area

| No of VESes | ρt Values in Ω.m of the Saturated Fractured B.R. in Ad Dar'ah Area | Thickness (h) in m | $\rho_W$ in Ohm.m | $F=\rho_t/\rho_W$ | $(\varphi)^2=1/F$ | (φ)% | Density of Fractures = $Min.\rho_t*(h/\rho_t)$ |
|---|---|---|---|---|---|---|---|
| 1 | 66 | 14.4 | 3.125 | 21.12 | 0.05 | 2.18 | 8.29 |
| 2 | | The Fractured Rocks is not recorded | | | | | |
| 3 | 76 | 14.3 | 3.125 | 24.32 | 0.04 | 2.03 | 7.15 |
| 4 | 75 | 17.1 | 3.125 | 24 | 0.04 | 2.04 | 8.66 |
| 5 | 38 | 7 | 3.125 | 12.16 | 0.08 | 2.87 | 7.00 |
| 6 | 53 | 10.1 | 3.125 | 16.96 | 0.06 | 2.43 | 7.24 |
| 7 | 40 | 7.5 | 3.125 | 12.8 | 0.08 | 2.80 | 7.13 |
| 8 | 72.5 | 8 | 3.125 | 23.2 | 0.04 | 2.08 | 4.19 |
| 9 | 71 | 10.8 | 3.125 | 22.72 | 0.04 | 2.10 | 5.78 |
| 10 | 62.5 | 14.1 | 3.125 | 20 | 0.05 | 2.24 | 8.57 |
| 11 | 61 | 8 | 3.125 | 19.52 | 0.05 | 2.26 | 4.98 |
| 12 | | The Fractured Rocks is not recorded | | | | | |
| 13 | | The Fractured Rocks is not recorded | | | | | |
| 14 | 54.5 | 15.2 | 3.125 | 17.44 | 0.06 | 2.39 | 10.60 |
| 15 | 50 | 15.6 | 3.125 | 16 | 0.06 | 2.50 | 11.86 |
| 16 | | | | The Fractured Rocks is not recorded | | | |

Table 6: Minimum and maximum values and their averages of the calculated physical parameters of the saturated rocks at the two areas.

| | Calculated Parameter and its Average | | |
|---|---|---|---|
| Rock Type and Area | Formation Factor (F) | Porosity (φ%) | Density of Fractures per meter |
| Weathered Rocks in Tir'ah Area | 3.52-6.88 (5.2) | 3.81-5.33 (4.57) | 1.74-4.89 (3.32) |
| Fractured Rocks in Tir'ah Area | 4.48-28.32 (16.4) | 1.88-4.72 (3.3) | 0.16-4.6 (2.38) |
| Fractured Rocks in Ad Dar'ah Area | 12.16-24.32 (18.24) | 2.03-2.87 (2.45) | 4.19-11 |

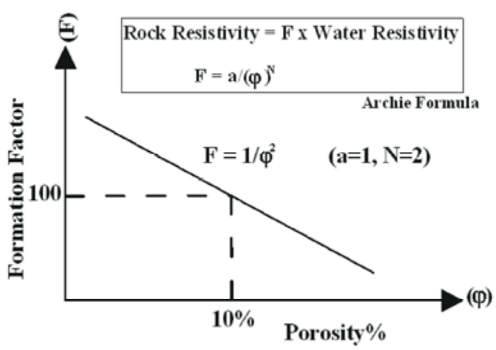
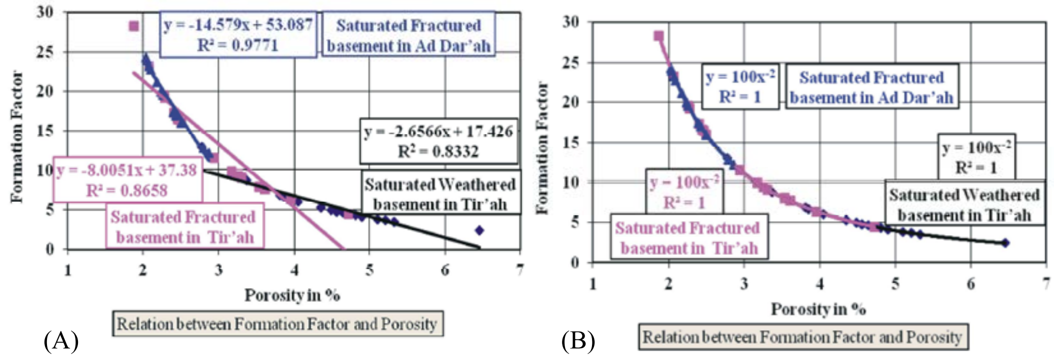



Fig. 12: General expected relationship between the formation factor and porosity.

especially for the saturated weathered and fractured basement rocks in the two areas which are controlled by several factors such as secondary porosity.

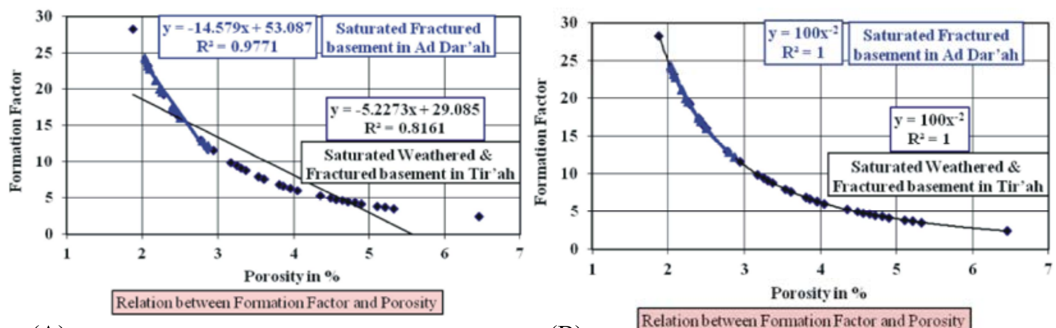
Generally from Figure 12, decreasing the formation factor gives indication about increasing of porosity of the recorded saturated layers (Fµ1/j). By judging the previous relationship, the distribution is normal and identical, the general trend of the data is linear and the model fit is valid. The evidence between the two variables is strong and this relationship is different and the correlation between these variables is high. There is a strong evidence of a relationship between both and this relation is linear and it means that porosity% differ significantly for different formation factor. The R2 of the two variables is around 83.3%, 86.6%, and 97.7% in case of the saturated weathered and fractured basement rocks in Tir'ah and fractured basement rocks in Ad Dar?ah, respectively. That refers to the formation factor cannot be interpreted more than 83.3%, 86.6%, and 97.7% of the porosity of the previous recorded saturated layers, respectively. This may be resulted from the effect of connection and saturation percentages of the fractures, the distribution and density of these fractures and their different types such as fractures, joints and fissures. Hence, it can be confirm the regressions between the two variables of the weathered layer and fractured layer in Tir'ah or of the fractured layer in Ad Dar?ah are linear (Figs 13 (A) and 14 (A)). Also, there is a strong evidence of a relationship between both and this relation is power regression and it means that porosity% differ significantly for different formation factor (Figs. 13 (B) and 14 (B)). The results of statistical analysis of this relationship are concluded in table No. 7.

Generally, it can be supposed that the density of fractures is function in formation factor where the density of fractures increases with decreasing the formation factor (Fig. 15) such as in case of the porosity which increases




(A) (B)

Fig. 13: Linear regression (A) and Power regression (B) relationship between the formation factor and porosity values of the saturated weathered and fractured basement rocks in Tir'ah area and saturated fractured basement rocks in Ad Dar ah area and their empirical formula and root mean square ($R^2$).




(A) (B)

Fig. 14: Linear regression (A) and Power regression (B) relationship between formation factor and porosity values of the saturated weathered with fractured basement rocks in Tir'ah area and saturated fractured basement rocks in Ad Dar ah area their empirical formula and root mean square ($R^2$).

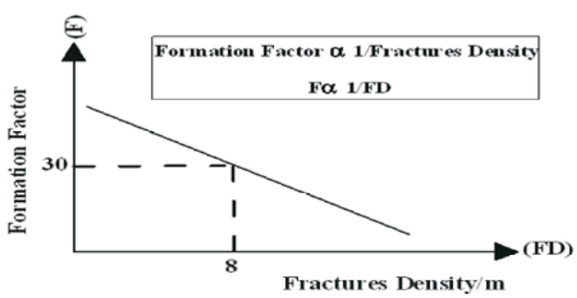
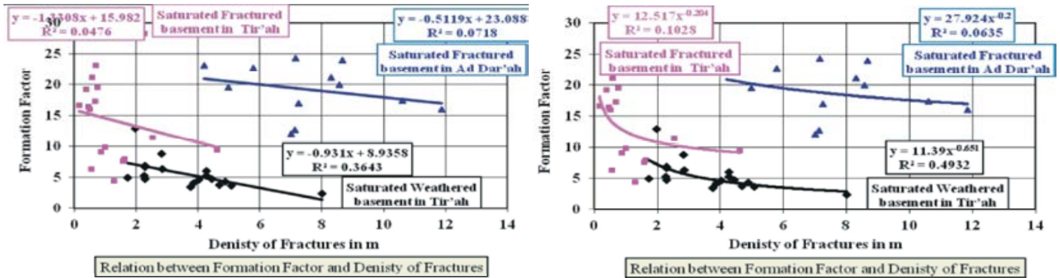



Fig. 15: General expected relationship between the formation factor and Fractures Density.

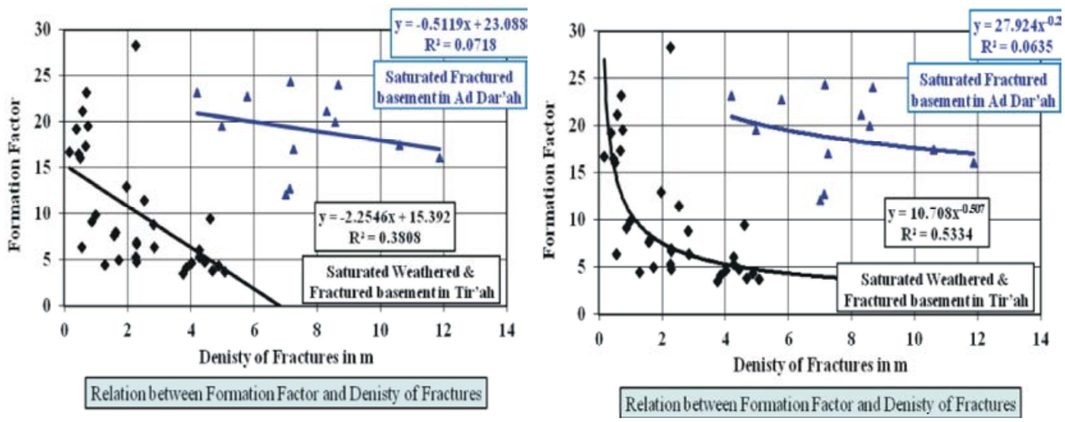
reasing the formation factor. This assumption is confirmed at this study from carrying out the relationship between the two variables. This relationship appears that occurring linear and power regression between both and there is strong evidence between both especially in case of the saturated weathered basement rocks in Tir'ah area (Figs. 16 & 17) but in case of the saturated fractured basement rocks in the two areas, the evidence is weak which may be resulted from depending of the two variables at this case on density and distribution of fractures and their water content. Therefore, the density of fractures and water content of the fractured layers are medium to low. These results were concluded from applying the previous statistical analysis concepts. The results of statistical analysis of this relationship are concluded in table No. 8.

According to the previous relationships between the formation factor with porosity or the formation factor with fractures density which were confirmed there are linear and power regressions and strong evidence between them and supposed that the porosity is function or factor in the density of fractures, it must be the porosity increases with increasing density of fractures and vise versa (Fig. 18). The statistical analysis between two these variables were carried and concluded that the previous assumption is right and true where the porosity of the recorded weathered or fractured basement rocks increases with increasing the density of fractures (Fig. 19 & 20). At the end, it can be used the density of fractures in determining and calculating the porosity of the saturated




(A) (B)

Fig. 16: Linear regression (A) and Power regression (B) relationship between formation factor and density of fractures values of the saturated weathered and fractured basement rocks in Tir'ah area and saturated fractured basement rocks in Ad Dar'ah area their empirical formula and root mean square ($R^2$).




(A) (B)

Fig. 17: Linear regression (A) and Power regression (B) relationship between formation factor and density of fractures values of the saturated weathered with fractured basement rocks in Tir'ah area and saturated fractured basement rocks in Ad Dar'ah area their empirical formula and root mean square (R2).

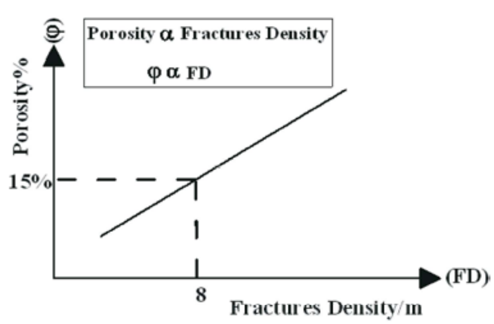
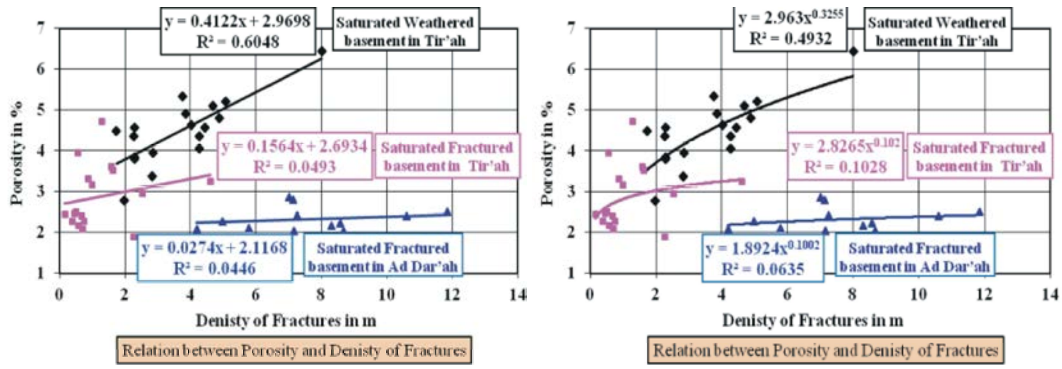



Fig. 18: General expected relationship between the porosity and Fractures Density.

weathered and fractured basement rocks. The results of statistical analysis of this relationship are concluded in table No. 9.

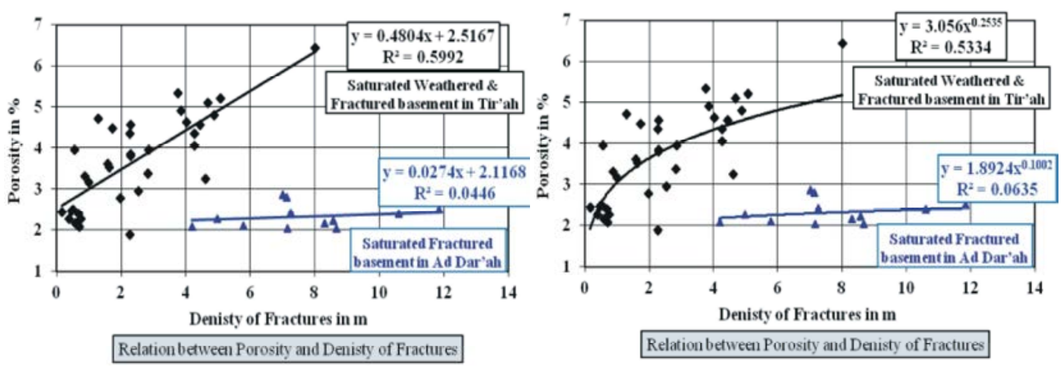
At the end and from the previous statistical analysis, it can be concluded that the porosity and fractures density differ significantly for different formation factor and the porosity differ significantly for different the fractures density especially in case of the saturated weathered basement rocks. But there was a weak evidence of relationships between the formation factor and fractures density and between the porosity and fractures density especially in case of the saturated fractures basement rocks.

**Summary, Conclusions and Recommendations:** The Wadi Al'Ays quadrangle is bounded by lat 25°00″ and 26° 00″ N and long 37o 30? and 39o 00? E and occupies 16360km2 in the northwestern part of the Arabian Shield. The Arabian Shield of the peninsula's igneous and metamorphic basement rocks is one of the several major features that influence the availability of groundwater resources in these areas. This shield consists of an outcrop of fresh hard rocks and it has limited groundwater storage in the alluvial deposits of Wadi channels, and geological joints and fracture zones. The Tir'ah and Ad Dar'ah sites are the two studied areas included at this quadrangle.




(A) (B)

Fig. 19: Linear regression (A) and Power regression (B) relationship between porosity and density of fractures values of the saturated weathered and fractured basement rocks in Tir'ah area and saturated fractured basement rocks in Ad Dar’ah area their empirical formula and root mean square ($R^2$).




(A) (B)

Fig. 20: Linear regression (A) and Power regression (B) relationship between porosity and density of fractures values of the saturated weathered with fractured basement rocks in Tir'ah area and saturated fractured basement rocks in Ad Dar’ah area their empirical formula and root mean square (R2).

Nineteen and sixteen vertical electrical soundings (VESs) were carried out in Tir'ah, as well as dug well data, and Ad Dar'ah areas, respectively, at Wadi Al'Ays quadrangle. These VESs were interpreted using Zohdy's technique [8] and Rinvert's software [5]. The thicknesses, true resistivities and lithologies of the subsurface geological layers are the results of interpretation, that were used for constructing four and three geoelectrical cross sections along these areas, respectively. Generally, the geologic layers are classified into Quaternary sediments and Precambrian rocks. These layers were classified into five to six geoelectric units in Tir'ah area, but in Ad Dar'ah area, they were generally six. The lithologies of these layers are formed from Wadi alluvium and alluvial deposits in the first and second geoelectric units (Quaternary age), while the four remaining layers are made up of basement rocks (Precambrian age). The basement rocks were classified into weathered, fractured and compacted rocks.

The weathered and fractured layers in Tir'ah area and the fractured layers in Ad Dar'ah area are considered the main water-bearing layers. The true resistivity values of these layers, referred to the fractures density and water content, are higher in the weathered layers than in the fractured layers. Consequently, the groundwater is expected to be more accumulating in Tir'ah area than in Ad Dar'ah area.

The true resistivity maps of the saturated rocks were constructed and concluded the parts of very low to low resistivity values of the weathered rocks, that were expected more fractured and more groundwater accumulations. The resistivity values of the fractured rocks in Tir'ah area, reflected locations in the northwestern part, were considered more fractured and more water content. In Ad Dar'ah area, these values delineated a conductive axis directed northeast-southwest and classified the rocks into two parts. The first part is expected to be more fractured and includes medium water content at the center of the area, but the second part characterizes by less fractured and low water content. The comparison between the resistivity values of these rocks was carried out and deduced overlapping between them. This overlapping assisted in differentiating between the hydrogeological properties of these rocks.

The thickness maps of the saturated layers were designed to reflect the high fractures density and high amounts of water of the small thickness were the more effective on the electrical current penetration than of the large thickness, which has lower fractures and lower water content. The groundwater depth maps were constructed as revealed the detection of ground water depth was shallow and its accumulation and flow direction were expected more in the parts that characterized by low resistivity, large thickness and high fracture density.

The zonings of resistivity values of the weathered, fractured and hard basement rocks at the two areas were determined and classified to high, medium and low, respectively. Also, the ranges of these values to the saturated rocks were calculated and exhibited overlapping between them. This overlapping showed that, these rocks are shared in some physical properties, such as fractures density and water content in some locations and differ in the other ones.

The porosity and fracture density of the saturated rocks were calculated and defined as the minimum value of porosity of the weathered rocks in Tir'ah area was 3.81% but the maximum value was 5.33% and their average was 4.57%. The minimum porosity of the fractured rocks at the same area was 1.88%, but the maximum value was 4.72% and their average was 3.3%. In Ad Dar'ah area, the minimum porosity of the last rocks was 2.03%, but its maximum value was 2.87% and their average was 2.45%. The minimum calculated values of fractures densities of the weathered and fractured rocks in Tir'ah area were 1.74/m and 0.16/m, but the maximum values were 4.89/m and 4.6/m and their averages were 3.32/m and 2.38/m, respectively. In Ad Dar'ah area, the minimum value was 4.19/m and the maximum value was 11.86/m and their average was 8.03/m. At the end, all the previous results reflected that, the weathered rocks in Tir'ah area are predicted including the good physical properties, then the fractured rocks at the same area, then the fractured rocks at Ad Dar'ah area. Consequently, the hydrogeological properties of the recorded aquifers are expected to be better in Tir'ah area than in Ad Dar'ah area.

From carrying out the statistical analysis between the formation factor and porosity, formation factor and fractures density and between the porosity and fractures density, it was concluded that the evidence of the relationship between them was strong and the relations are linear and/or power regressions. The porosity and fractures density differ significantly for different formation factor and the porosity differ significantly for different the fractures density especially in case of the saturated weathered basement rocks. It can be recommended with using the resulted empirical relationships especial in case of calculating the expected porosity from fractures density of the saturated weathered basement rocks. But there was a weak evidence of relationships between the formation factor and fractures density and between the porosity and fractures density especially in case of the saturated fractures basement rocks. This may be resulted from the changes of density of fractures and their saturation horizontally and vertically.


## ACKNOWLEDGMENT

El-Hashmey Establishment in Makkah and Thobaity Office for Water Engineering and Exploration in Jeddah, KSA are appreciated with their assistance in acquiring the data and field geoelectric measurements.


## REFERENCES


1. Lukes, J., L. Rukavickova and T. Paces, 2003. Borehole geophysics, hydraulic characteristics and chemistry of groundwater flow in fractured granite with very low permeability, Search by Internet.
2. Al Alawi, J. and M. Abdulrazzak, 1996. Water in the Arabian Peninsula: problems and perspectives. In: Rogers, P., Lydon, P., (Edi.), water in the Arab World: perspectives and prognoses, the American university in Cairo press, Egypt, pp: 171-202.
3. Kemp, J., 1987. Explanatory notes to the geologic map of the Wadi al Al'Ays quadrangle, Sheet 25C, Deputy Ministry for mineral resources, Ministry of petroleum and mineral resources, KSA, pp: 37.
4. Zohdy, A.A.R., 1989. A new method for automatic interpretation of Schlumberger and Wenner sounding curve geophysics. 54: 245-253.
5. Rinvert, 1999. Geophysical software package: Licensed to hydrogeology and engineering geology. Hochi Minh City-Vietnam., Reg., Number, RW 140032, February 03, 1999.

6. Sharma, P.V., 1997. Environmental and engineering geophysics. Cambridge Univ. press, United Kingdom, ISBN 0-521-57240-1, pp: 207-261.
7. Chapellier, D., 1992. Well logging in hydrogeology. Lavoisier, Paris, pp: 173.
8. Zohdy, A.A.R. and R.J. Bisdorf, 1989. Schlumberger sounding data processing and interpretation program. U.S., Geological Survey, Denver, Co.