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The Role of a Multi-Sensory Geophysical Survey to Unravel the Igneous Intrusions Controlling a Ground-water Aquifer in Saint-Katherine Area, Sinai, Egypt

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Abstract. The success of integrated seismic refraction, ground magnetic, and resistivity sounding techniques is demonstrated in delineating the actual setting of a wadi fill groundwater aquifer lying within Wadi El-Sheikh, Southern Sinai, Egypt. This aquifer, that is underlain by granitic basement rocks, has long been mistakenly thought to be controlled by a series of intrusive basic dykes cutting across the wadi fill, representing the main water aquifer body, thus controlling the groundwater level and hence its direction of flow. Such erroneous conclusions are the result of relying only on surface geological observations and on improper choice and inaccurate interpretation of geophysical data.

The inversion of seven compressional-wave seismic refraction profiles, using the reciprocal-time approach; nine closely spaced ground magnetic profiles, using the 2½-D magnetic modelling; and six resistivity soundings, using the automatic iterative techniques, has inferred the basic intrusions as a high velocity and high magnetic susceptibility material in contrast to the alluvial material constituting the wadi fill.

The integrated interpretation of geophysical results has revealed that the surface-exposed basic rocks are found underlain the wadi sediments in the subsurface across the investigated wadi. This indicates that, these dykes, in fact, play no role either in determining the aquifer configuration or in controlling the groundwater flow direction in the examined part of the wadi.

Introduction

Groundwater resources play a vital role in the spreading of urbanization and encouraging investments in Sinai. Since 1950's, groundwater resources of Sinai have been intensively investigated by many scientists (Paver & Jordan, 1956; Pavlov & Ayuty, 1961; Taha, 1968; Shata *et al*., 1978; Dames & Moore, 1982; El-Shazly *et al*., 1985; Mills & Shata, 1989; Hosney, 1991; and many others).

The search for groundwater aquifers in the remote areas of the Sinai Peninsula, Egypt, has long been conducted on the basis of resistivity sounding measurements controlled by general surface geologic features. However, this routine has frequently failed to correctly infer the actual hydrogeologic situation in areas dominated by complex geology. In these situations, integrated geophysical measurements provide more accurate picture of groundwater distribution.

The integrated application of several geophysical techniques to evaluate groundwater resources and to study the hydrogeologic conditions for prospective areas has been widely used (McGinnis & Kempton, 1961; Frohlich, 1974; Van Overmeeren, 1981; Aubert *et al*., 1984; Wolfe & Richard, 1991; El-Behiry, 1994; and others).

In the present investigation, seismic refraction, resistivity sounding and ground magnetic surveys are applied to examine the role of outcropping igneous dykes in controlling the entrapment, depth and groundwater flow in wadi El Sheikh area, Southern Sinai. Field observations and previous geophysical investigations (El-Shazly *et al*., 1985 and Hosney, 1991) implied that, the outcropping dykes, on both sides of the wadi, belong to a single major dyke, that extends in the subsurface and hence block the water flow from the south to the north and changes the water table levels along the wadi.

Location and Geologic Setting

The Sinai Peninsula is a part of the great arid belt of North Africa and Southwest Asia. Sinai is built of an ancient crystalline block, a portion of the African-Arabian Precambrian Shield that rose between two rifted areas and later tilted down to the north. Between Precambrian and Quaternary times, it was subjected to both long and short transgressions of the Tethys Sea and later, of the Mediterranean itself, resulting in the deposition of a sedimentary section over the igneous and metamorphic basement rocks (Mills and Shata, 1989).

The examined area occupies a small portion of Wadi El-Sheikh, which represents one of the most important wadis in the rugged mountainous belt of Southern Sinai. Wadi El-Sheikh runs in N-S direction and represents a major water collector for the inflow from the watershed areas represented by the highlands. It also discharges the smaller wadis connected to it (Fig. 1).

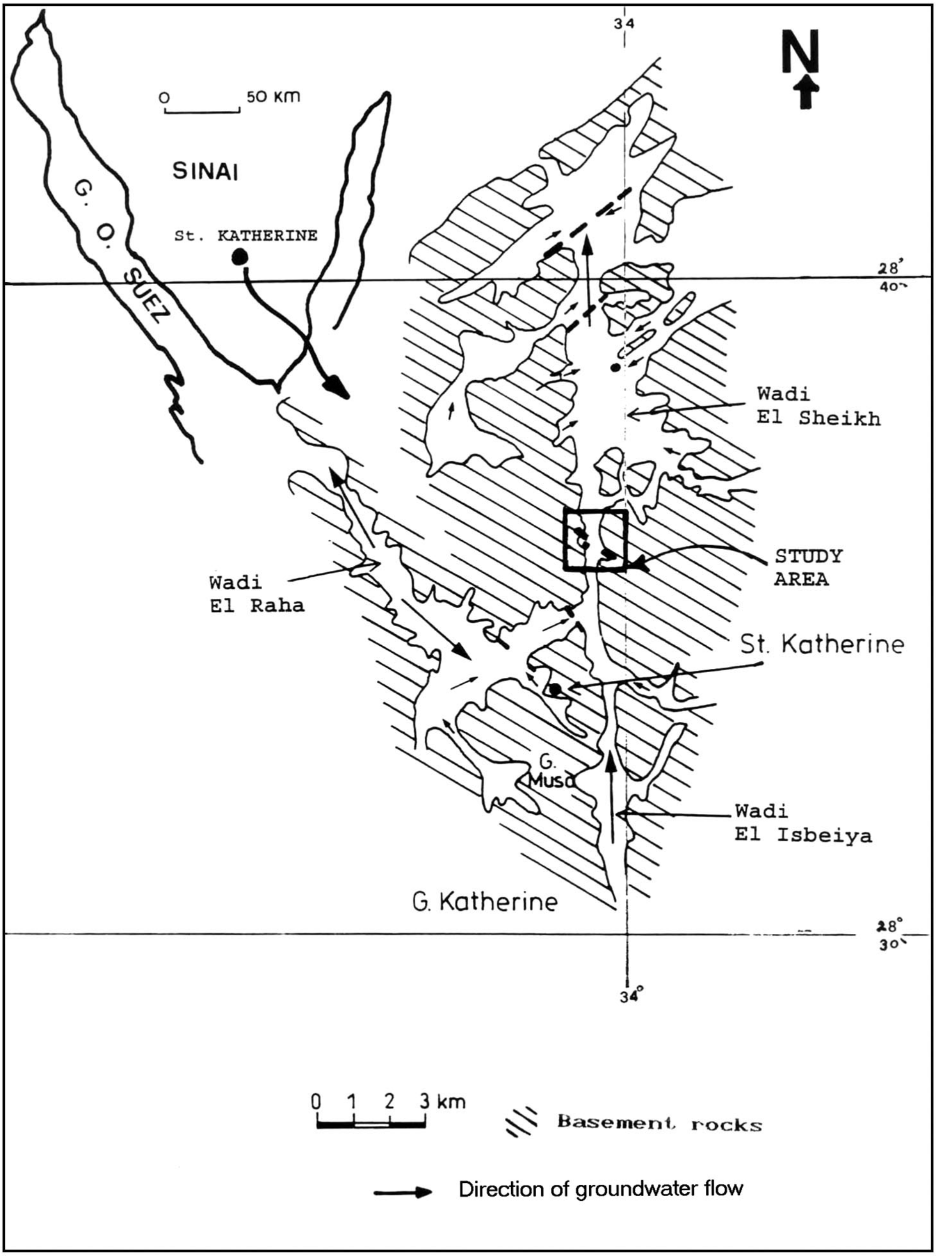

Fig. 1. Location of the study area.

Geological field observations in the examined area indicate that, Wadi El-Sheikh is flanked by several exposed NW-SE and NE-SW trending dykes. Figure 2 shows one of the NW-SE dykes in Wadi El-Sheikh area. It was believed that, the exposed dykes extend across the wadi and are buried under the wadi fill which consists of alluvial deposits of loose sand, gravel and silt covering the underlying weathered basement rocks. These dykes, therefore, acting as water barriers, were believed to control the groundwater flow and the configuration of the aquifer in the wadi, which comprises the bottom of the wadi fill and the underlying weathered and fractured basement rocks. The aquifer along the wadi, generally, follows the relief of the basement surface resulting in the formation of semi-isolated basins (El-Shazly *et al.*, 1985). Figure 2 shows also a schematic section of Zeitona well, which indicates that the groundwater level lies at a depth of 39.1m.

The evaluation of the hydrogeologic conditions of Wadi El-Sheikh draws its importance from the fact that, the Southern Sinai crystalline rock mountain province, including the examined area, appears to produce the highest quality water (TDS=530 mg/l) (Mills and Shata, 1989). It is of importance, therefore, to decipher the actual role of the observed intrusive dykes in controlling the groundwater entrapment, elevation and flow direction. For this purpose, a multi-sensory geophysical survey was planned and executed (Fig. 2), integrating refraction seismics, resistivity soundings and ground magnetics.

Geophysical Techniques: Data Acquisition, Analysis and Results

1. *Refraction Seismics*

Seven P-wave shallow seismic refraction lines (A-A', B-B', C- C', D-D', E-E', F-F' and G-G'), including four orthogonal lines (A-A', B-B' and C-C', D-D'), were conducted with different bearings (N-S, E-W, NE-SW and NW-SE) along and around the anticipated buried path of the exposed dykes across the examined part of Wadi El-Sheikh (Fig. 2). A sledge-hammer and a 12-channel, signal enhancement and computer operated seismograph were used to generate and record the refracted seismic waves. The seismic lines varied in length between 30 and 50 m, all with an inter-geophone spacing of 2 m.

The picked first-arrival times are inverted into the corresponding depth-velocity sections using in-house made software based on the Reciprocal Method (Edge & Laby, 1931 and Palmer, 1986). The depth sections of the orthogonal seismic refraction lines A-A' and B-B' (Fig. 3 & 4, respectively) show three main seismic layers: 1) A main surface layer with dry sand at the top (V1=440 m/s), which appears only in the N-S seismic line (A-A') attaining an average thickness of 1.25 m and disappears in the E-W seismic line (B-B'). Increasing

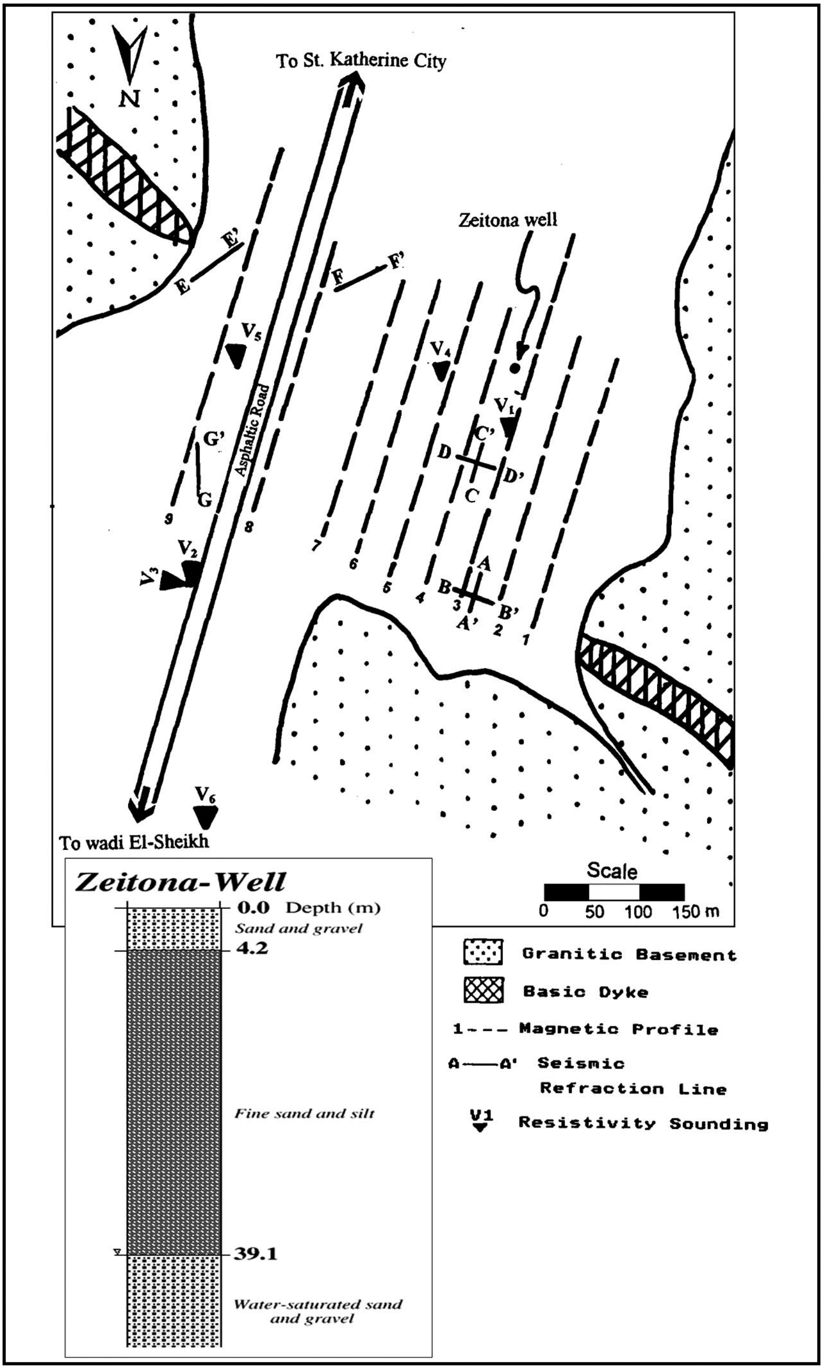

Fig. 2. Layout of the applied geophysical tools.

the gravel and silt content with depth results in increasing the seismic velocity to about 530-590 m/s. The average thickness of this layer is about 4 m; 2) A second layer of velocity V2=1304-1757 m/s, corresponding to the weathered part of the basic dyke to the west and having an average thickness of 5 m; and 3) A bottom layer characterized by a high seismic velocity of V3=3625 m/s, corresponding to the western intact basic dyke material, which dips to the east under the wadi fill (Fig. 4). This layer does not appear in the bottom of the N-S seismic model (A-A'). This may be the result of the presence of the surface low velocity dry sand layer, which attenuates the seismic energy to the limit that, no first-arrivals could be recognized on the seismic record.

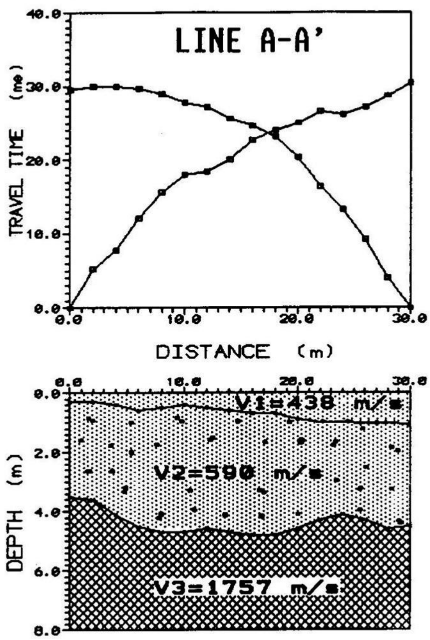

Fig. 3. Travel-time and corresponding velocity depth section of seismic refraction line A-A'.

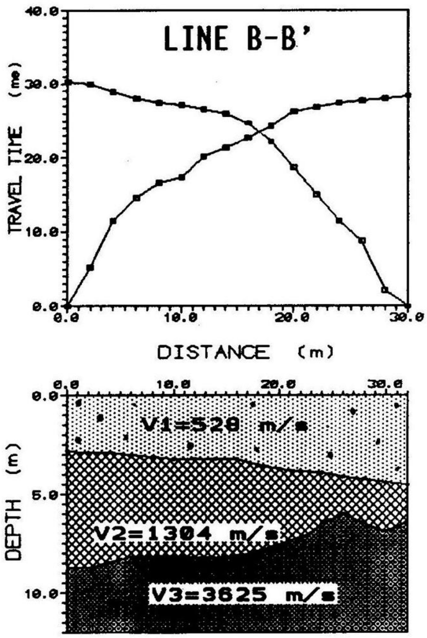

Fig. 4. Travel-time and corresponding velocity depth section of seismic refraction line B-B'.

On the other hand, the depth sections of the orthogonal seismic lines C-C' and D-D' (Fig. 5 and 6, respectively) and the three seismic lines E-E', F-F' and G-G' (Fig. 7, 8 and 9, respectively) show two seismic layers: 1) A first surface layer with velocity of V1=400-500 m/s, corresponding to wadi fill composed mainly of dry sand with an average thickness of about 3.0 m, and 2) A second layer with velocity of V2=610-730 m/s, corresponding also to wadi fill composed of dry sand, gravel and silt.

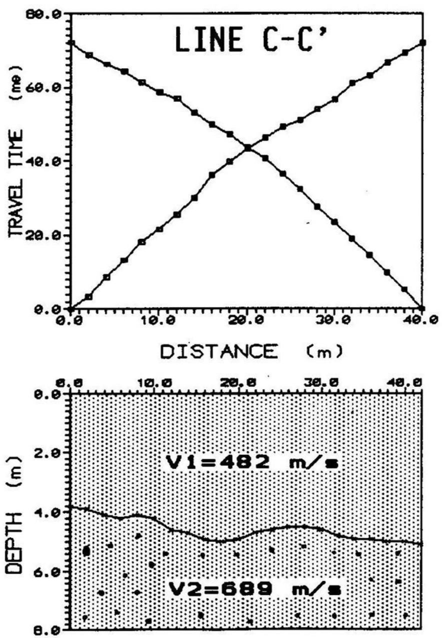

Fig. 5. Travel-time and corresponding velocity depth section of seismic refraction line C-C'.

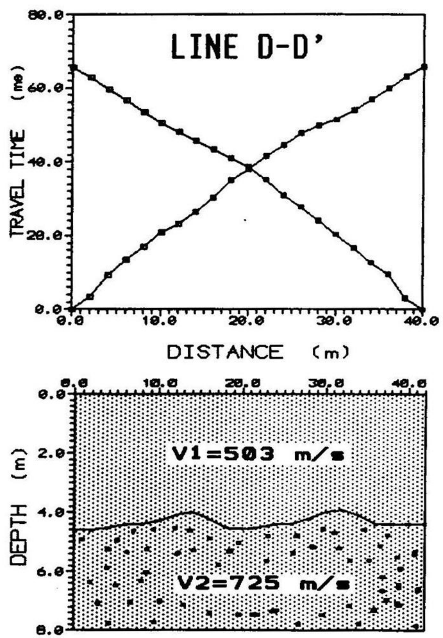

Fig. 6. Travel-time and corresponding velocity depth section of seismic refraction line D-D'.

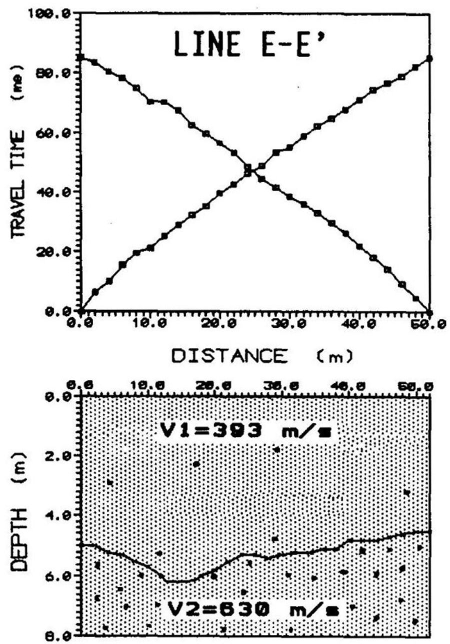

Fig. 7. Travel-time and corresponding velocity depth section of seismic refraction line E-E'.

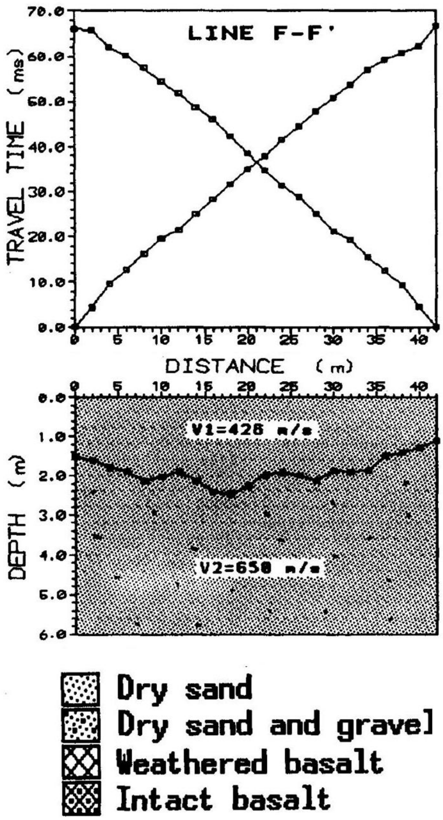

Fig. 8. Travel-time and corresponding velocity depth section of seismic refraction line F-F'.

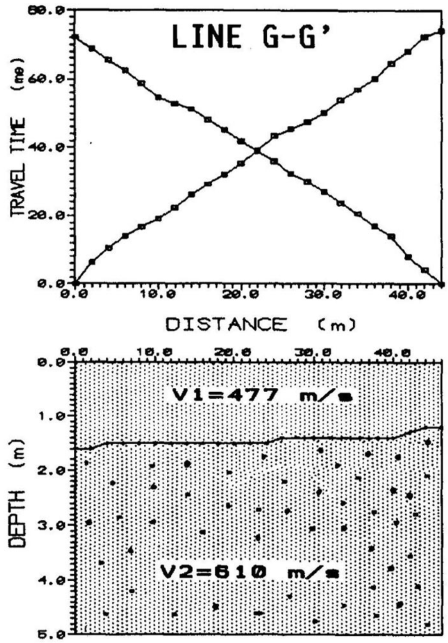

Fig. 9. Travel-time and corresponding velocity depth section of seismic refraction line G-G'.

From seismic results, it can be concluded that, the western basic dyke may extend in the subsurface only to a limited distance in the western part of the wadi and seems to disappear in the subsurface, even close to the eastern exposure.

2. Resistivity Sounding

Six Schlumberger resistivity soundings (VES's) were conducted through the examined area of Wadi El-Sheikh (Fig. 2). The maximum attained current electrode spacing (AB/2) was 316 meters; this enabled reaching the basement rocks underlying the wadi fill at all the sounding sites. Two of the six soundings (VES 2 and VES 3) were orthogonal and concentred to investigate resistivity anisotropy (Hosney, 1991).

The conducted resistivity soundings are reinterpreted using the software “Resist” (ITC, 1988) based on an automatic iterative inversion routine. The inversion process was constrained by: 1) The determined seismic layers; and 2) The lithologic log of the Zeitona water well (see Fig. 2), as described by Hosney (1991) to eliminate the equivalence and/or suppression effects. Figures 10 (a&b) show the resulting resistivity models with RMS-error between the observed and calculated apparent resistivity values. Resistivity anisotropy was ruled out on the ground, that the resistivity models for the two orthogonal soundings (VES's 2 & 3) were practically identical, and hence the comparison of resistivity models obtained from soundings of different bearings is justified. This is in accordance with the results of Hosney (1991).

Figure 11 shows a panel resistivity diagram combining the resulting resistivity models of the soundings # 1, 2, 4, 5, & # 6. It can be seen that, the resistivity section of the examined area is composed of the following resistivity layers, from top to bottom:

1. A dry sand layer having a resistivity of 300-530 Ω.m and an average thickness of 1.5m. This layer attains its maximum thickness (3.6m) at the eastern and middle parts of the wadi and is capped at the middle part, at VES-4, by a thin resistive layer (1000 Ω.m) of rock fragments and gravels.

2. A thin gravely sand layer having a resistivity of 600-1180 Ω.m and an average thickness of 1.3m.

3. A thick silty sand layer having a resistivity of 150-340 Ω.m and an average thickness of 37.7m.

4. A water-saturated sand and gravel layer having a resistivity of 100-110 Ω.m. This layer represents the upper part of the aquifer in the wadi. It attains its maximum thickness (19m) at the eastern part of the wadi and its minimum (2.7m) at the middle part. However, at the northern part of the wadi, this layer is underlain by another gravely sand layer having a resistivity of 467 Ω.m.

5. Weathered and fractured basement rocks having a resistivity ranged between 900 and 1300 Ω.m. The total depth to this bedrock ranges between 42m at the middle part of the wadi and about 61m at its eastern part.

From the above discussion of resistivity sounding results, it may be concluded, in contrast to the results obtained by Hosney (1991) that, the aquifer of the study area is continuous across the wadi (water table depth=38.1-42.1m), with no evidence of obstruction by the supposedly buried dyke.

This supports the seismic conclusions that, the exposed dykes are not connected underneath the examined part of Wadi El-Sheikh.

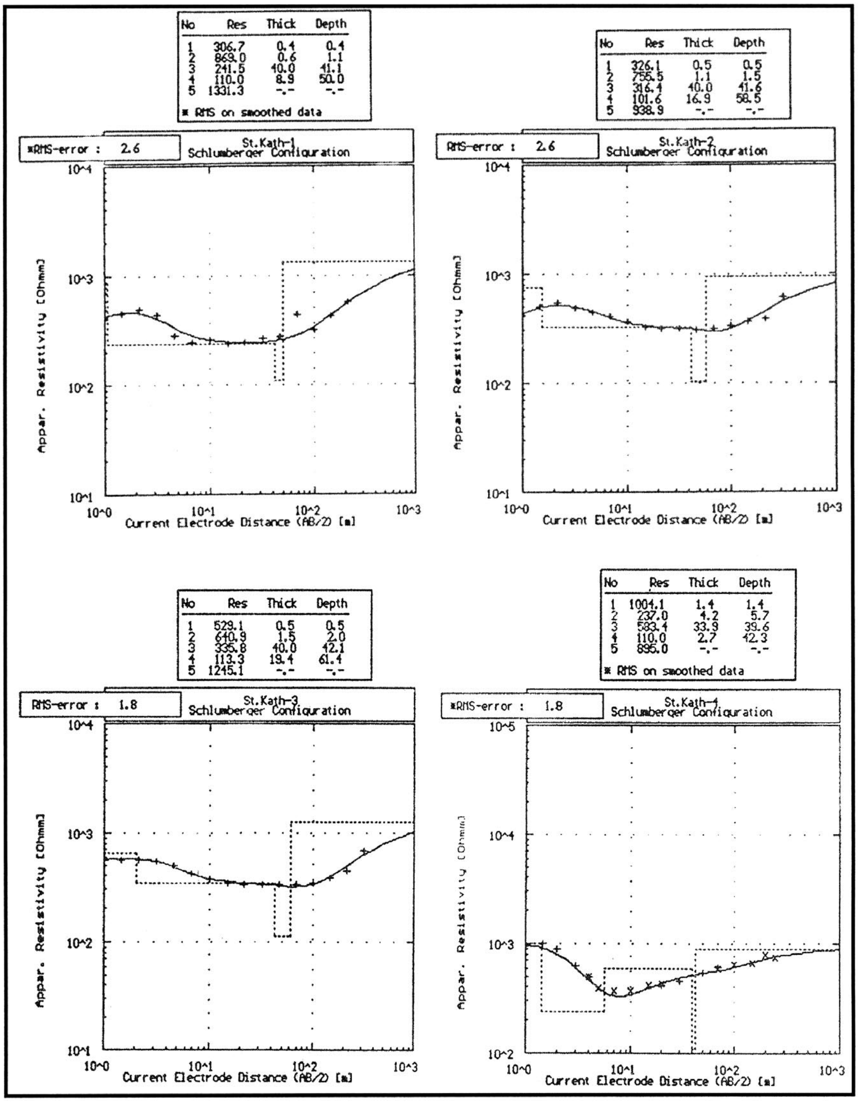

Fig. 10 a. Resistivity sounding field data and the calculated resistivity models of soundings (1, 2, 3 and 4).

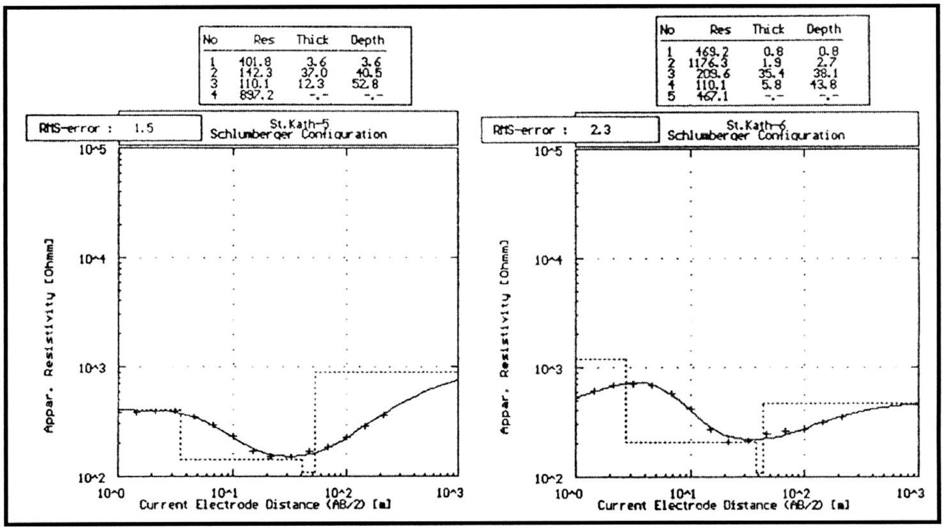

Fig. 10 b. Resistivity sounding field data and the calculated resistivity models of soundings (5 and 6).

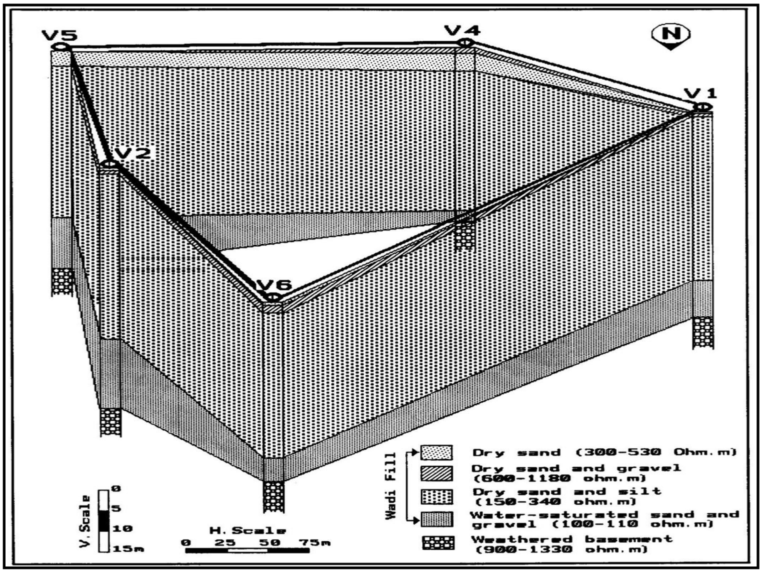

Fig. 11. Resistivity panel diagram for the interpreted resistivity models.

3. *Ground Magnetics*

A ground magnetic survey measuring the total intensity magnetic field, with accuracy of one gamma was conducted covering the examined area of the wadi, and comprising nine magnetic profiles with a total of 970 stations (Fig. 2). A close inter-station separation of two meters is used in most of the profiles to detail the subsurface configuration of the suspected dyke. The recorded field data were corrected for diurnal earth's magnetic field variations recorded by a magnetic base-station at a sampling interval of 2 min. The diurnally-corrected total intensity magnetic map (Fig.12a) features variable wavelength magnetic anomalies, especially the magnetic anomaly at the extreme northern corner of the mapped area is very close to the outcrop of the examined western dyke. Further, the short wavelength anomaly approximately at the centre of the map corresponds to the iron-work of the Zeitona well.

To decipher the nature of the variable wavelength magnetic anomalies, the total magnetic intensity map was deregionalized by removing a first-order regional (Fig. 12b) using Grav/Mag package (1995). The resulting residual magnetic map evidently demonstrates the absence of any anomalous magnetic bodies through the mapped area, except for the isolated magnetic anomaly close to the outcropping western dyke. The magnetic anomaly close to the Zeitona well is only represented by a feeble kink on the residual field.

For a more definite positioning of the suspected dyke, a Reduced-To-Pole (RTP) filter (Baranov, 1957 & 1975) was designed and applied to the total magnetic intensity map in Fig. (12a) and an RTP map was constructed (Fig. 12c). This map immediately reveals that, the eastern outcropping basic material is limited in extension to that surface exposure and does not have any extension into the examined part of the wadi. It also clearly demonstrates the isolated magnetic anomaly to the extreme northern corner of the mapped area, very close to the outcropping western dyke, with no anomalous magnetic bodies elsewhere through the mapped area. Further, the RTP anomaly has limited extension in an approximately E-W direction; *i.e*., away from the plane containing the two exposures. This rules out that, the two exposures belong to a single dyke crossing the examined part of Wadi El-Sheikh.

A magnetic profile, indicated by dashed line in Fig. (12a), was subjected to Analytical Signal processing and modelled using a 2½-D algorithm using the (Grav/Mag, 1995) software, that takes the end effect of limited strike length into consideration (Shuey and Pasquale, 1973). The analytical signal curve (Fig. 13a) shows a main peak indicating a location of contact. The obtained magnetic model (Fig. 13b) clearly features a vertical magnetic body (dyke) of limited spatial extension at the same location of the peaked analytical signal curve. This

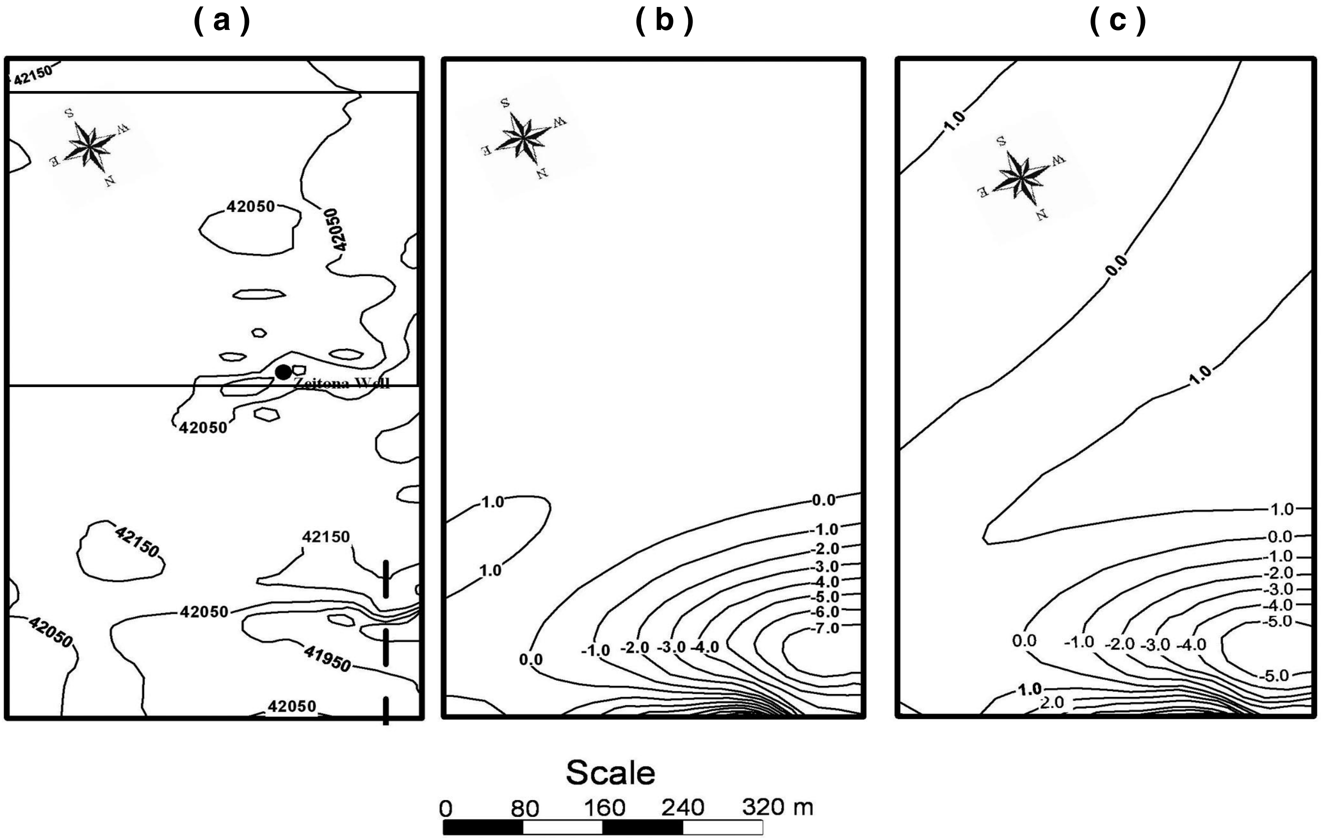

Fig. 12 a. Total magnetic intensity (dashed line indicate profile location), (b) First-order magnetic residual, and (c) RTP-magnetic maps.

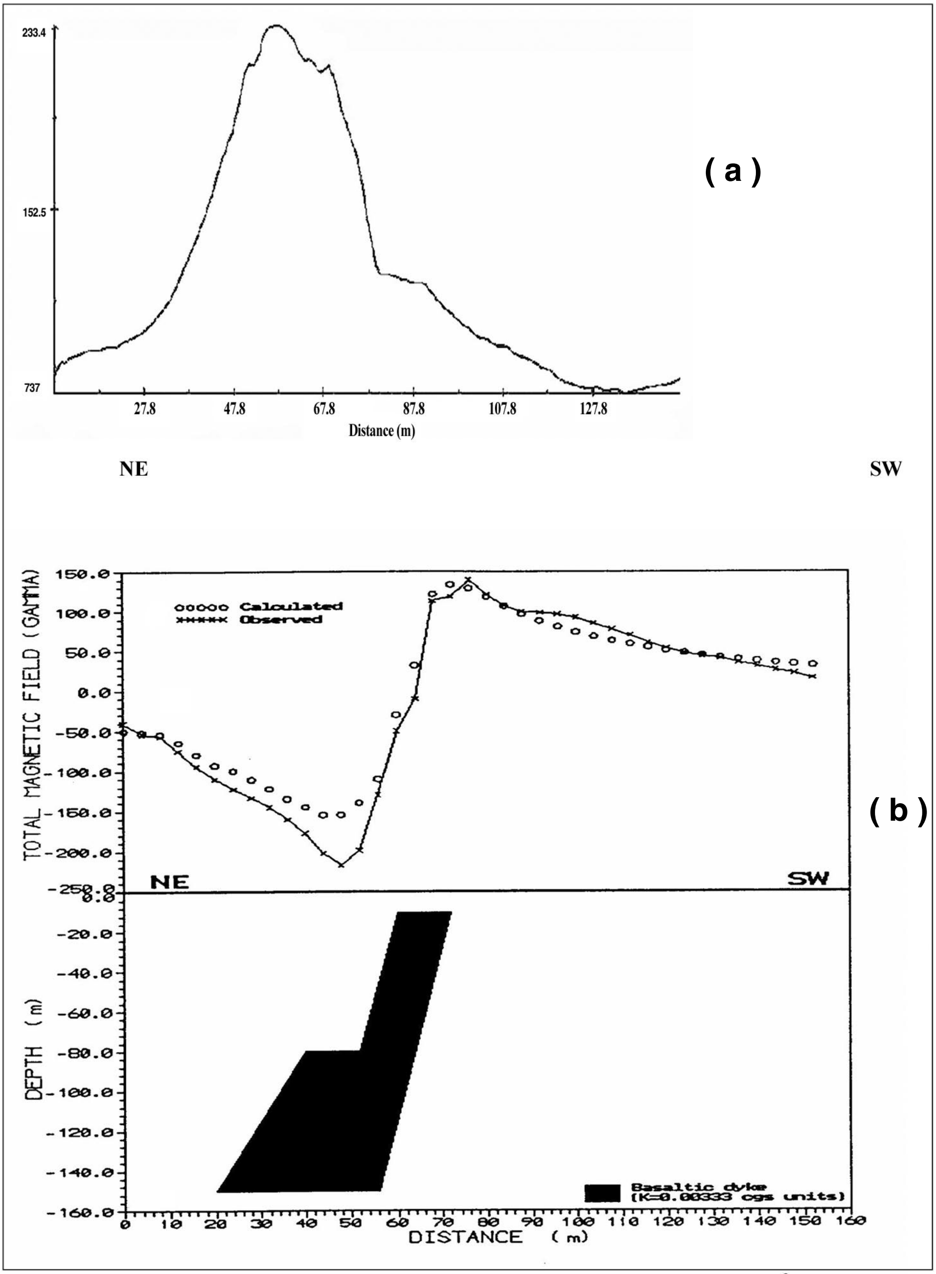

Fig. 13. Analytical signal analysis (a) and 2½-D magnetic model (b) for the magnetic profile shown in Fig. (12a).

dyke lies at a depth of about 10 m to the NE-direction and extends to a depth of about 155m.

An interesting and important feature of this dyke revealed by the magnetic modelling routine is that, its magnetization is essentially remnant and is 180 degrees out-of-phase with the present day earth's magnetic field. This feature is particularly important to the interpretation of magnetic surveys in the region, and in assessing the role of dykes in controlling the groundwater system in the area through magnetic-based age relations among the dykes frequently intersecting the groundwater aquifer in the area.

Summary and Conclusions

A multi-sensory geophysical survey was planned and executed integrating refraction seismics, resistivity sounding, and ground magnetics, to delineate a suspected buried dyke inferred from geological surface observations in a part of Wadi El-Sheikh, Southern Sinai. This deceivingly simple geologic setting and the injudicious choice and interpretation of geophysical data has led to misleading conclusions regarding the hydrogeologic setting of the groundwater aquifer all through wadi El-Sheikh.

The inversion of seismic refraction data has revealed the basic dyke material as having a high seismic velocity of about 3600 m/s extending not far from the western exposure and lying at a depth of about 9 m.

The resistivity sounding inversion indicated that, the aquifer is continuous across the wadi, as the water table ranges in depth from 38.1 to 42.1 m. with no evidence of obstruction by the supposedly buried dyke. This supports the seismic conclusions that, the exposed dykes are not connected underneath the examined part of Wadi El-Sheikh.

The 2½-D magnetic modelling routine demonstrated that, remnant magnetization should be duly considered in interpreting magnetic data in the area, as the modelled basic material possesses a remnant magnetization 180 degrees out-of-phase with the present day earth's magnetic field.

In conclusion, it can be emphasised that, magnetic results confirmed the seismic inferences in that, the depth of the dyke ranges between 9 and 10m with limited extension in the western side of the area. Also, a good agreement could be noticed between the magnetic findings and the geoelectric outputs that, the outcropping dykes are connected at deeper depths across the subsurface of the wadi. A 2½-D magnetic model, supported by analytical signal analysis, features a spatially limited extension of a high magnetic susceptibility basic material at a depth of 10m in the vicinity of the western basic exposure, and the absence of any such shallow extension close to the eastern basic exposure, in full agreement with the seismic and resistivity sounding conclusions. The integration of multi-geophysical approaches revealed that the dyke does not affect the groundwater flow in the study area and, therefore, it is shown effective in subsurface hydro-geophysical studies.

References

Aubert, M., Camus, G. and **Fournier, C.** (1984) Resistivity and magnetic surveys in groundwater prospecting in volcanic areas-Case history Maar de Beaunit Puy de Dome France, *Geophys. Prosp*., **32:** 554-563.

Baranov, W. (1957) A new method for interpretation of aeromagnetic maps: pseudo-gravimetric anomalies, *Geophys*., **22:** 359-383.

Baranov, W. (1975) Potential Fields and their Transformations in Applied Geophysics, *Geoexploration Monographs, Series* **1-6**, Gebrueder Borntraeger, Berlin.

Dames. J. and **Moore. R.** (1982) *Sinai Development Study, Phase I*, Final Report: Submitted to the Advisory Committee for Reconstruction, Ministry of Development, A.R.E., in association with Industrial Development Programmes SA.

Edge, A.B. and **Laby, T.H.** (1931) *The Principles and Practice of Geophysical Prospecting*, Cambridge University Press.

El-Behiry, M.G. (1994) Seismic Refraction and Electromagnetic Methods for Mapping Confining Layer in Central New Jersey, USA: SAGEEP, *Ann. Metg., Boston, USA.*

El-Shazly, H., Mohamed, S., Abdel Latif, T., Hisak, R. and **Habrouk, H.** (1985) Groundwater potential of St. Katherine Monastery environs, Sinai, Egypt, *Egypt. J. Geol*., **29** (1-2): 89 - 100.

Frohlich, R.K. (1974) Combined geoelectrical and drill-hole investigations for detecting fresh water aquifers in northwestern Missouri, *Geophys.*, **39** (3): 340-352.

Grav/Mag (1995) *Grav/Mag Interpretation Package*, Geosoft Inc., Toronto, Canada.

Hosney, H. (1991) Detailed seismic refraction and resistivity measurements around a dyke in St. Katherine area, Southern Sinai, Egypt, *Ain Shams Science Bull*., **28B:** 491-512.

Information Technology Center (ITC) (1988) *M. Sc*., *Research Project*, Delft, The Netherlands.

McGinnis, L.D. and **Kempton, J.P.** (1961) Integrated, seismic, resistivity, and geologic studies of glacial deposits, *Illinois State Geol. Surv., Circular*, **323:** 23.

Mills, A.C. and **Shata, A.** (1989) Groundwater assessment of Sinai, Egypt, *Ground Water*, **27** (6): 793-801.

Pa1mer, D. (1986) Refraction Seismics, *In:* Helbig K. and Treitel S. (ed's), *Section I: Seismic Exploration*, 13, Geophysical Press, London.

Paver, G.L. and **Jordan, L.N.** (1956) Report of Ministry of Public Works on Reconnaissance, Hydrological and Geophysical Observations in North Sinai Coastal Area of Egypt, *Desert Institute, Cairo. Publication no.7.*

Pavlov, H. and **Ayuty, H.** (1961) *Groundwater of the Sinai Peninsula*, Report to the General Director of the General Desert Development Authority, Cairo.

Shata, A., El-shazly, H., Diab, H., Abdel Latif, T. and **Tamer, H.** (1978) *Preliminary Report on the Groundwater Resources in the Sinai Peninsula, Egypt, Parts I and II*, Desert Institute, Water Resources Dept., Cairo.

Shuey, R.T. and **Pasquale, A.S.** (1973) End corrections in magnetic profile interpretation, *Geophys.*, **38** (3): 507-512.

Taha, A.H. (1968) Geology of the Groundwater Supplies of El Arish-Rafaa Area (North East Sinai, U.A.R.), *M.Sc. Thesis*, Cairo University.

Van Overmeeren, R.A. (1981) A combination of electrical resistivity, seismic refraction, and gravity measurements for groundwater exploration in Sudan, *Geophys*., **46:** 1304-1313.

Wolfe, P.J. and **Richard, B.H.** (1991) Integrating geophysical techniques to study a small confined aquifer, *8th Aust. Soc. Expl. Geophys. Conf., Paper No.2*, **91:** 457-460.

مسح جيوفيزيائى متعدد الوظائف لمعرفة دور قواطع الصخور النارية في التحكم بالخزان الجوفي بمنطقة سانت كاثرين، سيناء، مصر

محمد جميل البحيري، و محمد عبد المنعم الدفراوي
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المستخلص. يبين هذا البحث نجاح التكامل بين الطرق الجيوفيزيائية (السيزمية الانكسارية والمغنطيسية الأرضية والسبر الكهربائي) لمعرفة الوضع الحقيقي للخزان الجوفي الواقع بوادي الشيخ بجنوب سيناء، مصر. ساد في السابق اعتقاد خاطىء بأن مستوى المياه الجوفية واتجاه سريانها بهذا الخزان الجوفي، والذي تحده صخور قاعدة جرانيتية، يتحكم بها سلسلة من القواطع الصخرية التي تتواجد بعرض الوادي. هذا الاعتقاد الخاطىء كان مبنيا على الملاحظات الجيولوجية السطحية إلى جانب الاختيار غير الموفق لطرق تفسير البيانات الجيوفيزيائية.

في هذا البحث ، تمت معرفة الخواص الجيوفيزيائية العالية القيمة (السرعة السيزمية والقابلية المغنطيسية والمقاومة الكهربائية) للقواطع الصخرية القاعدية، بالمقارنة بخواص الرسوبيات التي تملأ الوادي. تم ذلك عن طريق تفسير سبعة بروفيلات سيزمية انكسارية، باستخدام طريقة مقلوب الوقت، وتسعة بروفيلات مغنطيسية أرضية متقاربة المسافات البينية، باستخدام نمذجة مغنطيسية ذات البعدين ونصف، بالإضافة إلى سبعة جسات للسبر الكهربائي باستخدام طرق تحول أوتوماتيكية.

أفضى التفسير المتكامل للنتائج الجيوفيزيائية إلى نتيجة هامة، مفادها وجود القواطع الصخرية الظاهرة على السطح والقاطعة للوادي على أعماق كبيرة وهى بذلك تحد رسوبيات الوادي من أسفل. وهذا يؤدى إلى استنتاج خلاصة هامة هي أن هذه القواطع لا تلعب أي دور في الشكل العام للخزان الجوفي ولا تسيطر على اتجاه سريان المياه الجوفية في المنطقة المدروسة من وادي الشيخ.