

Outline of The Ground Water Occurrences Beneath the area Around Ain Zubida by Integration of Magnetic, Electrical Resistivity Sounding, and Seismic Refraction Methods

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ABSTRACT. Ain Zubida lies in Wadi Numan east of Arafat, Makkah Al-Mukarramah, K.S.A. The study area is located between latitudes 21°17'-21°24'N and longitudes 40°00'-40°10'E. Wadi Numan discharges its water to the Red Sea. The area under investigation forms a part of the Arabian Shield of the Western Saudi Arabia. Accordingly, igneous and metamorphic rocks cover the study area. In the upstream of Wadi Numan, the escarpment is a conspicuous structural feature; besides, major and minor faults are dominant in Wadi Numan and adjacent areas.

The aim of this study is to define the distribution of ground water around Ain Zubida, and to select suitable locations for drilling exploratory wells. Therefore, the integration among ground magnetic, resistivity and seismic refraction methods is used to obtain the most useful results.

The ground magnetic survey conducted along eight profiles across Wadi Numan indicates that the depth of basement rocks in the area under investigation ranges between 25 and 121 m. The magnetic method was also used to define the main structural zones and the relatively thick sedimentary cover which affect the ground water distribution.

The vertical electrical sounding survey was conducted at 62 sites. This survey led to classifying the alluvium covering the basement rocks, according to its resistivity values, into two layers. The upper layer has relatively high resistivity values and the lower has relatively low values. This latter is expected to be water-saturated.

The seismic refraction method was used at three selected sites to emphasize the structures, layering and water saturation at those sites. The present study revealed the presence of a graben structure in Wadi Numan. This structure acts as a channel stream of water accumulation. Accordingly, this study suggests a number of suitable locations for exploratory drilling.

Introduction

Ain Zunida lies in Wadi Numan east of Arafat, Makkah Al-Mukarramah, K.S.A. The study area is located between latitudes 21°17'-21°24'N and longitudes 40°00'-40°10'E. The main access to the area is through Makkah-Mina and Arafat highways. Wadi Numan discharges its water to the Red Sea (Fig. 1).

The area under investigation forms a part of the Arabian Shield in Western Saudi Arabia. Except for the strips occupied by wadis, the study area is covered by igneous and metamorphic rocks (Brown *et al.*, 1963). In the upstream of Wadi Numan, the escarpment is a conspicuous structural feature. Major and minor faults dominate the escarpment, as well as, the adjacent areas. Figure (2) shows the main topography of the area under study. Wadi Numan is surrounded by a number of mountains composed of igneous and metamorphic outcrops. These crops are impervious in nature, but they are intensively jointed, brecciated and faulted. These fractures and fissures act as conduits which control the rainfall water to flow through Wadi Numan, while the impervious basement rocks underneath the alluvium cover of the Wadi are considered as surfaces preventing downward percolation of water. The alluvial deposits capping the basement rocks are composed of sand and gravel alternating with silts to boulders and represent the main aquifer within Wadi Numan.

The present study is a part of a main project, which is currently being conducted by the King Abdulaziz University for the reconstruction and development of the ancient Ain Zubida. The aim of this study is to define the distribution of the ground water around Ain Zubida and to select suitable locations for drilling a number of exploratory wells whose locations are critical for aquifer parameter determination. Therefore, the integration among ground magnetic, resistivity, and seismic refraction methods is used to obtain the most useful results.

Geophysical Field Surveys and Data Processing

The Total Magnetic Intensity Method

According to the geology of Wadi Numan, this area consists of different types of rock units with different properties. Each of these rock units has a special magnetic character. In addition, the subsurface structural features, faults,

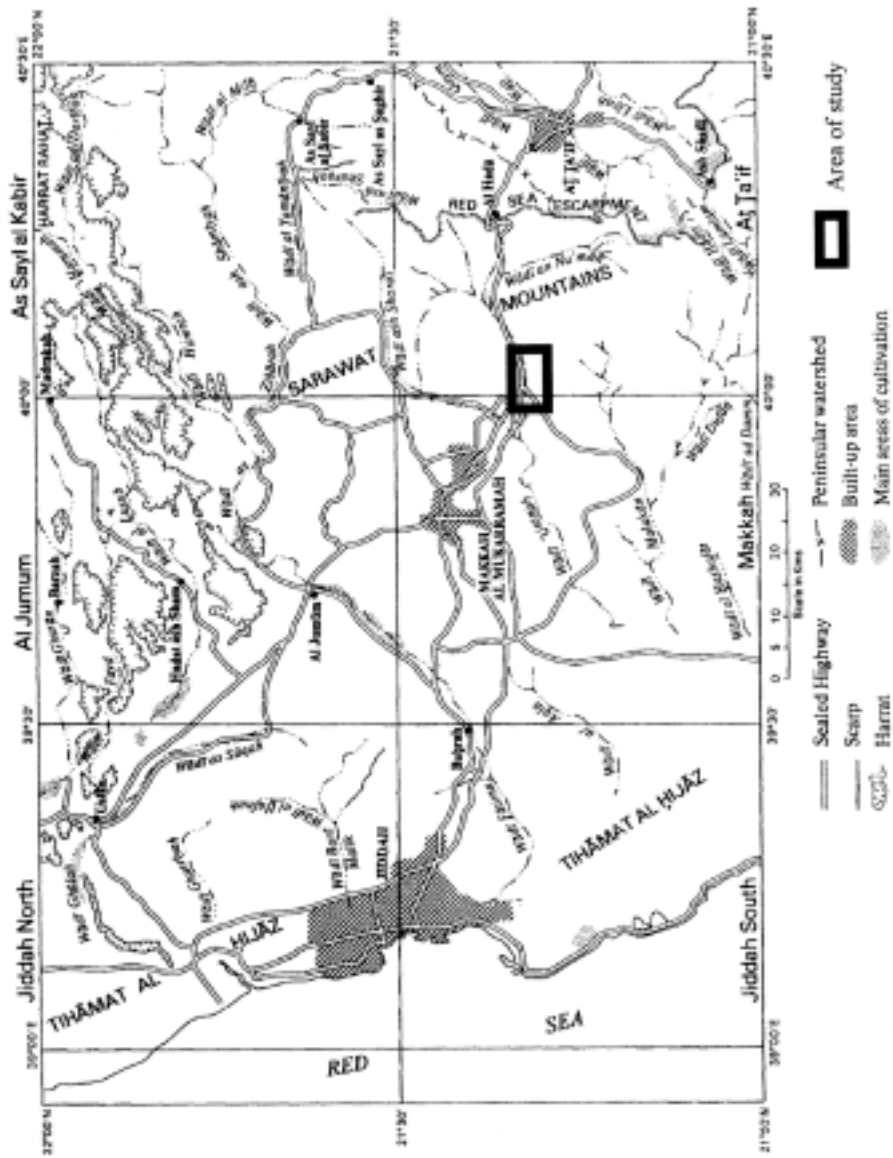


FIG. 1. Location map of the study area.

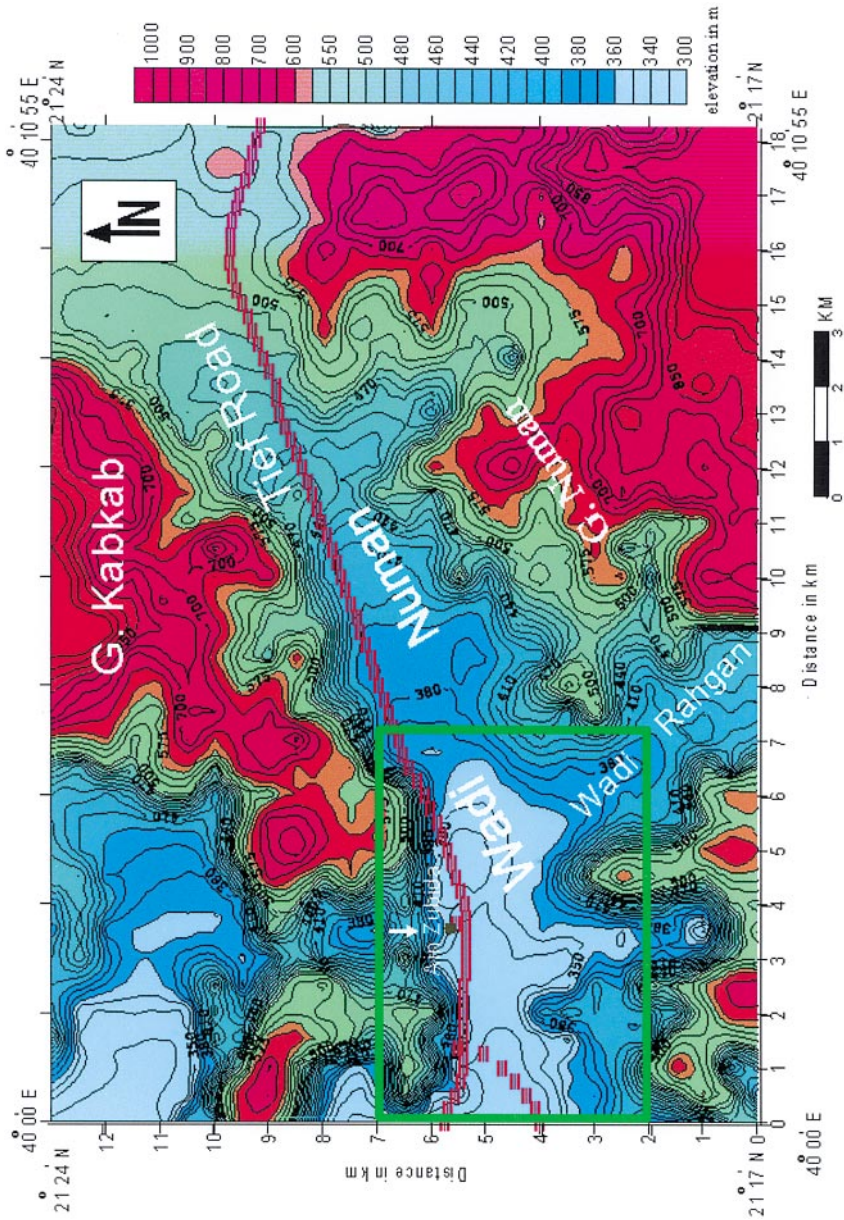


FIG. 2. Topographic map of Wadi Numan.

 The study area (Fig. 3)

fractures, and dykes, also have distinctive effects on the total magnetic field. Therefore, the main purpose of the magnetic survey is to explore the subsurface structural features along selected profiles.

The total magnetic intensity field survey was conducted along eight profiles extending from south to north across Wadi Numan strike. These profiles are coded 500, 600, 700, 800, 900, 1000, 1100 and 1200 (respectively from W to E, Fig. 3). The proton precision magnetometer model Envi-Mag, Scintrex, Canada, was used. This is a portable magnetometer that can also be used as “base station” magnetometer; its accuracy is about 0.1 nT. The field measurements were reduced and plotted as magnetic profiles.

As a result of the total magnetic intensity survey, eight profiles are presented. Each of these profiles, as shown in Figure (4), indicates that the sources of the anomalies beneath the ground surface along the eight profiles are located at various depth levels. Therefore, the frequency analysis technique (Sadek, 1987) was applied to determine the different average depths of these magnetic anomalies. The frequency analysis curve (Fig. 5) exhibits two straight line segments, indicating that the magnetic anomalies are generated at two average depth levels; namely, 25 m and 121 m, beneath the ground surface of Wadi Numan area. According to these results, the anomaly sources beneath the area under study are classified as; regional anomalies (deep-seated) located at 121 m average depth; and residual anomalies (shallow or near-surface anomalies) located at 25 m average depth. To isolate the magnetic response of each of these anomaly groups, matched filtering (Sadek, *et al.*, 1984) was applied using a special window designed according to the parameters determined from the frequency analysis curve of Figure (5). This window is used to calculate the regional magnetic component of each input total magnetic intensity measurement. The residual magnetic component was calculated by subtracting the regional magnetic component from the original total magnetic intensity value. Accordingly, Figures (6) and (7) show the residual and the regional magnetic component stacked profile maps, relatively.

The Vertical Electrical Sounding Method

The vertical electrical sound survey (VES) was conducted using the Schlumberger array at 62 sites distributed along eight south-north (S-N) trending profiles (Fig. 3). The VES specifications were selected as seven measurements per decade to obtain reasonable data continuity, while half current electrode spacing (AB/2) range from 1 m to 300 m. These specifications allowed considerable depth penetration beneath each sounding site. The survey equipment used was a modern 1200 Watts D.C. resistivity-meter, model ELREC-T (IRIS-instruments, France).

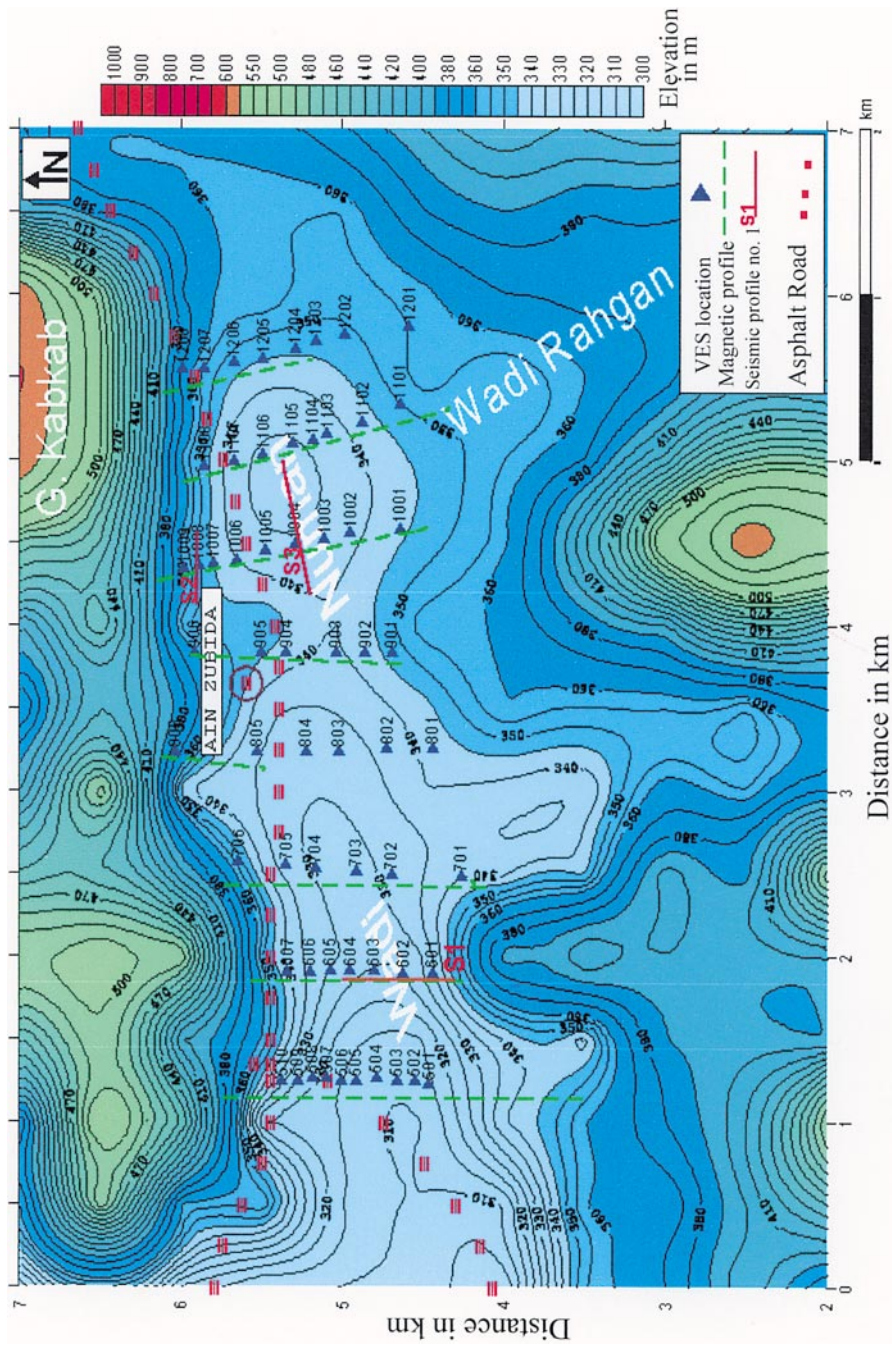


FIG. 3. Topographic map of the study area showing the location of magnetic, electrical sounding and seismic surveys.

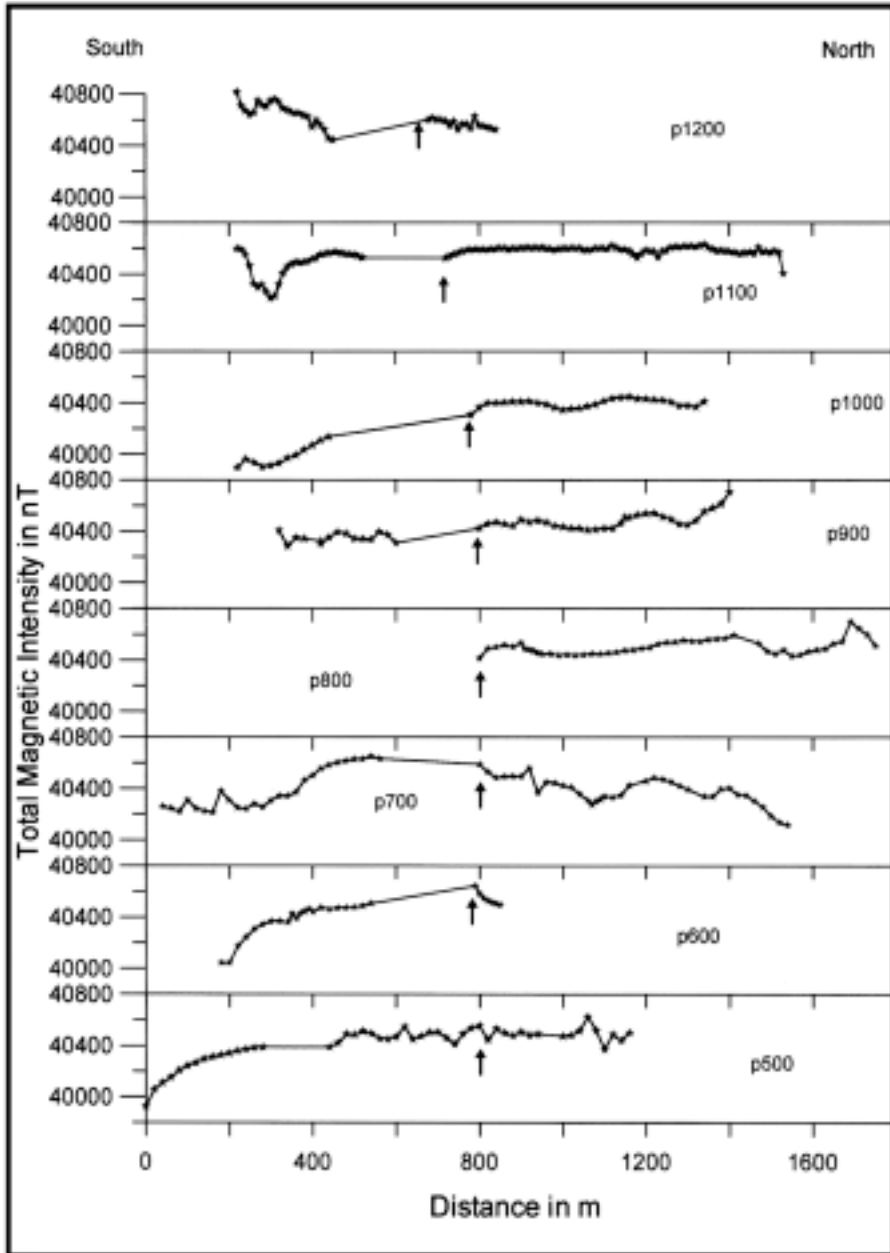


FIG. 4. Total magnetic stacked profile map. Vertical arrow indicates the location of paved road.

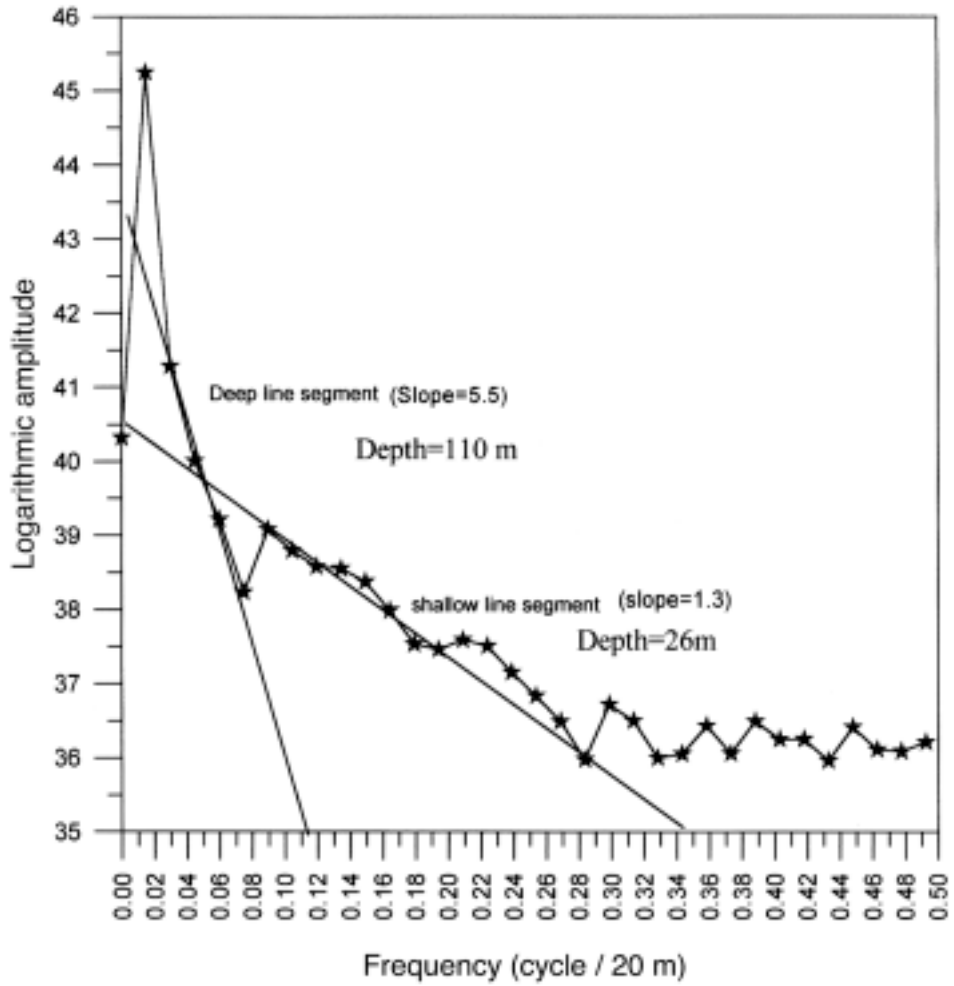


Fig. 5. Frequency analysis curve of the magnetic data.

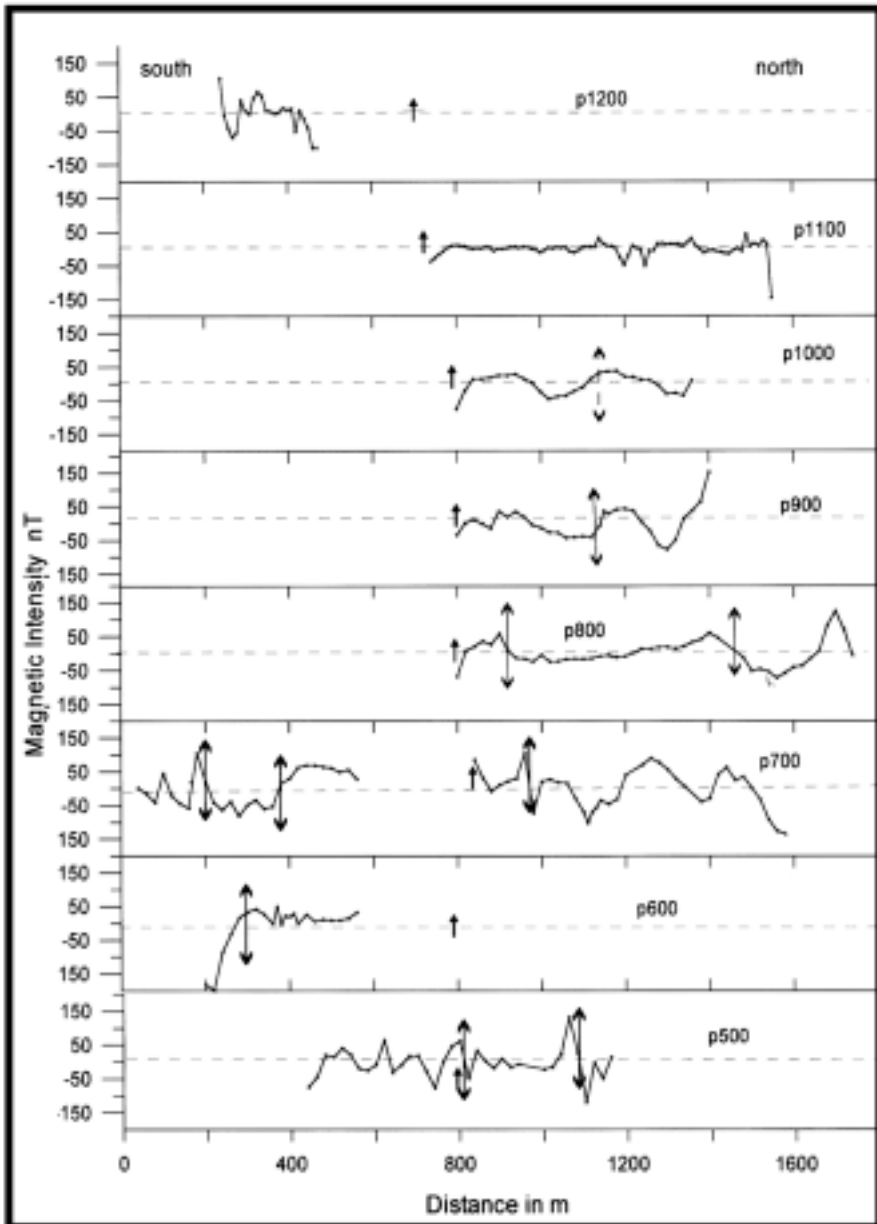


FIG. 6. Residual magnetic component (shallow) stacked profile map.
Vertical arrow indicates the location of paved road.

Structure trace

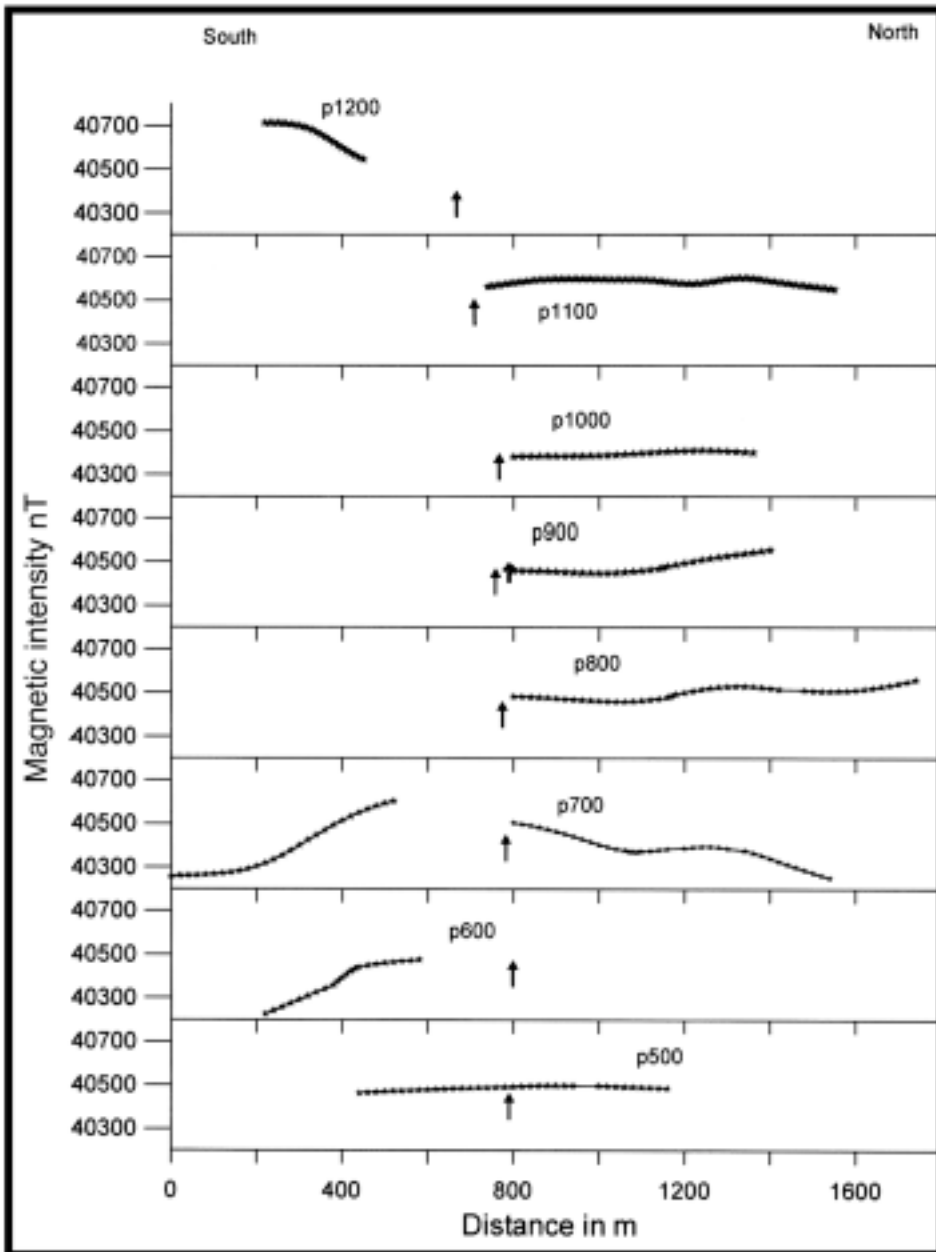


FIG. 7. Regional magnetic component stacked profile map. The vertical arrow indicates the location paved road.

The collected raw (field) measurements, (Fig. 8a), were reduced and analyzed, and each vertical electrical sounding curve was first compiled to describe the apparent resistivity (ρ_a) from its different segments. The continuous sounding curve was then smoothed and digitized to produce a six (ρ_a) readings per decade at half the electrode spacing. The digitized data of the reduced field curve was inverted using the inversion technique developed by Zohdy (1975) to obtain an equivalent-layer model (n-layered model; (Fig. 8b)).

The n-layer models of the different soundings were then used to construct the subsurface true resistivity contour section (SRCS) along each of the eight profiles (Figs. 9 to 16). The contoured values represent the logarithmic values of the resistivity.

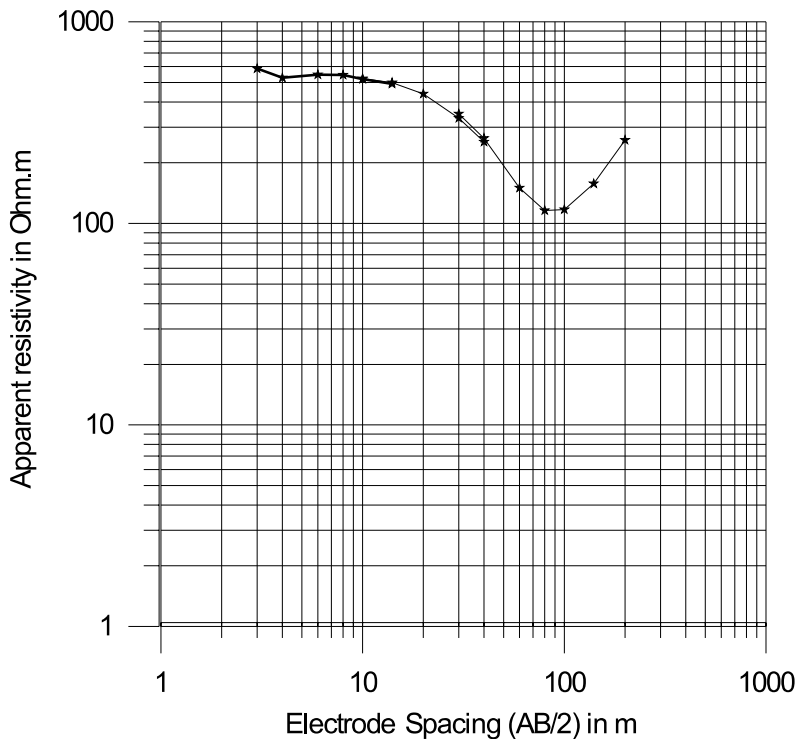


FIG. 8a. Vertical electrical sounding field (VES-1006) curve.

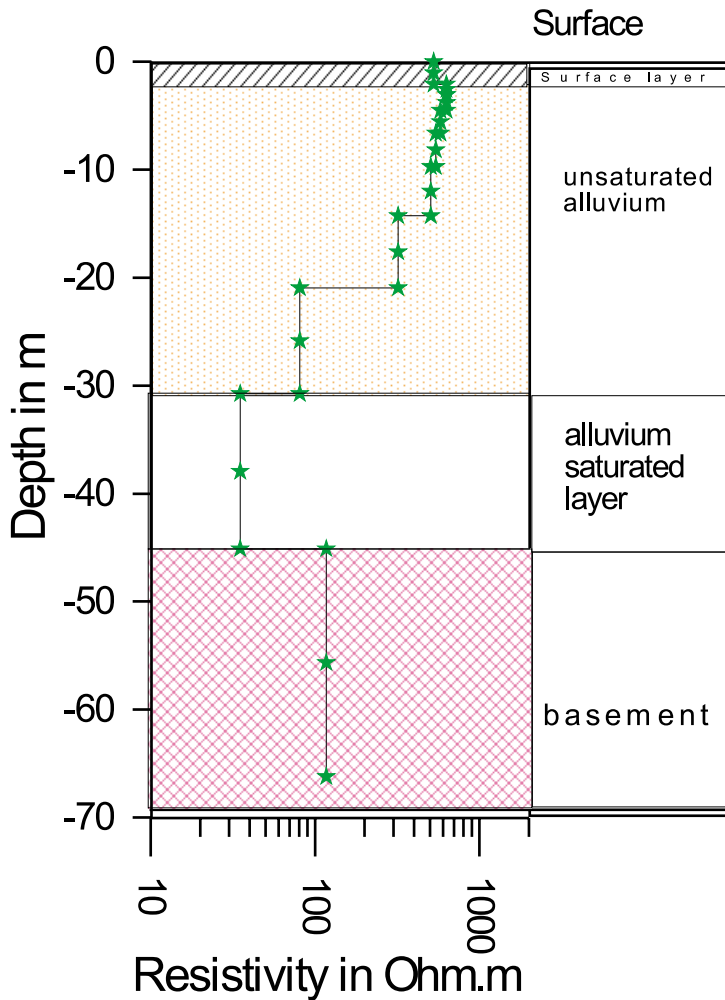


FIG. 8b. The interpreted model of layering as obtained after data analysis and processing (VES-1006).

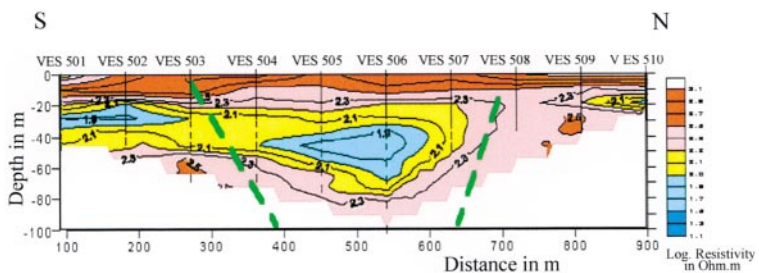


FIG. 9. Subsurface resistivity contour section (SRCS) across profile 500, Wadi Numan.

The Seismic Refraction Method

The seismic refraction technique is more suited for shallow investigations, particularly in engineering and hydrogeological applications. Therefore, it is used in the present study to provide information concerning the velocities of elastic waves and to determine the depth (shape) of bedrock and, to some extent, the lithology of inferred refractors (*e.g.*, Sheriff and Geldart, 1982; and Haeni, 1986).

The seismic refraction technique furnishes a convenient approach to the *in-situ* determination of P-wave seismic velocity in rocks which depends on several factors, including porosity, lithology, depth of burial, pressure regime, interstitial fluids, ..., etc. (*e.g.*, Sheriff and Geldart 1982).

In the present study, the sediments are in the form of channels filled with silt, sand and gravels overlying the basement rocks. As the velocity in the water-saturated sediments (about 1.5 km/sec) is generally higher than in dry sediments (generally less than 1.0 km/sec), their contact should act as a good refractor. Based on the foregoing arguments and on the magnetic and geo-electrical findings, we decided that the seismic refraction technique would be effective in determining the thickness of the sediments and, consequently, the irregularity of the basement surface which is of considerable hydrogeological value. Besides, at the expected relatively shallow depths of concern, the seismic technique possesses a superior spatial resolving power and is less ambiguous than either the magnetic or the resistivity techniques.

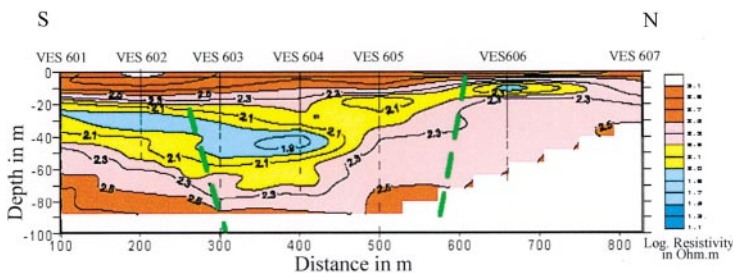


FIG. 10. Subsurface resistivity contour section (SRCS) across profile 600, Wadi Numan.

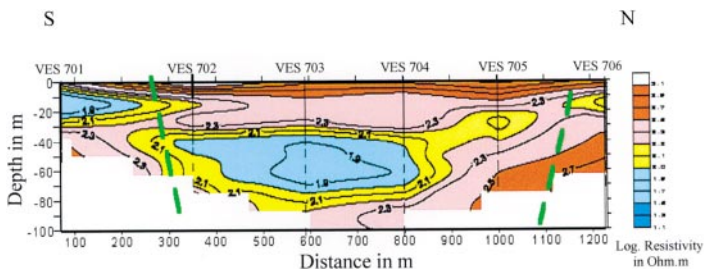


FIG. 11. Subsurface resistivity contour section (SRCS) across profile 700, Wadi Numan.

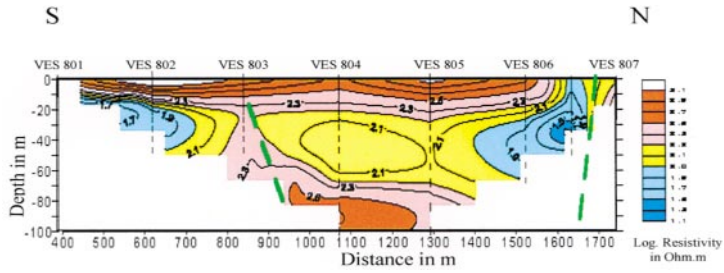


FIG. 12. Subsurface resistivity contour section (SRCS) across profile 800, Wadi Numan.

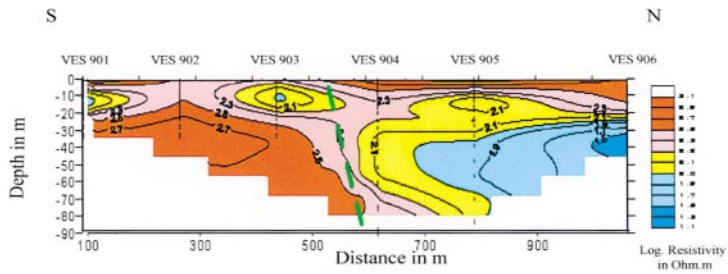


FIG. 13. Subsurface resistivity contour section (SRCS) across profile 900, Wadi Numan.

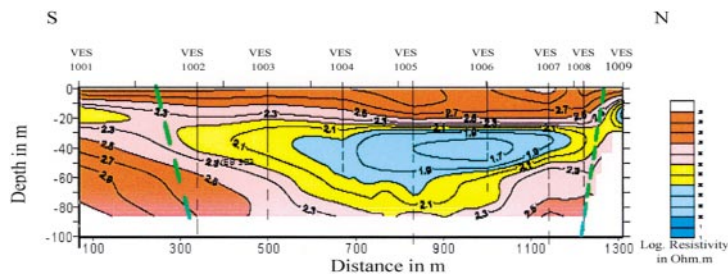


FIG. 14. Subsurface resistivity contour section (SRCS) across profile 1000, Wadi Numan.

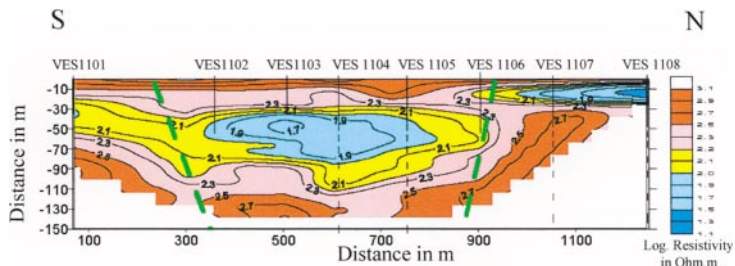


FIG. 15. Subsurface resistivity contour section (SRCS) across profile 1100, Wadi Numan.

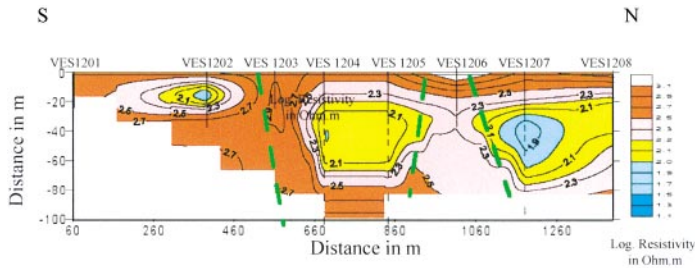


FIG. 16. Subsurface resistivity contour section (SRCS) across profile 1200, Wadi Numan.

The seismic recording system used in the present study was the Bison-7024 digital instrument floating-point (DIFP) signal-stacking seismograph. It is a 24-channel seismic data acquisition system (Bison 7000 series, 1990). Vertical component geophones were used to pick up P-wave arriving at the earth's surface. A 7 kg sledgehammer and an elastic wave generator (EWG-II), with 250 kg dropping weight, were used for P-wave generation.

Three locations were selected for conducting the seismic survey (Fig. 3) based on the results and recommendations of the magnetic and resistivity surveys. The first seismic profile (S1) was 450 m long (oriented S to N) and was conducted along the southern part of profile 600 (Fig. 3) passing through VES 601 through VES 604. The second seismic profile (S2) extended 380 m from E to W. It intersects profile 1001 at the location of VES 1007. The third profile (S3) was conducted south of the Makkah-Taif road (Fig. 3). This profile extended 860 m west to east and intersects profile 1000 at VES 1004.

The seismic refraction data acquired in the present investigation were inverted using the seismic refraction inversion software "SIPT-2" (Rimrock Geophysics Inc., 1993). The inversion algorithm uses the delay-time method (Pakisier and Black, 1957) to obtain a first approximation depth model. It is then trimmed up by a series of ray tracing and model adjustment iterations to minimize the discrepancies between the field measured arrival times and the corresponding times traced through the 2-¹/₂-D cross sectional depth model (Scott *et al.*, 1968; and Scott and Markiewicz, 1990).

The interpreted subsurface sections underneath the three seismic profiles are shown in Figures (17 to 19) depicting the respective subsurface structures and the associated seismic velocities which can be used to infer lithological and saturation conditions.

Interpretation of The Results

Interpretation of Magnetic Data

The integrated interpretation of the total magnetic intensity stacked profile map (Fig. 4), the regional magnetic component stacked profile map (Fig. 7) and

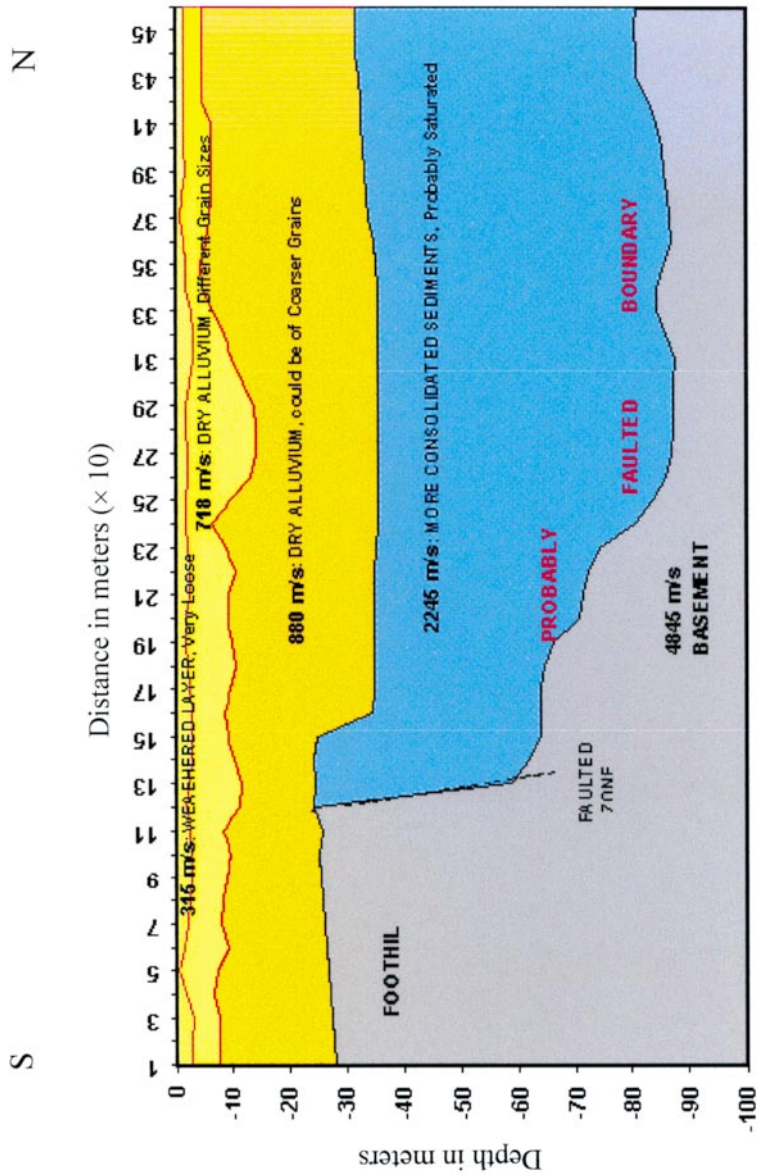


FIG. 17. Seismic refraction profile (S1); along profile 600.

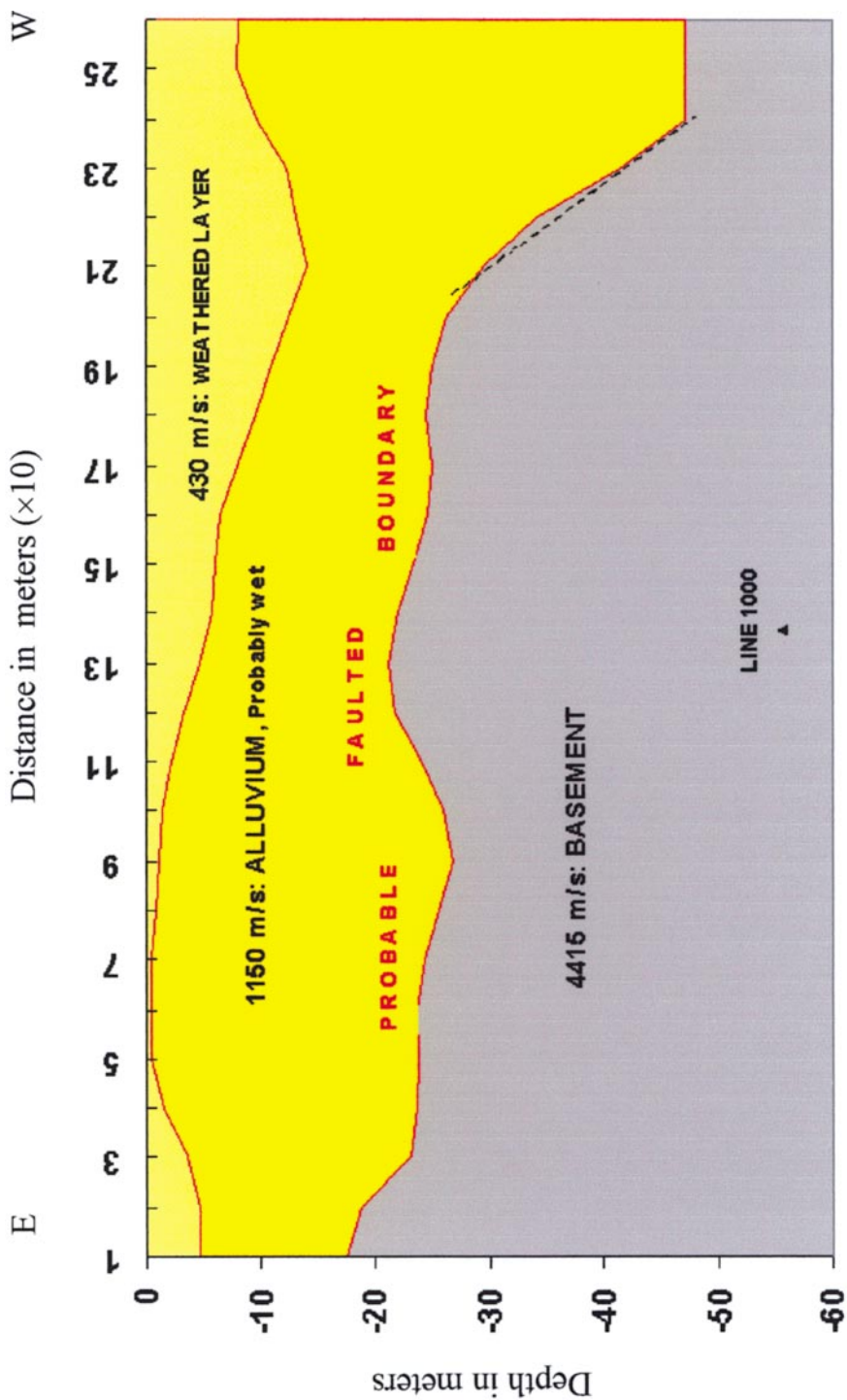


FIG. 18. Seismic refraction profile S2 (E to W); perpendicular to the northern side of profile 1000.

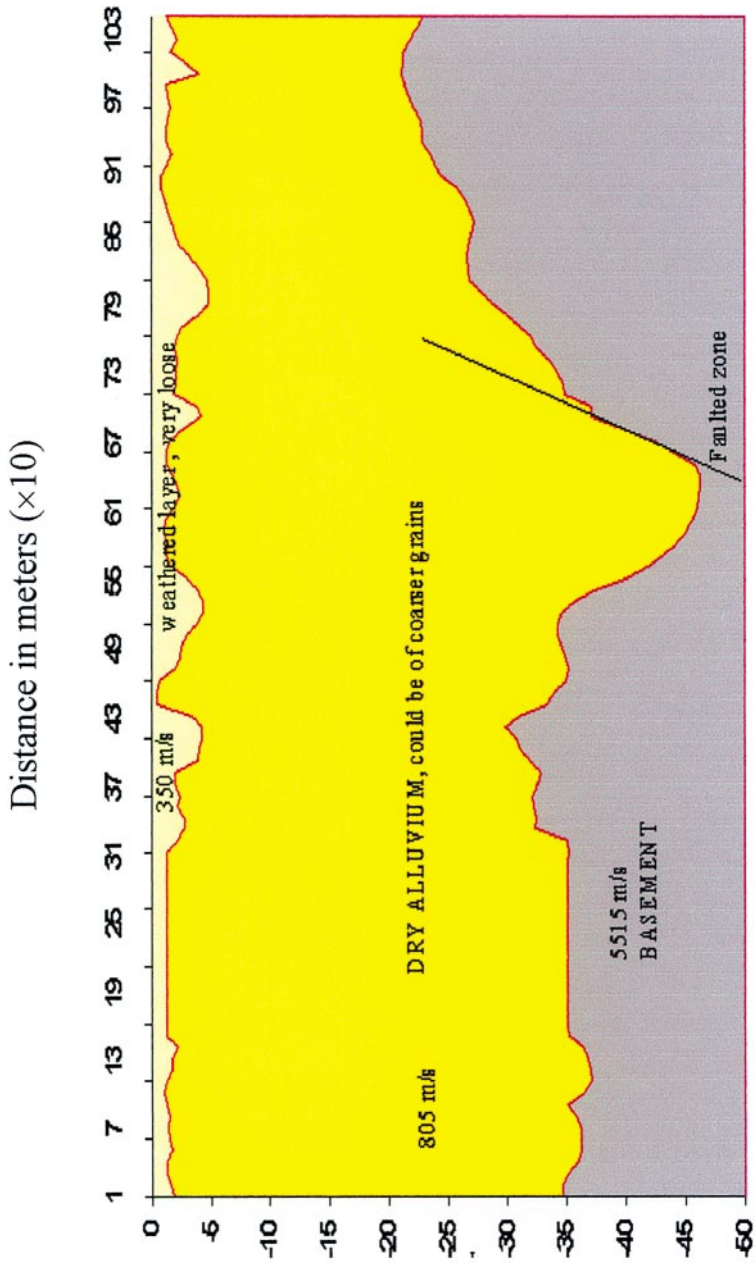


FIG. 19. Seismic refraction profile (S3); perpendicular to the southern side of profile 1000.

the residual magnetic component stacked profile map (Fig. 6) identifies a number of characteristic magnetic zones. These zones are distributed along each profile with different amplitudes and frequencies. In addition, the correlation of the magnetic characters among the profiles indicates that the area can be classified into three different structural zones. The first zone is represented by the area which includes profiles 500, 600 and 700, while the second zone is represented by the area of profiles 800 and 900. The third zone is the area which includes profiles 1100 and 1200. The average magnetic intensity values along each profile are distinctively different. The values along profiles 500, 600 and 700 are 40414, 40415 and 40388 nT, respectively. The values along profile 800 reach up to 40500 nT. On the other hand, the measurements decrease gradually along profiles 900 and 1000, where the values are 40441 and 40275 nT, respectively. Again, the values increase to reach 40553 and 40617 nT along profiles 1100 and 1200, respectively. These variations in magnetic features indicate that the subsurface geological structural setting of Wadi Numan is variable and that the main causative source of magnetic anomalies is the structural relief features of the basement rocks.

The frequency analysis of magnetic data has isolated the high frequency magnetic anomalies as generated by the shallow basement surface at a depth approximately of 25 m from the lower frequency anomalies caused by a basement surface depth (sediment thickness) approximately of 121 m.

Therefore, the present discussion indicates that the magnetic method can be used, in similar sites, in outlining structural zones controlling ground water distribution, as well as, the relative thickness of the sedimentary cover which is the main target in hydrogeological studies.

Interpretation of Vertical Electrical Sounding (VES) Data

The variations in the measured electrical resistivity may, in general, be used to differentiate the subsurface into different characteristic zones of different lithologies and water content. In fact, the careful examination of the subsurface resistivity contour sections (Figs. 9-16) does provide details of the subsurface lithology, structural setting and potential ground water occurrences.

The subsurface resistivity contour section SRCS-500 (Fig. 9) reveals that the thickness of the unconsolidated sediments, overlying the basement rocks, beneath VES locations 501, 502, and 503 is almost 30 m. The thickness of these sediments increases beneath VES locations 504, 505 and 506 to reach 45 m, 50 m and 56 m, respectively. The thickness generally decreases again under VES locations 507, 508, 509 and 510 to reach 32 m, 23 m, 16 m and 18 m, respectively. The upper layer of these unconsolidated sediments is characterized

by its high resistivity (ranging between 394 and 1195 Ohm.m). This layer was recorded in all SRCS's and is underlain by another lower resistivity layer (ranging between 83 and 121 Ohm.m). The latter layer is most probably fully or partially saturated with water.

The resistivity contours of the section indicate that Wadi Numan is affected by two E-W trending faults. One of these faults is observed in the southern side of the Wadi (between VES locations 502 and 503) dipping to the north. The second fault, dipping to the south, is observed at the northern side of the Wadi (between VES locations 503 and 504). This structural criterion indicates that Wadi Numan might represent a graben structure. If this was the case, then the second layer of the unconsolidated sediments might horizontally (laterally) be divided into three zones denoted as A, B and C (Fig. 20). Zones A and C are shallower than zone B. Under these structural and geophysical conditions, zone B might be considered the most significant zone for ground water exploration and, consequently, the suitable sites for drilling exploratory wells would be at VES locations 505 and 506.

The above speculated structural-geophysical subsurface model is indeed exhibited through the remaining subsurface resistivity contour sections, as evidenced by examining Figures (10 through 16). The fact that zone C is either missing or not recorded along the SRCS-800 (Fig. 12), SRCS-900 (Fig. 13), and SRCS-1200 (Fig. 16) does not contradict the inferred subsurface model, however.

Thus, supporting the magnetic findings, the geoelectrical interpretation indicates that Wadi Numan represents a graben structure. Further, based on the obtained subsurface model, the suitable sites for drilling exploratory wells are: VES locations 505 and 506 (Fig. 9); VES location 604 (Fig. 10); VES location 703 (Fig. 11); VES location 807 (Fig. 12); VES location 906 (Fig. 13); VES locations 1005 and 1006 (Fig. 14); VES locations 1103 and 1104 (Fig. 15); and VES location 1207 (Fig. 16).

Interpretation of Seismic Refraction Data

The subsurface section (Fig. 17), obtained from the seismic refraction measurements made at the first site S1 (Fig. 3), shows that four sedimentary layers overly the basement. The upper three layers have low seismic velocity ranging from 315 to 880 m/sec, respectively, with a total average thickness of 30 m. These values of velocity indicate dry, unconsolidated material with different grain sizes (alluvium). Whereas, in the southern 120 m of the profile, this dry formation directly overlies the basement (velocity 4845 m/sec). In the northern part of the profile, the basement rocks is covered by another sedimentary layer

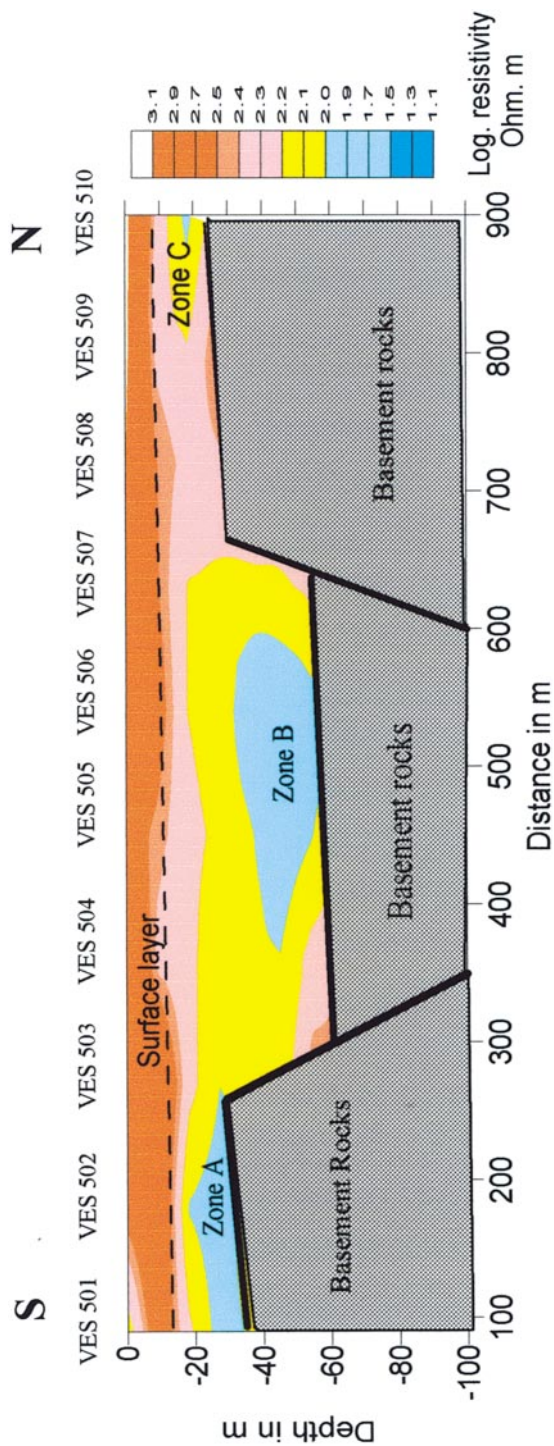


FIG. 20. Sketch of graben structural feature interpreted from geoelectric cross-section across profile 500.

of seismic velocity in the order of 2245 m/sec and an average thickness of 55 m. The seismic wave velocity of this layer confirms the result of SRCS-700 that this layer is probably water saturated. Accordingly, the thickness of the sedimentary cover ranges between 30 m and 85 m. The seismic section also supports the existence of an E-W trending fault with a vertical displacement of about 30 m and apparently dipping to the north.

The subsurface section (Fig. 18), obtained from the seismic refraction measurements at the second site S2 (Fig. 3), shows that two distinctive alluvial layers cover the basement rocks; their seismic velocities are 430 and 1150 m/sec, respectively. The velocity of the second layer indicates that this layer is probably wet. The thickness of sedimentary cover is about 22 m along the eastern 300 m of the profile. This thickness increases at the western side until it reaches 45 m. The variation in the depth of basement rock surface indicates that there is an N-S trending fault with a vertical displacement of the order of 25 m and apparently dipping to the west.

At the third side, the subsurface section (Fig. 19), obtained from the seismic refraction measurements of profile S3 (Fig. 3), shows that the sedimentary cover is composed of two different layers having seismic velocities of 320 and 805 m/sec, respectively. The velocity of the second layer indicates that this layer was dry (during the survey time). The total thickness of the sedimentary cover in the western 550 m of the profile is about 35 m. This thickness increases to reach 45 m at a distance of 610 m from the west, and decreases to 22 m at a distance of 980 m from the west. The variation of thickness of sediments overlying the basement rocks indicates that there is an N-S trending fault with a vertical displacement of about 13 m and apparently dipping to the west.

Conclusion

To accomplish the aim of this study, the ground magnetic, resistivity and seismic refraction methods were integrated to outline the ground water occurrences beneath the area around Ain Zubida.

The ground magnetic survey was conducted along eight profiles across Wadi Numan. The frequency analysis of magnetic data indicates that the depth of basement rock surface in the area under investigation ranges between 25 and 121 m. Also, the stacked profile maps of the total magnetic intensity, residual magnetic component and regional magnetic component are used to delineate the main structural zones and the relative thickness of sedimentary cover controlling ground water distribution.

The vertical electrical sounding survey was conducted at 62 selected sites along eight profiles. Careful examination of the subsurface resistivity contour

sections constructed for each group of soundings along each profile, and their comparison with the results of seismic sections indicates that:

1 – Both methods precisely determine the geometrical configuration and the physical properties of the subsurface layers constituting the sedimentary cover overlying the basement rocks. The results also assign the unconsolidated sediments characteristics.

2 – The unconsolidated sediments can be distinguished into two distinctive layers of different resistivity values. The upper one has relatively high resistivity values (ranging between 300 and 1000 Ohm.m) and low seismic velocities (ranging between 315 and 880 m/sec) and corresponds to a layer of dry unconsolidated sands, boulders and alluvial deposits. The second layer, overlying the basement rocks, is characterized by its relatively low resistivity values (ranging between 30 and 300 Ohm.m) and its relatively high seismic velocities (1150 m/sec at S1 and 2245 m/sec at S2). These latter values of the unconsolidated sediments indicate that this layer is saturated with ground water.

3 – The suitable sites for drilling exploratory wells are VES locations 505, 506, 604, 703, 807, 906, 1005, 1006, 1103, 1104 and 1207, with the most suitable sites being VES locations 703, 807, 906, 1005, 1006, and 1104.

The interpreted subsurface geoelectric and seismic refraction sections indicate that Wadi Numan may be considered as a graben structure, which represents the main target of water accumulation. The seismic refraction method defines the southern E-W trending fault of this graben structure and delineates its dip direction (to the north) and vertical displacement (~ 30 m). In addition, N-S trending faults cutting across Wadi Numan are recorded in two sites at the zone of intersection of Wadi Numan with Wadi Rahgan, one is located in the southern side and the other is located in the northern side of Wadi Numan. These faults dip to the west and have different vertical displacements (13 m at the southern site and 25 m at the northern site). These N-S trending faults construct suitable natural environment for developing an aquifer underneath the surface of this part of the Wadi. Finally, the distribution of the ground water occurrences can be inferred from the integration of this information.

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التعرف على وجود المياه الجوفية تحت سطح المنطقة المحيطة بعين زبيدة باستخدام طرق المغناطيسية والسبر بالمقاومية الكهربائية والسيزمية الانكسارية

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المستخلص . تقع عين زبيدة في وادي نعمان شرق عرفات ، مكة المكرمة . وتقع منطقة الدراسة بين خطي عرض ٢١١٧ و ٢١٢٤ شمالاً وخطي طول ٤٠٠٠ و ٤٠١٠ شرقاً . يصب وادي نعمان مياهه في البحر الأحمر .

تعتبر منطقة الدراسة جزءاً من الدرع العربي بغرب المملكة العربية السعودية ، لذلك فهي مغطاه بالصخور النارية والمتحولة . ينبع وادي نعمان عند منحدر تركيبي كبير بجانب التصدعات الأخرى الكبيرة والصغيرة المنتشرة في وادي نعمان والمناطق المجاورة له .

تهدف هذه الدراسة إلى التعرف على مدى انتشار المياه الجوفية في المنطقة المحيطة بعين زبيدة وتحديد عدد من المواقع المناسبة لحفر آبار اختبارية .

لهذا استخدمت الطرق المغناطيسية وسبر المقاومة الكهربائية والسيزمية الانكسارية متكاملة للحصول على نتائج مفيدة .

لقد وضحت طريقة المسح المغناطيسي الأرضي التي نفذت على طول ثمانية جانبيات تقطع مجرى الوادي ، أن العمق التقريبي لسطح صخور القاع في منطقة البحث يتراوح بين ٢٥ و ١٢١ متراً . كما أمكن بالطريقة المغناطيسية تحديد مناطق التراكيب الرئيسة وسمك الغطاء الرسوبي المؤثر في توزيع المياه الجوفية .

تم إجراء السبر الكهربائي العمودي عند ٦٢ موقعاً . مما أدى إلى تقسيم الرسوبيات غير المتماسكة التي تغطي سطح صخور القاع ، طبقاً لمقاوميتها

الكهربية، إلى منطقتين مميزتين. الطبقة العليا تتميز بقيم مقاومة كهربية عالية نسبياً والسفلى تتميز بقيم منخفضة نسبياً. تعتبر هذه الطبقة هي الطبقة المتوقع تشبعها بالمياه.

أكدت الطريقة السيزمية التي استخدمت عند مواقع مختارة التراكيب والطبقات مدى التشبع بالمياه في هذه المواقع المختارة. وأثبتت هذه الدراسة وجود منخفض تركيبي في وادي نعمان. هذا التركيب يعمل كقناة لتجمعات المياه. طبقاً لهذا، فقد اقترحت هذه الدراسة عدداً من الأماكن المناسبة للحفر .