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Preliminary Geophysical Characteristics ®f the Subsurface Shallow Structure of the Wadi Bishah Area, Southern Arabian Shield

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Abstract. A geophysical investigation has been conducted in the Wadi Bishah area using D.C. resistivity and seismic refraction methods. The results have been integrated with geological information in order to determine, where possible, the depth to the basement, any water-table variations, and the delineation of the hydrostratigraphy. The study area is complex due to the presence of ductile deformational structures which indicate polyphase folding. The major lithological units are: banded gneisses, metavolcanics, migmatites, and metasediments.

Preliminary analysis of vertical electric sounding curves reveals the occurrence of three distinct layers. The upper layer is *1-4* m thick with resistivity values between *250-400* ohm-m and this would generally be classed as a moderately resistive layer. This layer is interpreted as being composed of clean sand and unsaturated surficial sediments. The middle layer has a low resistivity *(40-150* ohm-m) and is *4-9 m* thick. It is proposed that within this layer, sediments and sand are intermixed with water. Evidence from these measurements indicates that the water-table varies in depth between *1-4* m below the surface becoming deeper towards the SE. The lower layer is characterized by a high resistivity (> *1900* ohm-m). This layer may represent the upper part of the basement. Minor fracture zones are defined by resistivity lows and are marked by V-shaped depressions in the basement rocks. The depth to the basement rocks is identified from the shallow seismic refraction profiles. This boundary, at a depth of 7-12 m below the surface, marks a change in average seismic velocities from 300 m/sec above this limit to 2600 m/sec below.

This study and previous geological evidence confirm the existence of severe weathering prior to the depsoition of the Tertiary sediments. This is indicated by the variation in sediment thicknesses and the ruggedness of the upper surface of basement rocks within the study area.

Introduction

The rocks of interest in the area are of Late Precambrian age and form the eastern part of the Asir mountains in the southern Arabian Shield.

The complexity of the area is due to ductile deformational structures which indicate polyphase folding [1]. The study area for this investigation is between latitudes 18° 20' -18° 26'N and longitudes 42° 37' - 42° 43'E , (Figs. 1 and 2). It lies about 6 km to the northwest of Khamis Mushayt city.

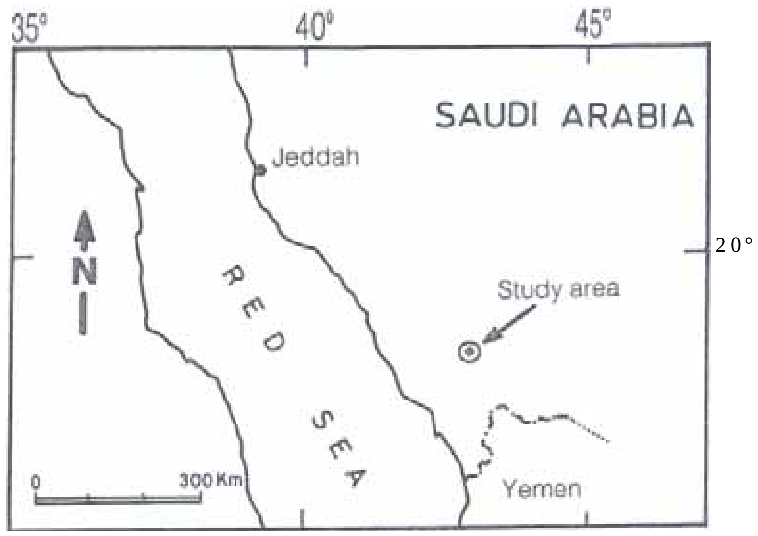


Fig. 1. Location map of the study area.

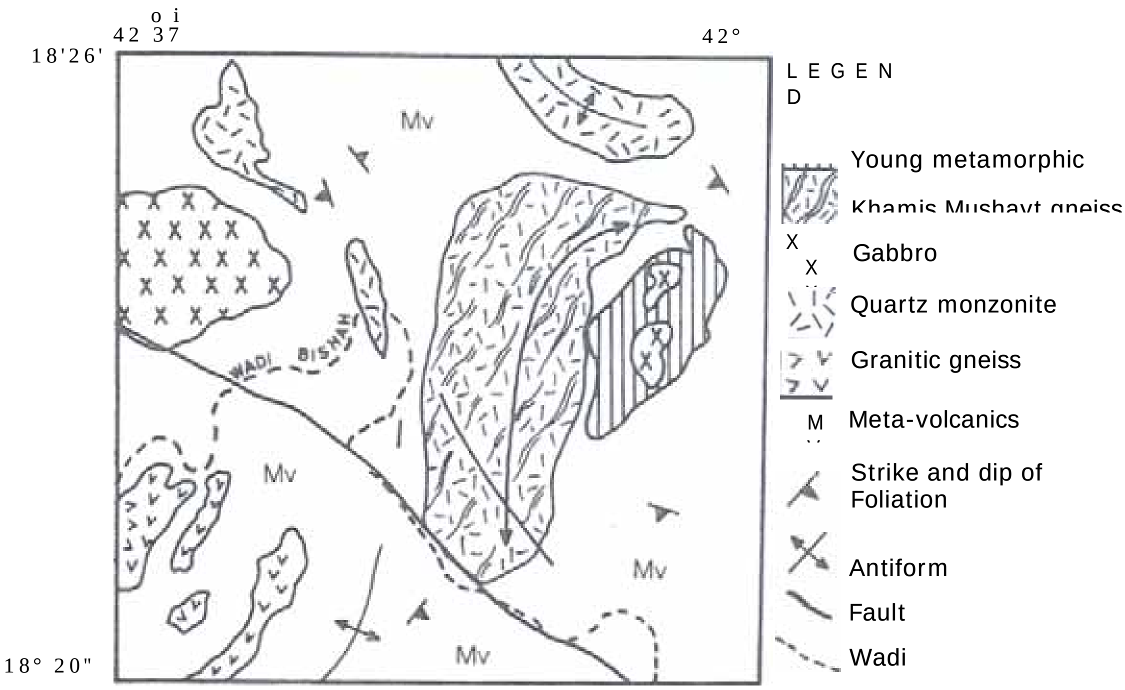


Fig. **2. Generalized geological map (Modified from Coleman [3]).**

One of the first works describing the geology of the southern Arabian Shield was a 1 : 500,000 - scale geologic map of the Asir quadrangle compiled by Brown and Jackson [2]. The Precambrian rocks were divided by Coleman [3] into two distinct units: (1) The basement complex of the Asir mountains, and (2) Younger metamorphic rocks. The former division is interpreted as the Khamis Mushayt Gneiss [4] and evidence has been found to support the fact that the latter belongs to the Hali, Baish, and Bahah groups [1]. The most recent lithological and structural studies of the area were carried out by Amlas et al. [1] who defined five major lithological units: banded gneisses, metavolcanics, metasediments, granitic gneisses, and migmatites. Qari [5] applied remote sensing technology to the geological mapping of the southern Arabian Shield. He indicated that i.andsat Thematic Mapping (TM) data can be used for lithological mapping and structural analysis in well exposed arid regions.

The primary importance of conducting resistivity and shallow seismic refraction methods stems from the lack of knowledge of the subsurface shallow structure of the area obtained using geophysical investigations. Good contrasts in electrical resistivity were expected between surficial and saturated sediment, between water-bearing layer and the basement rocks. Differences in seismic velocities were anticipated between the dry overburden, the saturated overburden and the bedrock.

The main objective of this study, therefore, is to integrate the existing geological information, with the results of D.C resistivity and seismic refraction surveys to determine, where possible, the variations in the water-table and the depth to the basement, to trace faults in the subsurface, and to delineate the hydrostratigraphy.

Geological Setting

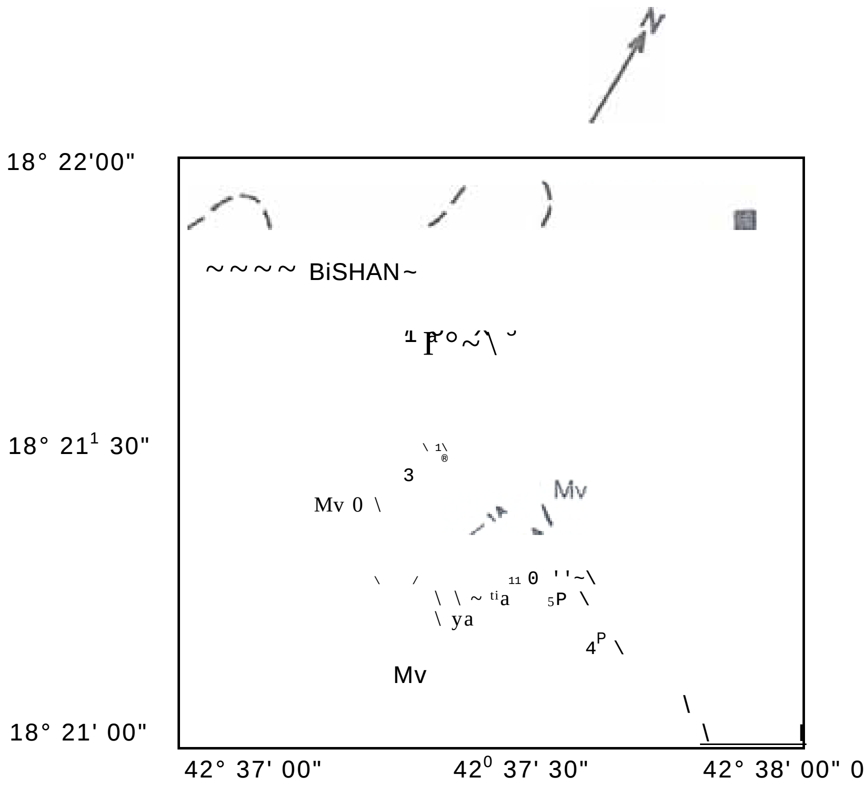
The Precambrian rocks of the study area exhibit a complex history of metamorphism and deformation. Khamis Mushayt Gneiss forms the older Precambrian unit, and consists of banded orthogneiss, migmatite with minor amphibolite, and paragneiss. The younger Precambrian unit represents an extensive group of metamorphic rocks which rest unconformably on the Khamis Mushayt Gneiss and consists primarily of metavolcanic and metasedimentary rocks (Fig. 2).

Coleman [3] indicates that numerous pegmatite dykes invaded the Khamis Mushayt Gneiss and their resistance to erosion has produced an erosional surface characteristic of the basement. The Khamis Mushayt Gneiss shows a complex deformational history. Migrnatites and ductile folding appear to occur later than the development of the banded gneiss structure.

The three dominant major structures: the western dome, the central synform, and the mushroom in the east have been affected by three phases of folding [1]. Coleman [3] considered that the Khamis Mushayt Gneiss occupies the core of the western dome, forming the basement of the metavolcanic - metasedimentary rocks.

Geophysical Results and Data Analysis

Most geophysical methods require a physical contrast between the target of investigation and the surrounding materials. In order to investigate the contrast in resistivities and seismic velocities within the Wadi Bishah, two geophysical methods were used, namely, D.C. resistivity and shallow seismic refraction (Fig. 3).



——— VES

s Seismic refraction spread

O Dug well -- - -Wadi

® Village Mv Meta-volcanics

Fig. 3. Location map of electrical resistivity and seismic refraction measurements within the study area.

Electrical resistivity measurements were obtained using ABEM-AC TERRAMETER equipment. D.C. resistivity involves using Vertical Electric Soundings (VES) to study the variations in resistivity with depth and lithology. The procedure is based on the fact that the current penetrates continuously deeper with increasing separation of the current electrodes. Shallow electrical soundings were carried out using the Schlumberger electrode array in which the distance between the potential electrodes (MN) is kept small compared to the distance between the current electrodes (AB) (AB/2 ~_>: 5 MN/2). Twelve VES curves have been selected for analysis in this study with a maximum current electrode spacing (AB/2) of 120 m. Six of them were measured along a traverse perpendicular to the trend of the Wadi with 150 m between each of the soundings (Fig. 4). The other six VES curves were taken at 50 m intervals along a traverse parallel to the trend of the Wadi (Fig. 5). If highly detailed information on the lithology and thickness of geological units is required, VES need to be more closely spaced (< 5 m).

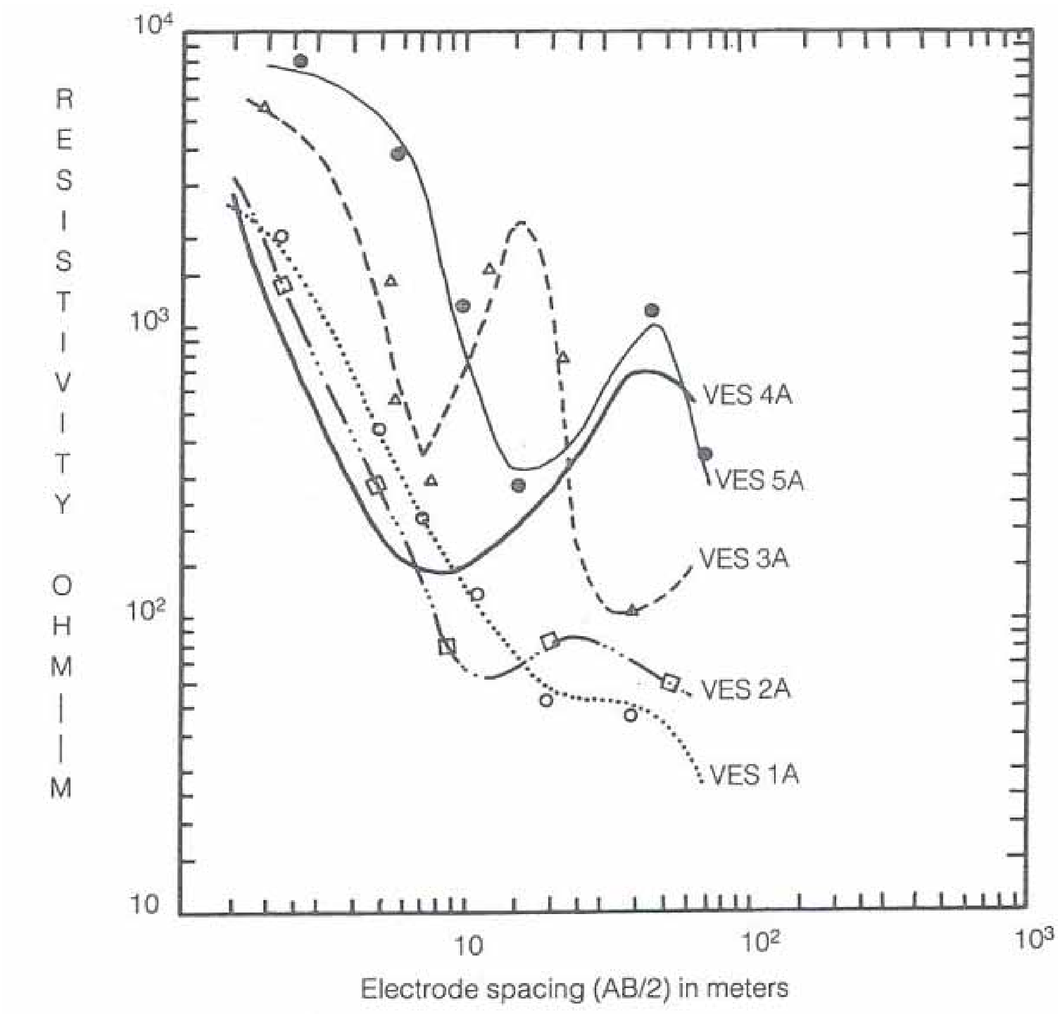


Fig. 4 Six VES curves with electrode spacing (meters) versus apparent resistivity (ohm-m) obtained along a traverse perpendicular to the trend of wadi Bisleale.

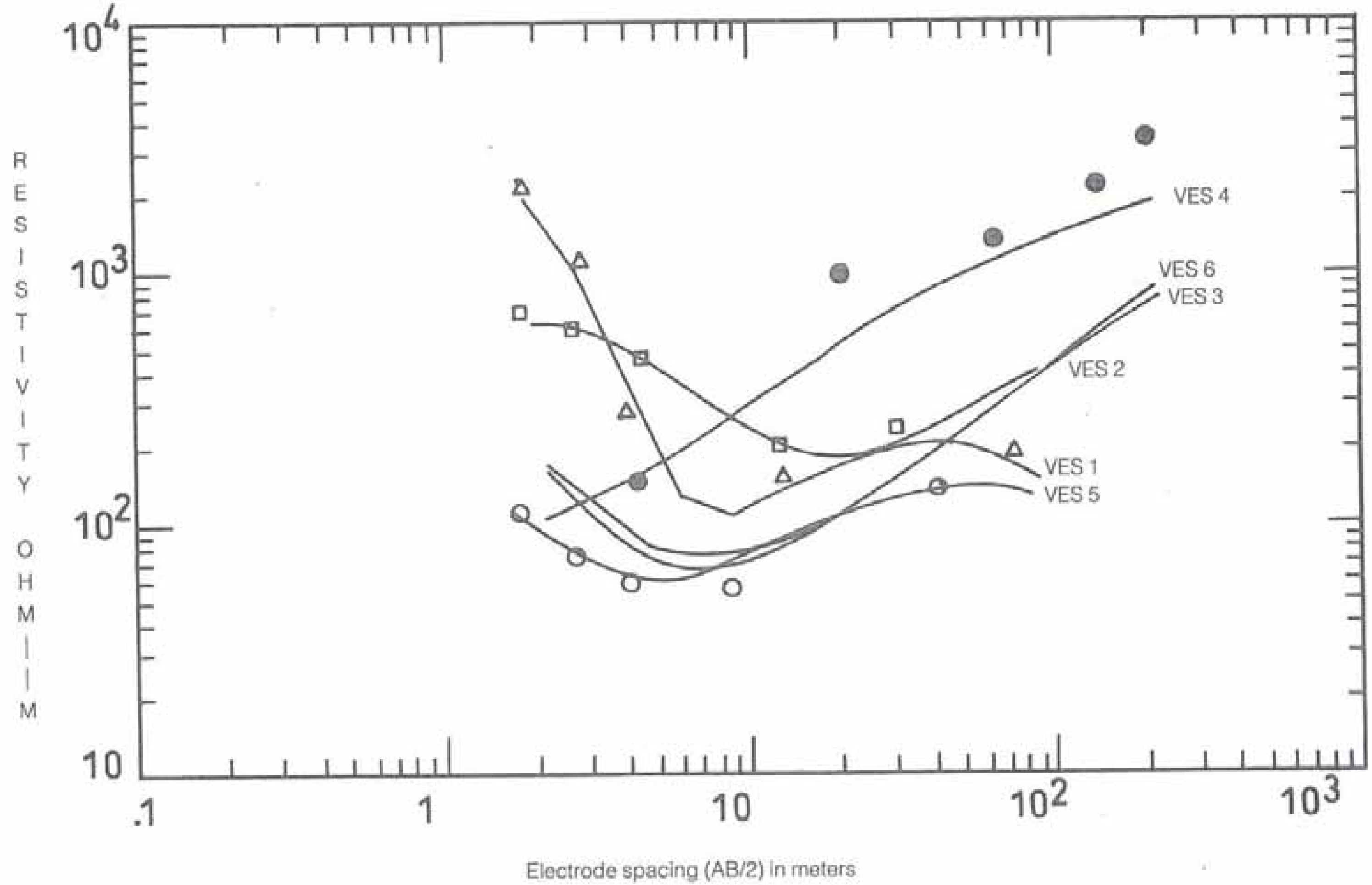


Fig. 5. Six VES curves with electrode spacing (meters) versus apparent resistivity (ohm-m) obtained along a traverse parallel to the trend of Wadi Bishah.

The apparent resistivities calculated in the field were reduced using an automated inversion computer program developed by Zohdi [6]. This program produced layered models, detailing the depth, thickness and bulk resistivity of each of the layers. The automatic interpretation is generally done in two sets of iterations (two passes). In the first set of iterations, the best fitting theoretical sounding curve is determined. If the least root mean square difference (between digitized and calculated apparent resistivities) is greater than 2 percent, the digitized curve is noisy and anomalous layers may have been created. Such layers are eliminated by considering the best-fitting curve from the first pass to be a smoothed version of the observed curve and automatically reinterpreting it (second pass).

Twelve 1D geoelectric sections were obtained from the reduced data. Firstly, a plot of electrode spacing versus apparent resistivity was produced for each sounding (Figs. 4 and 5). The sounding curves were then smoothed before being inverted to produce twelve one-dimensional geoelectric sections detailing resistivity versus depth. Figure 6 shows a severely distorted sounding curve measured at site VES 2. Outlying points on the digitized curve (6a) cause the automatic interpretation process to generate anomalous layer(s) in the first pass (6b) and there is a large misfit between the calculated curve and the measured data. The second pass (6c) eliminated the anomalous layer. Yet the calculated curve still did not fit the observed curve. The distortion of VES 2 curve could be caused by current leakage [6], errors in measurement or by lateral geologic inhomogeneities.

All of the geoelectric sections were interpreted using the above procedure and exhibit the same general profile, namely a section consisting of three major geoelectric layers. The uppermost layer has a thickness range of 1-4 m with resistivity values between 250-400 ohm-m and this would generally be classed as a moderately resistive layer. This layer is interpreted as being composed of unconsolidated and unsaturated surficial sediments. The middle layer has low resistivity (40 - 150 ohm-m) and is 4-9 m thick. It is proposed that within this layer, sediments and sand are intermixed with water. Evidence from these measurements indicates that the water-table varies in depth between 1-4 m below the surface becoming deeper towards the SE. The watertable contact can be recognized by a major drop in resitivity. The lower layer has high resistivity (> 1900 ohm-m) and may represent the upper part of the basement. Depths to the basement rocks range from 6-11 m.

The above depths and resistivity values for each layer obtained in this study are based primarily on the best fitting theoretical models to the different data sets. Although a number of models have the same degree of fit to our data, this number of possible solutions is reduced by mutual correlation of several sounding curves and by knowledge of the local geology [3]. A more reliable interpretation can be made when additional subsurface information, preferably lithological borehole descriptions and geophysical well logs, becomes available. Without such information, only a preliminary interpretation can be made on the basis of computer modelling of sounding curves and velocity graphs.

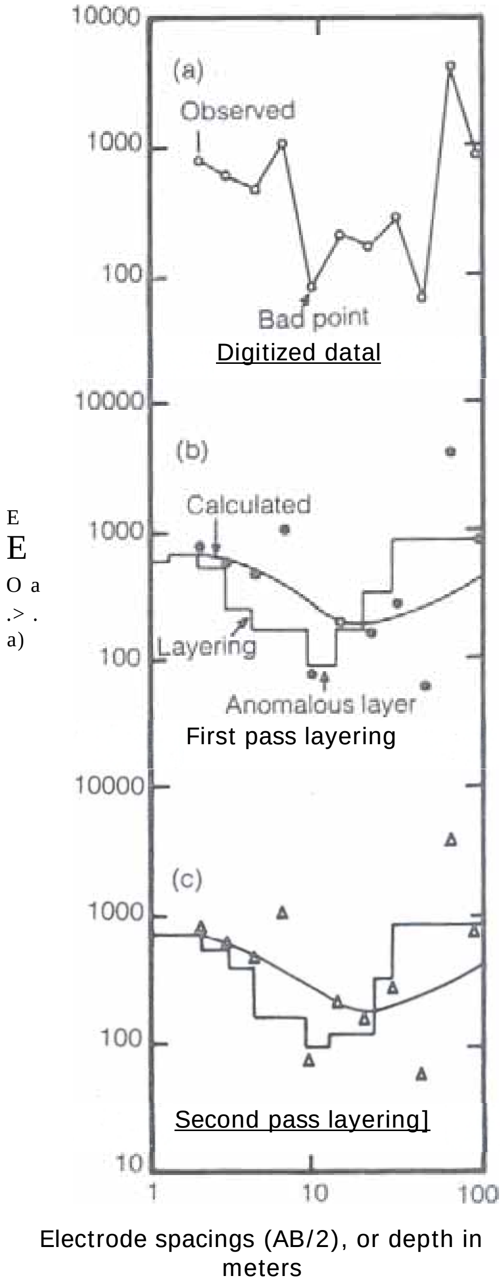


Fig. ,6. **Automatic interpretation of VES 2: (a) digitized curve, (b) first-pass results with anomalous layer and poorly-fitting calculated curve, and (c) second-pass results with anomalous layer eliminated and calculatzd curve still not closely matching the observed curve.**

In addition to obtaining VIES sounding curves, shallow seismic refraction measurements were carried out in order to solve the equivalence problem in resistivity interpretation and to investigate the depth and thickness of the above layers. Seismic refraction measurements were made using 12-channel ABEM-TRIO equipment. Symmetrical pairs of shots were fired into spreads with geophones placed at 3 m intervals.

Seven seismic refraction spreads were completed. The measurements from these spreads were plotted on distance versus depth graphs using a seismic refraction inversion program SIPT1 developed by Haeni [7]. The program is a two-dimensional modeling process in which the delay-time technique is used to obtain a first approximation of model layers and an iterative ray-tracing technique is then used to refine the model. Four of these spreads (Fig. 7) were recorded along the same traverse used to record the VIES shown in Fig. 4. This traverse

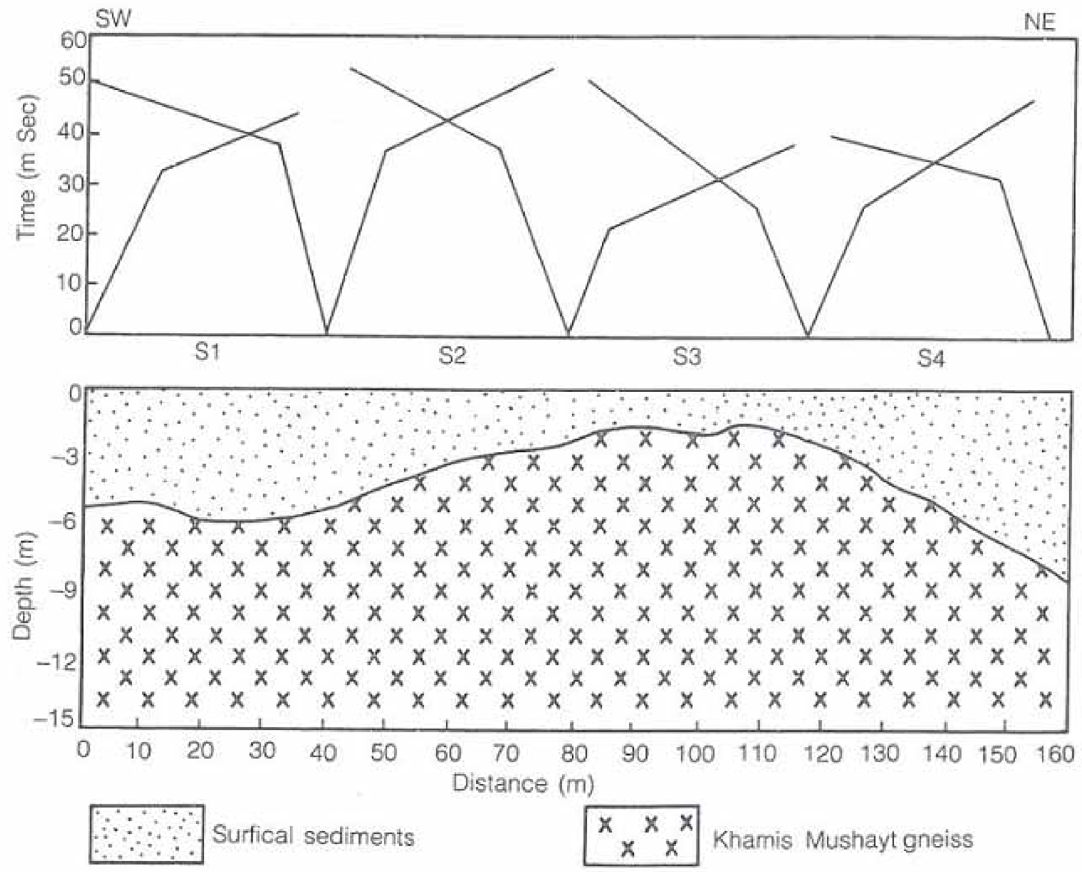


Fig. 7. Geological section and travel-time versus distance plot showing the general relationships of seismic velocities and cross-over distances between four seismic refraction spreads along a SW - NE traverse.

perpendicular to the trend of the Wadi. The other three spreads (Fig. 8) were taken along a 120 m long traverse parallel to the trend of the Wadi, located close to the locations of the VES shown in Fig. 5. The principle of reciprocity was used in the construction of travel-time plots to indicate the direction of any dip.

Cross-over distances could be calculated for all the spreads except for the first spread (SS) shown in Fig. 8. This was due to the surficial sediments being so thick below this spread that .only the direct wave could be recorded using the detectorsource distance used in this study. The subsurface below this spread may consist of uniform material extending to a depth not less than about one-third of the detectorsource distance (12 m). The actual depth extent the layer which is characterized by the direct wave velocity is not known and this section may include layers within this depth with velocities lower than the direct wave velocity. All other spreads indicate two distinct seismic layers.

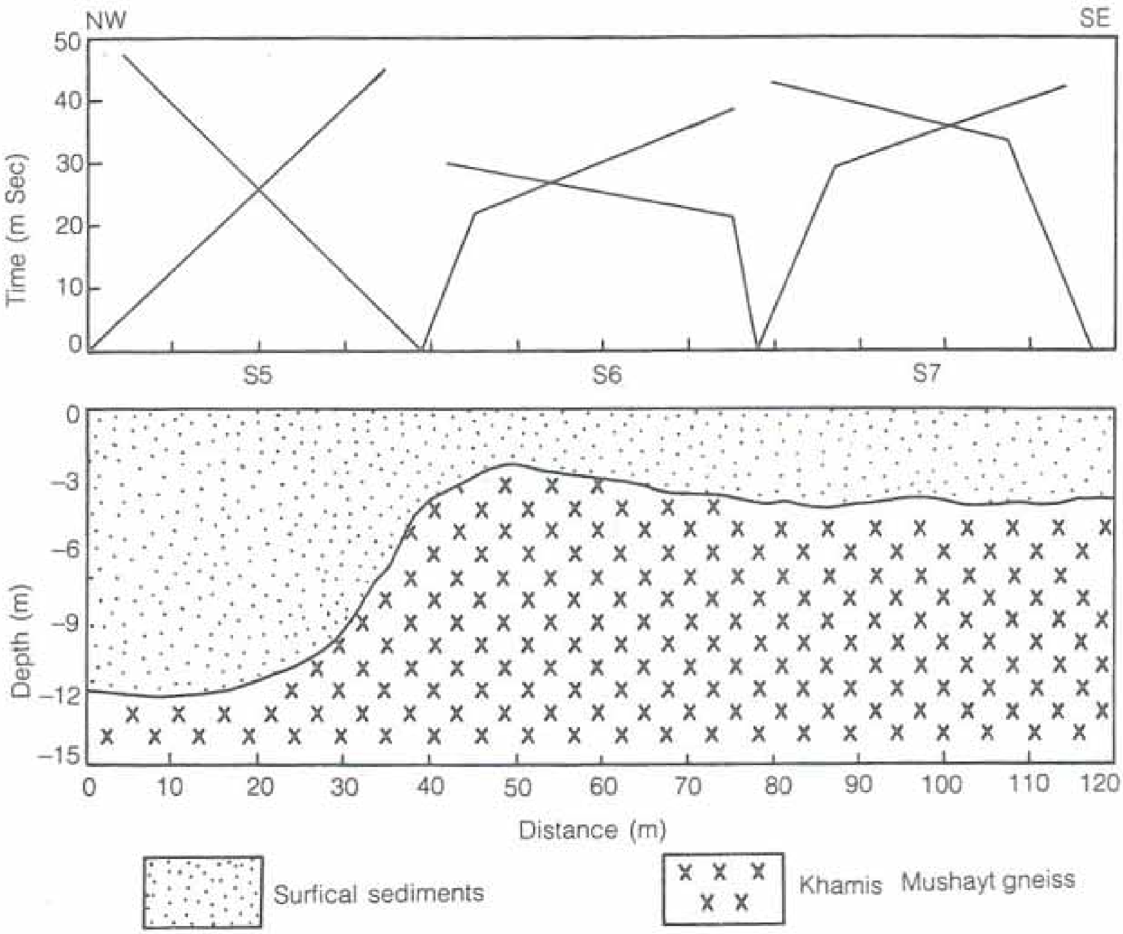


Fig. 8. Geological section and travel-time versus distance plot showing the general relationships of seismic velocities and cross-over distances between four seismic refraction spreads along a NW - SE traverse.

The first layer represents the surface layer and is characterized by the direct wave velocity. Within this layer seismic velocities vary between 300 to 500 m/sec. The thickness of saturated and surficial sediments, which make up the surface layer, ranges from 3 m in the SE to 12 m in the NW and is 2 m thick in the middle of the Wadi. VES 4 (Fig. 5) and the first seismic refraction spread (SS) shown in Fig. 8 indicate that variations in the thickness of this layer occur particularly in the NW of the study area.

Below the cross-over distance the refracted wave travels within the second layer with a velocity greater than the direct wave. The depth to the top of the basement rocks varies between 7 to 12 m below the surface. Below this boundary the refracted waves exhibit velocities > 2200 m/sec. Seismic velocities of the overburden and bedrock masured in this study were in good agreement with the velocity ranges obtained by Burger [8]. Seismic velocities are generally found to be greater in igneous and crystalline rocks than in sedimentary ones.

Discussion and Conclusions

In the Wadi Bishah area, significant and detectable contrasts in physical properties of the lithological units enabled the application of electrical resistivity and seismic refraction methods. Van Overmeeren [9] carried out integrated seismic refraction, electrical resistivity, and gravity methods in Sudan. He indicated that the problem of equivalence in VES can be solved using seismic measurements to obtain the depth to bedrock. He also indicated that the use of additional seismic data made it possible to obtain a unique solution of the VES, from which it could be concluded that all groundwater in Kosti area is saline.

In north-western Khamis Mushayt city, and particularly in the area of investigation, the dominant surficial deposits in the top of the 10 meters consist of unconsolidated sediments (clean sand, gravel, and silt deposits) and underlain by the basement rocks (Khamis Mushayt Gneiss?).

The variation in sediment thicknesses and the ruggedness of the basement surface in the study area does affect our interpretation of the VES and seismic refraction data. The existence of a 1D earth is implicit in the above interpretatoin, yet the layers delineated by the resistivity modelling are not horizontal planes, but are irregular in thickness and extent (Fig. 9). This variation is an indication of the existence of severe weathering of the basement rocks prior to the deposition of the Tertiary sediments and this varition may also indicate the complexity and polyphases of fracturing in the area.

The major feature of the VES and seismic refraction plots (Figs. 7, S, and 9) is the unconformable surface between the basement rocks and surficial deposits. This unconformable boundary is clearly identified from the sharp contrast in resistivity and seismic velocity values across it. Field mapping of the exposed parts of the weathered bedrock has proved the existence of shear zones or minor shallow fractures in the SE of the study area as a result of stress relief associated with Wadi erosion. Deep fracturing in the bedrock may have formed as a result of tectonic activity and may persist to great depths. Amlas et al. [1] indicated that these fractures are striking E-W and associated with the F_4 folding in the Gneisses and many of the pegmatities in the area. The final best fitting models of VES 3A and 4A (second pass) show V-shaped resisiivity lows within the top surface of the basement rock layer. These depressions in the basement rock layer may indicate the existence of minor fractures or severely weathered bedrock at shallow depths. The water-table varies in depth between 1-4 m below the surface. The lowering of the water-table in the SE is believed to be caused by the existence of the aforementioned minor fractures or some other concealed faults (Fig. 9).

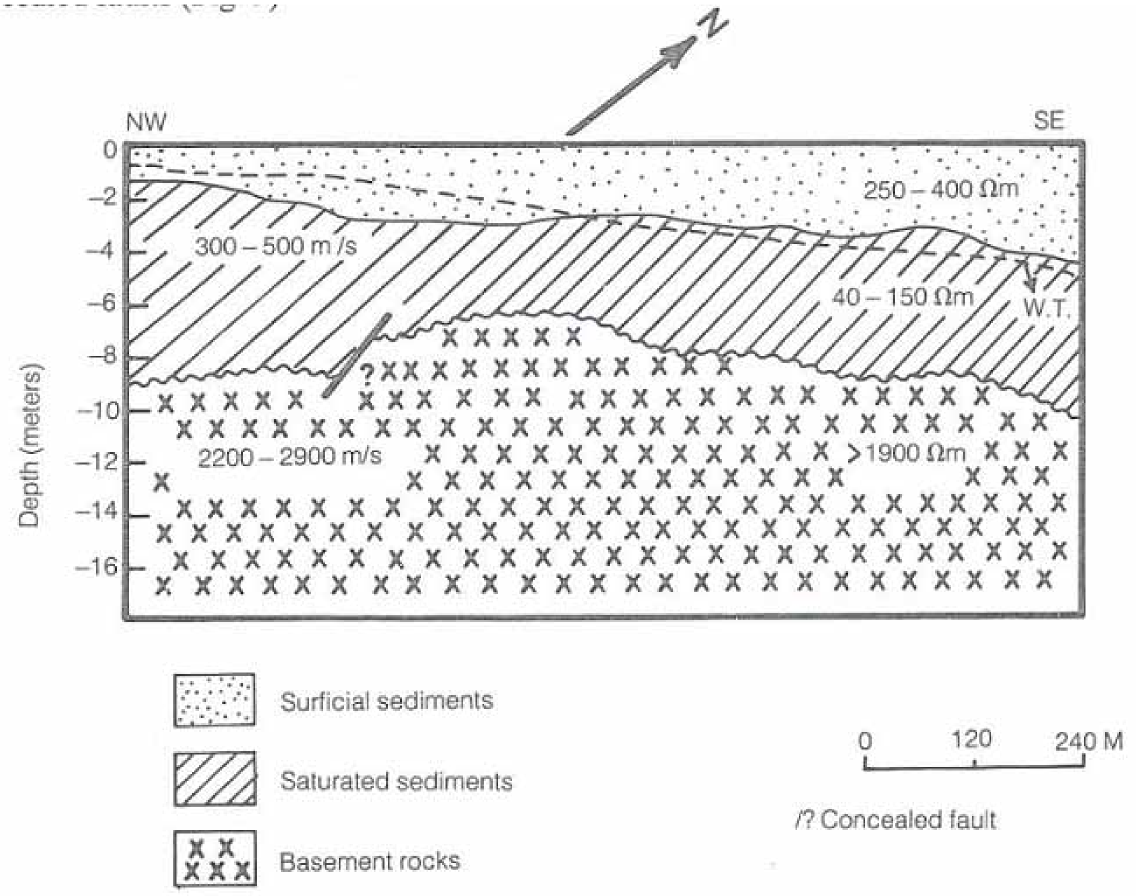


Fig. 9. Generalized subsurface geological section. Geological boundaries are based on resistivity and seismic velocity constrasts.

In order that these fractures to yield significant amounts of water, two conditions must exist. Firstly, the fractures must be closely spaced and open so that water can readily pass through them, and secondly there must be a source of recharge water. It was concluded from correlation of electrical soundings with data obtained from a nearby dug well (Fig. 3) that water-table varies in depth from 4 m in the wet seasons to 9 m below the surface in the dry seasons. Weathered bedrock is exposed in the dug well at depths of 8-10 m below the surface. This supports the reliability of the seismic refraction method in determining depths to bedrock in Wadi Bishah.

Coleman [3] showed that the Khamis Mushayt normal fault extends from northwest to southeast across Khamis Mushayt city. This fault offsets dykes along Wadi Bishah and truncates large basement structures. This study does not confirm the existence of the Khamis fault, but some concealed fault(s) are indicated from seismic velocity scattering at 9-11 m below the surface (Fig. 9).

In order to fully understand the subsurface geological picture, it is recommended that a detailed gravity study, lithological borehole descriptions and geophysical well logs be carried out to investigate structural trends of Khamis fault and to delineate the hydrostratigraphy.

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