

A GEOELECTRICAL STUDY OF THE SANA'A GROUNDWATER BASIN, YEMEN ARAB REPUBLIC¹

MOHAMED AHMED SHAABAN²

ABSTRACT

Shaaban, M. A. 1980 A geoelectrical study of the Sana'a groundwater basin, Yemen Arab Republic – Geol. Mijnbouw 59: 79-86.

The ground water conditions and possibilities in Sana'a Basin were analysed for the purpose of locating a suitable source of water supply, and to delineate the structural set-up of the area.

Resistivity vertical electrical soundings, previously performed in the area, were interpreted to construct geoelectrical sections of the subsurface along some selected profiles. Also, some parametric resistivity and conductivity measurements were undertaken at some locations for the different rock types and waters of wells encountered in the area. Correlation between the geoelectrical results and the available geological and hydrological data was made.

The study ascertained the groundwater potential in the investigated area and defined the electrical properties of its different rock types. Furthermore, a reliable source of adequate quality and quantity of groundwater was revealed, at an economic depth and distance, to the north-west of Sana'a city.

INTRODUCTION

The Yemen Arab Republic depends fundamentally upon its groundwater resources, and thus the development and exploitation of the available water resources is of utmost importance, especially for social and agricultural affairs.

Furthermore, during the last decades the country suffered a decrease in water resources, because rainfall has been reported to be exceptionally low. This was manifested by the decreased safe yields and the dangerous lowering of water tables (MINISTRY OF PUBLIC WORKS). In Sana'a, the increased requirements for water, and the increased pumping for irrigation made the effects of water supply deficiency more fearful. So, effective water-resource surveys were considered a task of urgent priority.

This study, which represents one of these surveys, is based on data extracted from a report by ITALCONSULT (1973) and submitted to the Ministry of Public Works in Yemen, as well as on other (unpublished) reports on the meteorological and hydrological limited studies on Sana'a Basin, and documented

in the files of the same ministry.

The survey covers some 1200 km², including the Sana'a Basin and its catchment area, as well as the surrounding territories.

Resistivity measurements, in the form of vertical electrical soundings (VESes), were conducted by ITALCONSULT (1973), mainly along seven profiles; six of them cross the area in an east-west direction, while the seventh runs north-south. Some parametric resistivity and conductivity measurements were also performed by the author to clarify the geoelectrical characteristics of the different rock types and waters of wells encountered in the area under consideration.

The present study aims to fulfil the following:

- (1) To ascertain the structural configuration of the area, particularly in the subsurface.
- (2) To assess the thickness of the alluvial cover, and to determine the depth of the bedrock.
- (3) To construct geoelectrical sections for the subsurface along the selected profiles, and to recognize the various lithostratigraphic members, especially water-bearing ones, if possible on the basis of their specific resistivities.
- (4) To define the best sites for locating producing water wells.

Results were correlated with the geological-hydrological data available. Some wells were sunk at sites selected according to the results obtained.

¹ Manuscript received: 1979-03-27.

Revised manuscript received and accepted: 1979-09-27.

² Geology Department, Faculty of Science, Sana'a University, SANA'A, Yemen Arab Republic.

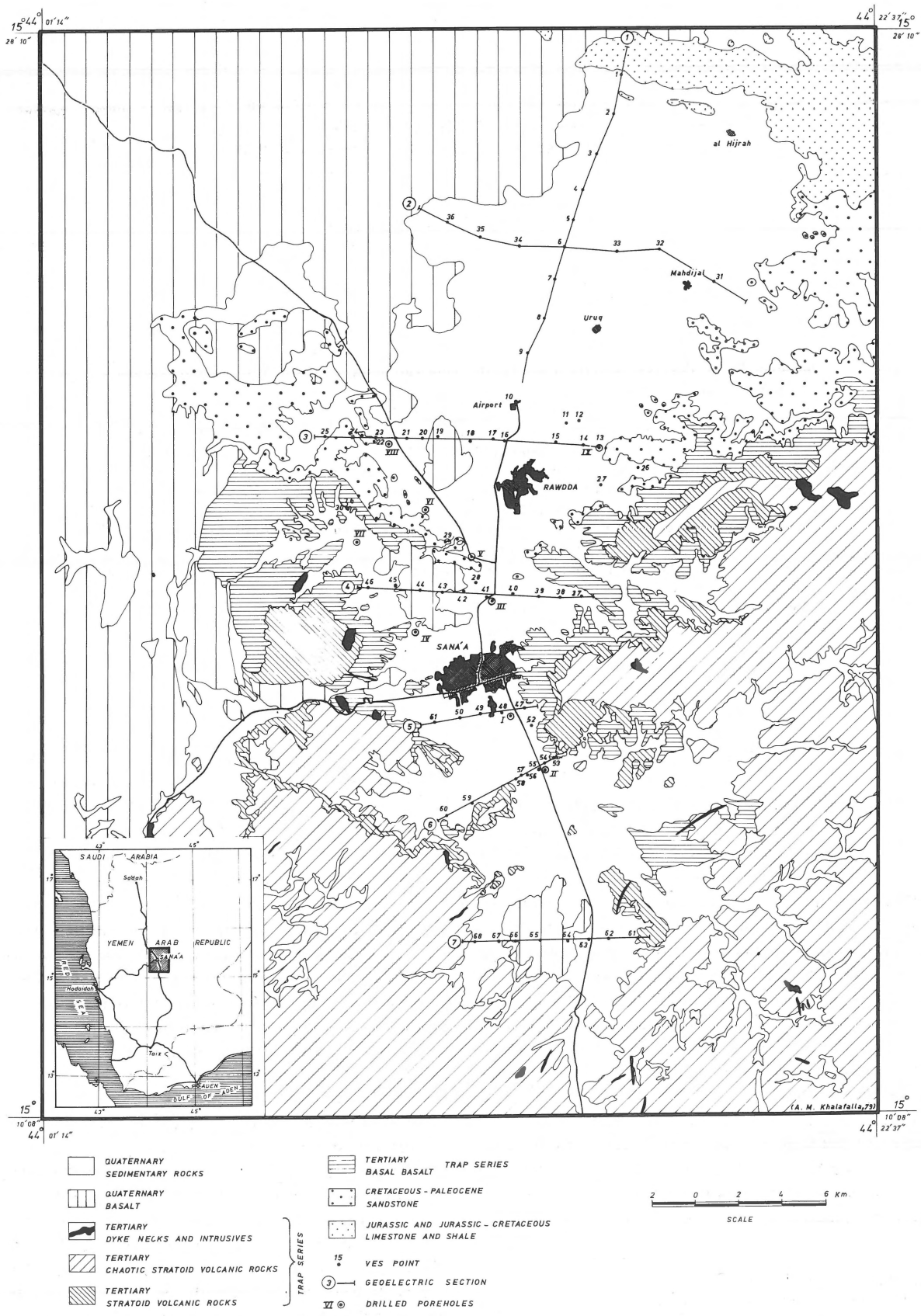


Fig. 1 Geological map of the Sana'a Basin, Yemen Arab Republic.

GEOLOGICAL AND HYDROLOGICAL SETTING

The investigated area covers some 1200 km², and lies between 15°10'09" and 15°28'00" N.L., and 44°01'14" and 44°22'37" E.L. The Sana'a plain is surrounded along most of its boundaries by mountains and higher land, especially to the east (Gebel Nuqum), and to the west, where the land rises in a series of steps formed by small escarpments.

The morphology of the area is typified by flat tabular forms with deeply entrenched valleys. The drainage network, away from the central plateau, is well developed. Terraces constructed by man for agriculture represent an important morphological feature with important consequences on hydrological conditions, since they serve to regulate and distribute the run-off, thus diminishing the recharge effect of floods.

Figure 1 shows the geology of the area, after GEUKENS (1966). The stratigraphic sequence ranges from Jurassic to Quaternary, comprising six main geological units.

Jurassic Amran Formation

This is the oldest formation, outcropping to the north of the basin. It is about 350 m thick, consisting of argillaceous limestones with some calcareous shale interbeddings. It may be water-bearing due to fracturing, but its water-bearing properties are very poor. It is underlain by a thick Early Jurassic sandstone complex: the Kohlan Formation. There are indications of good groundwater potential of the Kohlan Formation, which gives rise to a number of good yield springs (MINISTRY OF PUBLIC WORKS).

Jurassic – Early Cretaceous unnamed formation

This one overlies the Amran Formation and outcrops over a considerable area to the north of the basin. It is about 80-100 m thick, consisting of black bituminous pyritic shale, black limestone, variegated and finely bedded sandstone. It constitutes a well defined aquiclude (MINISTRY OF PUBLIC WORKS).

Cretaceous Tawilah Formation

The Jurassic-Early Cretaceous formation is conformably overlain by a thick stratified friable sandstone complex, frequently crossbedded, with layers of claystone, siltstone and ironstone. Its thickness is about 370 m and it crops out over considerable areas to the north and northwest of Sana'a, and along the eastern escarpment of the highlands. It is permeable and characterized by dense fracturing. Some major fractures are occupied by basalt dykes, frequently decomposed. The Tawilah Formation constitutes the most important groundwater reservoir in the area. It has a considerable lateral extension and notable thickness, as well as good hydraulic characteristics that make it the main reservoir in the area (ITALCONSULT, 1973).

Palaeocene Mejd Zir Formation

The Tawilah Formation is overlain, without break, by arenaceous-argillaceous beds composed of fine sandstones with interbedded siltstone, claystone and clay. Volcanic tuffs are encountered in it, which may indicate initial volcanic activity. The formation is about 100-120 m thick. Its hydraulic characteristics are much less favourable than those of the Tawilah Fm., because of the greater amount of clayey material encountered in it (ITALCONSULT, 1973).

Tertiary Trap Volcanic Series

The Palaeocene sediments are followed by a series of Tertiary volcanics, which are generally subdivided, from base to top, into three groups.

Basal Basalt – It consists of black dense lavas, overlying the Mejd-Zir Formation, and covers a wide area. It is probably more than 300 m thick. Because of its intense fracturing it is water-bearing, with good hydraulic characteristics.

Stratoid Rocks – The Basal Basalts are overlain by a pyroclastic formation, mainly of a rhyolitic nature, occurring as wellbedded tuffs and ignimbrites. It is about 100 m thick. The formation is considered to be an aquiclude, or an aquitard, due to its bedded attitude and the presence of decomposed argillaceous tuffs. Springs are reported to occur at its contact with the overlying volcanic formation, e.g. Hadda (ITALCONSULT, 1973).

Chaotic Rocks and Dtratoid Rocks – This is the most recent part of the Trap Series in the basin, consisting of flows of basalt and rhyolite lavas, chaotically intermingled. It is more widespread in the southern part of the basin. Its thickness amounts to several hundreds of metres. It is probable that the decomposed part of it is water-bearing, because of fracturing. Basic intrusives, represented by necks and dykes trending NNW-SSE and NNE-SSW, occur in the tectonic fractures (MINISTRY OF PUBLIC WORKS).

Quaternary Rocks

These rocks lie over the formations discussed before. They are essentially of two types.

Quaternary Sediments – These occur widely in the flatter lying parts of the plain and surrounding plateaux, as well as on the man-made terraces. Their thickness reaches 300 m, in the form of valley-fill or raised terraces. The characteristic feature of the deposits is their rather argillaceous nature: consisting of an alternation of coarse and fine horizons, with silty layers frequently resembling loess. Their water-bearing properties are conditioned by their clay content. Their hydraulic characteristics generally point to low permeability, except in some

scattered areas where the coarse beds are probably less argillaceous.

Quaternary Basalts – These occur widely in the western and northwestern parts of the basin. They are the result of very recent volcanic activity. They amount to several hundreds of metres in thickness, and are covered by loess-like silts. They have very favourable water-bearing properties due to the fractured and blocky character of the lava flows. This is shown by the largest spring in the whole area, emerging at Wadi Dhahr (ITALCONSULT, 1973).

Structurally, the Sana'a Basin has not been affected by the intensive regional tectonic movements that led to the creation of the Red Sea Rift (LOWELL & GERNIK, 1972). The structure is of a local style, which retains its original tabular form. The major effect of the tectonic movements is that they opened ample passages for the rise of magma, which led to the formation of the extensive volcanic extrusions. According to LAMARE (1930), tectonic movements are manifested in the basin by the following features:

- (1) Broad radius folding; this consists of what is presumed to be a large anticline with N-S axis, extending mainly along the northern half of the basin. It is defined by the regional dips seen essentially in the Cretaceous strata.
- (2) Faults; these strike generally NNW-SSE, and are almost vertical, with a maximum vertical throw of about 200 m.
- (3) Fracturing; this is the most important structural phenomenon from the hydrogeological point of view. Fractures are distributed in a non-uniform manner and their density indicates zones of greater weakness and tension.

The basin is of importance from the hydrogeological point of view, as the depression constitutes one of the main hydraulic base levels of the Yemen Highlands affecting the bedrock aquifers. From a more regional point of view, the various aquifers in the basin form part of a single system, due to the fractured nature of the bedrock and the absence of effective aquicludes. Fractures traverse the stratigraphic boundaries, making them permeable. Sometimes, perched groundwater bodies, generally of limited extent, are found. In this aquifer system water-table conditions are common in its upper horizons, whereas artesian conditions are associated with deeper ones.

Recharge of this great system is considerable and occurs on the plateaux and mountains which surround Sana'a Plain, with the depression as the main groundwater collector (MINISTRY OF PUBLIC WORKS).

FIELD SURVEYS

Some 68 resistivity vertical electrical soundings (VESes) were conducted in the area by ITALCONSULT (1973) along seven profiles which were supposed to cover more or less the area.

Six of these profiles have a more or less E-W direction, whereas the seventh has a N-S direction (Fig. 1).

The asymmetrical four-electrode Schlumberger configuration was used; it is generally preferred, since it requires a minimum number of shifting of the potential electrodes, thus saving time and effort, and minimizing the electrode effects on measurements. The AB/2 spacing ranged from 300-1500 m. In such arid conditions, field measurements necessitate high-power supply and watering of the electrodes.

Also, some parametric measurements were undertaken by the author to evaluate the specific resistivity of the different rock types, and the conductivity of water in wells encountered in the area. These are helpful in the interpretation of data.

RESULTS

Figures 2, 3, and 4 present the results. In figures 2 and 3 some representative VES curves are shown, especially for those located in the vicinity of drilled boreholes, whereas the results of quantitative interpretation (summarized in the form of subsurface geoelectrical sections) are given in figure 4.

Curves of VESes are more or less complicated, most probably due to the anisotropy and intercalated nature of the geological succession. They exhibit different shapes and type curves, as well as variable ranges of resistivity.

Curves were qualitatively interpreted by their correlation with each other, and with those obtained at well sites for which geological sections are available. On the other hand, quantitative interpretation of the curves was accomplished according to the graphical method (SEARA & CONAWAY, 1978; ZOHDY, 1968).

On correlating VES curves and the results of their interpretation with the borehole logs in their vicinity, the following could be clarified:

- (1) VESes conducted at volcanic rocks of the Trap Series exhibit curves with small ranges of resistivity variations, showing the transition of the superficial alluvium to the underlying volcanic rocks, e.g. the curves of VESes 52 and 68.
- (2) VESes executed at sites covered by wadi fill and Quaternary alluvium generally exhibit the three-layer minimum-type curve, showing inflections corresponding to changes from dry fill and stream wash to wet fill and top of the water-table, if present, as well as the change from fill material to the underlying bedrock (e.g. curves of VESes 18, 26, 27 and 41). The resistivity of the alluvium varies in accordance to its content of clayey and argillaceous material. In the cover there are sections with high conductivity, which may mark areas with the thickest alluvium (VES 18). Other highly resistive zones, denoting areas with Quaternary Basalts occur along profile No. 3 (VESes 21-25), and VESes 44, 45, 46, 64 and 66; there the resistivity of the cover exceeds 200 ohmm. At the sides of the plain apparent resistivity depends on the depth and thickness of

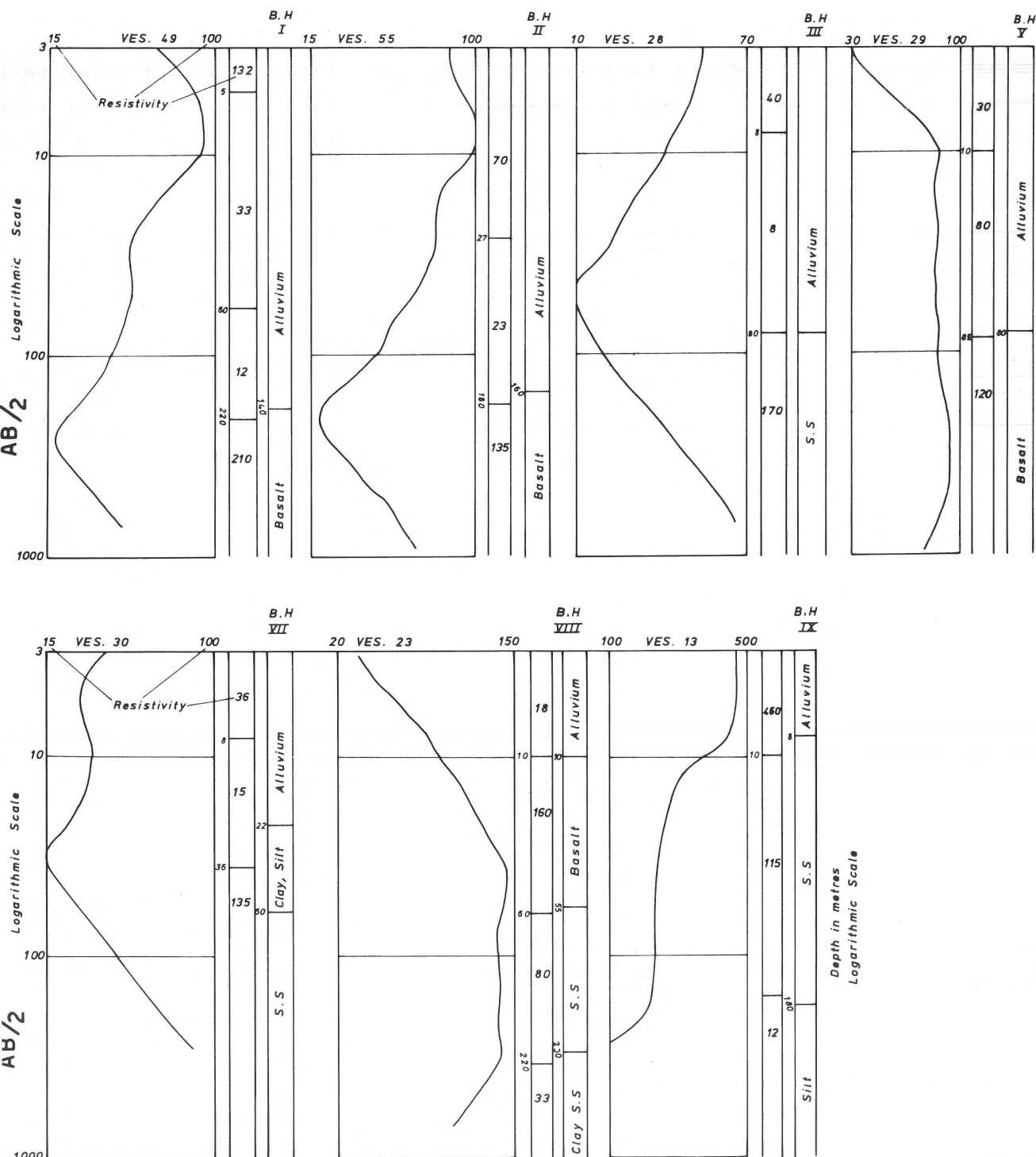


Fig. 2
Correlation of VES curves with geological sections of drilled boreholes

the bedrock. The variation of the alluvial cover thickness may reveal a succession of basins in the bedrock, with variable depths. The cover increases in thickness to the north, where it reaches about 400 m along the axis of the

Sana'a Depression and a series of tributary depressions perpendicular to it (Fig. 4). However, a conductive layer, corresponding to moist or clayey alluvium, is commonly prevalent in the cover.

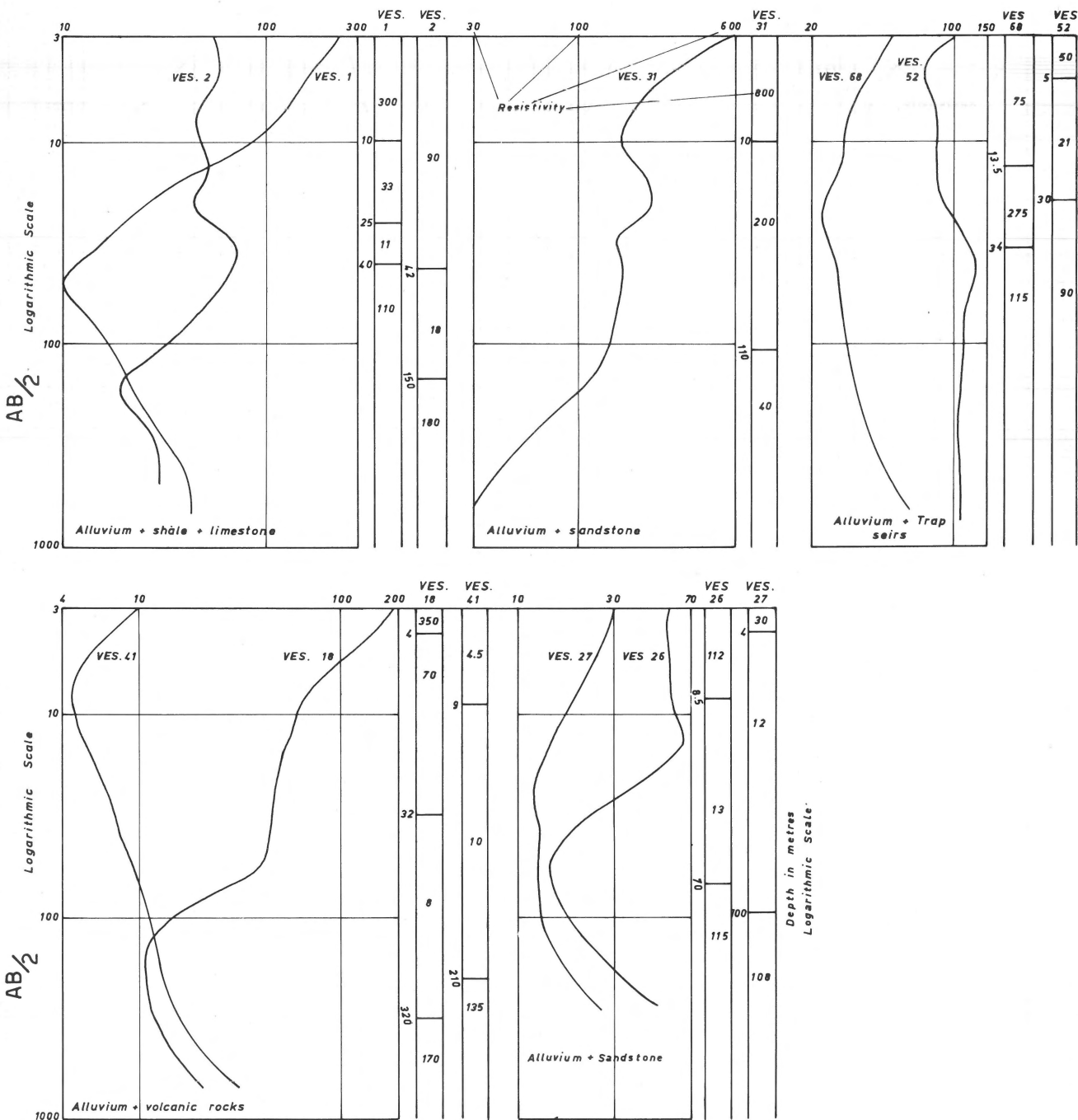


Fig. 3
Representative examples of VES curves obtained at different geological formations, with their interpretations.

(3) It is generally possible to distinguish the wadi fill-Quaternary alluvial cover from the underlying bedrock by the clearest-cut inflections indicated along the curves. Moreover, some curves exhibit a good asymptotic right hand rising, with an angle of about 45° with the horizontal; indicating the high resistivity of the bedrock horizon (e.g., curves of 1, 18, 26, 27, 28, 30, 41, 49 and 55). Also, it is easy to define the thickness of the volcanics included within the

cover, because of their high resistivity contact with the clayey alluvium.

(4) VESes executed at outcropping or near-surface sandstones usually show a descending type curve, on which resistivity decreases with depth, most probably due to the increased water content in deep sandstones. These curves also show a superficial thin alluvial layer with its resistivity higher or lower than that of sandstones (e.g., VES curves

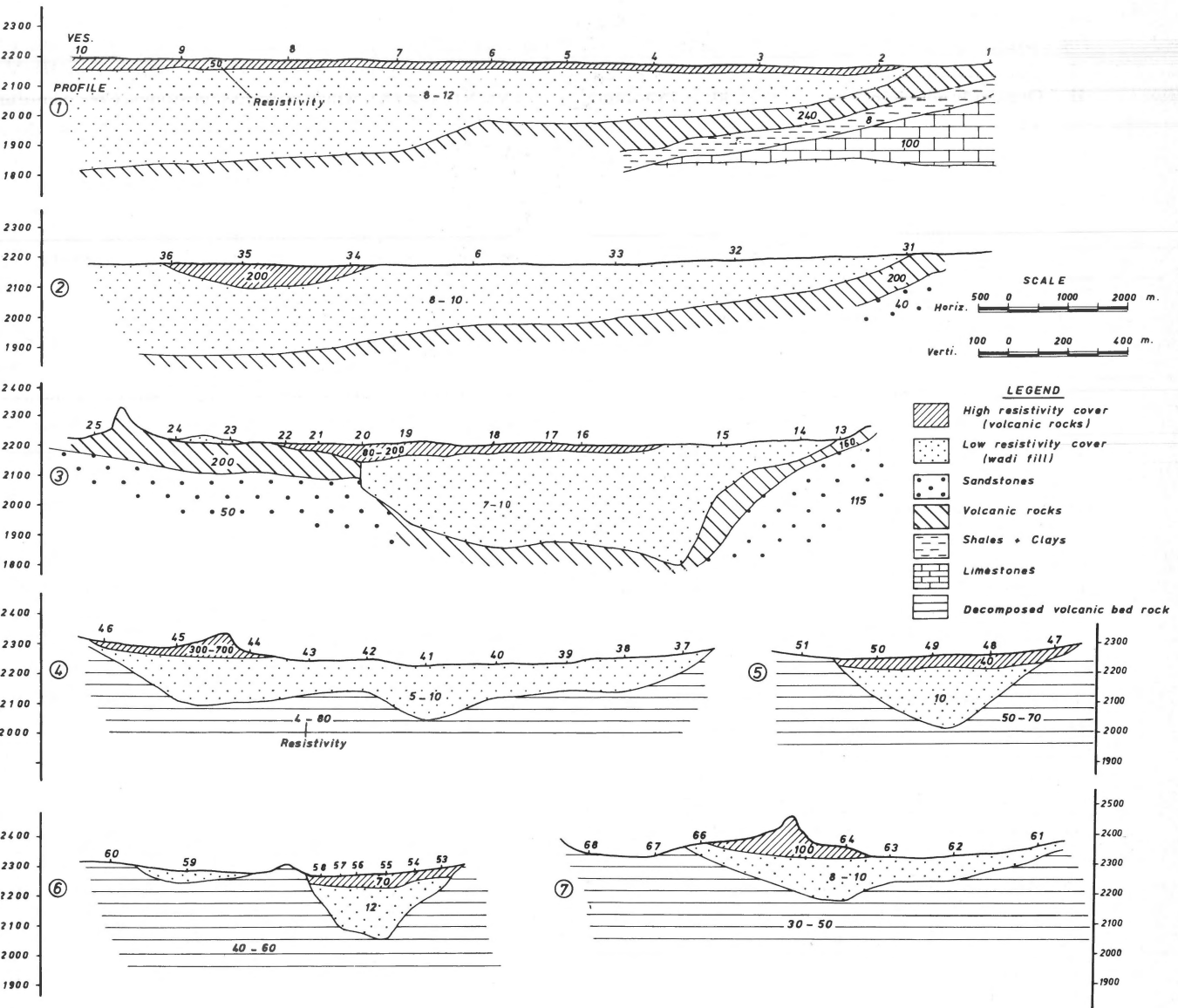


Fig. 4
Subsurface geoelectrical sections as interpreted from electrical data.

23, 29 and 31).

Sandstones with great thickness, between a hundred or so metres and 300-400 m, were defined as the bedrock horizon to the north of an electric discontinuity, roughly running along a line passing by boreholes III and VII. These are characterized by resistivities ranging from 50 to 100 ohmm, and sometimes more than 100 ohmm. To the south of the electric discontinuity, the bedrock is represented by volcanic tuffs, with their maximum thickness (between 300 and more than 500 m) in the Sana'a area and to its south, while their minor thickness may be at the locations of VESes 52 and 68.

5) Curves of VESes performed at or near limestone out-

croppings, generally exhibit the three-layer minimum-type curve referring to dry and wet alluvium, sometimes underlain by minimum resistivity beds of clay or shale, which overlie the high-resistivity limestones (e.g., curves of VESes 1 and 2 conducted in the vicinity of limestone outcrops to the north of the area.

(6) Sometimes the bedrock horizon contains some thin conductive zones, most probably of marls and shales. Also, the resistivity of the bedrock varies from one place to another within the area, since the complex may be formed of different formations, depending on the general geological framework, as well as on the degree of fracturing and water content.

(7) Resistivities measured for the different rock types are:

The Cover:

I – Quaternary Basalts	200 – 2000 ohmm.
II – Dry sandy alluvium	30 – 150 ohmm.
III – Moist or clayey alluvium	5 – 12 ohmm.

The Bedrock:

I – Tuffs of the Trap Series	30 – 50 ohmm.
II – Sandstones	50 – 120 ohmm.
III – Marls and shales	3 – 20 ohmm.
IV – Limestones	30 – 80 ohmm.

(8) Conductivity values measured for waters of numerous surveyed wells varied from 370-1200 Mmhos/cm.

CONCLUSIONS

From the present study, the following conclusions can be drawn.

- (1) It is possible to differentiate between the variable formations encountered in the area, especially between the alluvial cover and the underlying bedrock, on the basis of their resistivities.
- (2) It is ascertained that the alluvial cover, filling Sana'a Valley and its tributaries, has vast extensions and great thickness, ranging from 100 to 400 m, with its maximum value to the north and the least in the south. The trend of the valley is not even, but most probably composed of successive basins of tectonic origin with different depths. Alluvium covers an area of about 152 km², and the aquifer's volume may be estimated as some 17.5 km³. The low apparent resistivity values measured for the cover are certainly due to the presence of clayey and silty materials in it, which is the cause of low permeability.
- (3) Similarly, the characteristics of the Cretaceous sandstones, which represent the main aquifer, were ascertained. They crop out along the sides of the northern part of the basin, and their subsurface extensions were delineated by the electrical soundings. Their high resistivity may reflect their high permeability. In thickness they vary from about 100 m to about 350 m. The volume of this sandstone aquifer may be approximated at 300-500 km³.
- (4) In the Sana'a Basin, there may be a single groundwater system comprising all formations from the Cretaceous to the Quaternary, as no true aquicludes exist.
- (5) Bedrock is represented by tuffs of the Trap Series, and limestones at the southern and northern parts of the area respectively. Both are fractured and consequently may be

water-bearing.

- (6) Nine test wells were drilled at sites selected on the basis of the geoelectrical survey (Fig. 1). Five of these (No. III, V, VI, VII and IX), which crossed sandstones, gave plentiful and good-quality water supplies. These can be considered as productive wells.
- (7) The aquifer horizons here are of a vast extension and considerable thickness, especially the sandstones, a case that could guarantee a good long-term water supply.
- (8) Conductivity of waters of wells may be an indication of their quality and total solid content. The low conductivity values measured here, generally denote low salinity and good quality waters.
- (9) It can be concluded that the resistivity electrical sounding method proved very useful and a suitable prospecting tool for groundwater under conditions similar to those prevailing in the Sana'a Basin.

ACKNOWLEDGEMENTS

I wish to express my gratitude to the officials of the Ministry of Public Works in the Yemen Arab Republic, for permitting me to consult documents and unpublished reports. Also, I am indebted to Prof. Dr. M. G. Barakat, head of the Geology Department, Sana'a University, who kindly read the manuscript and provided helpful criticisms.

REFERENCES

- Geukens, F. 1966 Geology of the Arabian Peninsula, Yemen – Geol. Survey Prof. Paper 560-B (Washington).
- Italconsult 1973 Sana'a *Basin* ground water. In: Water supply for Sana'a and Hodeida, Prepared for World Health Organization and UNDP Program. Yem. 507, Yem. 3202 (Rome).
- Lamare, P. 1930 Sur la structure des montagnes environment Sana'a – Soc. Géol. France. Mem. N.S. 6 (14).
- Lowell, J. D. & G. J. Gernik 1972 Sea floor spreading and structure evolution of southern Red Sea – Amer. Assoc. Petr. Geol. Bull. 56.
- Ministry of Public Works, Y.A.R. – Unpublished reports prepared by American, Chinese, German and Czechoslovak teams on the meteorological and hydrological limited studies on Yemen and Sana'a Basin – Documented in the files of the ministry.
- Seara, J. L. & J. G. Conaway, 1978 On the properties of the reciprocal geoelectrical section – Accepted for publ. in Geophys. Prosp.
- Zohdy, A. A. R. 1968 A rapid graphical method for the interpretation of electrical sounding – Geophysics 33.