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## CAPE YORK PENINSULA GEOPHYSICAL AND GEOLOGICAL GROUNDWATER INVESTIGATION, QUEENSLAND 1974

by

G.R. Pettifer, J. Smart, M.I. McDowell, C.L. Horsfall
and D.L. Gibson

Appendix by

M. Idnurm

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## SUMMARY

A combined geological and geophysical investigation of the Bulimba Formation in the Aurukun area has shown that the unconfined permeable sand bodies which form the major shallow aquifers in the formation trend in an easterly direction. The sand bodies are of the order of 100 metres wide and cover less than three percent of the area investigated. Several resistivity methods were tested, including resistivity probing with surface and downhole electrodes, induced polarization sounding, and resistivity traversing using both conventional direct current and VLF techniques. The area is characterized by high and variable resistivity, aluminous laterite near the surface, and a low resistivity basement, which poses considerable problems in interpretation of resistivity data.

The resistivity sounding methods, VLF resistivity traversing, and Wenner traversing at small electrode spacings have proved to be uneconomical and unreliable as groundwater exploration techniques in this environment.

Areas of locally high-water table associated with the unconfined sand bodies appear as resistivity lows in pole-dipole (half Schlumberger) traversing at electrode spacings large enough to overcome problems of lateral variations in the high-resistivity layers above the water-table. Using follow-up auger drilling to drill resistivity lows indicated by traversing represents a considerable saving in cost over close-pattern drilling without geophysics.

# 1. INTRODUCTION

On the western side of Cape York Peninsula, in the Weipa - Aurukun area, surface water supplies are seasonal and mining and pastoral development relies on the availibility of underground water. Artesian water is obtainable from the Mesozoic sandstone units of the Carpentaria Basin throughout the area but the water is slightly saline (1000 ppm total dissolved salts) and unacceptably high in fluorine (about 15 ppm). Domestic and stock water is almost entirely taken from the Cainozoic Bulimba Formation, which is present in most of the area.

Several hydrological investigations of the Bulimba Formation have been carried out, and aquifers within it have been developed to provide the domestic and some of the processing water at Weipa, and the domestic water at Aurukun Mission. The results of drilling outside the Weipa Peninsula have generally been disappointing, as permeable material appeared to be absent in many areas. Resistivity methods were tried unsuccessfully during a comprehensive groundwater investigation in the Weipa Peninsula in 1970 (Coffey & Hollingsworth, 1971). However, this and other investigations lacked a sound geological basis until the area was mapped in 1972 as part of the regional geological mapping of the Carpentaria and Karumba Basins by the Bureau of Mineral Resources (BMR) and the Geological Survey of Queensland (GSQ), reported by Doutch et al. (1973 and in prep.) and Smart (in press a & b). This work recognized the problem of variable permeability within the Bulimba Formation and suggested that the variations are due to the preservation of old stream channel deposits within the formation. Smart (in Doutch et al., 1973 and in press, a & b) pointed out that drilling had indicated zones of high permeability trending easterly, normal to the depositional strike of the formation.

In view of the more complete picture of the geology arising from this recent work, it was considered that resistivity methods would be applicable to the location of permeable bodies within the formation and preliminary geophysical modelling using parameters from Coffey & Hollingsworth (1971) gave encouraging results. It was felt that the importance of groundwater from the Bulimba Formation in the area and the potential application to similar areas elsewhere warranted a combined geophysical and geological investigation.

In September - October 1974, a combined field party from the BMR Engineering Geophysics Group and the Geological Branch investigated in detail an area about 70 km south of Weipa on the road between Aurukun Mission and North Camp (Plate 1), using resistivity methods. The geophysics was supported by auger drilling using a Gemco 210B operated by a crew from Mineral Resources Branch (BMR). Drilling used both solid and hollow augers but the use of sampling tubes was unsuccessful.

TABLE 1

Stratigraphy for the survey area

| UNIT | Thickness (m) | LITHOLOGY | SEDIMENTARY ENVIRONMENT | PHYSICAL PROPERTIES (Qualitative) |
|---|---|---|---|---|
| Aluminous Laterite | 3 to 9 | Pisolitic bauxite with a wide range of matrix proportions, aluminous nodular ferricrete | Weathering process | Porosity and permeability high to very high. Resistivity very high |
| Bulimba Formation | 15 to 30 | Clayey quartzose sand, and gravel; interbedded with sandy clay | Fluvial: alluvial fan and floodout | Porosity and permeability vary with clay content. Resistivity varies with water content |
| Rolling Downs Group | 600 | Normanton Formation: labile, glauconitic sandstone and siltstone, some slate; calcareous in part | Shallow marine | Permeability low. Resistivity low (saline connate water and high clay content) |
| | | Wilyunya Subgroup: shale and siltstone, calcareous in part, minor labile glauconitic sandstone | Marine | |
| Gilbert River Formation | 140 | Slightly clayey quartzose sandstone and siltstone, minor conglomerate, glauconite in upper part | Fluvial; upper part estuarine to shallow marine | |
| Garraway Beds | 90 | Clayey micaceous quartzose sandstone and conglomerate, in places carbonaceous | Fluvial | |

After Smart (in press, b).

Personnel consisted of G.R. Pettifer and J. Smart (party leaders), M.I. McDowell and C.L. Horsfall (geophysicists), D.L. Gibson (geologist), D.K. McIntyre and W.A. Chadwick (mechanics), G. Brandon (driller) R.D.E. Cherry and L. Rickardsson (field assistants) and two field hands.

We wish to express thanks to the management and staff of Aurukun Associates for the use of the facilities of North Camp and for their generous assistance. We are also grateful to the people of Aurukun and the staff of the Mission for their co-operation and assistance during the survey.

## 2. REGIONAL GEOLOGY AND HYDROGEOLOGY OF THE BULIMBA FORMATION

### 2.1 General

The survey area lies on the western side of Cape York Peninsula, within the Mesozoic Carpentaria and Cainozoic Karumba Basins. The geology of the area has been described by Doutch et al. (1973), Smart (in press a & b) and Doutch et al. (in prep.). The stratigraphy is summarized in Table 1.

### 2.2 Bulimba Formation

The present investigation was concerned mainly with the Bulimba Formation and the overlying aluminous laterite which has developed from it by lateritic weathering. The term aluminous laterite was used by Doutch et al. (1973) for the areas of laterite in Cape York Peninsula where alumina was in greater abundance than iron, and in practice covered a wide range of alumina contents from less than 10% to over 60%. Areas of potential economic bauxite (in Cape York Peninsula) have over 50% alumina and a relatively low silica content. The present investigation was within the area of potentially economic bauxite and the term bauxite is used in this report to describe the aluminous laterite. The term sub-bauxite is used for the part of the Bulimba Formation between the water-table and the base of the bauxite. It is distinct in electrical properties from the bauxite and the Bulimba Formation below the water-table. It is not a geological unit but is a geophysical unit which needs to be recognized.

The Bulimba Formation extends along the west coast of Cape York Peninsula for a distance of about 650 km and underlies an onshore area of about 120 000 $km^2$. The formation was deposited as a large sheet of sediment in a fluvial environment, by streams flowing from provenance areas in the east (Smart, in press, a). It consists of sandy clay and clayey sand, with minor clean sand and gravel. Cementation is generally poor and much of the formation is unconsolidated. In the south, where it is buried by the Wyaaba Beds, the formation contains important aquifers which are locally artesian (Grimes, 1972; Doutch et al., in prep).

The area has been affected by several episodes of lateritic weathering (Smart, op cit.) which have converted the upper part of the Bulimba Formation into pisolitic bauxite of high to very high permeability. The remainder of the formation has been strongly leached and the feldspar clasts are now represented by kaolin pseudomorphs. Volume charges during the lateritic weathering have produced numerous vugs and fissures within the formation. This effect, combined with the intergranular pore space produces a relatively high permeability in many areas. However, bore development in such areas cause a collapse of the vugs and the kaolin pseudomorphs break down to soft clay, releasing quartz of silt to fine sand grainsize, originally present as inclusions within the feldspar clasts (Edwards, 1957, 1958; Smart, in press, a). This reduces the permeability of the formation by decreasing the sorting and causes problems of abrasion in pumps and other equipment.

Features of the formation which are important in understanding its hydrogeology are discussed below. In general these are based on the results of earlier groundwater investigations and BMR regional mapping. Drilling during the present survey confirmed the conclusions drawn by Smart (in Doutch et al., 1973).

The fluvial depositional environment caused Smart (in Doutch et al., 1973) to suggest that permeable material might be restricted to old stream channels, trending easterly, parallel to the original dip of the sediment. The present investigation suggested this to be the case (Plates 17, 18, 19). It also showed that the present-day distribution of permeability is related not only to the original depositional conditions and lithology, but also to the effects of lateritic weathering.

Much of the Bulimba Formation was originally fledspathic sand, the feldspar clasts being associated with quartzose sand of similar grainsize (Smart, op. cit.). The original grainsizes ranged from cobbles to clay, although very little material above granule size was encountered in the area of investigation.

During the present investigation eight bodies of permeable material were located along the 8-km traverse line, of which four were above the water-table. Their general trend is easterly and the length in the order of hundreds of metres, and the width tens of metres. The margins of the bodies are quite steep in some areas (Pls. 17, 18) while others pass laterally into more clayey sand. The geometry suggests stream channels filled with feldspathic sand, but the original grainsize is not determinable owing to the lateritic weathering effects on the feldspars (cf. Mousinmo & Amador, 1974) and it is difficult to establish a detailed sedimentary environment.

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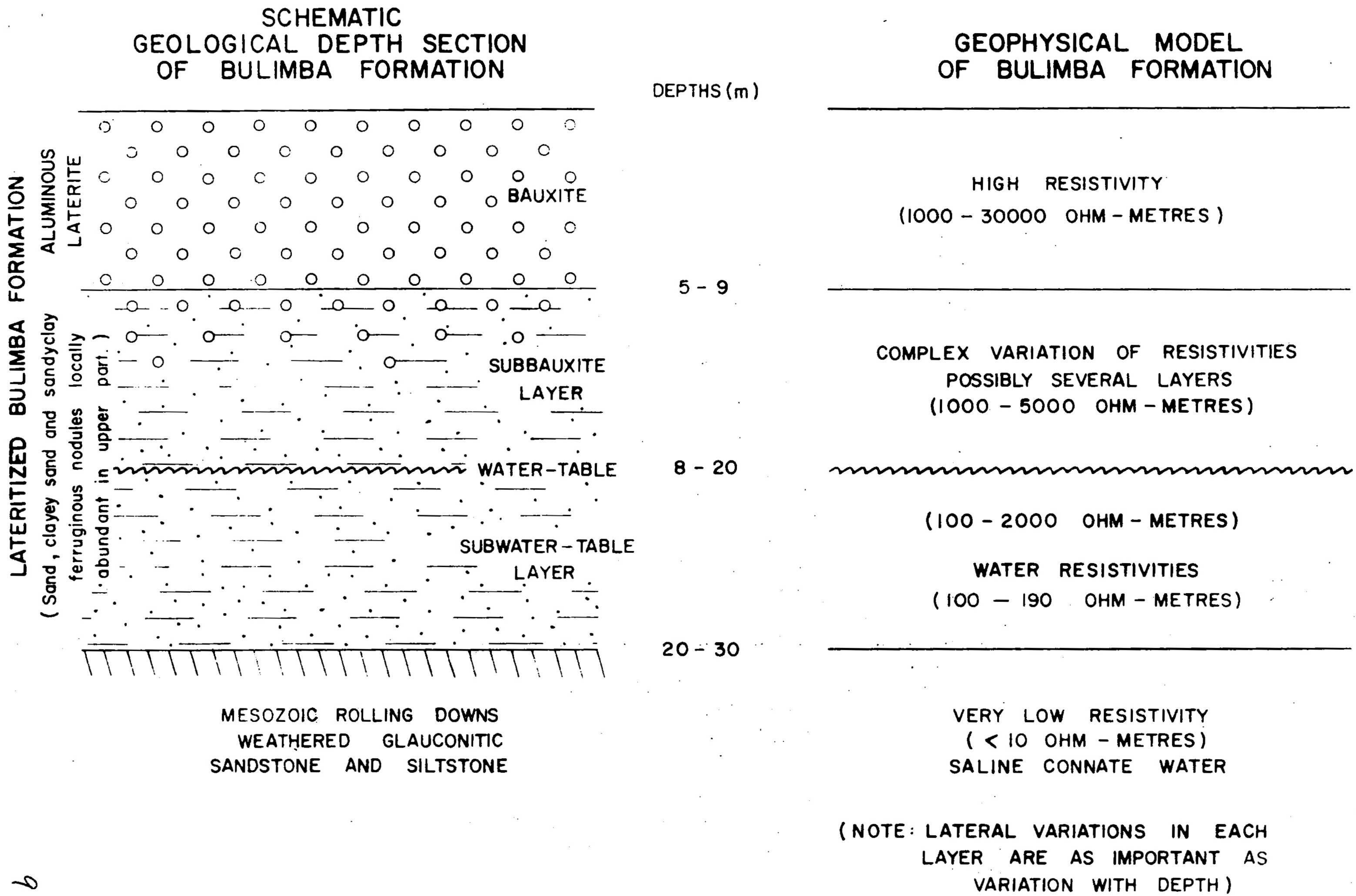


FIG 1

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## Groundwater

Previous groundwater investigations in the Weipa-Aurukun area (Section 3, below) indicate that, in that area, the Bulimba Formation has a fairly high overall permeability, and that elongate bodies of higher permeability trend east. North and south of the Weipa Peninsula, overall permeability is lower, but the same easterly trend of relatively permeable bodies is apparent.

In the Weipa Peninsula, Coffey & Hollingsworth (1971) concluded that there was an unconfined aquifer, with vertical recharge through the highly permeable aluminous laterite. Vertical recharge appears to be the only suitable mechanism throughout the Weipa-Aurukun area, but in many places the permeability of the upper part of the formation is sufficiently low to make the aquifer semi-confined. This is shown by the difference between the top of the water-table and the piezometric surface. In the larger permeable bodies, there is generally an unconfined aquifer and the water-table is fairly shallow in contrast to the adjoining areas of semi-confined aquifer. The high water-table is shown as a resistivity low on pole dipole (PDP) traversing. This is an important finding of the drilling during this survey. It was found that large permeable bodies were several kilometres apart and trended east. Their lithology ranges from degraded feldspar with minor sand, to sand with minor degraded feldspar. Only the latter type have potential for water supply, but discrimination can only be made by drilling.

The two sand bodies drilled in detail during the present survey (Pls. 17, 18) were respectively, about 120 m wide by 11 m thick and 90 m wide by 10 m thick along the north-south traverse line. They trended about east-northeast and were traced by drilling for several hundred metres in that direction, but their total lengths are unknown.

## 3. PREVIOUS GROUNDWATER INVESTIGATIONS

Previous hydrological investigations of the Bulimba Formation have lacked a full appreciation of the geological conditions. The first investigator was F.W. Whitehouse, who prepared an unpublished report for the Irrigation and Water Supply Commission (IWSC) on the water potential at Aurukun Mission in 1947. He considered that the Bulimba Formation had the best water potential in the area. A well was already in existence at that time, and a bore was subsequently put down by Comalco in 1963. In 1969, IWSC supervised a drilling program around the Mission. Water was located in all holes, but great difficulty was experienced in screening the fine quartzose sand present within the aquifer and several bores were abandoned.

On the Weipa Peninsula, investigations were carried out between 1959 and 1967 (Chapman, 1960, 1963; Green, 1962; IWSC, 1963, 1967). These were all of a hydrological nature and made little comment on the geology. In 1970 IWSC put down 24 bores near Hey Point, across the Embley River from the Weipa Peninsula, to test the water potential for a proposed prawning station. Their results are generally similar to those at Weipa, but most holes encountered impermeable material.

The most comprehensive investigation of the hydrology of the Bulimba Formation in the Weipa Peninsula was carried out for Comalco by Coffey and Hollingsworth in 1970 (Coffey & Hollingsworth, 1971). This consisted of a pattern of drillholes, including a detailed east-west line, to define aquifer geometry and properties. Some resistivity depth probes and traversing were carried out. Extensive pumping tests were conducted and conclusions drawn on the longterm yield of the aquifer.

The survey showed that in the Weipa Peninsula the Bulimba Formation was apparently more permeable than elsewhere, but Coffey & Hollingsworth failed to recognize the easterly trend of permeability shown by the aquifer geometry as defined by drilling and by the drawdown affects during pump tests. The drilling tends to have an east-west distribution, and the detailed drilling was along an east-west line, so that variations in a north-south direction are masked.

Variations in permeability were attributed to changes in the clay content and an attempt was made to measure the changes using resistivity probing and traversing techniques, but without marked success. Coffey & Hollingsworth suggested that probes could only locate the base of the aquifer and that traversing was unsuccessful because of lateral variations of bauxite thickness and resistivity. However, traversing was carried out in an east-west direction, so it could not show variations in permeability along the north-south depositional strike. It was also noted that the high resistivity of the bauxite and low resistivity of the Rolling Downs Group, which underlies the Bulimba Formation in the area, prevented accurate determination of resistivity and thickness of the intermediate aquifer layer and thus could not define clay content. The resistivity instrument used (Yokogawa Electrical Works Specific Earth Resistance Tester TY 3244) was very low-powered for the high surface resistance environment encountered and this restricted the scope of the investigation.

Resistivity logging of holes was carried out during the survey but the results gave little indication of resistivity distribution with depth, particularly above the water-table, in the bauxite and sub-bauxite layers. This is probably due to the use of conductive drilling muds.

In 1971, Coffey & Hollingsworth made an assessment of the water potential of the Bulimba Formation within the area of the bauxite A to P held by Tipperary Land Development Corporation (now held by Aurukun Associates). The investigation consisted of a terrain analysis, followed by reconnaissance drilling. Results were disappointing and the general level of permeability was found to be lower than at Weipa. It was also concluded the the bores at Aurukun Mission were not in the Bulimba Formation, but in sediments of the Watson River. However, the bore density was too low to preclude the existence of permeable bodies in which bores could be developed, particularly as the Aurukun Mission bores are undoubtedly in Bulimba Formation.

North of the Weipa Peninsula there has been little drilling to date, but results have been disappointing. The situation appears similar to that in the Aurukun area.

## 4. OBJECTIVES OF THE 1974 INVESTIGATION

The objectives of the survey are broadly: to define the detailed hydrology of the Bulimba Formation in the laterite areas by a combination of geophysical techniques and drilling and to determine whether geophysics can be used economically to locate permeable zones in the formation and thus eliminate the need for expensive close-pattern drilling over large areas.

Specifically, the objectives are as follows:

4.1. To determine the vertical and horizontal resistivity distribution in the laterite, enabling a more accurate description of the geophysical problem and the resistivity anomalies expected. Previous investigations (Section A) had not shown conclusively that a resistivity contrast existed between the permeable and impermeable material beneath the water-table. Also the nature of the resistivity variation in the sub-bauxite layer above the water-table is not evident from previous work.

4.2. To carry out the resistivity survey using more powerful and sensitive equipment than used in previous investigations and thus overcome instrumental limitations of effective depth of investigation in depth probing and traversing.

4.3. To determine the shape and orientation of any major permeable bodies encountered.

4.4. To carry out drilling of geophysical anomalies and enable good geological control and continuous assessment of the geophysical work as it is carried out.

Within this framework several more detailed objectives of the survey can be outlined.

4.5. Assessment of the high-powered resistivity transmitter in a dry environment with high surface resistivity.

4.6. Assessment of the effectiveness and economics of use of several resistivity probing and traversing techniques for locating permeable zones and defining resistivity variations, either individually or in conjunction with other geophysical techniques of drilling. The techniques assessed included

(a) Conventional resistivity probes

(b) Alfano probes using down hole electrodes

(c) Conventional traversing techniques using various effective depths of penetration

(d) VLF traversing

(e) IP methods

(f) Resistivity logging

(g) Gamma-ray logging.

To achieve these objectives an 8-km test traverse was chosen between Beagle Camp and Aurukun (Plate 1), for detailed investigation. The site chosen contained three drill-holes from a previous investigation by Coffey and Hollingsworth and was considered to be representative of the general area. In addition, to provide basic geological information on the area, nine auger holes were drilled throughout Aurukun Associates A.T.P. and around Aurukun Mission. The geological logs of these holes are presented in Appendix 2.

## 5. METHODS AND EQUIPMENT

### 5.1. Resistivity Probing and Traversing

The resistivity method involves measurement of bulk resistance of the sub-surface material by passing current (I) between two transmitting electrodes and measuring the resultant voltage difference (V) between two receiving electrodes. The value (V/I) thus obtained is callen an apparent resistance for the particular interelectrode distances chosen. The apparent resistivity ($\rho$) is generally used in resistivity work and is equal to the product of the apparent resistance and a geometrical factor (K). The geometrical factor depends on the electrode configuration used. Several conventional, collinear electrode configurations were used on the survey, including the Wenner, Schlumberger, and half-Schlumberger (or pole-dipole) configurations. If A and B denote the transmitting electrodes, M and N the receiving electrodes and O the centre of the electrode spread, then in the Schlumberger configuration the distance AB is at least five times the distance MN. In the half-Schlumberger (or pole-dipole) configuration, one of the current electrodes, say B, is placed effectively at infinity; In the Wenner configuration the four electrodes are equally spaced with AM = MN = NB = a. The geometrical factors for each configuration are given in Table 2.

Table 2 Geometrical Factor

| Configuration | Geometrical Factor (K) |
|---|---|
| Schlumberger | $\frac{\pi}{4}\left(\frac{(AB)^2}{MN} - MN\right)$ |
| Half-Schlumberger (pole-dipole) | $\frac{\pi}{2}\left(\frac{(AB)^2}{MN} - MN\right)$ |
| Wenner | $2\pi a$ (a = AB/3) |

The bulk apparent resistivity measured for a particular electrode spacing represents an average resistivity of sub-surface material over a volume with dimensions of the order of magnitude of the electrode spacing. For small electrode spacings the apparent resistivity is affected by near-surface resistivities and is influenced more by deeper resistivities as the electrode spacing increases. In the resistivity depth probing method, the electrodes are progressively expanded about the centre of the spread O. The Schlumberger and half-Schlumberger configurations were used for depth probing. The current electrodes are moved out until the voltage between the potential electrodes MN becomes very small. The electrodes MN are then expanded out and a repeat reading is taken with the large MN spacing. The current electrodes are then expanded further. Maximum AB/2 (AO) values of 500 m were used. The apparent resistivities are plotted against electrode spacing (OA = AB/2) on standard bilogarithmic scale paper to give a curve which gives an indication of the variation of apparent resistivity with depth penetration. The plots are shown in Plates 2 to 12. The apparent resistivity curve is interpreted by assuming a layered resistivity medium and by matching the field curve with model curve for layered medium. The field curves suggest as many as 8 layers are present. One main problem in interpretation of field curves of the type encountered in this survey is that no mathematical modelling program currently available can accurately model the large changes in resistivity between the high surface resistivities and the conductive Rolling Downs group beneath the Bulimba Formation, particularly where the apparent resistivity values decrease rapidly. The interpretation procedures are discussed more fully in Section 7.

In the field operations, considerable difficulty was experienced in transmitting the current into the ground because of the dry, heavily leached, highly resistive soils. Considerable effort was put into using multiple electrode systems, or buried aluminium foil electrodes. Electrodes were moistened with salt water. This slowed field work considerable and the quicker half-Schlumberger configuration with a fixed, remote aluminium foil electrode and one mobile current electrode was adopted instead of the Schlumberger technique.

The resistivity current source used was a Geotronics model FT10 (S/N 1011) induced polarization transmitter, which is capable of delivering a maximum voltage of 850 V and a maximum current of 10 A. In the conditions encountered 0.4 A was the maximum current attainable using surface electrodes. It is considered that a transmitter capable of delivering higher voltages (say up to 3000 V) would be more suitable for production work in this environment. The transmitter current was calibrated against the receiver by measuring, with the receiver, the voltage across a standard 100 m V/A resistor which is built into the output circuit of the transmitter. The calibration was necessary because of the very low currents employed.

The received voltages varied from 30 μV to 50 V with SP drifts in a ten-second period as high as three times the primary received voltages. The received voltage was fed through a BMR-constructed, spontaneous potential (SP) back-off box, either direct to a Data Precision Volt meter Model 245 or Hewlett-Packard 7100 B Moseley servo type pen recorder, or first through a Fluke High Impedance voltmeter (Model 845 AB) and then to the multimeter or Moseley recorder. The Fluke voltmeter was used as a differential DC amplifier. All probes were conducted using a standard 10-second period induced polarization (IP) waveform for the transmitted current. Porous pot non-polarizing electrodes were used for receiving electrodes.

In some probes IP measurements were made using the frequency domain method which measures the percentage decrease in measured resistivity as the transmitting frequency is increased. Square wave currents of 3 and 0.3 Hz were used with a Geomite R100 I.P. receiver. This instrument measures voltages up to 1 V only. The received voltages in the probings were commonly less than millivolt for AB/2 greater than 150 metres and less than 10 millivolt for AB/2 greater than 50 m. These low voltages made IP readings very timeconsuming and as a result the IP method is considered uneconomical in this environment.

To overcome the problems which arise in the interpretation of conventional resistivity probes due to the large resistivity contrasts between the surface laterite and the Rolling Downs Group, obscuring the influence of the intermediate layers, a down-hole transmitting electrode was used with a remote transmitting electrode and a moving receiving dipole length, b (Fig. 2). This technique was first investigated by Alfano (1962) and bears his name. The geometrical factor for

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this electrode configuration depends on the depth of the down-hole electrode (d). If a is the distance of the dipole centre from the top of the vertical hole, then the geometrical factor for the Alfano configuration is $2\pi \quad (a^2 + d^2)^{3/2} \; / \; a \; (MN)$. The method of interpretation is discussed in Section 6.5.

The resistivity traversing method involves measuring lateral changes in the bulk apparent resistivity. The electrode separations are kept constant but the whole electrode spread is moved at regular intervals along a traverse. As the effective depth of investigation depends on the electrode spacings the traversing can be 'focussed' to a particular range of depths. Traversing with small electrode spacings reflects the variations in resistivity of the near-surface layers whilst the influence of deeper layers can be investigated by a greater electrode spacing.

To obtain an indication of variations in resistivity of the bauxite and upper sub-bauxite layers, Wenner traversing was carried out with an electrode spacing a = 10 m and a station interval of 10 m, using an Evershead and Vignoles Megger Earth Tester (0-3000 ohm). Care had to be taken to water the electrodes well as this instrument was very sensitive to electrode contact resistance. It is considered that the Megger type instruments are not ideally suited to this high surface resistivity environment. The Wenner Traversing at 10 m interval could be carried out with 4 men covering 1.5 to 2 km per day.

A second traverse was surveyed with a larger electrode separation using a half-Schlumberger configuration (OA = AB/2 = 50 m, MN = 20 m, station interval 20 m). The half-Schlumberger (or pole dipole) traversing was carried out using a truck mounted with the high-powered transmitter and towing the trailermounted generator. The remote current electrode wire was let out 20 m at a time from the transmitter as the traversing progressed. In this manner, by connecting cables of 500 m and 1000-m lengths, the remote electrode need not be disturbed in a halfdays work. The receiving equipment was located in a Landrover 50 m ahead of the transmitter but could conceivably be mounted in the same vehicle for production work. In this manner a 5 to 6 men team, could cover 5 km per day by traversing. It should be noted that the main factors limiting the speed of the traversing method are the time taken to reduce current electrode contact resistance and difficulties with tangling of wires in broken tree roots on the very rough bulldozed tracks common in the survey area. For this reason the half-Schlumberger method, in which only one current electrode is shifted and short (less than 20 m) electrode wires are used, preferably with two vehicles, was found to be the most efficient method of traversing at AB/2 distances of the order of 50 m. The traversing method would also be greatly speeded by salting and watering buried aluminium foil strip electrodes, ahead of the traversing work.

## 5.2. VLF Resistivity traversing

In addition to the standard DC resistivity traversing techniques, resistivity traversing was also carried out using the Geonics Ronka EM16 VLF equipment with the EM16R direct reading resistivity attachment. The VLF prospecting technique (Paterson & Ronka, 1971) involves monitoring the signal of a VLF navigation transmitting station, in this case the Northwest Cape (22.3 kHz) station in Western Australia. This station produces a horizontal magnetic field which propagates in all directions. When these magnetic fields encounter conductive bodies in the ground, secondary magnetic fields are radiated. In addition, by the well-known skin effect, the strength of the magnetic field decreases with depth in the ground according to the vertical and lateral distribution of resistivities. The effective depth of investigation is governed by the depth at which the VLF electromagnetic wave strength is attenuated effectively to zero. This depth of investigation is the order of the skin depth. At 20 kHz, the skin depth varies from 30 to 300 m for resistivities varying from 100 to 10000 ohm metres, assuming an homogeneous earth. The EM16R measures the ratio and phase between the horizontal electrical field and magnetic field components of the V.L.F. signal. The electric field (Ex) is measured in the direction of the transmitting station and the magnetic field (Hy) at right angles. The ratio of the two fields is related to the apparent resistivity by the well-known Cagniard formula from magneto-telluric theory (Cagniard, 1953)

$$\rho = \frac{1}{2\pi fu} \left(\frac{Ex}{Hy}\right)^2$$

where u = permeability of the medium
f = frequency

The EM16R has two high-input resistance (100 megohm) probes which do not require watering, for measurement of the electric field. The probes are placed 10 m apart and the magnetic field sensing coil is oriented at right angles to the line of probes. The instrument has a direct reading resistivity reading range of 10 to 30000 ohm metres in three scales. Stated accuracy for the resistivity measurements is 10% and for the phase measurements $\pm$ 2%.

Measurements of the parameters of the ellipse of polarization formed by the primary magnetic field and the phase-shifted secondary magnetic field were also attempted with the EM16 unit alone. The instrument gives the secondary in-phase and quadrature signals as a percentage of the primary signal. For tabular bodies, such as were encountered in the survey area, the expected values of in phase and quadrature fields is very small and in fact readings showed little variation along the traverse line. The readings were discontinued for this reason and the

EM16 was used solely with the EM16 attachment to give direct readings of magnetotelluric resistivity at 22.3 kilocycles.

5.3. VLF Resistivities - Laboratory Measurements

A lump sample of bauxite was tested for variation of resistivity with frequency for dry, semi-saturated and fully saturated conditions by Dr M. Idnurm of the BMR Rock Testing Laboratory. The measuring techniques are described in (Appendix 1). Plate 21 shows the results. The principal result of these experiments is that dry bauxite shows a resistivity at 22.3 kHz which is at least half that of its DC resistivity. Fully saturated bauxite shows little decrease in resistivity, the resistivity at 22.3 kHz being 0.8 of the DC resistivity. Semi-saturated bauxite shows intermediate behaviour between the dry and fully saturated conditions. It was not possible to obtain undisturbed samples of the clays and sands of the Bulimba Formation so no similar measurements have been carried out on the material beneath the bauxite.

5.4. Resistivity Logging and Gamma-ray Logging

The logging of the holes was carried out initially using a Well Reconnaissance suitcase logger Model 9246 with a single-point resistance tool. However, instrumental trouble and poor penetration of the tool forced the abandonment of resistivity logging with this logger. Difficulty was experienced in maintaining the water-level of the hole during logging, particularly in areas of relatively high permeability. This problem could be circumvented with a large water tanker and sufficiently high capacity pump. Owing to the poor quality of the initial resistivity logs most of the holes were relogged for resistivity, in many cases a considerable time after drilling. Because of the tendency for holes to collapse beneath the standing water-level the resistivity logs are not as complete as would be desired.

As a replacement for the single-point resistance tool a four-electrode Wenner configuration (a = 0.5 m) logging tool was improvised and readings were taken every 0.3 m down the hole with the Megger earth-tester. This arrangement could easily be adapted to give a continuously recorded log on a chart drive recorder. This logging tool gave good penetration through the borehole fluid and clay coating and circumvented problems of contact resistance with surface electrodes as all current electrodes were in the borehole fluid. The principal advantage of this logging technique in auger holes is that the tool can be readily abandoned in the event of the hole collapsing.

The resolution of the four electrode system is not as good as three electrode systems (Guyod, 1944). However, the four-electrode system enabled quick logging time which was essential for the maintenance of water-level in the bore during logging. A total of 30 bores were logged out of 40 bores drilled along the geophysical traverse. Bores drilled elsewhere were not logged for resistivity.

Gamma-ray logging was carried out by the geologist on all holes drilled. The suitcase gamma logger was not calibrated against a standard source and the gamma log serves only as a qualitative guide to variation of clay content for each particular hole. A total of 56 holes were drilled and logged with the gamma tool during the survey. A time constant of 2 seconds and logging speeds of 10 m/minute were used throughout.

## 5.4. Resistivity of water samples

Water samples were collected from boreholes and resistivities were measured using a mud-cell (op. cit.) and the Megger. The results of these measurements are given in Table 3 below.

Table 3. Water Resistivities

| Sample Location and Description | Resistivity (ohm metres) |
|---|---|
| H5 | 166 |
| H7 | 160 |
| H8 | >190 |
| H9 | >190 |
| H10 | >190 |
| H15 | 147 |
| H16 | >190 |
| H17 | >190 |
| H26 | >190 |
| H27 | 177 |
| H28 | 180 |
| H29 | >190 |
| H33 | 149 |
| Clay Slurry | 150 |

# 6. RESISTIVITY PROBING RESULTS

## 6.1 General

This section will deal with the objective of determining the expected vertical distribution of resistivities and the economics of resistivity sounding techniques. Firstly a geophysical model of the Bulimba Formation is formulated and then a discussion of the possibilities of predicting lithology from resistivities measured both by surface techniques and downhole logging follows. Finally the reliability and economics of surface sounding, the Alfano probing technique and induced polarization soundings are assessed.

The resistivity probes were carried out at boreholes H1 to H11 and the field probe curves, interpretation and borehole geological logs for each probe are shown in Plates 2 to 12. The gamma-ray, resistivity, and geological logs are shown in Plates 13 to 16. The interpretations derived have utilized all available information from the half-Schlumberger and Alfano probes and the resistivity logging.

## 6.2. Resistivity model of the Bulimba Formation

The previous work (Coffey & Hollingsworth 1971) plus the detailed work of the present investigation has established a clear picture of the expected vertical distribution of resistivities. The relation between the geological section and the geophysical model used to quantify the geology is given in Figure 1. The geophysical model is simplified of necessity and divides the Bulimba Formation into layers of distinct physical properties rather than lithological characteristics.

The essential features of the geophysical model are firstly the high surface resistivity even in places where the bauxite is absent; secondly the large and generally continuing decrease in resistivity with depth which poses problems in interpretation of surface probes. Particularly important is the complex sub-bauxite layer. The logging results (Section 8) suggest that this layer in places may have an apparent resistivity depth variation which, to the first order, may be quantified as linear or exponential. In other places the resistivity distribution of this layer may be a simple, one or more layered distribution. The range of resistivities is generally from 1000 to 5000 ohm-metres - much less than the bauxite layers. The bauxite layer plus the sub-bauxite layer gives a complex high resistivity zone which varies in thickness from 8 to 20 m.

Generally the resistivity drops markedly at the water-table; however, resistivities as high as 2000 ohm metres have been interpreted from the logging. Minimum values of 100 ohm metres have been suggested by logging and the Alfano technique also.

The Mesozoic Rolling Downs Group forms a basal low-resistivity layer. The present investigation has shown variations in the resistivity of the Rolling Downs Group (5 to 10 ohm metres) which are presumably related to variations in pore water salinity, porosity, clay content and the presence of graphites and disseminated sulphide in the upper part of the Rolling Downs Group. The previous geophysical survey (Coffey & Hollingsworth, 1971), because of instrumental limitations was unable to define the resistivity or thickness of the conductive layer. Most depth probes in the current investigation show an increase in resistivity in the Rolling Downs Group to values of 10 to 30 ohm metres at interpreted depths ranging from 70 to 170 m. The determination of the thickness of the low resistivity layer at the top of the Rolling Downs Group is uncertain due to the small amount of data at $AB/_2$ values greater than 200 m and because of the approximate interpretation techniques used.

This increase in resistivity within the Rolling Downs Group is probably related to a localized decrease in shale content with depth in the Group. This deeper, high-resistivity layer is of secondary interest only to the present investigation and for the purposes of the interpretation in this report, the Rolling Downs Group is considered to form a low-resistivity half-space beneath the Bulimba Formation.

## 6.3. Relation between Bulimba Formation resistivity and lithology

Coffey & Hollingsworth (1971) concluded that the surface resistivity technique could not be used to map changes in clay content in the aquifer and hence changes in permeability.

The arkosic and lateritized environment of the Bulimba Formation with the complexities of occurrence of clay as 'free' clay and pseudomorphs after feldspar (Section 2.2) plus the high resistivities of the bore-water in the Bulimba Formation (Section 5.4, Table 3) make it difficult to quantify the lithology in terms of resistivity.

Saturated sediments can generally be readily distinguished by resistivity from the sediments above the water-table and there is evidence from logging and drilling to suggest that that resistivity of the saturated sediment increases with decreasing permeability. Evidence of this can be seen in H6 (Chainage, 500 m, Pl. 13) where the hole bottomed in highly compact sandy clay and the resistivity log shows an increase in resistivity just below the standing water-level at the time of drilling. The depressed standing water-level at the time of drilling indicates the lower permeability. Similarly on H8 (Chainage 1140, Pl. 13). In H55 (Chainage 4300, Pl. 15) the resistivity increases below the water-table in the impermeable clayey sand.

Because of low ionic content of the pore water in the Bulimba Formation, it is certain that the low resistivities generally associated with clays (say less than 50 ohm metres for most groundwaters), are not observed in this environment.

Generally the ions in solution react with the clay particles to produce an extremely complex pattern of conductivity variation with porewater salinity, for the sediment. Generally the presence of 10 to 20% clay in sandy sediments will lower the sediment resistivity to below that of pore water resistivity for groundwater resistivities in the range 20 to 50 ohm metres. Also estimates of porosity from sediment resistivity based on the Archie Formula for formation factors generally yield unrealistically high values of porosity if appreciable quantities of clay (say greater than 10%) are present in a sediment which has the normal range of groundwater salinities.

The sediments of the Bulimba Formation below the water table often show higher resistivities (100 to 2000 ohm metres) than the pore water resistivities (100 to greater than 190 ohm metres). This is despite the fact that clay contents are greater than 20% (commonly 40 - 50%). This illustrates the complex behaviour of clays in their conducting properties. Estimates of porosity using the Archie formula yield reasonable values of porosity (15 to 45%) suggesting that the clays are virtually 'inert' and can be effectively considered to form a high resistivity matrix for the more conductive pore water. Accepting this argument it follows that an increase in clay matrix or increase in quartz or feldspar grain size will decrease effective porosity and increase resistivity. The effective porosity and permeability rather than porosity is more likely to affect the resistivity, given the high clay contents. Effective porosity refers to the fractional volume of pore space able to take part in ionic conduction through the interstital fluid.

Thus we conclude that higher resistivities can generally be expected to indicate lower permeability (and effective porosity) for sediments saturated with fresh ground-waters. The resistivity cannot always give a good indication of clay content because of the high resistivity of the groundwater. The structure of the clay sand mixture may have a more important bearing on resistivity than clay content alone.

In the semi-saturated zone above the water table resistivities vary markedly. Generally the width of the capillary fringe above the water-table varies from 5 cm for coarse sands to 4 m to fine clays. Above the capillary zone the water content depends on the specific retention properties of the sediment. Clays have high specific retention (50% of pore volume) whilst sands have less than 10% retention. The zones above the water table are characterized by semi-saturated voids with the degree of saturation depending strongly on grainsize and clay content. (Bear, 1972).

The observed continuous variation of resistivity with depth (Section 6-1) is most probably due to this phenomena. Examination of cuttings from bore-holes H2 and H48 (Plate 15), for example, show an increase in grainsize from the water-table to the nodular zone beneath the bauxite and the resistivity logs show a continuous increase in apparent resistivity above the water-table. This hypothesis is certainly not discounted by the current drilling results; however, it can be fully verified by taking less disturbed samples than obtained by the current augering technique. Given the fragile structure of the clays, the value of sieve analyses is doubtful and visual examination of the sediment samples is considered a better method of assessing average grainsize.

The above discussion has attempted to explain the observed resistivity distribution and has shown that for saturated sediments generally resistivity has an inverse relation to permeability. In the semi-saturated zone there is evidence to support the hypothesis that resistivity decreases with increasing clay content and decreasing grainsize. Further work is needed to fully verify these assertions.

## 6.4. Interpretation of subsurface resistivities from surface probes

Having established that there is a general relation between subsurface permeability and resistivity (Section 6.3.), it remains to assess the ability of the probing technique to determine subsurface resistivity reliably and economically. This assessment will be considered under several headings.

### 6.4.1 Optimum spacing of resistivity probe locations

If only the probing method is used without any extra technique to locate favourable locations for investigation by probing, then from the evidence of the current investigation probes would have to be carried out at least every 100 m on a traverse along depositional strike to have any chance of locating a major permeable zone. In the test area the two major permeable zones (H7 and H10) occupy less than 4% of the traverse line length. The eleven probes by extremely good luck happened to be positioned over the two major permeable zones in the test area. There was a 1 in 35 chance of this occurring and this order of chance is considered unacceptable for an economic investigation technique.

Also the cost of depth probing at least every 100 m given the large areas to be covered is also considered prohibitive for most large scale water investigations. It follows that on purely statistical grounds the probing technique will be an uneconomical investigation technique unless a reliable traversing method is found to site depth probes in favourable areas (see Section 7).

### 6.4.2 Difficulties in interpretation of the sounding curves

The type of probe curves encountered on this area (types QQ, KQ and other variants) are extremely difficult to interpret reliably particularly in the field using auxiliary curve matching techniques. The final interpretation was carried out using indirect techniques by matching and adjusting models to fit the field data. A curve matching program using the convolution method of Ghosh (1971) written for the Wang 600-14 desk calculator and Wang 612 plotter, by B. Dolan, was used to calculate the theoretical probe curves. Because the Ghosh method cannot accurately model the large contrasts in resistivity between the Bulimba Formation and the Rolling Downs Group, auxiliary curve matching techniques (Orellana & Mooney, 1966) were used to calculate the approximate resistivities and thicknesses of the layers in the Rolling Downs Group. The interpretations given in this report include data from logging and the Alfano method and are considerably more complicated than would be justified for an interpretation carried out in the absence of the borehole and Alfano data. The Coffey & Hollingsworth data (1971) show generally a much simplified 3 or 4-layer interpretation and this type of interpretation is all that can be realistically expected from probing data alone.

Keller and Frischknecht (1966, P. 168) deal with problems of interpretation of the types of probe curve encountered in this high surface resistivity - conductive basement environment. From theoretical considerations considering simple 3 or 4-layered models the probing technique should be able to detect a decrease in resistivity of the subwater-table layer which (from Section 6.3) may indicate increased permeability.

This does not take into account, however, lateral variations in resistivity of both the layers above and below the water table. Given that the permeable zones are 100 to 150 m wide and are essentially a two-dimensional structure of east-west extent, probes carried out along the north-south traverse (depositional strike direction), with $AB/_2$ values up to 100 m, say, will necessarily be influenced by less permeable material either side of the permeable zone. This will distort the probe curve. The two-dimensional nature of the permeable zone invalidates the assumptions upon which the simple geophysical model (Section 6.2) and the depth probing interpretation techniques are based. Kunetz (1966, pp. 7185) considers in detail the effect of two-dimensional structures and his discussion suggests that the distortion of the probe curve owing to the deviation of the two-dimensional structure from an ideal-layered medium of infinite extent can be minimized by locating the probe over the centre of the structure and in a line with direction parallel to strike (in this case eastwest). In practice this involves extensive preparation of east-west lines perpendicular to the main north-south traverse and considerably limits the economics of the depth probing technique.

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In considering the interpretation of depth probes H10 (Pl. 11) and H7 (Pl. 8) the effect of lateral variations is illustrated. The interpretation of H10 shows a bauxite layer to 3 m and a 2000 ohm metre layer, extending from 3 to 9 m depth with an 800 ohm metre layer representing the permeable material. This interpretation was found to be the most consistent with borehole and Alfano data but is by no means a unique interpretation on the basis of the surface resistivity probing data alone. There is no clear indication of the permeable zone from the surface depth probe data alone. The Alfano probe data (see Section 6.5) for H10 show considerable distortions which are probably caused by subsurface lateral variations in resistivity. The detailed section of the permeable zone at H10 (Pl. 17) shows, in fact, the complex cross-sectional nature of the permeable zone and indicates that the probe has been carried out at a distance less than 20 m from the edge of the permeable zone. The resistivity traversing (Pl. 15) in fact shows that H10 is located on the southern flank of the resistivity low associated with the permeable zone.

The interpretation of H7 depth probe similarly is complicated by the proximity of the edge of the permeable sand body which is less than 30 m to the south of H7 (see Pl. 18). The logging results for H7 also show the effect of the edge of the permeable zone as resistivities greater than 1000 ohm metres were recorded down to depths of 12 m.

The above two examples indicate the effect of the uncertainties in sitting a resistivity probe in an optimum position to maximize the response of the anomalous permeable zone. It is apparent that lateral resistivity and thickness variations of the sub-bauxite along are sufficient to distort the surface probe data and hence reduce the reliability of the interpretation. The lateral variations of the surface bauxite layer will have a far greater influence on the probe curve than the sub-bauxite layers (Kunetz, 1966). It is considered, following on from this, that the lateral resistivity variations have as much influence on the shape of the resistivity probe curve as the resistivity variation with depth beneath the bauxite zone. On this basis, it is considered that the surface probe method cannot be guaranteed to give a reliable indication of the resistivity variation with depths. It may be useful for detailed follow up if sufficient probes are carried out close together (say 20 m apart) and changes in character of the probe curves from place to place are noted. The direction of the probe lines should preferably be east-west; however, in view of the field efford required, it is most likely that the cost of this approach on a large scale would be prohibitive.

A further consideration in interpretation is the continuous variation of resistivity in the sub-bauxite layer. Keller and Frischknecht (1966, p. 168) also consider the case of a continuously varying resistivity with depth in particular an exponential variation and show that it cannot be distinguished from a layered medium. They note that the KQ and QQ type curves most commonly arise from such situations in the field. Several Indian geophysicists (Rathar & Rather, 1971; Lal, 1970) have devoted considerable effort to studying the problem of exponential and linear variations of resistivity within a layer embedded in normal, constant resistivity layered medium. Construction of the Dar Zarrouk curve (Orellana, 1963) for the resistivity distributions revealed by the resistivity logs of the bore-holes shows that the continuous variation of resistivity from below the bauxite to the water-table can be approximated to one or two layers of constant resistivity. The surface probe method thus cannot predict the presence of a sub-bauxite layer of continuously variable resistivity in this environment and hence can only give the most simple estimate of the nature of the sub-bauxite layer. Mallick (1956) reports similar failure of the resistivity method to detect transitional layers in the case of infinite basement resistivities.

### 6.4.3 Economics of surface soundings versus drilling and logging

In section 8.1 the resistivity and gamma-ray logging techniques and the values of the information obtained by logging are discussed.

In comparing the economics of resistivity depth probes versus resistivity logging of bore-holes several factors must be considered. Firstly the reliability of the information obtained with each method, secondly the speed of data-gathering and thirdly the relative costs.

It is considered that drilling, resistivity and gamma-ray logging is a vastly superior method of obtaining reliable information. The results from each hole give the hydrogeologist first-hand information on resistivity and lithology in the field. In this geological situation the results obtained by either depth probing or drilling are applicable only over a small region in the area of the hole or probe because of the rapid lateral changes in lithology (Pl. 19). The important distinction to make is that results obtained by depth probing are influenced by these lateral changes and may bear no relation to the lithology immediately beneath the centre of the depth probe. The drilling and logging results are at least valid for the immediate vicinity of the hole.

The depth probing method is considered to be of slightly greater speed than drilling. In the present survey two to three holes could be drilled and logged per day. The speed of the depth probing method is mainly limited by the nature of the terrain and care taken in preparation of traverses. Four to five depth probes could be carried out per day.

When making a pure cost comparison between depth probing versus drilling and logging several assumptions of minimum costs have been made. A minimum cost of \$350 per day for a fiveman geophysical crew (including equipment hire) is estimated. This cost does not include cost of preparation of probing lines. At a rate of four to five depth probes per day the cost per depth probe is calculated as being at least \$70 to \$90. The cost of auger drilling and hire of logger are estimated to be \$300 per day for one drilling/logging crew. At a rate of two to three holes per day the cost per hole is estimated at between \$100 and \$150, only marginally greater (approximately 1½ times greater) than the cost of depth probing. Provided a reliable traversing method can be used to locate suitable drilling targets the authors consider that the consideration of reliability of results obtained with drilling and logging far outweigh the considerations based on pure coast comparisons.

Drilling and logging is considered a more reliable and efficient detailed investigation technique than depth probing. The use of drilling in an economic manner depends on the reliability of the traversing method. The cost of an investigation may be reduced by use of some depth probing in a detailed manner (Section 6.4.2) to supplement drilling but it is recommended that drilling and logging be the primary investigation technique for follow up of the resistivity traversing. Initial depth probing will also provide information on the optimum traverse spacing to be adopted for a particular area.

## 6.4 INDUCED POLARIZATION TESTS

The induced polarization (IP) measurements were carried out concurrently with the half-Schlumberger probes at H1 (Pl. 2), H5 (Pl. 6) and H8 (Pl. 9). The plot of frequency effect versus $AB/_2$ (shown as triangles on the plots) is on a linear-logarithmic plot with percentage frequency effect on a linear scale on the right-hand side of the plot. Frequency effect measurements were generally not possible beyond $AB/_2$ = 300 m with the equipment used.

Barker (1974) gives an interpretation scheme for IP probes in the frequency domain, which involves use of auxiliary curve matching techniques. Following Barker's methods a semi-quantitative interpretation is possible. The interpretation of the results indicates a layer (or series of layers) of low-frequency effect (le-s than 1% to 3%) overlaying a high-frequency-effect layer. The measured frequency effects peak at between 5 and 10%. At H8 (Plate 9) a decrease in frequency effect at $AB/_2$ values of 10 to 50 m indicates that the depth of the high frequency effect layer is between 50 and 150 m. The sharp rise indicates frequency effects of between 10 and 30% (approx.) and possibly more, in the second layer.

The high-frequency-effect layer is almost certainly due to metallic IP effects of the finely disseminated pyrite and

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carbonaceous material in the shales of the Rolling Downs Group (Doutch et al., in prep.). The discrepancy in depths to the top of the low-resistivity layer and high-frequency-effect layers is due to both the variable depth of weathering and lithological variations in the Rolling Downs Group. The depth of weathering is of the order of tens of metres and in this zone all polarizable material will be oxidized to give low-frequency effects. Also where the upper part of the Rolling Downs Group is predominantly sandstone lower-frequency effects can be expected. Although the Rolling Downs Group contains appreciable quantities of high IP montmorillonite clays, the clays will contribute little to the overall IP effect because of the high salinity of the connate waters (Vacquier et al., 1957).

The decrease in IP effect with depth in the Rolling Downs Group as noted on probe H8 (Pl. 9) is probably related to a lithological change to a less shaly formation and is consistent with the noted increase in resistivity (Section 6.2). A decrease in connate water salinity with depth, would produce the same effect; however, the first explanation is more likely as the connate water is saline throughout.

The significant results from the IP probing data of direct relevance of water investigation is the very-low-frequency effects of the sediments of the Bulimba Formation. The scatter in the field readings is of the order of $\pm1\%$ in probes H8 and H9 (Pl. 9 and 10) and this reflects both instrumental and environmental limitations of the IP method. This scatter is too great to conclude whether there is a relation between IP effect and lithology in the Bulimba Formation.

The low IP effects can probably be attributed to the combination of kaolin clay and the generally low $Na^+$, $Ca^{2+}$, $Mg^{2+}$ concentrations and relatively higher $H^+$ and $HCO_3^-$ concentrations in the groundwater. Evans (1965) cites pH values of 6 to 7; $Ca^{2+}$, $Mg^{2+}$ and $Na^+$ concentrations less than 10 ppm and $HCO_3$ concentrations of 10 to 40 pm for groundwaters at Weipa and conditions are probably similar in the survey area. Vacquier (et al., 1957) studied the IP effect of kaolin clays and found that kaolin clays generally show lower IP effects than other clay minerals, but particularly so when the concentration of the sodium, calcium, and magnesium cations are very low with respect to the concentration of $H^+$ ions. The kaolin shows higher affinity for $H^+$ ions and takes up these ions unless the metallic cation concentration is greater. An increased concentration of $H^+$ ions taken up in the kaolin clay structure dramatically decreases the IP effect of the kaolin clay. For this reason, given the observed water compositions in bauxite covered areas (Evans, 1965), the kaolin clays are showing uniformly low IP effects.

The IP method shows little promise as an exploration tool for groundwater in the Bulimba Formation.

## 6.5 ALFANO DEPTH PROBING METHOD

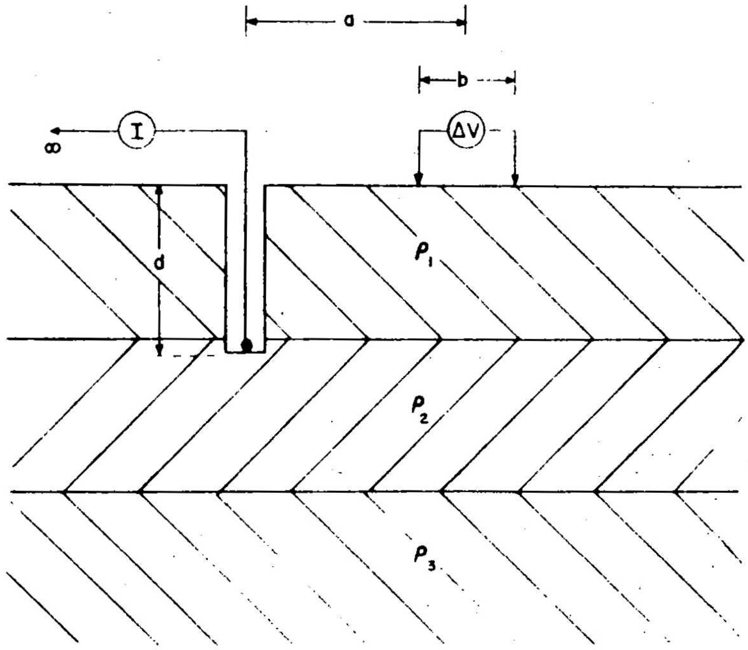
The Alfano probing technique (Alfano, 1962) uses a down-hole current electrode to overcome the problems in interpretation of probe curves which are obtained in environments with either highly conductive or highly resistive surface layers. It was decided to test the probing method in the high surface resistivity environment of the survey area. The technique has not been widely reported in the literature although recent work by Merkel (1971) refined the theory and also considered mise la masse type investigations for tabular and spherical ore bodies. The Alfano technique has been used near Elliston, South Australia, for a groundwater survey in an area of Tertiary sediments overlying gneissic bedrock (Hussin, 1967).

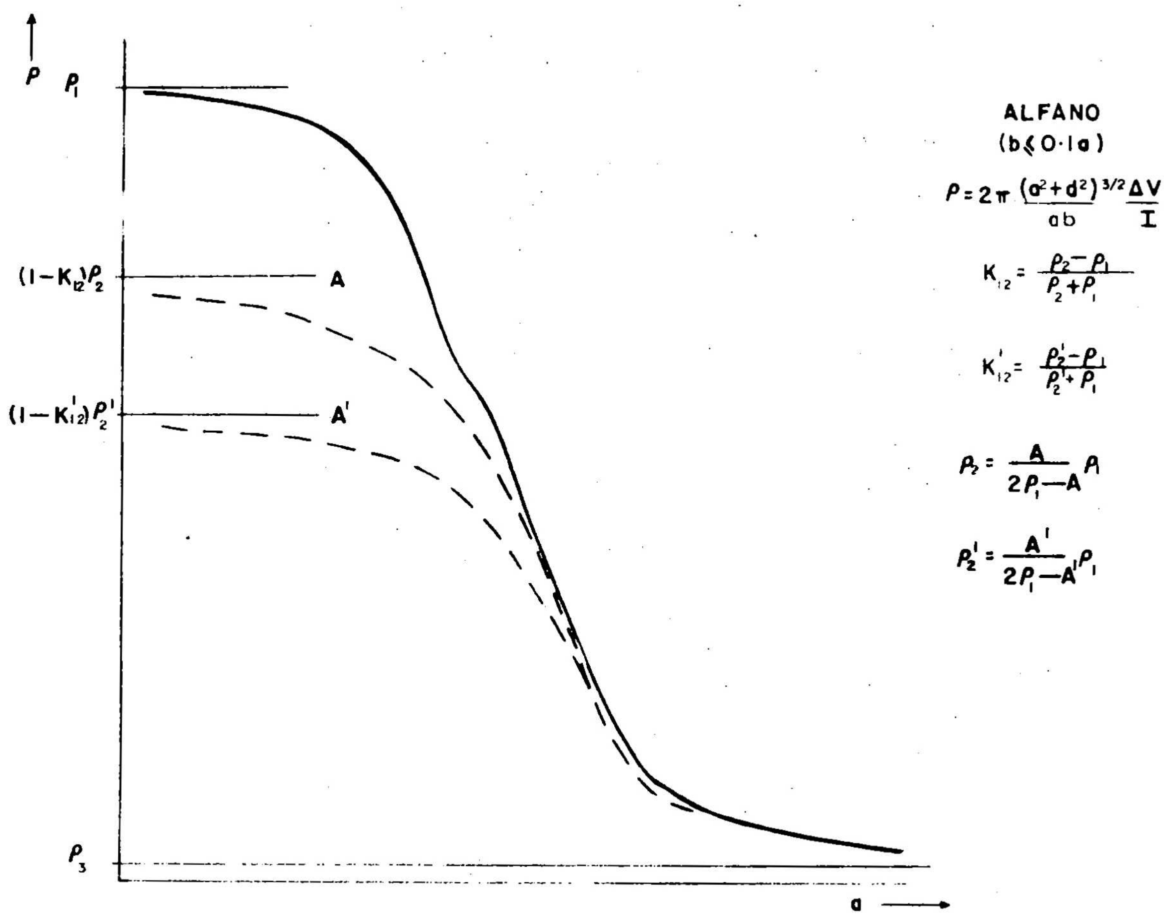
The basic field configuration and principle fo the method is illustrated in Figure 2. The conventional probe curve shown in Figure 2 could be obtained for several values of resistivity and thickness of the second layer owing to the fact that the major influences on the shape of the probe curve hare the highly resistive surface layer and the highly conductive basement layer. This phenomena is known as the 'principle of suppression' (Kunetz, 1966; Zohdy, 1974) and in the present survey area, is of the utmost importance as the sub-bauxite and subwater-table layers are the layers which are in many cases suppressed in the probe curves typically found in this environment. Generally to minimize the effect of the surface layer, one current electrode is inserted at a depth, d, equal to approximately 1.1 times the thickness of the upper layer. The second current electrode is placed effectively at infinity (1000 to 1500 m away, in this case) with the measuring dipole (length, b) centred a distance, a, from the top of the hole. The dipole is moved progressively away from the hole and the resistivity calculated using the equation given in Figure 2 is plotted against 'a' on the same bilogarithmic plot as the conventional probe curve.

In Figure 2, the two dashed curves represent Alfano probe curves for two extremes of values of the resistivity of the second layer which are compatible with the conventional probe. The Alfano probe curve is asymptotic to a value at low values of 'a', which depends on the resistivity of the second layer and the value of the second layer resistivity can be calculated from this asymptote by the equations given in Figure 2. The Alfano method thus resolves the ambiguity of the value of the second layer resistivity. In favourable cases the thickness of the second layer can then be calculated knowing the second layer resistivity.

In practice, however, the field conditions may correspond to a 4 or more layered medium and in these cases the electrode may be inserted in the third, fourth, or fifth layer. The Alfano probe curve is still asymptotic to a value which is

FIG 2




ALFANO DOWN HOLE ELECTRODE TECHNIQUE

related to the resistivity of the layer in which the electrode is placed (Merkel, 1971); however the relation of the asymptotic value to the layer resistivity is more complex and generally an approximate solution is obtained by combining the overlying layers into one layer using Maillet's relation (Maillet, 1947; see equations in section 7.6) and then proceeding as in the three layer case previously described.

In the present survey the existing auger holes or special holes drilled to the base of the bauxite zone were utilized and several depths were experimented with. The Alfano probe curves are shown with the conventional probe curve (Pls. 2-12). The curves show a high degree of scatter owing to the fact that a moving dipole is used and this scatter in many cases affects the asymptotic value. For the purposes of this investigation the asymptote has been taken generally neglecting the values for 'a' less than 2 m as the asymptote is very sensitive to the electrode placement errors and surface lateral resistivity variations near the hole, often caused by debris accumulated from the drilling.

It was found that by placing the electrode at the base of the bauxite or nodular zone (see H2, H3, H7, H8, H10, H11 in Pls. 3, 4, 8, 9, 11, 12 respectively), which is the shallowest major lithological boundary which is easily identifiable from drilling, that the Alfano method proved to be of little use. This was because of the high resistivity of the sub-bauxite layer. In some cases the asymptote showed a higher resistivity to be present at the depth of the buried electrode than at the surface.

The second easily identifiable change in drilling conditions is the change from unsaturated to saturated sediments at the water table and eleven Alfano probes were conducted with the electrode implaced near the top of the water table. In this case the results indicate dramatically the resistivity change which occurs at the water-table and generally resolved the ambiguity in resistivity of the subwater-table layer. However the logging results suggest the presence of thin high or low resistivity layers and the Alfano method, being very sensitive to the resistivity in the vicinity of the buried electrode, may be more affected by the resistivity of a thin layer in which it may have been inadvertently placed, rather than the overall resistivity of a layer. For example in H3 the Alfano depth probe with a hole depth of 3.8 m indicated a thin high-resistivity layer at the depth of the electrode. The resistivity of this layer is at least ten times that of the surface layer but is very difficult to determine exactly (Alfano, 1962). It is too thin to be detected by the resistivity logger (Chainage 6360 m, Pl. 16).

Also in H8, Plate 9, the Alfano depth probe with an electrode at 13.4 m depth indicates a thin layer of 75-100 ohm metres resistivity with an indication of increasing resistivity below the electrode depth. This resistivity of the layer is lower than the overall resistivity which is compatible with the conventional probing data (Pl. 9) and the logging data (Chainage 1140, Pl. 13). The interpretation presented in Plate 9 indicates a maximum probable thickness of the 100 ohm metre layer. The interpretation has been improved by the Alfano data in this case however the overall interpretation of resistivity variation with depth is not improved because of the importance of lateral variations in resistivity. A resistivity depth variation interpreted from a single Alfano probe may be invalidated by lateral changes in lithology and would not apply to a conventional probe in the vicinity.

The Alfano method may be more suited to an environment where lithological changes with depth are more distinct and where subsurface lithology and hence resistivity is uniform over a widespread area. This is generally not the case in unconsolidated sediments.

In evaluating the Alfano method in this environment it can be said that it may give meaningful results only when the electrode is placed beneath the water-table. This, however, is a futile exercise economically as a hole drilled into the water-table and logged will give much more reliable information than any resistivity depth probing method (see section 6.4.3).

In addition the Alfano method appears to be affected by subsurface irregularities more than surface probes. This is illustrated in H10 (Pl. 11) where a major lateral change in permeability and resistivity is apparent (Pl. 17 and Section 6.4.2) just south of H10. The two Alfano probes at H10 (depths 2.9 and 7.9 m) both show irregularities which cannot be attributed to the normal scatter observed with a moving dipole, as the conventional half-Schlumberger probe used the same moving dipole for potential measurements as was used for the Alfano measurements.

## 7. RESISTIVITY TRAVERSING RESULTS

### 7.1 Geological considerations

The traversing method to locate the more permeable sand bodies is undoubtedly the most important aspect of the investigation, given the difficulties of interpretation of the depth-probing technique and the fact that depth probing is uneconomic as a production investigation tool.

In considering the traversing methods important factors are the depth to the water-table and its relation to topography and subsurface permeability for the particular test traverse.

The drilling results (Section 2.2) show that the depth to the water-table varies from 10 to 15 m on the south of the test traverse (lower chainages, Pls. 13 and 14) to 7 to 12 m in the north of the traverse (Pls 15 and 16) surface elevation. The piezometric surface and water table coincide closely locally where the more permeably clayey sand is present but the piezometric surface tends to rise above the water-table in the pressure aquifer situation particularly where sandy clay predominates. Also the general level of the water-table rises where subsurface permeability is high. In short, the water-table depth appears to be more affected by subsurface permeability than topography.

Smart (in press) has pointed out the importance of subsurface permeability in the formation of bauxite, however the present drilling has established that no simple one to one relationship exists between subsurface permeability and the thickness of bauxite. This is particularly shown by the thick development (6.5 m) of bauxite around H7 and the relatively thinner (3.4 m) layer of bauxite around borehole H10. These two bore-holes penetrate the two main permeable zones in the test area. In the survey area, topography appears to be the main influence on the thickness of the bauxite.

## 7.2 Filtering of traverse data

The Wenner and VLF data show large scatter along the traverse and the possible reasons for this are suggested in sections 7.3 and 7.5. The pole-dipole traversing results at 20-m station intervals are much smoother. To aid in interpretation and visual presentation of the data, minimal smoothing was attempted using an approximate low pass filter (Fraser et al. 1966).

Plate 20 shows the actual filter frequency responses as compared to ideal low pass filters. The deviation of the actual from the ideal response is due principally to the finite length of the actual filter operator. The filters used are symmetric and take the sum of weighted values of the field data at the observation point and eight stations on both sides to produce a filtered value at the observation point. The relative weights W(k) for the three filter operators used are given in a table on Plate 20. It is stressed that the filtering technique is a mathematical tool only and the filter operators have no mathematical relation to the intrinsic properties of the potential distribution in the mathematical formulations of the theory of resistivity or magnetotelluric probing. The filters were applied using a convolution program written for the HP-9100B desk calculator by R. Almond.

The choice of a filter to be used in filtering the data is largely subjective. The criteria used in choosing the frequency cut-off values for each filter included the scatter or estimated error in the data, the effective depth of investigation of the profiling system and the wavelength of apparent anomalies present in the data. The filter lengths were 160 m for the VLF and Wenner data and 320 m for the pole-dipole data and these lengths also limited the possible upper values of the cut-off wavelength of the filter. The cut-off wavelength was kept to within one-half to one-third of the filter length.

For the Wenner data the filter used was chosen with a cut-off wavelength of 30 m, zero response for wavelengths less than 23 m and full response for wavelengths greater than 42 m. The aliasing wavelength of 20 m (i.e. twice the data interval) is close to the cut-off wavelength, but no evidence of aliasing can be found in the filtered data. In some sections of the traverse where large scatter in the data is evident (e.g. Chainage 7250 to 7700, Pl. 16) the filtered data show little improvement. However in the case of the Wenner profiling data which have the shallowest effective depth of investigation the minimal smoothing as applied was considered desirable.

The VLF data have been filtered with a filter of 60-m cut-off wavelength giving full response for wavelengths greater than 140 m and zero response for wavelengths less than 38 m. The VLF data are very scattered and a higher-wavelength cut-off was required to smooth the data. It is doubtful whether the smoothed data are any more valid than the field data (e.g. chainages 4900 to 6100 m, Pl. 15) as the scatter in the field data far exceeds the quoted 10% accuracy of the resistivity readings. The VLF results are discussed more fully in section 7.5.

The pole-dipole data shows little scatter because the effective depth of investigation was chosed so that variations of the high-resistivity layers above the water-table were minimized. The cut-off wavelength of 80 m allows wavelengths of 120 m to be fully passed and gives zero response for wavelengths less than 56 m. This means that resistivity lows less than 28 m wide are totally rejected. Slight attenuation of resistivity lows between 40 and 60 m wide can be expected. This is not considered a limitation given the width of permeable zones in the test area.

The principal advantages of the filtering technique are in reducing errors which are manifested as high-frequency anomalies with wavelengths of the order of 2 station intervals. Because the root mean square sum of the filter coefficients (see table, Pl. 20), is less than 0.05, random errors are drastically reduced by the filtering process. However, systematic errors which are indistinguishable from long-wavelength anomalies are fully passed and the final smoothed data are at best as valid as the original data.

## 7.3 Wenner traversing

The Wenner traversing in this investigation was carried out principally to give control of lateral resistivity variations both in the bauxite and sub-bauxite layers. Detailed analysis of the drilling and Wenner results show that some information is obtained from the Wenner data. The economic value of this information is a matter for the user to decide once a detailed water investigation is underway.

The Wenner apparent resistivity at an electrode spacing of 10 m is equivalent to the Schlumberger apparent resistivity measured at an $AB/_2$ value of between 1.36 and 1.4 times the Wenner spacing (i.e. between 13.6 and 14.1 m). The first estimate is derived empirically (Andrew & Wiebanga, 1965) and the second estimate is based on theoretical considerations (Koefoed, 1968, P. 30). For the purposes of this report we assume that the Wenner resistivities at 10-m spacing is equivalent to Schlumberger resistivities at 14 m. Coffey & Hollingsworth (1971) carried out Wenner traversing at spacings of 50 and 100 feet (15.2 and 30.5 m) which is equivalent to Schlumberger traversing of 21.3 and 42.6 m.

The results indicate that on a regional scale Wenner resistivities are slightly lower (600-1000 ohm metres) in the areas of thin bauxite (3-3.5 m), than values (1000-3000 ohm metres) in the area of relatively thicker bauxite (4-7 m). No correlation could be found between pisolite size and bauxite resistivity from field measurements, but the factors that determine bauxite resistivities are not fully understood. This may warrant further investigation. There was no indication of sub-bauxite layer lithology from the Wenner results except where hard impermeable clays were found beneath the bauxite in areas of the localized Wenner resistivity highs. These resistivity highs generally indicated difficult drilling conditions (e.g. H47, Chainage 4738 m, Pl. 15) due to the presence of low porosity, impermeable and dry, indurated clayey sands of high resistivity. The electric logging results (Section 8.2) indicate no clear distinctions in resistivity associated with sub-bauxite lithology and this is consistent with the above results.

A slight correlation was found to exist between the Wenner resistivities and the depth to the water-table, as could be expected. This correlation holds here mainly on a regional scale whereas local derivations from this rule may occur. Slightly lower resistivities (600-1000 ohm metres) were measured in areas of shallow (7-12 m) watertable. Resistivities of 1000 to 3000 ohm metres were measured over a deeper watertable (10-15 m) at the southern end of the traverse. The fact that a thin bauxite layer and shallow water-table coincide and that thicker bauxite is present in the area of a deeper water-table in the test area means that the Wenner resistivities are influenced by both water-table depth and bauxite thickness simultaneously and it is impossible to separate these two factors.

The present investigation has shown that the Wenner traversing at 10-m spacing can give useful information once knowledge of a particular area is gained with borehole control. However the Wenner traversing at this spacing can give little direct evidence of subsurface permeability.

## 7.4 Pole-dipole traversing

### 7.4.1 Results

The pole-dipole traversing results show much less scatter than the data from the Wenner traversing. This is firstly due to instrumental considerations - the instrument being more suitable to the high surface resistivity environment than the Megger instrument.

Secondly the traversing was carried out at an $AB/_2$ value of 50 m. This value was chosen to minimize random variations in bulk apparent resistivity of the bauxite and sub-bauxite layers. This is illustrated in Fig. 3 where the depth probe curves are plotted on the same graph. Below $AB/_2$ equals 50 m the curves show 'random' behaviour owing largely to the variations of resistivity of the individual layers above the water-table and particularly to the level of bauxite resistivity. This is consistent with the scatter observed in the Wenner data (14 m).

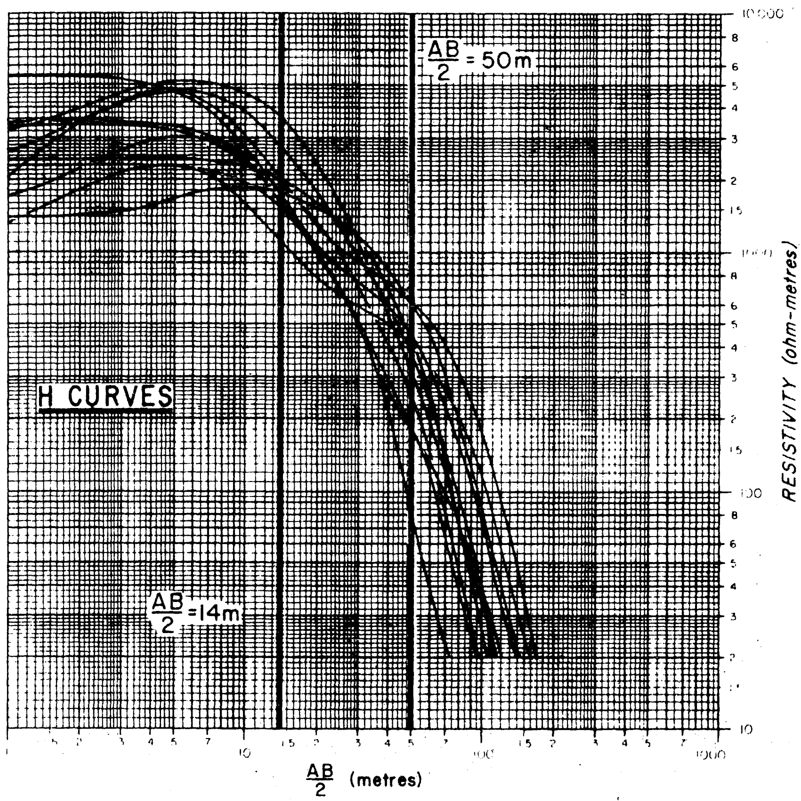
For values of $AB/_2$ greater than 50 m the curves show largely systematic differences which reflect systematic differences in the transverse resistance, T, of the Bulimba Formation. The transverse resistance is defined as the resistance per unit area across a series of layers

$$T = \sum_i \rho i \quad x \quad hi$$

where $\rho$ i and hi are the resistivity and thickness of the $i^{th}$ layer. The traverse resistivity $\rho_\perp$ is also a useful quantity and defines the average resistivity of a unit area column of i layers. $\rho_\perp$ is given by Maillet's relation (Maillet, 1947)

$$\rho_\perp = T / \sum_i hi$$

Fig 3




## BMR DEPTH PROBES

H1 to H11

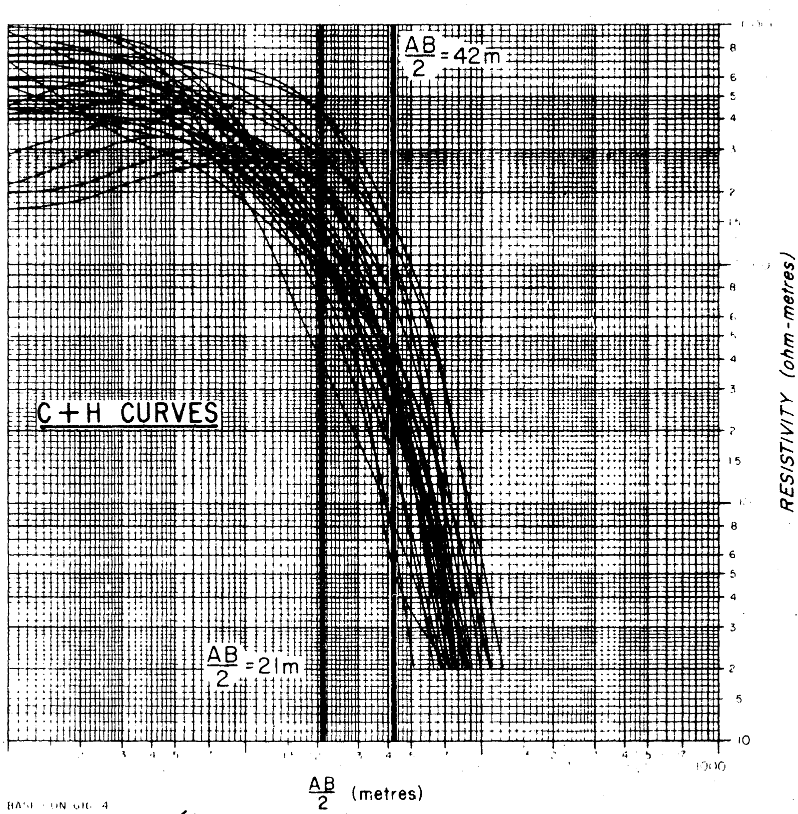
AURUKUN AREA

1974

WENNER TRAVERSING AT $\frac{AB}{2}$ = 14m (EQUIV.)

POLE DIPOLE TRAVERSING AT $\frac{AB}{2}$ = 50m

# RESISTIVITY DEPTH PROBE PLOTS




## COFFEY AND HOLLINGSWORTH DEPTH PROBES

S1 to S29

WEIPA AREA

1971

WENNER TRAVERSING AT $\frac{AB}{2}$ = 21m (EQUIV.)

WENNER TRAVERSING AT $\frac{AB}{2}$ = 42m (EQUIV.)

The transverse resistance is considered to be the appropriate resistance to use rather than the so-called longitudinal resistance defined by Hummel's relation (op. cit.) because the current flow will be largely vertical given the conductive basement present in the survey area. The longitudinal resistance is the resistance per unit area along the layers, rather than across the layers, and is more appropriate for near horizontal current flow as in the case of resistive basement.

For each of the depth probes H1 to H11 (Pls. 2-12), the values of transverse and longitudinal resistance were calculated using the interpreted thickness and resistivities of the layers. The correlation between the observed pole dipole traversing values and the parameters (depth of the Rolling Downs Group, transverse resistance, and longitudinal resistance) was calculated using a standard statistical correlation program on the HP-2100B desk calculator. The traverse resistance showed strong positive correlation with the field data; the transverse resistivity and the interpreted depth showed slightly positive correlation. The longitudinal resistance in fact showed strong anti-correlation with the field data. These results are subject of course to the limitations in interpretation of the sounding curves (Section 6.4.2) but generally support the contention that it is the transverse resistance which is the main parameter affecting the pole-dipole traversing results.

Variations in transverse resistance T can be caused by variations in resistivity and thickness of each or all of the layers. In the case of the Bulimba Formation transverse resistance can be decreased locally by several possibilities. A decrease in the resistivity thickness product of each or all of the bauxite, sub-bauxite and subwater-table layers will decrease T. Less locally, shallowing of the Rolling Downs Group, regional thinning of the bauxite or regional shallowing of the water-table will produce a regional change in transverse resistance.

Decreases in transverse resistance of the Bulimba Formation will thus be reflected as resistivity lows when traversing at $AB/_2$ values greater than 50 m. The particular value of $AB/_2$ must be chosen for the area to be studied. In this case 50 m was also chosen because of the rapid fall-off in received voltage for $AB/_2$ values greater than 50 m, and using an $AB/_2$ value much greater than 50 m would have slowed the measuring technique. With a higher voltage transmitter these instrumental limitations would be removed.

The Coffey & Hollingsworth depth probe interpretations have been used to reconstruct their probe curves and these have been plotted on the one graph in a similar manner on Figure 3 also. The data suggests that systematic differences in apparent resistivity due to variations in transverse resistance should have been apparent for traversing at $AB/_2$ values greater than 40 metres. Coffey & Hollingsworth suggest that their data from Wenner traversing at 100 feet spacing (equivalent to Schlumberger traversing at $AB/_2$ equals 42 m) reflects only near-surface bauxite variations. Their data show much greater scatter than the pole-dipole data obtained on the present survey and this suggests that the scatter may be due to instrumental factors. The Wenner traversing method employed by Coffey & Hollingsworth gives readings every 30 m which results in decreased horizontal resolution. From the present study, 20 m is considered to be the maximum traverse station spacing given the expected width of permeable zones.

In the present survey two aquifers were located by chance firstly by drilling. Later, traversing was carried out and the two aquifers were found to correspond to resistivity lows. This is illustrated in detail in Plates 17 and 18. The resistivity low over H10 (Pl. 17) is quite sharp particularly in the southern edge, reflecting the sharp boundary of the permeable zone. The resistivity low is not as clearly defined at borehole H7 (Pl. 18) and in fact extends from chainages 1450 to 2100 m (Pl. 13). The reason for this appears to lie in the persistance of a thick zone (4 to 8 m) of 1000 to 2000 ohm metre material beneath the bauxite as evidenced on the resistivity logs of H27, H28 and H29 (Pl. 13). The picture is further complicated by the presence of high-resistivity surface material to the immediate north of the resistivity low as shown in the Wenner data. A localized thinning of the Bulimba Formation could also account for the width of this low, but there is no direct evidence to support this. This example illustrates the complexity of factors operating to cause changes in the transverse resistance of the Bulimba Formation.

Several other resistivity lows were investigated by drilling to determine the applicability of the resistivity traversing method to the location of permeable zones. Boreholes H49, H50, H51, H53, (Pl. 16), H54, H55 (Pl. 15) and H26, H27, H28 (Pl. 13) were drilled for this purpose. Almost all of these lows revealed no major permeable zone. These lows were generally narrow (less than 100 m wide) and showed relatively lower amplitude than the lows around H7 and H10.

The resistivity low at Chainage 7700 (Pl. 16) is in fact an apparent feature related to the general decrease in pole-dipole ($AB/_2$ = 50 m) apparent resistivity north of the rapid topographic change in 7600 m, plus the resistivity high centred on 7800 m and associated with an apparent increase in bauxite resistivity as indicated in the Wenner data. The general decrease in pole-dipole resistivity north of 7600 m is almost certainly due to a thinning of the Bulimba Formation or effective shallowing of the Rolling Downs Group. This topographic influence on the apparent resistivity values is not apparent on the southern end of the test traverse (Pl. 13), because the regional dip of the top of the Rolling Downs Group is southwest to west-south-west and must closely parallel to topographic surface in this area.

In each case the major resistivity lows defining the presence of a permeable zone are caused by a local rise in the water-table owing to the locally high permeability. This increase in thickness of the lower-resistivity material (500 ohm metres or less) below the water-table and the accompanying thinning of the high-resistivity bauxite and sub-bauxite layers above the water-table account for the lateral decrease in transverse resistance. This principle is illustrated in Figure 4 for a simple case of a 7-m rise in the water-table over a relatively unconfined aquifer as compared to a partly confined aquifer with the water-table depressed to 15 m depth. In the case of the model in Figure 4 the worst conditions likely to be encountered have been simulated, in the sense that the same resistivity (500 ohm metres) has been assumed for the relatively impermeable clayey sand of the non-aquifer case and the permeable sands of the aquifer case. In fact the less permeable clayey sands show higher resistivities up to 2000 ohm metres (Section 6.3). The model presented in Figure 4 is essentially a simplification, but it accounts for the essential features of the observed lateral variation in pole-dipole apparent resistivity over permeable bodies.

The aquifer case in Figure 4 corresponds to a 20% decrease in transverse resistance T over the non-aquifer case. Assuming more realistic values for the resistivity of the impermeable clayey sands beneath the water-table in the non-aquifer case (say 1000 ohm metres) the transverse resistance T decreases 60% over the aquifer. This latter variation is more the order of amplitude of the resistivity lows observed.

From a consideration of the schematic geological section and traversing results (Pl. 19), eight sand bodies were located in the test area. Four of these (H50 to H51, H11, H26 and H28) are above the water-table, two (H9 and H1) were penetrated initially by a previous drilling investigation in the area (Coffey & Hollingsworth, 1975). The two main permeable sand bodies are around H10 and H7. Both of these and particularly the larger body at H10 are indicated by resistivity lows.

### 7.4.2 <u>Economics of pole-dipole traversing plus drilling versus pattern drilling</u>.

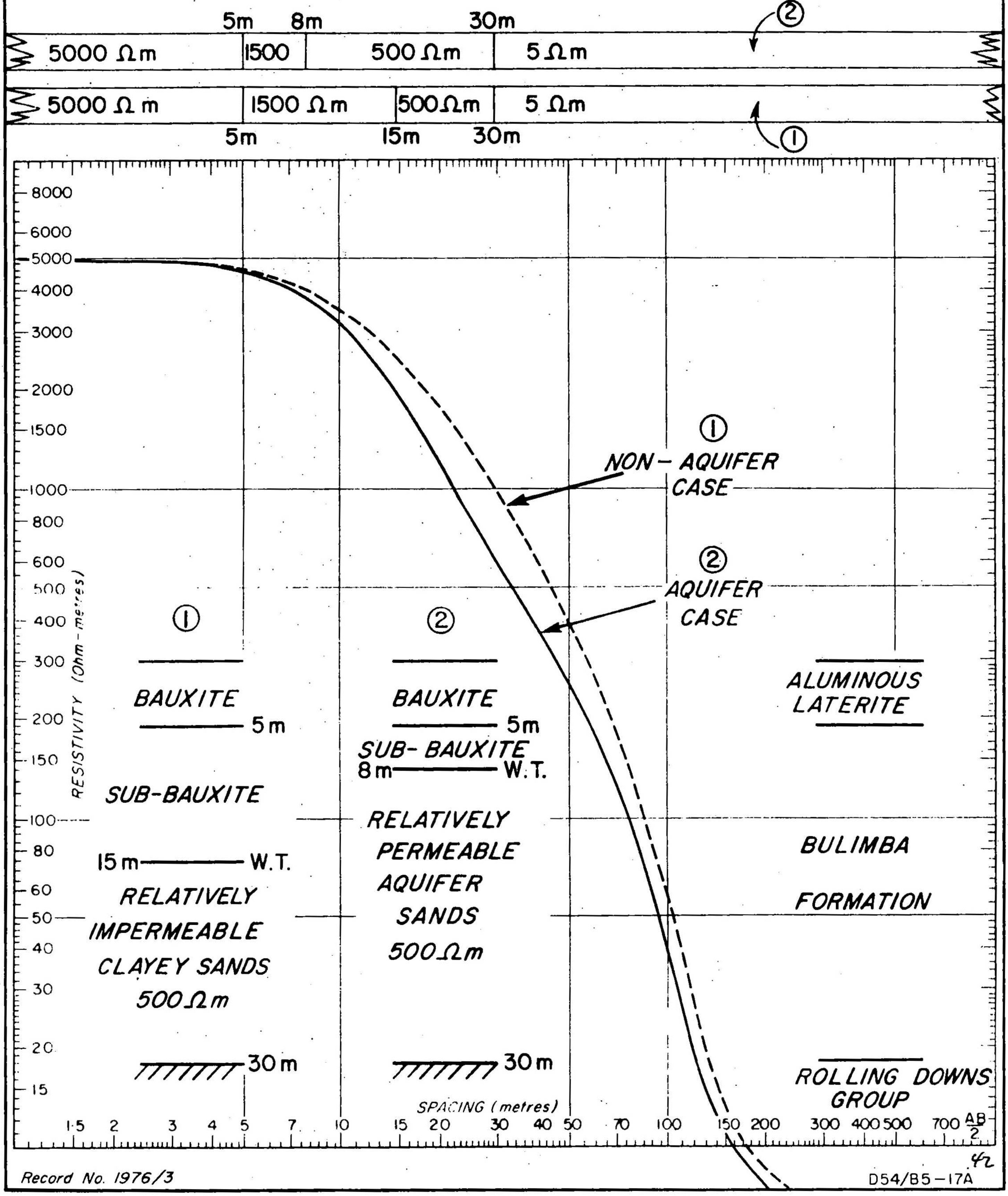
Using the frequency of occurrence of unconfined sand bodies within the test area and the crew costs for drilling/logging and geophysics given in Section 6.4.3 a comparison can be made of minimum costs of pattern drilling versus resistivity pole-dipole traversing with drilling follow-up. Accepting a minimum width of 100 m for suitable unconfined permeable sand bodies, pattern drilling every 100 m on a north-south traverse is required for a reasonable chance of location of such bodies. With a 1 in 35 chance of locating these bodies (Section 7.6.1.), 35 holes over 3.5 km at $110 each are required. The cost per unconfined permeable sand body located by drilling alone, is thus $3850. The pattern drilling may also find one or more smaller confined sand bodies.

With pole dipole traversing and follow up drilling, 3.5 km of traverse can be covered by geophysics alone, at a cost of at least $210, in less than one day. Assuming 10 auger holes are required to follow-up the geophysics and prove any permeable bodies indicated; the cost of geophysics and drilling is $1310 per permeable body. In fact much less drilling may be required to follow up the geophysics; three to five holes may be sufficient. The cost is then between $540 and $760 per permeable sand body. The major component of the cost of the dual approach of geophysics and drilling is the drilling cost and even allowing for a doubling of the cost of geophysics (say to $700 per day) the dual approach represents a saving of at least 70% in costs over pattern drilling. If Wenner traversing at 2 km per day is included in the geophysics, the saving in costs is reduced to at least 30%, although the present investigation has shown that the Wenner traversing is not essential. The geophysics will probably not give any indication of confined sand bodies, but this is not considered a limitation as these bodies are not considered to be a suitable long term source of groundwater.

In summary the pole-dipole traversing method (at sufficiently large values of $AB/_2$) is a reliable method of defining areas of locally low traverse resistance. This can be caused by a rise in the water-table over the more permeable zones causing a thinning of the complex high-resistivity zone comprising the bauxite and sub-bauxite layers, with the accompanying thickening of the low-resistivity layer beneath the water-table. Given that there is also generally a decrease in resistivity owing to increased permeability of the sub-water-table sediments then more than a 60% per cent decrease in transverse resistance may be possible. Other factors may cause a decrease in the transverse resistance of the sediments of the Bulimba Formation but the major consideration is that pole-dipole traversing is a viable technique for indicating favourable areas for accumulation of groundwater and this technique will significantly reduce the need for expensive pattern drilling.

Fig 4

WATER-TABLE RESISTIVITY MODEL



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D54/B5-17A

## 7.5 VLF TRAVERSING

The VLF method has proved to be unreliable in this environment. The reason for this is the large scatter in the measured resistivities. The reasons for this scatter, however, are not clear. The instrument was found to be operating correctly before and after the survey and gave repeatable results during the survey operations. The input impedance of the probes (100 megohms) is too high for variation in contact resistance to appreciably affect the results. Accepting then that the scatter is real and reflects bulk resistivity variations, it follows that large lateral changes in resistivity at VLF frequencies must occur in the sediments of the Bulimba Formation and the basal Rolling Downs Group.

The factors which affect VLF resistivities in the range of complexly structured clayey sand present in the Bulimba Formation, are poorly understood. The difficulty in obtaining suitable, representative undisturbed samples of the sediments to carry out meaningful laboratory experiments prohibited any investigation of these factors.

The laboratory measurements on the bauxite (Appendix 1, Section 5.3) show that at VLF frequencies the resistivity decreases to approximately half the DC resistivity for unsaturated bauxite. For saturated bauxite the DC and VLF resistivities are affected by the resistivity of the electrolyte and there is negligible dispersion of resistivity with frequency. Caution should be excercised in generalizing these results to the clay-bearing sediments of the Bulimba Formation.

In the absence of any data on the frequency dispersion of resistivity of the clay-bearing sediments however, the above results were assumed to apply to the interpretations of the resistivity depth probes, and the layer resistivities were corrected appropriately, depending on whether a layer was above or below the water-table. The models were then input to a magneto-telluric computer modelling program (Pollard, 1971) to yield the magnetotelluric resistivity at 22.3 kHz for each of the depth probes. The resistivities obtained with the modelling program bear no relation to the field measurements although the phase data show reasonable agreement (Table 4).

TABLE 4. COMPARISON OF FIELD AND COMPUTED VLF RESISTIVITIES

| Depth Probe | Field | | Computed | |
|---|---|---|---|---|
| | Resistivity (ohm metres) | Phase (degrees) | Resistivity (ohm metres) | Phase (degrees) |
| H1 | 220 | 70 | 138 | 77 |
| H2 | 200 | 71 | 138 | 75 |
| H3 | 210 | 73 | 230 | 74 |
| H4 | 120 | 75 | 118 | 77 |
| H5 | 250 | 70 | 197 | 75 |

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TABLE 4 (continued)

| | | | | |
|---|---|---|---|---|
| H6 | 130 | 78 | 220 | 67 |
| H7 | 190 | 75 | 190 | 79 |
| H8 | 180 | 73 | 163 | 75 |
| H9 | 210 | 72 | 152 | 77 |
| H10 | 250 | 73 | 180 | 78 |
| H11 | 180 | 73 | 233 | 76 |

There are two possible reasons for this disagreement. Firstly, the generalization of the results for bauxite to the clay-bearing sediments of the Bulimba Formation is probably invalid. Secondly, modelling has indicated that the VLF resistivity is more sensitive to variations in resistivity and depth of the Rolling Downs Group than variations of resistivity of any layer in the Bulimba Formation. The resistivity and depth of the Rolling Downs Group interpreted from depth probe data is uncertain because of the nature of the probe curve (Section 6.4.2). The depth interpreted from the probe data is probably a minimum value and this may explain why the VLF computed resistivity is generally less than the field value.

There appears to be no correlation between the VLF data and the Wenner or pole-dipole traversing data. The two main permeable bodies are not indicated by the VLF data. On this basis the VLF traversing method is not considered a useful water investigation technique in this area.

## 8. RESISTIVITY AND GAMMA-RAY LOGGING

The logging equipment which was available for use on the survey proved unsatisfactory for the task and the logging techniques used on the survey need to be improved for a production survey.

### 8.1 GAMMA-RAY LOGGING

The Well Reconnaissance suitcase logger gamma tool is a relatively low-sensitivity tool and this proved unsatisfactory in the environment of the survey area. The makers' recommended logging speed of 10 m/minute was used with a time constant of 2 seconds, but this tended to give poor definition of small-scale lithological changes. Chart slippage proved to be a problem with this instrument. From previous shallow logging experience in the area a high-sensitivity tool with a long time constant and logging speeds preferably much less than 2 m/minute is recommended. Normal calibration procedures should also be followed.

Despite the general poor quality of the logs, some indication of relative sand and clay contents is given. With better-quality logs, it should be possible to delineate aquifer sands more accurately. The aluminous laterite shows a high radioactivity (about 10 times the activity of the underlying material), probably owing to thorium. Airborne spectrometry over aluminous laterite areas in Cobourg Peninsula, N.T., indicated a high thorium content, although analysis of the laterite failed to detect any thorium (Senior & Smart, in press).

## 8.2 RESISTIVITY LOGGING

Although the single-point tool of the suitcase logger had poor penetration, the improvised four-electrode Wenner logging arrangement proved very satisfactory and generally resolved beds more than 1 m thick. The four-electrode logger gives a good indication of formation resistivity. The method could be used on a routine basis quite successfully. A drilling technique which does not use conductive drilling muds is considered most suitable for this environment from a resistivity logging point of view. The logging will be best carried out using the high-resistivity surface water as a borehole fluid as the water resistivity will match the formation resistivity closer than drilling muds. In this case a relatively cheap augering method could be used with the use of a large water tanker, and high-capacity pump to raise the water-level for logging purposes. With careful drilling the hole will generally stand for several hours after drilling, thus enabling logging to be carried out.

# 9. CONCLUSIONS

Appreciable supplies of water from the Bulimba Formation can be obtained only from small easterly-trending permeable bodies of clayey sand which occupy about 10% of the formation; about half of these bodies are below the water-table in the survey area. The larger permeable bodies come close to the surface and can be located by resistivity traverses supported by auger drilling considerably more cheaply than by pattern drilling alone.

Detailed conclusions which indicate the degree to which the specific objectives outlined in Section 4 were achieved are as follows:

9.1 The present survey has shown more clearly the expected distributions of resistivity both with depth and laterally. In particular, lateral variations in resistivity are probably more important than the vertical variation in resistivity.

Drilling and half-Schlumberger traversing indicate that lithology and resistivity changes occurring over distances of the order of 10-100 m. The lateritization process has made it difficult, however, to define a detailed geological model of the depositional environment.

9.2 For saturated sediments beneath the water-table there is evidence to indicate less permeable sediments have resistivities from 500 to 2000 ohm metres and the more permeable sands have resistivities in the range 100 to 500 ohm metres. There is no simple relation between resistivity and clay content. The structure of the clay/sand mixtures may be the more important factor in determining resistivity than clay content alone.

9.3 Resistivity logging using a four-electrode Wenner array has indicated in many places a continuous decrease in resistivity with depth between the base of the bauxite and the top of the water-table. There is evidence to suggest this may be related to a decrease in grainsize and hence an increase in specific retention properties of the sediment with depth. Further work is required to fully verify this assertion.

9.4 The resistivity surveying was carried out successfully with the high-power Geotronics IP transmitter. A transmitter with higher voltages (2000 to 3000 V) would be more suited for production work whereas the Megger type instruments are not considered to be suited to this high surface resistivity environment. The previous geophysical investigation failed principally because of this instrumental limitation. The present investigation using the higher-powered transmitter has overcome the instrumental limitation and has enabled a proper evaluation of the viability of the resistivity method.

9.5 Detailed drilling of two major permeable bodies in the test area has verified that the permeable zones trend about east-west. The thickness of permeable sand is at least 15 m in places. The thicker portions of these sand bodies are up to 100 m wide and one body has been proved to be at least 1000 m long. The two major permeable zones were several kilometres apart although six other sand bodies were defined (four above the water-table and two smaller confined bodies beneath the water-table). The major finding of drilling is the local rise in the water-table over the major permeable bodies which are unconfined. Elsewhere a pressure aquifer situation exists in areas of lower permeability and the piezometric surface is generally above the water-table.

9.6 The resistivity depth probe method has been shown to be unreliable as a production investigation technique because of the difficulty of interpreting the type of probe curve encountered in this environment. The lateral changes in resistivity may distort the probe curves. Because of the easterly trend of bodies the probes may need to be expanded in an east-west direction. Conceivably depth probes may be of some use in detailing a permeable zone provided the probes are expanded in an east-west direction and are spaced no more than 20 m apart on north-south traverse lines. Changes in character from one probe curve to the next may prove to be of diagnostic value. The economics of this approach is marginal compared with detailed drilling. The authors believe that the over-riding consideration in economic comparisons between resistivity probes and drilling for detailed follow-up work is the far greater reliability of information obtained with drilling and resistivity logging. Provided a cheap drilling technique similar to that used in this survey is used, the extra costs involved in drilling are negligible.

Resistivity probes will mostly be of use in providing control for the choice of a suitable pole-dipole spacing and depth of investigation, so as to minimise the effects of the large variations in near-surface-layer resistivities.

9.7 The Alfano method has proved to be both uneconomical and unreliable in this environment. This is largely because of the rapid changes in resistivity and lithology both laterally and with depth. Difficulties may be encountered in placing the electrode in a suitably representative layer. There is evidence to indicate that the Alfano method is more sensitive to lateral changes in subsurface bodies than surface probing methods. It is envisaged that the Alfano technique may be more suitable in an area where subsurface lithology is more uniform over widespread areas than in unconsolidated sediments and where the targets of investigation are not so easily accessible by drilling.

9.8 The Wenner traversing results (a=10m) have been shown to have a slight correlation with bauxite thickness and water-table depth on a regional basis. The value of the Wenner traversing results is considered marginal and the method is not absolutely necessary for a routine water-search project. The value of the technique will be largely a matter for the user to decide in a particular area. The Wenner traversing resistivity highs may indicate difficult drilling conditions of indurated impermeable clays but generally no indication of sub-bauxite lithology or permeability was obtained from the Wenner results in the test area. Two kilometres of traverse could be covered by 3 to 4 men per day at a 10-m station interval.

9.9 Pole-dipole traversing at $AB/_2$ = 50 m, MN = 20 m has been shown to be largely unaffected by bauxite resistivity variations and has indicated resistivity lows over the two major permeable areas. It is considered a reliable method of indicating local rises in the water-table over unconfined groundwater in permeable sand bodies. It is these types of permeable bodies which are envisaged as forming the major production aquifers in this environment. Two small confined permeable sand bodies were not indicated by the pole-dipole traversing method because of the depressed water-table. The resistivity low over the unconfined aquifer can be attributed to a thickening of the low-resistivity subwater-table layer and a thinning of the higher-resistivity sub-bauxite layer.

The parameters of the traversing technique must be chosen from a consideration of several resistivity probes carried out initially throughout the area of investigation. A sufficiently large value of AB/$_2$ can be chosen to minimize the 'random' variations of resistivity in the bauxite and sub-bauxite layers. For production work a 5 to 6-man team could cover 5 km per day at a 20-m station spacing. This technique will considerably reduce the need for drilling.

9.10 The VLF direct-reading magneto-telluric resistivity traversing technique proved to be disappointing as a quick, cheap reconnaissance method. The resistivities obtained often showed considerable scatter far exceeding instrumental error. The reasons for this are not clear but may be related to the complex behaviour of resistivity with frequency in a clayey sand sediment. Lack of suitable undisturbed sampling techniques prevented detailed investigation of this problem. Further work on this problem is recommended if the VLF technique is to be persisted with. The VLF resistivity is most sensitive to the depth and resistivity of the conductive Rolling Downs Group beneath the Bulimba Formation.

9.11 Experimental depth probes using the IP frequency domain technique indicate low (0 to 3%) frequency effects associated with the sediments of the Bulimba Formation. This is attributed to the presence of low-IP kaolin clays which exhibit even lower IP in the presence of the high-pH, low-cation-concentration groundwaters common in the bauxite-covered areas. High IP effects in the Rolling Downs Group dominate the shape of the IP probe curves and are attributed to metallic IP effects in the pyritic and carbonaceous shales preserved in the Group. The depth to the high-IP anomalies zone generally exceeds the depth of the top of the Rolling Downs interpreted from resistivity probing data. This is attributed to a combination of the presence of westhered zone of low polarizability and (or) low-IP sandstone near the top of the Rolling Downs Group. In one case a decrease in IP effect with depth in the Rolling Downs Group, corresponding to an increase in resistivity, is interpreted as being due to a less shaley formation at depth.

The IP method is not considered to be a useful technique for investigation for groundwater in the Bulimba Formation.

9.13 The resistivity and gamma-ray logging techniques were hampered by instrumental limitations and considerable improvement on the results obtained during the survey is a necessary prerequisite of any production survey in the area. An improvised four-electrode Wenner logger (a=0.5 m) proved most successful and although only capable of resolving beds of the order of 1 m thickness and more, is considered to have advantages over the single-point log. The use of high-resistivity groundwater as the borehole fluid has enabled a clear picture of the subsurface resistivity variations than obtained by previous logging in the area using conductive muds as a borehole fluid. Auger drilling, gamma-ray logging, and resistivity logging with the four-electrode logger are considered to be a much more reliable and hence ultimately more economical method than resistivity probing for detailed follow-up of reconnaissance resistivity traversing.

Detailed lithological information from the gamma-gay logs is possible using a high-sensitivity gamma tool, slow logging speeds, and a long time constant.

## 10. RECOMMENDATIONS FOR FUTURE GROUNDWATER INVESTIGATIONS

Experience gained on the present survey and from consideration of previous investigations has enabled guidelines to be established for future investigations for water in the Bulimba Formation.

Firstly the minimum size area to be investigated should be at least 100 $km^2$ for sufficient chance of permeable bodies being found. Continuous north-south resistivity traversing for several tens of kilometres with some follow-up drilling is advisable to define the more favourable areas for detailed investigation.

The choice of traversing parameters can be made from consideration of several preliminary probe curves throughout the area. Values of AB/2 = 50 m and MN = 20 m with a station spacing of 20 m will probably be adequate for most areas except where the water-table is deeper or the bauxite layer thicker.

Areas of higher water-table, lower altitude, and with minimum dissection will probably be the most favourable. These areas are more likely closer to the coast and as the subsurface water flow in the Bulimba Formation is generally towards the coast, the coastal regions are probably the most suitable from the point of view of recharge.

Once an area has been established for detailed investigation, several north-south resistivity traverses should be carried out generally spaced no more than 1 km apart. This will increase the chance that any major permeable body is intersected in an area where it is unconfined. Conceivably a major potential aquifer may in places by partly confined and it may not be indicated by the resistivity method. Once drilling has proved suitable unconfined aquifers defined by the resistivity traversing the east-west extent of these can be traced by either drilling or resistivity traversing.

The resistivity traversing should be carried out in a manner as discussed in Section 5.1 using a high-voltage transmitter (2000 - 3000 V output) and a suitably sensitive receiver. Careful traverse preparation will ensure the speed of the traversing method. It is conceivable that two drilling units can be kept occupied if a sufficiently large-scale investigation is envisaged.

The choice of drilling equipment lies between rotary drilling using air or water injection, and auger drilling. Rotary drilling has the advantage of speed and the availability of compressed air for developing and testing bores, but air or water injection gives poor samples below the water-table. The use of drilling mud, either bentonite-based or revertible organic polymer types can cause difficulties in electric logging with low-power equipment. Bentonite-based muds could reduce the aquifer permeability.

Auger drilling using solid augers is fairly rapid and gives reasonable samples but it is difficult to obtain representative samples of aquifer material. The use of suitable tube-sampling equipment could probably overcome this disadvantage. Hollow augers have some advantages for tube sampling and also permit gamma-ray logging inside the drill rods but they are much slower to handle, especially in large sizes. Screw-jointed hollow augers are easier to handle than the circlip jointed type but cannot be reversed for removal if stuck.

Drilling costs would be less with an auger drill owing to lower mobilization and running costs and, on balance, the auger drill is probably better for this type of investigation in such an area.

The resistivity logging using an improvised Wenner four-electrode system (a = 0.5 m) on a weighted wooden pole is a suitable technique in an auger hole where there is a danger of the hole collapsing. The improvised resistivity tool can then be abandoned in the event of a hole collapsing. This will circumvent both the need for costly mud drilling and the problems of resistivity logging in conductive muds.

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Pump tests should be carried out with pumping wells distributed along the aquifers and outside it as well. The assumption of a sheet aquifer in quantitative interpretation of well pumping tests is obviously invalid and caution should be exercised in this regard. It is envisaged that an east-west aligned network of bores will be necessary for exploitation of any major aquifers.

## REFERENCES

ALFANO, L., 1962 - Geoelectrical prospecting with underground electrodes. Geophys. Prosp., 10(3), 290-303.

ANDREW, T., & WIEBENGA, W.A., 1965 - Two layer resistivity curves for the Wenner and Schlumberger electrode configurations. Bur. Miner. Resour. Aust. Rec. 1965/18 (unpubl.).

BARKER, R.D., 1974 - The interpretation of induced polarization sounding curves in the frequency domain. Geophys. Prosp. 22(4), 610-26.

BEAR, J., 1972 - DYNAMICS OF FLUIDS IN POROUS MEDIA. N.Y., Elsevier.

CAGNIARD, L., 1953 - Basic theory of the magneto-telluric method of geophysical prospecting. Geophysics, 18(3), 605-35.

CHAPMAN, T.G., 1960 - Investigation of groundwater potential in the Weipa Peninsula 1959-60 (unpubl. Rep.).

CHAPMAN, T.G., 1963 - Groundwater hydrology of the Weipa Peninsula. J. Inst. Eng. Aust., 35(8), 181-6.

CHELIDZE, T.L., 1963 - Concerning the question of the frequency dependence of the electrical properties of rocks. Tr. Inst. Geofiz. Akad. Nauk. Georgian SSR 21.

COFFEY & HOLLINGSWORTH, 1971 - Comalco Limited shallow aquifer investigation Weipa, North Queensland (unpubl. Rep.).

COFFEY & HOLLINGSWORTH, 1975 - Summary report on water availability, Aurukun area - North Queensland (unpubl. Rep. 6441B/5).

DOUTCH, H.F., SMART, S., GRIMES, K.G., GIBSON, P.L., & POWELL, B.S. 1973 - Progress report on the geology of the Carpentaria Basin in Cape York Peninsula. Bur. Miner. Resour. Aust. Rec. 1973/187 (unpubl.).

DOUTCH, H.F., SMART, J., & GRIMES, K.G., in prep. - Geology of the Carpentaria and Karumba Basins, Queensland. Bur. Miner. Resour. Aust. Bull.

EDWARDS, A.B., 1957 - Quartz and heavy minerals in Weipa bauxite. CSIRO Mineragraphic Investigations Report 749, Nov. 1957.

EDWARDS, A.B., 1958 - Quartz and heavy minerals in bauxite of Weipa. N. 10 000/W. 15 000 Pit. CSIRO Mineragraphic Investigations Report 750, Jan. 1958.

EVANS, H.J., 1965 - Bauxite deposits of Weipa. In Geology of Australian ore deposits 8th Comm. Min. metall. Conf. 1, 396-401.

FRASER, D.C., FULLER, B.D., & WARD, S.H., 1966 - Some numerical techniques for application in mining exploration. Geophysics, 31(6), 1066-77.

GHOSH, D.P., 1971 - Inverse filter coefficients for the computation of apparent resistivity standard curves for a horizontally stratified earth Geophys. Prosp., 19(4), 769-75.

GREEN, G.W., 1962 - East to west investigations of aquifer evaluation details of sub artesian water supply for west Weipa area (unpubl. Rep.).

GRIMES, K.G., 1972 - A shallow artesian aquifer in the Tertiary deposits of southern Cape York Peninsula. Qld Govt Min. J., 73.

GUYOD, H., 1944 - ELECTRICAL WELL LOGGING. Halliburton Oil Well Cementing Company.

HUSSIN, J.J., 1967 - Report on resistivity groundwater survey, County Musgrave. S. Aust. Def. Min. Rep. 64/67.

IRRIGATION AND WATER SUPPLY COMMISSION, 1963 - Progress report on investigation of the shallow aquifer, Weipa peninsula - Cape York, North Queensland (unpubl. Rep.).

IRRIGATION AND WATER SUPPLY COMMISSION, 1967 - Initial report on the reappraisal of the shallow aquifer, Weipa peninsula Cape York, North Queensland (unpubl. Rep.).

IRRIGATION AND WATER SUPPLY COMMISSION, 1969 - Hey Point area, Weipa groundwater investigation (unpubl. Rep.).

KELLER, G.V., & LICASTRO, P.G., 1959 - Dielectric constant and electrical resistivity of natural state cores. U.S. Geol. Surv. Bull. 1052-4.

KELLER, G.V., & FRISCHKNECHT, P.C., 1966 - ELECTRICAL METHODS IN GEOPHYSICAL PROSPECTING, Oxford, Pergamon.

52

KOEFOED, O., 1968 - The applications of the kernel function in interpreting geoelectrical measurements. Geoexpl Monogr. 1(2), Getruder Borntraeger Berlin.

KUNETZ, G., 1966 - Principles of direct current resistivity prospecting. Geoexpl. Monogr. 1(1), Getruder Borntraeger Berlin-Nikolasee.

LAL, T., 1970 - Apparent resistivity over a three layer earth with an inhomogenous interstratum Pure appl. Geophysic, 82, 259-69.

MAILLET, R., 1947 - The fundamental equations of electrical prospecting. Geophysics, 12(4), 529-56.

MALLICK, K., 1956 - Can transition in the electric properties of the earth be detected? Geophys. Prosp., 19(1), 156-61.

MERKEL, R.H., 1971 - Resistivity analysis for plane layer half space models with buried current sources Geophys. Prosp. 19(4), 626-39.

MOUSINHO de MEIS, M.R., & AMADOR, E.S., 1974 - Note on weathered arkosic beds. J. sedim. Petro., 44, 727-37.

ORELLANA, E., 1963 - The properties and drawing of the so-called Dar Zarrouk curves Geophysic, 28(1), 99-110.

ORELLANA, E. & MOONEY, H.M., 1966 - MASTER TABLES AND CURVES FOR VERTICAL ELECTRIC SOUNDING OVER LAYERED STRUCTURES Interciencia, Madrid.

PATERSON, N.R., & RONKA, V., 1971 - Five years of surveying with the very low frequency electromagnetics method Geoexploration, 9(1), 7-26.

POLLARD, P.C., 1971 - Computer programme for producing magneto-telluric curves for a horizontally layered earth. Bur. Miner. Resour. Aust. Rec. 1971/35 (unpubl.).

RATHOR, B.P.S. & RATHOR, H.S., 1971 - A resistivity computation method for layered earth models with transition boundary Pur appl Geophysics, 85, 153-60.

SENIOR, B.R., & SMART, P.G., in press - Cobourg Peninsula and Melville Island, N.T. - 1:250 000 Geological Series. Bur. Miner. Resour. Aust. explan. Notes SC/53-13.

SMART, J., in press (a) - Weipa, Qld - 1:250 000 Geological Series. Bur. Miner. Resour. Aust. explan. Notes SD54/3.

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SMART, J., in press (b) - Aurukun, Qld. - 1:250 000 Geological Series. Bur. Miner. Resour. Aust. explan. Notes SD54/7.

VACQUIER, V., HOLMES, C.R., KINTZINGER, P.R., & LAVERGNE, M., 1957 - Prospecting for groundwater by induced polarization Geophysics, 22(3), 660-87.

VOLAROVICH, M.P., VALEEV, K.A., & PARKHOMENKO, E.I. - Resistivity of rocks in constant and alternating fields Izvestia Akad Nauk. SSSR Fiz/ Zemli 5.

ZOHDY, ADEL A.R., 1975 - The use of Dar Zarrouk curves in the interpretation of vertical electrical sounding data U.S. Geol. Surv. Bull. 1313.

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# APPENDIX 1

## Bauxite: Laboratory measurements of resistivity versus frequency

by M. Idnurm

### Measurement equipment

The measurements are carried out in a horizontal conductivity cell using standard audio-frequency techniques. The samples are contained in a 'Perspex' (Reg. Trade Mark) cylinder with perforated end-faces.

For saturated-sample measurements the potential electrodes are silver-plated in order to reduce electrode polarization effects. The electrodes for dry-sample measurements are aluminium discs in contact with the end-faces of the sample.

### Sample preparation

The samples were packed into the container by tapping and use of light pressure. All grainsizes from fine powder fraction to pisolites were included. The saturating electrolyte was introduced into the samples by capilliary attraction over a period of 24 hours or longer. The porosity of the samples as determined from the weight of absorbed water was approximately 25%.

### Electrolyte

The conductivity of the saturating electrolyte was measured before it was introduced into the sample and again at the end of the series of resistivity readings. The conductivity of distilled water saturant increased by 600% from 110 to 650 microsiemens owing to leaching of residual salts from the sample. For saturant of initial conductivity the increase was 10%. It seems therefore that the conductivity of the original pore water was somewhat larger than 3300 millisiemens.

### Results

The results are shown in the resistivity and phase angle diagrams (Pl. 21). It should be noted that the resistances measured here, as those measured in the field, are complex resistances which contain contributions from electrochemical-type dielectric effects.

The dispersion of resistivity decreases markedly as the moisture content is increased. This effect has been observed several times previously (Keller & Licastre, 1959; Chelidge, 1963; Volarovich et al., 1957). The explanation seems to lie in the non-dispersive nature of electrolyte resistance: as the moisture content in the rock increases so does the non-dispersive component of resistivity.

# APPENDIX 2

## Auger Drilling - Aurukun Associates A.T.P. and Aurukun Mission

BMR AURUKUN H 12 — Depth 23.2 m

LOCATION: 20 m west of pumped well at Aurukun Mission. Lat 13°22'S, Long. 141°43'E.

ELEVATION: 3.05 m

LOG:

| | |
|---|---|
| 0-0.6 m | grey-brown sandy soil, becoming red-brown at base. |
| 0.6-3.0 m | red-brown clayey sand, medium-grained, quartzose with soft pisolites up to 8 mm. |
| 3.0-5.5 m | red-brown and yellowish nodules and pisolites, 2-10 mm, with red-brown sandy clay matrix. Matrix more abundant and more clayey with depth. |
| 5.5-6.1 m | reddish brown sandy clay |
| 6.1-11.3 m | fawn clayey quartzose sand, medium to coarse-grained; some portions pinkish. |
| 11.3-19.2 m | pale creamy soft clayey ( < 10%) quartzose sand, medium to coarse-grained, poorly sorted; wet. |
| 19.2-23.2 | Stiff grey, very sandy clay, sand quartzose, medium to coarse-grained. |

SWL 6 m

INTERPRETATION: Bulimba Formation, aquifer sand 11.3 - 19.2 m.

BMR AURUKUN H13 — Depth 19.51 m

LOCATION: 100 m west of bore and tank at Aurukun Mission. Lat 13°22'S, Long. 141°43'E

ELEVATION: 3.05 m

LOG:

| | |
|---|---|
| 0-0.6 m | Brown-grey sandy soil. |
| 0.6-2.46 m | red-brown soft ferruginous pisolites 2.10 mm, average 5 mm, in red-brown clayey sand matrix, sand quartzose, medium - fine grained. |
| 2 - 3.7 m | Sandy clay, with yellowish nodules, about 4 mm. |

| | |
|---|---|
| 3.7-6.1 m | purple, with yellow and white patches, clayey sand, partly ferruginized. Sand medium-grained, quartzose, some kaolinized feldspar. |
| 6.1-8.5 m | generally as above, but lighter colour and grading to grey-white sandy clay, sand quartzose, medium to coarse-grained. |
| 8.5-13.7 m | white and pinkish clay, slightly sandy (quartzose, medium-fine grained), wet. Sand increasing with depth. |
| 13.7-18.3 m | grey-white clayey (< 10%) quartzose sand, medium to very coarse-grained. |
| 18.3-19.5 m | stiff white sandy clay, sand medium to coarse-grained, quartzose; similar to H12. |

Gamma-ray log to 13.7 m. SWL 5.8 m

INTERPRETATION: Bulimba Formation, aquifer sand 13.7 - 18.3 m

BMR AURUKUN H14 Depth 19.51

LOCATION: 100 m east of swamp at end of NW-SE airstrip. Lat. 13°22'S, Long 141°43'E.

ELEVATION: 3.05 m

LOG:

| | |
|---|---|
| 0-0.3 m | dark brown clayey soil |
| 0.3-1.2 m | pink, grey and red sandy clay, sand quartzose, fine to coarse-grained, with nodules, 4 - 12 mm. |
| 1.2-2.1 m | pink stiff sandy clay, sand quartzose, medium-grained |
| 2.1-2.4 m | as above, but dark red-brown. |
| 2.4-6.1 m | light grey stiff sandy clay, sand quartzose, fine to coarse-grained; same red staining to about 4 m. |
| 6.1-7.6 m | pink-brown sandy clay as above, but with minor ferruginous nodules up to granule size. |
| 7.6-9.4 m | light creamy grey, very clayey sand (more than 20% clay), sand quartzose fine coarse-grained, mostly medium-grained, poorly sorted. Wet from about 8.5 m |
| 9.4-14.0 m | white creamy clayey sand, quartzose fine to coarse-grained, mostly medium. |
| 14.0-14.6 m | slower drilling, stiff sandy clay. |
| 14.6-14.9 m | very slow drilling |
| 14.9-18.1 m | creamy clayey sand as above. |
| 18.1-19.5 m | dark grey clay with quartzose sand and granules; earthy appearance. |

Gamma-ray log to 14.0 m. SWL 5.5 m

INTERPRETATION: Bulimba Formation, aquifer sands 9.4-14.0 and 14.9-18.1 m

BMR AURUKUN H20 Depth 17.7 m

LOCATION: at HABA North Camp, 3 m W of unused 6" steel-cased bore, 100 m NNW of radio-telephone mast. Lat. 13°01'S, Long 141°47'E.

LOG:

| | |
|---|---|
| 0-0.9 m | red-brown fine sandy loam |
| 0.9-1.5 m | loam as above with some nodules of ferruginized clay and sand (average 5 mm). |
| 1.5-2.1 m | irregularly shaped nodules of ferruginized clay and sand. |
| 2.1-9.1 m | white, with red and yellow staining, medium to fine-grained sandy clay, iron cemented to form nodules in places. |
| 9.1-17.7 m | wet yellow, red and white, fine to coarse-grained sandy clay. |

INTERPRETATION: No suitable aquifer sands present.

BMR AURUKUN H21 Depth 21.3 m

LOCATION: 2.8 km NNW of Beagle Camp on track to Hey Point. 7 m N of existing bore, HABA 3. Lat 13°00'S, Long 141°47'E.

LOG:

| | |
|---|---|
| 0-0.6 m | grey-brown fine sandy loam with some pisolites less than 4 mm across. |
| 0.6-1.8 m | pisolitic bauxite, pisolites 2-10 mm, abundant sandy matrix. |
| 1.8-4.6 m | pisolitic bauxite, pisolites mainly about 4 mm, some about 10 mm, some sandy matrix, grading into: |
| 4.6-6.1 m | nodules of iron-cemented fine to medium-grained clayey sandstone. |
| 6.1-9.9 m | fine to medium-grained clayey sand, 30% clay mostly, but less in places towards base of interval. |
| 9.9-12.8 m | medium to fine-grained, very sandy clay and/or very clayey sand. Harder drilling than above. |
| 12.8-18.9 m | white with yellow and red staining, fine to medium-grained clayey sand. Clay about 30%, easier drilling than above. |
| 18.9-21.3 m | stiff white with red and yellow staining, very fine to medium-grained clayey sand or very sandy clay. |

INTERPRETATION: No suitable aquifer sands present.

BMR AURUKUN H22 Depth 17.7 m

| | | |
|---|---|---|
| LOCATION: | 1.3 km N of Beagle Camp on track to Hey Point. Lat. 13°01'S, Long. 141°47'E. | |
| LOG: | 0-0.6 m | grey-brown grading to orange sandy loam with a few small (4 mm) bauxite pisolites. |
| | 0.6-4.6 m | pisolitic bauxite, modal sizes of pisolites 4 and 10 mm, little matrix. |
| | 4.6-6.1 m | nodules of iron-cemented clayey sand. Nodules 4 to 8 mm. |
| | 6.1-12.2 m | pinkish brown, fine to medium-grained clayey sand. Clay 30-40%. |
| | 12.2-17.7 m | yellow-brown very clayey sand or very sandy clay. Sand is fine to medium-grained, with some coarse-grained sand towards bottom of interval. |

INTERPRETATION: No suitable aquifer sands present.

BMR AURUKUN H23 Depth 13.1 m

| | | |
|---|---|---|
| LOCATION: | 2.3 km S of Beagle Camp on track to Aurukun Mission. In bed of small creek. Lat 13°02'S, Long 141°48'E. | |
| LOG: | 0-0.6 m | grey-brown sandy loam. |
| | 0.6-1.5 m | pisolitic bauxite, generally 4 to 8 mm pisolites, with abundant sandy matrix. |
| | 1.5-7.0 m | clayey feldspathic quartz sand, reddish, grading to white with yellow and red staining by 3 m. |
| | 7.0-13.1 m | white with yellow and red staining, stiff, fine to coarse-grained sandy clay. |

INTERPRETATION: No suitable aquifer sands present.

BMR AURUKUN H24 Depth 21.3 m

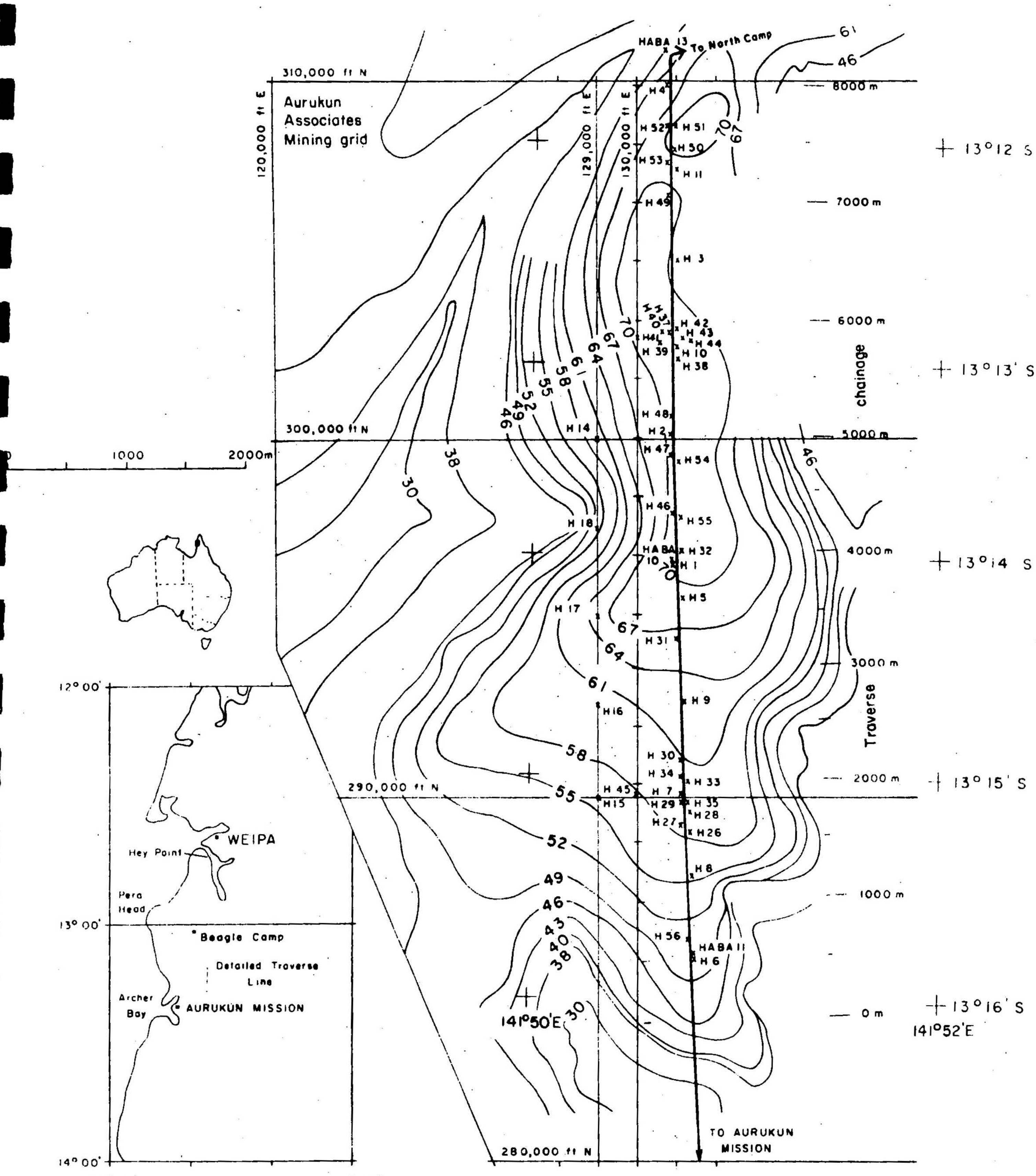
| | | |
|---|---|---|
| LOCATION: | 4.5 km S of Beagle Camp on track to Aurukun Mission. Lat. 13°03'S, Long. 141°48'E. | |
| LOG: | 0-0.3 m | grey sandy loam. |
| | 0.3-0.9 m | reddish orange sandy loam with small (2-4 mm) bauxite pisolites becoming more common with depth. |
| | 0.9-2.1 m | hard cemented pisolitic bauxite. |
| | 2.1-21.3 m | white, reddish-brown, and yellow-brown very clayey and clayey, fine to medium-grained sand. |

INTERPRETATION: No suitable aquifer sands present.

BMR AURUKUN H25 Depth 19.5 m

| | | |
|---|---|---|
| LOCATION: | 1 km S of Tapplebang Ck on Beagle Camp/Aurukun Mission track. Lat. 13°05'S, Long. 141°49'E. | |
| LOG: | 0-0.3 m | grey-brown sandy loam. |
| | 0.3-1.8 m | red sand with some bauxite pisolites (about 4 mm size). |
| | 1.8-2.4 m | pisolitic bauxite (size modes at 4 and 12 mm), with plentiful sandy matrix. |
| | 2.4-3.4 m | nodules of clayey, fine to medium-grained sandstone in sandy matrix. |
| | 3.4-19.5 m | white with pink and yellow staining clayey, fine to medium-grained sand. |
| INTERPRETATION: | | No suitable aquifer sands present. |

Plate I




x H9 BMR Auger hole, with reference number

x HABA 1 Coffey and Hollingsworth drill hole with reference number

Contours in metres above approx. msl from levelling and photogrammetry by Aurukun Associates

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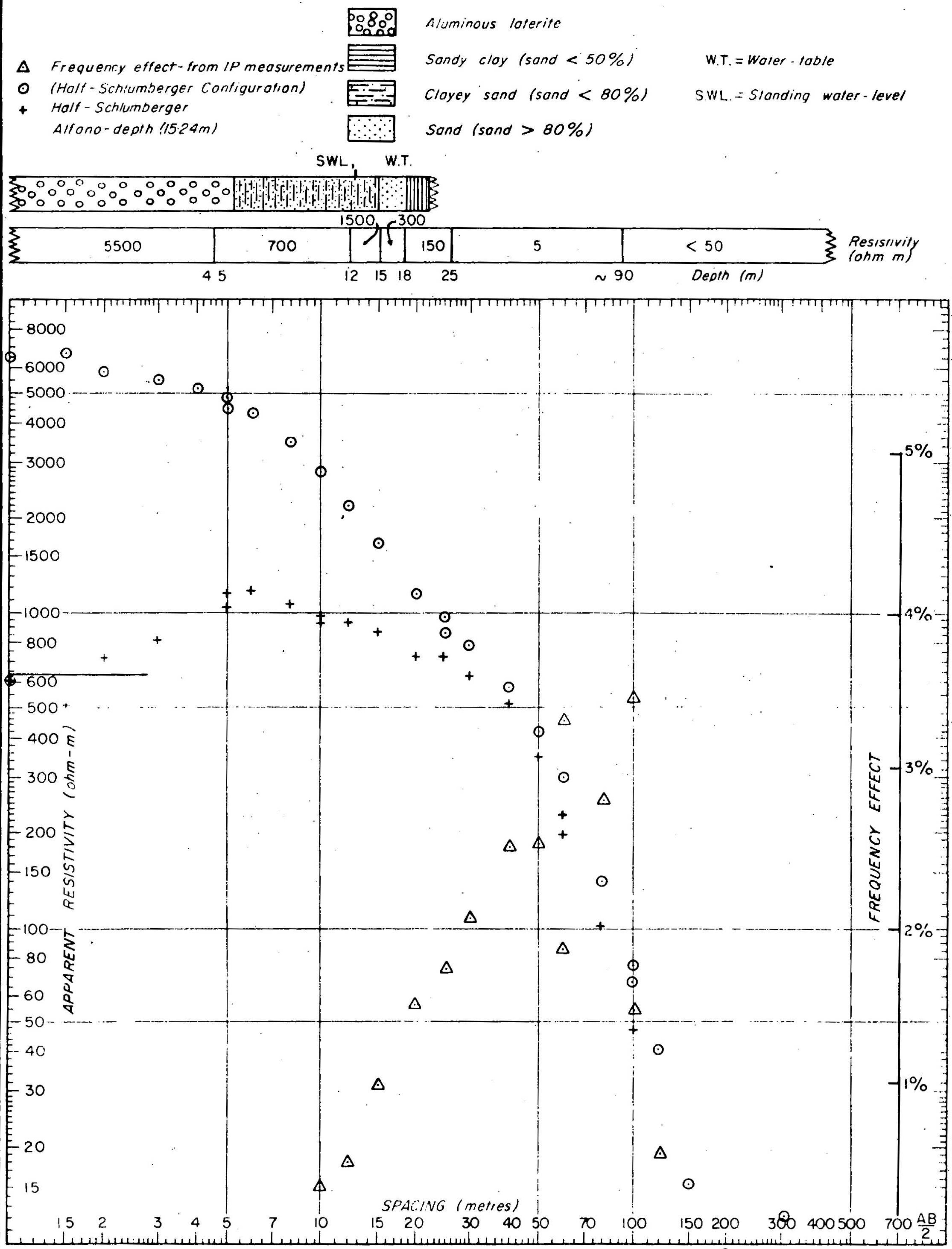
# Location of Detailed Traverse

*Record No. 1976/3*

D54/A

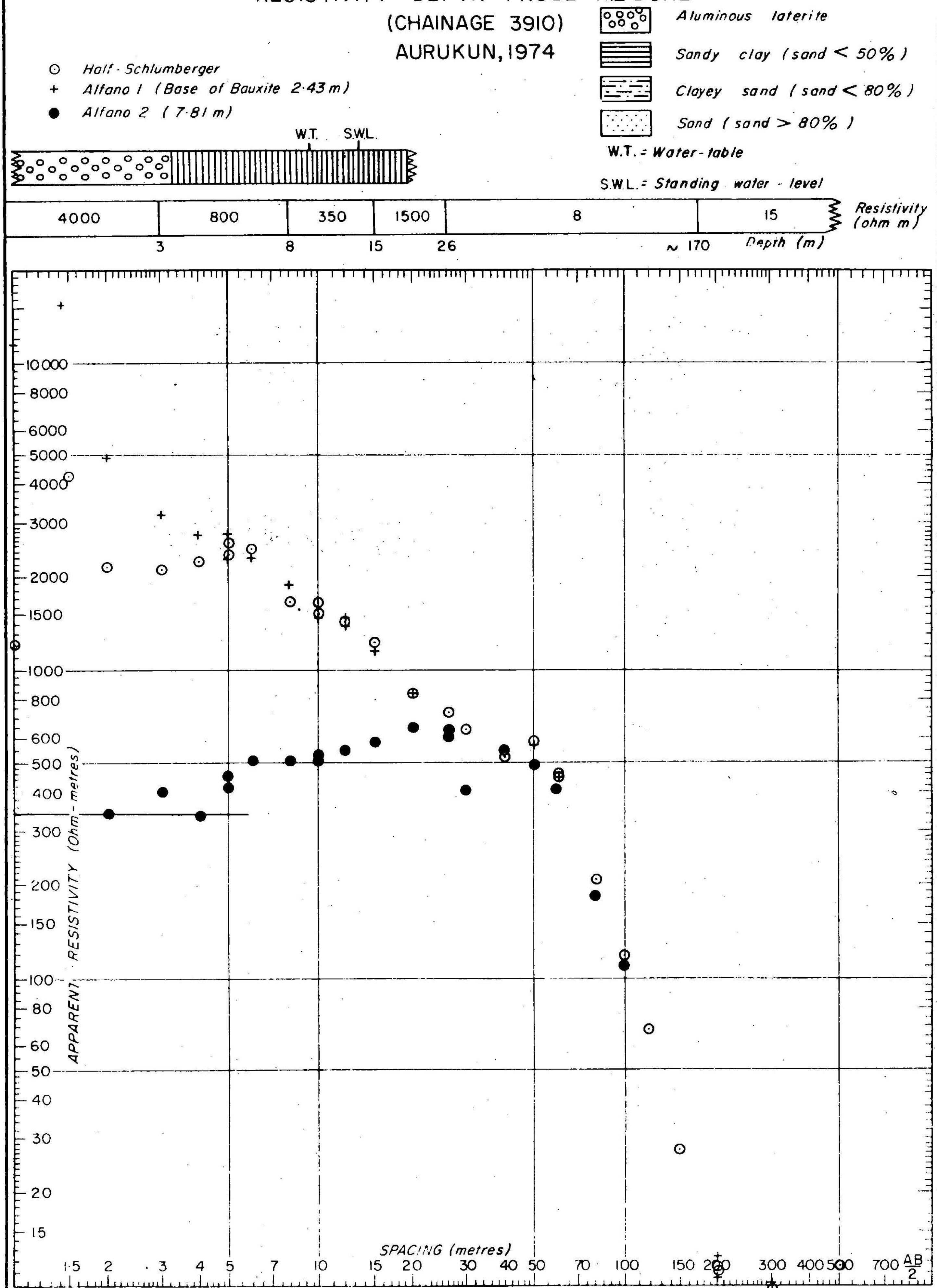
# RESISTIVITY DEPTH PROBE H.I BORE
## (CHAINAGE 3910)
## AURUKUN, 1974




Record No. 1976/3

D54/B5-1A

# RESISTIVITY DEPTH PROBE H.2 BORE (CHAINAGE 3910) AURUKUN, 1974



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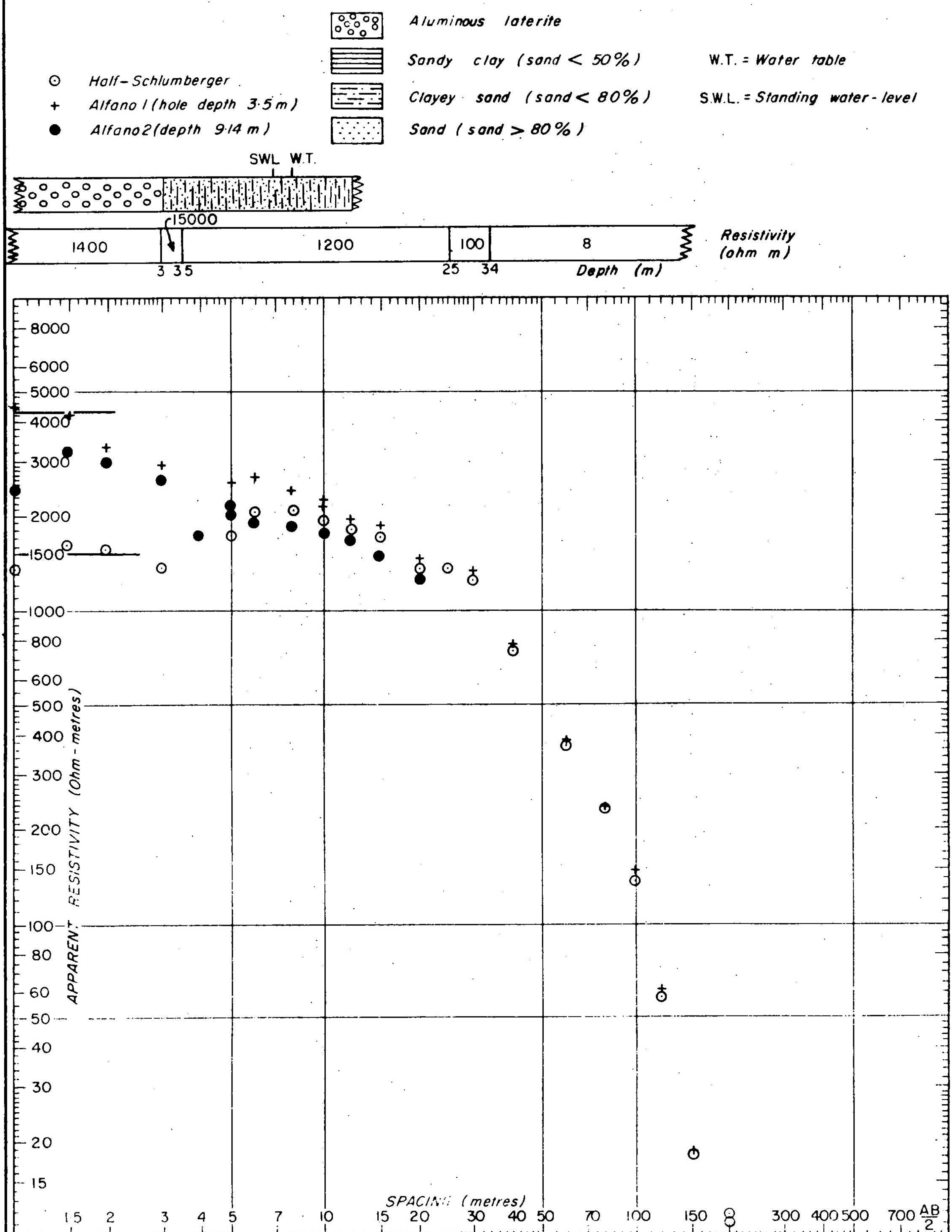
## (CHAINAGE 6360)
## AURUKUN, 1974




Record No 1976/3

D54/B5-3A

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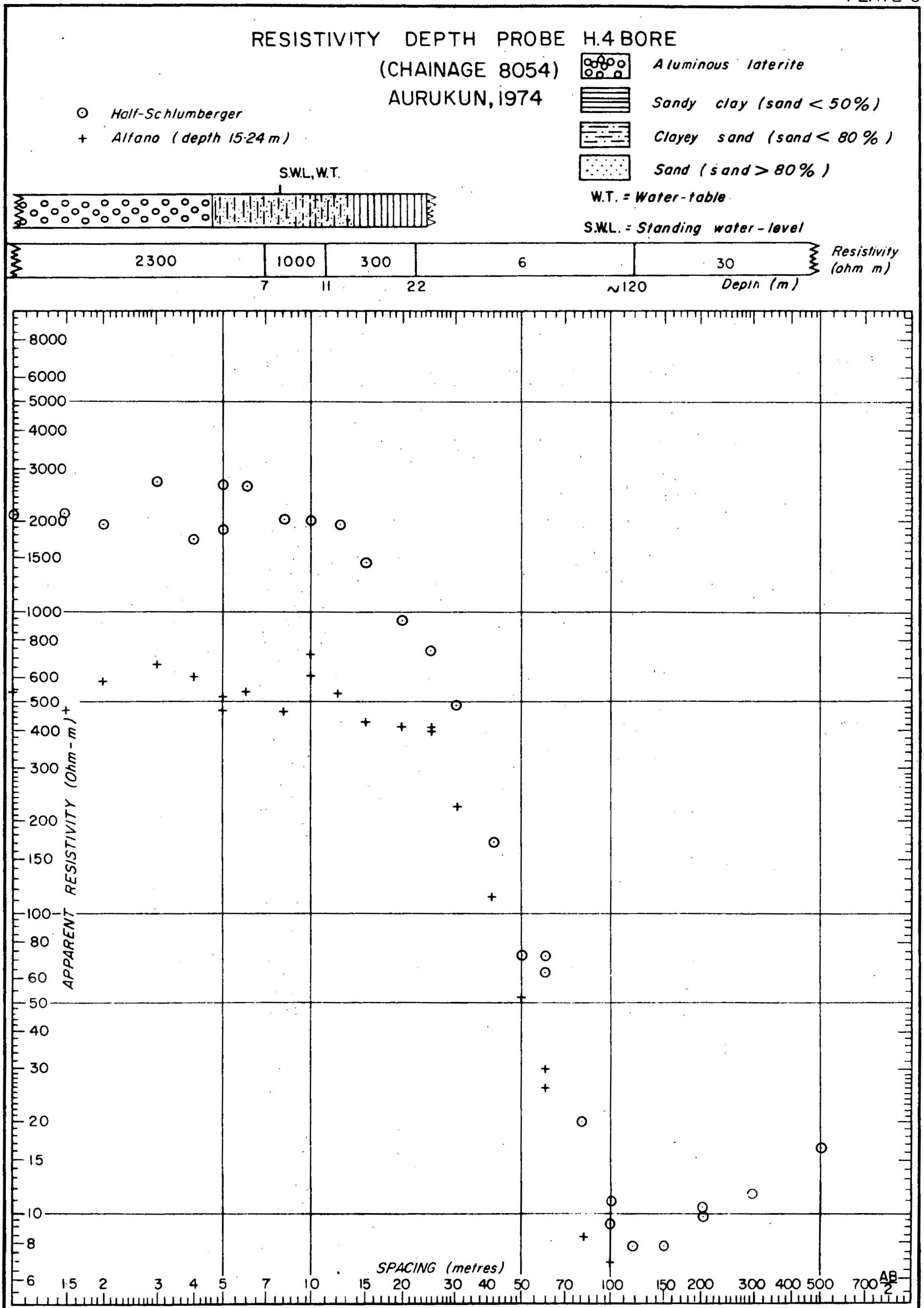
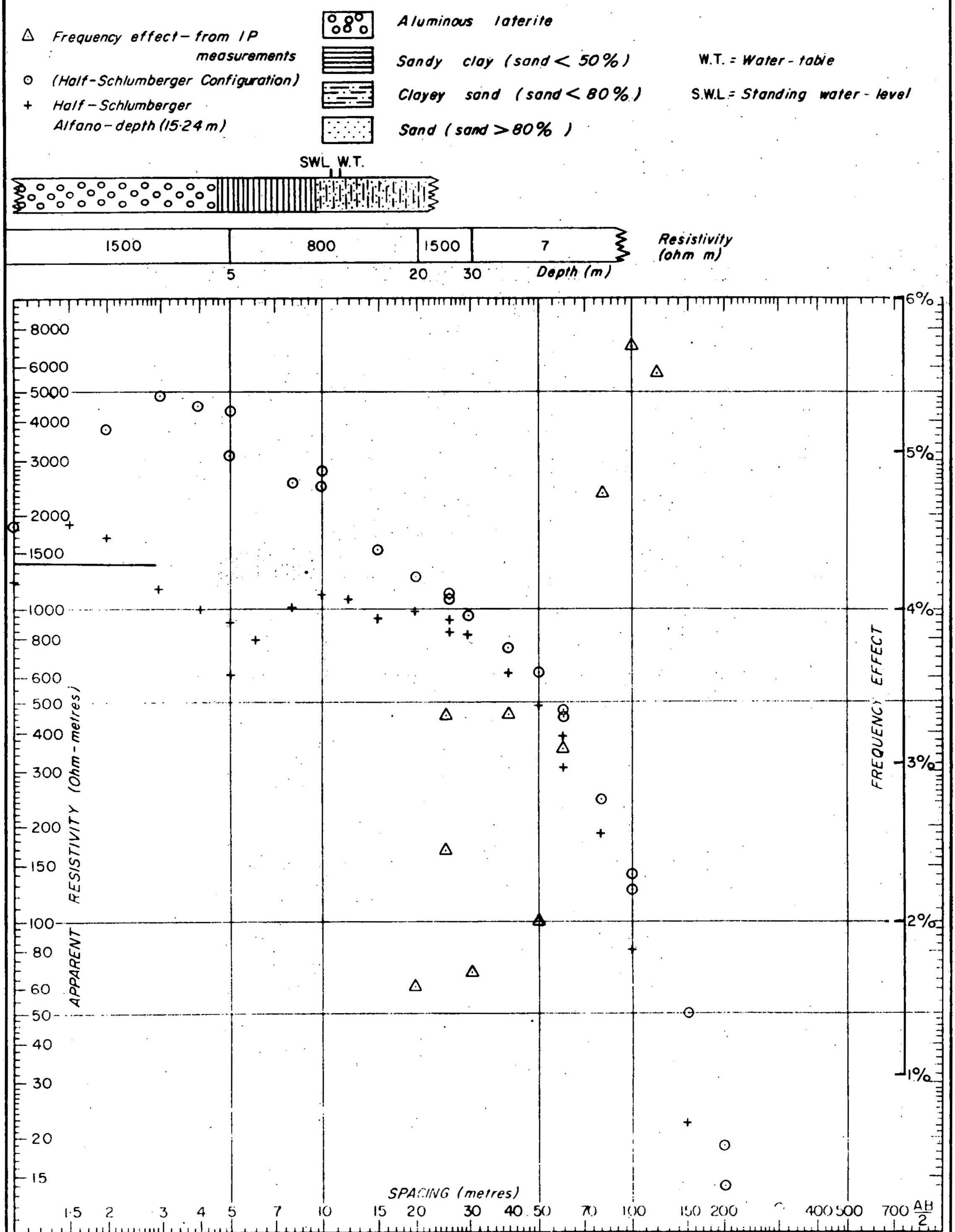



Record No. 1976/3

D54/B5-4A

# RESISTIVITY DEPTH PROBE H.5 BORE
## (CHAINAGE 3640)
## AURUKUN, 1974




Record No 1976/3

D54/B5-5A

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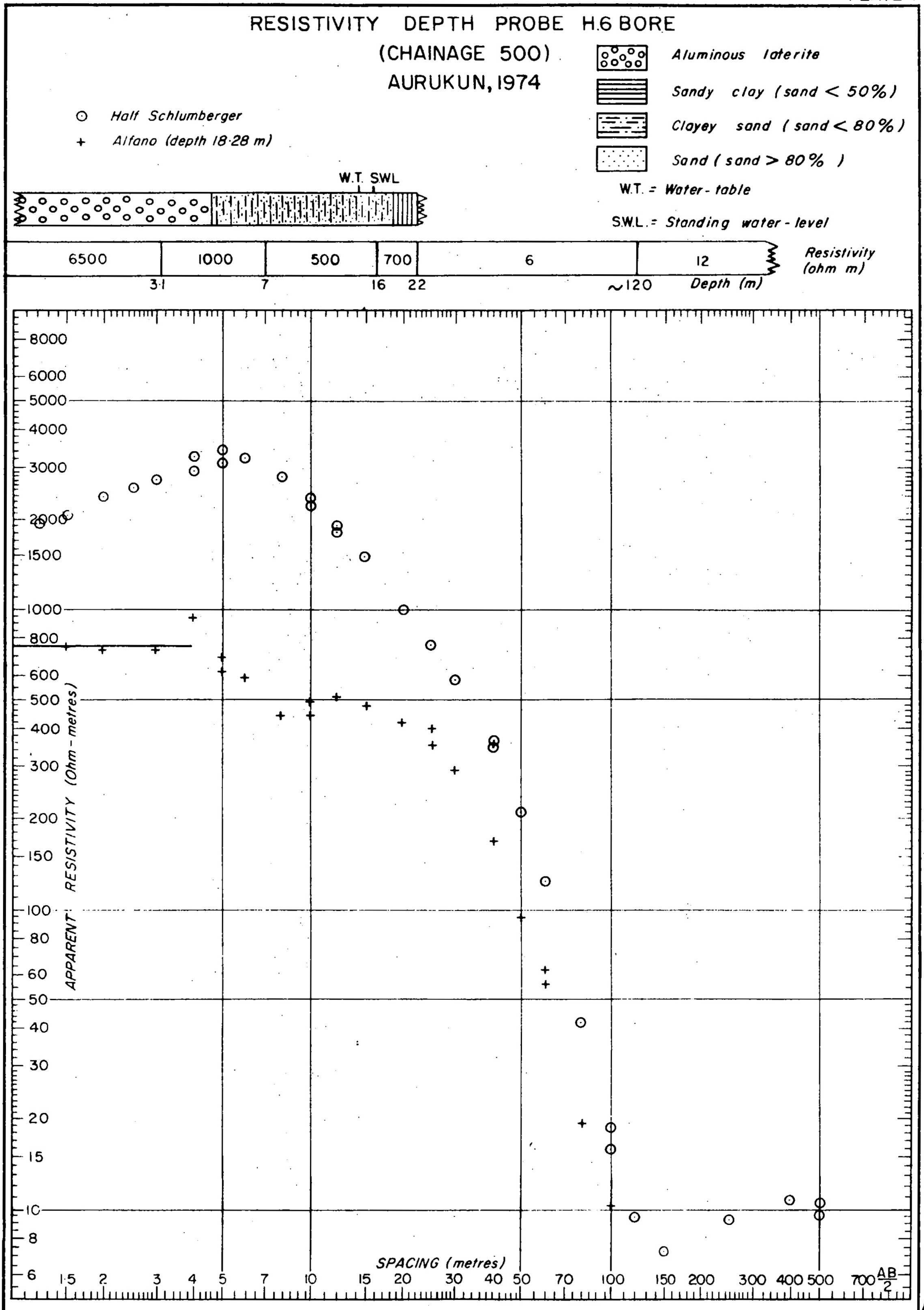
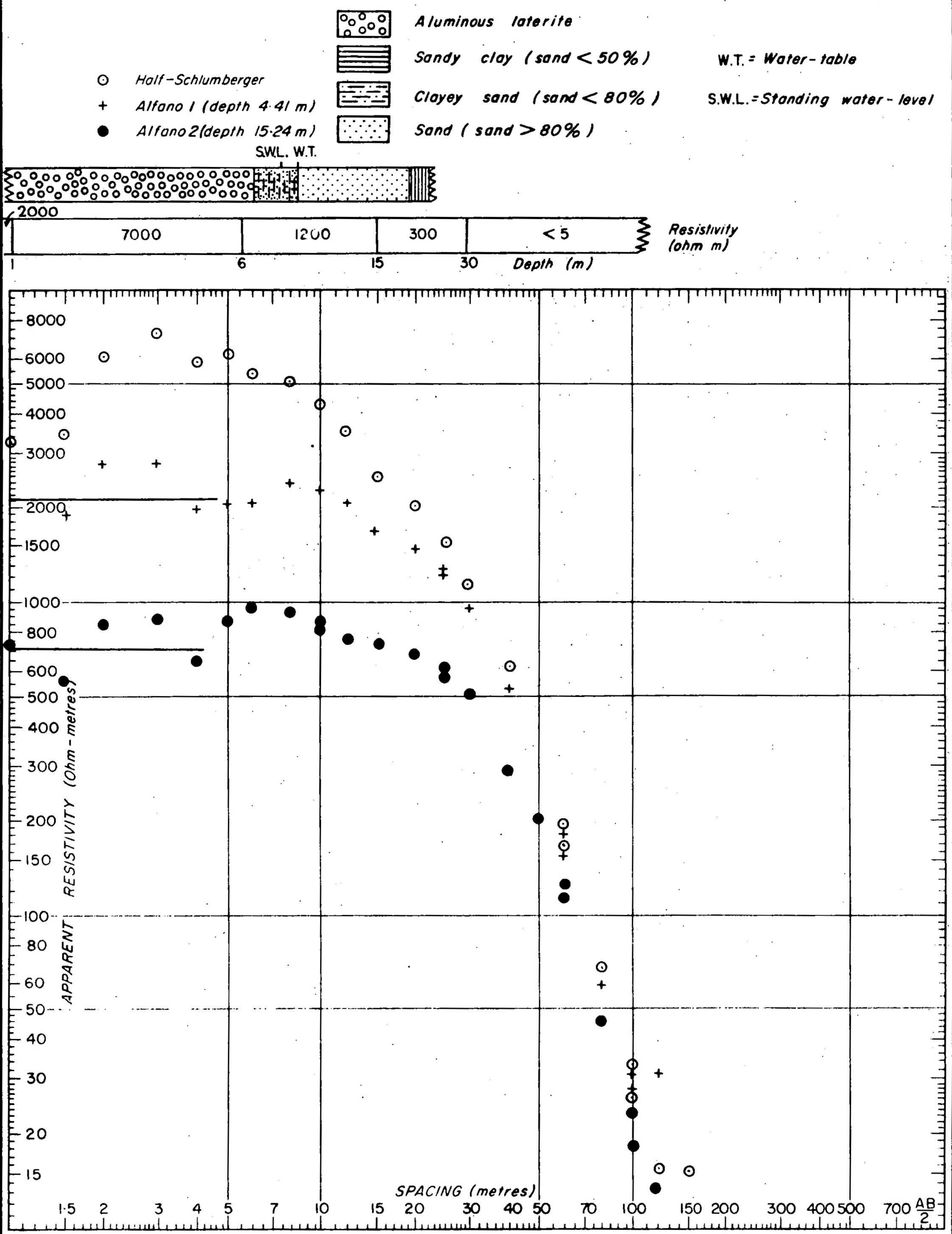
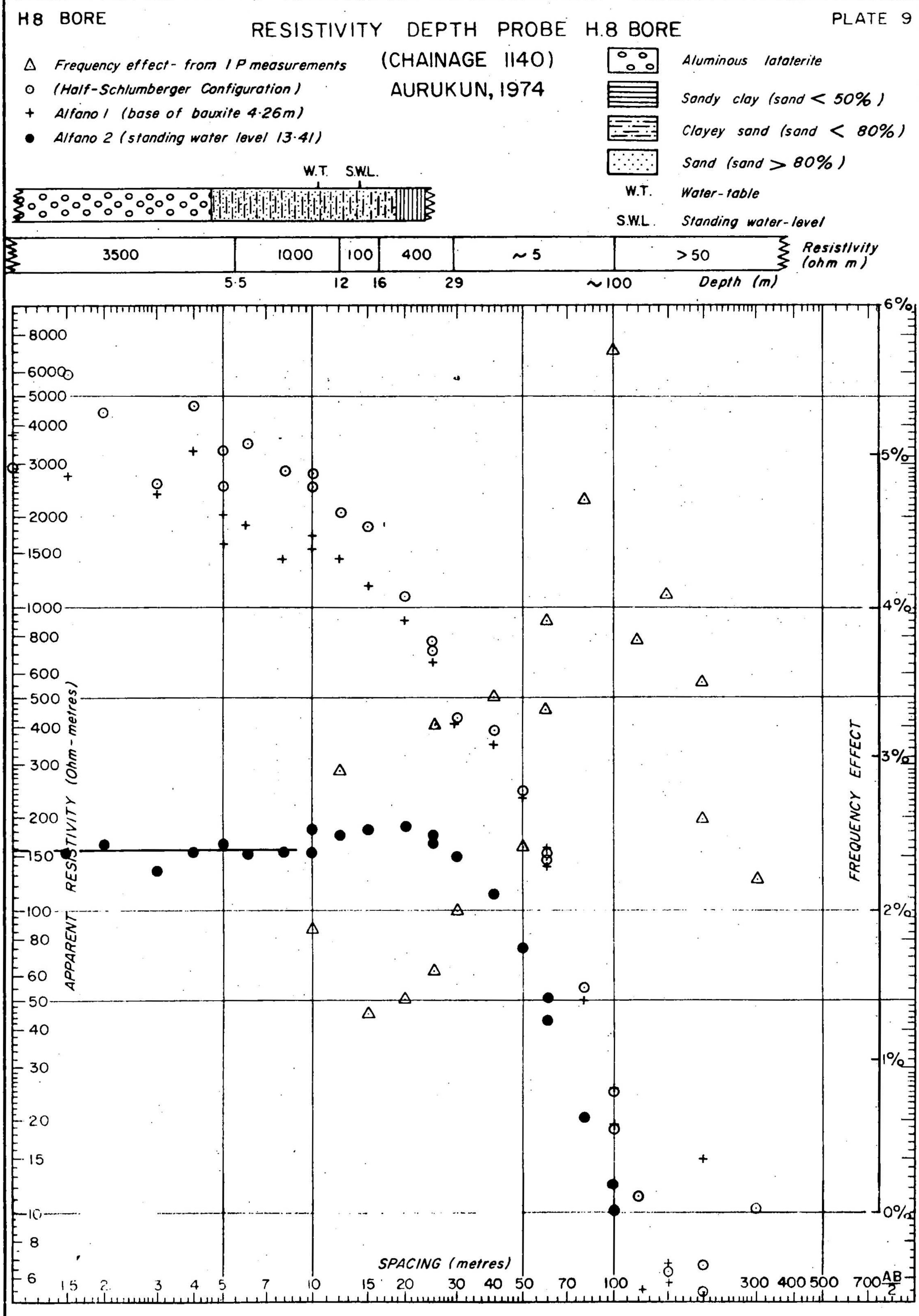

RESISTIVITY DEPTH PROBE H.6 BORE
(CHAINAGE 500)
AURUKUN, 1974
Half Schlumberger
Alfano (depth 18·28 m)
Aluminous laterite
Sandy clay (sand < 50%)
Clayey sand (sand < 80%)
Sand (sand > 80%)
W.T. = Water-table
S.W.L. = Standing water-level
W.T. SWL
6500
1000
500
700
6
12
Resistivity (ohm m)
3·1
7
16
22
~120
Depth (m)
APPARENT RESISTIVITY (Ohm-metres)
SPACING (metres)
AB/2

# RESISTIVITY DEPTH PROBE H.7 BORE
## (CHAINAGE 1950)
## AURUKUN, 1974





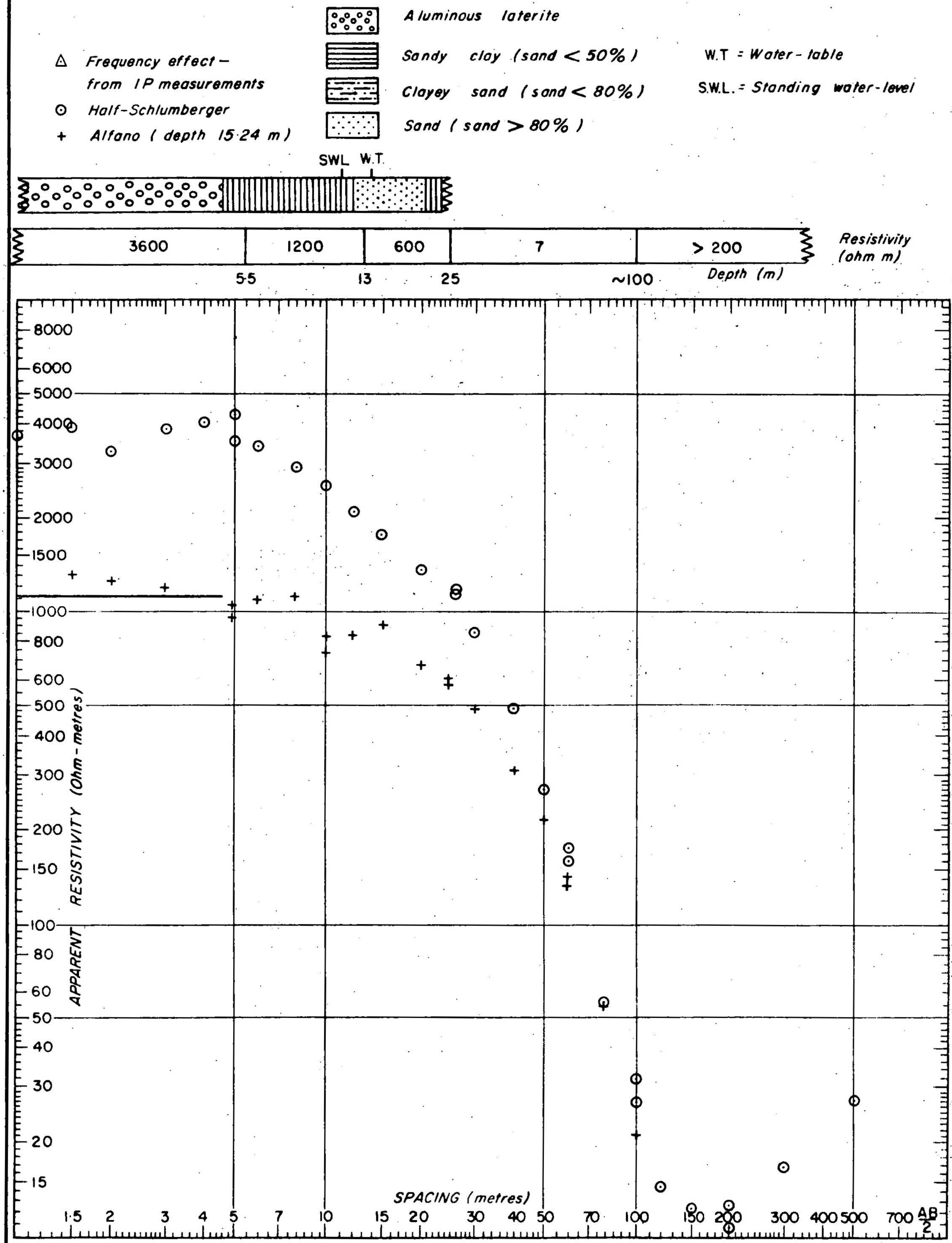

Record No. 1976/3

D54/B5-8A

H9 BORE

PLATE 10

# RESISTIVITY DEPTH PROBE H.9 BORE
## (CHAINAGE 2710)
## AURUKUN, 1974






D54/B5-9A

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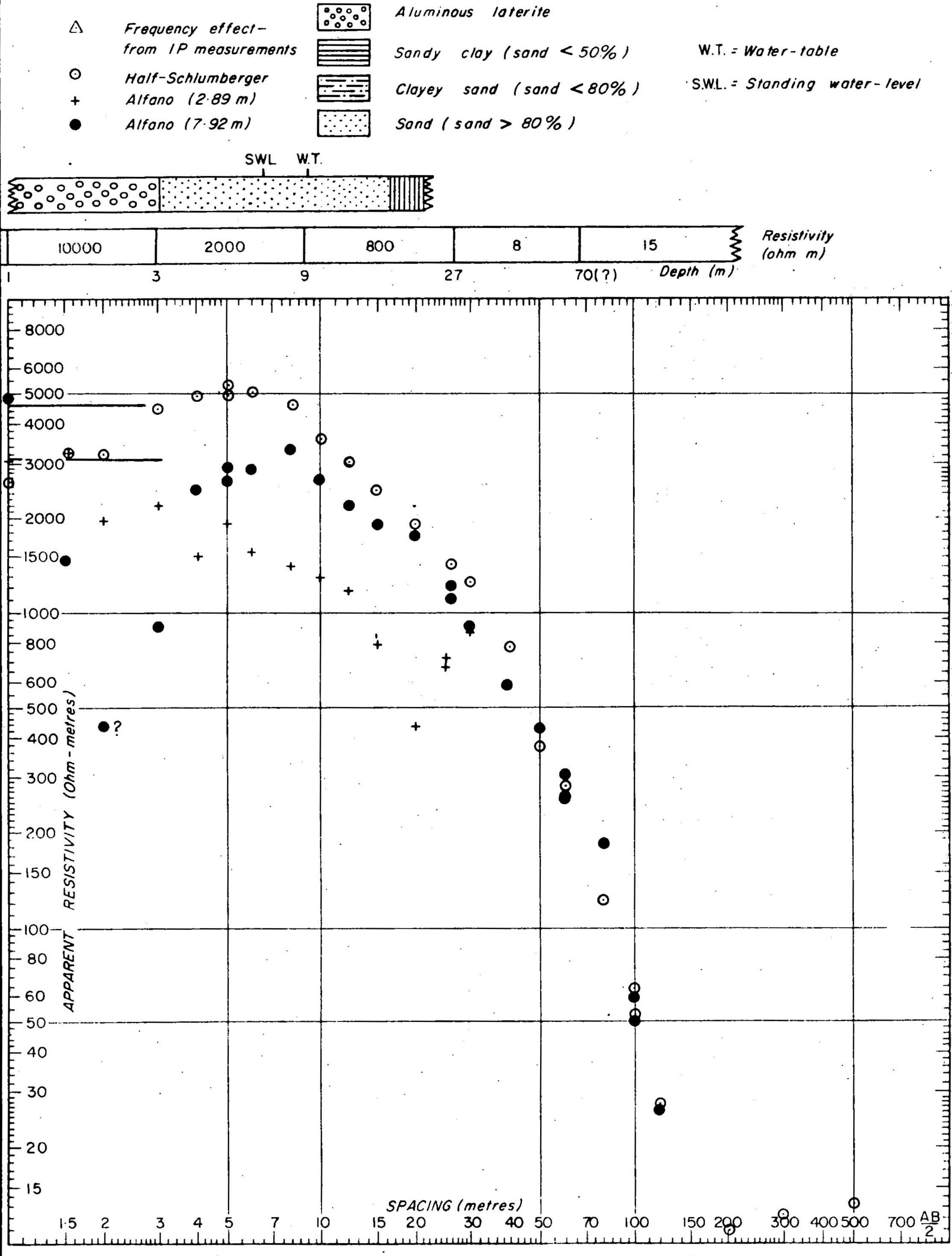
H 10 BORE

# RESISTIVITY DEPTH PROBE H.10 BORE (CHAINAGE 5770) AURUKUN, 1974

PLATE 11

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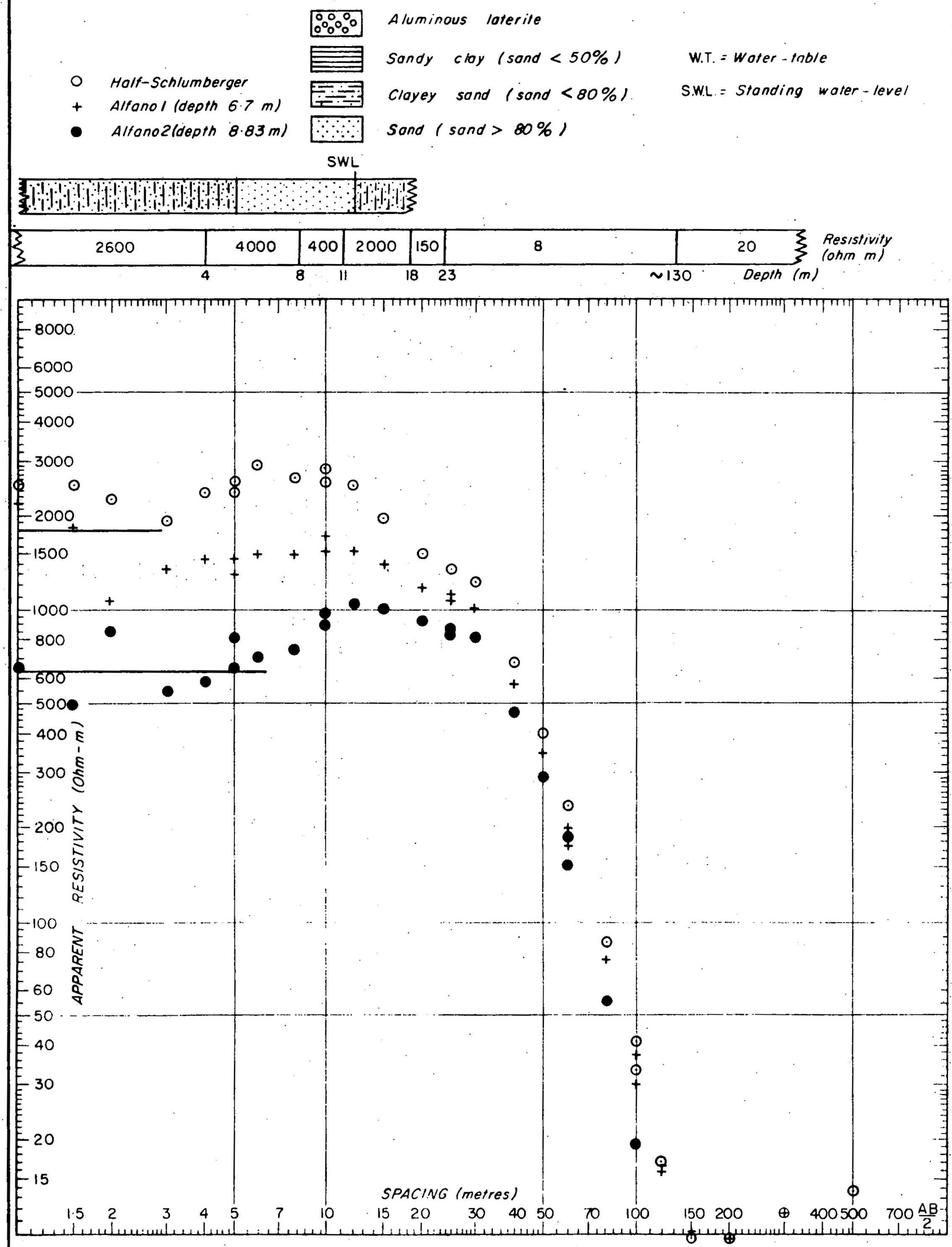
Record No. 1976/3

D54/B5-10A

# RESISTIVITY DEPTH PROBE H.11 BORE
## (CHAINAGE 7170)
## AURUKUN, 1974




TRAVERSE RESULTS
(0 to 2300 metres)
ELEVATION (metres)
SURFACE
OHM-METRES
C/s
H6
H56
H8
H26
H27
H28
H29
H35
H7
H33
H34
H30
WT
SWL
ch.sc.
LEGEND
Aluminous laterite
Sandy clay (sand < 50%)
Clayey sand (sand < 80%)
Sand (sand > 80%)
Gamma-ray log
Resistivity curve
SWL = Standing water-level (at completion of drilling)
WT = Water-table
C/s = Counts per second
ch.sc. = Change of scale
WENNER
PDP
VLF
RESISTIVITY (ohm-metres)
RESISTIVITY
TRAVERSING ELECTRODE CONFIGURATIONS
POLE DIPOLE (PDP)
METRES


TRAVERSE RESULTS
(2200 to 4100 metres)
ELEVATION (metres)
SURFACE
H9
H31
H5
H1
H32
OHM-METRES
C/s
ch. sc
SWL
WT
LEGEND
Aluminous laterite
Sandy clay (sand <50%)
Clayey sand (sand < 80%)
Sand (sand >80%)
Gamma-ray log
Resistivity curve
SWL = Standing water-level (at completion of drilling)
WT = Water-table
C/s = Counts per second
ch. sc = Change of scale
RESISTIVITY
TRAVERSING ELECTRODE CONFIGURATIONS
WENNER
POLE DIPOLE (PDP)
10m
20m
50m
WENNER
PDP
VLF
RESISTIVITY (ohm-metres)
METRES
Record No. 1976/3
D54/B5-12

PLATE 15

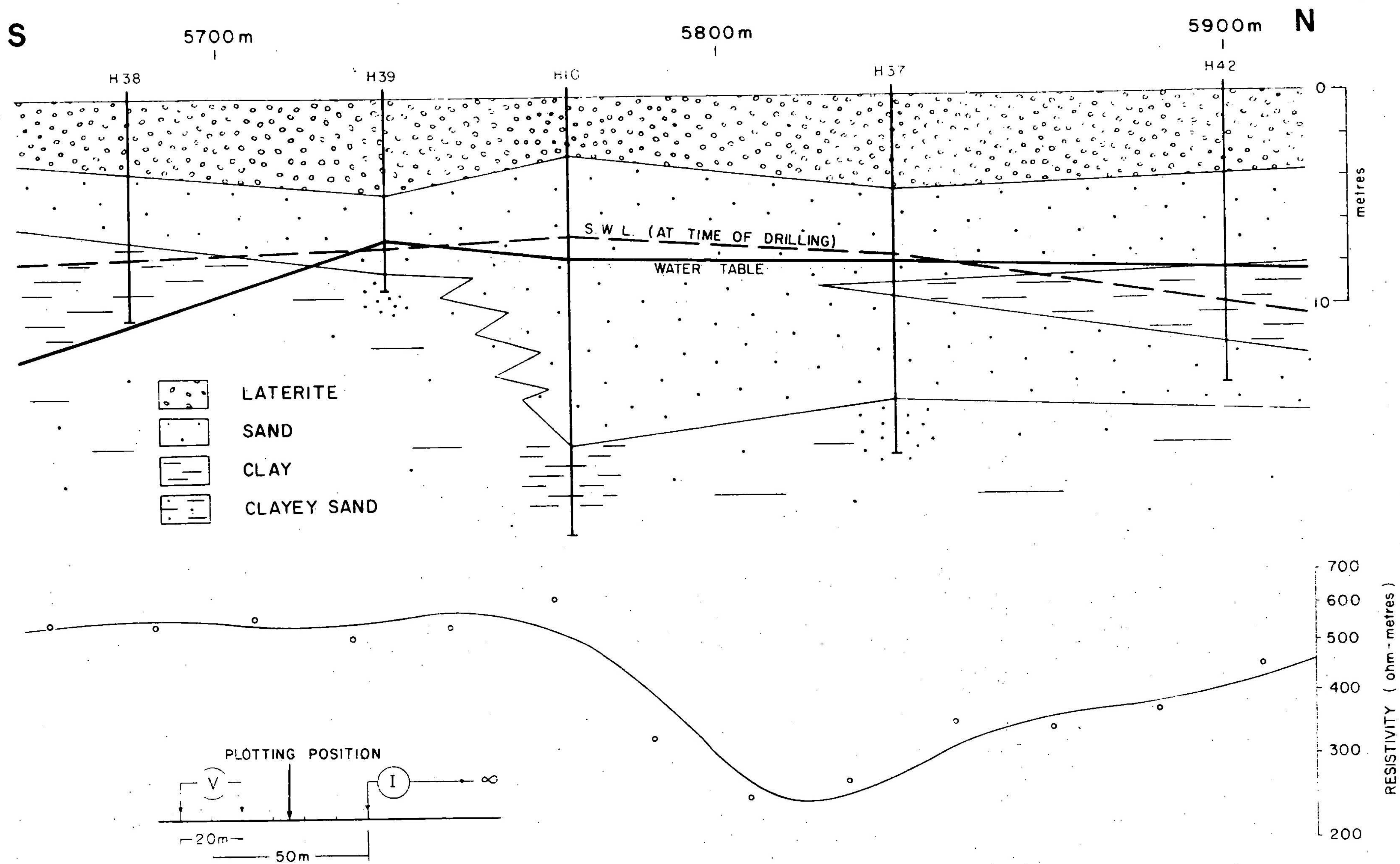
TRAVERSE RESULTS
(4000 to 6100 metres)
LEGEND
Aluminous laterite
Sandy clay (sand < 50%)
Clayey sand (sand < 80%)
Sand (sand > 80%)
Mudstone
Gamma-ray log
Resistivity curve
SWL = Standing water-level (at completion of drilling)
WT = Water-table
C/s = Counts per second
ch. sc = Change of scale
RESISTIVITY
TRAVERSING ELECTRODE CONFIGURATIONS
WENNER
POLE DIPOLE (PDP)
10m
50m
20m
H32
H55
H46
H54
H47
H2
H48
H38
H39
H10
H37
H42
SURFACE
OHM-METRES
ELEVATION (metres)
RESISTIVITY (ohm-metres)
WENNER
PDP
VLF
SWL
WT
4000
4100
4200
4300
4400
4500
4600
4700
4800
4900
5000
5100
5200
5300
5400
5500
5600
5700
5800
5900
6000
6100 METRES
Record No. 1976/3
D54/P5-13


## TRAVERSE RESULTS
(6000 to 8100 metres)

Record No 1976/3

D54/B5-14

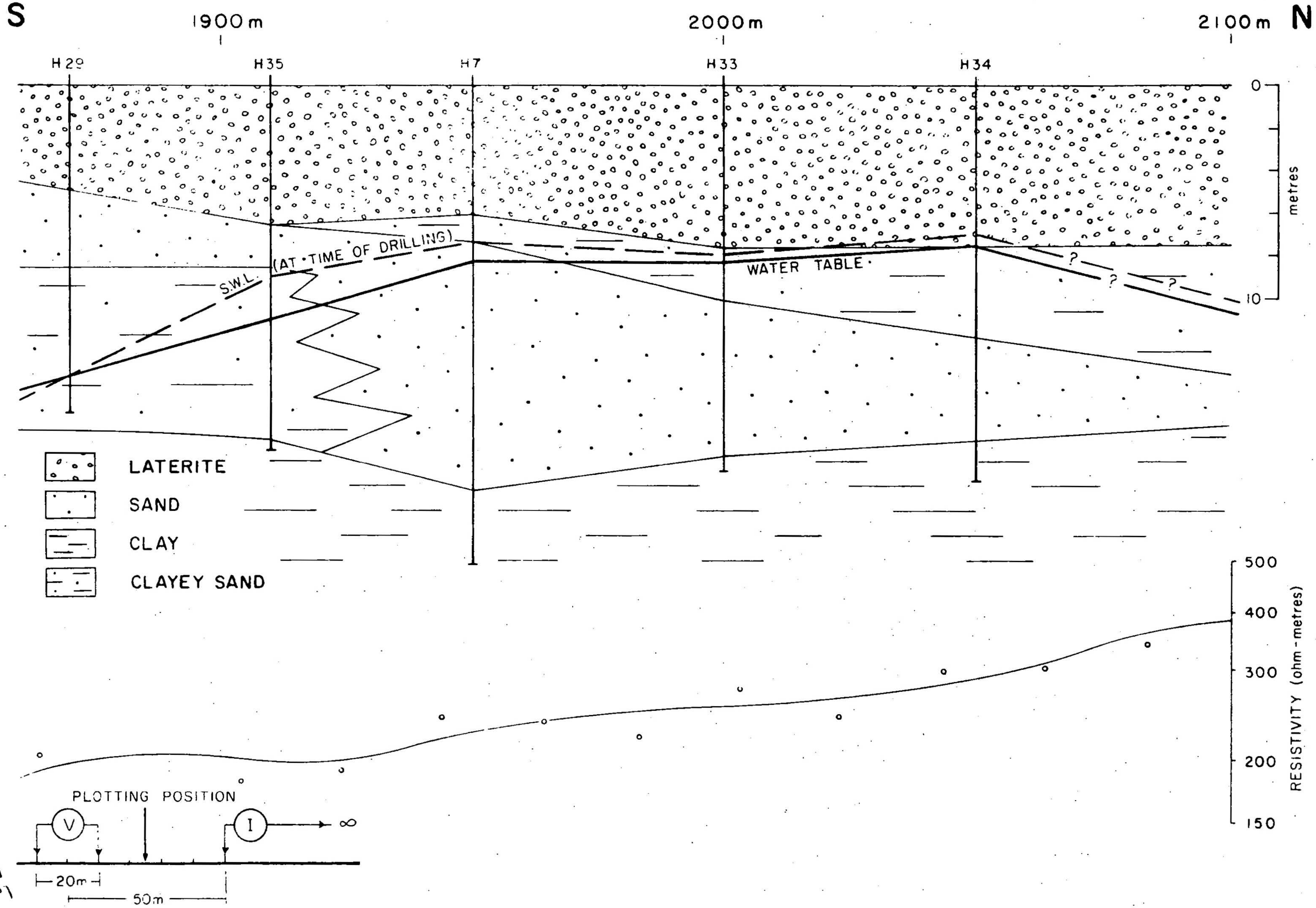
Record No. 1976/3




Detailed section, with pole-dipole traversing data

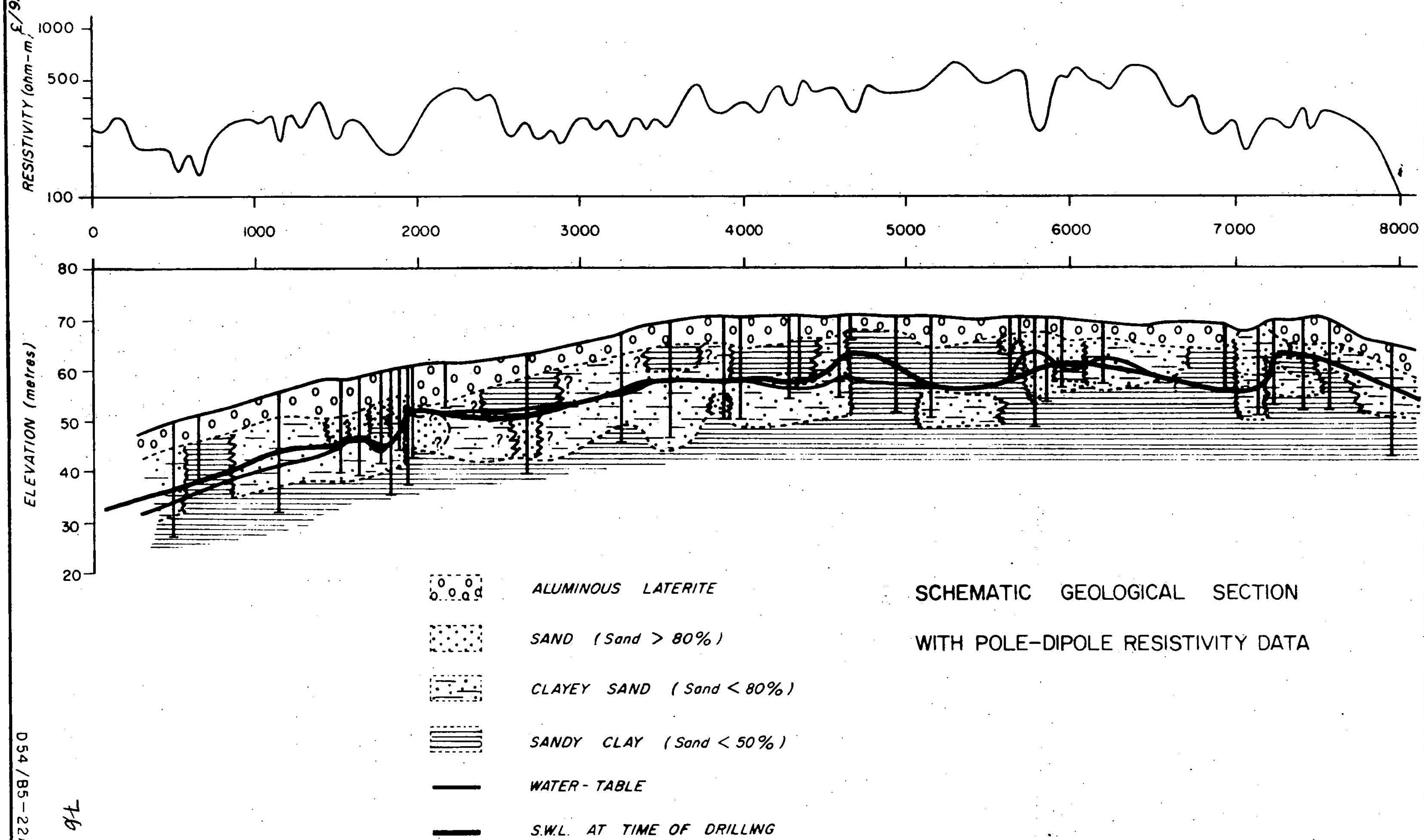
D54/A/14

Plate 18




Detailed section, with pole-dipole traversing data

D54/A/13




SCHEMATIC GEOLOGICAL SECTION

WITH POLE-DIPOLE RESISTIVITY DATA

Record No 1976/3

D54/B5-22A

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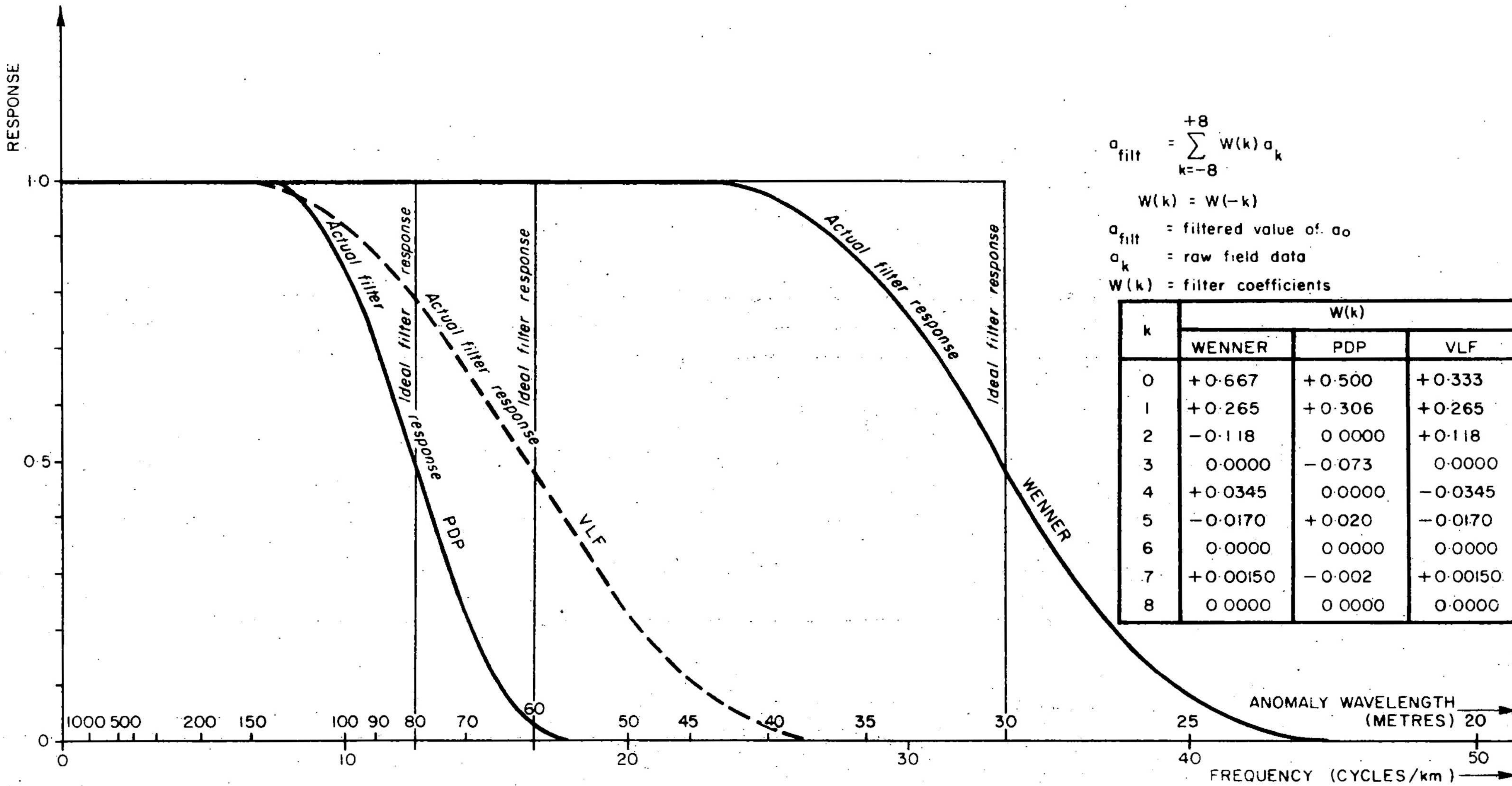


$$a_{filt} = \sum_{k=-8}^{+8} W(k)\, a_k$$

$W(k) = W(-k)$

$a_{filt}$ = filtered value of $a_0$

$a_k$ = raw field data

$W(k)$ = filter coefficients

| k | W(k) | | |
|---|---|---|---|
| | WENNER | PDP | VLF |
| 0 | +0·667 | +0·500 | +0·333 |
| 1 | +0·265 | +0·306 | +0·265 |
| 2 | −0·118 | 0·0000 | +0·118 |
| 3 | 0·0000 | −0·073 | 0·0000 |
| 4 | +0·0345 | 0·0000 | −0·0345 |
| 5 | −0·0170 | +0·020 | −0·0170 |
| 6 | 0·0000 | 0·0000 | 0·0000 |
| 7 | +0·00150 | −0·002 | +0·00150 |
| 8 | 0·0000 | 0·0000 | 0·0000 |

# FREQUENCY RESPONSE OF FILTERS

D54/B5-15A

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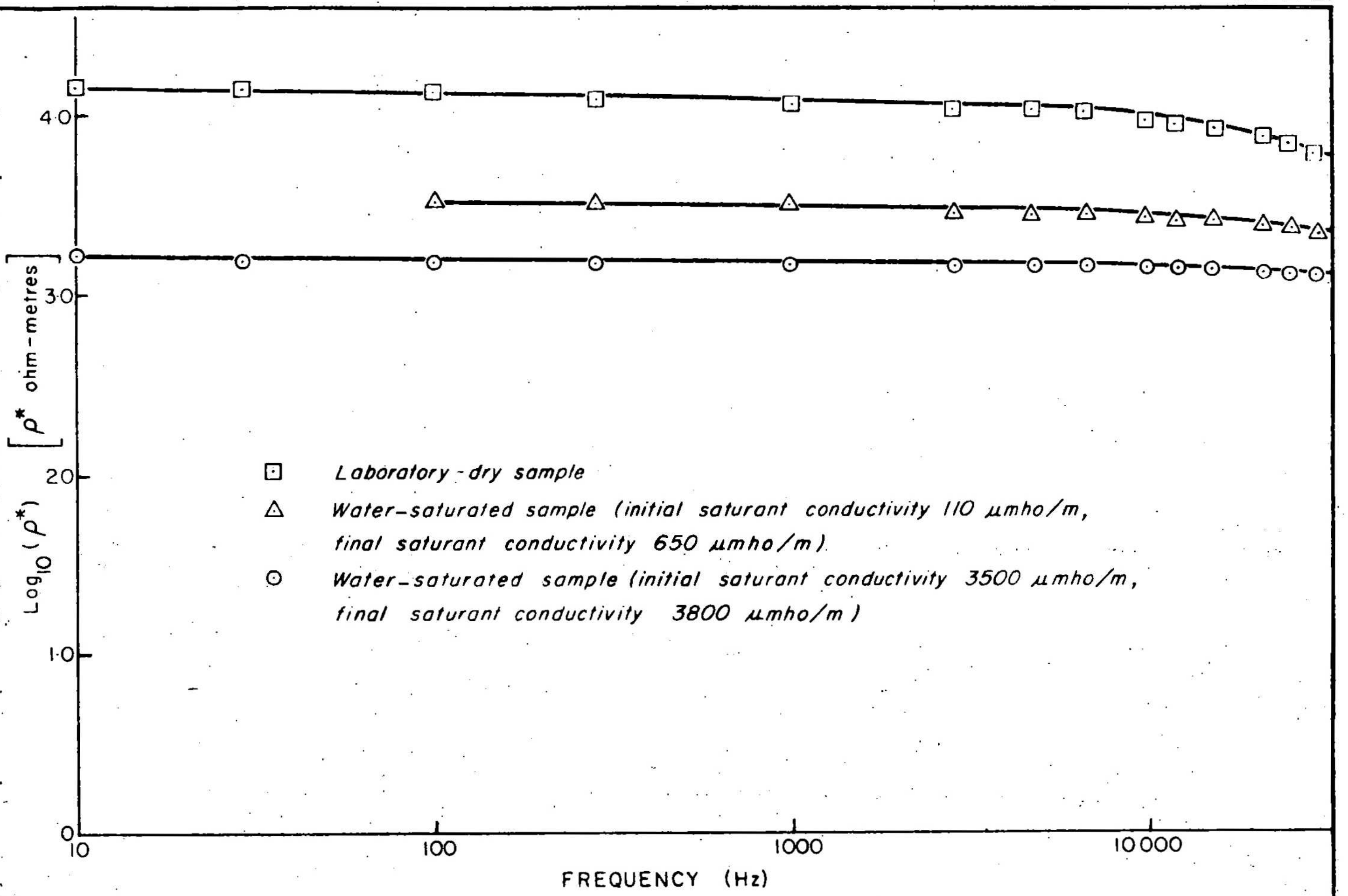
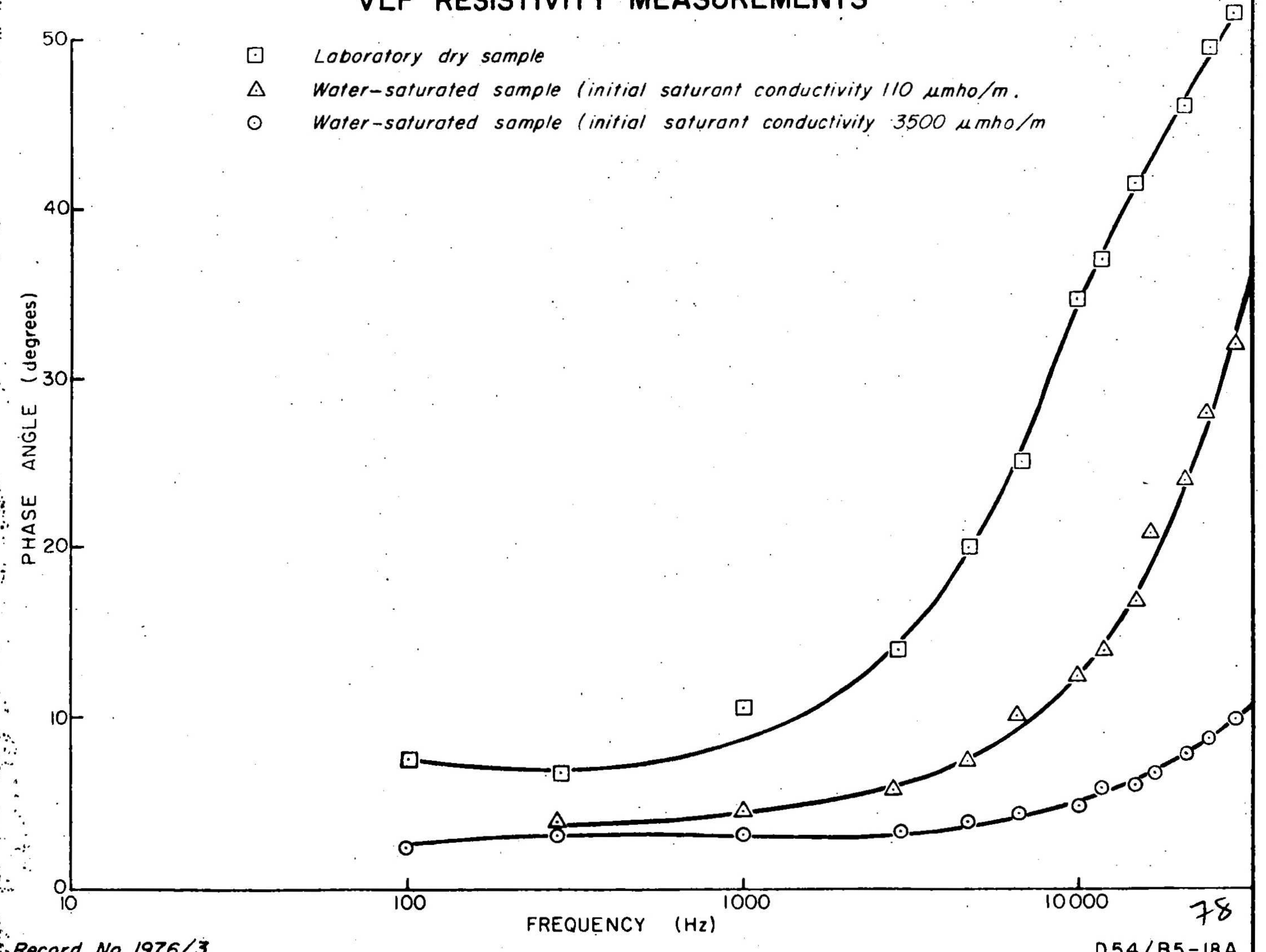
PLATE 20




## VLF RESISTIVITY MEASUREMENTS

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