DEPARTMENT OF
MINERALS AND ENERGY

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

RECORD 1975/63

KAVIENG (NEW IRELAND, PNG) RESISTIVITY DEPTH PROBING, 1974

by

B.H. Dolan, C.L. Horsfall, & E.J. Polak.

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CONTENTS

PLATES

SUMMARY

A resistivity depth probing survey was carried out by the Bureau of Mineral Resources, Geology & Geophysics in the Kavieng area of New Ireland, Papua New Guinea.

Twenty-five depth probes were measured using a Schlumberger arrangement with spacing AB up to 600 metres. The depth probes indicated a freshwater layer with resistivities between 48 ohm-metres and 900 ohm-metres overlying a salt-water layer of resistivity less than 2 ohm-metres. The depth of the saltwater/freshwater interface from resistivity results does not generally exceed 14 metres. It should be possible to monitor salt water intrusion using the resistivity method when pumping fresh water.

1. INTRODUCTION

Kavieng is located on the North Cape of the island of New Ireland, Papua New Guinea (Plate 1) on a latitude 2° south. The area is flat and low-lying (less than 10 metres above sea level) and is largely covered by jungle and kunai grass. The high rainfall, averaging 3172 mm per year, generally provides the water supply for the town and neighbouring settlements. During the dry seasons the water supply is supplemented by wells which provided hard but potable water. The danger of organic pollution from the surface requires that wells be located away from habitations, and withdrawal of the water must be carefully controlled to avoid contamination with salt water.

At the request of the Geological Survey of Papua New Guinea a survey was carried out by the Bureau of Mineral Resources, Geology & Geophysics (BMR). The purpose of the survey was to determine the distribution and thickness of the freshwater aquifer overlying the salt water.

The survey was carried out between 24 June and 3 July 1974 by a party consisting of B.H. Dolan, C.L. Horsfall, and E.J. Polak, (geophysicists from the Engineering Geophysics Group of BMR), R.B. Moana (a geophysicist from the Geological Survey of Papua New Guinea), and seven field hands provided by the Public Works Department. Topographical surveying was done by the Department of Lands, Surveys and Mines.

2. GEOLOGY AND HYDROLOGY

The geology of the area has been described by Harris (1971). The Kavieng area consists of raised old coral reefs interspersed with beds of coral limestone debris (the forereef facies) and lenses of clay (backreef facies). The coral limestone and debris, called coronus, forms a very porous permeable horizon. Some of the coronus and coral reef material has been altered by recrystallization of aragonite to calcite and some silicification, which has resulted in lower porosity and permeability.

The surface of the coronus is irregular and occasionally crops out. Usually, however, it is overlain by a residual deposit of red-brown ferruginous clay 30-50 cm thick.

The rainwater falling on the land sinks through easily to join the freshwater lens, as the beds are characterized by high permeability. The water-table is raised very little above the sea level, and consequently the thickness of the freshwater lens is not expected to be large. The fresh water travels horizontally to the sea, but its progress may be slowed down by a barrier of impervious reefs, (recrystallized and silicified). Where the line of reef along the shore is broken by erosion, freshwater escapes to the sea.

3. METHODS AND EQUIPMENT

The resistivity method of prospecting relies on the resistivity contrast between different rock bodies close to the point of measurement. The resistivity of a rock or fluid is expressed in ohm-metres. The resistivity of a formation depends upon three factors:

1. The resistivity of the dry rock matrix.
2. The resistivity of the fluid enclosed in the rock.
3. The proportion of fluid in the rock. In rocks below the water-table the proportion of fluid is equal to the porosity of the rock.

The resistivity of dry rock

In the dry state rocks have a very high resistivity. If they contain magnetite, pyrite, pyrrhotite, or graphite their resistivity will be lowered, but since these minerals are alien to the rock types at Kavieng this effect may be ignored.

The resistivity of fluids.

The resistivity of a fluid depends on the amount and kind of salt dissolved in the fluid, and the temperature. At Kavieng the upper aquifer contains Ca^{2+}, Mg^{2+}, Na^{+}, HCO_3^{-}, CO_3^{2-} and Cl^{-} in various concentrations (Harris, 1974). The lower aquifer contains sea water and the salt is therefore mainly NaCl. The small variations in temperature of the water at Kavieng would produce a negligible effect on the resistivity. An estimate of the total dissolved solids (TDS) given as its equivalent in parts per million (ppm) NaCl can be obtained from the resistivity of the formation water using the formula of Guyod (1944):

$Rw = 5000/c$

where Rw is the resistivity of the water in ohm-metres

c is the salt concentration in ppm or NaCl equivalent.

Archie's formula

The Archie's formula (Archie, 1942) states that at a given temperature,

$Rf = Rw/P^{m}S$

where Rf = formation resistivity in ohm-metres

Rw = water resistivity in ohm-metres

m = cementation factor equal to about 1.3 for Kavieng lithology

S = water saturation; S = 1 for formation below the water-table

P = porosity.

Assuming that the rock matrix of the aquifer is very highly resistive, the resistivity of the rock will depend on the resistivity of the fluid. Hence it is possible to predict the TDS from resistivity measurements providing the porosity of the aquifer does not change considerably.

Equipment

During the survey direct-current measuring equipment was used (Plate 2). A Hewlett-Packard regulated d.c. power supply, model 6220B, was used as the current source. The maximum current available was 1.3 amps and the maximum voltage 60 volts. High electrode resistance limited the current supplied to the ground to the order of 0.1 amp: The direct current was reversed by a transistorized switching device built by BMR. The frequency of the resultant square wave was 0.2 Hertz.

The ground potentials were measured through two steel electrodes hammered into the ground. The spontaneous potential (S-P) in the ground was compensated for by supplying an equal and opposing potential to the S-P from a battery-operated potentiometer. Thus a zero reading was obtained on the voltmeter before the current was switched on. The ground potential resulting from the current was measured with a Data Precision Model 245 digital multimeter. This instrument has an input impedence of 1000 megohms and a resolution of 100 microvolts.

Field procedure.

The resistivity method consists of introducing an electric current into the ground through two steel electrodes and measuring the resultant ground potential through two other electrodes. There are several possible spatial arrangements of electrodes in the field (Heiland, 1946). During the survey the Schlumberger arrangement was found most convenient; 22 of the probes were done with this arrangement, and the remaining three with the Wenner arrangement.

The Schlumberger arrangement (Plate 2) consists of four electrodes spaced along a line such that the outside current electrodes AB are equally spaced about the centre at a distance from the centre not less than 5 times that of the two inner potential electrodes MN.

The spacing AB was increased from 2 metres to 600 metres in steps with measurements of the applied current "I" and potential difference between the potential electrodes being made for each value of spacing AB. The spacing MN of the potential electrodes was increased at intervals so that the potential difference was not too low to be read accurately. The current electrodes were watered with sea water to reduce the high contact resistance which limited the input current.

The alternative Wenner arrangement consists of four electrodes equally spaced.

In order to interpret the data the 'apparent resistivity' which is a function of the ratio V/I and the geometry of the electrode arrangement was computed for each value of AB. For the Schlumberger arrangement, a (apparent resistivity)

$$a = \frac{\pi}{4} \frac{(AB^2 - MN^2)}{MN} \frac{V}{I}$$

If the Schlumberger arrangement is used the apparent resistivity is plotted against AB/2 on log-log graph paper. For small values of AB/2 the apparent resistivity approaches the true resistivity of the upper layer, and for large values of AB/2 it approaches the resistivity of the lower layer. If the Wenner arrangement is used the distance between adjacent electrodes is used for plotting in place of AB/2.

Plate 3 shows a set of curves from Kavieng. A preliminary examination of these curves show that there are three layers present.

The top layer has a medium resistivity, the centre layer a high resistivity and the bottom layer a very low resistivity.

To find the thicknesses and the resistivities of the three layers from the depth probes the method of superposition of precalculated standard curves was used. The curves chosen were prepared by the Compagnie Generale de Geophysique (1955).

For the four-layer curves (Plate 4) the method of consecutive superposition of two- and three-layer curves was used. The standard curves are applied to the top of the field curve and then the two upper layers are combined into a single layer of an average resistivity (Hummel, 1932), and the interpretation continued for the deeper part of the curve.

The resistivities and thicknesses obtained from the superposition of the curves were used to compute model curves which were used to check the accuracy of its interpretation. A Cyber 76 computer and a program developed by Zohdy (pers. comm.) were used. This procedure lessens the possibility of significant errors.

The errors in interpretation depend on many factors:

(i) field measurements - the errors in field measurement are considered to be very small in the conditions met in Kavieng. The repeatability of readings supports this fact.

(ii) the number, thickness, and resistivity of layers. In Kavieng the the resistivity of the top layer will have the lowest accuracy of determination as its thickness is not sufficient to give an asymptotic approach to the value of true resistivity. This is shown by the gradual increase of resistivity with depth in the first part of the curve. The second layer is generally thick enough for its resistivity to be reliably determined. The resistivity of the bottom layer is very accurately determined as the contrast of resistivities is very high. This low resistivity is generally not disturbed by the presence of a deeper bed.

For the reasons given above, the depth to the second layer is less accurately determined than the depth to the third layer with the three-layer curves. With the four-layer curves, which are of double descending type, the accuracy to the third layer will also be lower.

It is considered that the error in interpretation is less than 10 percent of the value of resistivity and depth.

4. RESULTS

Twenty-five depth probes were completed during the survey. The three Wenner probes were converted to equivalent Schlumberger arrangement (Andrew & Wiebenga, 1965) for uniformity of presentation of curves.

The location of all depth probes is shown in Plate 1. The distance AB between current electrodes is indicated by the length of the symbol on the plate. The orientation of the symbol shows the direction in which the movements were done.

Table 1 - Interpretation of the resistivity depth probes.

	Depth Probe Number	Surface Elevation (m)	Top layer		Second layer		Third layer		Fourth Layer	Elevation of salt water m
			R_1(ohm)	h1(m)	R_2	h_2	R_3	h_3	R_4	
	1	3.7	80	1.0	210	13.5	1.8	-	-	-9.8
+	2	7.05	120	1.0	1000	3.5	150	13.5	6	-6.4
+	3	5.35	300	0.8	600	8.8	140	16.8	4	-11.5
+	4	4.10	40	1.0	1000	3.0	120	14.0	3	-9.9
	5	2.70	35	1.0	140	17.3	1.75	-	-	-14.6
	6	5.65	240	1.1	6000	3.3	200	12.5	2.0	-6.9
	7	5.75	55	0.8	240	14.0	1.8	-	-	-8.3
	8	6.29	25	1.0	1000	4.5	70	35	high	
	9	4.05	220	1.0	1200	4.8	1.8	-	-	-0.8
	10	-	320	0.8	750	8.0	4.0	-	-	
	11	8.55	270	1.0	5000	4.8	100	15.0	2.0	-6.4
	12	4.65	350	0.7	3000	4.3	2	-	-	.4
	13	3.65	100	0.5	1500	5.0	100	16.0	2.0	-13.4
	14	5.55	120	1.0	230	4.7	120	6.3	2.4	- .8
*	15	1.66	90	1.8	20	12	2	-	-	-10.4
	16	3.60	80	0.6	240	13	2.1	-	-	-9.4
	17	2.65	420	4.0	40	4.5	150	18.0	3	-15.4
	18	4.85	30	1.4	1000	2.0	100	16.0	4	-11.2
*	19	2.95	150	0.7	700	2.5	100	13.0	2	-10.1
	20	6.50	65	0.7	1300	2.1	100	10.1	2	-3.6
*	21	1.45	60	2.0	40	16.0	1.0	-	-	-14.6
	22	4.60	50	0.8	2000	1.7	60	21	2	-16.4
	23	3.65	90	1.0	600	2.3	100	12	1.8	-8.4
	24	2.35	460	1.5	40	2.0	170	18.5	2	-16.2
	25	3.11	360	1.0	40	2.0	150	17.0	2	-13.9

* These depth probes show a large depth to salt water even though they are close to the shoreline. This is considered to be due to mixing of salt and fresh water and the possible angle of the freshwater/saltwater interface near the shoreline.

+ Are Wenner configurations that have been converted to Schlumberger equivalents.

The number in brackets shown on all but depth probes No. 8 and 10, gives the depth to the salt-water surface in metres. An allowance should be made for about 10% error in using the data. No surface elevation was available for depth probe No.10 and, depth probe No.8 is a special case that is discussed later. There are insufficient probes to satisfactorily contour the salt water horizon, but an inspection of the figures shows an irregular surface generally deeper towards the centre of the peninsula as would be expected.

The interpretation of the results was done by superposition of field curves on the standard curves published in the atlas of curves (Compagnie Generale de Geophysique, 1955). Table 1 lists the final interpretation of the depth probes,

The results obtained from the superposition were checked by use of the Zohdy computer program and a program developed by the Engineering Geophysic group of BMR for a Wang 600 desk calculator. Where the differences were small (within 0.5 m) the interpretation was accepted as correct; otherwise the depth probe was reinterpreted. Some examples of depth probes are shown in Plates 3 and 4.

In Kavieng, where a sufficient thickness of uniform coronus exists the vertical distribution of resistivity can generally be represented by a three-layer model.

Near-surface layer - moist mixture of red soil, humus, and coronus. The content of moisture increases with the depth, resulting in a gradual increase in resistivity. This fact makes an accurate determination of depth to the water-table impossible. The resistivity varies from tens to hundreds of ohm-metres.

Second layer -consists of coronus saturated with fresh water. Resistivity will generally vary in a narrow range depending on the change in the quality of water, if other conditions stated in Archie's formula do not change. Large variations in the resistivity of this layer are probably the result of cementation of the reefs.

<u>Third layer</u> - consists of coronus fully saturated with sea water with a resistivity of about 0.3 ohm-m. Using Archie's formula and assuming a formation factor of 1.3, a porosity of 29 percent would be obtained for a formation of 1.5 ohm-m resistivity and 23 percent for a formation of 2 ohm-m.

The boundary between the second and third layer is very sharp as is also shown by resistivity logs in coastal areas including logging in Madang (Dolan, Horsfall & Polak, in prep.).

In the second and third layers there may exist lenses of clayey and muddy material which give a non-uniform surface to the fresh-water/salt-water boundary and affect the resistivity curve, making interpretation more difficult.

Table 1 indicates that the resistivity of the second layer ranges from 20 ohm-m (probe No.15) to 6000 ohm-m (probe No.6). Harris (1971) gives a solids content between 100 and 800 ppm for Kavieng water. The use of the Guyod formula gives a resistivity for the water (containing mostly salts othern than NaCl) of 12 to 100 ohm-m. Also by the use of Archie's formula a formation resistivity of 70 to 700 ohm-m is obtained providing that the porosity of the coronus is between 23 and 29 percent. A decrease in porosity will be indicated by higher formation resistivity. Values lower than 70 ohm-m indicate either water with salt content in excess of 800 ppm or a clayey formation.

Plate 3 shows three depth probes; No.15 shows a second-layer resistivity of only 20 ohm-m; depth probe No.5 shows rock containing good water, and depth probe No.12 indicates rock of low porosity. Most of the depth probes in Table 1 can now be grouped into the three above types.

(1) Second layer of low resistivity: Nos. 15 and 21.

(2) Second layer resistivity 70 to 1000 ohm-m: Nos. 1, 2, 3, 4, 5, 7, 8, 10, 14, 16, 18, 19, 22, 23.

(3) Second layer resistivity more than 1000 ohm-m: Nos. 4, 6, 9, 11, 12, 13, 20.

Some of the depth probes do not fall into any of these groups and examples of these are shown in Plate 4.

Depth probe No.8 shows a third layer of 70 ohm-m but no evidence of the salt-water boundary. This bed must be of low permeability. The fourth layer at 34 m is of very high resistivity and must be bedrock. The area must be quite different geologically from other areas probed, and would be unsuitable for development of a water bore.

Depth probes 17, 24, and 25 show a relatively high-resistivity first layer followed by a low-resistivity second layer, overlying the very low resistivity salt-water layer. The resistivity pattern of the first two layers is exceptional and as the probes are in the one area they may represent different environmental conditions which may also be reflected in the Kunai grass cover of the area. In all probability the second layer represents clay and its permeability is low, resulting in the marshy conditions.

Plate 5 shows a set of theoretical three-layer curves with the second layer of resistivity 200 ohm-m overlying the salt-water layer of 2 ohm-m resistivity. By pumping fresh water the thickness of the second layer decreases and the curves show the effect of varying this thickness in steps of 2 m. The shape of the depth probes indicates that the rate of pumping and the rise of the salt-water horizon can be checked by resistivity depth probing.

5. CONCLUSIONS AND RECOMMENDATIONS

Conclusions:

(1) In the Kavieng area the freshwater layer is shown on the resistivity depth probes as a maximum with the resistivity between 70 and 1000 ohm-m.

(2) The freshwater/saltwater boundary varies from near surface to about 16 metres below the surface. It is irregular and generally deeper towards the centre of the peninsula as would be expected.

(3) The salt-water layer shows an apparent resistivity of about 2 ohm-m.

(4) The area south of the airport (depth probes 17, 24, 25) shows different resistivity features. A layer of low resistivity overlies the aquifer, and since it is probably due to clay it may reduce recharge in this area.

(5) The development of the water supply must take the form of water skimming. The skimming may be controlled by resistivity depth probing from the surface.

Recommendations:

(1) Drilling should be done on several types of depth probes. The bores should be geologically logged and the resistivity of water at different levels should be measured.

(2) The surface positions of the reefs should be mapped and the bores should be placed on coronus rather than reefs which may be less permeable. Localities where the reefs are eroded through should also be avoided.

6. REFERENCES

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

ARCHIE, G.E., 1942 - The electrical resistivity logs as an aid in determining sonic reservoir characteristics. Trans A.I.M.E. Petroleum Technology.

COMPAGNIE GENERALE DE GEOPHYSIQUE, 1955 - ABAQUES DE SONDAGE ELECTRIQUE. Geoph. Prospecting 3. Suppl. 3.

DOLAN, B.H., HORSFALL, C.L., & POLAK, E.J., - Madang, PNG, ground water investigation 1974, Bur. Miner. Resour. Aust. Rec. (in prep).

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

HARRIS, J., 1971 - Ground water supplies for Kavieng hospital and town, New Ireland district, PNG. Geological Survey, Note on investigation 70-012.

HEILAND, C.A., 1946 - GEOPHYSICAL EXPLORATION. Prentice Hall, New York.

HUMMEL, J.N., 1932 - A theoretical study of apparent resistivity in surface potential method. Trans. Am. Inst. Min. Met. Eng., 97, 392-422.

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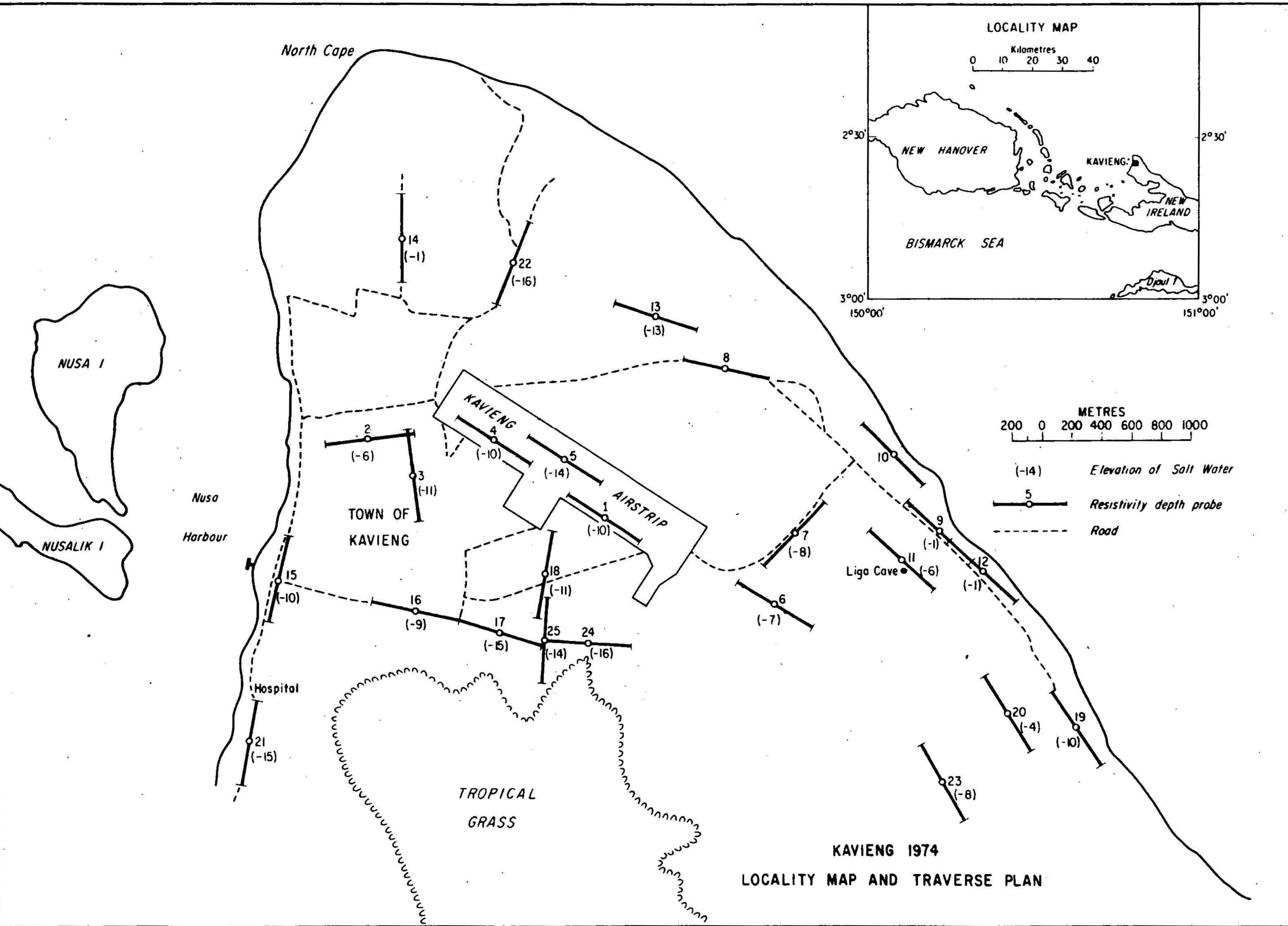

KAVIENG 1974

LOCALITY MAP AND TRAVERSE PLAN

PLATE 1

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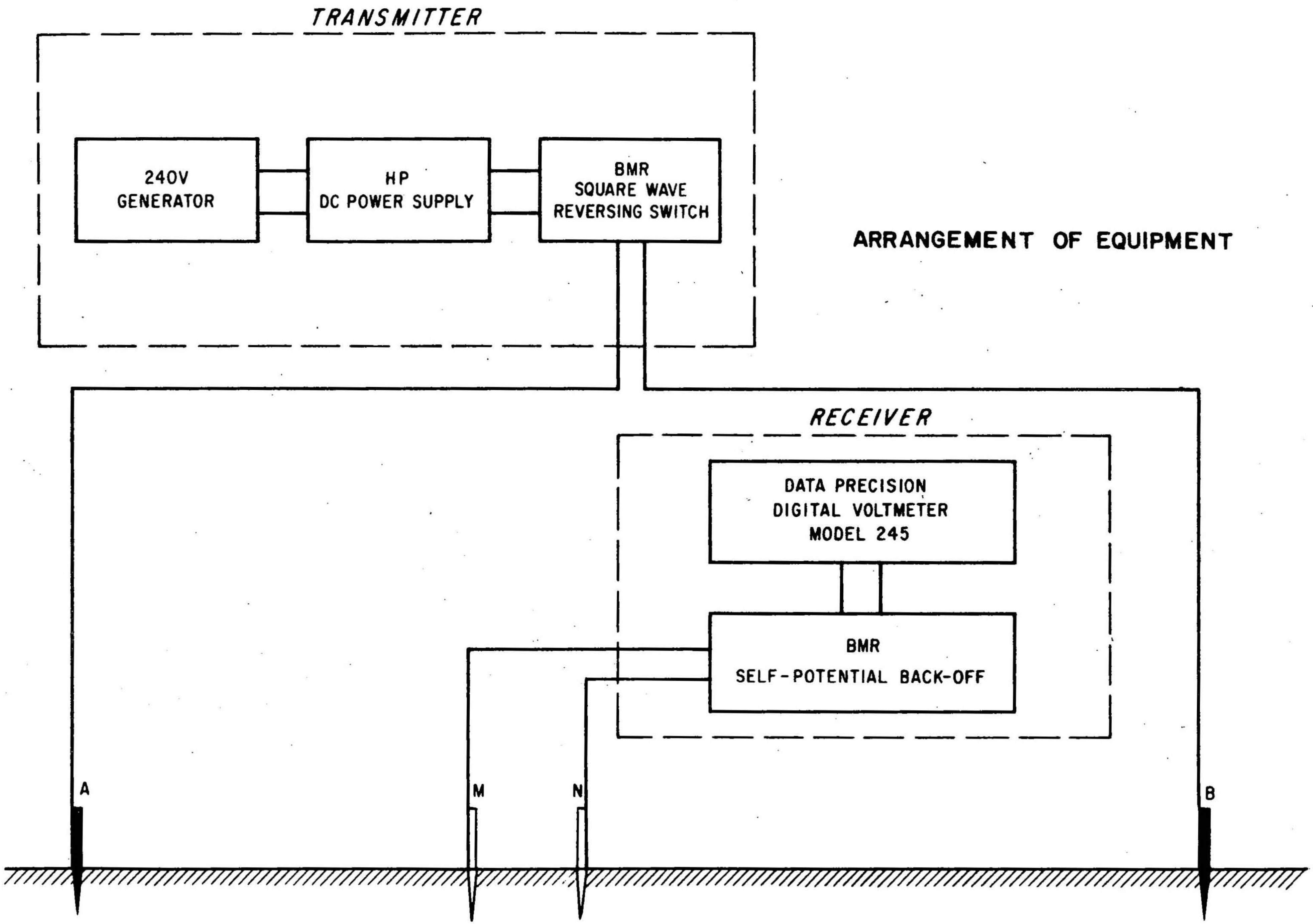

ARRANGEMENT OF EQUIPMENT

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PLATE 2

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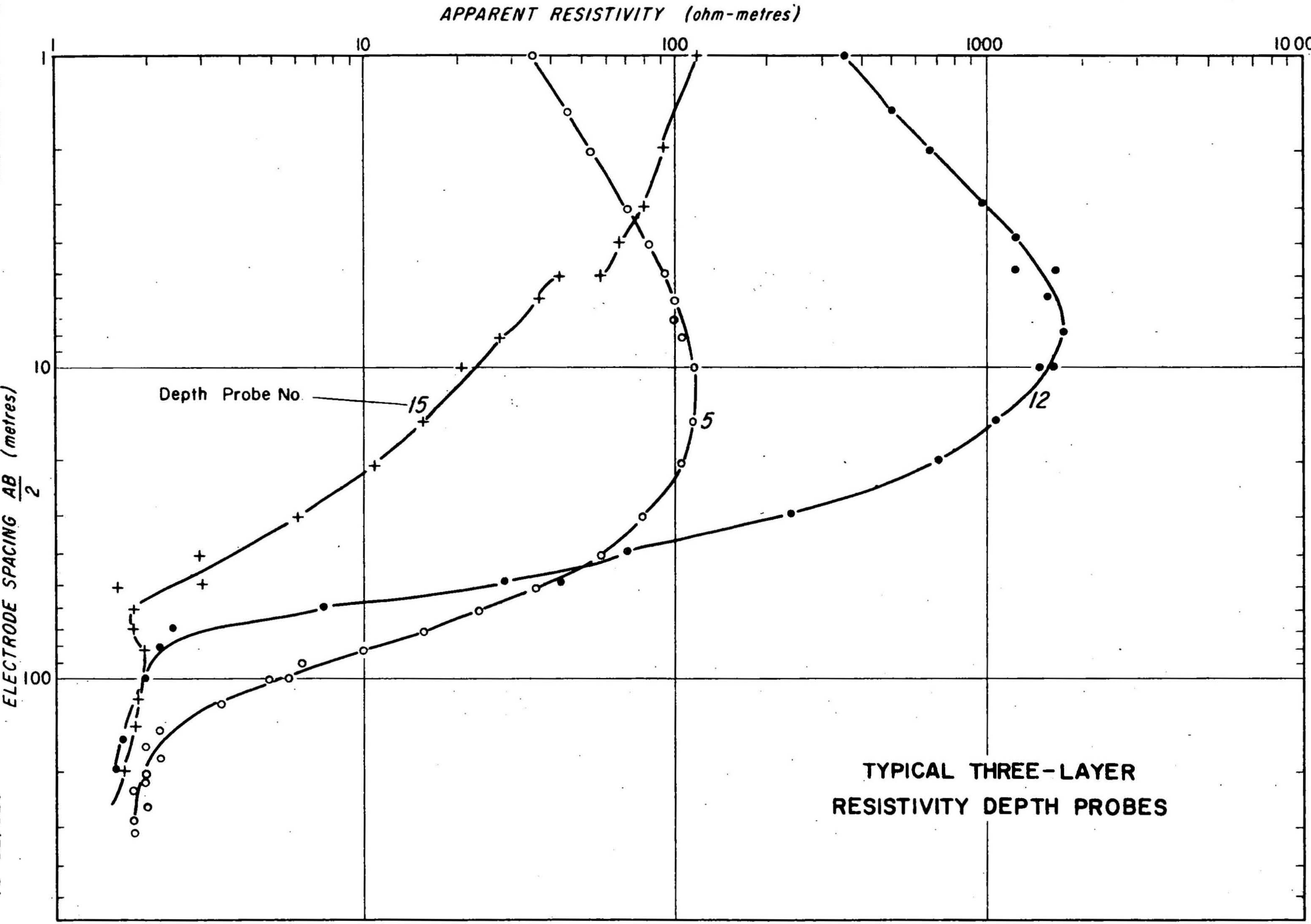

TYPICAL THREE-LAYER RESISTIVITY DEPTH PROBES

A56/B5-5A

PLATE 3

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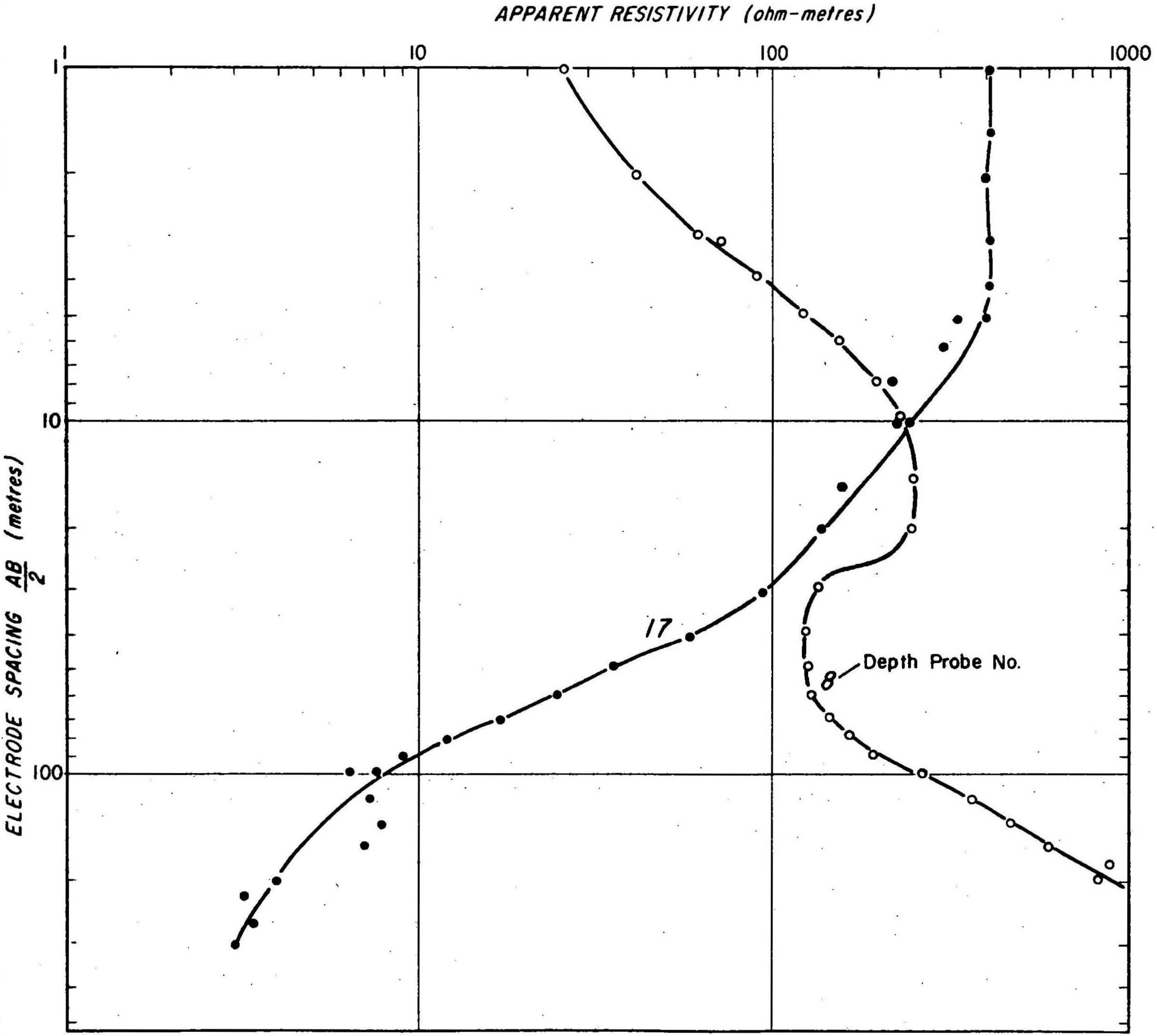
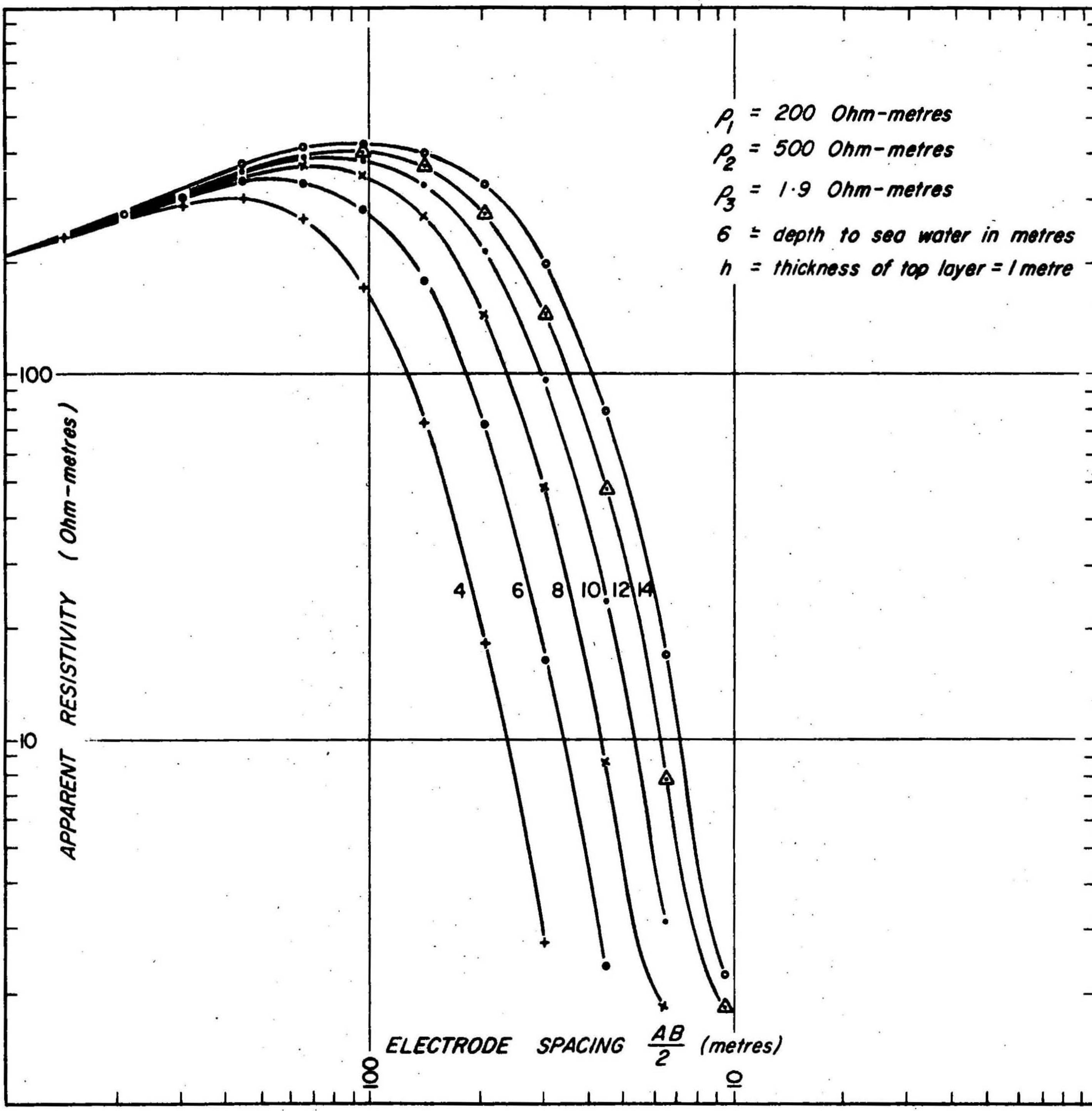


COMPLEX FOUR-LAYER RESISTIVITY DEPTH PROBES

A56/B5-3A

PLATE 4



CHANGE IN SHAPE WITH DEPTH TO SEA WATER DURING PUMPING