UNITED NATIONS ORGANIZATION

GEOPHYSICAL SURVEY OF THE GAMBIA USING ELECTRICAL AND SEISMIC METHODS

May 5 to July 25, 1983

C O N T E N T

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I N T R O D U C T I O N

On behalf of the United Nations Development Programme acting as executing agency for the UNITED NATIONS ORGANIZATION, Compagnie Generale de Geophysique carried out a comprehensive geophysical survey with a view to understanding the major potential aquifer systems of the GAMBIA. Seismic refraction and resistivity methods were applied.

This survey is one phase of the activities of the UNDP project "Preliminary Investigation of Groundwater and Experimentation of Pumping Systems - GAM82/T01" undertaken with the GAMBIAN Ministry of Water Resources & Environment (Department of Water Resources).

The present report describes field operations and data acquisition, explains the results of processing and interpretation and in conclusion recommends the positioning of several exploratory bore-holes.

1 - GEOLOGICAL OVERVIEW

To provide GAMBIA with permanent water wells for personal use, develop the livestock potential and increase agricultural production, a better knowledge of the aquifers and their hydrological potential is required throughout the country.

For this purpose, a preliminary geophysical survey applying refraction seismic and resistivity (Electrical Soundings : E.S.) methods should reveal the sand, sandstone or limestone layers thick enough to constitute good aquifer systems in the 0 to 250 meter upper ground formation.

Wide-diameter wells and boreholes already sunk in GAMBIA as well as, the data from the deep drill holes in similar formations in the near-by Casamance enabled an average lithological log to be established. The note written in February 1982 by Mr D. FERNANDOPULLE, Project Manager is summarized herunder.

From top to bottom the stratigraphy might be as follows :

1. Holocene Series : It is nearly suboutcropping and made up of alluvial deposits and laterite layers in places.

2. Pleistocene Series : It is 20-60 meters deep and made up of alternating sands, clays, silts and mottled laterites, all of them weathered. Few sandy aquifers may exist within this series.

3. Pliocene Series : It is 60-100 meters deep, and made up of non-weathered sandy clay and clay with vegetal debris. It might constitute an aquiclude substratum for the overlying aquifers.

These first three series belong to the "Continental Terminal".

4. Miocene Series : It is located at a depth of 100-200 (?)m and made up of unweathered sandy layers. This series is known to be an aquifer in the near-by parts of SENEGAL.

5. Eocene-Paleocene Series : It is 200-400 (?) meters deep and made up of marls, marly limestones and clays, but may include white limestone and sandstone layers. This series might constitute an aquiclude substratum for the miocene sands, and may contain possible aquifers in the fissured limestone and sandstone levels.

6. Maestrichian Series : It may be located at depths of 200-600 (?) meters and be made up of sandstones with clay horizons. This series is a well known artesian aquifer all over the western part of Africa. In the eastern part of the GAMBIA, it might be of hydrological interest, but elsewhere, its great depth will be a limiting factor for exploitation.

The permeable series may be expected to be impregnated by salt water near the sea-shore and along the Gambia river, at least in its downstream part which is largely affected by the tides.

Finally, we note that the water table is on an average 10-30 meters deep.

All the wells for which geological logs were made available, are shallow (less than 100 meters) and most often stopped in the pleistocene and pliocene series described above.

2 - OPERATIONS CARRIED OUT AND MEANS USED

2.1 - Schedule of operations

The C.G.G. expatriate staff composed of P.CREMIERE, Party Chief and J.C.LABARTHE, Operator arrived in Gambia on April 27th, 1983. The geophysical equipment air-freighted from France arrived four days later. After a week of preparation and organization, the first geophysical measurement was carried out on May 5th near Brikama. The complete geophysical survey took 77 days of effective field work. It ended on July 25th. C.G.G. equipment was sent back on July 30th and the crew left Gambia on August 3rd.

2.2 - Equipment used

2.2.1 - Electrical equipment

- 1 SERCEL AE 631 potentiometer unit.
- 1 SERCEL 1000 W power supply converter yielding a voltage up to 400 V.
- 3000 meters of insulated wire on 6 portable reels.
- Spare parts and all electrical equipment accessories.

2.2.2 - Seismic refraction equipment

- 1 SIE RS 44 amplifier unit with one R6B recording oscillograph.
- 3 geophone cables and 2 extension cables
- 30 geophones
- 3 blasting units
- 500 kgs of Ablonite explosives
- 300 "0 delay" electrical detonators
- ancillary equipment

2.3 - Work carried out

2.3.1 - Parameters of measurement arrays

In principle one E.S. (Electrical Sounding) was carried out every kilometer along selected lines. Several intermediate E.S. were added here and there, according to the initial results. An emitting AB line, 2000 meters long was laid out for most of the E.S. except for a few which had to be shorter (AB = 1000 or 1500 m) because of impracticable field conditions.

The S.S. (Seismic Spread) included 24 geophones and 7 shot points. Most of them were 690 meters long (distance between geophones : 30 m), a few others 345 meters (distance between geophones : 15 m). They were distributed along lines selected after the initial results of the resistivity survey.

2.3.2 - Survey areas (See pl. 1)

Four areas were surveyed. Measurement stations were distributed along lines which are designated after the names of towns or villages. From west to east the four areas are (see Pl. 1) :

- GUNJUR-BRIKAMA : lines GB between Gunjur and Brikama and between Sifoe and Kunkujang,

- KWINELLA-SOMA-FARAFENNI : line KS between Kwinella and Soma, line TK between Kwinella and Tendaba and line SF between Soma and Farafenni,

- BANSANG-SANKULI KUNDA : line BS,

- BASSE-JAR KUNDA : line BJ.

2.3.3 - Summary of surveys

Line	Electrical Soundings	Seismic Spreads	
		690 m long	345 m long
GB	41 (three of them for calibration)	2	1
KS	37 (one of them for calibration)	6	
TK	5		
SF	23 (three of them for calibration)	4	2
BS	15 (one of them for calibration)		
BJ	38 (three of them for calibration)	3	
SUB-TOTAL		15	3
T O T A L	159	18	

3 - QUALITY OF THE MEASUREMENTS

3.1 - Electrical soundings (ES)

Several resistivity diagrams are disturbed ; the four main causes are :

1) Electrode effects, generated by heterogeneities in the superficial layers, lead to quite different resistivity values for two lengths of the MN receiver dipole related to the same emissive AB line.

2) Highly resistive "masks", consisting of laterite layers, located at shallow depths lead to excessively high resistivity values for several AB line lengths. These values must be eliminated for interpretation in a 1-dimensional model.

3) Very weak measured signals lead to inaccurate resistivity values. These low amplitude signals are linked to high resistances of ground-electrode contacts and appear mainly for the longest AB lengths. The final branch of several resistivity curves had to be corrected or extrapolated taking into consideration the diagrams of bracketing stations.

4) Metal pipes, for example the borehole casings for the calibration E.S. may also generate disturbances on the resistivity curve.

All the resistivity diagrams were hand-smoothed taking into consideration :

- the 1-dimensional models (horizontal layers) provided by a set of master curves,

- the diagrams of near by stations wherever there were strong disturbances.

The difficulties in drawing these necessary smoothings led us to establish a classification of the resistivity diagrams reflecting their quality :

CLASS A	Outstanding to good	:	40 %
CLASS B	Fair	:	37 %
CLASS C	Mediocre	:	15 %
CLASS D	Poor	:	6 %

Thus 77 % of the diagrams (A+B) did not show any major smoothing problem.

Only three E.S. (2 % of the whole survey) had to be discarded for various reasons. They are KS9, GB9 and GUC11.

The KS9 diagram, although of apparently good quality, leads to an interpretation result inconsistent with the other diagrams of line KS.

Diagrams GB9 and GUC11 display very inaccurate resistivity values for the longest AB lengths. It was not possible to correctly extrapolate the final branch of the curves.

Our provisional interpretation of May 30, 1983 was in fact based on the calibration E.S. GUC11 (Brikama) which indicates a final rising branch of the curve incompatible with the diagram shape of the near-by stations. Therefore the slightly hasty conclusions drawn from a rather limited number of diagrams, will be avoided in this final report.

3.2 - Seismic spreads (SS)

The quality of the seismic records is good for the whole survey. This fact enabled us to pick up late energy arrivals on the records from the longer spreads (690 m) to make sure they were no relatively deep high velocity markers.

We will deal with this subject in paragraph 4.2.

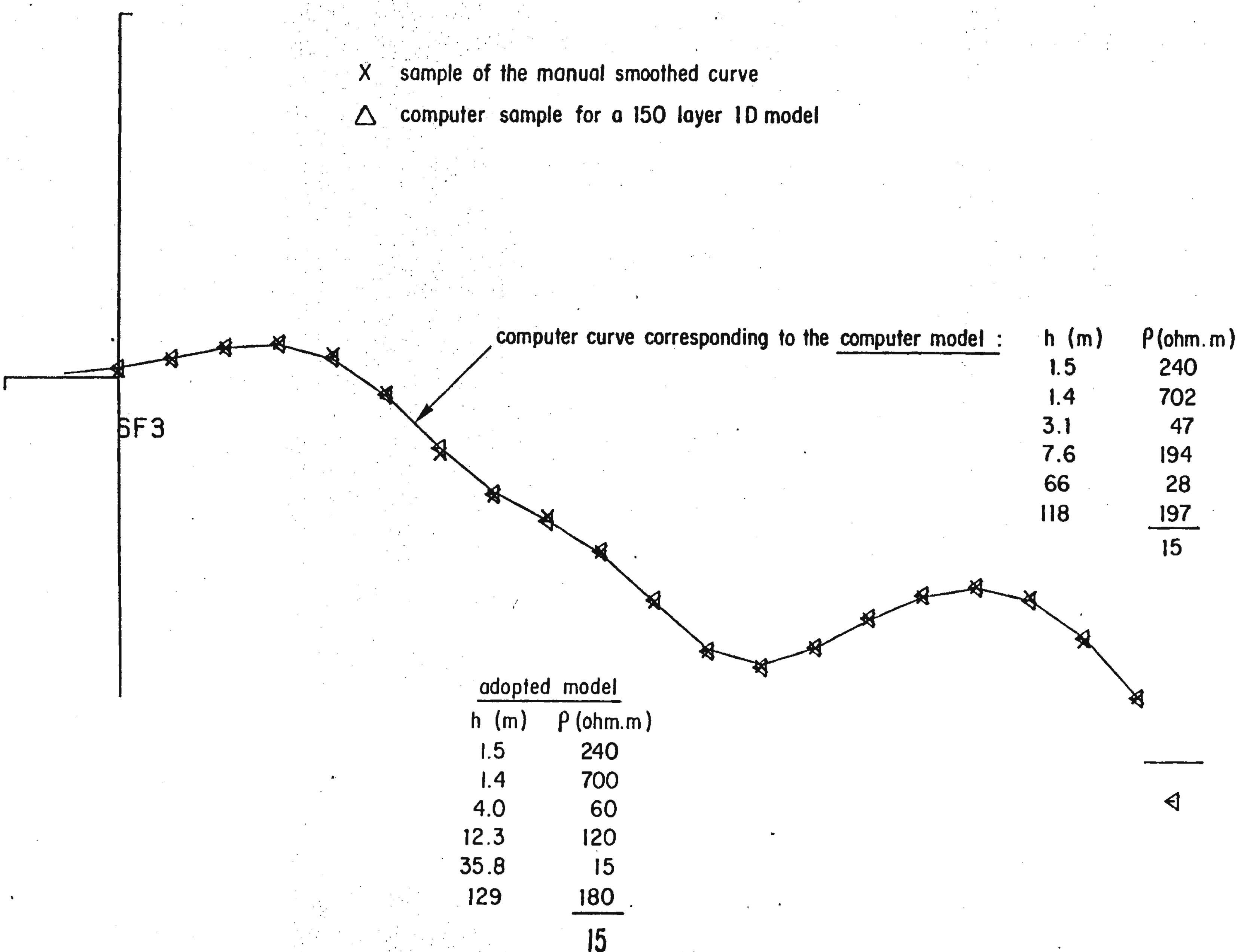
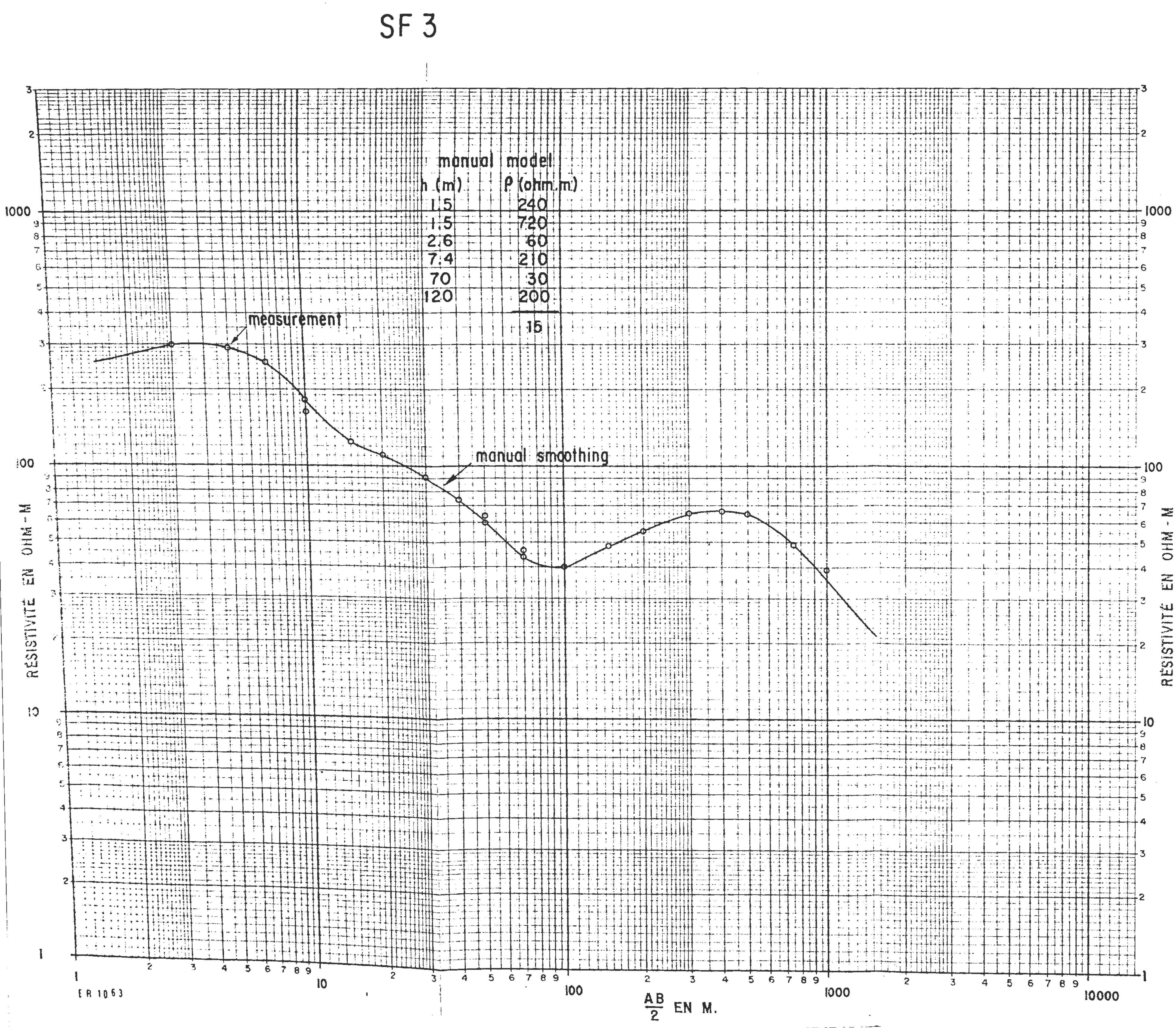

X sample of the manual smoothed curve
△ computer sample for a 150 layer 1D model
SF3
computer curve corresponding to the computer model :
h (m) ρ(ohm.m)
1.5 240
1.4 702
3.1 47
7.6 194
66 28
118 197
15
adopted model
h (m) ρ(ohm.m)
1.5 240
1.4 700
4.0 60
12.3 120
35.8 15
129 180
15

Fig. 2b

Fig. 2a


SF 3
manual model
h (m) | ρ (ohm.m)
1.5 | 240
1.5 | 720
2.6 | 60
7.4 | 210
70 | 30
120 | 200
15
measurement
manual smoothing
RESISTIVITÉ EN OHM - M
AB/2 EN M.
ER 1063

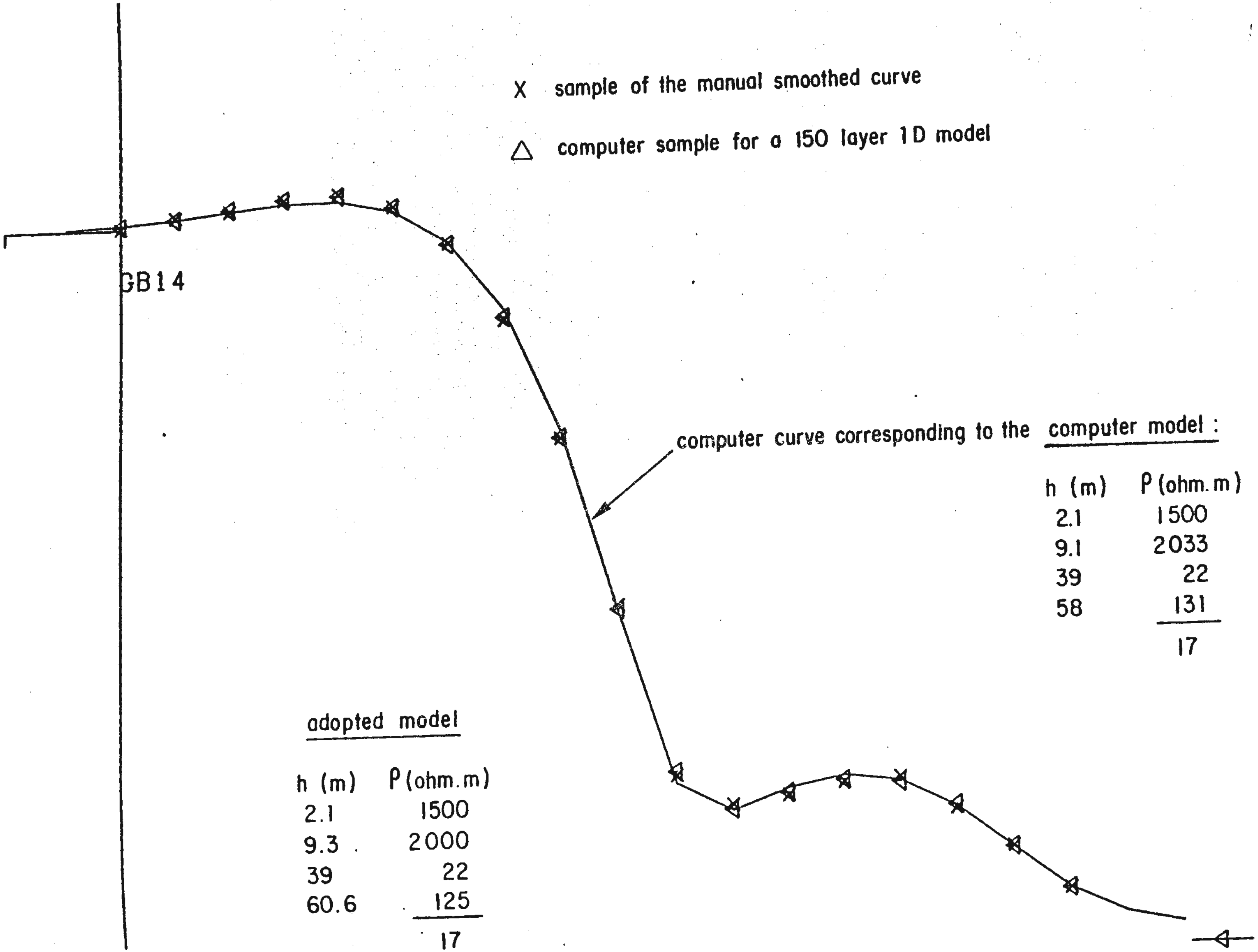
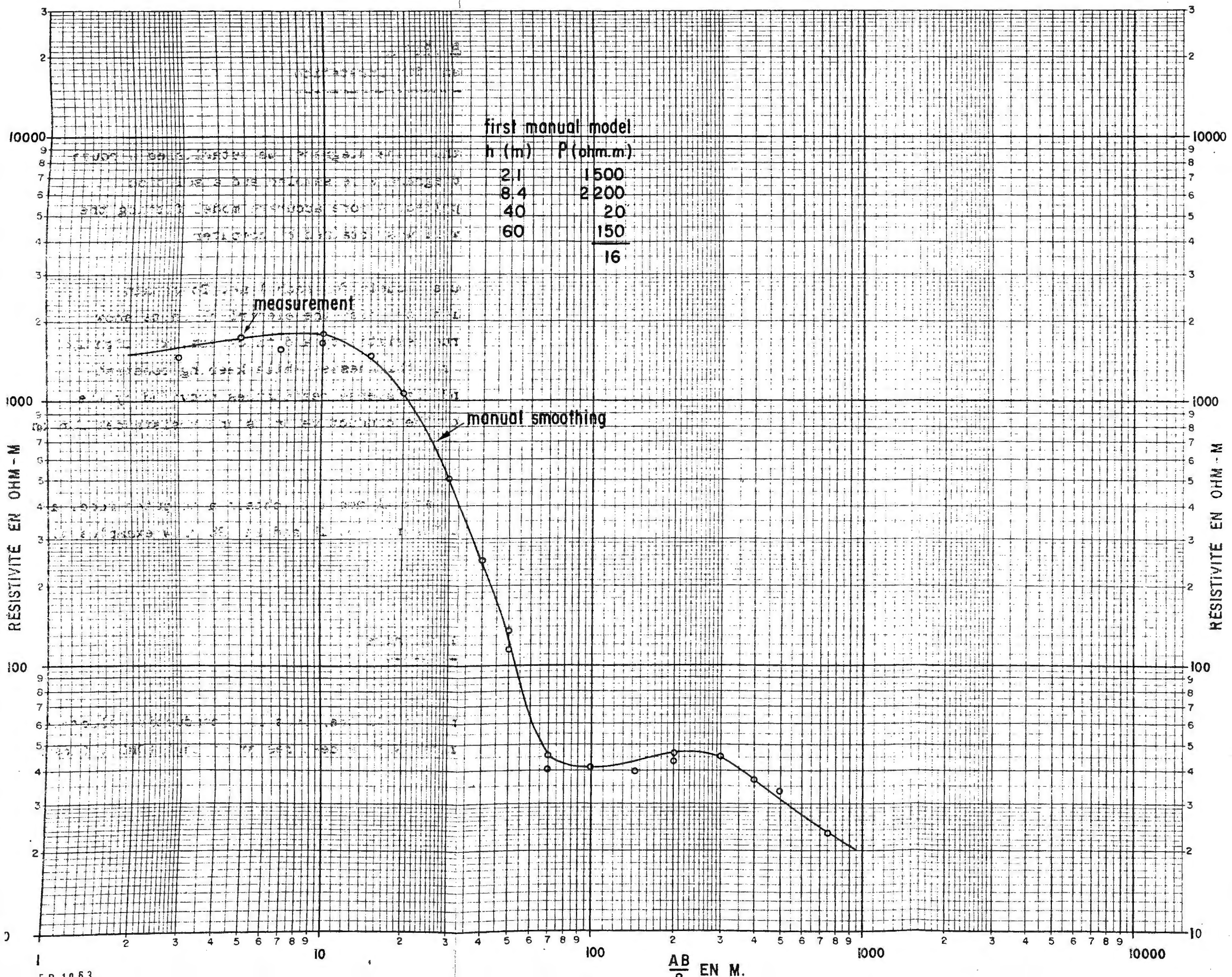

X sample of the manual smoothed curve
△ computer sample for a 150 layer 1D model
GB14
computer curve corresponding to the computer model :
h (m) ρ (ohm.m)
2.1 1500
9.1 2033
39 22
58 131
17
adopted model
h (m) ρ (ohm.m)
2.1 1500
9.3 2000
39 22
60.6 125
17

Fig. 1b

GB 14


first manual model
h (m) ρ (ohm.m)
2.1 1500
8.4 2200
40 20
60 150
16
measurement
manual smoothing
RESISTIVITE EN OHM - M
AB/2 EN M.

4 - RESULTS COMMON TO THE ENTIRE SURVEY

4.1 - Electrical soundings (E.S.)

4.1.1 - Processing and interpretation

After hand-smoothing the diagrams, we established a rough model. Then the smoothed diagrams were sampled and a solution improvement program was applied. A more accurate model fitting the smoothed diagrams fairly well was obtained by computer.

We plotted computer models for each line. To obtain interpretative cross-sections on which the electrical units show plausible variations in true resistivity and thickness, we slightly altered the resistivities and thicknesses while keeping constant horizontal conductances and transverse resistances provided by the computer : conductances for the conductive units and resistances for the resistive units.

We started from a manual model to obtain a computer model and finally the model adopted. Figures 1a, 1b and 2a, 2b show examples of E.S. GB14 and SF3.

4.1.2 - Main electrical units

The feature common to all the lines is a conductive electrical basement (CEB) always overlain with a deep resistive unit (DRU). Close

Fig. 4

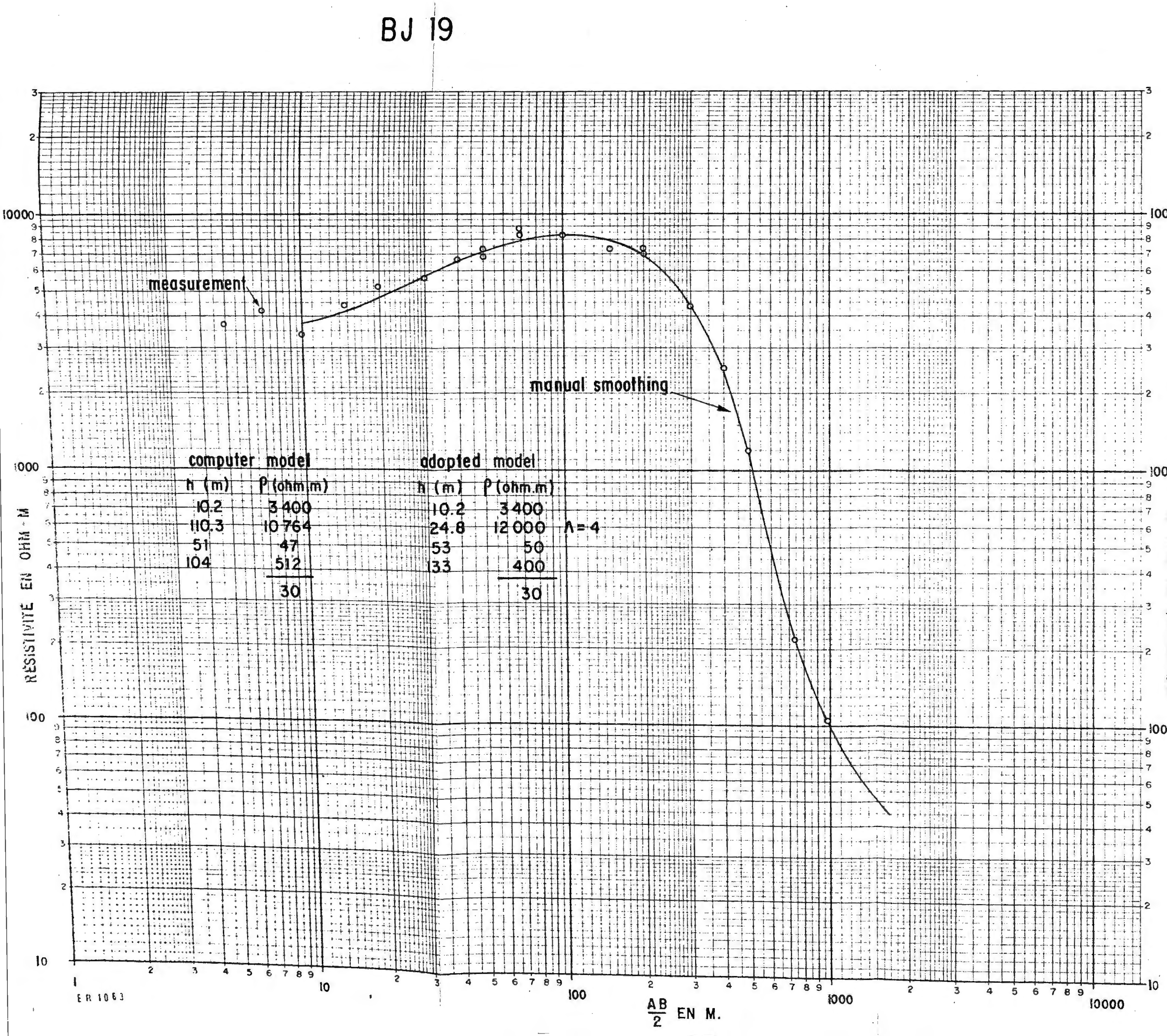
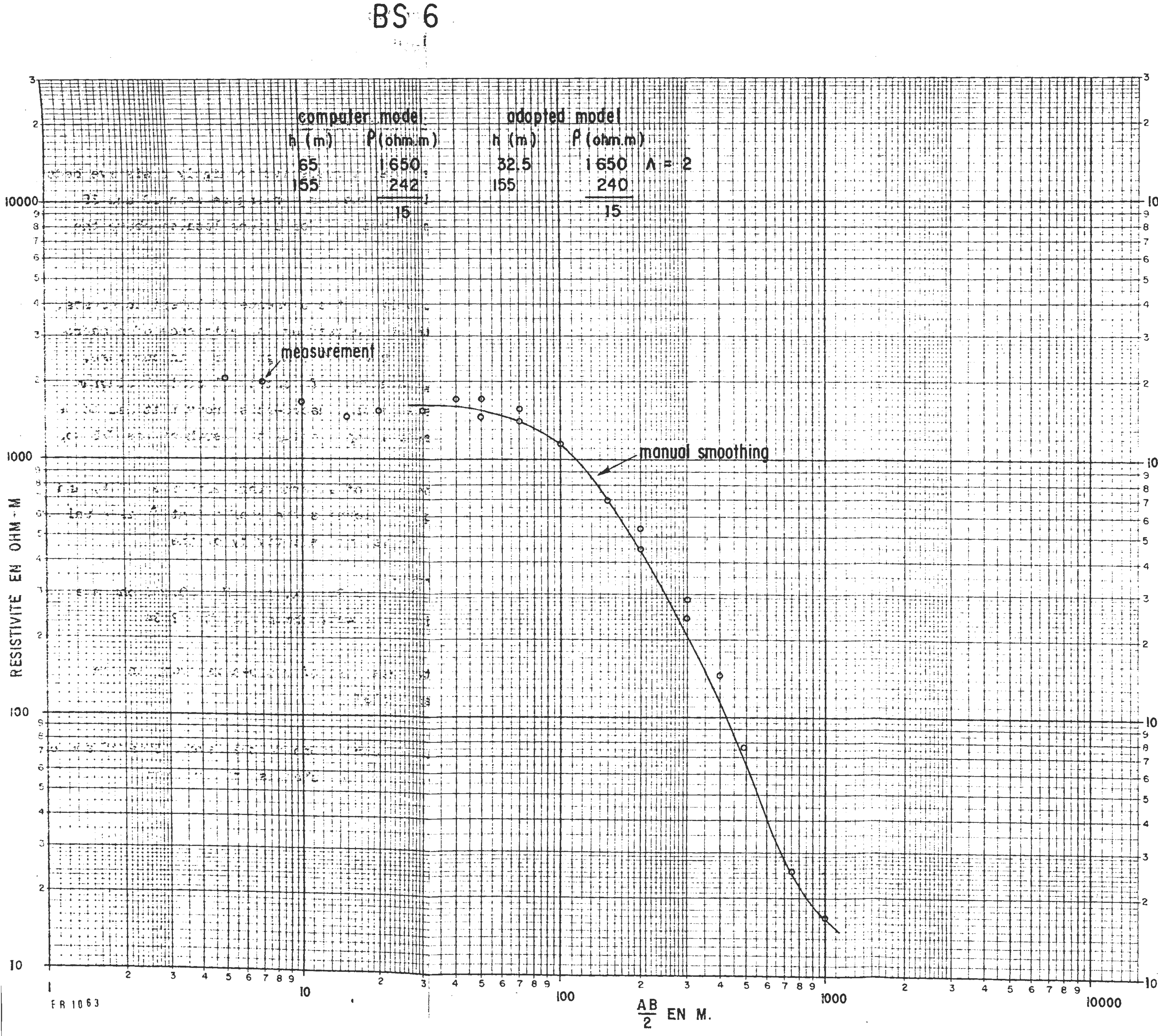

BJ 19
measurement
manual smoothing
computer model
h (m) ρ (ohm.m)
10.2 3 400
110.3 10 764
51 47
104 512
30
adopted model
h (m) ρ (ohm.m)
10.2 3 400
24.8 12 000 Λ = 4
53 50
133 400
30
RESISTIVITE EN OHM · M
AB/2 EN M.
ER 1063

Fig. 3


BS 6
computer model
h (m) ρ (ohm.m)
65 1650
155 242
15
adopted model
h (m) ρ (ohm.m)
32.5 1650 λ = 2
155 240
15
measurement
manual smoothing
RESISTIVITE EN OHM - M
AB/2 EN M.
FR 1063

to the surface there are superficial layers (SL) of highly variable (but most often, very high) resistivity. Bracketed between the DRU and the SL, there are sometimes one or two electrical units which are more or less continuous along the lines.

4.1.2.1 - The Superficial Layers (SL)

They often include several resistive to highly resistive beds (1000 to 50,000 ohm.m). Their thicknesses varying between 10 and 35 meters suggest that they constitute the formations located above the water-table.

In places, particularly in the presence of lateritic crusts, the SL are apparently very thick, suggesting the existence of a macro-anisotropy, the coefficient of which (Λ) might vary, in our case, between 1.5 and 4. A thorough analysis of certain electrical diagrams left no doubt as to the existence of a macro-anisotropy that had to be corrected for to avoid overestimating locally the depth of the CEB top.

To simplify, in the case of alternating resistive (ρ_M) and conductive (ρ_m) beds of equal thickness the coefficient Λ is equal to $\frac{\rho_M + \rho_m}{2 \rho_e}$ where ρ_e is the equivalent resistivity of the anisotropic medium ($\rho_e = \sqrt{\rho_M . \rho_m}$) . By taking ρ_M = 20.000 ohm.m and ρ_m = 1 000 ohm.m, we obtain ρ_e = 4472 ohm.m and Λ = 2.34.

Figures 3 and 4 show two examples of macro-anisotropy in the resistive SL (diagrams BS6 and B519).

In general, the SL roughly correspond to the layers located above the water table, but we did not try to establish the correct correlation since elevations of the E.S. were not measured and the water table depth is known in places only near the wells.

In rather rare cases, the SL are conductive, particularly where they are clayish or salty.

4.1.2.2 - The Deep Resistive Unit (DRU)

Everywhere directly overlying the electrical basement there is a resistive unit, with a resistivity varying between 100 and 500 ohm.m.

In places the DRU is, overlain by a more conductive electrical unit. In this case its thickness may be estimated : most often 100 to 150 meters (see Fig. 1, 2 and 4).

Sometimes this more conductive layer is absent or has a resistivity close to that of the DRU. In this case diagrams appear as if there was a single electrical unit between the SL and the CEB (see Fig. 3).

Wherever the SL are thick and highly resistive (phenomenon of macro-anisotropy) they mask the intermediate conductive layer (see Fig. 4). In the contrary case (see fig. 1 and 2) the latter clearly appears on the diagrams.

The presence of this DRU over the entire survey area is very important, since this electrical unit may constitute a good aquifer. However it is probable that the DRU does not represent a single homogeneous layer but is made by different, more or less permeable and more or less resistive layers.

4.1.2.3 - Electrical units between SL and DRU

As mentioned in the preceding paragraph, between the SL and the DRU there is sometimes a conductive unit. Its resistivity varies between 10 and 150 ohm.m and its thickness between 20 and 100 m.

This unit can be found directly under the SL, but is in places covered by a shallow resistive unit with a resistivity varying between 50 and 1000 ohm.m and a thickness between 20 and 75 m.

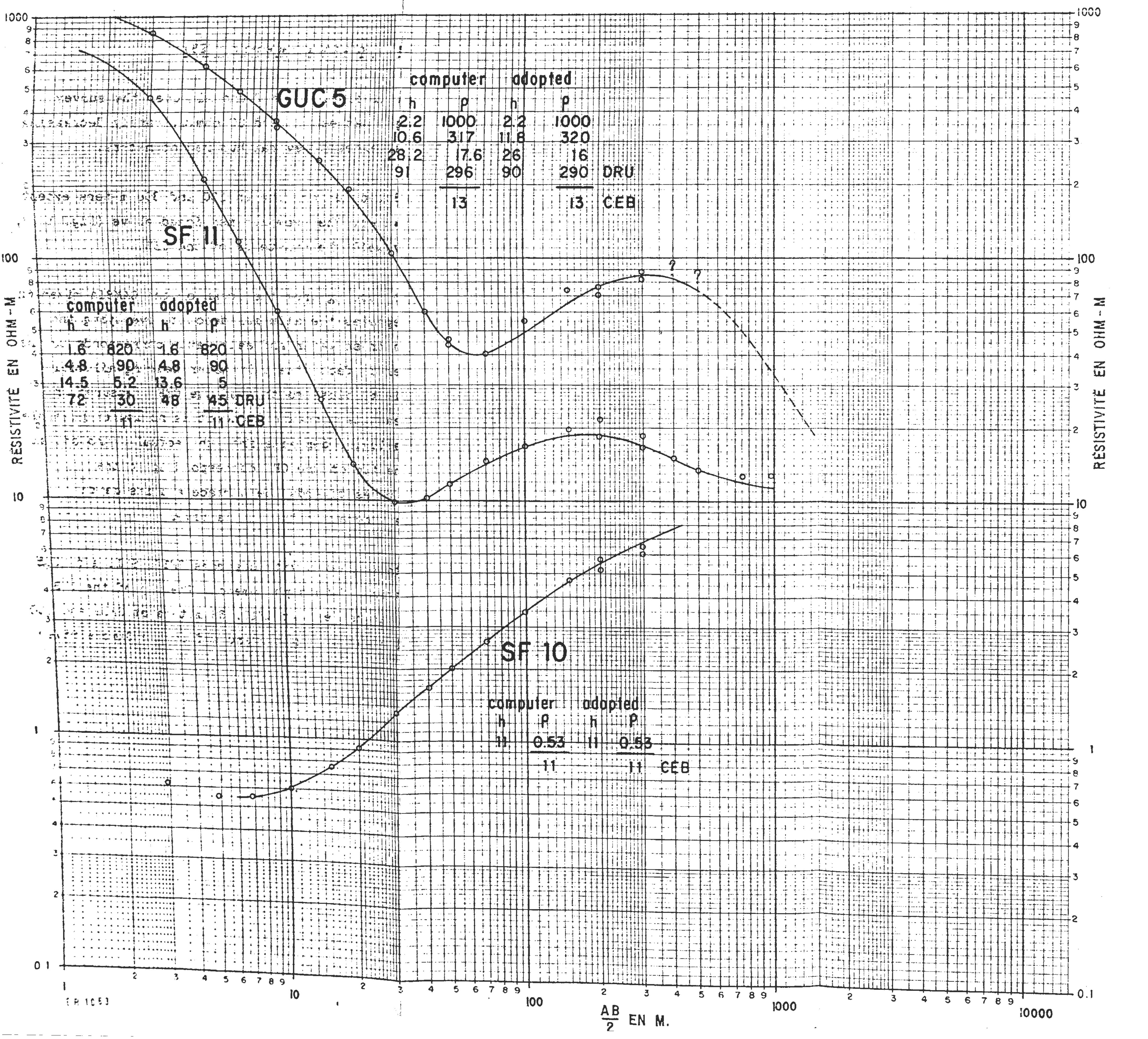
Whenever this conductive unit does not appear on the interpretative cross-sections, its absence may be due to :

- an actual disappearance caused by lateral variation of its lithological nature (increase of its resistivity),
- a decrease in thickness so that it is no longer possible to identify it on the resistivity diagrams,
- an anisotropic thickening of the SL, therefore masking its presence on the diagram curves.

It is quite obvious that whenever the conductive unit does not exist or is no longer perceptible by the resistivity method, the overburden part, located between the SL and the CEB, is entirely resistive and it is, thus, difficult to differentiate the shallow resistive unit from the DRU.

Fig. 5

SALT WATER INTRUSION



4.1.2.4 - The Conductive Electrical Basement (CEB)

A conductive electrical basement is found all over the survey area. Its resistivity ranges between 10 and 30 ohm.m, rarely decreasing to 4-5 ohm.m. Its thickness exceeds several hundred of meters.

The depth of the CEB top varies between 100 and 300 meters except in areas invaded by salt water. The examples mentioned above (Fig. 1, 2, 3 and 4) illustrate fairly well the existence of the CEB.

Where the salt water, coming from the ocean or the GAMBIA river in its downstream part, impregnates the alluvial deposits overlying the CEB, the interface between fresh water and salt water corresponds to the top of the CEB. As a matter of fact, the salt water bearing alluvial deposits display a resistivity close to that of the CEB (measured in areas where there is no sea water invasion) and it is no longer possible to distinguish the salty alluvial deposits from the actual lithological CEB. In such conditions the top of the CEB corresponding to the interface mentioned above rises towards the surface and its depth becomes nil along the ocean shore and the Gambia river.

Figure 5 shows the three resistivity diagrams SF10, SF11 and GUC5 and offers a fair illustration of this phenomenon. The top of the CEB (11-13 ohm.m) might be 11 meters deep at SF10, 68 meters at SF11 and 130 meters at GUC5 for gradually increasing distances from the Gambia river.

4.1.2.5 - Salt water intrusions

The resistivity method is quite suitable for detection of salt water intrusions, since layer resistivity is highly sensitive to the salt content of the impregnating water.

Comments in the preceding paragraph clearly indicate that, in this survey, the resistivity of salt water bearing alluvia (5 to 15 ohm.m) is close to that of the uncontaminated CEB (10 to 30 ohm.m).

In such conditions, based only on the resistivity, it is practically impossible to differentiate between :

- the lithological CEB (with no salt water intrusion),
- and the CEB corresponding to the fresh water-salt water interface located within the overburden.

It is the morphology of the CEB top and mainly its raising towards the salt polluting sources (ocean, Gambia river) that lead us to assume the presence of salt water intrusions on the cross-sections. The study of borehole resistivity logs may confirm the presence of this fresh water - salt water interface wherever it is not located at great depth (hole bottom rarely exceeds a hundred meters).

4.2 - Seismic spreads (S.S)

The interpretation of the S.S. provides the following results :

There is an initial superficial layer. Its velocity is rather low (0.5 to 1.6 km/s) and its thickness ranges between 10 and 30 meters. It generally corresponds to formations located above the water table.

In places, high velocity lateritic layers mask the underlying formations, the velocity of which is lower. But the seismic waves are quickly dampened in these rather thin lateritic layers and the refracted arrivals coming from deeper markers can be detected on the travel-time curves.

Alluvial deposits below the water table display velocities ranging between 1.8 and 2.0 km/s which can increase up to 2.2 km/s with depth and compression. The seismic refraction method does not allow us to distinguish sandy layers from clayey beds within these alluvia . It also provides no information on the salt water intrusions as the salt content of the impregnating water has no influence on the layer velocities.

At depths, taking into account that the spread length does not exceed 690 meters, we cannot distinguish any high velocity marker (higher than 3 to 4 km/s for instance).

The systematic picking of later arrivals shows that such markers do not exist at depths lower than 250 meters. On certain S.S however we could recognize, by means of later arrivals, a 2.2 - 2.4 km/s marker that can be differentiated from the sandy clay alluvial deposits and seems to correspond to the conductive electrical basement (CEB).

One might have thought that the long seismic spreads (690 m), with remote shot points located at a maximum 200 m distance from the first geophone, were poorly adapted to a 250 m deep investigation.

Travel-time curves of these remote shots, although of good quality, show no late energy arrivals corresponding to a possible high velocity marker (3 to 4 km/s). Should we assume that such late arrivals were not perceptible, the first "breaks" to be plotted would therefore be located at a minimum distance of 690 + 200 = 890 m. According to the formula $h = \frac{X}{2}\sqrt{\frac{V2 - V1}{V2 + V1}}$, that corresponds to a minimum investigation depth of 232 m by taking :

. X = 890 m,

. V1 = 2 km/s, overburden mean velocity,

. V2 = 3.5 km/s, possible velocity of the high velocity marker.

We can therefore consider that the seismic refraction method attained the objection : investigation of the various layers located to a depth of 250 meters.

It was necessary to test the seismic refraction method over the various areas selected. Afterwards, it was realized that the method was not very useful for solving the problem. However, it shows that the alluvial overburden and its substratum (CEB) are made up of rather unconsolidated sediments (velocities ranging between 1.8 and 2.4 km/s).

4.3 - Results from the boreholes

All the boreholes, for which geological logs were available, are shallow and rarely exceed 100 m in depth. Several of them encountered the fresh water - salt water interface. A few others penetrated into the upper part of the DRU. None reached the lithological CEB.

Their function as a calibration for the geophysical measurements is therefore rather limited.

We will however analyze data from each borehole when dealing with the results obtained in each area (chapter 5).

4.4 - Geoelectrical hypotheses

No calibration borehole has reached the lithologic CEB. In such conditions, it is difficult to correlate the various electrical units revealed by interpretation with the stratigraphical series described in chapter 1. Furthermore, between the various stratigraphical series there may not be resistivity contrasts high enough for these series to be revealed and identified by the resistivity method.

A hypothesis can however be set forward regarding the nature of the CEB at places where it does not correspond to the fresh water salt water interface . Its resistivity ranging between 10 and 30 ohm.m, its wave velocity possibly ranging between 2.2 and 2.4 km/s and the depth of its top ranging between 100 and 300 meters are indications that allow us to identify the CEB with the eocene-paleocene series made up of marls, marly limestones and clays.

Under such an assumption, the overlying resistive formations, particularly the DRU might wholly or partly, correspond to the miocene sands which are a possible aquifer.

Higher up, the pleistocene and pliocene series cannot with certainty be differentiated by the resistivity method, even when the diagram interpretation points out the presence of an intermediate conductive unit (pliocene series ?) overlain with a more resistive unit (pleistocene series).

Regarding refraction seismic results, we have seen that all the sandy clay series from Pleistocene to Miocene display very close velocities ranging between 1.8 and 2.2 km/s.

Only drill holes deeply penetrating the CEB will confirm or invalidate these hypotheses.

4.5 - Tectonic features

Within the scope of the geophysical campaign carried out in the Gambia, the electrical sounding and seismic refraction methods (seismic spreads quite distant from each other) provide no information on the presence of faults or fractures.

The gentle relief of the various electrical units does not suggest the existence of faults. The lateral variations of resistivity within these units suggest gradual variations of facies rather than sharp discontinuities due to faults.

In addition, geophysical measurements distributed along lines instead of a regular grid are not very suitable for revealing faults and discontinuities, since there is no check on several adjacent cross-sections.

In these conditions, we have avoided presenting geophysical results in the form of a structural sketch which might be very hypothetical. But is is understood that the existence of actual tectonic events cannot be rejected.

4.6 - Documents supplied

For each of the four survey areas, we supply a location map and the interpretation along the lines.

GUNJUR-BRIKAMA area

Pl. 2a : Location map (1/50,000)
Pl. 2b : Interpretation

KWINELLA-SOMA-FARAFENNI

Pl. 3a : Location map (1/50,000)
Pl. 3b : Interpretation

BANSANG-SANKULI KUNDA

Pl. 4a : Location map (1/50,000)
Pl. 4b : Interpretation

BASSE-JAR KUNDA

Pl. 5a : Location map (1/50,000)
Pl. 5b : Interpretation

On each plate concerning the interpretation, we supply both a cross-section and a profile of transverse resistance for each line.

The cross-sections show the results of the quantitative interpretation of the resistivity diagrams (thicknesses and true resistivities of the electrical units) and the interpretation of the seismic spreads (velocities and depths of the markers). For the S.S. we have plotted at the spread center the average value of the estimates at each shot point.

Calibration boreholes are also plotted on the cross-sections together with their depths.

The horizontal scale of the cross-sections is 1/50,000 as is that of the location maps. The vertical scale is 1/5,000. Dips of the electrical units that we have correlated along the lines are therefore amplified by a factor of 10.

The transverse resistance profiles are related to the resistive unit directly overlying the CEB. (transverse resistance, TR = the product of a layer's thickness by its resistivity). This resistive unit is either the DRU where it can be differentiated, or the entire resistive unit that overlies the CEB. In an alluvial deposit environment, the higher the transverse resistance is, the thicker or more numerous the resistive horizons liable to be aquifers. However, high resistivities that increase the transverse resistance value might be due to the presence of very fine and silty sands that would display a poor permeability.

5 - RESULTS OBTAINED IN EACH AREA

5.1 - GUNJUR-BRIKAMA area, lines GB (Pl. 2a and 2b)

On both GB lines, intersecting at station GB10, the electrical units, except the always resistive surface layers (SL), are the following :

There is a conductive unit below the SL, its resistivity varies between 20 and 160 ohm.m and its thickness between 20 and 75 meters.

Underneath, there is the deep resistive unit (DRU). Its resistivity varies between 75 and 550 ohm.m and its thickness between 25 and 125 meters.

The conductive electrical basement (CEB) has a 10-30 ohm.m resistivity and its rather flat top is located at a depth of 100-175 meters.

Only ES GB6, 27, 28 and 35 show a different electrical stratigraphy. The first one indicates a resistive intercalation in the conductive unit. The three others show a resistive medium from the surface to CEB.

To the southwest of line GB, near the Atlantic ocean shore (ES GB18, 20 and 21) there is in the alluvial deposit a contact fresh water/ salt water that makes the CEB rise towards the sea shore.

The same phenomenon occurs at ES 32 (calibration ES) located at 1.1 km off line GB. The CEB top rises and reaches a depth of 68 meters while the borehole was stopped at 57 meters in formations showing infiltrations of salt water.

The drill hole GUC 11, located 500 m off the line reached a 87 meter depth without penetrating the DRU. This borehole encountered aquifer sands between 62 and 87 meters that would correspond to the lower part of the 30-50 ohm.m conductive unit (it must be recalled that the resistivity diagram GUC 11 could not be interpreted : see paragraph 3.1).

The three S.S. GBD, E and F indicate undifferentiated alluvial deposits with velocities included between 1.8 and 2.0 km/s. The interpretation of spreads D and F, using later energy arrivals, shows the possible presence of a 2.2 - 2.3 km/s marker the top of which might correspond to that of the CEB.

The transverse resistance profiles show that the highest values (20.000 ohm.m2) are located between GB2 and 10, between GB25 and 30 and between GB33 and 37. These three areas would therefore be the most favorable locations for deep drill holes (200 m) although the area GB 25-30 near the Gambia river and near the borehole GB32 where salt water infiltrations were found, is not the best among the three areas.

5.2 - <u>KWINELLA-SOMA-FARAFENNI area, lines KS, SF, TK</u> (Pl. 3a and 3b)

Along the three lines KS, SF and TK, we again find the same units. However, between KS8 and KS33, between KS12 and KS15, between KS27 and KS30, between TK4 and TK5, between TK1 and KS2, and BETWEEN SF1 and SF18, there is a resistive electrical layer above the conductive unit ; its thickness varies between 20 and 75 meters and its resistivity between 70 and more than 1000 ohm.m.

Below this, the conductive electrical unit occurs almost everywhere (except at SF2, P5, SF11, 12, 13 and SF 19). Its resistivity ranges between 10 and 90 ohm.m and its thickness between 20 and 100 meters.

Below this electrical unit wherever it occurs, the DRU appears well differentiated. Its resistivity varies between 80 and 300 ohm.m and sometimes reaches 500 ohm.m and its thickness varies between 50 and 200 meters.

The CEB, the resistivity of which remains between 5 and 30 ohm.m, displays a rather flat top the depth of which varies between 200 and 300 meters.

The salt water invasion in the alluvial deposit is perceptible on ES TK5 near the Gambia river, but mainly on line SF, on each side of the river between stations SF5 and SF13. There the fresh water/salt water contact extends widely over 10 km probably because of the river meanders. At this place the CEB top gradually rises towards the ground surface and is nearly outcropping at E.S. SF9 and 10. The calibration borehole GUC8, 81 meters deep, at this depth penetrated in salty alluvial deposits, which is confirmed by the resistivity log, the values of which start to decrease steeply beginning at a depth of 60 meters.

Borehole P19, between SF1 and KS34 reached a 100 m depth and penetrated the upper part of the DRU that might correspond to the sands crossed by the drill hole between 71 and 96 meters.

Borehole P5, on the short line passing through KS6–KS5A was stopped at a depth of 46 meters in a 300 ohm.m electrical unit.

Borehole GUC5, in the northern part of line SF, was drilled to a depth of 89 meters. From 40 m to the hole bottom mainly sandy alluvial deposits were encountered. They correspond to the upper part of the formation that we call DRU and whose resistivity here is close to 300 ohm.m.

All the S.S. KSA, B, C, D, E and F show the existence of thick alluvial deposits the velocities of which vary between 1.8 and 2.0 km/s tending to slightly increase with the compression downwards (2.0 - 2.2 km/s).

Among the S.S. of line SF :

- Spreads D, E and F provide the same results as those of line KS.

- Spreads B and C show the presence of 1.9 km/s alluvial deposits on each side of the salt water/fresh water contact, since the velocity practically does not depend on the water's salt content.

- Spread A, through the picking of late arrivals, shows the probable presence below the alluvia, of a 2.3 km/s marker that might correspond to the CEB.

The transverse resistance profiles show that the highest values, exceeding 20 kohm.m2, lie between KS18 and KS27 (with a maximum at KS25, 26 and 27), between K30 and KS35, between SF14 and SF15, and between SF16 and SF18 (with a maximum at SF17).

Three hundred meters deep exploratory drill holes would certainly be advisable, for instance at stations E.S. SF16 and KS26.

5.3 - BANSANG-SANKULI KUNDA area, line BS (Pl. 4a and 4b)

Except for E.S. UN11, 12 and 13 at the northwestern end of line BS, the cross-section shows only a single resistive unit between the superficial layers (SL) and the conductive electrical basement (CEB). Its resistivity varies between 100 and 200 ohm.m. Of course, this resistive unit is certainly not homogeneous but should contain numerous thick sandy layers.

The CEB has a resistivity of 10-20 ohm.m and its top is 150-200 meters deep.

The calibration borehole UN11 located 850 meters off line BS was sunk to 83 meters and might have only crossed the 55 ohm.m conductive electrical unit that overlies the more resistive and deeper unit there.

The transverse resistance profile reveals two areas where values exceed 20.000 ohm.m2 : between BS11 and BS13 and between BS3 and BS6.

An exploratory drill hole to a maximum depth of about 200 meters and positioned at station BS3 or BS6 may be considered .

5.4 - BASSE-JAR KUNDA area, line BJ (Pl. 5a and 5b)

Below the surface layers the cross-section of line BJ provides the following results :

1) To the north between BJ11 and BJ29

There is a conductive electrical unit (except at BJ 17 and 17A). It is in places covered (BJ12, 16, 21, 22 and 23) by more resistive formations. Its resistivity varies between 40 and 150 ohm.m and its thickness ranges between 25 and 75 meters.

Below this unit the DRU appears displaying a resistivity between 100 and 600 ohm.m and a thickness of 50-170 meters.

The CEB has a 13-30 ohm.m resistivity and it top is 150-275 meters deep.

2) To the south between BJ10 and BJ31

The conductive unit is either absent or too thin to be visible on the diagrams.

A single resistive medium, probably heterogenous, is bracketed between the SL and the CEB. Its resistivity varies between 100 and 550 ohm.m, its thickness between 100 and 175 meters.

The CEB displays a resistivity slightly lower than in the northern part (5 to 15 ohm.m) and its top is located at depths of 125-200 meters.

Borehole UN14 located 850 meters off line BJ, reached a depth of 80 meters. Between 47 and 72 meters it encountered fine sands becoming coarser downwards. These latter correspond to the upper part of the 300 ohm.m resistive unit.

Borehole GUC2, stopped at 102 meters in the upper part of the 330 ohm.m DRU, in fact penetrated sands between 66 and 96 meters.

Drill hole GUC4, stopped at 85 meters in the 550 ohm.m resistive medium, mainly encountered sands or silty sands that may indeed be rather resistive.

The three S.S. BJA, C and E indicate the presence of alluvia the velocity of which, below the water table, is equal to 1.9 km/s.

Only on spread BJC, through a picking of later arrivals, a 2.4 km/s deep marker can be revealed and might be assimilated to the CEB (155 meter deep).

At stations BJ23, 24 - BJ16 to 19A and BJ7, GUC4 the transverse resistance profile displays values that are very high (50 Kohm.m2). These areas are not necessarily the most favorable locations for drill holes since high resistivities of 500-600 ohm.m may be caused by the presence of very fine sands of low permeability.

We think it would be preferable to select areas where the transverse resistance remains between 20 and 50 Kohm.m2 : for instance 200 meters deep drill holes at BJ5 and/or BJ11.

C O N C L U S I O N S   A N D   S U G G E S T I O N S

The seismic refraction and resistivity survey, carried out in the GAMBIA has provided valuable information for positioning new bore holes that should be drilled quite deeper than the existing ones.

In the four survey areas designated as :

- GUNJUR-BRIKAMA(Pl. 2a and 2b)
- KWINELLA-SOMA-FARAFENNI (Pl. 3a and 3b)
- BANSANG-SANKULI KUNDA (Pl. 4a and 4b)
- BASSE-JAR KUNDA (Pl. 5a and 5b)

the resistivity method points out the presence of a conductive electrical basement (CEB). Its resistivity generally ranges between 10 and 30 ohm.m (sometimes 5-30 ohm.m) and its depth between 100 and 300 meters.

Directly above the CEB there is a resistive electrical unit with a resistivity often ranging between 100 and 600 ohm.m.

This unit is frequently covered by a conductive electrical unit with a resistivity ranging between 10 and 150 ohm.m. More rarely, this conductive unit is, itself, overlain by more resistive horizons.

Wherever the conductive electrical unit occurs, the resistive unit directly overlying the CEB is referred to as the "deep resistive unit" DRU.

Close to the ground surface, related to the formations located above the water table, thin electrical layers are encountered ; we call them surface layers (SL). The SL are most often highly resistive (from 1000 to over 10,000 ohm.m) and sometimes anisotropic, probably linked to beds of laterite and dry sands.

The various electrical units described above certainly do not correspond to homogeneous lithological units, but are made of a piling of more or less resistive or conductive layers that the resistivity method is powerless to differentiate.

The seismic refraction method points out superficial dry formations the velocity of which is generally lower than 1.6 km/s. In places lateritic crusts display higher velocities (1.6 - 2.0 km/s).

Deeper, below the water table, the velocities recorded range between 1.8 and 2 km/s and sometimes increase up to 2.2 km/s with compression of rocks at depth.

No high velocity marker appears at a depth lower than 250 meters. However, through the picking of later arrivals, we could detect a marker on four seismic spreads, the velocity of which is slightly higher (2.2 to 2.4 km/s). This marker seems to correlate with the CEB.

As no drill hole reached the lithological CEB, we were unable to establish a correlation between the geophysical results and the assumed stratigraphy of the GAMBIA (see Chapter I).

From a lithological point of view, it seems that the CEB, displaying a 10-30 ohm.m resistivity and a 2.2 to 2.4 km/s velocity, might be identified with marls, compact clays or very marly limestones (perhaps clayish sandstones).

Between the water table and the CEB, the highly variable resistivities (10 to 600 ohm.m) and the poorly contrasted velocities (1.8 to 2.2 km/s) suggest the presence of rather loose alluvia made up of either clayish beds (10-50 ohm.m), or sandy clays (50-150 ohm.m) or predominantly sandy and gritty layers (150-400 ohm.m) or fine silty sands (400-600 ohm.m). But this differentiation is slightly arbitrary.

Although the CEB most often represents a lithological series, the correct nature of which should be reconnoitred by sufficiently deep drill holes and although it quite certainly constitutes an aquiclude substratum for the overlying alluvial deposits, some exceptions are noteworthy.

Indeed, close to the Atlantic ocean and in the downstream part of the Gambia river, alluvial deposits may be impregnated with salt water and, there, the CEB top represents the fresh water/salt water interface. This phenomenon is quite clearly visible on line SF crossing the river, and might also, wholly or partly, affect line GB located between the Atlantic ocean and the Gambia estuary. As a matter of fact the CEB depth along this line is quite lower than that of line KS.

Pumping fresh water in these areas, with drill holes sunk close to the top of the CEB, may bring up brackish water.

The "transverse resistance" profiles related to the resistive electrical unit directly overlying the CEB (product of the unit's thickness by its resistivity) provide additional information and help select the location of new exploratory drill holes.

The drill holes planned should deeply penetrate the CEB in an initial phase of geological exploration.

From a hydrological point of view, the bottom of the resistive electrical unit overlying the CEB must be reconnoitred, as it might be a good aquifer (no drill hole has yet reached it).

New drill holes should be located in the areas where the transverse resistance is rather high (20 to 40 kohm.m2) but not in areas where it exceeds 50 kohm.m2, since these very high values may be caused by high resistivities (500 - 600 ohm.m) which are probably an indication of the presence of fine silty sand of poor permeability.

We recommend that the reconnaissance drill holes be located at the following stations :

- line GB : ES 4 or 7, and ES 38 or 39. On this line one should be careful with regard to the CEB which might be correlated with a salt water invasion.

- line KS : ES 26
- line SF : ES 16
- line BS :ES 3 or 6
- line BJ : ES 5 or 11

This selection is based on considerations presented in this report and upon the quality of the diagrams obtained at the recommended stations.

The calibration drill-holes were not of great help in refining our interpretation particularly for adjusting the thickness of the electrical units or the CEB depth. Several discrepancies will certainly appear between our estimates and the results of the future drill-holes because of the well-known phenomenon of equivalence of the resistivity method that only provides "transverse resistances" or "horizontal conductances".

Several calibration drill holes, that penetrated the DRU (Deep Resistive Unit), have however shown that its upper part is mainly made up of sandy alluvia.

To complete this report, we would like to make a few recommendations to be used as a basis for setting up programs for future geophysical surveys.

Should the intended investigation depth be 200 - 300 m as in the present survey, electrical soundings (ES) are quite suitable with AB line lengths of 2000 to 4000 meters. They allow us to estimate a depth of the CEB which is likely to represent an impervious floor of the overlying alluvial deposits, or the fresh water-salt water interface in case of salt water intrusion.

In this case, the seismic refraction method provides no very useful information and can be rejected.

Should the intended investigation depth be much greater, for instance 300 to over 600 m, for seeking resistive and high-velocity deep markers located below the CEB and possibly corresponding to thick limestone or sandstone aquifers, a series of tests should be carried out. They would include :

- electrical soundings with a long AB line (10,000 to 20,000 m),
- long seismic refraction spreads (1000 m for instance with shot points at gradually increasing distances from the end geophones).

These tests will allow the parameters of the seismic and electric arrays to be determined, and the adequacy of both methods for deep objectives to be checked.

But for such depths (300 to 600 m), we think that the seismic refraction method should be replaced by high resolution seismic reflection that might provide information above the CEB (lower part of the DRU), within the CEB and below the CEB. Such a method of course more expensive, along with a few ES (long AB line) to measure the resistivity and/or the transverse resistance of the possible deep aquifers, is certainly the most suitable.

Massy, December 30, 1983

J.B./C.M.

PL. I

UNITED NATIONS

GEOPHYSICAL SURVEY OF THE GAMBIA
USING ELECTRICAL AND SEISMIC METHODS

GENERAL LOCATION MAP

COMPAGNIE GENERALE DE GEOPHYSIQUE
6, Rue Galvani - 91301 - MASSY - FRANCE

PL. 2a

UNITED NATIONS

GEOPHYSICAL SURVEY OF THE GAMBIA USING ELECTRICAL AND SEISMIC METHODS

GUNJUR - BRIKAMA AREA

LOCATION MAP

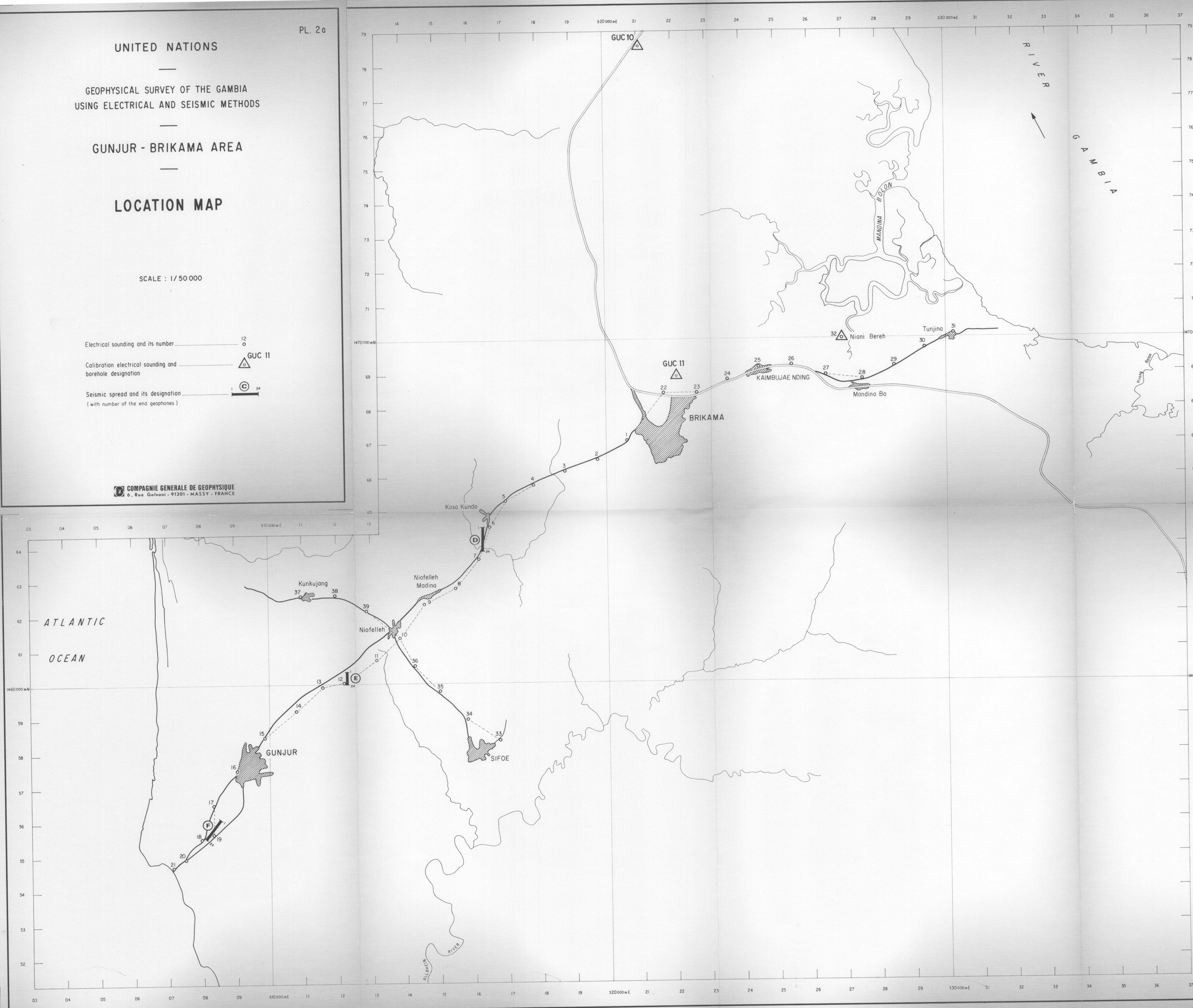
SCALE : 1/50 000

Electrical sounding and its number

Calibration electrical sounding and borehole designation

Seismic spread and its designation (with number of the end geophones)

COMPAGNIE GENERALE DE GEOPHYSIQUE
6, Rue Galvani - 91301 - MASSY - FRANCE



UNITED NATIONS

PL. 2b

GEOPHYSICAL SURVEY OF THE GAMBIA
USING ELECTRICAL AND SEISMIC METHODS

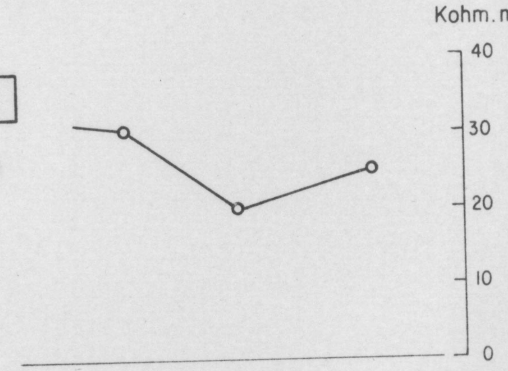
GUNJUR - BRIKAMA AREA

PROFILE GB

HORIZONTAL SCALE : 1 / 50 000
VERTICAL SCALE : 1 / 5 000

TRANSVERSE RESISTANCE

of the resistive unit overlying the conductive electrical basement (CEB) (expressed in 10^3 ohm.m^2)



GEOPHYSICAL CROSS-SECTION

Calibration ES and location of the well on or off the line

Seismic spread (SS) and its designation (velocity of the layers in Km/s)

Electrical sounding (ES) and its number

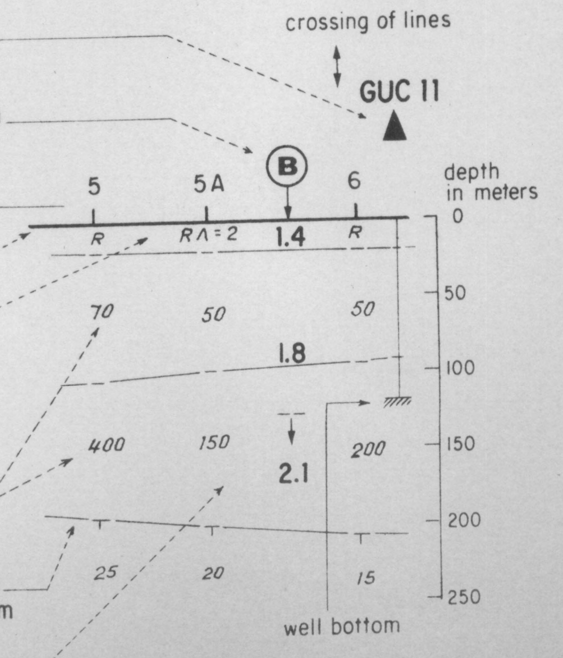
Surface

Superficial layers
C : conductive
R : resistive
Λ : anisotropy coefficient and the adopted value

Electrical units and their resistivity in ohm.m

Conductive electrical basement (CEB) and its approximate resistivity in ohm.m

Resistive unit overlying the CEB



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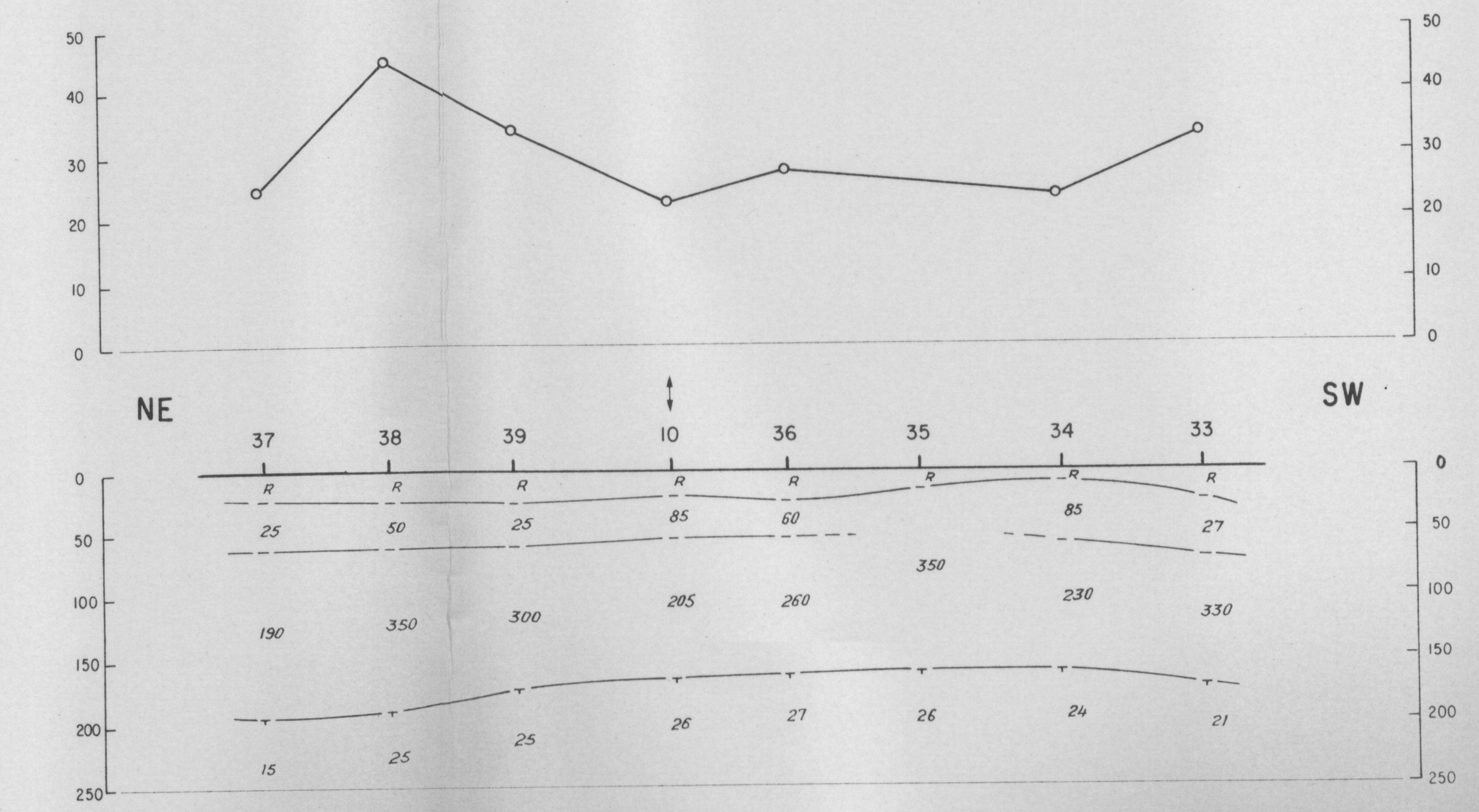

PL. 3a

UNITED NATIONS

GEOPHYSICAL SURVEY OF THE GAMBIA
USING ELECTRICAL AND SEISMIC METHODS

KWINELLA - SOMA - FARAFENNI AREA

LOCATION MAP

SCALE : 1/50 000

Electrical sounding and its number 12

Calibration electrical sounding and borehole designation GUC 11

Seismic spread and its designation KSB 1 24
(with number of the end geophones)

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6, Rue Galvani - 91301 - MASSY - FRANCE

UNITED NATIONS PL. 3b

GEOPHYSICAL SURVEY OF THE GAMBIA
USING ELECTRICAL AND SEISMIC METHODS

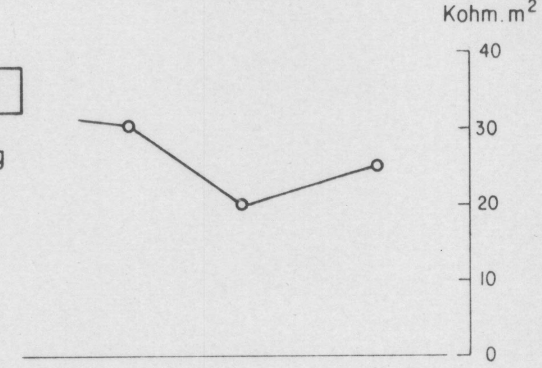
KWINELLA - SOMA - FARAFENNI AREA

PROFILE TK-KS-SF

HORIZONTAL SCALE : 1/50000
VERTICAL SCALE : 1/5000

TRANSVERSE RESISTANCE

of the resistive unit overlying the conductive electrical basement (CEB) (expressed in 10^3 ohm.m^2)



GEOPHYSICAL CROSS-SECTION

Calibration ES and location of the well on or off the line

Seismic spread (SS) and its designation (velocity of the layers in Km/s)

Electrical sounding (ES) and its number

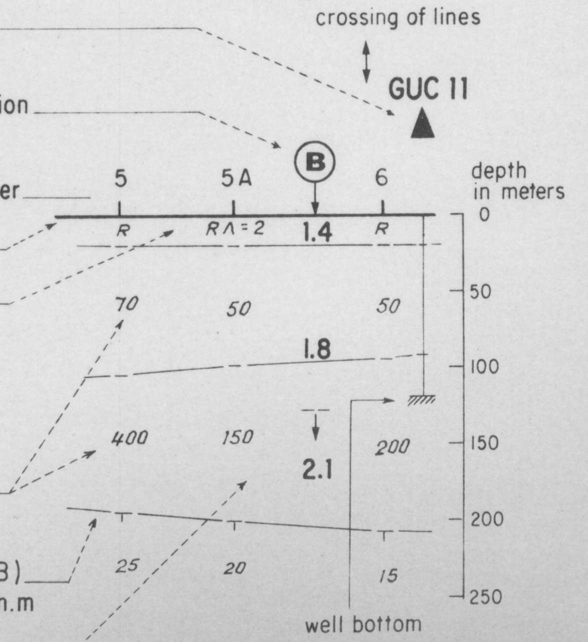
Surface

Superficial layers
- C : conductive
- R : resistive
- Λ : anisotropy coefficient and the adopted value

Electrical units and their resistivity in ohm.m

Conductive electrical basement (CEB) and its approximate resistivity in ohm.m

Resistive unit overlying the CEB



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PL. 4a

UNITED NATIONS

GEOPHYSICAL SURVEY OF THE GAMBIA USING ELECTRICAL AND SEISMIC METHODS

BANSANG - SANKULI KUNDA AREA

LOCATION MAP

SCALE : 1/50 000

Electrical sounding and its number ______ 12

Calibration electrical sounding and borehole designation ______ GUC 11

Seismic spread and its designation ______ 1 © 24
(with number of the end geophones)

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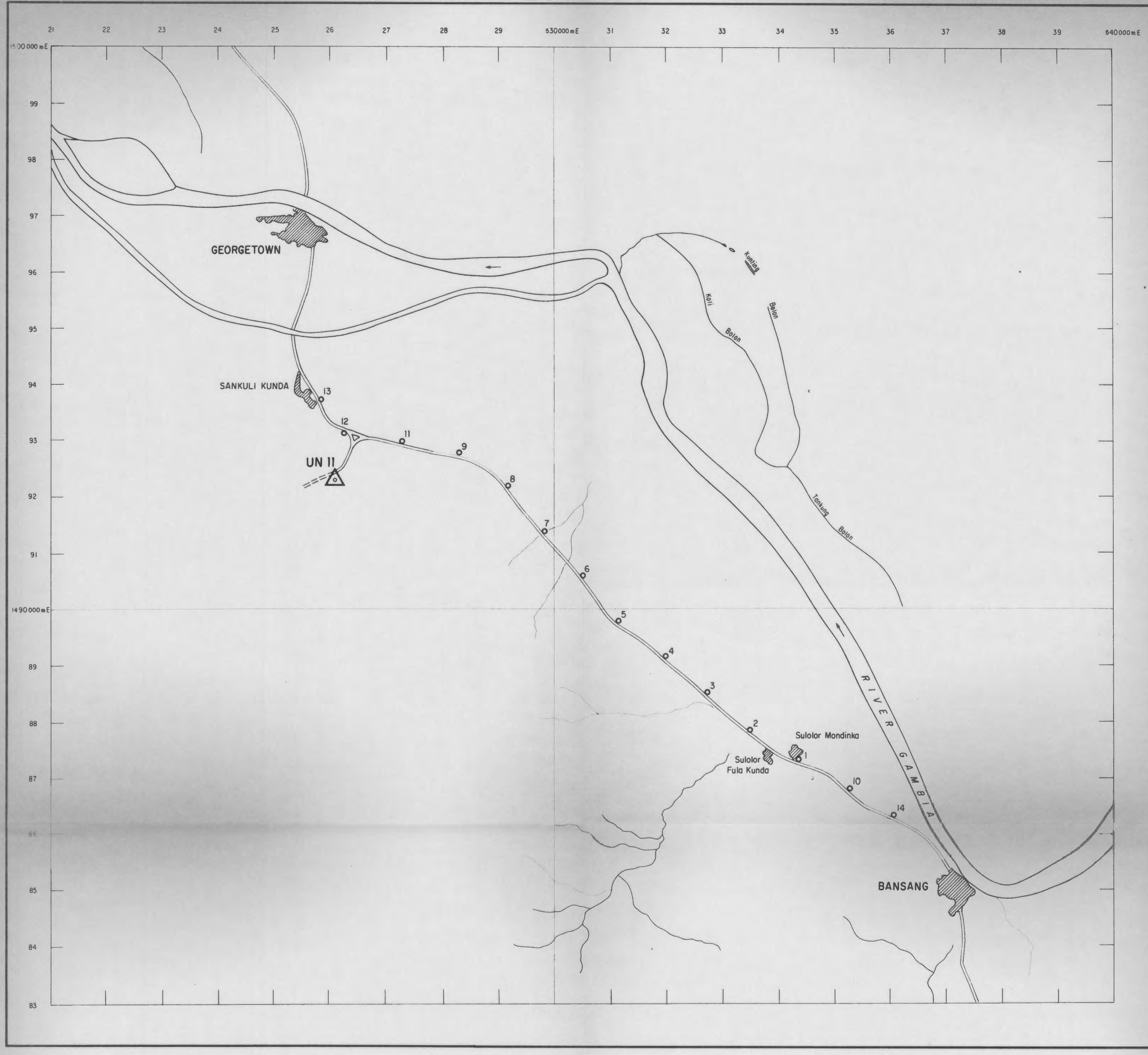


UNITED NATIONS

PL. 4b

GEOPHYSICAL SURVEY OF THE GAMBIA
USING ELECTRICAL AND SEISMIC METHODS

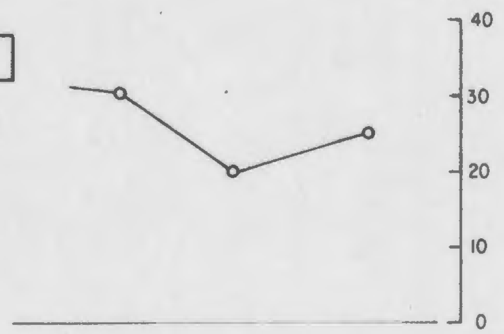
BANSANG - SANKULI KUNDA AREA

PROFILE BS

HORIZONTAL SCALE : 1 / 50 000
VERTICAL SCALE : 1 / 5 000

TRANSVERSE RESISTANCE

of the resistive unit overlying the conductive electrical basement (CEB) (expressed in 10^3 ohm.m^2)



GEOPHYSICAL CROSS-SECTION

Calibration ES and location of the well on or off the line

Seismic spread (SS) and its designation (velocity of the layers in Km/s)

Electrical sounding (ES) and its number

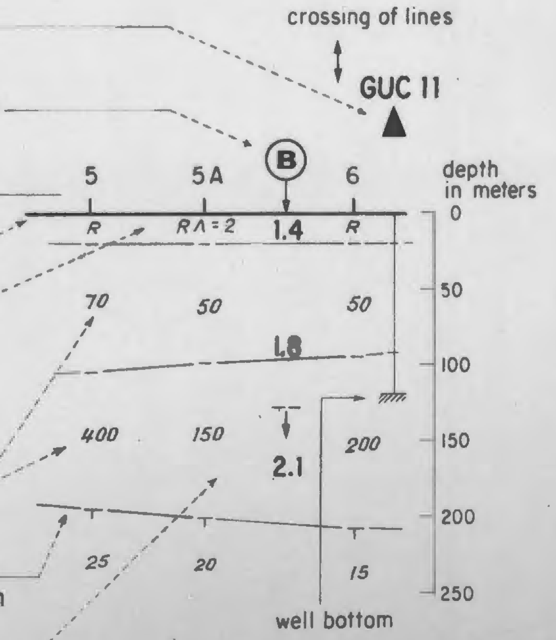
Surface

Superficial layers
C : conductive
R : resistive
Λ : anisotropy coefficient and the adopted value

Electrical units and their resistivity in ohm.m

Conductive electrical basement (CEB) and its approximate resistivity in ohm.m

Resistive unit overlying the CEB



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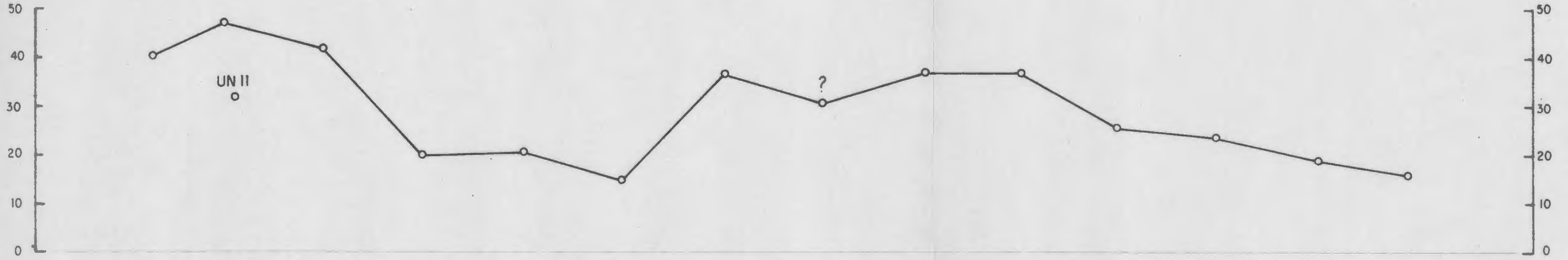

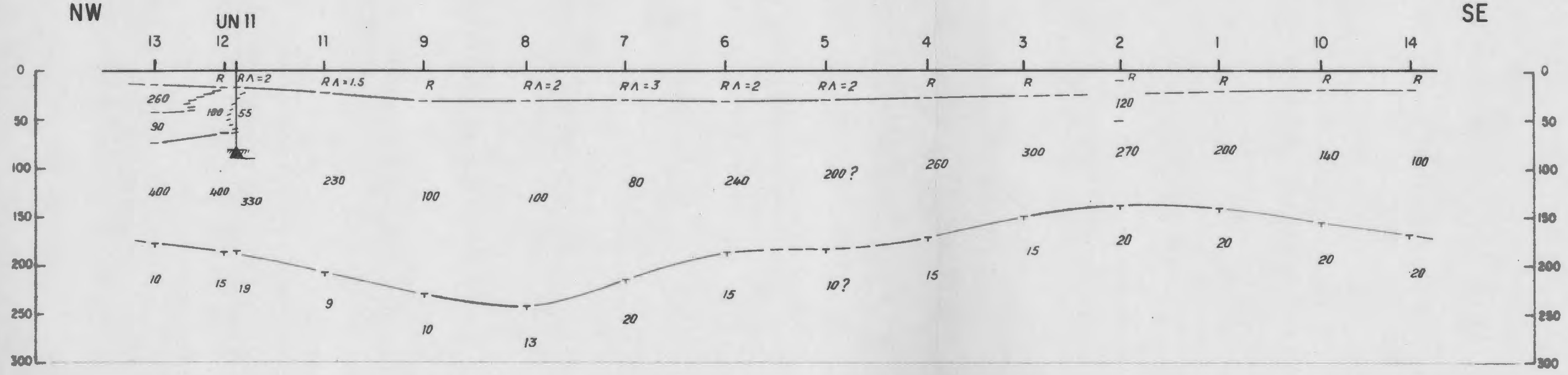

PL. 5a

UNITED NATIONS

GEOPHYSICAL SURVEY OF THE GAMBIA
USING ELECTRICAL AND SEISMIC METHODS

BASSE-JAR KUNDA AREA

LOCATION MAP

SCALE : 1/50 000

Electrical sounding and its number 12

Calibration electrical sounding and borehole designation GUC 11

Seismic spread and its designation (C) 1 24
(with number of the end geophones)

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6, Rue Galvani - 91301 - MASSY - FRANCE

UNITED NATIONS

PL. 5b

GEOPHYSICAL SURVEY OF THE GAMBIA
USING ELECTRICAL AND SEISMIC METHODS

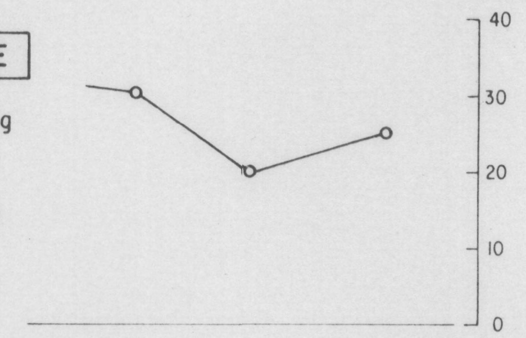
BASSE-JAR KUNDA AREA

PROFILE BJ

HORIZONTAL SCALE : 1 / 50000
VERTICAL SCALE : 1 / 5 000

TRANSVERSE RESISTANCE

of the resistive unit overlying the conductive electrical basement (CEB) (expressed in 10^3 ohm.m^2)



GEOPHYSICAL CROSS-SECTION

Calibration ES and location of the well on or off the line

Seismic spread (SS) and its designation (velocity of the layers in Km/s)

Electrical sounding (ES) and its number

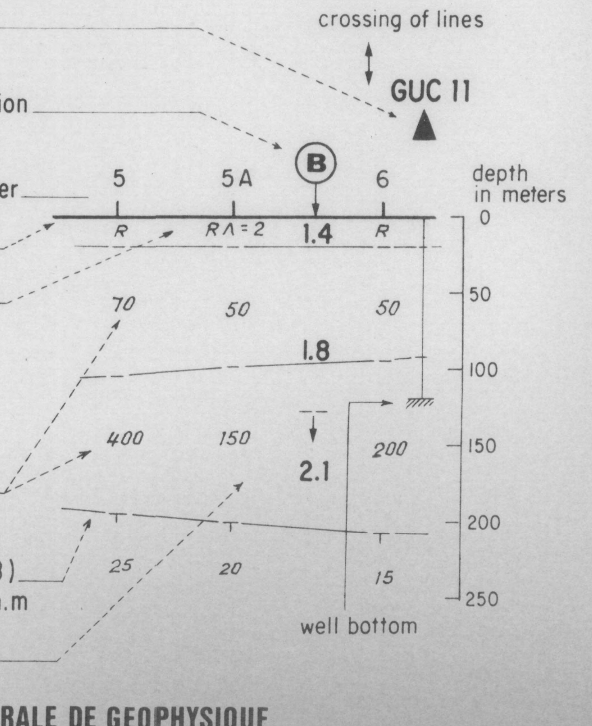
Surface

Superficial layers
- C : conductive
- R : resistive
- Λ : anisotropy coefficient and the adopted value

Electrical units and their resistivity in ohm.m

Conductive electrical basement (CEB) and its approximate resistivity in ohm.m

Resistive unit overlying the CEB



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