P10H

DEPTH OF PENETRATION OF AIRBORNE ELECTROMAGNETICS OVER STRATIFIED EARTH

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ABSTRACT

In order to evaluate the feasibility of helicopter-borne electromagnetics (HEM) for preliminary geotechnical and hydrogeological surveys in sedimentary basins, the work started by SINHA and COLLETT in 1973 was continued. The computer program was developed to supply ppm response and apparent resistivities for (1) any number of frequencies ; 375, 900, 3600 and 8000 Hz were selected ; (2) any bird length ; 10 m was chosen ; (3) any coil configuration ; (4) any height above the ground ; 30 m was chosen ; and (5) up to 8 layers.

The resistivities and depths selected were : first layer, 10 Ωm ; depths : 0, 3 or 6 m ; second layer, 400 Ωm ; depths : 7, 13, 20 m ; third layer, 0.5, 1, 2, 5, 7, 10, 30, 100, 400 Ωm ; depths : 20, 30, 50, 70, 100, 200 m, infinite ; and fourth layer, 1000 Ωm.

Depth of penetration to the basement was defined as the most severe of the following two criteria : 95 percent of maximum response (which corresponds to infinite thickness of the third layer) ; and change of response greater than 5 ppm. It should be noted that the various models selected correspond to quite a conductive environment and the response is usually comprised between 50 and 1500 ppm. Results show that the (— —) response is double that of the vertical coplanar configuration (0 0), which itself is double the vertical coaxial configuration (1 1), with an accuracy of less that 2 percent. Response of the orthogonal configuration is always much smaller, but variable (about 10 times less than the (— —)).

Conclusions of the study were that, for usual resistivities found in sedimentary basins (10 to 1000 Ωm), low frequencies (under 1000 Hz) could give information up to 50 to 150 m depth. Salt water would decrease penetration severely. It was also shown that resistivity inversion was possible with more complicated

models than the two-layer models presently available. For that purpose, a three-frequency system, with frequencies in the range of 300-600, 800-2000 and 3000-6000, with a long bird would be more suitable. Procedures for inverting the 4-layer model described above, taking into account a certain number of geologic constraints, are presently being studied.

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I. - INTRODUCTION

The present work was carried out for Electricité de France, the French State Power Board, in the objective of evaluating feasibility of helicopter borne geophysics, and particularly electromagnetics (H.E.M.) for preliminary geotechnical and hydrogeological surveys of sedimentary basins. In addition to a world wide enquiry among government agencies, manufacturers and contractors, we also engaged a theoretical investigation and established a detailed computer program.

The state of the act of heliborne electromagnetic interpretation procedures as applied to horizontal structures is generally the following as described by D.C. FRASER (1978) :

Parameters introduced	: - phase and quadrature response at a single frequency - real altitude ho
Computation hypothesis	: homogeneous earth "bird" at a fictitious altitude h
Results	: - apparent resistivity - apparent thickness H of a resistive first layer ; H = h - ho

This algorithm has the advantage of simplicity, and is therefore used systematically by the 4 main contractors we have met, all based in Canada. Computer profiling and mapping are done automatically. If two or three frequencies are used, generally separate maps can be supplied for each frequency.

In one case, over a lignite basin, the Ontario Geological Survey developed a more sophisticated algorithm, as described by H.O. SEIGEL and D.H. PITCHER (1978). Using a three frequency system, a true two layer model was used, and two resistivities and one depth computed. Unfortunately, this experimental algorithm does not seem to be presently in professional use. It should be noted that if modern H.E.M. methods are now about 10 years old, and that near 20 systems are currently in operation in the world, most of the surveys concern mining and vertical structures. Professional interest in resistivity mapping is quite recent.

These available methods and results not being sufficient to allow evaluation of depth of penetration and we returned to theory, as described by F.C. FRISKNECHT (1967) for a two layered earth, and by A.K. SINHA and L.S. COLLETT (1973) for a multilayer earth.

II. - THERETICAL RESPONSE OF A MULTILAYER EARTH

We can briefly summarize the response of a multilayer earth as follows (detailed theory is supplied by SINHA and COLLETT (1973)) :

Starting from a development of the Maxwell equations, SINHA and COLLETT define integrals T_0, T_1 and T_2, functions of thicknesses and resistivities of the different layers, of flying height, of separation between transmitter and receiver coils, and of coil configuration. SINHA and COLLETT's computer program supplies these integrals, as well as ellipticity and tilt of the secondary magnetic field.

Starting back from T_0, T_1 and T_2, we computed secondary impedance (Z) of different coil configurations, which is compared to primary impedance (Zo). Available equipments measure directly $\frac{Z}{Zo} \times 10^6$.

The various possible configuration can be classified as follows :

maximum coupled : — — horizontal coplanar

0 0 vertical coplanar

1 1 vertical coaxial

with $\frac{Z}{Zo} = 1 - f\,(T_0, T_1, T_2)$

(The primary field giving the unit value (1) is automatically nulled by bucking coils between transmitter and receiver)

null coupled : — 1 reciprocal whale tail

or 1 — standard (whale tail)

$$\frac{Z}{Zo} = f\,(T_0, T_1, T_2)$$

null horizontal response : — 1

0 —

1 0

0 1

These configurations only supply a response in presence of non horizontal structures ; over horizontally stratified earth Z = Zo = 0.

III. - SELECTED PARAMETERS

Our computer program supplies the following outputs :

- phase and quadrature ppm response
- separate apparent resistivities for phase and quadrature.

The "apparent" resistivities are computed with the real bird height, in the hypothesis of a homogeneous earth. It can be reminded that this is exactly what is done for D.C. resistivity soundings, "apparent" resistivities being the starting point for further interpretation.

The inputs to the program are the following :

- any number of frequencies : 375, 900, 3 600 and 8 000 Hz were selected, covering the range of commercially available values
- any vertical or horizontal coil configuration :

vertical coaxial	(1 1)
horizontal coplanar	(— —)
vertical coplanar	(0 0)
and "standard" or orthogonal	(1 —)

  were selected, other configurations either having null response over horizontal structures (— 0), (1 0), or being symetrical to previous configurations : (— 1), (0 —), (0 1).
- any bird length : 10 meters was chosen
- any height above the ground : 30 meters was chosen
- up to 8 resistivities and up to 7 depths or thicknesses.

The resistivities and depths selected were the following (figure 1) :

First layer	: 10 Ωm	Depth : 0, 3 or 6 meters
Second layer	: 400 Ωm	Depths : 20 meters and 7 and 13 meters for certain cases
Third layer	: 10,30,100,400 Ωm (and 0.5, 1,2,5,7 Ωm for certain cases)	Depths : 20,30,50,70,100,200 meters, infinite
Fourth layer	: 1 000 Ωm	

This four layer model covers a large part of French sedimentary basins. The first layer corresponds to top soil or clay, the second one to sand or gravel overburden and the fourth one to a granite or compact limestone basement. The variable third layer can correspond to :

- sand and gravel with brackish water (0.5, 1, 2, 5 Ωm)
- clay (7, 10, 30 Ωm)
- clayey or sandy limistone, marls (100 Ωm)
- thick sand and gravel deposits (400 Ωm)

"Depth of penetration" to the basement - a very arbitrary notion in all geophysical methods - was defined as the most severe of the following two criteria :

- 95 % of maximum response obtained with infinite third layer thickness
- change of response greater than 5 ppm. The second criterium is in fact slightly too severe, present day noise levels being around 1 ppm, and we could have fixed the limit at 3 ppm. It should be noted that the various models selected by us correspond to quite a conductive environment, with a response usually comprised between 50 and 1 500 ppm, much higher than the responses generally obtained over granite during mining surveys.

Before systematic use of our program, we checked the results on those published by FRISKNECHT (1967), SINHA and COLLETT (1973), FRASER (1978) and SEIGEL and PITCHER (1978).

On the total, the following quantities of earth configurations were tested :

homogeneous earth	:	14	
two layer	:	36	
three layer	:	9	
systematic four layer	:	96	
extra four layer	:	26	(variation of second layer thickness)
" " "	:	12	(brackish water)
variation of bird length	:	11	
		204	earth configurations

Considering 4 frequencies and 4 coil frequencies, a total of 3 264 cases were computed.

IV. - COMPARISON OF COIL CONFIGURATIONS

All the computed values confirm the well known differences between the 4 selected coil configurations :

(— —) response = 2 x (0 0) response, to less than 2 %

(— —) response = 4 x (1 1) response, to less than 5 %

(— —) response = 5 to 10 times) x (— 1) response.

The "5 to 10" factor is even greater than 20 for the phase component for resistivities greater than 100 Ωm, phase component of the (— 1) configuration being nearly null over resistive earth. Therefore, if the printed outputs were given for all configurations, our main subject of interest was the (— —) horizontal coplanar configuration whose response is the greatest over horizontally stratified earth.

V. - RESPONSE AS A FONCTION OF BASEMENT DEPTH

We shall consider here the following parameters :

Resistivities : 10 Ωm — 400 Ωm — 30 Ωm — infinite

Depths : 0 or 3 m — 20 m — 20 to infinite

The following curves are supplied :

Figures 2 and 3 : first depth Z1 = 0 m (phase and quadrature)
" 4 and 5 : " " Z1 = 3 m (" " ")

On each figure, ppm response is drafted as a function of depth Z3 to basement. It can be noticed that :

- ppm response is much increased by the presence of a superficial conductor, but more specially for high frequencies : for a 3 m, 10 Ωm superficial conductor, the 375 Hz response is generally increased by 7 to 8 ppm (20 %) while the 8 000 Hz signal is increased by 450 ppm (85 %).
- the influence of basement position is more clearly appreciable on in-phase response than on quadrature.
- basement position modifies response if around 100-150 meters deep for frequencies lower than 1 000 Hz ; this depth is reduced to 30-50 meters for higher frequencies.

VI. - DEPTH OF INVESTIGATION AS A FUNCTION OF THIRD LAYER RESISTIVITY

Another way of examining depth of investigation is considering the variable $\rho 3$, resistivity of the third layer. Starting from the many computed graphs, among which figures 2 to 5 are just a few examples, graphs were drawn for various values of first layer thickness, and for the four coil configurations.

Depth of penetration to the basement was defined as the most severe of the following two criteria :

- 95 % of maximum response (which corresponds to infinite third layer thickness)
- reduction of response greater than 5 ppm.

For each frequency, these graphs therefore include two parts : one corresponding to 95 % of maximum, the second, visible for small ppm responses (corresponding to high third layer resistivities).

Figures 6 and 7 correspond to the horizontal coplanar configuration :

Figure 6 : no first layer

Figure 7 : 3 m, 10 Ωm, first layer

On figure 6, it can be seen that depth of penetration exceeds 50 or 100 m for the following values of frequencies and third layer resistivities.

	over 100 m	over 50 m
375 Hz	11 to 110 Ωm	4 to 160 Ωm
900 Hz	25 to 150 Ωm	7 to 220 Ωm
3 600 Hz	87 to 400 Ωm	27 to 620 Ωm
8 000 Hz	not reached	70 to 660 Ωm

Figure 7 with a conductive first layer, shows little change for lower frequencies (375 and 900 Hz). However for higher frequencies, depths of penetration are much lower : for 3 600 Hz, the maximum depth is 58 m, and for 8 000 Hz, only 45 m.

Presence of very conductive third layer (due to brackish water) would notably reduce depth of penetration. For $\rho 3$ = 2 Ωm and a 375 Hz frequency, limiting depth would be 40 m ; for $\rho 3$ = 0.5 Ωm, limiting depth would only be about 22 m.

Figure 8 concerns the same resistivities as figure 6 (no conductive first layer) but with a vertical coaxial coil configuration. Response being a quarter of the horizontal coplanar response, the first part of the curves are identical to those of figure 6. However, the second part (maximum - 5 ppm) becomes much more severe, and maximum depths of penetration do not exceed 70 to 83 meters, whatever the frequency.

VII. - APPARENT RESISTIVITIES

An example of apparent resistivities is supplied on figure 9, which corresponds to the horizontal coplanar configuration, with the following resistivities and depths of the model :

First layer	: 10 Ωm, 3 meters
Second layer	: 400 Ωm; 20 meters
Third layer	: 10 Ωm, variable depth from 20 m to infinite
Fourth layer	: 1 000 Ωm

The apparent resistivity profiles, computed from in-phase response, show clearly the deeper penetration of low frequencies. For the two lower frequencies, the basement shows up up to about a hundred meters. When the basement is deeper, apparent resistivity is close to $\rho 3$. For the two higher frequencies, when the basement is over 40 meters deep, apparent resistivity is about 25 to 30 Ωm (instead of 15-17 Ωm for lower frequencies), showing that the second resistive layer has a more appreciable effect than on the low frequencies. Lower frequencies penetrate more, and "strip off" better the overburden.

VIII. - QUANTITATIVE INTERPRETATION

The main H.E.M. specialists and ourselves are just at the start of really quantitative interpretation techniques, compared to those used in D.C. resistivity soundings. Introducing a certain number of geological constraints, such as :

- imposed values of certain resistivities or depths
- principles of equivalence

Quantitative or semi-quantitative interpretation will shortly be possible.

Graph 10 gives an example of such methods. Starting with in-phase components at at least 2 frequencies for a three layer model, it supplies true third layer resistivity, supposing known first and second layer parameters ($\rho 1$, Z1, $\rho 2$, Z2). Introducing quadrature components, it would probably be possible, with a 2 frequency system, to evaluate transverse resistance ((Z2-Z1) x $\rho 2$) of the second layer. Addition of a third frequency would allow more sophisticated interpretation.

IX. - CONCLUSIONS

The feasibility study carried out by C.P.G.F. has shown that electromagnetic surveys seem to be the most appropriate airborne or heliborne technique for preliminary geotechnical mapping. It is suggested that multifrequency equipment (including at least one frequency lower than 1 000 Hz) with high signal-to-noise ratios (corresponding generally to longer "birds") should be used. Depth of investigation is around 100-150 meters, for resistivities regularly met in French sedimentary basins, except for very low resistivity areas associated with salt or brackish water.

Development of various quantitative interpretation techniques has been started ; however, much work seems necessary before reaching standards of D.C. resistivity interpretation methods.

An extensive field survey on 7 geologically well known test sites is shortly to be carried out, using the DIGHEM II equipment.

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D.C. FRASER (1978)

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Mapping earth conductivities using an airborne electromagnetic system, Geophysics, vol. 43, n° 3, April 1978, pp. 563-575.

LIST OF CAPTIONS

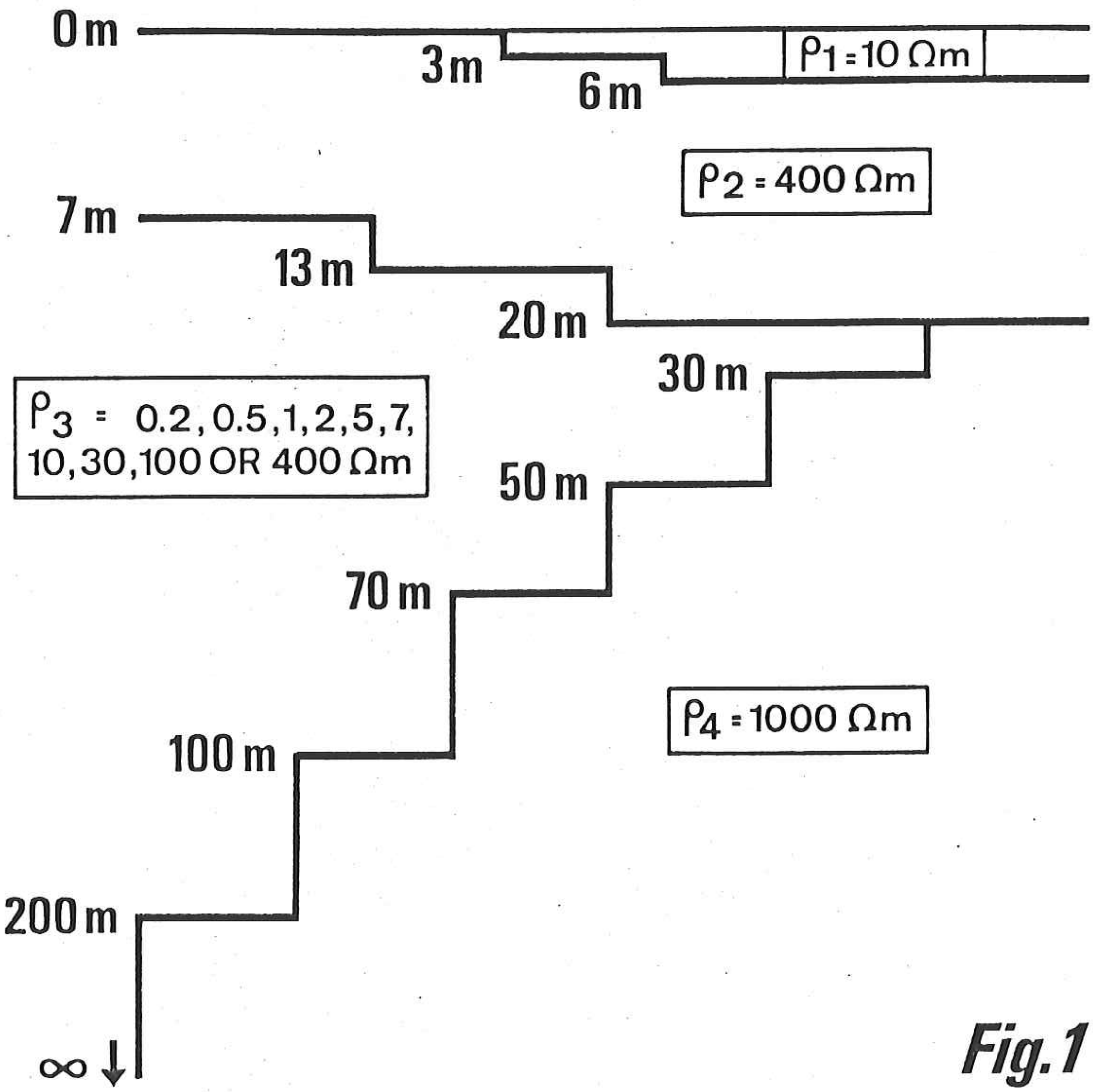
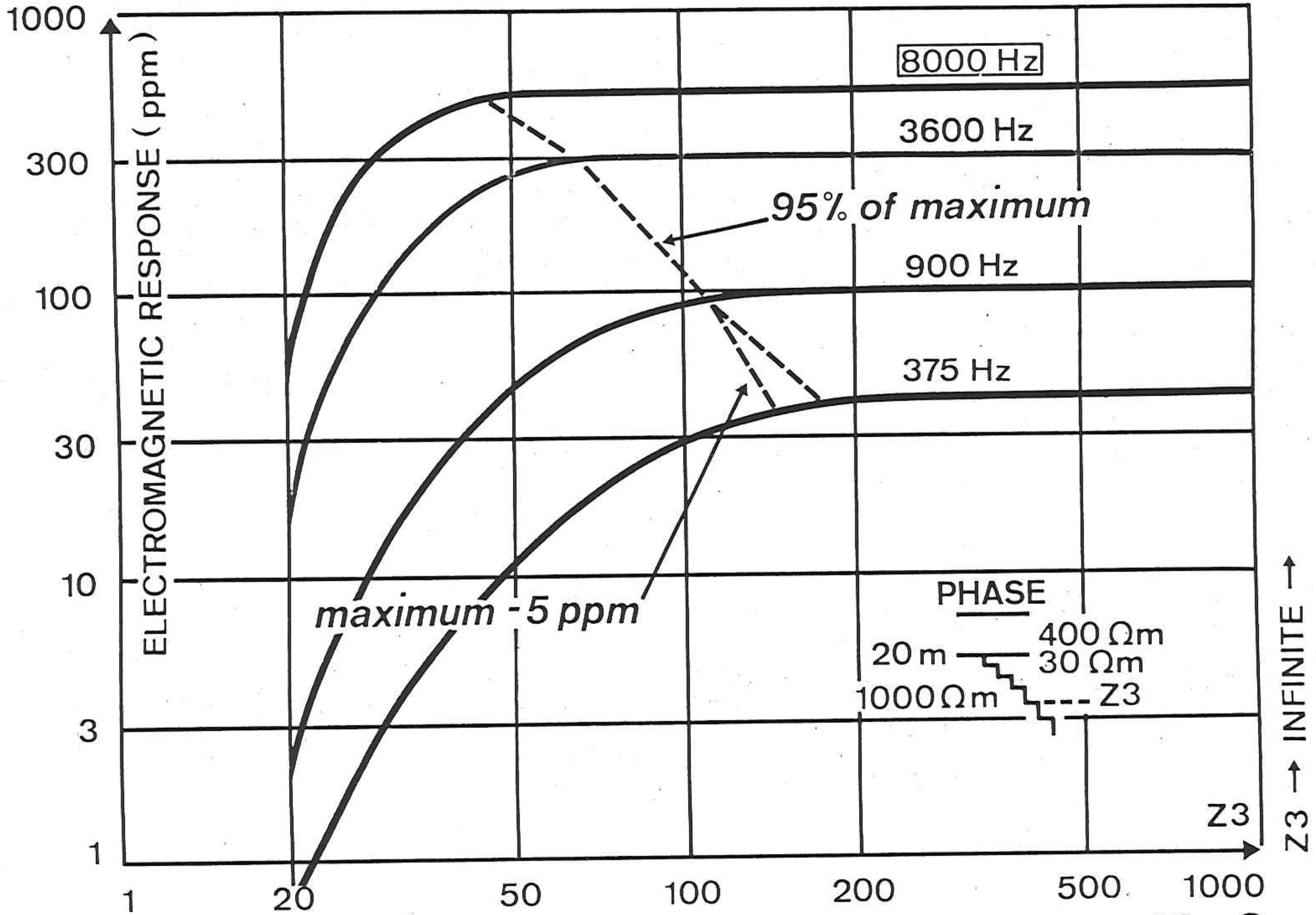
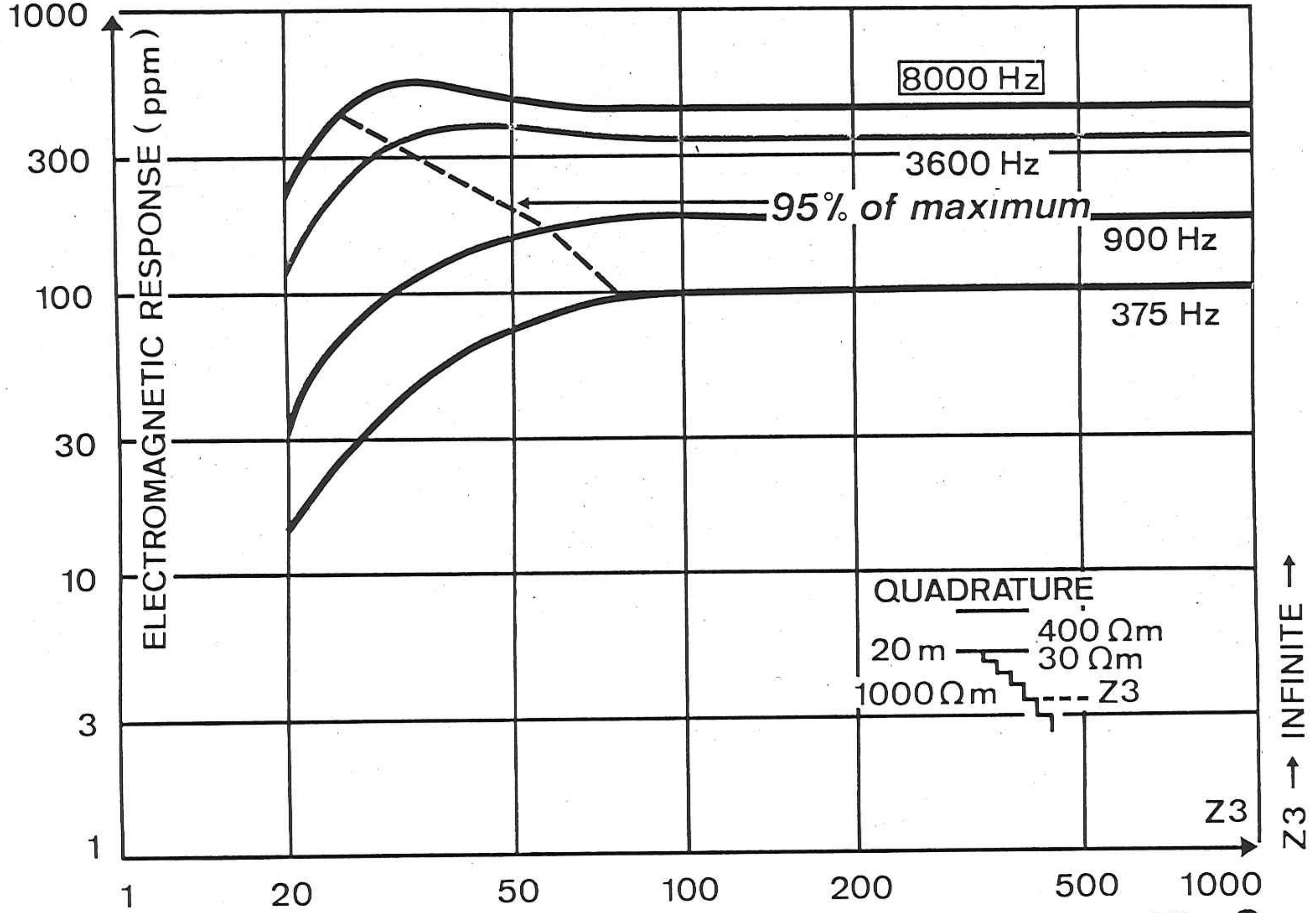

0 m
3 m
6 m
ρ1 = 10 Ωm
ρ2 = 400 Ωm
7 m
13 m
20 m
30 m
ρ3 = 0.2, 0.5, 1, 2, 5, 7, 10, 30, 100 OR 400 Ωm
50 m
70 m
100 m
ρ4 = 1000 Ωm
200 m
∞

Fig.1



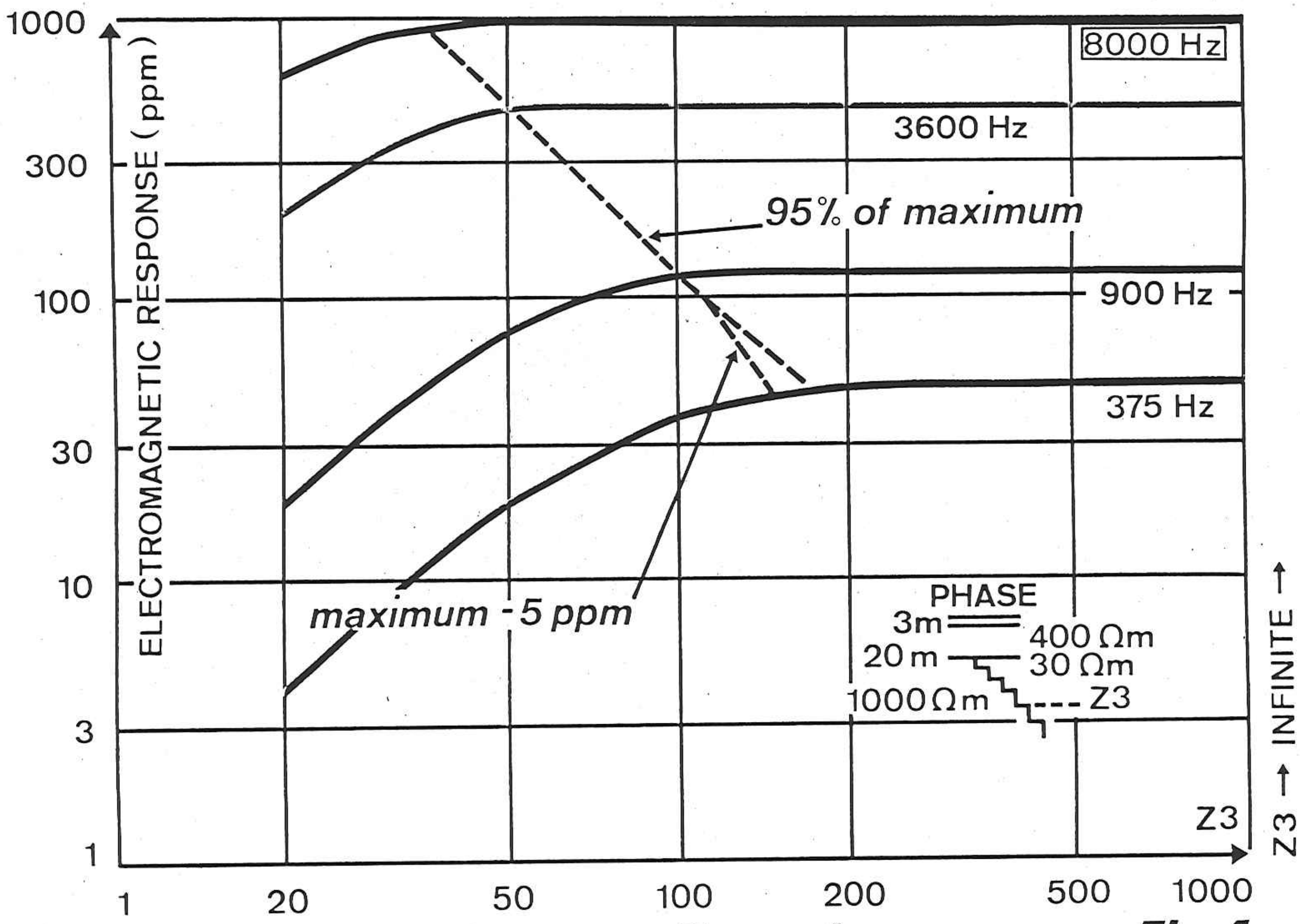
Horizontal coplanar configuration

Fig.2



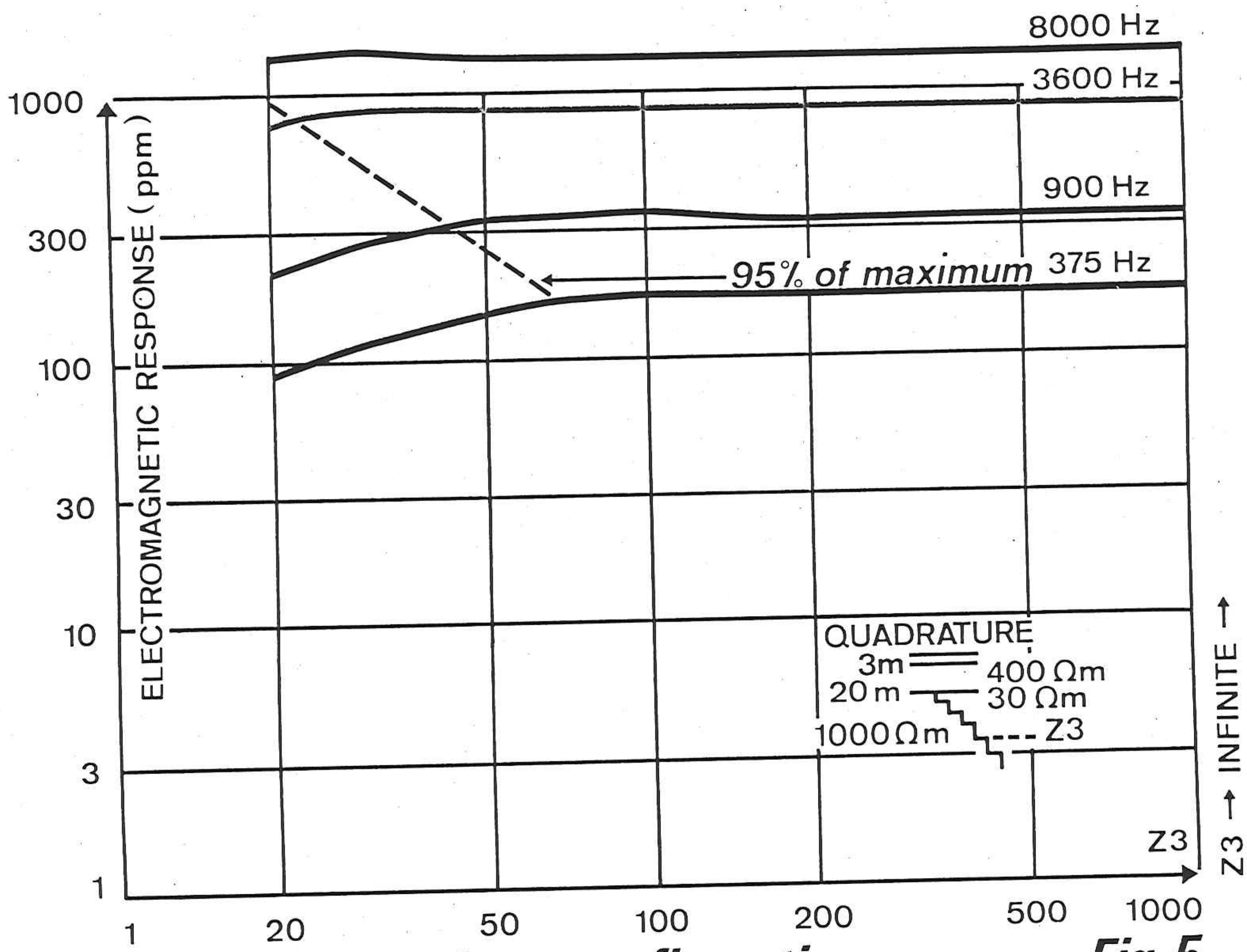
Horizontal coplanar configuration

Fig.3



Horizontal coplanar configuration

Fig.4



Horizontal coplanar configuration

Fig. 5

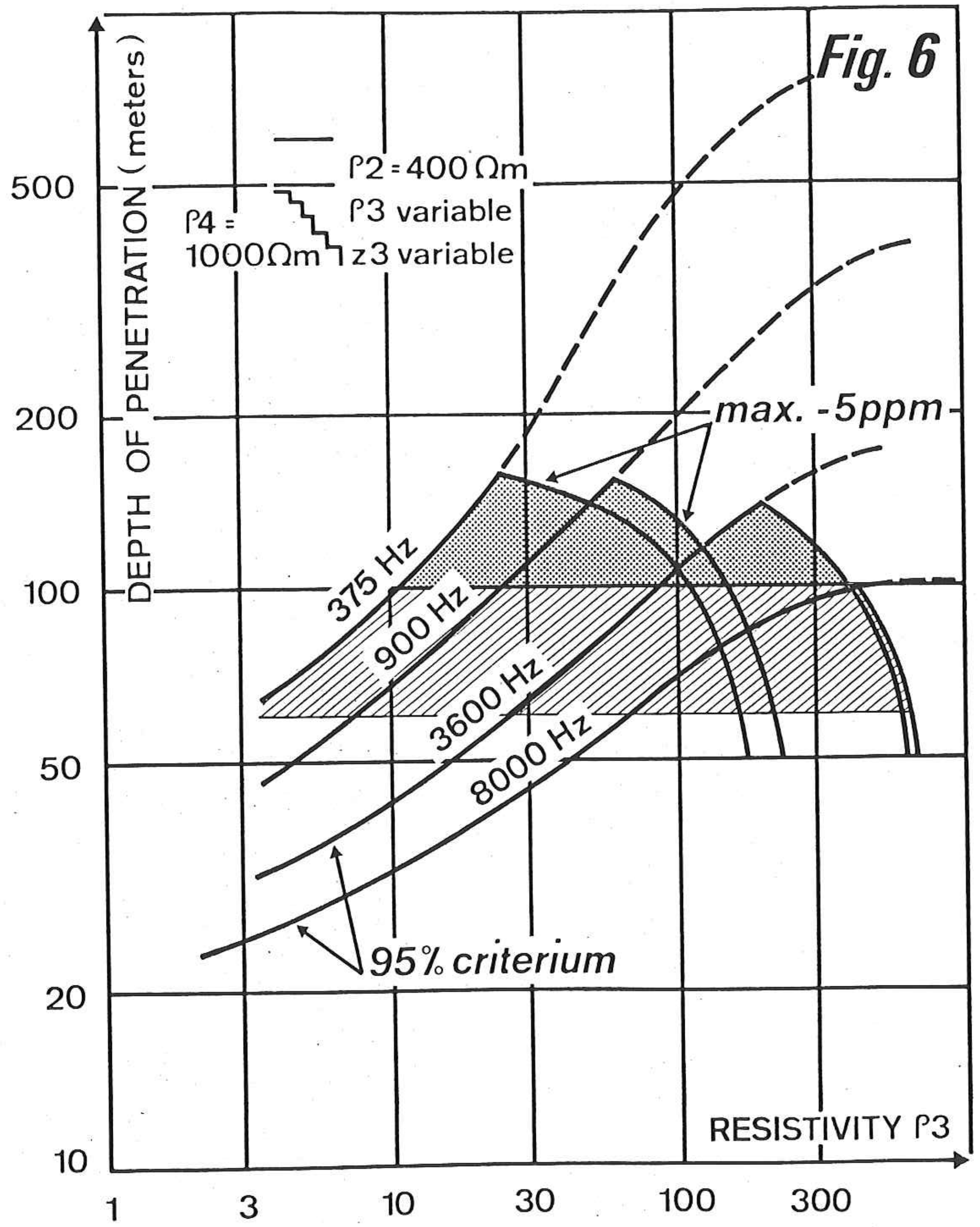


Fig. 6
DEPTH OF PENETRATION (meters)
500
200
100
50
20
10
ρ2 = 400 Ωm
ρ3 variable
ρ4 = 1000Ωm
z3 variable
max. -5ppm
375 Hz
900 Hz
3600 Hz
8000 Hz
95% criterium
RESISTIVITY ρ3
1
3
10
30
100
300

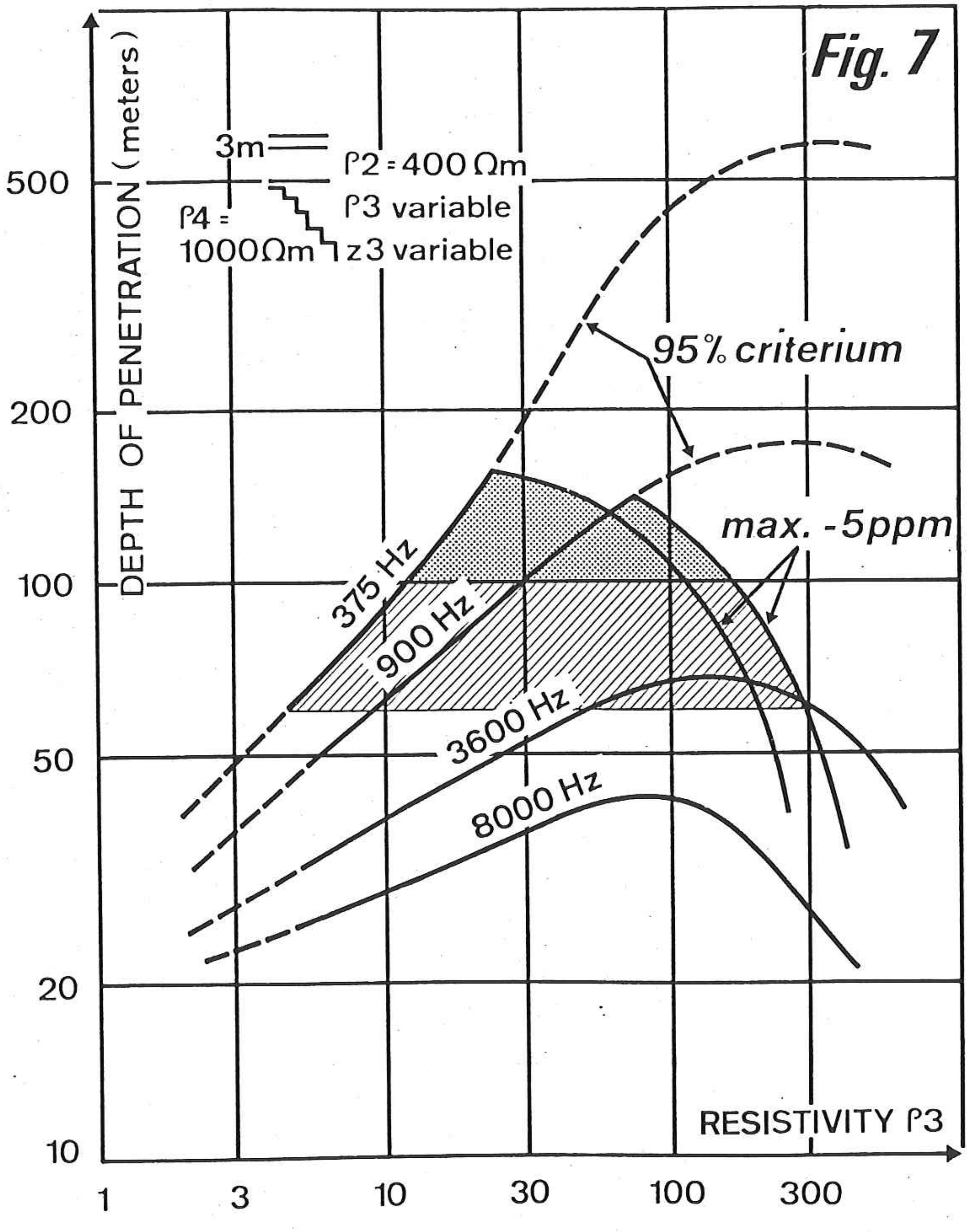


Fig. 7
DEPTH OF PENETRATION (meters)
500
200
100
50
20
10
3m
ρ2 = 400 Ωm
ρ3 variable
ρ4 =
1000Ωm
z3 variable
95% criterium
max. -5ppm
375 Hz
900 Hz
3600 Hz
8000 Hz
RESISTIVITY ρ3
1
3
10
30
100
300

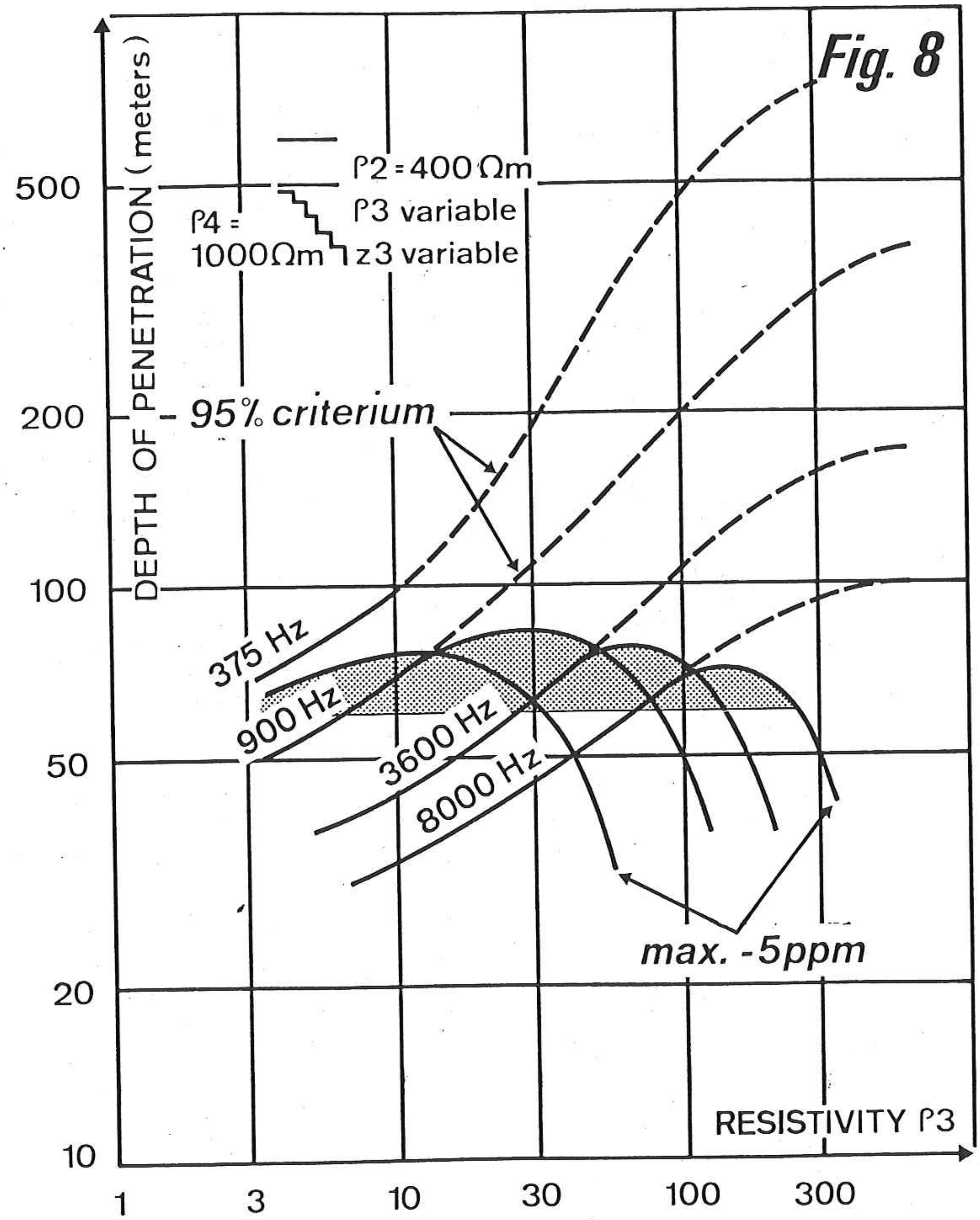
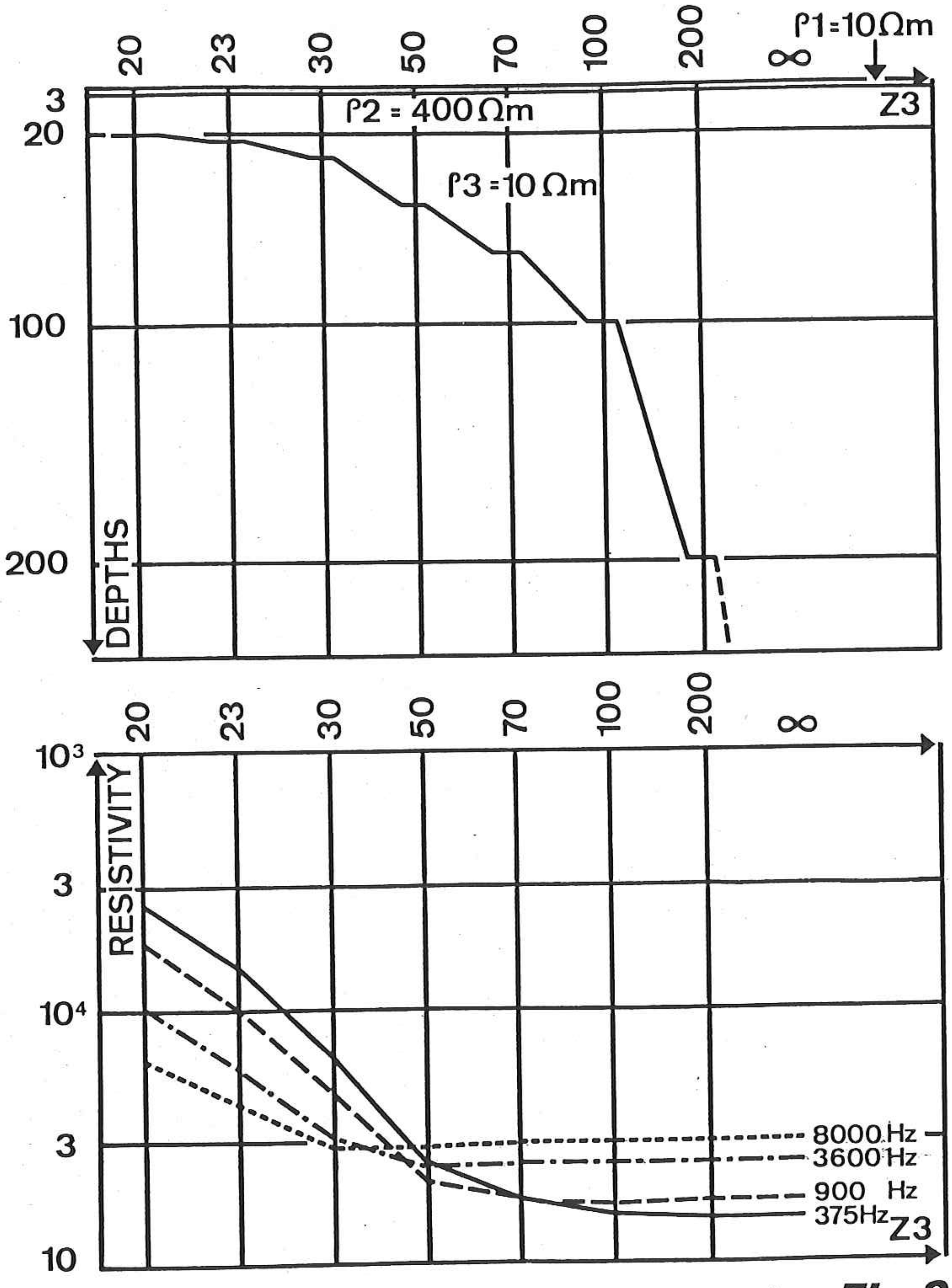


Fig. 8
DEPTH OF PENETRATION (meters)
500
200
100
50
20
10
ρ2 = 400 Ωm
ρ3 variable
ρ4 =
1000Ωm
z3 variable
95% criterium
375 Hz
900 Hz
3600 Hz
8000 Hz
max. -5ppm
RESISTIVITY ρ3
1
3
10
30
100
300



20
23
30
50
70
100
200
∞
ρ1=10Ωm
Z3
ρ2 = 400Ωm
ρ3 =10 Ωm
3
20
100
200
DEPTHS
10³
RESISTIVITY
3
10⁴
10
8000 Hz
3600 Hz
900 Hz
375Hz

Fig.9

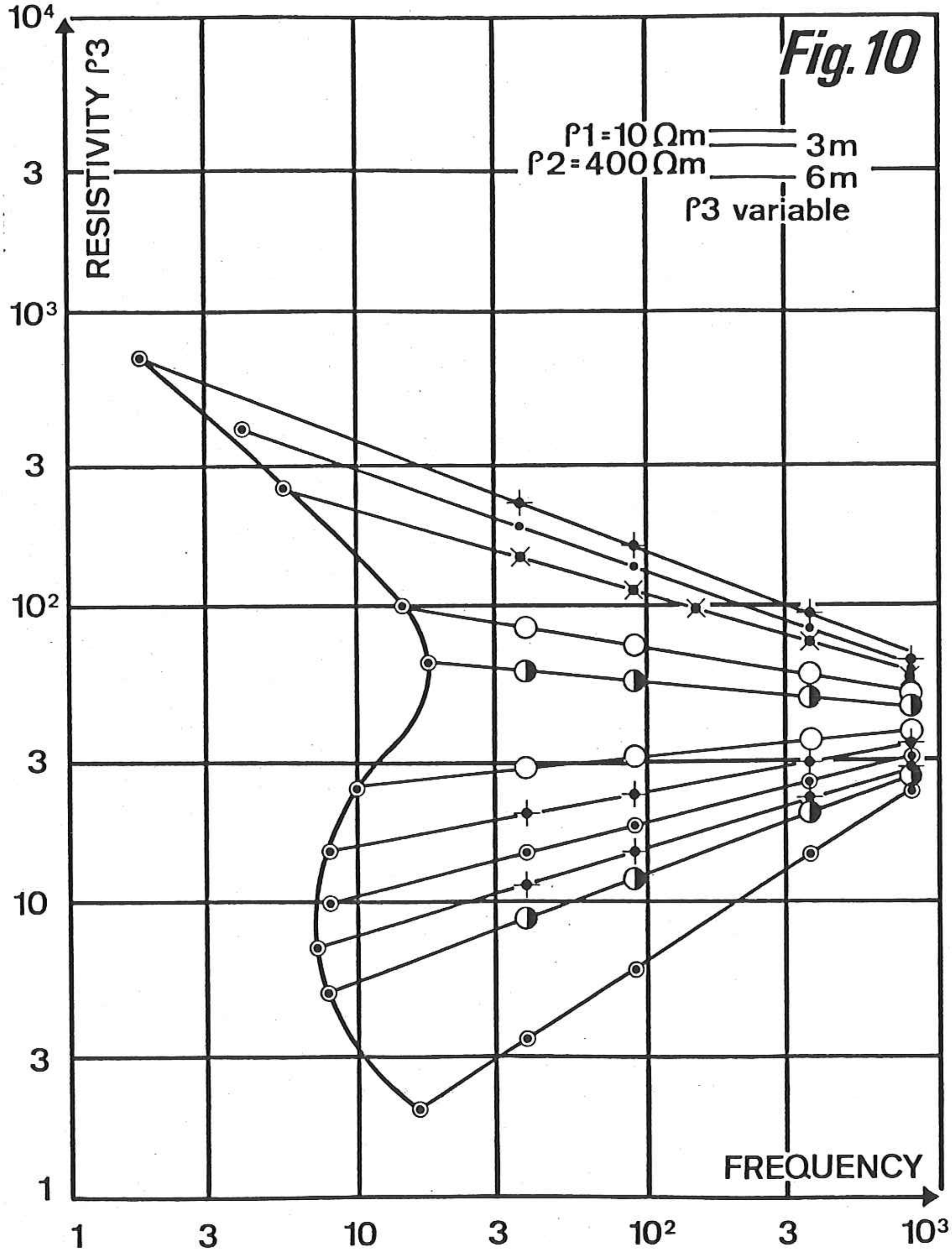


Fig. 10
ρ1 = 10 Ωm 3m
ρ2 = 400 Ωm 6m
ρ3 variable
RESISTIVITY ρ3
FREQUENCY
10⁴
3
10³
3
10²
3
10
3
1
1
3
10
3
10²
3
10³