WORKSHOP ON AIRBORNE RESISTIVITY

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AIRBORNE RESISTIVITY SURVEYING APPLIED TO NUCLEAR POWER PLANT SITE INVESTIGATION IN FRANCE

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RESISTIVITE HELIPORTEE APPLIQUEE AUX ETUDES DE SITES DE CENTRALES NUCLEAIRES EN FRANCE

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ABSTRACT

In 1981, Compagnie de Prospection Géophysique Française (C.P.G.F.) was asked by Electricité de France (E.D.F.) to study the feasibility of using airborne geophysics for site investigations for nuclear power plants. It was necessary to investigate soil properties of the first 100 m, mostly in horizontally stratified environment. Mathematical modelling showed that airborne EM surveys could give appropriate answers in at least 70 % of the geological situations of interest to E.D.F.

Test flying with the Dighem system was carried out in 1982. C.P.G.F. acted as supervisor on behalf of E.D.F. Seven sites were flown in different areas of central and southeastern France, totaling 2 000 line km. The flight line spacing was 100 or 200 m.

At some of the sites, large amounts of ground geophysical and drilling data were available. At Sennecey, in the Saône Valley, correlation with 50 drill holes showed that HEM surveys could outline resistive limestones beneath a layer of conductive clays and marls which was up to 100 m thick.

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RESUME

En 1981, la Compagnie de Prospection Géophysique Française (C.P.G.F.) a été chargée par Electricité de France (E.D.F.) de réaliser une étude de faisabilité sur l'application des méthodes géophysiques aéroportées à l'étude des fondations de centrales nucléaires. Il était demandé de prospecter les 100 premiers mètres de terrain, dans des milieux horizontalement stratifiés. Un modèle mathématique montra que l'électromagnétisme héliporté pouvait donner des réponses significatives dans 70 % des situations géologiques définies par E.D.F.

En 1982, des vols d'essai furent réalisés avec le système Dighem, C.P.G.F. ayant un rôle de conseil d'E.D.F. Sept sites furent étudiés dans différentes régions du Sud-Est et du centre de la France, avec 2.000 kilomètres de vols. L'écartement entre lignes était de 100 ou de 200 m.

Pour quelques uns de ces sites, d'importantes quantités de données (géophysique et sondages) étaient disponibles. A Sennecey, dans la vallée de la Saône, une corrélation avec 50 forages mécaniques a montré que les prospections électromagnétiques héliportées pouvaient suivre le toit des calcaires résistants, sous une couverture d'argiles conductrices, pouvant atteindre 100 m d'épaisseur.

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INTRODUCTION

In December 1980, the French State Power Board (Electricité de France), decided to investigate the possibility of preliminary site investigation of nuclear power plant sites by airborne geophysics. Obviously, it is advantageous to cover a large area without entering private properties. In follow-up, the most favorable zones are surveyed in detail by more conventional means.

Electricité de France made a catalogue of the main geological features found in those parts of France where nuclear power plants were to be constructed.

A feasibility contract was awarded to Compagnie de Prospection Géophysique Française (C.P.G.F.) in order to appraise all available airborne geophysical techniques. This study included :

+ The development of a mathematical model corresponding to the selected technique, and checking of its applicability,
+ Enquiries among users, universities, contractors and constructors,
+ Assistance to E.D.F. in calling for tenders among selected contractors.

It was soon realized that helicopter EM (HEM) surveying was the most appropriate technique. After a call for tenders, Dighem Ltd. was selected to carry out, under C.P.G.F.'s supervision, test flights over 7 selected areas (see figure 1). These sites were already well surveyed by ground geophysics and drilling. 2,000 line km were flown between February and March 1982.

GEOLOGICAL SITE CONDITIONS

The geological conditions at the nuclear power plant sites in France are sketched on figure 2. The selected test sites correspond to the following cases :

- Alluvium on Tertiary marls : Verdun-sur-le-Doubs, St. Pourçain
- Alluvium on Tertiary marls, with dipping Jurassic limestone at depth : Sennecey, Soyons
- Alluvium on variable Tertiary bedrock (clays and sandstones) : Limons

- Karstic limestone : Civaux
- Alluvium on faulted sedimentary structures : Arras-sur-Rhône
- Buried river channels : Soyons, Limons, St. Pourçain

The probable ranges of resistivities are as follows :

Alluvium	clay and top soil	: 7 to 30 Ω m
	sand and gravel	: 200 to 1,000 Ω m
Tertiary marls and clays		: 10 to 30 Ω m
Tertiary sandstone		: 100 to 300 Ω m
Jurassic limestone		: 200 to 800 Ω m

It was specified that the depth of investigation should exceed 100 m.

POSSIBLE GEOPHYSICAL TECHNIQUES

Application of the following airborne methods was examined :

- Gravity
- Magnetics
- VLF
- Frequency-domain EM methods
- Time-domain EM methods

It was shown that airborne gravity was not accurate enough, anomalies of less than 5 milligals, 3 km wide (corresponding to a horst over 200 m high) not being detectable.

Airborne magnetics has been used to calculate overburden depth, but in the sedimentary cases selected by E.D.F., there was not enough susceptibility contrast. However, a magnetometer was included in the equipment, but the results confirmed the lack of interest of this method.

Airborne VLF is mainly useful in delineating vertical faults and conductors in resistive environment. This was not the case in the French sites. Nevertheless, a VLF receiver was fitted on the helicopter. Field results confirmed that this was not the most appropriate methods.

Time-domain electromagnetics is probably the most extensively used detailed airborne mapping tool. However, at the time of the enquiry (1980-1981), quantitative interpretation tools in horizontally stratified media did not seem to be commercially available.

On the other hand, frequency-domain EM interpretation could supply resistivity and depth maps, in horizontally stratified cases.

After a detailed study, questionnaires were sent to 29 institutions, such as geological surveys, universities, contractors and manufacturers in 10 countries. The results confirmed their interest in helicopter EM surveying, but showed that 99 % of previous surveys had been applied to mining exploration.

MATHEMATICAL MODEL

In order to appreciate HEM response to the geological site conditions, and particularly to evaluate depth of penetration, a computer program was prepared on a CDC 7600 computer. It is based on the program written by Sinha and Collett (1973). The survey parameters were defined as follows, in order to cover, as best as possible, all commercially available systems :

- Flight altitude : 30 m
- Bird length : 9 m
- Frequencies : 375 Hz, 900 Hz, 3,600 and 8,000 Hz (on all 3 coil configurations)
- Coil configurations : vertical coplanar
  horizontal coplanar
  coaxial

For interpretation, the following model was suggested : horizontally stratified media with 4 layers. Typical thicknesses (t) and resistivities (ρ) are :

First layer (clay) : t = 0, or 3, or 6 m, ρ_1 = 10 Ωm
Second layer (sand and gravel) : t = 20, or 17, or 14 m, ρ_2 = 400 Ωm
Third layer (Tertiary clays and sandstones) : t = 0 to infinite, ρ_3 = 0.2 to 400 Ωm
Fourth layer (Jurassic limestone or granite), ρ_4 = 1,000 Ωm

These cases are summarized on figure 3. The main problem to be examined was whether the resistive fourth layer basement could be located under a thick conductive third layer.

Figure 4 shows the in-phase response for one of the cases which was described in greater detail by Lakshmanan and Bichara (1981).

For a frequency of 900 Hz, the maximum response of 130 ppm corresponds to an infinitely thick third layer. When the basement (fourth layer) is moved up to a depth of 100 m, the total response is reduced to 123 ppm, i.e. 95 % of the maximum response. This depth of 100 m can be considered to be "depth of penetration" for 900 Hz in the particular case, i.e., depth up to which the resistive fourth layer can be located.

The algorithm is used separately for each frequency. However, a way to combine results acquired at different frequencies is to compute the ratio of two apparent resistivities, or their logarithmic difference.

FIELD TESTS

Th system used included a two-frequency, 9 m bird, with 900 and 3,600 Hz coplanar coils. In addition, the VLF and magnetic fields were recorded but did not generally give significant results in the sedimentary basins studied. Resistivity processing was done, for each frequency, with the infinite half space algorithm (Fraser, 1978). This supposes an infinitely resistive first layer overlaying an infinitely thick conductor.

The algorithm first takes into account phase and quadrature, neglecting bird's height. It then computes the conductor's resistivity and its depth below the bird. In a second step, the actual bird elevation above the ground is substracted from the computed depth. If the difference is positive, it is equal to the apparent thickness of the first layer, supposed to be infinitely resistive. If one ends up with a negative thickness, the first layer is in fact conductive. In all cases, the computed second layer resistivity is quite stable, and is not much affected by variations in first layer resistivity.

The Sennecey site is described here in greater detail. Figure 5 shows the geological environment, also illustrated by two E.W. cross-sections (figure 6). The site is located in the Saône river valley, where quaternary sand and gravel, 8-15 m thick, overlay thick Tertiary marls. The western limit of the Tertiary basin is the Burgundy hills, formed by outcropping Jurassic limestone and marls. Under the Tertiary marls, the folded Jurassic formations are usually deeper towards the east. However, south of the test area, a limestone horst (A) outcrops. In the test area itself, about 50 drill holes had allowed plotting of the elevation of limestone bedrock below the Tertiary marls, as shown on figure 5 (average ground elevation is around 200 m). The limestone horst (A) dips gently north of its outcrop.

Figure 7 shows the Schlumberger apparent resistivities for a half electrode separation of $\frac{AB}{2}$ = 200 m, plotted from about 100 resistivity soundings. The apparent resistivities are maximum above the top of the horst (A), and confirm its dip towards the north.

Figure 8 is the HEM resistivity for 900 Hz, which has greater depth penetration than the 3,600 Hz frequency. It shows 4 elongated resistive zones, corresponding to limestone ridges, separated by more conductive zones, corresponding either to Oxfordian marls, or to thicker Tertiary marls. The eastern-most ridge corresponds to the main horst "A". The extension of horst (A) is clearly shown when geology (figure 5) and HEM resistivity (figure 8) are compared.

Figure 9 is a plot of the "logarithmic resistivity difference", D, where

$$D = 34.74\ (\ln \rho(3{,}600) - \ln \rho(900))$$

This concept was first used during this survey.

When D is negative, a conductor overlies a resistor. This map clearly shows the limestone horst extension towards the north (A), where D is negative ($\rho 900 > \rho 3{,}600$ Hz)

Figure 10 compares actual limestone depths (at drill hole locations) with apparent resistivities :

- Schlumberger for $\frac{AB}{2}$ = 200 m
- HEM 900 Hz
- HEM 3,600 Hz

All three apparent resistivities decrease when limestone depth increases. When the apparent resistivity decreases up to the actual resistivity of the Tertiary marls, i.e., 10 Ω m, one can consider that the maximum "depth of penetration", for the particular coil or electrode configuration, is reached. These depths are approximately as follows :

- 3,600 Hz : 70 m
- 900 Hz : 120 m
- Schlumberger (AB/2 = 200 m) : 150 m.

However, it should be noted that the correlation between depth to limestone and Schlumberger apparent resistivities is much poorer than the correlation between depth to limestone and HEM resistivities. This is due to superficial high resistivity lenses, which create local highs in Schlumberger apparent resistivities, but have practically no influence on HEM resistivities.

These field results confirm those of the mathematical model, which had shown that a resistive basement could generally be located below 100 m conductive (10 Ω m) overburden.

CONCLUSIONS

The 7 selected sites constitute about 75 % of the possible nuclear sites in France. Satisfactory results were obtained on :

- Horizontally stratified sedimentary sites
- Dipping sedimentary sites
- Lateral facies variations
- Buried river channels

At Sennecey, penetration through 100 m of conductive clays was proved. Less satisfactory results were obtained over karsts at Civaux. Coastal sites were not tested.

E.D.F.'s conclusion was that low cost, continuous coverage could be attained by using helicopter EM surveys. Satisfactory results were obtained at most test sites. Progress in technology and in interpretation techniques seem necessary to increase efficiency of quantitative data analysis.

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REFERENCES

Sinha, A.K., Collett, L.S., 1973

Electromagnetic field of oscillating magnetic field placed over a multilayer conductive earth, Geological Survey of Canada, paper 73-25.

Fraser, D.C., 1978

Resistivity mapping with an airborne multicoil electromagnetic system, Geophysics, 43, p. 144-172.

Lakshmanan, J., Bichara, M., 1981

Depth of penetration of airborne electromagnetics over stratified earth, Technical Program Abstracts, 50th S.E.G. Annual Meeting, Los Angeles, p. 32.

FIGURE CAPTIONS

Fig. 1 : Locations of test sites

Fig. 2 : Typical geological situations
- (a) Top-soil and clay
- (b) Quaternary sand and gravel
- (c) Quaternary clay
- (d) Karstic clay
- (e) Tertiary sands
- (f) Tertiary clay
- (g) Jurassic limestone

Fig. 3 : Geological parameters for mathematical modelling

Fig. 4 : Example of in-phase EM response

Fig. 5 : Sennecey site geology
- S : Sequanian limestone
- O : Oxfordian marls
- C : Callovian limestone
- F : Fault
- (A) : Main horst
- 100 : Limestone elevation (ground at 200 m)

Fig. 6 : Sennecey cross-sections
- QC : Quaternary clays
- QG : Quaternary gravel
- UTC : Upper Tertiary clays
- TG : Tertiary gravel
- TC : Tertiary clay
- S : Sequanian limestone
- O : Oxfordian marls
- C : Callovian limestone
- (A) : Main horst
- 30 : Resistivity (Ω m)

Fig. 7 : Schlumberger apparent resistivities (AB/2 = 200 m)
- (A) : Main horst

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Fig. 8 : HEM 900 Hz apparent resistivity

(A) : Main horst

Fig. 9 : HEM resistivity "difference" map

a : Conductor over resistor

b : Homogeneous

c : Resistor over conductor

Fig. 10 : Depth of limestone as a function of resistivity

a : 10 Ω m = clay resistivity

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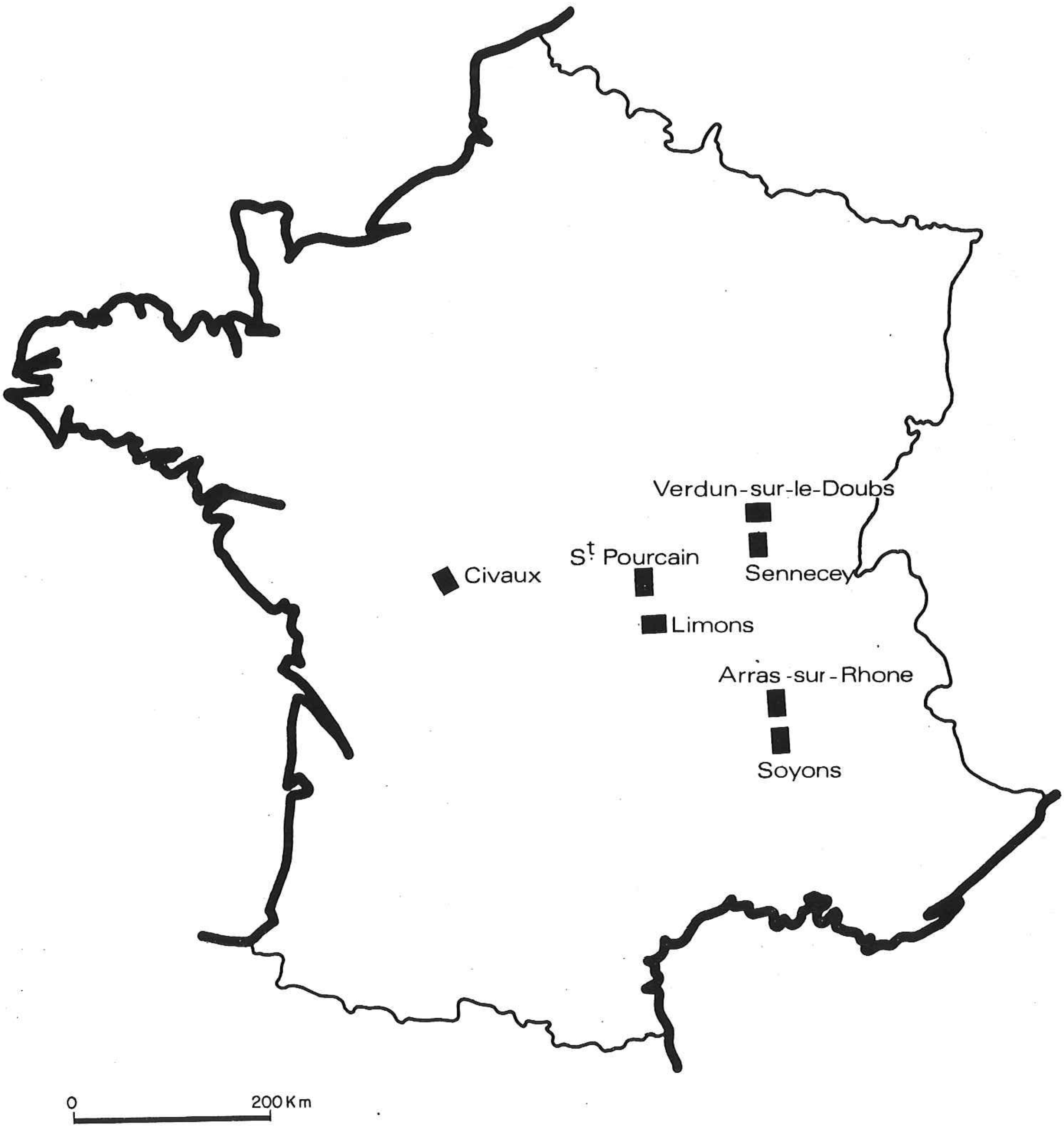
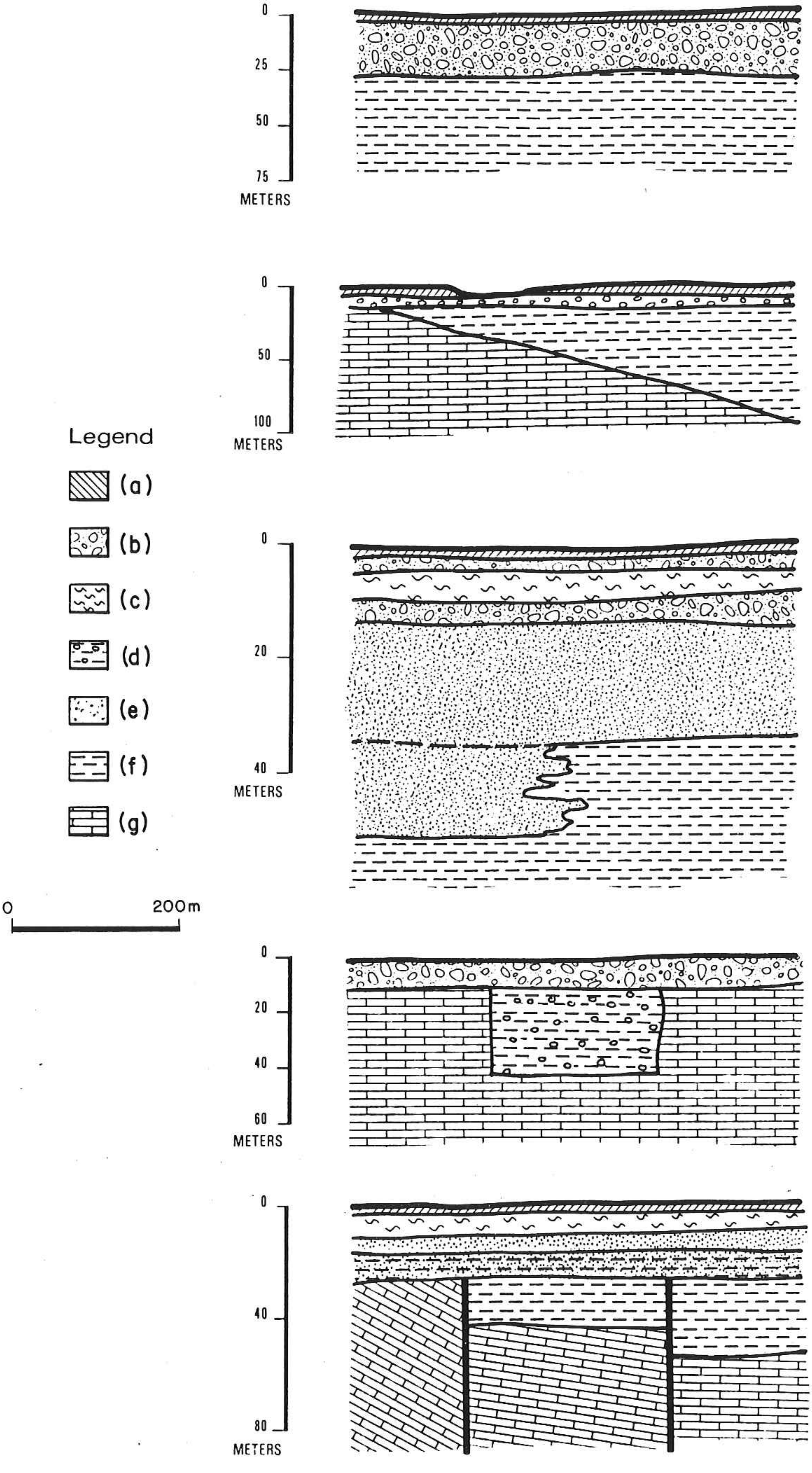


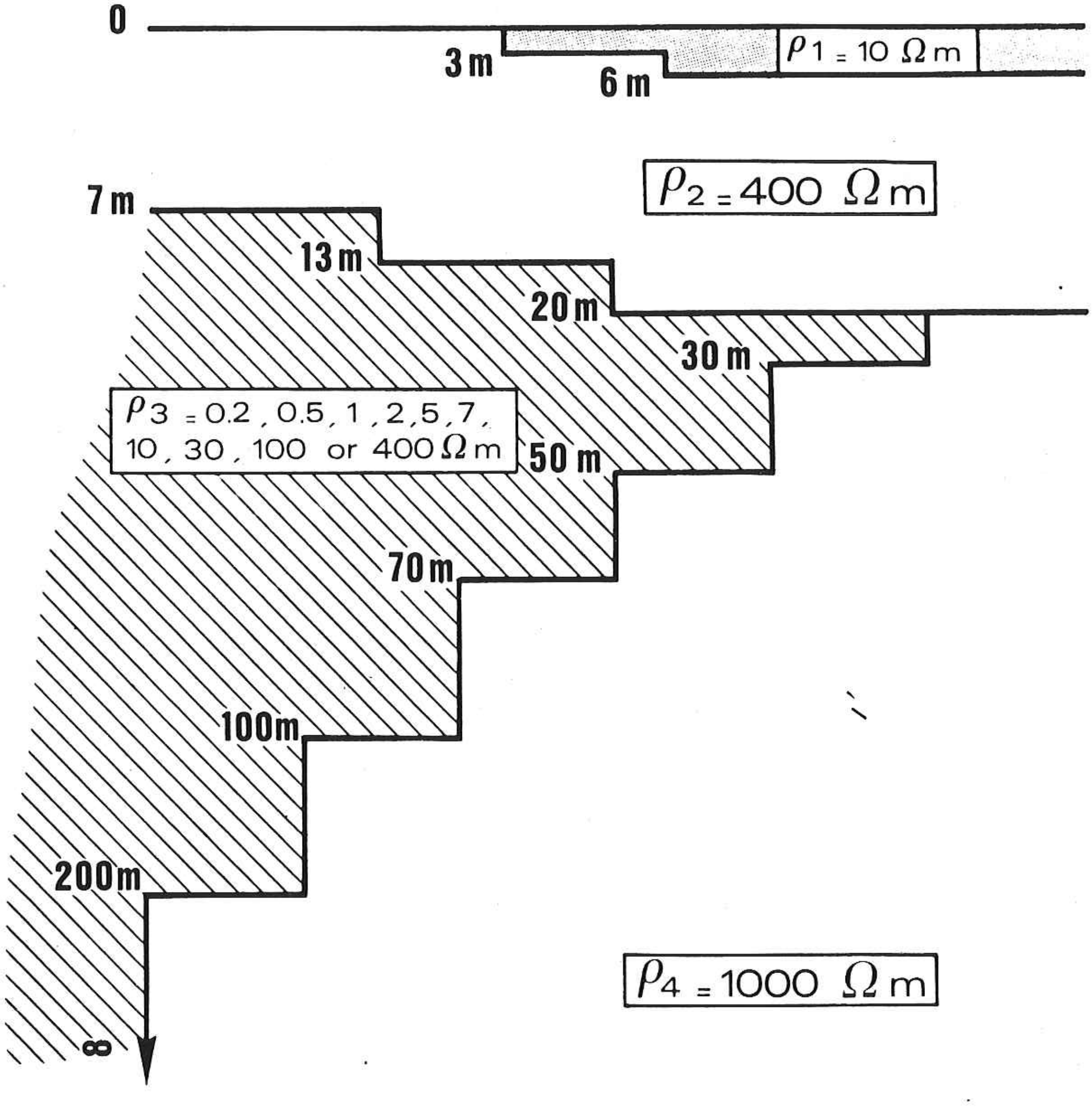
LOCATION OF TEST SITES

Fig: 1



TYPICAL GEOLOGICAL SITUATIONS

Fig.: 2



GEOLOGICAL PARAMETERS FOR MATHEMATICAL MODELLING

Fig : 3

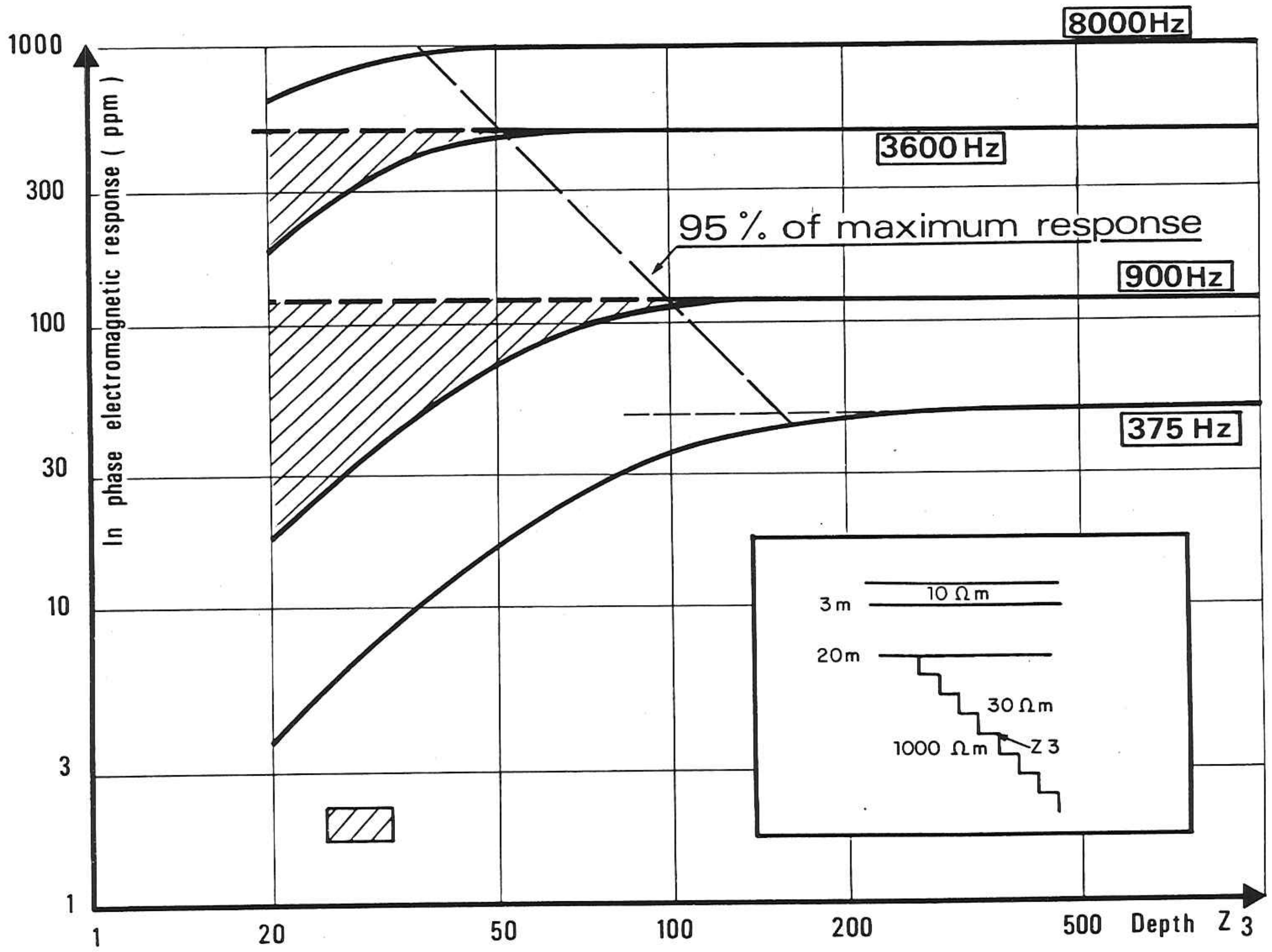
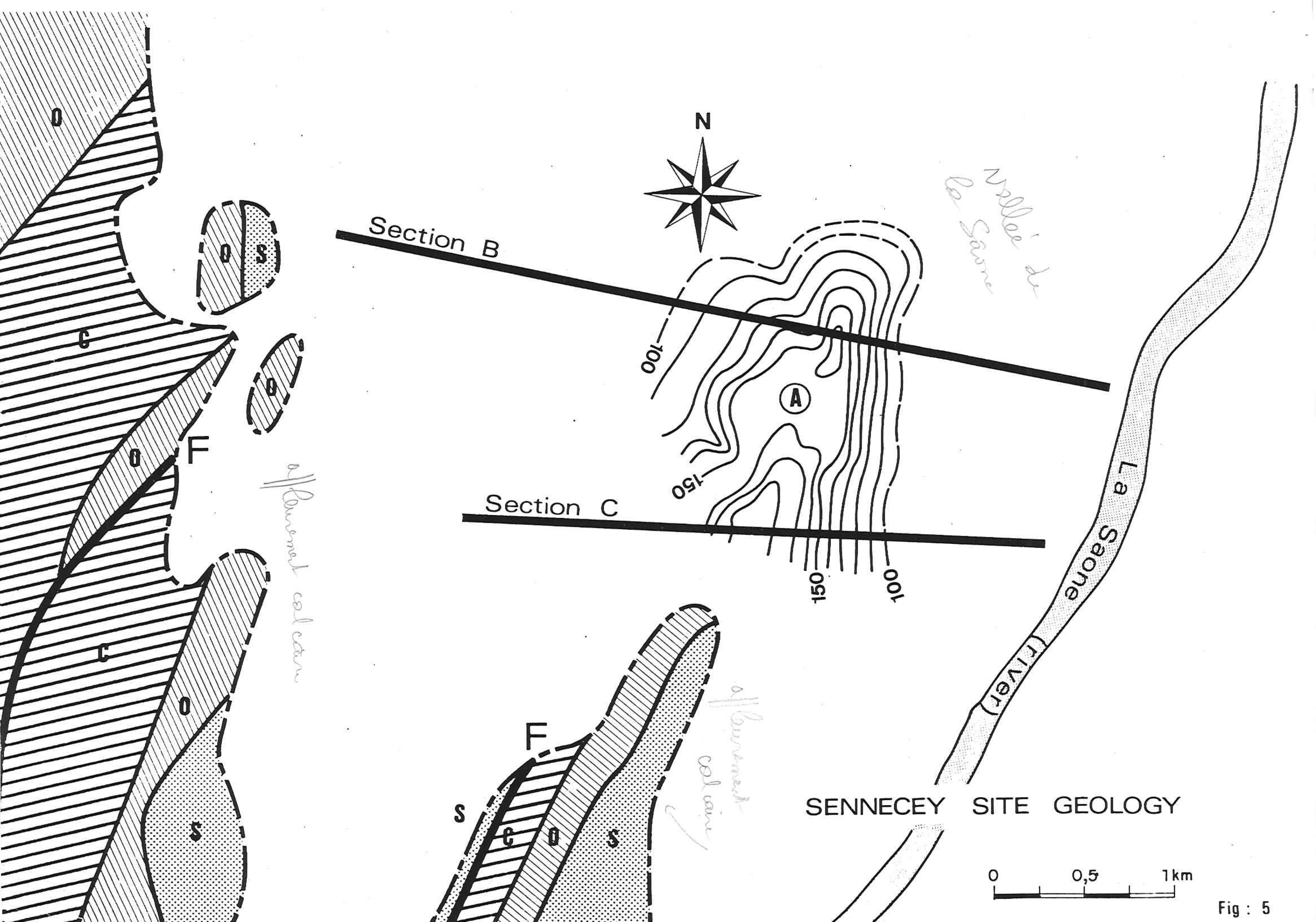
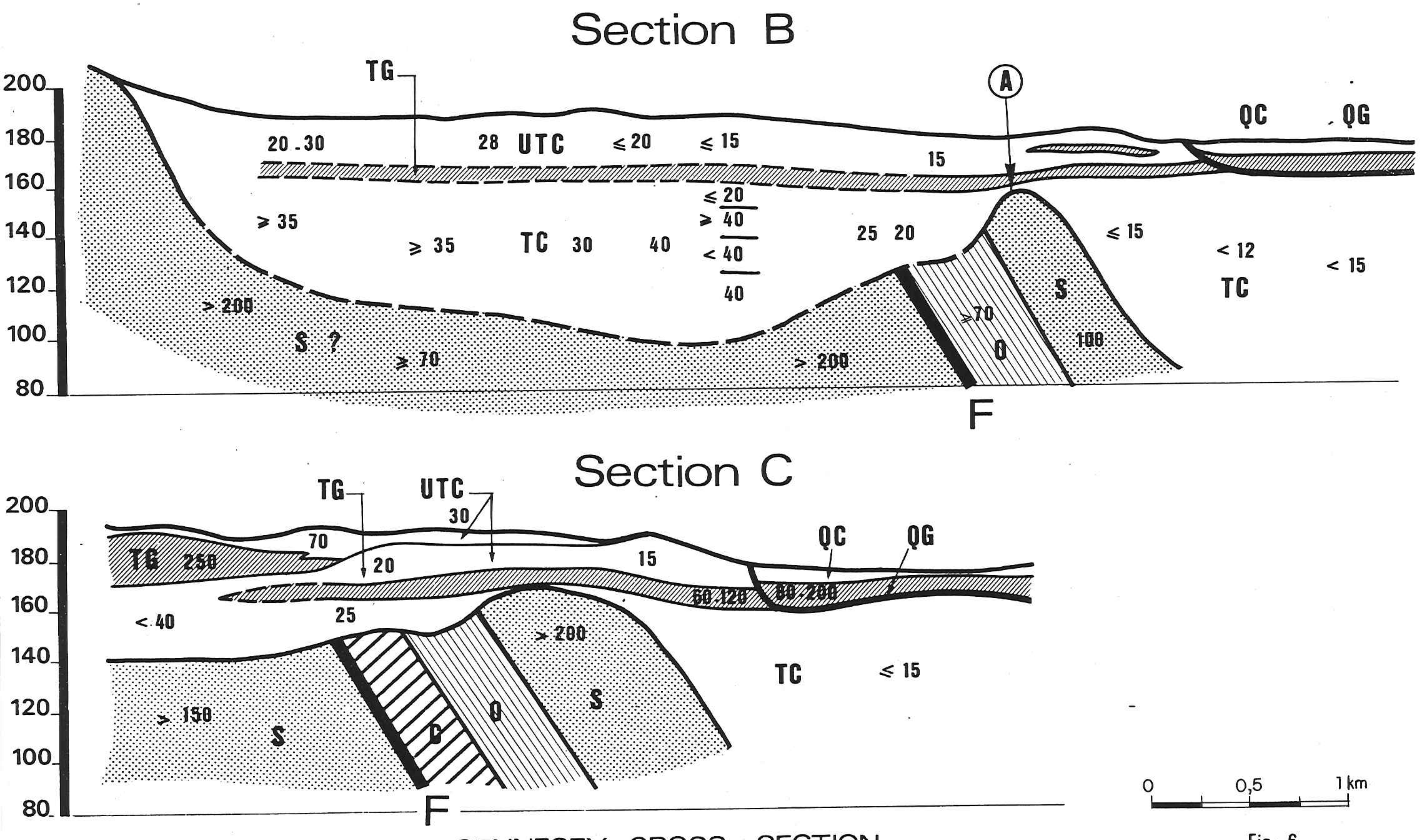

1000
300
100
30
10
3
1
In phase electromagnetic response (ppm)
8000Hz
3600 Hz
95 % of maximum response
900Hz
375 Hz
3 m
10 Ω m
20m
30 Ω m
1000 Ω m
Z 3
1
20
50
100
200
500
Depth Z 3

Fig : 4



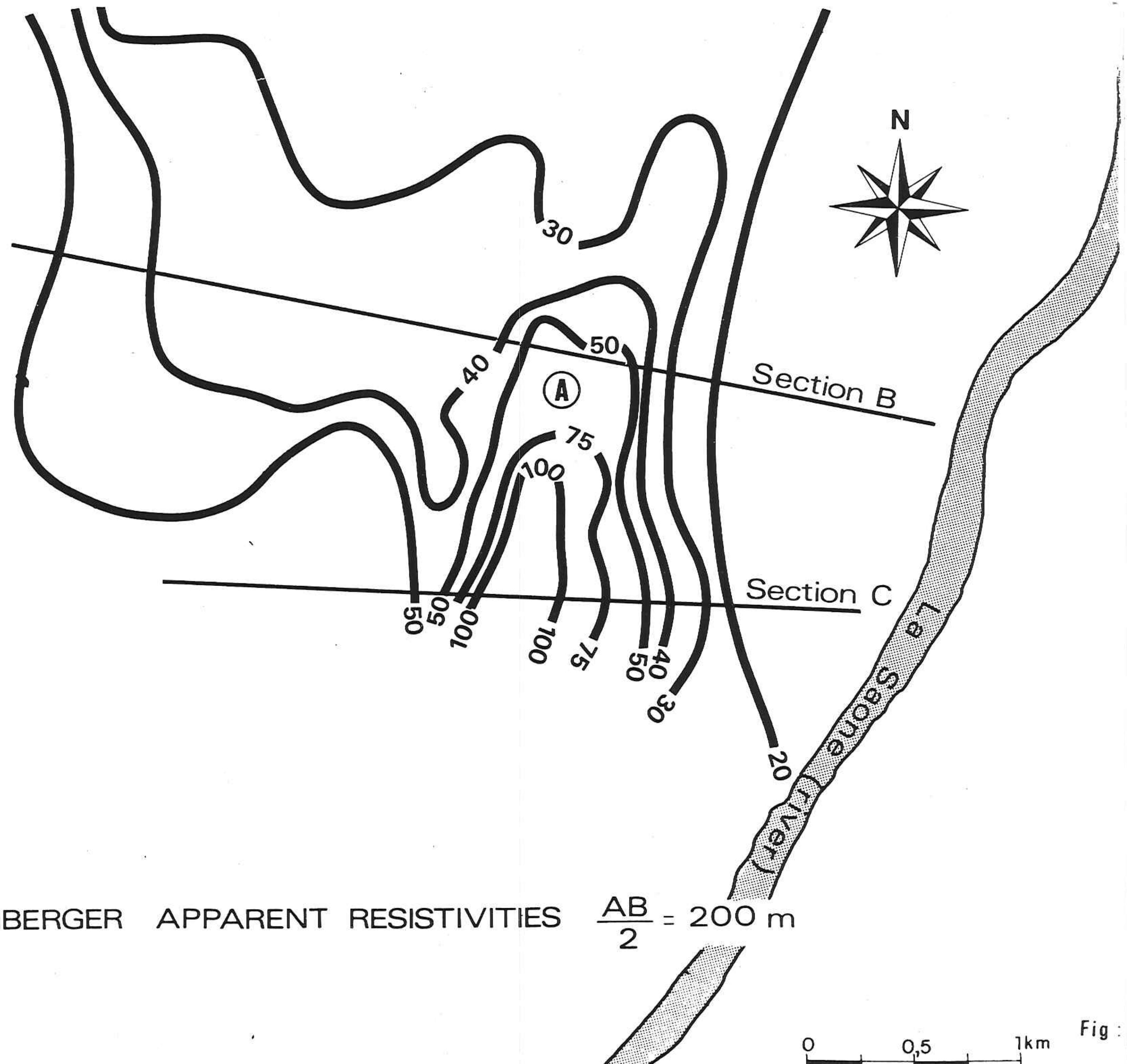
SENNECEY SITE GEOLOGY

Fig : 5



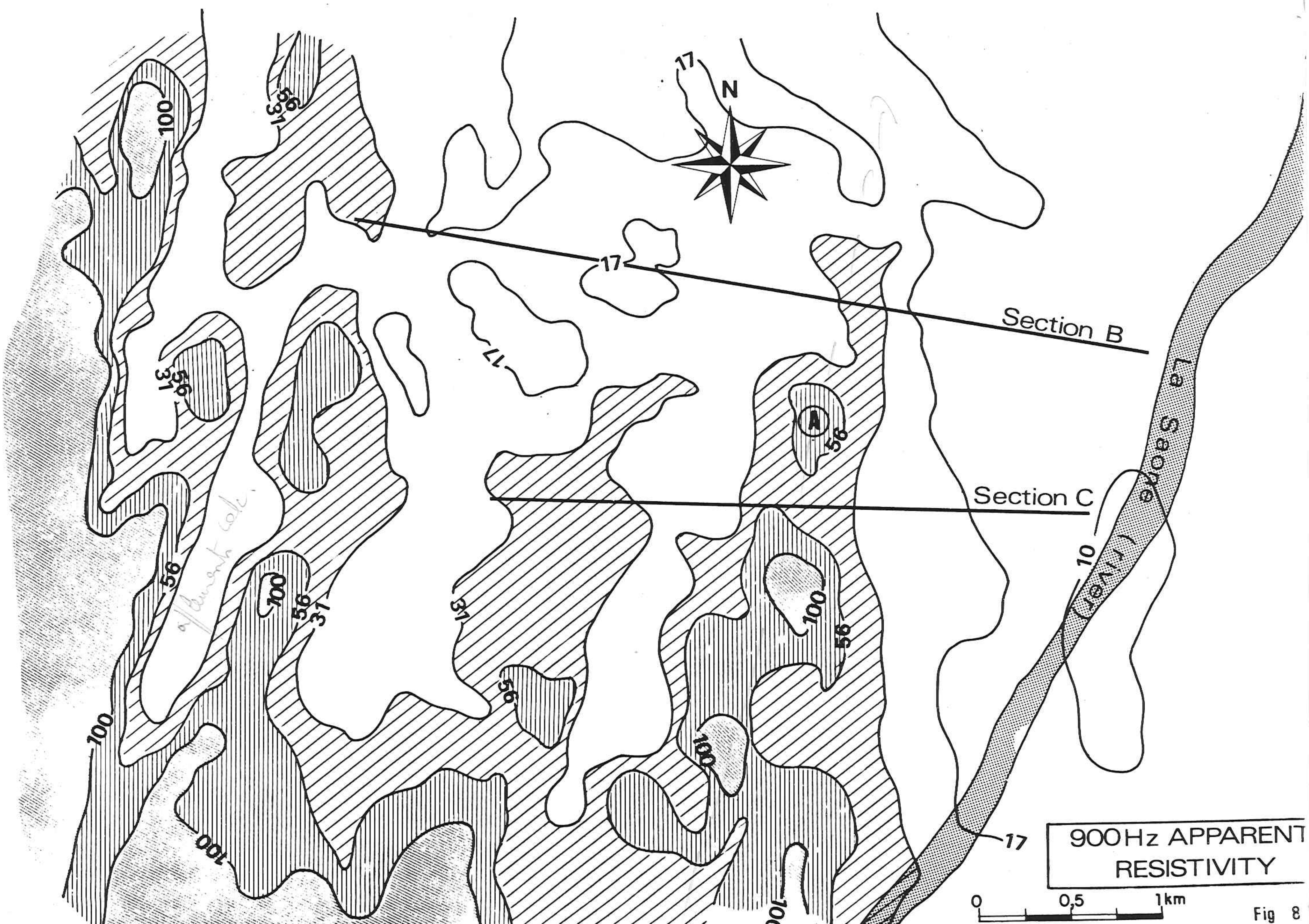
SENNECEY CROSS SECTION

Fig : 6



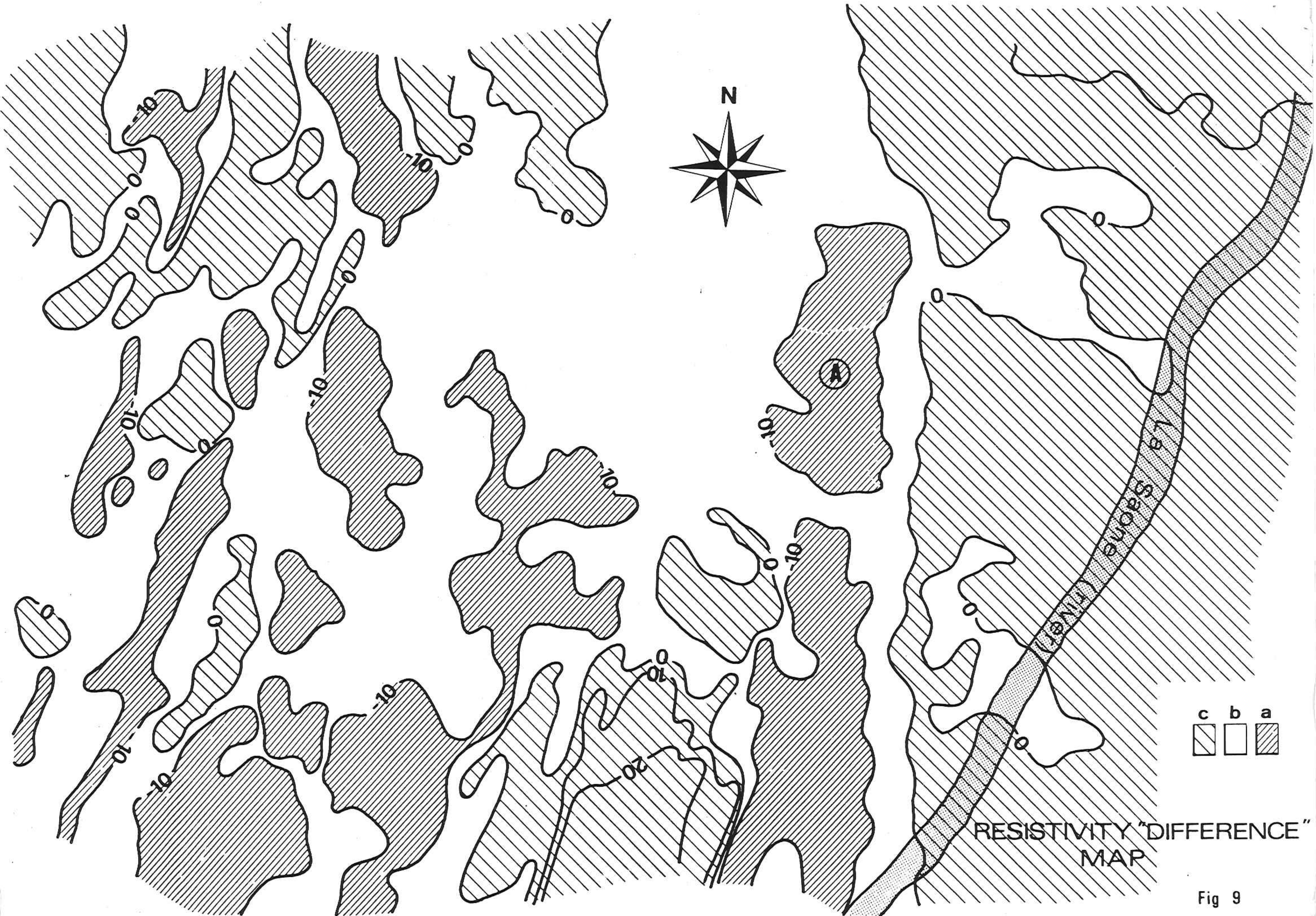
SCHLUMBERGER APPARENT RESISTIVITIES $\frac{AB}{2} = 200$ m

Fig :



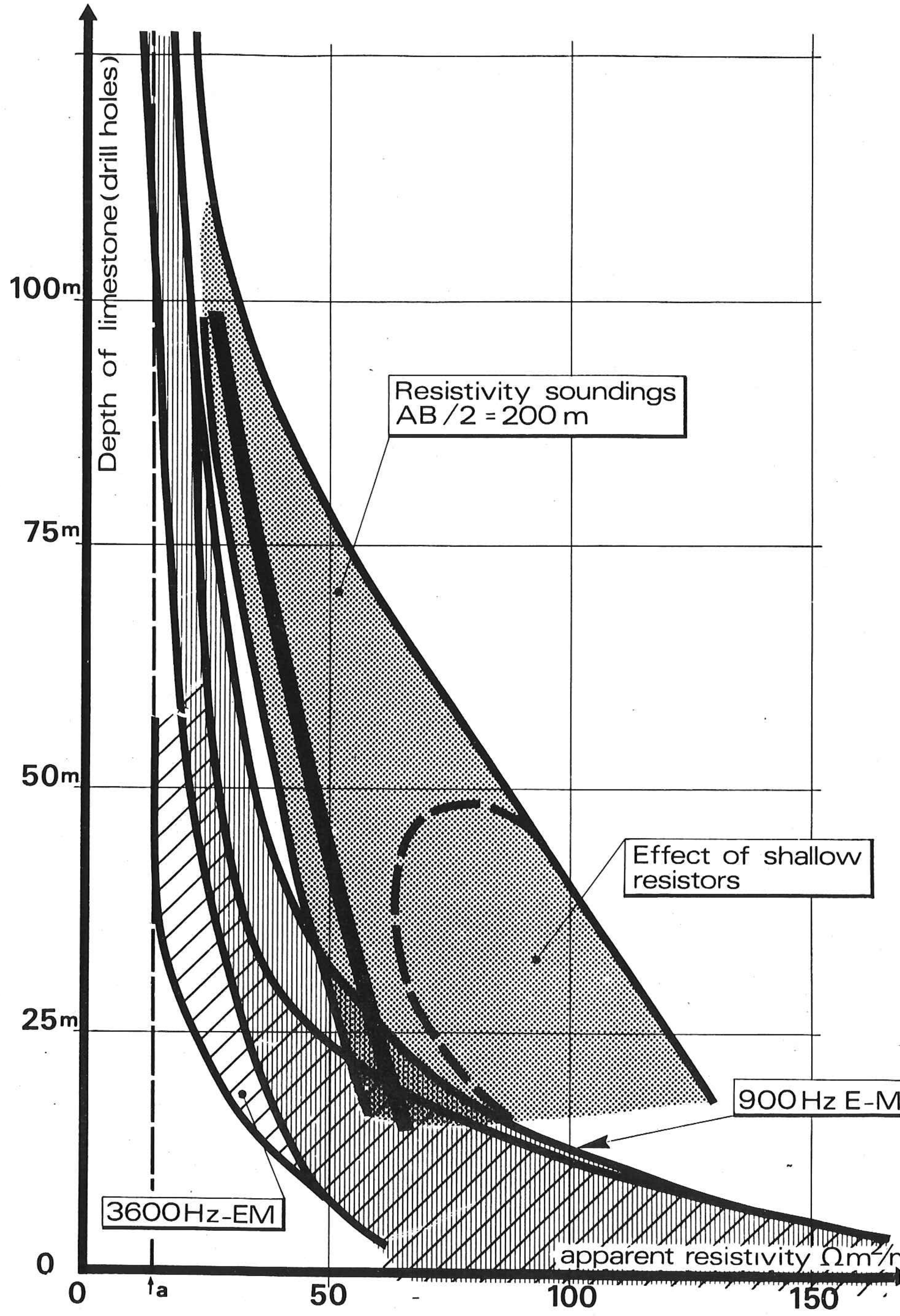
900Hz APPARENT
RESISTIVITY
0
0,5
1km
La Saone (river)
Section B
Section C
N
A
17
10
31
56
100

Fig 8



RESISTIVITY "DIFFERENCE" MAP

Fig 9



Depth of limestone (drill holes)
100m
75m
50m
25m
0
Resistivity soundings
AB / 2 = 200 m
Effect of shallow
resistors
900 Hz E-M
3600 Hz-EM
apparent resistivity Ωm²/m
0
a
50
100
150

Fig : 10