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Airborne resistivity surveying applied to nuclear power plant site investigation in France

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Abstract

In 1981, Compagnie de Prospection Géophysique Française (CPGF) was asked by Électricité de France (ÉDF) 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 environments. Mathematical modelling showed that airborne EM surveys could give appropriate answers in at least 70 % of the geological situations of interest to ÉDF.

Test flying with the Dighem system was carried out in 1982. CPGF acted as supervisor on behalf of ÉDF. 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.

Résumé

En 1981, la Compagnie de Prospection Géophysique Française (CPGF) a été chargée par Électricité de France (ÉDF) 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 ÉDF.

En 1982, des vols d'essai furent réalisés avec le système Dighem, CPGF ayant un rôle de conseil d'ÉDF. Sept sites furent étudiés dans différentes régions du Sud-Est et du Centre de la France, avec 2 000 km 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'argile conductrice pouvant atteindre 100 m d'épaisseur.

INTRODUCTION

In December 1980, the French State Power Board (Électricité 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 favourable zones are surveyed in detail by more conventional means. Électricité de France (ÉDF) 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 (CPGF) in order to appraise all available airborne geophysical techniques. This study included:

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1) The development of a mathematical model corresponding to the selected technique, and checking of its applicability.
2) Enquiries among users, universities, contractors and constructors.
3) Assistance to ÉDF in calling for tenders among selected contractors.

It was soon realized that helicopter electromagnetic (HEM) surveying was the most appropriate technique. After a call for tenders, Dighem Ltd. of Toronto, Canada, was selected to carry out, under CPGF's supervision, test flights over 7 selected areas (Fig. 17.1). These sites were already well surveyed by ground geophysics and drilling. 2000 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 17.2. The illustration corresponds to the following test sites:

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

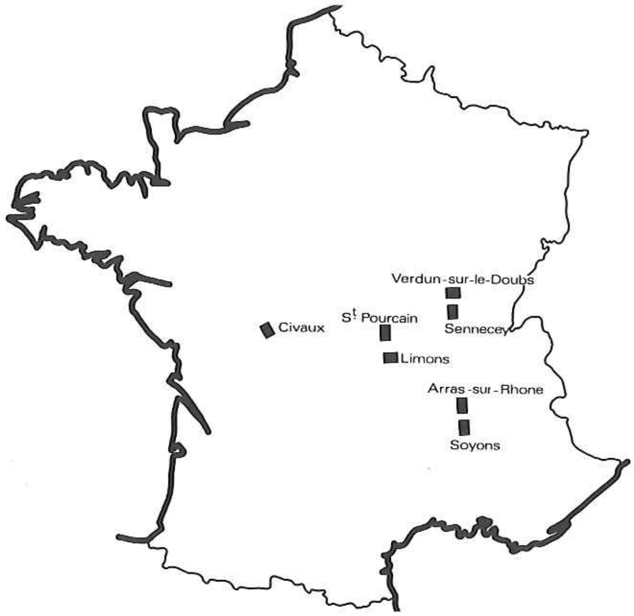

Figure 17.1. Locations of sites investigated by CPGF for nuclear power plants in France.

(e) Alluvium on faulted sedimentary structures: Arras-sur-Rhône
(f) Additionally buried river channels exist at Soyons, Limons, St. Pourçain (not shown in Fig. 17.2).

The probable ranges of resistivities are as follows:

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

POSSIBLE GEOPHYSICAL TECHNIQUES

In specifying the requirements for geophysical techniques, the depth of investigation had to exceed 100 m. Several methods were assessed during a preliminary investigation.

Airborne gravity was not found accurate enough. Anomalies of less than 5 mgals and 3 km wide (corresponding to a horst over 200 m high) are not detectable. Results of airborne magnetic surveys have been frequently used to calculate overburden depth elsewhere, but in the sedimentary areas selected by EDF the susceptibility contrast was not sufficient. A magnetometer was included aboard the survey helicopter and the results confirmed the initial skeptical assessment of the technique.

Airborne VLF has been mainly used in delineating vertical faults and conductors in resistive environment. Such situations do not exist at the investigated sites. Nevertheless, a VLF receiver was fitted on the helicopter. The field results confirmed that this method is not suitable for the mapping task.

Time-domain INPUT is probably the most extensively used airborne mapping tool. However, at the time of the enquiry (1980-1981), aids for quantitative interpretation of horizontally stratified media were not commercially available. Interpretation of frequency-domain EM data could supply resistivity and depth maps in horizontally stratified cases even at that time. 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 predict the HEM response at the given geological sites, and particularly to evaluate depth of penetration, computer software was developed for a CDC 7600 computer. It is based on the program written by Sinha and Collett (1973). The survey parameters were defined as follows:

Flight altitude : 30 m
Bird length : 9 m
Frequencies : 375, 900, 3600 and 8000 Hz (on all 3 coil configurations)

Coil configurations : vertical coplanar
horizontal coplanar
vertical 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, 3, or 6 m, ρ_1 = 10 Ωm

Second layer (sand and gravel): t = 20, 17, or 14 m, ρ_2 = 400 Ωm

Third layer (Tertiary clay and sandstone): t = 0 to infinite, ρ_3 = 0.2 to 400 Ωm

Fourth layer (Jurassic limestone or granite): ρ_4 = 1000 Ωm

These cases are summarized schematically in Figure 17.3. The main problem was whether the resistive fourth layer basement could be located under a thick conductive third layer.

Figure 17.4 shows the inphase 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 the "depth of penetration" for 900 Hz in this 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.

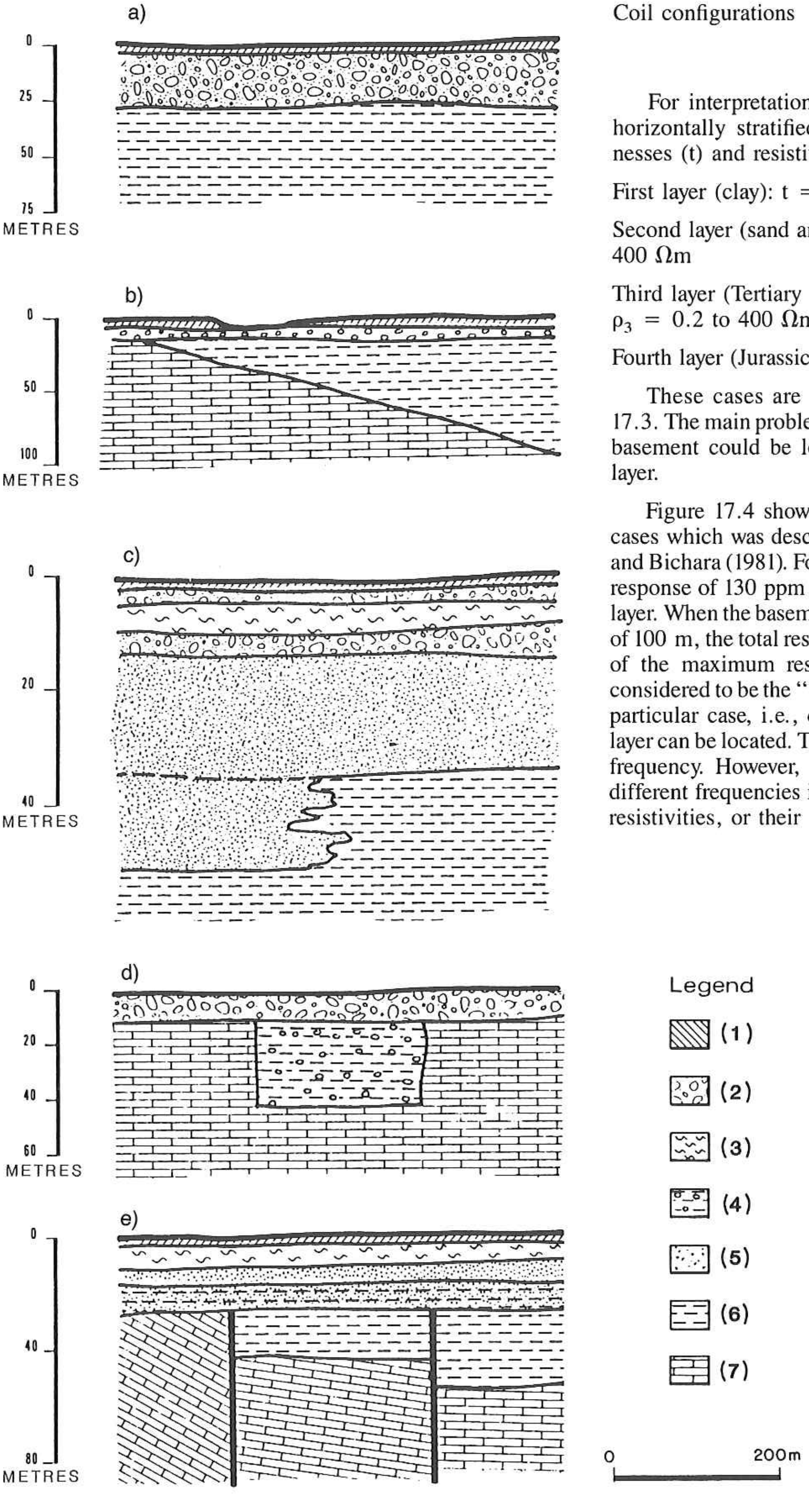

Figure 17.2. Typical geological situations (see text for their location and description). Geological units: (1) Top-soil and clay, (2) Quaternary sand and gravel, (3) Quaternary clay, (4) Karstic clay, (5) Tertiary sands, (6) Tertiary clay, (7) Jurassic limestone.

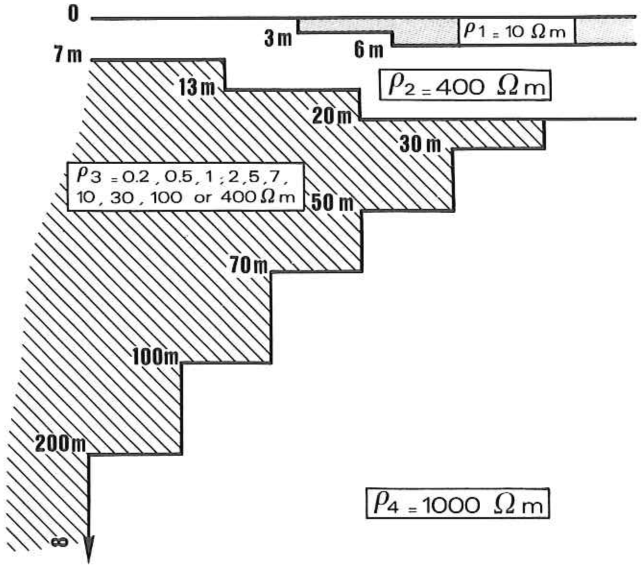

Figure 17.3. Sketch of geological parameters used in mathematical modelling. The situations should be considered as columns.

FIELD TESTS

The system used (Dighem) had two coplanar coils operating at 900 and 3600 Hz. They were placed in a 9 m long bird, which was towed by a helicopter. In addition, VLF and magnetic data 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 inphase and quadrature response and neglects bird's height. It then computes the conductor resistivity and its depth below the bird. In a second step, the actual bird elevation above the ground is subtracted 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 (Fraser, 1986).

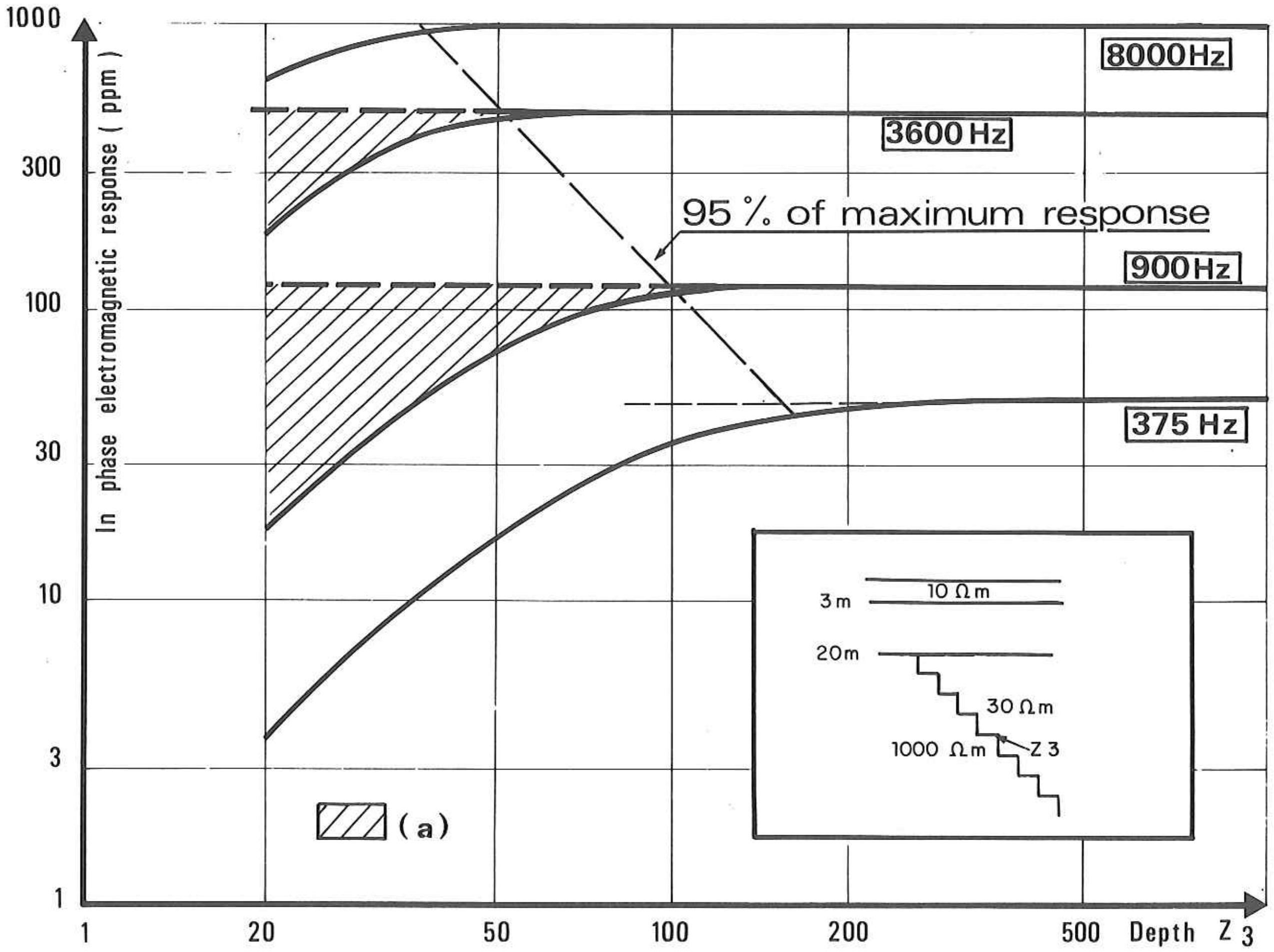

Figure 17.4. Inphase EM response for 4 frequencies as a function of depth. Resistivities and thicknesses are sketched.

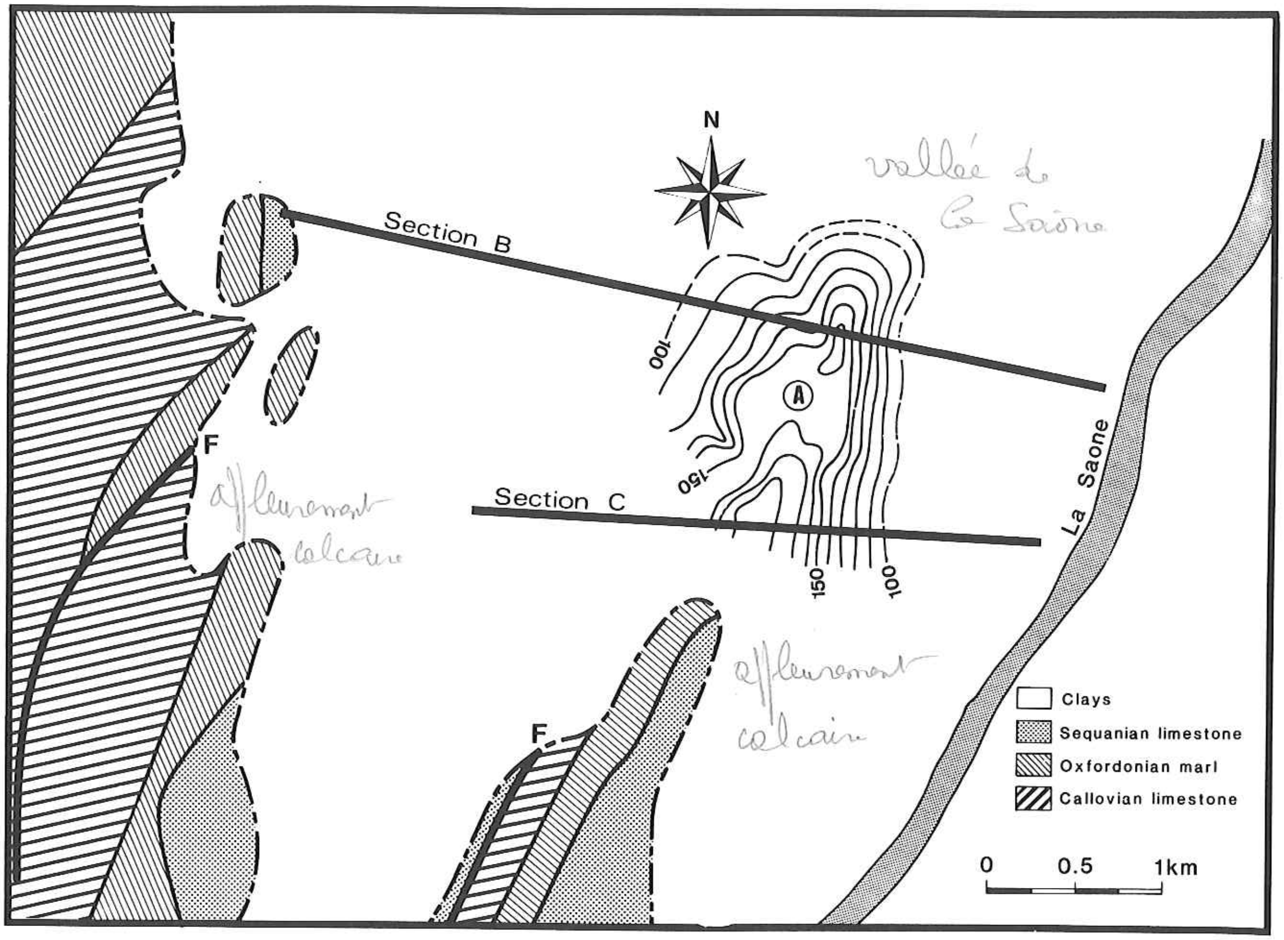

Figure 17.5. Geological map of the Sennecey test site. Letters indicate the following: S: Sequanian limestone, O: Oxfordian marl, C: Callovian limestone, F: Fault, A: Main horst. Contours indicate the elevation of the limestone horst above sea level. The mean elevation of the area is 200 m.

The Sennecey site is described here in greater detail. Figure 17.5 shows the geological map, and Figure 17.6 the east-west sections. The site is located in the Saône River valley, where Quaternary sands and gravels, 8-15 m thick, overlie thick Tertiary marl. At the western limit of the Tertiary basin lie Burgundy hills, which are formed by outcropping Jurassic limestone and marl. Under Tertiary marl, folded Jurassic formations plunge towards the east. South of the test area, a limestone horst (A) outcrops. In the test area, over 50 drillholes were used to trace the topography of the limestone below the Tertiary marl (Fig. 17.5). The average ground elevation is around 200 m. The limestone horst (A) plunges gently north of its outcrop.

Figure 17.7 shows Schlumberger apparent resistivities for a separation of $\frac{AB}{2} = 200$ m. The contour map was plotted from over 100 resistivity soundings. The highest apparent resistivities were observed above the top of the horst (A), and confirmed its plunge towards the north. Apparent resistivity computed from HEM data (frequency 900 Hz) is shown in Figure 17.8. Four elongated resistive zones have been detected corresponding to limestone ridges. They are separated by conductive zones, which are due either to Oxfordian marl, or thick Tertiary marl. The easternmost ridge corresponds to the main horst "A". The extent of horst A is clearly shown when geological map (Fig. 17.5) and HEM resistivity map (Fig. 17.8) are compared.

A novel concept of "logarithmic resistivity difference" D, was first tested during this survey. D is defined as 34.74 $[\ln \rho_{3600} - \ln \rho_{900}]$. When D is negative, a conductor overlies a resistor. This map (Fig. 17.9) clearly shows the limestone horst extension towards the north (A), where D is negative ($\rho_{900} > \rho_{3600}$ Hz).

Analyzing the depth of penetration reached by various techniques, one comes to the conclusion that HEM at 3600 Hz penetrates 70 m of conductive marls (10 Ωm). At the frequency of 900 Hz the penetration increases to 120 m. Schlumberger resistivity soundings with $AB/2 = 200$ m had a penetration of 150 m. Surficial high-resistivity lenses degrade the accuracy of the soundings, but have practically no influence on HEM measurements. The field results confirm the mathematical model, which had shown that a resistive basement could generally be located below 100 m of conductive (10 Ωm) overburden.

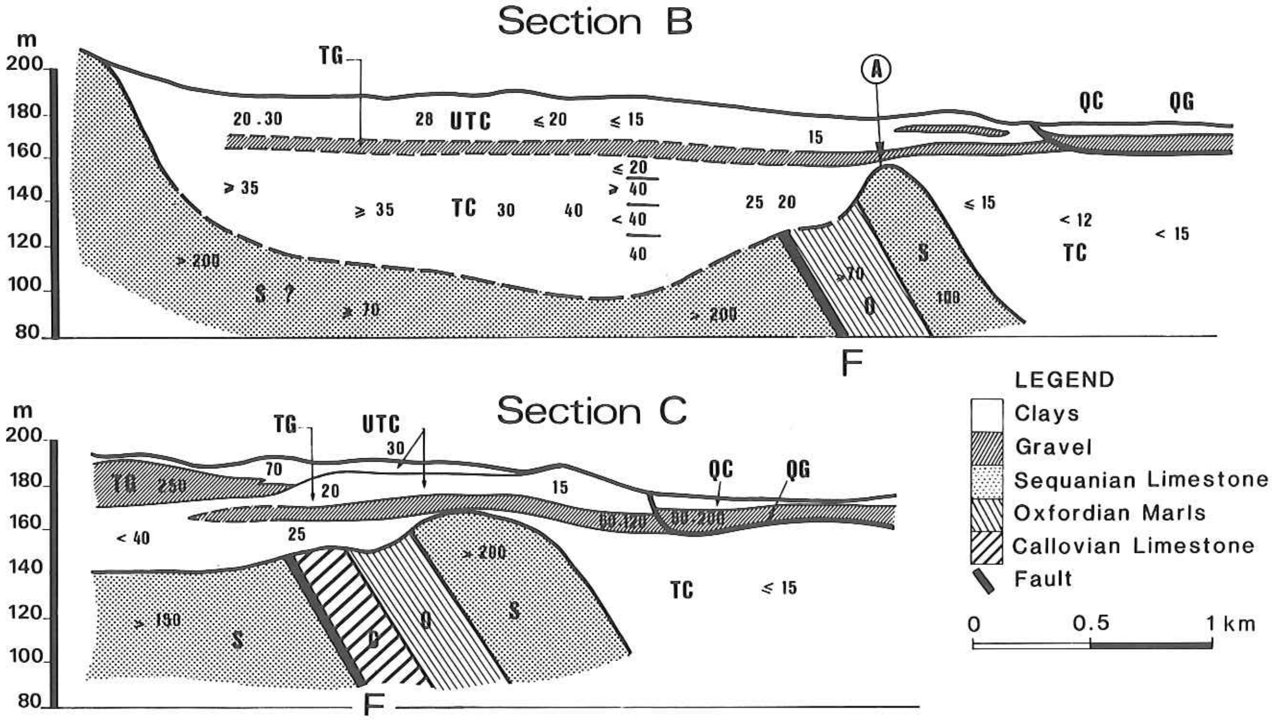

Figure 17.6. Sections at the Sennecey test site. Letters indicate: QC: Quaternary clay, QG: Quaternary gravel, UTC: Upper Tertiary clay, TG: Tertiary gravel, TC: Tertiary clay, S: Sequanian limestone, O: Oxfordian marl, C: Callovian limestone, A: Main horst, F: Fault. Numbers give resisitivites (in Ωm) interpreted from Schlumberger soundings.

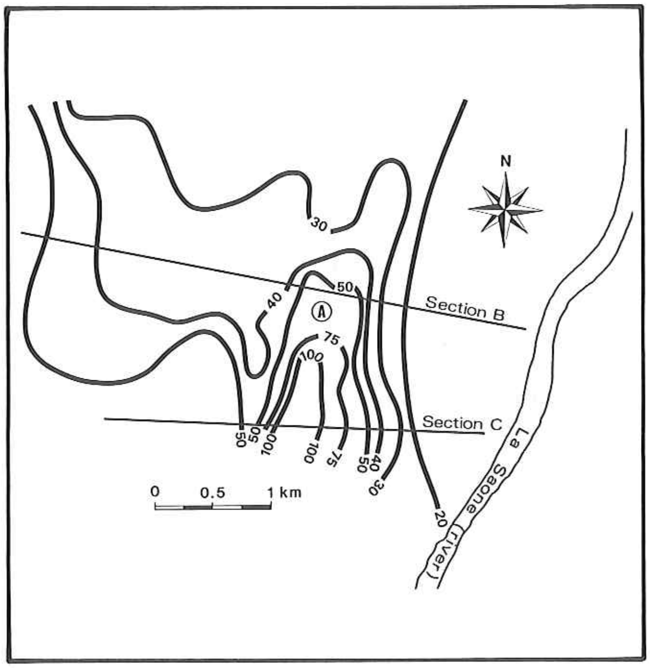

Figure 17.7. Contour map of apparent resistivities obtained along traverses B and C from Schlumberger soundings (AB/2 = 200 m). The area shown is the same as in Figure 17.5.

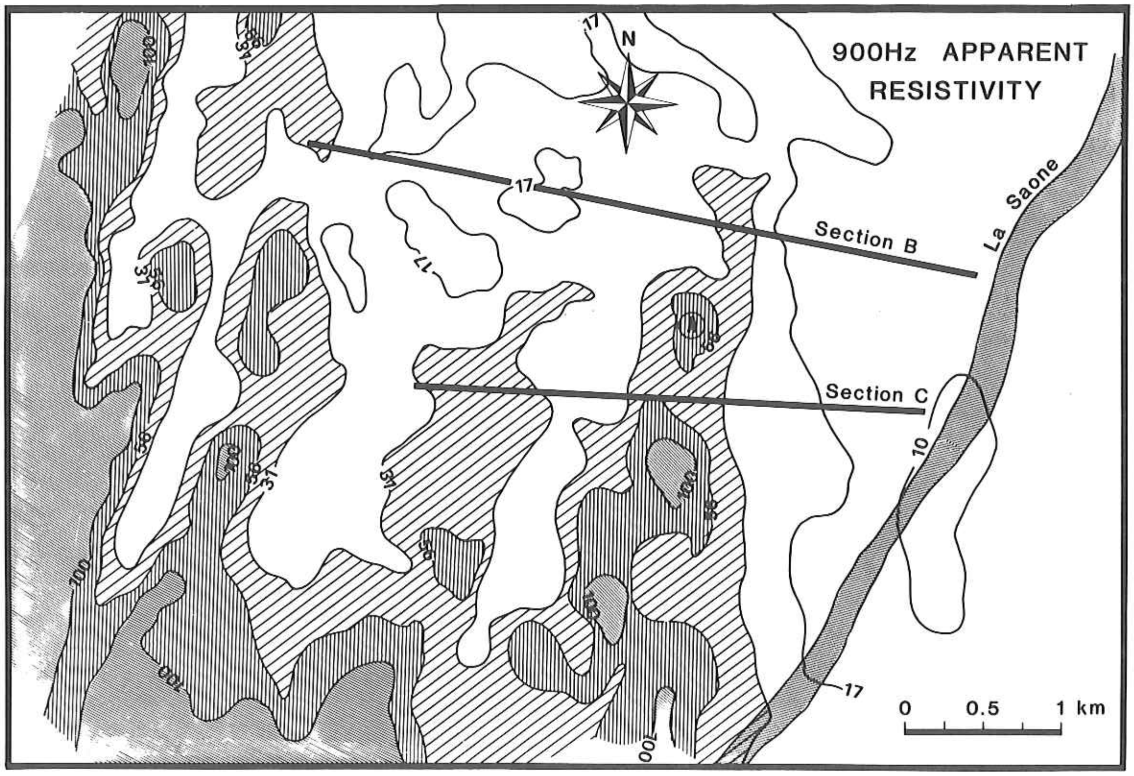

Figure 17.8. Contour map of apparent resistivities computed from HEM data at 900 Hz. The area shown is the same as in Figure 17.5.

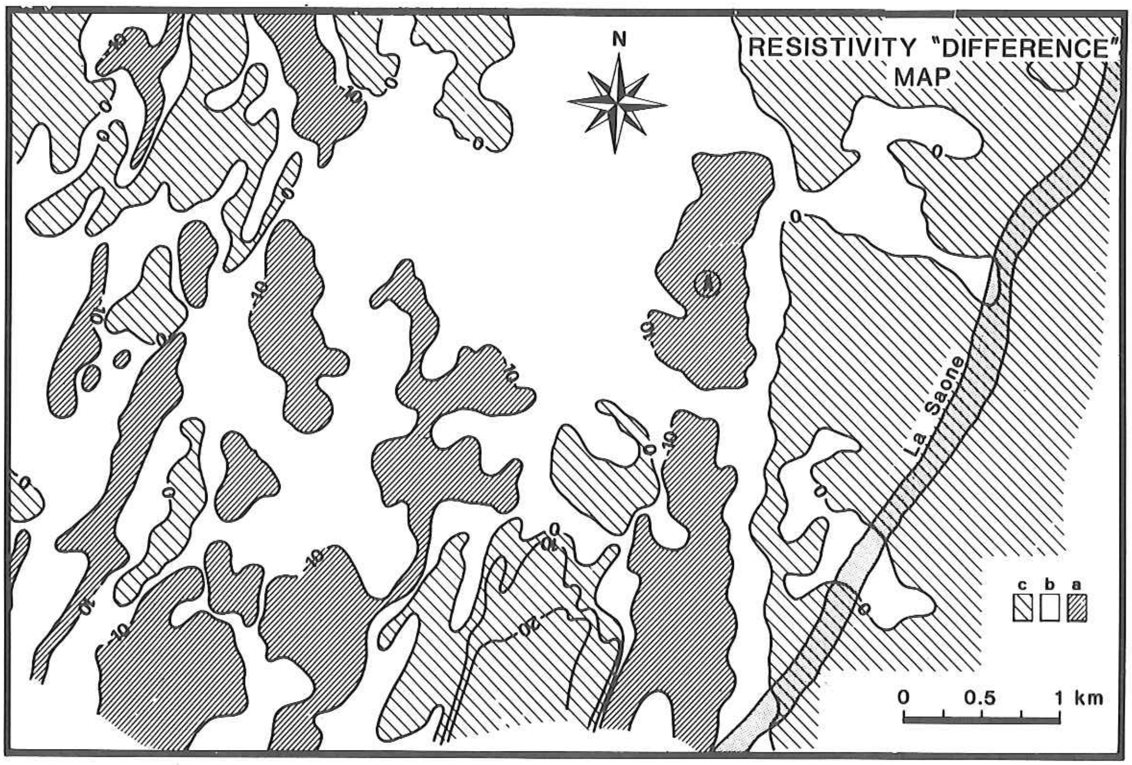

Figure 17.9. Map of HEM resistivity "difference" (for definition see text). Three situations can be distinguished: a–conductor over resistor, b–homogeneous medium, c–resistor over conductor. The area shown is the same as in Figure 17.5.

CONCLUSIONS

The seven selected sites constitute about 75 % of the possible nuclear sites in France. Satisfactory results were obtained at horizontally stratified sedimentary sites, dipping sedimentary sites, over lateral facies variations and buried river channels. At Sennecey, a penetration through 100 m of conductive clays was proved. Less satisfactory results were obtained over karsts at Civaux. Coastal sites were not tested.

EDF's conclusion was that low-cost continuous coverage could be achieved by using helicopter EM surveys. Progress in interpretation techniques seem necessary to increase the efficiency of the quantitative data analysis.

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