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Recent achievements and trends of research for geophysical prospection of archaeological sites

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Our times are characterized by an increasing need for prospection particularly within the context of rescue archaeology. Geophysics has an important part to play due to its ability to identify some well defined targets as well as to investigate large areas. Several recent surveys, using carefully selected methods chosen in accordance with the type of expected remain or a combination of methods in order to refine or confirm the interpretation, have demonstrated the expertise of several organisations in a wide variety of archaeological contexts. However, important improvements are still to be expected from the laboratories. Our team, working within the framework of three dissertations, is investigating several original subjects, for which the initial results are presented and discussed here: (1) The use of magnetic susceptibility measurements on wide mesh grids in order to survey extensive areas immediately prior to their occupation or destruction by large modern equipment; (2) Experiments to test a new survey device (Slingram – CS150) able to measure the magnetic susceptibility of the ground; (3) Interpretation of a series of geophysical measurements integrated with other types of data into a G.I.S.

Introduction

Current activity in the laboratories

Several recent surveys by different teams from various European countries have clearly shown an interest in investigating very large areas on archaeological sites. This assertion can be definitely established if we consider some recent publications in the journal “Archaeological Prospection” or the program of the “3rd International Conference on Archaeological Prospection” recently held in Munich (9–11 September 1999). Laboratories such as those from Bradford, Munich, Paris and Vienna, presented highly significant maps of well organised buried features belonging to ancient cities (urban networks) as well as to pre- and protohistoric settlements (pits, ditches, enclosures) or other types of large sites. They covered large areas with an extremely high definition resulting from the use of a very small grid interval between the readings. This kind of result has been a goal for a rather long time, but the challenge could not be met before significant improvements of the measuring rate of the instruments were achieved. Most modern tools have now reached an impressive speed in the field, thanks to automatic recording of the data, mechanical improvements for moving the sensors, simultaneous surveying of adjacent profiles either with one method (see Reference 1) or of one profile with different methods.[2] Such improvements are now immediately available and applicable for magnetic and electrical methods. Electromagnetic methods still need to be improved and developed for faster surveying. In all cases, increasing the rate and the significance of measurements is very much dependant on the particular conditions in open fields, and most methods are subject to physical limits, as is the case with G.P.R. which is still rather slow in comparison with other methods. Finally, if we turn to some less common methods, like thermography, gravimetry or seismics, it is clear that their applicability must be considered only in very specific cases (e.g., Reference 3).

Our laboratory participates in this evolution and we have also made or contributed to a series of large and/or high resolution surveys. Excellent results were obtained on sites from different periods, different typological types, with various methods and in many countries. A complete magnetic map of a probable religious pre-Columbian establishment was produced in Loma Alta (Mexico);[4] the exact location, (with an accurate plan of internal features) of a building destroyed by the Montagne Pelée eruption in 1902 was recovered with a G.P.R. at Saint-Pierre of Martinique;[5] a large portion of the Roman city of Wroxeter (England) was successfully surveyed with a light version of our Rateau system for fast recording of apparent resistivities.[6] Several other surveys of the same kind were continued or initiated recently in Apamea[7] and Pasargadae (Oct. 1999); other significant discoveries still need to be published in detail.

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Acquired knowledge and trends of research

In brief, we can say that technology and processes can be considered both operational and efficient since most can be worked out systematically in a wide range of city or camp sites located at shallow depth in open fields. A schematic list of typical archaeological targets with the common surveying solutions can be established as follows:

– for stone and brick buildings, roads and urban networks, surrounding walls, …, in open field, almost all methods can be conveniently applied, allowing for differences in quality results, speed and price. These differences are partly dependant on the local conditions but the legibility of resistivity maps is often remarkably good;

– for pits, wells, ditches or any other types of back-filled features in open field, several methods can be used but the magnetic method is often the most efficient;

– kilns, slag deposits and other features related to an intensive use of fire are typically and almost exclusively surveyed with the magnetic method;

– detection of metal objects is relatively easy at shallow depths, essentially with electromagnetic devices;

– caves, vaults, chamber tombs and other kinds of empty spaces, in spite of what is commonly expected, are generally difficult to investigate and this is partly due to the frequent existence of physical limits of detection when the ratio of the volume to the depth is small. The large variety of features to investigate, as well as the frequently unusual siting in an urban context, inside a building or in any other type of topographically complex area, add to the difficulty. Such features often need to be explored systematically with a rather large panel of methods such as electrostatic resistivity, G.P.R., or even gravimetry and seismics.

Generally speaking, one can argue that geophysical survey for archaeology has reached a sufficient level of expertise for allowing some general rules to be decreed.[8,9] We can also consider that scientific and technical knowledge is now available in several organisations either public or private, particularly within the European area. This should normally extend to all countries in a near future. Notwithstanding the excellent results to date, present research trends must be extended in new directions to meet our purposes and those of archaeologists. The obvious challenges of present methods can be classified into three major categories.

Tools improvements: Creation of entirely new tools (i.e., relevant to new methods) is rather limited since most theoretical possibilities have already been explored. The efforts should concentrate on technical improvements of existing tools and experimentation in the field for detection of unusual types of archaeological targets.

Data management and interpretation: Improving the legibility of survey maps and the modelling of anomalies is an interesting direction for enhancing archaeological interpretation of numerical data. This must be done in close relationship with all the available data, however, whether or not numerical or resulting from geophysical measurements; this obviously includes investigations such as those founded on historical documents, aerial photography, surface remains collection, topography, etc. This can be definitely helped and improved by the systematic use of a geographical information system (G.I.S.) for accurate simultaneous comparison of the data.

Thematic subjects: This third direction of research is of wide interest for the development of certain aspects of archaeological research. Some of them are, or were, relatively easy to develop as, for instance, detection of metal objects.[10] Others are more puzzling themes: despite its apparent easiness, detection of voids such as cavities, empty graves or vaulted cellars, etc. still remains a problem difficult to solve. This is probably due to the large number of non-typical aspects encountered on a site when such a question is put to the geophysicist by the archaeologist.

Another thematic question of much more general interest is the investigation of remains below present cities. These surveys are generally characterized by a relatively small area to investigate, deep features to detect through several superimposed layers, different kinds of disturbance due to the activities of the urban environment and various hard and non-uniform soil surfaces such as pavements, bitumen (e.g., Reference 11). A special theme session in the next Archaeometry Symposium in Mexico City (15–19 May 2000) is planned on the subject with the following title: "Geophysical study of archaeological remains under cities."

Investigating ancient garden locations around historical buildings or ruins also seems to be a currently emerging theme for prospectors.

Present research projects in our laboratory

Within the framework of these categories, our laboratory contributes to research for a better approach of archaeological sites by means of prospection. Three dissertations on the following subjects have been prepared and will be completed soon.

Magnetic susceptibility abilities for large archaeological surveys

Surveying with non-destructive methods allows a very upstream implementation of prospection in the process of archaeological planning. Making the decision which leads to the evaluation of archaeological potential and thereafter to excavation is thus facilitated and can be more efficient. Among these methods, geophysical prospection with a broad mesh (measurements of magnetic susceptibility and electric conductivity) makes it possible to outline rapidly the archaeological potentialities of the investigated zone. As it is often the case in such investigations, additional sources of information such as geological or landscape studies ("archaeomorphology") allow a better characterization of the areas with high archaeological potential.

Method: The correspondence between strong levels of magnetic susceptibility and zones with traces of past human activities is a basis for the use of magnetic susceptibility during archaeological prospection. Studies of the magnetic properties of archaeological soils have shown that the magnetic anomalies observed in prospection result, on the one hand, from human activity, and on the other hand, from significant pedological processes. Thus, the magnetic signal can be a marker of past human activities, which allows surveying of extensive surfaces using a large mesh. This is of great interest for site identification and archaeological diagnosis of a region within the context of rescue archaeology.

The selected meshes for sampling have a step which generally ranges between 5 and 20 m, allowing a fast survey. However, according to the theorem of SHANNON, a site is more likely to be discovered if its diameter is at least two times larger than the sampling mesh. To take the case of the A66 highway (near Toulouse, France), where the selected square mesh had a step of 14 m, to guarantee detection, a site would have to have a diameter greater than 28 m.

The established model should tend towards a recognition of natural phenomena and thus, by deduction, to archaeological identification.

Establishment of a natural reference frame: This aspect mainly concerns the surface cover, that is, essentially the soil but also the quaternary geological formations. The purpose of the investigations was to identify the response of the natural background and the factors ruling magnetic susceptibility.The geological subsoil in our areas of intervention was granitic in the case of the A89 highway, molassic and alluvial in the case of the A66 highway. At present, the relationship between the surface formations and the magnetic signal was better established in the case of A89 (according to measurements made in the laboratory).

Pedogenesis is the process of soil formation during time. The ground is thus a powerful agent of transformation, responsible for a significant modification of the magnetic signal of the parent material. The result generally reveals an increase of magnetic susceptibility but also sometimes a reduction.

Three factors are important in determining the ground's evolution and thus the magnetic signal: lithology, topography and vegetable cover.

Establishment of an archaeological reference frame: It is presently well known that archaeological sites are easily detectable by magnetic susceptibility measurements using a large mesh, in particular when products of combustion are present (see the kilns proximate to a castle in Fig. 1).[12] Similarly, a tumulus with traces of combustion could be discriminated from a tumulus which was only embanked by the natural sediment (Fig. 2).

In this process, geophysical anomalies are considered as marks of past human activities. This definition leads to a search which is not limited to the identification of potential sites but also extends to the identification of the so-called "anthropic" marks in a landscape. In this case, the site as object can be integrated into a larger but genetically dependent unit. The "anthropic" marks in the landscape are mainly due to the activities developed for exploiting elements of the natural environment (agriculture, forestry…) related to the vegetable cover.

One must also consider colluvial deposits due to the erosion of slopes. A high magnetic signal in these sediments can be due either to burning by deforestation techniques or to the transportation of archaeological sediments down the slopes, or to both effects simultaneously. Fossilisation of these traces of culture, or of forests, is still difficult to estimate, the time factor being then essential. However, research joining "archeomorphology" and geology, as carried out during field studies for the A66 highway, may provide evidence for confirming certain hypotheses and resolving certain problems.

As a conclusion, we can say that magnetic susceptibility measurements using a large mesh are efficient for detecting "anthropic" zones within a large area. However, it is necessary to keep in mind that detection is limited by the investigation depth, mesh size, and the nature of the increase of susceptibility due to combustion. So, an improved understanding of natural and "anthropic" processes of susceptibility enhancement should allow better detection of archaeological sites.

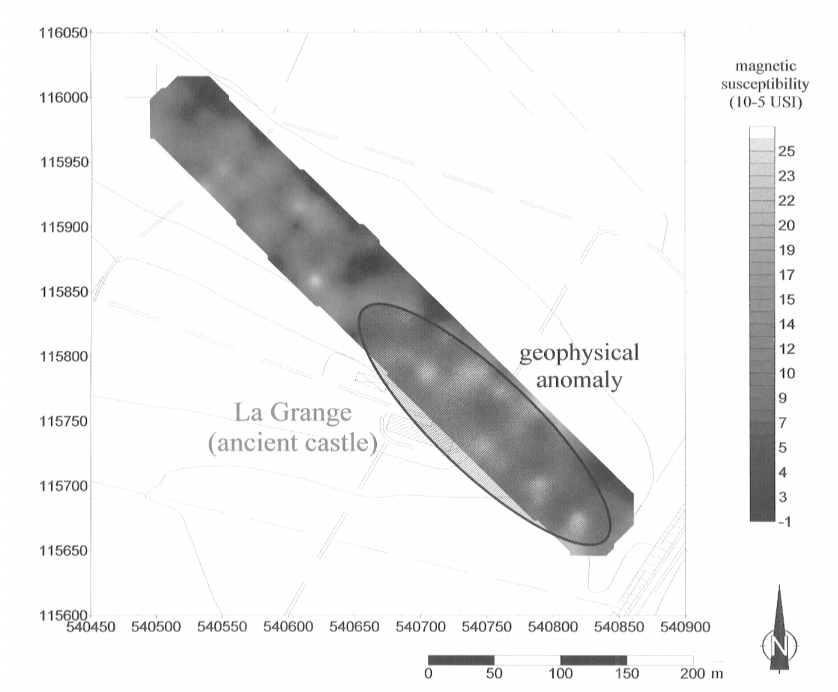

Fig. 1. Magnetic susceptibility measurements with a large mesh (A66 motorway); the magnetic anomaly (low values in white, covered by the elliptic shaded area) corresponds to the medieval site of La Grange

Development of a new survey device for measuring the apparent magnetic susceptibility of the ground and the relevant EM modelling

The instrument: The electromagnetic method, compared to the magnetic one, offers the advantage of allowing a direct measurement of the absolute value of the soil's magnetic susceptibility. This latter property is often influenced by anthropogenic activity and has been used in archaeological prospecting at both fine and coarse sample intervals in order to locate and define site limits. The devices employing the Slingram method are the most suitable ones for archaeological survey. These types of instruments are composed of two separate magnetic dipoles: with respect to the low induction number (LIN), the receiver coil measures the secondary field, which is proportional to the apparent magnetic susceptibility. The main disadvantage of Slingram devices is their small depth of investigation. The SH3, built at the Centre de Recherches Géophysiques of Garchy, was the best Slingram instrument adapted for archaeological survey with a depth of investigation of 0.70 m for the in-phase response. The SH3 was designed with a 1.5 m coil separation and a parallel (PARA) coil orientation (35° from the vertical). A theoretical study[13] comparing the different types of coil orientation showed that the perpendicular (PERP) configuration achieved the greatest depth of investigation for susceptibility measurements: in this configuration, the depth of investigation is estimated around 1 m for the in-phase response. The last Slingram instrument, called CS150, also built at the C.R.G. of Garchy, was designed with a 1.5 m coil separation and a PERP coil orientation (the PERP configuration provides the advantage of zero coupling between the coils). It operates with two frequencies: 4.4 kHz and 10 kHz[14] (Fig. 3). A greater distance between coils would increase the depth of investigation but would seriously reduce lateral resolution.

Field experiments: The prototype of the CS150 was first tested on an archaeological site from the Iron Age at Verdun-sur-le-Doubs (Saône et Loire, France). An area of 2 ha had been surveyed with the Caesium gradiometer G858 (Geometrics) which revealed an important settlement area. In this area, we chose a square of $20 \times 20\ m^2$ with well defined magnetic anomalies to test the CS150 (Fig. 4). The magnetic and electromagnetic maps look very similar and are characterized by three main anomalies. The archaeological excavations in this area revealed pits and semi-buried houses. The electromagnetic anomalies are more centred above the archaeological structures than the magnetic ones.

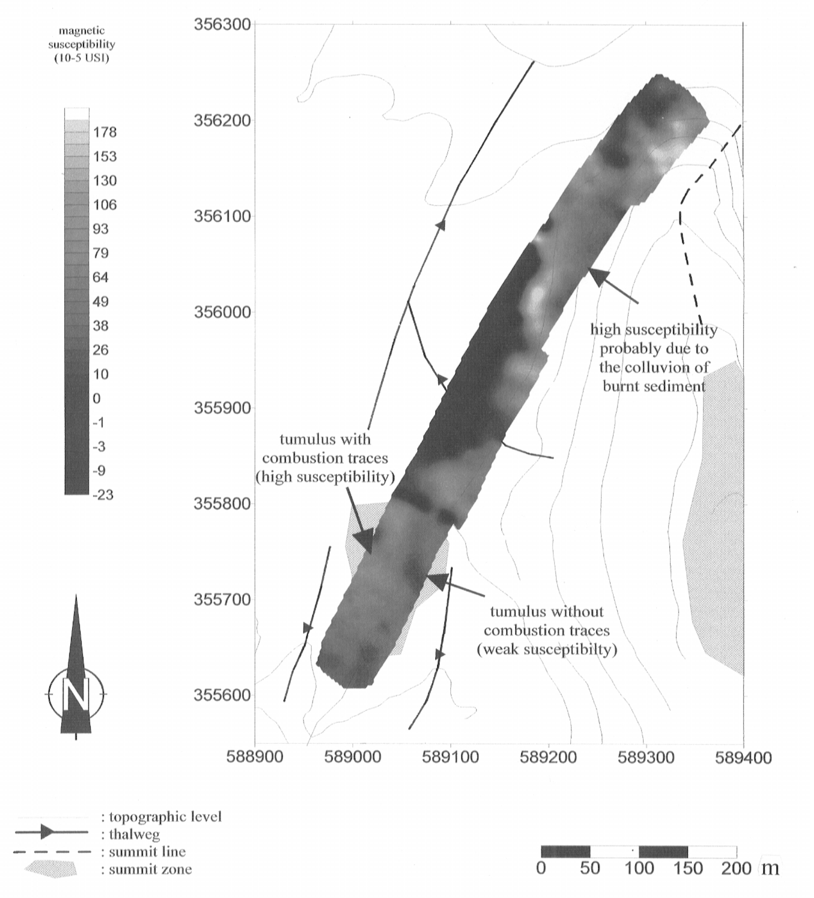

Fig. 2. Magnetic susceptibility measurements with a large mesh (A89 motorway); high magnetic susceptibility values correspond to combustion traces in a tumulus and in colluvial deposits. The tumulus without combustion traces is not yet identified

Models and prospects: The construction of a new Slingram instrument with a good depth of investigation was of interest for comparing both magnetic and electromagnetic maps. A linear filtering applied on electromagnetic data allowing a joint interpretation of both methods assisted the characterization of different types of magnetization present in the soil. An Euler deconvolution was applied on one of the three magnetic anomalies and showed that the magnetic source was at a shallower depth than the limit of the depth of investigation of the CS150. We can thus conclude that the difference observed between magnetic and filtered electromagnetic data is due to the presence of a type of magnetization which differs from the induced one. The joint interpretation by linear filtering revealed that part of the magnetic anomaly was due to the presence of a viscous magnetization in the pits. This information is important for the archaeological interpretation because it permits one to predict whether the structure has been disturbed by recent human activity or not. The pits of Verdun-sur-le-Doubs are characterized by a coefficient of viscosity of 5.3%; this value can be considered correct for a structure which has not been disturbed for 2000 years.

This method offers new perspectives for the study of magnetic anomalies and a better interpretation of them. The characterization of different types of magnetization present in the soil may provide a better understanding of both pedogenic and anthropogenic processes.

Integrated interpretation of various survey data with a G.I.S. at Vieil-Evreux, (Eure, France)

Within the framework of the public presentation of the Gallo-Roman thermal edifice of Vieil-Evreux (France), the Conseil Général de l'Eure appealed, in 1996, to the know-how and the experience of Terra NovA for an evaluation of archaeological risks and an analysis through non-destructive methods in order to map the edifice and its close environment.

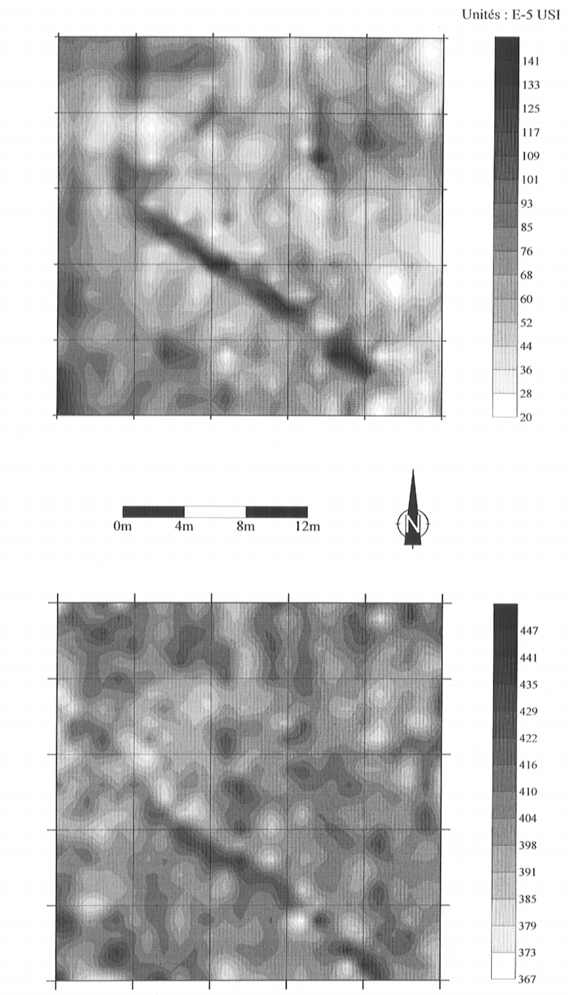

Fig. 3. Electromagnetic survey on the "L" shaped structure: with the SH3 Slingram apparatus (a); with the CS150 Slingram apparatus (both with a 1×1 m^2 mesh) (b)

A long-term scientific collaboration was established and is currently concretized by a specific research contract using several surveying methods. This original approach in France (study of an entire ancient city via non-destructive methods) cannot be conceived without the use of a geographical information system, allowing the integration and the exploitation of information from various origins.

Prospection of the zone of the thermal edifice: Since 1996, we systematically surveyed the zones located around the thermal building. The resistivity method (employing the twin probe electrode array) was selected to survey this area. This procedure allowed mapping of the various structures already known from oblique aerial photographs, such as the piers of the aqueduct, a nympheum associated with the aqueduct, a fanum (indigenous temple), the enclosure and the palestra (interior court) of the thermal building, as well as parts of the sewerage.

It also allowed detection and mapping of new major structures (invisible on the aerial photographs);[15] as an example, the second aqueduct connecting the nympheum directly to the thermal building, some ditches, a small square building (8×8 m^2) and the internal structure of the fanum were able to be described in detail (Fig. 5).

Study of oblique aerial photographs: Detailed knowledge of the site of Vieil-Evreux was enhanced thanks to an exceptional collection of oblique aerial photographs[15] particularly rich in traces of archaeological remains.

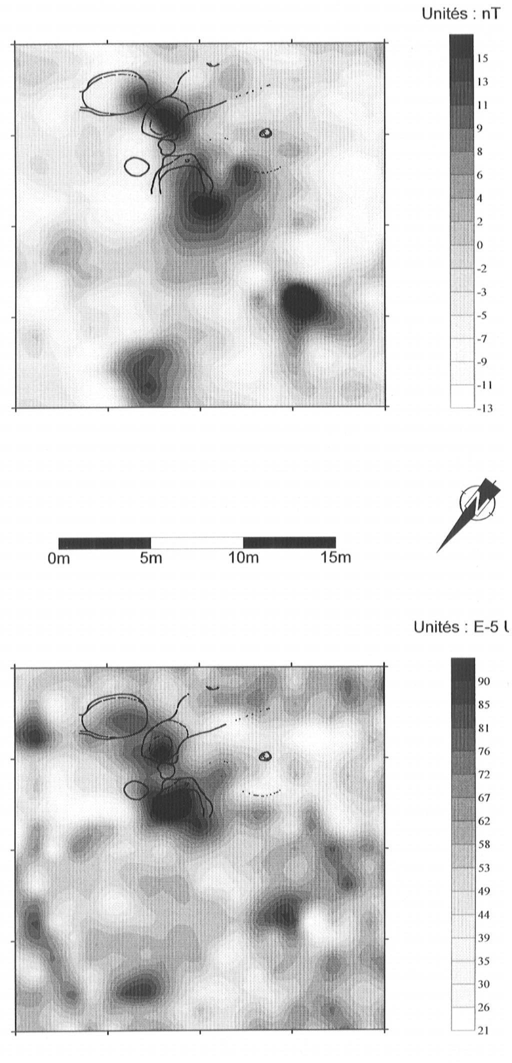

Fig. 4. Site of Verdun-sur-le-Doubs: location of the pits revealed by the archaeological excavations in correspondence with the magnetic survey (G850) (a); the electromagnetic survey (CS150) (b)

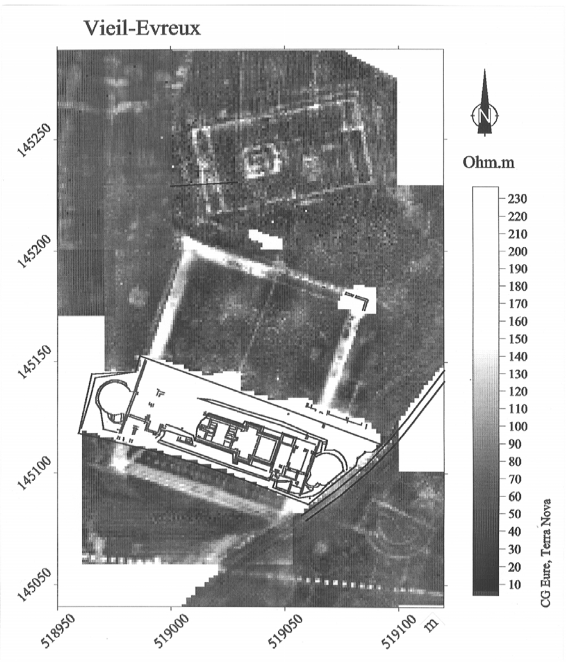

Fig. 5. Detection and cartography of hidden archaeological structures at Vieil-Evreux. The data were gathered in 1996, 1997 and 1999 in the surroundings of the thermal building with the electric method (twin electrodes resistivity map with $a = 1$ m) (geometrical scale in metres). The architectural map (drawn in black) was superimposed over the geophysical data

In addition to a photogrammetric study of this collection, the geophysical data were geographically located in order to be used as additional control points for rectifying the photos. This rectification allowed the crop marks visible on the photographs to be plotted on a map referenced in plane co-ordinates according to the Lambert I system used in France. Knowledge of the remains around the thermal edifice was thus extended to an area of about 500 by 350 meters.

The quality of the aerial photographs significantly increased the knowledge of this area. Most notably the street network, the pattern of built/non built areas, as well as the distribution of hydraulic elements were revealed (Fig. 6).

Prospection of the Roman theatre: In order to increase knowledge of the ancient city, it was necessary to survey the Roman theatre of Vieil-Evreux. Presently, this building lies under a meadow which shows a well marked topography (6 m of amplitude). The aims of the intervention were to highlight the major structures and the internal installations of the theatre and to solve the ambiguity and contradictions of the two available nineteenth-century excavation maps. A "multi-depth" electric survey with a twin electrode system (MPX 15 multiplexor and RM15 resistivity meter from Geoscan Research) where $a = 0.5$, 1, and 2 m, was used (Fig. 7).

The electric survey allowed mapping of the ancient theatre and the anomalies were referenced using the Lambert I system. The use of a GIS allowed an accurate geographical location of the known plans from the nineteenth century and, thus, gave us the ability to superimpose them for mutual comparison and, further, to solve the ambiguities between the observed and interpreted elements on these maps. This work provides a basis for serious reflection on monumental architecture, making it possible the better understanding of old discoveries without the necessity of excavating the ground.

Until now, survey work on the site of Vieil-Evreux was conducted within the local scale of an archaeological "site" due to the specificity of interventions (study of the thermal buildings and its surroundings, study of the theatre). The scientific cooperation between the Conseil Général de l'Eure, Terra NovA and the Université de Paris VI, allowing this kind of long-term project, brings a global dimension on the scale of the ancient agglomeration (250 ha) to our scientific approach. The study of the city of Vieil-vreux promises to fully integrate the use of GIS according to several research orientations.

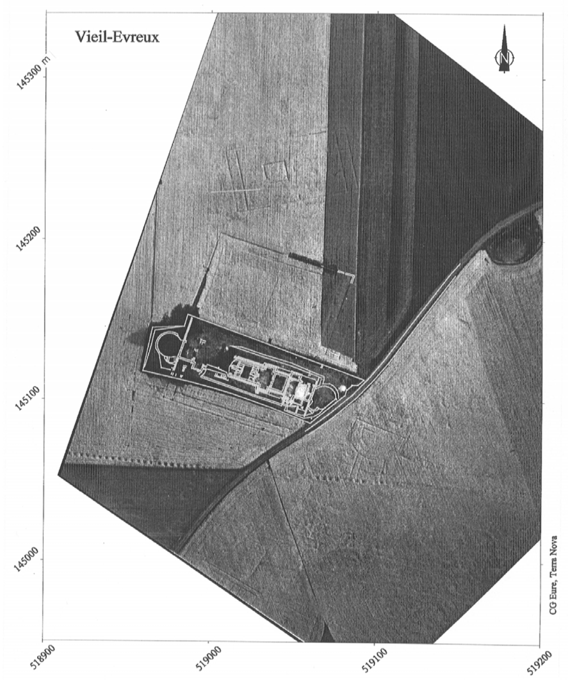

Fig. 6. Orthophotograph of the surroundings of the thermal building of Vieil-Evreux (geometric scale in metres).[15]

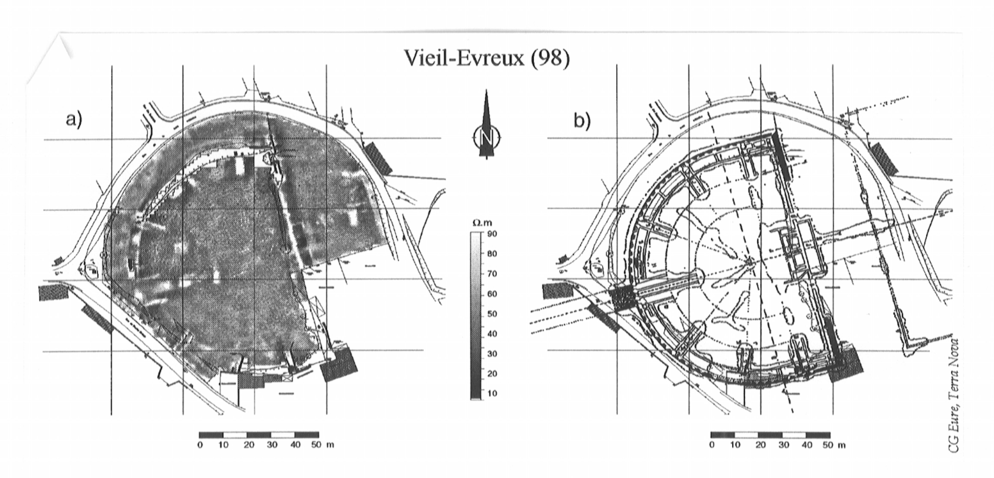

Fig. 7. Survey of the Roman theater of Vieil-Evreux: (a) electric method (twin electrodes resistivity map with $a = 0.5$ m); (b) nineteenth century method

Simultaneously, this technique offers a considerable decision making tool for the definition of archaeological problems and consequently for the choice of zones to study in priority. Accordingly, a Digital Elevation Model (DEM) currently under development will allow in the short term an extensive photogrammetric study of the existing crop marks on the aerial cover of the city, as well as the integration of the modern and ancient land division documents.

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