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Departament de Cultura i Mitjans de Comunicació
Direcció General del Patrimoni Cultural
Àrea de Coneixement i Recerca
Centre d'Informació i Documentació del Patrimoni Cultural

Prospeccions geofísiques a la catedral de Girona

Albert Casas, Josep M. Nolla

Amb data d'avui s'ha fet entrega a aquest Servei d'Arqueologia de la Generalitat de Catalunya, per part dels responsables del programa PROGRESS, de la memòria científica corrsponent a les prospeccions geofísiques dutes a terme a la Catedral de Girona .

Girona, 22 de gener de 1998

P.O.: Lluís Palahí i Grimal

Entre els dies 31 de maig i l'1 de juny va tenir lloc a Girona, en l'àmbit de la seu, una prospecció no destructiva, geofísica, mitjançant la utilització de radars i mesurament a través de pols electrostàtics de la resistivitat del sòl en continu amb la intenció de posar a punt uns nous models d'aparells, de polir la informació complementària proporcionada pels diferents equips i d'aconseguir un plànol fiable del subsòl de l'interior de la catedral i zones annexes per sota del poderós enllosat. Aquesta acció fou possible gràcies als ajuts del programa Acció Interactiva Programada (AIP PICASSO) als equips formats pel CNRS-Centre de Recherches Géophysiques (França) i de la Universitat de Barcelona, Departament de Geologia que, paral.lelament, treballaren de la mateixa manera a Saint Germain d'Auxerre. Que aquesta exploració s'efectués, precisament, a Girona fou possible gràcies a la decisió de Pere Freixas, director del Museu d'Història de la ciutat (ajuntament de Girona) que va fer els contactes i les gestions, a la col.laboració econòmica de la municipalitat i a les facilitats i ajuda que, en tot moment, va posar a disposició dels tècnics el bisbat i la catedral, concretats en la figura del dr. Gabriel Roure. La Universitat de Girona participà en la tria dels llocs més adients i, sobretot, en l'anàlisi del resultats.

L'equip que dirigí el professor Albert Casas, de la Universitat de Barcelona, féu servir un radar de freqüència bàsica d'alta penetració (més de cinc metres), mentre que l'equip francès (M. Dabas i Ch. Camerlynck) n'utilitzà un de complementari, menys potent però de més alta resolució espacial i, paral.lelament, un prototipus creat pel Centre de Recherches Géophysiques del CNRS que mesura a través de pols electrostàtics la resistivitat del sòl en continu. Aquest darrer aparell era el que feia preveure resultats més engrescadors car havia de proporcionar un estat en planta del subsòl en el ben entès que "llegia" només els primers senyals, els més pròxims a la superfície i, per tant, exposat, no cal dir-ho, a distorsionaments produïts, sobretot, per les tombes obertes a l'interior del temple.

LA PROSPECCIÓ AMB RADAR

Cal dir que no posseïm, encara, resultats definitius. Tanmateix, les dades fornides per l'informe preliminar no són sorprenents i concorden amb les dades arqueològiques i històriques conegudes. No creiem, però, que les conclusions definitives variïn substancialment.

L'equip de Barcelona treballà a l'interior de la seu efectuant lectures en sentit oest/est i nord/sud, seguint els mateixos eixos que el recorregut del prototipus i del radar complementari. A més, en solitari, efectuà un seguit de lectures en direcció nord/sud en l'ala occidental i oriental del claustre de la catedral, i en direcció oest/est en l'ala meridional i a dins del pati. Aquesta intervenció pretenia comprovar el subsòl d'aquest espai, elevat artificialment en el segle XI i mirar, en l'ala de migdia, si la vella muralla romana s'hi trobava a sota, tal com s'havia escrit alguna vegada o s'havia de cercar per sota dels murs del temple (o més enllà). Els resultats confirmen el que ja sabíem en relació a l'elevació artificial d'aquest espai, la inclinació clara sud/nord i la no existència, sota l'ala de migdia del claustre, de cap indici de la suposada muralla damunt de la qual degué cavalgar la paret septentrional de la catedral romànica, primer, i gòtica, després.

També efectuà prospeccions a l'exterior de la seu (plaça dels Apòstols, escales catedral i plaça de la Seu, del quals no en tenim dades i que, de moment, no podem comentar.

Dins del temple, el radar sembla constatar l'existència d'una sòlida plataforma rocosa, plana o aplanada més enllà (est) de l'àrea ocupada pel cor, una gran fondalada coincidint amb l'inici del presbiteri i terra de farcit i una inclinació constant en direcció a les escalinates (ponent). Aquestes dades, que caldrà matisar i disposar sobre la planta del temple, coincideixen i precisen allò que sabíem per algun petit sondeig arqueològic o que havíem suposat a través d'altres camins.

LA PROSPECCIÓ COM A PROTOTIPUS

Aquest aparell, aparentment simple i de fàcil utilizació, treballà exclusivament a l'interior de la seu, que fou repartida en dos sectors segons la disposició de l'orgue, el qual constituí una andròmina gegantina que condicionà la claredat de les conclusions finals. Del mur de façana a l'orgue, les lectures s'efectuaren en línies paral.leles disposades cada metre en direcció nord/sud (18 en total), mentre que de l'orgue al presbiteri les línies de lectura seguien la direcció oest/est i, també, en bandes paral.leles disposades cada metre (21 en total). Les línies nord/sud amidaven vint-i-cinc metres i les oest/est com a màxim quaranta-cinc, havent-se prospectat en total, cada metre, un rectangle teòric de 65 m. de llargària (oest/est) i de 25 m. d'amplada (nord/sud).

Al llarg dels murs septentrional i meridional del temple l'evidència física d'un seguit constant de tombes (perfectament identificades amb l'aparell), varen obligar a prescindir dels resultats d'aquestes dues bandes. No és possible saber, amb aquest mitjà, que hi ha per sota de les sepultures. Altres tombes dipositades al mig de la nau i ben documentades també foren tingudes en compte.

El resultat obtibgut, simplificat i corregit a partir de dades arqueològiques o documentals i de les proporcionades pel radar complementari de resolució espacial (per tant,dades contrastades a partir de dos sistemes absolutament diferents la qual cosa és indicador dades fermes) permet observar l'existència d'una (o unes) estructura disposada centralment, ocupant l'espai que hi ha del cor al presbiteri, ben orientada segons l'eix est/oest amb el mur(?) de llevant, corbat. Més cap a occident del cor no hi ha dades d'estructures, coincidint amb la porta lateral de Sant Miquel, que comunica amb el claustre i amb el museu de la seu. Més cap al sud-oest, es constata l'existència de clares evidències estructurals adoptant, pel que sembla, una disposició esbiaixada sud/est-nord/oest que continuaria per sota dels murs de la seu de Santa Maria. No sabem amb seguretat, sense una excavació del subsòl, de què es tracta, Tanmateix, l'existència ben documentada de l'anomenat <u>Cloquer Vell</u> de la seu pre-romànica, que continuà en ús fins a la costrucció de l'edifici gòtic i que sabem que es localitzava al sud-oest del temple, sembla ser la hipòtesi més versemblant. També podria tractar-se de les restes estructurals d'una illa de cases que hauria ocupat aquell sector.

Cap a l'escalinata els resultats de la prospecció assenyalen material de reble, com si aquell espai hagués estat farcit per aconseguir una cota plana de circulació davant la la portalada de la catedral, la Galilea on, recordem-ho, s'hi alçava el Pedró, indret en el qual tenien lloc algunes cerimònies pròpies de la vida ciutadana.

A partir d'aquestes dades sembla relativament senzill, explorant uns punts concrets de l'edifici, resoldre la major part dels problemes topogràfics que planteja aquest important sector de la ciutat.

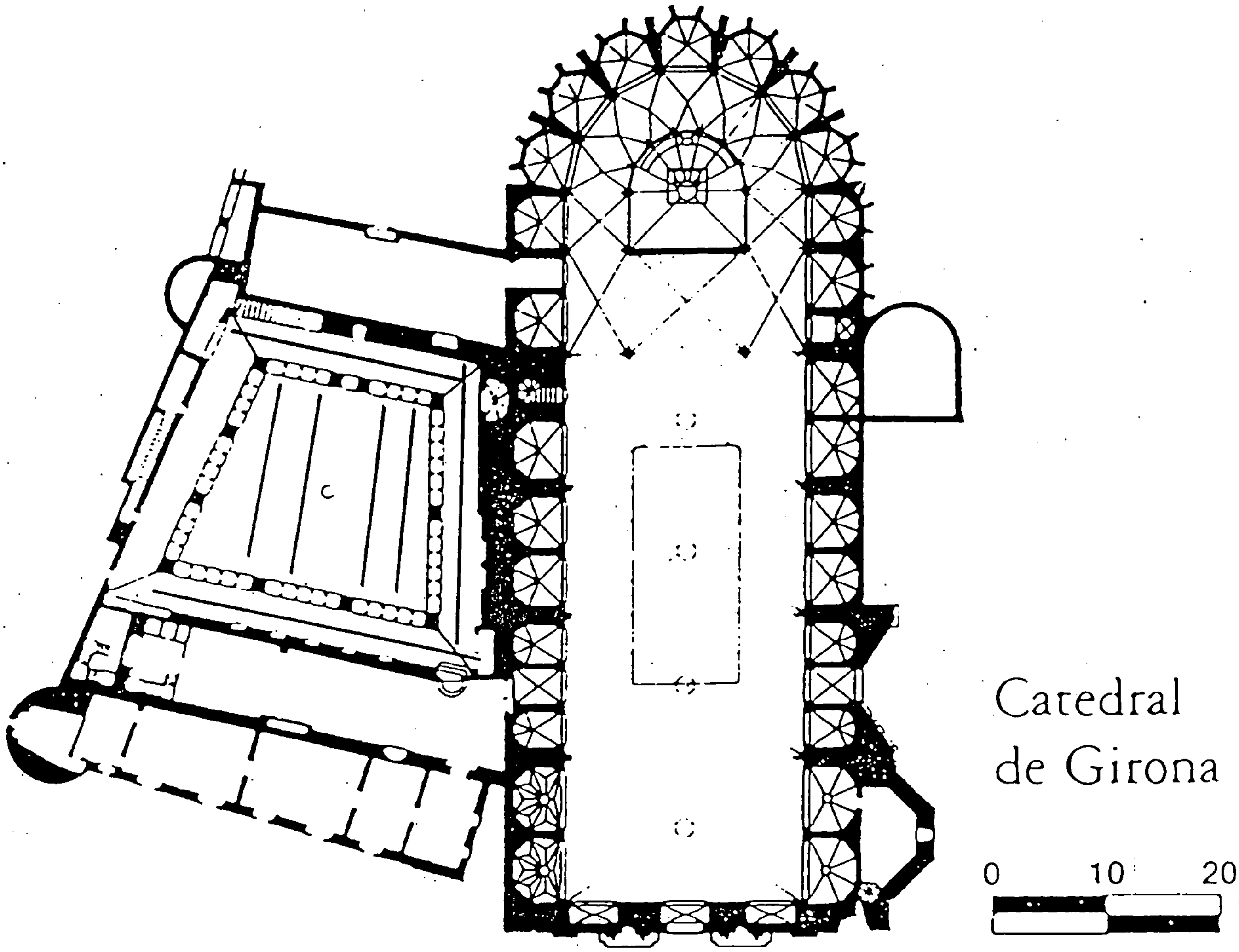

Fig.1: Planta de la catedral de Girona on s'assenyalen els indrets prospeccionats.

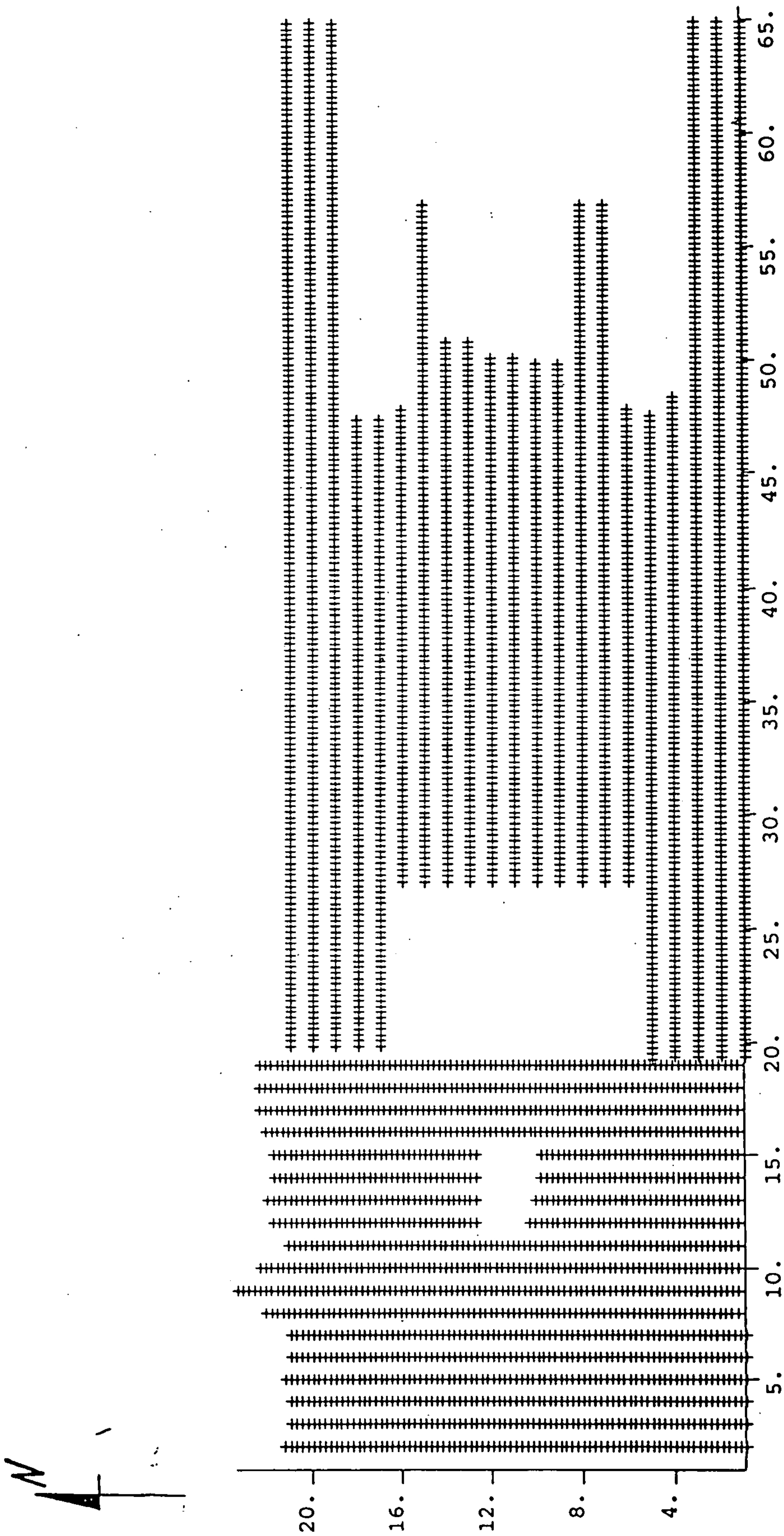

Fig.2: Prospeccions a l'interior de la Seu. Línies i distància de les lectures.

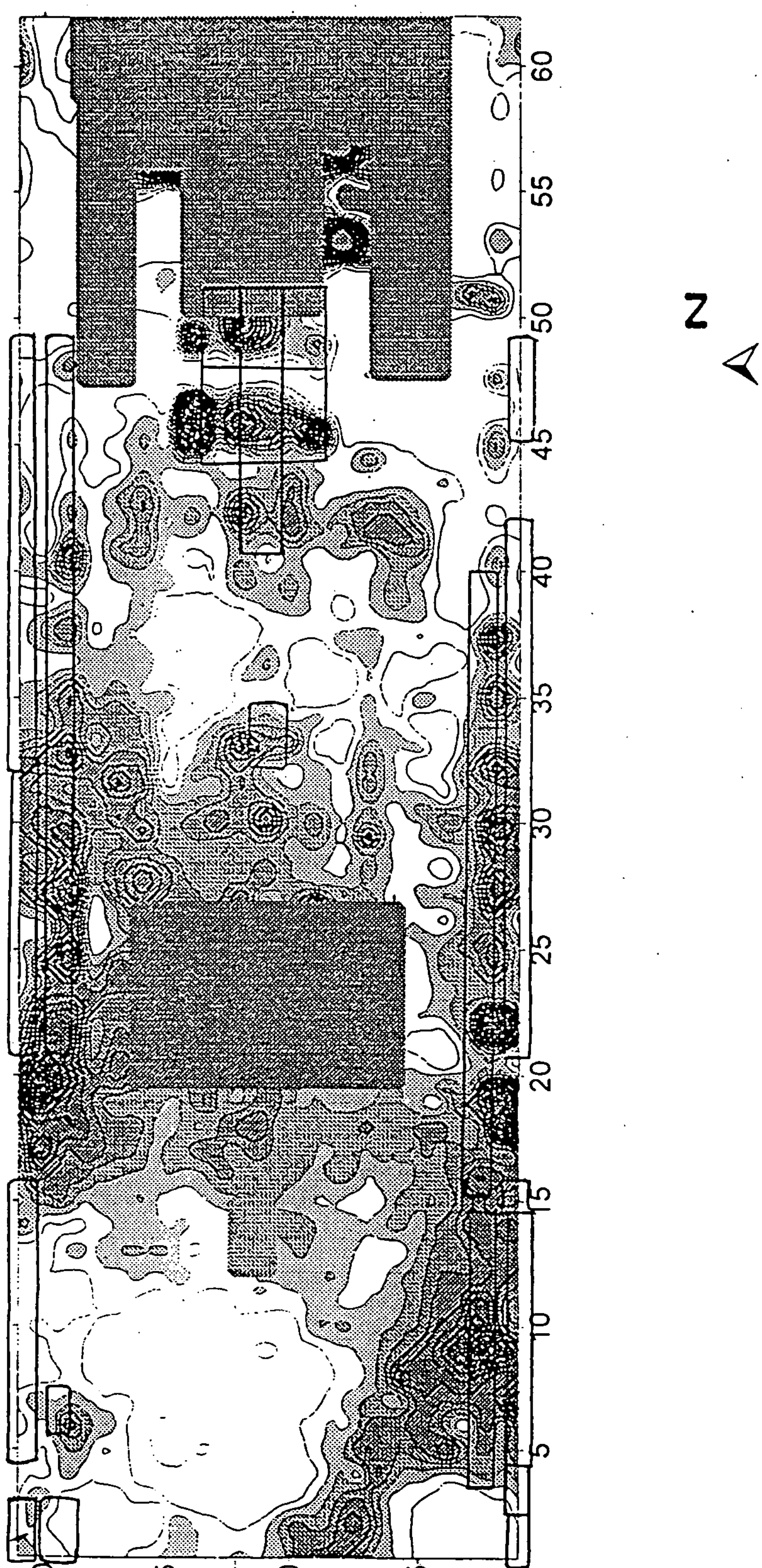

Fig.3: Interior de la Seu. Plànol conjunt de les evidències aconseguides amb el radar complementari i el radar de baixa freqüència.

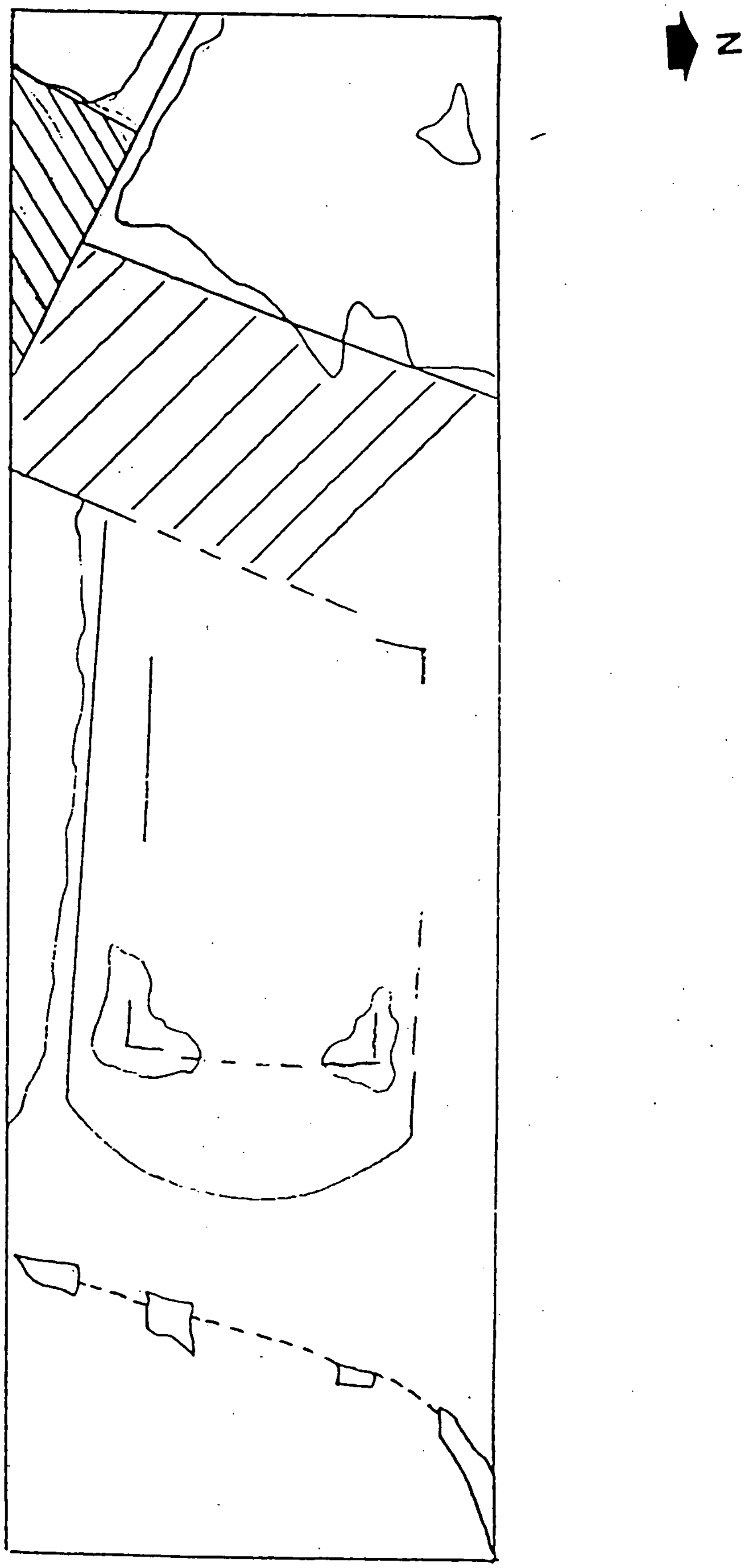

Fig.4: Interior de la Seu. Croquis interpretatiu dels resultats

GEOPHYSICAL INVESTIGATION OF THE BASEMENT OF STANDING MONUMENTS: THE CATHEDRAL OF GERONA (CATALUNYA- SPAIN)

(running head = geophysical investigation of a cathedral)

Michel DABAS (1), Christian CAMERLYNCK (2), Pere FREIXAS i CAMPS (3)

ABSTRACT

Within the frame of an international co-operation scheme (AIP PICASSO) between CNRS (France) and the University of Barcelona (Spain), two geophysical methods were used to assess the possible buried structures under the present cathedral of Gerona. The use of geophysical technics in an urban context has to face many problems in relation with the accessibility to the investigated surface or with the inherent electromagnetic noise: the combined use of electrostatic and radar surveying has proved to be very efficient in most cases.

The electrostatic apparatus, a prototype built in our laboratory for archaeological and civil engineering applications, enables the measurement of apparent electrical resistivities directly above insulating surfaces like those encountered in standing archaeological monuments (concrete, limestone or marble slabs).

Radar instrumentation an enables the measurement of apparent dielectric permittivity. Probing the very near sub-surface (0-2m) implies a major constraint: a very high spatial sampling has to be achieved in both directions. Both methods, electrostatic and radar, can achieve this goal. Moreover, both of them may be operated continuously allowing a fast sampling strategy.

Results of the comparison on one profile of the step by step and continuous reading electrostatic measurements points out the accuracy that can be obtained by the latest. An isoresistivity map was obtained for a 20x60m area. A set of punctual resistive anomalies are found in concordance with known structures (graves) but wider anomalies may be related to unknown structures linked with foundations of former buildings.

Parallel radar profiles were collected and CMP soundings were also performed to achieve the conversion between time and depth slices. The time slice centered at 14ns (depth of 0.8m) show surprisingly the same anomalies pictured by the resistivity map. This coincidence has already been observed for other surveys. Since two different physical properties are measured -electrical resistivity and a reflectivity coefficient function of the contrast in dielectric permittivity- we suggest that both methods are mainly sensitive to the water content of the volume under investigation.Finally a global interpretation is proposed to the archaeologist.

INTRODUCTION

The use of geophysical technics for archaeological investigations is well established for more than forty years (REF. N0 SPECIAL GEOPHYSICS...). The usefulness of different geophysical technics (resistivity, magnetometry etc.. to quote the most used), for archaeological site investigation such as roman towns, old fields boundaries, Neolithic enclosures etc... is well known. But when considering all the possible fields of application, some restrictions do apply due either to the complexity of the site or the "state" of the investigated surfaces or volumes. In the first case, the stratigraphy of the archaeological site can be too complex to be pictured by existing technics. This is specially true for areas where human settlements occur at the same geographical position for centuries. Such a case happen very often in urban areas or artificial hills (tell) for example. In the second case, the "usable" surface or volume for surveying is not appropriate for geophysical surveying. This is of course the most important restriction. We consider in this case two categories:

- the restriction comes from geometry: the sensor is too large or the surface/volume too small to operate properly. This can be the case if we want to use a Slingram apparatus in a cave for example or a bad shielded radar in the same context. Moreover, interpretation to be reliable needs as much possible data as possible over a wide area and specially if the origin of the anomalies is deep;

-the restriction comes from noise: magnetic anomalies due to archaeological objects are interpreted with a resolution of 0.1 nT and this cannot be achieved in urban areas. Another example is the use of classical galvanic methods which cannot be used over insulating surface (tarmac, slabs, etc.) due to the high contact resistance encountered in urban areas.

When considering the case of "urban" Archaeology, most of the restrictions quoted before unfortunately do apply. This is why, apart from specific investigations over limited volumes , more related to civil engineering (tomography of pillars, search of voids), it is hard to find any application of archaeological geophysics in urban areas.

But the demand for an expertise is urban areas is growing as a consequence of the development of new infrastructures (parking, lanes, buildings) and a consciousness for the preservation of our cultural heritage.

During the last four years, we have developed a new approach for the survey of historical buildings and especially for the location of previous foundations. Investigation of the upstanding walls is not within the frame of this paper but is also a facet of this problem and is addressed by our research team (Soufiche etc...). Several historical buildings were investigated with the same questions which can be summarised as follows: " Where are the foundations of the previous buildings"?

The two following technics were tested and operated during the last four years: Ground Penetrating Radar (GPR) and electrostatic resistivity. Several monuments were investigated: the cathedral of Chartres (Dabas & al., 1993)and the abbey of Saint Germain d'Auxerre (France), the cathedral of Gerona (Catalunya, Spain) and very recently, the cathedral of Varszawa (Poland). The survey of Chartres revealed the porch of Fulbert -named after an XI century

Future improvements in radar surveying will be the use of continuous measurement with a distance encoder and a high speed interface. But first trials show that the maximum speed for displacement of antennas is still very slow compatible with a high spatial sampling. Automatisation of data processing is done and script files enable the production of time slices very easely thus minimizing the time needed for data manipulation.

On the other hand, with different electrode spacings corresponding to different electrostatic quadrupoles, it is now possible to get an idea of the vertical variations which is only possible nowadays with the radar. This prototype was built and is under test. But work has still to be done to invert the true resistivities from apparent resistivities (Dabas &al., 1995). Nevertheless, limitations of the accessible surface in monuments also limits the maximum extension of the quadrupole.

ACKNOWLEDGMENTS

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bishop who ruled the reconstruction, of the ancient cathedral which burned in 1122. During the survey of the cathedral of Varszawa, an unknown crypt - part of an existing funerium- was discovered and is not yet excavated.

The survey of the cathedral of Gerona takes place within the frame of an international exchange program (AIP Picasso) between CNRS (Centre de Recherches Géophysqiues) and the University of Barcelona.

Like in any archaeological investigation, a very high spatial sampling must be achieved as a consequence of the burial depth of the searched structures which can be as low as 0.2m. Moreover, using radar pulses at a frequency of 450MHz implies a spacing between measurements of the order of 5cm to avoid aliasing effects. To be time-effective, the instrument must have some kind of logging capabilities and must be operated quasi-continuously. Moreover, the instrument must be insensitive to external electromagnetic noise, and not (too) sensitive to very shallow structures like metal pieces which could saturate the electronics of the sensors.

INSTRUMENTATION :COMBINED USE OF ELECTROSTATIC AND RADAR SURVEY

The two main methods used in archaeological investigations that is resistivity and magnetometry cannot clearly be used. Resistivity has to face the problem of injection of a current and measuring a potential where the surface is an insulator (tarmac, pebbles, concrete or marble slabs). This is why we have turned to electromagnetic methods. The use of magnetometric methods is not possible due to the presence of metallic objects like grilles, ancient re-bars, etc., in the vicinity of the sensors.

the electrostatic quadrupole was designed as an alternative to galvanic (DC) surveying. The principle has been discussed by Grard and Tabbagh (Grard, Tabbagh, 1991; Tabbagh al., 1993) and can be summarized as follows: an insulating plate which is lain on the ground surface is charged with an alternative charge Q(t). Consequently, a charge -Q(t) exists by symmetry in the ground of permittivity ε. The potential induced at a distance R is:

$$V(r) = \frac{-Q(t)}{4 * \Pi * R} * \frac{2}{(1+\varepsilon_r * r)}$$

with ε = εr * ε0

The measure of the potential between M and N follows the same principle, the sensors (insulating plates) being passive. The measure is that of an impedance Z = Vr/I, I being the current injected (= j ω Q).

$$Z = \frac{1}{(4 * \Pi * j * \omega) * r} * \frac{2}{(1+\varepsilon_r)}$$

The four sensors are assembled in a fixed quadrupole which can be towed continuously on the ground surface. The impedance for a quadupole canbe expressed in the same manner as in eq.

When considering a complex permittivity expressed by $\varepsilon^* = \varepsilon - (j/\omega\rho)$ where ρ is the resistivity of the medium, it can be shown that within the classical low number induction aproximation ($1/\rho\varepsilon\omega << 1$) , the in-phase component of the potential is directly proportionnal to the resistivity. The equation is similar to the one in DC electrical surveying.

The application of radar in the field of Archaeology dates back to ... (reprendre l'expérience de Chypre ou de Sutton Hue ...). Some recent surveys (reprendre Nishimura, Camerlynck ...) has proved the potential of such technic when appropriate data analysis is performed and a correct 2D sampling scheme used in the field. Our experience has laid us to dismiss any interpretation of the profiles and we have focused on the creation of time-slices which represent the back-scattered energy summed over a time-window of a few nanoseconds. These slices can be converted to depth slices if we assume that the velocity (computed by a CMP shot) is constant over the whole area surveyed. These three-dimensional images of a site resulting from a radar survey is -up to now- unique even if the application of radar in Archaeology is very expensive.

texte christian ......

SITE

The cathedral of Girona (Catalunya- Spain), is located in the North part of the old town limited by a still standing roman (enceinte ...). The town was founded by the roman general Cneius Pompeius Magnus in 72 BC but a prehistoric settlement may have existed (Girona, Fabre i Fornaguera). The town is centured by a wall with a triangular shape. This unusual shape for a roman settlement, is the result of the topography (éperon...).Even during the decline of the roman empire, Gerona remains an important town and became the siège épiscopal... (Vith century). The cathedral is built in ... vestiges du XII et XVII siècle....

FIELD SURVEY OPERATION

The available surface for surveying is (20x70m). The areas which were not surveyed corresponds to the place of a gisant, the organ and an area delimited by the choir. For practical considerations, 19 profiles in the North-South direction was collected over the West part of the cathedral and 21 profiles perpendicular for practical considerations in the East part of the cathedral. Profiles are parallel and one meter apart. The size of the square quadrupole is 1.3m which gives a maximum investigation depth of the same order.

Acquisition of data is done continuously along these profiles with a fixed time-base (the resultant distance interval is of 3cm with a mean walking pace). Every meter, a distance mark is manually recorded. Post-processing of the data consists in two steps:

(i) filtering the data with a moving window of 31 points (approximately 1.0m). A simple average was performed due to the high quality of the data . There is no need of a more robust filter like median because there is nearly no outlier.

(ii) linear reinterpolation of the data between two fiducial marks in order to obtain equally spaced (1.0 m) data.

The position of the data is pictured in figure 2.

To test the new acquisition device and the feasibility of a continuous measurement over an uneven surface, we have made a comparison between data acquired point by point (manually) and data acquired continuously by our data acquisition system. (Figure 1).

Correlation between step by step and continuous measurement is not obvious : two effects has to be taken into account : irregularity uneveness) of the pavement of the cathedral and possible voids between the pavements. On the first hand, the electrnic circuitry should cope with any rapis change of the impedance (like 'a coup de prise' in DC electrical surveying) due to any change of the distancebetween the poles and the pavement. On the other hand, voids and/or heterogeneous fillings betweens the slabs may create a periodic artefact.

The last one have been filtered slightly over a window of 0.7m and an arbitrary shift was introduced for the resistivities acquired manually in order that the two curves do not overlap. A very good accordance is observed and this test proves the feasibility of a continuous measurement with an electrostatic quadrupole. The correspondence between data obtained with this E.S. quadrupole and resistivities measured with a resistivimeter was previously shown (Mounir, 1995).

DATA INTERPRETATION

It is then possible with such a device to measure continuously the apparent electrical resistivity of the ground . The depth of investigation is the same as the one obtained in DC electrical surveying and is mainly limited by the geometry of the quadrupole.

In order to elaborate an isocontour map, variogram of the data was computed with the 4392 resistivities. The variogram observed is linear with a nugget effect equal to 0 and a length of 4 m. Resistivities span between 41 and 1440 Ω.m with a median value of 252 Ω.m (mean 276 Ω.m, standard deviation 129 Ω.m). As opposed to the data taken in the field and submitted to meteorological conditions, we want to stress the fact that these values should be constant with time.

Data were then spatially reinterpolated in both directions using the above parameters with a 0.25 x 0.25 m grid size. The map obtained (Fig 3) use grey scale levels (high resistivities in white, low in black).

When considering the spatial content of the map, it is clear that short wavelengths (<2m) are observed in the East part of the cathedral and that, beyond a limit which is under the location of the organ, longer wavelengths are observed between the organ and the porch. This fact cannot be explained by already known structures but a difference in the time of construction is known to exist between the western part (XVIIs.) and the eastern part (XVs.).

Some of the short wavelength anomalies can be explained by known objects. Along both sides of the cathedral, two rows of tombs are visible and are clearly seen on Figure 3. Even if some of the anomalies are coalescent , individual tombs were clearly delimited.

On the South-western part of the cathedral, a linear resistive anomaly is seen which runs in the NW-SE direction. At the SE termination, the anomaly widens and this could be in relation with the basis of the south tower.

When considering the other anomalies, an interpretation was made which has to be tested by field excavation. Apart from the previous anomalies, attention is drawn on a curved conductive anomaly just in front of the actual choir. This anomaly seems to go on on the southern side of the cathedral and an interpretation is drawn on figure 4. We think that this anomaly could be the result of a previous construction of the cathedral (that is before the XII century). The anomaly being conductive, we can consider that what is seen is the filling of the basement of this structure from which stones were removed.

The strike of this possible construction is not the same as the actual one, but this fact is known to happen for other religious monuments.

Texte Christian .....

CONCLUSION

The combined use of GPR and electrostatic survey for the assessment of possible buried structures below standing historical monuments has proved to be feasible in the context of the cathedral of Gerona. Their use was also tested on other monuments (cathedral of Chartres and Warswawa, abbatiale of Saint Germain d'Auxerre) and the conclusion are identical: Electrostatic survey enable a very rapid survey of the investigated areas by the use of continuous readings now triggered by a distance encoder in the last version of the apparatus. This gives a good insight of the lateral variations of the resistivity below the insulating surface which is often made of slabs, tarmac or concrete. But it is clear that the structures under the historical monuments are the result of a very complex history and they certainly overlap each other. Moreover, anthropic deposits may attain 10 meters or more and it is clear that up to date, it is impossible to separate individually two walls for example which are 1 meter apart at a depth of two meters or more with a non destructive survey. Even if it is the hope of the archaeologist, it is not possible to get a clear idea of the 3D structure of the ground. This is why we have turned to the use of GPR to get a better insight of the vertical variations. Data collection and processing is also more time-consuming. Getting time slices by computing the reflected energy over a vertical time window allows the display of maps which can be computed for different time intervals. The knowledge of the velocity is necessary for the conversion of these time slices into depth slices. This is normally achieved by CMP sounding, but we must no forget that the velocity changes both laterally and vertically and the velocity used for the conversion is just an approximation. The archaeologist should be aware of this hypothesis and he must not take the depth slices as a true image of the stratigraphy with which he is accustomed.

The similarity between the repartition of apparent electrical resistivities obtained with the electrostatic quadrupole (a=1.3m) and the reflectivity map for a depth of X m is striking and is the major contribution of this paper. We think that a common physical parameter play a major role in both electrostatical and radar surveys. Water content is known to play a significant role in electrical surveying. In radar surveying, the contrast between permittivity of water and soil (10 to 80) is the highest encountered. As a consequence, we think that both methods are mainly sensitive to the water content of the investigated volume. The main advantage of using radar, despite its slowness and the heavy data processing, is the ability to get the vertical variations of the soil down to a depth where the signal to noise ratio tends to one.

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