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MAGNETIC AND GEOELECTRICAL MEASUREMENTS ON THE EASTERN HILL OF THE ARCHAEOLOGICAL SITE OF SELINUNTE

Abstract. Geophysical research into the archaeological site of Selinunte involved magnetic and geoelectrical investigations, which were based on knowledge of the characteristics of coeval settlements found at other archaeological sites. Detailed surveys were carried out in two areas suggested by the archaeologists. The main goal of these investigations was to test the reliability of the methods and to find the magnetic and geoelectric response of the shallowest materials in the eastern hill of Selinunte. The magnetic gradient maps show the signals from buried magnetic sources, which cannot generally be identified; however, a correlation can be established between the natural local background disturbed only in some spots, with weak and variable intensity, which correspond to the surficial features of the agricultural terrain. The very low values of the measured magnetic susceptibility do not reveal any significant magnetization of the surficial materials. The resistivity contour maps show a resistivity decrease towards the east, with scattered maxima which do not show any particular pattern. The maps of data collected from electrodes 1, 2 and 3 meters apart show that lithological and structural variations extend downwards. The geoelectrical section highlights three main levels: (a) a first layer, composed of surficial agricultural soil and containing remnants of the underlying bedrock; (b) biocalcarenite composed of cemented and very porous sediments, and (c) argillites underlying the biocalcarenites and occurring at limited depths (4-5 m). From a geoelectrical point of view, the general behaviour of the areas under investigation shows a resistivity decrease with depth. However, in the horizontal direction the situation is extremely variable and suggests the occurrence of more complex structures.

INTRODUCTION

The ancient settlement of Selinunte along the south-western coast of Sicily (Italy) is located on two small hills: on the eastern side there is the ancient township, whereas to the west there are remains of the Acropolis (Fig. 1).

The area selected for our geophysical investigations was regarded as a possible center of pre-colonial settlement, destroyed at the end of the 6th century B.C. and partially rebuilt after 409 B.C. On the northernmost part of the hill, there is also a Roman building complex, which represents the subsequent settlement of the area.

Within this area, two zones of small dimension were identified, measuring 90×90 m and 40×40 m, respectively; the first is located directly to the north of Temple G, and the second on the northwestern part of the hill (Fig. 1). They have a detrital cover of calcarenite, gravel with chert, and rare clay fragments; this cover overlies very compact, fine-grained biocalcarenites rich in quartz and in fragments of felsic magmatic affiliation (Amadori, personal comunication).

The program of geophysical investigation was based on our knowledge of the characteristics of coeval settlements found at other archaeological sites. There the foundations of the dwellings were formed by excavating quadrangular areas of bedrock; stone walls were then built around these excavations.

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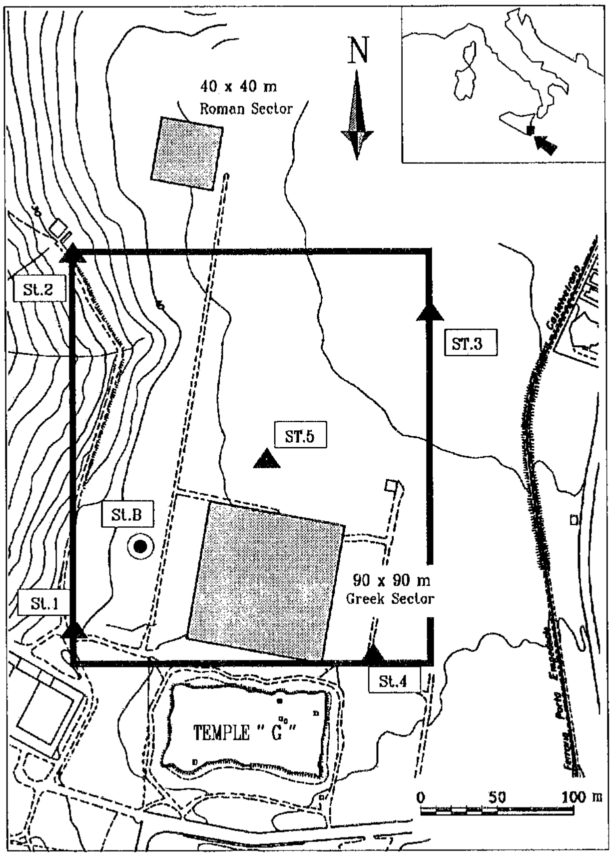

Fig. 1 — The western hill of the archaeological site of Selinunte. The two surveyed areas (90×90 m and 40×40 m), the magnetic site net (St. 1-5) and the magnetic station base (St. B) are reported.

METHODS AND INSTRUMENTS

The magnetic techniques used in this investigation were selected according to the most suitable types of instruments, which would provide the required types of response. In particular they were aimed at:

i) providing information of the magnetic environment under investigation;

ii) defining the distribution of the local anomaly field;

iii) evaluating some of the physical properties of the surficial materials, which directly influence the previous observations.

In order to achieve the first goal, it was necessary to evaluate the quality of the natural magnetic response from the area of investigation as a function of man-made noise, to establish the limits of its spatial variations, and to find the type and intensity of its time variations, apart from the measuring techniques adopted to minimize the error caused by such factors. Proton precession magnetometers, both in portable and in base-station mode, were used for this purpose, together with a magnetic theodolite. With these instruments, two Scintrex model MP3's and one Eda model DIM 100B, the absolute measurements in both space and time of the total intensity and dip of the local geomagnetic field were taken.

The second goal was achieved using gradiometric techniques, which have the advantage of receiving almost simultaneously the signals from two sensors located at a fixed height above

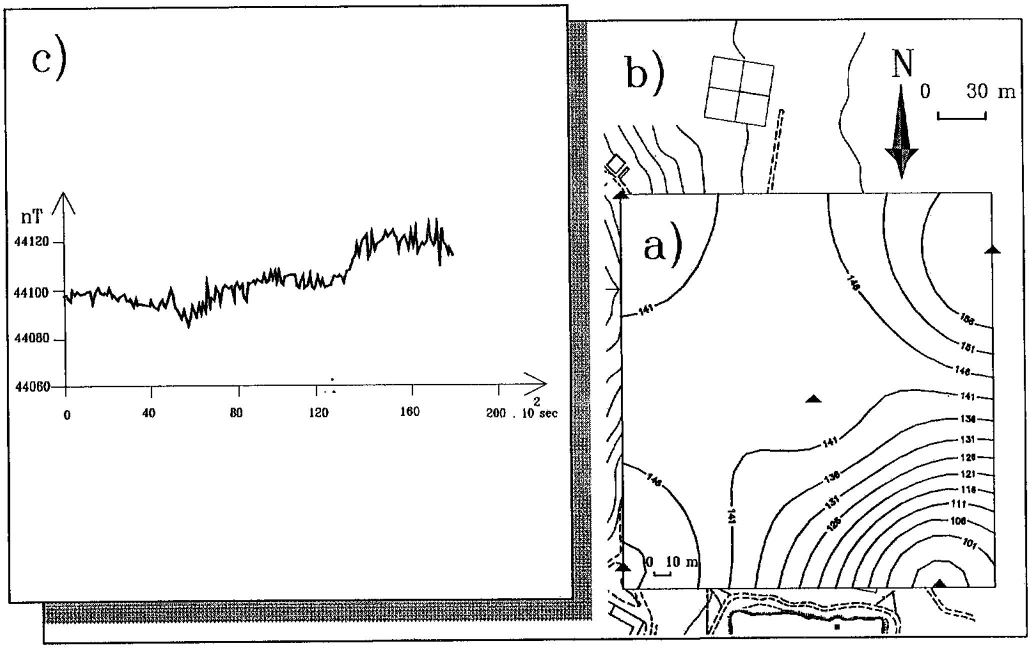

Fig. 2 — Contour map (a) of F intensity field (values in excess of 44000 nT); the operations area (b); time variations (c) recorded at St. B.

the ground. The use of the differential value avoids time correction of the field and adds information on its vertical gradient. The areas were gridded at a standard size of 1 m, and measurements taken using both a Scintrex MP3 proton magnetometer and a Geoscan FM 36 fluxgate magnetometer.

In order to achieve the third goal, we measured the magnetic susceptibility on a part of the same grid where the gradiometric measurements were taken. The induced magnetization of the surface layer and of the main rock types present in the area were investigated using a Bartington MS2 field susceptibility meter.

Two geoelectrical field methods were used: (i) electrode profiling according to the tripotential system; and (ii) vertical electric sounding using the Offset Wenner (OW) array. Both methods were adapted for measurements at shallow depths, as required by our investigation.

For the same profile, high density measurements (method 'i') can be used to obtain values of apparent resistivity with Wenner, axial dipolar and mixed arrays (Carpenter, 1955). The profiles can be analysed one at a time, and combined to form resistivity pseudo-sections or contour maps for different depths. Small dimension electrode arrays are used to investigate very small structures with resistivity contrasts which are not too high. The selection of the dimensions is based upon the hypothesis that the investigated structures are of limited extent (in meters), occur at depths of the same order of magnitude in the cover or in the upper part of the calcarenitic sublayer.

Offset Wenner sounding was used to determine the electrical response of the near surface layers. Such data allow a hightly controlled one-dimensional representation with respect to the lateral variations and evaluations of the errors which cannot be obtained otherwise (Barker, 1981).

The instrumentation, assembled at the Geophysical section of the Earth Sciences Department, Genoa University (Merlanti, 1990a), consists of: (a) a system of energizing source and measurement with polarity inversion of the type Pasi Digit E2; (b) a switching mechanism for the electrode array; and (c) a series of electrodes fixed in the chosen devices, formed by 24 Cr-steel elements, which are used to obtain N—3 measurements for each profile, N being the number of electrodes.

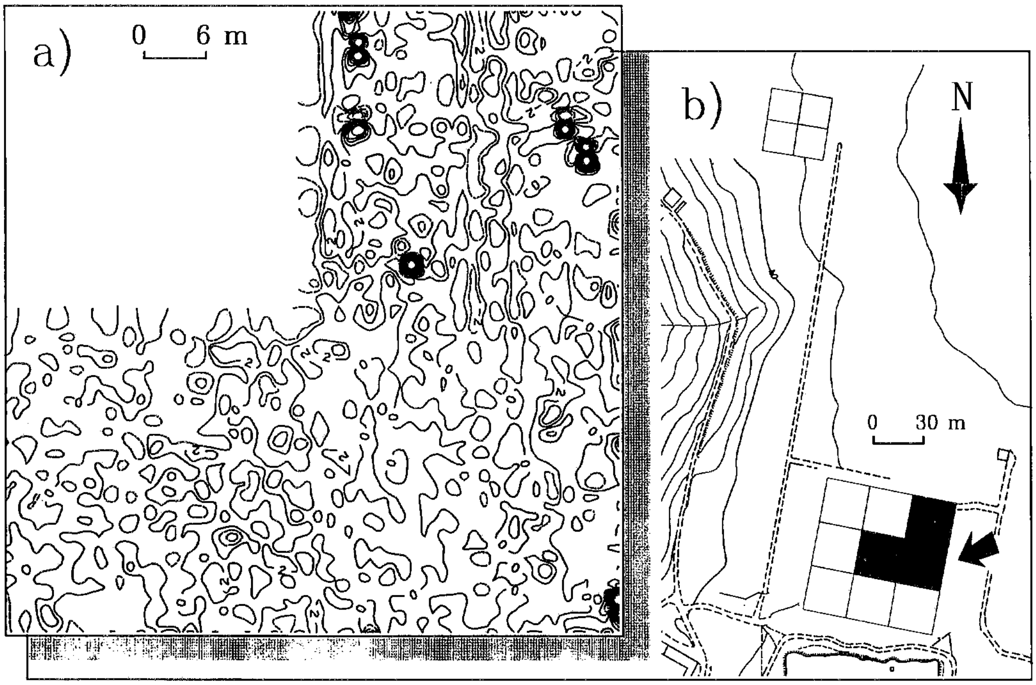

Fig. 3 — dF/dh gradient distribution map (a) in some sectors (b) of the 90×90 m area .

In the Offset Wenner electrical drilling, the electrode series, laid out in geometrical progression 2^n up to AB/2=16 m, is composed of 11 elements fixed while the measurements are taken (Barker, 1981; Merlanti, 1990b). Control of the whole cycle of measurement is done using the same evaluation criterion, as for the profiles obtained with the tripotential system.

DATA ACQUISITION

A general magnetic survey of the area was carried out, as previously mentioned, by measuring the geomagnetic field at five reference sites (Fig. 1). At each site (St. 1-5), we made simultaneous and absolute measurements of the total intensity F and the dip value I, then we calculated the H and Z components of the local geomagnetic field.

The observations were taken over a period of five hours, while a base station (ST. B) was monitoring F, to record the temporal variation of the geomagnetic field (Fig. 2c) and to make the reduction for its daily variation at the five test sites.

The detailed magnetic and electrical investigations were carried out in the two areas of Fig. 1. The main goal of these investigations was to test the reliability of the methods applied to specific problems. For this reason, we did not cover the two sectors entirely, but took measurements to understand the type of magnetic and geoelectric response of the materials closest to the surface on the eastern hill of Selinunte.

The parameter directly measured in a proton magnetometer survey is the vertical gradient of the total intensity F, whereas when using the fluxgate magnetometer it is the vertical gradient of the vertical component Z of the field.

Magnetic susceptibility measurements were obtained over a small area of the sites surveyed with the magnetometer MP3 (Fig. 4), in order to give a comparison between the distribution of the magnetic anomaly field and that of the induced ground magnetization.

The operational criterion of the detailed geoelectrical survey followed two different approaches:

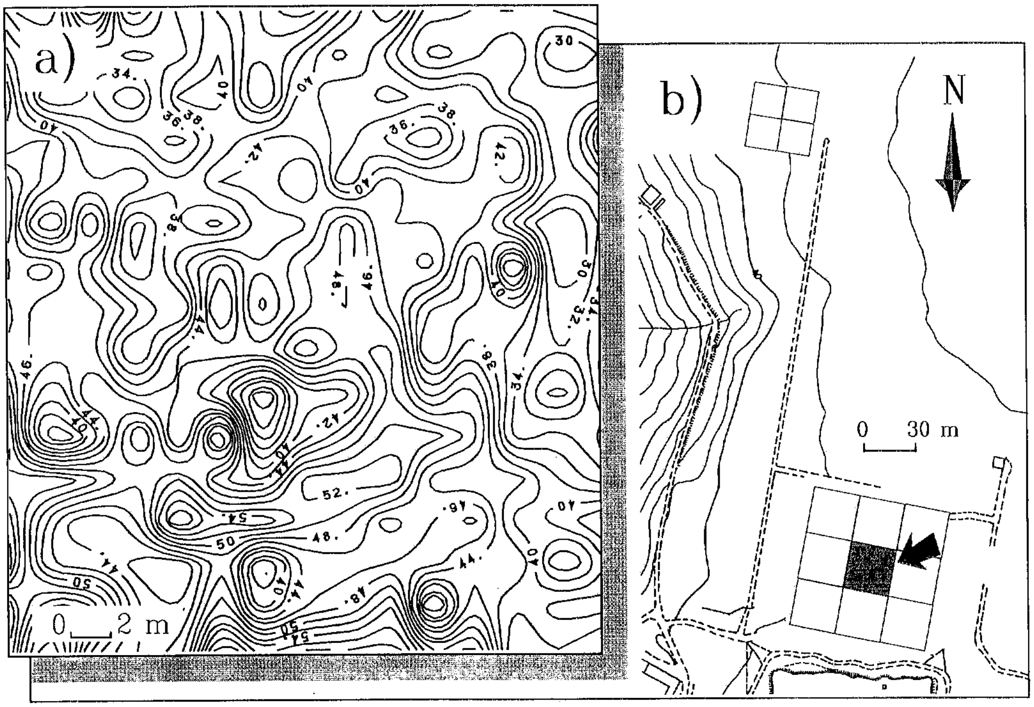

Fig. 4 — Susceptibility map (a) of the central sector (b) of the 90×90 m area.

it was mainly focussed on investigation of the surface cover with close profiles aimed at establishing a horizontal correlation, despite the presence of three different levels; whereas the OW geoelectrical sounding was employed to obtain the response of the vertical distribution of the electrical resistivity.

18 profiles were obtained using the tripotential method over the 90×90 m area (Fig. 7) with a series of electrodes located 1 m apart and aligned in an E-W direction 2 m apart.

10 of the OW soundings were carried out in the same sector: they were located 10 m apart and oriented roughly E-W with a maximum AB/2 distance of 16 m (Fig. 9).

An example of the tripotential profiles carried out in the 40×40 m sector is shown in Fig. 10. The purpose of such profiles is to arrange the data as pseudo-sections; thus they were aligned with distances of 1 to 5 m between electrodes. This implies that, with a series of 24 electrodes, 21 values can be determined for distances of 1 m between electrodes, but only 9 for distances of 5 m. The pseudo-sections, although not of immediate geometrical significance, allow a 2-D representation, which gives useful indications on the electrical behaviour of the subsoil and allows us to detect any possible deep extensions of surficial structures (Edwards, 1977).

EXPERIMENTAL RESULTS

The results of the geomagnetic test sites are summarized in Fig. 2a, which shows the contour lines for F, which was measured directly. The maximum horizontal gradient measured for F is about 0.3 nT/m, whereas the minimum is about 0.2 nT/m. For the 90×90 m sector within the area limited by the data points, a gradient of about 0.25 nT/m was measured along the NW-SE direction of the local trend.

The vertical gradient dF/dh shows small shifts from the medium value of a few nT/m units in the elements of the 90×90 m sectors, and the contour lines do not generally show characteristic patterns (Fig. 3). In the 40×40 m sector, the SE and NW squares show some discontinuities in the gradient; in particular, one of them has a dF/dh value of about 42 nT/m (Fig. 5).

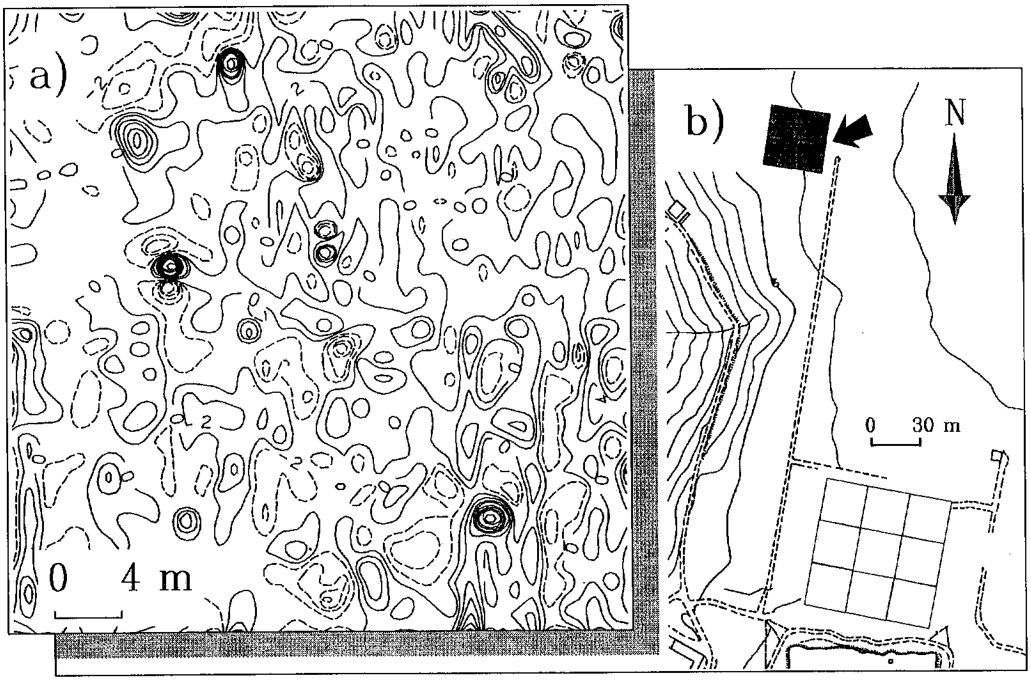

Fig. 5 — dF/dh gradient distribution map (a) in (b) the 40×40 m area.

The vertical gradient dZ/dh also does not show particularly high values with respect to its average distribution, even if some values suggest a comparison with the results of other geophysical investigations in the area (Fig. 6).

The values of the susceptibility fall between 30 and 60×10^{-6} SI, and the most common variations appear to be concentrated in the southwestern part of the sector (Fig. 4). In Fig. 7 the maps related to the distribution of the apparent resistivity for distances of a = 1 m between electrodes are shown. Beside the alpha, beta and gamma configurations, the pattern of the beta/gamma ratio is presented. Of all the possible values measured with the tripotential method, this ratio appears the most sensitive to lithological heterogeneities and is the best to interpret quantitatively. Within a homogeneous medium, the beta/gamma ratio is, of course, equal to 1, but, where some heterogeneities are present, it is higher or lower than for positive or negative resistivity contrasts, respectively.

The spread of the values shown in the maps is partly due to the signal fluctuations caused by structures with sizes comparable to those of the electrical device in use. These effects can be removed using linear digital filters with characteristics dependent upon the length of the profile, the size of the structures creating the interference, and the assumed depth of the structure under investigation (Pattantyus, 1986; Merlanti, 1990b). In Fig. 8 an example of the application of such filters is shown: it is an expanded offset filter with four non-zero coefficients (Acworth and Griffith, 1985).

The OW soundings were initially processed analytically (Barker, 1981), and then interpreted with classic inversion methods. The resistivity soundings were then joined to form the resistivity section shown in Fig. 9.

For the 40×40 m sector, Fig. 10 shows the group of pseudo-sections obtained for profile 2, including the beta/gamma ratio derived analytically. Along each profile, for different spacings between electrodes, preliminary filtering was carried out before contouring the data in pseudo-sections. The pseudo-sections related to the other profiles are not shown here because of restricted space; however, they correlated well with them.

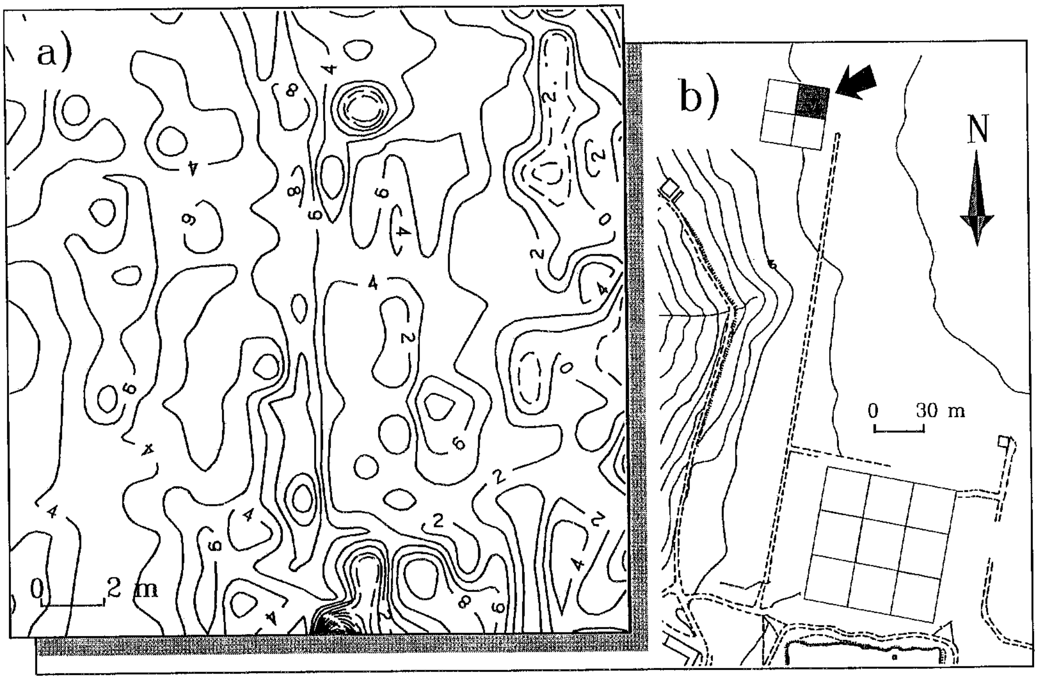

Fig. 6 — dZ/dh gradient distribution map (a) in (b) the NE sector of the 40×40 m area.

DISCUSSION

These preliminary geomagnetic observations are of course influenced by the nearby of Selinunte. In general, the variations of the magnetic field are higher towards the zone which borders the railway line (currently not in use) between Porto Empedocle and Castelvetrano, and the road which follows the railway tracks. Regarding temporal variations, the magnetic field illustrated in Fig. 2c recorded on the test site adjacent to the 90×90 m sector (St. B) is "typical" of the temporal pattern of F during the days the magnetic measurements were obtained on the eastern hill of Selinunte. It is observed that the geomagnetic variation does not appear to be influenced by strong man-made noise. The values of the dF/dh gradient in three of the nine sectors of the 90×90 m area (Fig. 3) show similar features. Small magnetic anomaly spots can be correlated with small, burnt areas used to dispose of agricultural waste. No other signal coming from the subsoil, except for the one with a surficial ("pellicular") response, appears to significantly polarize the local field. The central sector gives a typical such signal and highlights a pattern which cannot be correlated with any buried structure, but shows a style of variability similar to that of the magnetic susceptibility of the ground (Fig. 4). In the 40×40 m sector, the two gradiometric techniques do not reveal any more significant patterns than those of the previous sector. The only exception might be the anomaly of the NW sector; however, its small diameter in a type of ground where numerous ceramic fragments can be found at surface limits its significance. Conversely, the SE sector shows a stronger perturbation than the others. Overall the 40×40 m area presents features which will be more easily interpreted when more geophysical data are available.

In conclusion, the measurements on the net formed by the test sites defined, although only schematically, the geomagnetic environment where subsequent detailed measurements were carried out. Its geophysical significance can be found, to a certain extent, in the geological-lithological characteristics of this area, which show no significant variations of the magnetic properties of the materials which form the basement of the archaeological site. From a

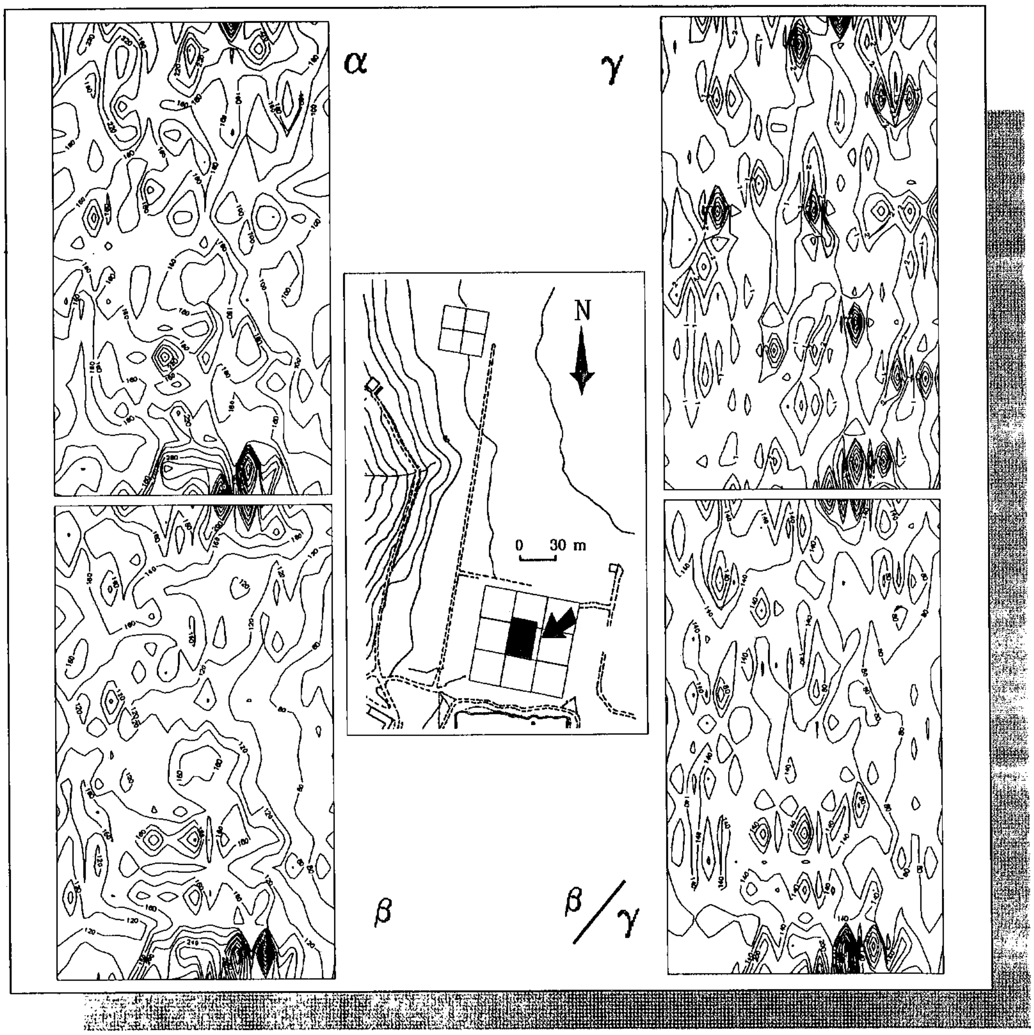

Fig. 7 — Isoresistivity maps, for the α, β, γ, β/γ electrical configurations, from tripotential measurements in the central sector of the 90×90 m area.

methodological point of view, the strong correlation between signal and disturbance, and the high spatial and temporal continuity of the local geomagnetic field bring us to the conclusion that the magnetic methods do not apparently exclude their use on the eastern hill of Selinunte.

The proton and fluxgate magnetometer measurements were used to produce maps of the spatial distribution of the local magnetic field and of its vertical component in some sectors of the eastern hill of the archaeological site. Such maps show the extreme variations of the measured parameters.

Signals coming from buried magnetic sources generally cannot be identified; however, for the intensity and distribution, a correlation can be established between the natural local background and some small areas of disturbance of weak and variable intensity. These appear to correspond to the surficial features of the agricultural ground. This hypothesis is supported by the distribution of the induced magnetization of the ground itself. The very low values of the measured magnetic susceptibility do not suggest a significant magnetization of the surficial materials.

In any case, we measured values of the same order of magnitude on calcarenitic outcrops

Fig. 8 — Filtered maps of Fig. 7.

to the north of the area under investigation, i.e. on a rock type which appears to underlie the soil cover. At least, as far as this aspect is concerned (taking also into consideration the full action of possible sources of residual magnetization), there seem to be no natural magnetic contrasts strong enough to explain the occurrence of induced magnetic anomalies masking those possibly produced by an archaeological level rich in relics, which can be the source of a strong magnetic signal.

The resistivity contour maps (Figs. 7 and 8) for the 90×90 m sector show a resistivity decrease towards the east, which is supported by other types of electromagnetic measurements (EM-31 and VLF) from the same area, with scattered maxima (except for that close to the southern boundary) which do not show any peculiar pattern. This fact is evident in Fig. 7, where the processing was carried out on data obtained from electrodes which were set 1 m apart. The same pattern of the beta/gamma ratio shows a series of small or very small islands, which suggest the occurrence of scattered surficial structural elements.

The maps (not presented here) of data collected from electrodes 2 and 3 meters apart show that, although the scatter of the anomalies decreases, the minima and maxima previously indicated still remain evident. This supports the speculation that lithological and structural variations extend

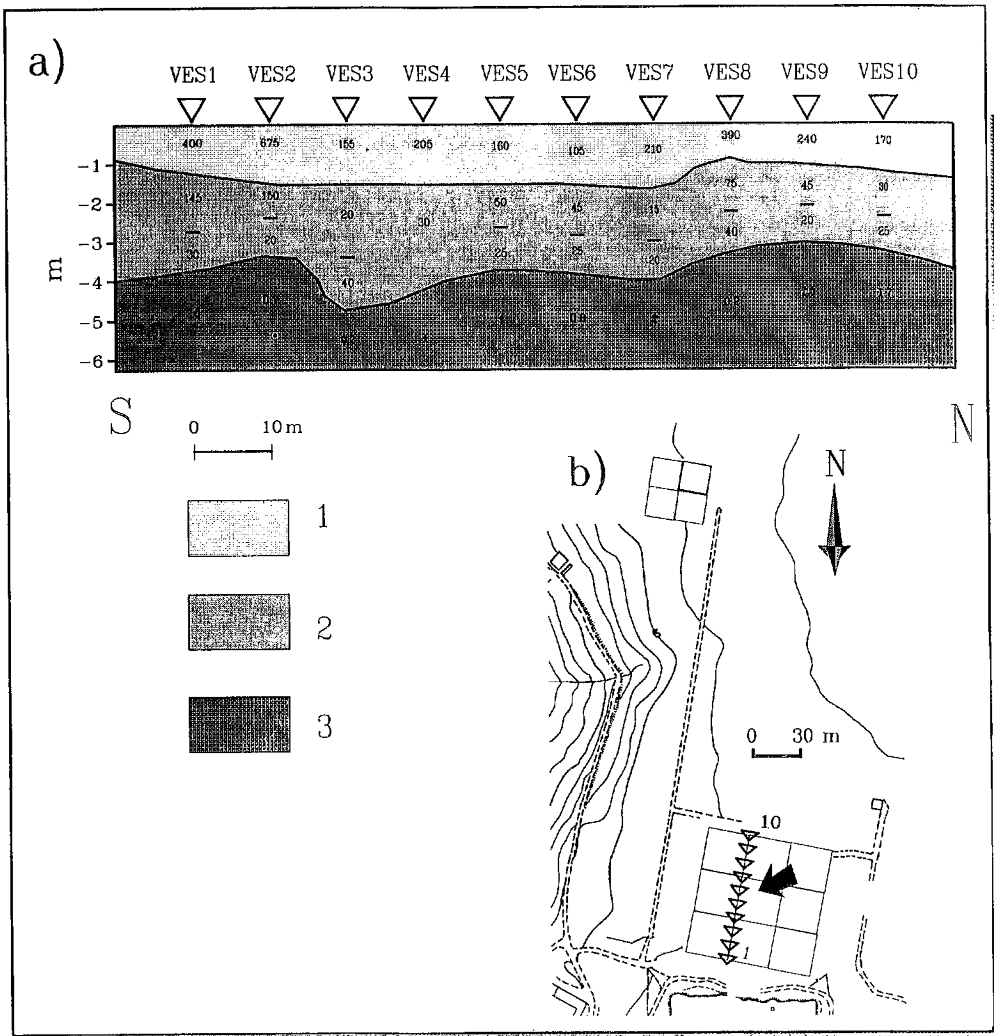

Fig. 9 — Offset Wenner (OW) soundings (Ves 1-10) and resistivity section (a) across (b) the 90×90 m area.

downwards.

The pattern of the beta/gamma ratio shown in Fig. 8 seems less casual than in the unfiltered data. The depth reached through this set of profiles is, as stated in the previous section, about 1.5 m.

The geoelectrical section of Fig. 9 highlights the patterns shown in the maps of Fig. 7. This section can be described according to the three main levels:

(a) the first layer, ranging in thickness from 0.5 to 1.5 m, composed of surficial agricultural soil and containing remnants from the underlying bedrock, is texturally heterogeneous and therefore, electrically anisotropic;

(b) a biocalcarenite composed of cemented and very porous sediments of variable (2-4 m) thickness and irregular shape, with resistivity values strongly influenced by the degree of alteration;

(c) argillites underlying the biocalcarenites and occurring at shallow depths (4-5 m) and characterized by high electrical conductivity.

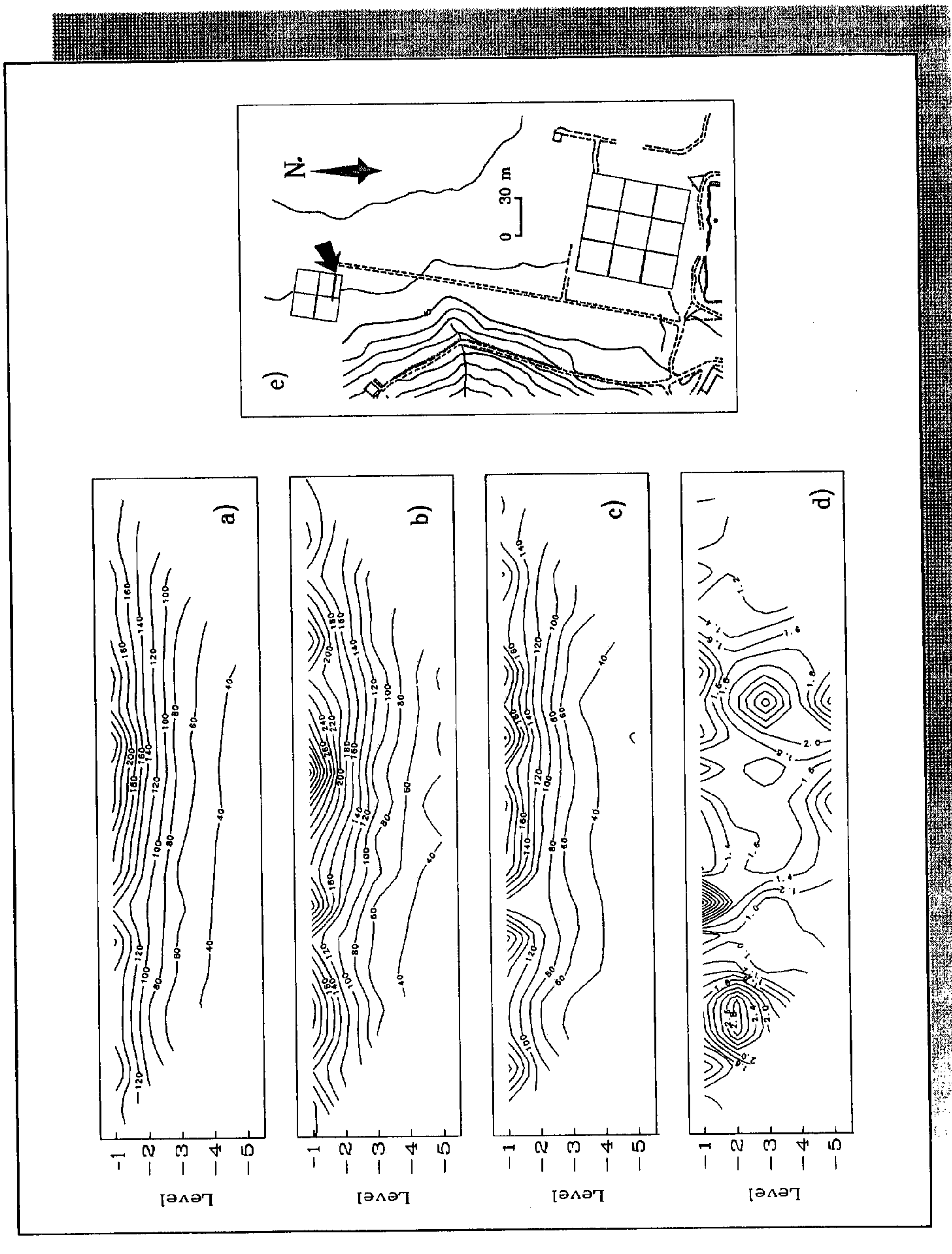

Fig. 10 — Resistivity pseudo-sections (a), (b), (c), (d) along the tripotential profile 2 in (e) the 40×40 m area.

The profiles taken in the 40×40 m sector give information on the geoelectrical behaviour of the subsoil. In Fig. 10 it is seen that the alpha resistivity (Wenner-configuration) pseudo-section is the most suitable to describe the distribution of the resistivity. The decrease of the latter with depth is evident and in agreement with what happens in the 90×90 m sector (Fig. 3). The pattern of the 40 ohm-m contour line is significant, because it seems to represent the characteristic value of the apparent resistivity at the depth investigated by the tripotential system.

The strongest variations are observed in the surficial part which has recently been plowed and is the site of frequent agricultural activity. In Fig. 10d the occurrence of very strong lateral heterogeneities can be observed. This strong (greater than 2) vertical pattern can be strictly correlated with those present in the same type of pseudo-sections in profiles 1, 3 and 4. As the profiles are 5 m apart, the correlation involves a linear element extending for more than 15 m and oriented approximately along the N-S direction. The depths, which were reached and are represented in the pseudo-sections, can be approximately estimated as 2 to 3 m.

From a geoelectrical point of view, the general behaviour of the areas under investigation shows a resistivity decrease with depth, as in Fig. 5. However, in the horizontal direction, the situation is extremely variable. In the 90×90 m sector, there are lithological irregularities extending downwards: they are probably related to a discontinuity or alteration of the underlying calcarenite, which is present in this area at very shallow depths (around 1 m). In the 40×40 m sector, the pseudo-sections show the occurrence of more complex structures: their possible anthropic origin is only speculative at this stage of our investigation and it needs confirmation.

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