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MAGNETIC SURVEY IN THE SELINUNTE ARCHAEOLOGICAL PARK

Abstract. Geophysical methods are a common tool used in the search for archaeological evidence before excavation. In the Selinunte Archeological Park, two test sites have been prospected with a fluxgate gradiometer and a proton magnetometer in gradiometric configuration. Many difficulties arose during data acquisition due to the small magnitudes and the low signal-to-noise ratio. The paper presents techniques for eliminating i) isolated values, ii) the systematic stretching of isolines in the N-S direction, iii) discontinuities in the average trend of contiguous subzones. In spite of such improvements, it was necessary to use a numerical process to increase the signal-to-noise ratio in order to single out and locate anomalies. Bidimensional cross-correlation was employed using theoretical models calculated specifically for the sought anomalies. It proved possibile to define the sample zones where excavation could be carried out.

INTRODUCTION

Geophysical methods are commonly used in archeological research before excavation in order to delimit the areas of interest. These methods can detect anomalies caused by buried archeological structures. Since archeological targets are small bodies located at shallow depths, the associated anomalies are of limited amplitude and are often masked by superficial noise of the same order of magnitude. This may be caused by ground inhomogeneities, anthropological disturbances and/or residuals of the paleosettlement.

Among the different geophysical methods, magnetometric survey is widely adopted for archeological targets, and uses the differences in magnetic susceptibility which can exist between the ground and materials used in constructions, and/or artifacts such as furnaces, remains of fireplaces and segments of brick constructions (Aitken, 1974).

Modern instruments allow very precise measurements in short times; and in order to discern the effects of shallower structures they must be used in gradient configuration, so that the effects of stratigraphic contacts or lithological variation are minimized.

Experience with the magnetometric technique in the test sites selected for the Selinunte Area revealed the difficulty in acquiring the data and, also, in recognizing and interpreting the anomalies.

FIELD SURVEY

Fig. 1 shows the two investigated areas; the first is near Temple G and is 90x90 m^2; the

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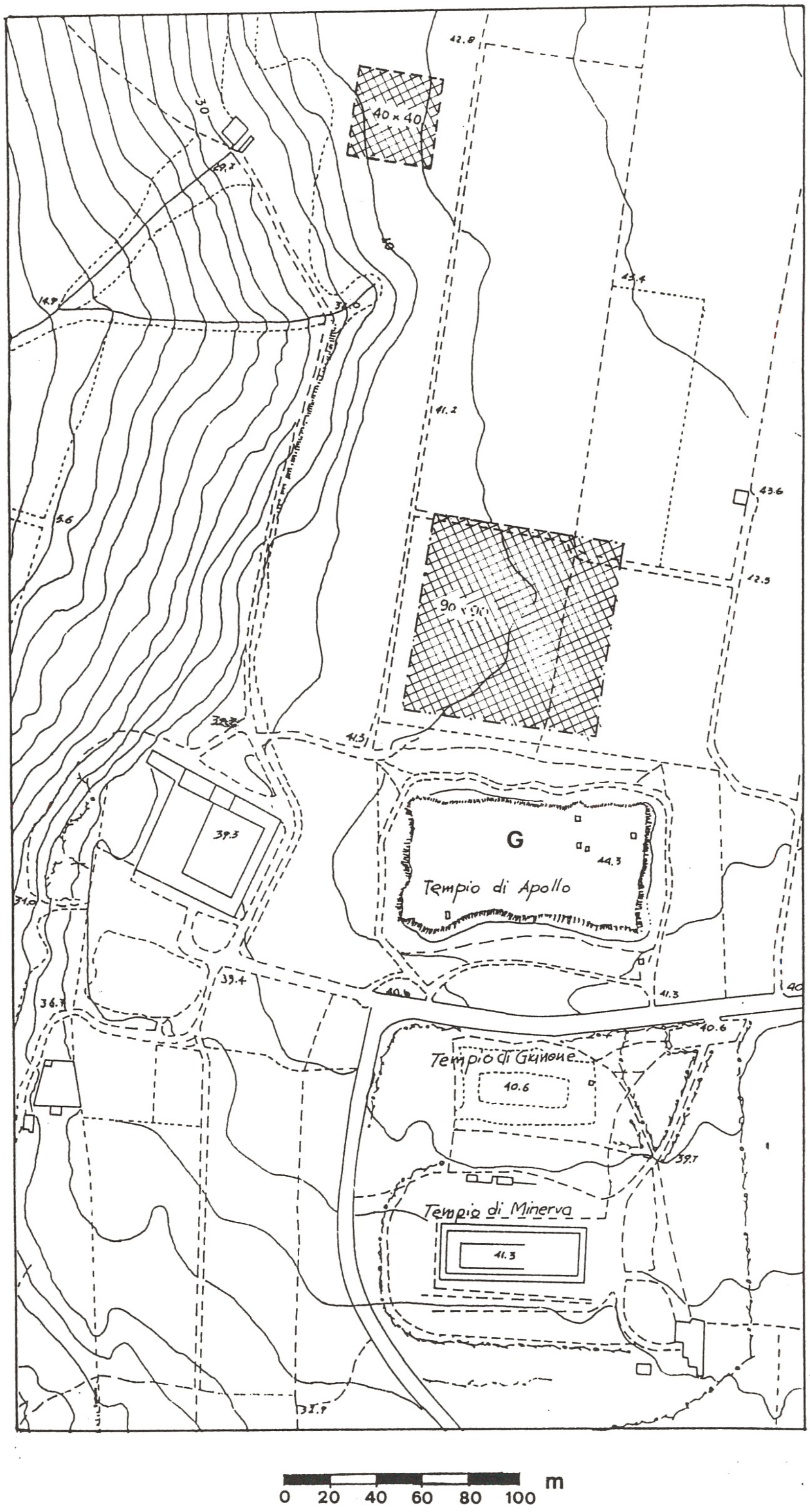


Fig. 1 - Map of Eastern Hill (Selinunte). Location of 40x40 and 90x90 test areas.

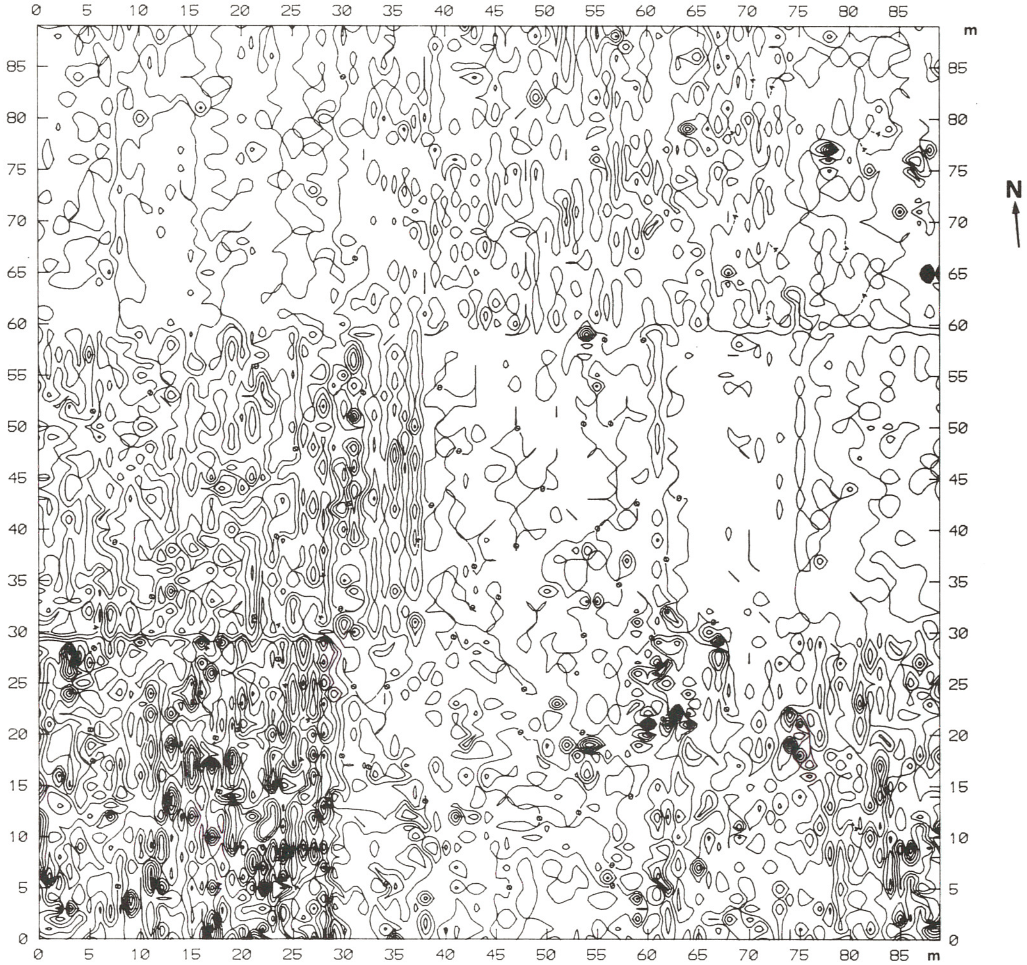


Fig. 2 - Contour lines of the field data in 90x90 area. Gradient of Z component of magnetic field. Contour interval: 2 nT/m. Range from -14 to +12 nT/m.

second is located some 200 m northwards and is 40x40 m^2. A G856 nuclear proton-precession magnetometer from Geometrics and an FM 36 fluxgate gradiometer from Geoscan were used. The G856 magnetometer was used in the gradient configuration by fixing the two sensors at 0.6 and 1.6 m above ground. This configuration does not require a reference station for correction of the diurnal variation of the earth's magnetic field.

The two areas were subdivided respectively into i) 9 squares of side 30 m, and ii) 4 squares of side 20 m, due to instrument memory capacity and/or logistic reasons. Measurements were carried out with the Geoscan magnetometer at a sampling interval of 1 m along N-S parallel profiles spaced 1 m apart. A total of 1600 measurements were taken in the northern area and 7744 measurements in the area near Temple G. Nuclear measurements were also carried out at a sampling interval of 1 m over the entire 40x40 area for a total of 1681 measurements.

Fig. 2 shows the countouring of the field measurements obtained in the 90x90 area with the fluxgate gradiometer. The strong variability of the data can be explained both by the proximity of the sensors to the ground and the instrument sensitivity (1 nT/m). The same situation occurred for the measurements in the 40x40 area.

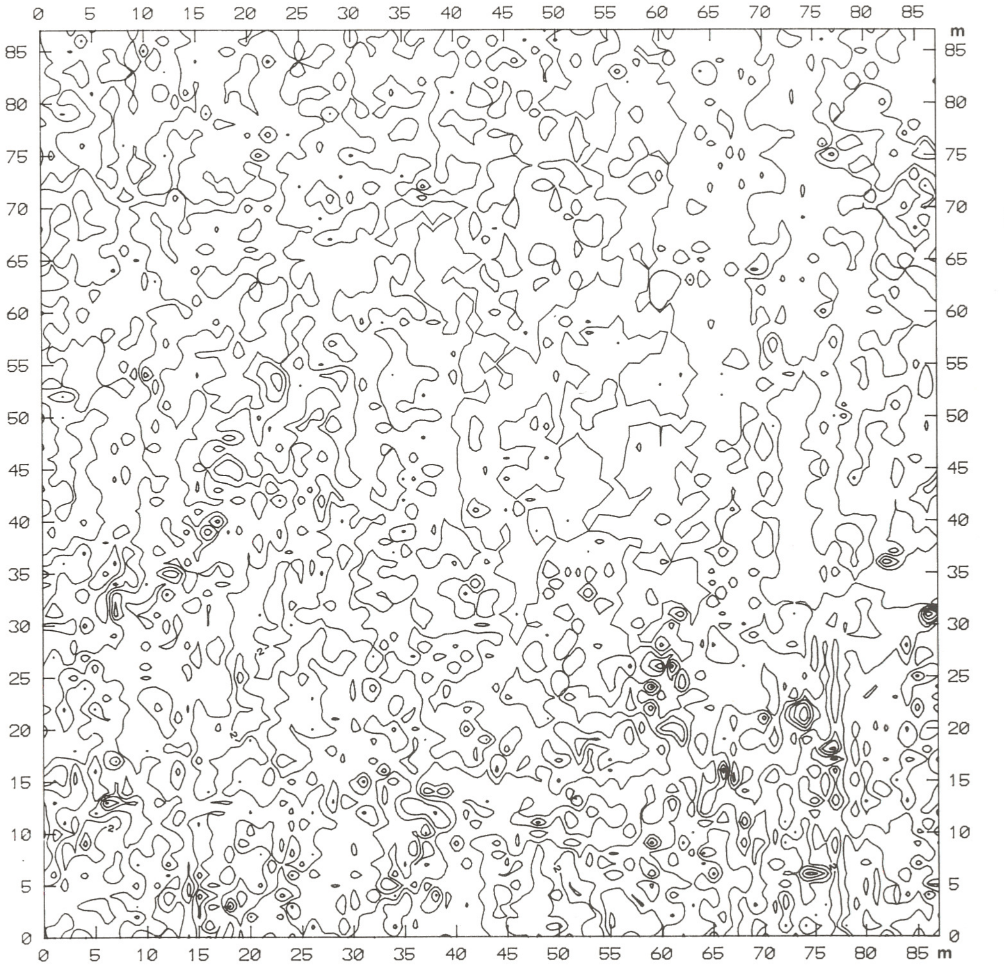


Fig. 3 - Contour lines of the residual values of the gradient of Z component of the magnetic field, in 90x90 area. Contour interval: 2 nT/m. Range of data: -8; +8 nT/m.

ANALYSIS AND PREPARATION OF DATA

In Fig. 2, one can see that a) there are isolated values, as shown by high gradients of the contour lines, which are anomalous with respect to the surrounding trends; they could be attributed to the presence of metallic remnants that cannot easily be identified (fragments of wire or agricultural tools); b) there is a systematic stretching of the isolines in the N-S direction, which may be the consequence of how the data were acquired (i.e. along profiles oriented in such a direction); c) discontinuities at the borders of contiguous squares, with values ranging differently from square to square as shown by the density of the isolines.

Hereafter, observations a), b) and c) will be considered separately in order to find the possibile causes and to propose remedial measures (Brizzolari et al., 1990).

Isolated anomalous values

In order to eliminate the isolated anomalous values in a non-arbitrary manner, a statistical algorithm was adopted for each subzone, after calculating the mean and the standard deviation σ of the measured values. The absolute values which are greater by $\pm 6\ \sigma$ than the mean are

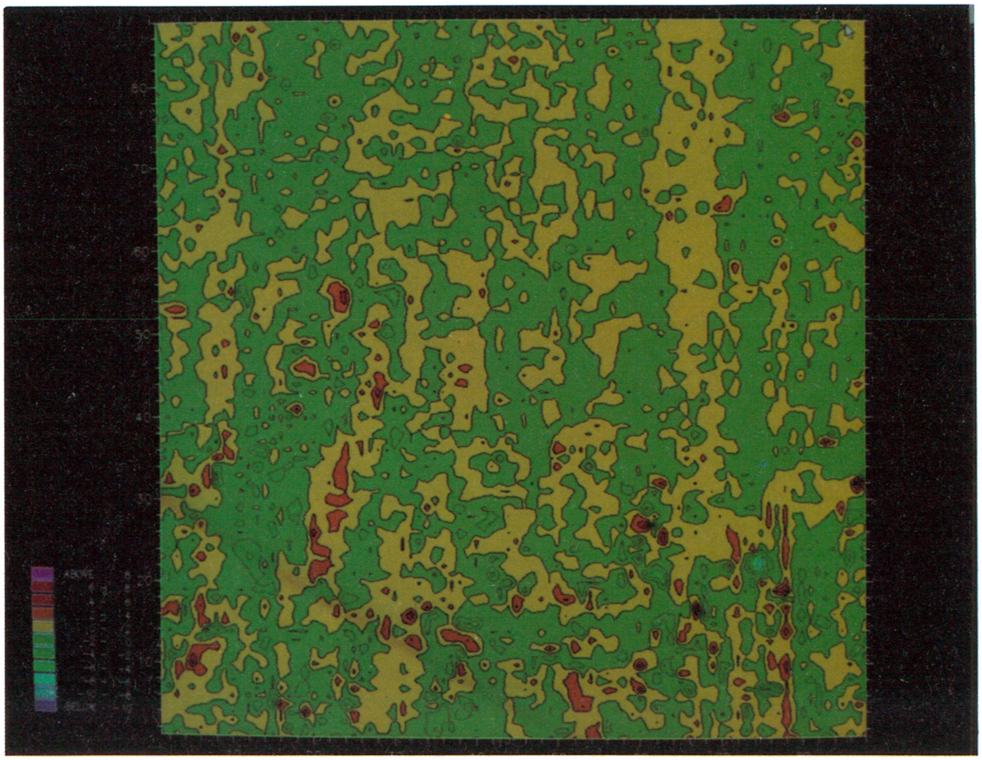


Fig. 4 - Colour contour map of the residual values of the gradient of Z component, in 90x90 area.

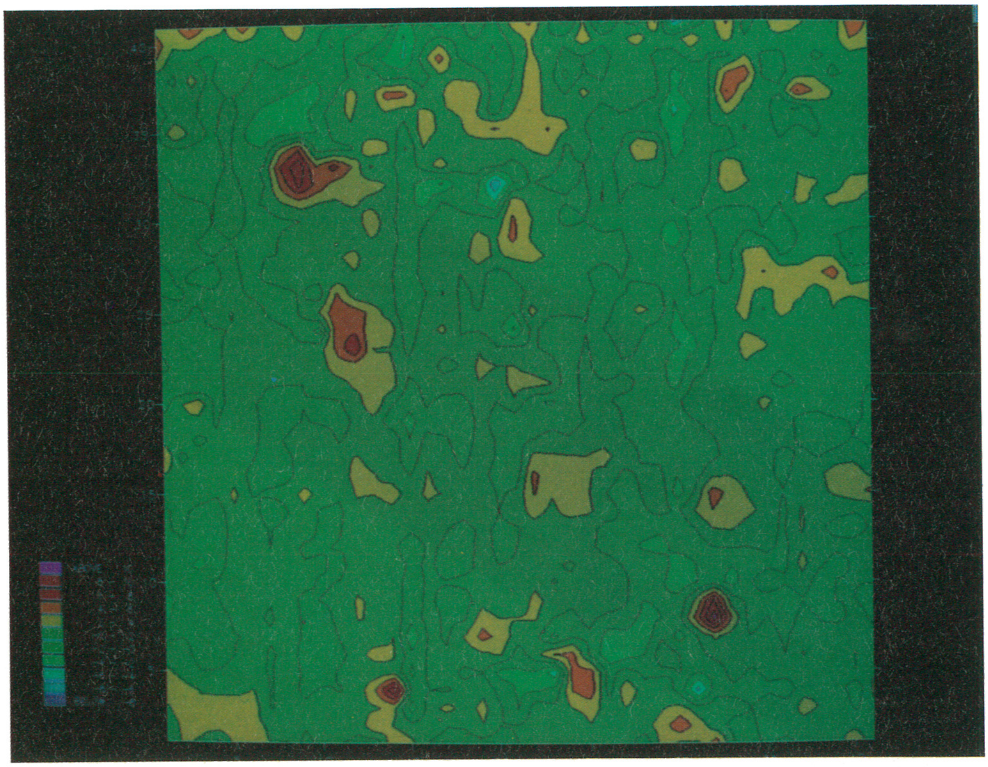
selected and compared with the 8 nearest values: 4 measurements at a distance of 1 m, and 4 at a distance of $\sqrt{2}$ m. It is thus possible to distinguish whether the considered value is actually an isolated value or is surrounded by similar values. In the first case, the value is substituted by the mean weighted by the distance between adjacent values. Then, a new mean and standard deviation can be recalculated, and the operation repeated until one obtains values greater than the fixed limit (mean $\pm 6\ \sigma$). If a more precise refinement is required, the deviation from the mean can be reduced and the selection repeated.

Stretching of the isolines

This (see Fig. 2) is caused by the difference between mean values in contiguous profiles, and cannot be univocally determined. Can be attributed to either geometric or magnetic asymmetries caused by the operator, who has to hold the Geoscan alternatively with the right and left hand in carrying out measurements on contiguous profiles with the field technique used. Other data acquisition techniques can be employed to reduce the probability of isoline stretching, but the time involved becomes too great. It should be observed that, although one cannot exclude a priori that a thermal deviation of the measurements could be caused by exposing the instrument alternately to the sun and to the shade behind the operator, this possibility was excluded by making many measurement tests with the instrument in the sun at a fixed position and in a zone with no anthropogenic disturbances. The analysis of these tests shows that there are no significant variations in the measured values, and that variations are of the order of 1 nT (i.e. the instrument sensitivity) even in the case of temperature changes of more than 7 °C.

In order to correct the stretching of the isolines, residual values using a first order surface were calculated (Brizzolari et al., 1990).

A



B

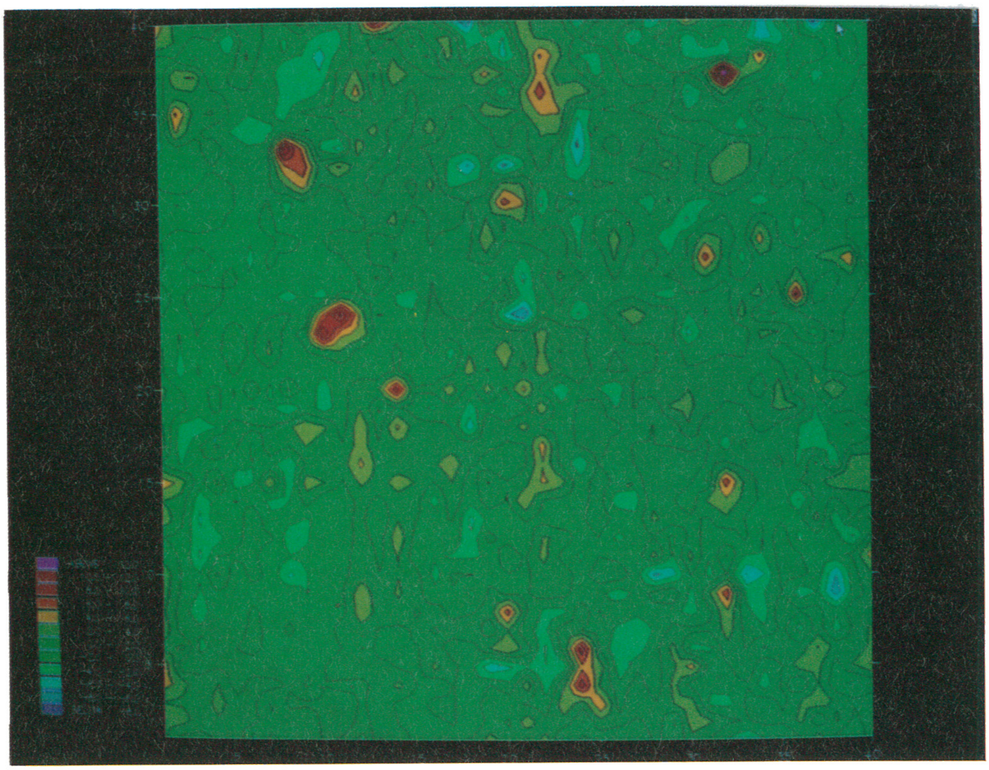


Fig. 5 - Colour contour maps of the residual values of the gradient of total intensity (a) and Z component (b) of the magnetic field, in 40x40 area.

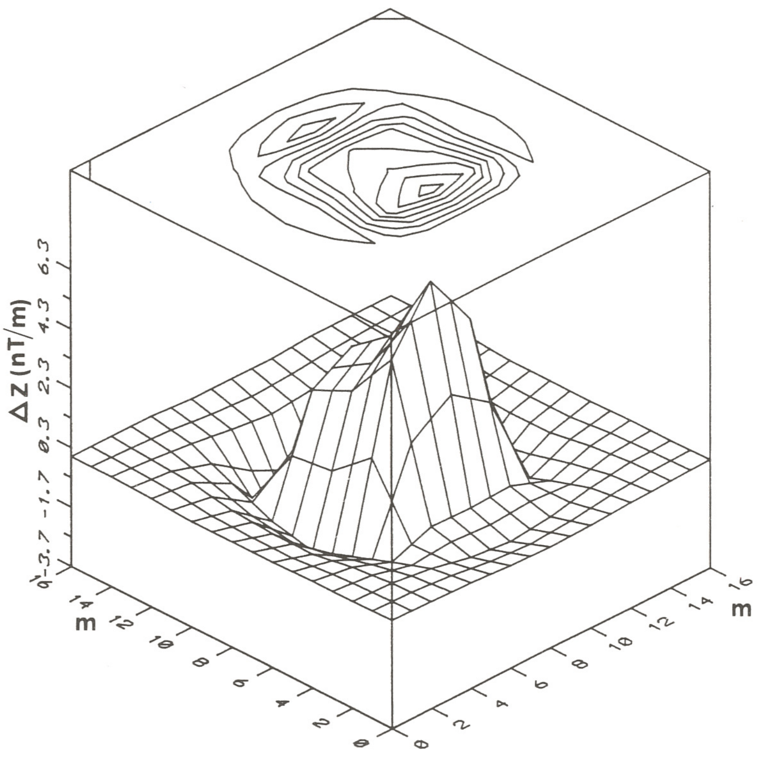


Fig. 6 - Theoretical anomaly of ΔZ. Body dimensions: length=width=0.3 m; height=0.3 m; depth=0.3 m; F=44128 nT, I=55°, D=0°, $\Delta\chi=2x10^{-4}$.

Variation range of values between contiguous subzones

Taking Fig. 2 into consideration again, a marked nonuniformity in the density of isolines in contiguous subzones can easily be seen. This is due to the different ranges of variation in measurements from one subzone to another.

By comparing the various measurement ranges with the heights of the operators who took the measurements, clear correlation was found: the greater the range of variation in the measurements the shorter the operator. In this case, in fact, the instrument is systematically closer to the ground surface, and thus the measurements are much more sensitive to inhomogeneities and superficial bodies. In order to verify this hypothesis, it was decided to continue the magnetic data upwards as proposed by Henderson and Zeitz (1949) by recalculating for each knot in the grid the value of the vertical component of the magnetic field for a higher position using the nearest measurements to it.

As written by Brizzolari et al. (1990), "the contribution of the nearest points is greater and the maximum is reached for values on circumferences whose radii are equal to h $\sqrt{2}$, where h is the height from the measurement plane as expressed in grid units, (Henderson and Zeitz, 1949).

In our case, because the grid unit used in the fields is 1 m and the difference in height of the instrument from the ground due to the different heights of the operators is 10 cm (h=0.1 grid unit), there are no measurements points close enough to those for which we have to recalculate the corresponding values for a higher elevation. If the proposed equations are used, the mean of the values on a circumference of unit radius affects calculations by only 13%, and the values on greater circumferences affect them even less.

It was therefore preferred to take into consideration, as a first approximation, the contribution of each measurement point, also because the anomalous bodies causing the various mea-

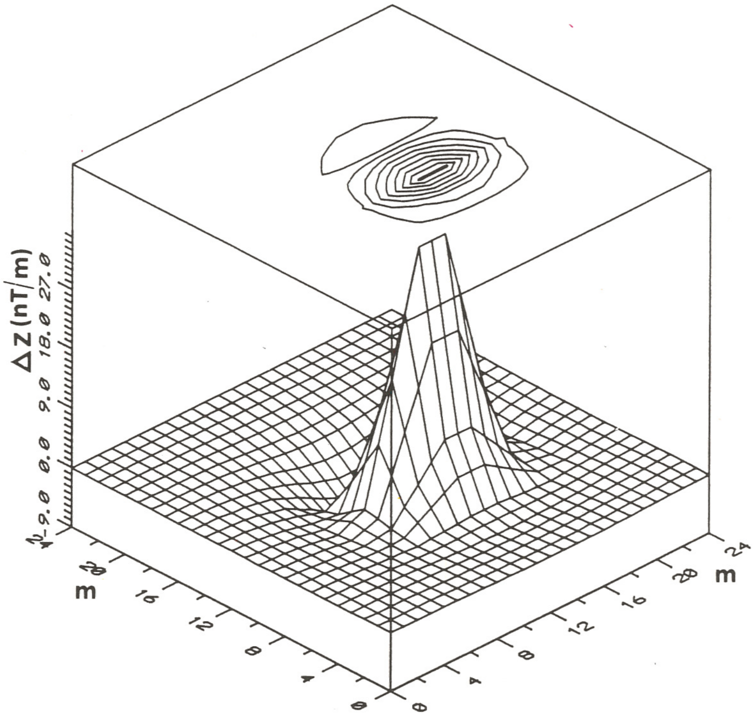


Fig. 7 - Theoretical anomaly of ΔZ. Body dimensions: length=2 m; width=0.5 m; height=0.5 m; depth=0.3 m; F=44128 nT, I=55°, D=0°, $\Delta\chi = 1x10^{-3}$.

surement ranges are certainly at a shallow depth and of small size.

Keeping in mind that the value of the maximum anomaly produced by a dipole is inversely proportional to the cube of its distance from the sensor (Breiner, 1973), the correction coefficient was calculated simply as the ratio of the cube of the various elevations.

With the application of the correction coefficient to the subzones of Fig. 2, it was possibile to homogenize the measurement ranges as shown in Fig. 3.

It is worth noting that the above conclusions also show that isoline stretching can be caused by the different elevation of the instrument from the ground when it is held in the operator's right or left hand. In fact, a few centimetres difference in sensor elevation produces a detectable variation in the measured values.

ELABORATION AND INTERPRETATION OF FIELD DATA

The contour maps of the field data residual values for the 90x90 and 40x40 areas are shown in Figs. 4 and 5, respectively. It can be seen that, although there are the improvements with the corrections mentioned in the previous paragraph, anomalies attributable to buried bodies are still not evident. In particular, in the map of fig. 4, the absence of well defined anomalies is evident, except for a certain structure trending SW-NE in the southwestern portion of the area. Thus, it can be said that the area is characterized by irregularly distributed anomalies of small amplitude and that the density of these anomalies, in the portion of the area to the north of the NW-SE diagonal, is lower than in the southern portion. The absence of regularly distributed anomalies leads to the conclusion that either the presumed structures are absent or that they give rise to anomalies that are too small and masked by noise caused by recent human activities and by the weathering of the calcarenite layer. This further com-

Fig. 8 - 90x90 area. Colour contour map of normalized bidimensional cross-correlation of the data of Fig. 4, using the theoretical anomaly of Fig. 6.

plication is confirmed by the fact that more than 75% of the values in the 90x90 area is in the interval $m \pm \sigma$ (from -1.2 to +1.2 nT/m), namely in a range that is little greater than the instrument sensitivity (1 nT/m).

In Fig. 5, the good correspondence between data from the differential nuclear magnetometer (Fig. 5a) and the data from the fluxgate gradiometer (Fig. 5b) can be seen; it can also be observed that there are clear anomalies of large amplitude both in the northern and southern portions of the studied area. Both contour maps show regular trends which do not match the profile direction, suggesting the presence of structures formed of materials having a susceptibility different from that of the boundary materials.

From such observations it was considered necessary to increase the signal-to-noise ratio so as to identify and interpret actual anomalies. As already proposed (Bernabini et al., 1988; Brizzolari et al, 1989), this can be done both by filtering and cross-correlation techniques. Filtering can be used when the signal frequency spectra do not coincide completely with the noise spectra. Cross-correlation between field data and suitable theoretical anomalies is possible when the assummed buried bodies can be modelled to a fairly good approximation.

In the studied case, 3-D theoretical anomaly curves were calculated for a bidimensional cross-correlation (Brizzolari et al., 1991a, 1991b). In fact, targets have finite dimensions in all directions, and measurements were taken at the nodes of a grid of 1 m.

For the calculation of the magnetic field generated by a body of arbitrary shape, we used the relations proposed by Talwani (1965) which give the three components of the magnetic field at any point on the ground surface. The software can take into account the contributions of several bodies together, for different values of the geometric and magnetic parameters (Briz-

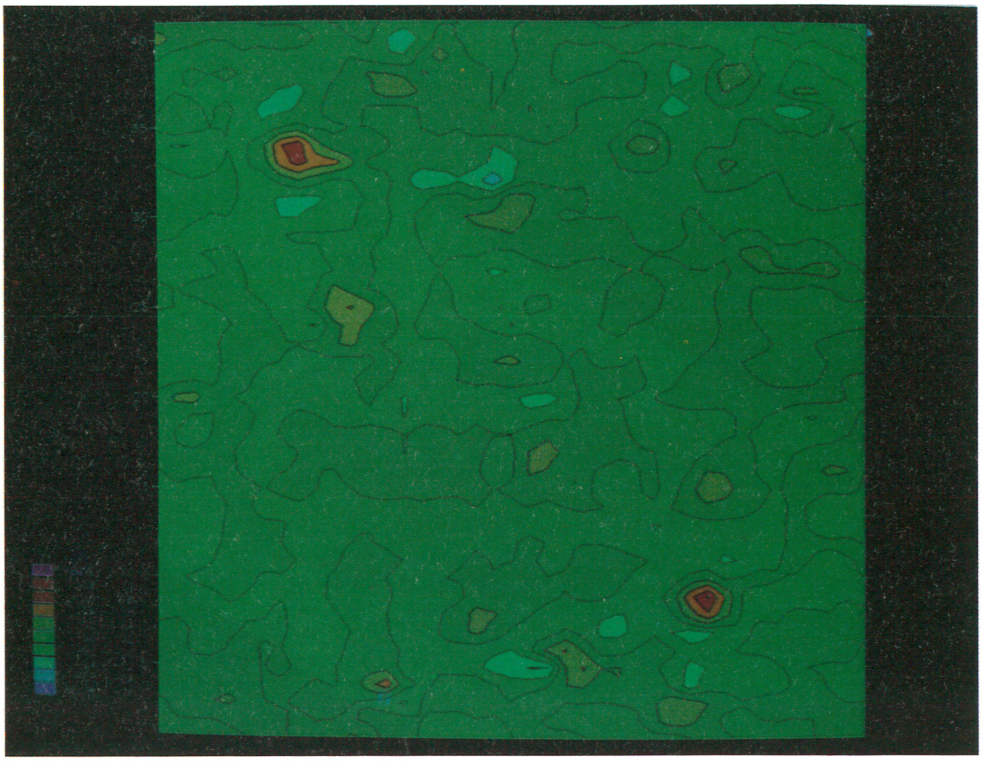


Fig. 9 - 40x40 area. Colour contour map of normalized bidimensional cross-correlation of the data of Fig. 5a.

zolari et al., 1991b).

Fig. 6 shows the theoretical anomaly of the vertical gradient of the magnetic field Z component for a parallelepiped located at a depth of 0.3 m, having dimensions as indicated in the caption and a susceptibility contrast of $\Delta\chi = 2x10^{-4}$. This theoretical body simulates trenches in the calcarenite representing the bases of the precolonial settlement houses. In order to sketch out the targets (graves) we were looking for in the 90x90 area, it must be remembered that the presence of the assumed anomalous body and its position can be determined only if cross-correlated data show a shape similar to that of the autocorrelated theoretical anomaly. Note that the autocorrelation maximum value is always positive.

Fig. 7 shows the theoretical anomaly of the vertical gradient of the Z component for a parallelepiped located at a depth of 0.3 m, having dimensions indicated in the figure caption and a susceptibility contrast of $\Delta\chi = 1x10^{-3}$. This parallelepiped simulates the wall that were expected in the 40x40 area. For the same parallelepiped, the theoretical anomaly of the vertical gradient of the modulus of the total magnetic field was calculated.

The theoretical anomalies were sampled with the same grid interval (1 m) used in the field measurements. By applying bidimensional cross-correlation to the surveys carried out in both areas, the results depicted in Figs. 8, 9 and 10 are obtained. The cross-correlation values have been normalized (Brizzolari et al., 1991b) with respect to the maximum autocorrelation value of the thoretical models elaborated for the two areas.

For the 90x90 survey area, the contour map (Fig. 8) suggests the presence of many anomalies. Among them, those anomalies having the highest cross-correlation values and shapes similar to the autocorrelations of the models are assumed to correspond to the sought ano-

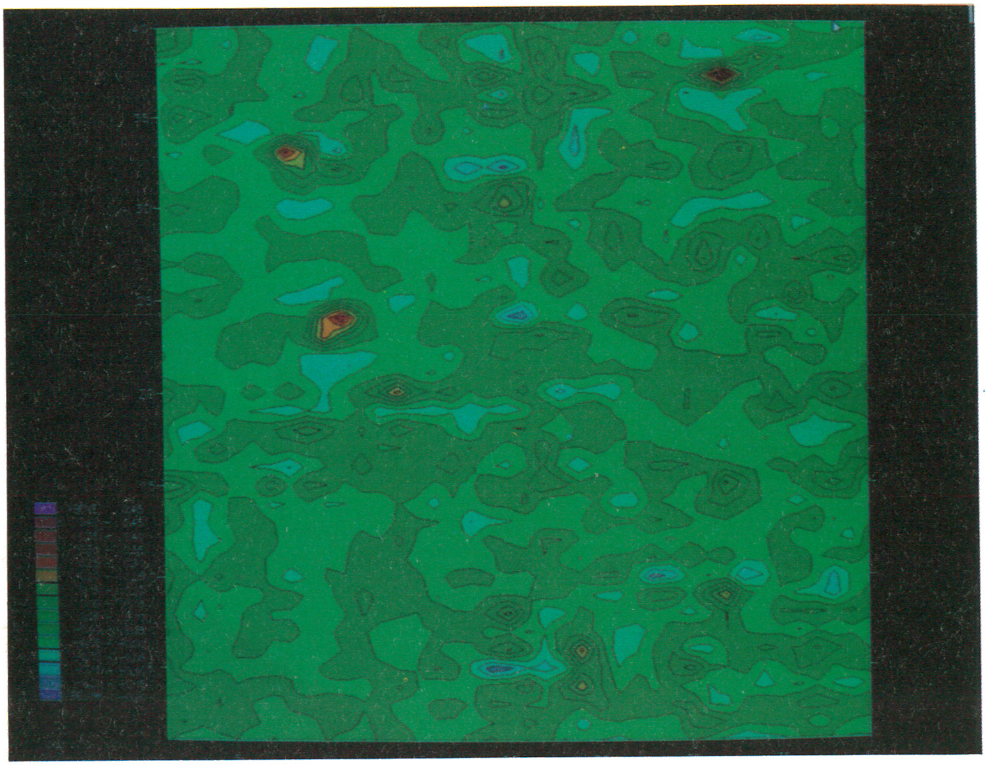


Fig. 10 - 40x40 area. Colour contour map of normalized bidimensional cross-correlation of the data of Fig. 5b, using the theoretical anomaly of Fig. 7.

malous bodies.

For the 40x40 area, the bidimensional cross-correlation maps (Figs. 9 and 10) suggest the presence of anomalous bodies, in particular in the north-west and south-east corners of the area.

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