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A Magnetic and Electrical Study of Archaeological Structures at Loma Alta, Michoacan, Mexico

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ABSTRACT This paper describes the results of high spatial resolution magnetic and resistivity surveys of the Loma Alta site in Michoacan, Mexico. This site is the largest of a series of man-made earthen islands built up within an ancient freshwater basin. Occupied during three main phases from 100 BC to AD 850, the site now shows no surface detail of the underlying structural complexity. Test pits and trenches excavated during several field seasons revealed a fraction of the large ceremonial complex and provided isolated archaeological data difficult to interpret.

Geophysical prospection aimed to investigate the so far unknown settlement pattern and detect architectural remains. Magnetic prospecting of the stone architecture turned out to be excellent due to the high contrast between the volcanic rock and the sedimentary fill. A fluxgate gradiometer survey of the entire mound surface defined a large number of small aligned positive and negative magnetic anomalies. Electrical surveys complemented and verified the magnetic results. A series of verification excavations exposed structural elements predicted by the prospecting and aided a further interpretation of the data. The major results of the study are discussed, as they provide a clear image of the orthogonal layout of the highly structured ceremonial site. © 1997 John Wiley & Sons, Ltd.

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Introduction, aims and objectives

There are many wetland basins within the neo-volcanic range of Mexico, some of which are still lakes, whereas others, such as the basins of Mexico City and Zacapu, have been drained artificially (Figure 1). Tectonic movements altered the lake floor of the Zacapu basin, leaving long ripples in the ancient lake bed. These slight topographical undulations were built up to support structures thanks to a huge amount of human labour, which extracted and transported building materials to the site. The Zacapu basin was drained at the beginning of this century to expose the rich lake bottom for modern agriculture. This fully revealed the ancient islets and left them standing as small rises, the largest (6 ha) of which is called Loma Alta (High Hill), and was a major centre of human activity during the Loma Alta, Jarácuaro and Lupe periods (100 BC to AD 850) (Figure 2).

Archaeological research into Loma Alta has proposed that it was used mainly as a centre for ceremonial and funerary activities. This is based on the results of a series of excavation pits and trenches, which uncovered a large number of

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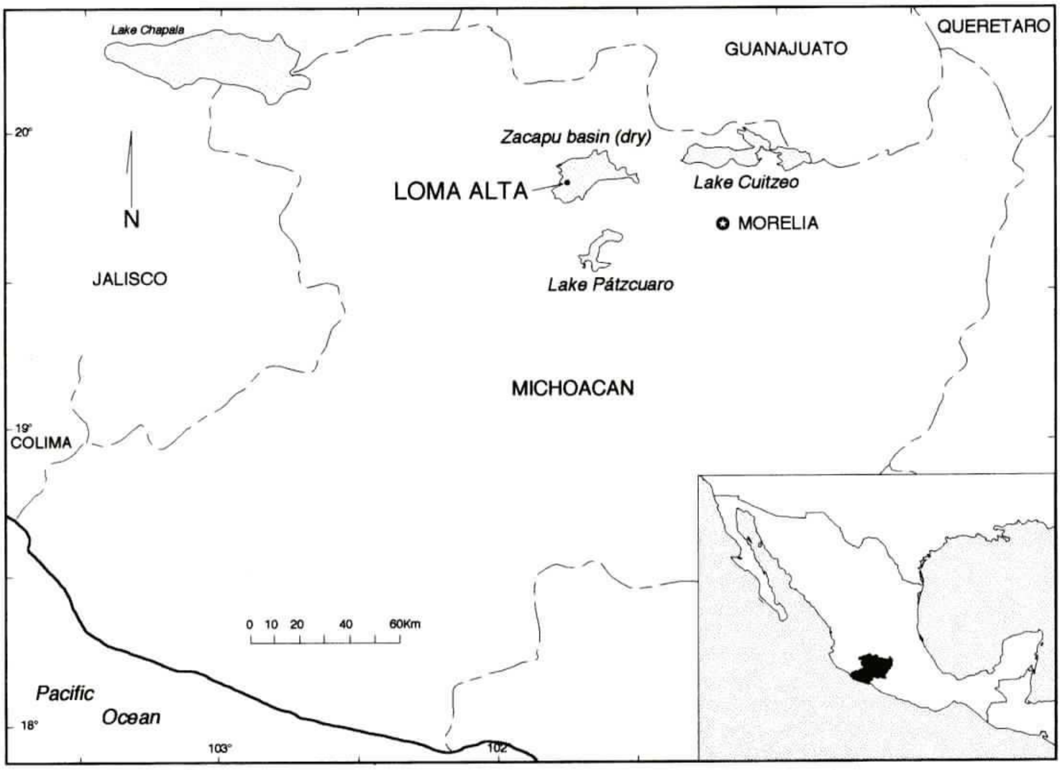

Figure 1. Map of western Mexico and the location of the Zacapu basin and Loma Alta site (after Arnauld *et al*, 1993, p. 20).

Figure 2. General view of the Loma Alta site as seen from the north-east ridge.

graves, ritual objects, and portions of monumental architecture, but no remains of domestic dwellings (Arnauld *et al*, 1993). Nevertheless, we cannot rule out the possibility that the many islets in the area were initially settled to take advantage of the abundant natural wetland resources.

Up to this point the archaeological data were difficult to interpret because the relatively small areas excavated revealed disjointed portions of a large and complex site. A map of the entire site with a good level of detail was necessary to integrate the dispersed architectural and cultural elements located as well as to better direct future archaeological research. This is precisely the scale of problem that can be approached using archaeological prospecting techniques.

The main objectives of the archaeological prospecting project were to differentiate between anthropic soils and natural sediments, localize and map any perceivable subsurface structures, delimit the outer limits of the mound as defined by the extent of architectural remains, and if possible, reconstruct the layout of the prehistoric settlement along with pinpointing possible funerary areas.

Methods

Consideration of several on-site conditions, such as the total surface survey area, indications of subsurface structures obtained from earlier excavations, and the available instrumentation, led us to implement two main geophysical techniques: magnetic and electrical surveying, with the additional possibility of a back-up survey using electromagnetic techniques (Barba, 1990; Scollar *et al*, 1990). In general, time limitations dictated the extensive implementation of magnetometer surveying due to its advantages of speed and ease of ground coverage, whereas the electrical techniques were applied to specific areas and problems.

Grid layout

The orientation of the working reference grid was established in such a way as to avoid coinciding with the orientation of previously excavated walls, thus making it easier to recognize interesting anomalies.

The survey was conducted over a grid based on 20m squares oriented 12.5° north-east of magnetic north in an area where the local magnetic declination from true north is 8.75°E (Figure 3).

Magnetometer survey

The survey was conducted using a Geoscan FM36 fluxgate gradiometer with readings of the local gradient of the vertical component of the Earth's magnetic field recorded to the nearest nanotesla (nT) (Figure 4, top right). An initial zero reference point was established 100 m to the east of the hill, and later transferred to a more convenient location on the summit. A preliminary study line (N70,E100–140) using various sampling densities established that the magnetometer signal would be optimally sampled at 0.50 m intervals along alternating N–S traverses 1.0 m apart. Based on the survey grid, 43 grid squares 20 m to a side were subsequently covered over a period of 8 days. Four survey grids (N0–20,E80–100; N0–20,E100–120; N20–40,E100–120, and N120–140,E100–120) were sampled at a lower density (1 m intervals along lines 2 m apart) in order to expedite completion of the survey. Two magnetic grids were later added in order to determine the presence of archaeological structures in the north-eastern part of the mound. Readings for these two grids were taken every 0.5 m along lines 1 m apart.

The data were captured in the internal memory of the gradiometer, and after each grid was completed, downloaded to a solar powered Macintosh Powerbook Duo 270c for storage and initial visualization. The data were subsequently transferred to a Quadra level workstation in the mobile laboratory and processed using a suite of commercial and in-house programs.

The data from the entire local magnetic gradient survey were non-linearly transformed (Figure 4, centre) using arctangent compression (Scollar *et al*, 1986), bi-cubicly resampled, and visualized as a coloured raster image (Figure 5). The data were then converted into absolute (positive) values, filtered with a high-pass convolution mask to accentuate anomalies (Scollar

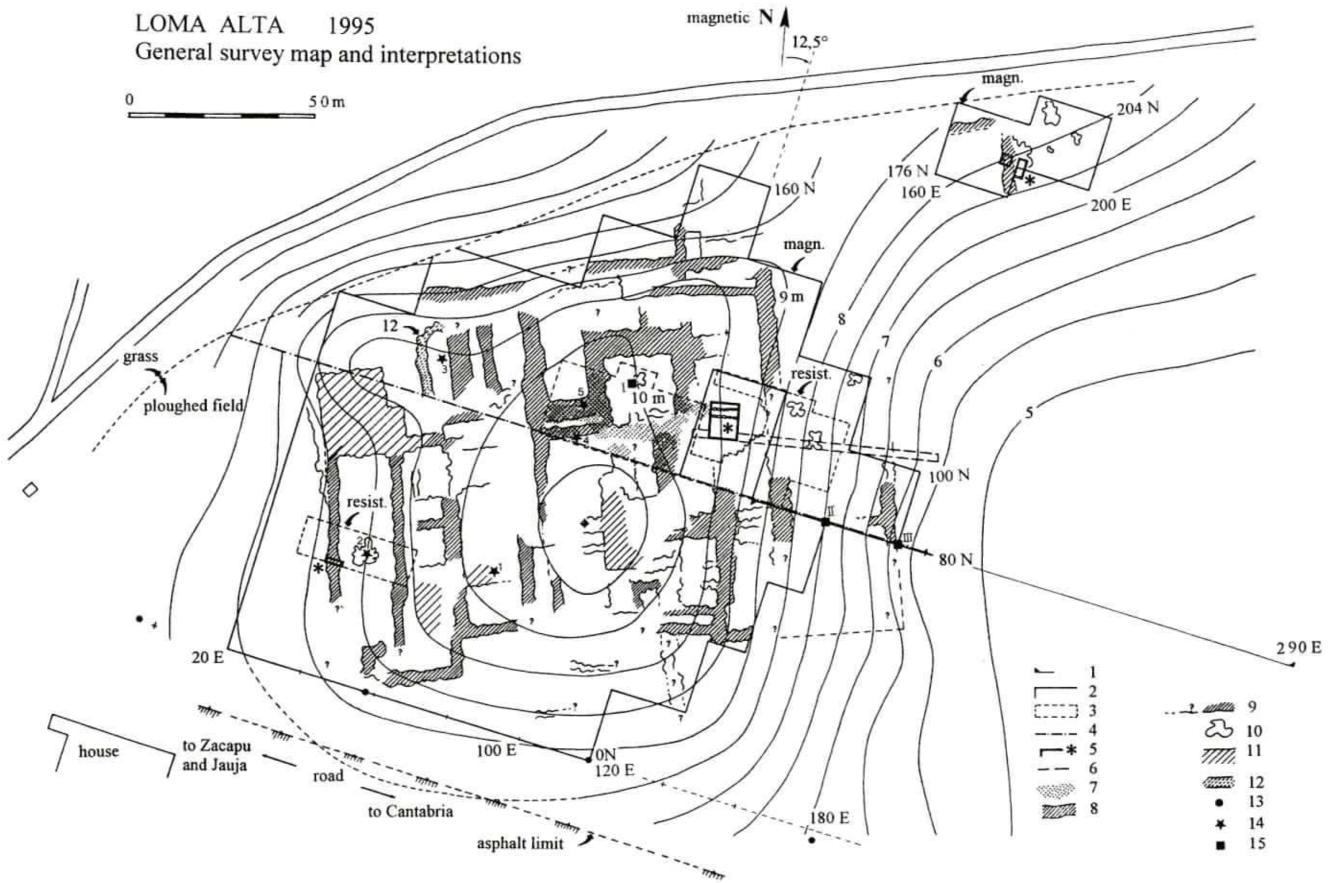

Figure 3. General map of the Loma Alta site showing the location of the various investigations. 1, magnetic profile (80N); 2, magnetic map; 3, resistivity map; 4, resistivity pseudo-section (80N); 5, 1995 excavations; 6, refilled trench; 7, resistivity anomalies; 8, linear magnetic anomalies; 9, uncertain magnetic anomalies; 10, concentrated magnetic anomalies; 11, platform or amount of magnetic stones; 12, probable induced magnetic anomaly; 13, electric poles; 14, mechanical sounding (1 to 5); 15, electrical sounding (I to III); 20E to 180E, 0N to 204N, east and north grid scales in metres.

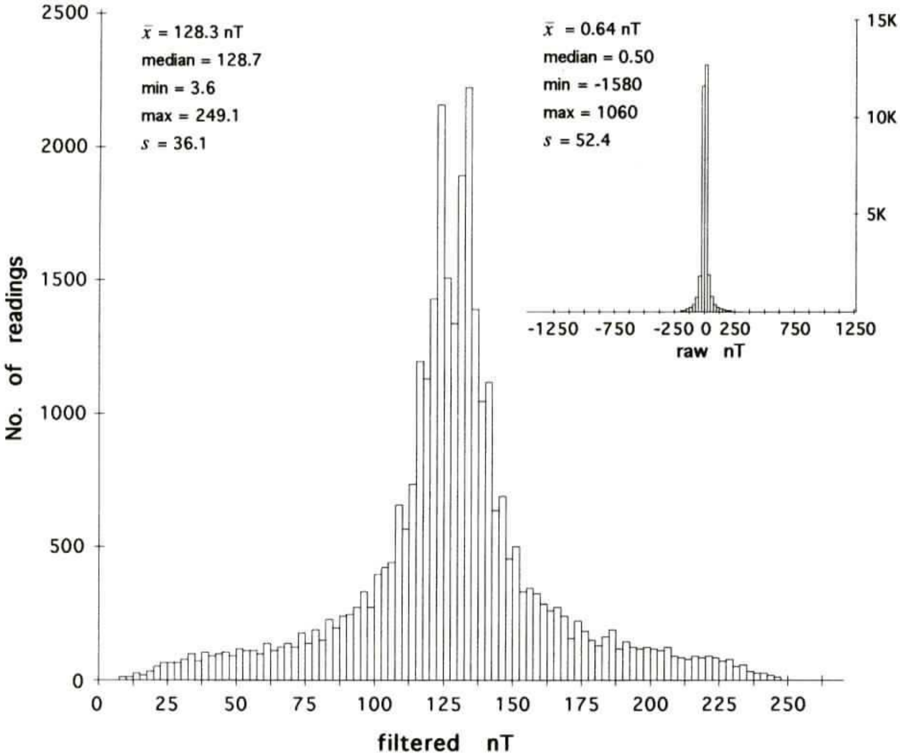

Figure 4. Histogram of raw (top right) and non-linearly filtered (centre) magnetic readings data.

et al, 1990), and partially recombined with a Gaussian low-pass filter version of the same data in order to suppress image noise. For a better archaeological legibility, the final representation was shaded with a directional (northwest) convolution mask (Figure 6).

A final survey line was sampled every metre (1 m) using a Varian Portable Caesium VIW2302Al magnetometer with 0.01 nT sensitivity along line N80,E0–290. This was carried out in order to obtain information about the contexts beyond the topographical limits of the mound and complement the gradient data with total magnetic field readings (Figure 7).

Resistivity survey

The survey was conducted mainly using a Bradphys IV four probe resistivity meter in the normal Wenner and dipole–dipole configurations. Three different techniques were used to solve specific types of questions: electrical maps to observe the horizontal distribution of resistivities, electrical soundings to observe vertical variations, and electrical profiles at different depths (pseudo-section) to observe variations in both the vertical and horizontal dimensions.

Electrical maps

The first and largest of the maps that were produced (40 m by 30 m) was located in the central section of the survey grid, in an area of the mound where previous excavations and the topography suggested the existence of a large number of buried structures. This survey had the intention to determine the continuation of a series of monumental structures that had already been uncovered in adjacent excavations. In this case dipole–dipole and normal Wenner arrays were used simultaneously with $a = 1$ m (Hesse and Spahos, 1979) partly on a 1 × 1 m, partly on a 2 × 1 m mesh grid. These measurements were taken as close as possible to the excavation, up to where the mounds of extracted earth permitted (Figures 3 and 8). The data were processed using in-house programs of grey-scale

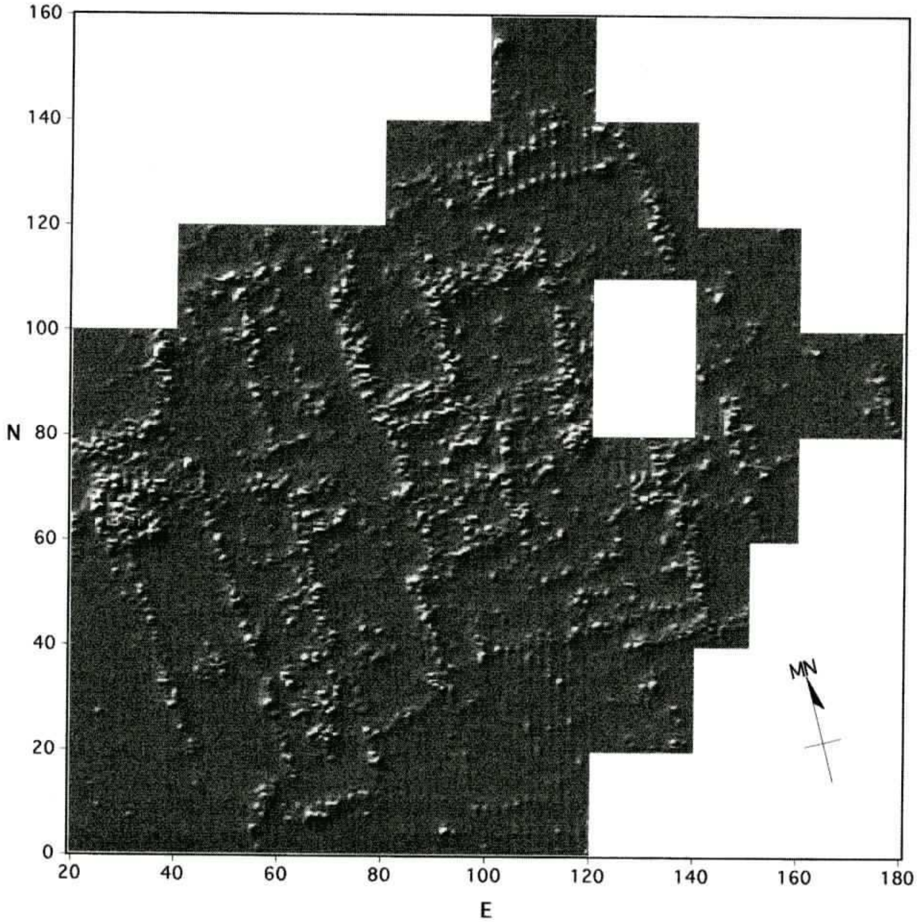

Figure 6. Shaded relief map of vertical gradient of the magnetic field.

map representation (Hesse *et al*, 1992; Tabbagh, 1997).

Another area was surveyed in the south-western part of the grid from coordinates N30,E30 to N40,E60 with resistance equipment built by the Laboratory for Archaeological Prospecting of the Instituto de Investigaciones Antropológicas, UNAM, using the Wenner array with a distance between electrodes of $a = 1$ m, partly on a 1×1 m, partly on a 1×2 m mesh grid. This was performed in an attempt to verify the presence of two walls and a central structure located during the magnetometer survey. Data visualization of this grid detail involved two variables: the electrical resistivity and the local magnetic gradient (Figure 9). Both data sets were treated in the same manner as described above and then composed in Adobe Photoshop as a coloured cell array, where hue and saturation individually correspond to each variable (Keller, 1993; Link, 1996). Each cell is coloured according to a blue to red colour spectrum to represent the local magnetic gradient: blue, minima; red, maxima. The colour saturation changes from low (saturated colour) to high (pale or grey) to show the magnitude of electrical resistance of each cell. A binary colour key shows the relative magnetic and electrical values. This is an original and complex representation of the superposition of resistivity data (grey scale and isolines) and magnetic data (blue to red colour component).

Electrical pseudo-sections

Given that a pseudo-section provides information about both lateral and vertical variations, this technique was applied to better understand

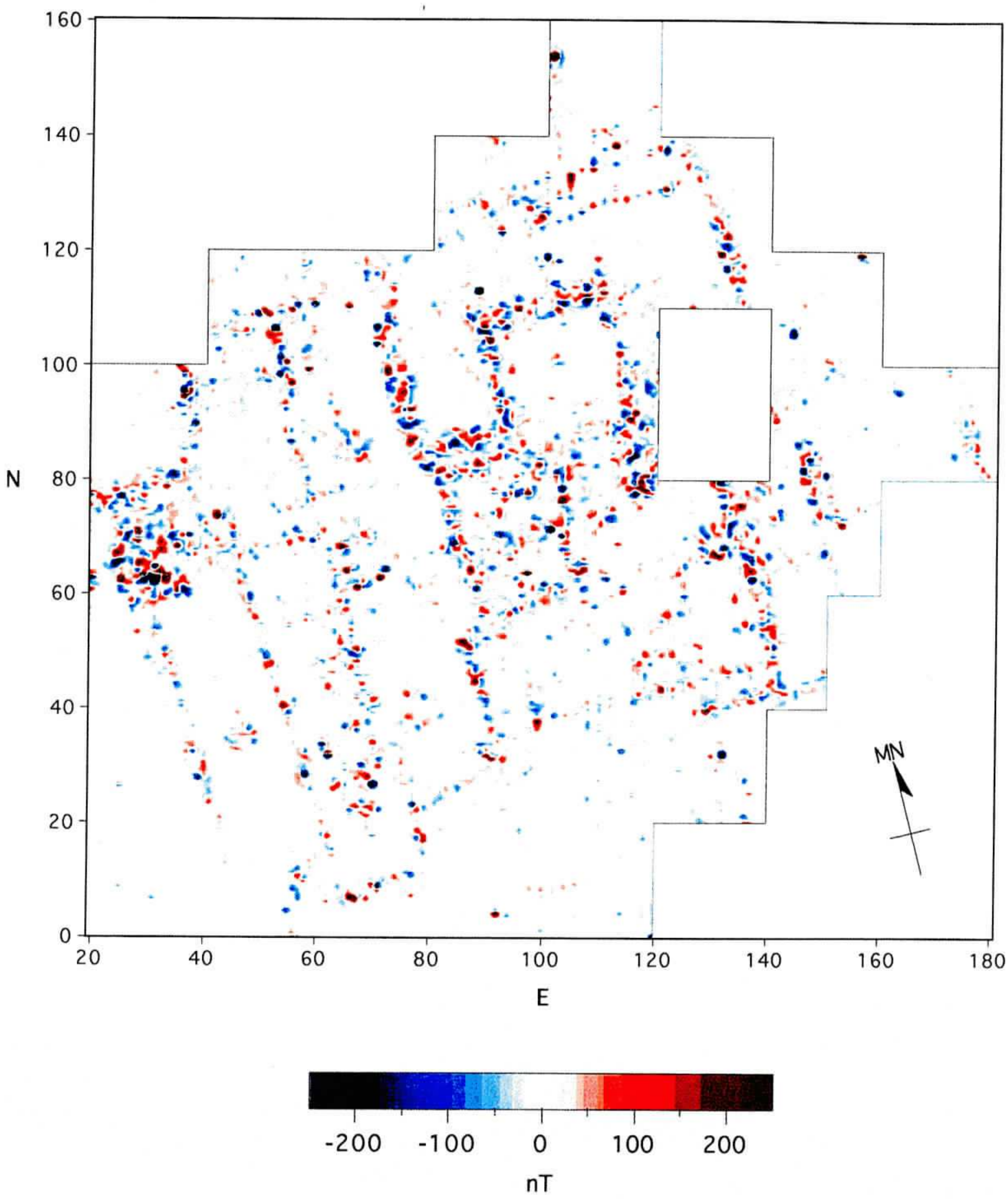

Figure 5. Coloured map of vertical gradient of the magnetic field.

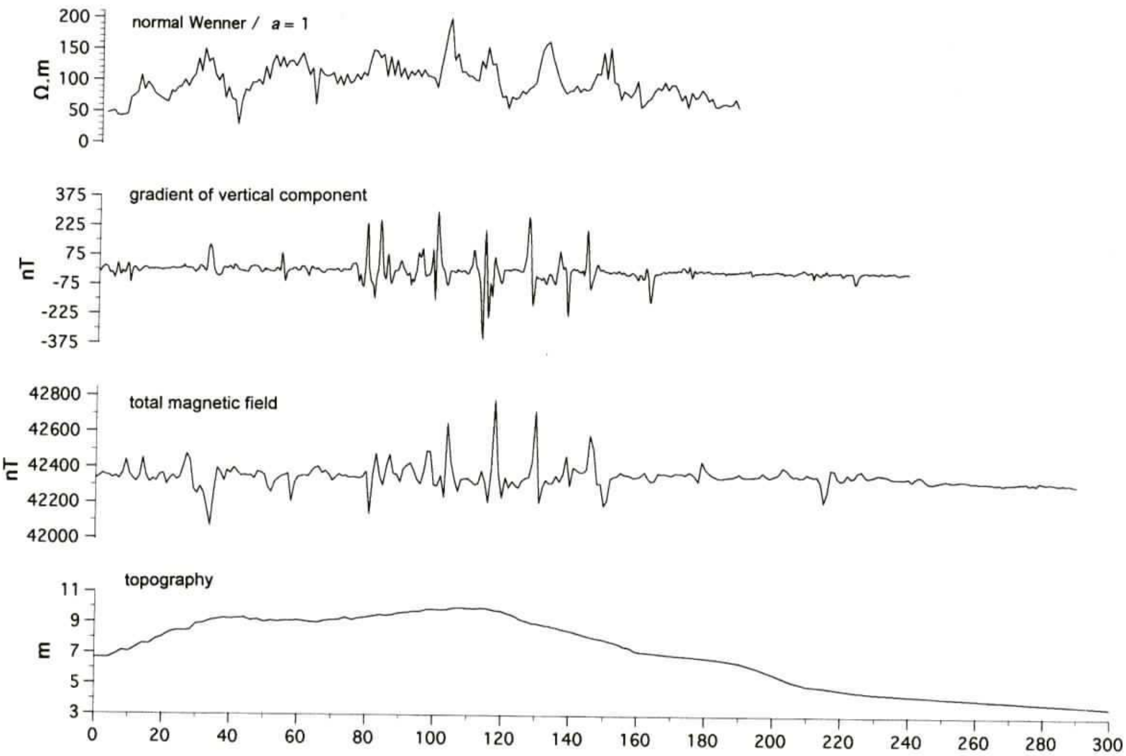

Figure 7. Electrical resistivity, magnetic (vertical gradient), total magnetic field, and topographical profile from west to east, along the N80 line.

the behaviour of the terrain along the length of the grid line N80. This line runs from east–west through the mound from side to side (Figure 3). A Bradphys IV resistance meter was used in the dipole–dipole and normal Wenner configurations, with $a = 1$, 2 and 4 m. Although the correspondence between the two arrays is very good, the dipole–dipole configuration exhibits better precision but more noise, whereas the Wenner produces the inverse: less noise and less precision (Figure 10).

Electrical soundings

Three electrical soundings were carried out at points of the main mound of particular interest to confirm resistivity values and depth attained. At each one of the points, measurements were taken using a normal Wenner array and with growth intervals from 0.1 to 11 m, this being the limit of the equipment's detection capability (Figure 11).

Sounding I was placed on the higher part of the mound, which would probably correspond to the architectural nucleus (N100,E100) of the deepest archaeological deposits, and could provide information about the base level of human occupation, or perhaps identify the floor of the recently detected central quadrangular space. The two other soundings (II and III) were located on the lower parts of the mound (N80,E160 and N80,E180) to verify the meaning of the diminishing values that appeared in the pseudo-section at both extremes of the mound when $a = 4$ m (Figure 10). Interpretation of the readings was carried out using the program of J. Tabbagh (in-house program for a model of n horizontal layers).

Magnetic susceptibility

Samples of the most representative types of construction materials utilized as well as anthropic and naturally occurring soils were recovered. The samples were neither sieved nor dried prior to measurement at the Paleomagnetism Laboratory of the Instituto de Geofísica, UNAM. The

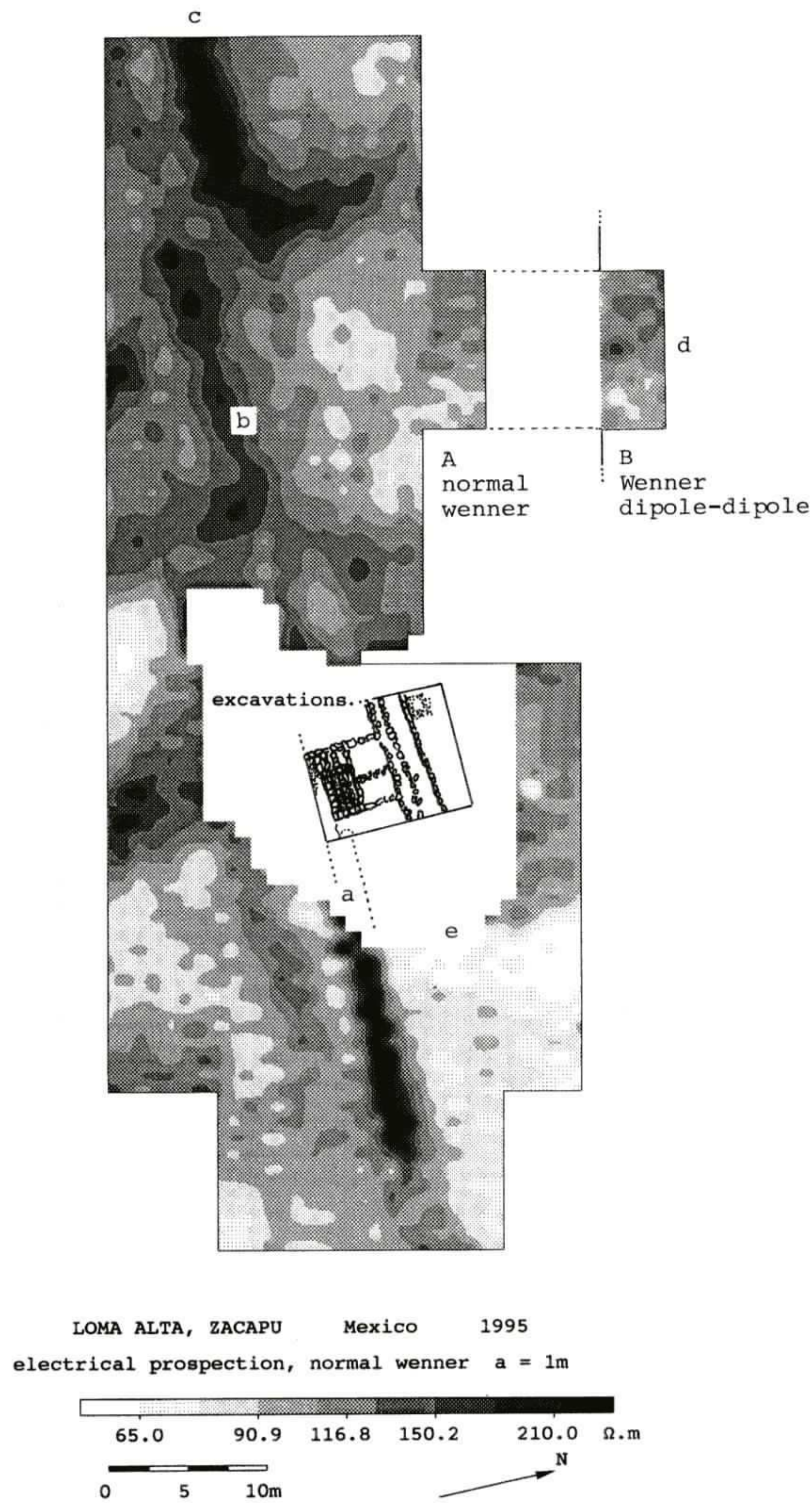

Figure 8. Resistivity map in the central area of the Loma Alta site (A, with normal Wenner, $a = 1$ m; B, detail with dipole–dipole Wenner, $a = 1$ m).

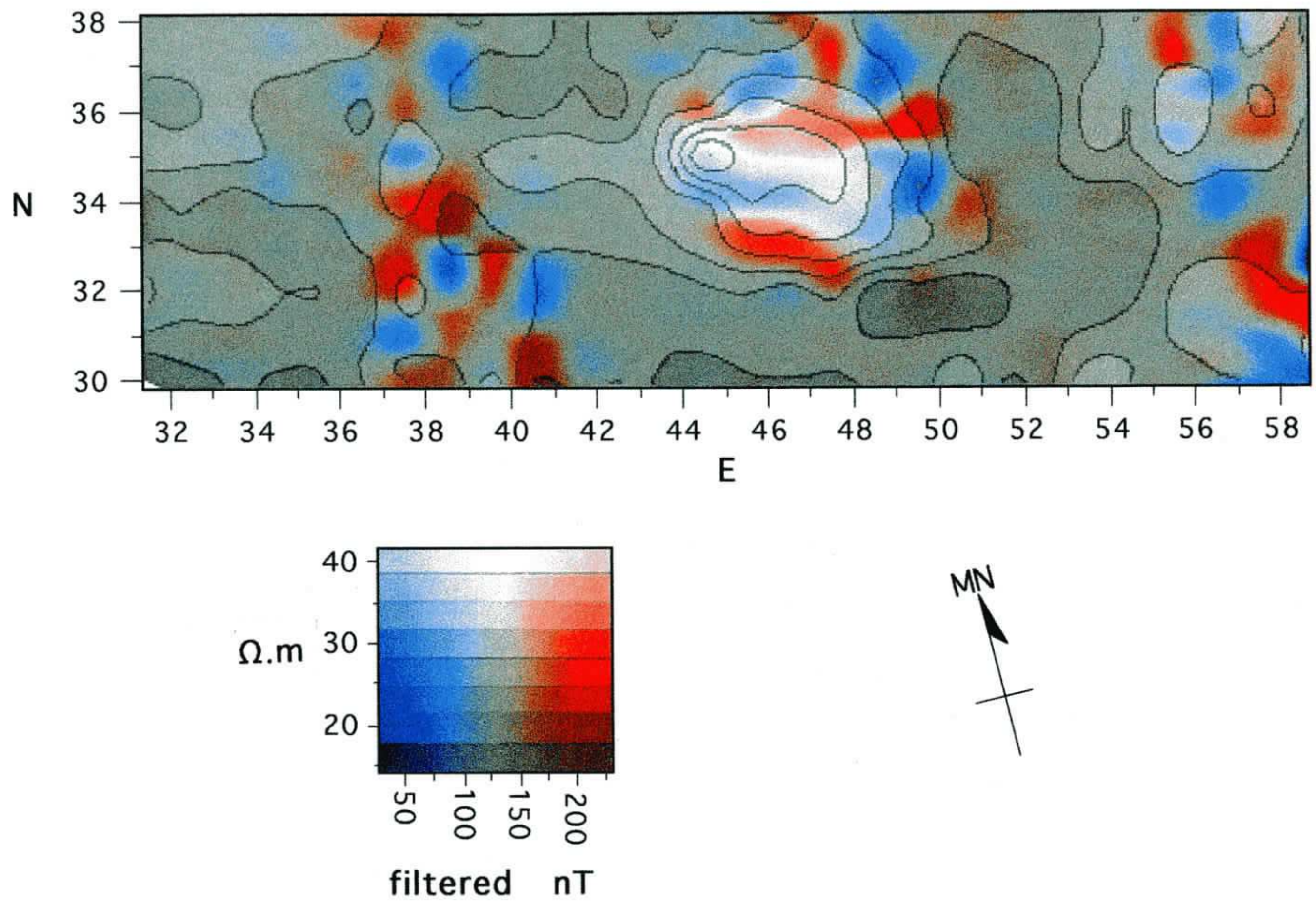

Figure 9. Resistivity and magnetic gradient detail map in the south-west area of the site (with normal Wenner $a = 1$ m). This is an original and complex representation of the superposition of resistivity data (grey scale and isolines) and magnetic data (blue to red colour component). The double response of the central structure is obvious; the two N–S walls (left and right) are revealed only by the magnetic readings.

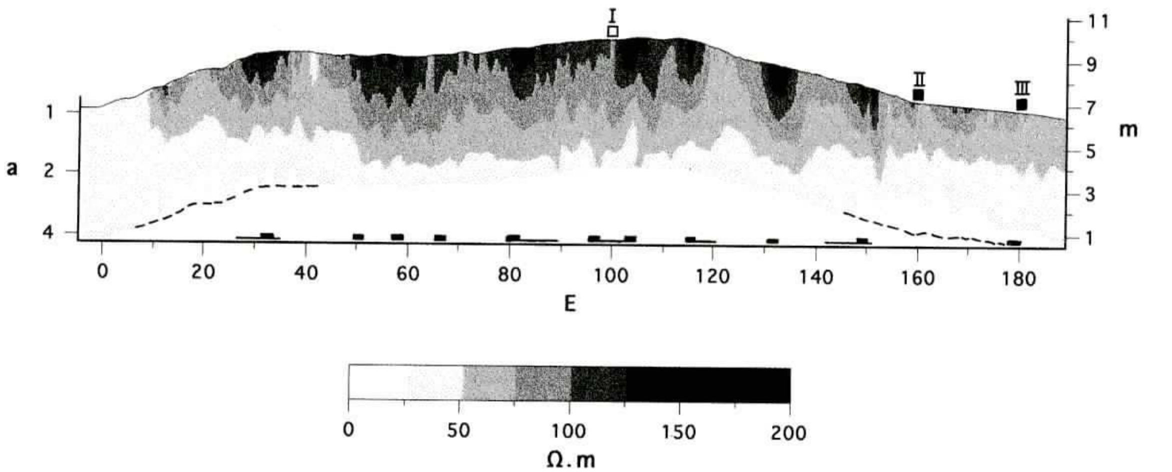

Figure 10. Electrical pseudo-section adjusted to topographic relief from west to east along the N80 line (with normal Wenner, $a = 1$, 2, and 4 m). Small squares represent the position of electrical soundings (I is located 20 m towards north from the N80 line). Black marks on the horizontal axis correspond to the position of main magnetic anomalies on the same line. The approximate depth of investigation of the Wenner $a = 4$ m is delineated by the bottom of the dotted grey area, completed by the dashed line where resistivity reaches values below 20 Ω.m. The corresponding areas (E20 and E160) are more or less symmetrical on both sides of the mound and could correspond to concentrations of clay at the bottom of walls on the limits of the original mound.

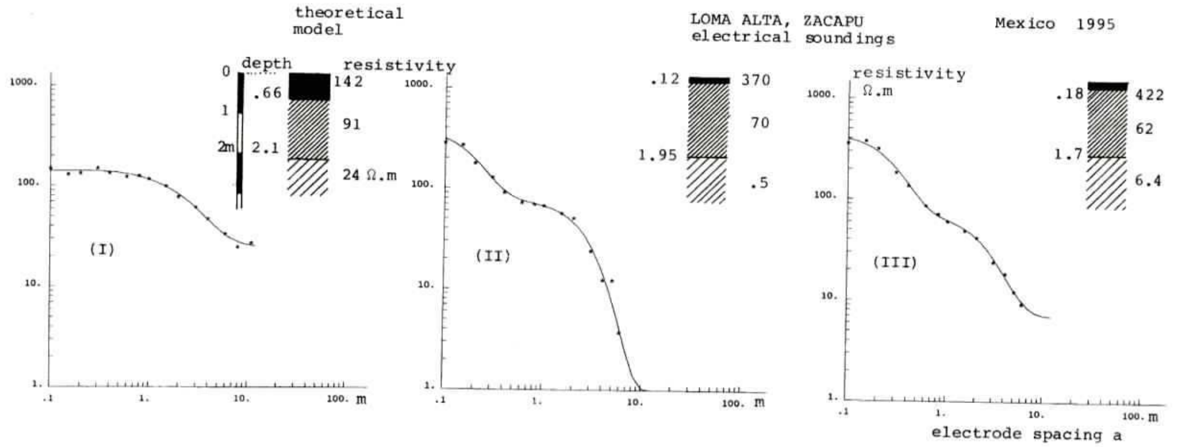

Figure 11. Electrical soundings I, II and III (with normal Wenner) and interpretation according to the horizontal layers model.

measurements of magnetic susceptibility in volume were obtained using Bartington MS2F equipment with the small probe being in contact with samples of approximately 500 g (the results of five measurements were averaged). Additionally, measurements of remanent magnetization with an ACS Minispin Rock Magnetometer were performed on cut samples of approximately 10 cm^3 (Table 1).

Mechanical sounding

In the final stages of the field work, soil bore samples were recovered at five (N40/E80, N36/E46, N90/E50, N82/E90, N90/E90). A 7.5 cm gouge auger was used to recover samples of soil directly into plastic bags at 0.1 m intervals from the modern ground surface until rock was hit or the auger's maximum depth of 1.2 m was

Table 1. Magnetic properties of geological materials.

Sample	Description	Susceptibility (10^{-5} U.S.I.)	Induced magnetization (10^{-6} emu cm^{-3})	Remanent magnetization (10^{-6} emu cm^{-3})	Koeningsberger coefficient (Q)
1	Dense basalt with plagioclase	632	278	47.2	0.17
2	Dense basalt with plagioclase and olivine	187	82	525.0	6.40
3	Vesicular basalt	67	29	704.0	24.2
4	Microcrystalline streaked basalt	303	133	120.0	0.90
5	Basalt in flat layers	402	177	120.0	0.68
6	Reheated black basalt	677	298	353.0	1.18
7	Red scoria	370	163	14.5	0.09
8	Dull grey scoria	440	194	28.7	0.15
9	Tuff mixed with slag	473	36	315.0	8.75
10	Pumice tuff	430	189	105.0	0.56
11	Andesite	115	51	61.9	1.21
12	Grey conglomerate	218	96	20.4	0.21
13	White argillite with carbonates	4	2	0.8	0.40
14	Surface soil	82	35	—	—
15	Lacustrine sediments	67	29	—	—

reached. This kind of sounding is frequently used to recover soil samples for chemical analysis as well as to verify geophysical anomalies. Once in the laboratory, each sample was subjected to a series of simple tests, such as Munsell colour comparison, phosphate assay, carbonate assay and pH determination.

Surface materials survey

During the magnetic survey an inventory of archaeological materials seen on the surface of certain squares was made. The presence of construction materials (stone blocks and slabs), stone artefacts, and ceramic sherds were registered in 13 grid squares. The results indicate that the distribution of materials is definitely not homogeneous, and that the different concentrations may be associated with specific areas of activity within the site. Although it was not possible to fully develop this procedure in a systematic manner at this time, it was evident that this aspect of the investigation would be worth continuing in the future.

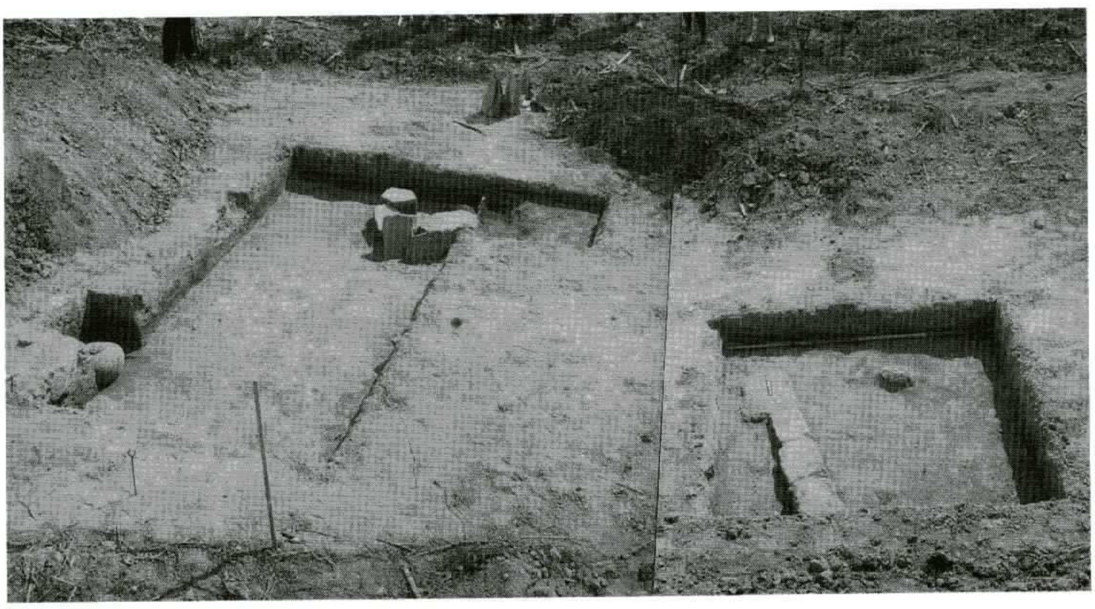

Figure 12. North-east test dig (N180,E180) with burial (left) and stone block structure (right).

Verification excavations

Two test digs (4×2 m and 3×3 m) were excavated in the north-east sector of the site to verify a series of anomalies located during the magnetic survey (Figure 3 shows location and Figure 12 the excavation). Another test dig (4×2 m) was excavated to locate a wall in the south-west sector of the site after magnetic and electrical surveys revealed a pair of parallel linear anomalies enclosing a central circular structure (Figures 3, 9 and 13).

Results and discussion

Magnetometer survey

In total, almost 35 000 magnetic readings were taken over an area of 17 200 m^2. The anomalies found are very large, considering the amplitude of the magnetic field. At high geomagnetic latitudes, the anomalies of induced magnetism are highly dissymmetrical with two differentiated lobes: a small minimum towards the north and a high maximum towards the south (Linington, 1964). This is true for the total magnetic field and for the vertical component as well. This aspect disappears when approaching the geomagnetic equator but is still important at Loma Alta's geomagnetic latitude ($I = 45°$). The dissymmetry is reflected on the vertical gradient, which would usually show a non-normal statistical distribution with few small negative values and a lot of high positive values if the anomalies were due to induced magnetism. Surprisingly, in our particular case, the statistical distribution of the readings of the vertical gradient of the terrestrial magnetic field is quite symmetrical around 0 nT on raw data (Figure 4, top right) as well as around the average on filtered data (Figure 4, centre). This normal statistical distribution of the field data refutes almost any hypothesis involving anomalies of induced magnetism and suggests the existence of randomly oriented anomalies with equilibrium of maxima and minima. This statement is confirmed by the following independent considerations.

Considering the size and distribution of the magnetic anomalies represented in the maps, we can clearly appreciate that this is a singular case and, in our opinion, one which has not been frequently considered in the literature. The anomalies are very small in lateral extension, although quite recognizable at a scale of approximately 1:1000. Maxima and minima are of large amplitude (±150 nT) and cannot be related to the orientation of the magnetic field (Figure 5). In all cases, the anomalies form straight lines which can be identified as the responses of stone walls. It should be noted that four of the 20 m grid blocks were sampled at half of the density (0.5 m $\times$ 2 m, as was mentioned in the methods section of the magnetic survey) and therefore give the impression of tilt errors in these grids.

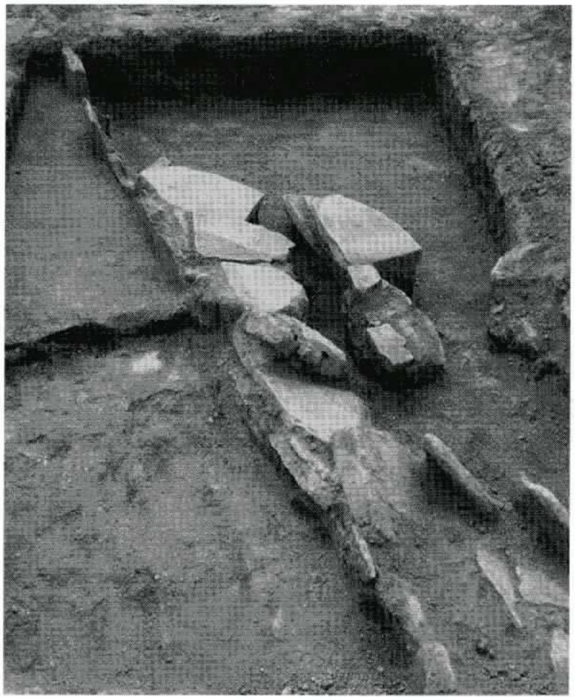

Figure 13. Southwest test dig (N30,E40) with long wall made of stone slabs.

We interpret the small anomalies as the individual response of each of the stones which constitute the walls. We propose that the permanent magnetization of these stones, which are of volcanic origin, may be of the same order of magnitude as, or even greater than, the magnetization induced by the magnetic field of the Earth, and can locally produce a stronger anomaly than the one produced by the magnetization induced by the total volume of the wall. The dipoles of magnetization are in disorder and the stones forming the upper part of the wall, those closest to the surface, produce stronger randomly oriented anomalies which conceal the anomaly produced by the wall itself. In Figure 5 we can observe a unique case of the classical linear type of anomaly at N95,E45 (Figure 3, ref. 12) which might correspond to a wall at a greater depth.

In order to verify this hypothesis, it was necessary to obtain additional data on the magnetic susceptibility (MS) of the geological materials present. The results of the MS studies are shown in Table 1: samples 1 to 6 are various kinds of grey basalts, 7 and 8 represent two colours of scoriaceous volcanic ejecta locally called 'tezontle'. Samples 9 and 10 are volcanic tuffs, 11 to 13 are miscellaneous materials found in archaeological context and, finally, the last two samples represent the soil matrix that forms the very distinct geophysical context. An estimation of the Koeningsberger coefficient (Q = remanent magnetization/induced magnetization) presents various contrasting values, half of them being close to 1 or higher.

The results clearly confirm that all individual stones generally present a high level of magnetization within the relatively low magnetic context produced by the surface soil and earth matrix. Some of these stones, with high induced but low remanent magnetization ($Q < 0.5$), could produce a normally oriented anomaly. Most of them, with a similar order of magnitude of magnetization ($0.5 < Q < 1.5$) or even higher remanent magnetization ($1.5 < Q$), typically produce randomly oriented anomalies. The pattern of blue and red spots in Figure 5 is representative of this disorder: it does not permit an accurate association between pairs of blue and red lobes to individual stones but behaves like a realistic (or even 'impressionist') representation of the stones accumulated by the walls. The result was a very legible map showing the presence of these dipoles placed one after another. There are broad walls for which the presence of several dipoles are added together, but there are also narrow lines of anomalies which have been interpreted as thin structural or containment walls.

At the same time, Bevan (1994, p. 93) was studying the magnetic anomalies of a brick foundation at St Mary's City, Maryland. He mentions that 'the magnetic map does not show a uniform band with a high magnetic field along the line of the foundation; instead it shows a series of high readings spaced unevenly near the foundation. This irregularity is caused by the addition and subtraction of the remanent magnetization of randomly oriented bricks in the foundation.' It happens that the magnetic survey performed at Loma Alta is a detailed and large case example of the Bevan explanation.

Taking into account the pattern observed on Figure 6 (complemented by resistivity data) a preliminary reconstruction based on the lines of walls forming the architectural structure of the site can be seen in Figure 3. Some sort of symmetry can be noted in the structures, with an almost square central element and surrounding walls forming a complex system, all of which is oriented 351° in relation to magnetic north. The central structures form a square almost 100 m by 100 m, surrounded by lines of anomalies interpreted as more containment walls and rooms. There is a considerable accumulation of stones forming another square element in the western part of the site (grid square N60–80, E20–40), which also corresponds to a local high point in the topography.

Two further magnetic survey grids in the north-eastern part of the map discovered several lines of anomalies with the same orientation as those found in the main survey. Verification excavations revealed the foundations of a N–S wall built of rectangular blocks of basalt, as well as a stone slab box which contained the remains of two adults and funerary offerings characteristic of the Jarácuaro period. A funerary urn containing the remains of a neonatal was also located on the east side of this same wall. The neighbouring 3 × 3 test dig revealed another N–S foundation which leads to a corner and then continues to the east (Figures 3 and 12). Another verification excavation in the south-western part of the terrain uncovered a pair of linear stone slab walls, precisely at the spot where the magnetic map suggested it should be (Figures 3, 9 and 13). In both excavations cultural remains were located starting at 20 cm below the surface and clearly coincided with the previously detected magnetic anomalies, supporting the overall interpretation of the magnetic data.

The survey line along N80 sampled with the total field magnetometer localized a group of anomalies between E200 and E230, which together with the results of the simultaneous excavations carried out in this area, suggest the presence of human activity in what was previously considered ancient lake bottom (Figure 7). Archaeological excavations have recently confirmed the presence of human activity beyond the limits of the mound.

Resistivity survey

Electrical maps

In Figure 8 certain aspects shown on the magnetic map were verified. The map presented was produced with the normal Wenner array. Half of this same map was made with the dipole–dipole array, but seeing as there were no appreciable differences, we present only a small interesting detail.

Unfortunately, the most clearly noticeable anomaly (point a in Figure 8), is that produced by the excavation of a trench in 1994. As the filling is looser, it presents a much higher resistance than the original earth that surrounds it. On the other hand, this anomaly is shown to be wider than the trench that was excavated and conceals a part of the remains that were uncovered. The remainder of the anomalies are more interesting as they disclose an exact agreement between the magnetic and electrical anomalies. The presence of walls was confirmed, moreover in greater detail, and appear in corresponding symmetry to the elements that had been excavated recently (Figure 3). Both the magnetic and the electrical data suggest that the difference between the values may be due to unevenness in level, which can be noted in the excavation. The larger responses are produced by the elements nearer to the surface whereas weaker signals may come from a greater depth.

We can detail certain electrical anomalies in Figure 8 if we take their characteristics into consideration.

(i) At point b, in the east–west direction, we observe a thin line in a zone that is difficult to read on the magnetic map due to 'noise'. It is possible to observe how, in this case, we have been able to discriminate well-preserved remains from stones dispersed on the surface.

(ii) At point c, towards the east, a high resistivity anomaly suggests that this set of stones must be more relevant, and bringing symmetry into account, may be related to the three walls discovered in the neighbouring excavation. The right-angled turn this anomaly makes at its western limit fits perfectly well with the shape described by the magnetic data (Figure 3, close to the mechanical sounding 5).

(iii) At point d, which seems to correspond with the centre of the architectural organization. The magnetic map presents a small and isolated anomaly which corresponds with a slightly larger electrical anomaly on the normal Wenner map, but which is much more clearly defined in the dipole–dipole map. Because of its central location within the structure, this may be a point of archaeological interest requiring future study.

(iv) At point e, near the excavation, one of the previously detected magnetic alignments was interrupted. Previous excavations in this area inferred a dismantled wall where the stones were removed by the local people (Arnauld *et al*, 1993, p. 88). The detailed electrical verifications confirmed that even if this area could have contained the described wall, no electrical or magnetic anomaly can now be located (Figures 5 and 8).

The other smaller electrical survey, carried out in the southwest portion of the mound, was performed to verify the presence of two walls and a central structure located during the magnetometer survey (Figure 3). The correspondence between the electrical and magnetic data is very precise: although simple walls cannot be discerned with the same clarity in the electrical map (Figure 9), the central structure can be clearly noted as a strong anomaly. A 2 × 4 m verification excavation was carried out at coordinates N30,E40 and confirmed the existence of one of the detected walls (Figure 13).

Electrical pseudo-section

The result was a section through the entire mound which indicated the presence of a large number of superficial anomalies concentrated at the higher part of the mound, with scattered series of anomalies near the periphery (Figure 10). The majority of the electrical anomalies were found within 2 m of the surface, in contrast to the very few responses obtained between 3 and 4 m as a consequence of the near-surface water table.

The highest peaks, with amplitudes of 100 Ω.m correspond exactly with the presence of walls on the magnetic map. A broad section can also be noted where all readings remain above a value of 100 Ω.m and correspond to the section N80,E50–E120. This is the nucleus of the mound and indicates that the material in this area has a higher resistance to current than the material in the periphery of the mound. Therefore the central part of the mound is where there is a higher density of buried substructures.

Towards the edges of the mound, the walls become progressively simpler and it appears that the proportion of clay in the earth increases, resulting in diminishing resistivity values; in fact, it is possible to note a change in electrical conductivity before and after the wall at N80,E150. Two noteworthy points (E20 and E160) in the same figure show minimum resistivity values (<20 Ω.m) when the distance between electrodes is $a = 4$ m, and it is probable that these correspond to the limits of the original mound that was later expanded.

The pseudo-section is interesting because it shows that a considerable part of the information which can be observed through the electrical and magnetic data is to be found very near the surface. In other words, the information recovered probably represents the last major occupation of the site and is exactly related to the dipoles expressed by the magnetic maps.

Electrical soundings

Based on the analysis of the data, a remarkable similarity between all soundings can be clearly noted (Figure 11). Three subsurface layers were identified: the first corresponds to the recently ploughed terrain surface, and since it is thin and dry, it presents a high resistance to current with values of up to 400 Ω.m in soundings II and III. In sounding I this layer is less resistant (142 Ω.m) but is thicker and probably includes archaeological horizons. The second layer appears between 1.4 and 1.80 m below the first one and presents resistance values between 62 and 91 Ω.m. The greater thickness and very homogeneous fillings of the second layer are noteworthy. At sounding I, a higher proportion of stones in the second layer may account for the slightly higher resistance observed in the pseudo-section. The third layer cannot be clearly interpreted, but appears at the same depth (2 m) in the three soundings. The very low level of resistivity (less than 25 Ω.m) represented by this last layer indicates a higher content of water and clay.

It would seem clear therefore that the soundings did not confirm the proposed hypotheses and resulted less sensitive (in this case there was a strong contrast in the resistivity between the surface and lower levels) than the Wenner profile with $a = 4$ m. The homogeneity observed by archaeologists during their excavations is consistent with these results and was confirmed by the chemical analysis of the samples collected at depths of up to 120 cm. It is also possible to confirm that at point I there are no deep archaeological substructures containing any significant quantity of stones and that geotectonic movements produced the foundation for the islet.

Mechanical soundings

Semi-quantitative chemical analysis of the 29 soil samples recovered demonstrated a high level of homogeneity: Munsell Colour 10YR 3/2 (very dark greyish brown), pH near 7.1, low content of carbonates, and high concentrations of phosphates (Barba *et al*, 1991). Additionally the soundings provided the datum of the depth at which contact with stones was made. In the verification of certain points on the electrical map, it was possible to establish that what had been observed as a difference in resistivity was the consequence of differences in the depths at which the walls are buried. Sounding points 4 and 5 confirmed the hypothesis of a symmetrical structure to the one excavated in 1995.

Sounding 5 reached large stones at 15 cm below the surface, while sounding 4 hit rock at 80 cm. Soundings 1 and 2 also confirmed the existence of the predicted stone alignments. However, sounding 3 did not verify the predicted alignments despite reaching a depth of 1.20 m.

Conclusions

Considering that the archaeological data were difficult to interpret because the relatively small areas excavated only revealed disjointed portions of a large and complex site, the prospection survey of the entire islet provided the necessary information to integrate the dispersed architectural and cultural elements located.

One of the most interesting results was the pattern of low and high gradients (blue and red spots) in the magnetic map due to dipoles placed one after another representing the stones forming the buried walls. It was possible to discriminate between broad composite walls by the presence of several dipoles added together as well as narrow lines of anomalies which have been interpreted as thin structural foundations. The high resolution provided by modern gradiometers helps produce maps that can discern the dipoles generated by every major stone surveyed. The theoretical explanation provided by Bevan's research and the example presented here enrich the knowledge base for interpreting cultural anomalies.

Despite the improvements in the field work speed proposed by one of us (Hesse and Spahos, 1979), electrical resistivity maps were always more time consuming than gradiometric survey but provided a high degree of discrimination and verification that made interpretation easier. Electrical pseudo-sections were the most informative technique, by producing an exact correlation between the magnetic maps and providing information from deeper layers.

Geophysical data and excavation resulted in a clear image of the orthogonal layout of the highly structured ceremonial site and are a good example of the complementary information provided between archaeological excavation and prospection.

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