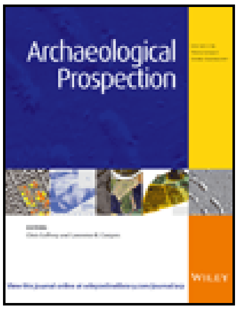
MANUSCRIT ACCEPTAT	
Multimethod Geophysical Survey at the Iron Age Iberian Site of El Molí d'Espígol (Tornabous, Lleida, Catalonia): Exploring Urban Mesh Patterns Using Geophysics	
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Abstract

This paper presents the results of a multisystem survey using magnetometry and dual frequency ground-penetrating radar (GPR) carried out at the Iron Age Iberian site of El Molí d'Espígol, Tornabous, Catalonia, dated from the seventh to third centuries bce. The surroundings of the current urban area were explored with magnetometry in order to describe possible features related to the settlement. In the non-excavated part of the urban area was surveyed by GPR in order to describe the urban mesh. The interpretation of the data has allowed not only the identification of new areas of archaeological interest and priority action, but also the proposal of a new hypotheses on the evolution of the town planning and the defensive system of the site.

1. Introduction

In order to establish a new strategy of excavation at the Iron Age Iberian site of El Molí d'Espígol (Lleida, Catalonia; Figure 1 in the forthcoming years, a geophysical project consisting of a multisystem survey (magnetometry and dual frequency ground-penetrating radar (GPR)) was proposed. Two specific objectives were defined: identifying and describing the suburban features related to the settlement and overviewing the non-excavated urban area.

Figure 1.

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Location of the El Molí d'Espígol.

Iberian Iron Age urban settlement of El Molí d'Espígol

The pre-Roman Iberian settlement of El Molí d'Espígol is placed on a small and smooth elevation northeast of the Tornabous village (Lleida, Catalonia; Figure 1). The local geology consists essentially of clays and marls, which are also the main building materials found during previous excavations performed at the site (Maluquer de Motes *et al.*, 1971; Maluquer de Motes, 1982; Cura, 1994, 2006; Principal *et al.*, 2010). It includes two well-defined archaeological areas: on the one hand, the large urban area where the remains are visible today; and, on the other, the suburban perimeter extending northwards and westwards beyond the walls of the settlement (Figure 2A).

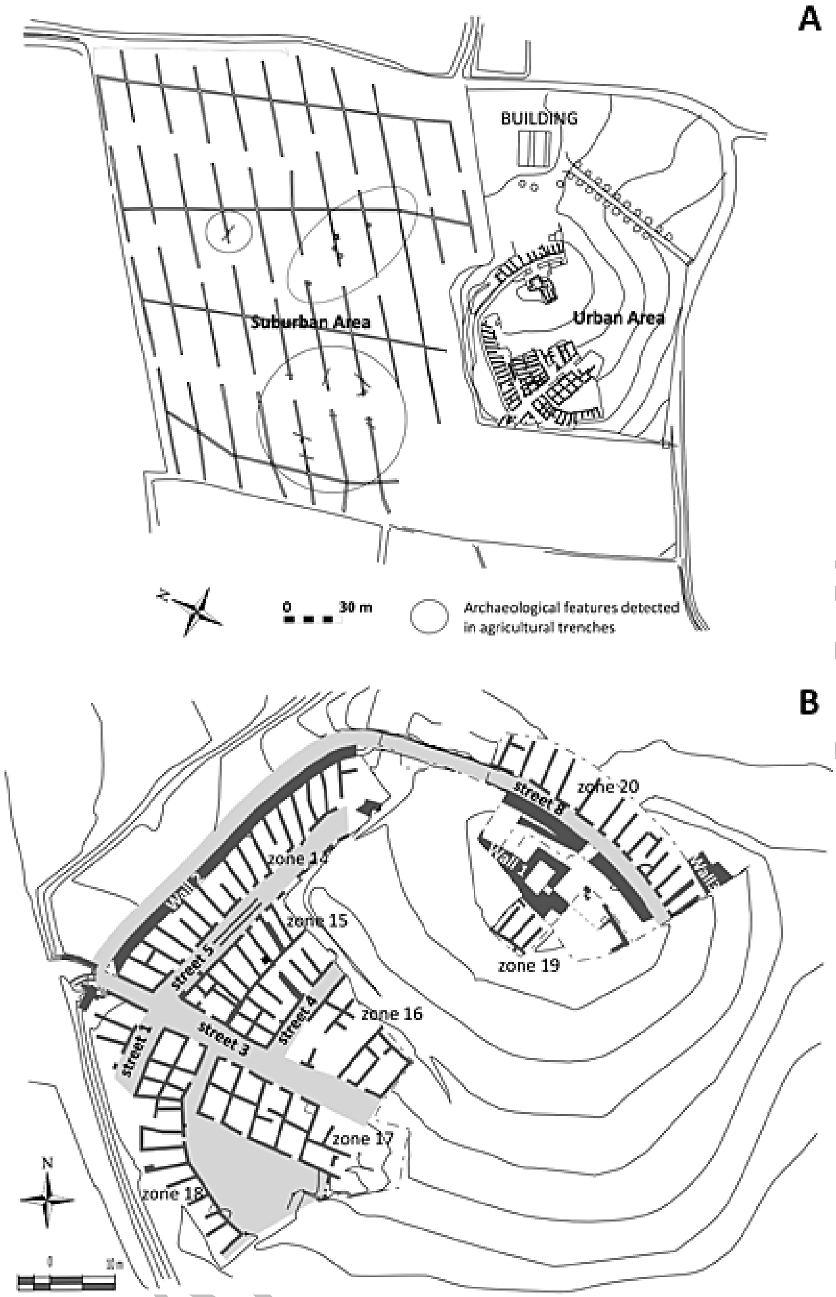

Figure 2.

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(A) The El Molí d'Espígol complex. (B) The urban area.

The earliest archaeological evidence is attributable to the first Iron Age (late seventh century bce), when a small habitat surrounded by a strong wall with square towers (Wall 1 in Figure 2B), and seemingly a ditch, was built (Principal, 2007). In the second half of the sixth century bce the site already showed signs of significant growth, when a new and broader defensive perimeter (a plain wall without towers; Wall 2 in Figure 2B) replaced the previous one, and a particular urban infrastructure developed (Principal *et al.*, 2010). By the beginning of the fourth century bce, however, a remarkable structural change took place in the settlement: the habitat expanded outside the physical limits of Wall 2 and a complex urban layout was developed, leading to the construction of a new defensive perimeter (Wall 3 in Figure 2B) encompassing the whole urban area (little is known about this third wall because only a small portion of the structure has been excavated, in the northeastern sector of the site; in addition, parts of the wall were probably ruined or plundered in ancient times). There is also evidence of a new suburban quarter built beyond Wall 3, where manufacturing activities would be fulfilled (Principal *et al*., 2012). El Molí d'Espígol appears to have become a sort of city, a focus or capital, residence of a certain political power or elite within the historical territory of the *Ilergetes*, the Iberian pre-Roman people inhabiting the region (present western Catalonia). During the fourth to third centuries bce, the settlement reaches its peak, but it is suddenly abandoned at ca. 200 bce as a result of the Second Punic War and the defeat of the *Ilergetes* at the hands of the Romans (Cadiou, 2008, p. 36; Edwell, 2011, p. 324). There is evidence, however, of reoccupation in some parts of the site ca. 100 bce, when a small community settled for a short period of time. It was definitely abandoned by ca. 50 bce.

The urban area presents a complex organization (Figure 2B). It is seemingly defined by a pseudoelliptical perimeter, organized according to an east–west axis (Street 3), which divides the habitat into two parts. The other streets, in contrast, follow a concentric layout (Streets 1, 4 and 5), parallel to the outer walls. The urban planning shows a network of different districts comprising domestic, storage and community structures and features, delimited by streets and open public areas. Urban infrastructures, such as sewers, are also present. In contrast, the remains found west and north of the settlement, beyond Wall 3, appear to correspond on the one hand to a manufacturing area dedicated to metalworking; and on the other, to a silo field intended for agricultural surplus storage.

Survey areas and archaeological questions

The last investigations around the urban settlements of Iron Age Iberian culture revealed extensive, complex suburban areas that had not been studied systematically by the archaeological investigations of the twentieth century (Belarte and Plana, 2012).

As in other cases, the investigations carried out in El Molí d'Espígol discovered an important urban settlement, with an apparently clear delimitation. In the early 2000s, agricultural works required the excavation of a mesh of trenches to install irrigation systems in the surrounding fields (Figure 2A). The trenches showed the existence of other archaeological remains outwards of the first known perimeter, including pits, kilns and walls (Principal *et al*., 2012). Thus, the configuration of this suburban area, its function, its total extension as well as its relation with the known urban settlement, became new investigation issues for the archaeological team.

Regarding the urban area, it has been excavated since the early 1970s (Cura, 2006), revealing several occupation phases, with a dense mesh of buildings connected by narrow streets, as stated above and shown in Figure 2B. The current research team showed an interest in obtaining a general overview of the non-excavated area in order to plan further investigations related to the configuration of the defensive system or the possibility of a planned urbanism.

According to these considerations, a geophysical survey was planned aiming to first ascetain the delimitation and contents of the outer area, and to describe the continuity of excavated buildings in the urban area (Figure 3).

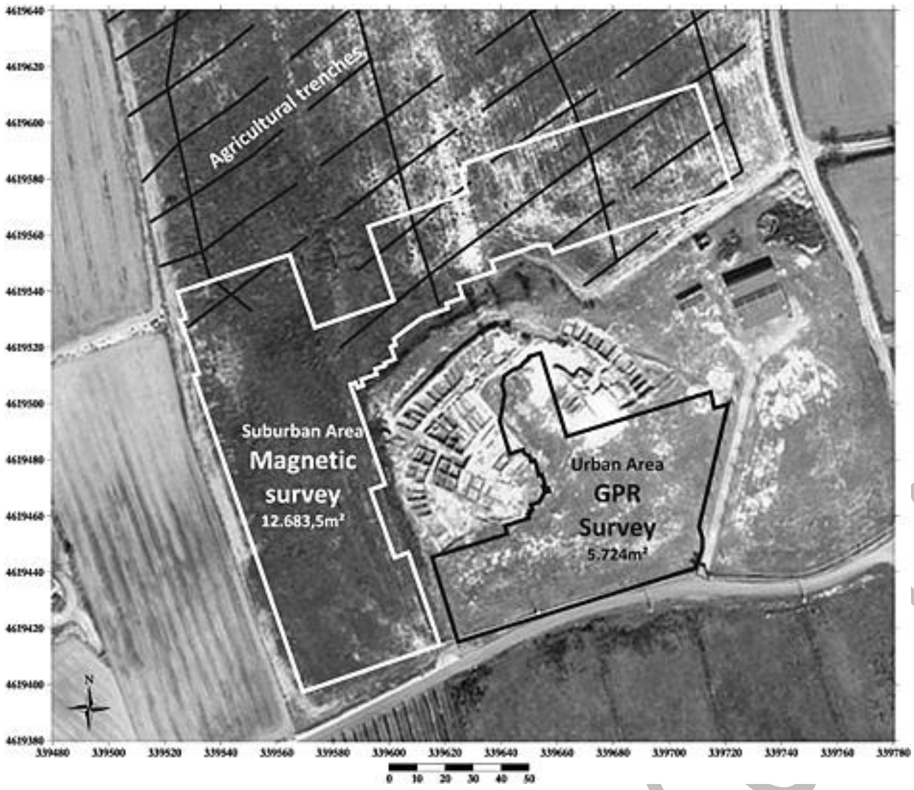

Figure 3.

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Aerial view of El Molí d'Espígol (2009), with the survey areas overlain (image courtesy of Institut Cartogràfic de Catalunya (ICC)).

Survey strategy and methodology

To achieve these objectives, the survey of the two areas was planned taking into consideration their specific characteristics, the questions to solve and a limited budget.

In previous tests that took place in 2009 in the suburban area (Sala and Garcia, 2009), a Bartington G-601 fluxgate gradiometer was used to survey two grids of 60 × 30 m. The results showed a low magnetic contrast between the soil and the local building materials as linear anomalies, which were interpreted as building remains being detected between -1 nT m^{-1} and -3 nT m^{-1}. Several extensive positive anomalies were detected and interpreted as ditches or trenches as well as high contrast anomalies, such as iron objects or thermally altered areas.

With this information and the remains discovered during the agricultural works, there was evidence that the actual perimeter of the city, or at least its defensive system, was larger than that defined by the current urban core.

To delimit and describe other possible limits of the site, a 1.3 ha area was chosen, covering part of the north and west cultivation fields next to the known settlement (Figure 3). Even though the contrast between the soil and local stone was weak during the first tests, a magnetic survey was performed using a Bartington G-601 fluxgate gradiometer because of its capability to describe features such as ditches, pits or kilns cost-effectively.

In the urban settlement a survey was planned to obtain first an overview of the non-excavated area, covering 5700 m^2 (Figure 3). The facilities provided to visitors, such as panels or explicative displays, the iron fence that encloses the monument and the closeness of the laboratory buildings excluded the possibility of a magnetic survey. In addition, this survey aimed to describe presumably small buildings, which could be better described using GPR (Sala *et al.*, 2012).

Magnetic survey of the suburban area

As mentioned above, the Bartington G-601 dual sensor was selected to survey the suburban area. The data were collected with a 0.5 × 0.25 m spatial resolution, with an amplitude range of ±100 nT. (This particular system uses an autorange function that can collect up to ±3000 nT m^{-1}, when anomalies grow over ±100 nT m^{-1}.)

Processing and visualization of the magnetic data

The original data showed some severe disturbances from modern iron objects, such as iron fences or electricity pylons, as well as the mesh of irrigation trenches mentioned above (Figure 4A). As a first step in the data processing, the most disturbed areas were deleted to avoid matching problems on further mean corrections. The resulting data were processed using a zero mean line routine and a second zero mean line application with ±3 standard deviation thresholds (Figure 4B). A low-pass filter of 0.5 × 0.5 m and a linear interpolation were then applied to obtain smoother images, with a final spatial resolution of 0.25 × 0.25 m (Figure 4C).

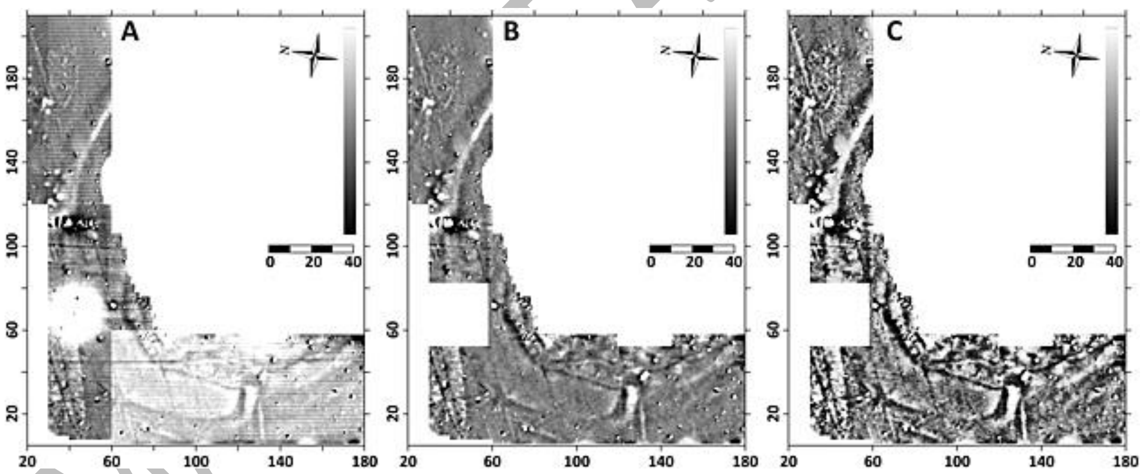

Figure 4.

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Magnetic survey. (A) Raw data. The large positive anomaly is produced by an electric pylon. (B) Processed data. The electric pylon area was eliminated to obtain better results in mean-line correction process. (C) Data compression. A scaling factor of 2 and a pre-multiplication factor of 12, with a logarithmic weighting, were applied.

Interpretation of the magnetic data

The processed data were examined for interpretation in several ranges, including data compression and using contour lines to study the shape of diffuse anomalies. The most striking features of the magnetic survey are two groups of anomalies that surround the urban core, one to the north and the other to the west, and that are shown in Figure 5A. The northern part, named M1, consists of a curved positive anomaly 55 m long and 3–4.5 m wide. Group M1 is connected to two new groups of anomalies named M2 and M3 that show linear features and intense bipolar anomalies, respectively. Although the data were interrupted by disturbances from a concrete electric pylon in the western end of M1, anomalies such as M5 or M10 with similar characteristics were detected. A second group of anomalies named M67 showed a subtle increase in magnetic values on the western side of the suburban area. This area was clearly limited by the negative anomalies M6 and M7, defining a curved fringe of 18–22 m around the urban area. The inner zone closed by M6 showed higher contrast linear features, as visible in the M4 group of features. Other groups of higher contrast bipolar anomalies, named M8 and M9, cross M67 in the east–west direction, pointing to the center of the urban area. Other interesting anomaly groups have been defined, such as M11, which shows a group of subtle linear features in a radial disposition.

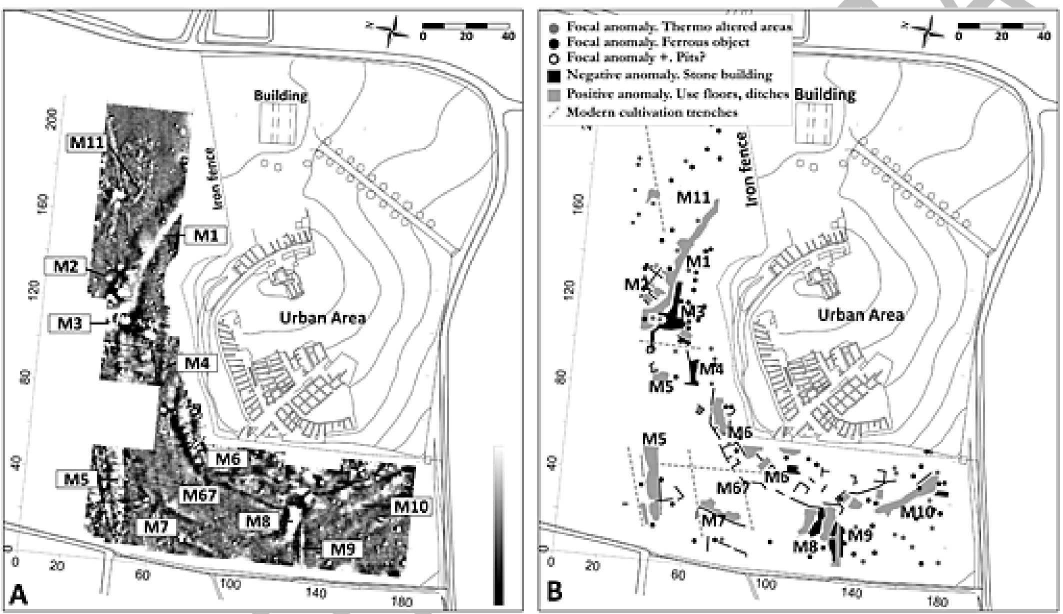

Figure 5.

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Magnetic survey of the suburban area. (A) Greyscale plot with labels of main anomalies detected. (B) Interpretative diagram.

According to these data and their characteristics, an interpretative diagram was traced (Figure 5B). Anomaly groups M1, M5 and M10 were interpreted as parts of a peripheral ditch (Aspinall *et al.*, 2008) on the assumption that the positive value anomalies are a product of the filling of the ditch with sediments. Anomalies M2 and M3 are connected to M1, and are interpreted as a group of buildings related to the defensive perimeter. Anomaly M3 also contains two strong (more than 120 nT m^{-1}), south–north oriented dipoles, which are interpreted as a possible fired area of the building. Anomaly M67 was also interpreted as a defensive feature, as this area contains no other relevant anomalies and a slight positive value, which we relate with a sediment filling. Anomaly M8 was interpreted as a possible footbridge or walkway that crossed the M67 area, by interpreting the negative anomalies as the product of building walls, and the positive anomalies as the filing of the footbridge. Anomaly M9 is also interpreted as a part of the footbridge. Indeed, the group of described perimeter anomalies defined a circular fringe around the urban area, limited by the groups of features M4 and M6, which were interpreted as a first line of buildings and defensive structures in relation with the urban area. In addition, the feature named M11, located outside of the perimeter defined by M1, is consistent with the continuity of archaeological remains outside of the defensive perimeters.

The GPR survey of the urban area

The extensive GPR survey over the urban area was carried out with the IDS Ris MF Hi-Mod system, using the IDS double antennae box, which offers simultaneously 200 MHz and 600 MHz data. The GPR profiles were acquired with 0.4 m separation, using a sample rate of 40 scans per metre (trace increment of 2.5 cm). Time windows were fixed to 50 ns for 600 MHz data and 80 ns for 200 MHz data.

Processing and visualization of the GPR data

Due to the complexity of the data obtained, this part will concentrate on the 600 MHz dataset, which showed a higher resolution in the description of small building features. The 200 MHz data obtained a greater depth penetration, but showed low-frequency noise and poor resolution results in time-slice views. Time-slice plots have been generated using GPR-Slice software, following the typical processing string, which consists in data conversion and gaining, signal processing and resampling.

After a first overview of gained and phase-corrected data, an average velocity of 0.08 m ns^{-1} was calculated using hyperbola morphology. The processing sequence of gained data consisted in eliminating system and static noises, direct coupling, or line noises using a bandpass filter (low cut-off at 285 MHz, high cut-off at 864 MHz) and a background removal filter (Figure 6). The resulting data were resampled and interpolated in plan views (time slices) testing several vertical gaps and overlappings to check the information changes with depth and the effective penetration of GPR (Conyers and Goodman, 1997). Although several sets of parameters were tested during the data interpretation, the plots shown in this paper are generated from a sequence of 25 time-slices from two-way traveltime 0 to 25.5 ns (Figure 7). In this particular time-slice sequence, the processed profiles were resampled to a trace increment of 0.1 m and the mean of the absolute amplitude was computed in time windows of 30 samples (3.52 ns), overlapped at 2.74 ns. The resulting data were interpolated using an inverse distance algorithm in an elliptical neighborhood of 0.5 m × 0.5 m to create 0.2 × 0.2 m pixel maps. A final low-pass was applied on the resulting grids in order to obtain smoother views.

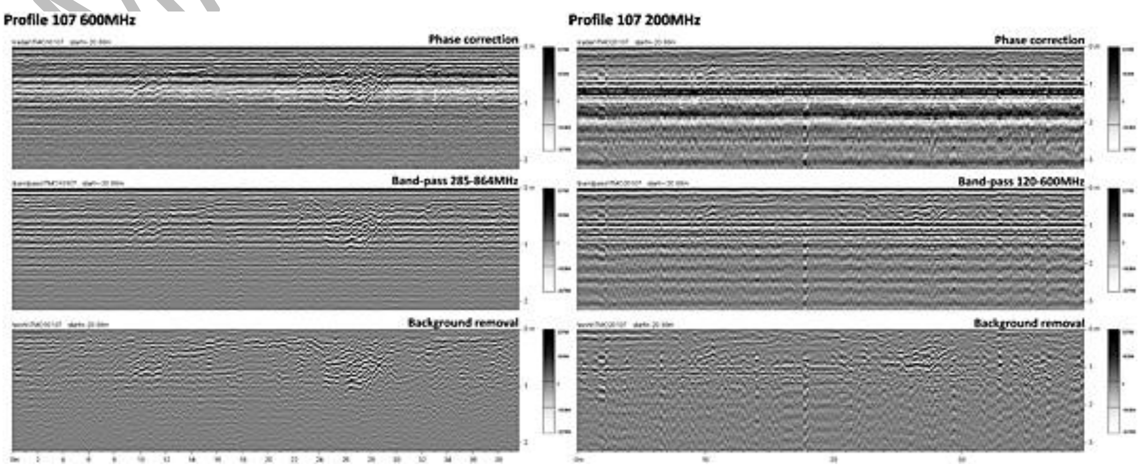

Figure 6.

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Signal processing. Processing of ground-penetrating radar profiles for 600 and 200 MHz. The bottom radargrams are used in the time-slicing process.

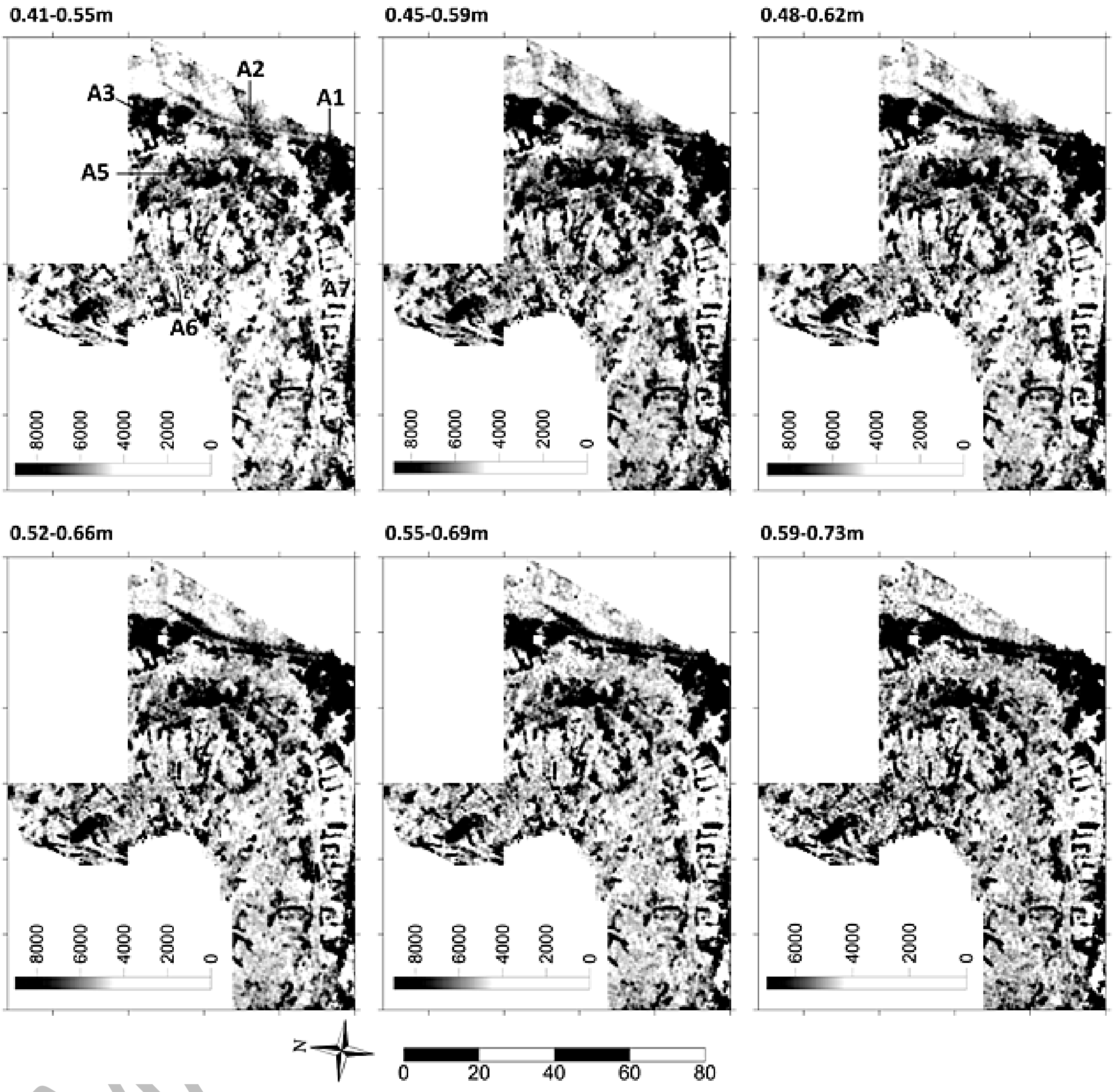

Figure 7.

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Time-slice sequence from 0.41 m to 0.73 m depth (two-way traveltime 10.2 ns to 18.28 ns at v = 0.08 m ns^{-1}) generated from processed ground-penetrating radar data.

Due to the complexity of the results, alternative views were used for the interpretation of the data. A high-pass filter was applied in a moving window of 3.2 × 3.2 m (Figure 8C) and an *X*–*Y* gradient directional filter was computed, which returns the directional derivative in the direction of the bisector of axes *X* and -(Figure 8D). The objective was to remove the large scale variations and enhance local variations.

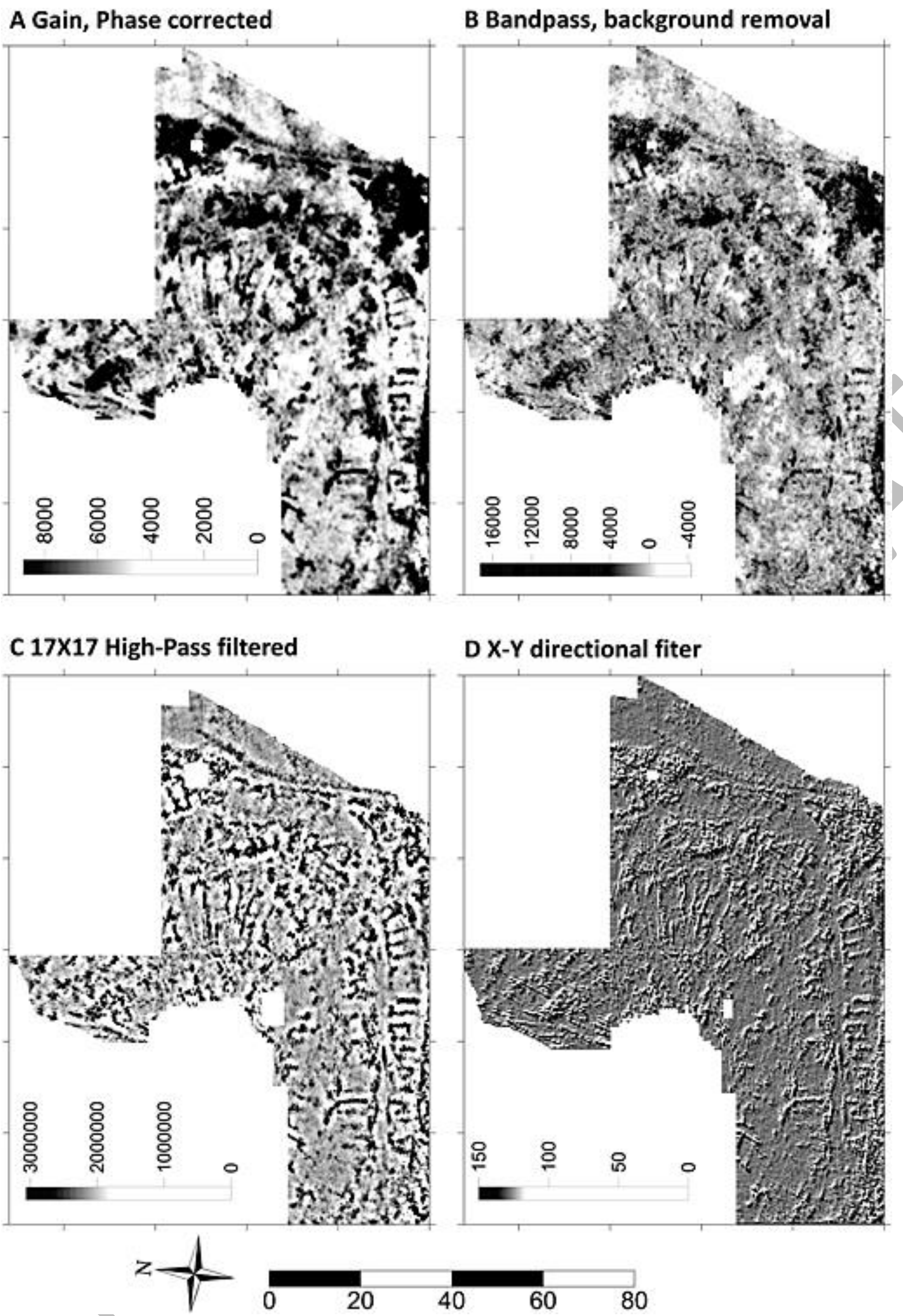

Figure 8.

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Time-slice results at 0.45–0.59 m and grid filtering on 600 MHz data. (A) Time-slice generated from gained and phase-corrected data. (B) Time-slice generated from processed data (gain, phase correction, bandpass 285–864 MHz, background removal). (C) 17 × 17 high-pass filter over (B). (D) *X*–*Y* difference directional filter over (B).

The summarized complete processing sequence is presented hereafter:

1. gain and phase correction;
2. band-pass filter 285–864 MHz;
3. background removal filter;
4. slicing – absolute amplitude (25 slices of 3.52 ns, overlapping at 2.74 ns with resampling units of 0.1 m);
5. gridding – inverse distance elliptical (0.5 × 0.5 m searching radius with 0.2 m pixel);
6. grid processing sets (low-pass filtering, high-pass filtering, directional X–Y filtering).

Interpretation of GPR data

A first overview of the generated time slices indicated that most of the relevant information about the archaeological remains was located between two-way traveltime of 9 and 20 ns (0.3–0.8 m below the surface). In order to simplify the interpretation process, the high-amplitude anomalies described in time-slices were divided in two main categories: extensive areas with a diffuse morphology and linear features.

The first kind of anomaly was mainly visible on the eastern side of the explored area and included groups A1–A5 (Figure 9). A comparative analysis of these groups using alternative views as contour plots or filtered grids (Figure 8) allowed partial recognition of their geometries. Comparing these anomalies to the global results, the stratigraphical context of the eastern area appeared to be different from the other areas. This could be explained by the presence of massive buildings, presumably related to the defensive system. In addition, the use of massive mud structures in the aerial parts of defensive walls, which are usually composed by a mix of clay and gravels, is not unusual in Iberian architecture (Moret, 1996, pp. 71–76). The erosion of these structures could also account for this kind of diffuse, reflective signal in an extensive GPR survey. The description of the morphology of collapsed building remains in debris stratigraphical contexts could be a complex problem in any geophysical survey technique. This is especially difficult if the walls do not contain mortar or if the collapsed buildings have complex geometries. In this particular case, the comparative depth information brought by the time-slice technique helped to compensate for the spreading of the GPR signal in the debris areas.

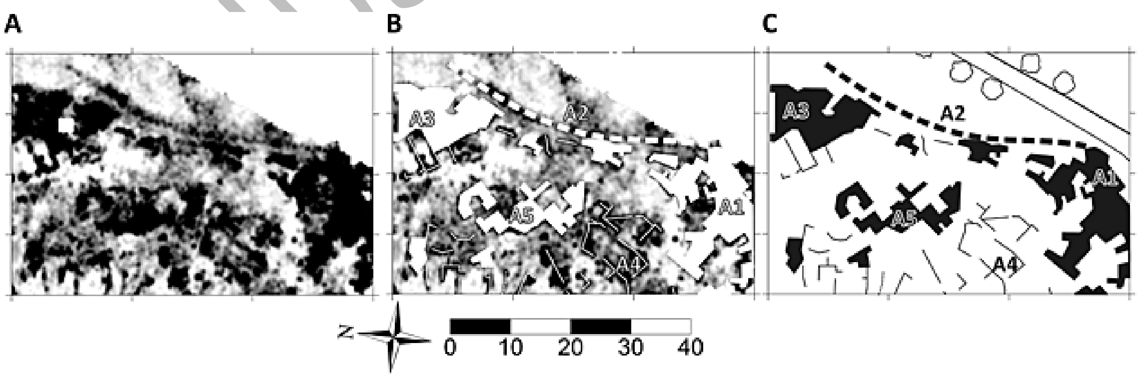

Figure 9.

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Interpreting data. (A) Detail of eastern area at 0.45–0.59 m depth (11.1–14.6 ns at $v = 0.08$ m ns^{-1}). (B) Sama as (A) but with selective contour lines and resulting interpretation overlain. (C) Interpretative diagram.

The complete results of the interpretation of the GPR data are displayed in Figure 10 with a map of the excavated features. Groups A7, A12 or A14, at the centre and on the south side of the survey area, showed sharper images than the groups described previously. We interpreted these groups as concentrations of buildings, disposed in a progressive radial geometry (A12, A14) or as stacks of buildings such as those described in the excavations (S, A7). Other linear features with larger dimensions, such as A2, A13 or A9, were interpreted as wall remains that were seemingly related to the first line of the defensive system (Wall 1 in Figure 2B) of the urban area. More specifically, as a certain symmetry was expected in the urban complex, the features A2 and A9 were interpreted as the eastern and southern limits of the urban area respectively, even if the continuity of the urban structure through the south could not be discarded completely.

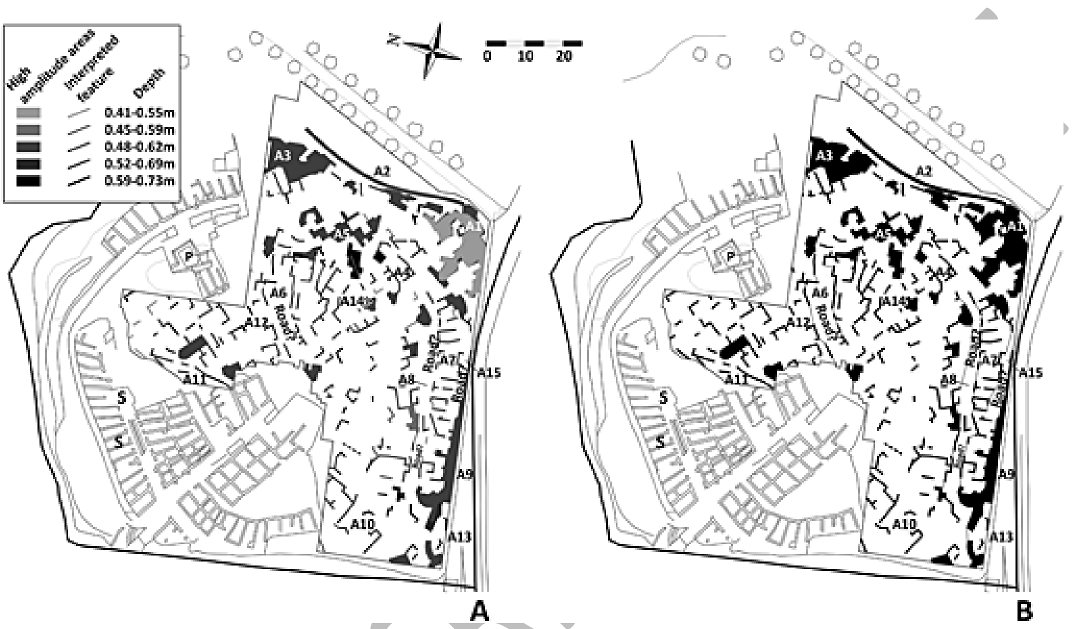

Figure 10.

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Interpretative diagrams. (A) Interpretation of time-slice sequence of Figure 7, using grey tones as depth scale. (B) General interpretative diagram.

Archaeological interpretation

The archaeological implications of the results had to be studied taking into consideration the fact that the effective range of depth described in the GPR survey was shallow. Therefore, only the information from the last phase of the settlement could be analysed. The sum of the interpretative diagrams and of the topographical excavation maps in the same view (Figure 10) helped to establish archaeological working hypotheses about urbanism and functions of the different features detected.

According to the resulting interpretation diagrams (Figure 10), an urban complex, delimited at the east and south by walls (A2) and several possible defensive buildings related to them (A1, A13), can be easily perceived. Inside this perimeter, some groups of buildings are described with, at least, three streets or paths connecting the internal structure of the complex (A6, A8, A15). As far as the town planning is concerned, the survey plainly shows the continuation in the unexcavated areas of the urban pattern brought to light by the archaeological works. Therefore, the idea of a complex and rationally organized 'city' developed according to a preconceived plan, at least for the late fifth to early fourth centuries bce remodelling, is fully confirmed. On the other hand, the excavations conducted in 2006–2008 discovered a new internal perimeter in the central area of the settlement (Principal, 2007; Principal *et al.*, 2010, pp. 20–24). The GPR survey results show that groups A14 and A10 could geometrically match this perimeter (Figure 10).

Nevertheless, the most remarkable results produced by the geophysical survey occurred in the outer suburban area. Contrary to expectations, the detection of a series of features mainly attributable to the late fifth to early fourth centuries bce rampart allows us not only to outline the theoretical perimeter of the city at that time (Figures 4 and 5), but also to consider the issue of its construction and its geometric design as a whole (Figure 11).

Figure 11.

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Aerial view of El Molí d'Espígol with the geophysical data and its theoretical regular plan based on circular patterns. The outer dashed line circle corresponds to the hypothetical perimeter of the mid-Iberian ditch, and that immediately inside it would define the layout of Wall 3.

Geometric design of the site: evolution of a preconceived pattern

In the first instance, the topography of the terrain where the settlement is located should be considered: a flat depression, with no prominent elevations, conferring natural building advantages in order to devise a regular preconceived plan according to a radial model. During the first Iron Age (seventh century bce) the geometric outline of the site was formally established (Figure 12A), lasting for almost three centuries, until it started to expand (Figure 12B) at the beginning of the mid-Iberian period in the fifth to early fourth centuries bce.

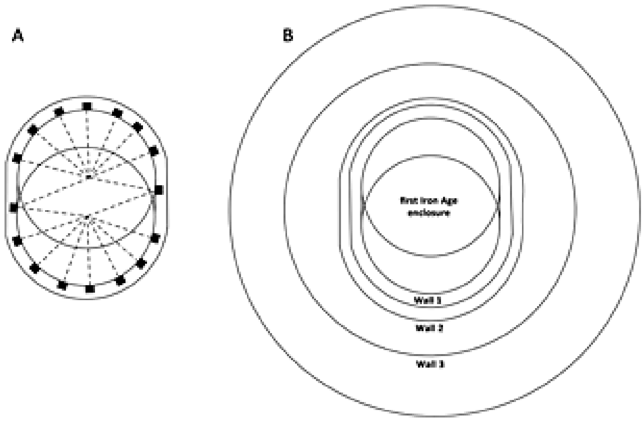

Figure 12.

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Restitution of the El Molí d'Espígol geometric design. (A) First Iron Age rampart and towers. (B) Evolution between the first Iron Age (seventh century bce) and the mid-Iberian period (fourth to third centuries bce).

Although the present plan and surface remains date to this period, the archaeological evidence concerning the original first Iron Age occupation is very scant. Amongst it, a wall (Wall 1) and three square towers have been identified, as well as a fragmentary mural structure fronting the fortification in the northeast area (Principal *et al.*, 2010, pp. 16 and 20–22). Despite the lack of a complete view of the urban plan, a hypothesis on its theoretical design can be proposed on the basis of the partial evidence provided by the defences: a pattern for the first Iron Age settlement, in use until the late fifth to early fourth centuries bce, based on two secant circles, drawn from an axis, and resulting in an oval shape. This axis would be built on two central points, from which the disposition of the main elements, such as the wall and the towers, would have been fixed. If a line of bisection is drawn for every tower, their converging point would correspond to the centre of the circle; a few metres below, another midpoint would be marked in order to design the rest of the site. From these central points, by means of ropes and pegs, the geometric planning would be traced.

How would the perimeter of the site then be defined? Wall 1 would outline it, corresponding to the secant circles, about 60.1 m in diameter. The towers would be disposed at a regular distance, following a constant opening angle of 23–26°. Finally, the mural structure fronting the fortification would have been traced from these central points, defining two new secant circles (ca. 72.2 m in diameter).

We have established then a theoretical design of the first occupation based on a radial oval-shaped plan, identical to that proposed for the pre-Roman Ilergetan settlement of Els Vilars (Arbeca, Lleida) shown in Figure 13 (GIP, 2003, p. 238; Alonso *et al.*, 2005, pp. 27–28), where the square towers are disposed following a constant opening angle of ca. 41° (Olmos, 2010, pp. 132). Regarding the pattern we have observed, the projection of the smaller opening angles of El Molí d'Espígol towers would result in 16 towers (Figure 12A). Both sites share chronology (first Iron Age), cultural affiliation (pre-Iberian Ilergetan) and a similar topographic location (both situated in a lowland setting and not far from each other – ca. 21 km). The use of an identical pattern in these two contemporary sites becomes evident, with only a few modifications of the regular planning: in Els Vilars, the whole length of the plan is about 61.05 m, whereas in El Molí d'Espígol it would be slightly longer (77.81 m). To a lesser degree it is also possible to find this pattern in the first Iron

Age free-standing building of El Turó del Calvari (Vilalba dels Arcs, Tarragona), designed on the basis of two 9-m-diameter secant circles (Moret, 2006, pp. 204); and also in the urban planning of the Ilergetan site of Estinclells (Verdú, Lleida), dated to the third century bce, displayed in Figure 14 (Olmos, 2010, pp. 131).

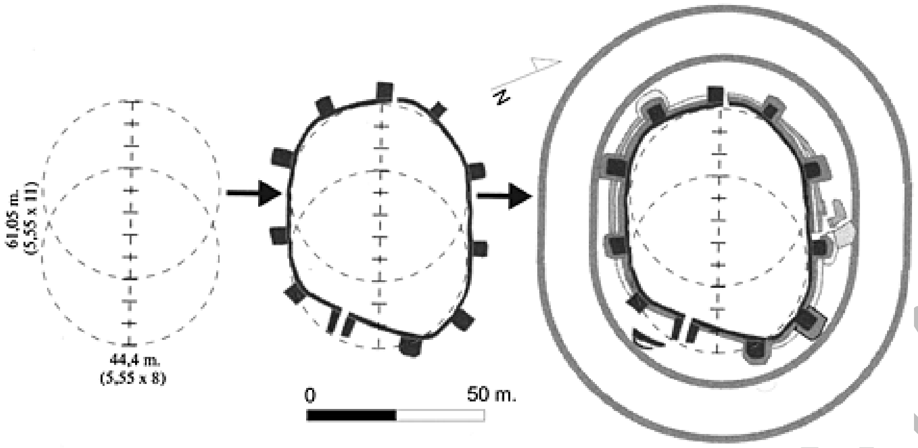

Figure 13.

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Urban constructive model of the site of Vilars using two intersecting circumferences. (Adapted from Alonso *et al*., 2010, p. 28).

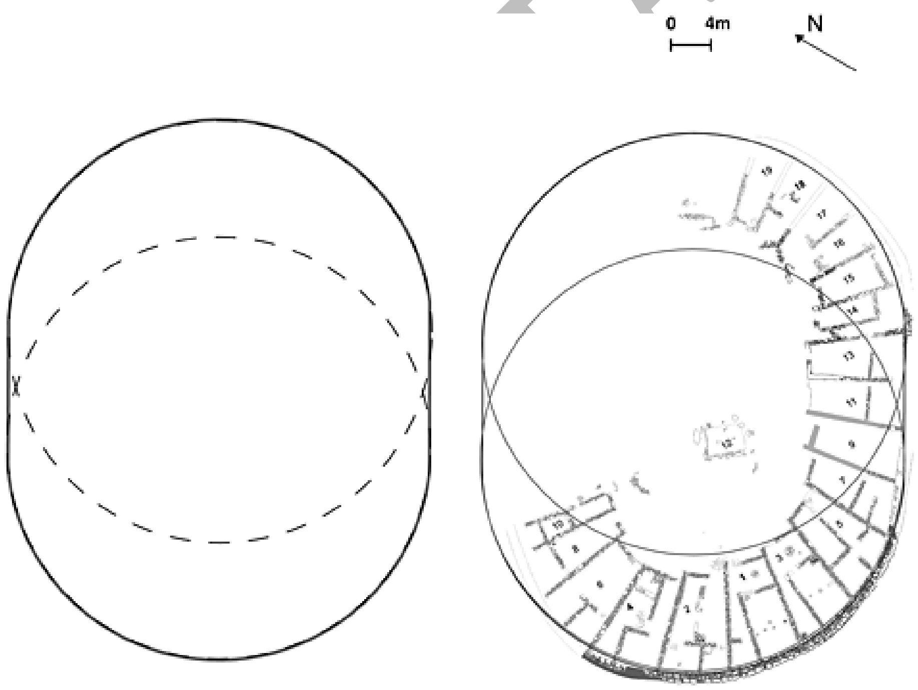

Figure 14.

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Planning of the settlement of Estinclells using two intersecting circumferences and superposed on the habitat map.

Comparison of the different case studies showed the existence of simple building models and of technical knowledge that was transmitted between protohistoric communities from the Bronze Age. During this period, the beginning of the sedentary process for the societies of western Catalonia includes the establishment of simple urban and architectural planning designed with the help of measurement tools.

With regard to the first Iron Age urban planning, although the archaeological evidence for this period is rather fragmentary, we think that the semicircular disposition of the central quarter of the mid-Iberian site (excavation zone 18) would correspond to the fossilized perimeter of the first Iron Age settlement (Figure 15). This model could also be observed if a theoretical axis from its walls is drawn, which actually coincides with the central point of this circle. This design would remain until the next phase.

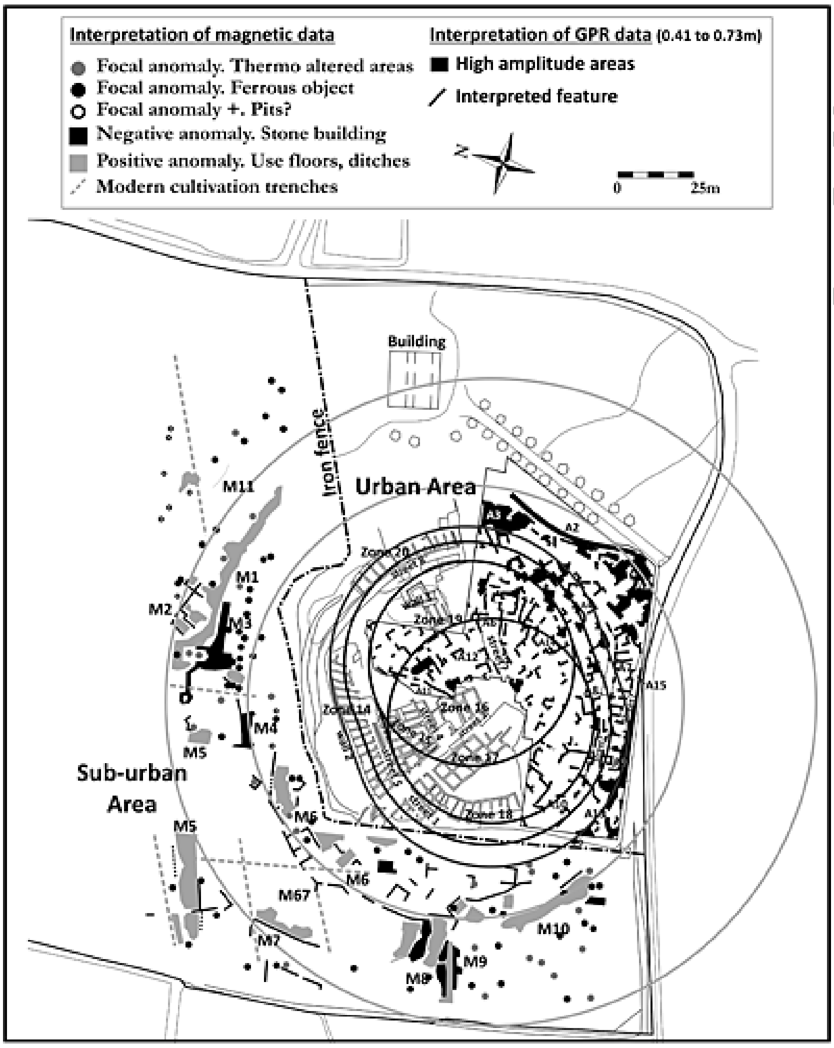

Figure 15.

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Plan of El Molí d'Espígol between the first Iron Age (seventh century bce) and the early Iberian period (second half of the sixth century bce). Secant circles: first Iron Age enclosure (Wall 1); the design of the southwest quarter during the mid-Iberian urban planning seems to show the fossilization of the first Iron Age perimeter. First concentric ring: hypothetical layout of the first Iron Age ditch and scarp. Outer dashed line ring: layout of the early Iberian period perimeter/enclosure (Wall 2).

On the other hand, the finding of a mural structure fronting the fortification, plausibly a scarp, within the first Iron Age defenses implies the existence of an ancillary perimeter ditch to the wall and the towers. As recently pointed out, the increasing evidence of ditches in the defensive systems of the Ilergetan and the Ebro valley settlements could indicate a local/native origin for this kind of feature (Junyent and Moya, 2011, p. 117), although the chronology assigned to the majority of the examples in the area is later, already within the Iberian period, in which the ditch–barrier pattern predominates. However, the case of El Cabezo de la Cruz (La Muela, Zaragoza), in the mid-Ebro valley, offers a good example and is a parallel both chronologically and architecturally: a ditch, datable to 800–660 bce, complements a wall with towers and a scarp (Rodanés *et al.*, 2011, p. 213), which is same pattern seen in the El Molí d'Espígol first Iron Age enclosure.

In the second half of the sixth century bce the site was extended. A new rampart to enclose the enlarged habitat was built, wider and more oval in shape, but without defensive towers. This planning is designed from two secants circles of 80.3 m in diameter (Figure 12A). However, the geometrical planning was completely changed by the end of the fifth to early fourth centuries bce when the oval-shaped plan turned into a circular one of 126.88 m in diameter. The perimeter of this remodelled settlement would correspond to Wall 3, designed from a central point located in the middle of the main street (Street 3). During this period the urban planning would have been readapted to a radial pattern.

The diffusion of ideas and cultures between peoples of the protohistoric period through migration led to the emergence of various models in a large region. One of these models is the apsidal plan based on two intersecting circles, which can be found in the urban planning of settlements such as Vilars d'Arbeca, Molí d'Espígol or Estinclells, and in the planning of smaller isolated buildings, as in the case of Turó del Calvari (Figure 16). Direct references to this type of construction are found in the 'maison absidiales' of the south of France, such as Monedière, Saint-Blaise, Gailhan or Mailhan. In a recent synthesis by D. Garcia and H. Tréziny the existence of such constructions in the south of France can be dated to at least the Pottery Neolithic/Chalcolithic (Garcia and Tréziny, 2010, pp. 347–348). Such houses are located in grouped settlements without internal organization, as observed in western Catalonia. In this context we see a fusion of architectural traditions of southern France with the development of a proto-urban model, which started in the eleventh century bce and was based on enclosed settlements with a central space, such as at Genó (López Cachero, 1999).

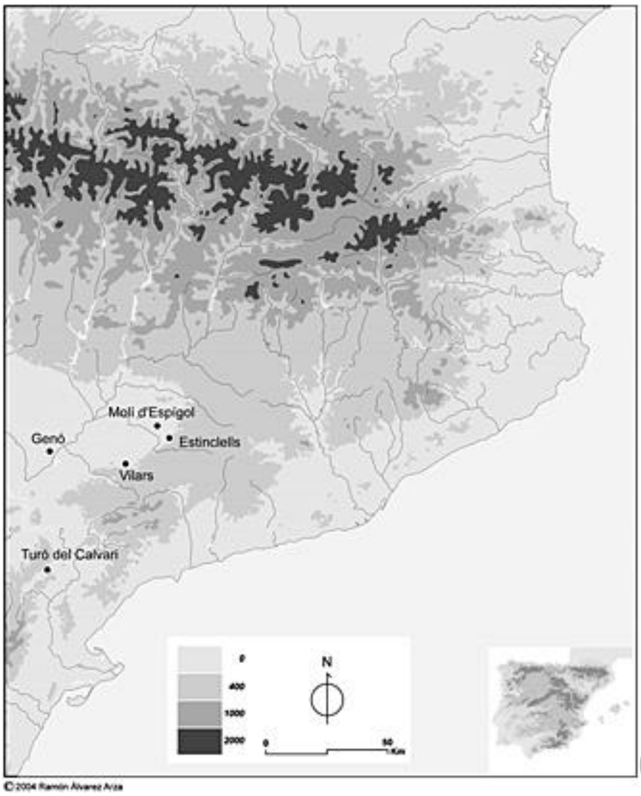

Figure 16.

- Open in figure viewer

Northeast of the Iberian peninsula with the location of the settlements were the apsidal plan is used, north and west of the current Catalonia.

Geometric design of the site: the geophysical evidence

The theoretical model shown in Figures 12, 13 and 15 conforms, with some variations, to the results emerging from the geophysical prospection. Regarding the interpretation of the survey carried out in the internal area of the site, the images representing deeper features show the existence of two walls, easily identifiable as Walls 2 (clearly A9) and 3 (clearly A1, A2, A3) in Figure 15. These features follow the radial scheme of the oval-shaped model. As to the first defensive system, the projection of this design shows several anomalies that could be related to the remains of the perimeter wall, especially in the southern and eastern parts of the site, such as groups A10 and A14.

This fortification would be externally complemented with a wide ditch surrounding the whole site (e.g. M1, north, and M10, south in Figure 5), which would follow the pattern previously identified in the Els Vilars mid-Iberian phase. Likewise, in the southwest suburban area, cutting across the trace of the hypothetical ditch, a complex set of anomalies were detected (M8, M9), which could be interpreted as an access ramp to the habitat, as also documented in the Els Vilars contemporary fortification (Junyent and Moya, 2011, pp. 106–109).

The scarp of the ditch conforms to the perimeter of Wall 3 (e.g. M4, north, M6/M67, west; Figure 5), developing a circumference of 126 m in diameter, while the counterscarp (e.g. M7) would be inscribed in a circle of 178 m in diameter (Figures 11 and 15). The survey shows that the layout of the scarp almost matches the theoretical location and disposition of Wall 3. Another remarkable item of this fortification is the evidence of an access in the western part of the site (probably the junction of Street 1, 3 and 5), which should be related to the original defenses (Wall 1), in coincidence with one of the radial axis drawn from one of the above mentioned opening angles.

Concerning the second fortification (Wall 2), the survey shows how the oval-shaped model is the only possible scheme allowing us to explain the western design of the fortification, where the original shape of the wall would have been adapted and enlarged. This design can be seen in the northwest, southwest and east areas (A9, with the corresponding lean-to structures backed against its inner margin, A7, as seen in excavation zone 14), while in the southeast this scheme could not have been followed (Figures 11 and 15).

As for Wall 3, which is related to the last defensive system, this layout is rather conspicuous in the northern (M1 and M4), western (M6–M9 and M67) and southern (M10) areas of the site (Figure 15), while in the southwest, modern agricultural activity ruined and destroyed the outer features. The survey shows that the lean-to structures backed against Wall 3 (excavation zone 20; survey structures identified behind A3) maintained the radial model from a central point. It also helps us to confirm the continuity of the urban planning as already established by the archaeological works. The only exception is the southern area, where it does not appear to conform with the oval shape but rather with a straight and oblique line, probably connected to an access, as seen in Els Vilars.

This theoretical design that seems to be drawn with the aid of a compass should be associated to a metrical pattern. The layout of the circumferences would not have a random disposition but it would have been drawn by means of a rope with a previously fixed length. The next step would be then to define an anthropometrical unit of measure or module, allowing the radius of the circumferences to be divided into natural numbers. This unit could be related to a foot. The regular measure of a foot is set between 0.27 and 0.35 m, and the best way to group them is the step, which corresponds to 5 ft. Therefore, a unit of measure that could be obtained by the division of the measures between 5 in order to obtain a round number would be a reasonable option. A definite magnitude offering both an integer value and a rational division would correspond quite well with a unit ca. 0.30 m. According to this 0.30 m pattern, an oval shape based on two circles of 100 ft radius would be possible, while the scarp should be a 120 ft radius oval and Wall 2 another oval of 130 ft; on the other hand, Wall 3 would be a circumference of 210 ft radius and the subsequent ditch would conform to a circumference of 220 and 300 ft (scarp and counterscarp).

In summary, from the combined analysis of both the survey and the archaeological remains a complex scheme of the site is recognizable: one that was developed in the earliest period and partially modified a few centuries later. It is an apparently simple design, based on several central points from which the main structures would have been drawn with the aid of a pre-established unit of measurement. In the second Iron Age (Iberian period), this central point would have been displaced and relocated in the centre of an axis dividing El Molí d'Espígol into two almost symmetrical parts (Street 3), which would also act as a main street for this period. The location of the towers belonging to the first fortification would have been disposed following a constant opening angle (Figure 12A). Unlike in rectangular plans, in which sides can be divided in order to obtain a module, in circular plans this system is difficult to implement in an effective manner, and it invokes greater variability concerning the units of measurement. Despite the evidence, however, this hypothesis remains subject to verification, pending further archaeological work.

Conclusions

From a technical and methodological point of view, the results of this survey have provided important archaeological information. We believe that, at least in part, this success comes from a group of defined elements.

First, the survey strategy was established according to a good compilation of previously established information, both from excavation and from geophysical tests. In addition, the data collected have been processed, plotted and interpreted taking into consideration the archaeological questions defined during the survey planning. Indeed, the data processing and the creation of images have been produced in order to create comprehensive plots and information that could be used as another archaeological template.

Second, regarding the GPR survey, the sum of the IDS system data and the possibilities offered by the GPR-Slice software has been critical in the analysis and interpretation of results. The GPR-Slice software allowed managing the data from signal processing to the creation of plots, due to its bespoke adaptation to archaeological GPR surveys. In the El Molí d'Espígol case, leaving aside the simple and effective signal processing toolbox, the comparison between time-slice metrics and the grid processing algorithms was important. Likewise, the view possibilities of the OpenGl 3D menu allowed the raw and processed data to be worked simultaneously and the easy comparison of alternative three-dimensional views. All these elements constitute an essential wirthwhile tool, both for processing and for interpreting GPR data.

In relation to the IDS Hi-Mod system, it is based on the Fast-wave Module, which with its particular technology allows working with multiple transducers simultaneously, offering a new range of methodologies at a low cost. Taking into account the consequences in time efficiency and methodology, these attributes represent important progress by comparison with the monostatic traditional systems of similar costs. Another noteworthy point is that with the TR Dual 200/600 MHz antenna, it is possible to acquire two datasets in a single survey. This ability is useful when facing interpretation problems or when different levels of depth resolution are needed.

Nevertheless, the Hi-Mod system showed some disadvantages for its use in archaeology, which are due mainly to mechanics designed for use in an urban context. Even admitting that the entire system is based and adapted to area surveys, the small diameter of the wheels of the cart (26 cm) generates problems in rugged terrain, tending to produce positioning errors (stagger).

As for the archaeological aspect, the survey has answered some questions, but as usual, has also raised new ones. In the suburban area, the anomalies interpreted as ditches configure a defensive system seeming to enclose the urban area. Far from solving the delimitation of the settlement, the magnetic survey revealed other features (e.g. M2 and M11) beyond these defensive systems, which need to be described more accurately in order to interpret their functions. In fact, other contemporary groups of structures and archaeological remains have already been documented to the west, north and southeast of the site, even far beyond the late fifth to early fourth centuries bce enclosure (Principal *et al*., 2012), which raises the question of the actual extent of the city (suburban quarters and other areas), at least for the mid-Iberian period.

The GPR survey in the urban area has produced remarkable maps of building structures. The study of these features in the known archaeological context suggests a typical pre-Roman Iberian urbanism, with an organic disposition of groups of buildings and a preconceived town planning. The results also revealed, however, possible geometrical symmetries between the northern and southern areas that should be investigated in order to further determine building and metrological patterns.

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