

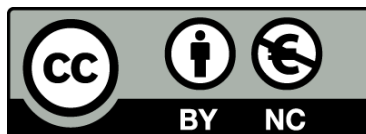


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From archaeological prospection to communication using learning theory

Multi-variable mapping and 3D representations
in archaeology and built heritage

Robert Tamba



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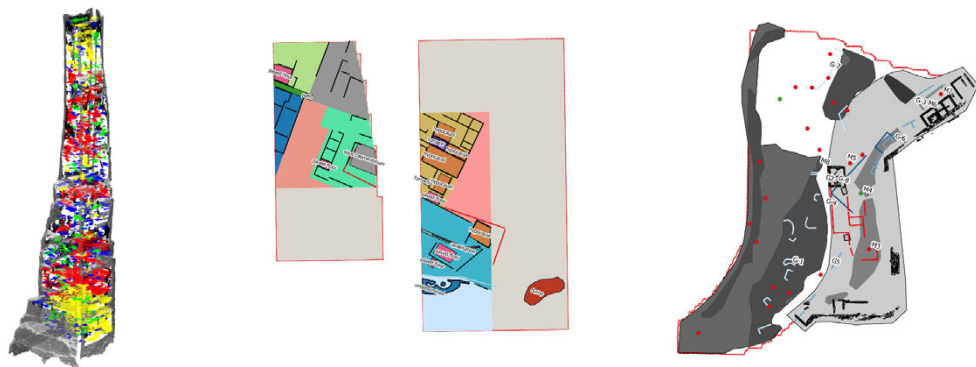
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Departament de didàctica de les ciències socials

Promotor: Francesc Xavier Hernández Cardona

Copromotor: Xavier Rubio Campillo



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BARCELONA

Facultat d'Educació
Departament de Didàctica de les Ciències Socials
Tesi doctoral

De l'exploració arqueològica a la comunicació didàctica

Elaboració de mapes multivariables i models 3D
en arqueologia i patrimoni



Robert Tamba

Director de tesi: Francesc Xavier Hernández Cardona
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Programa de doctorat:
Didàctica de les Ciències Socials i del Patrimoni
Bienni: 2011-2013

Barcelona, Octubre de 2015

Agraïments

Aquesta recerca no hagués estat possible sense el compromís de l'empresa SOT Prospecció Arqueològica. Va facilitar totes les dades que es van utilitzar pels casos d'estudi. En particular, voldria agrair a Roger Sala per la llibertat que em va donar i la paciència que va tenir durant tota la duració de la tesi. Agraïxo també a l'Ekhine Garcia pel seu suport, tan científic com emocional, les seves correccions i els seus comentaris.

Vull donar les gràcies al meu director de tesi, Francesc Xavier Hernández, per acollir-me al seu departament i per la confiança que va tenir en el projecte. Aprofito per agrair també a tots els membres del departament de Didàctica de les Ciències Socials que em van acompanyar.

El present document va agafar la coherència que necessitava gràcies a les judicioses aportacions del meu co-director, Xavier Rubio Campillo. Gràcies Xavi per les discussions, correccions i més avaluacions.

Most of the processing of the data that is presented was done with the software Isatis from Géovariances. Several licenses were graciously granted in support of the research. I would like to thank more specifically Jean-Jacques Péraudin and Nicolas Jeannée for their trust and support.

Tres casos d'estudi es presenten aquí i van comptar amb les col·laboracions de nombroses persones.

En l'estudi de l'agulla de la pedrera romana de El Mèdol, em cal agrair l'ajut de Jordi López Vilar i l'Anna Guitiérrez de l'Institut Català d'Arqueologia Clàssica, a la Nuria Guasch Ferré i el Dr. José-Luis Prada del Grup de Recerca Aplicada al Patrimoni Cultural - Centre de Tecnologia per la Conservació del Patrimoni i a

Josep Balsco i Oscar Aparicio de l'empresa Global Geomàtica.

En el treball sobre la vila romana de La Mina, agraïm les dades i la col·laboració del Dr. Enrique Ariño i el seu equip de la Universitat de Salamanca.

Pel jaciment de Puig Ciutat, hem comptat amb el suport inestimable de l'Àngels Pujol Camps, en Carles Padrós Gómez i tot l'equip d'excavació. També gràcies a en Pablo Del Fresno Bernal, de l'empresa SGP.

During the research, I was welcomed for a stay at the Ghent University in the Department of Soil Management. I would to thank Pr. Marc Van Meirvenne for his trust, Philippe De Smedt for his invitation, his help and his support, and all the members of the department for their warm welcome. I would also like to thank Lieven Verdonck from the endless discussions that we had on GPR data.

Merci Ysée, pour Abraham Moles, "Information is beautiful", et le reste.

Per acabar, voldria agrair a l'Agaur per les beques de suport a la recerca i d'estada que van concedir al projecte.

Abstract

The research was placed at the confluence of three fields: Archaeological Geophysics, Archaeology and Learning Theory. The two latter were considered in order to improve the transmission process of archaeological geophysics results.

Archaeological Geophysics is based on the use of methods that measure the contrast in physical properties. It is applied to map the context of archaeological sites. The mapping helps with the management of the research. The outputs of Archaeological Geophysics projects are produced through a nested sequence of decisions and actions. The sequence was separated in three phases: field, data transformation and data finalisation. The field phase includes the design of the project and the data acquisition survey. The transformation phase is dedicated to the processing of the acquired data and to their interpretation. During the finalisation, the data and metadata of the project are archived and the results are transmitted to the end-user.

Geophysical results are not often integrated in the communication process of archaeological findings. The main hypothesis of the research was that this absence can be explained by failure situations that occur during any phase of a project. Failure situation can be explained by results with insufficient resolution, not adequately transformed or poorly transmitted. The main objective of the research was to propose solutions to identify and limit these failure situations in order to improve the final transmission of the results.

Three approaches were proposed. The transmission process was analysed considering the different Learning Theory currents. A behaviourist approach gave a linear understanding of the information. It is based on standards and clearly defined contents. Its main vector would be the technical report. The cognitive contribution was the diversification of the formats of transmission. In addition to the technical

report, a graphical report, an animated sequence and a model of the results were systematically produced. This associated material was created taking into account the relation between text, image and sound in order to improve the understanding process. The model represented the constructivist current. It enables the end-user having a personalised experience of the created environment through increased control and interactivity.

The second approach was to describe in detail the workflow of an Archaeological Geophysics project. The description aimed to define control points that could favour a better quality of the produced material. Control points were defined at each phase. In the field phase they include (1) the use of questionnaire during the design of the project, (2) the production of a diagram stating the archaeological objectives, the used methods and their limitations and (3) an appropriate preparation of the environment of the site prior to the acquisition of the data. The control points of the transformation phase were (1) the characterisation of the acquisition noise, (2) the vectorisation of the results with associated attributes and (3) the production of synthetic maps. The finalisation phase should include (1) the metadata of the project, (2) several parallel formats of transmission of the results and (3) open source formats for the digital archive.

In the third approach, the combination of geophysical results with archaeological objects was considered. Three case studies were presented. In the first case study the digital model of the surface of a monumental artefact was combined with GPR data for the assessment of its state of preservation. In the second case study, the data of an intensive surface sampling survey were combined to geophysical surveys to characterise the sequence of occupation of a site. In the third case study archaeological excavations and geophysical results were integrated in one platform to document the destruction of a Roman settlement.

Resum

La geofísica arqueològica es basa en la mesura de propietats físiques. S'aplica per la documentació de jaciments arqueològics. A través de la presentació de tres casos d'estudi, la recerca presentada aquí il·lustra diverses aportacions. Primer, es planteja una aproximació didàctica dels resultats per millorar els formats de transmissió de la informació. Després, s'ha avaluat la seqüència de tasques d'un projecte per proposar punts de control de la qualitat i consistència de les dades. Finalment, s'ha estudiat la interacció de diferents tipus de dades arqueològiques amb la informació obtinguda de la geofísica.

L'aproximació didàctica dels resultats ha permès classificar els formats de lliurament de resultats. La memòria tècnica representa una presentació conductista. L'estructura és fixa i lineal. Amb una presentació cognitiva es varien els formats. En suplement a la memòria tècnica s'ha generat una memòria gràfica, una seqüència animada i un model. El model representa una visió constructivista, ja que permet a l'usuari tenir un control directe de la interpretació de les dades i observar-les des de diferents perspectives.

L'avaluació de la seqüència de treball ha permès definir punts de control. Durant la fase de camp es recomana l'ús d'un qüestionari pel disseny de l'estratègia de prospecció, es defineixen els objectius arqueològics i les limitacions del projecte, i es prepara l'entorn del jaciment prèviament a l'adquisició de les dades. La transformació de les dades requereix la identificació i caracterització del soroll d'adquisició, la vectorització de les dades i la producció de mapes sintètics. La finalització ha d'incloure les metadades del projecte, les representacions dels resultats en diferents formats i l'ús de formats oberts de fitxers.

Finalment, s'ha estudiat la combinació de tres tipus d'informació arqueològica amb

dades geofísiques: un model topogràfic digital, dades de prospecció de materials superficials i resultats d'excavacions. El model topogràfic digital va ser combinat amb dades de georadar per avaluar l'estat de conservació d'un artefacte monumental. Les dades de prospecció superficial s'han interpretat conjuntament amb les dades geofísiques per caracteritzar la seqüència d'ocupació d'una vila romana. Les dades d'excavació arqueològica s'han integrat amb els resultats geofísics en una plataforma comuna per documentar la destrucció d'un assentament romà.

Graphical Abstract

1.1 From hermetic to adapted communication

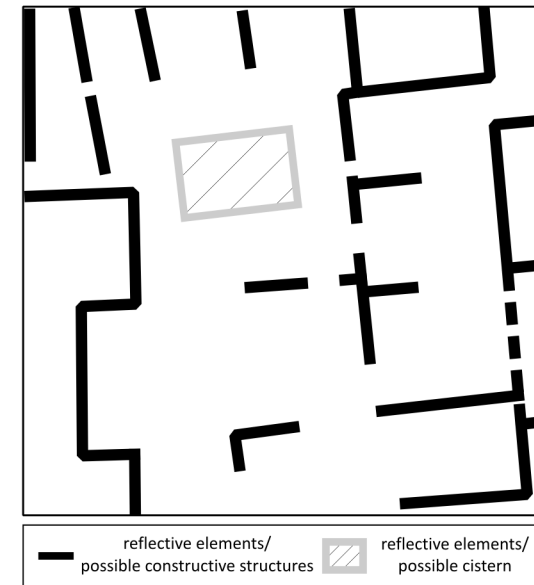
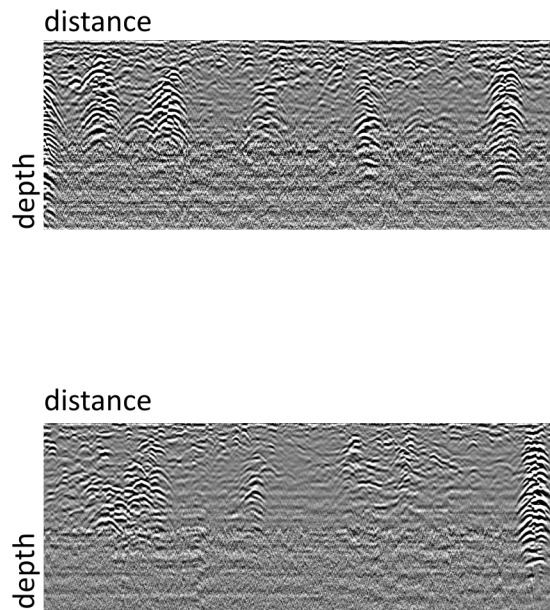
Independent profiles



Integrated image plot



Interpretation

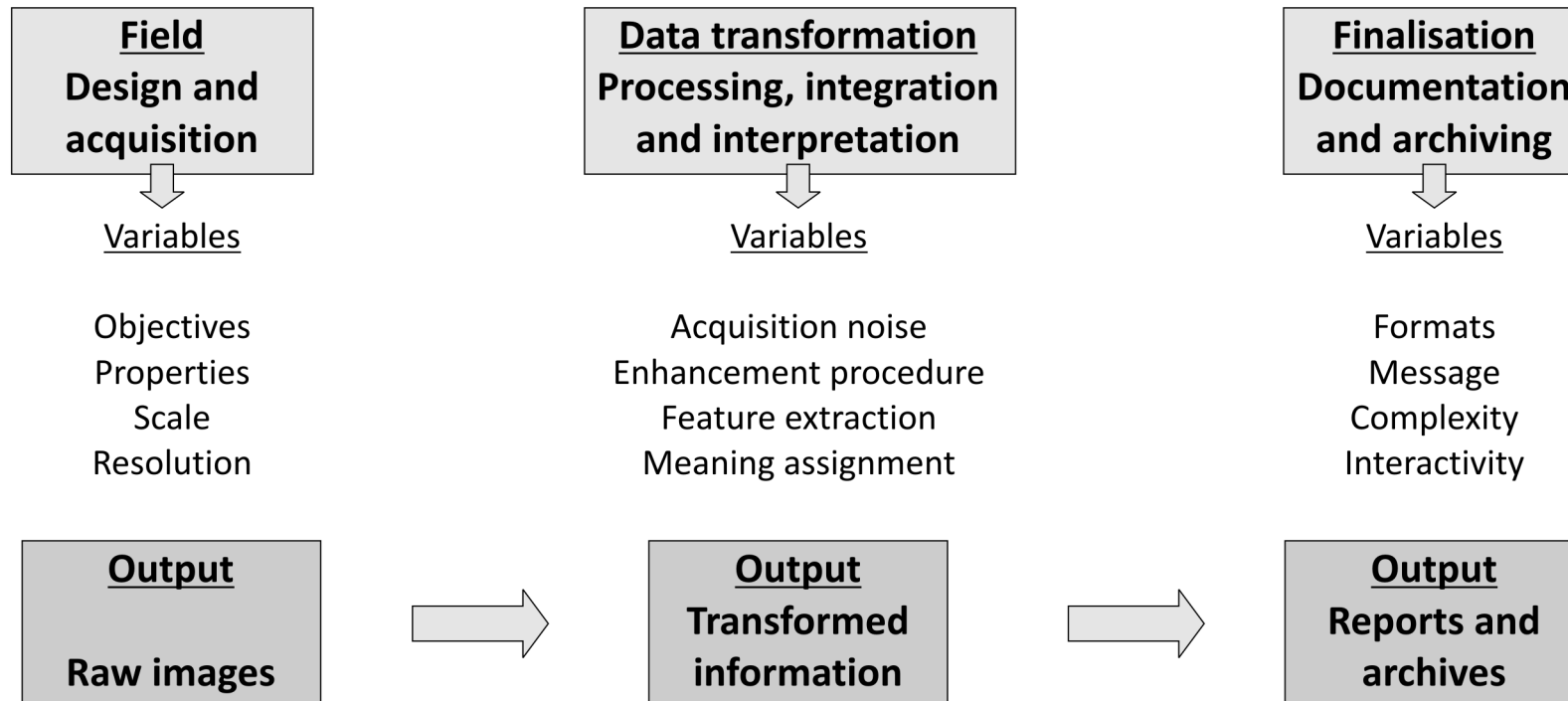


Independent profiles give a partial counter-intuitive view of the soil information

The integration of parallel profiles into image plots gives a more realistic representation of the buried features

Image plots can then be transformed into vectorial information with an assigned archaeological meaning

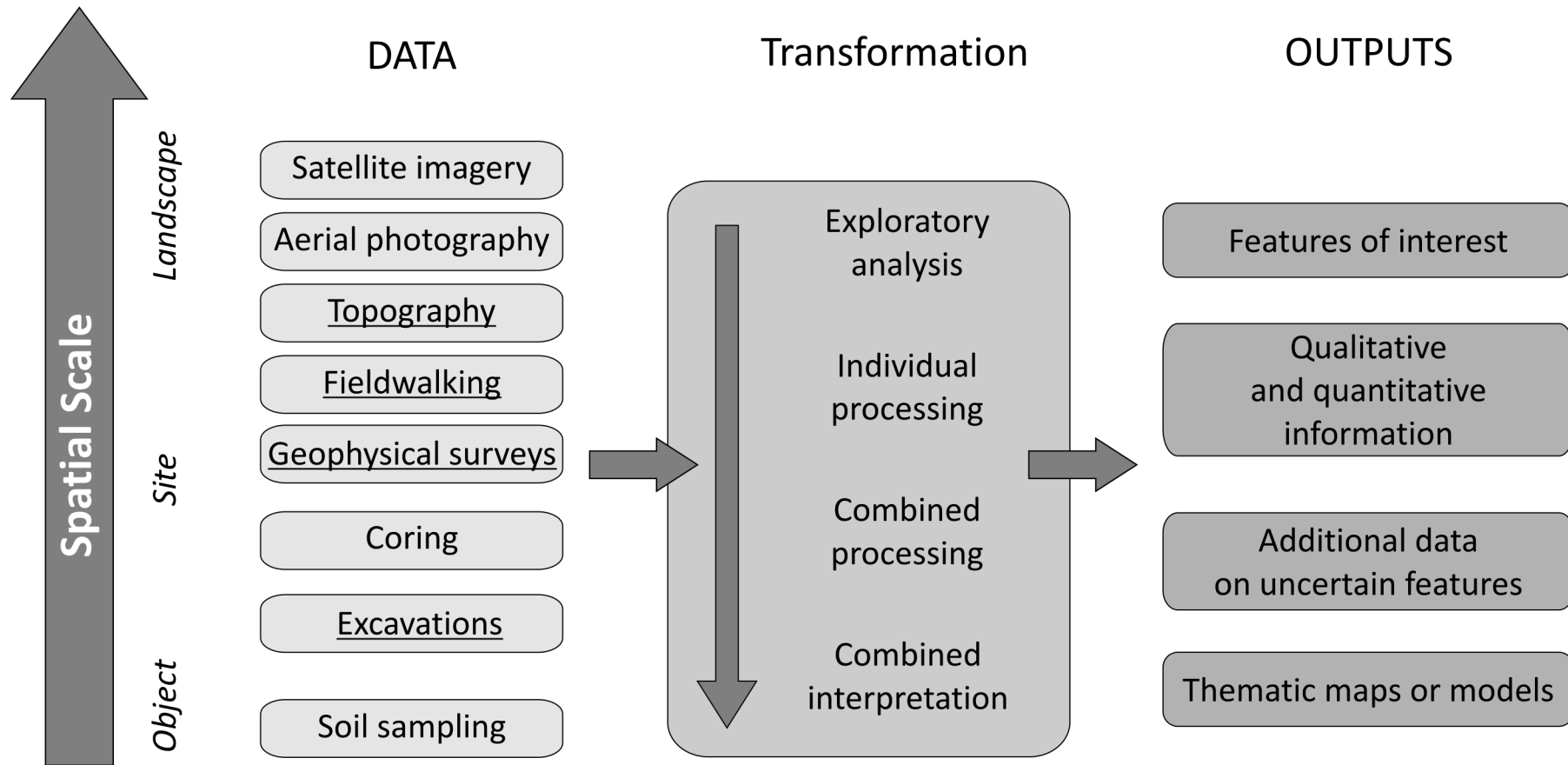
1.2 Archaeological geophysics: A nested workflow



The workflow of archaeological geophysics is a nested sequence of operations
The final outputs depend on the initial decisions
Standards and guidelines help controlling the process

The formats of dissemination were evaluated using Learning Theory tools

1.3 Multi-method projects



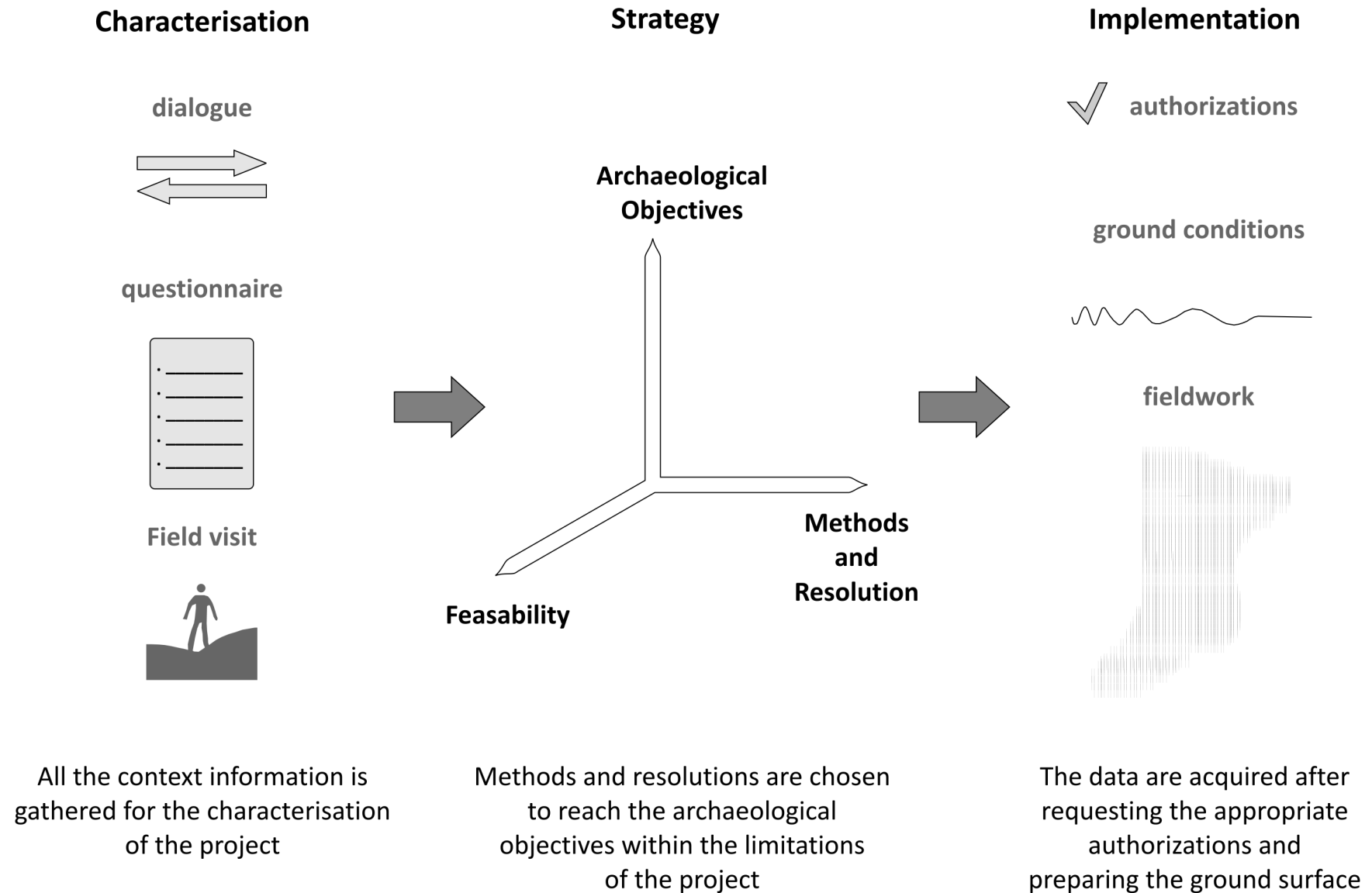
Multi-method projects favour the acquisition of complementary information and the validation of results.

The use of multi-method projects will be illustrated on case studies in built heritage, archaeological exploration and archaeological research. The categories of data used for the research are underlined

2.1 Main methods used in archaeological geophysics

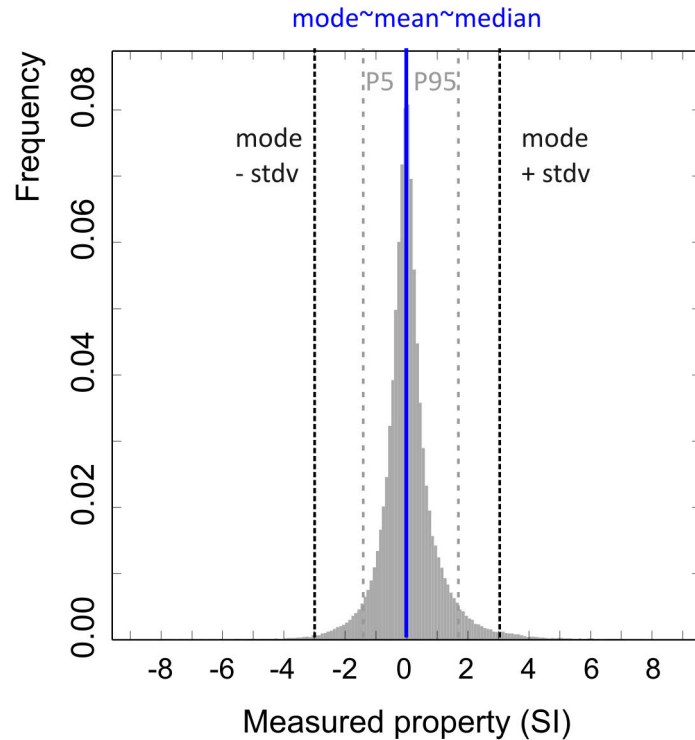
<u>Method</u>	magnetic	electric	electromagnetic	gpr
<i>Main characteristics</i>				
<u>In one word</u>	fast	stable	landscape	3D
		frequency 		
		50-500 Hz equipotentials	10-100 kHz induction	10-1000 MHz wave
<u>Measured property</u>	magnetisation	resistivity	magnetic susceptibility electric conductivity	dielectric permittivity
<u>Main application</u>	thermo-alterations soil movements	constructive structures and cavities	clay contents metals	constructive structures and cavities
<i>Importance of main elements to consider for the design of a project</i>				
<u>Ground conditions</u>	+++	+	++	+++
<u>Processing</u>	+	++	++	+++
<u>Water content</u>	+	+++	++	+++
<u>Cost</u>	+	+++	++	+++

2.2 Designing a project



2.3 Exploratory analysis

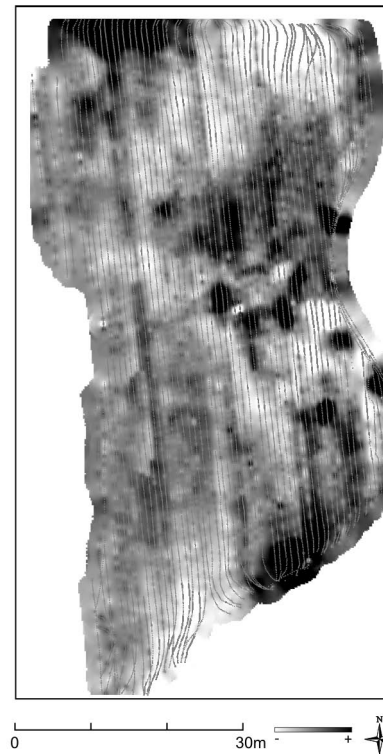
Descriptive statistics



Min	Max	Average	Mode	Stdv	Mode - stdv	Mode + stdv
9.33	33.55	0.08	0.00	3.01	-3.01	3.01
P5	P50 / median	P95				
-1.44	0.01	1.84				

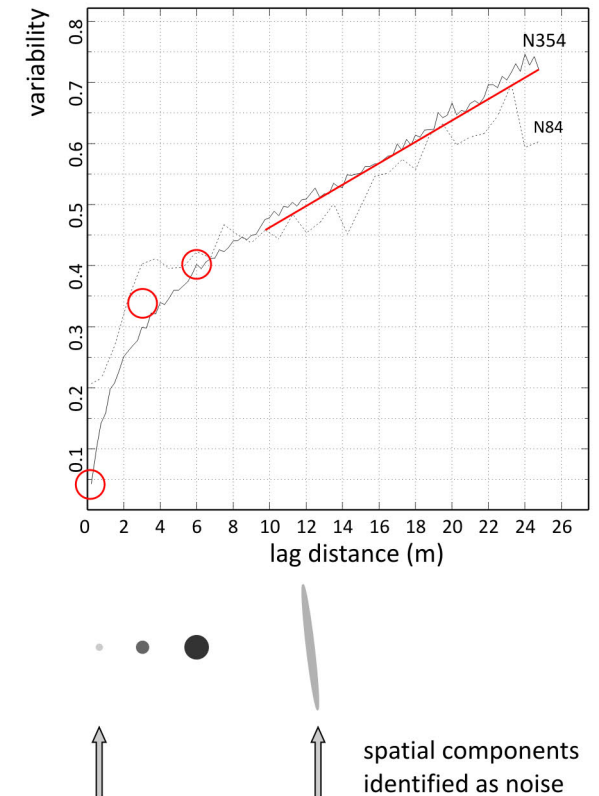
Statistics and histograms help understanding the numeric distribution of the data

Spatial representation



A first visual assessment gives information on quality, contrast and main results

Spatial characterisation

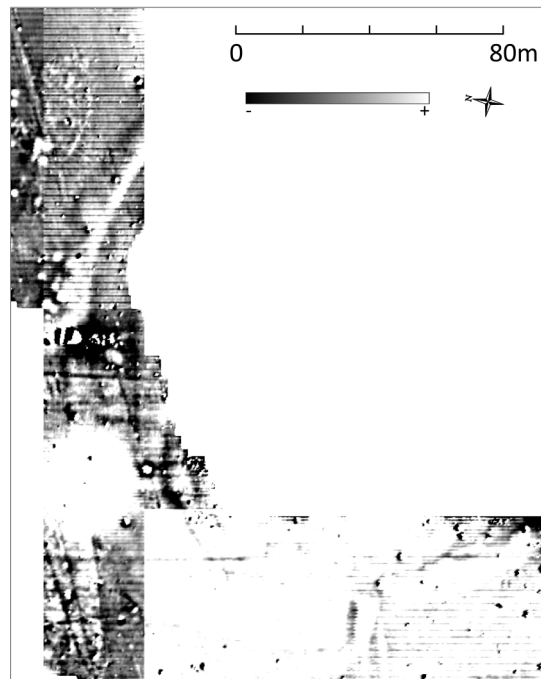


The experimental variogram is used for the characterisation of the main spatial components present in the data

2.4 From a geophysical representation to archaeological features

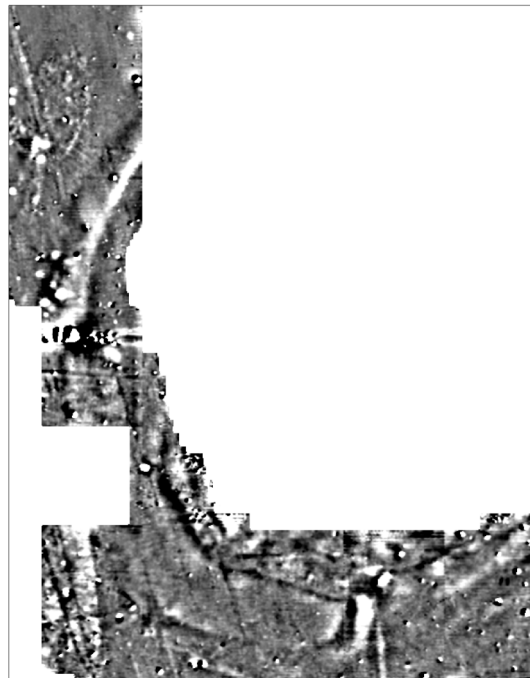


Raw data



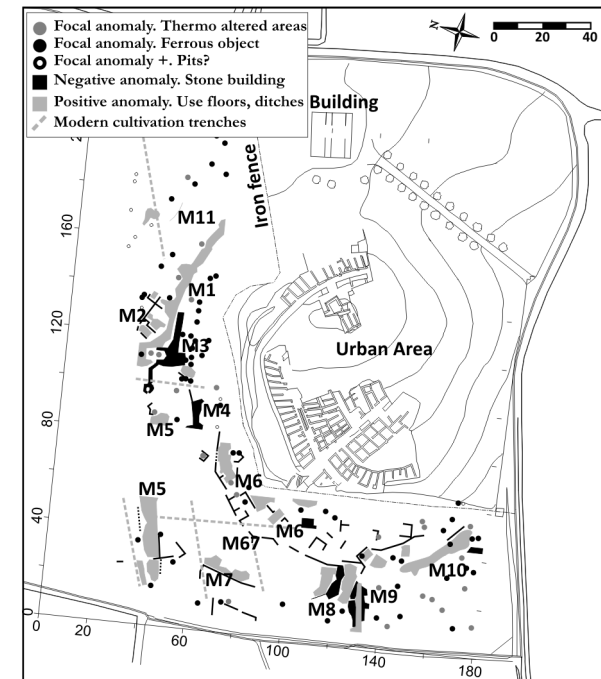
After fieldwork, raw data contain overlaid information

Processed data



The processing removes the acquisition noise and enhances the visualisation of the features of interest

Interpreted data



The interpretation gives an archaeological meaning to geophysical anomalies

2.5 Contributions of learning theory to the dissemination process

Contents

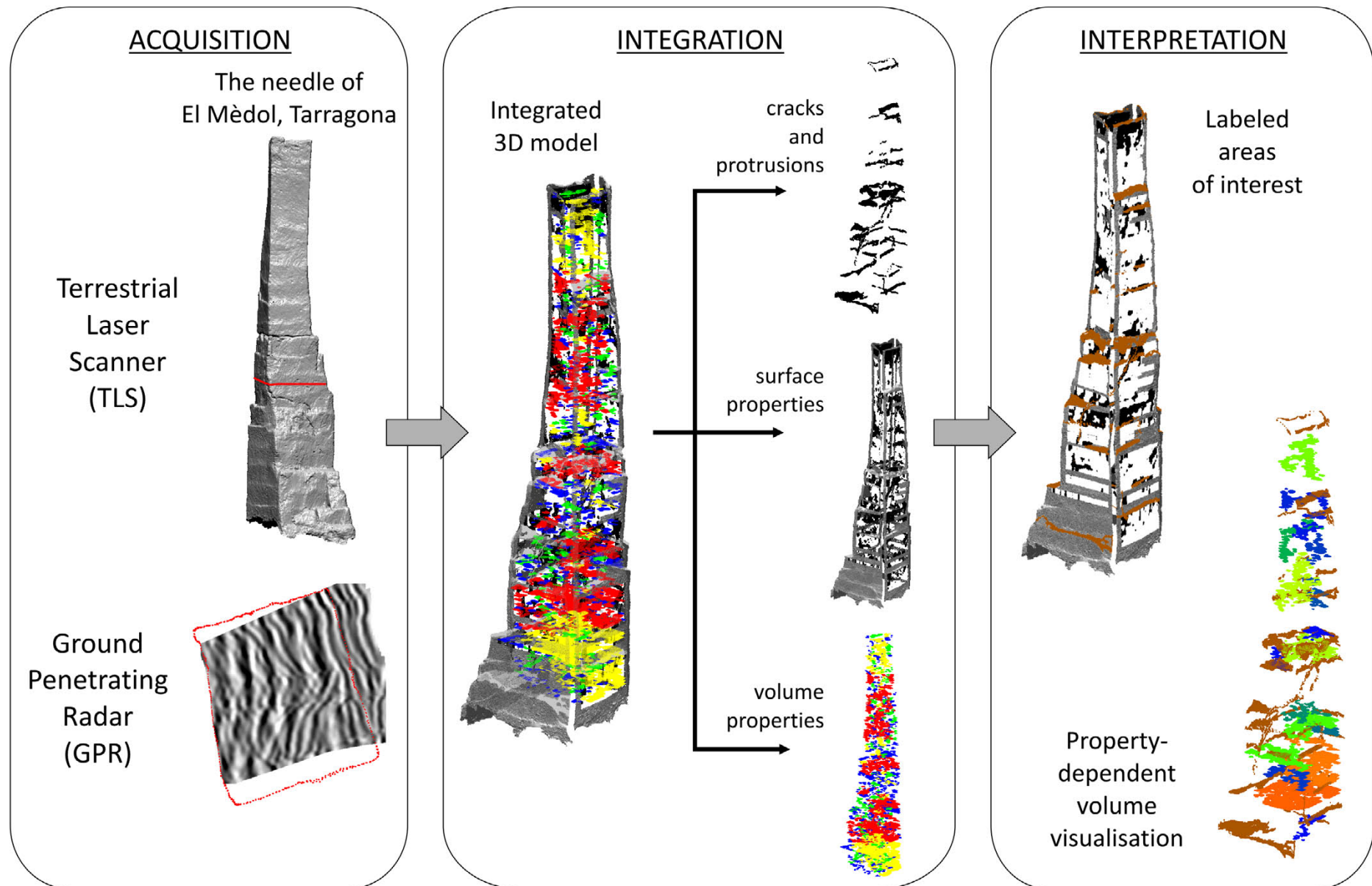
Environment



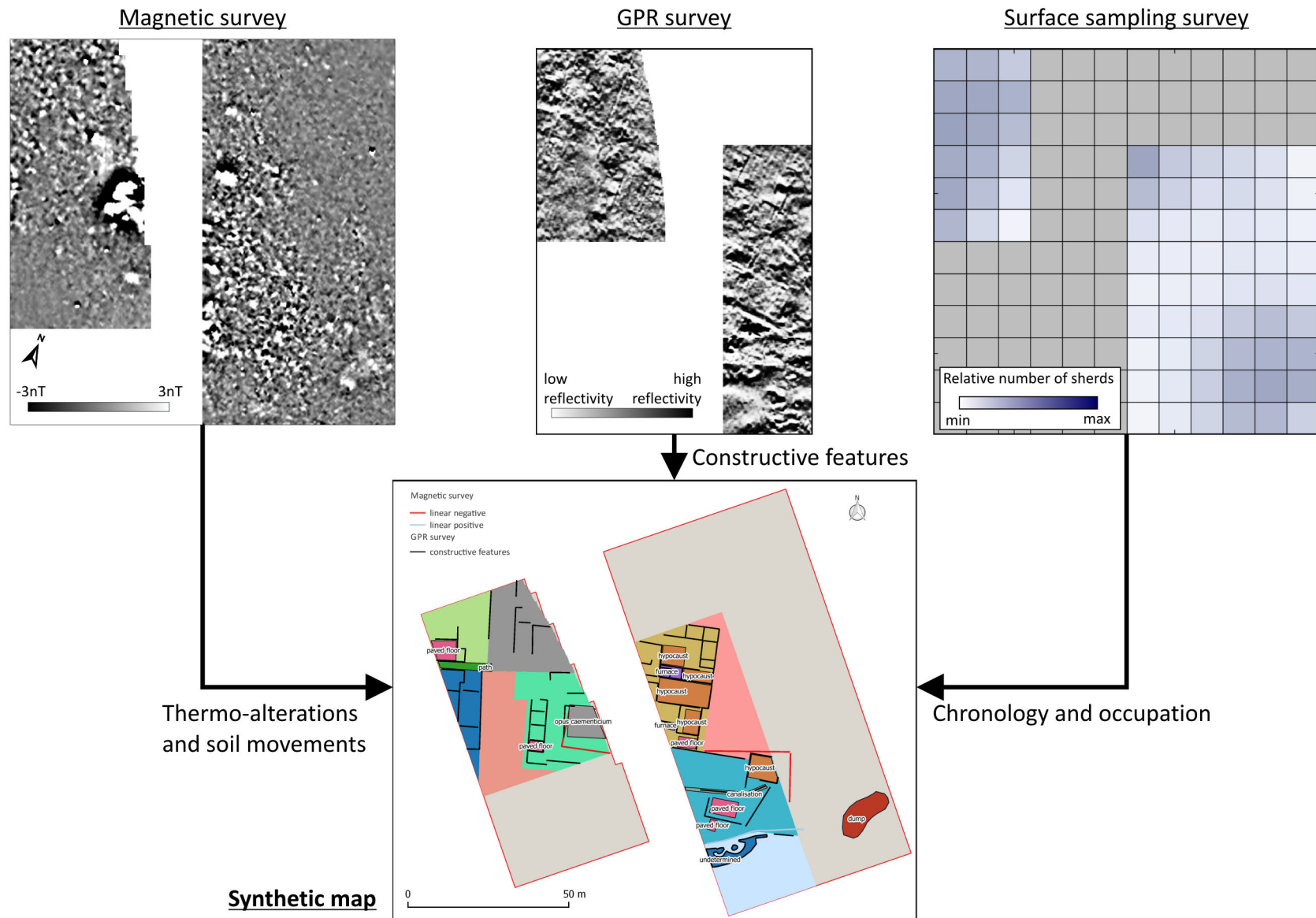
**There is no best approach to present the results.
Each approach serves a purpose and is more adapted to specific targets.**

Behaviourist	Cognitive	Constructivist	Connective
Metadata Summary Objectives Methodology Acquisition parameters Processing parameters Results Conclusions	text  ▶ video <u>links</u>	GIS and WEB-GIS solutions	Discussion groups Forums Mailing lists Networking
Report should contain standard information	The results are transmitted using several parallel formats	The exchange of information is favoured by common platforms	The contributions of the community to the interpretation of the results is enabled

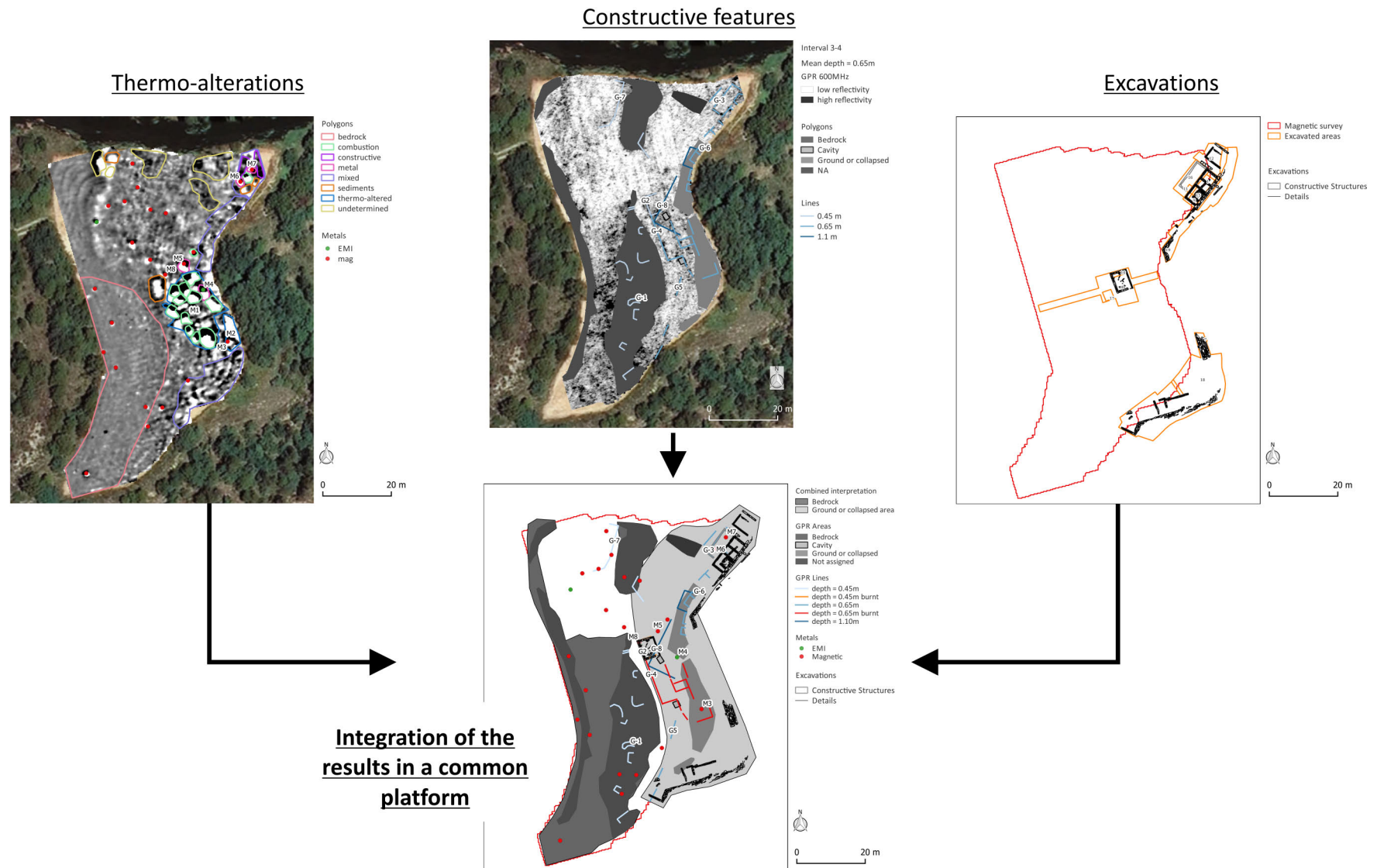
3.1 Assessing the state of preservation of a monumental artefact



4.1 Combined interpretation of intensive surface sampling and geophysical data



5.1 Multi-method research program for the documentation of a destruction



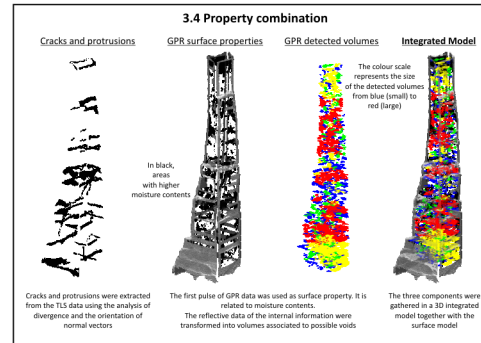
6.1 The proposed formats of dissemination

Report

- Summary
- Objectives
- Context
- Methodology
- Results
- Interpretation
- Limitations

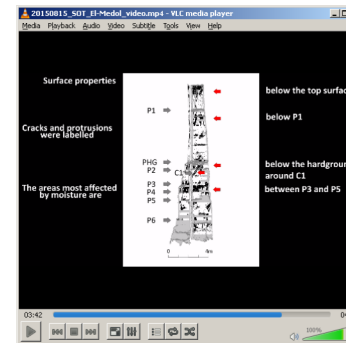
**Fixed structure
with summary and
references**

Graphical report



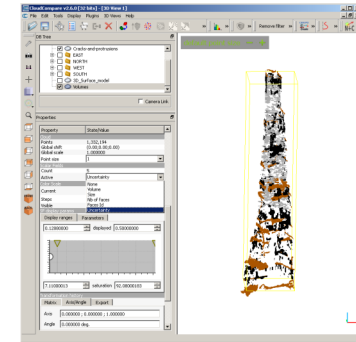
**Commented
graphical outputs
with highlights**

Video



**Video presentation
with audio, text
annotations and
highlights**

Model

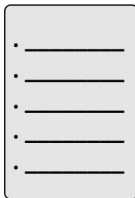


**Features of
interest with
attributes**

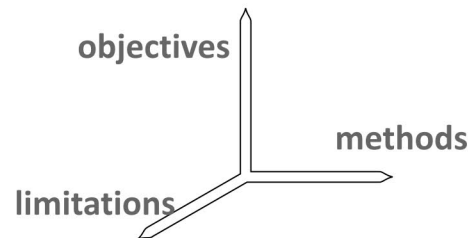
6.2 Using control points to identify failure situations

Field

questionnaire



design diagram

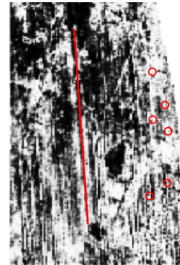


ground conditions



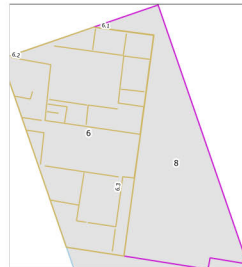
Data transformation

noise identification

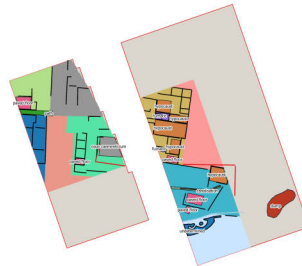


ploughing
lines and
random
noise

vectorisation and meaning assignment



synthetic maps



Finalisation

metadata

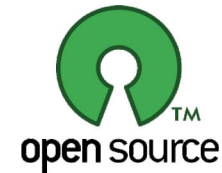
GPR
System
Antennas
Frequency
Number of antennas
Spacing between antennas
Spacing between profiles
Spacing between measurements
Time window
Samples per trace
Covered area

several parallel formats of transmission

report graphic report

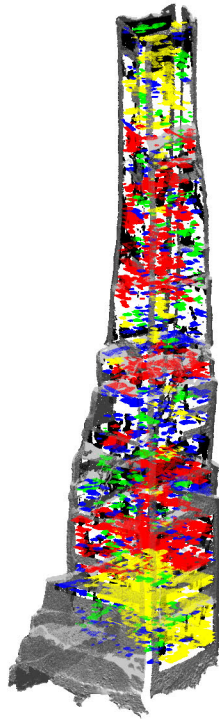
video model

archives in open formats



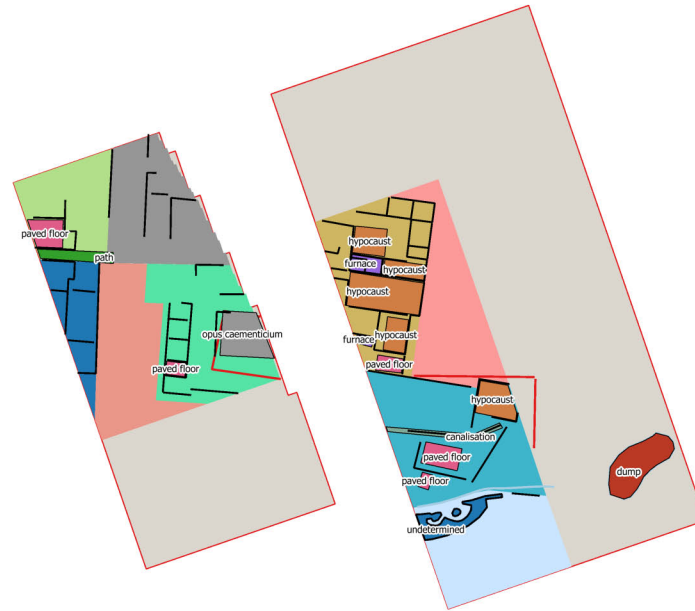
6.3 The results of the case studies

**The needle of
El Mèdol**



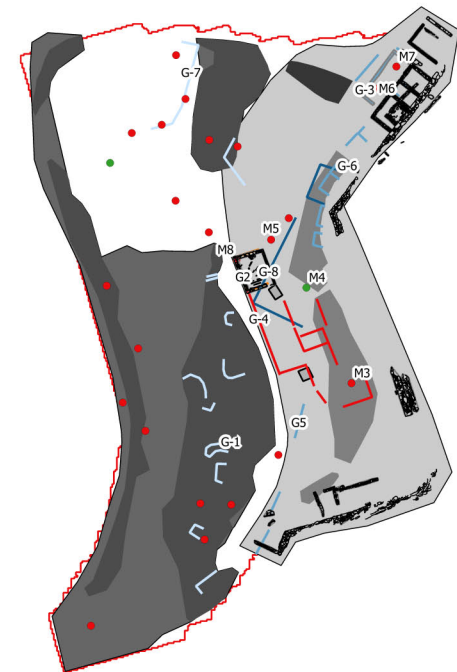
**3D integrated model
with surface and volume
properties**

**The Roman villa
of La Mina**



**2D GIS model of the constructive
structures of the villa with attributes
related to their source and function**

**The Roman settlement
of Puig Ciutat**



**2D GIS model with constructive
areas, bedrock, metals and
burnt areas**

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Chapter 1

Introduction: The place of geophysical imagery in archaeology

The expression geophysical imagery is used here to refer to geophysics applied to archaeology. It is also known as archaeological geophysics or geophysical archaeology. It falls in the more generic field of archaeological prospection. The denomination geophysical imagery is not an accepted one. It could also refer to other fields of application. It is used here as a reference to medical imagery. Although the context and the object are of different natures, archaeology is hopefully experimenting the same transformation medicine has undergone with the introduction of non-invasive technology. The parallel between disciplines also shows the distance archaeological geophysics still has to cover in order to become a standard in archaeology. In this document, archaeological geophysics will be used when referring to the field of geophysics applied to archaeology and geophysical imagery when the focus is on the visual outputs.

Archaeological geophysics is now well established as a non-invasive tool for archaeologists to plan excavations and document sites. It offers a fast diagnostic and improves efficiency and control of the archaeological research process (Horsley et al., 2014). Nevertheless, archaeological geophysics can be limited by insufficient contrast between the background and the features of interest or insufficient spatial resolution. It does not provide a realistic representation of the hidden features. The results must be interpreted and an archaeological meaning must be given to the geophysical signal. Multi-method projects are used to offer complementary representations of the same objects and improve the interpretation of the data (Kvamme, 2006; Clay, 2001; Hesse, 1999). Still, the complementarity of the surveys is not straightforward and

can end in a meaningless collection of data (Gaffney, 2008). In addition, between the raw data and the final results, a complex sequence of processes transforms the information into a more abstract format. All the steps are documented and transmitted to the team responsible of the site. The transmission of the information should enable a subsequent use of the results for re-evaluation or dissemination. This is not always possible as the geophysical methods are complex and archaeologists are not trained to understand their limitations, interpret them and use them.

1.1 Archaeological geophysics, a matter of experts?

At the beginning of the application of geophysical methods in archaeology and still occasionally, raw geophysical imaging could be perceived as hermetic representations that could only be understood and interpreted by specialists. Geophysical data were visualized in vertical sections or contour plots showing the variations of properties of the soil. As a consequence, the archaeological meaning assignment of the observed variations could not be straightforward (N. T. Linford, 2006). The spatial integration of the acquired profiles into continuous representations similar to photographs was the first step towards the access of the results to non-specialists, as they were directly enabled to identify the geometry of detected features (Sala et al., 2012). Figure 1.1 illustrates this aspect of the evolution of data representation in archaeological geophysics.

Nevertheless, more problems had to be overcome and the field has known several periods more focussed on research or on applications of relative success (Gaffney, 2008). More specifically, the absence of a specific and dedicated training led to failure situations and a certain lack of trust between geophysical and archaeological communities. Wrong strategies applied at a point of the workflow, from design to transmission, ended in a bad exchange experience with the archaeological community. This latent miscommunication was present at different levels. It was partially compensated by specialized trainings in archaeological geophysics for geophysicists and archaeologists and by the growing importance of landscape archaeology. The latter enlarged the context and the scale of application of archaeological geophysics. It also brought archaeological geophysics to define standards of application and to start reviews on the achieved projects of the last decades (Bonsall et al., 2014) Jordan.

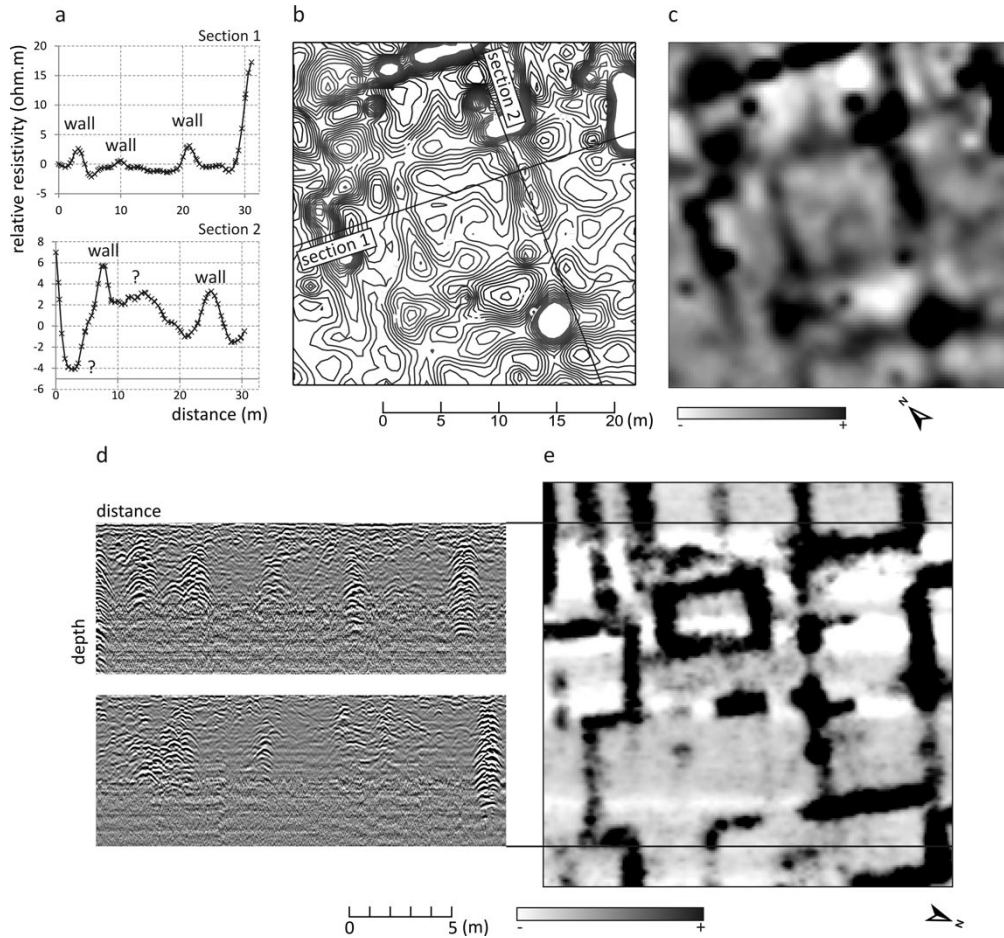


Figure 1.1: Illustration of the changes in geophysical imagery. Relative variations of the apparent resistivity of the soil represented in a). vertical sections b) contour plot c) image plot. GPR results displayed as d) independent vertical sections e) horizontal section of integrated gpr profiles.

1.2 Standards as a solution to limit failure situations

Geophysical imagery is the output of a sequence of operations. This sequence of operations is a nested sequence (Figure 1.2) and as a consequence the quality of the output of each step has a significant impact on the final result. For example, if the design of the project is not adequate to the archaeological objectives or if the quality of the acquired data is low, then all of the following steps will be compromised and the project might not be successful. The complete sequence was divided in this research in three phases defined as the workflow of archaeological geophysics:

1. Field: the field includes the design of the project and the acquisition of the data. This phase is where the problem is characterised gathering context information in order to get as outputs clear archaeological objectives and data which resolution and quality are adapted to them.

2. Data transformation: the limits between the processing, the integration and the interpretation are not always clear to define. As a consequence, it was chosen to gather them in one stage of operations which objective is to identify, enhance and extract features in the acquired data that could help answering the archaeological questions.
3. Finalisation: the finalisation step is where the strategy of communication is decided. The objective is to show and describe how the project answers to the initial objectives and archiving the outputs in the perspective of a re-use.

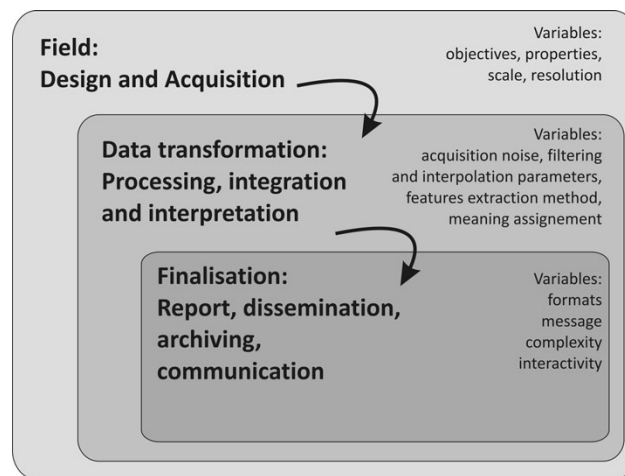


Figure 1.2: Diagram of the nested workflow in archaeological geophysics.

Failure situations can accordingly be divided in three categories: wrong strategy, wrong data transformation, wrong visualisation (Munzner, 2009). A wrong strategy occurs when the design of the project is not adapted to the archaeological problem. A wrong data transformation focuses the processing and interpretation on the wrong features. A wrong visualisation uses a representation system that is not adapted to the target.

Standards and guidelines for good practice are one way of limiting failure situations by spreading the cumulated experience of previous projects. The main standards currently available are the ones established by the English Heritage (David et al., 2008; Schmidt and Ernenwein, 2011). They have inspired other projects as the European guidelines (Schmidt et al., 2014) of the Europae Archaeologicae Consilium (EAC). Independent works were also achieved as the Dutch quality standards in archaeology (Willems et al., 2004) and the report delivered by the University of Arkansas to the US Department of Defense (Kvamme et al., 2006; Ernenwein and Hargrave, 2009).

These standards give a broad perspective on best practice of archaeological geophysics. They include the description of the entire workflow with considerations on legal issues, on the registration of metadata and on the importance of archiving. Metadata and archiving are key elements for a critical re-evaluation of the projects and for the creation of databases. Some considerations are also given on the communication of the results. They include indications on the contents of official reports and on visualisation techniques that are more suitable to the nature of the geophysical information. Nevertheless, this part is less developed than the other steps of the workflow.

1.3 The dissemination of the results

Most of the efforts in research still remain nowadays in the acquisition and processing of the geophysical information. With the emergence of multi-channel systems, the amount of acquired data has known a brutal expansion. It required adapted strategies of control, processing and interpretation. It left little space to research on visualisation and dissemination of the results when it seemed to be one of the major reasons of the slow expansion and integration of geophysical imaging in archaeology. As a consequence, the communication and dissemination steps are still underdeveloped and research on a more didactic approach of transmitting the outputs of geophysical imagery projects is needed.

The main communication vector for geophysical results is the technical report. After the description of the objectives, methods and acquisition parameters of the project, the reports offer a static representation of the results with a proposed interpretation. The results may also be described through animated or interactive layered formats but these considerations are mainly decided by the surveyor. As a result, the final user has a restricted access to the geophysical information which decreases his options of including the results in his research and communication.

The use of common platforms as geographical information system (GIS) helped improving the integration of geophysical and archaeological results. But although these platforms have been promoted as a spatial link between geophysics and archaeology for more than a decade (Kvamme, 1999; Neubauer, 2004), their integration and use in the workflow of projects is still in progress and standards are slow to be defined. The use of GIS in archaeological geophysics is also important as a tool for the integration and analysis of multi-method projects.

1.4 Multi-method projects

“To be able to see, all is needed is a detectable variation of a physical property of the matter” (Rohmer, 2012). In medicine, the influence of medical imagery has radically and profoundly changed the application of the discipline. In geophysical imagery, the lack of contrast between the target and the background remains the main obstacle to a systematic application of geophysical methods. During the design of a survey, assessing what properties will be measured considering the expected contrast, the archaeological objectives and the site conditions will have a major, although sometimes unexpected, impact on the final output. In these conditions, multi-method projects almost always prevail, first for the mapping of the underlying structures and then to be able to give a broader interpretation of the results.

Archaeological geophysics mainly depends on the contrast between the features of interest and the surrounding environment (Clark, 2003). An absence of contrast or a masked contrast due to survey conditions cannot always be anticipated and will systematically lead to limited results. Furthermore, a geophysical sensor can detect features that cannot be distinguished visually during excavations. As a consequence, archaeological excavation should not be used as the only validation method of geophysical results (Kvamme et al., 2006). Multi-method projects are one of the solutions that are being suggested as a strategy for the confirmation or complementation of a geophysical evaluation.

Multi-method projects can be designed combining geophysical surveys with other type of methods as coring, topography, fieldwalking or aerial photography. They also include projects where more than one geophysical method is used. Setting multi-method surveys as a standard gives more importance to the integration of the data. A strategy for a combined processing and interpretation is then required. The current main challenge of multi-method projects concerns the platforms for the integration of the data. As each method has specific dimensions, formats and processing software, there is a need of a common platform where three-dimensional data could be integrated and visualized (Rink et al., 2012).

In addition, as multi-method projects require more complex and inter-related strategies, it will be even more important to maintain the main archaeological questions as a guide for decision making and for the design of the final outputs.

1.5 Objectives and context of the research

The objectives of the research can be divided in two levels. The first level is related to the research presented in this document. The second is related to the archaeological objectives of the case studies. These were chosen to develop and explore the global objectives. The two levels of objectives are presented in Figure 1.3 in relation with the structure of the document.

1.5.1 Global objectives

The main objective of the research is to propose an approach of transmitting the results of archaeological geophysics projects in a way that could improve their understanding and integration in the archaeological process. The proposed approach included (1) using tools of learning theory, (2) evaluating the workflow of archaeological geophysics and (3) promoting the use of multi-method projects as a vector of integration.

1. Using learning theory was considered in order to study the relation between text and image in geophysical imagery. Text and images are mixed in reports, in spatial representations of the results, in animated sequences and even in GIS platforms. After classifying the current transmission methods using learning theory currents, strategies were proposed in order to improve the transmission of the results.
2. As described in the previous sections, the workflow of archaeological geophysics is a complex sequence of operations. Many decisions have to be taken during the workflow. They require the collaboration of the archaeological team responsible of the explored site. It is then important for the archaeological team to have a global vision of the process in order to provide the surveyors with the appropriate information. The workflow was described in order to identify the main variables that could lead to failure situations.
3. Archaeology uses several methods that require a spatial representation of the results. In order to improve the integration of geophysical results in the archaeological process, it was proposed to include these methods in the design of multi-method projects. The general pattern was to consider common archaeological objects and to evaluate the outputs of their combination with geophys-

ical information. The three selected fields were built heritage, archaeological exploration and archaeological research with as archaeological objects a digital model, fieldwalking results and archaeological excavations respectively.

The case studies selected to develop the global objectives of the research were chosen in order to characterise theses different heritage fields where geophysical methods can be used. Each case study had specific archaeological objectives.

1.5.2 Case study objectives

In built heritage, huge efforts are being deployed on the digitalization of monuments and artefacts. Their use in archaeological dissemination is in constant evolution and gives applications in digital modelling, virtual archaeology and augmented reality. A case study on a monumental needle was selected in order to illustrate how geophysical imaging, as other non-destructive technologies, can bring significant qualitative and quantitative information to the initial digital models. The archaeological objective of the project was the assessment of the state of preservation of the monument. More specifically, possible internal cracks and voids had to be detected.

In archaeological exploration, the use of different scales and approaches, and their combination is a key to the characterisation of the landscape. Satellite imagery, aerial photography and field walking are used for the detection of new sites and the evaluation of areas. A case study was then selected to illustrate their combination with geophysical results. A Roman villa detected by aerial photography and documented with field walking was used. The objective was to characterise the underlying features in relation with the chronological sequence of occupation of the site.

In archaeological research, digital cartography can almost be considered as a standard. The integration in a common exchange platform of the current state of excavation with geophysical results and interpretations are being implemented. A case study based on a long-term collaboration between archaeological and geophysical teams is presented. The concern was to generate interactivity between geophysical and archaeological teams and to elaborate a common plan of communication. The site is a Roman fortified settlement which last occupation ended in a brutal destruction. As this case study is a long-term collaboration, the archaeological objectives of the project were continuously re-evaluated. The ones presented here concern (1) the

description of the variations of the bedrock, (2) the description of the constructive features and (3) the identification of burnt areas possibly related to the destruction of the site.

1.6 Structure of the document

The document can be divided in three parts. The first part includes this introduction chapter (Chapter 1) and the methodological background described in Chapter 2. Chapter 2 focuses on the description of the complete workflow described in section 1.2. It also includes the description of the basic concepts related to archaeological geophysics and learning theory used in the research.

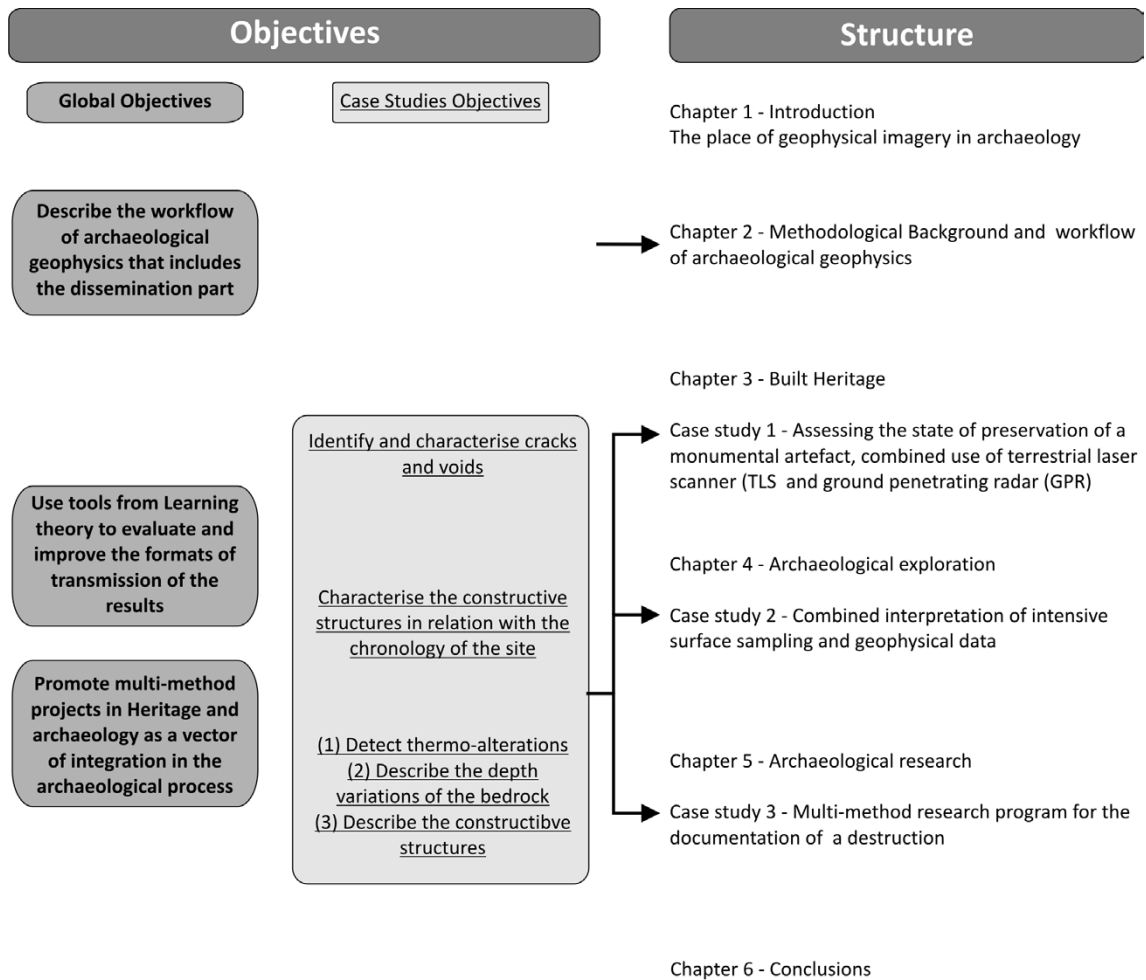


Figure 1.3: Objectives and structure of the research.

The second part, Chapters 3, 4 and 5, is dedicated to the case studies. Chapter 3 presents the results in the built heritage field of the combined interpretation of ground penetrating radar and digital topography data. It describes the geophysical

project conducted on the needle of El Mèdol in the Roman quarry of the same name. In Chapter 4 the global project of the Ager Salmanticensis area is introduced with a more detailed attention to the case of the Roman villa of La Mina. Chapter 6 presents the Puig Ciutat project and the structure for the integration of excavation and geophysical results.

The final part, includes a conclusion chapter, Chapter 6, and appendices. The conclusion chapter mainly focuses on the achievement of the global objectives. The tools inspired from learning theory and used on the case studies are evaluated in comparison to standard reports and documentation. The variables extracted from the description of the workflow in archaeological geophysics are gathered. Problems and drawbacks of the final integrated models are discussed. Finally, possible applications and outputs of the research were considered.

The appendices include the first reports produced for the case studies and a commented list of the software used for the research.

For of each chapter, a graphical abstract or a graphical report was produced. All the graphical abstracts were also gathered in one and are displayed after the written abstract.

1.7 Graphical abstract

1.1 From hermetic to adapted communication

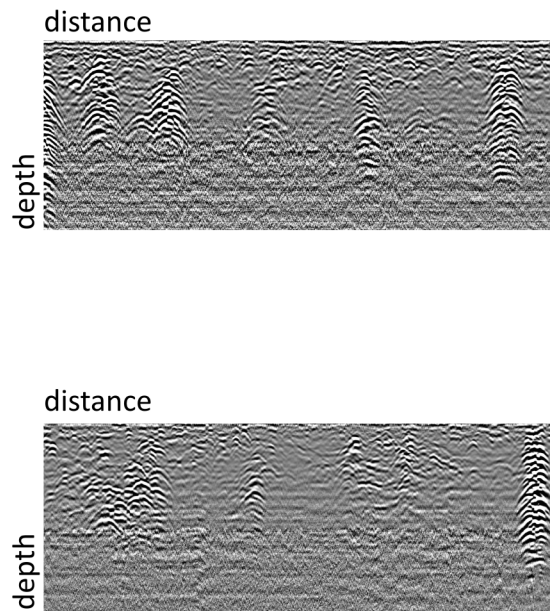
Independent profiles



Integrated image plot



Interpretation



Independent profiles give a partial counter-intuitive view of the soil information



The integration of parallel profiles into image plots gives a more realistic representation of the buried features

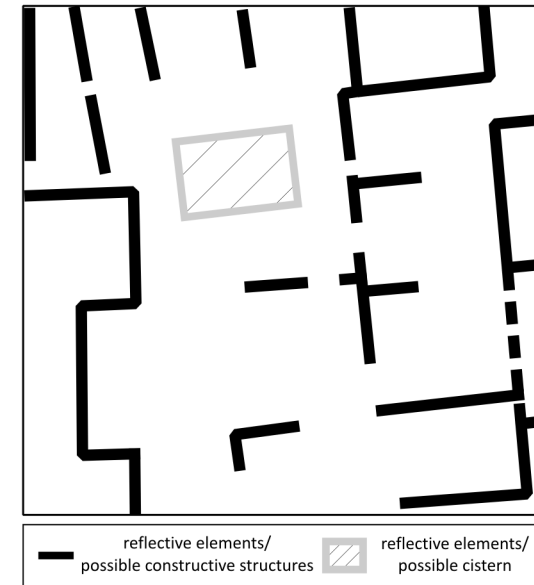
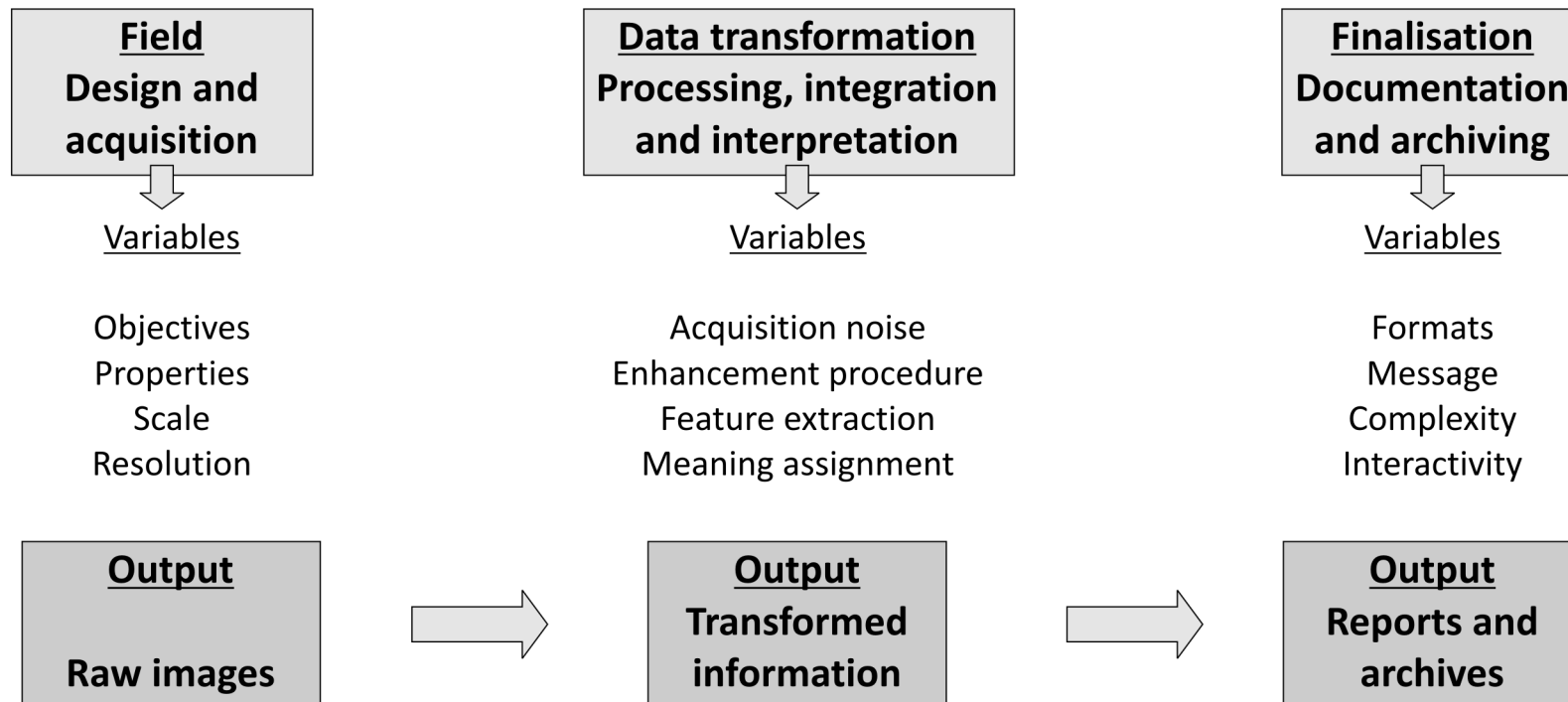


Image plots can then be transformed into vectorial information with an assigned archaeological meaning

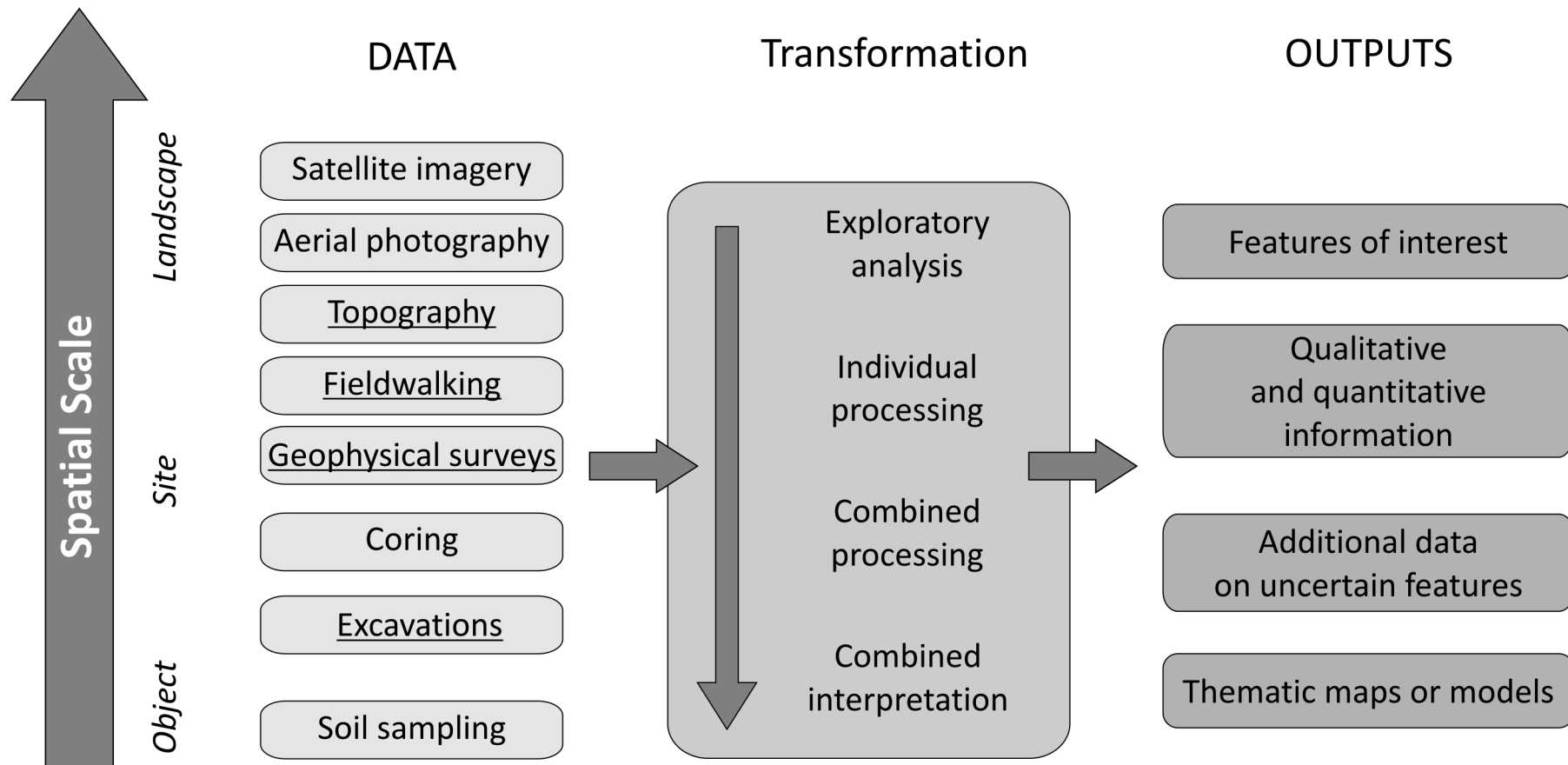
1.2 Archaeological geophysics: A nested workflow



The workflow of archaeological geophysics is a nested sequence of operations
The final outputs depend on the initial decisions
Standards and guidelines help controlling the process

The formats of dissemination were evaluated using Learning Theory tools

1.3 Multi-method projects



Multi-method projects favour the acquisition of complementary information and the validation of results.

The use of multi-method projects will be illustrated on case studies in built heritage, archaeological exploration and archaeological research. The categories of data used for the research are underlined

Chapter 2

Methodological background and workflow of archaeological geophysics

In this chapter, the description of the workflow of archaeological geophysics is presented together with the methodological background. It gives a complete overview on the production of the visual representations of the results. In this perspective, the transmission of the information is a key factor that should not be neglected. Based on learning theory, a special attention is given to the preparation of the material presenting the surveys and their results.

This chapter starts with a summary of the workflow. The main elements of each phase were briefly described in order to give a first view of the complete sequence. Then, the three main phases were described in detail with additional sections on the methodological background: (1) the field (2) the transformation of the acquired data and (3) the finalisation of the project. The phases are illustrated with the results of several case studies. More specifically, the exploration of the Iberian site of Molí d’Espígol (Sala et al., 2013) was used to illustrate the complete sequence.

The structure of this chapter was also used as the guide for the description of the case studies in chapters 3, 4 and 5. The phases of the selected projects were described in the same order and the chapters start with a brief summary presenting the main results.

Some contributions of learning theory were also used in the structure of the chapters. The information was presented in several parallel formats and the relations between text and image were considered.

The graphical representation of the contents of this chapter is presented in the Graphical Abstracts [2.1](#) to [2.5](#).

2.1 Summary of the workflow

For the purpose of the research, the general workflow of archaeological geophysics was divided in three phases. In the first phase, the data are acquired taking into account the contextual information. The objective is to obtain the higher possible fidelity. In the second phase, the data are transformed. The original data include interferences, noise and elements not related to the objectives as geological variations or modern infrastructures. In the transformation phase, the data are transformed from high fidelity data to abstract data containing the information of interest. The last phase was defined as the finalisation phase. It is the phase where the survey is documented and the results are transmitted to the end-user. For all phase, the main guideline is to always refer to the archaeological objectives.

2.1.1 Field

The field phase is defined as the phase where the archaeological objectives are defined, all the contextual information is gathered and an adapted survey strategy is proposed. It ends with the fieldwork and the acquisition of the data.

2.1.1.1 Design of the strategy

The design of the strategy consists of defining an approach that would help reaching the archaeological objectives. The archaeological objectives, the context of the site and the limitations of the project, both financial and physical, must be considered. This previous information will help deciding the methods to be used and the resolution of acquisition. The main characteristics of the methods are presented in [Table 2.1](#).

2.1.1.2 Data acquisition

For the data acquisition, local legal considerations must be taken into consideration. With the required authorisations, the fieldwork can be scheduled and must include the preparation of the ground conditions for a better quality of the acquired data. The acquired data must be checked on a regular base in order to detect system

Method	Magnetic	Resistivity	EMI	GPR
In one word	Fast	Stable	Multivariate	3D
Measured property	Magnetisation	Resistivity	Magnetic susceptibility/ Electric conductivity	Dielectric permittivity
Main use	Thermo-alterations, soil movements	Constructive structures, paths and roads, cavities	Landscape	Constructive structures, cavities
Main limitation	Iron	Contact of electrodes	Resolution	Complexity
Coverage	0.5 to 5Ha	0.2 to 2Ha	0.5 to 2 Ha	0.5 to 2 Ha

Table 2.1: Characteristics of the main geophysical methods.

failures and to be able to adapt the strategy depending on the results.

2.1.2 Data transformation

The acquired data must be transformed to a format that can be transferred to the archaeological team and with the information of interest. The goal is to show how the data contribute to answer to the archaeological questions.

2.1.2.1 Data analysis

The distribution and spatial attributes of the data are characterised. Statistical operators are used to describe their variations and decide the parameters of visualisation and processing.

2.1.2.2 Processing

The acquired data are altered by acquisition noise that depends on the system, the operators and the environment. The processing phase includes the removal of the acquisition noise and the enhancement of the features of interest. For multi-method projects it can also include the combination of the data.

2.1.2.3 Interpretation

The interpretation phase includes the extraction of the features of interest and assigning them an archaeological meaning. The geophysical data are first described using geometric and quantitative information. An archaeological interpretation is then associated to the geophysical object. It should always be referred to raw data

in order to avoid misinterpretation of acquisition or processing artefacts.

2.1.3 Finalisation

The finalisation of a project means the delivery of the documentation and of the files relative to the surveys.

2.1.3.1 Documentation

The documentation of a project can include a written report, a graphical report, additional animated sequences that highlight the main results of the survey and optional interactive models with processed and interpreted data. Presenting the results in several parallel formats favours the understanding of the results. The interactive models can be presented through shared platforms that enable the communication with the archaeological team, the scientific community and the public. Web-GIS solutions offer the best perspectives.

2.1.3.2 Produced files

Original acquisition and processed data are archived and delivered to the final end-user. The files are delivered in open formats favourable to a posterior reuse of the data. The delivered data are associated to metadata that include the parameters of acquisition and of processing.

2.2 Field: From project design to data acquisition

During the field phase, the first images are produced. Their extension, quality and resolution are determinant as they will define the interpretation possibilities. They will depend on the design of the project and on the conditions of the acquisition of the data. The subsequent processing steps can help enhancing the results but will not compensate for a wrong strategy or insufficient data quality.

The design of the project includes the choice of the methodologies to apply. This choice depends on the archaeological objectives and on project limitations as the budget and the environment of the archaeological site. The most usual methods and their main characteristics are briefly described in the next section. The design of projects and the organisation of the fieldwork are then described.

2.2.1 Most used methods

All geophysical methods that can give information on properties of the near-surface can theoretically be applied to archaeology and built heritage. They can be classified in two generic categories: passive methods where a property is directly measured and active methods where the property values are inferred by the reaction to a stimulus. The most common and used ones for archaeology are magnetometer survey, resistivity survey, ground penetrating radar (GPR) and electromagnetic induction (EMI) (Gaffney and Gaffney, 2011). The physical theory beneath each method is not given here. Instead, the main characteristics and archaeological applications of each method are briefly described. The compared characteristics of the methods are presented in the Graphical Abstract 2.1.

It should also be stated that the properties measured during the data acquisition are considered to be apparent properties. This means that there are computed under the assumption that the media is homogeneous, which is never the case. As a consequence, archaeological geophysics tends to focus on the relative variations of the properties rather than on their absolute values. The archaeological interpretation relies more on the geometrical identification of features than on the physical interpretation of property values.

2.2.1.1 Magnetometer survey

The magnetic method is a passive method. It is considered to be the fastest method. The property measured is the intensity of the magnetic field. The main goal is to map the local contributions of elements beneath the ground surface. These contributions can be classified in two categories (1) induced: the presence of a body with magnetic properties in a magnetic field as the earth magnetic field generates an induced magnetic field (2) permanent or remanent: inherent to the material. This kind of magnetisation can be acquired through physical processes as heating (Schmidt, 2007). The magnitude of the measurements for the first category tends to be much lower than for the second. For example, the soil filling a trench is of category 1 and a kiln is of category 2. Figure 2.1 shows a graphical representation of these two objects.

Different types of instruments exist. The most used ones are the fluxgate and the caesium vapour sensors (Linford et al., 2007). The fluxgate systems are gradiome-

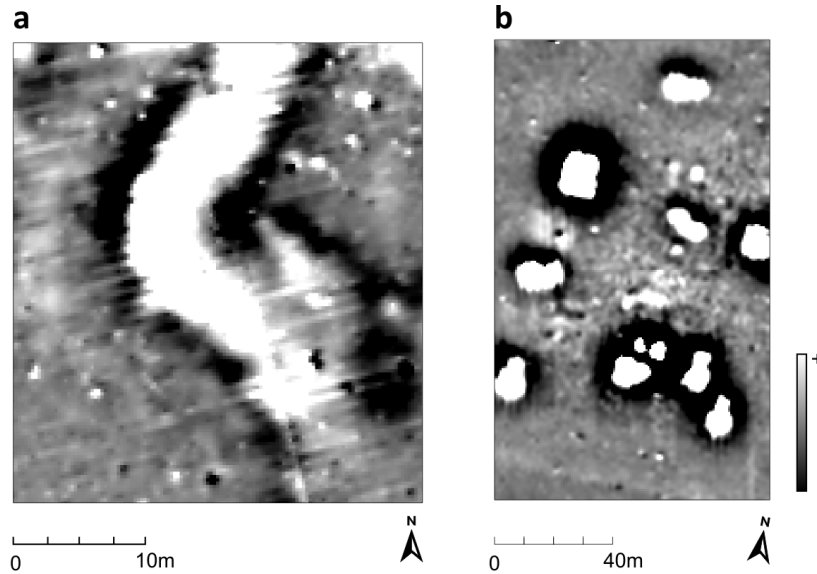


Figure 2.1: Some typical objects detected by magnetic surveys a) ditch b) kilns.

ters, which means that the sensors are paired and give a differential value. The caesium vapour sensors can be used with single sensors. They give access to the magnetic field value. In practice they are used in a configuration similar to the flux-gate one with two sensors vertically aligned. The output is one measurement per sensor from which the vertical gradient can be extracted. The most usual systems used for magnetometer surveys measure the intensity of the vertical component of the magnetic field. Multi-channel solutions are commonly used and allow covering 1 to 5 hectares per day (Becker, 2001; Schultze et al., 2008).

The measurement parameters will also condition the detected variations. As the most used configuration is the gradient one, the distance between sensors is the first parameter to consider. For fluxgate systems, this distance is fixed but can vary from one brand to another. For caesium vapour systems, as the sensors are independent, the distance between them can be modified by the user. The distance between sensors will have an impact on the scale of the variations that can be detected and on the depth of investigation. Typical distances used for archaeology are 0.65m, 1.00m and 1.80m. The depth of investigation grows with size of the system. The most effective one in terms of definition and depth of investigation would be the 1.00m one. Another parameter of acquisition to consider is the distance to the ground of the lower sensor. It determines the impact of surface contamination and has an impact on the magnetic contrast. It is usually set around 0.20m.

The clearest use of magnetometer surveys are for the description of soil movements

such as ditches (Křivánek, 2006; Alistair Marshall, 2001), pits (A Marshall, 1999 or trenches (Masters and Stichelbaut, 2009), of thermic alterations and kilns (Gustafsson and Viberg, 2012; Linford and Canti, 2001), and of the scattering of iron material (Vernon et al., 2002). They can also be used for the description of constructive features and interpretation of urban planning (Benech, 2007) but the results will be more dependent on the contrast between the soil and the building material. As it is the fastest system, it is often used for exploration in order to delimit areas of interest.

The magnetic data are strongly affected by uneven ground surfaces, metallic structures and superficial contamination. They can mask features of archaeological interest. As for the interpretation of the data, information on the depth of the identified features is not possible to retrieve without additional assumptions on the nature and geometry of the object (Abdelrahman et al., 2007; Desvignes et al., 1999). In addition, the magnetic data of thermo-altered areas do not preserve the geometry of the features.

2.2.1.2 Resistivity survey

The resistivity survey is an active method where an electric current is injected and a resultant difference in potential between two points is created. The measured property represents the capacity of the explored media to resist to the current that is being injected and is called resistivity (ρ). The main physical properties that will influence the measurements are the water content that varies with porosity and saturation, and the salinity of the water (Samouëlian et al., 2005).

The injection of the current and the measurement of the difference of potential are achieved using electrodes that can be either inserted in the media or placed above it (Tsokas et al., 2008). The relative geometry of the electrodes determines the depth of investigation. Two modalities exist which have led to two instrument families. In the first one, the distance between the electrodes is fixed and the system is moved in order to perform measurements in extension for a fixed depth of investigation. Several depth of investigation can be measured simultaneously (Walker, 2000). It is the cartographic modality. In the second one, the location of the measurement is fixed and the distance between electrodes is increased progressively. The values resistivity values corresponding to different depth positions are then measured at the same location at the same location. It is the vertical sounding modality. A vertical

section or “pseudo-section” of the soil is created repeating vertical soundings along a profile. Parallel profiles can be prepared placing a mesh of electrodes on the surface for a 3D resistivity imaging (Papadopoulos et al., 2006)

The parameters that have to be considered for the measurements are (1) the relative geometry of the electrodes (2) the nature of the injected current and (3) the nature of the used electrodes. In archaeological geophysics the most used configurations include four electrodes per measurement. The relative position of the electrodes or geometry of the system will determine the anisotropy, the vertical sensitivity and the maximum depth of investigation of the measurements. The current references are the wenner, twin, pole-pole, “vol de canard” and square configurations (Dahlin and Zhou, 2004; Szalai and Szarka, 2008). Usually an alternative current of frequency lower than 1000Hz is used. As for the electrodes, they are usually in stainless steel. The depth at which they are inserted, and the type of electrolytes in the case of capacitive electrodes, should also be considered during acquisition.

The cartographic modality is usually applied for the description of constructive features (Neubauer and Eder-Hinterleitner, 1997) or road and paths (Tsokas et al., 2009). The potential of multilevel high resolution resistivity mapping is very well illustrated in a research project centred on the evolution of the design of a Victorian municipal park (Parkyn, 2010). The pseudo-section modality is used when a larger depth of investigation is needed or if the site presents a complex topography. Typical applications would be the detection of cavities or the exploration of tumuli (Papadopoulos et al., 2010). Innovative methodologies are applied for the detection of areas of interests in bodies with complex topography using a tomography approach (Tsokas et al., 2014).

Although fast acquisition system exists (Dabas, 2009; Walker et al., 2005), resistivity surveys tend to be slow. Furthermore, they require a good contact between the sensor and the media, which can be difficult to implement, especially in dry conditions.

2.2.1.3 Electromagnetic induction

The electromagnetic induction (EMI) survey is an active method based on the induction of currents in the soil. The frequency domain electromagnetic method (FDEM) will be described here as it is the most used for archaeology. An electromagnetic

field (primary field) is created using the passing of alternate current in a coil. In the induction domain, i.e. for frequency lower than 100 kHz considering the spatial dimensions used in archaeology, the propagation of the electromagnetic field and the presence of conductive bodies will generate eddy currents in the media which will generate a secondary magnetic field (Callegary et al., 2007). A second coil at a known distance from the first one will measure the currents induced by both primary and secondary fields. After compensation of the primary field, the in-phase and the out-of-phase components of the secondary field can be extracted and converted in magnetic susceptibility (μ) and in conductivity (σ) respectively (Simpson, 2009). The magnetic susceptibility is the capacity of the material to align its magnetic field to an external magnetic field and the conductivity is the inverse of resistivity.

Instruments can be classified in two main categories: (1) metal detectors and (2) survey systems. Metal detectors can be used for pedestrian exploration of the ground surface (first 0.3m). Survey systems are used for large scale mapping. Systems with different separations between the transmitter and the receivers and different relative orientation are available.

Several parameters will affect the volume of soil considered for the measurement: (1) the orientation of the transmitter coil in reference to the ground surface (Vertical or Horizontal), (2) the respective orientation of the transmitter and receiver coils (coplanar CP or perpendicular PRP), (3) the distance between coils and (4) the distance to the ground (De Smedt, 2013). In addition, the volume considered will be different for the in-phase and the out-of-phase signals. The measurements will also depend on the size of the coils and on the intensity of the current, which combined gives the characteristics of the primary field, and on the used frequencies. No direct contact is needed with the ground surface.

The induction methods have great advantages in comparison to the other methods for landscape characterisation (Saey et al., 2008) and metal detection (Saey et al., 2011). They behave better in conductive soils, e.g. clayey environments. On the other hand, they give poor results on resistive soils. Similarly to the magnetometer survey, they are influenced by close metallic elements. Electromagnetic measurements suffer rapid drift issues. This has to be taken into account during the acquisition and the processing of the data.

The use of fast towed multi-receiver systems enabled large scale acquisitions with

several simultaneous depths of investigation and high resolution (De Smedt et al., 2013). As a consequence, this method that tended to be neglected is now reconsidered.

2.2.1.4 *Ground penetrating radar*

Ground penetrating radar is an active method based on the emission and recollection of an electromagnetic signal in the high frequency or radar domain. In the radar domain, the signal propagates in the media (low-loss media) as a wave. It gives nearly continuous but indirect information on depth. The recollected signal is measured in terms of magnitude or instantaneous amplitude (strength), phase (polarity) and times of arrival of the waves (Annan, 2009; Lekebusch, 2003). The main properties of interest of the explored media are the dielectric permittivity (ϵ), which is strongly related to the moisture content (Huisman et al., 2003; Pettinelli et al., 2014), and the electrical conductivity (σ). The variations in dielectric permittivity (ϵ) and electrical conductivity (σ) of the media will affect the velocity of propagation (v) of the waves, their attenuation (α) or the related depth of investigation, their impedance (Z) or reflectivity and the directions of propagation (Verdonck, 2012). The main goal is to map the lateral and vertical variations in reflectivity of the signal.

The signal is emitted using a transmitting system and recollected in a receiver system. These systems include one or several antennas (Novo et al., 2012; Verdonck et al., 2013). The signal can have one or multiple central frequencies (e.g. dual-mode systems), with a variable spectral range depending on the brand, or a nearly continuous range of frequencies (Nicolaescu and Genderen, 2012). The antennas can be used in contact with the media surface or air-launched. In the air-launched configuration a layer of air between the antenna and the surface is kept constant. The resulting signal will mainly vary in terms of anisotropy, which means its sensitivity or capacity to detect will vary with the direction of propagation, and of depth of investigation.

There are two main modalities. The monostatic modality where the distance between the antennas is kept fixed which is used for cartography and the bistatic modality where the distance between antennas is progressively increased and which is used for the calculation of the propagation velocity of the waves (Conyers and Lucius, 1996).

At low frequencies (10-100MHz), the GPR method is mainly used for geological or hydrological characterisation as well as for deep large cavities. At medium frequencies (200-600MHz), the GPR method is usually used for the description of constructive features as it can give a high fidelity image (Verdonck et al., 2012). The nearly continuous depth information enables the 3D visualisation of the features and the identification of several phase of occupation. Built heritage projects will often require high frequencies antennas (600MHz-3GHz) which can be used for the mapping of internal structure (Goodman and Piro, 2013) or for a diagnosis of the state of conservation (Binda et al., 2005; Cosentino et al., 2011).

Although the air-launched possibility exists, the depth of investigation is lower in this modality than in ground coupled systems. In both cases ground surface irregularities or obstacles have a great impact on the quality of the data. The water and clay contents will also be important as they may drastically attenuate the signal and limit the depth of investigation. In general, the GPR signal is complex and requires thorough processing, which increases its cost.

The main advances in GPR imaging have been brought by acquisitions with full 3D resolution (Grasmueck et al., 2005). At this resolution, the resulting maps enable a straightforward interpretation of detected features.

2.2.2 Design of the project

Given the characteristics of the main available methods, a strategy must be chosen for the implementation of archaeological geophysics projects. The main concern is then to gather all the relevant information available in relation to the archaeological objectives and the context of exploration. This information will then be used to choose an adapted strategy. The collaboration between the archaeological and survey teams is absolutely necessary at this stage as the strategy of exploration depends on the archaeological information. The last step of the design of the project is to decide the acquisition methodology and to prepare the fieldwork. The steps of the design and the execution of a project are presented in the Graphical Abstract 2.2.

2.2.2.1 Project characterisation

The first step of the project design is to exchange information with the archaeological team. This exchange of information aims to describe the context of the project and identify the main variables that will influence the strategy to adopt. The main elements that are needed are the archaeological context, the description of the environment and the economic resources.

During the recompilation of the information related to the project, a dialogue must be started with the archaeological team. This dialogue can include a field visit and a questionnaire (Sala et al., 2012). The objective is to obtain all the information needed for the characterisation of the project. A field visit gives updated information of the environment of the site but is not always possible. The questionnaire is a formalisation of the characterisation of the site. The questions should be short and precise in order to avoid misinterpretation.

The archaeological context includes the description of the objectives. What is needed here is to understand what the archaeological question is and to gather information on the expected features. For example, the needed information can consist of the depth of the structures, the nature of the constructive material, the chronology, the presence of several occupation phases. The information to gather should be adapted to the chronology of the site.

The environment of the archaeological site also has a direct influence on the design of the project. The variables that should be considered are (1) the type of site, urban, suburban, rural (2) the geology (3) the presence of possible interference sources as metal fences, electrical installation or nearby emission antennas (4) the ground conditions and the (5) the accessibility of the site.

All this information will then be used to decide which methods are the most adapted to the project, what strategy to use and to prepare the logistics. Working in collaboration with the archaeological team will strongly improve the decision making. The important point here is then to involve the archaeological team in the design of the project.

2.2.2.2 Strategy

Once the preliminary data are gathered, the strategy can be elaborated. It involves choosing the methods to use and how to apply them. Tables matching geophysical methods to archaeological features and geological contexts exist (David et al., 2008) but should be considered as guides. The tables were created using theory and past experiences but theory is based on assumptions practice sometimes contradicts and the possible combinations of parameters such as pedology, geology, archaeological features or weather conditions are infinite. The main question should always be: What physical properties show a measurable contrast between the archaeological features to be documented and the background?

The design of a project can be divided in three main parts: (1) the archaeological objectives (2) the strategy and methods used to answer to the objectives (3) the feasibility. These three aspects of a project need to be consistent. The choice of the geophysical method should be justified using the archaeological objectives and the feasibility parameters. In Figure 2.2, each part is represented by an axis. The parameters of the project can be stored in this diagram in order to offer a synthetic view of its main components.

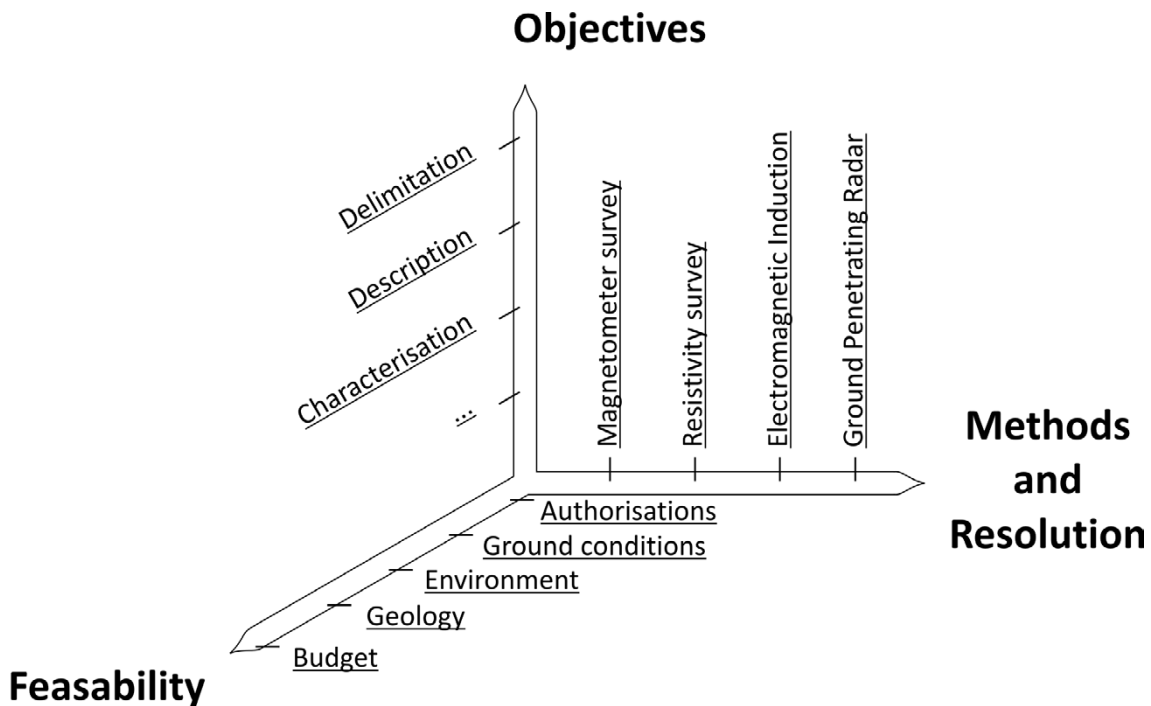


Figure 2.2: Parameters to be considered for the design of an archaeological geophysics project.

The main strategies for the application of the methods are (1) an exploration strat-

egy, (2) a focus strategy and (3) an on-site strategy.

1. Exploration strategy: A first fast low cost method is applied on the total extension to delimit areas of interest. Additional surveys are applied on selected targets (Figure 2.3a)
2. Focus strategy: Methods are chosen based on specific archaeological questions for their qualitative information on soil properties (Figure 2.3b)
3. On-site strategy: Several methods are tested at the beginning of the survey in order to choose the one that offers the best contrast. This list is not exhaustive and mixed strategies are possible if not recommendable. At the end, the proposed strategy should be set in order to try to answer to the archaeological questions in the most efficient way given the external constraints of the project identified during the characterisation of the project.

2.2.2.3 Acquisition methodology

Once the strategy is chosen the methodology of acquisition must be decided. It includes deciding the configuration and resolution of each applied method and the positioning system. The configuration of the systems will mainly depend on the information gathered during the characterisation phase (section 2.1.2.a). Each method has a set of parameters that can be adjusted to the requisites of the project and that are described in section 2.1.1. Some of these parameters, as the intensity of the injected current in a resistivity survey or the acquisition time window of a GPR survey, can only be decided on-site. The resolution of the acquisition will also depend on the method. It will determine the minimal size of the features that can be detected. It must be decided taking into account the archaeological objectives, budget and system limitations.

The two main modalities for positioning the data are (1) an integrated relative positioning through the operating hardware and (2) an external automated positioning system through a Differential Global Positioning System or a robotic total station (Barratt et al., 2000; Grasmueck and Viggiano, 2007).

1. Integrated positioning surveys have to be referenced, need a segmentation of the area to explore in grids and visual and metric references on the field.

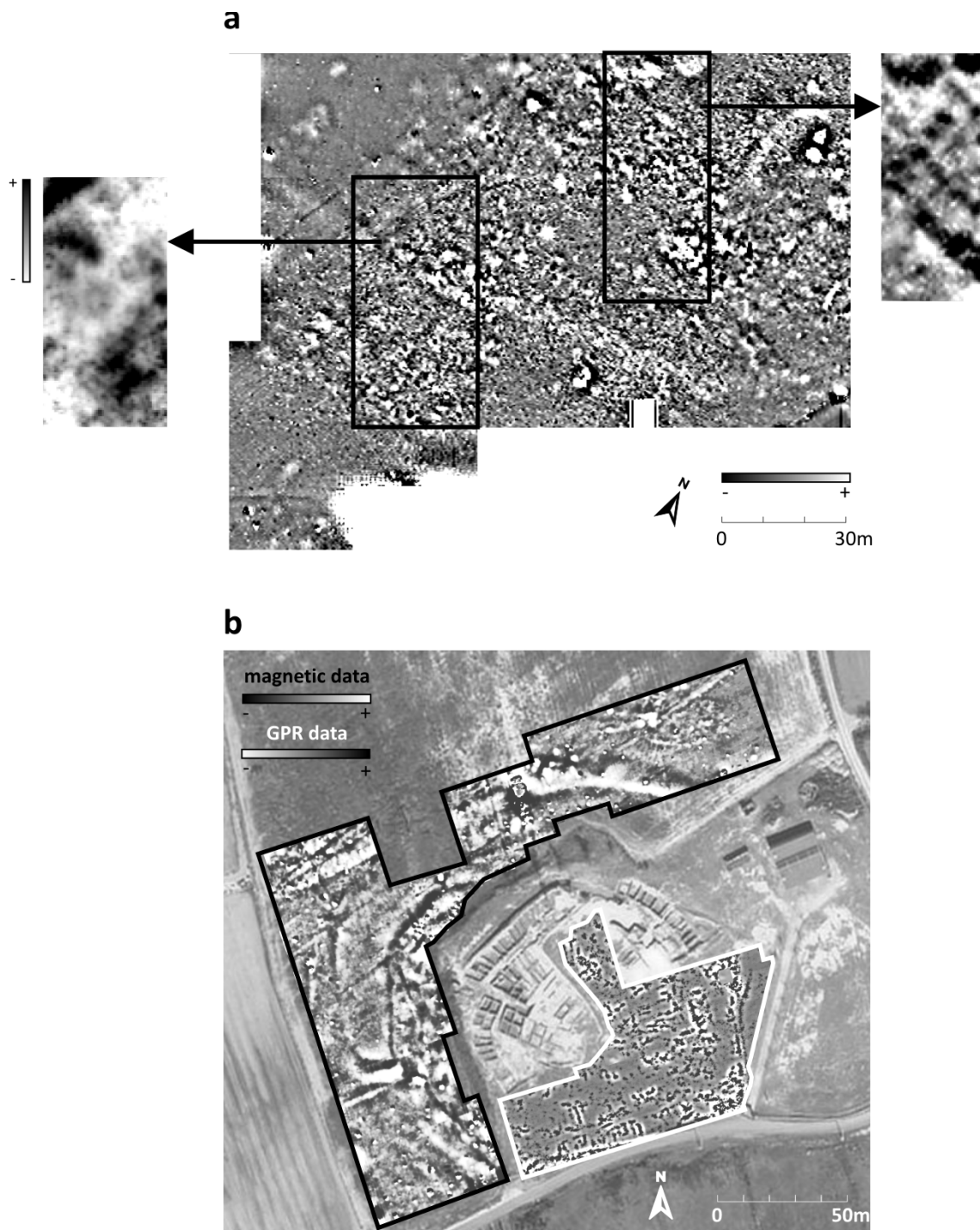


Figure 2.3: Examples of strategies. a) exploration: first magnetic survey is applied. A resistivity survey is then applied on selected targets b) focus: the magnetic survey is applied outside the urban nucleus in order to detect possible ditches. A GPR survey is used to map the urban mesh.

2. When using automated solutions, an additional navigation system is needed in order to survey in parallel lines and to ensure a homogeneous cover of the explored extension.

Both systems are illustrated in Figure 2.4. Other elements have to be considered when planning an automated survey: the connectivity between devices, the satellite coverage, the differential correction needed to maintain a low uncertainty on the position of the measurements, or the synchronisation of position and data measurements. They require specific tools and processing. Combined solutions also exist and enable a faster correction of the positioning when the external positioning system has failed.

With all systems, the complexity of the geometry of the area to explore and the presence of obstacles should be considered for the estimation of the time of acquisition that is needed to complete the survey.

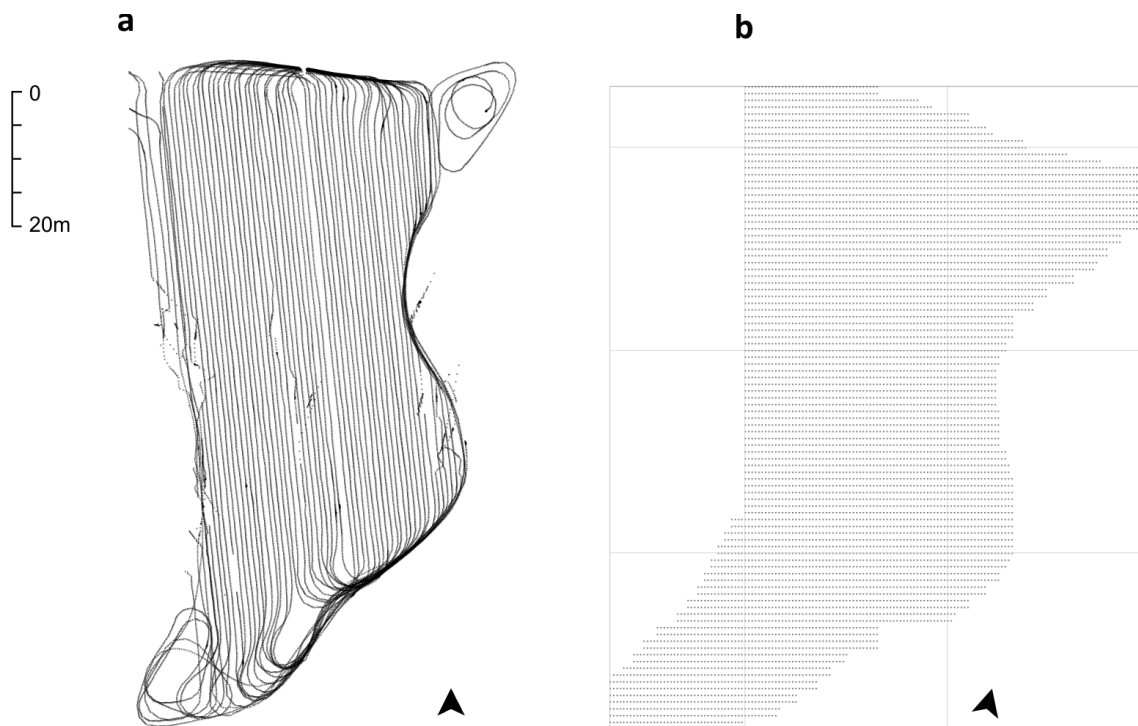


Figure 2.4: Acquisition methodology for the positioning of the data a) GPS driven acquisition b) integrated positioning with local references.

The most important factors to consider at this phase are to ensure a homogeneous coverage of the area to survey and a high precision on the position of the survey and of the data.

2.2.3 Data acquisition

Once the frame of the project has been set, other considerations have to be taken into account as legal authorizations, ground conditions and fieldwork.

2.2.3.1 *Legal considerations*

The legal considerations concerning archaeological geophysics are still very variable. European guidelines are being proposed using the English Heritage standards as reference for future legislations in other countries of the European space. In the Spanish state, each autonomous region has the authority to regulate on local heritage but there is no specific legislation for geophysical projects. Because of this absence of legislation, there is no legal obligation to register an archaeological geophysics project. When they are registered, the same procedure as archaeological excavations is used. It includes the permits of the properties affected by the survey and the project dossier with objectives, context, methodology and costs.

2.2.3.2 *Ground conditions*

During fieldwork, the main preoccupation is to ensure the quality of the data. One major factor is the surface condition of the field. Even for methods where no direct contact is required, an indirect one is needed through the operating system (surveyor, moving platform). The height of the vegetation, the ploughing, obstacles as trees or stones, and the superficial contamination, are all parameters that can severely damage the quality of the data. They have to be carefully taken into consideration before the start of the acquisition in order to take the adequate measures for the preparation of the area to survey. The basic requirements on the ground conditions should always be stated in the proposal of a project.

2.2.3.3 *Fieldwork*

Fieldwork requires field documentation. The main goal here is to enable an easier processing and interpretation of the data. More specifically, parameters as the surveyors, the weather conditions, problems during acquisition, breaks or battery changes, remarkable objects visible on field, should be documented.

During the fieldwork, a check on a regular base of the quality of the data should be

performed. This can help with the detection of system failure not visible on the field or with contrast issues. The download and first processing of the data at the end of each day enable both data quality check and strategy modifications considering the daily results. For multiple-channel systems, the visualisation of the data during the acquisition is proposed as a solution for quality check (N Linford, 2014).

At the end of the fieldwork, the acquired and integrated information form the raw dataset. At this stage, the objective is to gather as much information as possible considering the limitations of the project. This can be described as the need of a high iconicity level of the information. The iconicity is defined as closeness to reality. At the acquisition stage, the data have to be the more realistic as possible in terms of definition and resolution (Graphical Abstract 2.4).

2.3 Data transformation

'Finding a representation of the raw data that will address the initial problem requires transforming the data into derived data of different form' (Munzner, 2009). This citation extracted from an article on data visualisation can also be applied to archaeological geophysics. The initial information consisting of the acquired data have to be transformed before dissemination. The transformation must extract from the data the information in relation with the archaeological objectives. It includes the identification and removal of acquisition artefacts and the creation of a new representation of the information. Although the main transformation steps can be described, many tools and methodologies are available. The processing should be adapted to the requirements of each project. The ultimate goal of this step should be the transformation of the data from their initial representation to a more abstract one. The abstract representation is needed to enhance the part of the data that are of interest (Graphical Abstract 2.4).

2.3.1 Exploratory data analysis

During the exploratory data analysis, the main objectives are to get to understand the data and assess their quality. The quality of the data is assessed by the characterisation of the acquisition noise and of what should be considered as signal. The analysis can be numerical, visual or spatial, although the three aspects are usually combined. The analysis can be univariate or multivariate. Understanding the data and the raw images is a preliminary step that can help with the design of

the processing. Exploratory data analysis should also be used for the control of the processing steps. A combined approach of exploratory data analysis is presented in the Graphical Abstract [2.3](#).

2.3.1.1 Descriptive statistics

The descriptive statistics aims to characterise the distribution of the data in terms of magnitude, range and shape. It can give information on the presence of outliers, on the spreading of the values and therefore on the contrast or on a possible saturation during acquisition. The descriptive statistics can include the minimum and maximum values, the mean value, the mode or the most represented value or range of values, the median, the standard deviation and the percentiles. The most usual descriptive statistics are described below:

Mean: ratio of sum of the values to the total number of samples.

$$Mean(x) = \bar{x} = \frac{\sum_1^n x_i}{n} \quad (2.1)$$

Variance: mean of the square differences between the data values and the mean. The standard deviation is the square root of the variance.

$$Variance(x) = \sum_1^n \frac{(x_i - \bar{x})^2}{n} \quad (2.2)$$

$$Stdv = \sqrt{Variance} \quad (2.3)$$

Percentiles: value for which the cumulated frequency of the data reaches X per cents. The median is the 50th percentile or P50.

A visual representation of these operators can be displayed on a histogram. Histograms are generated by dividing the total range of the data in intervals referred to as classes. The number of samples in each class is computed and represented as a number or as a frequency (ratio of the number of samples in the class by the total number of samples). The histograms in Figure [2.5](#) show two typical distributions: a

symmetric distribution centred on 0 and an asymmetric or skewed distribution. The descriptive statistics can be considered interactively with the plotting of the data. The visualisation of the data will enable a spatial representation of the numerical classes of interest.

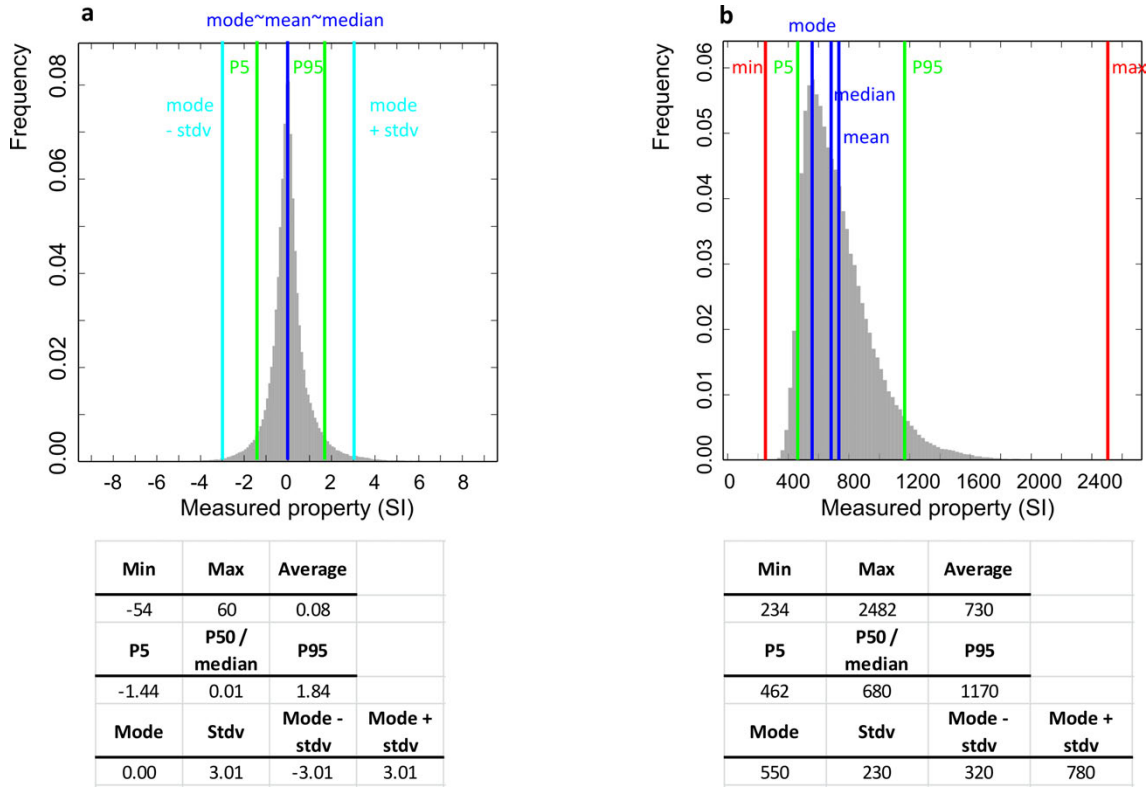


Figure 2.5: Histogram analysis a) symmetric distribution centred on 0 b) asymmetric distribution.

2.3.1.2 Spatial representation

The spatial representation of the data is a dynamic representation of the spatial information. It is generated using parameters as the bounds of visualization and the colour scale. The interactivity between quantitative information and a spatial representation helps understanding the data. Figure 2.6 shows the same dataset in three representations. In the first one (2.6a), the bounds of visualisation are set to the minimum and maximum values. In this case, the high range values, which are metals, are highlighted and the more subtle information is masked. 2.6b shows the same dataset with the bounds of visualisations set using the percentiles P5 and P95. Now the subtle variations can be seen and they contain the archaeological information of interest. Finally 2.6c shows the data with the same bounds as 2.6b but with a different colour scale that highlights the areas of greatest alteration.

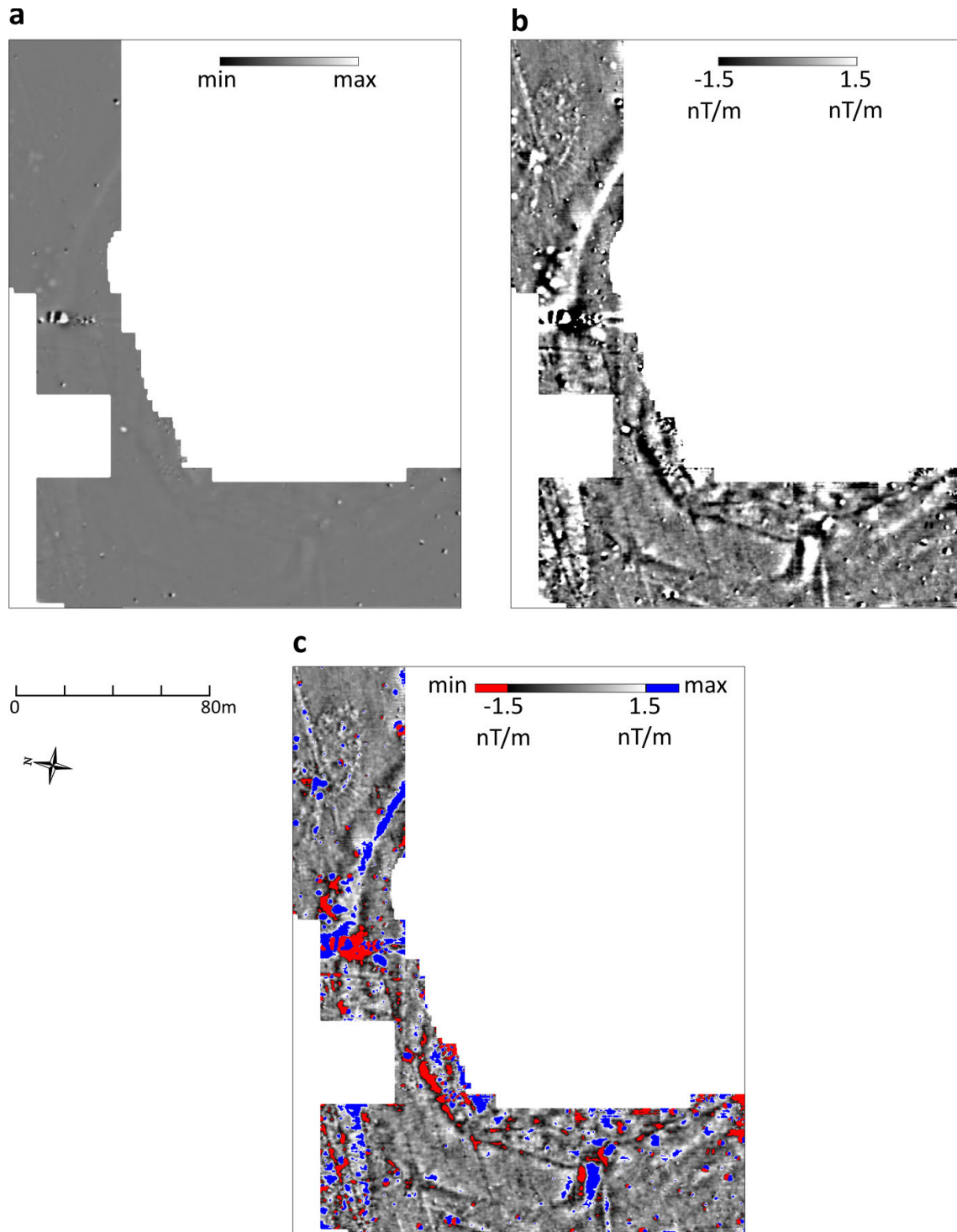


Figure 2.6: Dynamic spatial representation of the data a) the bounds are set using the minimum and maximum values of the data b) the bounds are set using P5 and P95 c) the bounds are set using P5 and P95 and the saturated values are highlighted with different colours.

The plotting of the data gives a visual representation of their quality. It also gives a first assessment of the results and of their possible interpretation. The acquisition data that were generated with a regular sampling should first be visualized at the acquisition sampling without interpolation. That means that each pixel of the display or each cell of the supporting grid has the dimensions of the acquisition sampling and is assigned with the corresponding value. Scattered data usually need to be interpolated to be visualized. It is strongly recommended to overlay the position of the acquired points over the interpolated representation during the analysis of the data. The overlay enables the discrimination between the data and the effects of the interpolation.

The most used colour scales are the monochromatic ones, more especially the grey scale, which is the one recommended by the English Heritage guide of best practices (David et al., 2008). Polychromatic colour scales can also be used when specific features need to be highlighted. The bounds of visualization tend to be determined manually. Several systematic determination methods can be used when needed (Figure 2.7). The mains ones are

1. a percentiles based approach: the P5 and P95 values can be used as minimum and maximum values respectively (2.7b and 2.7d)
2. a histogram approach: the combination of the mode and the standard deviation give the bound values (2.7a)
3. an iso-frequency approach: the classes for the representation of the data are defined in a way that they include the same number of points (2.7c). The bounds of the classes are then irregular
4. the triangle method approach (Tsai and Lee, 2002): on a histogram, the line between the mode value and the extremum is used as reference for the computation of orthogonal distances between the line and the different classes of the histogram (2.7e). The maximum distance gives the bound value for visualization (2.7f).

The first approach is the most effective one as it adjusts to the distribution of the data. The second approach is mainly adapted to symmetric distributions. The last

two ones are useful for the spatial representation of data with asymmetric or skewed distributions.

A visual analysis through the spatial representation of the data gives a qualitative characterisation of the spatial attributes of the data. It can be combined with a quantitative approach.

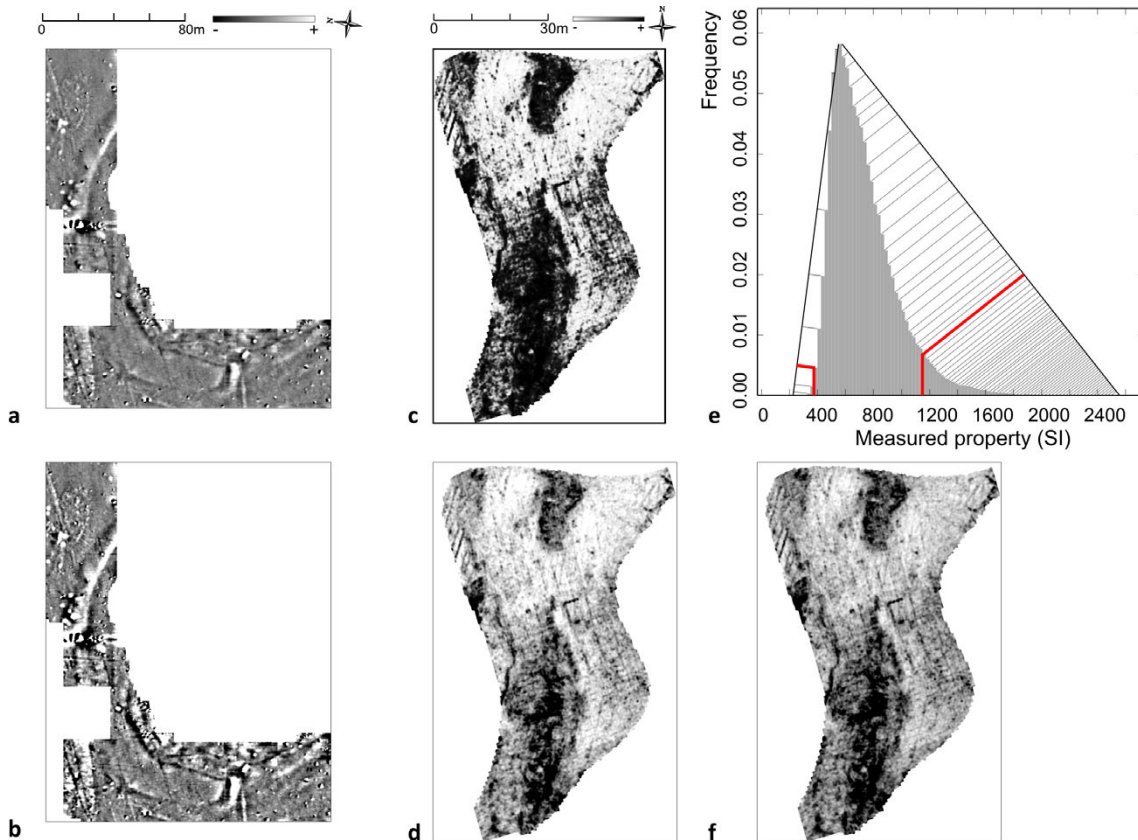


Figure 2.7: Determination of the bounds of visualisation a) histogram approach: min= mode -stdv max= mode + stdv b) quantiles approach on a symmetric distribution min= P5 max= P95 c) iso-frequency approach d) quantiles approach on an asymmetric distribution e) bounds determination using the triangle method f) display using the bounds determined in 'e'.

2.3.1.3 Quantitative characterisation of spatial attributes

The characterisation of the spatial attributes of a dataset is the main objective of geostatistical methods (Olea, 1999). More specifically, the characterisation of the spatial variability can be performed with a variogram analysis. A variogram analysis helps characterising the spatial components identified during the visualisation of the data (Bourges et al., 2012).

The experimental variogram is represented by the curve of variability of pairs of points separated by a fixed distance (lag). The curve is constructed computing for

entire multiples of a minimal lag the mean of the variability of all the pairs of points separated by this distance as described in the equation 2.4 (Geovariances, 2013).

$$Variability = \frac{1}{2n} \sum_n (Z_\alpha - Z_\beta)^2 \quad (2.4)$$

where n designates the number of pairs of data separated by the considered distance, and Z_α and Z_β stand for the value of the variable at two data points constituting a pair.

In geophysical prospection in general and in archaeological geophysics in particular, the data cover homogeneously large areas. In that configuration, the characterisation of the spatial correlation of the data can be performed for specific directions, namely the acquisition direction and its orthogonal direction. This approach is to be opposed to the approach used for heterogeneously distributed dataset. When the data are heterogeneously distributed, an omnidirectional experimental variogram is computed. This implies that for a lag or fixed distance of the curve of variability, the dataset was scanned in all directions.

It is important to understand that the lag that is used for the computation of an experimental variogram is a spatial frequency or a distance between pairs of points. For each lag, all the pairs of points in the dataset separated with this distance are considered. For directional experimental variograms, only the pairs of points oriented in a specific direction are selected for the computation of the variability.

For scattered data, e.g. DGPS driven acquisitions, the experimental variogram is computed using a searching angle and a tolerance on the lag distance in order to build a curve with a significant number of pairs of points. For regularly spaced data or gridded data, the experimental variogram is computed for exact directions and with the minimal lag equal to the minimum distance between two points in that direction.

The analysis of the experimental variogram relies on identifying the significant points of the variability curves and the relative position between the curves. This can be done manually through a visual analysis or automatically using an algorithm that fits a model to the experimental curves.

The main significant points are the y-intercept and the inflexion points. They are characterised by their range which is the lag distance at which they are identified and their sill which is the variability value. The y-intercept gives the ratio of variability that can be assigned to random noise. It represents the data that are not spatially correlated. The inflexion points give the ranges where a higher correlation is detected for each of the computed directions. The relative position of the curves gives the orientation of the main spatial components present in the data.

In order to associate the ranges detected in each directional variability curve, a visual assessment of the spatial representation of the data is made. An experimental variogram can be described with several underlying models. The visual assessment helps determining a model that describes the dataset.

An example of a bi-directional experimental variogram is presented in Figure 2.8. The Figure includes the experimental variogram and an indication on the inflexion points (2.8a), a diagram with the spatial components used to model the experimental variogram (2.8b) and the spatial representation of the data (2.8c). The interpretation of the variogram includes four spatial components. The smallest corresponds to a random noise which size is the acquisition sampling. Two spherical patterns of around 3 and 6m are used to describe spatial components of mid-scale. Finally, the difference in variability between the two directions is used to model the line effect in the direction of acquisition.

For large volumes of data covering areas with different behaviours, other strategies are used for the computation of the experimental variogram. It can be computed on selected areas of interest or with a moving neighbourhood and an automatic detection of ranges and sills.

2.3.1.4 Multivariate analysis

All the tools described in the previous section can be applied on multivariate datasets. The main concern is then to characterise the correlation between variables. Multivariate statistics include the computation of the coefficient of correlation r . Several methods exist for the computation of this coefficient (Niven and Deutsch, 2012) the most used one being the Pearson coefficient described by equation 2.5.

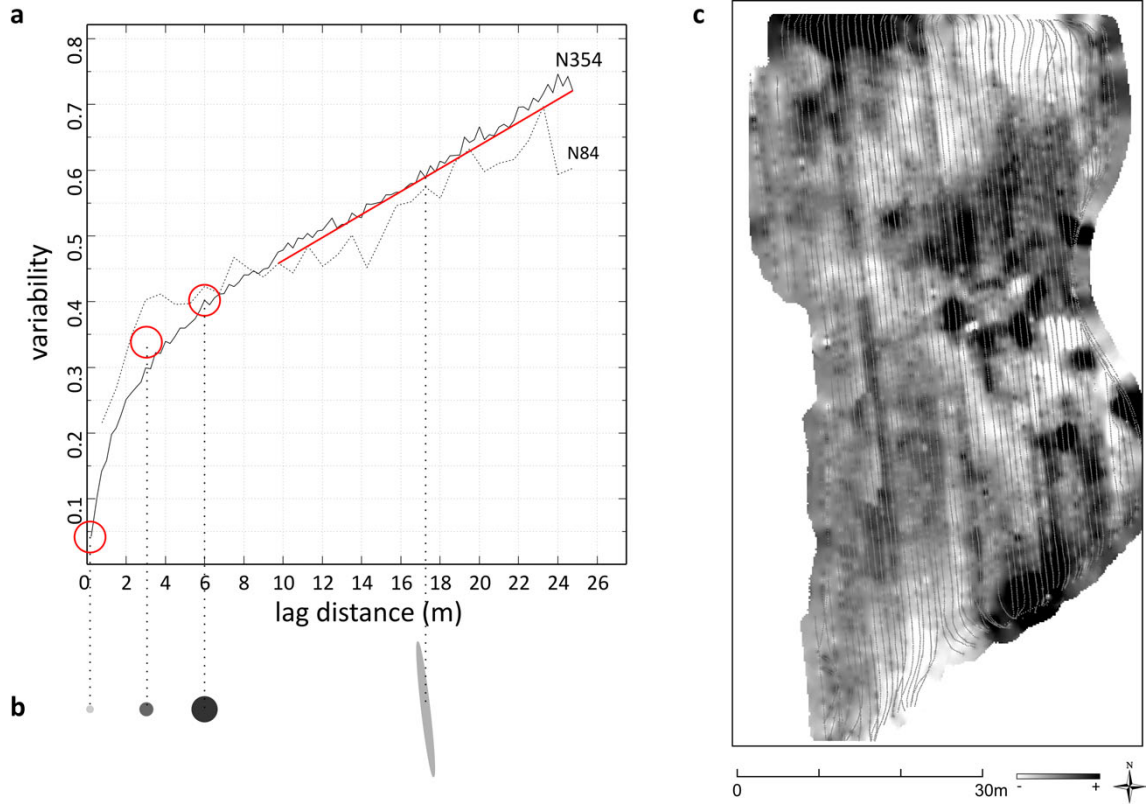


Figure 2.8: Variogram analysis a) experimental variogram with in red the interpretation of the main features b) visual representation of the interpretation of the variogram c) visual representation of the the interpolated data and of the acquisition points used for the computation of the experimental variogram.

$$r_p = \frac{\sum_1^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_1^n (x_i - \bar{x})^2 \sum_1^n (y_i - \bar{y})^2}} \quad (2.5)$$

The correlation can be graphically represented by a scattered plot where each variable is displayed on a different axis (Figure 2.9a). When the relation between variables is linear, a regression can be computed and a mathematical function of the relation between variables expressed. An experimental cross-variogram can also be computed (Figure 2.9b). It compares the variability of pairs of points for both variables. It represents the variation of the correlation with scale. Figures 2.9b shows a low correlation of around 50% for short scales ($\leq 2\text{m}$) and a higher correlation of around 85% for large scales ($\geq 4\text{m}$). It means that the differences between the datasets in Figures 2.9c and 2.9d will be more visible at short scales. Finally, correlation maps can be generated. The correlation coefficient is then computed in a moving window (Figure 2.9e).

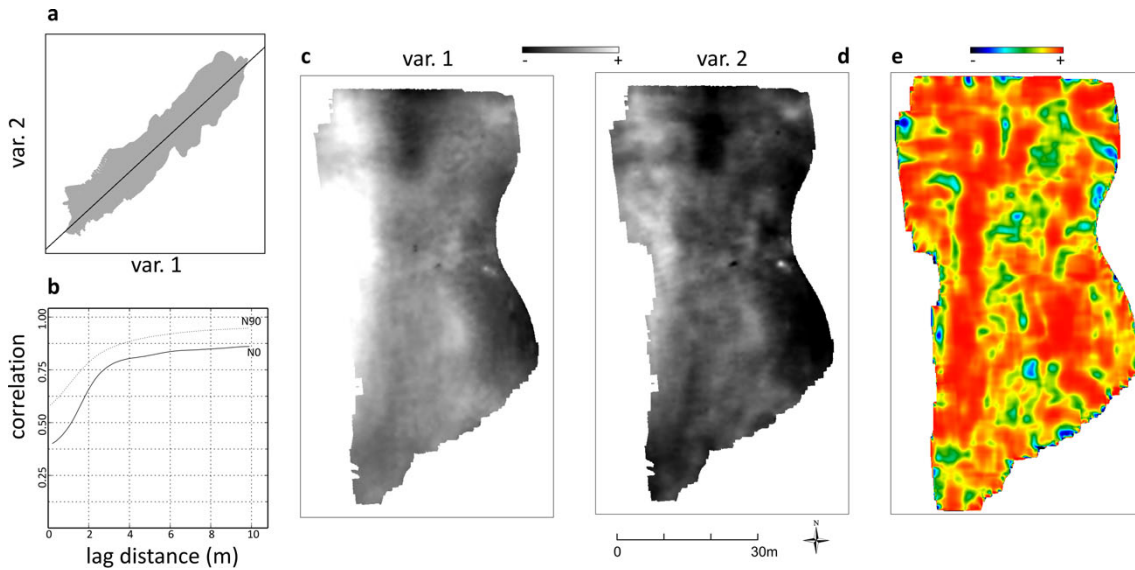


Figure 2.9: Correlation analysis a) scatter plot b) cross-variogram c) spatial representation of variable 1 d) spatial representation of variable 2 e) correlation map of variables 1 and 2 computed in a moving window. High correlation areas are in red, low correlation areas in blue.

2.3.2 Processing

Once the acquisition noise and the identified signal are characterised, the data can be processed. The objectives of this part are to (1) remove the identified acquisition noise (2) enhance the signal associated to the archaeological objectives (3) combine the available data using a defined strategy. The sequence of processing will depend on the used method, on the conditions during the acquisition of the data and on the archaeological objectives. The processing options and approaches are diverse. Nevertheless, the strategy of processing is common to all signal processing fields and can be described in generic terms as in section 2.1.2 of the summary.

The global strategy used for the processing of the data is described in this section. The specific approaches used during the research will be described in the chapters dedicated to the case studies.

2.3.2.1 Removing the acquisition noise

The acquisition noise can be defined as the variations in the data due to a change in the conditions of acquisition or inherent to the used technology. The sources of this change can be numerous and include a change of operator, of battery, rainfalls, breaks during the survey, change in the relative position between the sensors and the ground, speed of acquisition, positioning parameters, the proximity of interference

sources and so on. It can also include the screening of the information due to elements on or above the surface of exploration as metallic contamination, electric pylons or fences.

These change factors will appear in the data as (1) spikes or values out of range, (2) a grid effect where each unit of exploration or group of units appear in a different global range, (3) a higher continuity in the direction of acquisition or line effect and (4) problems in the alignment of features due to positioning problems. Examples of acquisition problems and how to solve them are well described in literature (Ciminale and Loddo, 2001; Ernenwein and Kvamme, 2008).

In Figure 2.10a, the raw data of a magnetic survey are presented. Metallic elements as an electric pylon and a metallic fence screen the information of interest near them. They were removed before the processing. The survey was conducted in two days which appears in the data as two different background mean value. The grid effect was removed subtracting the mean value of each grid of acquisition (Figure 2.10b). The differences between the sensors are highlighted by a line effect in the direction of the acquisition. It was removed subtracting the mean of each acquired line. For the calculation of the mean, a threshold was applied on the values in order to exclude outliers such as metals scattered on the surface (Figure 2.10c).

One specific tool was used on several datasets during the research and is detailed here. Random and spatially continuous noise can be removed using factorial kriging (Bourges et al., 2012; Tamba, 2012). It consists of the separation of spatial components present in the data and identified in the experimental variogram. It includes (1) the computation of the trend of the data which represent the large scale variations (2) the computation and variographic analysis of the residuals, difference between the initial data and the trend (3) the interpolation of the residuals based on the variographic analysis and selecting the spatial components to be discarded and (4) the sum of the interpolated residuals to the trend to produce the final filtered data. The final result of the sequence is illustrated in Figure 2.11. The variogram analysis of Figure 2.8 gave the main spatial elements present in the data. For the interpolation of the data, the first and the last structures of the model are considered as acquisition noise and the two mid-scale spherical models as signal.

After removing what was defined as noise during the analysis of the signal, the pregnancy of the data has to be improved. Improving the pregnancy of the data

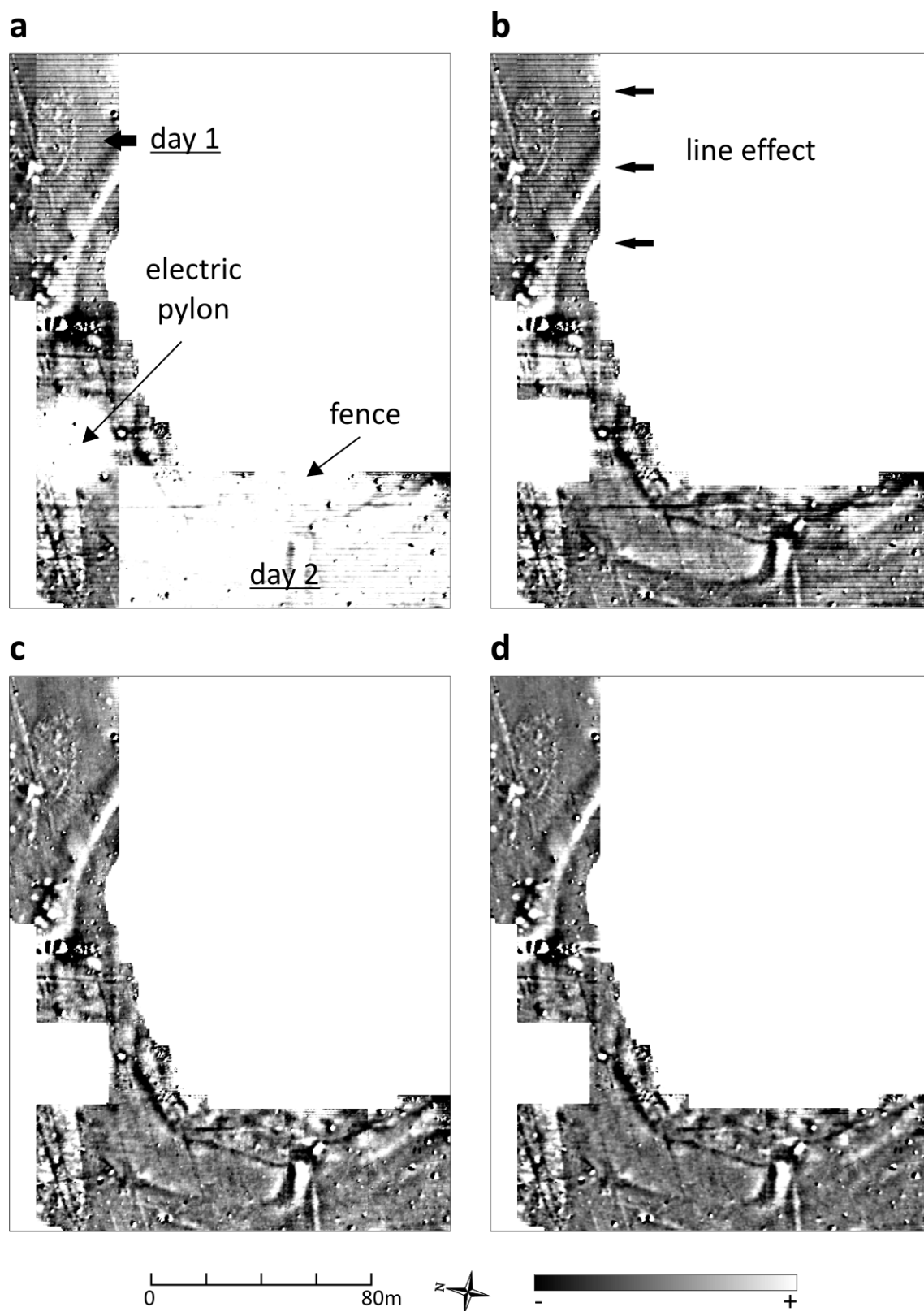


Figure 2.10: Processing of the acquisition noise a) raw data b) grid homogenisation c) line homogenisation d) smoothing and interpolation to a finer mesh.

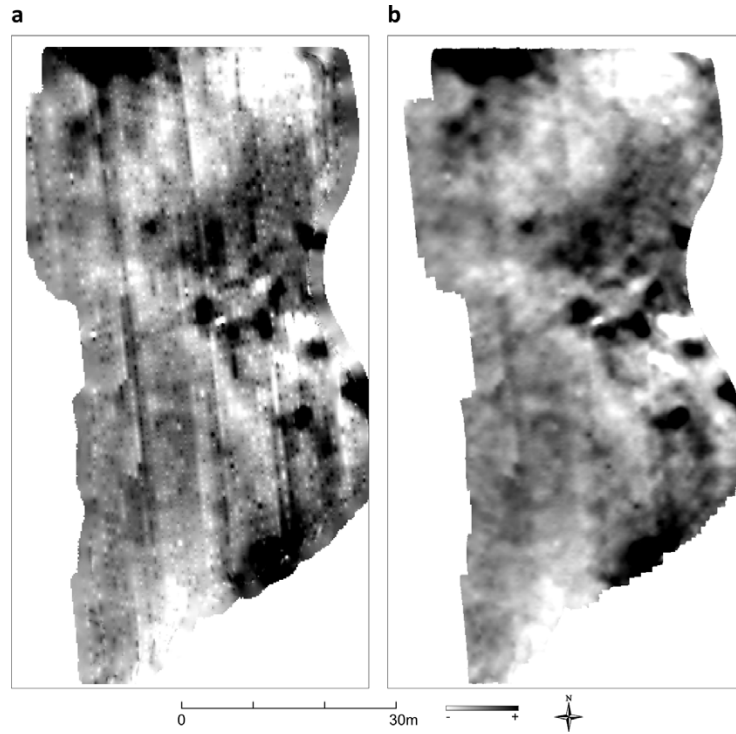


Figure 2.11: Factorial kriging a) interpolation of the raw data b) data after factorial kriging.

consists of adjusting the contrast between the features of interest and the background and can also be described as an enhancement of the visualisation.

2.3.2.2 *Enhancing the visualisation*

Enhancing the visualisation of the features of interest is best applied once the acquisition noise is removed. Before enhancing the signal, the part of the data that is of interest should be clearly defined. Commonly in archaeological geophysics the signal include large scale variations mostly related to geology and small scale variation that can be related to the archaeological features of interest.

The large scale geological variations, although containing valuable information, can mask the features of interest or decrease their contrast. Part of the enhancement of the signal will then consist of removing the large scale variations, or trend, in order to highlight the features of interest. This operation is also referred to as high pass by analogy to the data processing in the frequency domain.

The large scale variations can be extracted by calculating the mean or the average of the values in a moving window or by a local polynomial fit. With a polynomial fit approach, a polynomial of order n is used to fit the data in a moving window. The

size of the moving window is determined by the operator. A general rule should be that it includes a large scale object identified in the image. The second option requires more processing time but offers a higher flexibility on the parameters of processing. The result of this operation is then subtracted from the original data to produce the residual small scale variation data.

Figure 2.12 shows an example of removal of the large scale variation components of a dataset. The objective was the documentation of the urban mesh. The large scale variations present in the data did not allow to observe the more subtle variations related to walls. Removing the large scale variations helped enhancing them.

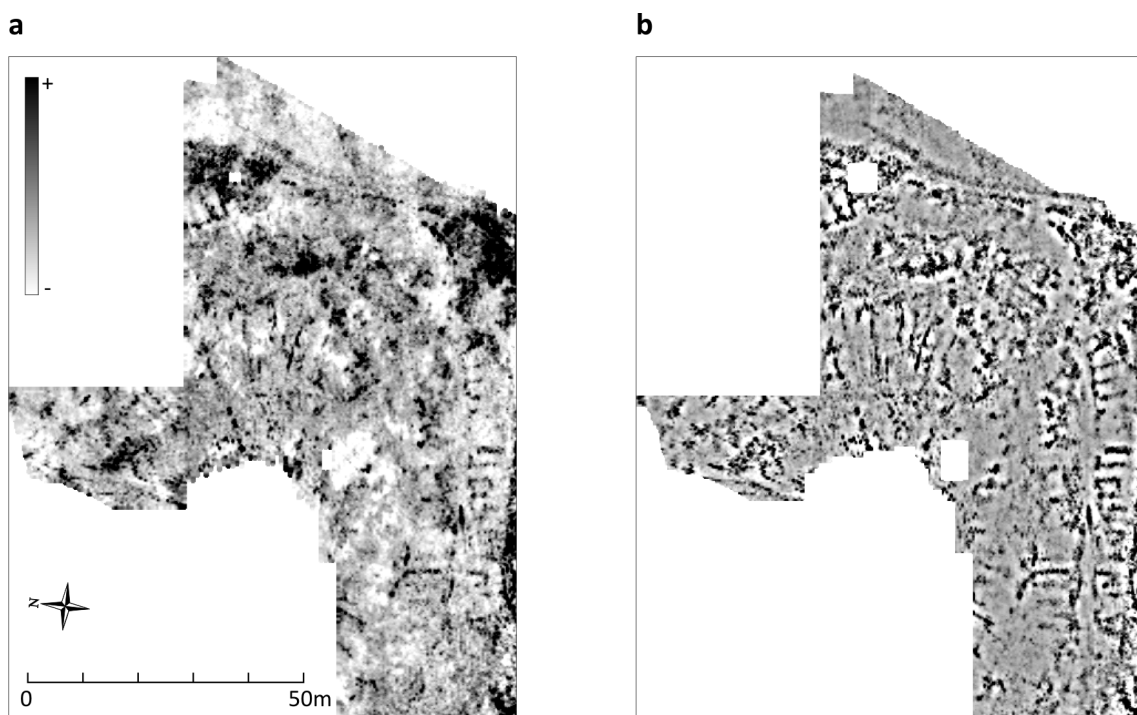


Figure 2.12: Enhancing the features of interest a) original data b) data after the removal of the large scale variations. The urban mesh appears more clearly.

With the enhancement of the features of interest and of small scale variations, residual noise that was not properly removed can also be enhanced. An additional step can then be applied in order to mask these variations that distract the observer from the main features. This step often consists of a smoothing of the data or low pass filtering using a moving average or median in a small moving window. The small moving window is defined to include the direct neighbours of the processed points.

With the acquisition noise removed, the data can be interpolated to a finer resolution (Figure 2.10d). The interpolation strategy can be chosen depending on the data

and on the objectives. It consists of selecting the number of points, their spatial distribution and their weight for the interpolation of the new values. This step can be applied to compensate the asymmetry of the resolution of acquisition. It can also be applied as a previous step for the combination of several datasets as the combination requires all the data to be on the same support.

2.3.2.3 Combining the data

With only one method, the interpretation of the data can be limited. In order to increase the possibilities of interpretation, it can be suggested to apply several methods (Clay, 2001; Hesse, 1999).

Applying several technologies in a project provides with data of different nature with specific resolution, range and covered extension. A first approach for the combination of the data is to overlay the remarkable features of each method. Some data combinations as the combination with topographical information are necessary to the processing. They enable the visualisation of the data in their context and a correction of the geometry of the detected features. In some cases, more complex approaches are needed where the data have to be processed simultaneously in order to produce new information not retrievable from separate parallel analysis.

No systematic approach can be offered as the process should be guided by the archaeological objectives. Survey should be collected and combined as tools to document specific aspects of the archaeological objectives. Nevertheless systematic approaches are described in literature. Piro (Piro et al., 2000; Piro and Gabrielli, 2009) describes the methodology to integrate magnetic with other geophysical data. Kvamme (Kvamme, 2006) made a complete review of different possibilities of integrating data from arithmetical sums, to classification, including binary and geostatistical approaches.

The first common basic steps to the combination of geophysical data are (1) the normalisation of the data and (2) the interpolation on a common support. When combining data, the main preoccupation is to clearly define the geophysical or archaeological objectives. These objectives will determine the success of the operation in terms of usefulness. The combination of data should help to obtain complementary information and support the interpretation process.

2.3.3 Interpretation

The increase of the spatial resolution of the data and of the explored extensions generated higher expectations on semi-automatic interpretation and integration strategies (Paasche et al., 2013). Manual interpretation can no longer be the only option and semi-automatic strategies are being investigated for a faster detection, identification and extraction of selected patterns (Kvamme, 2013; Leckebusch et al., 2008). The term semi-automatic is used because the operator is required to set the parameters of the detection and to edit the final results. The limit between what is archaeologically relevant and what is not still requires at some stage a subjective decision taken by the operator. The step of assigning an archaeological meaning to geophysical processes is a major step of the interpretation. It is when the data are transformed in archaeological information and related to the objectives of the survey. It also raises the question of the validity and validation of the results.

2.3.3.1 *Feature identification*

In most of the archaeological geophysics projects only the relative values of the measured physical properties are considered. The relative values provide qualitative information on the nature of the anomaly. For example, a trench filled with sediments will have a specific geophysical signature. The qualitative approach is completed with a geometrical description of the features.

As it is the geometry of the structures that will enable the interpretation of the data, it is important to stress out once again the importance of defining adequately the extension to cover and the resolution of acquisition (section 2.2.2). The identification of the geometry of the underlying structures will also depend on their state of conservation. The identified features were described in this research using a vectorial representation of the data combining the geometry and the qualitative information.

2.3.3.2 *Vectorisation*

The vectorisation can be manual or semi-automatic (Schmidt and Tsetskhladze, 2013). A manual vectorisation implies the use of vectorial drawing tools and a user-dependent interpretation. A semi-automatic approach will enable a systematic process of the data but will require an editing that once again will be user dependent.

As the identification of the features of interest is subjective, the operator is required to edit the results of the processing in order to highlight the features identified as of interest. The vectorial approach transforms complex images in simpler objects that can be integrated in archaeological environments. The isolated vectors can be assigned qualitative or quantitative data in addition to their geometrical characteristics.

2.3.3.3 Meaning assignment

Simple vectors can help focusing the attention on the features of interest but also require a description or the assignment of a meaning. The meaning assignment is usually performed in two steps. The first step consists of the geophysical description of the feature in terms of geometry, range and sign. The second step is the assignment of an archaeological meaning.

The operator is assigning an archaeological meaning to a geophysical representation. The second step is not always possible and its validity will depend on the complementary data available. Figure 2.13 shows an example of the vectorial interpretation of magnetic data. The features identified in the data were classified and labelled. The classification was based on the geophysical signature of the features and an archaeological meaning was assigned to each class.

At this stage, geophysical anomalies are transformed into archaeological features. The main risks are to be too cautious and to only interpret the most evident anomalies and to over-interpret. Too detailed information on individual anomalies can also be confusing (David et al., 2008) and synthetic representation of the data presenting group of anomalies as structures are encouraged.

2.3.3.4 Validation

The main tools for the validation of an interpretation are excavation results and the application of complementary methods. Both data are determinant for the interpretation. As they are often acquired in subsequent phases, a feedback from the archaeological team can enable a reassessment of the first interpretation. As a consequence, the validation of an interpretation requires communication and collaboration between archaeological and geophysical teams. An interpretation is a dynamic output that can be adjusted as additional information is obtained.

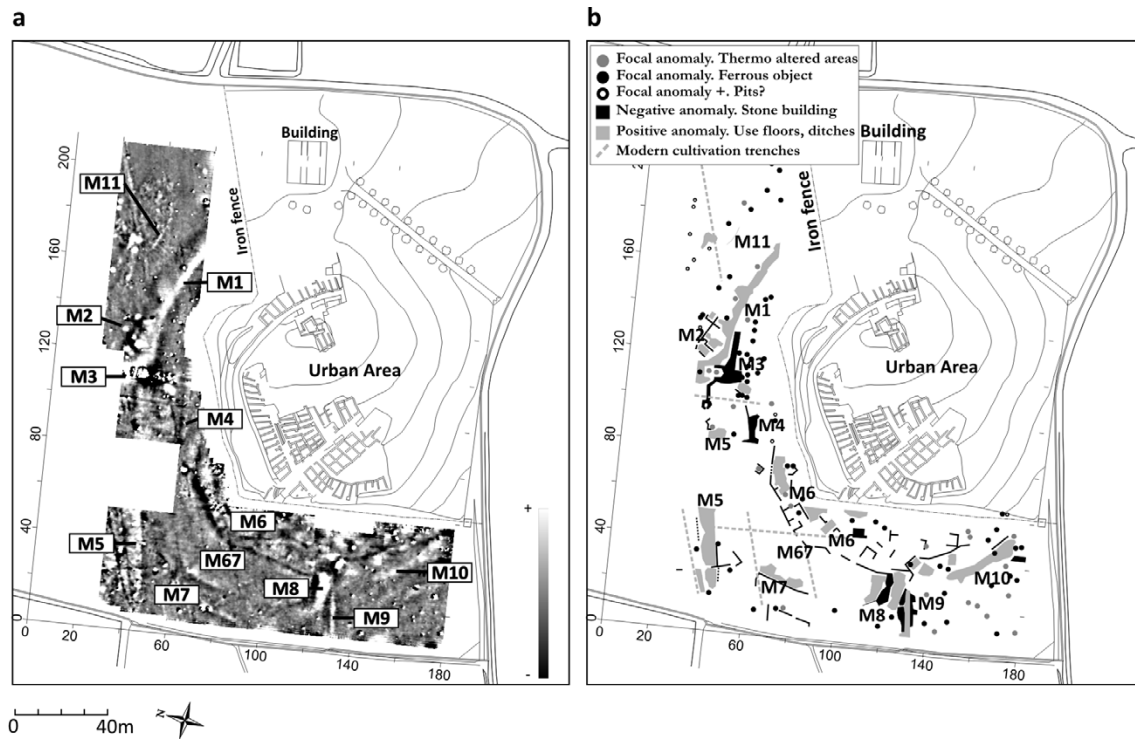


Figure 2.13: Meaning assignment a) magnetic data b) vectorial interpretation

The two main barriers of communication in understanding geophysics can be described as follows: (1) what the sensor sees is not what the eye sees (Ernenwein and Hargrave, 2009) (2) what the surveyor interprets as anthropogenic can be of another nature (Dirix et al., 2013). The validation of an interpretation is then a complex task that cannot only rely on excavation results and helps stressing out once again the importance of multi-method and transdisciplinary projects.

The transformation phase ends with the interpretation of the data. The description of all the previous steps must then be transmitted to the end-user of the results.

2.4 Finalisation

The main objectives of the finalisation phase are to ensure the understanding of the main results of the survey and the repeatability and posterior re-use of the data (Schmidt and Ernenwein, 2011). The first part is relative to the discourse and the presentation of the results. The second part concerns the documentation of the parameters of prospection and the archiving of the data. In other terms, the finalisation of a project includes a communication part that will depend on the involved parties and a technical part defined by guidelines and best practice documents.

After describing the main current in learning theory, the main elements used for the documentation of a project are revised and strategies to enable a higher control of the information by the end-user are discussed. The objective is to offer possibilities of improving the transmission of the information for a better understanding and integration of archaeological geophysics.

2.4.1 Contributions of learning theory

Learning theory is a science developed to improve the transfer and assimilation of the information. With the spreading of digital media, new approaches were introduced where the importance of the environment is growing over contents. The documentation of a project is evaluated using the different currents of the learning theory. Tools are defined in order to improve the transmission of the information.

2.4.1.1 Currents

This section is adapted from Guerrero and Flores (Guerrero and Flores, 2009). The four main currents in learning theory are (1) the behaviourist, (2) the cognitive, (3) the constructivist, and (4) the connective. The behaviourist approach gives a higher importance to the contents of the shared information. The connective approach gives a higher importance to the environment where the information is shared. The main characteristics of the four approaches are described in Figure 2.14.

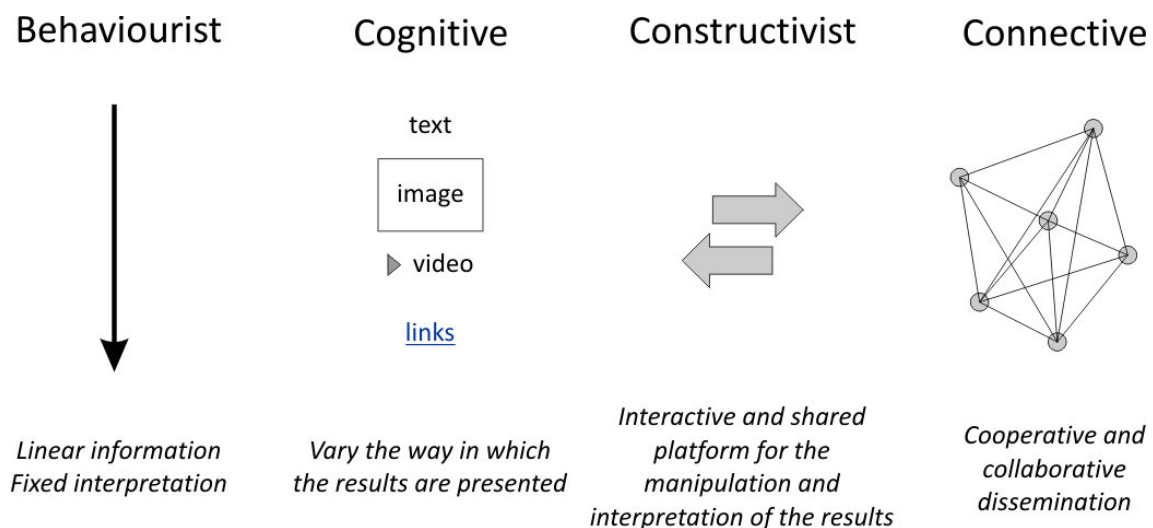


Figure 2.14: Main Learning Theory currents

In a behaviourist approach, the information is presented linearly and hierarchically from the simplest to the most complex. The interpretation is fixed and the emphasis

is given on the memorisation of the information.

With a cognitive approach, several ways of presenting the information are offered simultaneously. Strategies are implemented to attract the attention on specific points. The assimilation of the information is guided and supported by a follow-up.

With a constructivist approach, the end-user is given the tools to build his own information. The environment gain importance over the contents. The information is transmitted through a shared interactive platform. Access to support on the environment and complementary information is given without any imposed sequence.

With a connective approach, the main objective is to promote feedback and the actualization of the information. It is based on a cooperative and collaborative dissemination through groups of discussion and networks. The understating of the information is then a continuous process and not a fixed product.

2.4.1.2 Tools

In order to enable an active participation of the end-user, the interactivity of the access to the information is a key factor. It can be implemented at three main levels: (1) within the report of a project (2) in additional graphic material (3) in the transmission of the results. Interactivity gives the control to the end-user but is best used by users with a basic knowledge of the subject (Betrancourt, 2005). It is related to the cognitive approach of offering several formats of presenting the results. The links between the different formats should then be enabled. Within the reports, possibilities to explore the subject through links and references can be offered. Additional graphical material, whether static or animated, should be offered in relation to the main text and with the possibility to freely navigate through the information.

Finally, when the results are transmitted through a shared platform, the end-user is enabled to act directly on the results. He then controls the representation of the results and can modify the interpretation based on his knowledge of the project. GIS and Web-GIS platforms are now commonly considered as tools for research and education (Gläß er et al., 2010; Rink et al., 2012). They can be 2D or 3D and enable a constructivist approach.

2.4.2 Documentation

The documentation of geophysical survey has as main vector of communication the grey literature. The components of grey literature are defined by standards. Nevertheless, the actors of archaeological geophysics are free to present the results as they wish as few or no official standards exist outside the United Kingdom.

The learning theory approach states that the understanding of the results is improved when several simultaneous possibilities of communication are offered (Guerero and Flores, 2009; Moles, 1978)). In archaeological geophysics, the results can be presented, in a report, in a graphical report, as an animated sequence and as vectorial and raster information. The creation of the material, in addition to helping communication, also enables a verification of the consistency of the results.

The other key factor developed here is the relation between the text and the images. For each format, the contiguity between verbal, graphical and, for animated sequences, oral information, should be ensured. It favours a better understanding of the results by the end-user (Moles, 1978).

The formats of communication described here are (1) the report (2) the graphical report (3) the animated sequence (4) files and models. Their relation and highlights are described in Figure 2.15. The documentation of projects will be illustrated on the case studies in Chapters 3, 4 and 5.

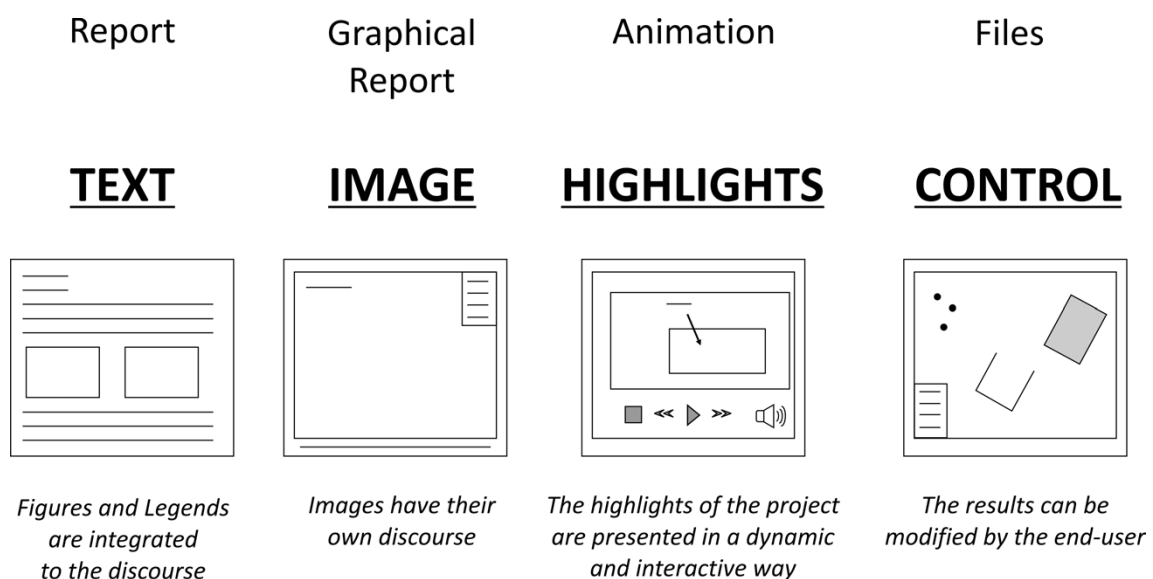


Figure 2.15: Relations between text and image and formats of transmission of the information

2.4.2.1 Report

The report is the most common and basic vector of transmission of the results. It is often preceded by an interim report delivered as a first visualisation of the results during the interpretation of the data. It is considered as grey literature and is the main source of information when similar case studies are needed. Some specifications are given in the English Heritage Guidelines (David et al., 2008). The report should include the metadata of the project as described in the ADS Guide to good practice for Geophysical Data in Archaeology (Schmidt and Ernenwein, 2011) and presented in Table 2.2. The metadata of a project contain all the information that is relative to the acquisition and processing of the data. They can be associated to the global project or to the methods applied. They help referencing and controlling the quality of the project.

Project	GPR	Magnetic	EMI
Dates of execution	System	System	System
Surveyors	Antennas	Sensors	Sensors
Province	Frequency	Number of sensors	Number of receivers
Municipality	Number of antennas	Vertical separation between sensors	Configuration of transmitter
Land use	Distance between antennas	Horizontal separation between sensors	Configuration of receiver
Ground conditions	Distance between profiles	Distance between profiles	Distance to receiver
Ground cover	Distance between measurements	Distance between measurements	Distance between profiles
Geology	Time window	Covered area	Distance between measurements
	Samples per trace		Covered area
	Covered area		

Table 2.2: Example of metadata for the documentation of an archaeological geophysics project

The report gives the information on the project and should contain the following sections: (1) a one page summary with the basic characteristics of the project and the main results (2) the objectives and a description of the context (3) a description of the methodology (4) a description of the acquisition parameters (5) a description of the processing (6) a description of the results and their interpretation (7) a conclusion (8) a description of the available additional material.

The limits of the methods and of the interpretation should always be clearly stated in order to avoid problems of communication. A balance should be found between a cautious approach where the results are mainly described as geophysical objects and a timorous one where only definitive archaeological conclusions are stated.

The figures included in the report should be synthetic figures supported by the text. The images are then a visual support to the description of the project. An alternative format of presentation of the result can be offered as a graphical report.

In both cases, images should always follow the standards of the field. In the case of archaeological geophysics this means that they should be accompanied by a metric scale, the indication of the North, the colour scale used for the representation and the legend of additional material.

2.4.2.2 Graphical report

The objective of a graphical report is to unload the report of the graphical raw material and to describe the results of the project graphically. The sequence of the document is similar to the report. It can include: (1) a graphical abstract (2) the localisation of the covered areas (3) selected processed data (4) alternative visualisation including contour lines or different colour scales (5) additional processes as coefficient of variation or gradient maps (6) the overlay of the result with the interpretation (7) the vectorial interpretation (8) possible appendices with the full sequence of results and raw data.

The graphical report offers large and full images of the results. It has an independent scope but can be referred to in the main report. It offers an alternative static presentation of the results. Additional text and highlights should be added for the understanding of the displays. The graphical report can be complemented by animated sequence.

2.4.2.3 Animated sequences

Animated sequences offer the possibility of giving a short and dynamic version of the presentation of the results. They give the highlights of the project. Some basic concepts can be followed when creating animated material in order to optimize the transmission of the results.

The pace of the animated should be controlled by the end-user (Betrancourt, 2005). With the control of the animation, the end-user can choose to pause, replay, skip, rewind the material and enables a better understanding of the results.

The images should be modified using vectorial information and text (Münzer et al., 2009). With raw images, the central information of the images can be missed. This central information should be reinforced using arrows or overlays and textual information.

The written textual information should also be provided in a vocal format. Textual information in animated sequences is better assimilated when provided both in written and vocal formats (Betrancourt, 2005).

2.4.2.4 Files and models

The last format of transmission presented is the transmission through vectorial and raster information that can be integrated in an interactive model. The model can include georeferenced files of the results and of the interpretation. The vectorial information can be associated to tables of properties as geophysical characteristics, depth of the structures, dimensions and assigned function. This format enables a full control of the result by the end-user.

Once the interactive environment fixed, it can be supplied with any new relevant information with a spatial representation. It can then be used for subsequent communication related to the project, whether it is for research or for education (Gläß er et al., 2010).

Files can have complex formats and their transmission needs further specifications that are developed in the next section.

2.4.3 Files

The delivery of a digital archive of the project is defined in best practice guidelines. The included data can be divided in two main categories: (1) regularly spaced and (2) scattered. In GIS environments they correspond to raster and vectorial formats. The formats, the metadata and the archiving of the files are discussed here.

Regarding the presented research applied on the case studies, the produced files were described in the corresponding sections and listed in Appendix F. They cannot be directly consulted. Only the animated sequence and the GIS or 3D models are provided as additional material in the attached CD.

2.4.3.1 Formats

Regarding the formats, open format should be preferred to proprietary ones. Open format enable interoperability and posterior re-use of the data. Proprietary formats depend of specific software and software version and the possibility to explore the

files might be lost. Communicating in accorded formats allows the end-user to explore the data and a correct archiving.

Regularly spaced data can be stored in two main formats: (1) ASCII coded files (2) generic binary files.

1. In ASCII files, the data are organized in columns or matrix. The geometry of the data is included within the files through the coordinates stored in columns or through a header that includes the coordinates of the origin, the number of samples in each direction and the distance between samples in each direction. ASCII files stored in columns enable adding columns of properties to the coordinates. The main advantages of ASCII files are that they can be opened with text editors. The inconvenient is that the volume of the files is very large and that they can be difficult to manage when dealing with large extensions.
2. Binary files present reduced volumes. They need specific tools to be explored. The standards for the storage of the geometrical information can vary, be incomplete or inexistent. When working in GIS environment two main visualisation options exist: (1) 1-band rasters that contain the values of the property to be visualised (2) 3-bands rasters where the property is converted in a RGB scale. The inconvenient of the second option is that the original information is lost.

The scattered data refer to data that are not regularly spaced. Each point need to be located by individual coordinates. They are usually stored in ASCII coded format. Only the column version is then possible. Additional columns can be used to store attributes. Other formats are used in 3D or vectorial environments.

In GIS environments, the most used vectorial format is the shapefile format from ESRI. It is a proprietary format but with an open code. It enables storing the geometry of the information in points, lines or polygons. Attributes can be added to each feature of the file. The files can include the projection information of the used reference system. The shapefile format should be preferred to other proprietary formats as dxf from autodesk. These are not version stable and do not allow informing the created data with attributes.

2.4.3.2 Metadata and archiving

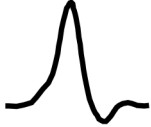
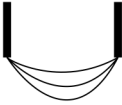
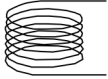
The archives should include the complete documentation including the metadata, the raw and the processed data in an open format and the interpretation files in a vectorial format. The data should be georeferenced in order to be able to locate the results and the projection used clearly and fully stated.

When using a platform where all the metadata, cartographic material and grey literature are gathered, a direct assessment of the quality of the data and of their impact is possible. Furthermore a control of the parameters of the project can then be performed by a third entity. The most advanced example of recipient currently in use is the one created by the ADS and the English Heritage. All entities operating in archaeological geophysics can register to a database and declare their on-going project through a common protocol. It enables a standardised approach of the projects and ensures that the basic requirements are fulfilled.

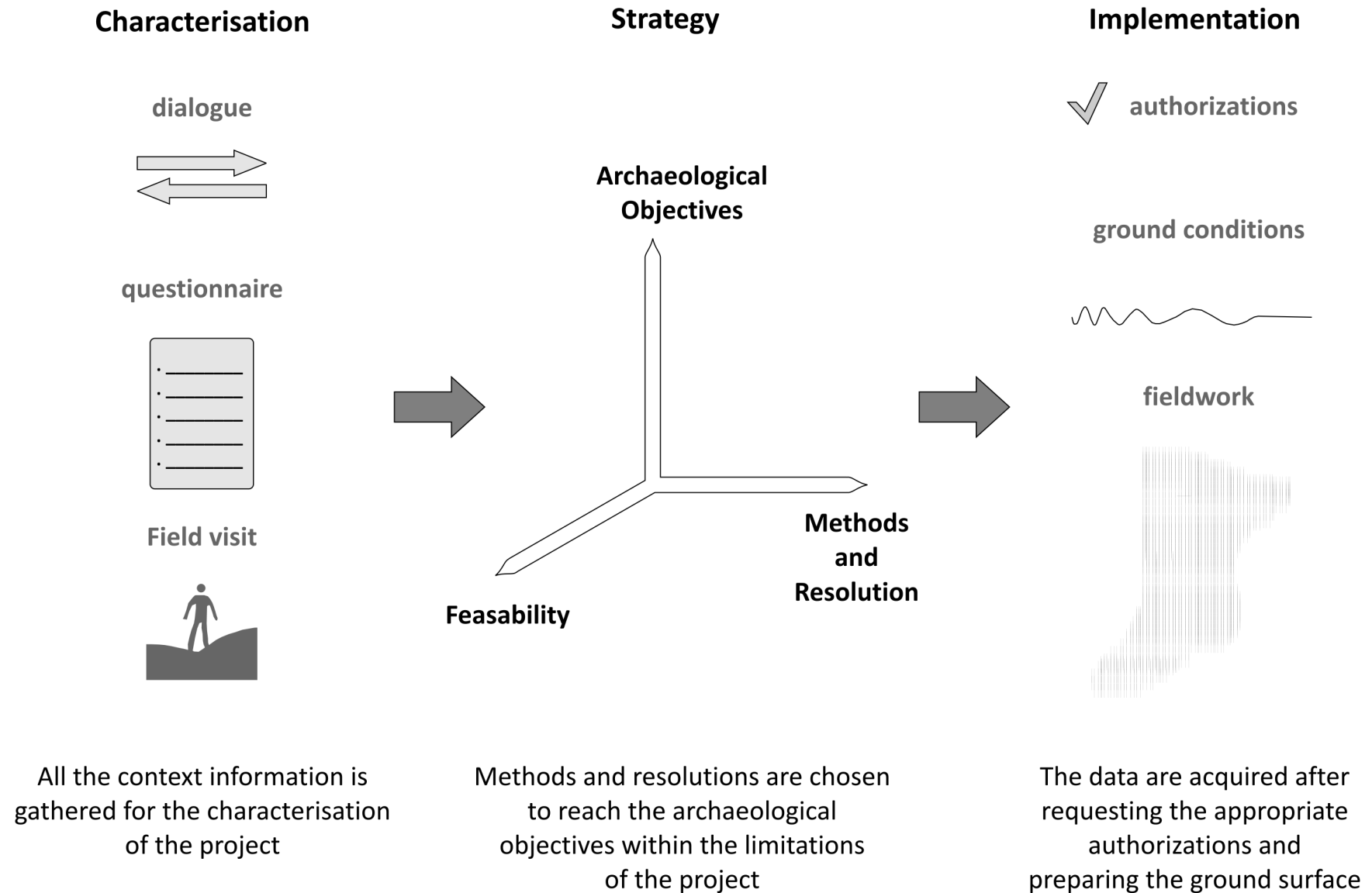
In most of the countries, the public frame consists of an authorisation and of the delivery of a report. The recipient will then depend on the operator. It must guarantee the registration of the main parameters of the project (metadata) and the geo-localisation of the survey.

2.5 Graphical abstract

2.1 Main methods used in archaeological geophysics

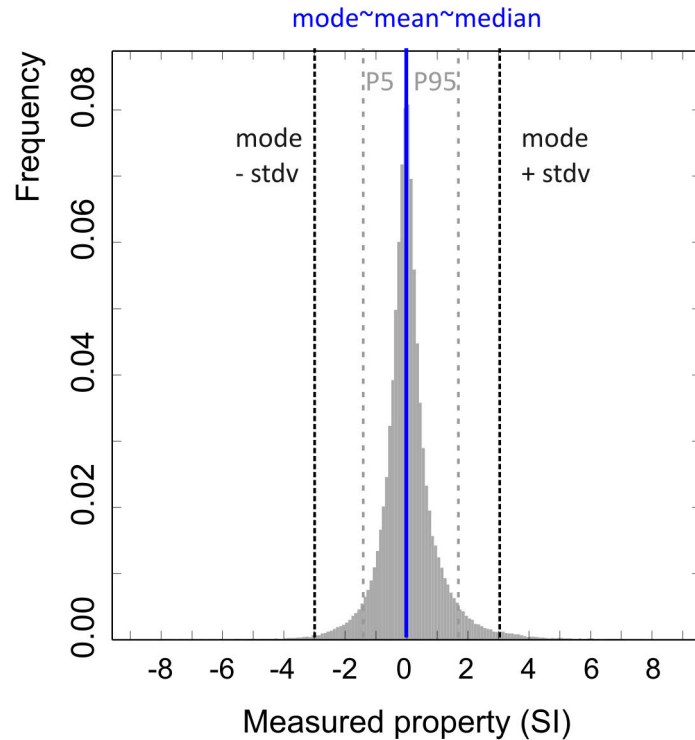
	magnetic	electric	electromagnetic	gpr
<u>Method</u>				
<i>Main characteristics</i>				
<u>In one word</u>	fast	stable	landscape	3D
		<i>frequency</i> 		
		50-500 Hz equipotentials	10-100 kHz induction	10-1000 MHz wave
<u>Measured property</u>	magnetisation	resistivity	magnetic susceptibility electric conductivity	dielectric permittivity
<u>Main application</u>	thermo-alterations soil movements	constructive structures and cavities	clay contents metals	constructive structures and cavities
<i>Importance of main elements to consider for the design of a project</i>				
<u>Ground conditions</u>	+++	+	++	+++
<u>Processing</u>	+	++	++	+++
<u>Water content</u>	+	+++	++	+++
<u>Cost</u>	+	+++	++	+++

2.2 Designing a project



2.3 Exploratory analysis

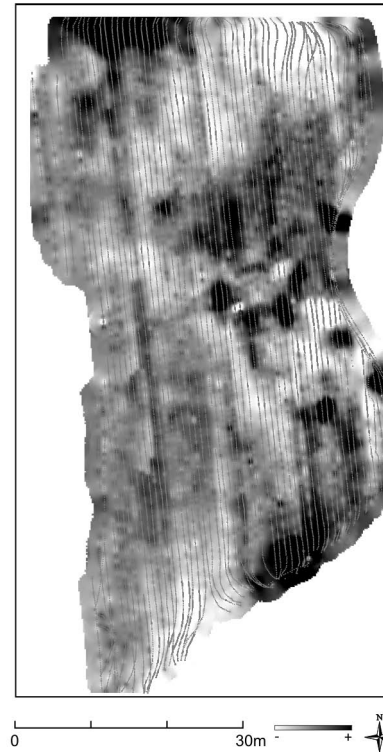
Descriptive statistics



Min	Max	Average	Mode	Stdv	Mode - stdv	Mode + stdv
9.33	33.55	0.08	0.00	3.01	-3.01	3.01
P5	P50 / median	P95				
-1.44	0.01	1.84				

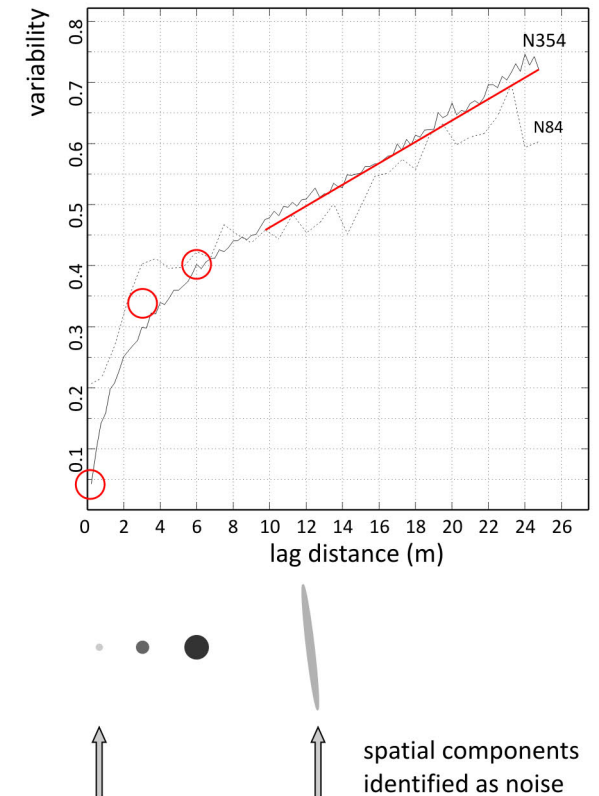
Statistics and histograms help understanding the numeric distribution of the data

Spatial representation



A first visual assessment gives information on quality, contrast and main results

Spatial characterisation

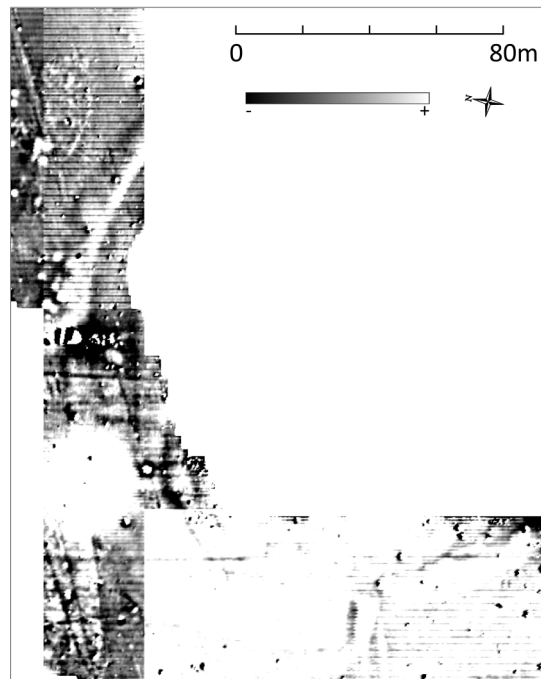


The experimental variogram is used for the characterisation of the main spatial components present in the data

2.4 From a geophysical representation to archaeological features

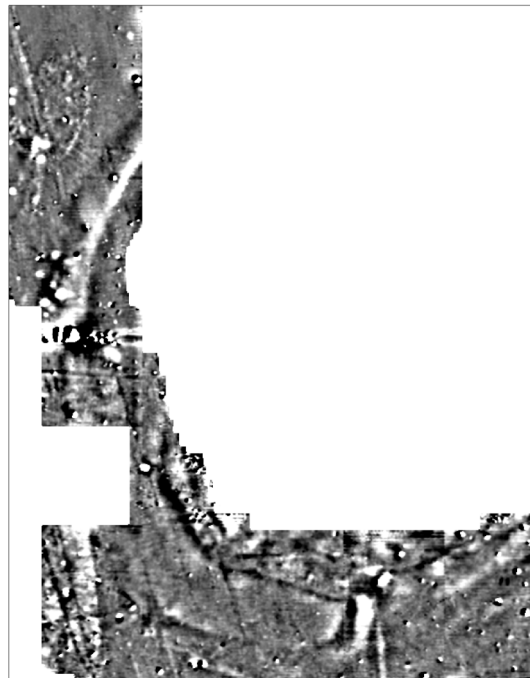


Raw data



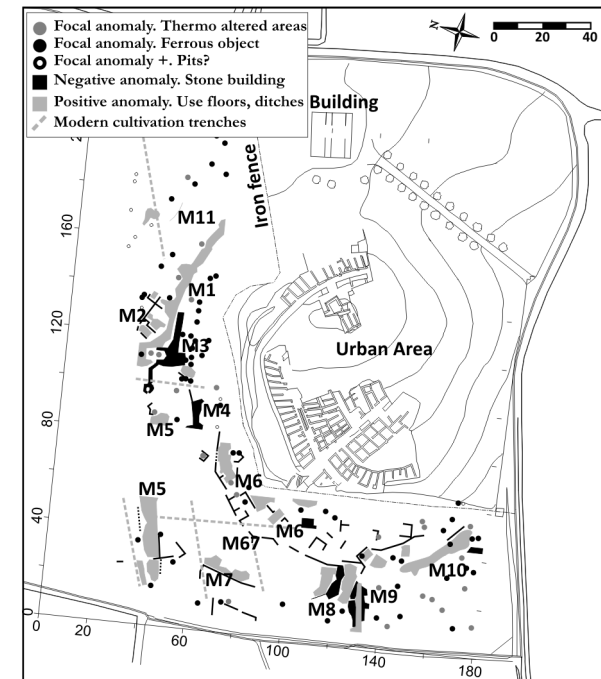
After fieldwork, raw data contain overlaid information

Processed data



The processing removes the acquisition noise and enhances the visualisation of the features of interest

Interpreted data



The interpretation gives an archaeological meaning to geophysical anomalies

2.5 Contributions of learning theory to the dissemination process

Contents

Environment



**There is no best approach to present the results.
Each approach serves a purpose and is more adapted to specific targets.**

Behaviourist	Cognitive	Constructivist	Connective
Metadata Summary Objectives Methodology Acquisition parameters Processing parameters Results Conclusions	text  ▶ video <u>links</u>	GIS and WEB-GIS solutions	Discussion groups Forums Mailing lists Networking
Report should contain standard information	The results are transmitted using several parallel formats	The exchange of information is favoured by common platforms	The contributions of the community to the interpretation of the results is enabled

Chapter 3

Case study 1: Assessing the state of preservation of a monumental artefact: Combined use of terrestrial laser scanner (TLS) and ground penetrating radar (GPR)

In this first case study, geophysical data are combined with a 3D surface model and the resultant outputs are presented. The chapter includes the description of the methodology that was applied for the production of an integrated interactive 3D model. The model is composed of a skin which represents the visible part of the monument and of an inner volume representing possible non-visible voids and fractures. The skin was produced using terrestrial laser scanner (TLS) technology and the inner volumes using GPR. The methodology was applied on a monumental structure of the opencast quarry of El Mèdol known as the needle.

The analysis and documentation of built heritage have known an incremental influence of non-destructive technologies. A large diversity of systems can give direct or indirect information on the structure and the state of preservation of a monument (Binda et al., 2000; McCann and Forde, 2001; Moropoulou et al., 2013) or on the impact of a restoration intervention (Binda et al., 1998; Pérez-Gracia et al., 2008). These investigations can help with the planning and monitoring of the restoration process. More specifically, the use of ground penetrating radar (GPR) in built heritage has been proven to be effective in combination with other technologies for the detection and mapping of cracks and voids (Leucci et al., 2007; Orlando and Slob, 2009) or for the three dimensional mapping of the internal structure of an object or monument (Binda et al., 2005; Cosentino et al., 2011)). In addition, the quick

development of three dimensional solutions is offering new possibilities for the systematic documentation and monitoring of built heritage at the same time as it raises new questions on how to manage this new information (Aliaga et al., 2011; Koller et al., 2009). The analysis of the state of conservation of a monument can require the description of its internal and external structures. Combined approaches have been proposed (Tapete et al., 2013; Teixidó et al., 2013) but few integrated models are presented.

3.1 Summary

Objectives

Creation of an integrated model of the needle of El Mèdol to give access to a cross-analysis of external and inner features and to a deeper understanding of its current state of preservation.

Applied strategy

A non-destructive exploration using ground penetrating radar (GPR) was applied on the monumental needle present in the quarry. The referencing and the visualisation of the results were done using a 3D acquisition of the surface of the monument using Terrestrial Laser Scanner (TLS).

Main results

Parts that suffer a higher exposition to possible weathering were identified through the analysis of properties of the 3D digital model. With the GPR results, additional information related to moisture contents were added in order to assess the possible degradation of these exposed area. In addition, possible voids and fissuring inside the needle were extracted from the GPR results and represented with the surface features. The relation between the identified exposed areas and the possible voids were then studied.

Main limitations

The use of a scaffolding for the acquisition of GPR data did not allow a full coverage of the monument and some areas were left unexplored. The geometry of the monument is complex, larger at its base than at its top and with torsion. The main

consequence is that there is a higher uncertainty on the results of the lower part.

Methods	Resolution (m)	Surface covered	System
Ground Penetrating Radar (GPR)	0.10x0.001x0.005	75 m2	GSSI SIR300 400MHz
	(1) correction of the position of the surface (2) background removal (3) gain: compensation of the attenuation with depth (4) migration: focusing of the signal (5) transformation to reflected energy		
Ground Penetrating Radar (GPR)	0.01x0.01	full coverage	Faro Focus 3D
	Processing (1) identification of common references (2) cloud alignment (3) noise filtering (4) removal of the objects not related to the project (5) georeferenciation (6) resampling of individual scanning sessions (7) merge (8) second resampling		
	Results		
Combined	(1) delimitation of areas with higher moisture contents (2) extraction of the main inner reflectors (3) extraction of cracks and protrusions (4) classification of the monument in separate sections (5) identification of possible voids associated to high moisture contents		

Table 3.1: Main characteristics and results of the survey of El Mèdol.

3.2 Field

3.2.1 The design of the strategy

3.2.1.1 The Roman quarry of El Mèdol

The Mèdol opencast quarry is part of the Archaeological Ensemble of Tarraco listed as world heritage by the UNESCO. It is located 5 kilometres north of the city of Tarragona, in the North-east of the iberic peninsula (Figure 3.1a). Within a global plan of the restoration of the archaeological ensemble, a specific project was set to complement the previous archaeological studies achieved on the site (Gutiérrez Garcia-M. 2009) and to improve the accessibility of the quarry to the public.

The most remarkable feature of the site is the monumental structure called the needle of around 17m height and 4m width at its base. It stands in the centre of the main extraction area and is known as "l'Agulla del Mèdol" (Figure 3.1b). Its purpose is not known although several theories are advanced as (1) its use for the

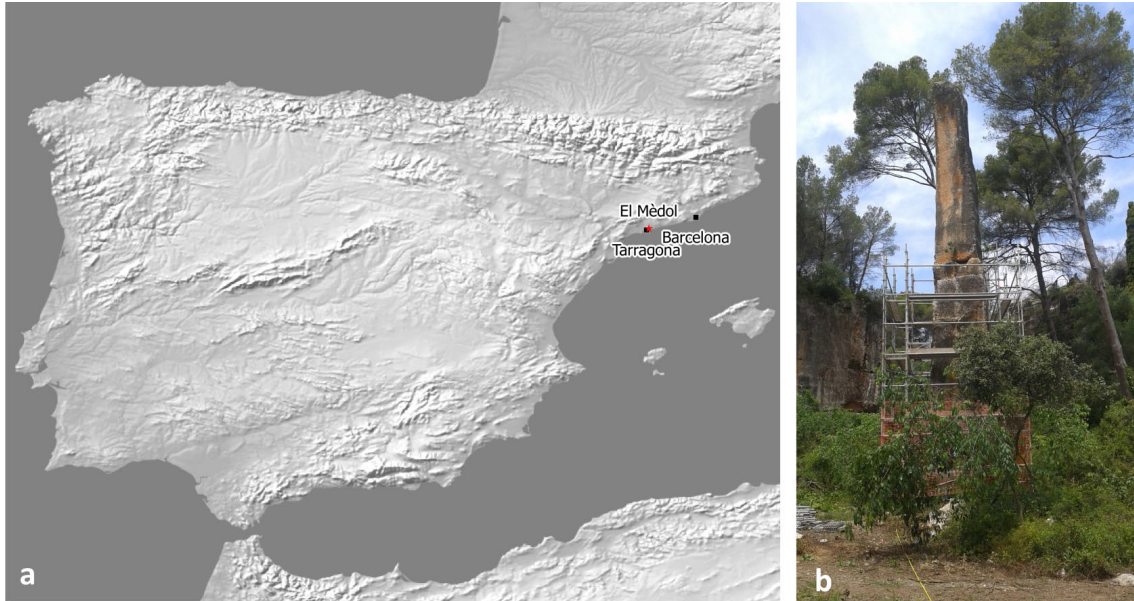


Figure 3.1: The open cast quarry of El Mèdol a) Location of the quarry b) Photograph of the needle.

calculation of the volume of extracted stones, (2) a marker of the original level before the start of the extraction, (3) a representation of the technical skills of the Romans or (4) an element related to the organization of the quarry (Gutiérrez Garcia-M. 2009)

The needle is composed of Miocene bioclastic limestone to sandy limestone belonging to the Tarragona Depositional Sequence. It presents a tilted interruption at a height of 16.5m above the sea level which is identified as a sedimentary break and referred to as hardground (Prada, 1995).

The opening of the area to the public included an exhaustive study of the needle.

3.2.1.2 Objectives of the project

The first objective of the research was to establish a methodology for the processing and the integration of the TLS and the GPR datasets. Once the data were integrated, properties that could help with the analysis of the relations between the external cracks and internal voids were determined. The final stage consisted of the qualitative and quantitative interpretation of the results and of the export in a format that could enable non-specialists to explore the results in an interactive way. The sequence of work is summarized in a diagram Figure 3.2.

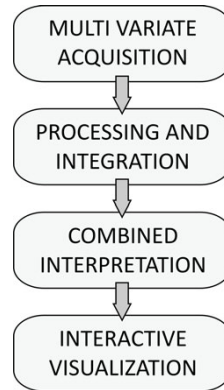


Figure 3.2: Workflow of the project.

3.2.1.3 *Applied methodology*

The acquisition of the TLS and the GPR data were operated separately. The GPR survey was designed taking into account the availability of the topographical model for the spatial integration of both datasets.

The design of the GPR survey had to offer a full coverage of the monument taking into account its variations in dimension. The strategy implemented had to offer a spatial resolution adapted to the identification of voids and cracks using an antenna with sufficient depth of penetration to cover the monument in all its depth.

GPR systems present several limitations. The resolution of the data varies with depth due to a conical radiation pattern of the signal (Figure 3.3a). The shape of the envelope of propagation varies with the explored media, the frequency and the used system (Verdonck, 2012). Furthermore, the signal is also strongly attenuated with depth and affected by spreading. The attenuation also depends on the media and the frequency. The needle presents a complex geometry with variable distances and orientations between faces, which would represent a variable maximal depth of penetration to reach. These limitations had to be considered for the design of the acquisition.

The main decision that was taken in order to optimize the resolution of the data was to explore the needle from its four faces. An exploration using only two faces would have had as a consequence a differentiated resolution for the data near the acquisition surfaces and the data near the opposite faces. It would also limit the spatial resolution of the data in the direction of propagation. The decision of using the four faces had then as objective to acquire data with optimized and comparable

resolutions in the vicinity of each face.

The other decisions relative to the design of the survey were choosing the central frequency of the system and the sampling of acquisition. The central frequency determined the maximal depth of penetration. Based on literature, an estimated velocity was used for the computation of the maximal depth of penetration of the signal. Using a velocity of 0.10m/ns, which is lower than the minimum value expected for the medium (Cassidy, 2009a), a central frequency of 400MHz and a time window of 40ns, the maximal depth of exploration would be of 2.00m. This value ensured a full exploration in depth of the monument when combining the results of the four faces.

3.2.1.4 Feasibility

The parameters of acquisition and processing were set considering the complex geometry of the monument, the objectives of the project and the economical restrictions. Because of the scaffolding and of the size of the structure to be explored, automated positioning systems as differential global positioning system or total station were discarded in favour of a manual positioning. This decision implied the use of the existing topographical model to position the geophysical data. Furthermore, the data relative to each face, although representing the same object, had different behaviours. A strategy had to be established in order to produce a combined interpretation of the four faces of the monument.

3.2.2 Data acquisition

3.2.2.1 Terrestrial laser scanner

The topographical information of the needle was extracted from a larger model of the quarry conducted by the private company Global Geomática. It was provided in a resolution specifically adapted to the processing of the GPR data.

A global model of the opencast quarry was produced using the Terrestrial Laser Scanner (TLS) Faro Focus 3D. The sequence of acquisition included the design of the survey, the positioning of external reference points, the calibration of the system and the scanning sessions. The survey was designed defining the locations of the different scanning sessions necessary to cover the target area. The total

number of scanning sessions was of 340. White spheres located at points of known absolute coordinates were used as external references for the cloud alignment and georeferencing of the scanning sessions (Barber and Mills, 2011). The calibration of the equipment was performed in order to ensure the stability of the data during the survey. It included the analysis of acquisition noise and of atmospheric conditions. The scanning sessions were performed from the upper boundaries of the quarry and from internal locations. The first and last session were done from the same station in order to be able to reduce the error on the coordinates. The scanning sessions were then processed in order to produce the final digital model.

3.2.2.2 Ground penetrating radar

A GPR survey was performed. The parameters of acquisition and processing were set considering the complex geometry of the monument, the objectives of the project and the economical restrictions.

The profiles were acquired in the horizontal direction with a separation between profiles of 0.10m and a 0.01m resolution in the profile direction. The distance between profiles was determined considering the time available for the survey, which was of one day. The full parameters of the acquisition are described in Table 2.

System	Model	Antenna type	Antenna frequency
GSSI	SIR 3000	monostatic	400MHz
Time window	Number of sample per trace	Spatial Resolution	Acquisition filter
40ns	512	0.01x0.10x0.004m	bandpass of 200-1000MHz

Table 3.2: Parameters of acquisition.

Due to the geometry of the antenna and to the attached encoder, each profile was acquired positioning the centre of the antenna at a fixed distance (0.25m) from the edge of each face. This fixed distance is the distance between the wheel of the encoder and the centre of the antenna (Figures 3.3b and 3.3c).

When the scaffolding was an obstacle, an offset had to be added or the profile had to be stopped. The vertical position of the antenna was set using measuring tapes fixed

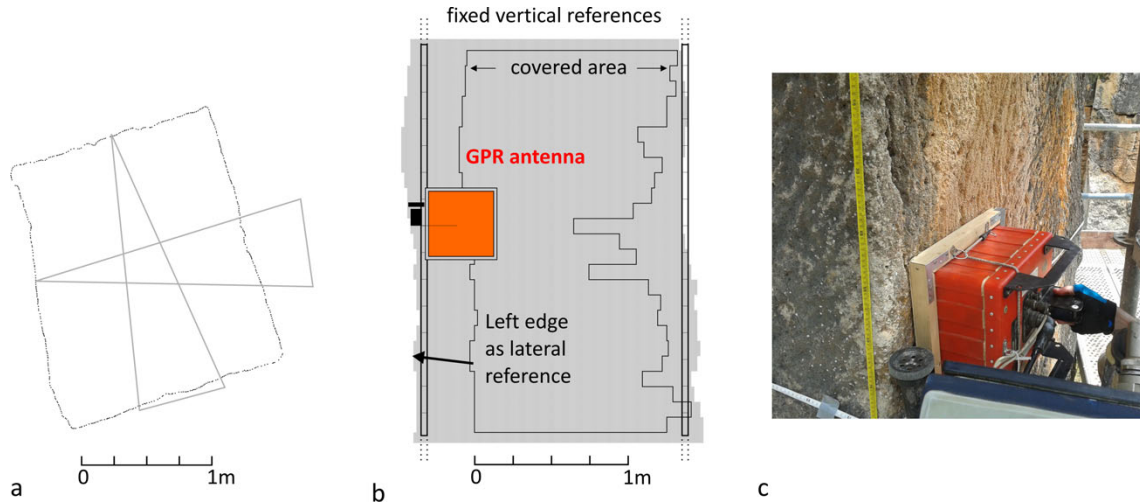


Figure 3.3: Characteristics of the GPR acquisition. a) Radiation pattern of the GPR signal b) Local references c) Photograph.

at the same elevation at the top of the monument. As the slope of the faces is in average lower than 3 degrees, the maximum vertical deviation between the vertical plane and the slope is of 0.02m which was considered negligible. The total extension covered by the acquisition was of 75 square meters and is displayed in Figure 3.4.

3.3 Data transformation

3.3.1 Individual processing

3.3.1.1 Terrestrial laser scanner

The processing included several steps. For each scanning session the workflow included (1) the identification of the spherical objects, (2) a cloud alignment in the local coordinates system, (3) a noise filtering, (4) the removal of objects not related to the project, (5) the georeferencing of the point clouds using the absolute coordinates of the external references and (6) the resampling of the point clouds to a lower density preserving a high density for the edges. The resampled and corrected scanning sessions were then merged into one dataset which required a second resampling in order to optimize data density in the overlapping areas and remove redundant information.

The data relative to the needle area were extracted with an average sampling of 0.01m for GPR data referencing and processing. They are presented in Figure 3.5. Each point of the model was characterised by its coordinates (X, Y, and Z) and by

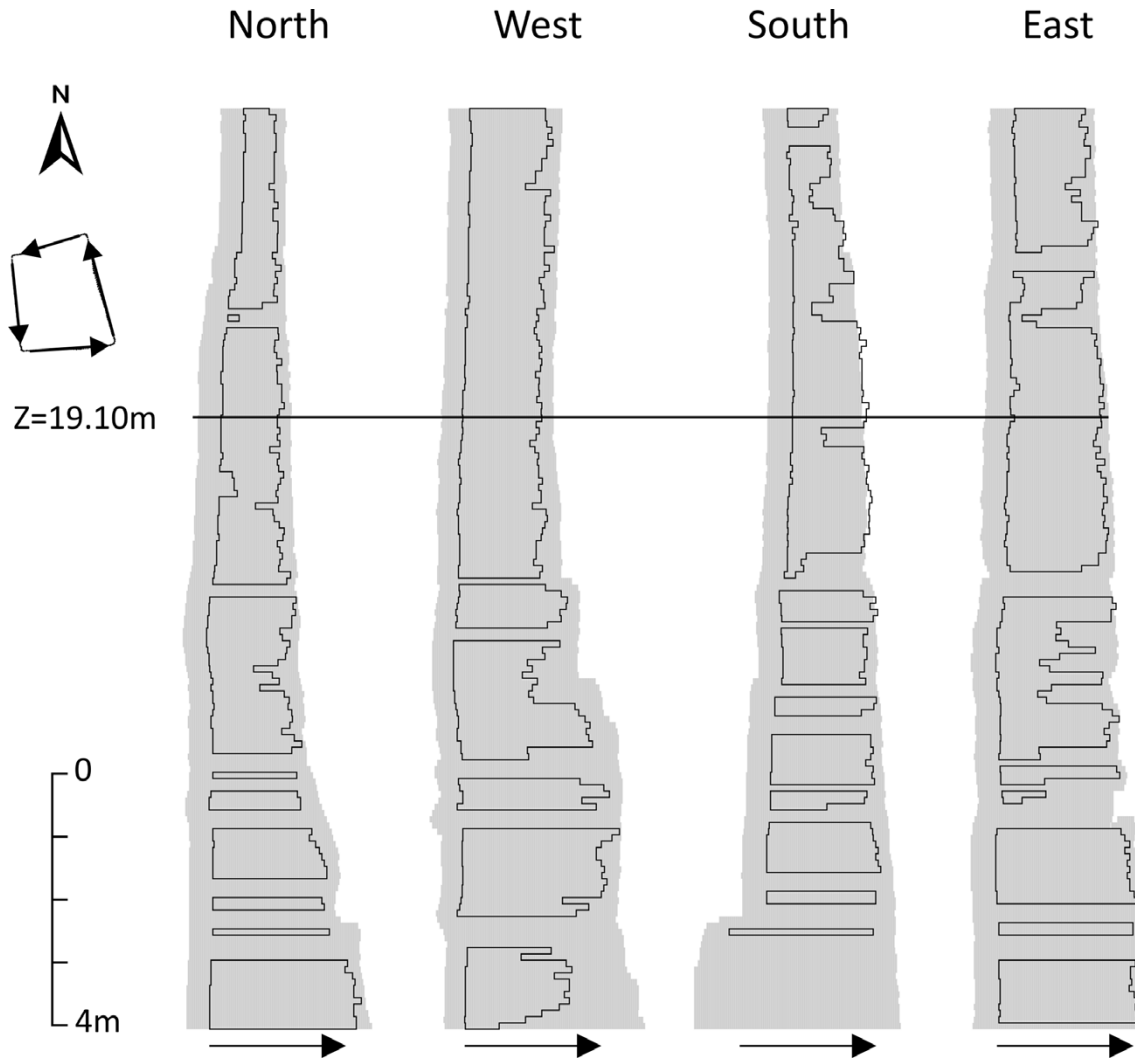


Figure 3.4: Areas covered by the GPR acquisition (black lines) on the four faces of the monument (grey surface). Arrows indicate the direction of acquisition.

the components of the normal vector, vector locally orthogonal to the surface. The components of the normal vectors are referred to as N_x , N_y and N_z when mentioning their scalar values in the X, Y and Z directions respectively.

3.3.1.2 Ground penetrating radar

The processing applied on the individual profiles included several steps from the correction of the position of the surface to the transformation in reflected energies (Figure 3.6). It was applied using the software Isatis from Geovariances (Geovariances, 2013) and Reflexw (Sandmeier, 2011).

The correction of the surface position was performed aligning the individual traces of the profiles using the first negative peak. This processing step is necessary to correct

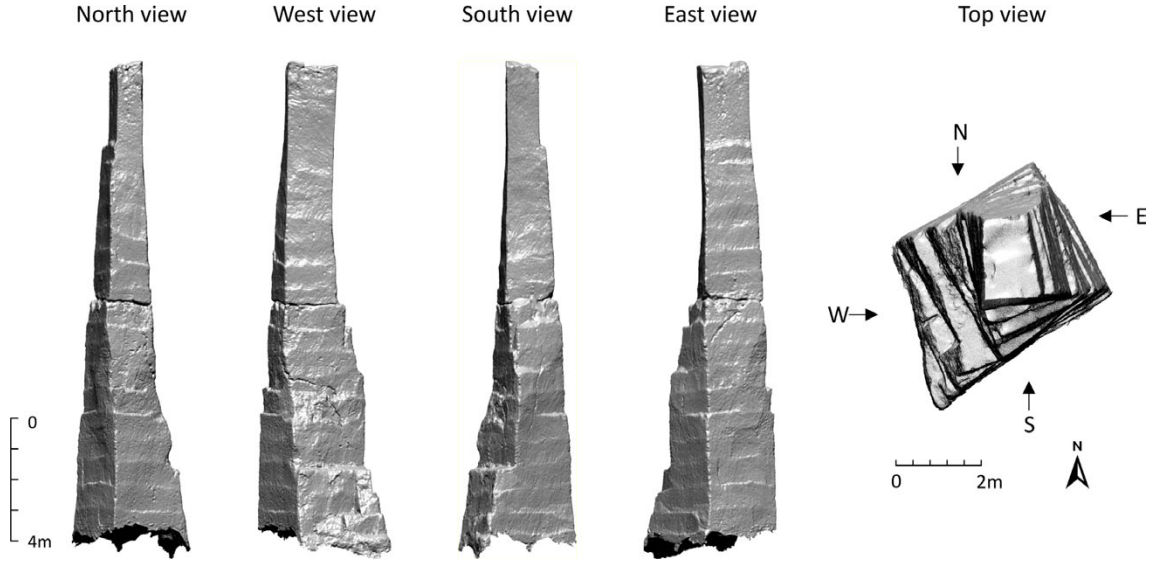


Figure 3.5: Surface model of the needle.

the acquisition noise derived from the variations of the conditions of acquisition and of the emitted signal (Ernenwein and Kvamme, 2008). The alignment of the traces was complemented by the setting of the surface position. The parameters of both operations were computed before the background removal but applied after the gain correction. The position of the surface in GPR data has been discussed in literature (Viriyametanont et al., 2008; Yelf and Yelf, 2006), the main conclusions being that it depends on the antenna being used and on the media. In this study the time correction was performed using equation 3.1.

$$T = TWT - T_{min} - \frac{1}{4F} \quad (3.1)$$

Where T is the corrected time, TWT is the two-way acquisition time, T_{min} the time of the first negative peak and F the central emitted frequency.

After computing the shift to apply for the trace alignment, a background removal was performed subtracting a mean trace to each profile (Figure 3.6b). It was applied in order to remove the horizontal ringing noise and to improve the visualization of the data in the near surface (Annan, 2009).

The attenuation of the signal with depth, typical of GPR signal (Annan, 1999), was then compensated with the application of a gain (Figure 3.6c). The compensation curve was estimated using a neighbourhood around the target of 5 samples in the crossline direction (0.40m), 21 in the inline direction (0.20m) and 1 in the time

direction. A mean average using a moving window of 21 samples in the time direction was then applied on the resulting curve. The amplitudes were multiplied by the inverse of the final curve.

In order to remove the diffractions of the scaffolding and of internal voids (Nuzzo, 2005), the GPR data were also migrated (Figure 3.6e). The migration velocity was set to the velocity of propagation in the monument as the most problematic diffractions were the one generated at lateral contact points between the scaffolding and the needle. A kirchhof migration (Sandmeier, 2011) was applied with a width of 20 samples (0.20m) and a velocity of 0.116m/ns, average of the velocity model described in section 3.2.

Finally, the bipolar amplitude data were transformed in energy (Figure 3.6f) using the average of the square value of the amplitude in a time window of 21 samples. The time window was identified as representative of the spatial resolution of the data by a variogram analysis in the time direction (Tamba, 2012).

3.3.2 Spatial data combination

Once the individual processing was applied, the GPR data were integrated in the digital model. The spatial integration of the GPR data can be resumed in three phases (a) the positioning of the surface defined by TWT=0 (b) the construction of a velocity model to transform the two-way travel time into depth values (c) the positioning of the propagated rays based on the surface information and the velocity model.

3.3.2.1 Position of the ground surface

The surface model is defined in the 3D space with coordinates (X0, Y0, Z0) in the UTM 31N ETRS89 projection. The ground surface of the GPR data is the surface defined by TWT=0. It has as local coordinates the distance relative to the edge of the face, D, and the elevation Z0. The first step of the spatial integration of the GPR data was enabling the transformation from the (X, Y, Z) space to (D, Z). The transformation was defined using the following steps: (1) separate the faces of the surface model (2) extract the edges of the faces (3) compute the distance to the edge.

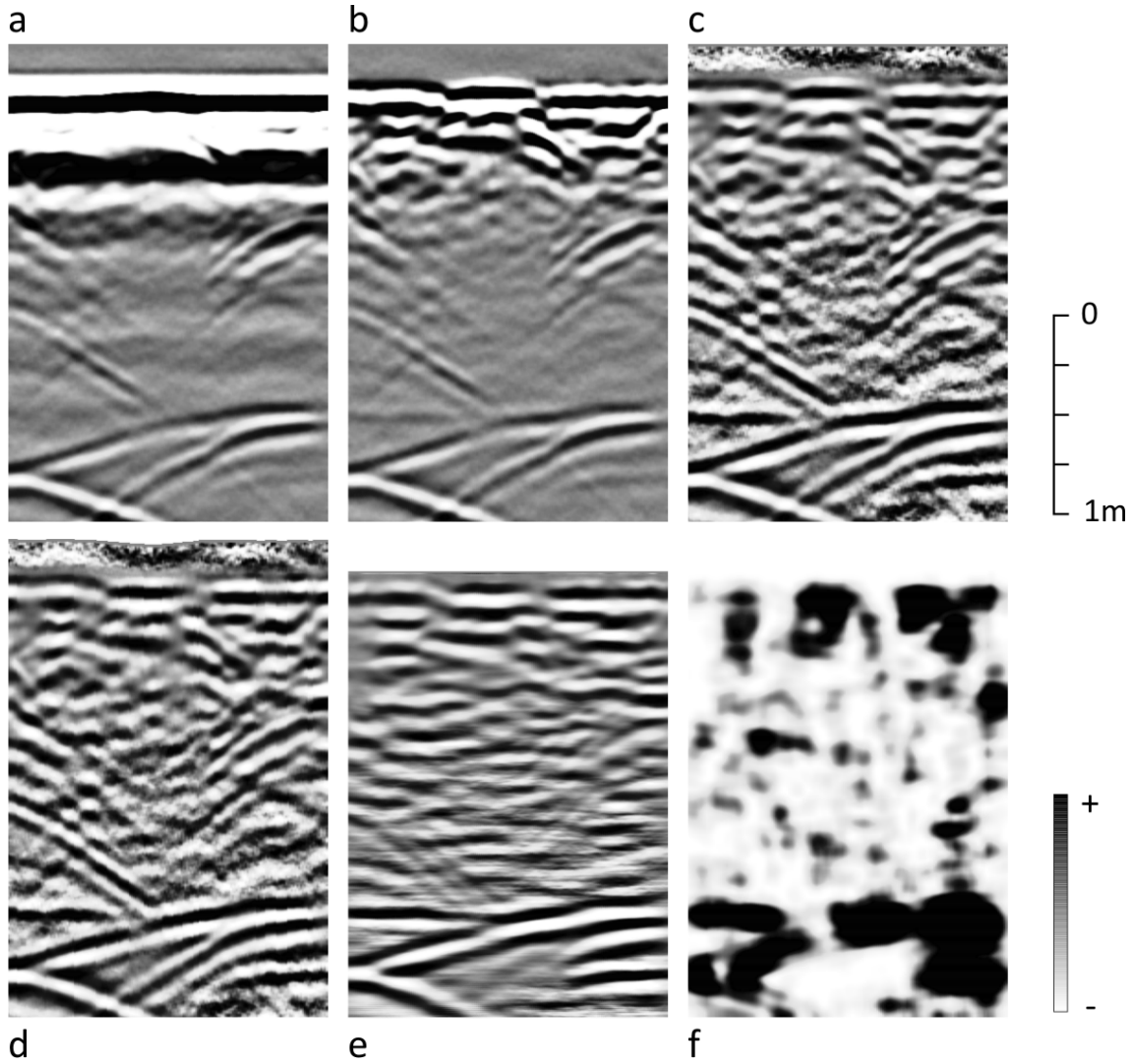


Figure 3.6: Sequence of processing of the GPR data a) Acquisition data b) Background removal c) Gain d) Phase correction e) Migration f) Energy.

The separation of the faces was achieved using their orientation. A threshold was applied on the smoothed component of the normal vector. As the north-western and south-eastern faces are globally oriented in the West-East direction, N_x was used to separate them. As the south-western and north-eastern faces are globally oriented in the South-North direction, N_y was used to separate them. Once the faces were separated, they were vertically resampled to fit the GPR acquisition elevation Z and sampling (0.10m). The first sample of each Z level was extracted to reconstruct the edge of each face. Then, for each point of the resampled surface, the distance to the edge was computed.

With the distance to the edge computed, it was then possible to change the surface model from the (X, Y, Z) space to the (D, Z) space. All the properties of the surface

model, i.e. X_0 , Y_0 , N_x , N_y , N_z , were then transferred to the GPR data. An offset was added to the computed distance in order to correct the relative positions of the GPR profiles. The origin was set at the topmost point of the edge and the offset between the edge and the origin was computed and applied for all the vertical levels. The results of the transformation can be seen in Figure 3.4 with, in grey, the surface model and in black lines, the areas covered with GPR, both represented in the $(D+\text{offset}(Z), Z)$ space.

In order to achieve the global topographical correction of the GPR data, the position of the GPR traces had also to be corrected. They were acquired measuring the two-way travel time, which must be converted into depth values (Goodman et al., 2006). This time to depth conversion required a model of velocity of propagation.

3.3.2.2 *Velocity model*

There are several possibilities for the evaluation of the velocity of propagation of GPR waves, the most common and practical one being the hyperbolic velocity analysis (Cassidy, 2009b). One of the other methods is based on the identification of reflections caused by objects of known depth (Conyers and Lucius, 1996). The signal in the upper part of the needle completely passes through the opposite face and the transition from the rock to air is a good reflector visible even before the correction of the attenuation of the signal. Therefore, at the position of the exit of the signal, both distance and two-way travel time of the GPR waves could be extracted, which made the exit signal a good calibration parameter of the velocity of propagation.

The exit wave was easy to identify as it appears as a local maximum of amplitude. As the exit signal was not always present and could be altered by the reflections of the scaffolding, the picking of the exit signal was performed and corrected manually profile by profile. For each profile where the exit signal was clear, the maximum phase was automatically followed using the software Reflex (Sandmeier, 2011). The automatic picking was then corrected in order to remove the points related to the reflection of the scaffolding (Figure 3.7). The position of the picked points in two-way travel time and the distance between the two considered faces at the same position were used to compute the velocity of propagation as described in equation 3.2.

$$V = \frac{2D}{\tau} \quad \text{with} \quad D = \sqrt{d^2 + \frac{\delta^2}{4}} \quad (3.2)$$

Where V Is the velocity of propagation, τ is the time of propagation picked following the exit signal, D is the distance correspondent to the wave path using a distance delta between receiver and transmitter of 0.1525m (Geophysical Survey Systems, 2004) and d is the orthogonal distance between faces computed from the digital model.

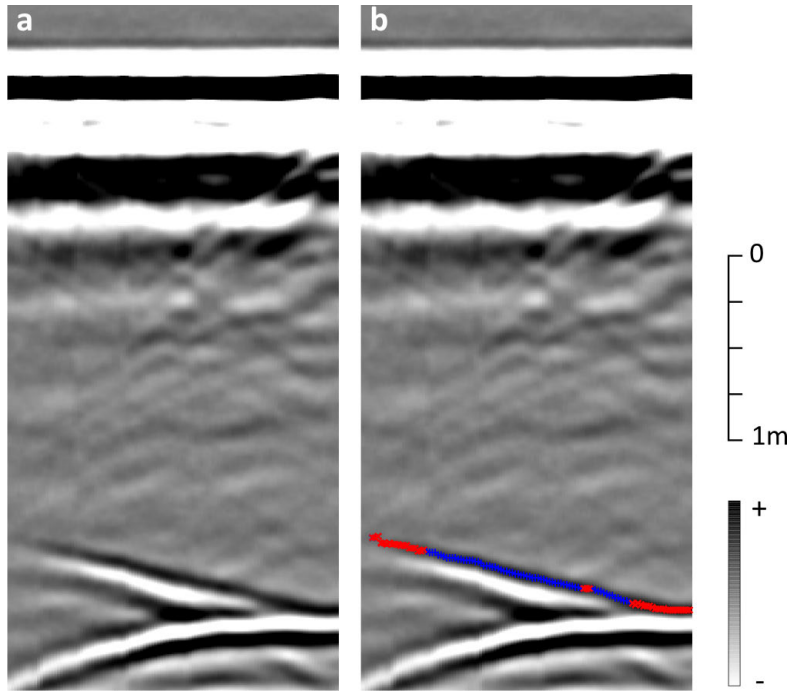


Figure 3.7: Picking of the exit signal for the calculation of the velocity of propagation a) Radargram used for the automatic picking b) Radargram with the result of the automatic picking: in blue the selected points and in red the discarded ones.

The result of the operation was a point cloud with the velocity values at the selected locations. The velocity values were then used as the input of a variogram analysis and were interpolated with their associated standard deviation on the faces of the needle using ordinary kriging (Goovaerts, 1997). The interpolated velocity model was transferred to the GPR data for the time to depth conversion and the global positioning of the profiles.

3.3.2.3 Global position and antenna tilt correction

With the positioning of the ground surface (section 3.1.1) and the computation of the velocity model (section 3.1.2), the GPR data now include additional properties as

variables. These properties were used to transform the local system of coordinates of the 3D GPR data (D+offset(Z), TWT, Z) to the UTM projection. The properties are (1) the coordinates of the surface model X0, Y0, (2) The components of the normal vectors Nc and (3) the velocity values.

As the local variations of the topographic model are much higher than the plane on which the GPR antenna was moved, the computed normals and the coordinates at the surface were averaged using a moving window of the size of the 400MHz antenna which is of 0.30mx0.30m (Geophysical Survey Systems, 2004). The computation of the UTM coordinates is described in equation 3.3. The transformation of the position of the acquired profiles is illustrated in Figure 3.8.

$$C = C_0 - N_C \frac{vT}{2} \quad (3.3)$$

where C is the absolute coordinate (X, Y or Z), C_0 is the C coordinate value at the surface, N_C is the component of the vector normal to the surface in the C direction, v is the propagation velocity value and T is the two-way corrected travel time.

The transformation takes into account both the position of the antenna and its orientation or tilt. The tilt determines the direction of propagation of each trace. In order to check the validity of the transformation, the position of the exit signal through the opposite face was compared to the correspondent surface model as illustrated in Figure 3.8b.

3.3.3 Property combination

Once the GPR data were referenced, the relevant properties from the digital model and the GPR data were extracted. The main property of interest of the digital model is the location of the external cracks. As for GPR, a strategy had to be established in order to produce a combined interpretation of the four faces of the monument using selected properties. The GPR properties of interest were divided in two categories: properties relative to the variations of moisture contents and that can be displayed on the surface and high energy volumes possibly related to voids and internal cracks.

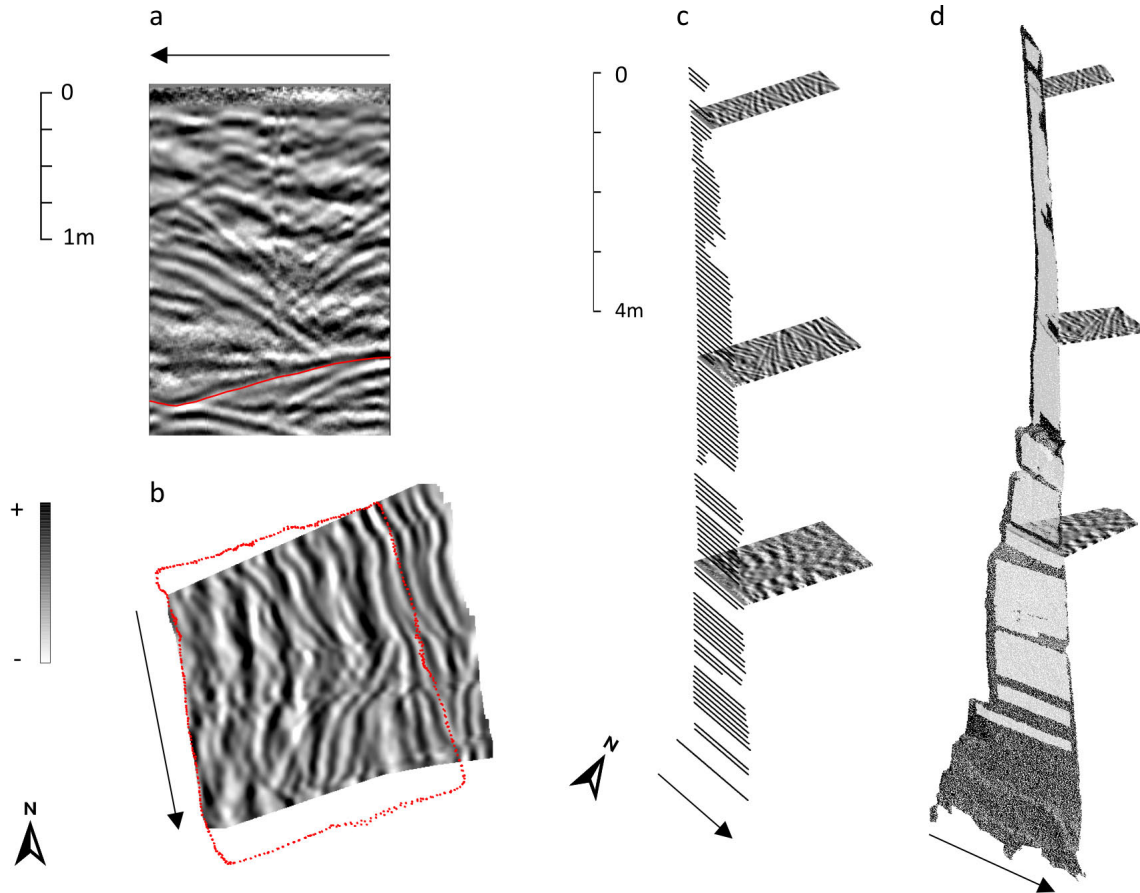


Figure 3.8: Positioning of the GPR data using the topographical information. a) profile in the local reference system (in red, the exit signal) b) top view of the profile after topographical correction c) lateral view of profiles in the local reference system d) lateral view of profiles after topographical correction and internal data selection.

3.3.3.1 Extraction of external cracks and protrusions from the digital model

As one of the goals of the research was to study the relations between the external cracks and GPR properties, the first step of this part was to extract the locations of the external cracks from the digital model. In addition, protrusions of the monument are locations where water can accumulate and were also extracted. Cracks and protrusions are characterised by different topographic properties and were extracted independently. In the case of cracks, the surface is oriented inwards when the plane surface is oriented outwards. The orientation of the surface was computed using the divergence operator described in equation 3.4 on the vector of the position of each point. The divergence of the position is equivalent to a 3D gradient and enables the detection of abrupt changes in the topography.

$$divergence(V) = \frac{\delta X}{\delta x} + \frac{\delta Y}{\delta y} + \frac{\delta Z}{\delta z} \quad (3.4)$$

where $V(X, Y, Z)$ is the vectorial expression of each point of the model

Protrusions are defined as surfaces oriented upwards. The points with an upward orientation are easily located using the normal vectors. An upward orientation is equivalent to the Nz component equal to 1 and the Nx and Ny components equal to 0. A threshold was then applied on the Nz component in order to extract all points globally oriented upwards. The results of both operations were merged.

3.3.3.2 *Moisture related properties*

With the acquisition parameters of the study, (400MHz mono-static antenna in contact with the surface), the first arrivals of the GPR signal contain both the direct wave and the surface wave (Yelf and Yelf, 2006). Nevertheless, although it is not possible to separate the two waves, the first arrivals can give information on the relative variations of properties related to moisture contents and by extension on the affected areas around the visible cracks (Binda et al., 1998; Pettinelli et al., 2014). The amplitude of the first arrivals was defined as the difference between maximum and minimum amplitudes of the first wave and was extracted from the acquisition data, i.e. before the processing additional to the acquisition band pass. At the same time, the moisture content is also reflected by the model of velocity of propagation of the GPR wave (Huisman et al., 2003). The integration of the first arrivals information on the surface of the 3D model and the variations in velocity before interpolation are shown in Figure 3.9a. The first arrival property was separated by face in two sections delimited by the hardground. A histogram analysis was operated on each section in order to apply thresholds and visualise the lowest values possibly related to higher moisture contents. The thresholds were applied using the mode of the histogram (abscissa of the maximum frequency peak) minus one standard deviation. The results are displayed in Figure 3.9b.

3.3.3.3 *Extraction and characterisation of the major reflectors*

The major reflectors can be extracted from the GPR data detecting the high energy values. As energy values were heterogeneous, their mean absolute deviation (MAD equation 3.5) was considered for this extraction (Xie et al., 2013). The MAD was

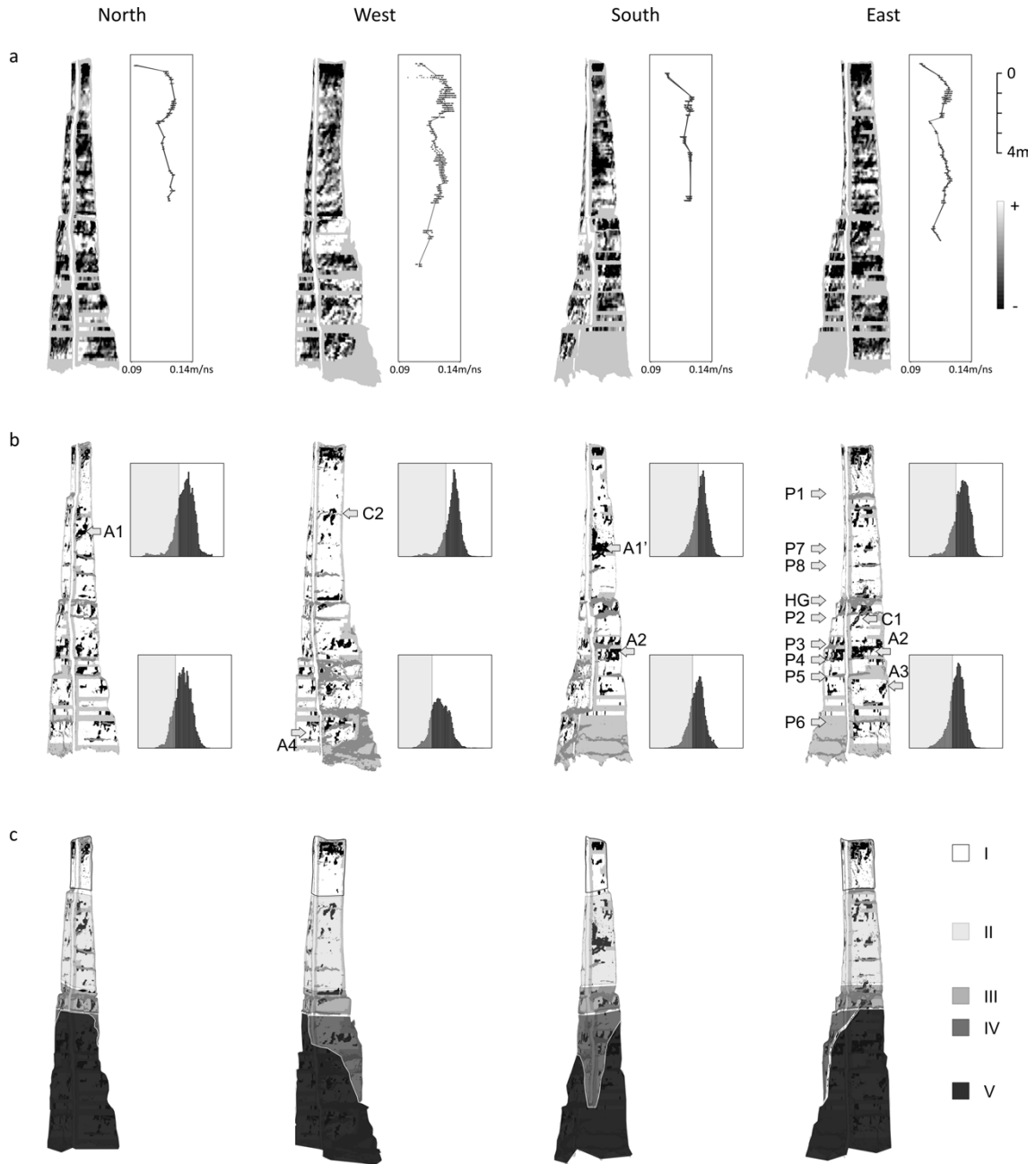


Figure 3.9: Surface properties analysis a) display of the first arrivals on the topographical surface and of the velocity curves b) results of the histogram analysis of the first arrivals. The highlighted gray histogram values are represented as black areas on the topographical surface and indicate lower time first arrivals values that can be associated to higher moisture contents. Areas of interest (A), protrusions (P) and cracks (C) are also indicated c) classification of the needle based on surface properties and topography analysis.

computed on the individual profiles with a moving window of 0.15x0.15m.

$$MAD = \sum_{i=1}^{i=n} |x_i - \bar{x}| \quad (3.5)$$

where n is the number of samples in the moving window, $\bar{x}$ is the mean of x computed on the n samples, X_i is the value of the considered variable at the ith sample.

The histograms of the MAD resultant values showed different main features. It was then decided to determine the thresholds to apply for the extraction of the points of interest for each face separately. As the distribution of the data was asymmetrical, the second triangle method was used for a systematic calculation of the thresholds (Tsai and Lee, 2002). This method consists of the computation of the orthogonal distance between each class of the histogram and the line that joins the mode and the maximum. The longest distance is set as threshold. These thresholds were then used for the extraction of the samples. The resulting points were merged into one point cloud.

The final point cloud consists of scattered data with variable density. The points form groups that can be associated to volumes. A strategy had to be established in order to detect and characterise the extracted volumes. The chosen strategy consisted of

1. a gridding of the point cloud to a regular 3D volume: the resolution of the gridding was of 0.02x0.02x0.1m
2. detect the informed cells: the cells containing points were affected with a value of 1 and empty cells with 0
3. for each informed cell, explore the adjacent ones and detect connections: the connectivity analysis was performed considering the 26 cells around each target
4. associate a numeric label to each group of connected cells: when the cells are in connection they are affected with the same numeric label and the number of cells is registered, which enables the computation of the volume. The numeric label changes for each new group of connected cells (Geovariances, 2013)
5. transfer of the label and volumes properties back to the original point cloud.

The operation is illustrated in Figure 3.10.

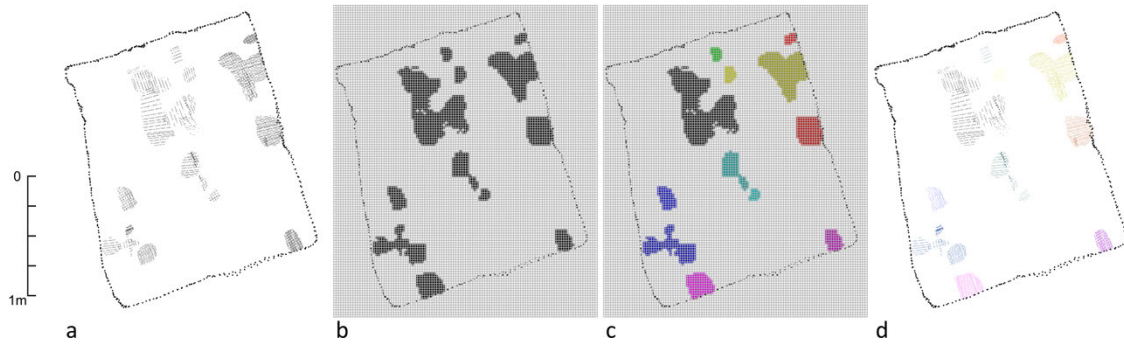


Figure 3.10: Labeling strategy illustrated on a horizontal section of the needle a) extracted high energy points b) transfer of the points to a mesh c) connected cells are associated to a numeric label based on their connectivity d) transfer of the label and of the volume property to the point cloud.

A systematic physical validation of the reflectors was not possible. As a consequence, the connectivity and volume properties were used as guides for interpretation and additional properties were added to the reflectors in order to be able to evaluate their validity. The additional properties were: (1) the average distance defined as the cube root of the volume. This property represents the average size of a component and allows excluding the small volumes which are not of interest and the large volumes that are not realistic. (2) The number of faces from which they were detected, given that a component detected by more than one face is more reliable. (3) An identifier of the faces. This property allows identifying from which faces a component was detected and ensures traceability. (4) The normalized spatial uncertainty derived from the velocity model. It allows detecting the components with a higher uncertainty on their geometry and volume.

3.3.4 Data interpretation

In the final step of the research, the focus was on the interpretation of the results and on their transmission. The integration of the GPR data to the digital model enabled a combined interpretation of the survey. The integrated model was used for qualitative and quantitative analysis of the results and was exported with the objective that end-users could explore and interpret them.

3.3.4.1 Cracks and surface properties

The relation between external cracks and surface properties are described in Figure 3.9. As most of the low first arrival values are located around cracks and protrusions,

these features of interest were labelled. Six main protrusions (P1 to P6), one main crack (C1) and the hardground (HG) were identified as the most sensitive areas and indicated in Figure 3.9b. Figure 3.9c shows the classification of the monument into five blocks identified from the combined interpretation of the velocity values, the low first arrivals values and the locations of the external cracks and protrusions.

Block I was defined as the top block above protrusion P1. It presents low velocity and first arrivals values at its upper section. These low values could be explained by water infiltrations from the top surface of the monument. The affected area is of around 1m.

Block II was defined as the volume going from the velocity decrease observed at m 21 and the hardground, leaving a buffer distance of 0.20m. The velocity decrease is located below protrusion P1 and can be associated with low first arrivals values visible on all faces. Two additional low first arrivals areas named A1 and A1' are visible. These areas are not associated to visible external cracks and a relation with the protrusion P1 cannot be stated from these data. A minor crack named C2 also showed associated affected areas.

Block III corresponds to the hardground area. It includes an upper part where accumulated water could raise by capillarity, a large opening, and the affected areas identifiable from the surface properties below the opening.

Block IV and V are the blocks below the hardground and are separated by the major crack named C1. In block IV, the most affected area was named A2. It was associated to protrusion P3 which is in contact with the crack C1 on the southern face. In block V, the largest affected area is the continuation A2 apparently related to protrusion P4 and crack C1. Additional affected areas were identified in relation to protrusions P5 and P6 and were named A3 and A4.

The block identification will now be used for the analysis of the high energy values in order to describe possible relations between cracks, protrusions and inner voids.

3.3.4.2 Cracks and volumes

The interpretation of the surface properties in combination with the geometrical features of the monuments allowed the detection of areas with a higher possibility of

degradation due to water accumulation. These defined areas were then considered in order to detect associated possible voids.

Figure 3.11a shows the point cloud of extracted high energy values in the different blocks defined in section 4.1.1. Large volumes are detected for block I below the top surface, block III below the hardground and block V below the crack C1 and between protrusions P3 and P6. The lower part of block V, below protrusion P6, was less documented and had a higher spatial uncertainty due to the velocity model. Additional volumes were identified in block II. They are located between protrusions P7 and P8 and were not detected by the surface property analysis.

The additional properties added to the volumes were used to offer alternative visualisations. In Figure 3.11b the volumes of average distance included between 0.30 and 0.70m are displayed discarding the smaller volumes of less importance and the largest ones with higher uncertainty. In Figure 3.11c, only the volumes detected by at least three faces were kept to show the volumes validated by other faces although the large volumes with a higher spatial uncertainty are also kept. In Figure 3.11d only the volumes with an uncertainty inferior to 50% of the maximum uncertainty are showed, removing the volumes of the lower part of the monument where the velocity model was extrapolated.

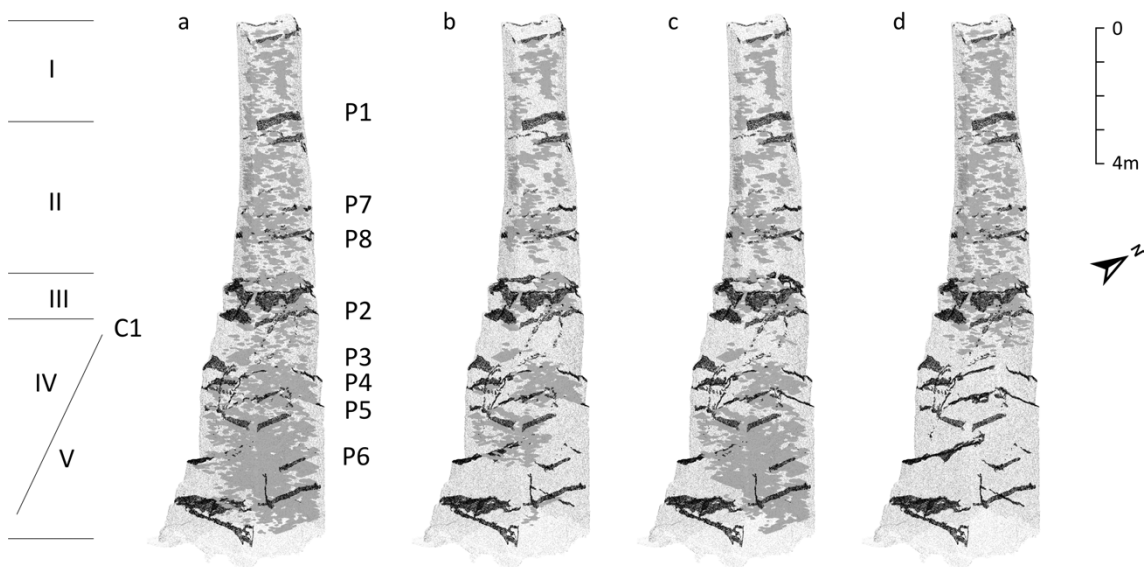


Figure 3.11: Volume properties analysis. The protrusions and cracks extracted from the topographical model are labeled and represented in black. a) volumes resulting from the extraction of high GPR energy values b) volumes of average distance included between 0.30 and 0.70m c) volumes detected by at least 3 faces d) volumes with a spatial uncertainty lower than 50% of the maximum uncertainty value.

The results of both surface and inner properties helped with the identification of parts of the monument with higher possibilities of degradation. The combination with the geometrical analysis of the topography showed a relation between the detected anomalies and the protrusions of the monument. In the absence of a physical verification of the results, additional properties were added to the model in order to offer a validation method. The results were gathered in a final model to enable alternative interpretations.

3.3.4.3 Limits and drawbacks

The first difficulty of the survey was related to the complex geometry of the monument to be explored in addition to its large dimensions. The elevation method available for the project being a scaffolding, an automated referencing of the positioning of the GPR data had to be discarded. The combination with the topographical information was then a necessity. The referencing of the GPR data rely on a similar recognition of the edges of the faces during the acquisition of the GPR data and in the digital model, which introduced an uncertainty on the lateral positioning difficult to quantify.

Regarding the quality of the GPR data, the contact between the antenna and the surface, although maintained as constant as possible, suffered variations. With variations in the contact conditions, the analysis of the first pulse information may be questioned and some of the highlighted areas could be explained per a contact issue. One possible solution could have been operating with an air configuration but it would have raised problems both of infrastructure and depth of penetration. Multiples due to reflections from adjacent or opposite faces were not identified.

Another drawback of the geometry of the needle was the variability of the depth to be explored, lower than a meter in the upper part and around three meters at the bottom. With the chosen frequency, a velocity model could not be elaborated for the lower part of the monument. Using a lower frequency could have allowed a complete velocity model but with a loss in the resolution of the data and in the coverage due to the size of the antenna. The chosen design was a compromise given the economic limitations of the project. Additional measurements with a bistatic system could have allowed additional inputs for the velocity model and limit the derived uncertainty on the spatial positioning of the GPR data.

The choice of coverage of the four faces of the monument added the difficulty of the fusion of the data to the larger amount of collected data. The different behaviour of the GPR signal from face to face and the high uncertainty on spatial position in the lower part of the monument made a direct fusion of the data not advisable. Furthermore, the resolution of the data varies with depth, which made the results from separate faces not directly comparable. Therefore it was chosen to extract the relevant information face by face and to fuse only the positions of the extracted points, adding the information on face number, face origin and uncertainty as properties in order to be able to contrast interpretations.

The final problem was related to the exchange format of the data. As the model is multi-components with different properties affected to each component, one unique file could not allow an interactive exploration of the data. The ideal solution would have been the implementation of the complete model on a web platform with a programmed interface that would allow the end-user to explore the results spatially and to be able to modify the values of the properties. This option goes beyond the scope of the project and the final step was the export of each component in an ASCII format.

Due to the complexity of the project, the restoration of the needle was operated based on a preliminary report which showed the projection of possible volumes on the faces. The restoration process mainly focussed on the large cracks and the opening at the hardground.

3.3.4.4 Conclusions of the project

This research project is an illustration of the benefits of combined models that include topographical information and the results of surveys using non-destructive technologies. These systems offer extensive coverage of the inner part of a monument which is complementary to the topographical information. The global results offer a start point to monitoring with an access to quantitative information.

As the processing and integration parts are complex operations with several sequences possible, it was important to limit the research to clear objectives. Focussing the characterisation of the visible external cracks and on the detection of associated possible voids oriented the processing parameters and gave a purpose to the combination of the data.

Another highlight of the research was not to limit the results to a methodological description on how to build a model but to add qualitative and quantitative interpretations. In the absence of validation by a physical exploration of the monument, properties that allow contrasting the reliability of the detected elements were proposed.

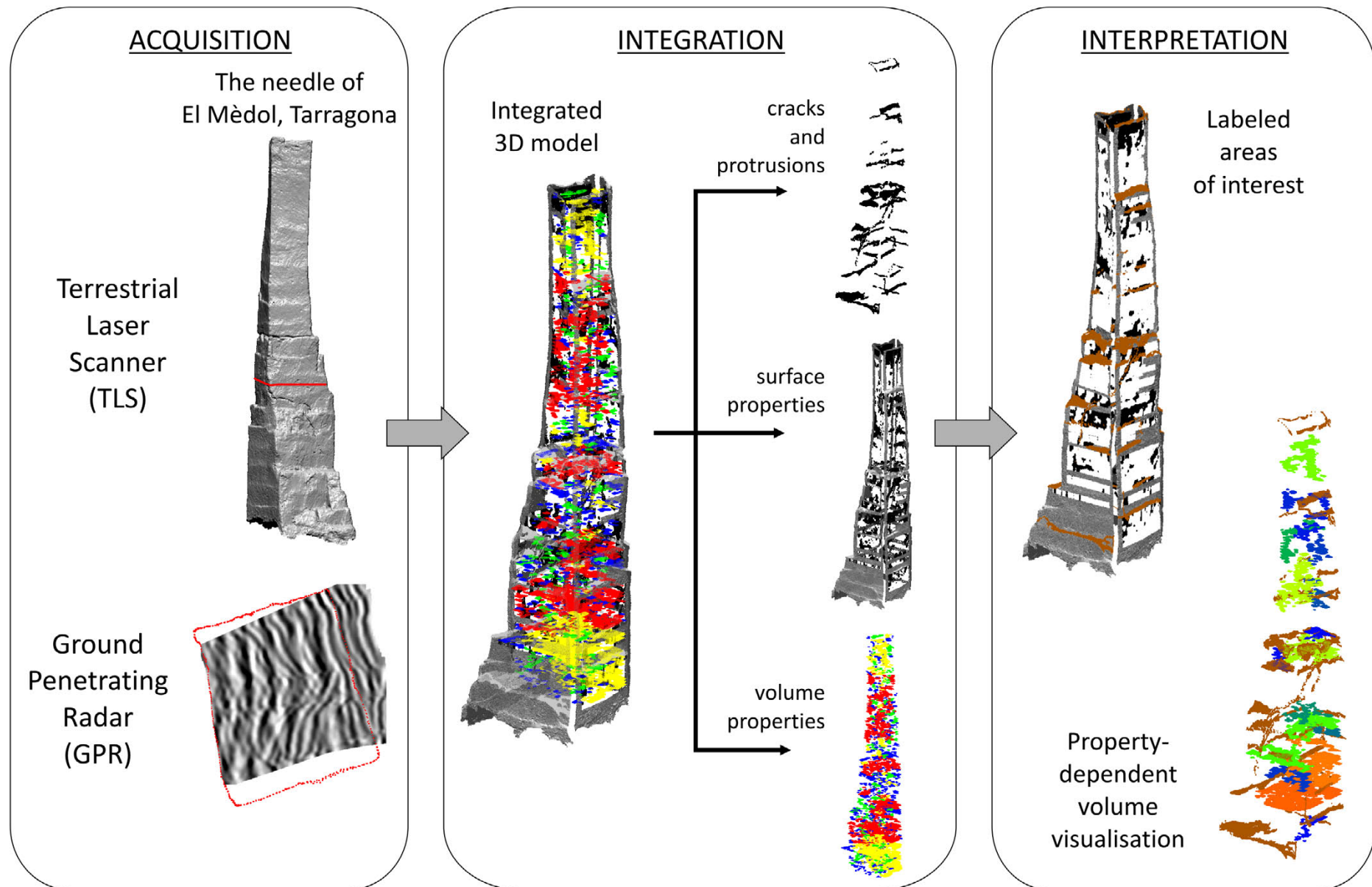
Finally, offering the possibility of an interactive exploration of the results is an advance in comparison to a classical transmission through reports, static or animated representations. This last part should be further investigated with the implementation of a platform that would give access to information on the usability of the model and on feedbacks from end-users.

3.4 Data finalisation

The finalisation of the project consisted of the production of several outputs. First, a written report detailed in the previous sections of this chapter. The main results were presented through a graphical report (section 3.4.1) and an animated sequence (3.4.2). Finally, the resulting model and the files generated during the project were exported in open formats and classified. The animated sequence and the model are available as additional material. The produced files are listed in Appendix F.

3.4.1 Graphical report

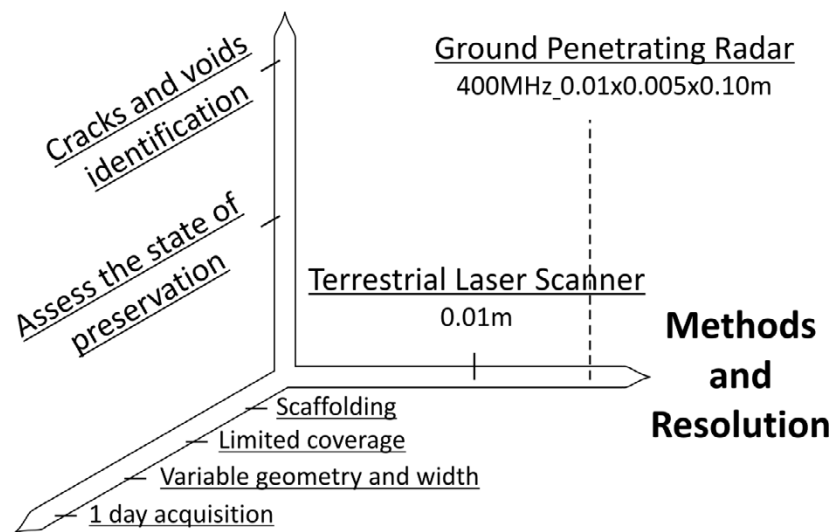
3.1 Assessing the state of preservation of a monumental artefact



3.2 Design of the Project

Characterisation

Objectives



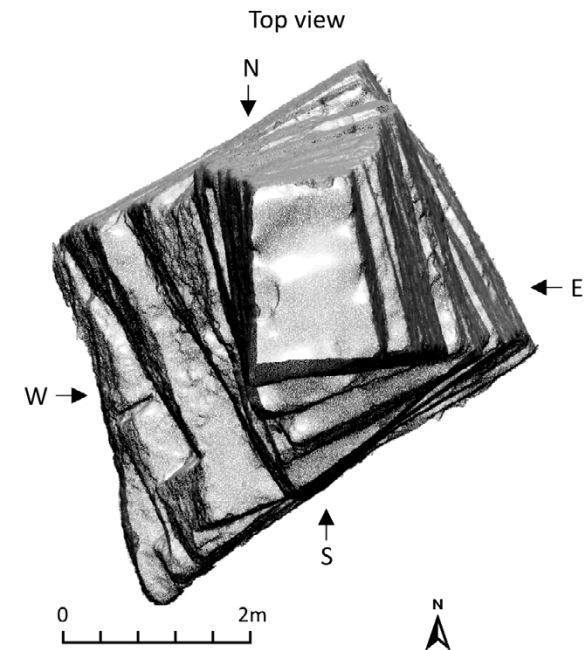
Feasibility

The objective of the exploration of the needle of El Mèdol was to identify possible cracks and voids through the production of an integrated model with surface and volume properties.

Terrestrial Laser Scanner and Ground Penetrating Radar were used.

The main limitation was the use of a scaffolding and the adaptation to the geometry of the needle

Strategy

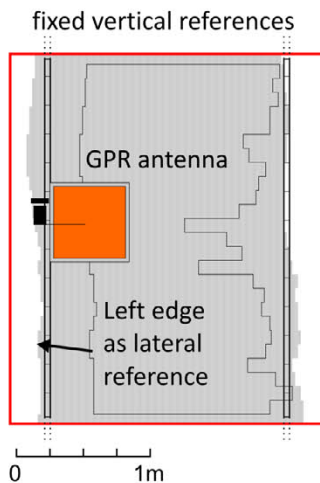
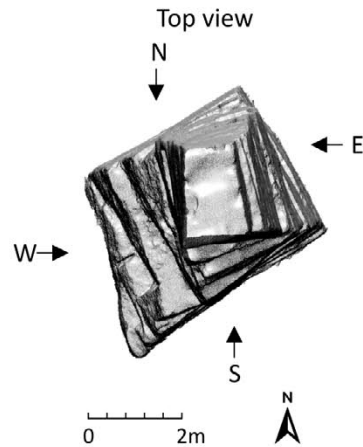


The needle had to be explored in all its depth without losing resolution. It was then decided to use a 400MHz antenna and to acquire data from the 4 faces.

Common references between the GPR acquisition and the TLS model were used to position the data.

3.3 Data acquisition

Acquisition methodology



The left edge of each face was taken as reference for the acquisition.

Explored areas



In grey, the projection of the surface model for each face.

In black, the areas covered by GPR (75m²)

The horizontal section shows the direction of acquisition for each face.

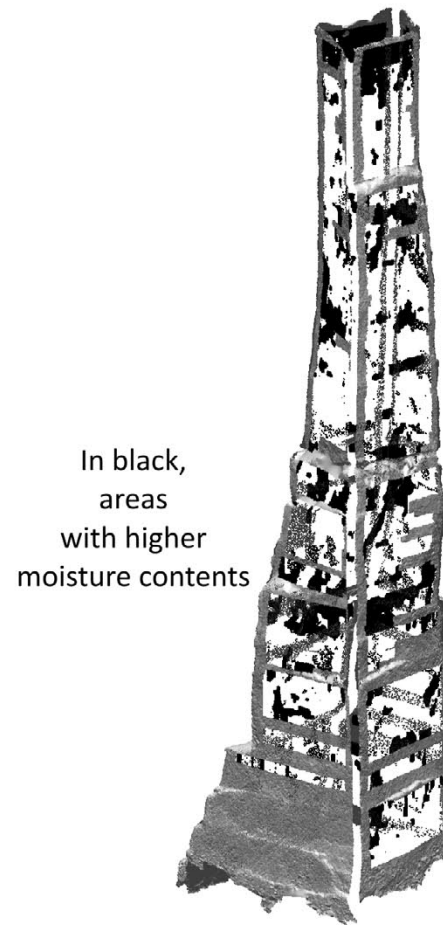
3.4 Property combination

Cracks and protrusions



Cracks and protrusions were extracted from the TLS data using the analysis of divergence and the orientation of normal vectors

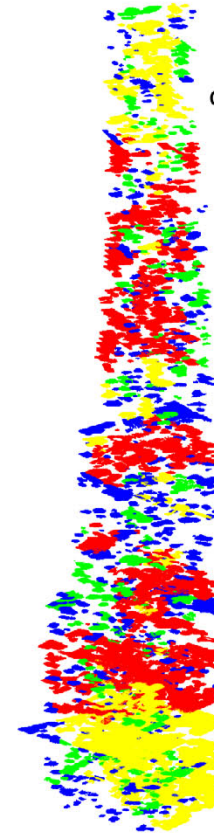
GPR surface properties



In black, areas with higher moisture contents

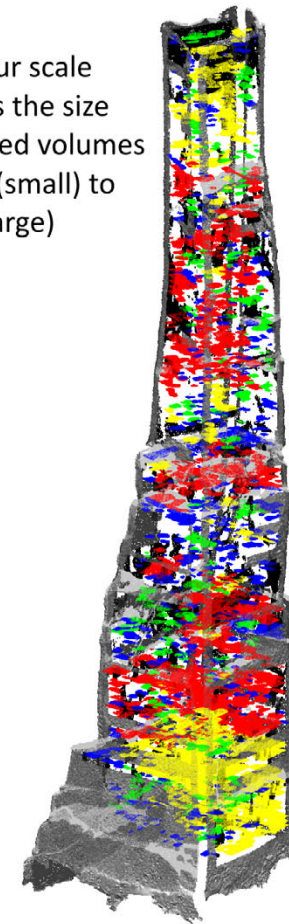
The first pulse of GPR data was used as surface property. It is related to moisture contents. The reflective data of the internal information were transformed into volumes associated to possible voids

GPR detected volumes



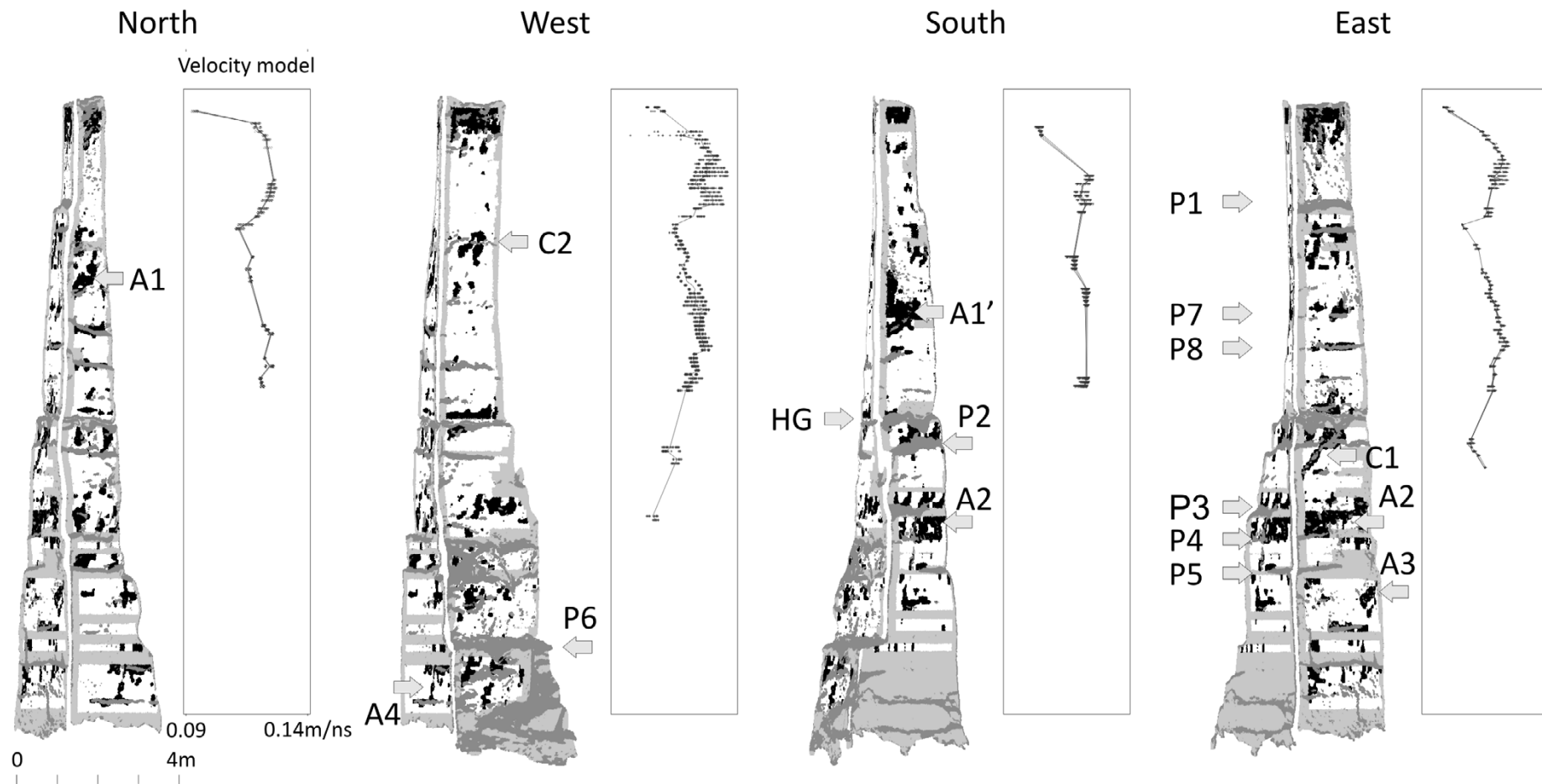
The colour scale represents the size of the detected volumes from blue (small) to red (large)

Integrated Model



The three components were gathered in a 3D integrated model together with the surface model

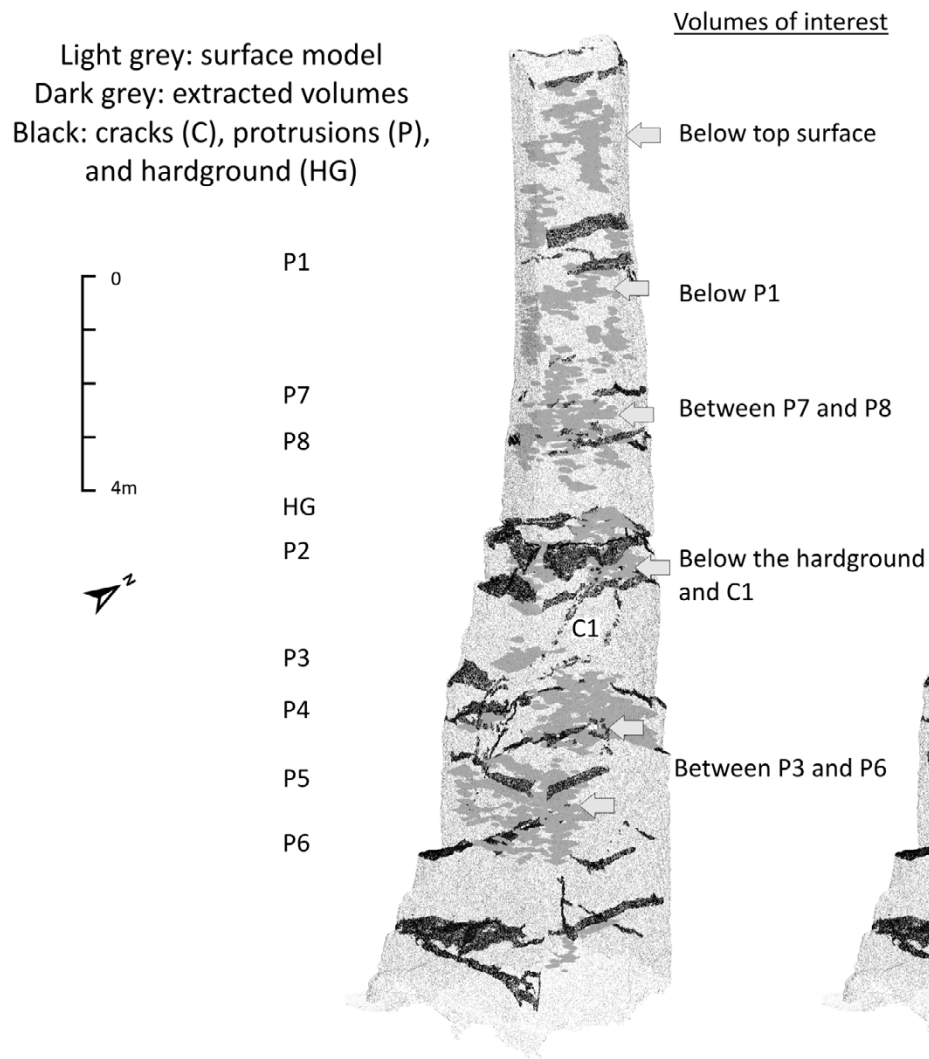
3.5 Interpretation of surface properties



White: area covered with GPR
 Light grey: surface model
 Dark grey: cracks (C), protrusions (P) and hardground (HG)
 Black: areas with higher moisture contents (A)

Most of the high moisture contents areas are related to crack and protrusions. The most affected areas are the area below the top surface, below protrusion P1, below the hardground, around C1 and between P3 and P6. The velocity model show the drop in velocity values due to higher moisture contents below the top surface and P1.

3.6 Interpretation using volume properties



Smaller volumes of less interest and larger volumes of higher uncertainty are removed

The areas detected with the surface property interpretation also show internal volumes

This could be due to a link between the surface condition and internal degradation

Additional areas of interest are detected between protrusions P7 and P8.

The exploration of the lower part of the monument has higher uncertainties due to a higher width

Volume of average dimension included between 0.30 and 0.70m.

Volumes with a spatial uncertainty lower than 50% of the maximum uncertainty.

3.4.2 Animated sequence

The animated sequence was divided in four parts

1. Part 1: description of the objectives the project and of the correspondent applied strategy
2. Part 2: description of the acquisition methodology
3. Part 3: description of the integration of the measured properties in one model
4. Part 4: description of the main final results

The animated sequence can be found as additional material in the attached CD. The file is named 20150815_SOT_El-Medol_video.mp4 and is located in the folder CH3_EL-MEDOL.

3.4.3 3D model

The produced model was built with the software CloudCompare (CloudCompare, 2014). This software can handle scalar fields. This means that the measured properties were added to the 3D objects and can be visualised as texture. The model can be explored either with the complete software or with the simpler version ccViewer. Both versions can be installed using the installation files provided in the attached cd in the folder SOFTWARE. It includes:

1. the 3D surface model with normal vectors
2. the extracted external cracks and protrusions
3. the areas with high moisture contents
4. the volumes associated to high energy values with the additional properties described in section 3.3.3.3
5. the separated faces (East, North, West and South) that include the four previous elements relative to each face

The 3D model is provided as additional material in the attached CD. It is located in the folder CH3_EL-MEDOL and named ELMEDOL_Integrated-3D-Model.bin.

3.4.4 Files

The produced data were classified in four categories: (1) the raw data which are the data acquired and downloaded without any change (2) the processed data which are the data after the applied transformations (3) the documentation that were generated for the description of the project and of the results and (4) the generated 3D model. The list of all the delivered files is described in Appendix F.

3.4.4.1 *The raw data*

The folder 01_RAW_DATA only includes the GPR individual files. For each profile acquired during fieldwork, one file is created. 501 profiles were acquired, which correspond to 501 files. The files were named using a prefix relative to the project (MEE) and the number of the profile in three digits. The name of the files is then structured in the following way: MEE_____XXX.DZT. 'XXX' is the number of the profile and DZT is the extension, which correspond to the native format of the used system.

3.4.4.2 *The processed data*

The delivered processed data were limited to the final results. The intermediate steps were not saved and exported. They were only described. The folder 02_PROCESSED_DATA includes GPR data and TLS data.

The GPR data were transformed into surface data and into volumes. The surface data correspond to the areas of the needle that were explored. One file per face with the complete data was exported. One additional file was created with the main areas of interest of all faces. The main areas of interest are the areas with high moisture contents. These areas are the most affected by weathering and are the ones that should be monitored.

The surface data were exported in ASCII format with a 'xyz' extension. The files relative to the faces include several properties which name is given in the first line and that will now be described. The total number of fields included in the files is 10, one per described property. The first 6 properties are the coordinate properties. They include the X, Y Z coordinates that position the points and the Nx, Ny, Nz values which are the values of the coordinates of the normal vector. The normal vectors

was extracted from the TLS data and used to position the GPR data as described in section 3.3.2. The following properties are the ones used for the transformation and the interpretation of the data. They include the time of arrival of the first pulse. The first pulse was defined by its minimum and maximum amplitude values. The times of arrival corresponding to the minimum and maximum amplitudes values are given in nanoseconds. They were used to detect the position of the data corresponding to the ground surface (section 3.3.2.a) and to extract the first pulse amplitude. The next property is the velocity of propagation in nanoseconds per meter (section 3.3.2.b). It was used both for the positioning of the data and the detection of the data with high moisture contents. The last property is the first pulse amplitude used for the detection of areas with high moisture contents.

The high moisture contents areas were defined detecting thresholds for each face (section 3.3.3.b). The thresholds were applied on the data in order to extract the points relative to the areas to monitor. These points were gathered in one separate file. The file has a similar structure as the individual files but limited to the coordinates, the normal vector and the first pulse amplitude.

The GPR data also contained high energy values. The high energy values were interpreted as possible voids. These voids had to be monitored. For each face the high energy values were extracted and stored in an ASCII file with a 'xyz' extension. The file contained 7 fields. 6 fields correspond to the coordinates and the normal vector. The last field correspond to the energy value. All the volumes were merged in one file with the same format but different fields. Only the coordinates were stored for the positioning. Additional properties were added. They correspond to the properties that were used to characterise and classify the volumes. They are described in section 3.3.4.b. In order of appearance in the file the properties are: the volume, the mean distance, the number of faces from which it was detected, an identifier that gives which are the faces and the uncertainty on the geometry of the volume.

TLS data were also processed. The process resulted in two outputs. The first output was the 3D model of the surface. It contains the coordinates of the points and the normal vectors. The model was used to extract the sensitive areas which are cracks and protrusions. The extraction is described in section 3.3.3.a. The resulting points were stored in one file.

3.4.4.3 Documentation

The folder 03_DOCUMENTATION groups contains the material that describes the project and its results. It includes the written and graphical reports in pdf format and the animated sequence file in mp4 format. The files are archived using (1) the date of issue (2) the name of the contractor (3) the name of the site and (4) the type of document. For the written and graphical reports, two versions are presented. The first version is the one originally produced at the execution of the project presented in Appendices A and C. The second version is the one created during this research.

3.4.4.4 The 3D model

The model is described in section 3.4.3. It was delivered in a binary format and was stored in the folde 04_MODEL.

Chapter 4

Case study 2: Combined interpretation of intensive surface sampling and geophysical data

This case study is centred on the use of exploration surveys in archaeology. Based on the scale and on the resolution of the exploration, the surveys can be used to identify possible archaeological sites and then to characterise and document them. More specifically, the combination of surface sampling and geophysical data is considered. The chapter includes the description of the methodology applied for the creation of a synthetic interpretation gathered in a GIS model. The methodology was applied on the Roman villa of La Mina (Salamanca, Spain). The spatial model is composed of features with associated properties determined during the interpretation of the data. The features represent possible archaeological structures detected by a GPR survey. The structures were characterised using the results of a magnetometer and a surface sampling survey.

The systematic recollection of sherds can help understanding the relations between sites, their extension, their sequence of occupation or their function. Nevertheless, it is limited by numerous factors as the sampling process, background scatter (Gallant, 1986) or the conditions of acquisition. The sampling process depends on the cultural and geological context. It determines the fraction of sherds available during the survey and cannot be controlled (Gregory and Kardulias, 1990). These considerations limit the interpretation of the results and have to be considered when evaluating the relation between superficial sherds and underlying structures.

The underlying structures can be characterised in terms of extension and geometry by geophysical methods. These survey method also present limitations. The results

mainly depend on the contrast between the targets and the environment. The contrast will change with the nature of the target and of the environment, which means it is not constant within a site. This can lead to partial results. The contrast will also depend on the used method. At the end, negative results will not imply the absence of cultural remains (Bonsall et al., 2014). It can only mean that in the context of the site and with the chosen methods no cultural feature could be detected. Even with positive results, the variable contrast makes the interpretation incomplete.

In order to compensate the limitations of the survey methods, a multi-method approach was proposed. The first information was obtained using large scale surveys as aerial photographs and surface sampling. Once the villa was identified, geophysical and intensive surface sampling surveys were applied. Multi-method projects are recommended in order to cross information and improve the interpretation of the individual surveys.

4.1 Summary

Objectives

The area of the Roman villa of La Mina was explored in order to delimit the extension of the site, understand its geometry and characterise its sequence of occupation.

Applied strategy

Based on the interpretation of aerial photographs and a first surface sampling survey, a magnetometer survey was applied for the delimitation of the site. A ground penetrating radar survey was then applied for the description of the detected structures. Finally, an intensive surface sampling survey was applied for the characterisation of the sequence of occupation.

Main results

All methods showed that the site was not fully explored and extends in the north-western direction. Magnetic and GPR data allowed the identification of a heating system which could correspond to the main occupied area. The magnetic and surface sampling data helped identifying a dump deposit at the south-eastern part of the

site. The surface sampling indicated a main occupation during the late Roman Empire with a possible continuity during the Visigoth period.

Main limitations

One of the main limitations of the survey was the secondary road that goes through the settlement. It separates the site in two parts with no clear connexion. In addition, all methods showed a poor contrast between the cultural features and the environment. This limited the definition of the results and their interpretation. Finally, the limited resources of the project had an impact on the covered extension and on the resolution. The limited extension combined with a poor resolution limited the interpretation of the results.

Methods	Resolution (m)	Surface covered	System
Magnetic	0.5x0.25	10 850 m ²	Bartington Grad 601 - 1m vertical separation between sensors
	Processing (1) range limitation (2) positioning correction (3) average removal per grid (4) average removal per line (5) smoothing (6) interpolation to a final resolution of 0.25x0.25m		
Ground Penetrating Radar (GPR)	0.40x0.02x0.006	4 900 m ²	GSSI SIR300 270MHz
	Processing (1) correction of the position of the surface (2) gain: compensation of the attenuation with depth (3) transformation in reflected magnitude (4) filtering of striping (5) Filtering of short range noise and interpolation to a final resolution of 0.20x0.20m		
Surface Sampling	10.00x10.00	7 290 m ²	-
	Processing (1) classification (2) numerical analysis (3) spatial representation (4) random noise removal (5) interpolation to a resolution of 1.00x1.00m		
	Results		
Combined	(1) the site is larger than the expected dimensions (2) the heating system of the villa was identified (3) a large deposit outside the villa was detected (4) the main occupation of the site was during the late Roman Emire possibly continued during the Visigoth period		

Table 4.1: Main characteristics and results of the survey of the Roman villa of La Mina.

4.2 Field

4.2.1 The design of the strategy

4.2.1.1 *Archaeological context*

The archaeological site of La Mina was discovered during the surveys of Fernández Moyano in 1994. It was revealed by an aerial photograph survey conducted between 1995 and 1997. Its classification as Roman villa is based on the ceramic context identified from prior works of surface sampling (Ariño, 2006; Ariño et al., 2002; Ariño and Rodríguez Hernández, 1998). During the surface sampling surveys, abundant material was recollected including *tebula* fragments, limestone windmill fragments and constructive elements. The remains of a built aqueduct that carried water to the villa from a spring located about 2,200 m to the south were also discovered. The presence of the aqueduct characterised the site of La Mina as monumental.

The aerial photograph taken on 17th April 1997 (Figure 4.1) shows an exposed large pool covered with *opus caementicium* (lime mortar). Its dimensions are of 11x14x1.10m. Its walls are 0.65m wide. It was interpreted as a possible cistern. During a visit of the site in the year 2000, it was documented that the pool had been recovered with soil. The aerial photograph also shows several possible buried structures with the same orientation and regularity arranged around the cistern.

4.2.1.2 *Objectives of the project*

The site of La Mina was one of the sites selected for the research project of “Poblamiento y cultura material entre la Antigüedad Tardía y la Alta Edad Media en el valle medio del Duero” (HAR2008-00096/HIST). The project was directed by Dr. Jesús Liz and Dr. Enrique Ariño. The overall objective was the characterisation of the sequence of occupation of the area. La Mina was one of the sites selected to characterise the Roman period (Ariño et al., 2015).

Given the context of the site, the archaeological team considered the possibility of conducting prospection surveys in order to further document it. The main objectives were to delimit the extension of the site and to characterise possible constructive features. The project included geophysical and surface sampling surveys. The combined approach aimed to analyse the relation between the sherds dispersion and



Figure 4.1: Aerial photograph dated from 1997 (Enrique Ariño) with visible excavated area (red) and traces of underlying structures (blue).

the underlying structures detected by geophysics. The results could allow a larger perspective of the site, its geometry and its main characteristics in terms of spatial and temporal occupation. The analysis was used to produce a synthetic map of the combined information.

4.2.1.3 *Applied methodology*

The exploration of the site involved two parts (1) the geophysical exploration (2) the surface sampling survey. The two surveys were executed simultaneously.

As the objectives of the geophysical survey were both to delimit the site and to describe its structures, a multi-method strategy was proposed. The extension of the site estimated from previous works suggested the use of a fast system for the delimitation. The site is located in a cultivated plain with no main obstacles and no electromagnetic interference source beside the main road crossing it. In this context, a gradiometer survey was proposed in order to identify the areas of most archaeological interest. A standard resolution of 0.50x0.25m was set for the survey.

The proposed approach consisted of dedicating the first day of survey to cover a first extension with the gradiometer. The decision on the strategy for the rest of the survey would be based on these first results. In the case of an adequate description of constructive features by the gradiometer data, the survey would be completed with this method in order to explore the largest area possible. If the constructive features are not well described, an alternative method would be used. In the case of La Mina, ground penetrating data was proposed. In order to cover the largest possible area, the proposed spatial resolution was of 0.40x0.02m.

In parallel to the geophysical survey, a surface sampling survey was conducted using the same referencing system as the one used for geophysics. The population to be sampled was defined by the boundaries of the geophysical survey. The survey was designed taking squares of 10x10m as work unit. Each of the 10x10m acquisition square was surveyed by 5 individuals, covering a 2 m strip each. All the sherds found during the survey were to be collected with no discrimination of type or period.

4.2.1.4 Feasibility

The main limitations of the project were (1) the road that crosses the site (Figure 4.1), (2) budget considerations and (3) ploughing lines.

1. The road had two main drawbacks. It left a 16 meter wide blank stripe in the centre of the explored area and it could introduce interferences from the passing of vehicles. As it was a secondary road, the latter effect was limited.
2. The budget available for the project allowed two days of surveys. Within this frame a compromise had to be found between the extension to explore and the applied spatial resolution.
3. The surveys were performed after the ploughing of the fields. The ploughing lines were visible on the surface and affected the data. In addition, the field was covered with small stones that had to be removed during the GPR survey (Figure 4.2).

4.2.2 Data acquisition

The aerial photographs taken at the site of La Mina enabled the identification of the nucleus of the site. Therefore the geophysical prospection was carried out around



Figure 4.2: Photographs of plough lines (left) and stones (right).

this central area. The first exploration done with the magnetic gradiometer did not allow a geometrical description of the constructive features. The areas that showed the greatest alteration were then selected for an extensive exploration with GPR. The area was simultaneously covered for surface sampling. The extensions the surveys are shown in Figure 4.3.

4.2.2.1 Gradiometer survey

The gradiometer survey was conducted with a Bartington Grad 601-dual system (Figure 4.4). It is equipped with two fluxgate sensors that measure the vertical variation of the magnetic field in a 1m vertical separation. The positioning of the data is based on regular time triggering. No encoder or GPS were used. The direction of the acquisition was SSE-NNW. The area to explore was divided in units of acquisition or grids which dimensions were of 30x30m. The position of the acquisition units is displayed in Figure 4.5a. The results showed a poor contrast between the features of interest and the background. The most altered areas were highlighted calculating the standard deviation of the data in a moving window of 2x2m and are indicated in Figure 4.5b. The total extension of the gradiometer survey was of 10850m².



Figure 4.3: Areas covered with the applied methods.

4.2.2.2 GPR survey

A GSSI SIR-3000 system was used for the GPR survey (Figure 4.4). It was equipped with an antenna having a central frequency of 270MHz. The central frequency was chosen for its depth of investigation and for its stability in rugged environments. The time window, which controls the time it takes the antenna to capture the reflections from the subsoil, was adjusted to 70 nanoseconds. It was estimated that with the chosen time window a maximum depth included between 2.5 and 3 meters could be reached. Each acquired trace included 512 samples. The spatial resolution of the data in the depth direction was then of around 0.005m. An acquisition bandpass was set to centre the signal and to remove part of the acquisition noise. The minimum bound was of 100MHz and the maximum of 600MHz. The direction of the acquisition was SSE-NNW. The data were acquired in zig-zag mode. This means that they were acquired in alternate directions. The total extension covered with GPR was of 4900m².



Figure 4.4: Used systems. Bartington gradiometer (left) GSSI GPR equipped with a 270 MHz antenna (right).

4.2.2.3 Surface sampling survey

The covered extension included fields of the same landlord that were ploughed before the survey. The topography of the site is displayed in Figure 4.6. It shows a slope of around 3 degrees in the south-eastern direction in the southern section of the explored area. The degree of visibility was considered homogeneous and did not affect the retrieval of the material. The total extension covered was of 7290m².

4.3 Data transformation

4.3.1 Individual processing

The details of the processing of the 3 datasets are described in this section. The objective is to prepare the data for their interpretation removing the acquisition artefacts and enhancing the visualisation of the data of interest. The gradiometer data were processed with the software Geoplot version 3.0 (Geoscan research). The GPR and surface sampling data were processed with the software Isatis v13.3 (Geovariances, 2013).

4.3.1.1 Gradiometer survey

The raw data are displayed in Figure 4.7a. They present several acquisition artefacts which are (1) positioning problems or stagger that was corrected shifting adjacent lines (2) a random noise (3) a mean difference between the acquisition units which is corrected removing the mean of each unit (4) and a line effect in the direction of

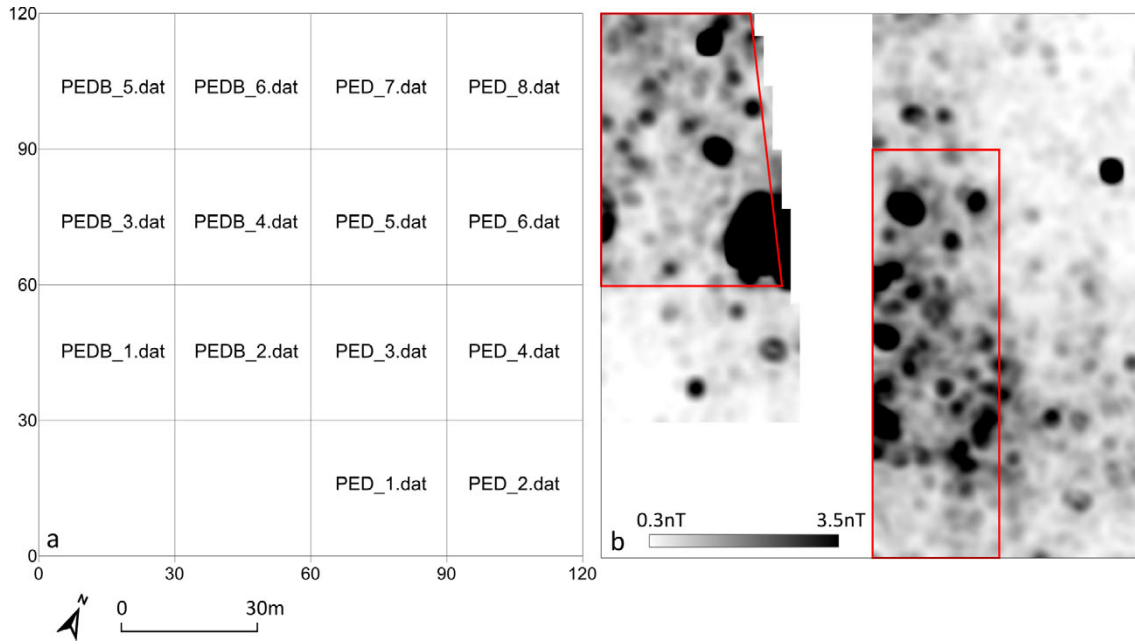


Figure 4.5: First results of the gradiometer survey. a) acquisition units b) standard deviation of the raw data computed in a 2m moving window. In red the area of interest surveyed with GPR.

acquisition corrected removing the mean of each line.

Two additional operations were applied in order to enhance the visualisation of the data: (1) a weighted mean value was computed in a moving window of 0.5×0.5 m (2) the data were interpolated in the direction perpendicular to the acquisition direction to a final resolution of 0.25×0.25 m. The final data are displayed in Figure 4.7b.

4.3.1.2 GPR survey

GPR data are 3D data and require a complex processing sequence. The processing was divided in two parts. First, the system specific processes were applied. Then, the acquisition problems were solved and the visualisation enhanced. The first part included (1) the correction of the position of the surface (2) gain: compensation of the attenuation of the signal with depth (3) the transformation into reflected magnitudes.

1. Due to the movement of the antenna on the ground and the presence of obstacles, GPR data can present an offset in the direction of propagation. This offset had to be corrected. The correction was applied detecting the position of the maximum peak for each acquired trace. It was set as the position of the ground surface (Yelf and Yelf, 2006).



Figure 4.6: Topography of the explored area. Contour lines (in white) were computed every 0.2m. The red arrow indicates the direction of the slope with a maximum of 3 degrees.

2. When propagating in the soil, the electromagnetic signal of the GPR is attenuated. The attenuation depends on the media and on the used frequency. The correction of the attenuation was applied in 3 steps. First, using the entire dataset, for each level of two-way travel time, the mean value of the absolute amplitude was calculated. It represents the average trace. The bipolar variations were then removed computing the average in a moving window including 17 samples (i.e. 2.2ns and 0.08m). The final curve represents the attenuation of the signal with depth. The amplitudes were then multiplied by the inverse of the curve in order to apply the gain.
3. The GPR signal is registered with varying amplitude and phase. This means that the signal is bipolar and that one event as a stratigraphic change is represented by negative and positive extrema. In order to visualize the data, the positive envelope of the signal was computed. Several methods can be applied (Goodman, 1995). In the case of la Mina the magnitude of the data

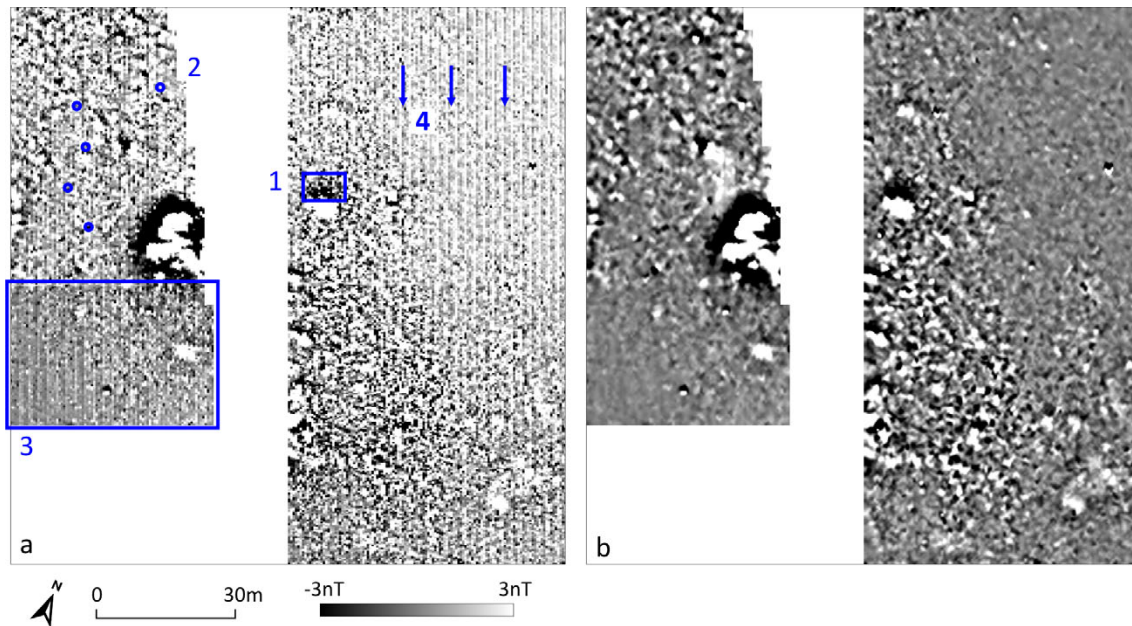


Figure 4.7: Processing of the magnetic data a) identified acquisition artefacts b) processed data.

was used. It was computed by calculating the average of the absolute value of the amplitude in a moving window. The size of the moving window was determined using the first peak of the experimental variogram in the time direction (Tamba, 2012) and was of 17 samples (i.e. 2.2ns and 0.08m). The resulting data are displayed in Figure 4.8a.

In this map representation of the survey the acquisition artefacts are visible. They consist of an edge discontinuity between the units of acquisition, the effect of the ploughing lines and of a random noise due to contact problems with the ground surface and rugged movements of the antenna. In addition, large scale variations probably related to the geological background are visible and partially mask the smaller variations of the features of interest. The following processing steps were applied in order to remove the acquisition artefacts and enhance the visualisation.

4. In order to correct the edge discontinuity, a small area of 0.20m around the edge was blanked and the correspondent data were interpolated.
5. The impact of the ploughing lines was removed applying a procedure described by Oimoen (Oimoen, 2000). The procedure consists of (1) computing the average value in a moving window in the direction of the effect to remove. The size of the moving window was set to the mean size of the effect of the

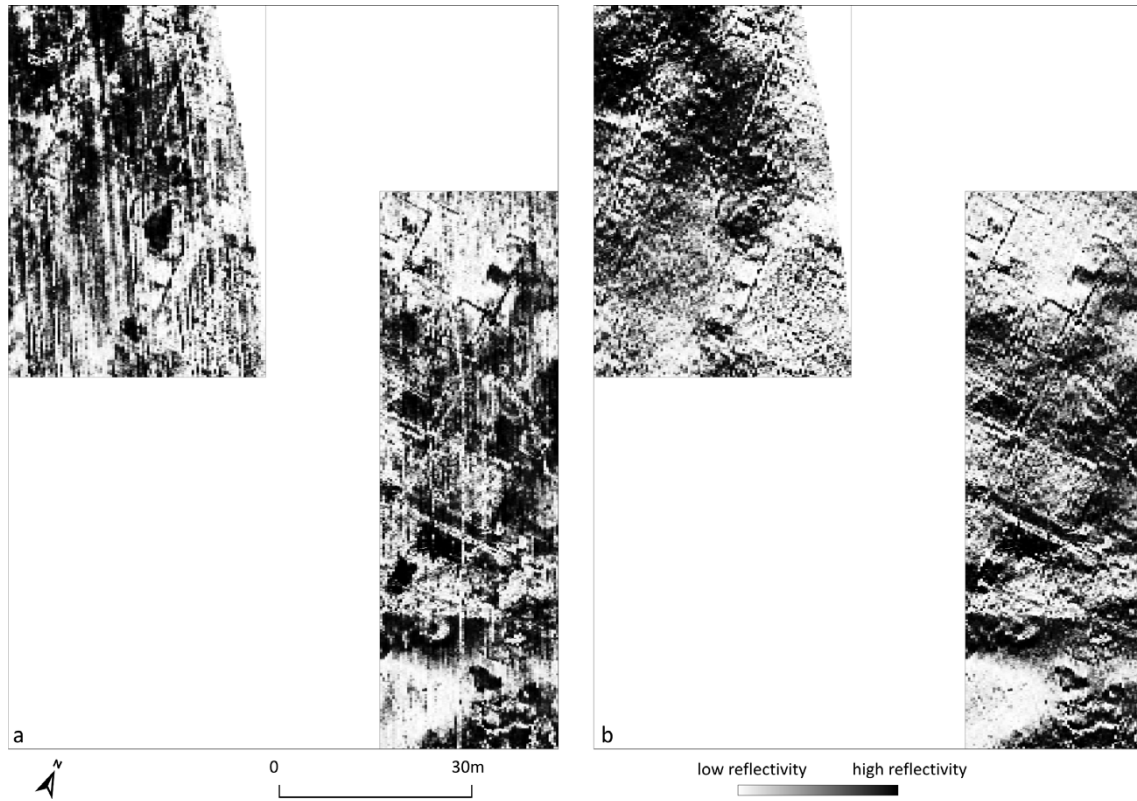


Figure 4.8: GPR data - First processing phase a) acquisition data with artefacts b) removing ploughing lines.

line in the direction of acquisition which was of 4m. (2) applying on the resulting data an average in the orthogonal direction and subtract it from (1). (3) subtract the resulting data from the original data. The results are displayed in Figure 4.8b.

6. The large scale variations were removed by computing the average value in a moving window of diameter 8.0x8.0m and by subtracting the result from the input data. The resulting data are shown in Figure 4.9a.
7. The filtering of short range noise was applied using a factorial kriging algorithm (Bourges et al., 2012). It is based on the use of the experimental variogram described in Chapter 2 section 2.3.1c. The spatial components identified in the variogram were gathered in a model. The model was used for the computation of the weights of interpolation removing the spatial components associated to the acquisition noise. The western and eastern areas were processed separately. The used models are described in Table 4.2. The result of the filtering is displayed in Figure 4.9b.
8. The results were then interpolated to a final resolution of 0.20x0.20m in order

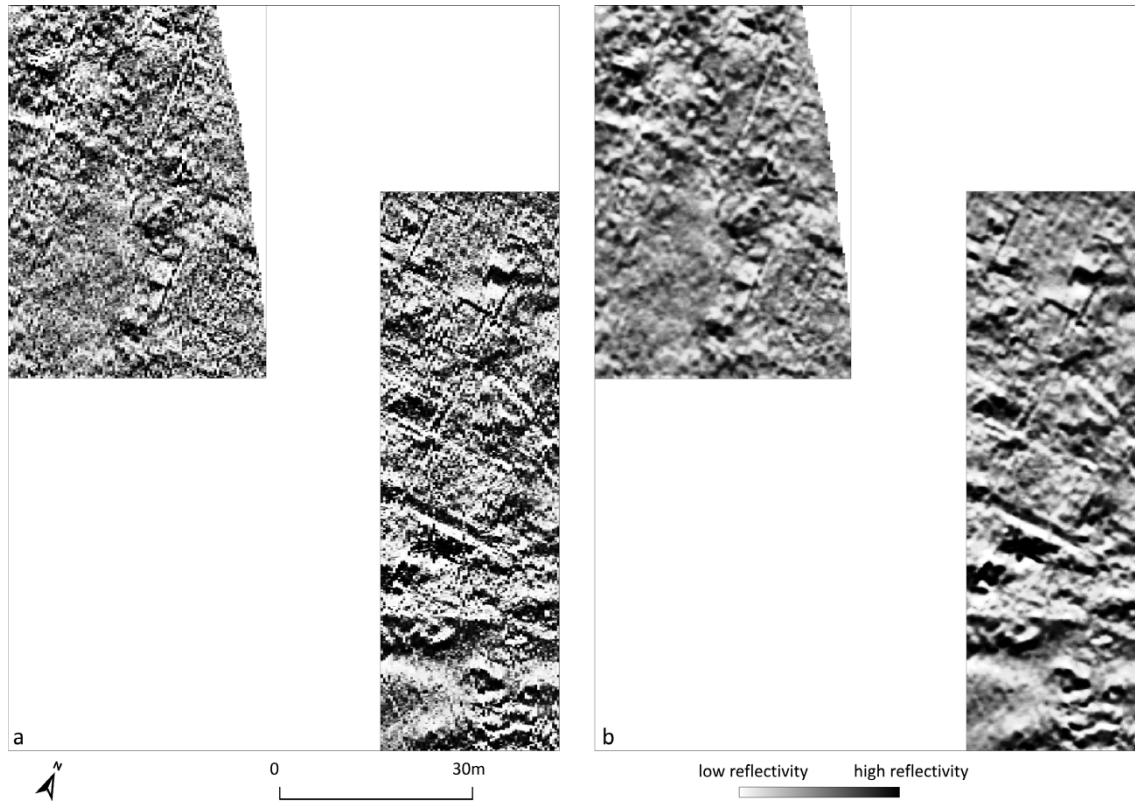


Figure 4.9: GPR data - Second processing phase a) removing large scale variations b) removing random noise.

to improve the visualisation of the data.

	Type	Range X	Range Y	Sill West	Sill East
S1	spherical	0.4	0.02	0.059	0.123
S2	spherical	0.4	0.4	1.000	1.000
S3	spherical	0.8	0.8	0.353	0.308
S4	spherical	1.6	1.6	0.235	0.154
S5	spherical	5	5	0.147	0.185

Table 4.2: Parameters of the used model for the factorial kriging of the GPR data. The structures S1 and S2 were considered as acquisition noise.

4.3.1.3 Surface sampling survey

The processing of the data recollected during the surface sampling survey required the classification of the sherds and their spatial representation. The classification to be used was based on the chronological markers defined for the characterisation of the sequence of occupation (Ariño and Dahí, 2012; Rodríguez, 1985). They are presented in Table 4.3.

Sherd type	Chronology
HTS (pt): Hispanic terra sigillata (plain type)	I AD - III AD
HTS (mt): Hispanic terra sigillata (mould type)	I AD - III AD
LHTS (pt): Late Hispanic terra sigillata (plain type)	IV -VI AD
LHTS (mt): Late Hispanic terra sigillata (mould type)	starts at 375-380 AD
T-WP: Thin-walled pottery	II BC - III AD
CW: Common ware	no chronology
CCW: Common cooking ware	no chronology but very abundant between IV and VIII AD
CCWb: Common cooking ware decorated with burnished lines	starts at VI AD

Table 4.3: Chronological markers used for the classification of the recollected sherds.

The results of the classification are displayed in Figure 4.10 with the correspondent statistical analysis. Four of the chronological markers show significant populations: the common cooking ware, the late Hispanic terra sigillata, the mould type of the late Hispanic terra sigillata, and fine ware. Additional classes show significant populations. The common ware was not considered as it is not specific to a chronology or use. The modern sherds data were analysed in order to use them as a reference of random data. The last considered category was the one with the total number of recollected sherds. This last category is highly correlated to the common cooking ware category as it is the most populated one.

The selected categories were spatially represented (Figure 4.11) and processed. The processing consisted of (1) the computation of the large scale variations of the data (2) the visualisation of the resulting difference and (3) the interpolation of the trend data to a finer resolution of 1.00x1.00m.

1. The large scale variations of the data were computed using a second degree polynomial algorithm for the calculation of the weights of interpolation in a moving window of diameter 40x40m (Figure 4.12).
2. The large scales variations were then subtracted from the original data in order to visualise the residuals. This residual part can be associated to the random noise of the survey.

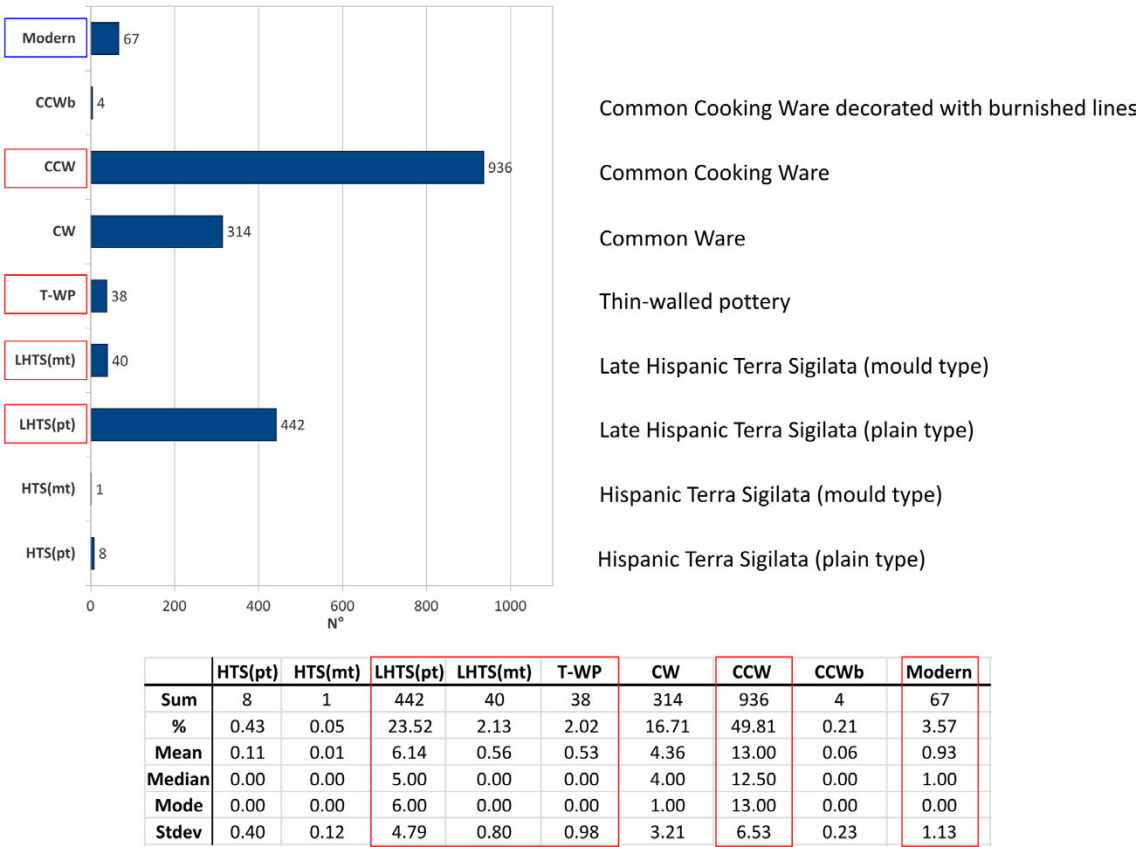


Figure 4.10: Results of the surface sampling survey and selected chronological markers.

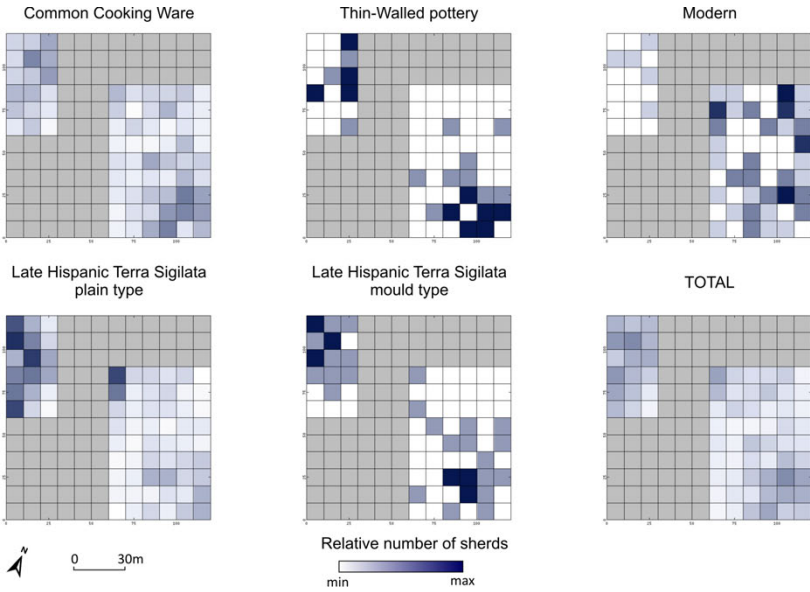


Figure 4.11: Spatial representation of the recollected sherds.

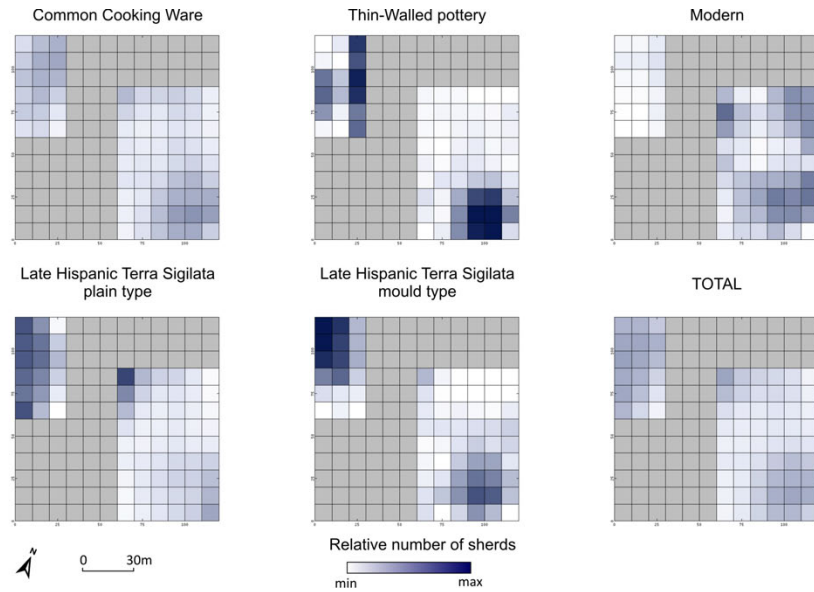


Figure 4.12: Filtered spatial representation of the recollected sherds.

3. The large scale variations were also interpolated to a finer resolution in order to be compared to the geophysical data (Figure 4.13).

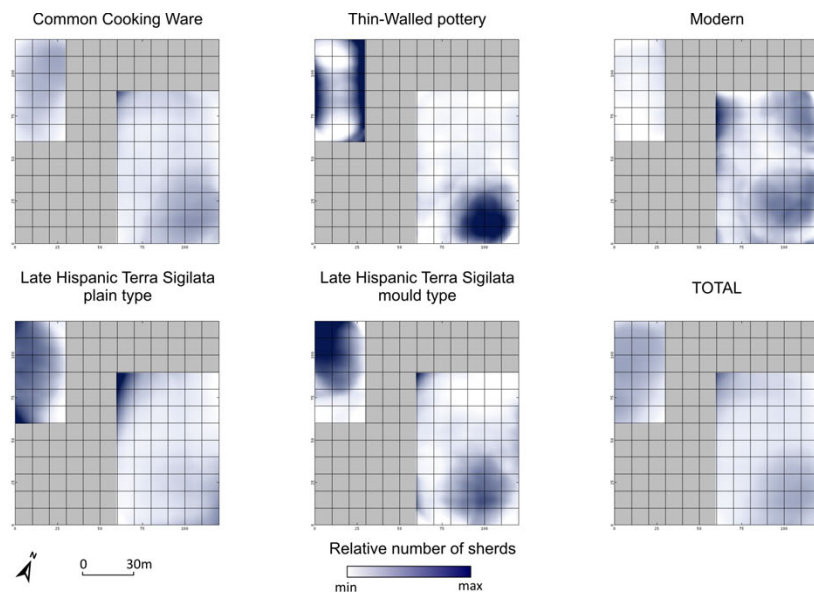


Figure 4.13: Interpolated spatial representation of the recollected sherds.

4.3.1.4 Georeferencing

The data integration consisted in changing the local system of coordinates into UTM coordinates. The main objective was to produce a georeferenced final dataset that that can be combined with existent materials as topographical information or aerial photographs, or new surveys.

ID	XUTM	YUTM	Xlocal	Ylocal
2	297521.15	4551501.09	60	0
3	297510.95	4551530.26	60	30
4	297501.42	4551559.52	60	60
6	297481.69	4551615.29	60	120
7	297538.14	4551632.06	120	120
8	297548.28	4551603.67	120	90
10	297569.98	4551546.29	120	30
11	297580.3	4551518.23	120	0
12	297551.73	4551509.57	90	0
13	297522.97	4551500.04	60	0
14	297485.36	4551519.85	30	30
15	297456.57	4551509.54	0	30
16	297445.11	4551538.63	0	60
17	297435.11	4551566.36	0	90
18	297425.46	4551594.29	0	120
19	297453.02	4551602.86	30	120
20	297539.3174	4551540.022	90	30

Table 4.4: UTM (EPSG 3042) and local coordinates of the reference points used for the georeferencing of the surveys. The highlighted points are the ones used for the computation of the parameters of transformation.

In order to transform the data, a series of points was referenced in both systems. Three of these points were used to determine the parameters of the affine transformation from the local to the UTM system. The computation of the parameters is described in equation 4.1.

$$X_{UTM} = a_1X_{local} + b_1Y_{local} + c_1 \quad Y_{UTM} = a_2X_{local} + b_2Y_{local} + c_2 \quad (4.1)$$

The referenced points were acquired during the survey using a GPS system with an average precision of 1.0m. The acquired points are displayed in Figure 4.14. The coordinates of the points are listed in Table 4.4.

The points with the best relative precision were selected for the transformation. The relative precision was estimated comparing the distance between the points computed in both reference systems. The parameters of the transformation using the three selected points are presented in Table 4.5.

The data to be transformed from the local system to the UTM system were the geophysical surveys and the results of the surface sampling. The geophysical data

X parameters labels	a1	b1	c1
X parameters values	0.945581	-0.325111	297463.968
Y parameters labels	a2	b2	c2
Y parameters values	0.325387	0.944778	4551482.393

Table 4.5: Parameters of the georeferencing as described in equation 4.1.

were transformed as rasters but the surface sampling data were processed as vectorial information due to their coarse resolution.



Figure 4.14: GPS points selected for the georeferencing of the surveys.

4.3.2 Data interpretation

The processing of the data enabled a visualisation limiting the noise acquisition. It also enabled the enhancement of the features of interest. These features must now be analysed and associated to an archaeological meaning. The surveys were first interpreted independently. The data and the interpretations of the different surveys were then compared to produce a combined interpretation.

4.3.2.1 *Gradiometer survey*

The interpretation of the results of the gradiometer survey was separated in two parts: (1) interpretation of focal features (2) interpretation of linear features.

1. The focal features were classified using their polarity, their geometry, their orientation and their intensity. Five classes were defined. Features of high intensity, bipolar and of random orientation were associated to metals. Features of high intensity, bipolar, oriented in the north direction and with a characteristic geometry were associated to kilns. Features of limited intensity, bipolar, oriented in the north direction and with no defined geometry were associated to combustions. And the features presenting a positive polarity and with a circular geometry were associated to silos. An additional class was created for remarkable features that could not be classified. The classes are resumed in Table 4.6.

The results of the interpretation are displayed in Figure 4.15. The dispersion of metals visible on the map is random with no area with higher concentrations. Most of the metals could be explained by recent contaminations.

The combustions are either outside the limits of the complementary surveys or near the limits of the gradiometer survey and were not further characterised. The most remarkable features, i.e. kilns and silos, were labelled.

The kiln k1 presents a minimum of -11nT/m , a maximum of 25nT/m and a standard deviation of 7.4nT/m . The dimensions of the magnetic signature are of around $6\text{m} \times 6\text{m}$. They are function of the properties of the kiln and of the depth at which it is located. With a feature of these characteristics it was estimated that it is deep and that it reached high temperatures.

The kiln k2 presents a minimum of -10nT/m , a maximum of 27nT/m and a standard deviation of 10.2nT/m . The dimensions of the magnetic signature are of around $3\text{m} \times 3\text{m}$. With a feature of these characteristics it was estimated that it is shallow and that it reached high temperatures.

The silo s1 presents a minimum of 1nT/m , a maximum of 7nT/m and a standard deviation of 1.4nT/m . The magnetic signature has a circular shape with a radius of around 1.5m . It was estimated that its source is deep and contains a large volume of soil.

Class	intensity	polarity	orientation	geometry
kiln	high	bipolar	North	defined
combustion	medium	bipolar	North	undefined
metal	high	bipolar	random	undefined
silo	low	positive	none	circular
undertermined	-	-	-	-

Table 4.6: Classes used for the interpretation of focal anomalies of the magnetic survey.

2. The results of the gradiometer survey did not show clear geometrical features. The constructive structures of the site, that was expected to be a Roman villa, were not visible. The signal was heterogeneous and indicated areas with higher alterations. Nevertheless, some elements of interest were described.

The features were classified in two classes using their polarity which can be positive or negative. The main negative feature was associated to the pool that was excavated and documented. It was labelled L1. The intensity of the signal is high. This could mean that the walls of the pool were consolidated before they were buried. L1 delimits an area that is heterogeneous and mostly positive. It could be explained by metals left during the excavation and by the caementicum floor that is highly magnetic.

L2 was defined as a 26x15m area. Its signal is week and is mainly visible in the northern and eastern parts of the area. Internal divisions cannot be discarded. It could indicate an area either with a higher concentration of constructive features or with constructive elements built with a different material and with different characteristics than in the rest of the site.

L3 delimits an elliptic area of around 15x8m. The area presents a minimum of -2nT/m, a maximum of 6nT/m and a standard deviation of 1.5nT/m. It was associated to an accumulation of sediments which origin and function are not clear.

L4 is a positive feature that defines the southern limit of the altered area where L2 was located. Its geometry is irregular. Its total extension is of around 30m. No assumptions were made on its source.



Figure 4.15: Interpretation of the magnetic survey.

4.3.2.2 Constructive features

A sequence of horizontal sections was selected for the interpretation of the GPR data. It is displayed in Figure 4.16. Each section is representative of a depth interval of around 0.08m. They have a relative distance of 0.08m. The first section is representative of depths included between 0.33 and 0.41m and the last one, of depths included between 0.87 and 0.95m. The first selected section is where features start to be visible in the data. The main constructive features are visible in the third and fourth sections, for depths included between 0.48 and 0.64m. The following sections show deeper layers relative to the main structures and the last section shows the limits of penetration of the signal. This means that data below a depth of 0.95m could not be retrieved.

Based on the selected sections, the explored extension was divided in several areas. The zonation was performed based on the geometrical characteristics of the identified structures. The limits of the areas are shown in Figure 4.17. The results of the interpretation of each area is presented separately.

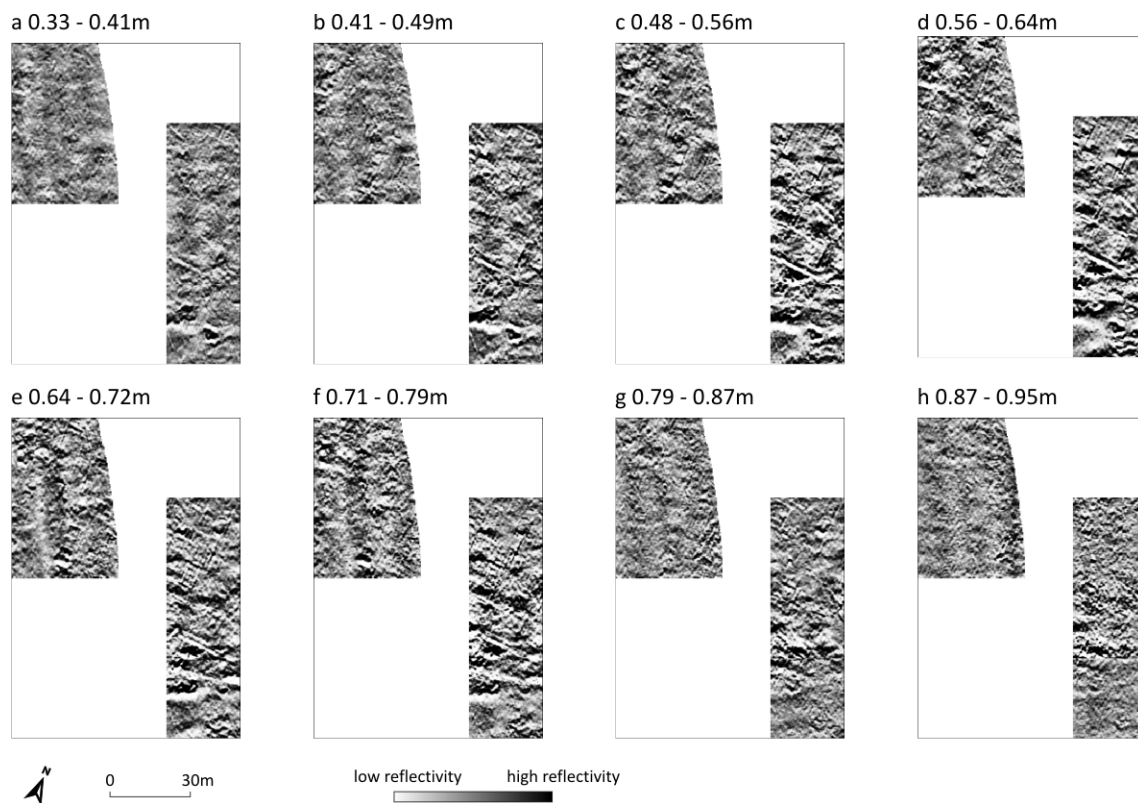


Figure 4.16: Sequence of 8 depth slices of the final processed GPR data from a depth of 0.33m to a depth of 0.95m.

Area 1 (Figure 4.18): this area corresponds to the previously excavated structures where a pool was detected. The description of this area is incomplete as it is interrupted by the road. The dimensions of the defined area is of a minimum 25 meters in the direction NE-SW and of 28 meters in the direction SE-NW. A group of structures with internal divisions (1.1) was identified in the western part. It is 20 meters long and 5 meters wide. It could be constituted by 5 independent rooms. One of the rooms may conserve a paved floor as its interior appears as reflective in the horizontal section 5 (Figure 4.16e). The rest of the walls delimiting this space are not clearly defined.

Area 2 (Figure 4.19): Area 2 is located north-west from area 1. Their connexion is not clearly defined. The structures visible in area 2 are very subtle and can only be visualised in the fourth horizontal section (Figure 4.16d). The main structure (2.1) could be interpreted as a thin wall of around 20 meters with an opening of 3.5 meters.

Area 3 and 4 (Figure 4.20): These areas are located in the most western part of



Figure 4.17: Areas defined for the interpretation of the GPR data.

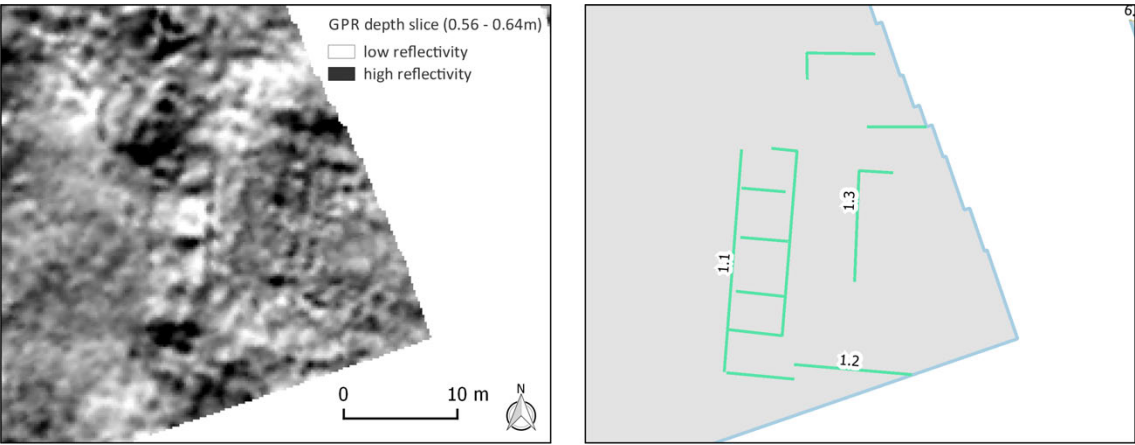


Figure 4.18: GPR Interpretation: area 1.

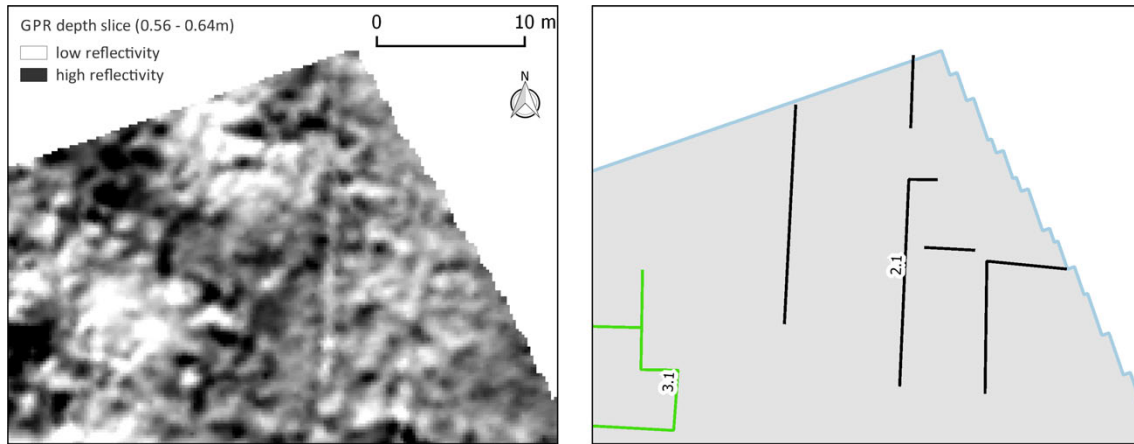


Figure 4.19: GPR interpretation: area 2.

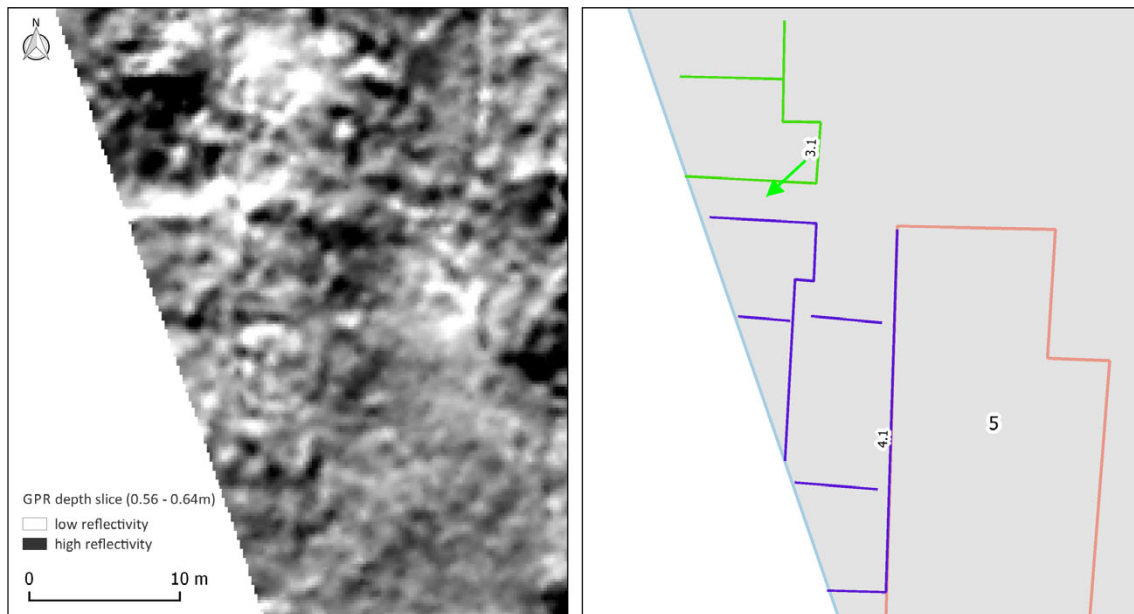


Figure 4.20: GPR interpretation: areas 3, 4 and 5.

the explored area. They are separated by an anomaly (3.1) of low reflectivity of 2.5 meters wide and around 15 meters long. 3.1 could correspond to a circulation area. Areas 3 and 4 only show partial results as the identified structures seem to continue outside the explored area. A larger context would be needed to further develop the interpretation.

Area 5 and 8 (Figure 4.20 and Figure 4.21): areas 5 and 8 are the two areas where no clear structures were identified. They could correspond to large open spaces. Area 5 is 15 meters wide and around 30 meters long. The extension of area 8 could not be defined as it continues outside the explored area.

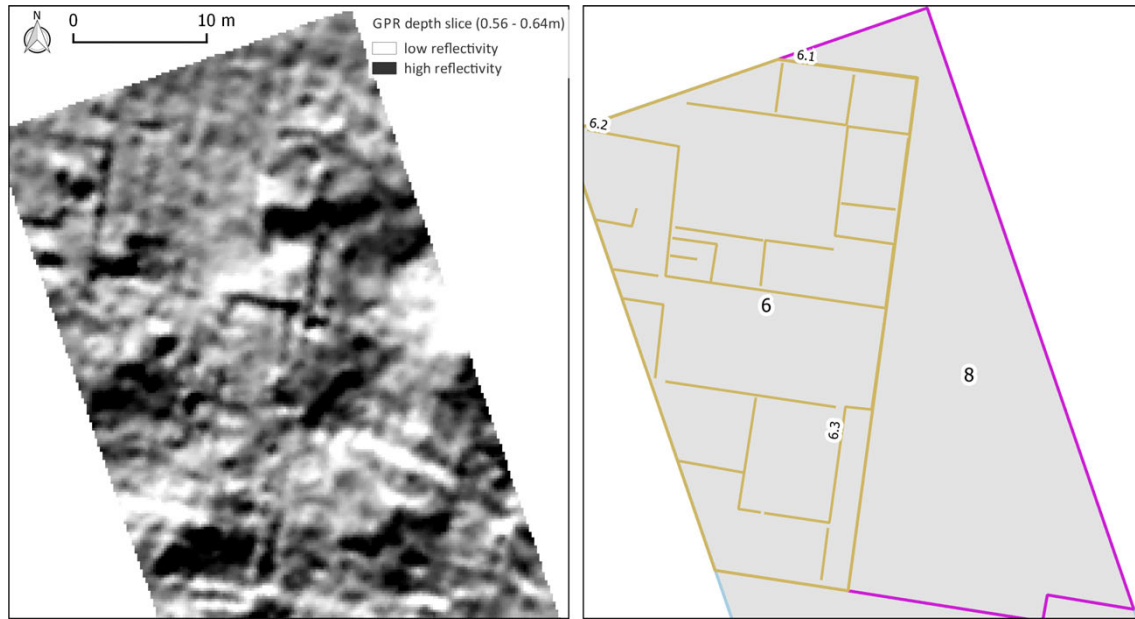


Figure 4.21: GPR interpretation: areas 6 and 8.

Area 6 and 7 (Figure 4.21 and Figure 4.22): area 6 and 7 present the clearest structures. They can be followed from section 2 and a depth of 0.40m to section 7 and a depth of 0.87m. At least two levels can be distinguished, the first one around a depth of 0.50m and underlying structures around a depth of 0.70m. In area 6 a large room can be identified (6.1). It is a square room of 17x17m and with several internal divisions. Additional rooms can be identified south (6.3) and west (6.2) of the main one 6.1. The area 7 is characterised by a large open space (7.2) 9 meters wide and at least 24 meters long. In addition, a linear anomaly was identified in section 5 (7.1) at a depth included between 0.64 and 0.72m. It goes from the road to the feature 7.3. The linear anomaly could be associated to a canalisation. It can be linked to at least another linear anomaly. South to the canalisation, two rectangular reflective areas were identified and associated to possible pavements or to collapsed areas. They could be surrounded by constructive features (7.4). The lower level shows a mesh of reflective points below some rooms in features 6.1, 6.3 and 7.3 .

Area 9 (Figure 4.22): area 9 is the most different one. No clear linear feature is visible. The most remarkable feature is a large reflective anomaly (9.1). It is delimited by a 2 meter wide low reflectivity band. It is in the direction of the linear anomaly 7.1. This could mean it could be related to the canalisation system. The rest of the area is characterised by large scale variations that could be associated to geological features.

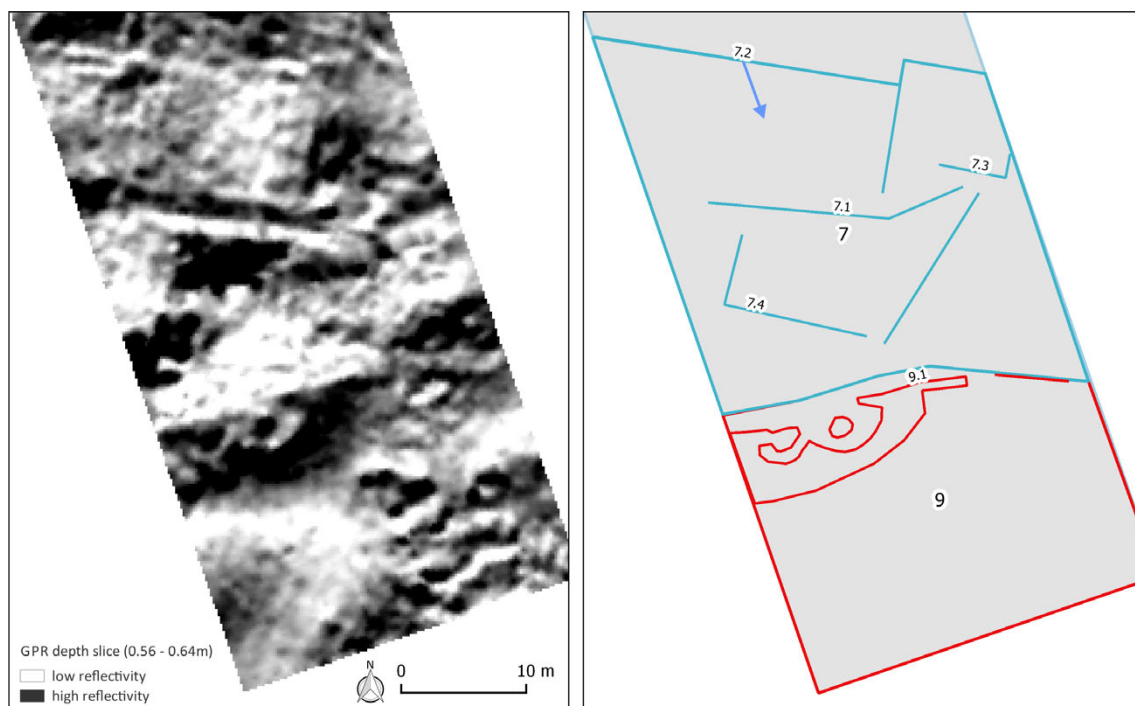


Figure 4.22: GPR interpretation: areas 7 and 9.

4.3.2.3 Chronology

The chronology of the explored area was studied using the surface sampling. The selected chronological markers were described in section 4.3.1c. Based on literature (Gregory and Kardulias, 1990), three concepts helped with the understanding of surface sampling data: (1) the absolute frequency: the proportion of sherds of each marker collected in the explored area, (2) the ubiquity: spatial representation of where sherds are found, (3) density: spatial representation of the relative frequencies of collected sherds in each unit of exploration. In addition, the degree of correlation between markers was studied, although the possibility to compare sherd categories is often doubted in literature (Orton, 2000). Classes of sherds vary in abundance, physical characteristics, fabrication process, use and abandon, which can all have a direct contribution on the available population of each marker and on the sampling fraction. Nevertheless, some classes can have similar characteristics as it is the case of the late hispanic terra sigilata plain and mould types. The correlation values between classes of sherds before and after the computation of the large scale variations (section 4.3.1c) are presented in Table 4.7.

The higher correlation values, included between 0.40 and 0.60, were found between the chronological markers, i.e. common cooking ware, late hispanic terra sigilata

Raw	T-W_P	CCW	Modern	LHTS-pt	LHTS-mt	Total
T-W_P	1.00	0.41	0.00	0.04	0.05	0.37
CCW		1.00	0.17	0.35	0.38	0.84
Modern			1.00	-0.07	0.00	0.16
LHTS-pt				1.00	0.40	0.74
LHTS-mt					1.00	0.46
Total						1.00
Trend10	T-W_P	CCW	Modern	LHTS-pt	LHTS-mt	Total
T-W_P	1.00	0.64	0.11	0.07	0.38	0.48
CCW		1.00	0.17	0.48	0.60	0.86
Modern			1.00	-0.27	-0.06	-0.01
LHTS-pt				1.00	0.57	0.83
LHTS-mt					1.00	0.68
Total						1.00

Table 4.7: Correlation values between classes of recollected sherds before (raw) and after (trend10) the computation of the large scale variations. The highest values are highlighted.

plain and mould types. The lowest correlation values were found for the fine ware and for the modern ware. The fine ware fraction is the lowest with the late hispanic terra sigilata mould type. Different cultural transforms for this special ware could be considered in or order to explain its behaviour. In addition, the fine ware is lighter and more easily fragmented which could have a direct impact on the visibility during the survey and on the movement of the ware in the superficial soil layers. The low correlation of all categories with the modern ware is very encouraging. It suggests that the distribution of the sherds is not homogeneous, not random and that differentiated processes occurred on the sherds in relation with the underlying structures.

Four areas were defined based on the spatial distribution of sherds and are displayed in Figure 4.23. Area A in the south-east is populated in all sherd classes, modern ware included. Area B is defined as the area where the lowest densities of sherds were found. Areas C and D are the areas where the chronological markers are the most populated and are separated by the road.

Area B corresponds to the area with a low density of sherds but also to a high density of constructive structures as seen in the GPR data. It encouraged studying

the spatial distribution of the data in combination with the slope variations of the explored area. The slope values are presented in Figure 4.6 with the contour lines of the height values. The general slope goes in the south-eastern direction with a maximum value of 3 degrees. The slope could explain the low density of sherds in area B and the sherd accumulation in area A.



Figure 4.23: Delimitation of the main areas identified in the surface sampling survey.

4.3.3 The combined approach

4.3.3.1 Combined interpretation

The first interpretation developed in section 4.3.2 is limited to the results of each independent survey. The results were then compared to produce a combined interpretation and the final model of the site. The combined interpretation had as main objective to complete the structural information acquired from the GPR data with qualitative information from the magnetic and surface sampling surveys.

One contribution of the interpretation of the magnetic survey was the identification of the two kilns k1 and k2 and of burnt areas. The kiln k1 is located in area 6

within the feature 6.1 and adjacent to features 6.2 and 6.3. At the same location, a reflective area is visible in the GPR data. It starts at a depth of around 0.30m and is visible until a depth of 0.95m. The feature is 4 meters wide and 5 meters long. At a depth of 0.75m, it is surrounded by a layer of low reflectivity where a mesh of reflective focal anomalies can be identified. The focal anomalies were associated to possible pylae and the kiln k1 was then associated to a furnace of a hypocausta or heating system. The kiln k2 is located 18m south from k1. It seems to be included in the same heating system. The same function was then attributed to this anomaly although the data in the GPR results are less clear. The anomaly starts at a deeper level (0.50m) but ends around 0.80m. Its geometry is not clearly defined but its dimensions could be of around 2x1m. Furthermore, it is located at the edge of the explored area which gives less context for interpretation. It could be a support furnace of smaller dimensions.

The magnetic data also showed an alignment of positive anomalies at the southern part of the explored area (feature L4 in Figure 4.15). This feature clearly delimits the GPR anomaly 9.1 at its northern part. It is not clear if these anomalies are related to the canalisations 7.1 (Figure 4.22) or are due to natural processes.

The last feature of interest for the combined interpretation in the magnetic data is feature L3. It was interpreted as an accumulation of sediments. It corresponds to area A of the surface sampling interpretation. In this area sherds of all types were found. It is globally parallel to the slope and was interpreted as a possible dump deposit.

Finally, all magnetic, GPR and surface sampling data show a high degree of alteration in the north-western part of the explored area. The altered areas is not delimited and seems to exceed the extension of the survey. The main conclusion was that all surveys indicated that the site was not fully delimited and extends in the north-western direction.

The combined interpretation lead to a synthetic map displayed in Figure 4.24. It shows the constructive features per zone with the contribution of the magnetic and the surface sampling surveys.

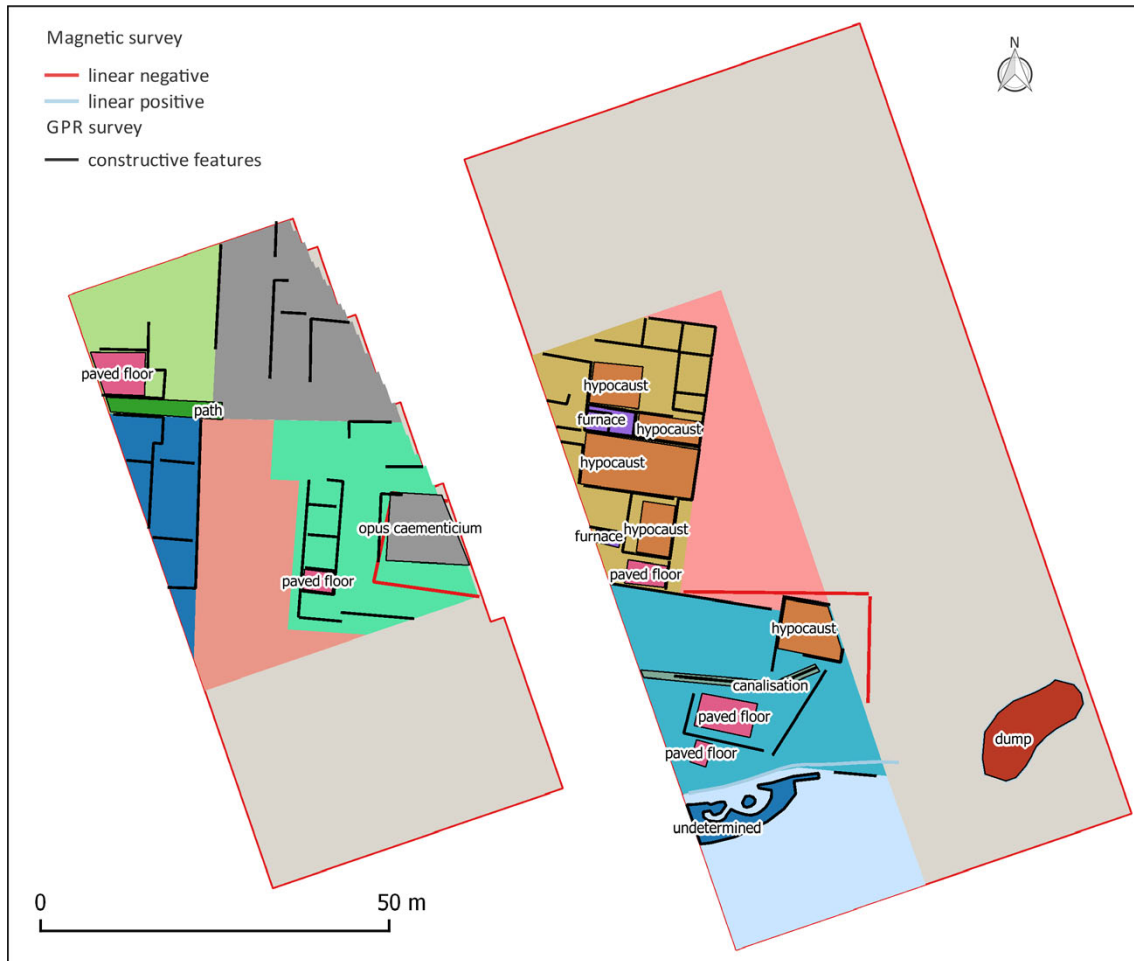


Figure 4.24: Synthetic map of the Roman villa of La Mina.

4.3.3.2 Limits and drawbacks

The interpretation of the results present limitations related to the design of the project and to the contrast of the data.

The survey of La Mina was scheduled within a broader project which aimed to study the occupation sequence in the valley of Douro (Ariño, 2006; Ariño et al., 2015). Within this perspective, a global understanding of the site was sufficient for the project. As a consequence, a limited budget was allocated to the survey of La Mina. It limited the explored area and did not allow delimiting the extension of the site. For the same reasons, the resolution of the GPR and surface sampling surveys (0.4x0.02 for GPR and 10x10 for surface sampling) were in the lower limit of usual standards. The results clearly give sufficient information of the global context of the site but the interpretation would have been more complete with a finer resolution, especially for the description of the constructive features.

The surface sampling methods have many limitations. Sherds recollected depend on cultural and natural processes that cannot be controlled. Furthermore, the results also strongly depend on the intensity of the survey. It can be evaluated that the collected samples represent a small fraction of the total population (1 to 5%). Some authors recommend repeating the survey after each ploughing event in order to increase the sampling fraction (Shott, 1995) which was not possible for this project. As a consequence, the surface sampling survey only gave some indications on (1) the main occupation period through the analysis of the absolute frequencies of the chronological markers, and (2) areas of interest of the site through the analysis of the ubiquity of the collected sherds.

The geophysical surveys showed a poor contrast and noisy data mostly affected by ploughing, scattered stones and sherds. The magnetic data were not able to show any constructive feature. Furthermore the main road that crosses the explored area gave a fragmented representation of the site and made the interpretation incomplete.

The combined interpretation enabled a global evaluation of the site through the comparison of the independent surveys. The combined approach was limited to the interpretation of the data. It was evaluated that a fusion or a mathematical combination of the data during the processing would not be efficient due the differences in nature of the signal and in resolution of the different surveys.

4.3.3.3 Conclusions of the project

In the absence of archaeological excavations, the most determinant aspect of the survey was its multi-method design. Each method had limitations but gave independent documentation of the site. The magnetic data allowed the identification of thermo-altered areas and of features possibly associated to the accumulation of sediments. The GPR data allowed describing the physical characteristics of the site. The surface sampling survey gave indications on the sequence of occupation. All three methods were coincident regarding the localisation of structures and the extension of the site. The combination of all contributions enabled the production of a synthetic map (Figure 4.24). It included the geometrical characteristics of the identified features and the assignation of an archaeological meaning based on the global assessment of the data.

The surface sampling surveys were used in two phases. The first survey was global

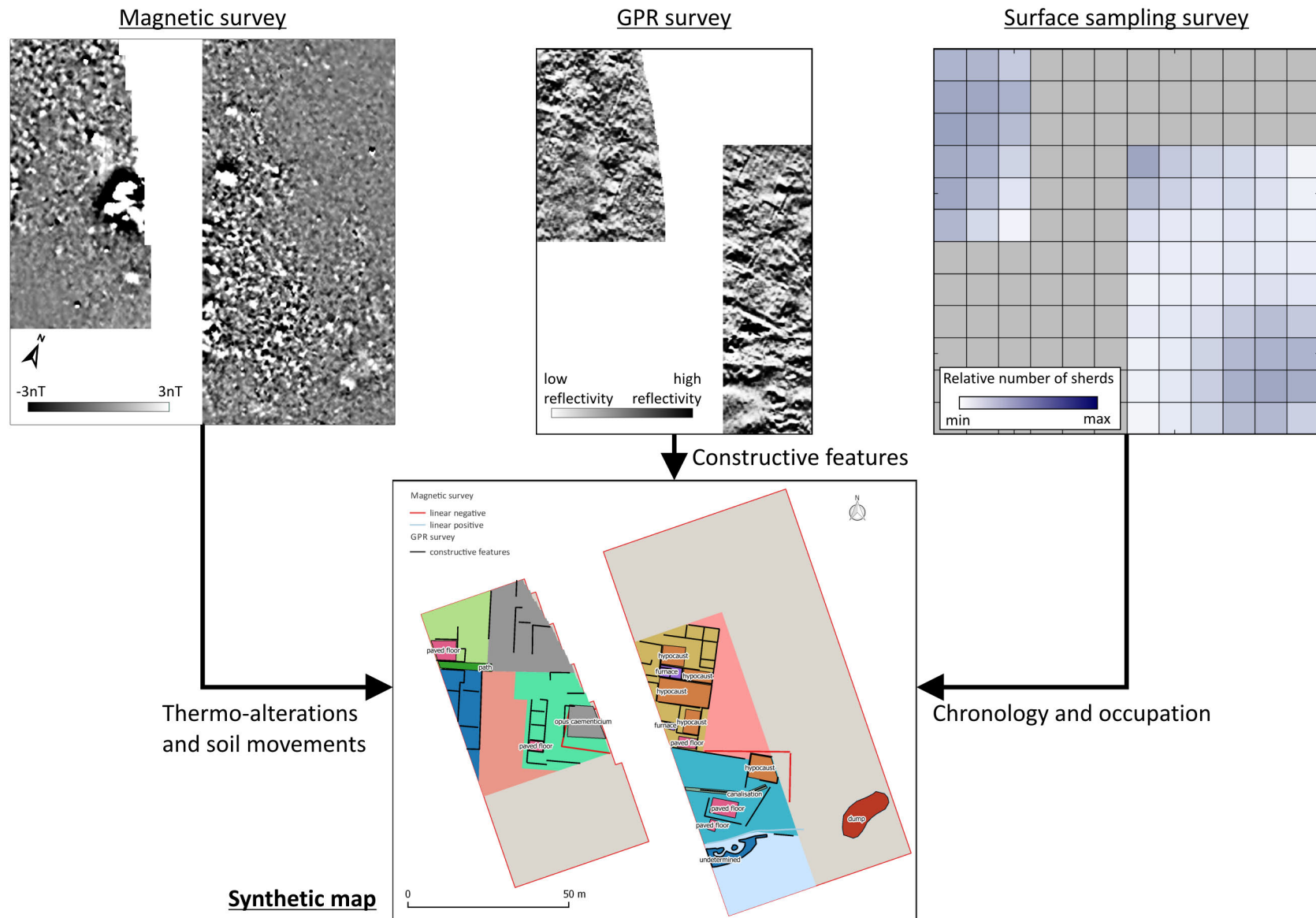
to get an indication on the chronology of the site. The second survey, systematic and extensive, had as objective to further document the site and understand the relation between the superficial material and the underlying structures. This relation, although altered by natural and cultural processes, gave a cultural context to the geophysical results. The archaeological record completed and supported the description of the physical properties of the soil. It helped with the interpretation and the assignment of an archaeological meaning to the physical anomalies.

In this perspective, the final result included both the detailed information of the independent surveys and the synthesis product of the combined interpretation. In the following section, the material produced to record and describe the survey will be described. A special attention will be given to the description of the final model that includes the results in an interactive format.

4.4 Data finalisation

4.4.1 Graphical report

4.1 Combined interpretation of intensive surface sampling and geophysical data

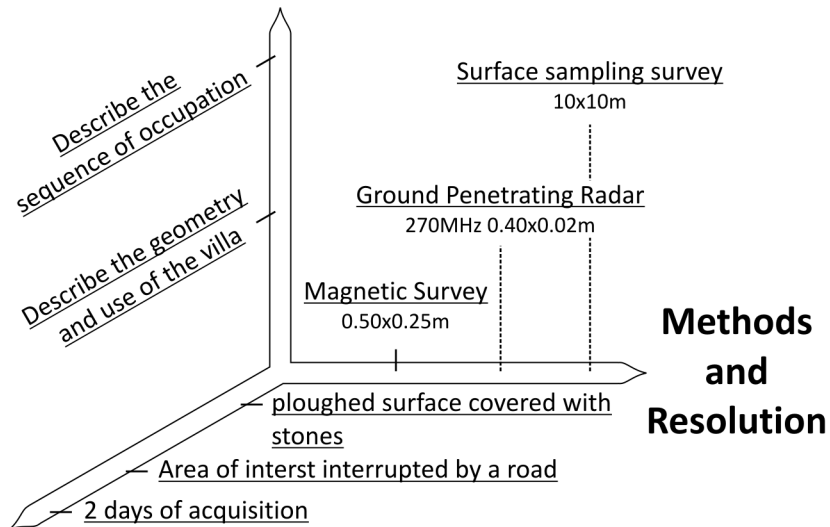


4.2 Design of the Project

Characterisation

Strategy

Objectives



Feasibility

The objective of the exploration the roman villa of “La Mina” was to characterise its sequence of occupation and to describe its geometry.

A magnetic survey was used for a first evaluation of the distribution of the site. A GPR survey was applied to describe the constructive features. A surface sampling survey was applied to characterise the chronology and the sequence of occupation of the site.

- Test the magnetic method as it is the fastest one
- Use the GPR method as a complementary method to describe the constructive features
- Use the surface sampling survey to characterise the sequence of occupation and the use of the site

The survey had in to be conducted in two days which limited the explored area. The ploughing of the ground surface and the scattered stones affected the quality of the acquired data. A secondary road interrupts the area of interest which affected the interpretation of the data.

4.3 Areas covered with the different survey methods



The magnetic survey (in red) was acquired the first day.

The GPR survey (in blue) was conducted the second day in the main areas of interest defined by the magnetic survey.

The surface sampling survey (in green) was conducted in parallel to the geophysical surveys using the same reference system.

Covered areas

Magnetic survey 10 850 m²

GPR survey 4 900 m²

Surface sampling survey 7 200 m²

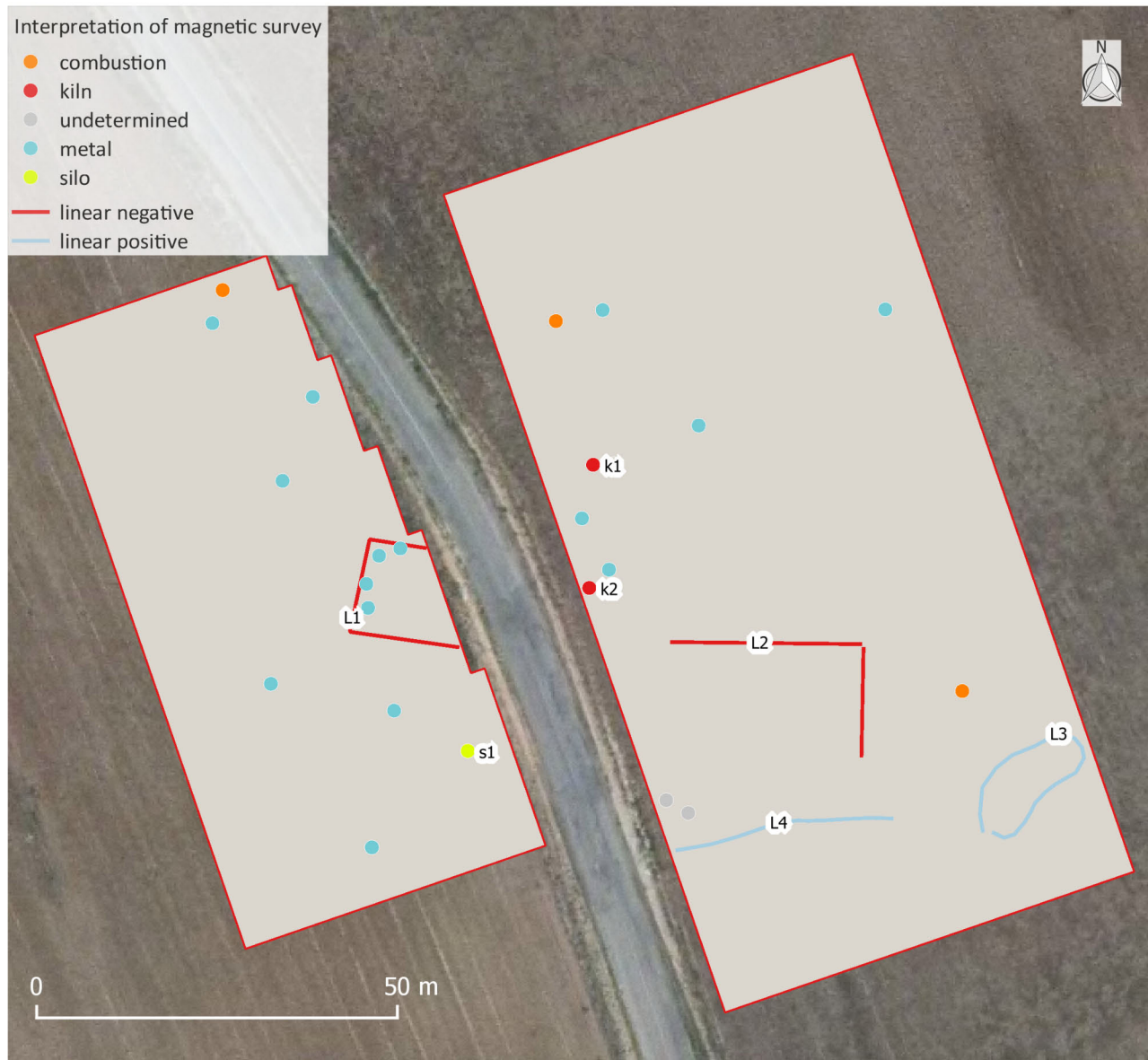
4.4 Results of the magnetic survey



The results could not describe constructive features. They mainly showed thermo-alterations and soil movements.

The area to be explored with GPR was decided based on the results of the magnetic survey.

4.5 Interpretation of the magnetic survey



The main results of the magnetic survey were:

- strong bipolar anomalies oriented in the north direction and identified as kilns (k1 and k2)
- linear negative anomalies L1 and L2 identified as constructive features
- an elliptic positive area L3 identified as an accumulation of sediments
- undetermined aligned positive anomalies L4

4.6 Results of the GPR survey



GPR data showed several constructive features.

The explored area was divided in 9 zones for a clearer interpretation of the results.

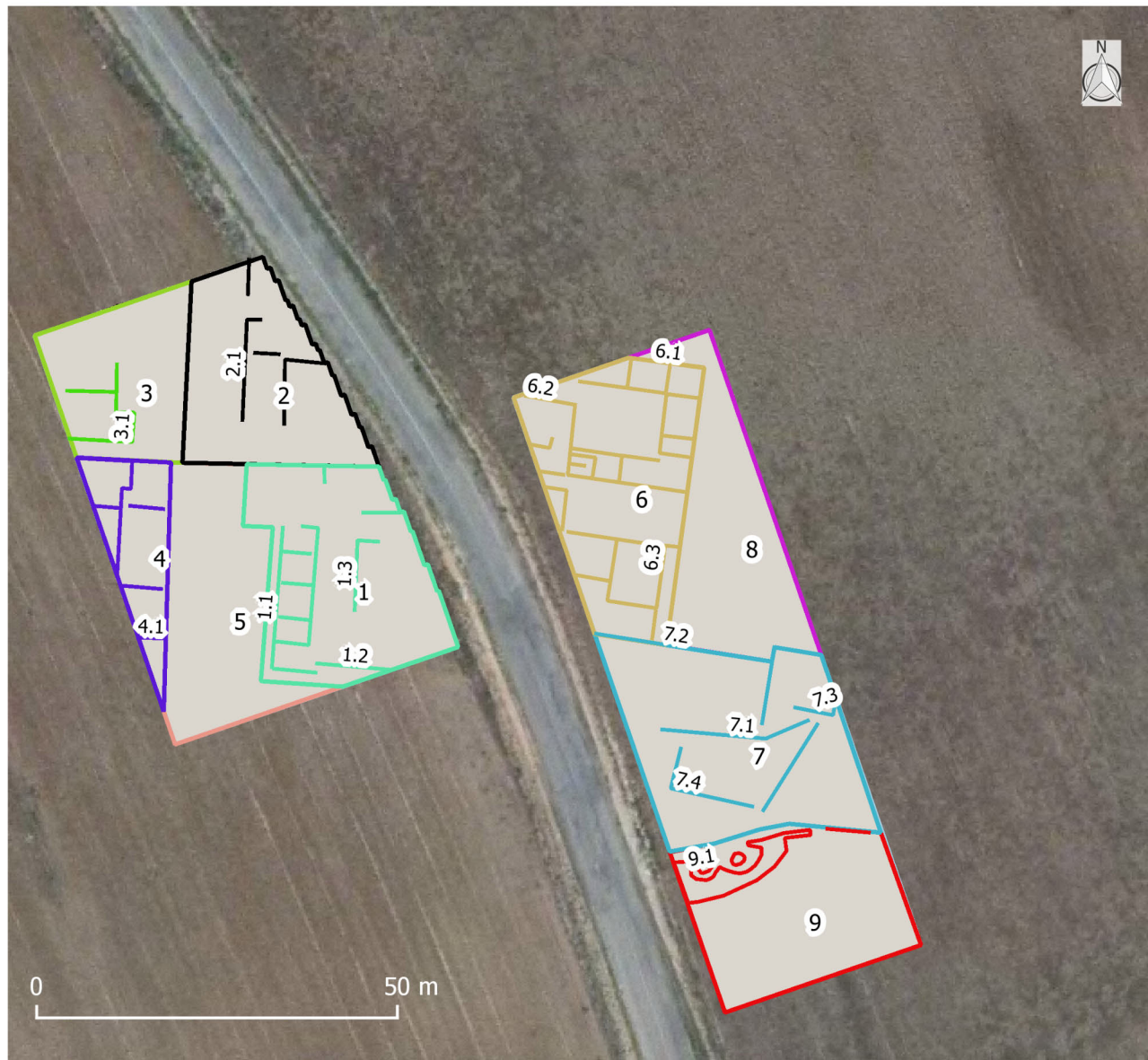
Area 1 corresponds to the area where the pool and the opus caementicium were excavated and documented.

Areas 2, 3, 4 6 and 7 show constructive features.

Areas 5 and 8 show no clear feature.

Area 9 show large scale variations.

4.7 Interpretation of the GPR survey



Feature 1.1 in area 1 shows several small rooms of around 5x5m parallel to the documented pool

Area 2: no clear connection with area 1 was identified. The anomalies are more subtle which could indicate they are in a worse state of conservation.

Areas 3 and 4 show constructive features but the interpretation was limited as these features seem to continue outside the explored area.

Area 6: it is the main space with the clearest features. Several rooms were identified.

The main feature of area 7 is the linear anomaly 7.1 associated to a possible canalisation

Area 9 shows a large reflective area possibly related to the canalisation 7.1

All features but feature 9.1 have the same orientation.

4.8 Surface sampling survey

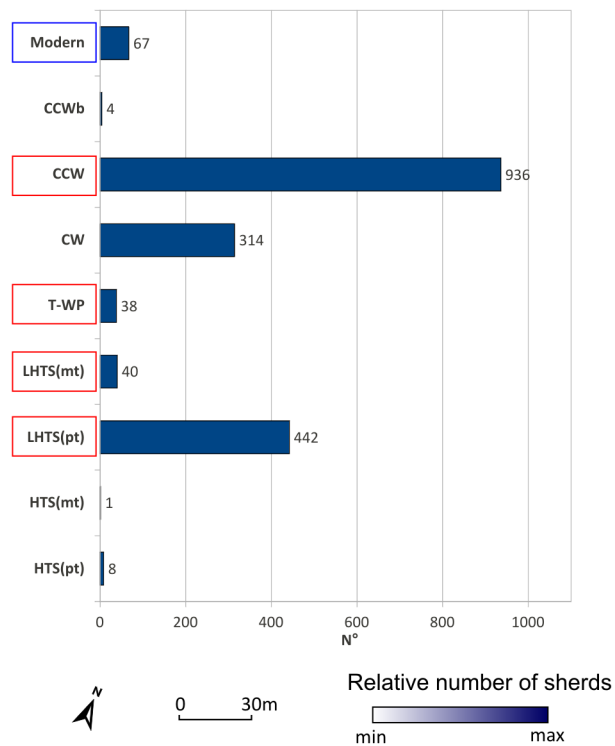


The surface sampling survey was conducted using labeled squares of 10x10m.

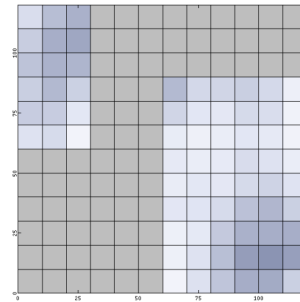
The total number of sherds in each square was collected and represented spatially.

The recollected sherds were analysed and classified using selected chronological markers.

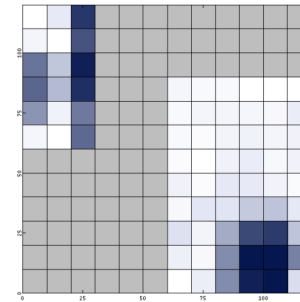
4.9 Chronological markers



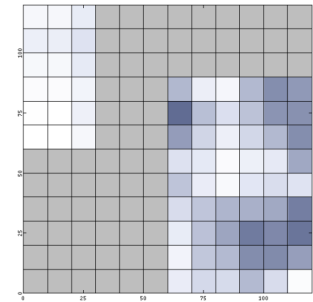
CCW: Common Cooking Ware



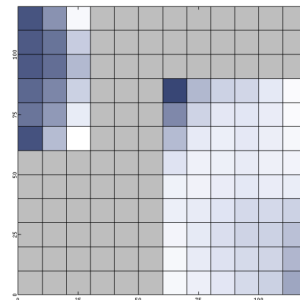
T-WP: Thin-Walled pottery



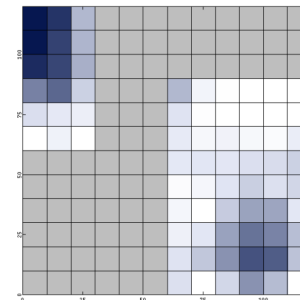
Modern



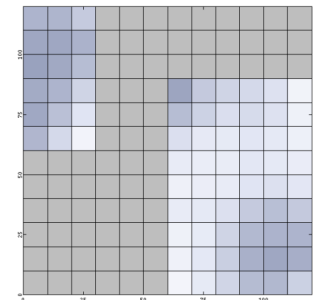
LHTS-pt: Late Hispanic Terra Sigilata-plain type



LHTS-mt: Late Hispanic Terra Sigilata-mould type



TOTAL



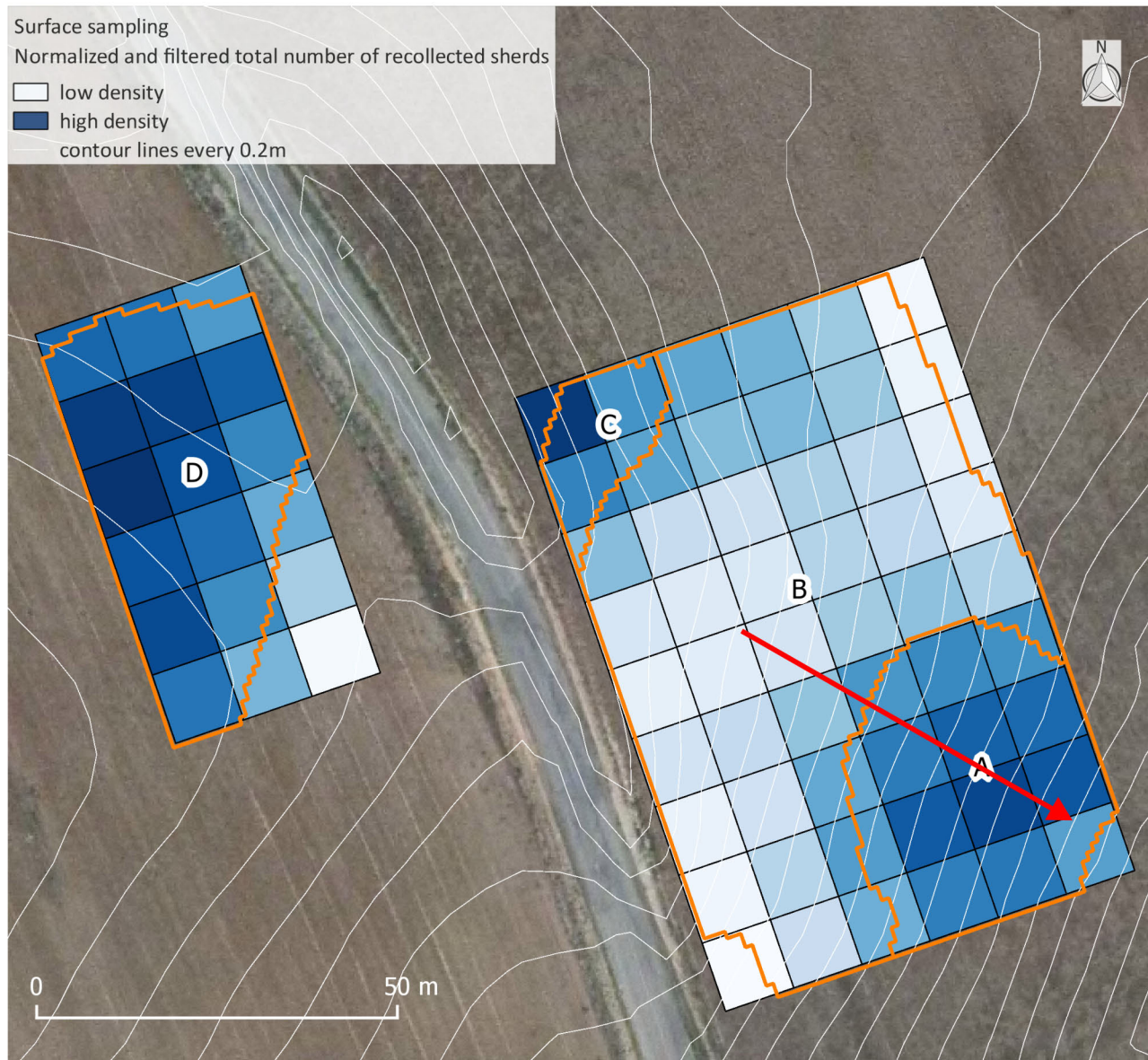
The largest population of sherds were analysed spatially.

The abundance of the Late Hispanic Terra Sigilata placed the main occupation of the site during the late roman empire (IVth-VIth AD).

The abundance of Common Cooking Ware may indicate a continuation of the occupation of the site until the VIIIth AD.

The modern sherds showed little correlation with the other populations. This suggests that the chronological markers are not randomly distributed.

4.10 Spatial interpretation of the surface sampling survey



The area covered by surface sampling was divided in four zones.

Zone A is populated for all sherds categories, modern sherds included. It is in the direction of the slope. The high density of sherds in this area and the low density of sherds in zone B could be explained by the topography.

Zone C and D show the occupation the site. It could not delimited as it exceeds the limits of the surveyed area.

4.11 Synthetic map



The interpretation of the different surveys were gathered in one synthetic map.

The combination of the magnetic and the GPR surveys enabled the identification of a heating system.

The combination of the magnetic survey with the surface sampling survey allowed characterising the south-eastern structure as a possible dump.

The extension of the site could not be determined as it is larger than the explored area.

4.4.2 Animated sequence

The animated sequence was divided in three parts

1. Part 1: description of the objectives, of the used methods and of the limitations of the project
2. Part 2: description of the individual surveys. It includes the magnetometer, the GPR and the surface sampling surveys
3. Part 3: description of the combined interpretation of the results and of the main conclusions

The animated sequence can be found as additional material in the attached CD. The file is named 20150930_SOT_La-Mina_video.mp4 and is located in the folder CH4_LA-MINA.

4.4.3 GIS Model

The GIS model was created with the open software QGIS version 2.8.1 Wien. The data of the survey were transformed into vectorial and raster information and included in one platform. The objective was to enable an interactive utilisation of the results and to improve their integration in the archaeological process. The QGIS project enabled a visualisation of the results as described in this section. The created data can be imported to any other GIS platform for an alternative representation. The project was created using the UTM projection with the EPSG code 3042.

The GIS project is available in the attached CD. It is located in the folder CH4_LA-MINA and named CH4_GIS. The contents of the folder are described in section 4.4.4.4 and listed in Appendix F. The contents of the model is described in the following section and can be opened installing the software QGIS available in the folder SOFTWARE and loading the file named La_Mina.qgs.

4.4.3.1 Raster information

The raster information can be divided into two types. The RGB rasters are rasters that have a color associated to each pixel. The dynamic rasters have the value of the

acquired and processed data associated to each pixel. The display of dynamic rasters can be modified adjusting the bounds of visualisation. The raster information of the project included:

1. PNOA_89HU30_0453_extract (RGB): an extraction of the aerial photograph related to the area of interest
2. Magnetic survey (dynamic): the processed results of the magnetic survey
3. GPR survey (dynamic): the processed results of the GPR survey. This includes the 8 selected sections named Ped_GPR_X_YYY_ZZZ, where X is the section number, YYY is the top of the depth interval in centimetres and ZZZ is the bottom of the depth interval in centimetres.
4. Surface sampling survey (dynamic): the processed and interpolated results of the surface sampling survey. This includes the 6 classes selected for the interpretation of the data.

4.4.3.2 Vectorial information

The vectorial information can be in the format of points, lines or polygons. They include entities that can be defined by one element or a set of multiple elements. To each entity were associated a set of properties. The characteristics of the vectorial information including the type and the properties are described in Table 4.8.

Vectorial information was created to introduce the results of the surface sampling surface. Each unit of acquisition is represented by a polygon of 10x10m. The polygons have their label and associated data included as properties.

The contextual information included (1) the area covered by each method, (2) the points used for the referencing and (3) topographical data.

Finally, the interpretation of the results was also presented as vectorial information. Each method has associated interpretation files. For the magnetic survey the interpretation was divided in focal and linear anomalies. The GPR interpretation included the zones defined using the data and the linear anomalies representing the constructive features. The interpretation of the surface sampling survey was summed

Vectorial information	Type	Properties
Ped_Surface_sampling	Polygons	Local coordinates of the center of each square (X, Y); Label of the square, Number of sherds for each selected marker (LHTS-pt, LHTS,mt, T-WP, CCW, Modern, Total), Normalized and fileterd number fraction of sherds for each selected marker (LHTS-pt, LHTS,mt, T-WP, CCW, Modern, Total)
Covered_Areas	Polygons	Id, Method, Area
GPS_points	Points	Id, XUTM, YUTM, Selected
Topography_contour_lines	Lines	Id, Elevation
Ped_synth_polygons	Polygons	Id, Type
Ped_surface_sampling_zones	Polygons	Id, Zones
Ped_mag_interp_points	Points	Id, Type, Label
Ped_mag_interp-lines	Lines	Id, sign, type, Label
Ped_GPR_interpretation	Lines	Id, label, Id_2 (zone), Section N, Depth min, Depth max
Ped_GPR_zones	Polygons	Id

Table 4.8: Properties of the delivered vectorial information.

up in a zonation created using the variations in density. In order to create the synthetic map, an additional polygon file was created. It included the archaeological meaning assignment of the results.

4.4.4 Files

The delivered data were classified in four categories: (1) the raw data which are the data acquired and downloaded without any change (2) the processed data which are the data after the applied transformations (3) the documentation that were generated for the description of the project and of the results and (4) the generated GIS model. The list of all the produced files is described in Appendix F.

4.4.4.1 The raw data

The folder 01_RAW_DATA includes (1) the GPR individual files, (2) the acquired reference points, (3) the magnetic acquired data per grid unit, (4) the results of the classification of the surface sampling survey.

1. For each GPR profile acquired during fieldwork, one file was created. 253 profiles were acquired, which correspond to 253 files. The files were named using a prefix relative to the project (PED) and the number of the profile in three digits. The name of the files is then structured in the following way: PED ____XXX.DZT. “XXX” is the number of the profile and DZT is the extension, which correspond to the native format of the GPR system. The positions of each profile in the local coordinates are specified in the “info_all.dat” file. It includes for each profile the coordinates of the starting and the end points. The profiles acquired in the reverse direction were specified in the “info_all_rev.dat” file.
2. The acquired GPS points were downloaded in an ASCII format. It includes the coordinates as longitude and latitude in the WGS 84 projection, a label, and the type of point.
3. The magnetic raw data were downloaded in the native format. The area was explored in 14 acquisition units. This corresponded to 14 files. The relative position of the acquire grids is described in the file “Acquisition_geometry.png”.
4. The results of the classification of the sherds were stored in an ASCII file. The file contains the number of collected sherds per category and per square. Each square is defined by an identifying number, the local coordinates of the centre of the square and the label used during field work.

4.4.4.2 The processed data

The folder 02_PROCESSED_DATA includes (1) GPR data (2) the transformed GPS points (3) magnetic data and (4) surface sampling data.

1. The processed GPR data included the selected horizontal sections of filtered data and of filtered data without the large scale variations. All the files are in ASCII format. The data were organized in columns with in order: the local X coordinate, the local Y coordinate, the processed scalar value, the UTM X coordinate, the UTM Y coordinate. The filtered data are named: Ped_filt_X_YYY_ZZZ.dat. The filtered data without the large scale variations are named: Ped_filt_res_X_YYY_ZZZ.dat. X is the number of the horizontal

section. *YYY* is the minimum depth of the section. *ZZZ* is the maximum depth of the section.

2. The raw GPS data were transformed from the WGS84 projection to the UTM EPSG 3042 system. The correspondent coordinates in the acquisition system were added.
3. The processed magnetic data were stored in an ASCII file. The columns of the file are the coordinates in the acquisition reference system (*X*, *Y*), the processed gradient value and the UTM coordinates (*X*, *Y*).
4. The stored processed data were the results of the normalisation, the filtering and the interpolation. One file per class of sherds was saved with the name *Ped_class-of-sherds_trend01.dat*. They include the coordinates in the acquisition system, the processed value, and the coordinates in the UTM system.

4.4.4.3 Documentation

The folder 03.DOCUMENTATION groups contains the material that describes the project and its results. It includes the written and graphical reports in pdf format and the animated sequence file in mp4 format. The files are archived using (1) the date of issue (2) the name of the contractor (3) the name of the site and (4) the type of document. For the written and graphical reports, two versions are presented. The first version is the one originally produced at the execution of the project also presented in Appendices B and D. The second version is the one created during this research.

4.4.4.4 GIS

The GIS files were detailed in the section describing the GIS model. The names of the files are the same as the ones visible in the GIS project and the archiving respect the same categories. The files were stored in RASTERS and VECTORS folders.

The rasters files were archived in tiff format. They include the processed results of the GPR, magnetic and surface sampling survey and an extraction around the area of interest of the ortho-rectified aerial photograph produced by the IGN (National Geographic Institute of Spain) in 2009. All the information related to the production of the aerial photograph is included in the associated “xml” file. The survey tiff

files were produced converting the processed ASCII files. The conversion enabled including the reference system in the new format. The files were separated in three folders (1) GEOPHYSICS for the geophysical data, (2) OF for the aerial photographs and (3) SURFACE_SAMPLING for the surface sampling data.

The vector files were archived in “ESRI shapefile” format. It is a proprietary format with an open code and is the standard for vector files in GIS project. They allow including properties to the produced material. These properties were used for the visualisation and interpretation of the data. The produced files and the associated properties are presented in Table 4.8. The VECTORS folder includes five folders.

1. AREAS includes the areas covered by the different survey methods
2. INTERP includes the interpretation files
3. MDT the topographical information
4. REF includes the reference points
5. SURFACE_SAMPLING includes the coarse (10x10m) surface sampling results

Chapter 5

Case study 3: Multi-method research program for the documentation of a destruction

The third and last case study considered was centred on the integration of geophysics in the archaeological research process. The described surveys are part of a long-term research project. They were used as a base to create a common platform including geophysical and archaeological results. The chapter includes the description of the strategy of exploration and documentation of the Roman site of Puig Ciutat.

A complete interpretation requires the integration of the geophysical results with the archaeological information. The mapping of the excavations can help with the characterisation, the validation or the reinterpretation of the geophysical results. The methodology of the archaeological mapping will have a direct impact on the ability to integrate them with geophysical data. GIS solutions have been promoted as the bridge between the two disciplines (Kvamme, 1999; Neubauer, 2004). They give a common platform and a common language for the visualisation, the interpretation and dissemination of the results.

5.1 Summary

The aerial photographs and topographic information used in this project are property of the ICGC (Institut cartogràfic i geològic de Catalunya) and can be consulted at www.icgc.cat.

Objectives

The main archaeological objectives of the project were to (1) identify areas where

possible fire and destructions traces could be found, (2) to delimit the areas where the bedrock is superficial (3) to describe the occupation the site.

Another objective of the project was to create a common platform to gather archaeological and geophysical results.

Applied strategy

The project was conducted as a research project and the means to answer to the archaeological objectives were evaluated before each survey. The EMI, GPR and magnetic methods were combined to the archaeological excavations in order to study the occupation of the site. All the results were integrated in a common platform.

Main results

Thermo-alterations were mainly identified in the eastern part of the site. They are in contact with an excavated area where carbonised beams were documented. They cover an area of 25x12m where similar traces of fire and destruction are expected.

The bedrock variations were described in the areas where the penetration of the GPR signal was sufficient. The western part of the site is mainly covered by superficial bedrock with a depth included between 0.20 and 0.50m. Some areas show geometric shapes that could be associated to cuts in the bedrock.

The constructive structures were partially described due to a low contrast. They were mainly detected in the eastern part of the site. When no constructive features could be described, the altered areas were delimited as they could correspond to collapsed structures or to occupation traces.

Main limitations

The geophysical surveys were conducted with ground conditions that deteriorated the quality of the signal. Furthermore, the constructive features showed a low contrast with the surrounding sediments. Finally, a systematic deep ploughing was conducted by the owner. This led to the deterioration of some structures and to the creation of artificial linear features that could be confused with constructive features. As a consequence, the description of the constructive structures was incomplete.

The reference system of the site was set on the third year of the project. The first surveys had to be referenced. The operation created uncertainty on the relative position of the results.

The lack of common platforms to use and study archaeological and geophysical results made the integration of the survey slow.

Methods	Resolution (m)	Surface covered	System
Magnetic	0.5x0.25	3 975 m2	Bartington Grad 601 - 1m vertical separation between sensors
	Processing (1) average removal per line with a threshold of 5nT (2) positioning correction (3) smoothing of 0.5x0.5m (4) interpolation to a final resolution of 0.25x0.25m		
Ground Penetrating Radar (GPR)	0.20x0.02x0.006	3 712 m2	IDS HI-MOD Dual 200 and 600MHz
	Processing (1) correction of the position of the surface (2) correction of the difference between the measuring channels (3) removal of the system drift (4) gain: compensation of the attenuation with depth (5) background removal (6) transformation in reflected magnitude (7) Filtering of short range noise and interpolation to a final resolution of 0.10x0.10m		
EMI	0.75x0.25	2 950 m2	Dualem 1S
	Processing (1) removal of temporal variations (2) removal of outliers (3) filtering of short range noise and interpolation to a mesh of 0.10x0.10m		
Excavation	Digitised excavation results including the position of the excavated artefacts, the limits of the stratigraphic units and the description of the associated details. Graph paper, robotic total station, 2D ortho-photographs and 3D photogrammetry were used.		
Results			
(1) The main areas with fire traces and possible metal accumulation were identified., (2) the variations in depth of the bedrock were described (3) the constructive fetures were partially documented and the occupied area was delimited (4) a front-end was tested for a systematic entry of the excavation results (5) a GIS platform was used for a combined visualisation and interpretation of the surveys.			

Table 5.1: Puig Ciutat: Main characteristics of the surveys and main results.

5.2 Field

5.2.1 The design of the strategy

5.2.1.1 *Archaeological context*

The archaeological site of Puig Ciutat is located in the area of Lluçanès, 60km North of Barcelona, Catalonia. The settlement occupies a high plain of around 5 hectares. The location is strategic for the control of the surrounding paths. It is surrounded by the meander system of the Gavaressa river and protected on its northern limit by a cliff. Three main areas can be distinguished. Two open fields on the western and eastern limits of the site and a central area filled with woods (Figure 5.1).



Figure 5.1: Topography and geometry of the site of Puig Ciutat. The project is centred in Zone 2.

The settlement was discovered casually in the early 1980's, but the investigations started in 2006 with a first geophysical survey. The magnetic survey of one of the open fields revealed a complex urban structure with evidences of several burnt houses. The research started again in 2010 and the site has then been under continuous study since. The results of the first campaign can be found in (Garcia et al., 2010). The cultural material found during the excavation works indicated a chronology of the site of the Roman Republic period with a last occupation included between 80-30 BC. Nevertheless, the first excavations and geophysical results did not show

an urban planning similar to Roman ones. The presence of abundant weaponry and military artefacts inside and outside the settlement (Figure 5.2) as well as burnt areas and structures (Figure 5.3) indicated a possible violent destruction of the site (Padrós et al., 2013).



Figure 5.2: Excavated weaponry a) iron shoe hobnail b) dagger c) hand lead projectile d) head of a catapult projectile.

The sediments of the site are mainly silty clay and the underlying bedrock varies from marly clay to marly limestone. The main difficulties that were raised during the first years were due to the short scale variations of the underlying geology and to the low contrast between the building material and the surrounding sediments and bedrock. Both the geology and the nature of the archaeological features (weaponry, burnt areas) made the independent interpretation of the geophysical data difficult and incomplete.

5.2.1.2 Objectives of the project

A strategy of combined processing and interpretation was decided in order to optimize the information that can be extracted from the geophysical data. It had three main goals. The first goal was to map the bedrock variations. The second goal was to focus on the constructive elements and extract them from the geophysical data.

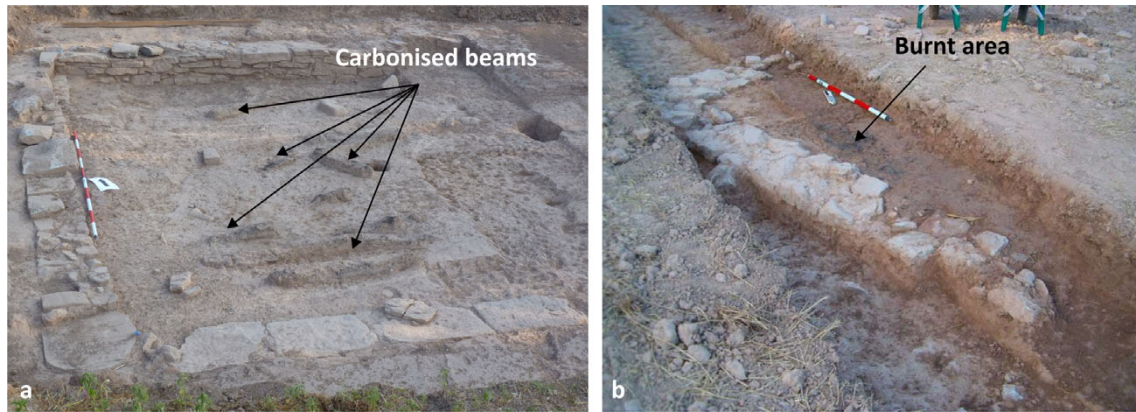


Figure 5.3: Excavated burnt areas a) carbonised beams b) fire traces.

The last goal was to identify metals and thermo-altered areas and to map them on the final model with the bedrock variations and the constructive features.

These results extracted from the geophysical data have to be available during the archaeological process. The common platform for the exchange of the information was then at the centre of the project and the aim was to produce a 2D environment where both geophysical and archaeological results could be consulted and interpreted.

5.2.1.3 Applied methodology

The project was implemented as a research project. It depended on the excavation campaigns and was self-managed by the team. Each year, the budget allocated to the project was studied and funds were distributed between surveys and excavations. This gave a great liberty for the decisions on the systems to be used and the time to adapt the methodology campaign after campaign. Furthermore, the team includes both archaeologists and geophysicists which proved to be useful for decision making. Archaeologists participated in fieldwork of the geophysical surveys and geophysicists participated in the excavation campaigns. This enabled a better understanding of the results and a better communication.

Several survey and excavation campaigns were conducted since 2010 (Table 5.2 and Figure 5.4). The main fields were covered with three different geophysical methods. In order to get a first idea of the site, a gradiometer survey was implemented with a standard resolution of 0.50x0.25m. It showed several thermo-altered areas but the description of the constructive features was limited. A GPR survey was then applied in order to describe the constructive features. The resolution was set to 0.20x0.02m

as a compromise between definition and time of acquisition. The clayey environment limited the depth penetration to between 1.00 and 1.50m. Furthermore, the bedrock and constructive features were difficult to separate. Complementary methods were then needed. An EMI survey was decided in order to map the geological variations. As the goal was to map variations at a larger scale, the resolution was of 0.75x0.25m.

Id	Year	Description
PC1	2006	Magnetic survey of Z1
PC2	2010	Magnetic survey of Z1, Z2, Z3 and Z4
PC3	2010	Surface sampling of surrounding fields
PC4	2010	Excavations in Z1 and Z2
PC5	2011	GPR of Z1 and Z2 and additional high resolution areas
PC6	2011	Metal detector survey in surrounding fields
PC7	2011	Excavations in Z1 and Z2
PC8	2011	Excavations in Z1 and Z2
PC9	2012	Excavations in Z2
PC10	2013	Excavations in Z2
PC11	2014	Magnetic survey of Z1, gpr survey of the south of Z2 and electrical resistivity tomographies in Z3
PC12	2014	Excavations in Z2

Table 5.2: Main geophysical and archaeological campaigns

In parallel to the geophysical surveys, excavations were conducted in areas mainly decided by the geophysical results. The archaeological excavations were then used to improve the interpretation of the geophysical results. When possible, a photogrammetry of the remarkable 3D features was acquired. Additional surveys were carried out in the surroundings of the site in order to apprehend the importance of the site at larger scales.

5.2.1.4 Feasibility

The geological environment of the site and its low contrast with the constructive material were the main limitation for the identification of the structures of interest and the interpretation of the data. Furthermore, until the archaeological research project started, the fields were used for agricultural purposes. The fields were ploughed on a regular base for farming, which made the ground surface irregular. Deep ploughing was also identified in the data. It was carried out in order to destroy the superficial bedrock and improve the productivity of the fields. As a consequence, some areas were strongly affected by the ploughing which both endangered the structures and

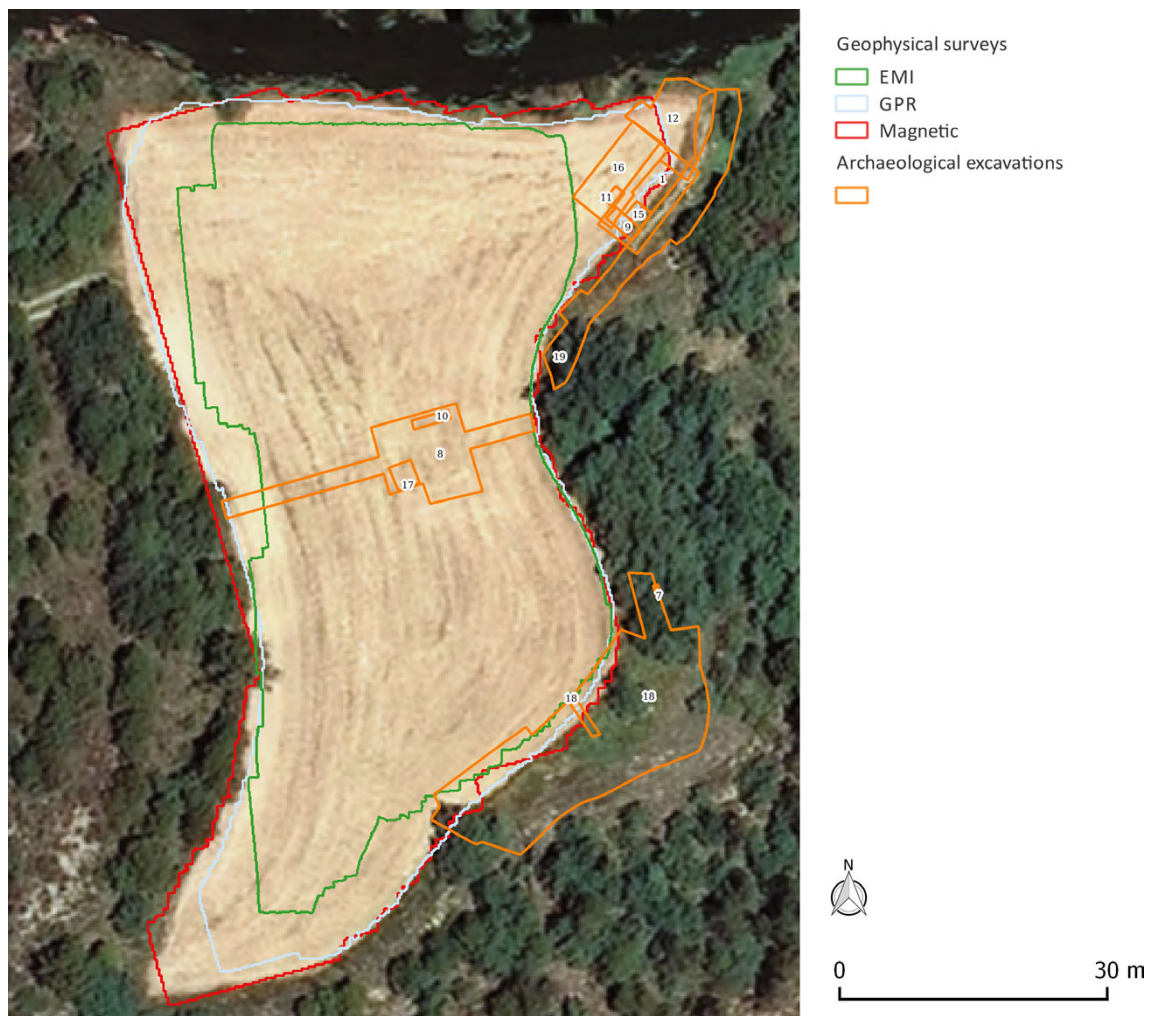


Figure 5.4: Areas covered by geophysics and by archaeological excavations.

complicated the interpretation of the data.

Another limitation for the acquisition and interpretation of the data was the presence of a large extension of woods between the two main fields. The woods are areas where the data acquisition is much slower, when possible. For the moment, only the open fields were explored, which limits the global understanding of the organisation of the site.

Finally, the access to aerial photographs dated of 1956 (Figure 5.5) gave information on the previous organisation of the fields. It appeared that the extension of the woods was larger and that the cultivated fields were extended. This transformation of the environment may have affected the cultural remains and destroyed part of the site.



Figure 5.5: Aerial photographs of the site a) 1956 b) 2010. Source: Institut Cartogràfic i Geològic de Catalunya.

As the study is part of a research project and in order to test the methodology from acquisition to modelling, it was selectively applied on one of the open fields (Zone 2 in Figure 5.1).

5.2.2 Data acquisition

5.2.2.1 Gradiometer survey

The gradiometer survey was conducted using a Bartington gradiometer Grad 601 with two pairs of sensors. The vertical and horizontal distance between sensors was of 1.00m. The profiles were acquired in zig-zag mode with a distance between profiles of 0.50m and a distance between acquired points of 0.25m.

The data were acquired in two phases during the summer of 2010. Each phase was of half a day and there was a two-week separation between them. The northern area was acquired during the first phase, the southern area during the second phase. The ground conditions and weather were equivalents. The soil was dry and ploughed.

The profiles were acquired in the west-east direction using units of acquisition of 20x20m. The total covered area was of 3975m². The condition of the acquisition are

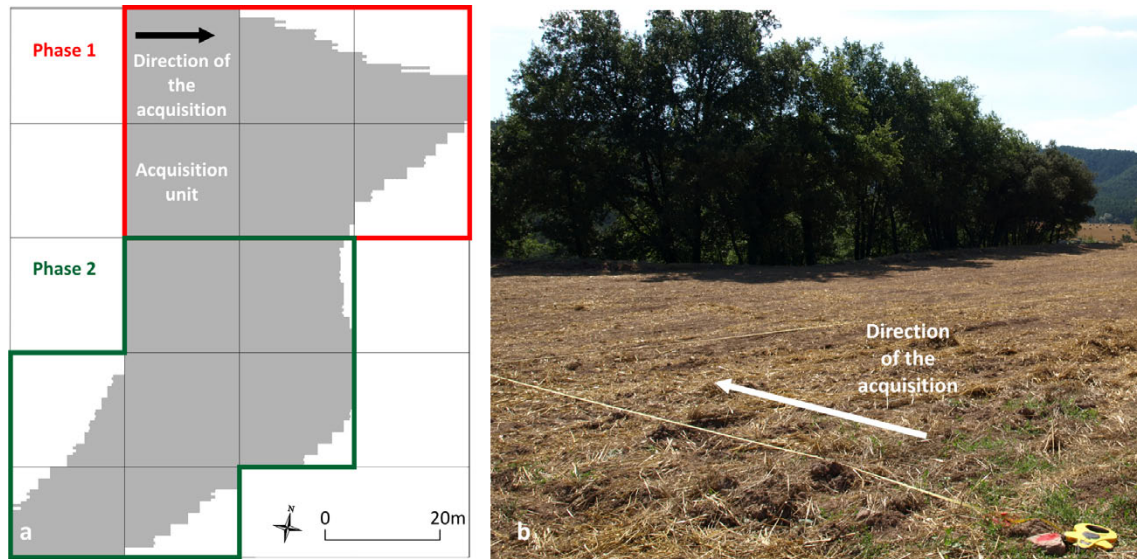


Figure 5.6: Parameters and ground conditions of the gradiometer survey a) parameters of the acquisition b) photograph of the ground conditions.

displayed in Figure 5.6

5.2.2.2 GPR survey

The GPR acquisition was performed using a IDS RIS MF Hi-Mod system with two pairs of antennas separated 0.40m. Each pair of antenna contained frequencies of acquisition of 200MHz and 600MHz. The profiles were acquired in zig-zag mode with a distance between profiles of 0.20m and a distance between acquired traces of 0.02m.

The GPR data were acquired during the spring of 2011. The acquisition was achieved in two consecutive days. The ground was covered with high vegetation and the surface was rugged due to ploughing (Figure 5.7a). Several interruptions occurred during the data acquisition including breaks and battery changes. These interruptions can be identified visualising the two-way time value corresponding to the maximum amplitude value of the first arrivals (Figure 5.7b).

The profiles were acquired in the north-south direction. The area to explore was divided in two parts of around 45m each (Figure 5.7b). The total covered area was of 3712m².

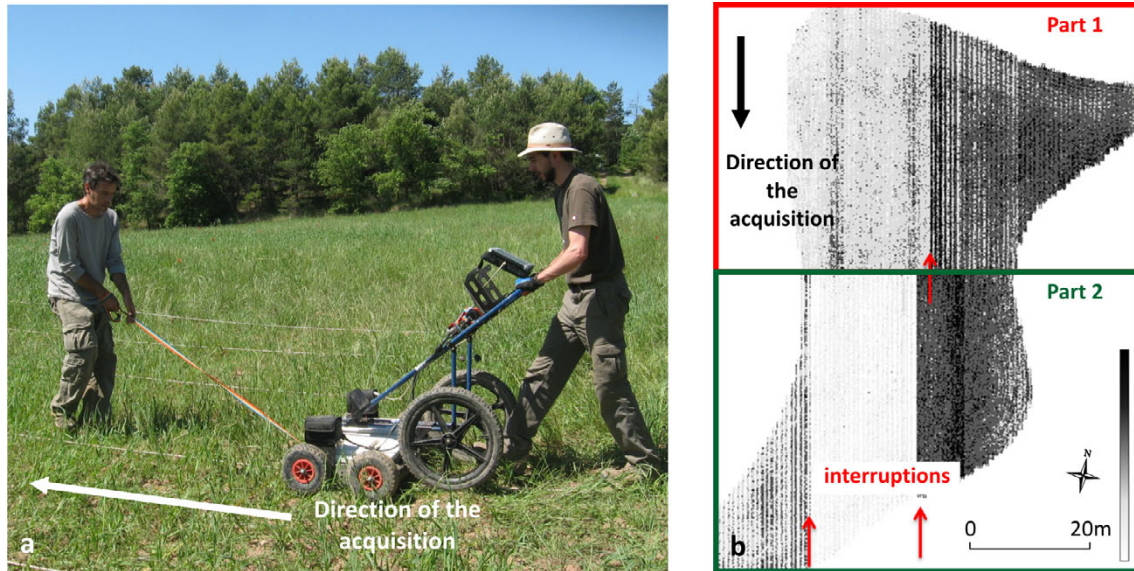


Figure 5.7: Parameters and ground conditions of the GPR survey a) photograph of the used system and of the ground conditions b) interruptions during the acquisition of the data.

5.2.2.3 EMI survey

The EMI survey was scheduled in collaboration with ORBIT, group of the department of Soil Management, Ghent University. A dualem 1S system was used. It includes three coils, one transmitter and two receivers. The transmitter was used in a horizontal configuration. The first receiver is coplanar and positioned at a distance of 1.00m from the transmitter. The second is perpendicular and at a distance of 1.10m. The acquired profiles were separated 0.75m and measurements were taken every 0.25m along the profiles.

The survey was conducted at the end of the spring of 2012 in one day of fieldwork. The ground was covered with dried vegetation and had previously been flattened using adapted equipment (Figure 5.8a). The profiles were acquired in the north-south direction. The EMI system was dragged by a quad and the positioning of the acquired values was ensured by a differential GPS system (Figure 5.8b). The total covered area was of 3209m².

Before the survey, a calibration line was acquired driving across the area to correct for potential measurement drift following (Simpson, 2009).

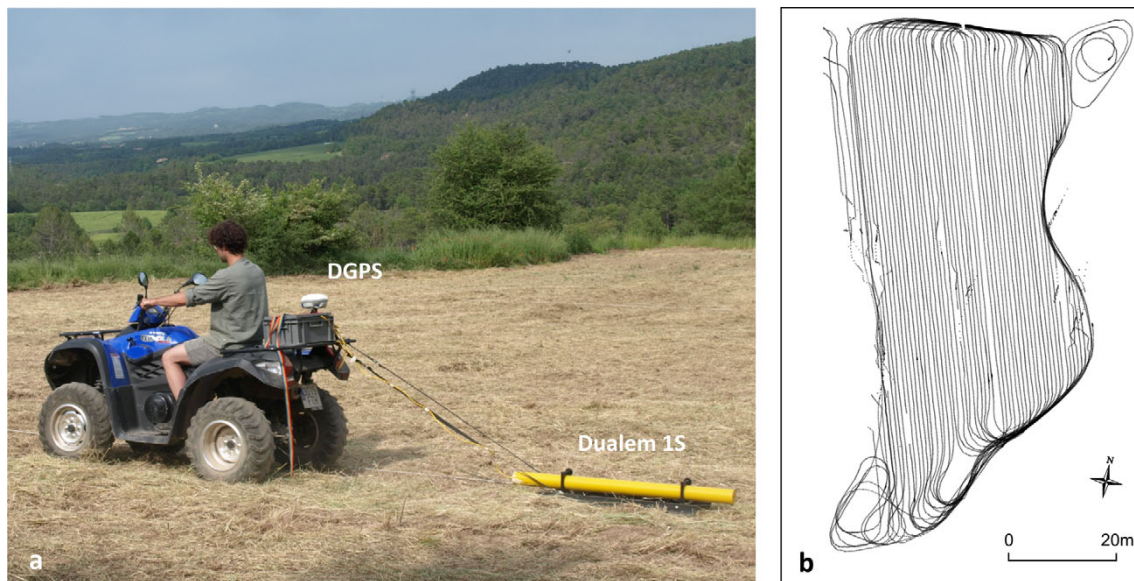


Figure 5.8: Parameters and ground conditions of the EMI survey a) photograph of the used system and of the ground conditions b) location of the acquired points.

5.2.2.4 Excavations

Between 2010 and 2014, three main areas were opened for excavations (Figure 5.3). The decision on where to open was based on two factors: (1) the position of the defensive wall and (2) the results of the geophysical surveys. The areas 1, 8, 12 and 16 were excavated during summer campaigns. The summer campaigns lasted two weeks and were based on volunteer work. The team was mostly formed by students in archaeology with a variable experience in fieldwork. The areas 18 and 19 were excavated during the fall of 2014. The campaign lasted one month and was executed by a team of professional archaeologists.

The excavation methodology follows E. C. Harris (1989). It consists of the delimitation and documentation in extension of stratigraphic units. The stratigraphic units were defined based on the main constructive feature to which they are related (room, street, defensive wall. . .). A first classification of the stratigraphic units was decided by the archaeological team. It was then adapted to enable the migration of the results to the GIS platform Sigarq which has its own classification (del Fresno Bernal and Torrecilla, 2009). Three main categories of stratigraphic units were used: (1) deposits (2) constructive structures (3) interfaces. Each stratigraphic unit was documented using a record card with its main characteristics, vertical sections, two photographs (general and close-up), a technical drawing that was progressively substituted by an ortho-rectified photograph. For some specific group of features that

presented vertical variations and that had to be documented in 3D a photogrammetry was also acquired. The photogrammetry is a tri-dimensional documentation technique. It consists of the extraction of the structure of an object based on a movement around it. The movement is produced by high resolution overlapped photographic captures. Reference points are placed on and around the object for the corrections of the deformations of the model and for its referencing.

The mapping of the archaeological features was first done manually on paper and with local references. This material had then to be digitised and georeferenced in order to be integrated with geophysical results. The introduction of reference points in the site and the use of a robotic total station had as a consequence the need of an adapted strategy for the acquisition of the digital information. A nomenclature was established that determined the method for the documentation of the archaeological objects. The objects to be documented are (1) artefacts (2) soil samples (3) stratigraphic units (4) vertical sections (5) reference points (6) photogrammetries. When needed, each object was associated to an ortho-rectified referenced photograph. The ortho-rectified photograph had as main objective to enable the digitisation of complex objects during the processing phase.

The nomenclature for the digital documentation of the archaeological objects is presented in Table 5.3. The objectives of the nomenclatures was to enable a preprocessing of the acquired points. The fields that form the code of each acquired point define its characteristics. These characteristics are separated by a hyphen which are transformed in columns of a spreadsheet or fields of a database during the loading of the data. They are used to classify the points by category and to produce the excavation information during the processing.

5.3 Data transformation

5.3.1 Individual processing

5.3.1.1 *Gradiometer survey*

The acquired gradiometer data are displayed in Figure 5.9a. Two main problems affect the data.

First, the difference between the sensors creates a line effect. For each sensor,

Object	CODE	Example
Artefacts	A-NumA-NumSU	A-3-2119
Samles	Sa-NumSa-NumSU	Sa-4-2110
Stratigraphic Unit	SU-TYPE-NumSU	SU-DEP-2119
Detail	DET-NDET-Nelement-NumSU	DET-2-5-2120
Section	S-number and section-SU	S-3A-2120
Photogrammetry	P-numero	P-3
Elevations	Z-CAT(num)-NumSU	Z-P-2119; Z-A3-2119
Ortho-photographs	OP-CAT(num)-NumSU	OP-SU-2119; P-A3-2119
References	R-var-Num	R-SUPI-8; R-SA-1; R-BT-20131

Table 5.3: Nomenclature of the digital mapping of the excavations.

the centre value is different which creates a line effect. Then, at some areas, a displacement of the data was identified. This displacement was due in general to an error in the positioning of the markers during the acquisition.

The line effect was corrected removing the mean value of each line. The mean value was computed considering each line separately and removing the outliers. The threshold for the outliers was set to $5\sigma T/m$.

The displacement problem was solved correcting the shift between lines for two of the acquired grids. The applied shift for grid 1 was of 0.5m and for grid 2 of 0.25.

Two additional operations were applied in order to enhance the visualisation. First a smoothing with Gaussian weights was applied in a window of $0.50 \times 0.50m$. The smoothing had as main objective to stabilise the signal reducing the effects of peaks and random noise. Then, the data were interpolated to a $0.25 \times 0.25m$ mesh. The processed data are displayed in Figure 5.9b.

5.3.1.2 GPR survey

The acquisition noise affecting GPR data is displayed in Figure 5.10. One of the main problems was the difference in calibration between the two acquisition channels. It is visible in the data as a line effect in the direction of acquisition (Figure 5.10a). The other acquisitions problems were the effect of the ploughing lines, a random noise due to bumps and variations in the contact between the ground and the antennas,

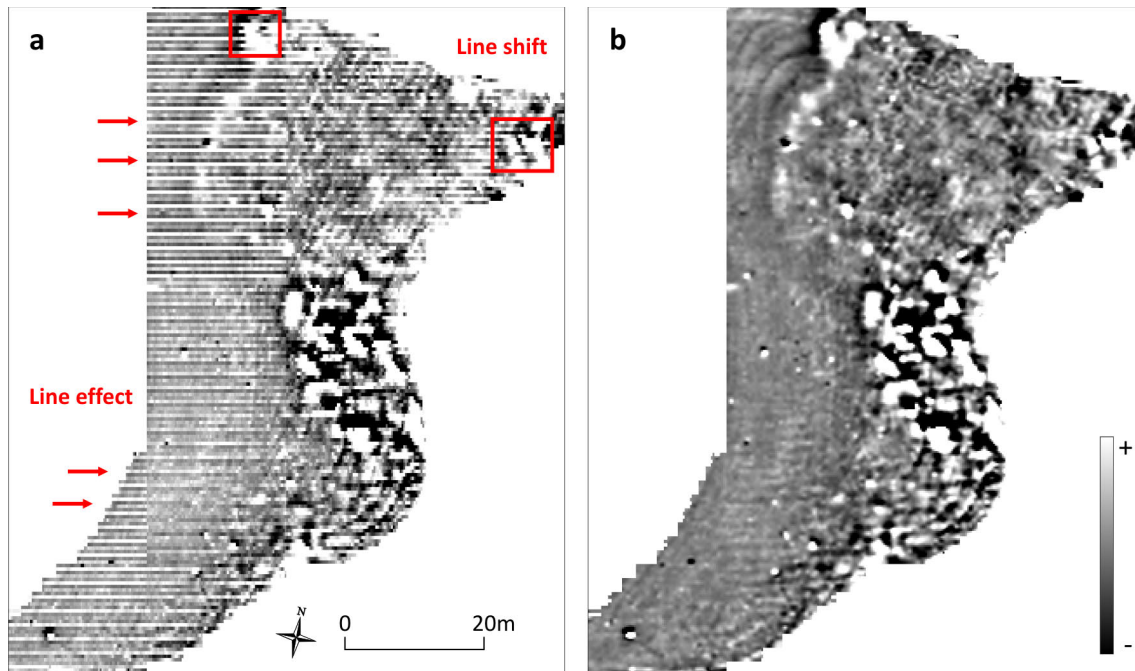


Figure 5.9: Processing of the gradiometer data a) acquisition data b) processed data.

and the variation in the attenuation of the signal between the two days of acquisition (Figure 5.10b). Finally the drift of the used system also had to be corrected.

The strategy of the processing of the GPR data was based on the recommendations of Ernenwein and Kvamme, 2008. The steps of the first part of the processing, from the raw data to the computation of slices representative of a two-way travel time (TWT) interval are presented below and described in Figure 5.11.

1. Characterisation of the first pulse of the signal: The TWT and the amplitude corresponding to the maximum and minimum peaks of the signal of each acquired trace were extracted and stored as 2D maps.
2. Definition of the ground surface: The TWT of the maximum peak was set as $TWT=0$ (Figure 5.11b).
3. Correction of the line effect: It consisted of the computation of the mean amplitude value for each TWT level of each profile, the computation of the difference between the channels in the same direction, and of the removal of the resulting difference from the original data. This operation was based on a filter described by Oimoen (Oimoen, 2000). The result is a signal with equalised channels of acquisition (Figure 5.11c).

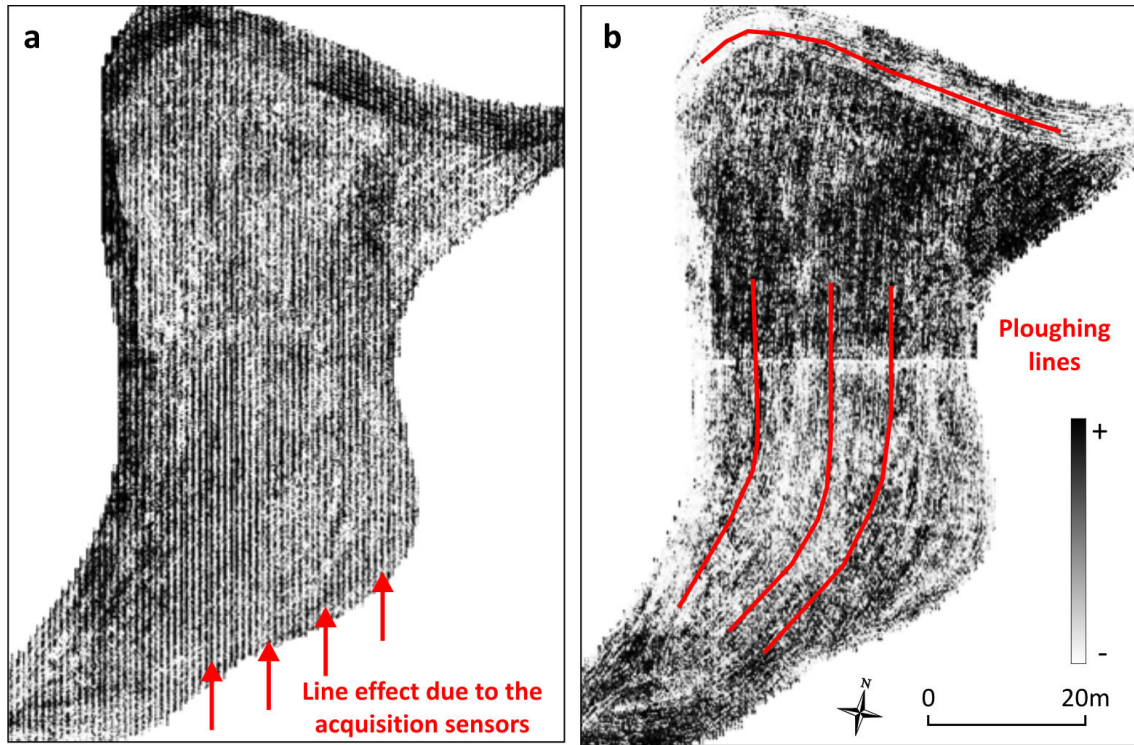


Figure 5.10: GPR acquisition noise a) line effect due to difference in calibration between the sensors b) ploughing lines and random noise.

4. Correction of the system drift: The drift of the signal was corrected computing for each trace the mean value of the amplitudes in a moving window of 23 samples and removing it from the data (Figure 5.11d). This operation is also called “dewow” in data processing (Sandmeier, 2011).
5. Gain application: A gain was applied to compensate the attenuation of the signal with depth. The gain curve was computed using the envelope of the data. A moving average of 13 samples was computed on the absolute value of the amplitudes. The gain was applied by multiplying the amplitudes by the inverse of the resulting curve.
6. A background removal: It consisted of the removal of the mean amplitude value for each TWT level of each profile (Figure 5.11e).
7. “Time slices” computation: the sections representative of a time interval were computed for all TWT levels of acquisition. They were computed using the mean of the absolute value of the amplitudes in a moving window of 13 samples (1.17ns) for the 600MHz data and of 17 samples (2.5ns) for the 200MHz data (Figure 5.11f). The number of samples used was determined based on the

analysis of the experimental variogram computed in the time direction (Tamba; 2002).

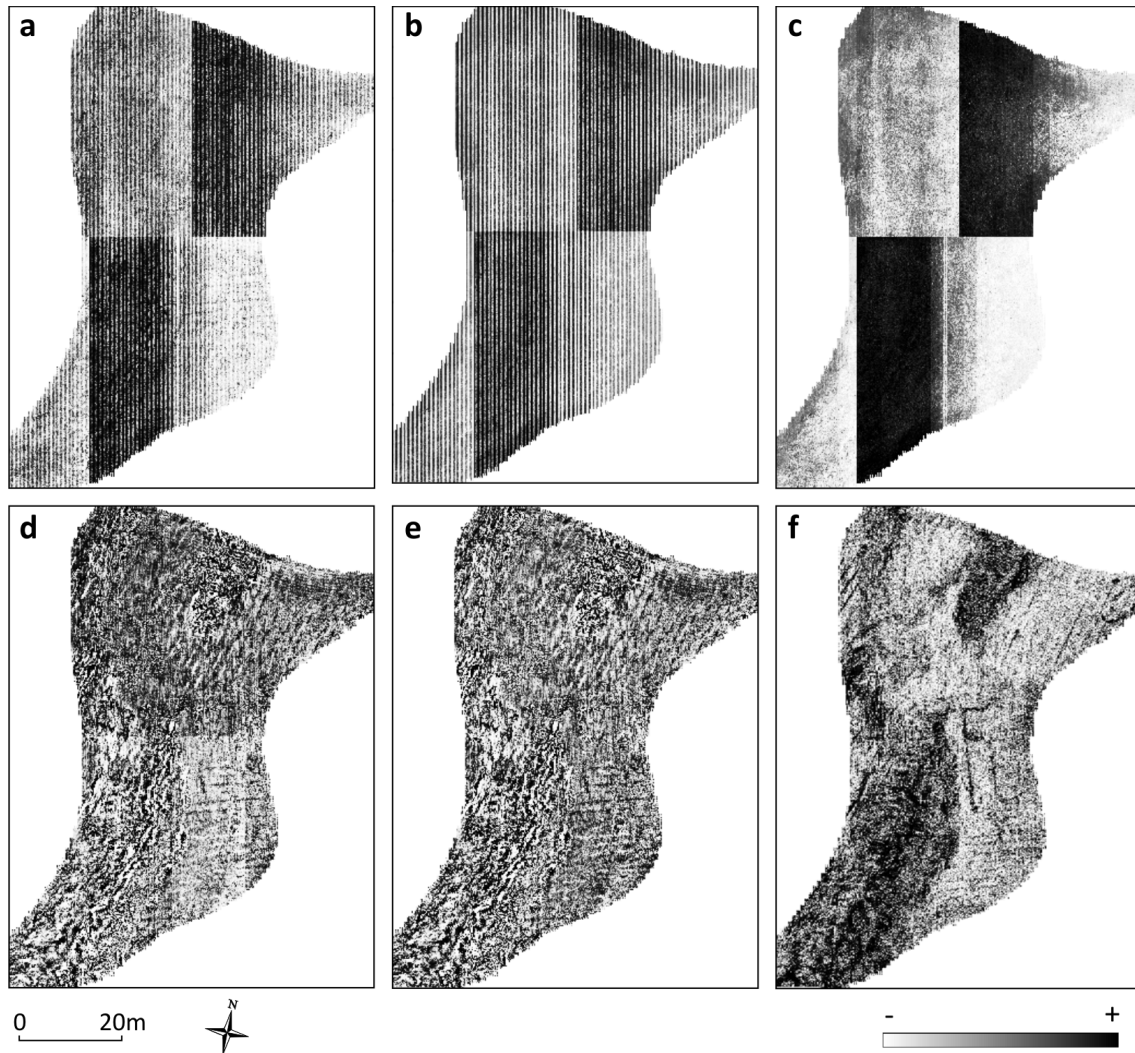


Figure 5.11: GPR processing part 1 a) acquisition amplitudes b) correction of the ground position c) correction of the difference between sensors d) correction of the system drift e) 'background' removal f) mean magnitude of the absolute amplitude

The same sequence of processing was applied for the data of 200 and 600MHz. The velocity of propagation of the signal was estimated by an analysis of hyperbolas identified in the data (Cassidy, 2009b). The velocity used was of 0.09m/ns. The result of this first phase of processing removed most of the system related artefacts. The random noise was still present in the data. It was removed using a factorial kriging approach (Chapter 2 section 3.2a).

The additional steps for the removal of the random noise using factorial kriging included:

600MHz	range X	range Y	sill	filtered
s1	0.2	0.1	0.22	yes
s2	0.2	0.3	1.00	yes
s3	0.4	0.4	0.67	no
s4	1.2	1.2	0.50	no
200MHz	range X	range Y	sill	filtered 1/2
s1	0.2	0.1	0.14	yes/yes
s2	0.2	0.35	1.00	yes/yes
s3	0.6	0.6	0.43	no/yes
s4	1.2	1.2	0.36	no/no
s5	0.4	20	0.14	yes/yes

Table 5.4: Spatial components of the variographic model used for the filtering of the GPR 3D data.

8. The extraction of the trend of the data: the trend was extracted using a moving average in a moving window of 1.0x3.0m
9. The computation and analysis of the residuals: the residuals were computed subtracting the trend from the input data. A variogram analysis combined with the visualisation of the data was used to identify the spatial components. The results of the variogram analysis are presented in Table 5.4. The random noise is represented by the components s1 and s2. It can be associated to bumps of the system. S3 and s4 represent the spatial variation of the signal. S5 represents the residual line effect still present in the 200MHz data.
10. The filtering of the residuals: The spatial components identified as noise were removed from the data using a factorial kriging algorithm in a moving window of 0.60x0.40m for the 600MHz data and of 1.00x0.80m for the 200MHz data.
11. The computation of the filtered data: The filtered data were computed adding the filtered residuals to the extracted trend.

The 200MHz data were filtered twice. The first filtering had as objective to remove the random noise. The second filtering had as objective to remove the variations with a range inferior to 1.00m keeping only the large scale variations possibly associated to geology. The results of the filtering are presented in Figure 5.12.

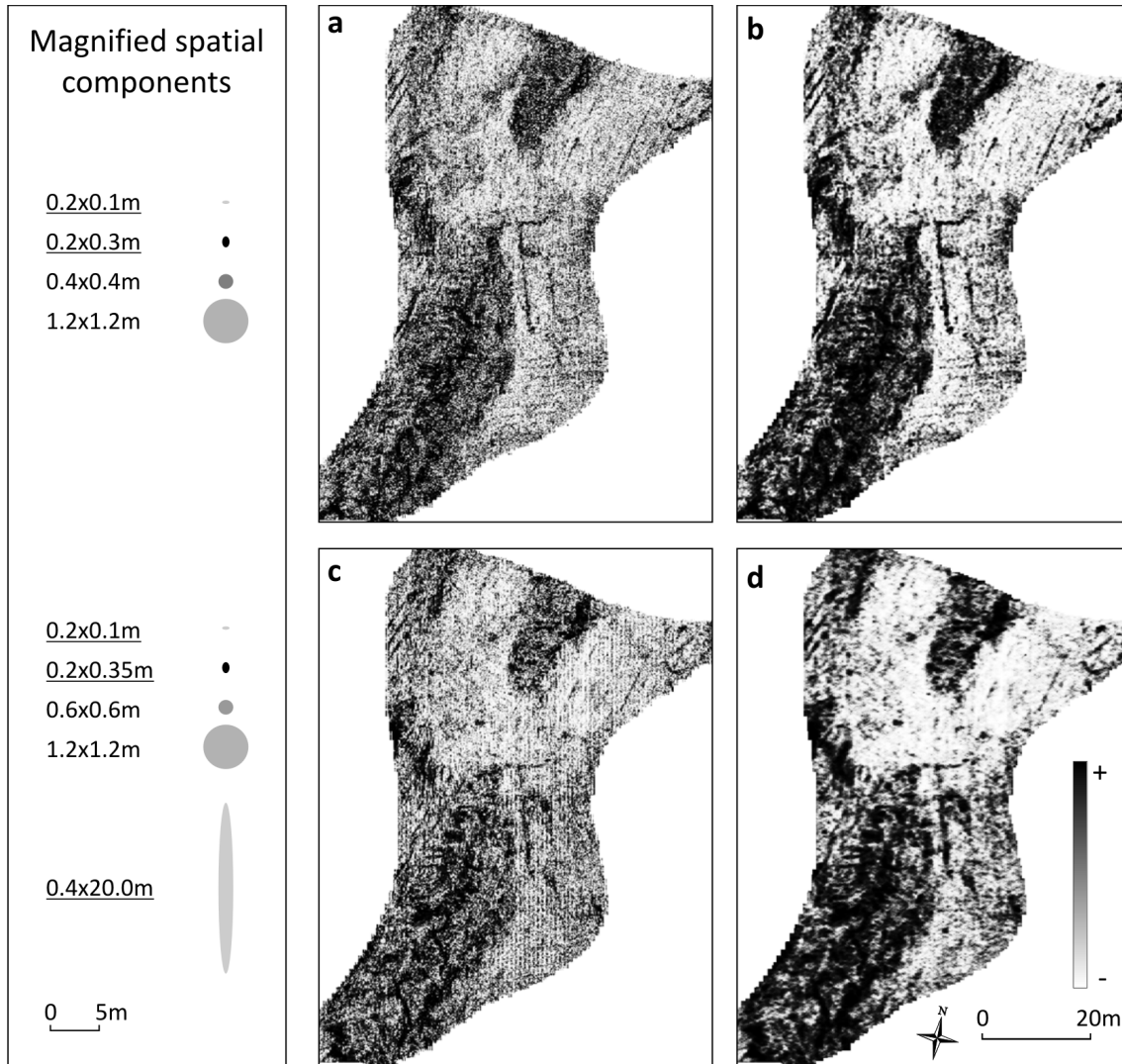


Figure 5.12: Factorial kriging of the GPR data a) 600MHz depth slice b) 600MHz filtered depth slice c) 200MHz depth slice d) 200MHz filtered depth slice. The spatial components represents the range of the spatial variations in the data.

5.3.1.3 EMI survey

Four datasets were produced from the survey. As seen in chapter 2 section 2.1c the in-phase signal of the parallel and perpendicular receivers correspond to apparent magnetic susceptibility. The out-of-phase signal corresponds to the apparent electric conductivity. The coplanar and perpendicular configurations enable the simultaneous exploration of two different volumes of soil of 0.5 and 1.5m respectively (Simpson, 2009).

First, the calibration line acquired before the survey was used to remove the temporal variations of the signal during the acquisition. Then the outliers of each dataset were

removed using adapted minimum and maximum thresholds. The last step was the interpolation of the data from the original DGPS irregular positioning to a regular mesh of 0.1x0.1m.

EC PRP	range U	range V	Sill	Filtered
s1	0.50	0.50	0.02	yes
s2	1.00	1.00	0.18	yes
s3	4.50	4.50	0.80	no
EC HCP	range U	range V	Sill	Filtered
s1	0.50	0.50	0.11	yes
s2	1.00	1.00	0.22	yes
s3	4.50	4.50	0.67	no
MS PRP	range U	range V	Sill	Filtered
s1	0.30	0.40	0.17	yes
s2	1.00	1.50	0.23	yes
s3	3.00	4.00	0.46	no
s4	1.00	20.00	0.14	yes
MS HCP	range U	range V	Sill	Filtered
s1	0.30	0.50	0.15	yes
s2	0.75	1.50	0.26	yes
s3	3.00	2.00	0.59	no

Table 5.5: Spatial components of the variographic model used for the filtering of the EMI data. EC Electric conductivity MS magnetic susceptibility HCP Horizontal coplanar PRP Perpendicular.

The interpolation method was based on factorial kriging and is illustrated on the PRP susceptibility data in Figure 2.11. The same steps as for the filtering of GPR data were followed. The trends were extracted using a second order polynomial function computed in moving of 7.5x15.0m. The results of the variogram analysis of the corresponding residuals are presented in Table 5.5. They include three main spatial components. S1 and s2 were associated to random noise and were filtered. S3 was associated to signal. A fourth component was identified for the perpendicular magnetic susceptibility data. It was associated to the line effect in the direction of acquisition. The filtered data are displayed in Figure 5.13.

5.3.1.4 Excavations

The processing of the excavation data was separated in two parts, the processing of the mapping information and the processing of the 3D documentation.

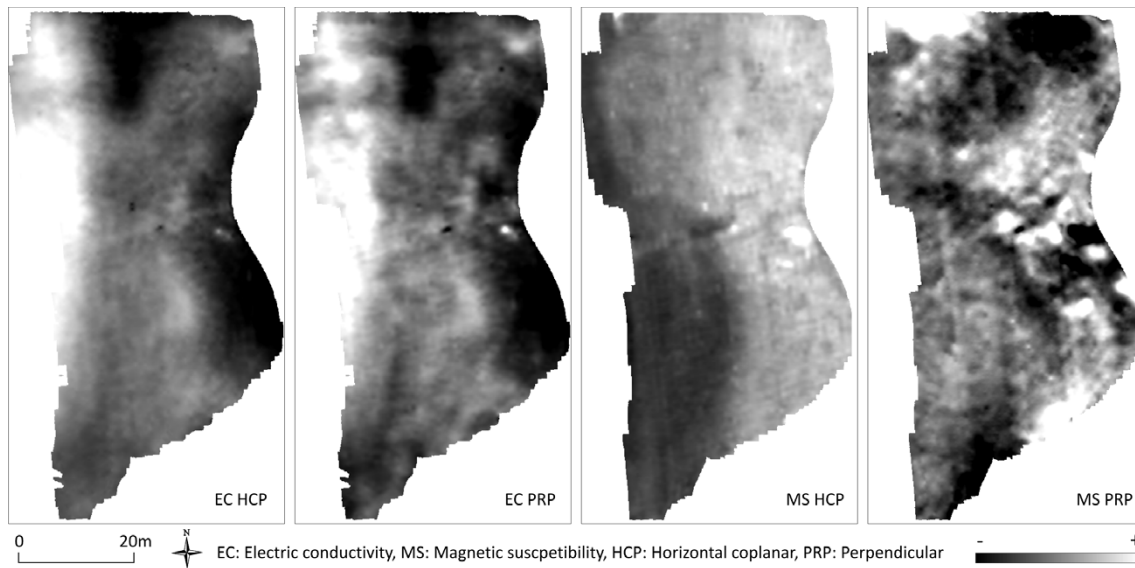


Figure 5.13: EMI filtered data

The mapping information consisted of the digitised data of the points acquired with total station and of the digitised data based on the ortho-rectified photographs. All were classified based on their nature and collected as vectorial information in a spatial database. The planimetry points were transformed into polygons that define the limits of the stratigraphic units. The detail information was transformed in lines associated to the corresponding stratigraphic unit. The artefacts and soil samples were gathered as point information. An example of the resulting data is displayed in Figure 5.14.

The photographs acquired for the 3D documentation of selected features were transformed into photogrammetry following a standard sequence of “Structure from Motion” processing . The first step consists of identifying the relative position of the photographs. The positioned photographs are then transformed in a textured and georeferenced point cloud. The cloud point can then be used to create a textured mesh or maintained as cloud point with only the features of interest. An example of final result sis displayed in Figure 5.15. A total of 6 photogrammetries were produced both for 3D documentation and to introduce the corresponding 2D ortho-photographs. The 2D ortho-photographs were used for the mapping of the details of stratigraphic units in post processing.

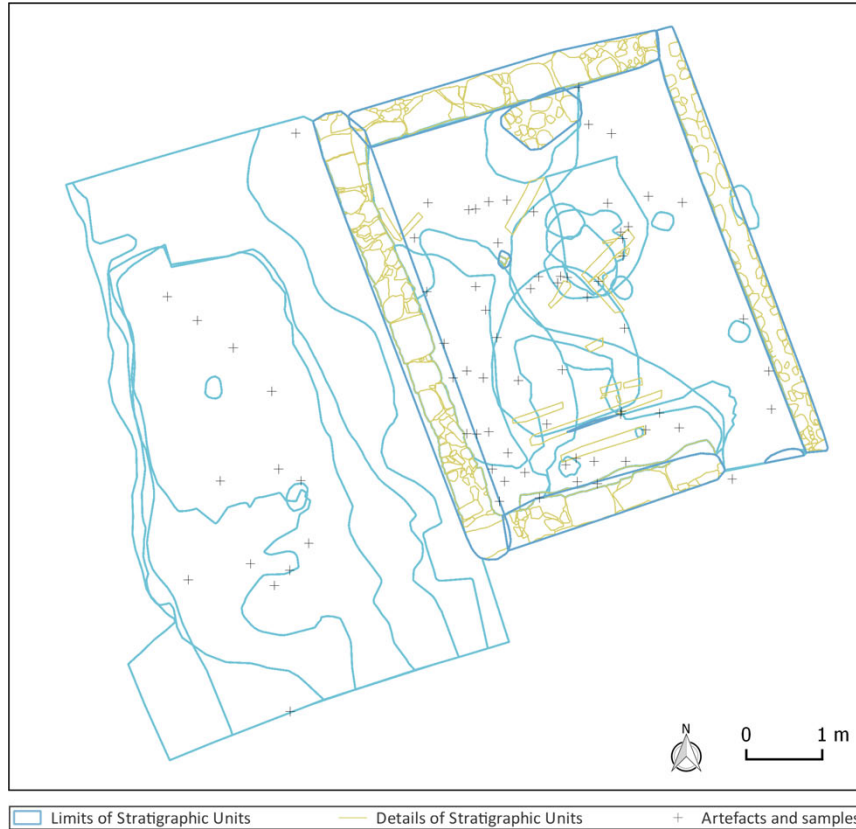


Figure 5.14: Digitised excavation results

5.3.2 Data Integration

The integration of the data included two parts. The first part was to combine the two GPR datasets. Using the 200MHz data, the vertical variations in magnitude were detected and extracted. These variations are possibly related to the stratigraphy of the site and are referred to as horizons. The results were then used to produce depth slices. One depth slice was created per detected interval.

The second part was to integrate all the produced information in one common platform. The project was conducted during several years by different teams. As a consequence the surveys had different coordinate systems and were independent. The integration of the surveys consisted of the homogenisation of the referencing of the surveys. It was done using the topographical references set up for the site.

5.3.2.1 Extracting the phase information from the 200MHz GPR data

The 200MHz data are the low frequency data. The signal penetration is higher and the resolution is lower than with the 600MHz antenna. They were used to detect

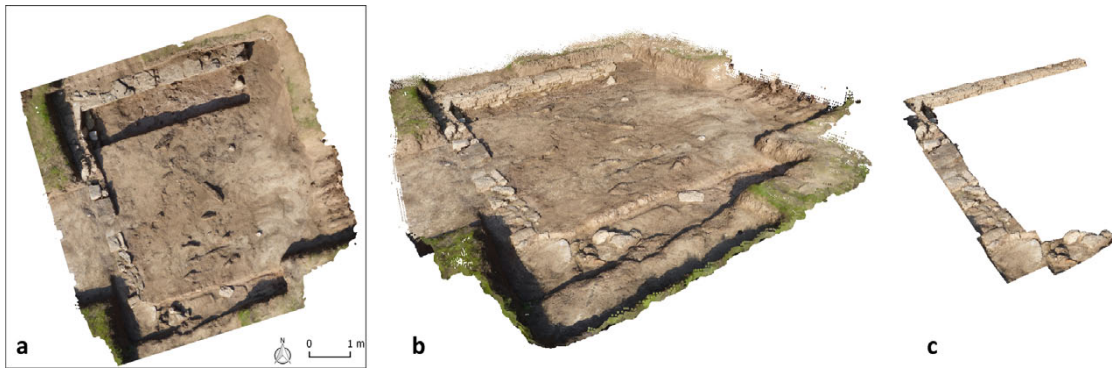


Figure 5.15: Photogrammetry of the excavations a) 2D ortho-rectified view b) perspective view 3D c) selected constructive structures.

and extract the vertical variations in magnitude of the GPR signal. These vertical variations are related to the significant changes in the phase of the signal. They can be related to stratigraphic events.

The bedrock showed the highest values in magnitude of the GPR data. It also presented important slope variations. In order to extract it from the data, the modulus of the 3D gradient was computed. It was defined as the norm of the 3D gradient vector. The gradient vector had as coordinates the gradient of the magnitude in the three directions X, Y and Z. Once the 3D gradient was computed, a threshold was set in order to keep the highest values. The result was a 3D group of data delimiting the high magnitude values. The bedrock was associated to the points with the shallower depth values. The areas of interest were well detected but additional areas were also extracted. They correspond to the high magnitude constructive feature built with the same material as the bedrock. These data were removed manually. Finally, the bedrock horizon also presented holes. These holes can be due to interruptions or to variations in the quality of the signal. They were filled by a simple interpolation.

The vertical variations in magnitude were delimited computing the gradient in the depth direction. The gradient was then normalised in order to enhance the more subtle variations. The normalisation was done for each profile using the maximum value computed in a window of 0.20x0.20m. The extreme values of the normalised gradient were then considered in order to extract the detected layers.

Thresholds were set on the extreme values in order to extract the data associated to horizons or layers. The thresholds were set using the P5 and P95 quantiles of

the data. The selection with the threshold generated point clouds around the horizons. The point clouds were separated using a histogram analysis. The horizons were created extracting the top value for the top layers (positive normalised gradient) and the bottom values for the bottom layers (negative normalised gradient). The extracted horizons presented rugged variations and internal interruptions. The rugged variations were eliminated with a smoothing of the data. The interruptions were completed by interpolation.

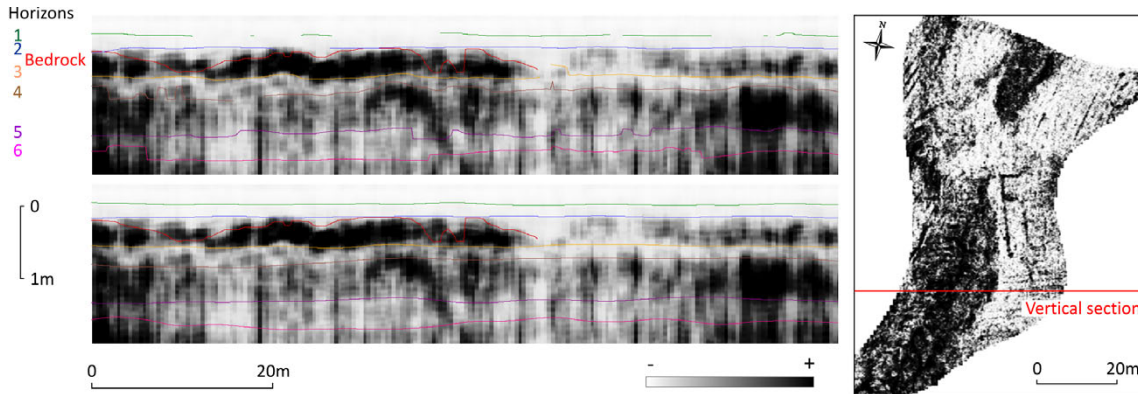


Figure 5.16: Extraction of the horizons on a vertical section (up) extracted raw horizons (down) extracted horizons after smoothing and interpolation (right) position of the vertical section.

Seven layers were detected and extracted (Figure 5.16). One was based on the highest magnitude values and was associated to the bedrock. The six others were based on the vertical variations of the magnitude and were associated to significant changes in the GPR signal.

5.3.2.2 Depth slicing based on the extracted horizons

The extracted horizons were used to define intervals of data. These depth intervals were then used to create new depth slices. The depth slices were created based on the top and bottom of each interval. The depth slicing was operated on the non-filtered data, that is, before the factorial kriging. The more superficial layers were created with the 600MHz data. The deeper layers were created with the 200MHz data. A new filtering was applied on each resulting map. This decision was based on the fact that the filtering of the 3D data is based on one global variogram. With the definition of new intervals, the variogram analysis is restricted to the area of interest and is more adapted to the data.

Five depth slices were created and are presented in Figure 5.17. They show the evolution with depth of the GPR signal. The first depth slice shows the superficial

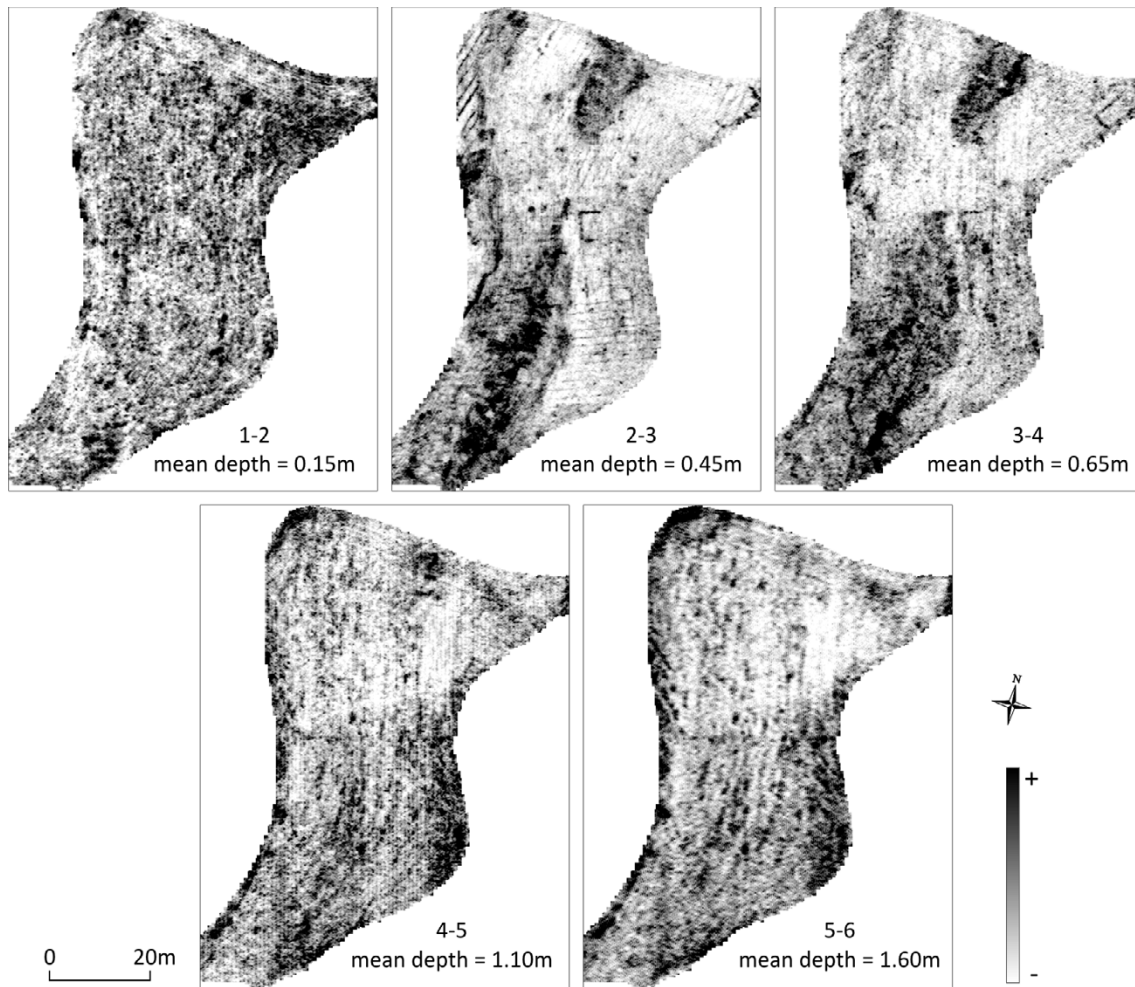


Figure 5.17: Depth slices computed using the extracted horizons.

layer. It starts at the surface and its mean thickness is of 0.17m. This layer shows no constructive structures and is representative of the superficial ploughed soil. The second depth slice shows the top of the constructive structures and the superficial bedrock. It starts at a depth of 0.20m and its mean thickness is of 0.40m. The third depth slice shows the main constructive structures. It starts at a depth of 0.58m and its mean thickness is of 0.20m. The fourth depth slice shows the deeper constructive structures. It starts at a depth of 0.79m and its mean thickness is of 0.54m. The fifth depth slice is represents the limit of penetration of the GPR signal. It starts at a depth of 1.34m and its mean thickness is of 0.33mm. The characteristics of the intervals are presented in Table 5.6.

Three depth slices represent the main constructive features detected in the site. The first show the top of the structures. The second is main circulation level. The third represent deeper levels possibly associated to a prior phase of occupation.

Interval	Depth min (m)	Depth max (m)	Mean thickness (m)	Used dataset	Function
01-02	0.03	0.26	0.17	600MHz	Superficial soil layer
02-03	0.2	0.7	0.4	600MHz	Top of the structures and bedrock
03-04	0.58	1	0.2	600MHz	Main circulation level
04-05	0.79	1.44	0.54	200MHz	Possible prior phase
05-06	1.34	1.82	0.33	200MHz	Limit of penetration of the signal

Table 5.6: Characteristics of the intervals used for the depth slicing.

5.3.2.3 Integration in a common platform

During the project, geophysical and archaeological material was produced and processed. The processed data was used for the interpretation of the results. For a combined interpretation the data had to be integrated in a common platform. The platform included (1) the results of the magnetic survey (2) the depth slices based on the extracted horizons (3) the depth variations of the superficial bedrock (4) the results of the EMI survey and (5) the planimetry of the archaeological excavations.

All these elements were converted from the acquisition to the final reference system. The final reference system was the UTM projection ETRS89 31N which EPSG code is 25831. In order to convert the data from the local reference system to the UTM system, reference points were set on the site and measured with a differential GPS. These points were defined both in the local and UTM reference systems. The coordinates of the points are listed in Table 5.7. The referencing was done using equation 4.1 and the transformation parameters are described in Table 5.8.

ID	XUTM	YUTM	Xlocal	Ylocal	Method
1	422629.4339	4644566.773	20	150	Mag
2	422640.3469	4644528.41	20	110	Mag
3	422648.6619	4644572.247	40	150	Mag
4	422629.4339	4644566.773	-60	-2.1	GPR
5	422640.3469	4644528.41	-60	-2.1	GPR
6	422648.6619	4644572.247	-40	-2.1	GPR

Table 5.7: Reference points used for the georeferencing of the surveys.

X parameters labels	a1	b1	c1
X parameters GPR values	0.961400	-0.272825	422686.831
X parameters Magnetic values	0.961400	-0.272825	422651.130
Y parameters labels	a2	b2	c2
Y parameters GPR values	0.273700	0.959075	4644584.202
Y parameters Magnetic values	0.2737	0.959075	4644417.438

Table 5.8: Parameters of the georeferencing.

5.3.3 Data interpretation

The referenced data were included in a GIS project for the interpretation of the results. The archaeological excavations put in evidence the existence of several burnt areas and of military weaponry. The main objectives of the interpretation were then to (1) detect thermo-altered areas possibly related to the burnt areas, (2) to identify the location of possible metal accumulations and (3) to delimit the areas where the bedrock is superficial and (4) to describe the constructive features using both the GPR and excavation results.

5.3.3.1 Thermo-altered areas

The identification of thermo-altered areas was done combining the results of the gradiometer survey with the susceptibility data of the EMI survey. Thermo-altered areas give high magnetic intensity and high susceptibility values (Linford and Canti, 2001). They were first delimited and characterised in the magnetometer survey and then compared to the high susceptibility areas of the EMI data.

The results of the gradiometer survey were characterised using the absolute value of the data. The mean of the absolute value was computed in polygons where a differentiated signal could be identified. The possible thermo-altered areas have both negative and positive values, and a high absolute value. When the thermo-alteration occurred in situ and was not disturbed or destructed, the anomaly is oriented in the north direction. The resulting polygons are displayed in Figure 5.18a.

The main thermo-altered area was identified in the eastern part of the site. Two main areas were delimited and labeled M1 and M2 (Figure 5.18b). M1 contains a

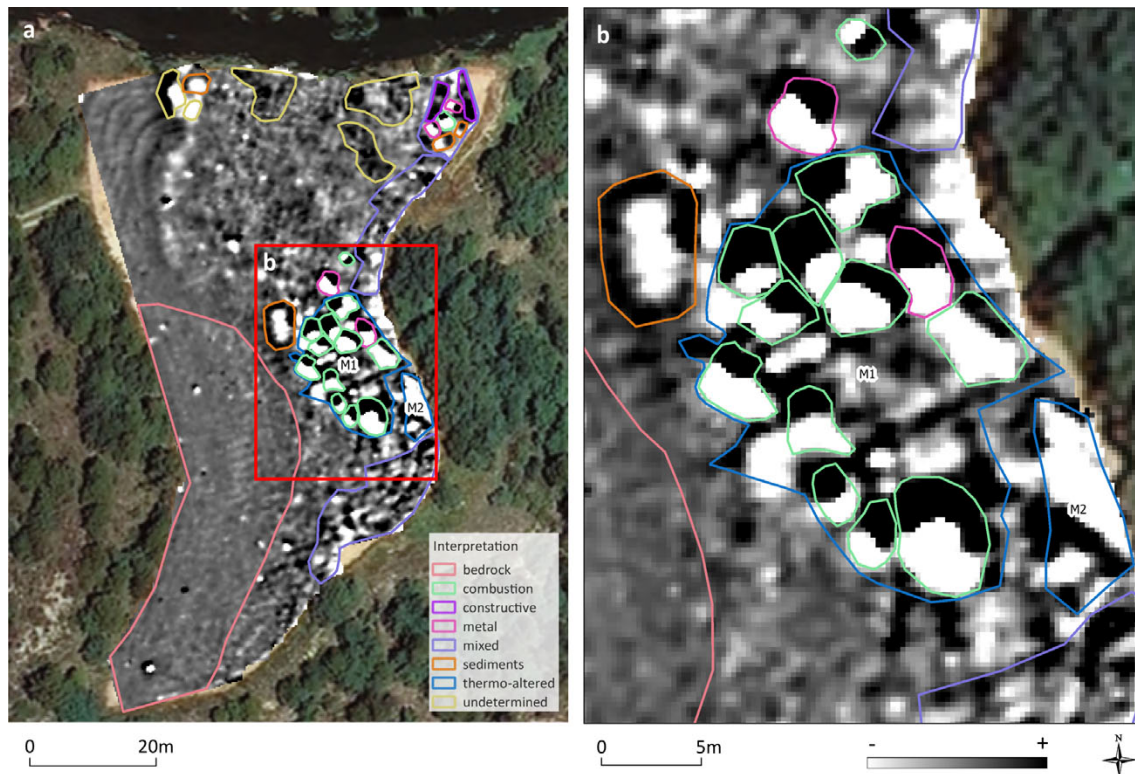


Figure 5.18: Identification of the thermo-altered areas a) interpretation of the gradiometer data b) Close-up on the main area of interest.

set of anomalies which dimensions are of about 4x4m. The mean of the absolute value is of between 3 and 9 nT/m. The orientation of the anomalies is random. This could mean that these areas were modified after the burning event or that the signal is distorted by metals. M2 is a 10x4m area that includes negative a positive extensive values. The mean of the absolute value computed in the polygon is of 4 nT/m. The extension of the anomaly could be explained by constructive features that were exposed to a fire. The geometry of the constructive features could not be retrieved.

The high magnetic susceptibility values were also delimited (Figure 5.20). They can be explained by the presence of metals or by the action of fire on the soil.

5.3.3.2 Metals

The identification of possible metals was done using the gradiometer and the conductivity (EMI) results. Metals give both high conductivity and high magnetic intensity. Furthermore, the dipole signature in the gradiometer data has a random orientation and tends to be sharp for superficial metals.

The identified metals are represented in Figure ???. The points identified with the gradiometer survey are displayed in red and the ones identified with the EMI survey are in green.

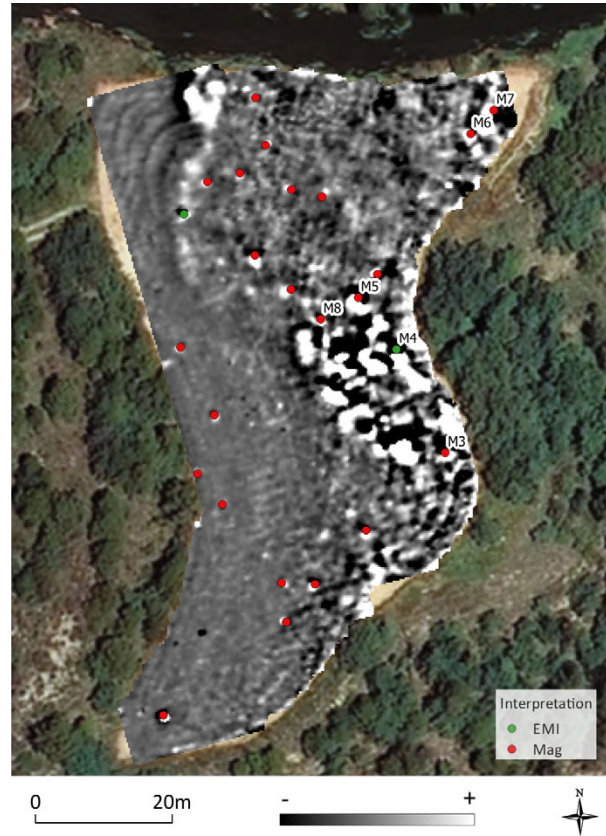


Figure 5.19: Identification of anomalies related to metals.

The metals possibly related to the Roman occupation were labelled from M3 to M9. M6 and M7 are located in an area excavated during the campaign of 2013 (Figure 5.22). Abundant weaponry in iron was found there.

The other metals are possibly due to modern contamination.

5.3.3.3 *Bedrock*

The superficial bedrock was detected by all methods. In the gradiometer data (Figure 5.18a). It correspond to very low magnetisation values (0.15 nT/m). It also corresponds to the low susceptibility values of the EMI data (Figure 5.20). Finally The bedrock variations could also be detected with the GPR data Figure 5.21a) and partially with the electric conductivity data (Figure 5.21b). With the GPR method the variations in depth of the bedrock were mapped.

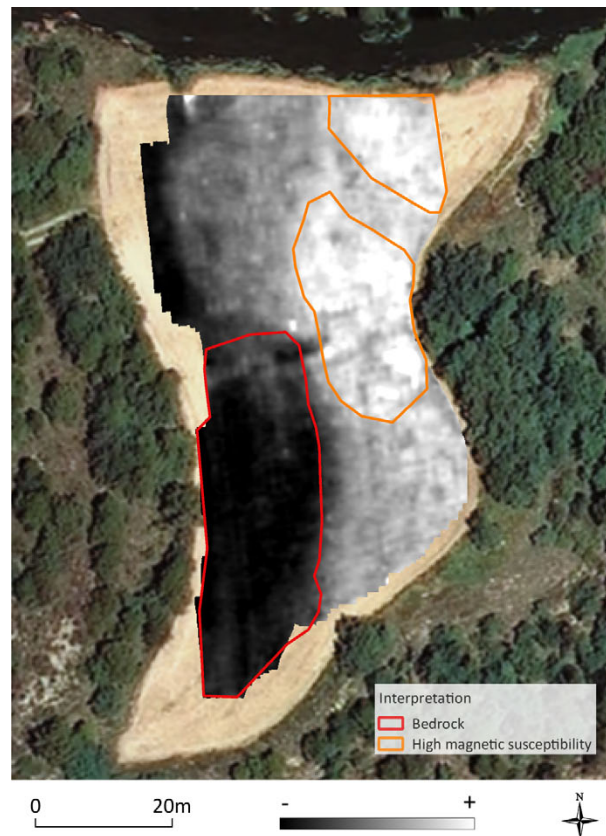


Figure 5.20: Interpretation of the magnetic susceptibility data.

We can notice that the northern part of the bedrock is only detected by the GPR and the electric conductivity. This is due to a thicker layer of sediments above the bedrock in this area.

5.3.3.4 *Constructive features*

The description of the constructive featured was mainly based on the results of the GPR survey and on the excavations. Some linear features from the gradiometer survey were also considered. Areas of high conductivity were included as areas with possible structures (Figure 5.21b). These areas did not give any information on the geometry of the structures. They only gave the possible limits of the occupation of the site.

The archaeological excavation allowed describing the constructions material and the state of preservation of the structure. The building material is the surrounding bedrock. It is friable and little consolidated. As a consequence, the contrast of constructive features in GPR data is low and the general state of conservation is

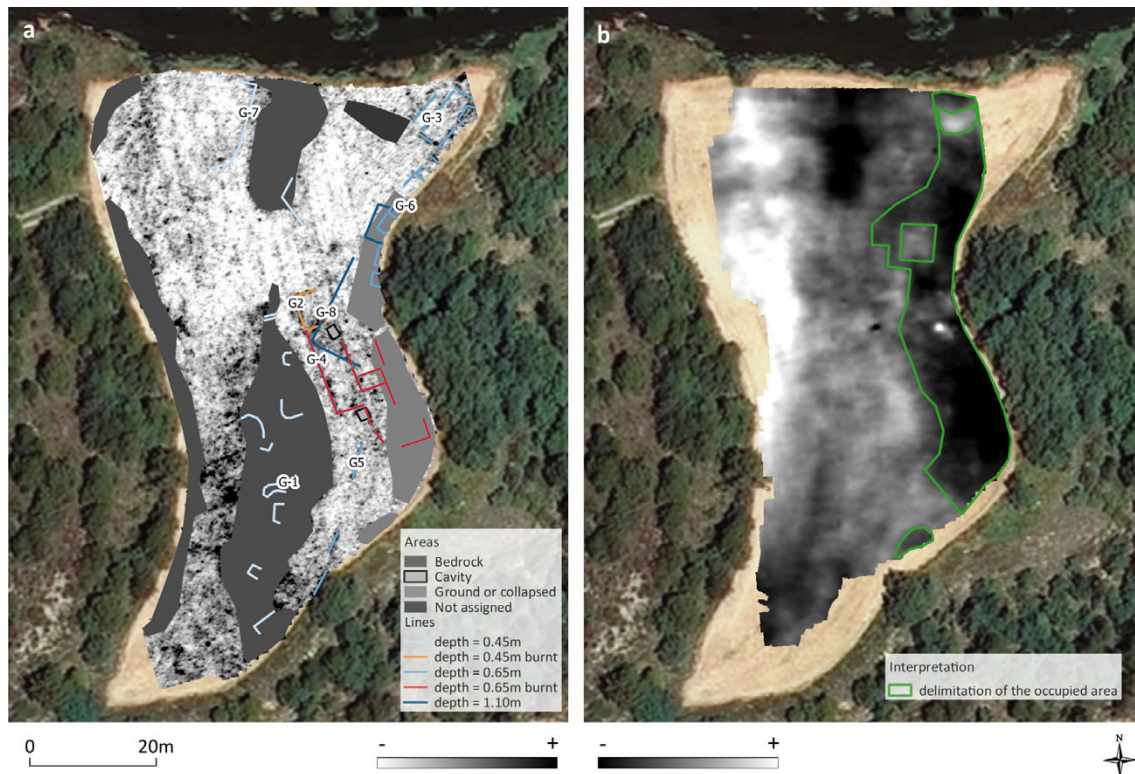


Figure 5.21: Description of the constructive structures a) interpretation of the GPR data b) interpretation of the electric conductivity data.

limited. The excavations enabled identifying several portions of the defending wall (Figure 5.22) that could not be covered by the geophysical surveys.

The GPR results were analysed in detail. They were transformed in polygons that delimit areas of interest and in lines that represent the constructive features.

The polygons were classified in 4 categories (1) Bedrock (2) Ground (3) cavities (4) Not assigned. The bedrock category delimits the superficial bedrock. It was delimited in order to put in evidence possible cuts that were made and that could define archaeological features. The ground category includes the area where the density of constructive features is high. These areas show high magnitude values. They could be explained by a compacted soil or by collapsed elements. Two cavities were identified G-Cav1 and G-Cav2 and were grouped in the cavities category. Finally, the feature labelled NA correspond to a deep (depth superior to 1.10m) high magnitude anomaly with no defined geometry. It also corresponds to a high conductivity area in EMI data. No meaning was assigned to this feature. It could be related to water circulation.

The lines were classified using their mean depth. The most superficial structures were assigned a mean depth of 0.45m. They include the structures labelled G-1, G-2 and G-7. G-1 represents the cuts that are visible in the bedrock. They could be related to anthropogenic features due to their geometry. G-2 is a 5.5x4.0m space delimited by walls. The eastern wall was not detected by the GPR but was described during the excavations. G-7 includes linear features in relation with the superficial bedrock of the northern part of the site.

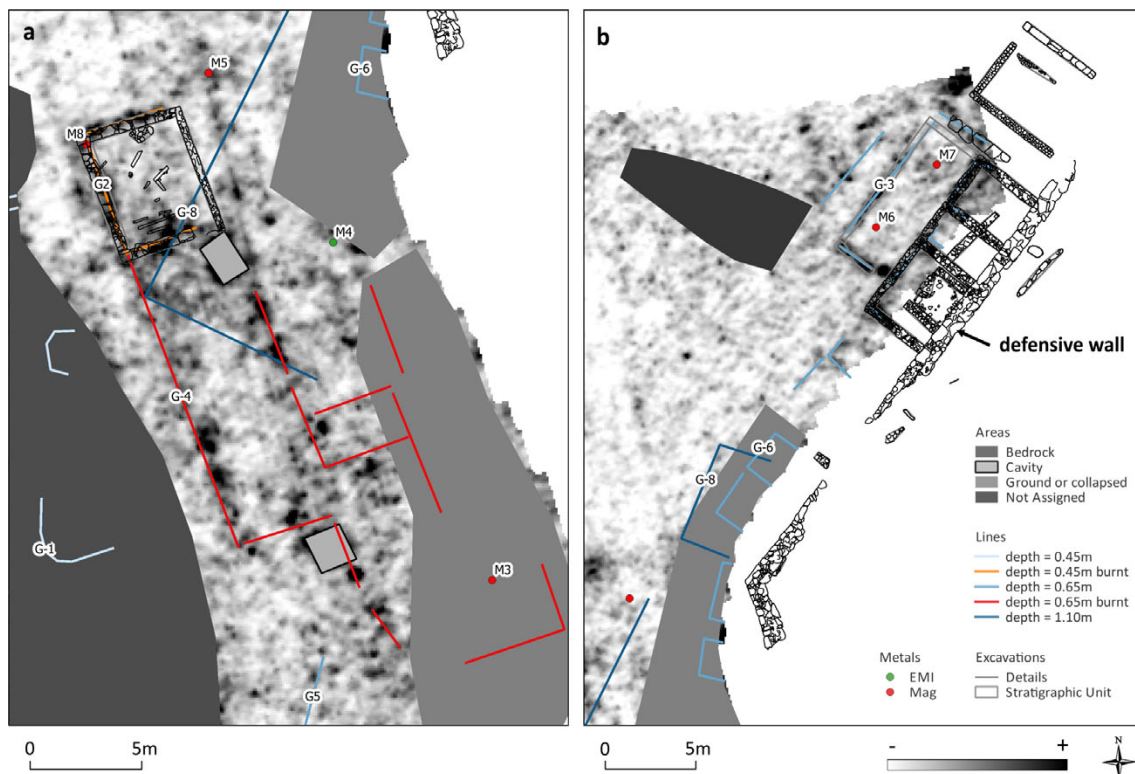


Figure 5.22: GPR data and excavation results a) eastern area b) north-eastern area

The intermediate features were located at a mean depth of 0.65m. This is the level where most of the constructive features were detected. G-3 was partially excavated and is formed by a set of rooms backed by the defensive wall (Figure 5.22a). G-6 is the continuation of G-3 but has not been excavated yet. It shows how the orientation of the room changes following the orientation of the defensive wall. G-4 is the continuation of G-2 at a deeper level (Figure 5.22b). It shows continuous constructive features in an area of 22x12m. This area corresponds to the thermo-alterations M-1 and M-2 of the gradiometer survey. It can be expected that all the structures in this area will show traces of a fire that might have destroyed the site. The fire was partially documented with the excavations of the structure G-2. G-5 includes linear constructive structures partially detected. The anomalies and the

connection with the rest of detected structures are not clear. These structures have a high degree of uncertainty.

The constructive features were not all well detected. Internal division were not defined. Some walls are incomplete. Several factors can explain the difficulties in detecting the structures. First, the depth at which the structures are located is at the limit of the depth penetration of the signal. In addition, the contrast between the building material and the environment is low. This makes difficult to detect thinner structures. Finally, the field was deep ploughed by the owner. This might have deteriorated the constructive structures.

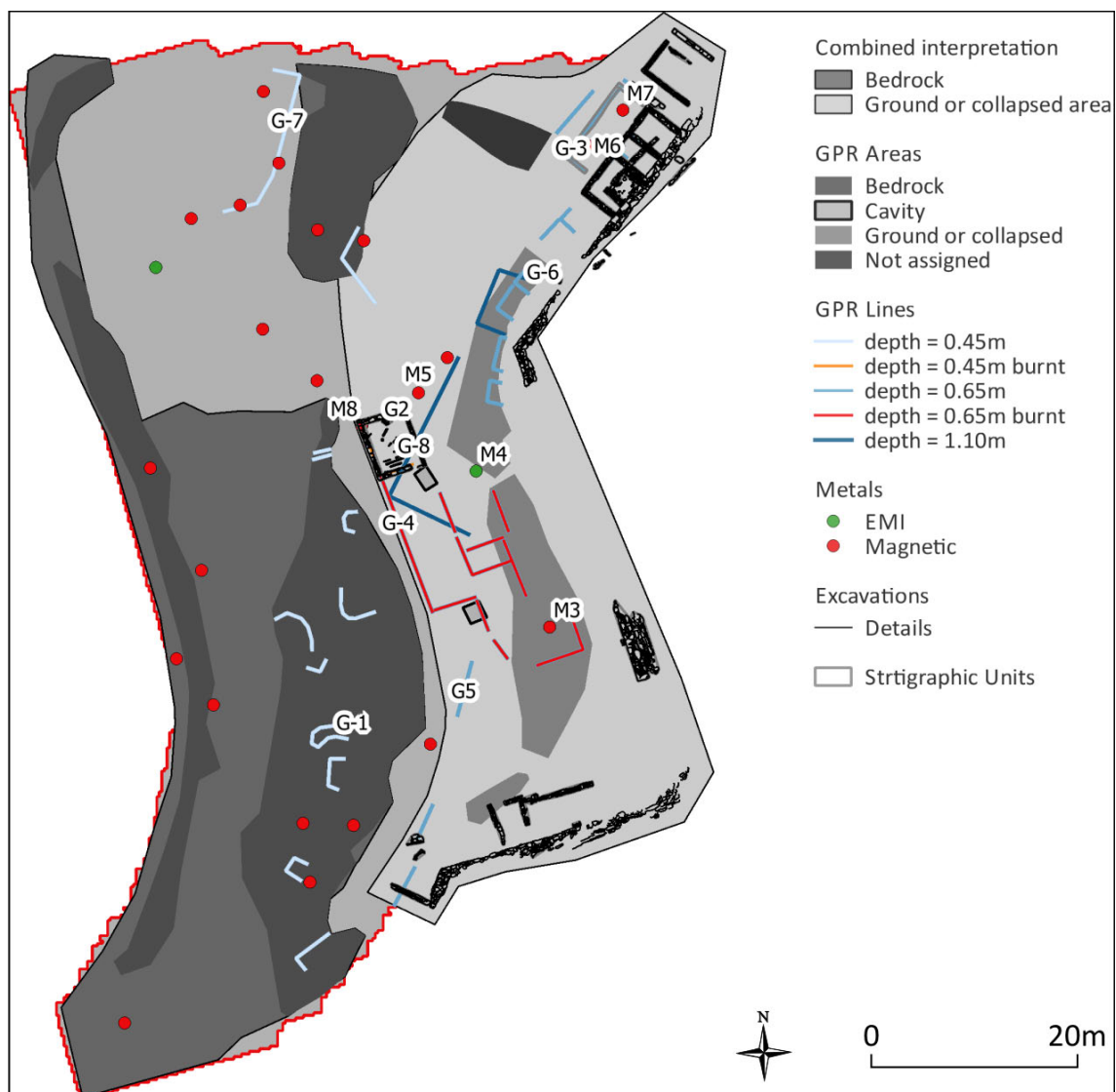


Figure 5.23: Synthetic map of the Roman settlement of Puig Ciutat (eastern area).

The deepest level detected had a mean depth of 1.10m. The structures are not clearly

defined. Constructive features seem to be present with a different orientation. They could be related with a previous phase of occupation.

The description of the extension of the occupation of the site depends on the ability of the GPR to detect the constructive features. As seen in different areas (G-2, G-4), the structures are not always well detected. The conductivity data of the EMI data were then considered in order to see if additional information could be retrieved on the occupation of the site. The extension of the low conductivity values (in black in Figure 5.21) was delimited and associated to constructive features and bedrock. The extension defined with the EMI data is larger than with the GPR data. The geometry of the possible structures could not be retrieved. The EMI data lead to propose a large area of occupation although the constructive structures could not be described.

A synthetic map was produced to describe the detected limits of occupation of the site and the constructive features. It is displayed in Figure 5.23.

5.3.4 Discussion of the results

The archaeological project of the site of Puig Ciutat is a long-term collaboration between archaeologists and geophysicists. The objectives of the research had then different levels. The first level included the use of geophysics to answer to the archaeological questions. The second level was related to the use of the geophysical results by the archaeological team during their research process. The results were then evaluated considering these two levels.

5.3.4.1 Limits and drawbacks

The methodology used for the application of archaeological geophysics had several limitations. They can be separated in limitations due to the acquisition of the data and limitations during the interpretation of the results.

As seen in Figure 5.4, the coverage of the site with the different applied systems was variable. The main difference came from the EMI survey. It was operated using a DGPS navigation and a quad. This configuration enabled a fast survey. Nevertheless, the size of the system limited the coverage in the narrow areas. As a consequence, the combined interpretation was limited in these areas. In addition,

the ground conditions were also variable. In general, the ground conditions were not acceptable. The continuous ploughing of the field prior to the beginning of the project could not be properly corrected and affected the acquisition of the data in terms of quality of the signal.

The interpretation of the results was limited because of (1) the deep ploughing of the field, (2) the presence of both metals and burnt areas and (3) the limited depth of penetration of the GPR signal.

1. The deep ploughing created aligned bedrock material in the main documented level. These linear anomalies could be mistaken with archaeological features when the orientation was the same. Furthermore, the deep ploughing destroyed part of the structures in the southern area of the site.
2. As shown by the excavation results, the destroyed areas contained both burnt areas and weaponry. The overlapping of weapons made of iron and of the burnt areas gave a complex signal in the gradiometer survey. It could be partially solved using the EMI results. Nevertheless, they had a coarser resolution and could not detect all the metals.
3. The main level of occupation of the site was located at a mean depth of around 0.65m. Deeper structures were detected at a mean depth of 1.10m. Due to the conditions of acquisition and to the composition of both soil and building material, the signal at these depths had a low resolution. It did not allow a systematic detection and description of the constructive structures.

The archaeological methodology had also limitations that had to be overcome. The mapping of the first excavation campaigns was done using hand-made drawings and local references. This was a major problem in the first years as geophysical and excavations results could not be precisely compared and the strategy could not be properly re-evaluated. The problem was partially solved transforming the results from the acquisition local references to UTM absolute references. The remaining decision concerned the common platform to use for the integration of the results. The archaeological register requires a systematic entry of the excavated elements. They require specific tools or front-end that ensure the consistency and reliability of the entered information. In the absence of a global policy regarding the archaeological

record, each team has to define the environment in which the results are entered. In the specific case of the site of Puig Ciutat, the environment had to consider both archaeological and archaeological geophysical results. A front-end is still being tested for the entry of the excavation results (del Fresno Bernal and Torrecilla, 2009). The common platform for the visualisation of the results was QGIS. This solution improved the integration of the results but could only be used for horizontal representations. Elements as vertical sections could not be included and had to be managed externally. Considering the difficulties of having a complete integration of both archaeological and geophysical data, the geophysical results were mainly used as an orientation for management of the excavation. With an improved integration, a combined interpretation could be enabled. A reassessment of the strategy could then be possible (Horsley et al., 2014).

For both archaeological and geophysical surveys, the reference system was problematic and created uncertainty on the positioning of the results. The fixed topographic bases were set on the site at the third year of the project. The first surveys were acquired with local references and stakes that were sometimes lost due to fieldwork and had to be replaced. In addition to the 2D integration of the data, a 3D integration was also considered. Research is being done in this field (De Reu et al., 2014). No reference platform both suitable to geophysical and archaeological 3D data exist. The changes in the technology and in the methodology are fast.

5.3.4.2 Conclusions of the project

The conclusions were divided in two sections (1) conclusions on the archaeological objectives (2) conclusions on the integration of geophysical and archaeological results.

The first archaeological objective was to map the variations in depth of the bedrock. The bedrock could not be mapped in the entire extension. It was only mapped where the bedrock was superficial. These areas do not show constructive structures. They show possible anthropogenic cuts.

The excavation gave results consistent with the geophysical interpretation. They gave reference results for the planning of future surveys. The room labelled G-2 showed the nature of thermo-alterations that can be expected in the other areas with the same signal. It contained carbonised wood beams and indications of destruction.

The same kind of results can be expected in the area labelled G-4.

The constructive structures were partially described. The areas labelled G-2 and G-3 both showed consistent results with the geophysical data. The room G-2 also showed the limitations of the geophysical survey. Three walls of the room were well described but the eastern wall was not detected. This could be due either to the depth at which it was located or to the dimensions of the wall that was thinner than the three others and in the direction of the acquisition. Similar problems can be expected in the other areas with a partial description of the constructive structures. On the other hand, both GPR and EMI results gave consistent results on the main occupied areas where constructive structures can be expected.

Although no clear structure was detected in the north-western part of the site, the occupation of this area cannot be discarded. The integration and interpretation strategies should now be applied on the other explored area of the site, zone 1 in Figure 5.1.

The collaboration between archaeological and geophysical team was useful at different levels. The participation of the geophysicists to the excavations and to the mapping of the structures helped improving their knowledge of the expected structures. This knowledge was then used for the interpretation of the results. It also increased the necessity of creating a common platform and accelerated the process. Conducting the geophysical surveys during the excavations also helped introducing the geophysical methods to the archaeological team. It also showed the necessity of insisting on the limitations of the methods.

As the common platform is still being created, the systematic use of the geophysical interpretation by the archaeological team was not possible. It will be possible to evaluate it in the future surveys. The evaluation criteria are the use of the results for the planning of the surveys and the integration of the geophysical results in the documentation of the excavations.

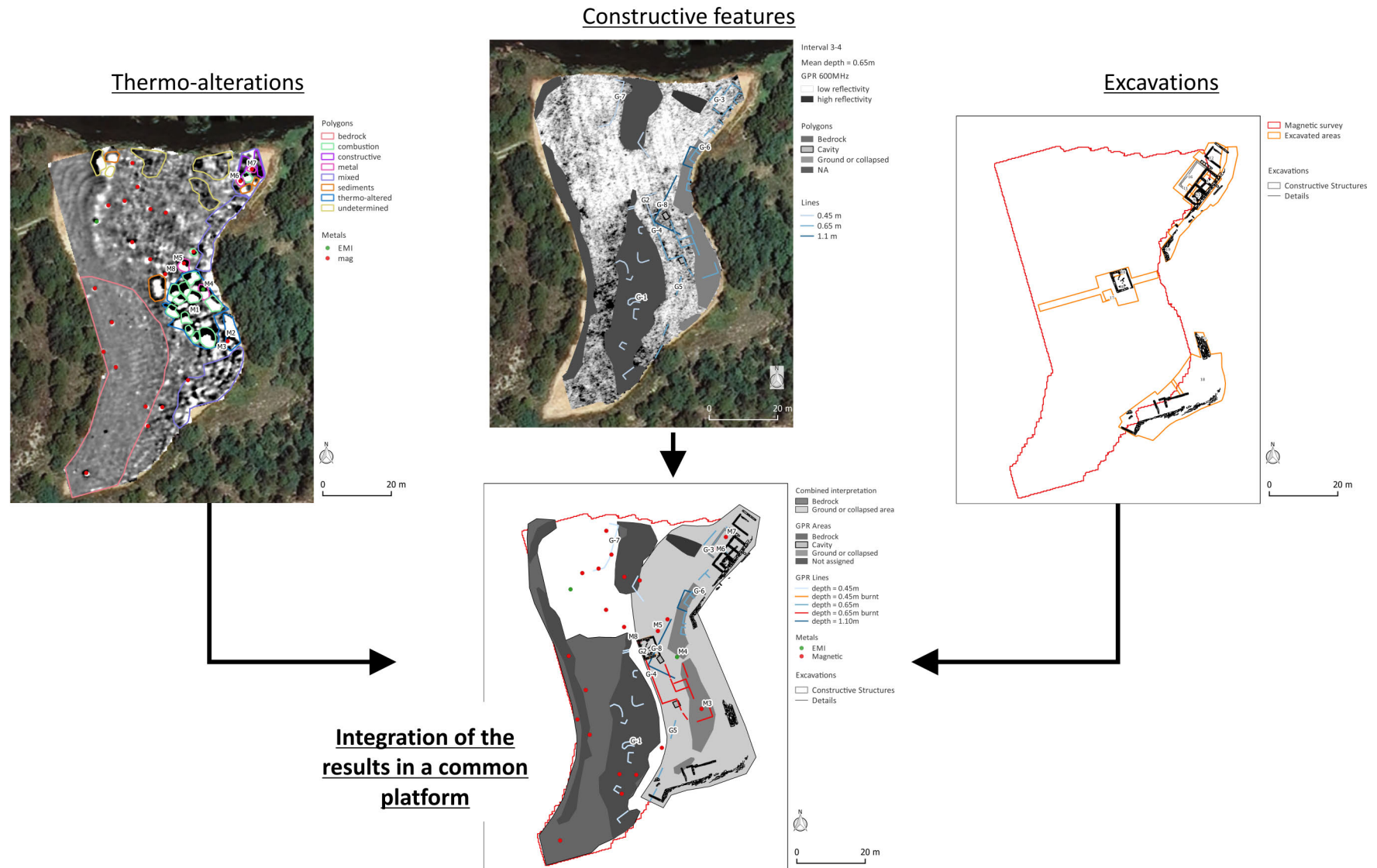
5.4 Data finalisation

As the project is a long-term collaboration, this section only gives the intermediate documentation of the results. The same documentation should be done on the surveys already conducted in the other areas of the site. Then, new objectives

must be set that will define the strategy of future surveys. The new surveys should be integrated in the platform created based on this research. The documentation includes (1) the present report presented as a chapter (2) a graphical report (3) an animated sequence which can found in the supplementary material (4) a 2D model created in GIS platforms and (5) the archived files of the project listed in Appendix F.

5.4.1 Graphical report

5.1 Multi-method research program for the documentation of a destruction

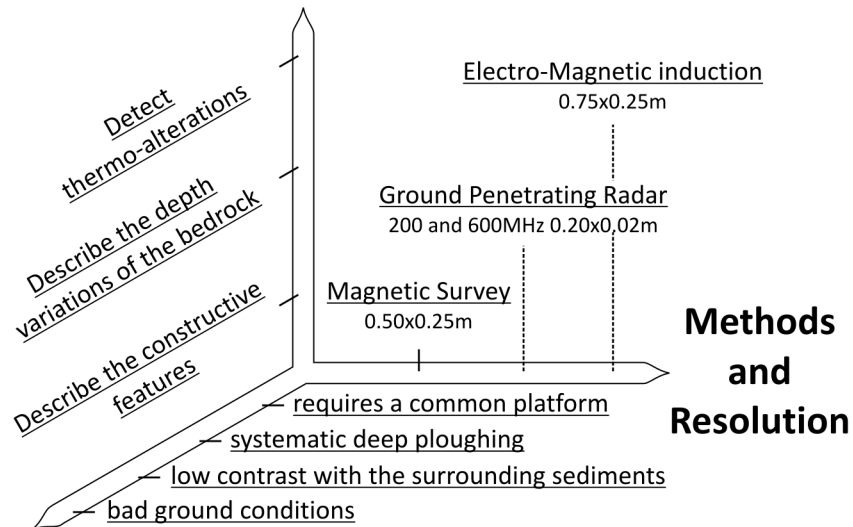


5.2 Design of the Project

Characterisation

Strategy

Objectives



Feasibility

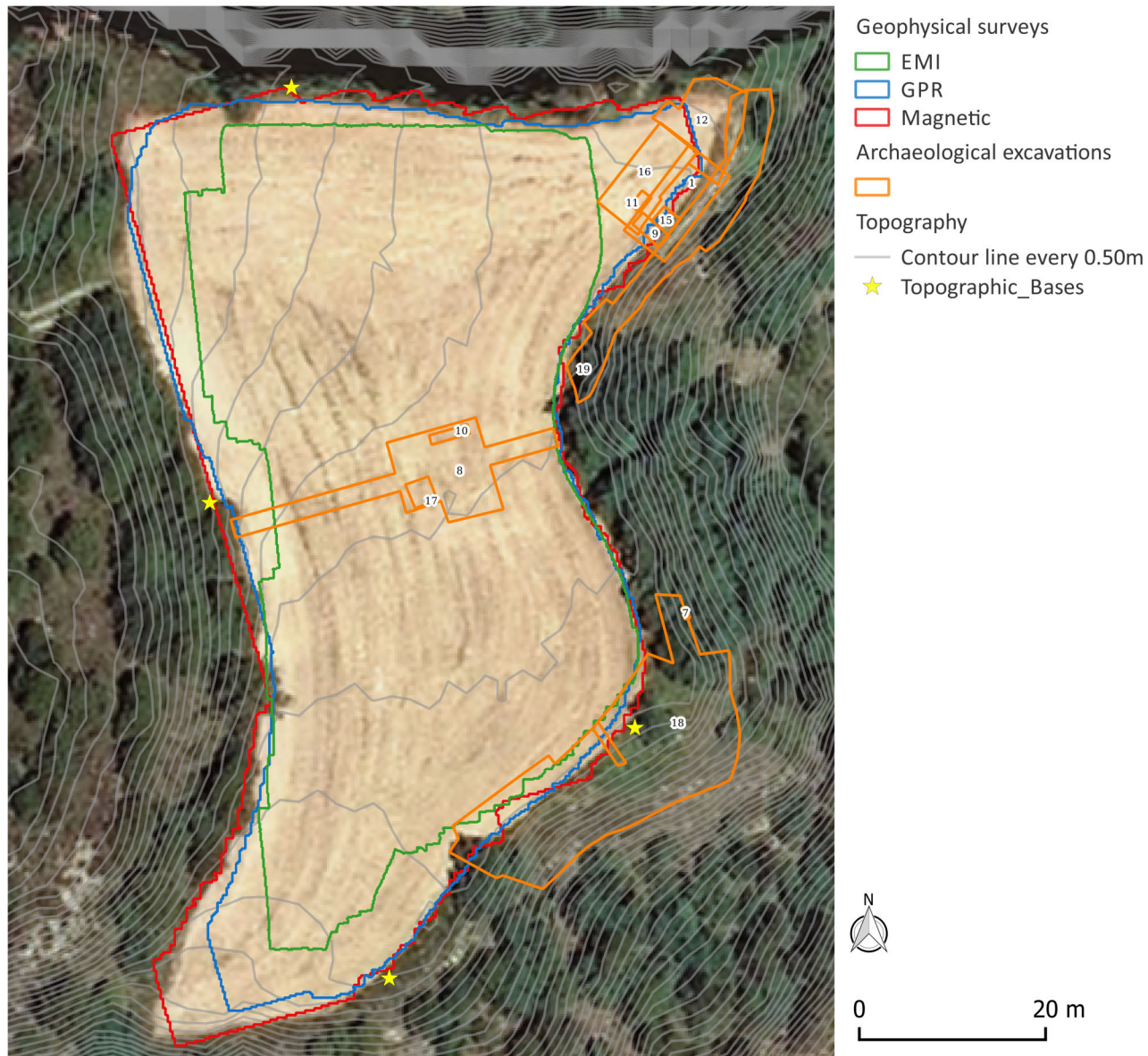
- Adapt the geophysical campaigns to the archaeological results
- Long-term project and integrated geophysical team
- Implement a common platform for the management of the project

The objectives of the project of Puig Ciutat were both methodological and archaeological.

The creation of a mixed team, including geophysicists and archaeologists had as objective to enable a broader use of the results.

The archaeological objectives were to detect the thermo-altered areas possibly related to the destruction of the site, to describe the variations in depth of the bedrock and to map the constructive structures.

5.3 Areas covered with the different survey methods



The geophysical methods covered the entire area. The EMI survey was limited by the size of the used system and could not cover the corners.

The locations of the archaeological excavations were decided based on the position of the defensive wall and on the results of the geophysical surveys.

Covered areas

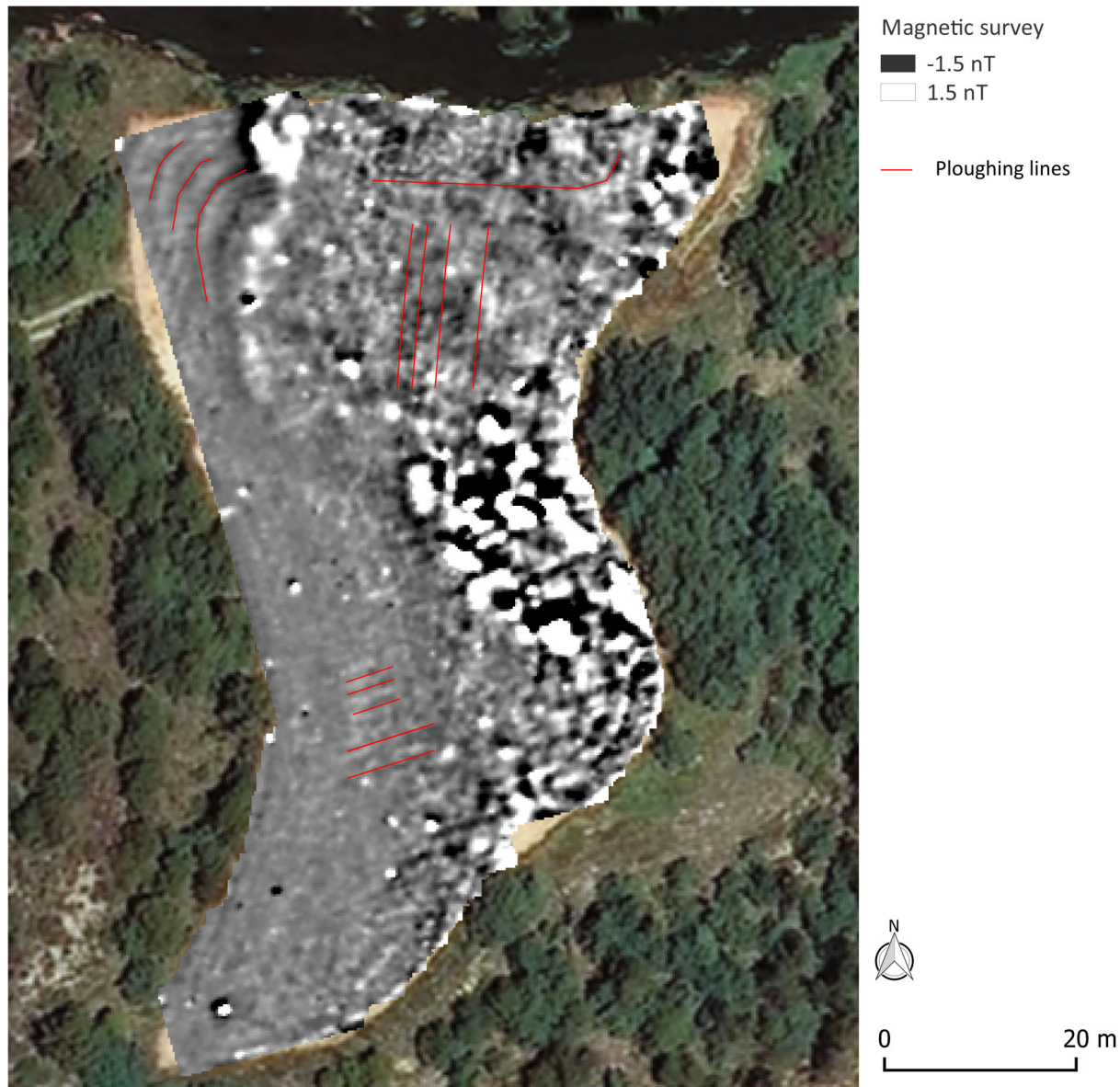
Magnetic survey 2010
3 975 m²

GPR survey 2011
3 712m²

EMI 2012
2 950m²

Excavations 2010-2014

5.4 Results of the magnetic survey

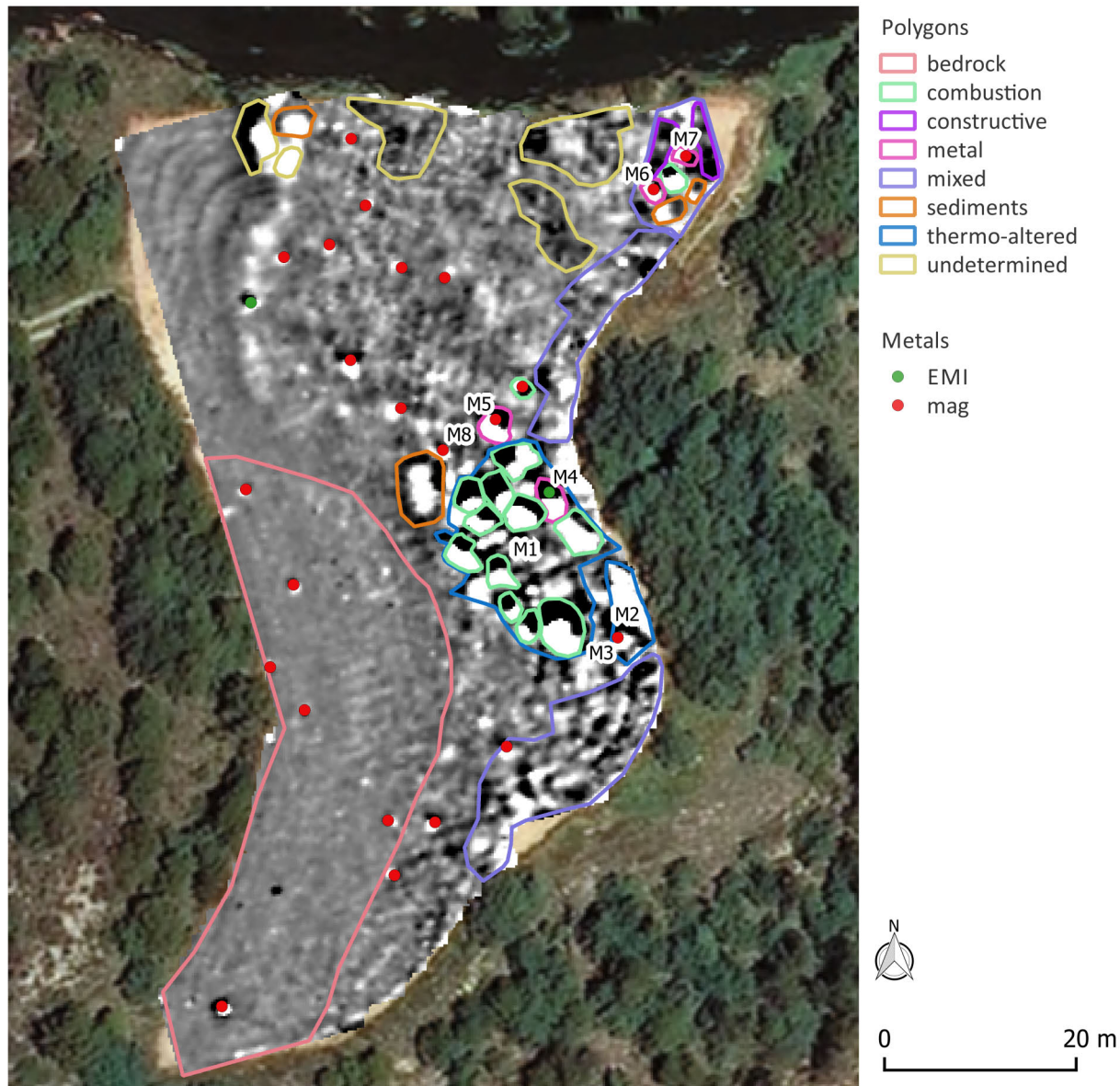


The magnetic survey show a low contrast (90% of the data are included between -2 and 2nT).

The ploughing of the field is visible on the resulting data.

The constructive structures could not be described. The high values mainly corresponded to thermo-alterations and metals.

5.5 Interpretation of the magnetic survey

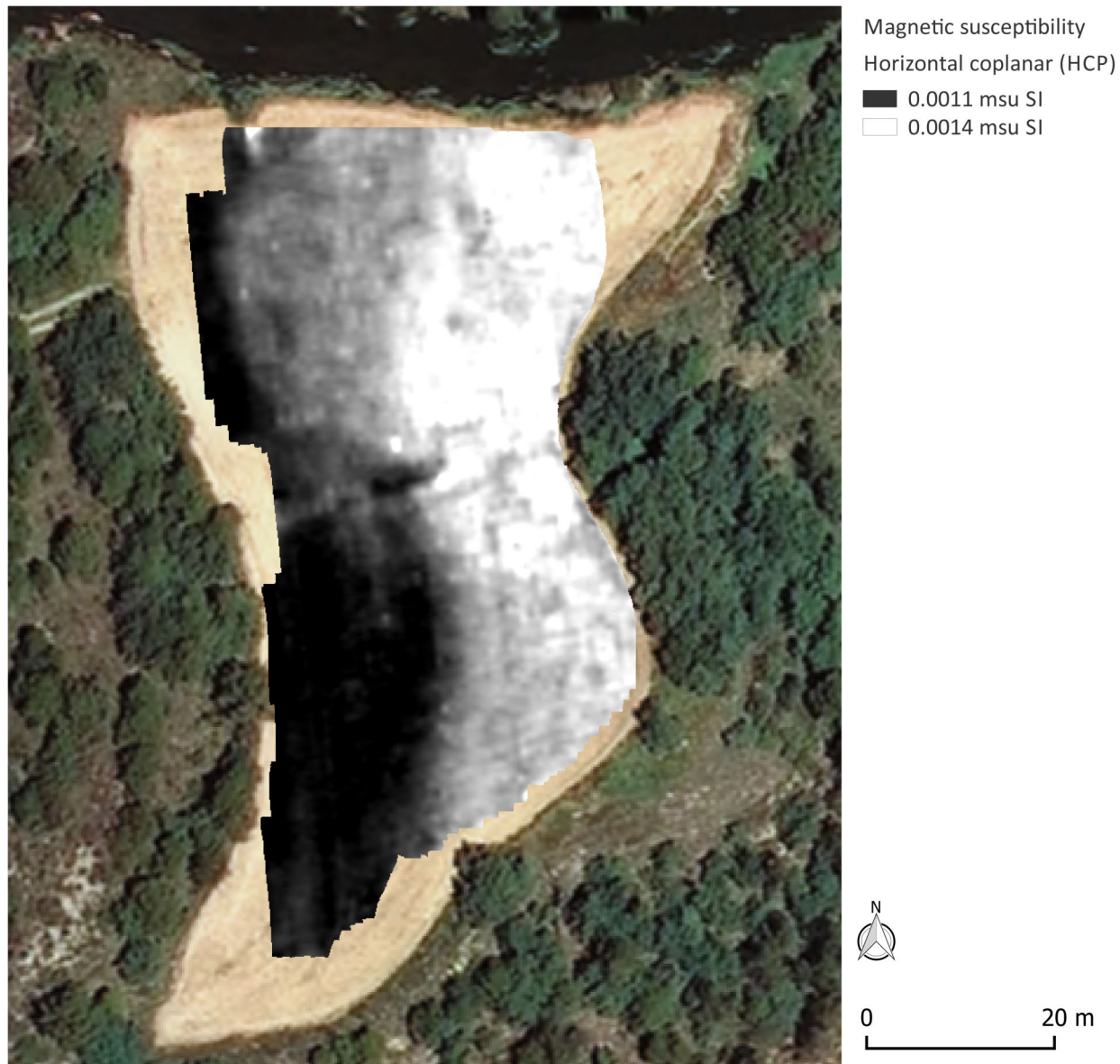


The magnetic data were interpreted delimiting the areas of interest with polygons and using points to identify focal anomalies.

The polygons were used to compute the mean absolute value of the magnetic gradient. The results were used to classify the delimited areas. Areas M1 and M2 showed the highest values and were associated to thermo-alterations.

The focal anomalies related to metals were identified using the magnetic and the EMI data. The ones possibly related to archaeological artefacts were labelled (M3-M8).

5.6 Results of the EMI survey - Magnetic susceptibility



The magnetic susceptibility data showed large scale variations.

They showed low values in the western part and high values in the northern and eastern parts.

No details on the structures could be retrieved from the data which mainly showed areas of interest.

5.7 Interpretation of the magnetic susceptibility data



The areas of low and high susceptibility were delimited with polygons.

The red polygon delimits an area with low susceptibility values. It was associated to an area where the bedrock is superficial.

The polygon in orange delimits an area with a higher susceptibility. The higher susceptibility can be explained by the action of fire on the sediments or by the presence of metals.

5.8 Results of the EMI survey - Electric conductivity



Low conductivity are shown in black. They correspond to resistive material that can be associated to constructive structures or bedrock.

The high value of conductivity are shown in white. They correspond to areas where the sediments have a higher porosity and a higher content in water.

5.9 Interpretation of the electric conductivity data

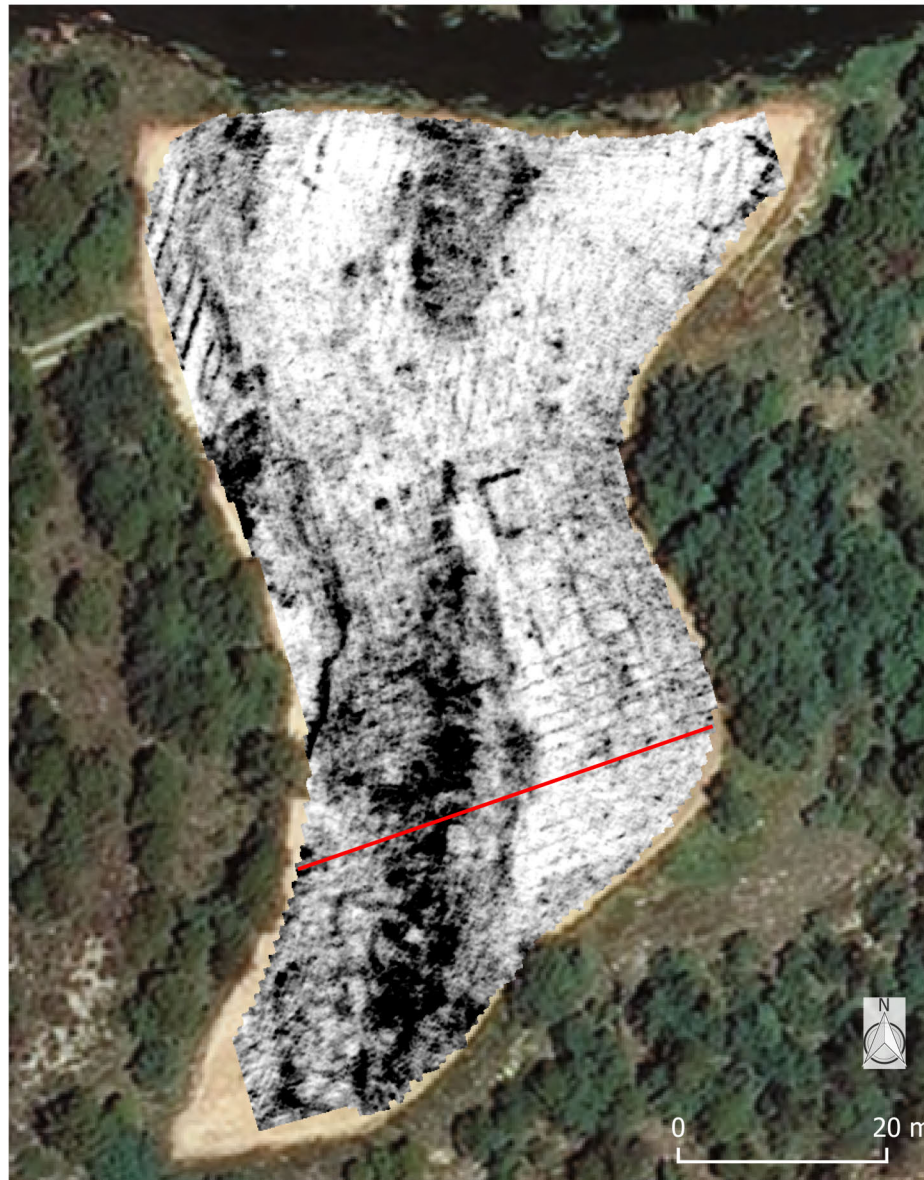


The low conductivity data were delimited using polygons.

The red polygons were associated to bedrock.

The green polygon was associated to an area with a higher density of constructive structures.

5.10 Results of the GPR survey - Interval 2-3

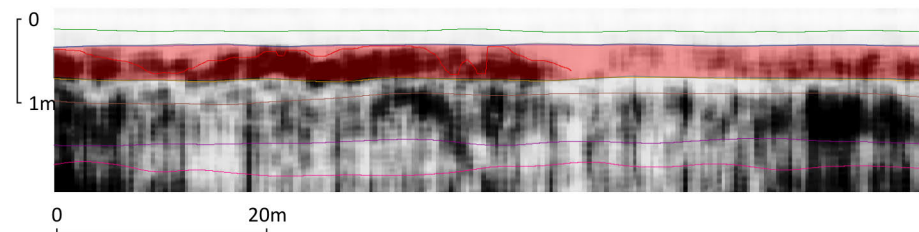


Depth slices were created using intervals of varying depth. The intervals were extracted from the 200MHz data and represent the major changes in magnitude.

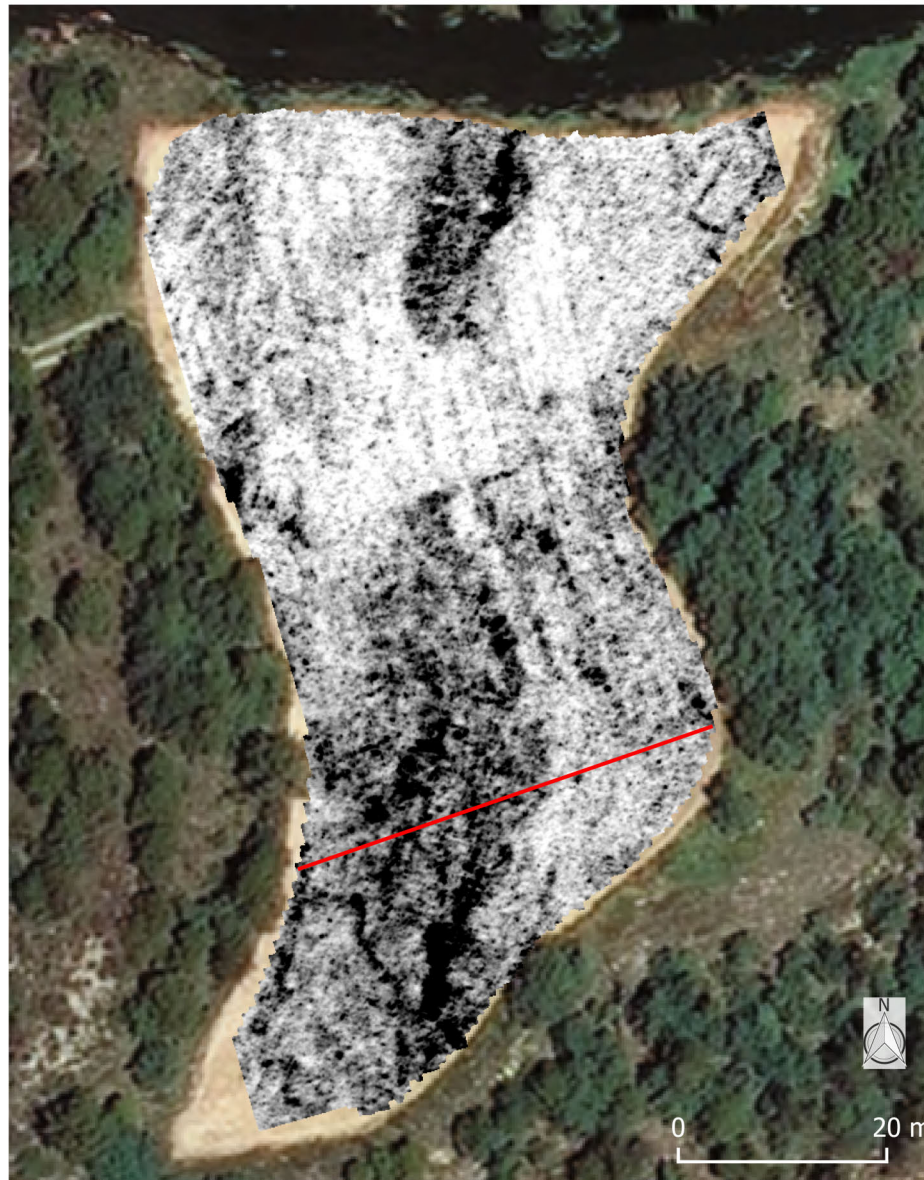
The interval 2-3 represents the top of the level with constructive structures and shows the superficial bedrock.

It is located at a depth included between 0.20 and 0.70m. Its mean thickness is of 0.40m

Vertical section showing the interval



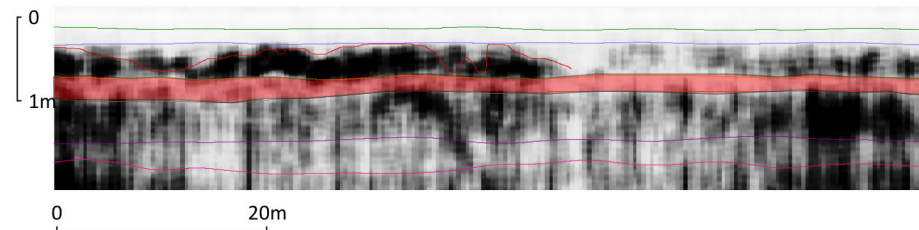
5.11 Results of the GPR survey - Interval 3-4



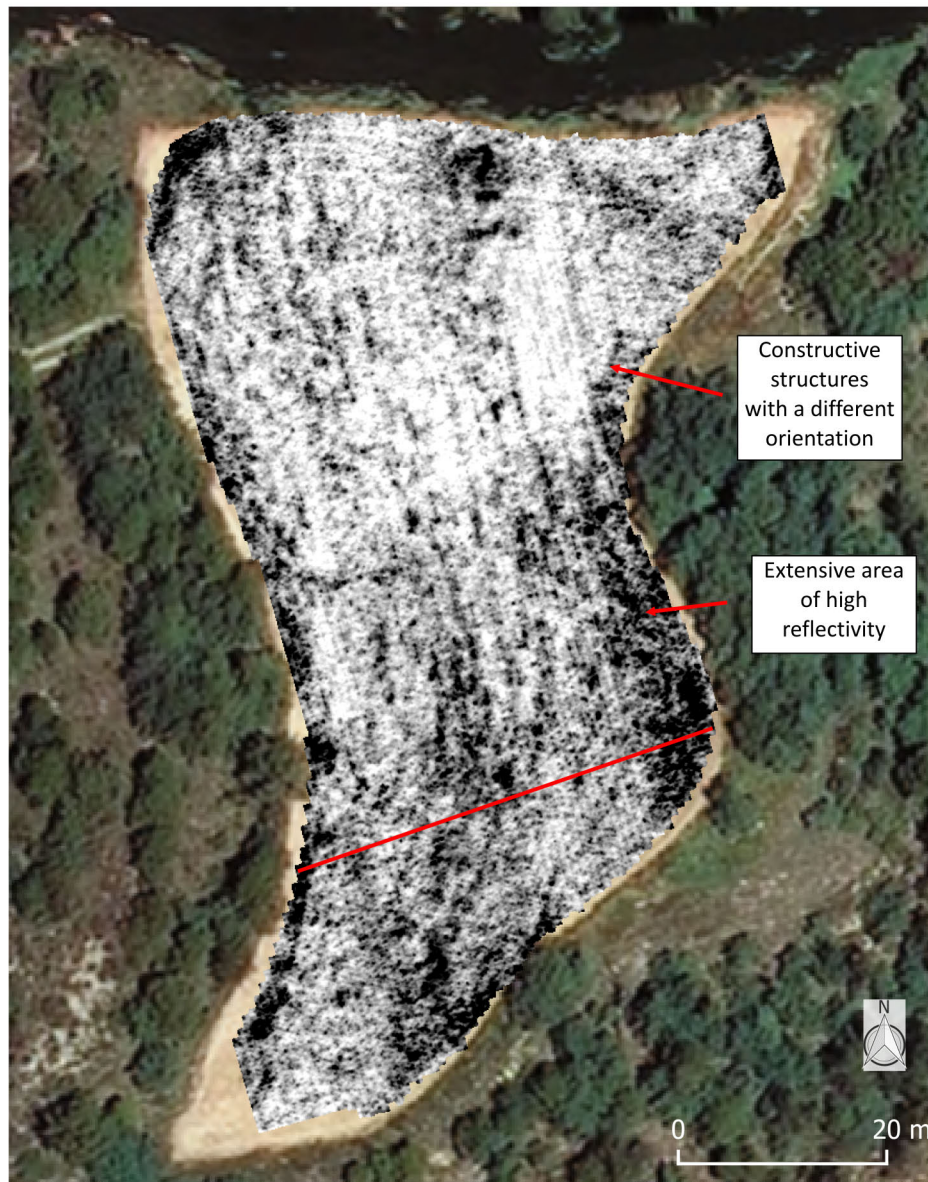
The interval shows the main level where the constructive structures can be observed.

It is located at a depth included between 0.60 and 1.00m. Its mean thickness is of 0.20m.

Vertical section showing the interval



5.12 Results of the GPR survey - Interval 4-5

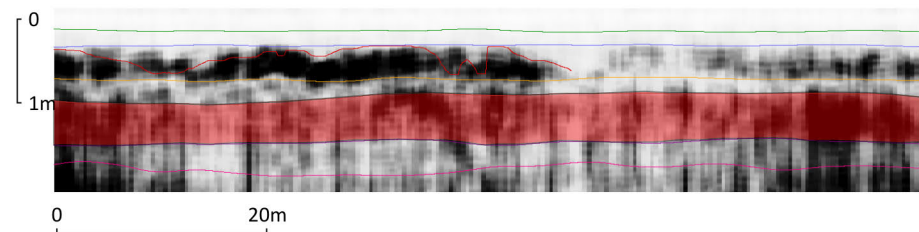


This interval has a lower resolution because of the depth at which it is located and because it was produced with the 200MHz data.

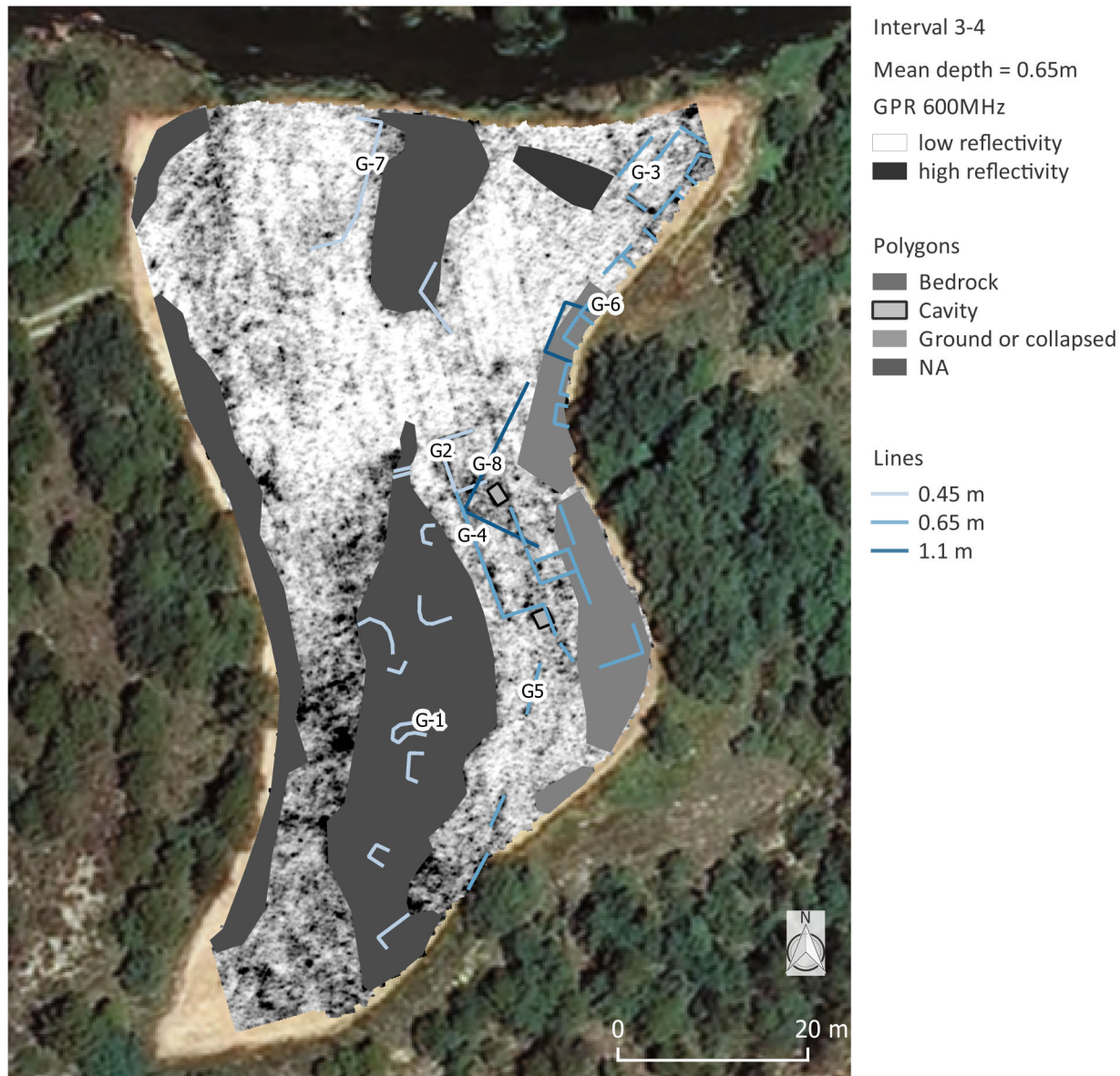
It shows an extensive area with high reflectivity values below the previously described constructive structures and constructive features with a different orientation. It could be associated to a previous phase of occupation.

It is located at a depth included between 0.80 and 1.45m. Its mean thickness is of 0.55m.

Vertical section showing the interval



5.13 Interpretation of the GPR data



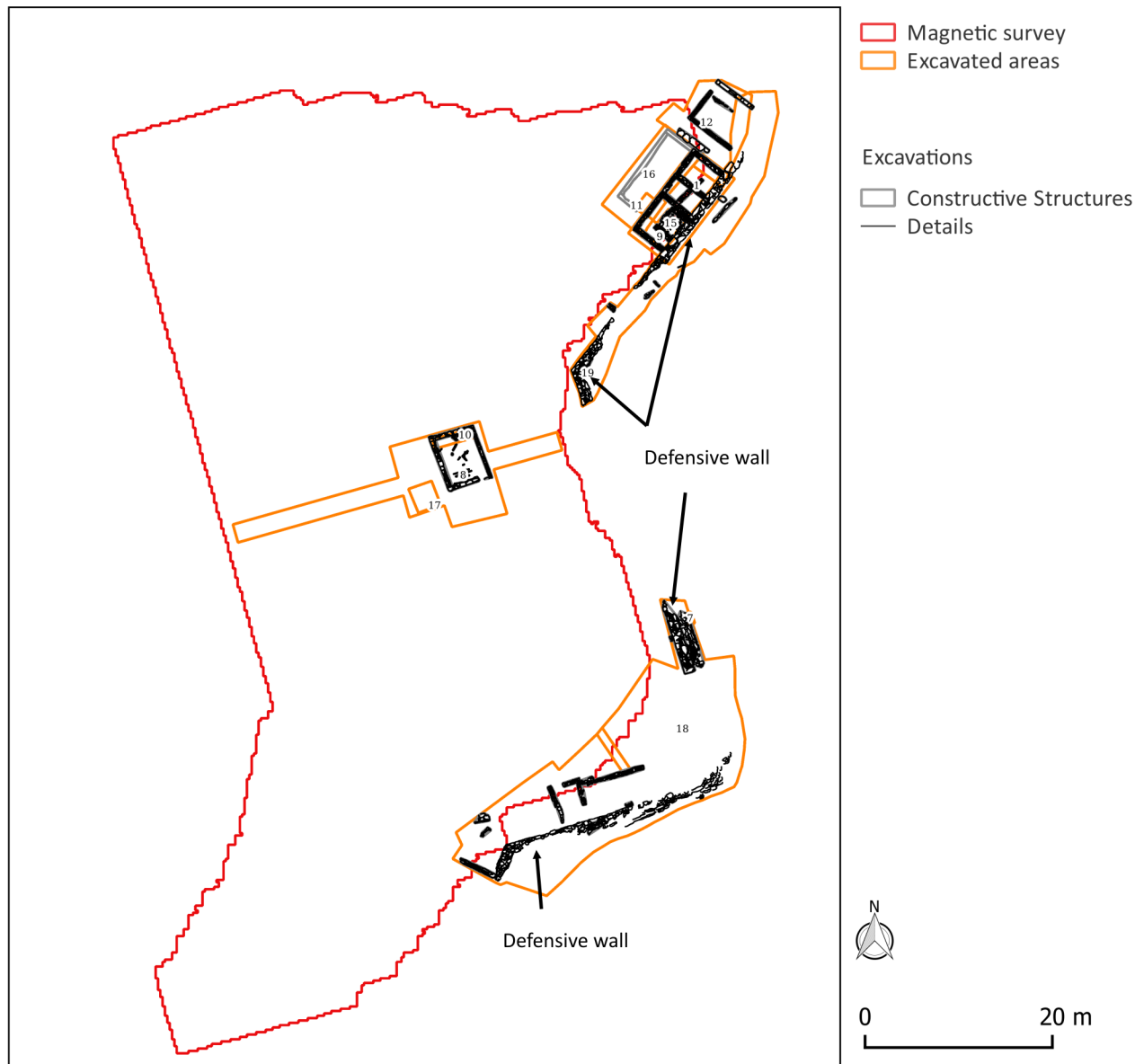
Polygons and lines were used for the interpretation of the GPR data.

The polygons represent the extensive areas. They were classified using their assigned archaeological meaning.

The lines represent the constructive structures. They were classified using the interval from which they were extracted and their mean depth.

The main areas of interest were labeled.

5.14 Digital mapping of the excavations



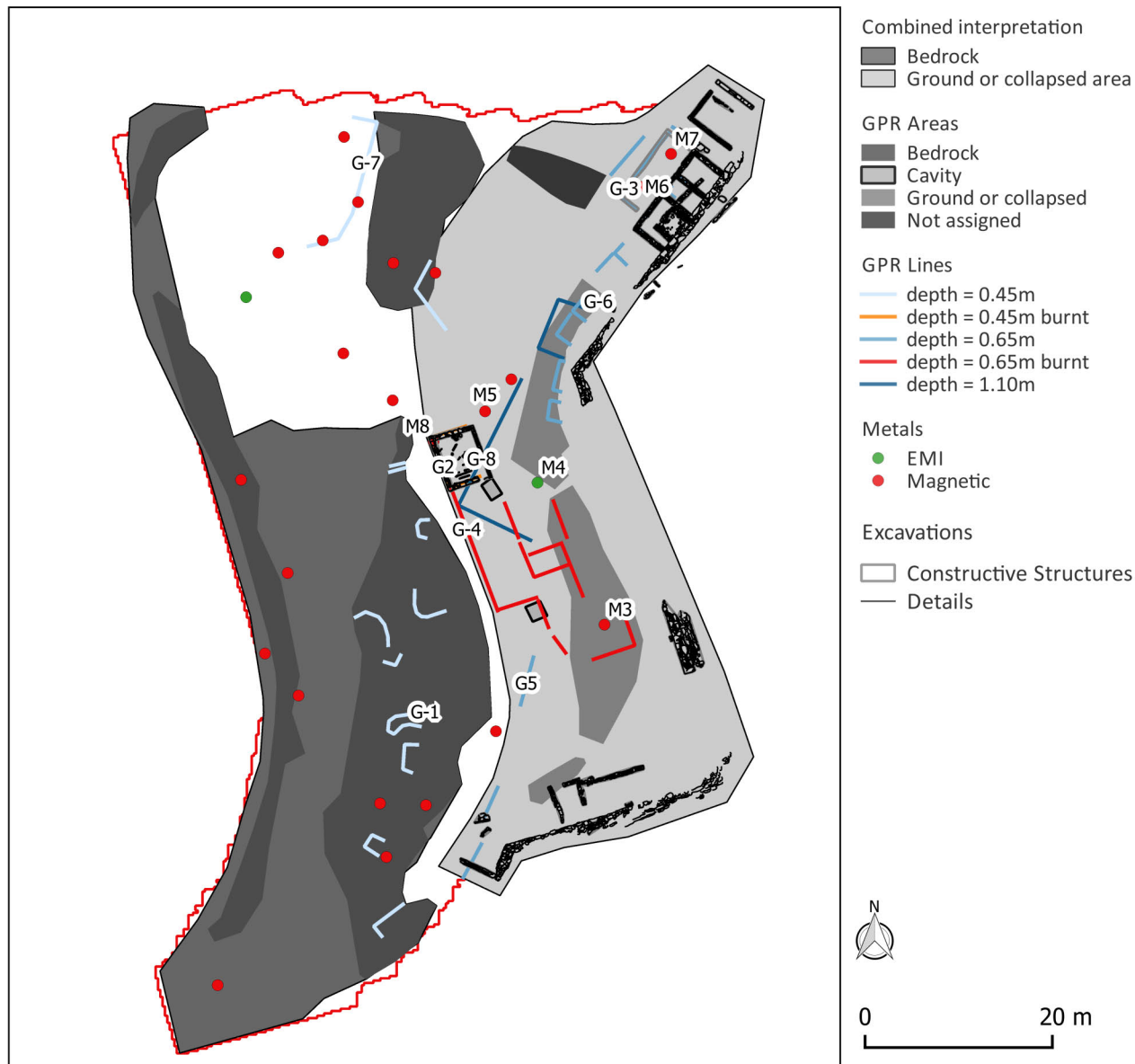
Excavations were conducted in parallel to the geophysical surveys.

They were decided based on the position of the defensive walls and on the areas of interest delimited by the interpretation of the geophysical results.

The results of the excavations were separated in polygons with the limits of the stratigraphic units and in lines with the details of each stratigraphic unit.

The stratigraphic units related to constructive features are shown here.

5.15 Synthetic map of the results



A synthetic map was produced combining the main results of all the surveys.

The main contributions were the delimitation of the area where the bedrock is superficial and of the extension of the occupation.

The contrast between the building material and the surrounding sediments is low. As a consequence the constructive structures could only be partially described with the geophysical methods.

The constructive structures possibly associated to fire traces and destruction were identified and are indicated in red.

5.4.2 Animated sequence

The animated sequence was divided in three parts

1. Part 1: description of the the archaeological context and objectives, of the used methods and of the limitations of the project.
2. Part 2: description of the individual surveys. It includes the magnetometer, the GPR and the EMI surveys, and the excavation campaigns
3. Part 3: description of the main conclusions

The animated sequence can be found as additional material in the attached CD. The file is named 2015_Puig-Ciutat_video.mp4 and is located in the folder CH5_PUIG-CIUTAT.

5.4.3 GIS model

The GIS platform was used as a visualisation tool that enabled importing survey results for assessment and interpretation. The assessment of the results required setting a common reference system and associating properties to the vectorial information. In order to ensure the consistency between campaigns, the archaeological information was introduced in a database. This database required the use of a front-end in order to enter the properties of associated to the archaeological record. The properties used for the geophysical information files were set based on the needs and specificities of the project.

The GIS project is available in the attached CD. It is located in the folder CH5_PUIG-CIUTAT and named CH5_GIS. The contents of the folder are described in section 5.4.4.4 and listed in Appendix F. The contents of the model is described in the following section and can be opened installing the software QGIS available in the folder SOFTWARE and loading the file named PC_GIS.qgs.

5.4.3.1 Raster information

The raster files include RGB files and dynamic rasters files. The RGB files are photographs. The dynamic files contain the values of the processed properties in single band.

The RGB files included were extracted areas of the aerial photographs produced by the ICGC (Institute Cartogràfic i Geològic de Catalunya). The source file can be found using an identification code included in the name of the file. The files were named using the identification code followed by the extension PC.

The dynamic rasters gather the results of the processing of the geophysical surveys.

1. The gradiometer data are store in the PC_Mag file. The values represented are the processed gradient values and represent variations in nT/m.
2. The bedrock elevations are stored in the Z_Bedrock file. The values were produced subtracting the depth values from the elevations provided by the ICGC.
3. The GPR data are gathered in one group. They include the depth slices produced using the extracted horizons. Their name is formed with the following fields Slice_Frequency_Interval. Their represent variations in the magnitude of the signal.
4. The EMI data were gatehered in the group EMI. They give the relative variations in susceptibility and conductivity. The files are named '00_PC_EMI_Property_configuration_version'. The property field can be MS that stands for magnetic susceptibility or EC for electric conductivity. The configuration field can be HCP that stands for horizontal coplanar or PRP, perpendicular. The version field states the filtering version.

5.4.3.2 Vectorial information

The vectorial information was grouped in three categories (1) General, (2) Interpretation and (3) Excavations. The general group includes the information related to the acquisition of the data in terms of covered areas, references and topographic information. The interpretation group includes the vectorial interpretation of the geophysical surveys and the excavations group includes the the results of the excavations. All the files are in shapefile ESRI format. Each file has associated properties that are listed in Table 5.8 and described below.

1. General

- (a) PC_Mag_contours_02nT: contour lines every 0.2nT/m extracted from the gradiometer processed data. 'Id' is an identifier, 'Grad' is the gradient value in nT/m.
- (b) PC_ICC_MDT_contours_50cm: contour lines every 0.50m extracted from the LIDAR data provided by the ICGC. 'id' is an identifier and 'ELEV' is the elevation value in meters.
- (c) PC_Zones_clean: delimitaion of work areas in the site. The project is centred in zone 2. 'id' is an identifier, 'nom' is the label of the area, 'X_L' and 'Y_L' are the coordinates of the positioning of the labels.
- (d) PC_Geophysics_areas: areas covered with the geophysical surveys. 'Id' is an identifier, 'Year' is the year when the survey was conducted, 'Method' is the used method, 'System' is the used system, 'Comment' stores comments on the surveys and Area (m2) is the covered area in square meters.
- (e) PC_ARQ_SUPI: delimitation of the excavated areas. 'Id' is an identifier, 'SUPI' is the label of the excavated area.
- (f) Topgraphic_Bases: topographic references of the site. 'Id' is an identifier, 'Num' is a number formed with the coordinates of the points in the local reference system, 'XETRS89' and 'YETRS89' and the UTM coordinates of the points and 'Z' is the elevation value.

2. Interpretation

- (a) PC_Mag_points: identification of the focal anomalies of the gradiometer survey. 'id' is an identifier, 'Comment' is a comment on the nature of the point, 'Source' states if the points was cross-interpreted with the EMI electric conductivity survey, and 'Label' is the label affected to the points during the interpretation of the data.
- (b) PC_Mag_lines: identification of the linear anomalies of the gradiometer survey. 'id' is an identifier.
- (c) PC_GPR_Lnes: identification of the linear anomalies of the GPR survey. 'Id' is an identifier, 'interval' designates the depth slice in which it was identified, 'Mean_depth' is the mean depth of the interval, 'Label' is the label used for the description of the structures, 'Burnt area' states if the constructive features are located in areas with thermo-alterations.

- (d) PC_Mag_polygons: identification of the extensive anomalies of the gradiometer survey. 'Id' is an identifier, 'Abs_magmean' is the mean value of the absolute gradient computed in each polygon, 'Type' describes the possible function of the area, 'Comment' adds a description to the area and 'Label' is the label used during the description of the results.
- (e) PC_GPR_polygons: identification of the extensive anomalies of the GPR survey. 'Id' is an identifier, 'interval' designs the depth slice in which it was identified, 'Mean_depth' is the mean depth of the interval, 'Label' is the label used for the description of the areas. Gr stands for ground, Cav stands for cavity, BR stands for bedrock and NA stands for not assigned.
- (f) PC_EMI_polygons: identification of the extensive anomalies of the EMI survey. 'id' is an identifier, 'Property' is the physical property that was used to delimit the area and 'Comment' describes the function of the delimited area.
- (g) PC_synth_polygons: delimitation of the areas of interest. 'id' is an identifier and 'label' is the description of the results.

3. Excavations

- (a) PC_P: polygons delimiting the stratigraphic units. 'CODI' is the stratigraphic unit number and 'TIP' is the type of stratigraphic unit. DEP stands for depositional, EC stands for constructive elements and SC stands for solution of continuity.
- (b) PC_Det: lines describing details in the stratigraphic units. 'CODI' is the number of the detail and 'UE' is the number of the associated stratigraphic unit.
- (c) PC_OD: location of the excavated artefacts. 'CODI' is the number associated to the artefact and 'UE' is the number of the associated stratigraphic unit.

5.4.4 Files

The delivered data were classified in four categories: (1) the raw data which are the data acquired and downloaded without any change (2) the processed data which are the data after the applied transformations (3) the documentation that were

	Vectorial information	Type	Properties
General	PC_Mag_contours_02nT	Lines	Id, Grad(nT)
	PC_ICC_MDT_contours_50cm	Lines	Id, ELEV(m)
	PC_Zones_clean	Polygons	id, nom, X_L, Y_L
	PC_Geophysics_areas	Polygons	Id, Year, Method, System, Comment, Area m2
	PC_ARQ_SUPI	Polygons	Id, SUPI
	Topgraphic_Bases	Points	Id, Num, XETRS89 (m), YETRS89 (m), Z (m)
Interpretation	PC_Mag_points	Points	Id, Comment, Source, Label
	PC__Mag_lines	Lines	id
	PC_GPR_Lnes	Lines	Id, Interval, Mean_depth, Label, Burnt area
	PC_Mag_polygons	Polygons	Id, Abs_magma, Type, Comment, Label
	PC_GPR_polygons	Polygons	id, Interval, Mean_depth, Label
	PC_EMI_polygons	Polygons	Id, Property, Comment
	PC_synth_polygons	Polygons	id, Label
Excavations	PC_P	Polygons	CODI, TIP
	PC_Det	Lines	CODI, UE
	PC_OD	Points	CODI, UE

Table 5.9: Properties of the created vectorial information.

generated for the description of the project and of the results and (4) the generated GIS model. The list of all the produced files is described in Appendix F.

5.4.4.1 The raw data

The folder 01_RAW_DATA included (1) the EMI files, (2) the magnetic acquired data per grid unit (3) the GPR individual files.

1. EMI files: there is one file per measured property. The files are named 'PC_1config-property.csv', where the configuration can be hcp (horizontal coplanar) or prp (perpendicular) and the properties are ec (electric conductivity) and ms (magnetic susceptibility). The files are ascii files with the header in the first line and four field (1) the X UTM coordinate, (2) the y UTM coordinate (3) an identifier of the the point and (4) the property value.
2. For each GPR profile acquired during fieldwork, four files were created. The

system contained two channels and each channel produced one file with the 600MHz data and one with the 200MHz data. A total of 1144 files were produced. The files were named 'TXXNYYYYY.dt'. T gave the direction of acquisition. It stands for transversal which means that the profiles were acquired in the X direction. XX is an alphanumeric code that is changed when a new acquisition is created. Three acquisitions were created for this survey and were named AA, AB and AC. N is the number of the channel. Channels 1 and 2 are the 600MHz channels. Channels 3 and 4 are the 200MHz channels. YYYY is the number of the profiles and is reset with each new acquisition. 'dt' is the extension of the files. It is specific to the IDS system. The positions of the created data are specified in the local coordinates in the "info_frequency(200 or 600)_Z2.dat" file. It includes for each file the coordinates of the start and end points. All the even-named files were acquired in the reverse direction.

3. The magnetic raw data were downloaded in the native format. The area was explored in 13 acquisition units. As two grids were repeated, 15 files were generated. The relative position of the acquire grids is described in the file "Acquisition_geometry.png".

5.4.4.2 The processed data

The folder 02_PROCESSED_DATA includes (1) the EMI data, (2) the GPR data, (3) the magnetic data

1. The EMI processed data are the result of the interpolation and filtering using factorial kriging. There is one file per property. They were named PC_EMI_property_configuration_krig. They were saved in 'grd' ascii format. It is an ASCII format with a header and the data organised in a matrix. The number of rows correspond to the number of Y positions. The number of columns correspond to the number of X positions. The first five lines of the file contain a header with (1) an alphanumeric code that identifies the software with which it was generated (2) number of rows and columns respectively (3) minimum X and Y values respectively (4) maximum X and Y values respectively (5) minimum and maximum values of the property.
2. the GPR data include two folders. The 'HORIZONS' folder contains the horizons that were extracted from the 200MHz data. They represent variations

in elevation (m) of events associated to possible stratigraphic changes. They were named 'Z_horizon'. They were saved in ASCII format with 5 columns. The first line of the files contain the header with the description of the fields. The folder 'SLICES' contains the depth slices created using the GPR data. Two categories of slices were produced. For the first category, a constant depth interval was used. These slices were named Slice_IZ_XXX.dat. The 'XXX' is the depth index of the 3D cube from which the data were extracted. The correspondence in depth is described in table 5.10. The second category gathered the slices created using the extracted horizons. They were named Slice_Frequency_interval.dat, where Frequency is the frequency of the GPR dataset used for the depth slicing and interval the considered interval. The characteristics of the intervals are described in 5.6. All the files were saved in ASCII format with 5 columns. The first line of the files contain the header with the description of the fields.

3. The magnetic processed data are the results of the filtering of the acquisition noise and the interpolation to a finer grid of resolution 0.25x0.25m. The file was named PC_mag.grd. It was saved in the same format as the EMI files.

Depth Index IZ	Mean depth (m)	Minimum depth (m)	Maximum depth (m)
160	0.54	0.40	0.67
170	0.58	0.45	0.71
180	0.62	0.49	0.76
190	0.67	0.54	0.80
200	0.71	0.58	0.84
210	0.76	0.62	0.89
220	0.80	0.67	0.93

Table 5.10: Correspondence between depth values and depth index of the GPR depth slices created with a constant interval.

5.4.4.3 Documentation

The folder 03_DOCUMENTATION groups all the documents that were produced for the description of the surveys and the excavation campaigns. It includes the official reports delivered to the local authorities for the years 2010, 2011 and 2012 and a graphical report of the geophysical survey produced in 2011. This last report

can be consulted in Appendix E. It also includes a video file in wmv format that was produced for the 2011 campaign.

The new documentation created during this research starts with the prefix PC2015. It includes a written report, a graphical abstract and a video file in mp4 format.

5.4.4.4 GIS

The GIS files were detailed in the section describing the GIS model. The names of the files are the same as the ones visible in the GIS project and the archiving respect the same categories. The files were stored in RASTERS and VECTORS folders.

The RASTERS folder separates the aerial photographs (AERIAL_PHOTOGRAPHS) and the geophysical data (GEOPHYSICS). The geophysical data were classified by method (EMI, GPR, MAGNETIC).

The VECTORS folder includes five folders.

1. AREAS includes the covered areas with the geophysical methods and the limits of the excavation units.
2. CONTOURS includes the contours lines extracted from the topographical and gradiometer data.
3. EXCAVATIONS includes the processed results of the excavations with the location of the artefacts, the limits of the stratigraphic units and the associated details.
4. INTERPRETATION includes the interpretation of the geophysical data. It was classified by method (EMI, GPR, MAG).
5. REFERENCES includes the information relative to the topographic bases.

Chapter 6

Conclusions

This final chapter describes how the objectives were reached, what were the main limitations and what are the possible applications and outcomes of the research.

The transmission of the results of an archaeological project is mainly done through the production of grey literature. The main preoccupation is to register properly the conducted survey. Most of the efforts in archaeological geophysics are still done on how to conduct a survey and little attention is given on how to transmit the results. In this research, the format of transmission were reconsidered. Improvements were proposed based on a learning theory approach. These improvements were applied on three case studies. The case studies were chosen based on the archaeological object they contained.

The major purpose of the research was to identify key points of the dissemination of the results of an archaeological geophysics project. It was to understand why the produced material is only used to manage excavations when they can also give a visual support to explain and describe them in a broader context. It involved (1) describing the archaeological geophysics workflow, (2) using a learning theory approach for the modification of the formats of transmission and (3) including systematically archaeological objects in the process.

1. The workflow of the projects was described in detail. The goal of the description was to identify what were the main causes of failure situations and to propose control points to avoid them.
2. Modifications of the current formats of transmission were proposed. This re-

search is a first step towards a quantitative evaluation of transmission methods. It was centred on the processing of the data and the creation of the formats. Possible targets were identified. The next step would be to evaluate the use of the produced material. This should be done within a long-term collaboration program.

3. The combination of the geophysical results with archaeological object was proposed as an improvement. It aims to favour the integration of the geophysical results in the archaeological and dissemination processes.

These three aspects of the research are further described below. The description is followed by a discussion on what where the main encountered problems and on possible applications

6.1 Control points during the project

During the description of the research and more especially during the description of the methodological background, it was stated that geophysical imagery is based on a nested sequence of decisions and operations. The quality and impact of the final outputs depend on the entire sequence from design to archiving. The description of the complete sequence had as objective to stress out the importance of the parameters of the project. The outputs of this description were the division of the sequence in three major phases and the identification in each phase of key points and variables. Most of these key points are already described in guidelines (David et al., 2008; Schmidt and Ernenwein, 2011). The contribution of this research was to select three of them for each of the defined phase.

6.1.1 Field

The field phase includes the design of the project and the acquisition of the data. At this stage the main goal is to understand the archaeological objectives and to propose an adapted strategy given the context of the site. During the field phase a proposal is produced. The proposal aims to describe the context of the site, the archaeological objectives of the project and the proposed strategy to answer to the objectives. After approval, it is followed by the acquisition of the data. Three control points were proposed to improve the quality of the proposal and of the acquired data.

1. The context of the site and the archaeological objectives can only be understood through a dialogue with the main actors of the site. The systematic use of a questionnaire with standard questions and its integration to the initial proposal can give a standard approach to the retrieval of the context information. Furthermore, it can be used to evaluate if the proposed strategy is adapted to the archaeological objectives.
2. The archaeological objectives are compulsory to the design of the project. They should be clearly stated in the initial proposal together with the strategy and the limiting factors. In this research a diagram gathering these three aspects of the design a project was proposed. It gives a quick view of the main aspects of the survey to conduct.
3. The quality of the data greatly depends on the conditions of the environment of the site. The proposal must include the requisites on the conditioning of the site before the survey acquisition. The survey should be postponed if the requirements are not met.

6.1.2 Data transformation

The main objectives of the data transformation phase were defined in this research as (1) separate the acquisition noise from the signal, (2) extract the features of interest and (3) produce a final product that answers the initial question.

In order to control the progress of the objectives, three key steps are proposed.

1. The acquisition noise should be described through exploratory analysis. Describing the acquisition noise gives an evaluation of the quality of the data and on the uncertainty of the results.
2. The extracted features should be presented in a vectorial format. They should be assigned with attributes. The attributes must help identifying the source of the features and their archaeological interpretation.
3. The interpretation should be presented using a synthetic map and relating the results with the initial question.

6.1.3 Finalisation

The finalisation phase includes the documentation and the archiving of the project. The documentation accounts for how the results will be disseminated and the archiving for their possible re-evaluation and re-use.

The proposed control points for the finalisation of a project are:

1. Present the parameters of the surveys and of the processing through a table of metadata.
2. Present the results through several parallel formats. The format must improve the interactivity with the results and their control by the end-user.
3. Archive the raw and the processed data in open formats.

6.2 The formats of transmission

The main contribution of the research was to stress out the importance of producing several parallel formats of transmission. The grey literature gives a linear approach of the information that can be complemented with other formats. The other formats aimed to involve more sense in the transmission process and to improve control and interactivity.

6.2.1 Reports

The required contents of reports are described by guidelines. Reports should contain a set of basic elements and a fixed structures. This includes (1) the archaeological objectives (2) the context of the site (3) the applied strategy to answer to the objectives (4) the parameters of acquisition (5) the parameters of the processing (6) the description of the results (7) conclusions.

This structure was used for the first reports of the case studies (Appendix A and B). The new reports included in addition (1) a first section with a summary of the project (2) a table with all the parameters (3) references.

1. the first page of summary gave a first approach of the main results of the project. The archaeological objectives are stated. The main results and limi-

tations are described. It enabled having at the beginning of the document a clear idea of the results. The description of the limitations were also considered important. They give a statement on the uncertainty of the results. They describe what can be expected from the results.

2. the table of parameters is based on the requirement to include the metadata of the project. Storing these data in one table enabled an easier indexing of the parameters. The final objective of producing the metadata of a project is to introduce them in a database. As this database is not defined, the parameters of the tables should be re-evaluated and adjusted considering the evolution of the projects.
3. the references give the opportunity to the reader to further explore the results. They included similar case studies or more detailed information on the applied processes.

6.2.2 Graphical reports

Geophysical imagery produce extensive representation of the contents of the soil. It gives the context of an archaeological site. In that perspective, the visual outputs of a survey give a first idea of the main results. As a consequence, the graphical report is often used as a complement to the written report. It includes large representations of the surveys with sometimes varying parameters of visualisation.

There are no standards defining what a graphical report should contain. Nevertheless, it should respect the visual codes of the field. Geophysical imagery is based on the representation of maps with the variations of selected properties. The basic rules of map representation should then be respected. This means including the North direction, the metric scale, the legend and choosing properly the colour scale. In addition, the scales should be maintained constant when possible.

The first graphical reports produced for the case studies can be consulted in Appendix C to E. They contain graphical representations of (1) the covered areas (2) the results of the different applied methods (3) alternative visualisation using statistical approaches (4) the vectorial interpretation of the results (5) a synthetic map of the main results.

The contributions of the research to the graphical approach are listed below:

1. In a similar way to the written report, a first page with an abstract was added. It presents the methods used and the global approach. It is followed with a page presenting the archaeological objectives of the project and the chosen strategy to reach these objectives.
2. The graphical representations are complemented with highlights, arrows and text indications on where the en-user should center his attention.
3. The main message of the graphical representation is stated.
4. The available archaeological material is added. This material is the reference that sets the context of the produced outputs.

6.2.3 Animated Sequences

Geophysical imagery gives outputs that can be dynamic and need a third dimension of representation. This third dimension can be provided by animated sequences of images. The best example of these dynamic representation is given by GPR data. They represent the evolution with depth of the contents of the explored object. Reports are based on a selection of depth values that were chosen as most representatives. With 2D representations the link between the different chosen sections can be lost. Animated sequences give a continuous approach of the visualisation of the data.

These animated sequences can be designed in different ways. The basic animated sequence only shows the produced images. In the case of GPR data, the result is a sequence of depth slices with correspondent depth value. This kind of video can be part of preliminary work material used to communicate with the end-user on the results of the project.

A second kind of animated sequence can include more features as (1) the position and context of the survey (2) the description of the used system (3) an interpretation of the results.

In this research, the animated sequences were considered as a final output with equal importance as the report or the graphical report. It was used to give an additional perspective on the projects and their main results. The main contributions of the research to the production of video files were:

1. Adding text and highlights to the images: in order to improve the understanding of the sequence, text and indications were added to the images. They aim to focus the attention of the end-user on the points of interest.
2. Adding an audio channel to the animated sequence: the audio repeats the text visible in the images. The number of senses involved in the visualisation of the sequence is increased in order to improve the understanding process.
3. Separating the different part of the video in sections: the possibility to choose the sections of interest using titles improves the control of the end-user on the visualisation.

6.2.4 GIS and 3D Models

The production of models enables an interactive exploration of the results by the end-users. They can have their own experience of the interpretation and directly act on the outputs. Having a personalised experience of the project improves the understanding process (Runlee and Daley, 1998).

No models were included in the first delivery of the results for the three presented case-studies. As a consequence, the outputs of the survey could not be included in the archaeological process. The results of the geophysical survey were used as a punctual and independent evaluation of the resources of the site.

The models described in this research are included as supplementary material. They enable the production of (1) new material as images or maps, (2) a direct re-evaluation of the interpretation and (3) the possibility to integrate new results. Most of all, it gives the control on the outputs to the end-users. The end-users are the main actors in the dissemination of the information about the archaeological site. Giving them the control on the outputs increases the possibility of including the geophysical results to new produced material.

6.3 Multi-method projects

Designing the projects as multi-method projects was a proposal which objectives were to improve the validation of the results and their integration in the archaeological process. The design included at least one archaeological object. It was tested on three case studies where the archaeological objects were (1) the digital model of

a monumental artefact, (2) a surface sampling survey and (3) the digitised mapping of archaeological excavations. The respective case studies were (1) the assessment of the state of preservation of the needle of El Mèdol, (2) the characterisation of the sequence of occupation of the Roman villa of La Mina and (3) the documentation of the destruction of the Roman settlement of Puig Ciutat.

The case studies also corresponded to different collaboration configurations. The project of El Mèdol was a commercial project related to the works on a highway. The project of La Mina was integrated in a broader program research on the Duoro Valley. The access to the site was limited in time. The third project consisted of a long-term collaboration with no limitations on the access to the site. Considering these configurations, the outputs in relation to the objectives of the research were considered.

6.3.1 3D surface model and GPR data

The project of El Mèdol enabled the identification of areas with higher moisture contents and associated possible voids. The results were gathered in a 3D model with scalar fields as attributes used as visualisation parameters. It represented both the surface of the artefact and the major reflections of its interior.

The assessment was incomplete due to the geometry of the artefact and the limited resources of the project. The lower part of the artefact had a larger depth. The GPR exploration could not go through the artefact at these lower locations. This caused a higher uncertainty on the positioning of the inner volumes for the lower part. Furthermore, no verification was done as the global project was already finalised when the research was conducted.

The main challenge of the project was in the design of the survey. The global project centred on the quarry was conducted by a coordinator that supervised all the actors. No direct communication was engaged with the archaeological team in charge of the restoration of the needle. As main consequence, the survey was scheduled in the last phase of operations. It gave no time to produce a detailed report. Furthermore, no validation cores were included to the project. They would have enabled a validation of the detected volumes and completed the assessment on the state of preservation.

The produced model should be evaluated by possible end-users. Two main targets

were identified: (1) the visitor centre opened in the quarry and (2) the geological team in charge of the research on the quarry.

6.3.2 Intensive surface sampling and geophysical data

The project of La Mina was based on the combined interpretation of archaeological geophysics and intensive surface sampling data. The main results were the identification of the constructive structures of the site and their characterisation in terms of function and chronology. The delivered documentation included a GIS model with the processed data and their interpretation.

The main limitation of the project was identified during the interpretation phase. The extension of the site could not be defined based on the covered areas. The site extends in the north-western direction. The area to be covered was decided based on the results of the first sampling survey and on the position of an already excavated structures. It was also limited by the available budget. A larger area could have been covered if only the gradiometer survey was conducted but the constructive features showed no contrast with this method.

The main challenge was in the design of the project. The surface sampling and the geophysical surveys were scheduled to be conducted during the same period. Surface sampling surveys require a recent ploughing in order to be able to detect sherds on the surface. The recent ploughing of the field affected the quality of the signal of the geophysical surveys. More specifically, the constructive structures identified in the GPR showed artificial interruptions and a lower contrast due to the irregular surface.

The integration of the surface sampling results with the geophysical data showed two main difficulties: (1) the coverage and (2) the spatial resolution. The areas covered were different. This did not enable a systematic comparison of the results. The resolution of the surface sampling survey was of 10x10m when the geophysical surveys had spatial resolutions of 0.50x0.25m and 0.40x0.02m for the gradiometer and GPR survey respectively. This was partially compensated by an interpolation of the surface sampling results. Considering a finer resolution for the sampling survey is not realistic in terms of fieldwork efficiency. It would not have a methodological justification neither as sherds tend to suffer displacements due to topography and ploughing.

The main identified end-user of the GIS model was the archaeological team in charge of the research. It was delivered together with the other documentation files. Feedback on the use and structure of the model is expected.

6.3.3 Geophysics and archaeological research

The research on the Roman settlement of Puig Ciutat was centred on the eastern part of the site where the defensive wall is located. The first excavations showed traces of a destruction. They showed burnt areas and abundant weaponry material. They also showed a variable depth from the ground surface to the bedrock. The surveys were designed with as main objective the documentation of the destruction.

The main identified limitations were the late setting of the topographic bases and the creation of a common platform. Setting a common absolute reference system at the beginning of a project is a basic compulsory step that reduces uncertainties during the interpretation of the data. The creation of the common platform was delayed by the necessity of finding a common visual language between archaeological and geophysical data. In addition, the introduction of the information in a spatial database required a modification of the fieldwork methodology. This was possible for the archaeological data and is still under study for the geophysical data.

Once again, the design and the conditions of the ground surface were challenging. The fields were still used as cultivation fields during the first years and there was no control possible on the preparation of the ground surface. Furthermore, there was no solution to the deep ploughing that was identified and that caused permanent damage.

The project was a long-term collaboration. It enabled constant follow up and re-evaluation of the results. The interaction between the archaeological and geophysical teams favoured the building of a common knowledge on the results of the excavations and of the geophysical surveys.

The created platform was designed to gather new excavations results and to be directly and independently used by the archaeological team. It already enabled the production of combined material for conferences (Padrós et al., 2013) and a publication (Garcia et al., 2010).

6.4 Encountered problems

The research presented here was at the confluence of several disciplines. It used learning theory tools to present geophysical information and favour its integration in the archaeological process. These three disciplines have different methodological background and priorities. Compromises had to be found in order propose realistic improvements that can be operated during the course of archaeological geophysics projects.

6.4.1 Training

One proposal to improve the understanding of geophysical results was to integrate them in a model. This model would enable a direct control and a personalised experience of the results. The proposed platform to interact with the model was mainly based on GIS solutions. In a constructivist approach, they represent the link between disciplines.

In order to be able to use the common platforms, a basic training is required in both GIS solutions and geophysics. In the Spanish state, the actual teaching program dedicated to both disciplines in the archaeology career is minimal. They are more developed in specialised courses and masters programs (Farjas and Rejas, 2007).

In order to improve the integration of geophysics in archaeology, a first requirement would be to achieve increasing the efforts dedicated to teach geophysics and GIS solutions in the graduate program.

6.4.2 The processing of the data

Even with an appropriate training, the processing of the geophysical data represent a challenge to unspecialised archaeologists. The transmission of all the details and steps applied during the project, as done in this research, is tedious. The language used is technical and can confuse the end-user. Standard procedures are not always possible and the processing strategy must be adapted to each dataset.

One solution would be to limit the description of the processing to a table with the main steps and the used parameters. The table should be accompanied by the associated references. The references would allow the end-user to develop the steps

of interest when needed.

The processing is also more complex when the quality of the data is not sufficient. Additional procedures are used to filter noise and enhance the features of interest. This additional processing time and efforts can be significantly reduced by increasing the importance of an adequate preparation of the site before a geophysical survey. The improved quality of the data will both reduce the processing time and improve the interpretation of the results.

As seen with the case studies, different processing strategies can be applied on the data. Testing different strategies in order to find an adequate visualisation of the results is time consuming. A balance should be kept between the time dedicated to the processing and the time dedicated to the interpretation of the data. The interpretation step is where the archaeological meaning is given to the geophysical anomalies. It is when the archaeological objectives can be reached. It should not be neglected in favour of an improved processing.

6.4.3 Production of the models

In this research, the interpretation gave as output an archaeological model of the results. The model was based on vectorial information and assigned attributes or properties. The attributes represent elements of a possible database. There are no current standards for the definition of the attributes of vectorial information in archaeological geophysics.

The use of such standards would only be clear in case of an expanded or public integration of the results. In the current situation in the Spanish state, the creation of a common database for archaeological projects is already a challenge. Archaeological geophysics is still not acknowledged as a separate discipline. In this perspective the creation of a specific database for geophysical results is not realistic. The attributes should be adapted to the considered site and to the convenience of the end-users. Nevertheless, feedback from the end-users on the model could help improving the definition of these attributes.

6.5 Applications

Geophysical imagery can give in one campaign the archaeological context of an entire site. The visual outputs of geophysical surveys can give realistic representations of the geometry and function of sites that still need years to be excavated.

The main applications of the outputs of the research are (1) dissemination in museums and archaeological sites, (2) 3D environments for research and education and (3) starting to define standards of archaeological geophysics in the Spanish state

1. Dissemination: Images and maps produced with integrated models can be used for the creation of contents describing sites. They give a larger context than the excavations. The projections on the non-excavated areas can be based on field information instead of using only written sources. These broader images can be used in museums and in the dissemination material produced to explain archaeological sites. They offer a visual support that can be completed and updated while a site is being studied.
2. Research and education: In a similar way, the produced models can be used as a base for 3D reconstructions of sites or for virtual environment. 3D environments are being explored as tools for research and education. They are being used as new vectors for the transmission of the information. The information retrieved from archaeological geophysics would give a base to create environments for sites that have not been excavated yet. Examples are available as the Ludus of Carnuntum (Neubauer et al., 2014). The 3D modellers based their work on the inputs from the archaeologists and from the geophysical maps. It also raises the question of the integration of archaeological and geophysical results in 3D environments. Excavation methods are experimenting new advances with the use of photogrammetry for 3D documentation. (De Reu et al., 2014). This 3D documentation can be directly integrated with 3D geophysical objects as volumes extracted from GPR surveys.
3. Standards: archaeological geophysics still encounters difficulties in being recognised as a discipline. An improved communication can help improving the image of the methods and extending its use.

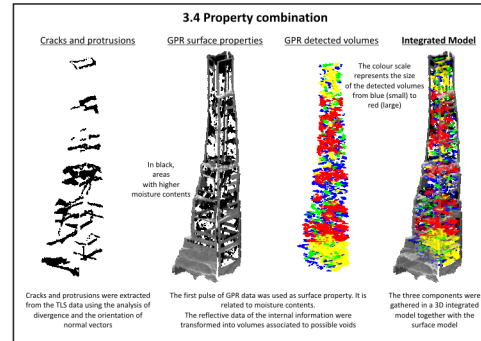
6.1 The proposed formats of dissemination

Report

- Summary
- Objectives
- Context
- Methodology
- Results
- Interpretation
- Limitations

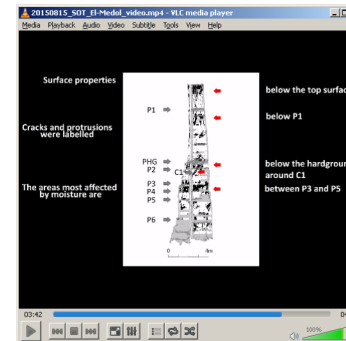
**Fixed structure
with summary and
references**

Graphical report



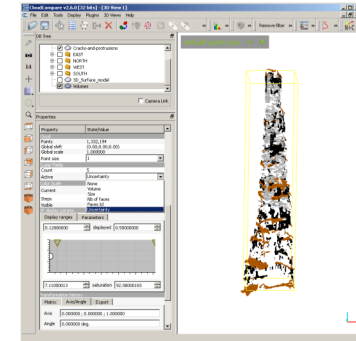
**Commented
graphical outputs
with highlights**

Video



**Video presentation
with audio, text
annotations and
highlights**

Model

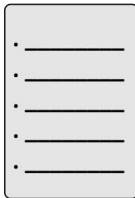


**Features of
interest with
attributes**

6.2 Using control points to identify failure situations

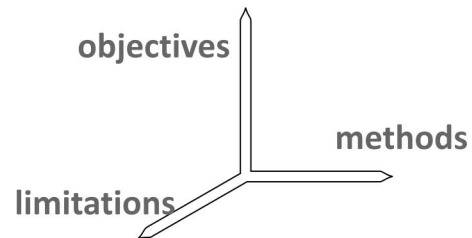
Field

questionnaire



A simple icon of a questionnaire form with a header and several horizontal lines for text entry.

design diagram

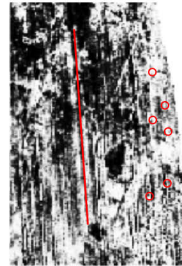


ground conditions



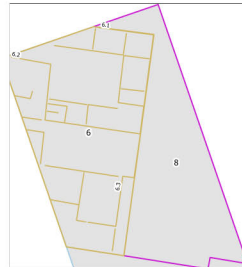
Data transformation

noise identification

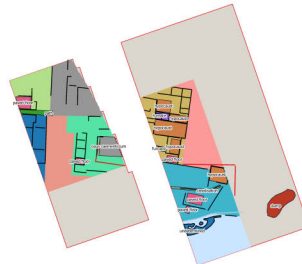


ploughing
lines and
random
noise

vectorisation and meaning assignment



synthetic maps



Finalisation

metadata

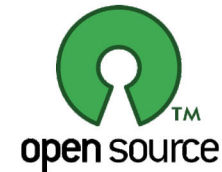
GPR
System
Antennas
Frequency
Number of antennas
Spacing between antennas
Spacing between profiles
Spacing between measurements
Time window
Samples per trace
Covered area

several parallel formats of transmission

report graphic report

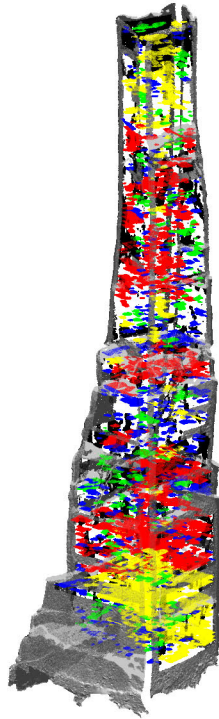
video model

archives in open formats



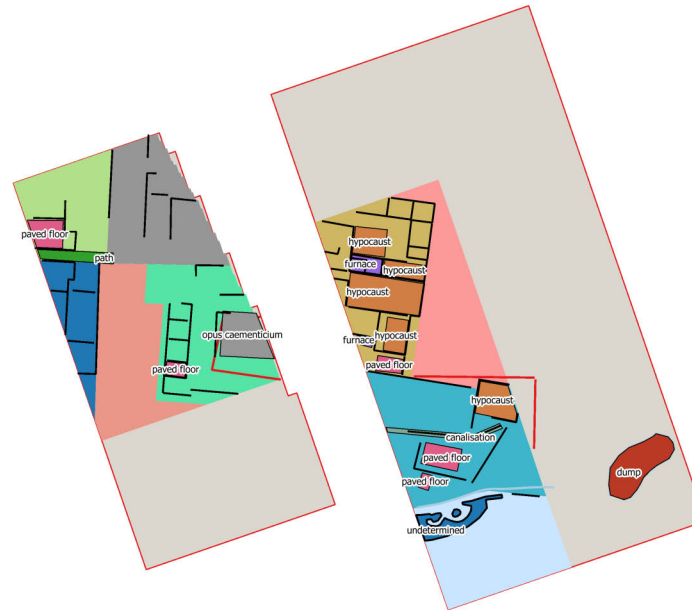
6.3 The results of the case studies

**The needle of
El Mèdol**



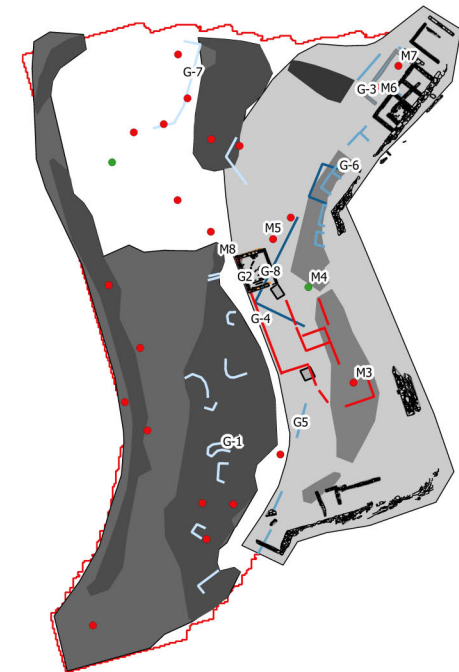
**3D integrated model
with surface and volume
properties**

**The Roman villa
of La Mina**



**2D GIS model of the constructive
structures of the villa with attributes
related to their source and function**

**The Roman settlement
of Puig Ciutat**



**2D GIS model with constructive
areas, bedrock, metals and
burnt areas**

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Appendix A

First report: El Mèdol



MEMORIA D'INTERVENCIÓ

Jaciment arqueològic de la Pedrera Romana de el Medol

Tarragona, Barcelona

Georradar de 400MHz - Exploració geofísica del monòlit

Roger Sala, Ekhine Garcia, Robert Tamba

Mètode	Sistema	Resolució espacial (m)	àrea (m ²)
Georadar	GSSI SIR 3000 400MHz	0.10x0.01	75

Taula 1: Resum de les característiques de la exploració geofísica

1. Motivació de la intervenció

En el marc de la rehabilitació de la Pedrera Romana de el Medol es va decidir fer una exploració d'alta resolució del monòlit ubicat al centra de la pedrera. L'objectiu va ser documentar les possibles fissures i cavitats internes del monument.

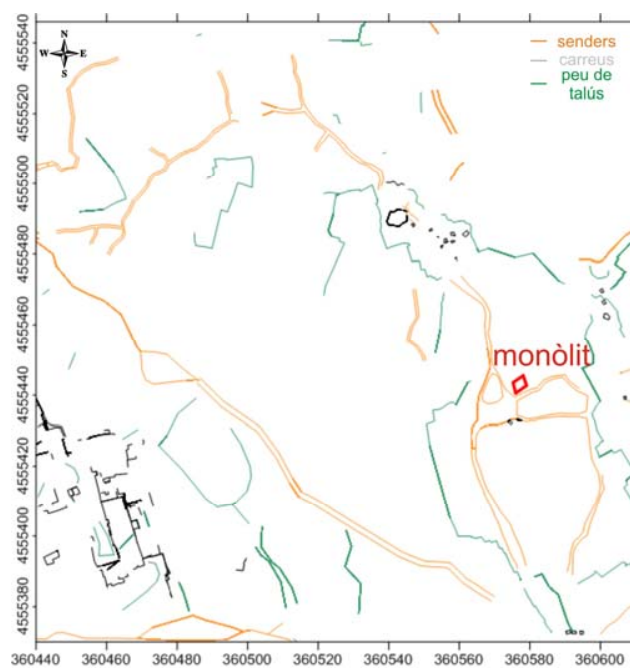


Figura 1. Localització de la intervenció.

2. Àrees explorades

Les 4 cares del monòlit es van explorar. La posició de la bastida va impedir l'accès a algunes àrees, creant perfils curts e interrupcions

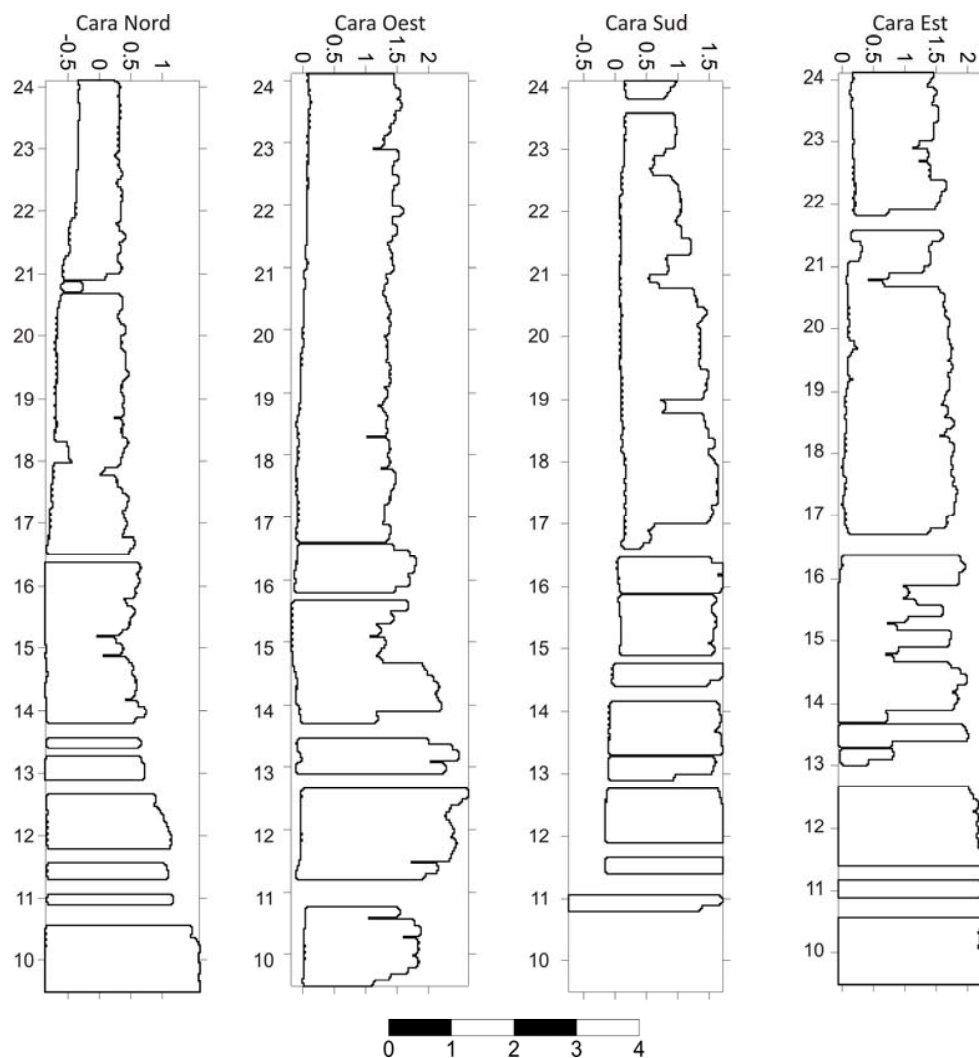


Figura 2. Extensions explorades per les 4 cares del monòlit.



Figura 3. Bastida montada per la exploració del monòlit

3. Metodologia

Per la prospecció georradar, es va fer servir el sistema GSSI SIR-3000 equipat amb una antena de 400MHz. La freqüència es va decidir en funció de la geometria del monument. Amb aquesta freqüència es podia assegurar l'exploració de la part alta, més prima (0.5m), amb una bona definició de les dades, i explorar tota la part baixa que és més ample (3m). Es van explorar les 4 cares del monòlit per obtenir visualitzacions alternatives de l'interior del monument. L'exploració va consistir en perfils horitzontals amb 10cm de separació. El posicionament lateral dels perfils es va referenciar amb respecte a l'aresta esquerra de cada cara.

Les dades obtingudes s'han processat per eliminar-ne interferències. En una primera etapa s'han integrat en un bloc de dades tridimensional per cara que s'expressa en talls horitzontals (time-slices) o bé seccions verticals. En una segona etapa es van comparar les dades de les 4 cares per identificar les zones de més interès a partir d'un sol bloc de dades. D'acord amb els resultats obtinguts, s'han seleccionat els talls horitzontals més rellevants per a delimitar els elements de més interès. De cadascun d'aquests talls se'n facilita un esquema interpretatiu, que simplifica la geometria dels elements detectats i permet entendre'n la disposició vertical.

4. Paràmetres i ajustaments dels sistemes aplicats

Adquisició de les dades

Sistema georradar: GSSI SIR3000 amb antena de 400MHz

Time window: 40 nanosegons (400MHz)

Velocitat estimada: model de velocitat que varia amb l'alçada e incloses entre 0.11 i 0.15cm/ns

Seqüències de procés de les dades (Figura 4)

Posicionament de les dades

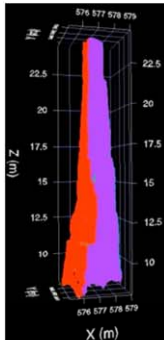
- Extracció de les 4 cares a partir de les dades topogràfiques
- Extracció de les arestes de cada cara
- Posicionament lateral dels perfils a partir de les arestes
- Identificació de la superfície i de les sortides de la senyal per la cara oposada
- Càlcul de les distàncies entre cares oposades
- Creació d'un model de velocitat a partir de les sortides i de les distàncies entre cares
- Conversió de les dades de temps a profunditat
- Correcció topogràfica i del "tilt" de l'antena a partir de la superfície de cada cara i de les normals

Procés de les dades

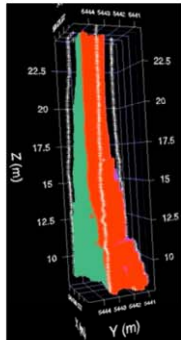
- Filtre "background"
- Amplificació de la senyal
- Càlcul de l'energia reflectada
- Supressió de les dades externes
- Combinació de les 4 cares
- Selecció de les dades d'alta amplitud representatives de les zones d'interès

1. Posicionament de les dades

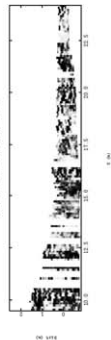
Selecció de les cares



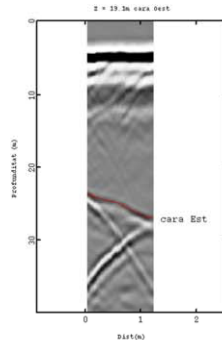
Detecció de les arestes



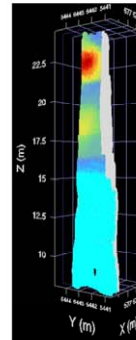
Posicionament lateral



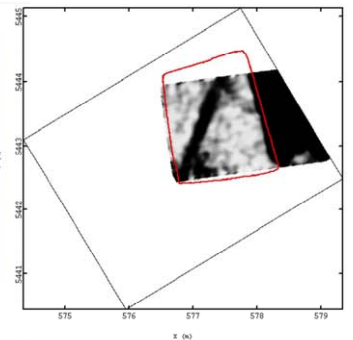
Detecció de l'entrada i de la sortida de la senyal



Model de Velocitat

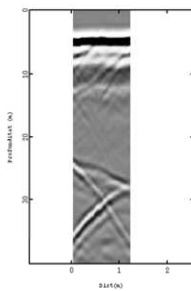


Posicionament del perfil

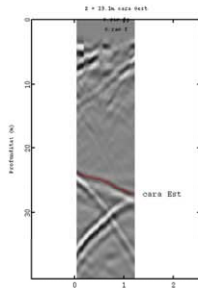


2. Procés de les dades

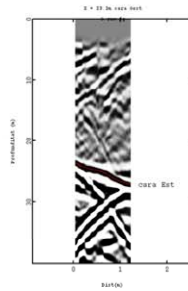
Perfil original



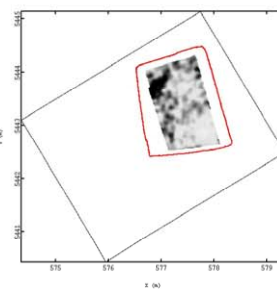
Filtre «background»



Amplificació



Selecció de les dades internes



Visualització 3D de les dades internes de interès

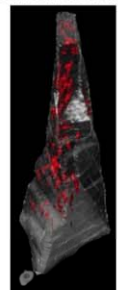


Figura 4. Seqüències de processos aplicats

5. Resultats

Per la interpretació dels resultats, en una primera etapa s'analitzen les dades de les 4 cares de forma independent fent servir l'aixecament topogràfic i mapes en definides profunditats des de la superfície. En una segona etapa es presenta un anàlisi combinat de les 4 cares amb vistes zenitals i tridimensionals de les zones d'interès.

5.1 Interpretació independent de les 4 cares

Per analitzar les dades es va fer servir l'aixecament topogràfic del monòlit. Per cada cara, es detecten les fissures i llocs de geometries susceptibles de provocar acumulacions d'aigua i es comparen amb les zones detectades amb el georradar.

5.1.a Cara Nord Gràfic 1

L'aixecament topogràfic de la cara Nord presenta fissures i vores assenyalades al gràfic 1. Les dades de georradar van permetre detectar 3 zones d'interès. L'anomalia GNA està ubicada entre els metres 23 i 24 d'alçada, l'anomalia GNB entre 18 i 21m i l'anomalia GNC entre els metres 10 i 12. L'anomalia GNA comença a apareixer a 0.45m de la superfície i té una resposta màxima als voltants de 0.95m de la superfície. Fa 30cm d'ample i la seva direcció fa un angle de 25° amb la vertical. L'anomalia anomenada GNB al gràfic 1 es molt extensa en la direcció vertical. La seva ubicació es desplaça amb la profunditat el que vol dir que fa un angle amb respecte a la superfície de la cara Nord. És de geometria irregular. Podria estar relacionada amb les vores anomenades TB i TC. L'anomalia GNC es extensa però fragmentada. Té una resposta màxima a la vora dreta de la cara. Podria estar relacionada amb la vora TH que segueix per la cara Oest. La fissura més notable visible des de la superfície es la TE, sot l'interfaç entre els 2 blocs. Està ubicada entre els metres 14 i 18 i té continuació per la cara oest. Les dades de georradar hi detecten una cavitat d'extensió limitada i a prop de la superfície (<0.4m) que està en connexió amb altres anomalies (GOD) que es podria explicar per l'espai obert al nivell de l'interfaç.

5.1.b Cara Oest Gràfic 2

A més a més dels elements topogràfics descrits per la cara Nord, es senyala al gràfic 2 una vora adicional anomenada TI. A les dades de georradar es veuen les continuacions de les anomalies GNB, GNC i GND, anomenades per la cara Oest GOB, GOC i GOD. L'anomalia GOB està ubicada entre els metres 17 i 19 i es detecta per profunditats entre 0.20 i 0.30m de la superfície. L'anomalia GOC està encara més fragmentada que per la cara Nord i es detecten zones amb poca connectivitat i amb fortes amplituds entre els metres 10 i 13. L'anomalia GOD no està en connexió amb l'anomalia GND. Està ubicada sota l'interfaç a l'extrem dret de la cara Oest. En aquesta ubicació les cares oest i sud estan descobertes per la part superior el que facilita les infiltracions d'aigües i la degradació del monument. A la zona de la fissura TE, les dades de georradar no presenten altes valors d'amplitud

5.1.c Cara Sud Gràfic 3

A la cara Sud, les vores TA descrita a la cara Nord i TI descrita a la cara Oest es poden identificar. Es detecta una fissura anomenada TJ de geometria irregular i ubicada entre els metres 13 i 16 d'alçada, i una vora anomenada TK ubicada a 13.5m d'alçada. A les dades de georradar, es torna a identificar l'anomalia GNA indicada aquí com GSA. Es detecta des de 0.30m fins mes d'1m de profunditat. L'anomalia GSB està al mateix nivell que les anomalies GNB i GOB però indica una nova àrea ubicada a la banda esquerra de la cara Sud. La seva extensió augmenta amb la profunditat amb una màxima extensió a 1.20m. Per sota de l'interfaç, es detecta l'anomalia GSD. És superficial a uns 0.30m de la superfície. L'anomalia GSE està ubicada a la part esquerra de la cara Sud entre

els metres 12 i 14 d'alçada. La seva extensió lateral es de 0.20m i es detecta fins 0.90m de profunditat. Està a la continuació de la fissura TJ. La part baixa del monòlit, per sota de 11m d'alçada estava coberta de vegetació i no accessible al moment de l'adquisició de les dades. L'anomalia GNC no es va poder documentar per aquesta cara.

5.1.d Cara Est Gràfic 4

A la cara Est es veu la continuació de la fissura TJ identificada a la cara Sud, la vora TA present a les altres cares, l'interfaç entre els 2 blocs i dues vores adicionales anomenades TL i TM. L'anomalia GEA ubicada entre els metres 23 i 24 d'alçada presenta característiques similars a les descrites per les altres cares. L'anomalia GEB té una part vertical d'uns 0.40m d'ample, ubicada entre els metres 18 i 20 d'alçada i detectada a una profunditat de 0.70 per sota de la superfície. Com per les altres cares la seva extensió i posició lateral canvia amb la profunditat el que indica que té una orientació diagonal. L'anomalia GEC presenta una morfologia similar que per les altres cares, es a dir fragmentada i extensa, ubicada entre els metres 9.5 i 12 d'alçada. L'anomalia GED està ubicada per sota del interfaç i a uns 0.20m de la superfície. No es detecta per profunditats més altes. Presenta una extensió en la zona baixa que correspon amb l'ubicació de la fissura TJ.

5.1.e Interpretació general

Amb l'exploració de les cares es van identificar i descriure 4 zones principals d'interès i una adicional associada amb una fissura. La zona GA està ubicada entre els metres 23 i 24 d'alçada i a uns 0.20m de la superfície de la cara Sud. La zona GB està ubicada entre els metres 17 i 22 d'alçada. Té una geometria variable. Les relacions entre la seva expressió per cada cara no queda clara amb aquesta visualització.

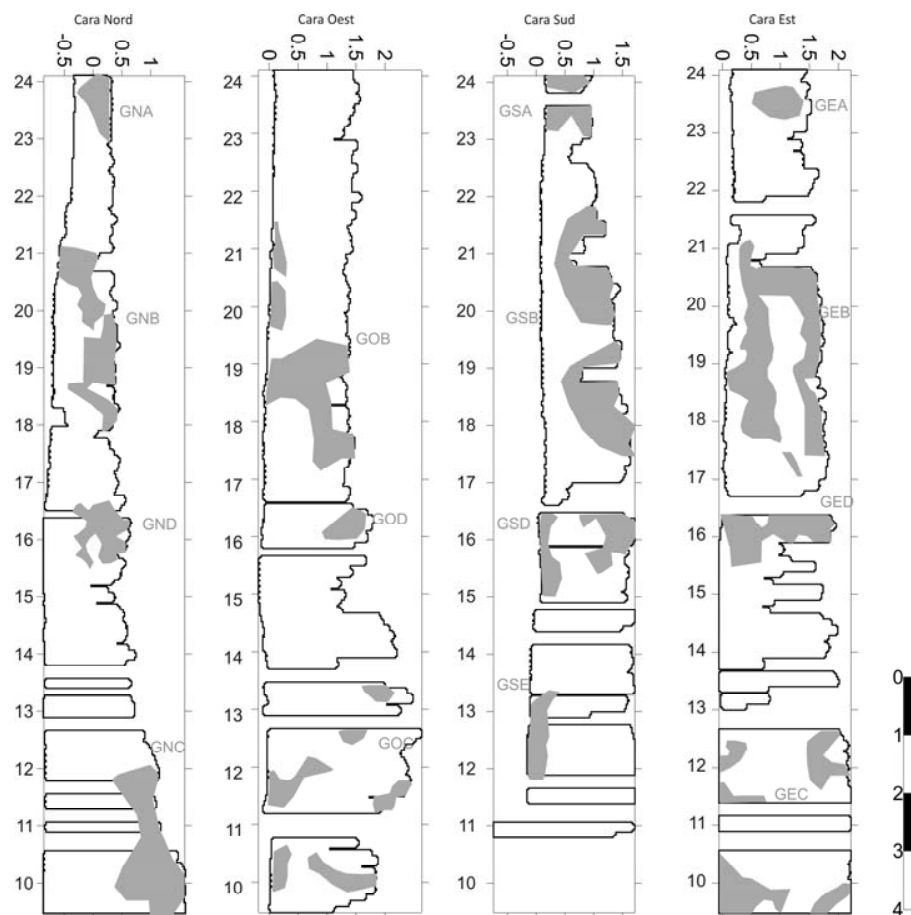


Figura 5. Resum de les interpretacions

La zona GC està ubicada entre els metres 9.5 i 13 d'alçada. Es fragmentada i de gran extensió. L'anomalia GD està ubicada per sota de l'interfaç entre el doc blocs. Es detecta per les 4 cares però es manté a prop de la superfície de les cares a uns 0.30m de profunditat. L'anomalia GE es detecta per la cara Sud. Està associada amb la fissura anomenada TJ.

5.2 Interpretació combinada amb vistes zenitals i 3D

Per les zones d'interès descrites es van seleccionar una vista zenital i una 3D (Gràfic 5). Les característiques de les geometries de les anomalies estan resumides a la taula 1.

L'anomalia GA apareix com fragmentada amb un part a uns 0.30m del centre de la cara Sud i altre en connexió amb les cares Nord i Est. La zona GA pot estar relacionada amb les infiltracions d'aigües a partir de la part superior del monolit. Es limitada verticalment a 1m ,entre els metres 23 i 24 d'alçada.

L'anomalia GB està composta principalment d'una fissura interior detectada sobre tot a partir de la cara Oest. La fissura està orientada amb un angle de 28° amb respecte amb la cara Oest. Fa 0.25cm d'ample. L'alçada mínima es de 17.15m i la màxima es de 19.60m.

L'anomalia GC es fragmentada i composta de zones d'alta energia i de petites dimensions i de l'anomalia GE amb més connectivitat. L'anomalia GE es veu sobretot des de la cara Sud. Està ubicada a uns 0.30m de la cara Sud entre els metre 12 i 13 d'alçada i podria estar relacionada amb la fissura anomenada TJ.

L'anomalia GD ubicada sota l'interfaç entre els 2 blocs presenta alteracions sobre tot a poca distancia de les cares del monolit. No presenta alteracions a la zona central. Les zones detectades son de geometries variables i se podrien relacionar amb infiltracions d'aigües des la part oberta entre els 2 blocs. Les alçades de les anomalies estan incloses netre 15.5m i 16.5m.

Zona	Zmin (m)	Zmax (m)	Comentaris
GA	23	24	Fragmentada
GB	17.15	19.6	Fissura orientada amb un angle de 28° amb la cara Oest
GC	9.5	13	Fragmentada
GD	15.5	16.5	Paral·lel a les cares
GE	12	13	En relació amb la fissura TJ

Taula 1. Característiques de les zones d'inter[es

Appendix B

First report: La Mina



MEMORIA DE INTERVENCIÓN

Yacimiento: Villa Romana de La Mina

Fecha de intervención: 16 al 18 de diciembre de 2010

Dirección arqueológica: Enrique Ariño

Operarios: Roger Sala (Arqueólogo y especialista en geofísica)
Ekhine Garcia (Licenciada en física y especialista en geofísica)
Robert Tamba (Ingeniero geólogo y especialista en geofísica)

Sistemas de prospección	Superficie explorada	Densidad de lectura
Gradiómetro magnético Bartington Grad 601-dual	>10800m ²	0.25 x 0.5m
Georadar IDS HI-MOD dotado con antenas de 600 y 200MHz	>4770m ²	0.02 x 0.40m

1. Motivación de la intervención

El yacimiento arqueológico fue descubierto en las prospecciones de Fernández Moyano en 1994 y ha dado resultados positivos en diversas prospecciones aéreas realizadas entre 1995-1997.

En las prospecciones arqueológicas se ha encontrado abundante material en superficie como fragmentos de tegula, fragmentos de molino circular de arenisca, elementos de construcción (baldosas, ladrillos,...). Junto a la carretera se observaba una estructura rectangular en opus caementicium excavada por un furtivo cuyas dimensiones son de 11 x 14 x 1.10m, con muros de 0.65m, y que ha sido atribuido a una posible cisterna. Junto a esta estructura, que se encuentra colmatada con tierra en la actualidad, se había encontrado fragmentos de estuco pintado. En labores posteriores se ha documentado la existencia de un acueducto que proporcionaba agua a la villa.

En este contexto la dirección arqueológica ha planteado la necesidad de una prospección geofísica en extensión y en detalle para la cartografía de las estructuras de la villa. Aunque se desconoce la extensión total del yacimiento los indicios sugieren que se trata de la zona nuclear del yacimiento.

El objetivo de la presente intervención es la delimitación y descripción de los eventuales restos arqueológicos detectables en el entorno de las estructuras conocidas para obtener una visión de conjunto que optimice futuras intervenciones arqueológicas.

El conjunto de indicios ha aconsejado una prospección geofísica multisistema para asegurar que uno de los sistemas pudiese dar un mapa detallado de las estructuras detectadas relacionadas con la Villa.

2. Ámbito de intervención

El área a explorar se delimitó de acuerdo con las investigaciones previas del Dr. Ariño, basadas en el reconocimiento aéreo y la dispersión de materiales entorno a una antigua estructura en *opus caementicium* visible en superficie a pie de carretera.

De acuerdo con estos estudios se delimitaron dos espacios de prospección a este y oeste de la carretera, aplicando en primer término una exploración magnética para delimitar las áreas de mayor variabilidad. En esta primera exploración se cubrieron 10.844,25m². En función de esta primera exploración se delimitó un segundo espacio de exploración de 4.901m², centrado en las zonas más alteradas magnéticamente y que se prospectaron mediante georadar para obtener visualizaciones de los eventuales restos constructivos.

La superficie del yacimiento está actualmente ocupada por campos de cultivo, en fase de crecimiento en la época de la adquisición de los datos. Como detallaremos más adelante, la superficie de adquisición ondulada por los caballones de cultivo ha afectado a la calidad de los datos de georadar, especialmente sensibles a las perturbaciones en la superficie de contacto de las antenas.



Imagen 1: Área de exploración sobre imagen aérea y zonas exploradas mediante los diferentes sistemas geofísicos: Gradiómetro magnético: 10.884,25m² (color), georadar antenas de 270MHz: 4.901m² (tramado).

3. Introducción de los sistemas geofísicos empleados

La mayoría de los sistemas de prospección geofísica aplicables en arqueología se basan en la medición ordenada (en el espacio, y en el caso del georadar también en el tiempo) de las diferentes magnitudes del subsuelo. Expresando gráficamente estas medidas se generan mapas de propiedades físicas del subsuelo que servirán para identificar las posibles estructuras arqueológicas.

Para tomar estas medidas se proyecta una cuadrícula o *grid* en la zona de exploración, que servirá para ubicar la posición de cada lectura que efectúen los sensores.

Magnetometría

El método magnético consiste en medir las variaciones del campo magnético terrestre a escala local. Esta variación está creada por el efecto de los minerales magnéticos que componen los materiales del subsuelo, que actúan como pequeños imanes. Las estructuras constructivas tienden a ser menos magnéticas que el entorno, lo que permite detectarlas con este método. En cambio, los silos, las zanjas y en general las zonas receptoras de sedimentos tienden a provocar un contraste positivo al ser más magnéticos que la tierra no removida de alrededor.

Por otra parte, esta técnica está especialmente indicada para la detección de hornos, hogares y zonas de incineración. La combustión provoca una serie de cambios físico-químicos en los materiales que transforman la traza magnética de los objetos.

Es un sistema sensible a la contaminación magnética típica de las zonas urbanas, por lo que se utiliza en entornos rurales o periurbanos. Los últimos desarrollos de los sistemas de prospección magnética los han convertido en los más utilizados en campo por su rapidez de adquisición y versatilidad.

Los aparatos de magnetometría (magnetómetros, gradiómetros) miden la intensidad del campo magnético en un punto. Mientras que el magnetómetro mide la intensidad del campo total, el gradiómetro -que consta de dos sensores posicionados a una distancia fija- proporciona la diferencia de intensidad entre los dos sensores (gradiente). Los sensores del gradiómetro deben situarse uno sobre la vertical del otro, de forma que lo que se obtenga sea el gradiente vertical del campo magnético. Esta magnitud es más sensible a las anomalías superficiales que la magnitud campo total, por lo que su utilización resulta más interesante en arqueología. Ambos pueden ser calibrados de forma que den las variaciones (del campo total o del gradiente) con respecto a una referencia local.



Imagen 2: Sistema de gradiometría magnética doble Bartington G601 con 1m entre los sensores.

El radar de subsuelo o GPR

El georadar es un sistema de prospección geofísica basado en la emisión hacia el subsuelo de pulsos electromagnéticos de frecuencia conocida, y el registro de los ecos que

vuelven a la superficie. A medida que la onda emitida penetra se altera siguiendo las leyes generales del electromagnetismo. En particular la velocidad varía en función de una propiedad llamada permitividad dieléctrica. Cuando la velocidad en una estructura es diferente a la velocidad del entorno se produce una reflexión en la discontinuidad, siendo más intensa cuanto mayor sea el contraste de permitividad entre los dos medios. La onda reflejada vuelve a la superficie y es registrada por la antena.

Este proceso se repite en cada punto de un perfil: se emite un pulso y se obtiene un registro de la energía recibida en ese punto en función del tiempo. La información de cada perfil se plasma en un radargrama, que representa la cantidad de energía recibida en función del tiempo (eje vertical) y en función del avance del radar (eje horizontal). Como el tiempo que tarda cada reflexión está vinculado a la profundidad a la que está el objeto, se obtiene información sobre la dimensión vertical, siendo una de las mayores ventajas de este sistema.

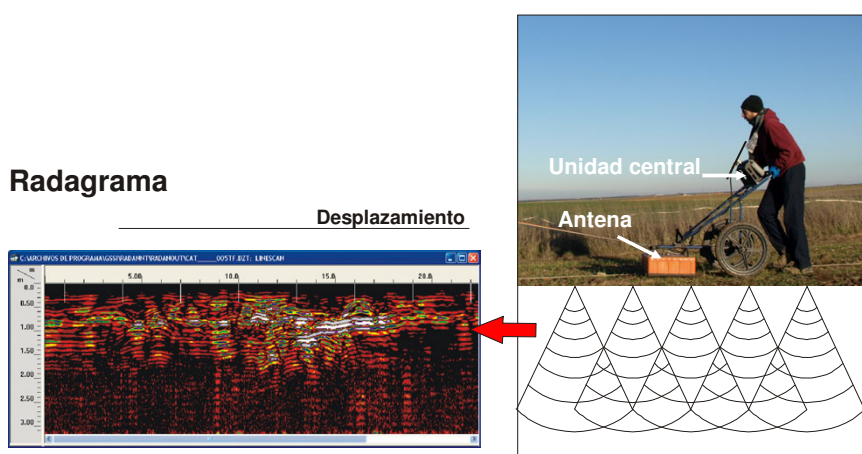


Imagen 3: Esquema de funcionamiento del georadar.

El georadar GSSI utilizado en esta prospección está dotado de una antena con una frecuencia de 270MHz. La antena emite los pulsos electromagnéticos y a su vez registra las reflexiones provocadas por el subsuelo (Radar Monostático).

La profundidad de penetración es función de diferentes parámetros, que incluyen la frecuencia del impulso emitido por la antena y la conductividad eléctrica del terreno. Es importante tener en cuenta que la permitividad dieléctrica del agua es tan importante que en caso de saturación provoca un apantallamiento y el sistema no puede “ver” más profundo. En cuanto la frecuencia, influye al mismo tiempo en la profundidad de penetración y en el poder de distinguir entre dos estructuras que están cerca. A menores frecuencias la penetración es más profunda, pero a su vez la resolución espacial disminuye.

Tradicionalmente, toda esta información se ha plasmado en los radargramas. Cada radargrama se puede interpretar como una sección del subsuelo bajo el perfil, pero donde lo que está representado es la energía reflejada desde cada punto del subsuelo. Para una visualización más comprensible de los resultados, aplicamos la técnica *time-slicing* (cortes de tiempo), que permite generar imágenes del área explorada a diferentes profundidades.

Parámetros de la exploración

Con el objetivo de obtener un bloque de datos con el que trabajar después, primero se realizan perfiles o transectos simples cubriendo toda el área a explorar.

Se utilizó una ventana de tiempo de 70ns. Estas magnitudes se deben de ponderar en función de una estimación de la velocidad de propagación por el subsuelo de los pulsos de georadar. En este caso se ha estimado una velocidad de propagación de entre 7 y 9cm/nanosegundo.

La densidad de lectura se ha establecido en 2cm para el sentido de avance del sistema y una separación de 40cm entre perfiles.

Generación de los cortes de tiempo

Para crear cortes de tiempo o representaciones en planta del área explorada, primero se crea un bloque tridimensional de toda la superficie cubierta en la prospección. Para llenar los espacios sin lectura (entre perfiles y entre las lecturas en el sentido de avance) se realiza una interpolación matemática de los datos.

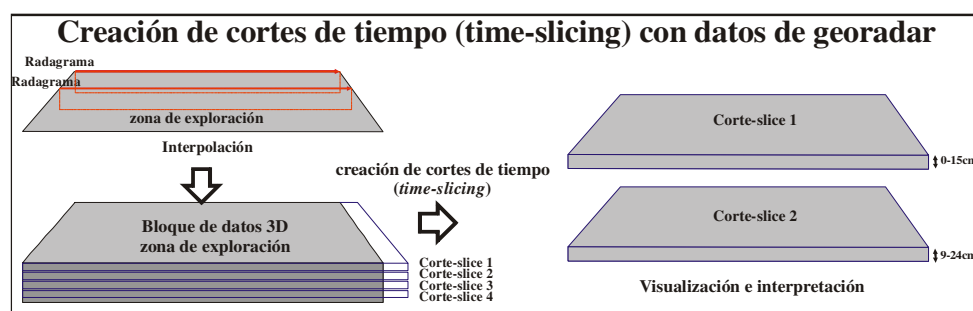


Imagen 4: Esquema de la metodología de generación de cortes de tiempo a partir de datos de georadar (radargramas)

Una vez creado este bloque de datos, se divide su dimensión vertical en cuantos cortes o secciones horizontales se consideren adecuados para visualizar los resultados. El resultado de esta operación es una secuencia de plantas horizontales donde se representan las diferencias de reflectividad de los objetos del subsuelo mediante la asignación de una carta de colores a los valores de respuesta de cada punto.

4. Metodología, ajustes del sistema y tratamiento de datos

La exploración mediante gradiómetro magnético se ejecutó en base a una densidad de lectura de 4 lecturas por metro en el sentido de avance y en transectos separados 50cm entre ellos.

Las zonas seleccionadas se exploraron mediante el sistema de georadar SIR-3000 equipado con una antena de 270MHz de frecuencia.

Prospección magnética	Prospección Georadar
-----------------------	----------------------

Sistema Bartington G-601, 2 sensores	Sistema GSSI SIR-3000
Sensibilidad: 0.1nt	Antenas: 270MHz
Rango: 100nt (reajuste automático hasta 3000nt)	Resolución de lectura: 16bits
Resolución: 0.5x0.25m	Resolución espacial: 0.02m x 0.40m
	Profundidad (tiempo) de investigación nominal: 3m-70ns

Tabla 1: Parámetros utilizados en cada tipo de prospección.

5. Resultados

Basándonos en los mapas geofísicos, proponemos aquí una interpretación de los datos. Se trata de extraer la parte arqueológicamente relevante y de construir un modelo que pueda explicar las anomalías geofísicas detectadas desde la superficie. La comparación entre los resultados obtenidos con cada sistema servirá para cruzar y ajustar las interpretaciones, utilizando también la información arqueológica y geológica disponible.

Prospección Magnética (Gráficos 2-9)

Los mapas magnéticos de los gráficos 2-6 muestran diversas visualizaciones de los resultados para extraer de ellos información cualitativa y morfológica.

El gráfico 2 muestra los resultados en escala de grises, asignando el negro a los valores negativos y el blanco a los positivos. En el gráfico 3 se muestra un mapa estadístico que representa la desviación estándar de los datos. Esta visualización permite discriminar las áreas con mayor alteración sin tener en cuenta la morfología de las anomalías.

En el gráfico 4 se aplica una nueva carta de colores que permite distinguir más fácilmente las zonas alteradas, que aparecen en rojo y azul, de las zonas sin alteración en blanco. El gráfico 5 muestra los mismos resultados que el gráfico 3 con la superposición de líneas de contorno que permiten distinguir las continuidades entre los valores de gradiente magnético registrados. Los mapas resultantes de la prospección magnética no han aportado información morfológica clara. Así, se ha realizado una primera interpretación apuntando sólo los elementos muy bien definidos geoméricamente, así como los focos que podrían corresponder a combustiones, hornos y metales.

En el gráfico 6 se pueden ver la interpretación de los resultados magnéticos superpuestos al mapa en escala de grises. El principal elemento estructural visible, denominado **M1**, está cortado por la carretera. Es de geometría rectangular, con dimensiones aproximadas de 15.5mx19.5m, aunque los cierres de la estructura no se detectan en el Sureste y el Noreste por donde pasa la carretera. La zona de la anomalía tiene variaciones incluidas entre -1000 y 100nT con una media de 0.1nT y un desviación estándar de 35nT. Esta anomalía corresponde en sus dimensiones y en su posición a la estructura documentada como posible cisterna por la excavación arqueológica. Se detecta dentro de la estructura dos focos que podrían corresponder a combustiones o zonas rubefactadas.

Las zonas rubefactadas a altas temperaturas y los metales generan una señal típica de anomalías bipolares, pero las combustiones de gran envergadura, como incendios u hornos, son claramente reconocibles debido a la polarización de las anomalías en coherencia con el campo terrestre. Así se puede destacar la anomalía denominada **M2** en el

mapa magnético. La zona anómala mide 7.8mx7.8m. Presenta valores incluidos entre -11nT y 25nT con una media de 1.5nT y una variación estándar de 7.3nT. No se identifican elementos morfológicos que delimitan la anomalía.

Otros focos que corresponden a combustiones o a metales están señalados por círculos de color naranja y azul respectivamente en el gráfico 6.

Debido a que la prospección georadar ha proporcionado una imagen más clara de la morfología de los elementos detectados, los resultados de la prospección magnética se han utilizado para delimitar las zonas de afectación del yacimiento. Como se puede ver en el gráfico 8, gracias al mapa estadístico de desviación estándar se definen dos zonas. La primera, señalada con sombreado denso, delimita las áreas con restos constructivos i zonas termoalteradas. La segunda, señalada mediante sombreado con líneas espaciadas, delimita las zonas de influencia y de dispersión de los restos constructivos.

Prospección GPR (Gráficos 9-17)

Los resultados de la prospección magnética se utilizaron para designar las zonas más alteradas y posteriormente realizar una exploración mediante georadar. El objetivo de la exploración mediante el georadar es la descripción de los restos constructivos. Tal como se aprecia en el gráfico 1, la zona explorada mediante georadar cubrió una extensión de 4.901m² dividida en dos partes, a este y oeste de la carretera.

En términos generales, la calidad de la señal obtenida ha sido pobre debido al contacto deficiente de la antena con el suelo. La presencia de caballones de cultivo tiende a ofrecer una señal irregular debida a la presencia de aire entre la antena y la superficie, hecho que condiciona el trayecto de los pulsos emitidos por la antena en el subsuelo y su retorno a la antena.

El grueso de la información aportada por el georadar se centra en los primeros 80cm bajo superficie, sin excluir la continuidad de las estructuras por debajo de estas cotas. El conjunto de anomalías descritas en los resultados revelan la presencia de restos constructivos en prácticamente toda la extensión explorada des de cotas cercanas a 0.4m bajo superficie, aunque los extremos noroeste y sureste son los que han ofrecido resultados más confusos.

La mayoría de las anomalías descritas se han identificado con muros y pavimentos, aunque una parte importante de las estructuras descritas se ven ensombrecidas por anomalías difusas que identificamos con la presencia de sedimentos de composición irregular e incluso derribos.

En los gráficos 10-13 se representan los cortes horizontales más representativos del contenido del subsuelo y se proponen interpretaciones para los mismos. El gráfico 10 corresponde a una profundidad estimada de 0.53-0.61m, y el corte del gráfico 12 se centra en 0.61-0.69m bajo superficie.

En las interpretaciones de los gráficos 1 y 13 se hace patente la existencia de un conjunto de anomalías lineales y extensivas con un juego de orientaciones cardinal, coherente en los dos ámbitos explorados a este y oeste de la carretera.

El grupo 1 lo conforman un grupo de anomalías que definen una retícula de espacios rectangulares de 18X3.5m. En conexión con este grupo, al este, se detecta una nueva anomalía de baja amplitud que hemos llamado grupo 2, que forma un perímetro en forma de U de 24X10m. Interpretamos el conjunto de 1 y 2 como un grupo de habitaciones y un espacio de circulación asociado que se ve interrumpido por la carretera.

Ya al este de la carretera, se detecta un nuevo conjunto formado por los grupos de anomalías 3 y 4. El grupo 3 consiste en una retícula de anomalías lineales que identificamos como muros. Los espacios delimitados por este grupo muestran interiores de baja reflexión, que interpretamos como espacios rellenos de sedimento. Aún así, se detectan otros espacios rectangulares con una fuerte reflexión en toda su extensión, como los grupos 5 y 6. En este caso no se detectan delimitaciones lineales, lo que nos induce a interpretar estas anomalías como espacios pavimentados o bien habitaciones colmatadas por derribos.

El grupo 4 consiste en una extensión rectangular con una respuesta de baja amplitud, que identificamos como un nuevo espacio de circulación, posiblemente exterior, colmatado por sedimentos. La delimitación más clara de este grupo se encuentra al este, con el grupo 4b, que identificamos con un grupo de muros. Inmediatamente al sur de este grupo se encuentra 4c. Este grupo consiste en una anomalía lineal de baja amplitud delimitada por otra paralela de alta reflexión. Interpretamos este grupo como una posible zanja o conducción delimitada.

En el extremo norte del ámbito oeste se detecta un nuevo grupo de anomalías que hemos llamado grupo 10. En este caso se trata de anomalías lineales claramente ortogonales que definen nuevos espacios rectangulares que interpretamos como habitaciones que enlazan con el grupo 3.

En el gráfico 14 se representa un corte horizontal representativo de 0.72m bajo superficie. Dentro de los procesos ensayados para la visualización de los resultados se ha hecho patente que algunas estructuras se podían describir únicamente en base a visualizaciones muy específicas. Este es el caso de los grupos 11 y 12, ubicados al norte del conjunto y descritos gracias a un proceso de visualización basado en cortes horizontales de menor dimensión.

Fuera de estos grupos con una geometría y respuesta aparentemente coherentes, se han detectado un conjunto de anomalías de más difícil interpretación, especialmente en los extremos noroeste y sureste de la exploración con georadar.

En los gráficos 10 y 12 se aprecia la evolución en profundidad de los grupos 7 y 8. El grupo 7 parece en las imágenes como un área de 12X7m, de alta reflectividad, donde se aprecia un recorte circular. Aún más al sur, se detecta el grupo 8, conformado por anomalías de alta y baja reflexión sin una morfología clara. Interpretamos estos conjuntos como restos constructivos, aunque su orientación y respuesta diferenciada del resto de anomalías descritas indican que se podría tratar de restos de construcciones con funciones diferenciadas o pertenecientes a época distintas.

Conclusiones

Las representaciones de los restos constructivos aportadas por la prospección georadar muestran un conjunto de edificios extenso cortado por la carretera. Aún contando con que la calidad de los datos no es la deseada por problemas de contacto de la antena con la superficie, los filtros de datos aplicados y los diversos sistemas de representación empleados para la interpretación han permitido proponer una interpretación que se ajusta a los patrones de un gran asentamiento como el esperado por el Dr. Ariño basándose en los indicios materiales y la imagen aérea (ver simplificación de la interpretación GPR del gráfico 17).

Un aspecto destacable del conjunto es la descripción de un conjunto adaptado a una pendiente descendiente de norte a sur, lo que posiblemente implica más de un nivel de circulación. Esto se hace patente en los posibles pavimentos detectados en la zona sur (4c, 4b, 5, 6). Estos posibles suelos de circulación, ubicados a profundidades de entre 0.5 y 0.65m bajo superficie no encuentran una correspondencia en las dependencias detectadas más al norte (grupos 3, 10, 12), posiblemente cubiertas por una mayor sedimentación.

La correspondencia entre los datos de prospección magnética, empleados para la delimitación inicial, y los obtenidos mediante georadar es buena en el sentido cualitativo. Las zonas de mayor variación estadística en los datos magnéticos han coincidido con el núcleo constructivo del conjunto. Aún así, la divergencia en cuanto a la descripción formal de las estructuras bajo la superficie es importante. Al igual que otros casos arqueológicos estudiados por este equipo, atribuimos esta disparidad a la abundancia de material cerámico vinculado a la construcción (restos de tegulae, ibrex, ladrillo, signinum).

Por otra parte, los datos obtenidos han puesto en evidencia la continuidad de los restos constructivos, especialmente en sentido Norte y Oeste. El extremo Sureste del área explorada presenta otros puntos de interés. Si bien el grupo 7 parece clara una delimitación del conjunto constructivo, el grupo 8, que se encuentra a menos de 10 metros de distancia, presenta una morfología poco clara que cabrá investigar y verificar.

La Floresta 27-1-2011

Appendix C

First graphical report: El Mèdol

Model - 1x1cm

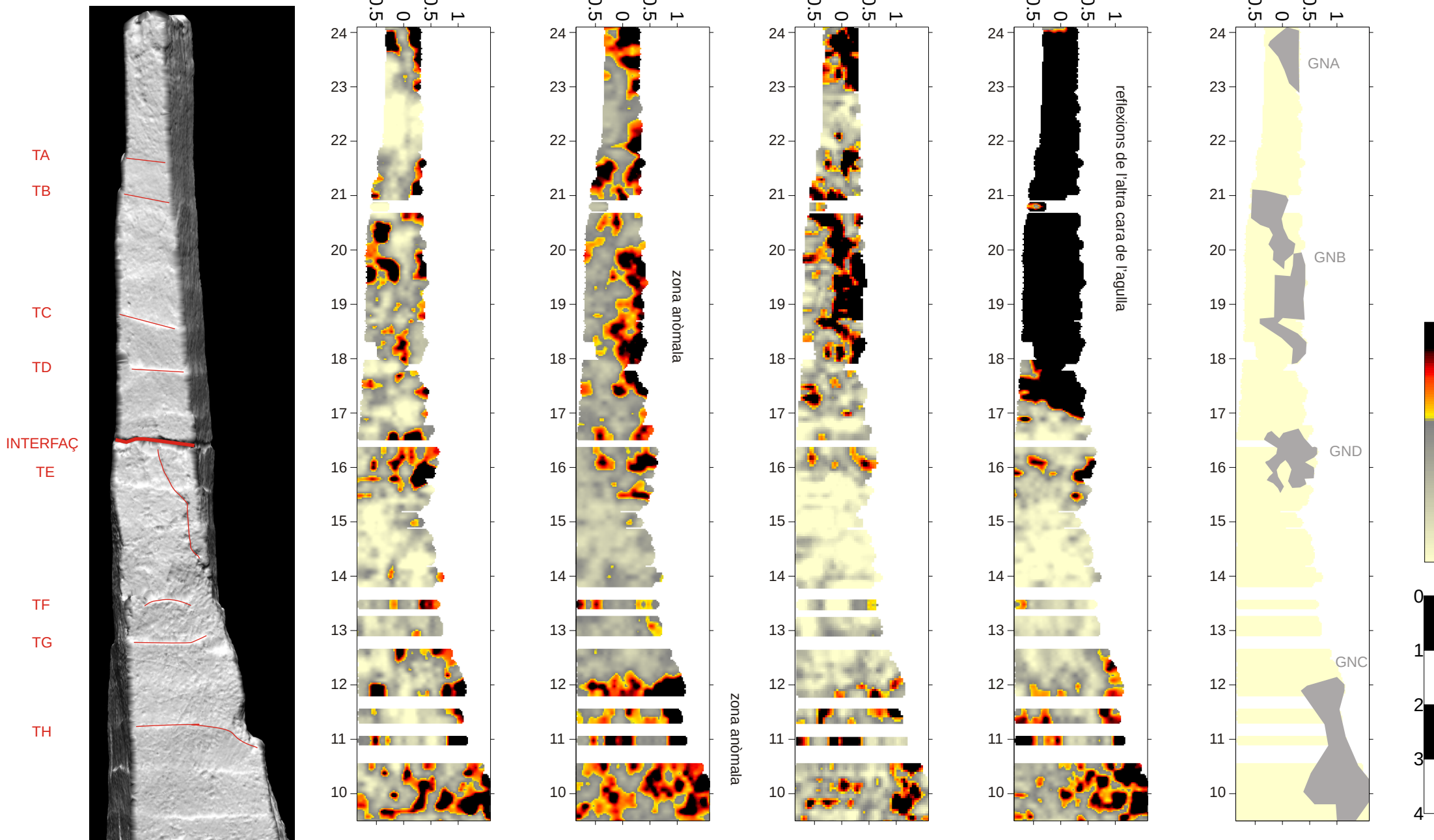
Secció entre 0.16 i 0.25m
de la superfície

Secció entre 0.41 i 0.49m
de la superfície

Secció entre 0.91 i 0.99m
de la superfície

Secció entre 1.32 i 1.40m
de la superfície

Zones identificades
com anòmales



Model - 1x1cm

Secció entre 0.25 i 0.33m
de la superfície

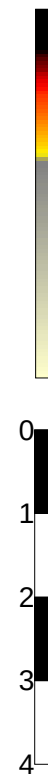
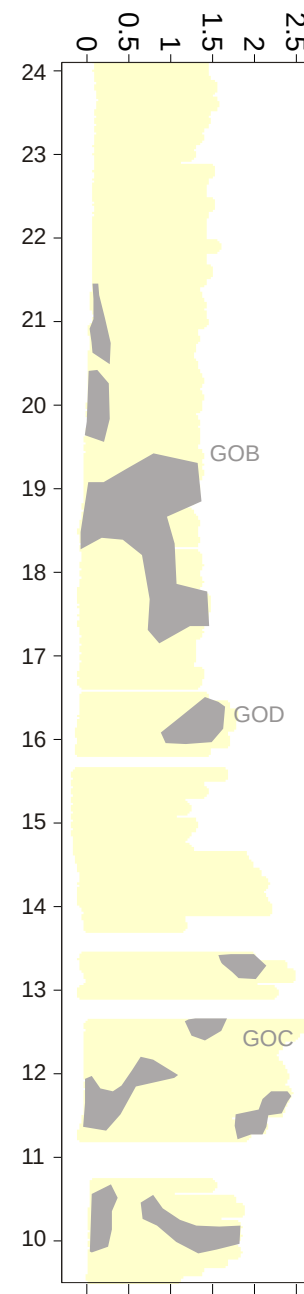
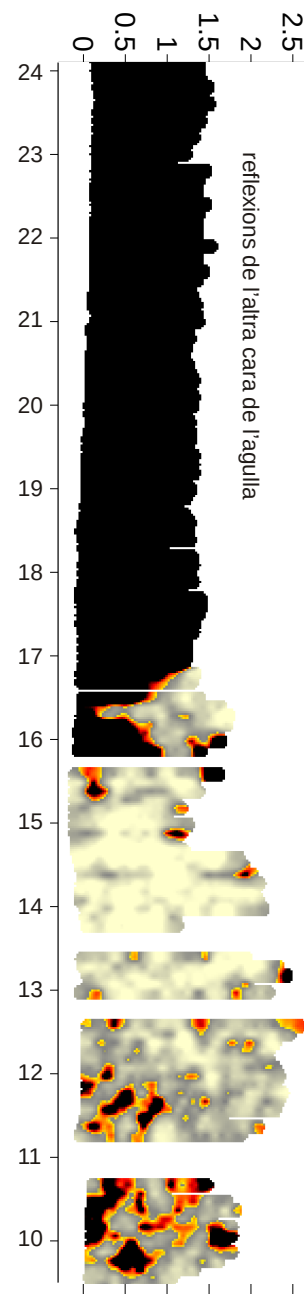
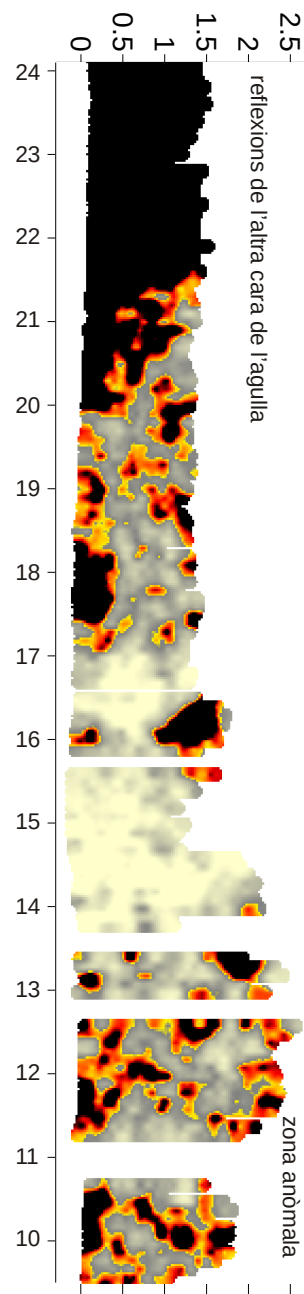
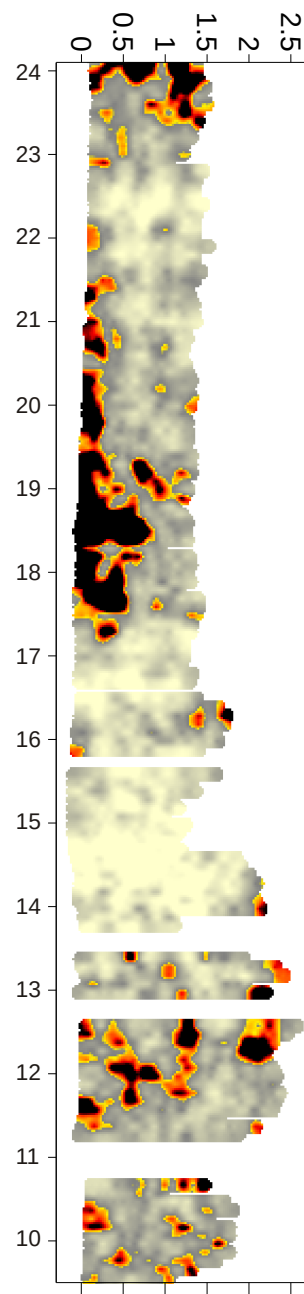
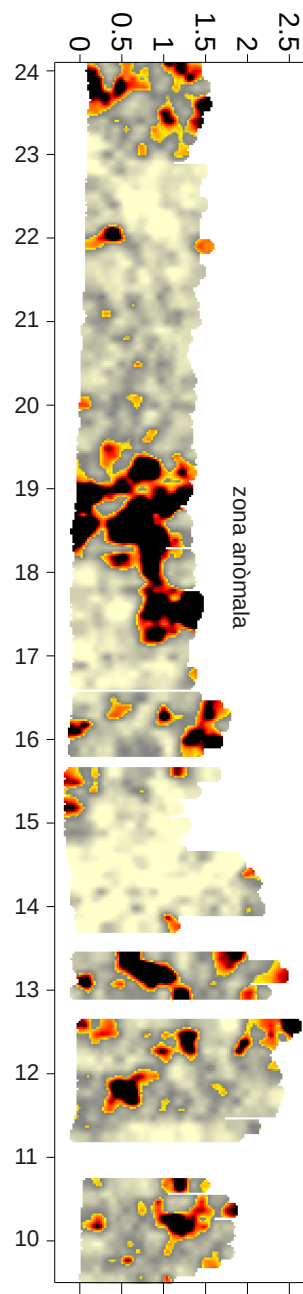
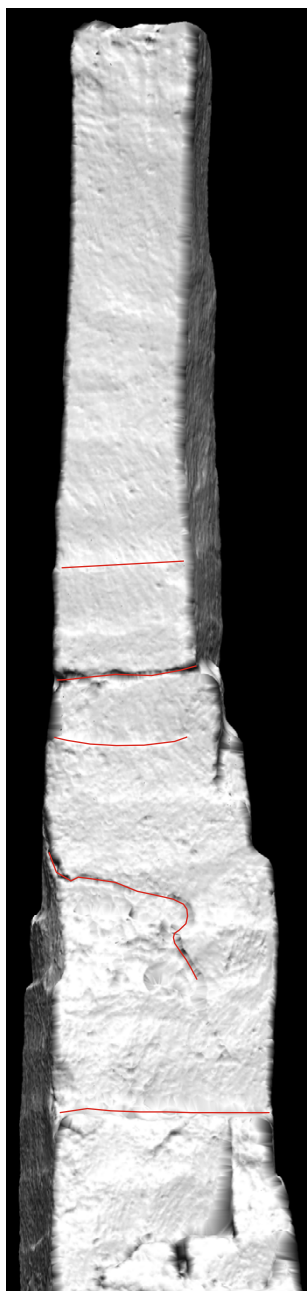
Secció entre 0.49 i 0.57m
de la superfície

Secció entre 0.74 i 0.82m
de la superfície

Secció entre 1.32 i 1.40m
de la superfície

Zones identificades
com anòmales

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Model - 1x1cm

Secció entre 0.33 i 0.41m
de la superfície

Secció entre 0.66 i 0.74m
de la superfície

Secció entre 0.82 i 0.91m
de la superfície

Secció entre 1.15 i 1.23m
de la superfície

Zones identificades
com anòmales

TA

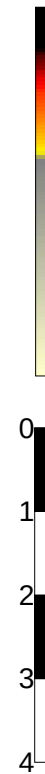
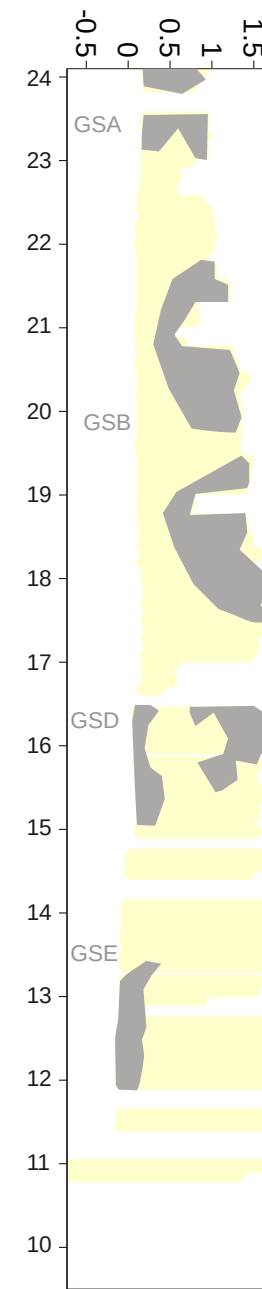
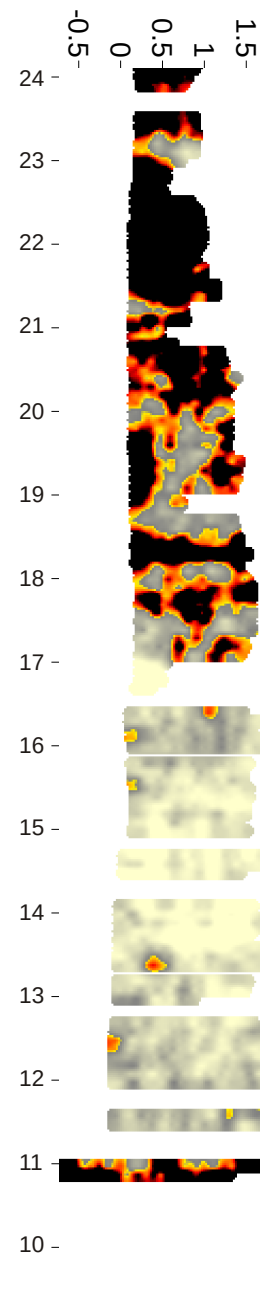
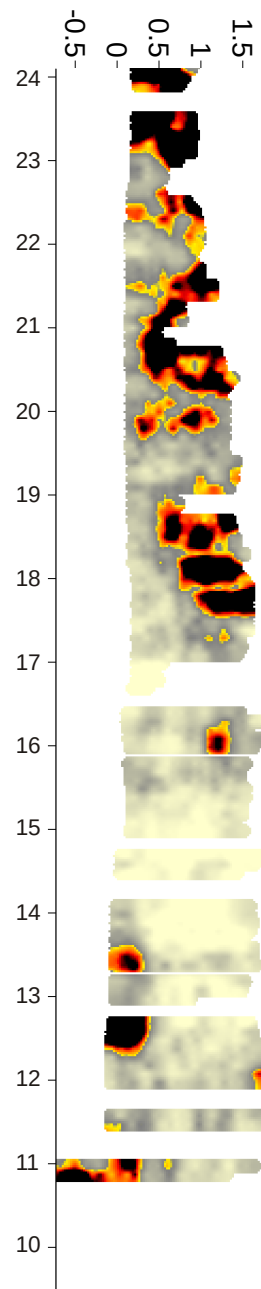
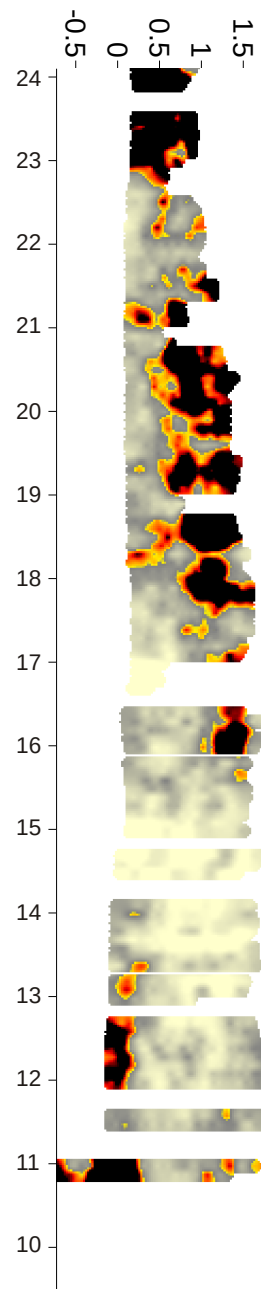
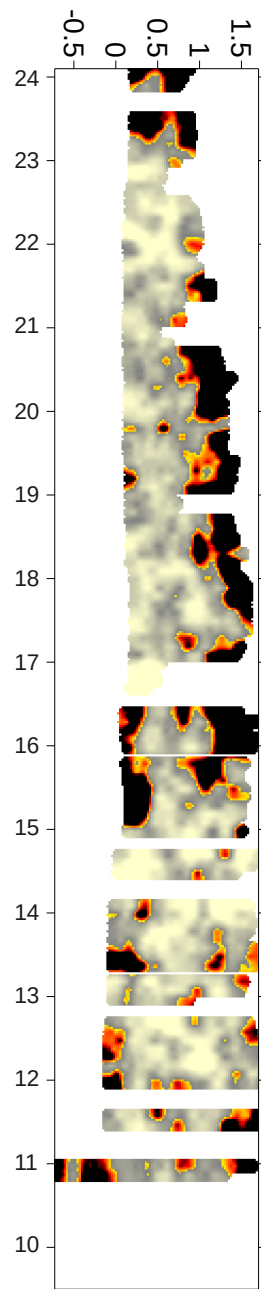
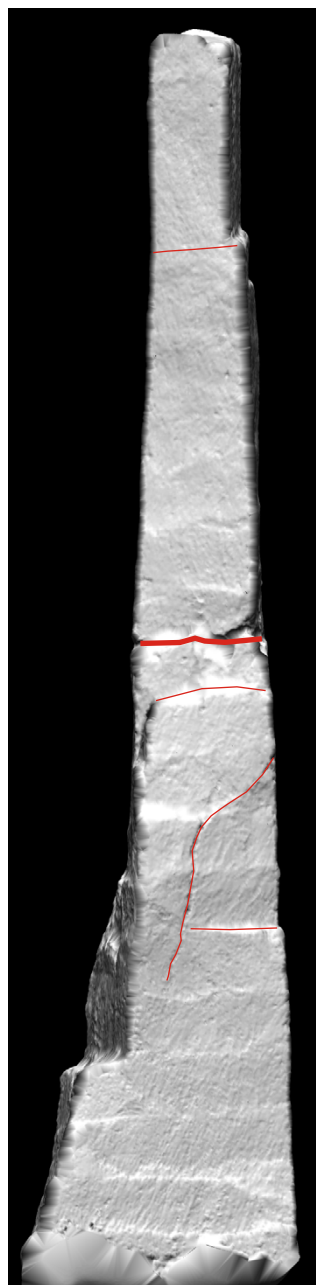
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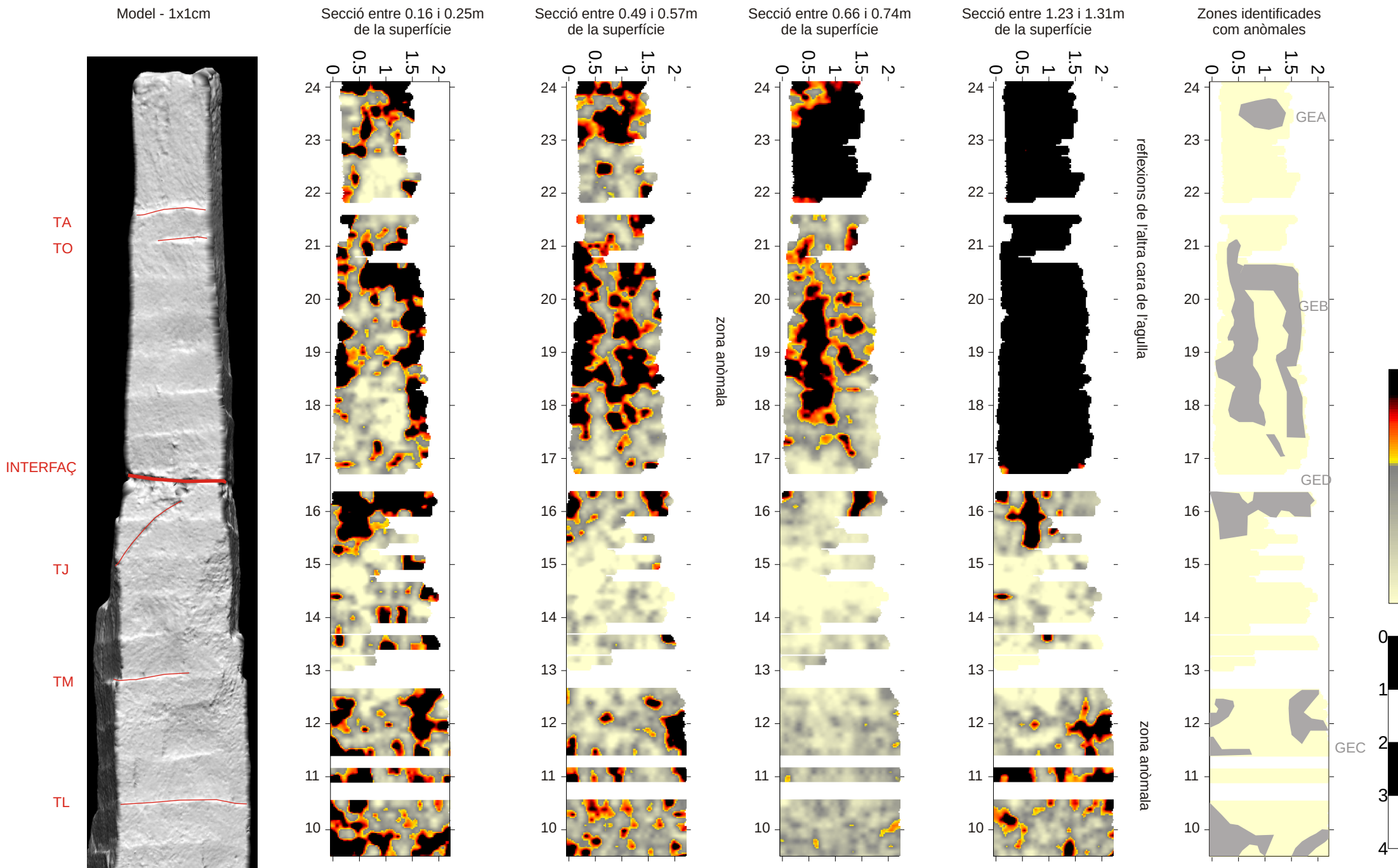
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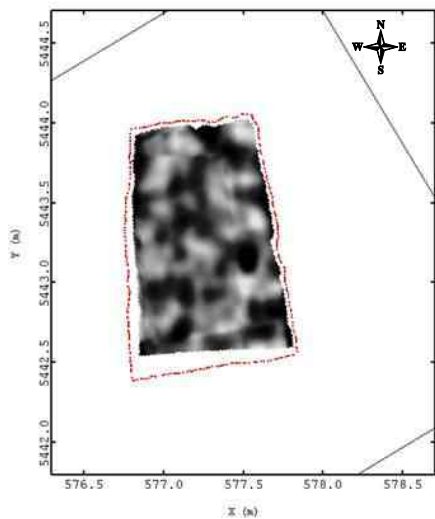
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zona anòmla

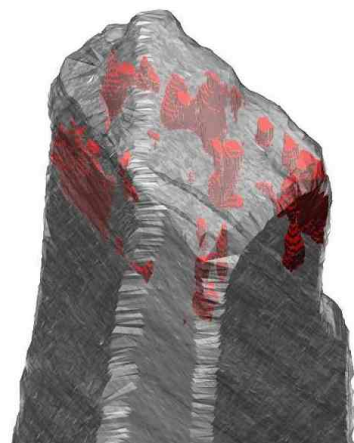




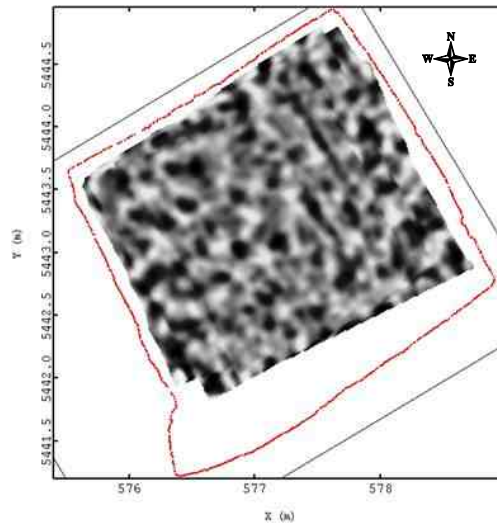
Zona GA



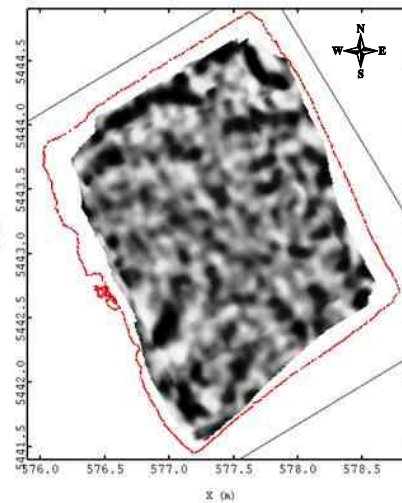
Vista zenital - Z=23.6m



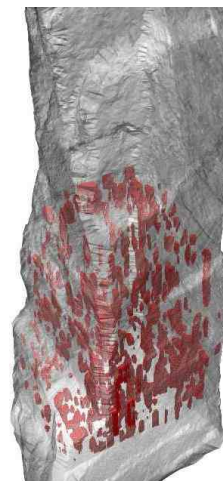
Vista 3D Zmin=23m Zmax=24m



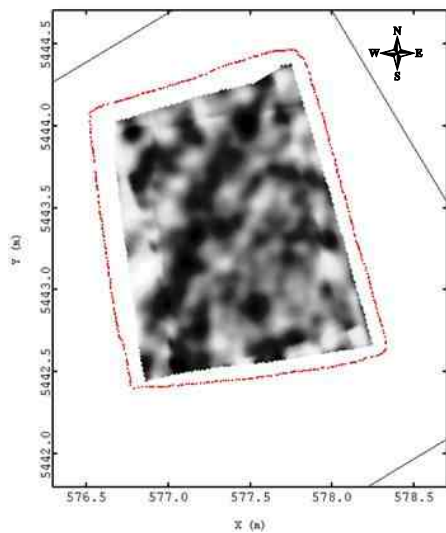
Vista zenital - Z=10.5m



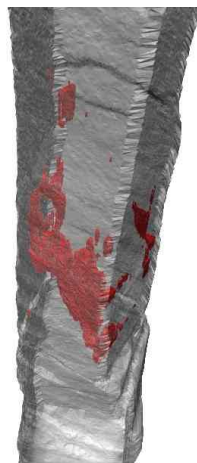
Vista zenital - Z=12.7m



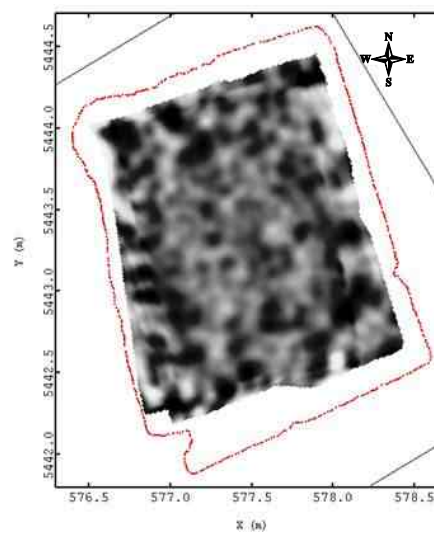
Vista 3D Zmin=9.5m Zmax=13m



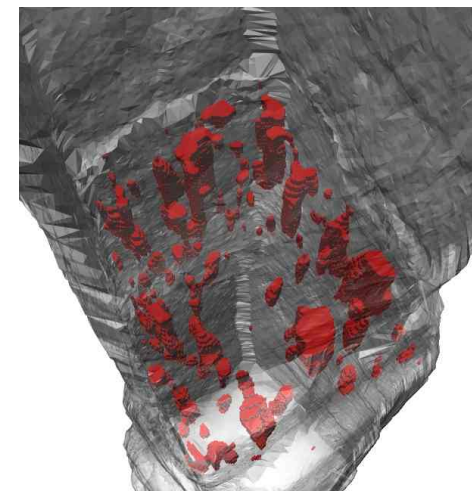
Vista zenital - Z=17.7m



Vista 3D Zmin=17.15m Zmax=19.6m



Vista zenital - Z=15.7m



Vista 3D Zmin=15.5m Zmax=16.5m

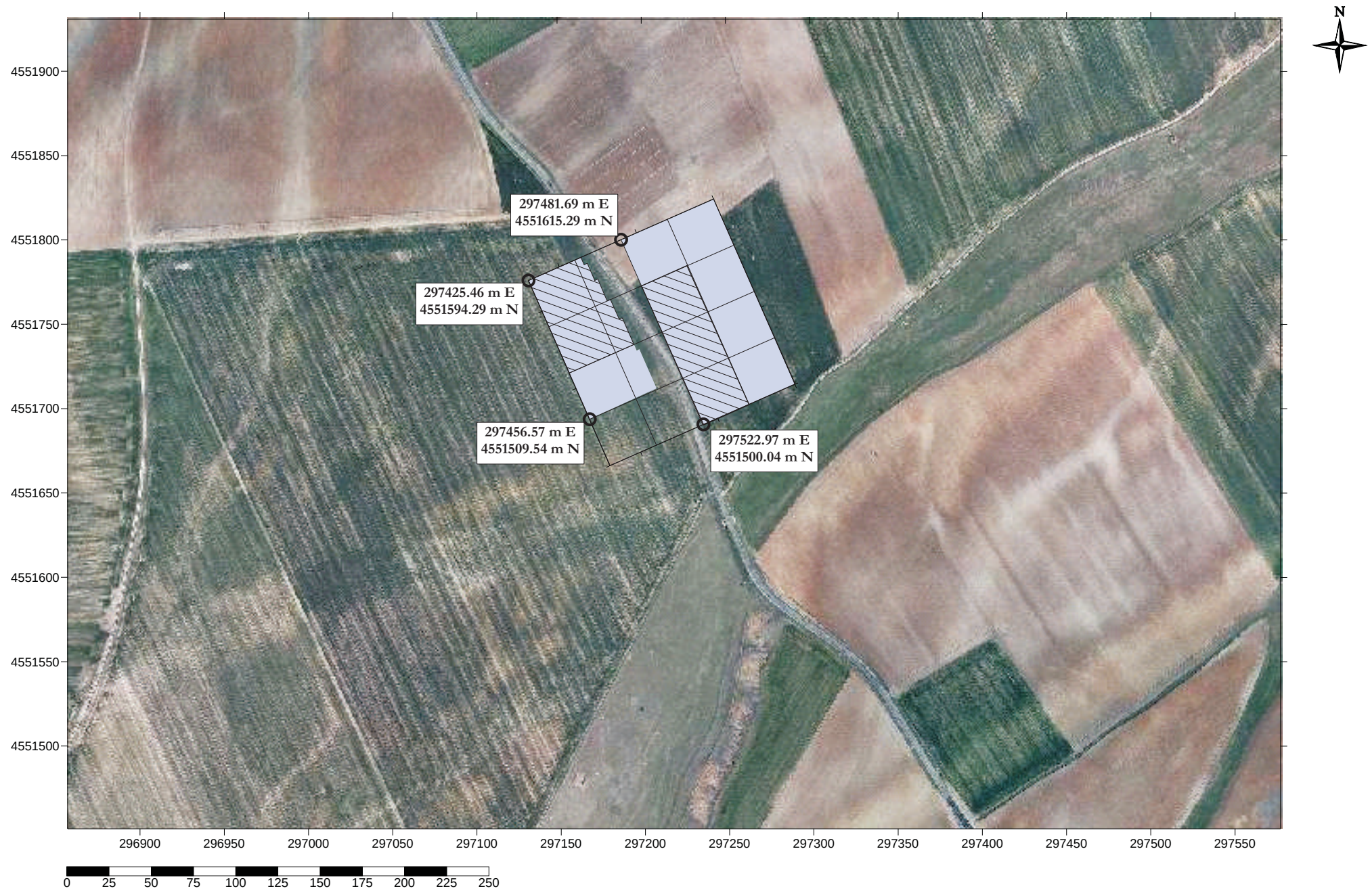
Appendix D

First graphical report: La Mina



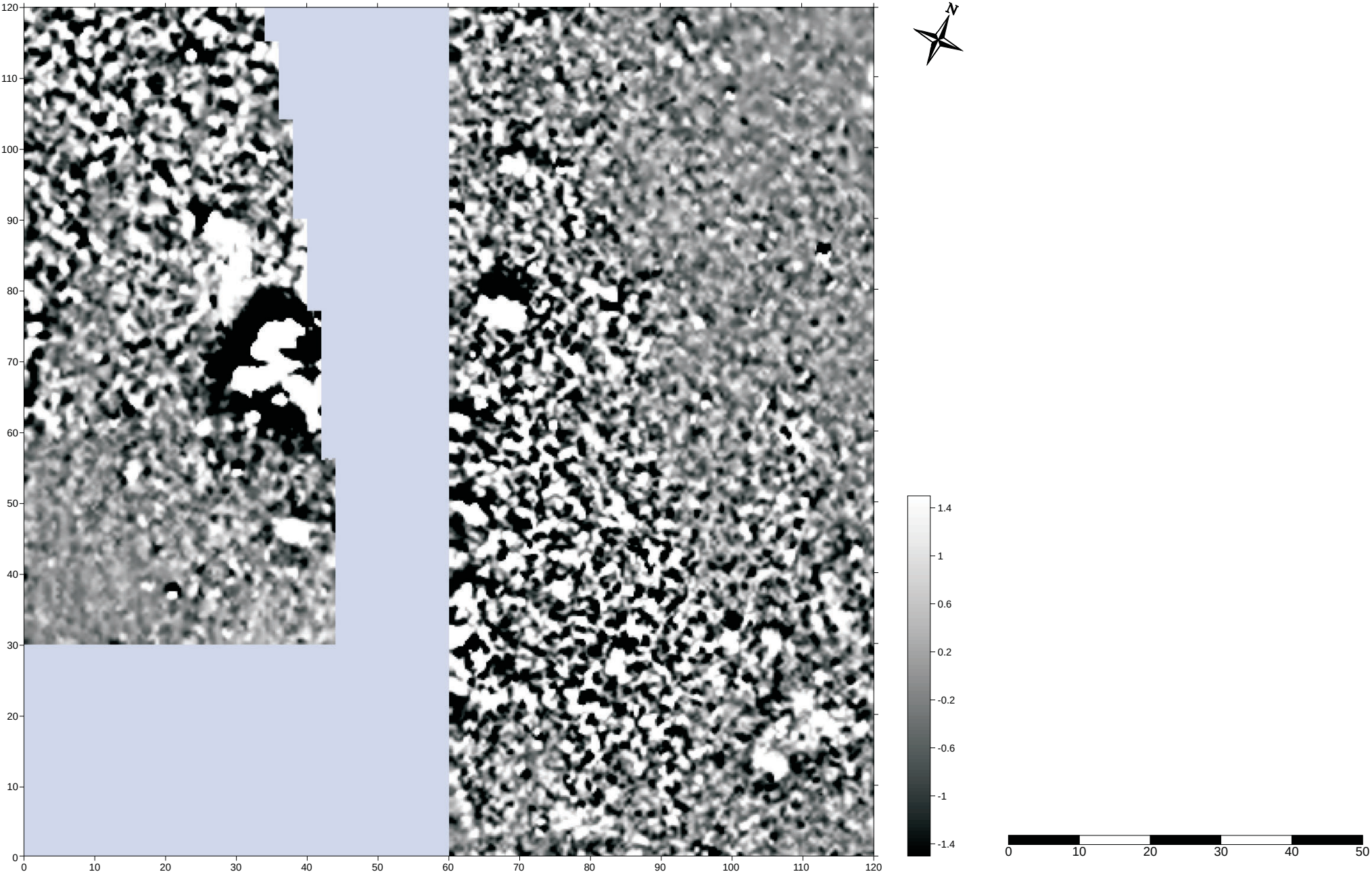
Yacimiento Arqueológico de la Mina, Pedroso de la Armuña, Salamanca
Prospección geofísica multisistema
Gráfico 1. Áreas exploradas

- Prospección magnética
- Prospección GPR



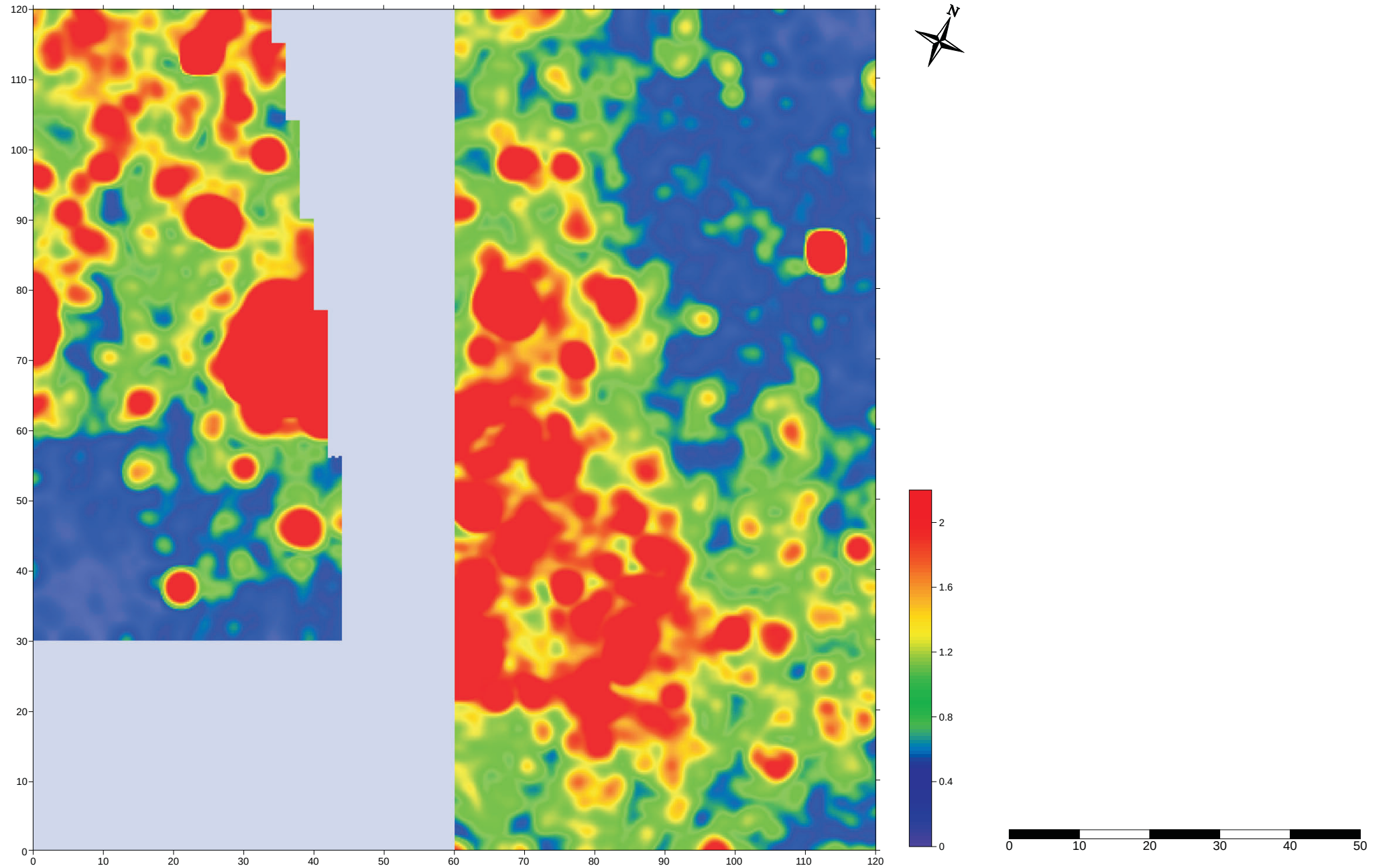


Yacimiento Arqueológico de la Mina, Pedroso de la Armuña, Salamanca
Prospección geofísica multisistema
Prospección magnética.
Gráfico 2. Resultados en escala de grises



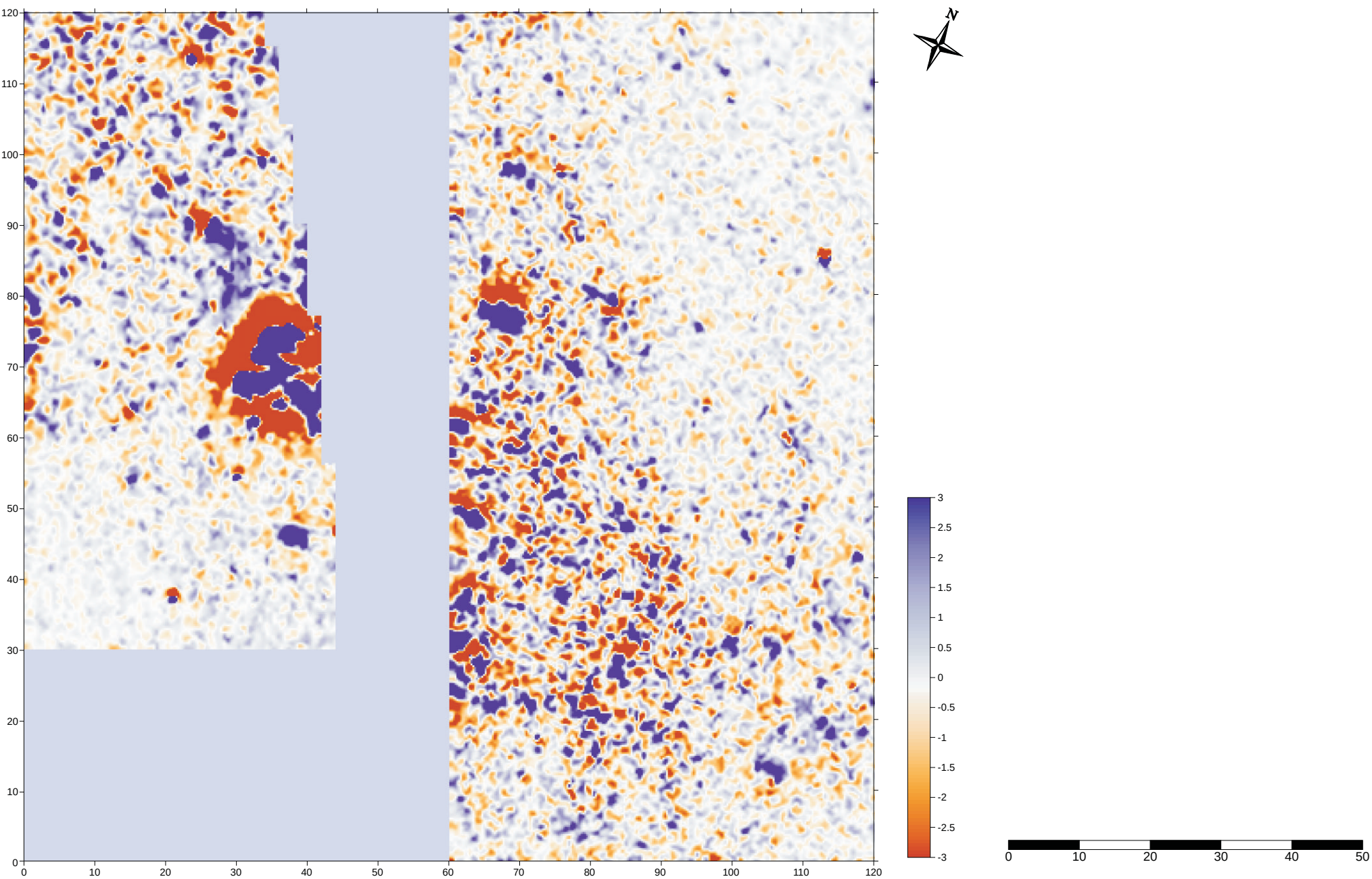


Yacimiento Arqueológico de la Mina, Pedroso de la Armuña, Salamanca
Prospección geofísica multisistema
Prospección magnética.
Gráfico 3. Mapa de desviación estandar de los datos. Radio=2.5m



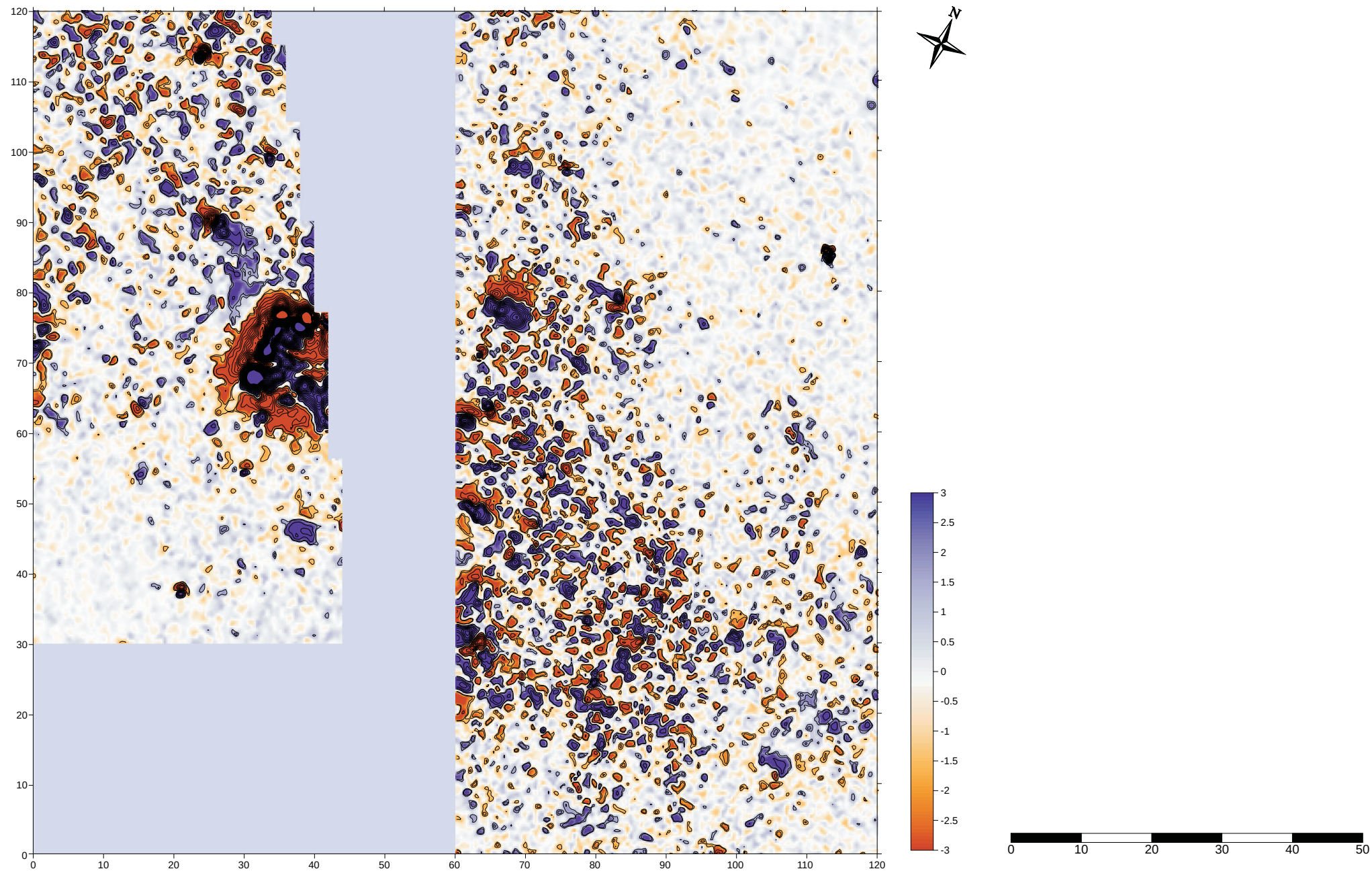


Yacimiento Arqueológico de la Mina, Pedroso de la Armuña, Salamanca
Prospección geofísica multisistema
Prospección magnética.
Gráfico 4. Resultados en escala mixta



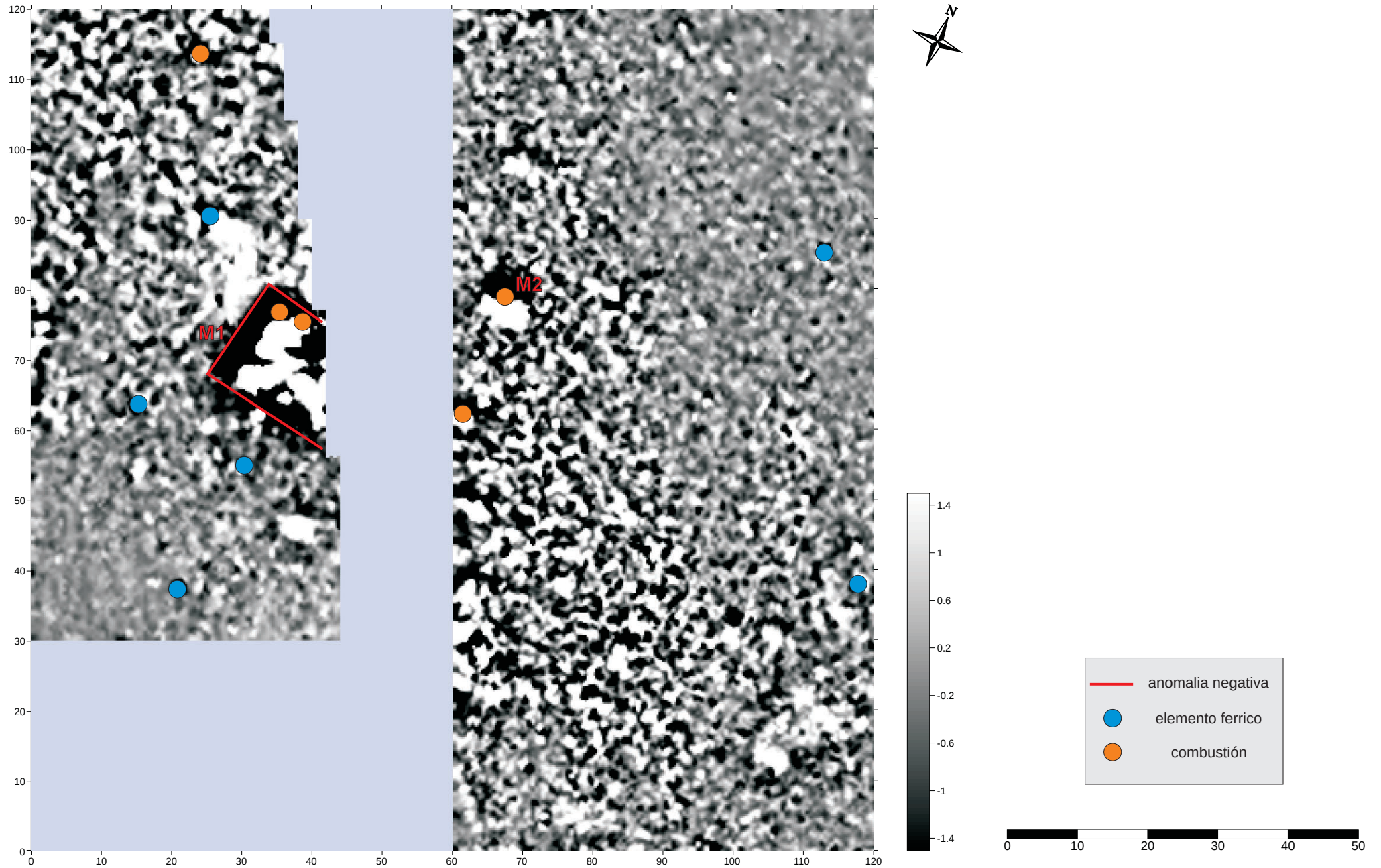


Yacimiento Arqueológico de la Mina, Pedroso de la Armuña, Salamanca
Prospección geofísica multisistema
Prospección magnética.
Gráfico 5. Resultados en escala mixta con superposición de isolíneas



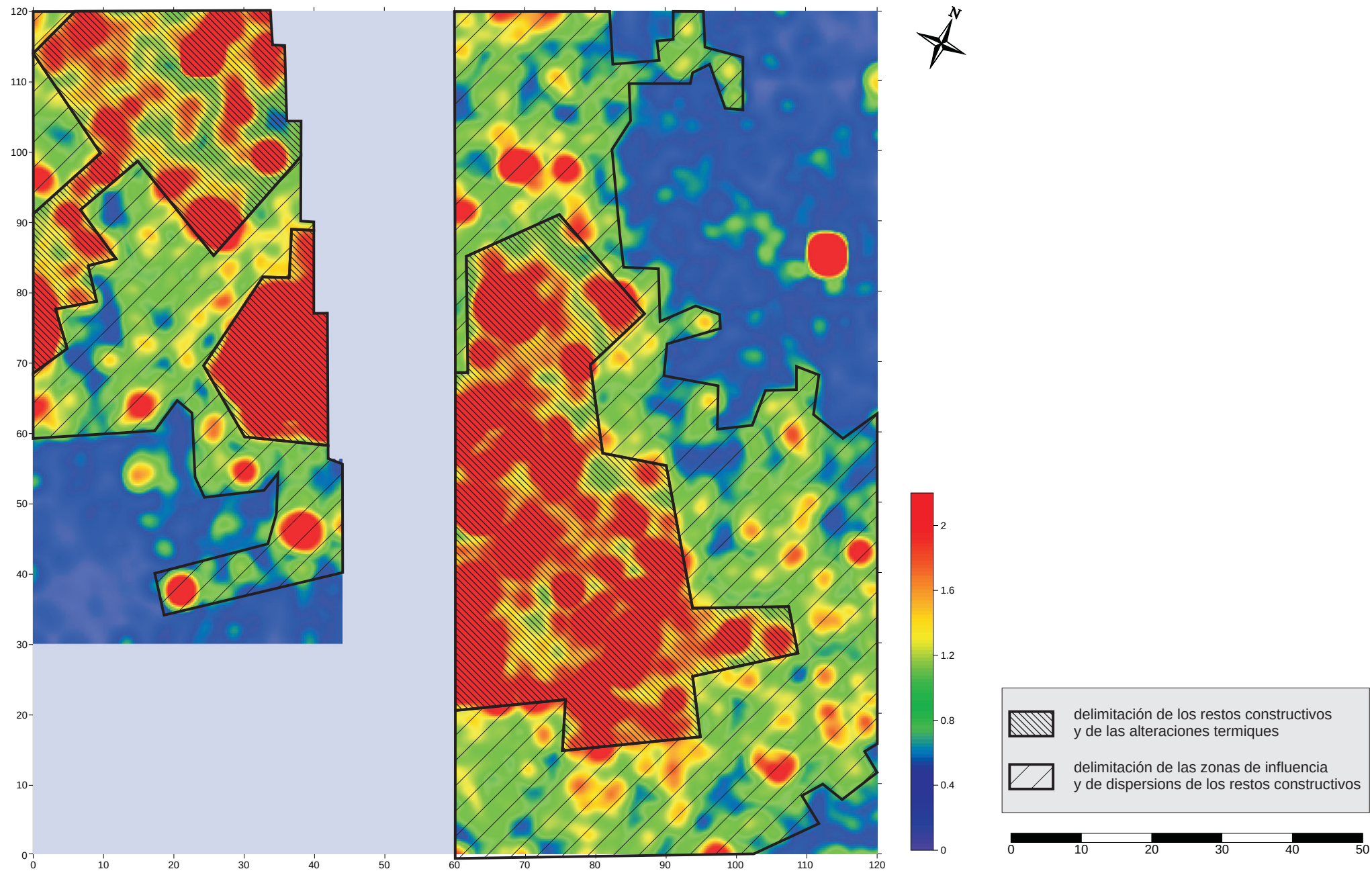


Yacimiento Arqueológico de la Mina, Pedroso de la Armuña, Salamanca
Prospección geofísica multisistema
Resultados preliminares
Prospección magnética.
Gráfico 6. Resultados en escala de grises con superposición de la interpretación



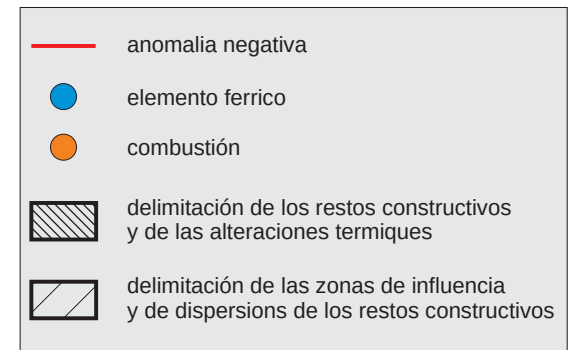
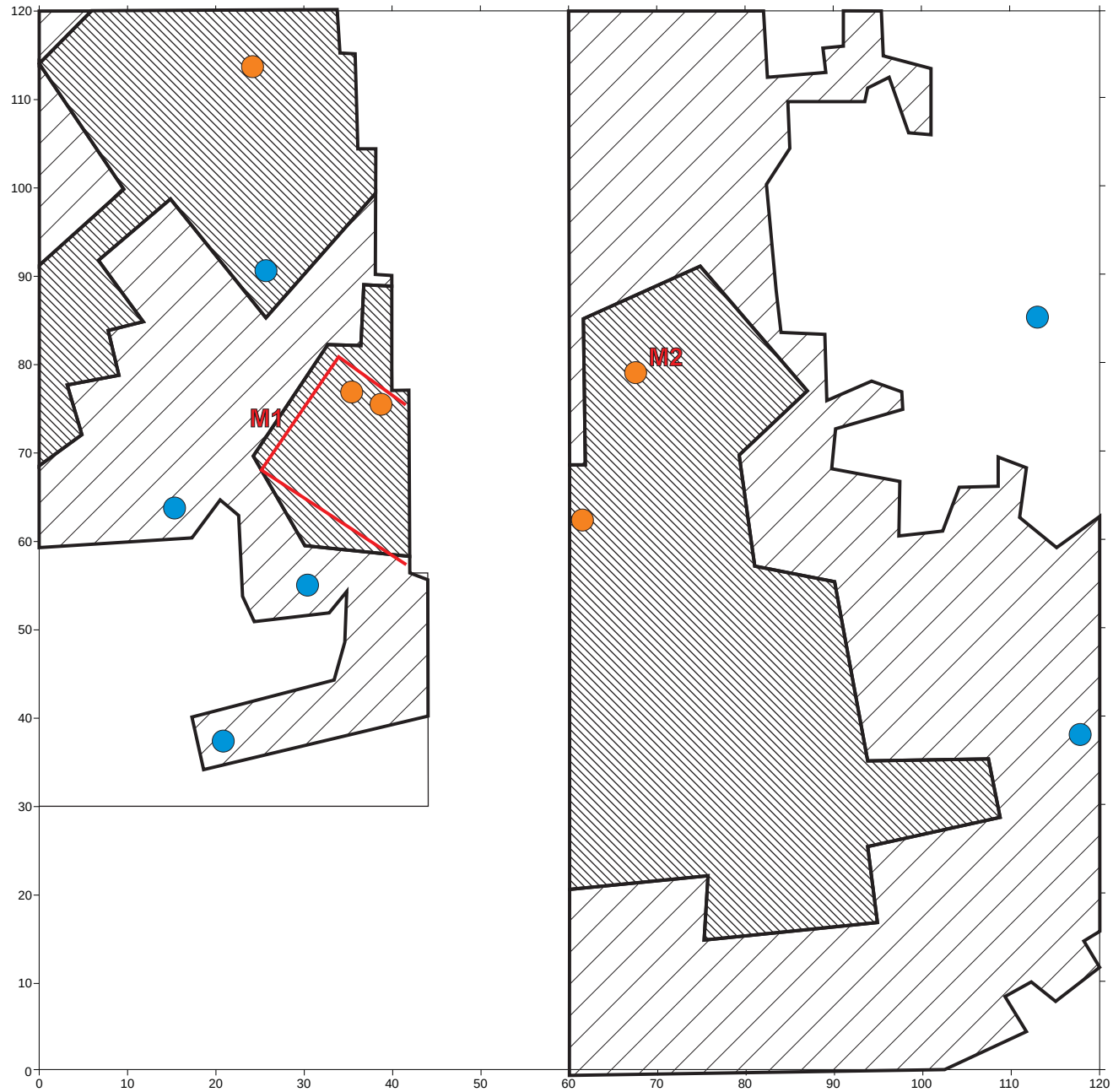


Yacimiento Arqueológico de la Mina, Pedroso de la Armuña, Salamanca
Prospección geofísica multisistema
Prospección magnética.
Gráfico 7. Mapa de desviación estandar con superposición de la interpretación.



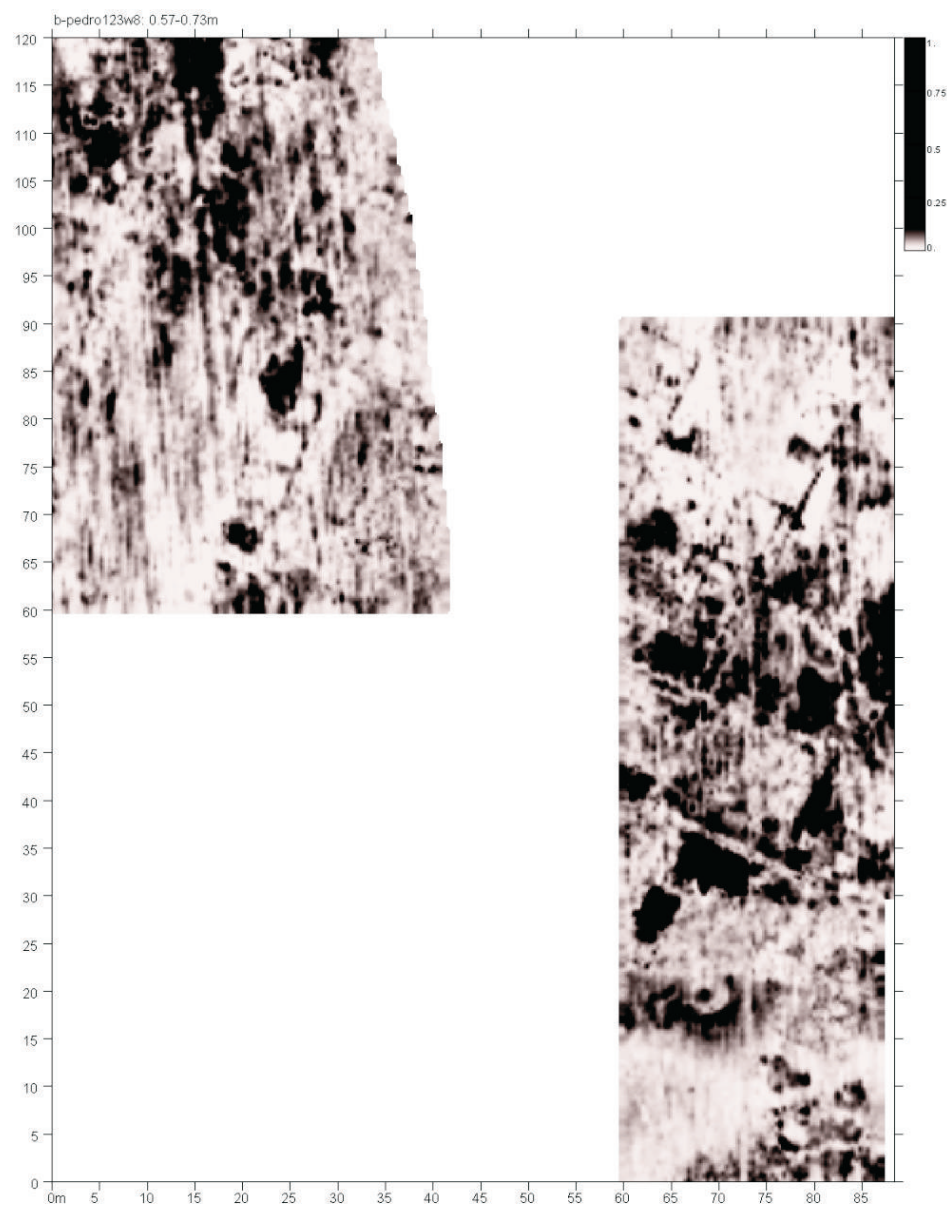
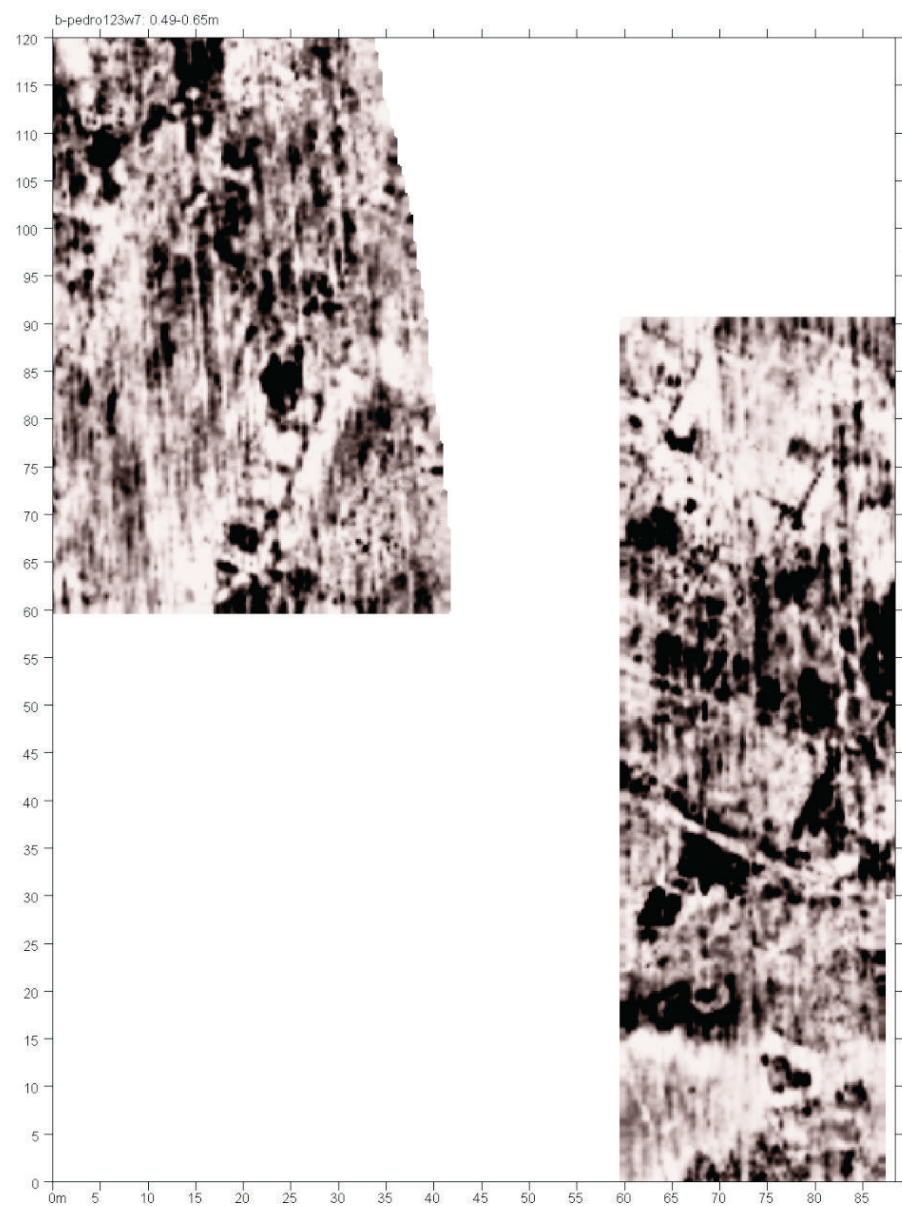


Yacimiento Arqueológico de la Mina, Pedroso de la Armuña, Salamanca
Prospección geofísica multisistema
Prospección magnética.
Gráfico 8. Interpretación de los resultados magnéticos.



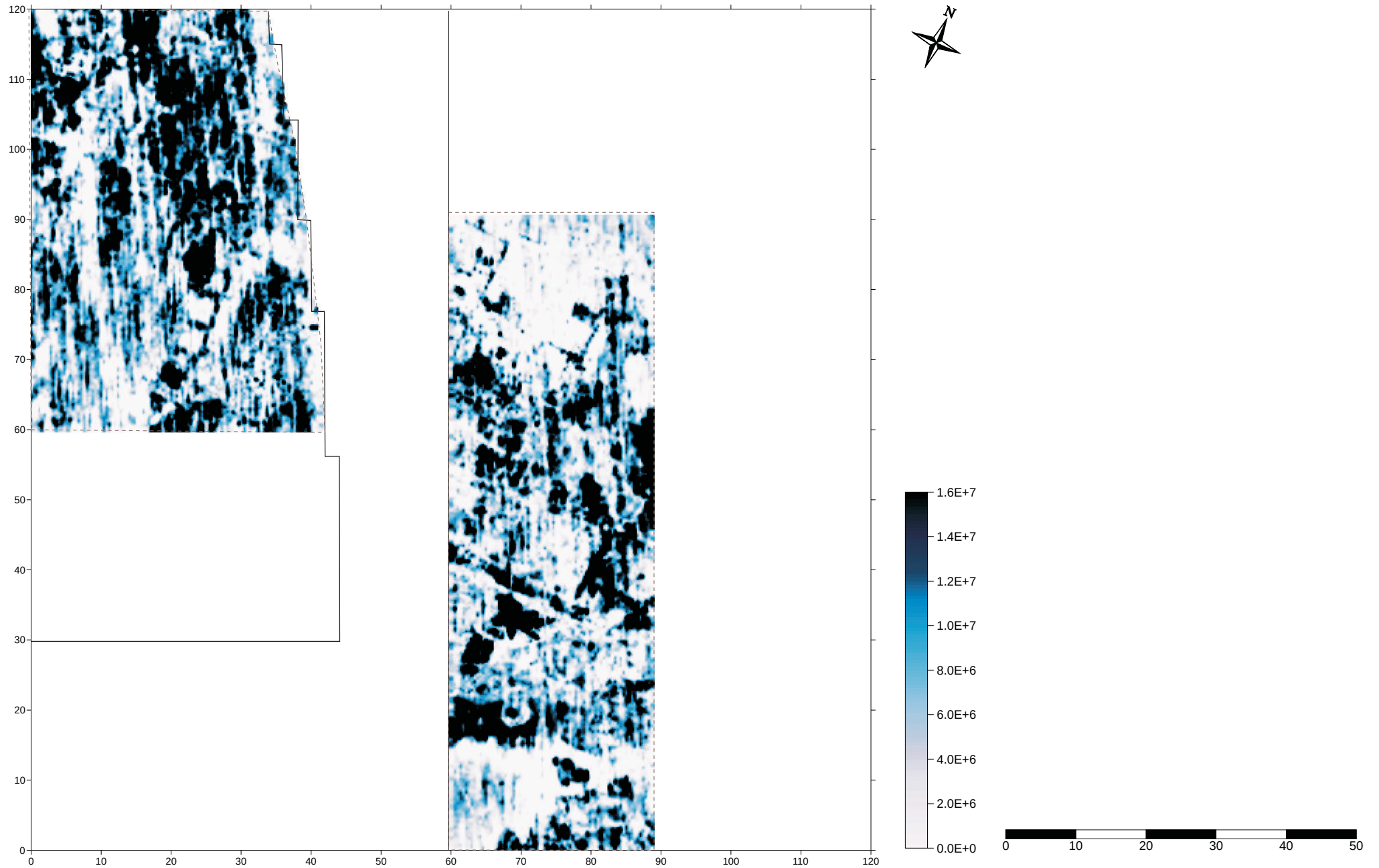


Yacimiento Arqueológico de la Mina, Pedroso de la Armuña, Salamanca
Prospección geofísica multisistema
Prospección Georadar.
Gráfico 9. Secuencia de cortes horizontales entre 0.49m y 0.73m b.s.





Yacimiento Arqueológico de la Mina, Pedroso de la Armuña, Salamanca
Prospección geofísica multisistema
Prospección GPR.
Gráfico 10. Mapa de las estructuras presentes entre 13.37ns y 15.42ns (53.5cm y 61.7cm b.s.).



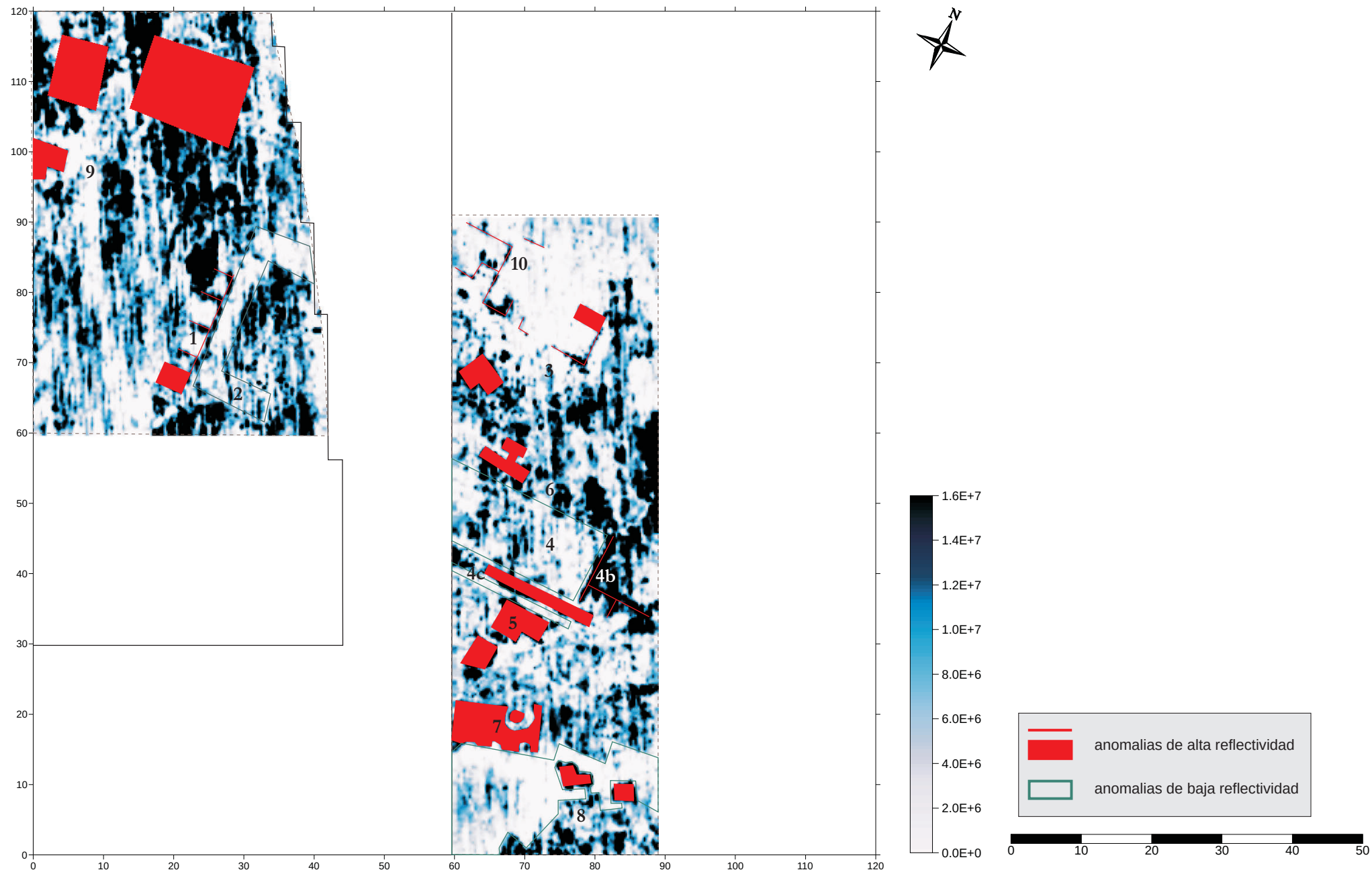


Yacimiento Arqueológico de la Mina, Pedroso de la Armuña, Salamanca

Prospección geofísica multisistema

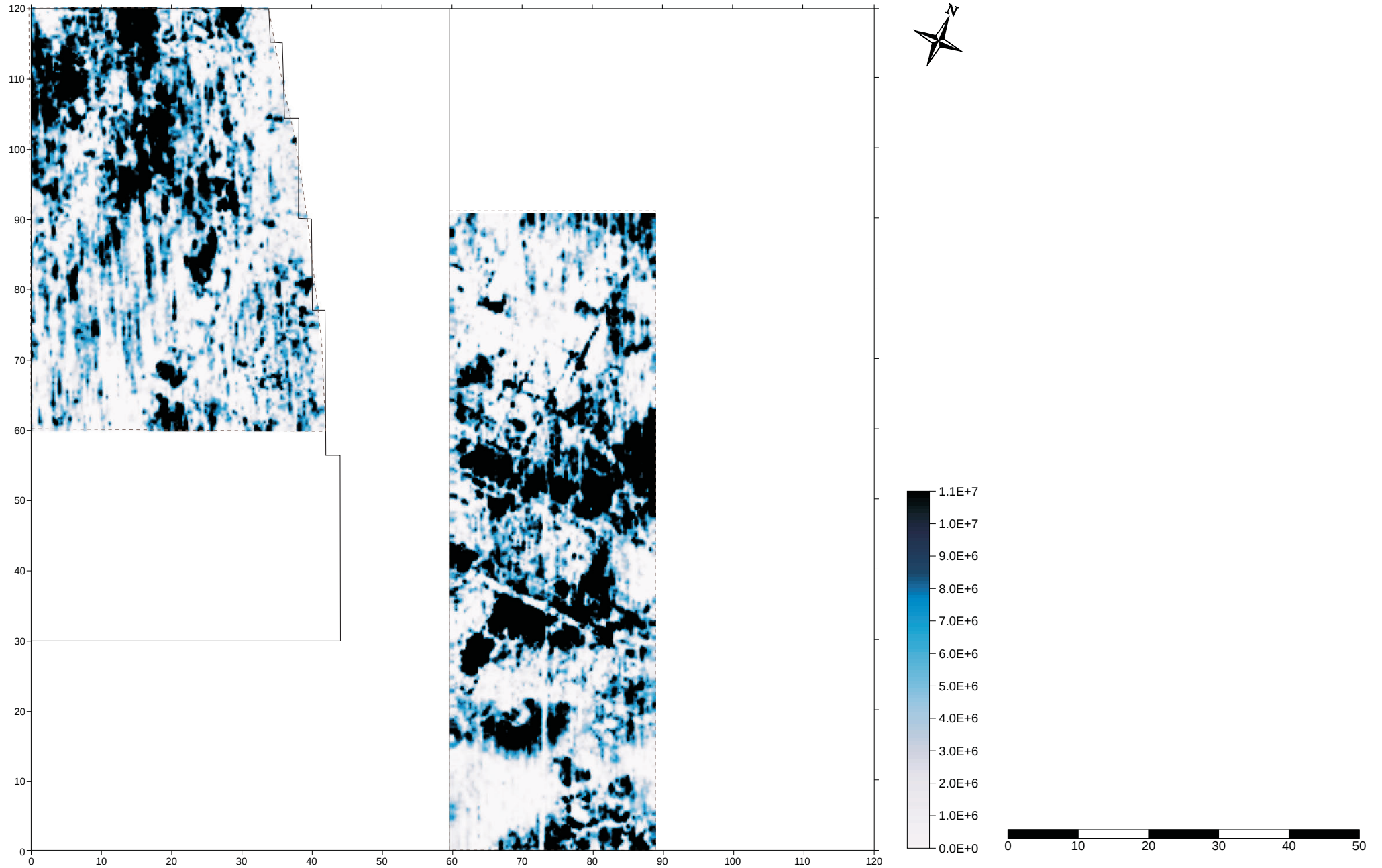
Prospección GPR.

Gráfico 11. Mapa de las estructuras presentes entre 13.37ns y 15.42ns (53.5cm y 61.7cm b.s.) con superposición de la interpretación.





Yacimiento Arqueológico de la Mina, Pedroso de la Armuña, Salamanca
Prospección geofísica multisistema
Prospección GPR.
Gráfico 12. Mapa de las estructuras presentes entre 15.28ns y 17.33ns (61.1cm y 69.3cm b.s.)



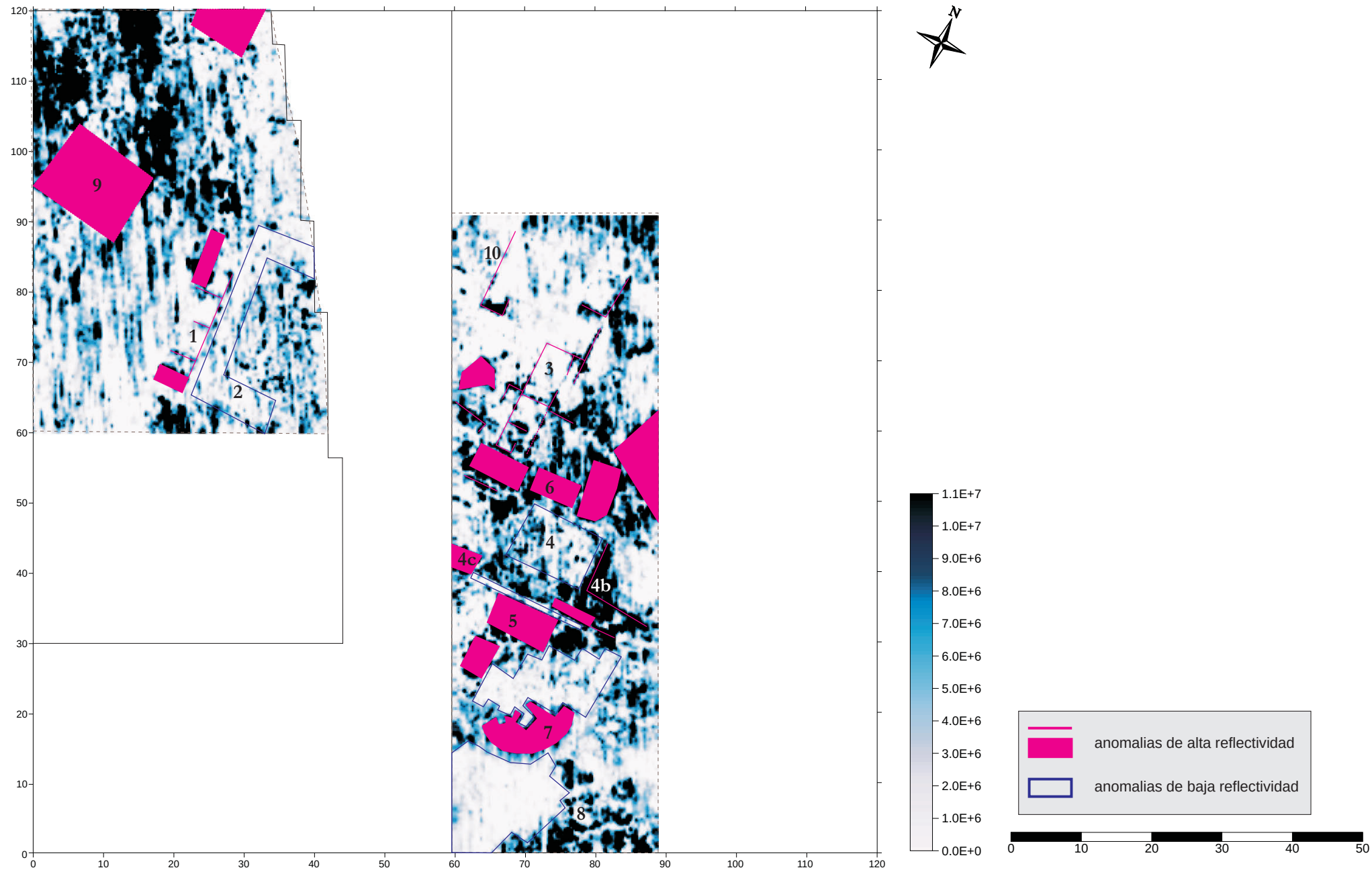


Yacimiento Arqueológico de la Mina, Pedroso de la Armuña, Salamanca

Prospección geofísica multisistema

Prospección GPR.

Gráfico 13. Mapa de las estructuras presentes entre 15.28ns y 17.33ns (61.1cm y 69.3cm b.s.) con superposición de la interpretación.



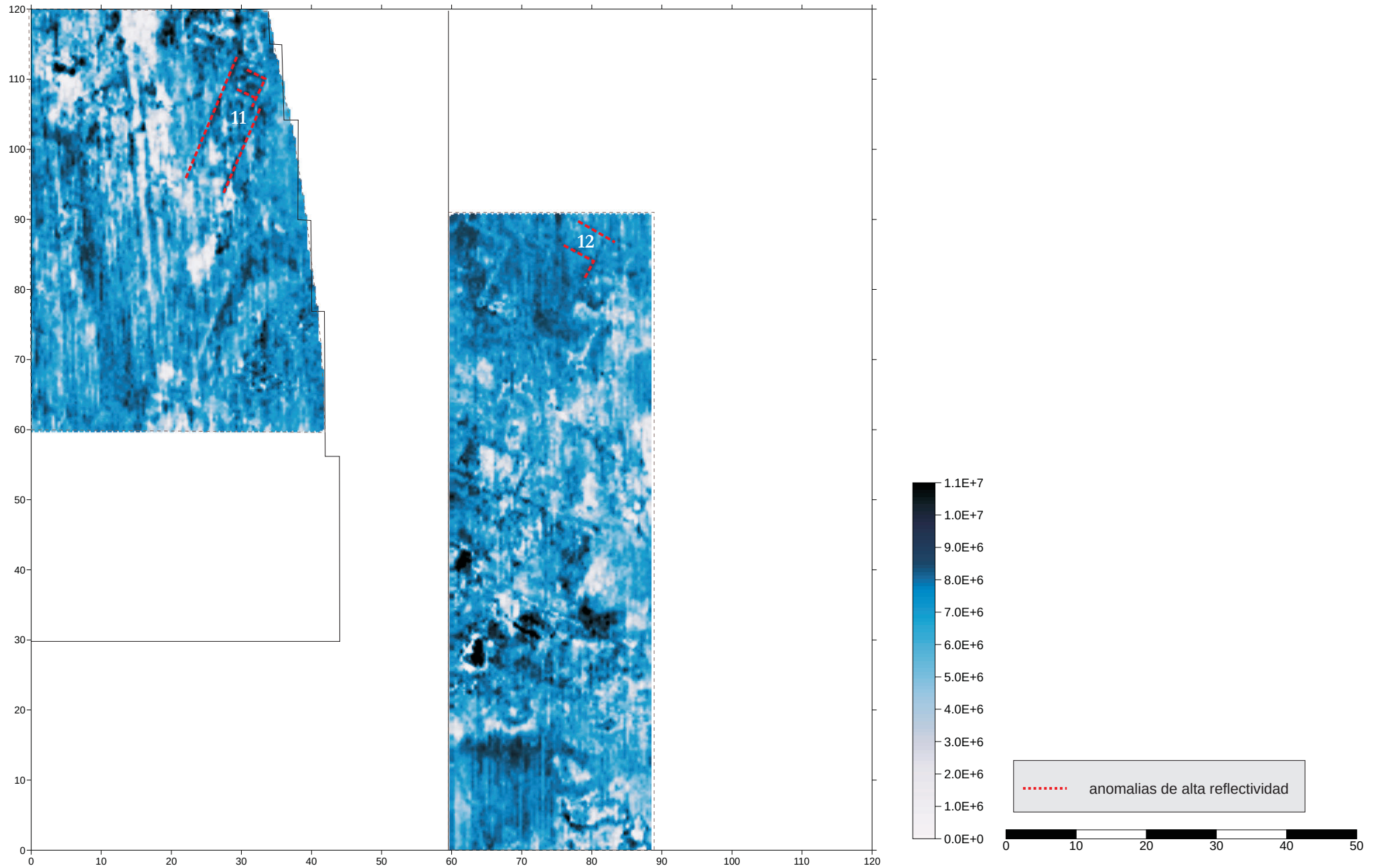


Yacimiento Arqueológico de la Mina, Pedroso de la Armuña, Salamanca

Prospección geofísica multisistema

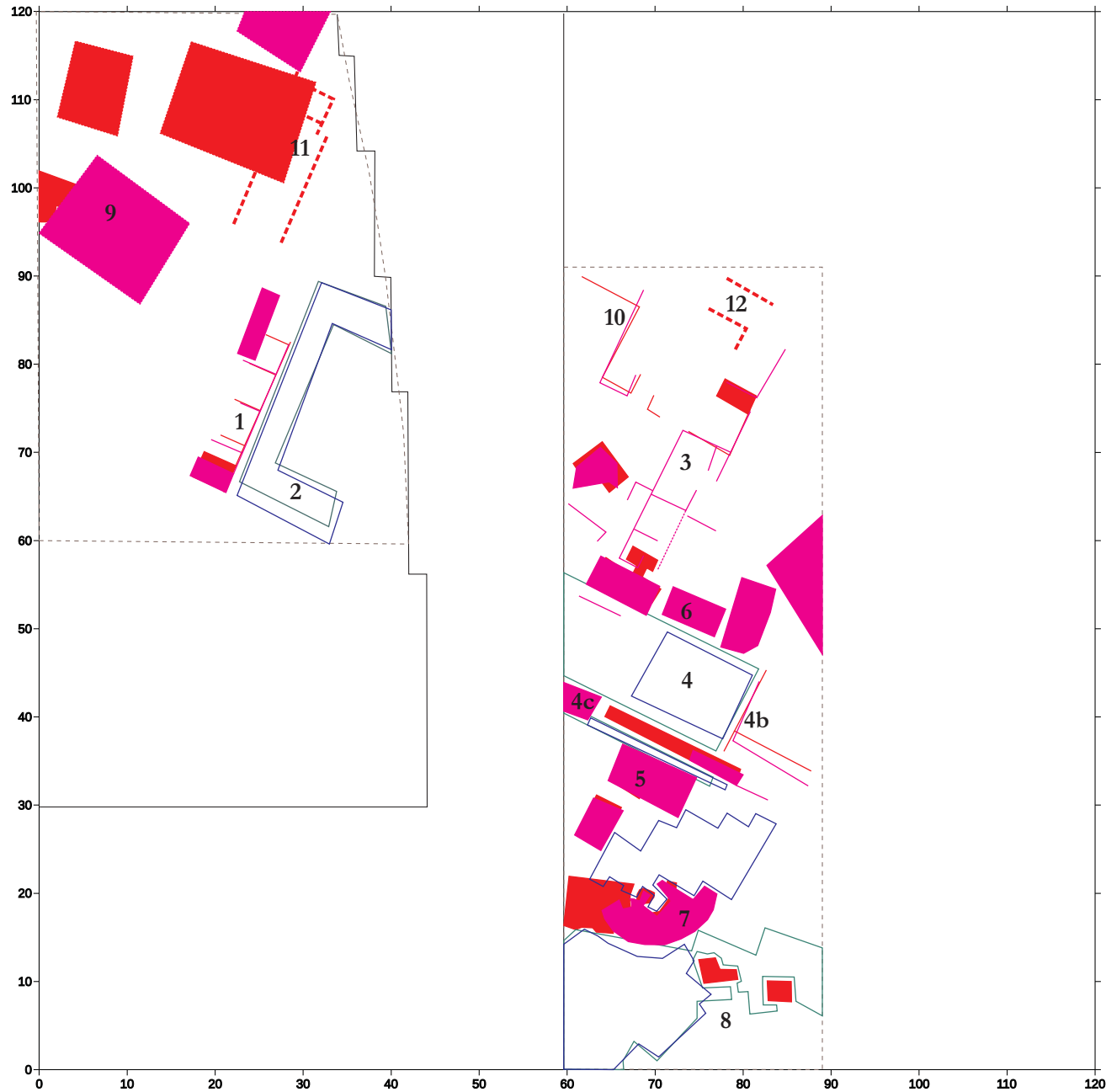
Prospección GPR.

Gráfico 14. Mapa de las estructuras presentes a18ns (72cm b.s.) con superposición de la interpretación.

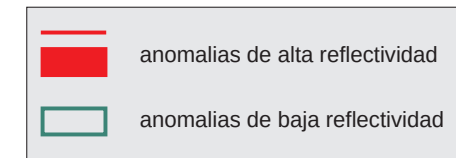




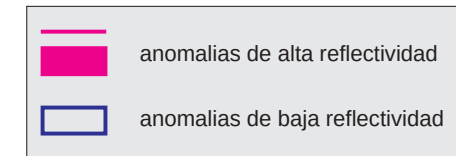
Yacimiento Arqueológico de la Mina, Pedroso de la Armuña, Salamanca
Prospección geofísica multisistema
Prospección GPR.
Gráfico 15. Superposición de las interpretaciones de los datos GPR.



Nivel entre 53.5cm y 61.7cm b.s.



Nivel entre 61.1cm y 69.3cm b.s.



Nivel a 72cm b.s.





- anomalía negativa
- elemento ferrico
- combustión
- delimitación de los restos constructivos y de las alteraciones termiques
- delimitación de las zonas de influencia y de dispersiones de los restos constructivos

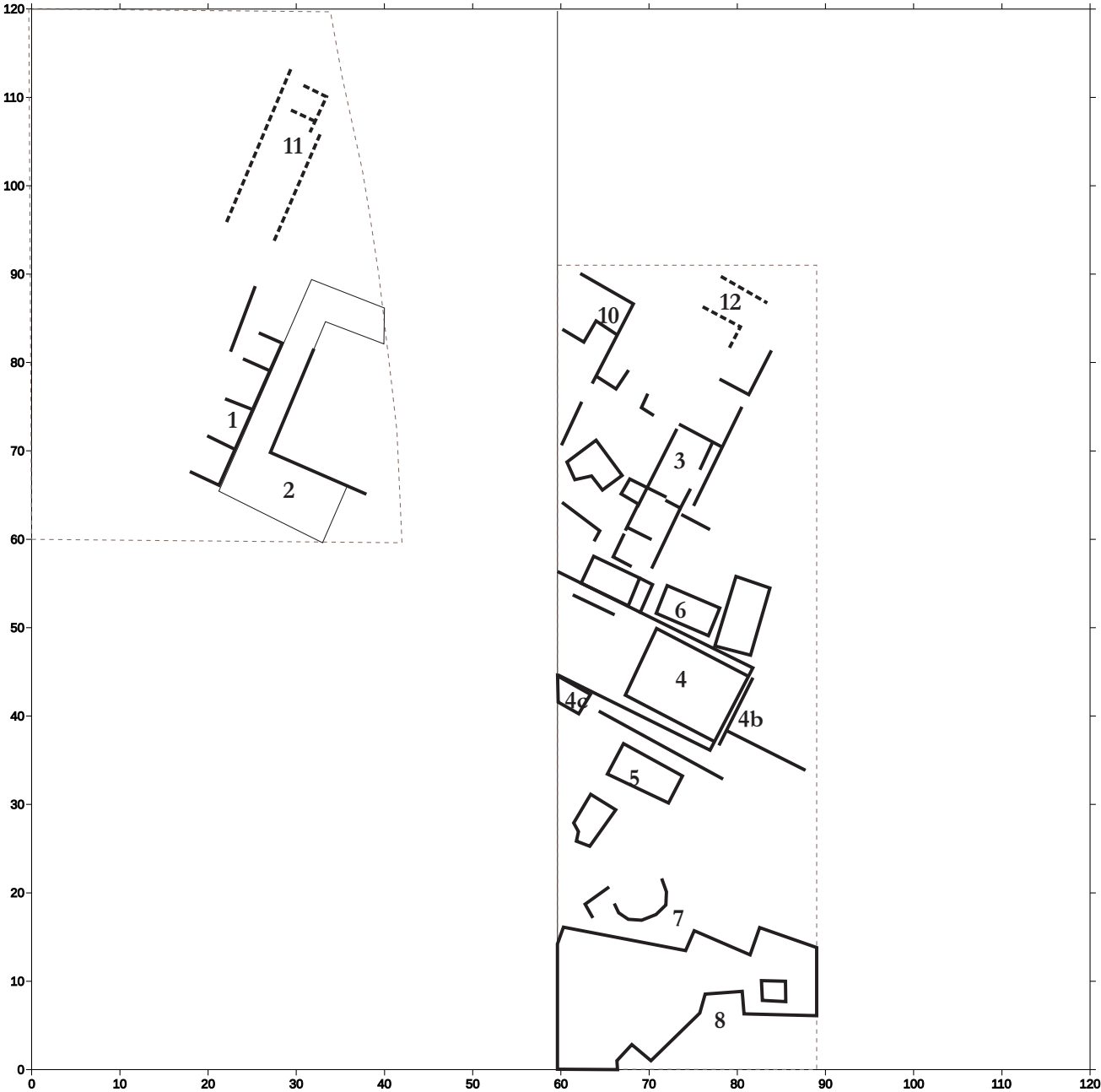
anomalías de alta reflectividad

anomalías de baja reflectividad

 anomalías de alta reflectividad
 anomalías de baja reflectividad

..... anomalías de alta reflectividad





Appendix E

First graphical report: Puig Ciutat



Jaciment arqueològic Puig Ciutat (Oristà-Torre d'Oristà)
Campanya 2010
Gràfic 1
Ubicació de les àrees explorades

Ubicació de La Torre d'Oristà



Vista aèria del jaciment i indicació de les exploracions geofísiques realitzades





Jaciment arqueològic Puig Ciutat (Oristà-Torre d'Oristà)

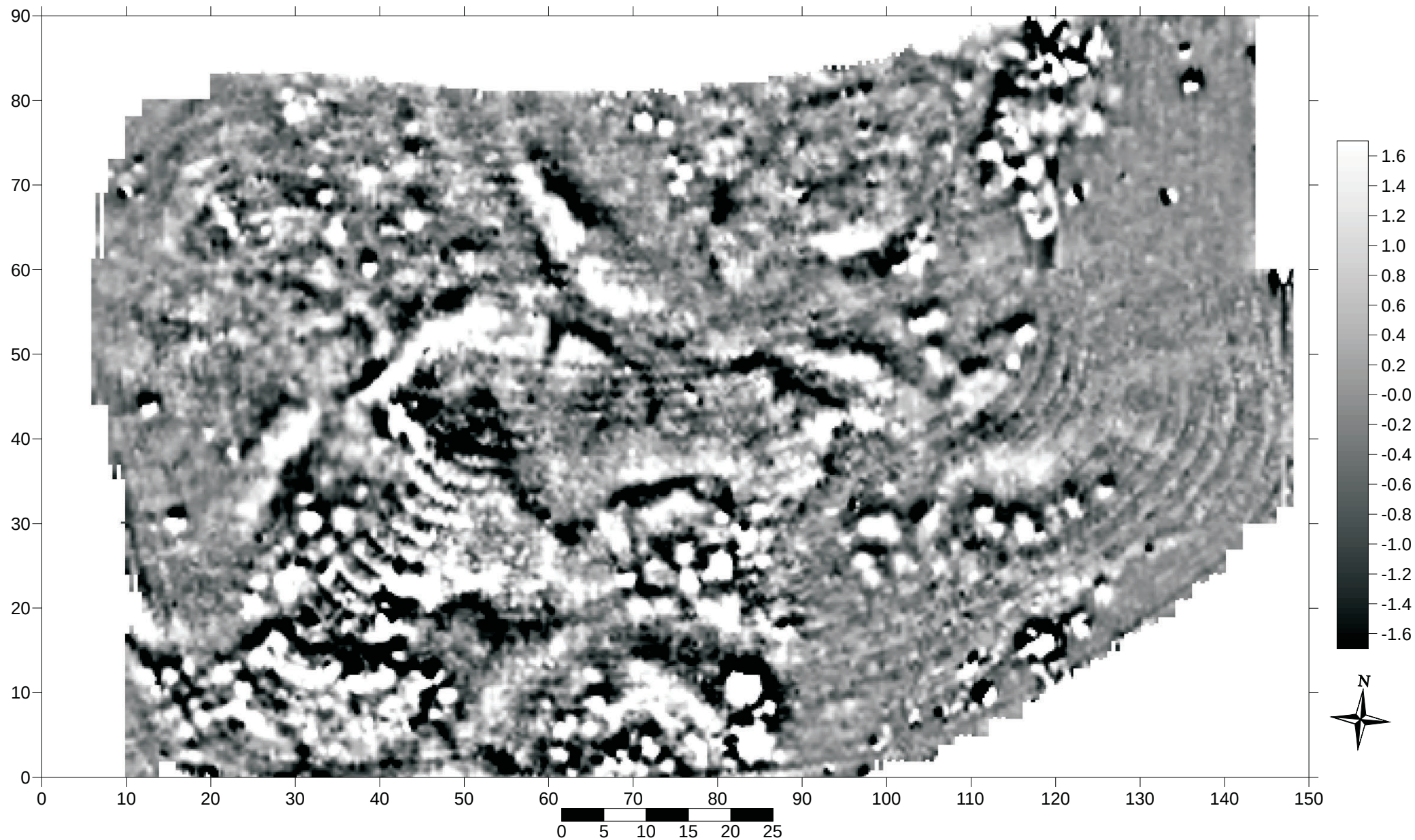
Campanya 2010

Gràfic 2

Prospecció magnètica.

Camp 1. Mapa magnètic en escala de grisos

Ubicació de l'àrea representada





Jaciment arqueològic Puig Ciutat (Oristà-Torre d'Oristà)

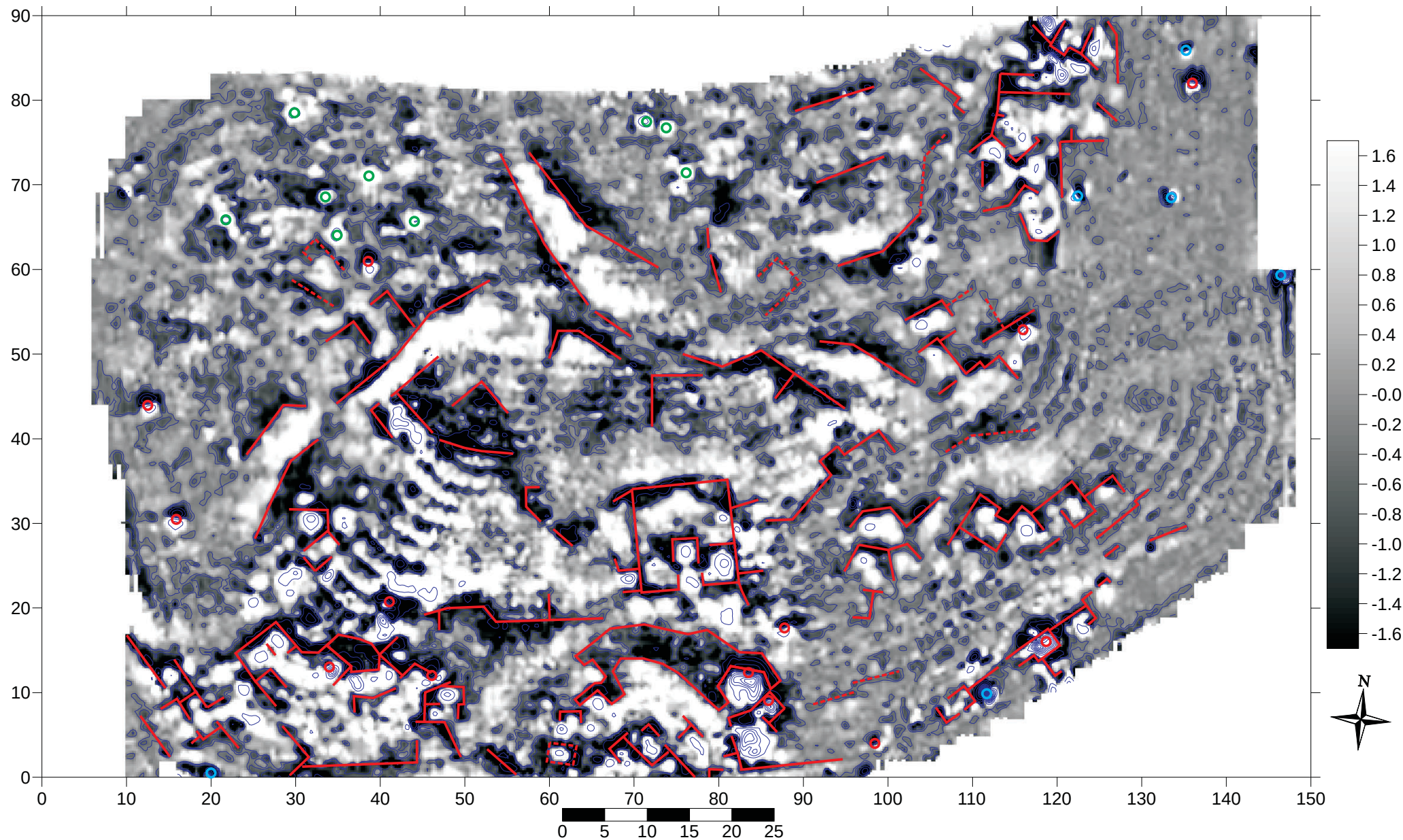
Campanya 2010

Gràfic 3

Prospecció magnètica.

Camp 1. Mapa magnètic en escala de grisos

Ubicació de l'àrea representada





Jaciment arqueològic Puig Ciutat (Oristà-Torre d'Oristà)

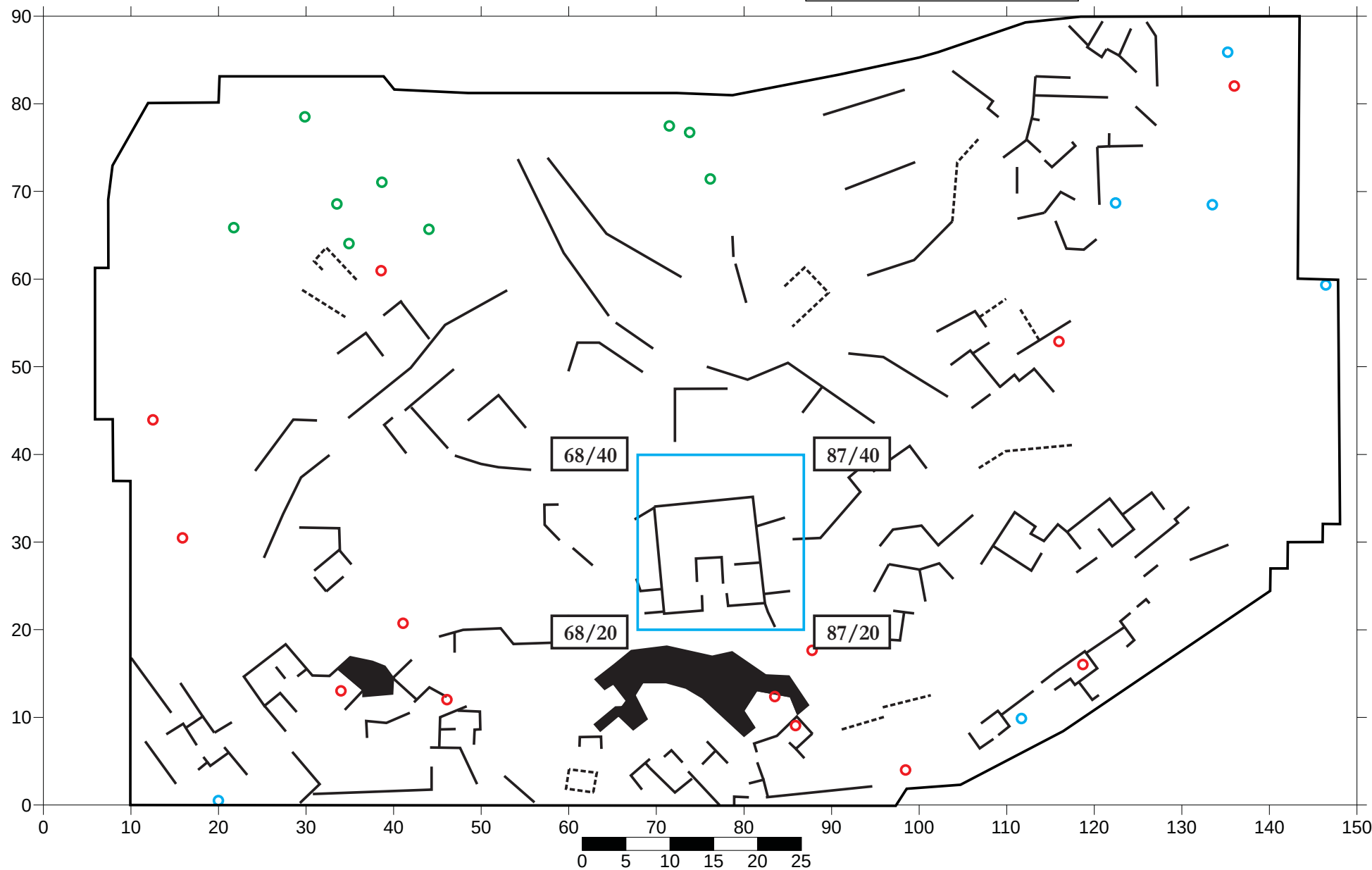
Campanya 2010

Gràfic 4

Prospecció magnètica.

Camp 1. Esquema interpretatiu

- Estructura interpretada
- - - Estructura dubtosa
- Zona anòmala de polaritat -
- Zona anòmala de polaritat +
- Element fèrric
- Combustió
- Possible sitja





Jaciment arqueològic Puig Ciutat (Oristà-Torre d'Oristà)

Campanya 2010

Gràfic 5

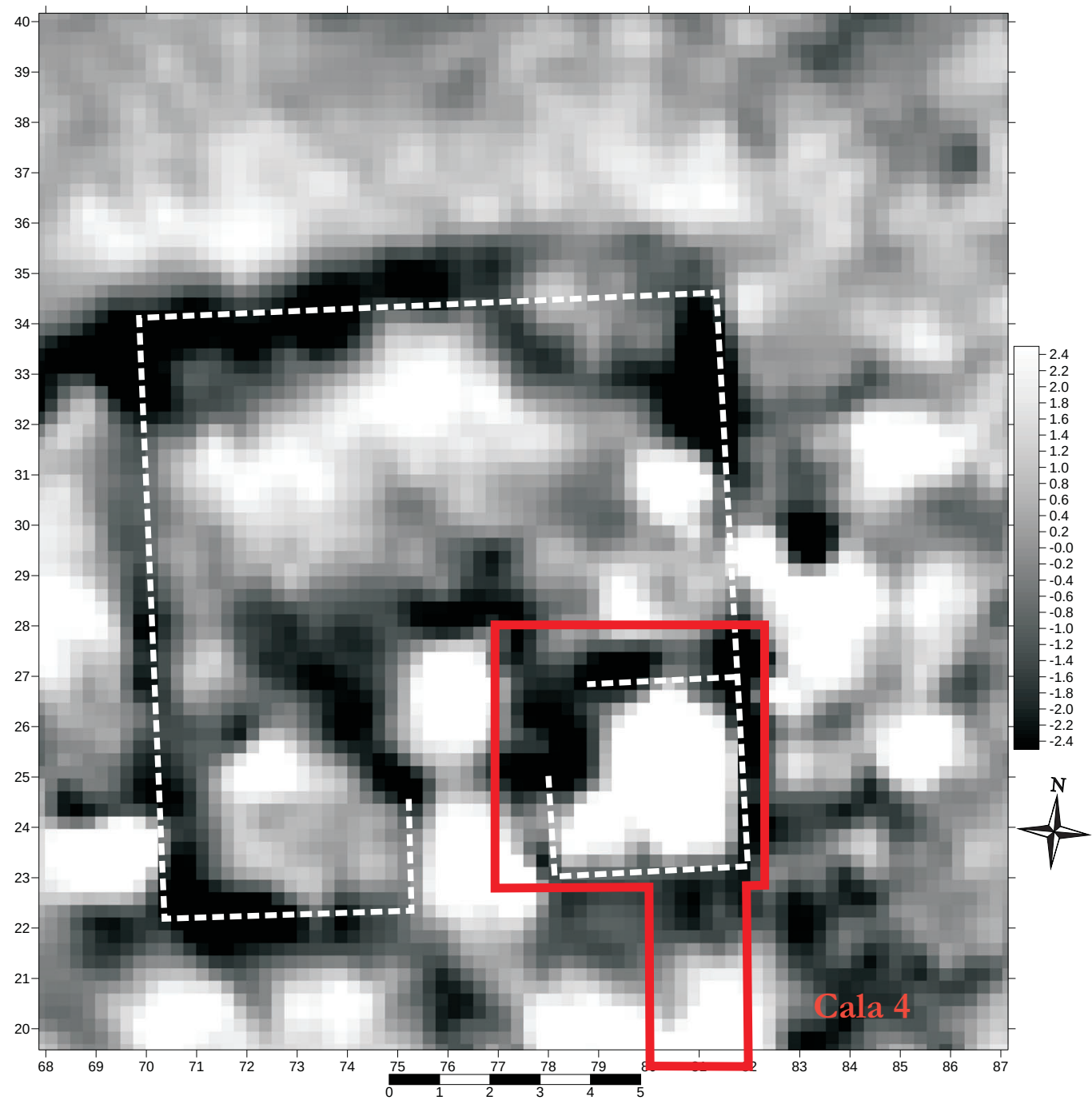
Camp 1

Cala 4. Detall del mapa magnètic

Ubicació de l'àrea representada



Imatge de la cala 4





Jaciment arqueològic Puig Ciutat (Oristà-Torre d'Oristà)

Campanya 2010

Gràfic 6

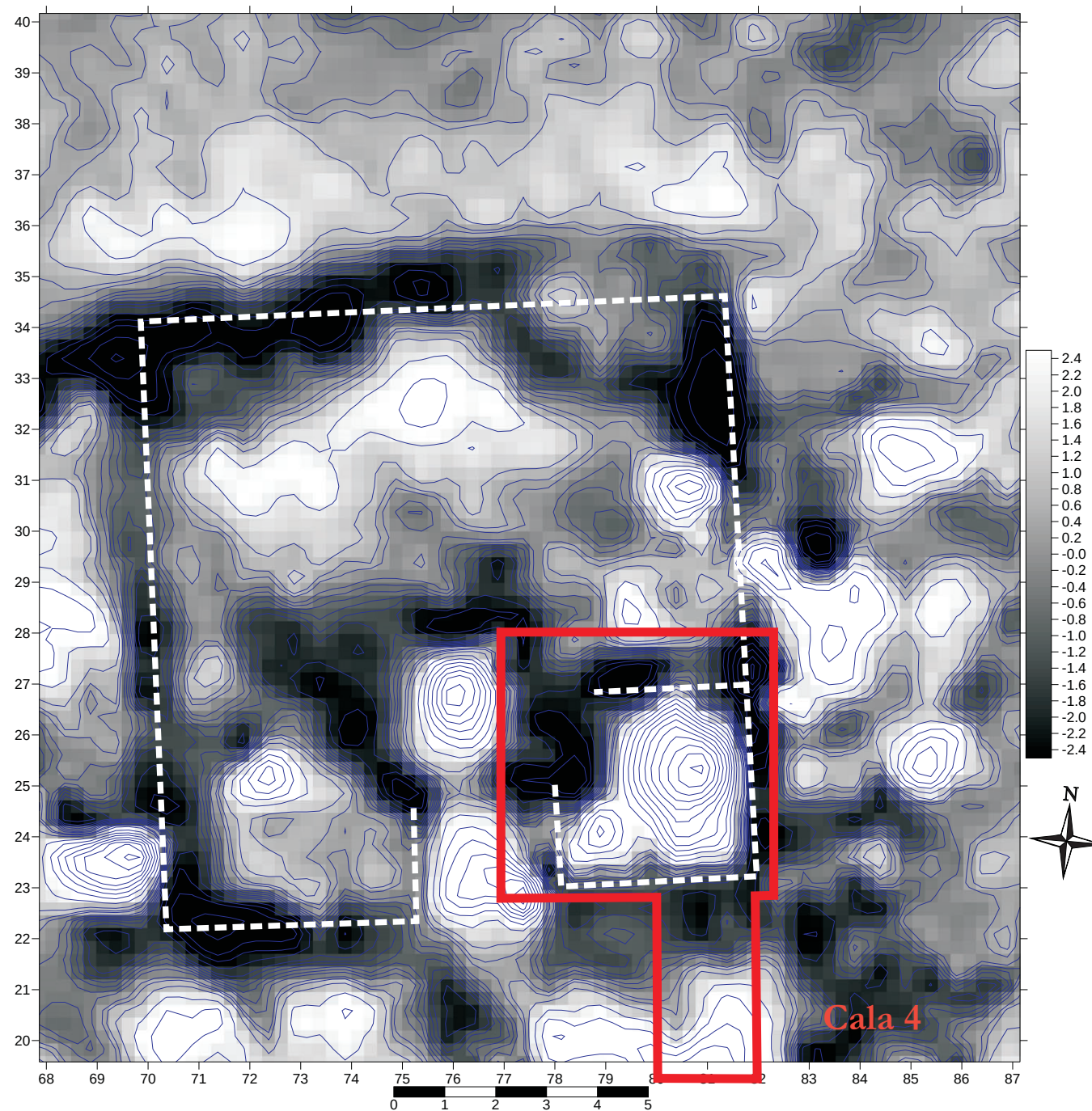
Camp 1

Cala 4. Detall del mapa magnètic isolínies

Ubicació de l'àrea representada



Imatge de la cala 4





Jaciment arqueològic Puig Ciutat (Oristà-Torre d'Oristà)

Campanya 2010

Gràfic 7

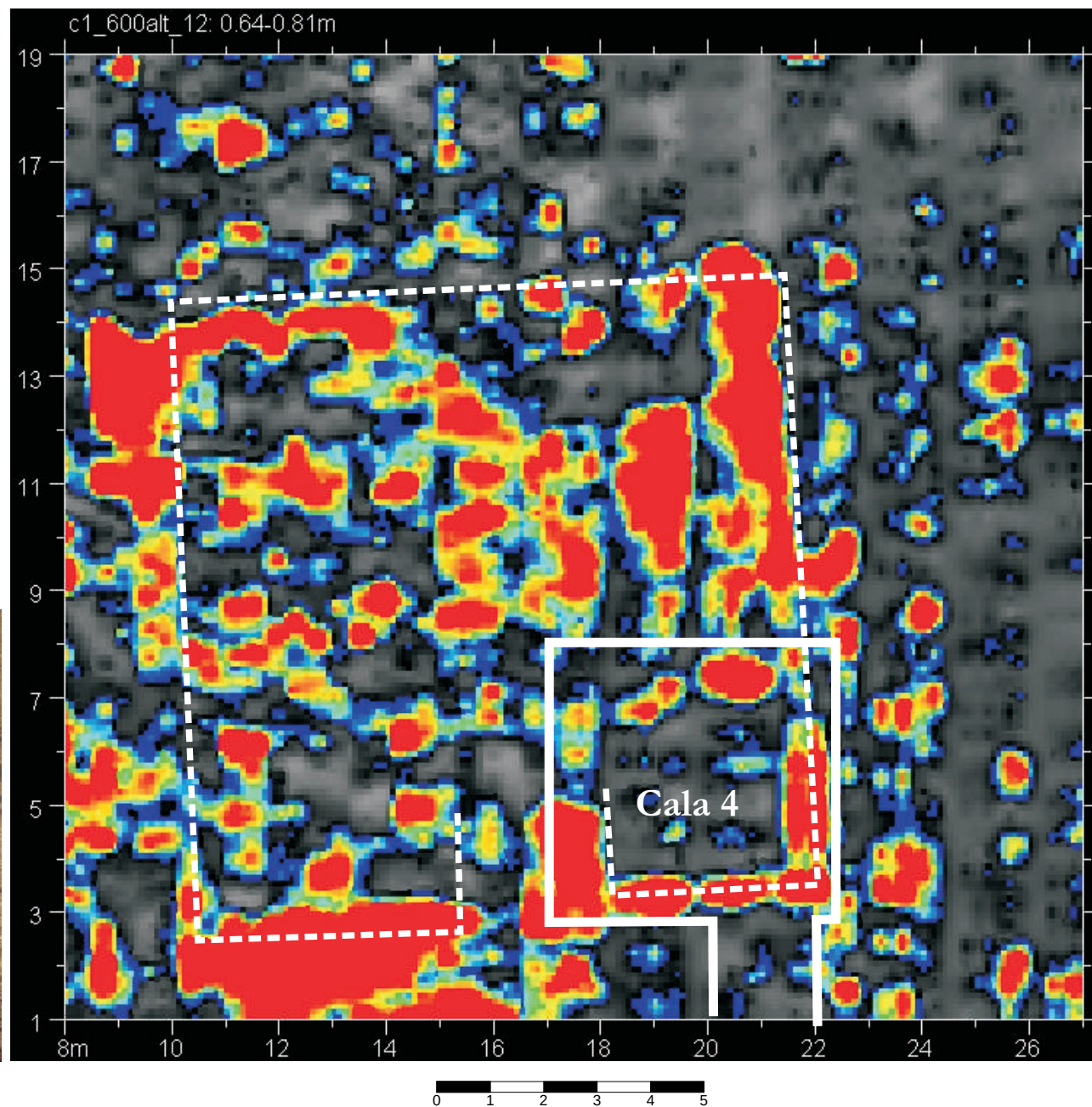
Camp 1. Cala 4

Prospecció georadar (IDS 600MHz)

Ubicació de l'àrea representada



Imatge de la cala 4





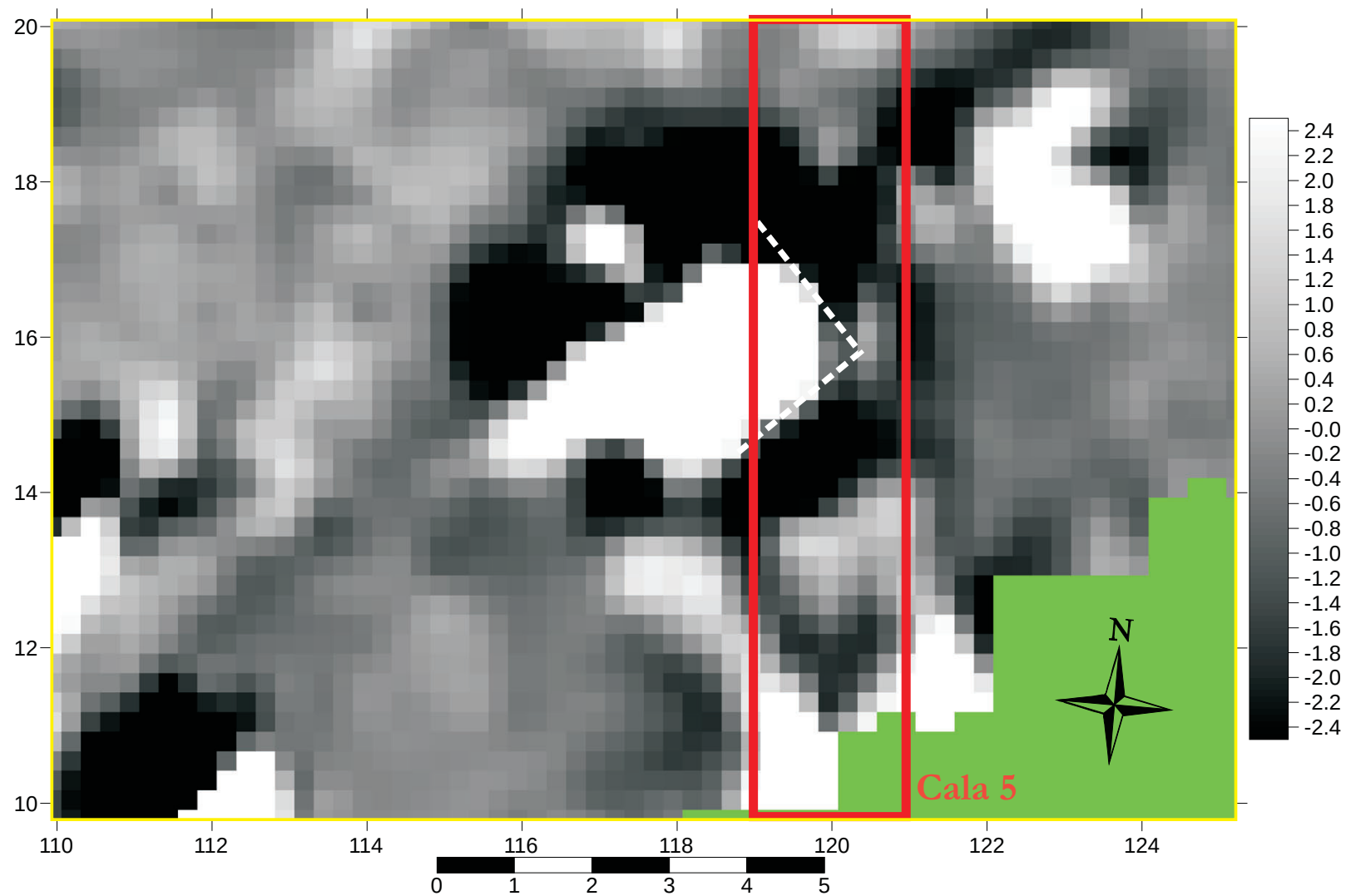
Jaciment arqueològic Puig Ciutat (Oristà-Torre d'Oristà)

Campanya 2010

Gràfic 8

Camp 1

Cala 5. Detall del mapa magnètic.



Ubicació de l'àrea representada



Imatge de la cala 5



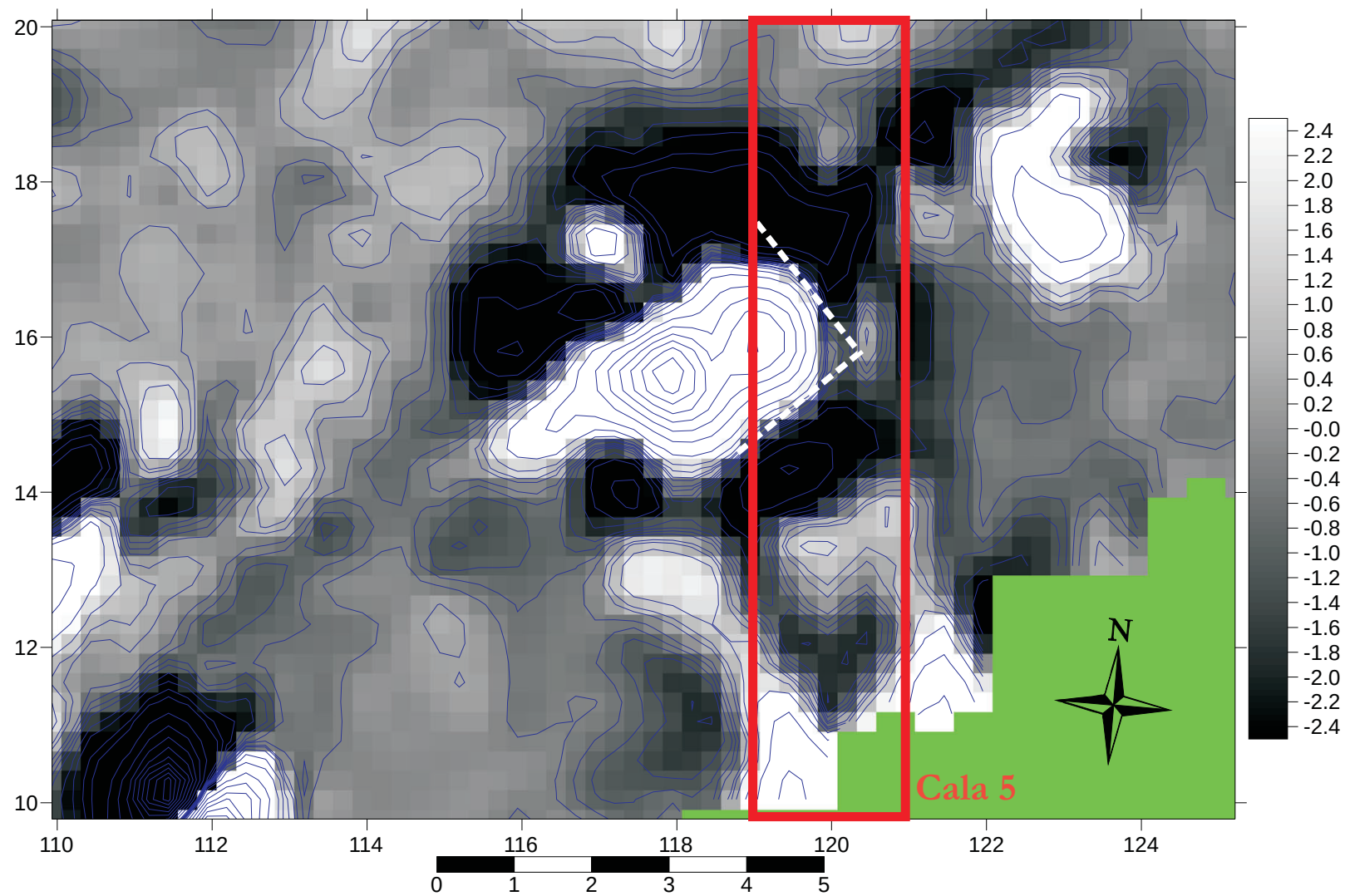
Jaciment arqueològic Puig Ciutat (Oristà-Torre d'Oristà)

Campanya 2010

Gràfic 9

Camp 1

Cala 5. Detall del mapa magnètic amb isolínies



Ubicació de l'àrea representada



Imatge de la cala 5



Jaciment arqueològic Puig Ciutat (Oristà-Torre d'Oristà)

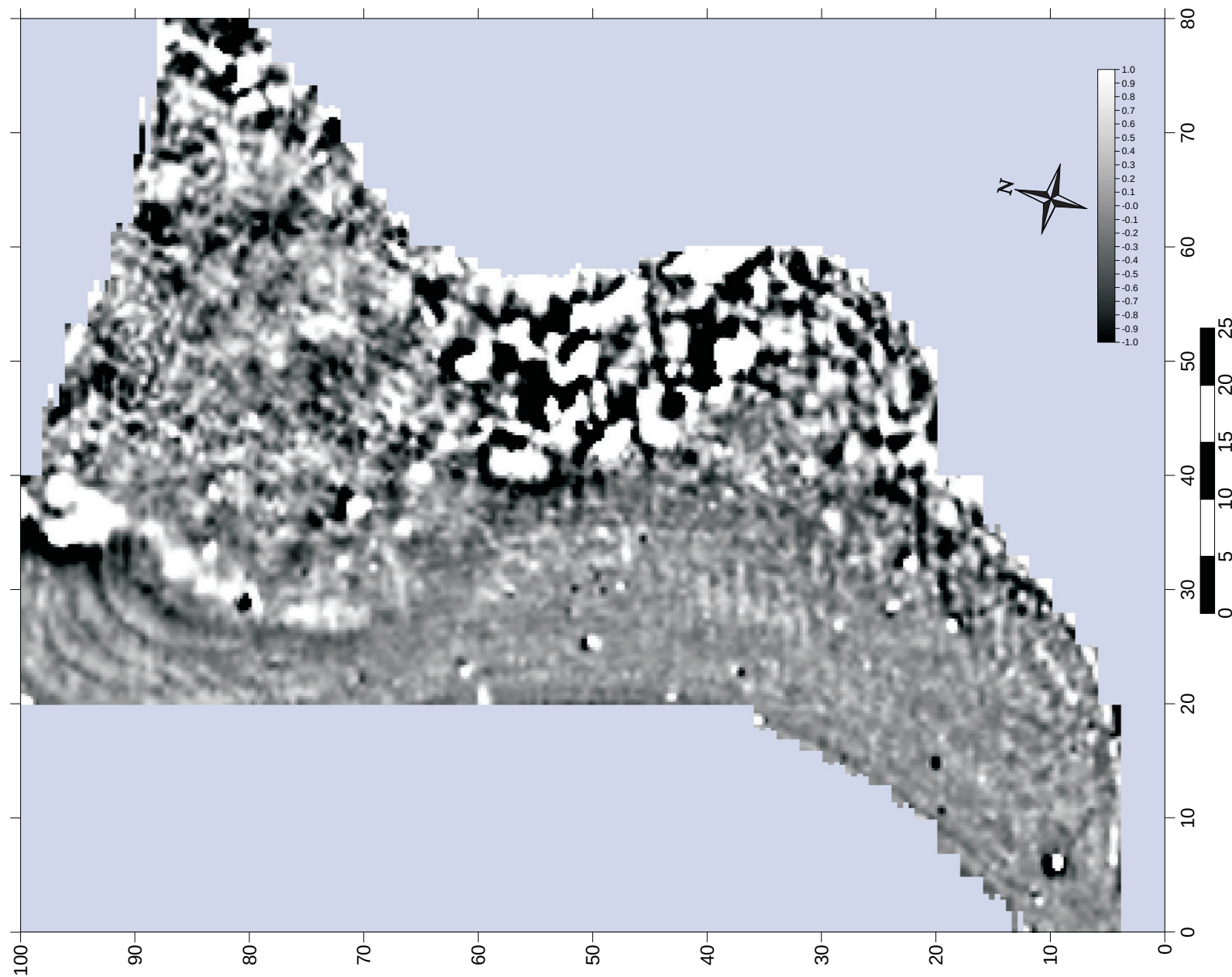
Campanya 2010

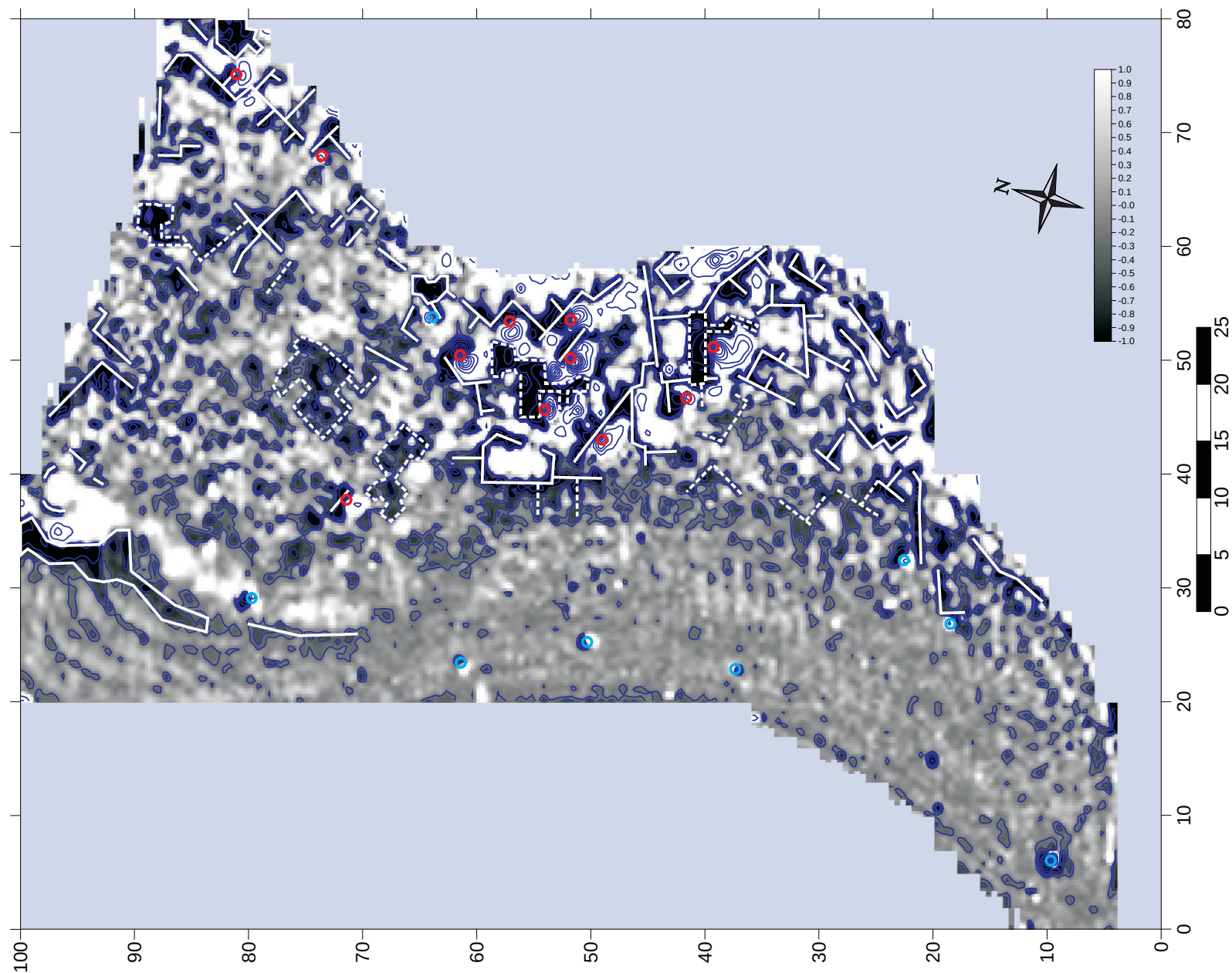
Gràfic 10

Prospecció magnètica

Camp 2. Mapa magnètic en escala de grisos

Ubicació de l'àrea representada







Jaciment arqueològic Puig Ciutat (Oristà-Torre d'Oristà)

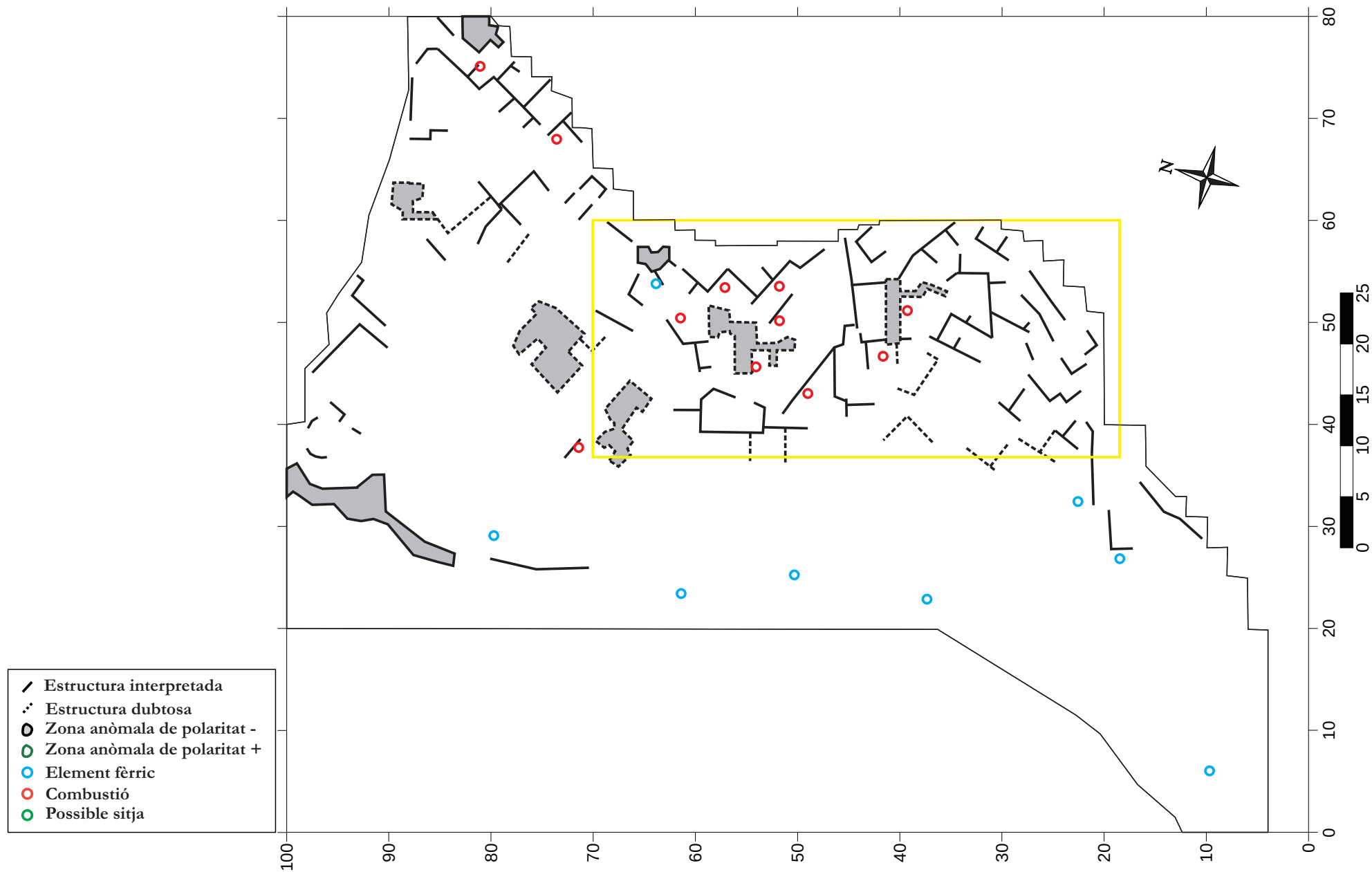
Campanya 2010

Gràfic 12

Prospecció magnètica

Camp 2. Esquema interpretatiu

Ubicació de l'àrea representada





Jaciment arqueològic Puig Ciutat (Oristà-Torre d'Oristà)

Campanya 2010

Gràfic 13

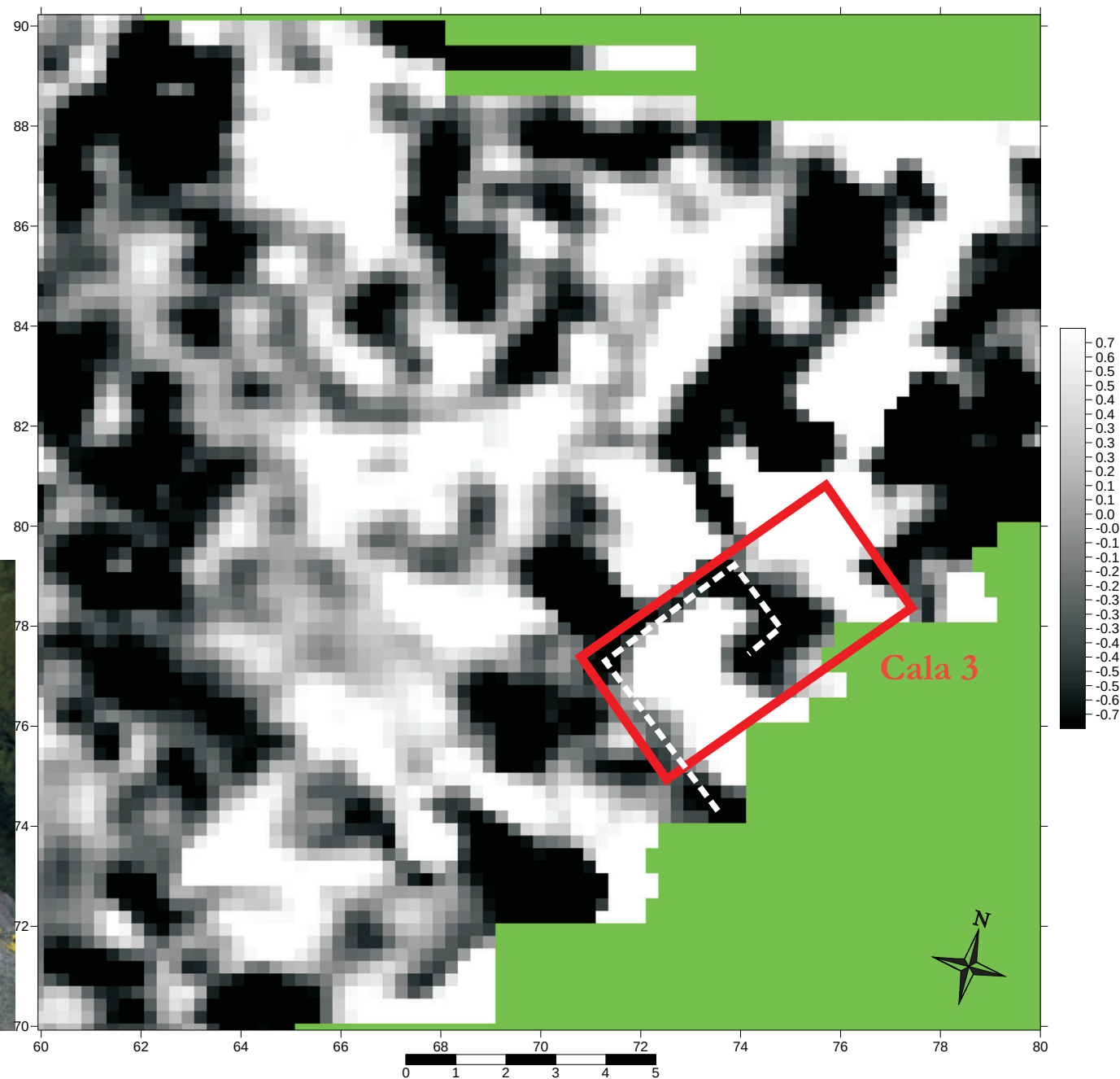
Camp 2

Cala 3. Detall del mapa magnètic

Ubicació de l'àrea representada



Imatge de la cala 3





Jaciment arqueològic Puig Ciutat (Oristà-Torre d'Oristà)

Campanya 2010

Gràfic 14

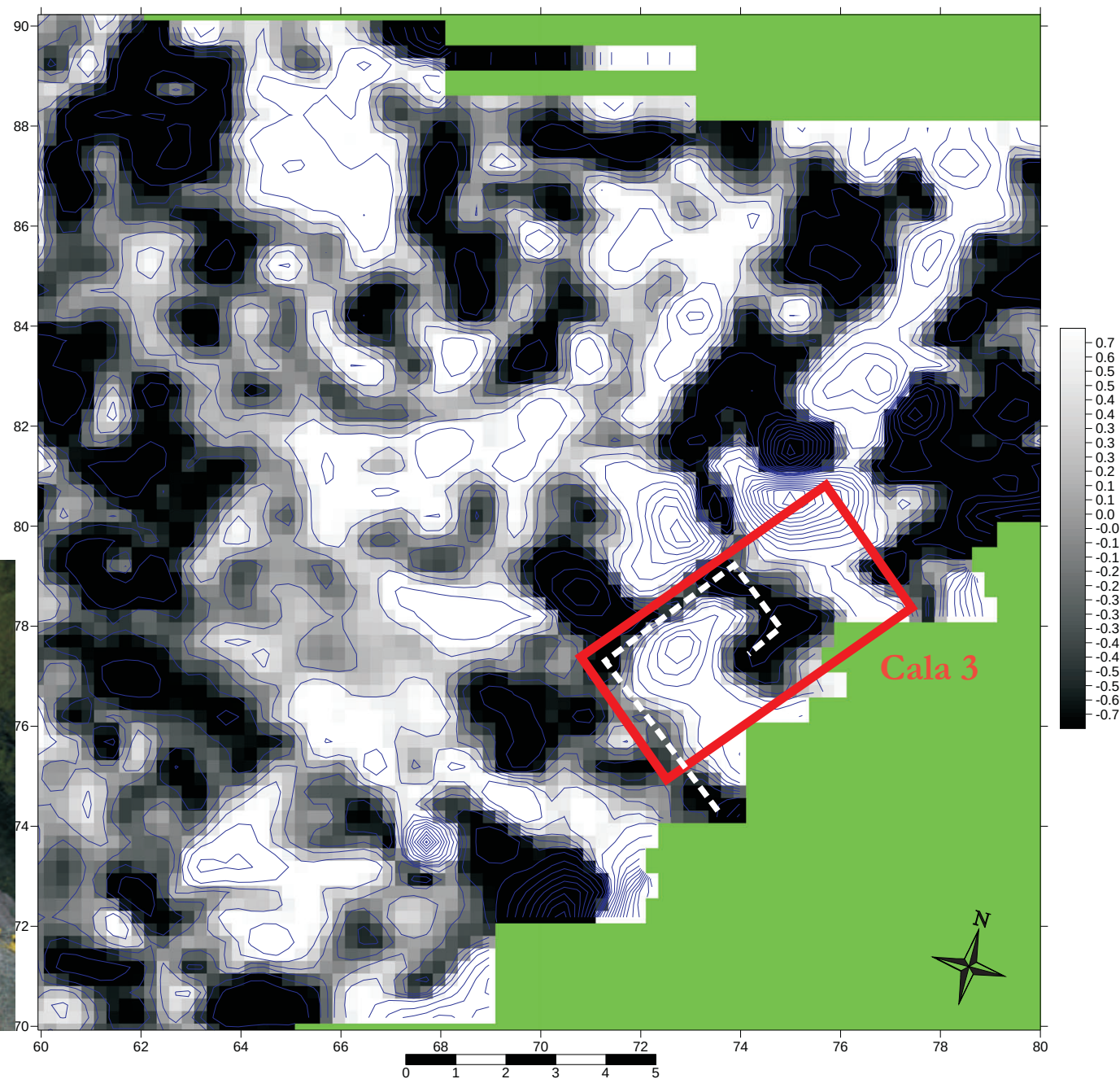
Camp 2

Cala 3. Detall del mapa magnètic amb isolínies

Ubicació de l'àrea representada



Imatge de la cala 3





Jaciment arqueològic Puig Ciutat (Oristà-Torre d'Oristà)

Campanya 2010

Gràfic 15

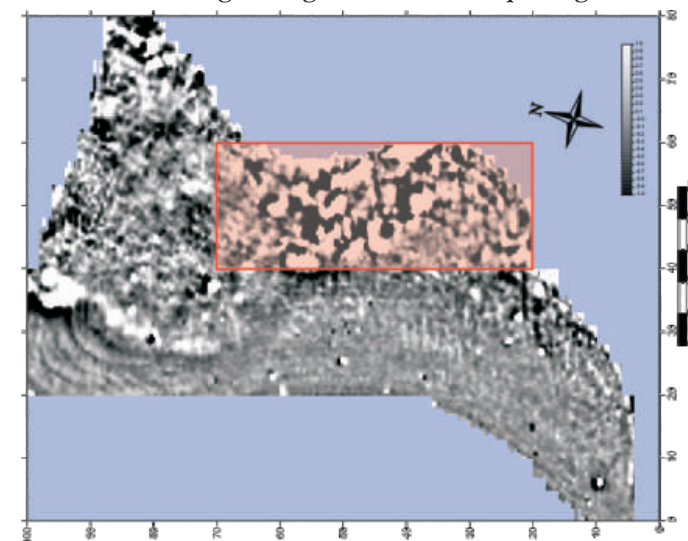
Camp 2. Resultats de la prospecció georadar.

Tall 13 (0.7m-0.8m s.s.)

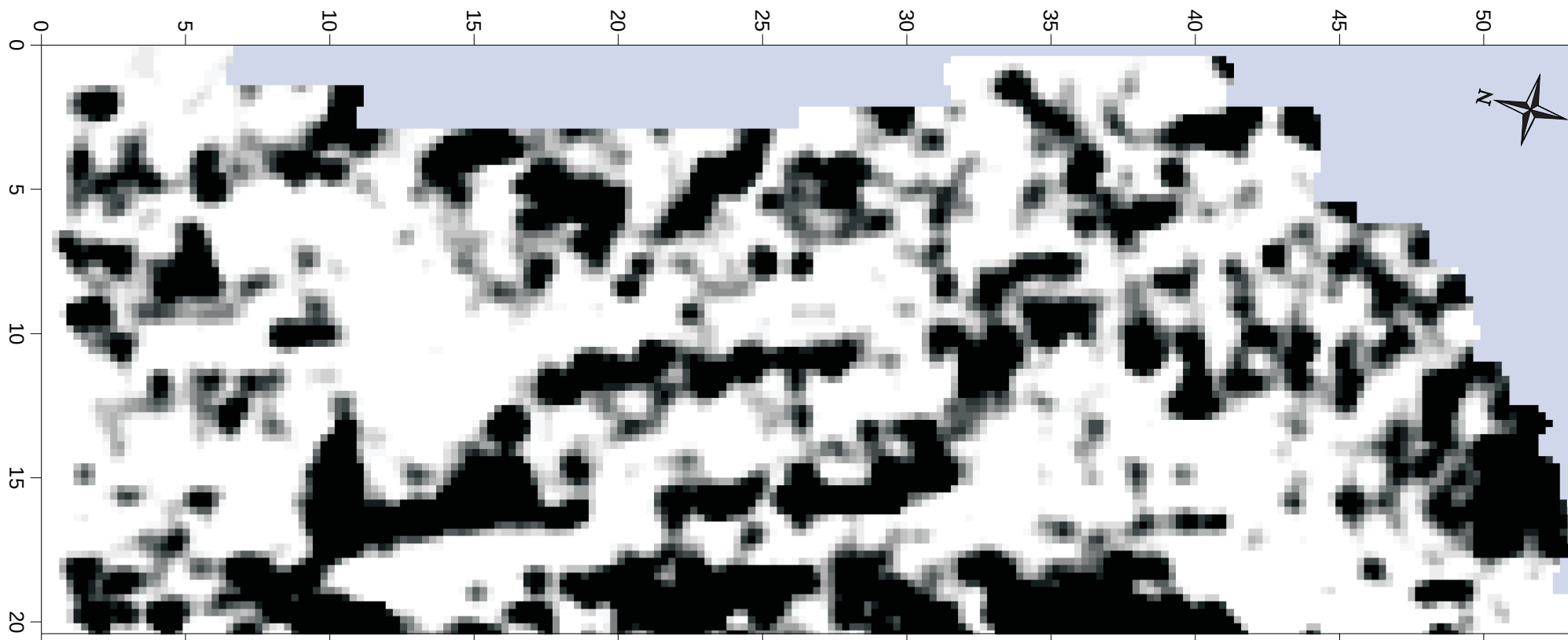
Ubicació de l'àrea representada



Ubicació del grid de georadar sobre mapa magètic



Tall horitzontal 0.7m-0.7m s.s.





Jaciment arqueològic Puig Ciutat (Oristà-Torre d'Oristà)

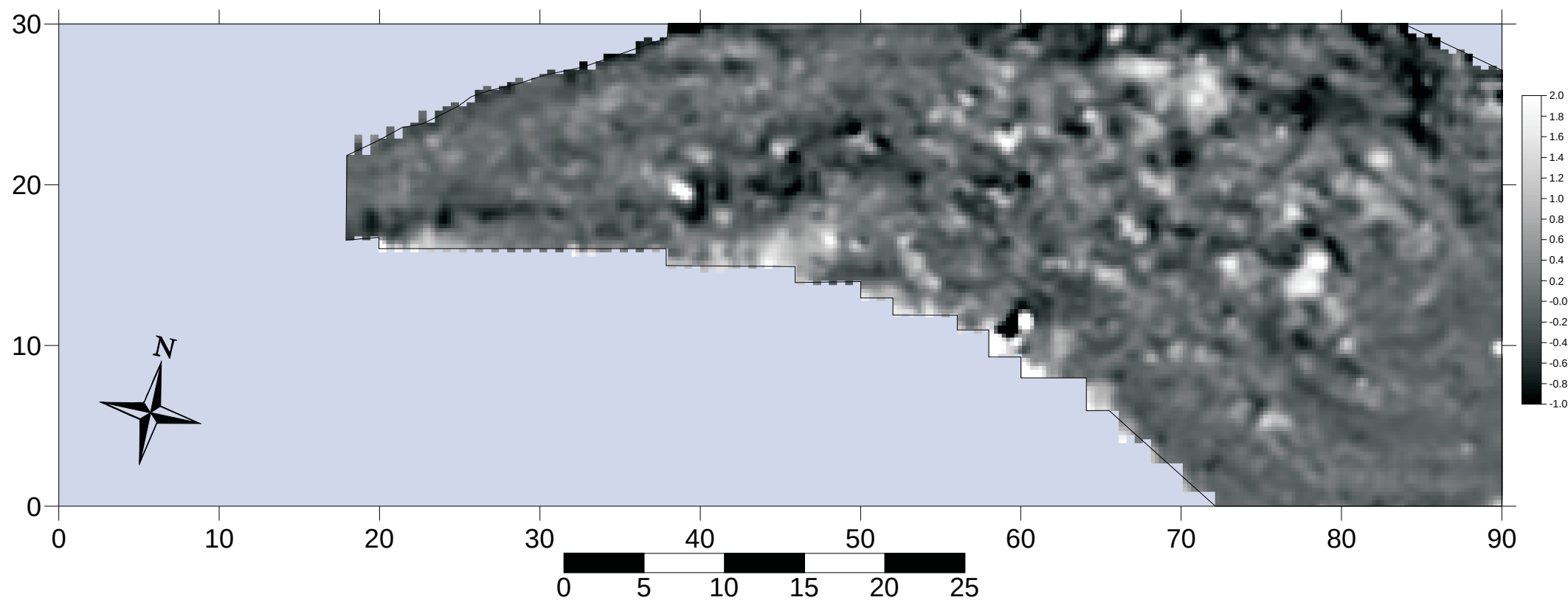
Campanya 2010

Gràfic 16

Prospecció magnètica

Camp 3. Mapa magnètic en escala de grisos

Ubicació de l'àrea representada





Jaciment arqueològic Puig Ciutat (Oristà-Torre d'Oristà)

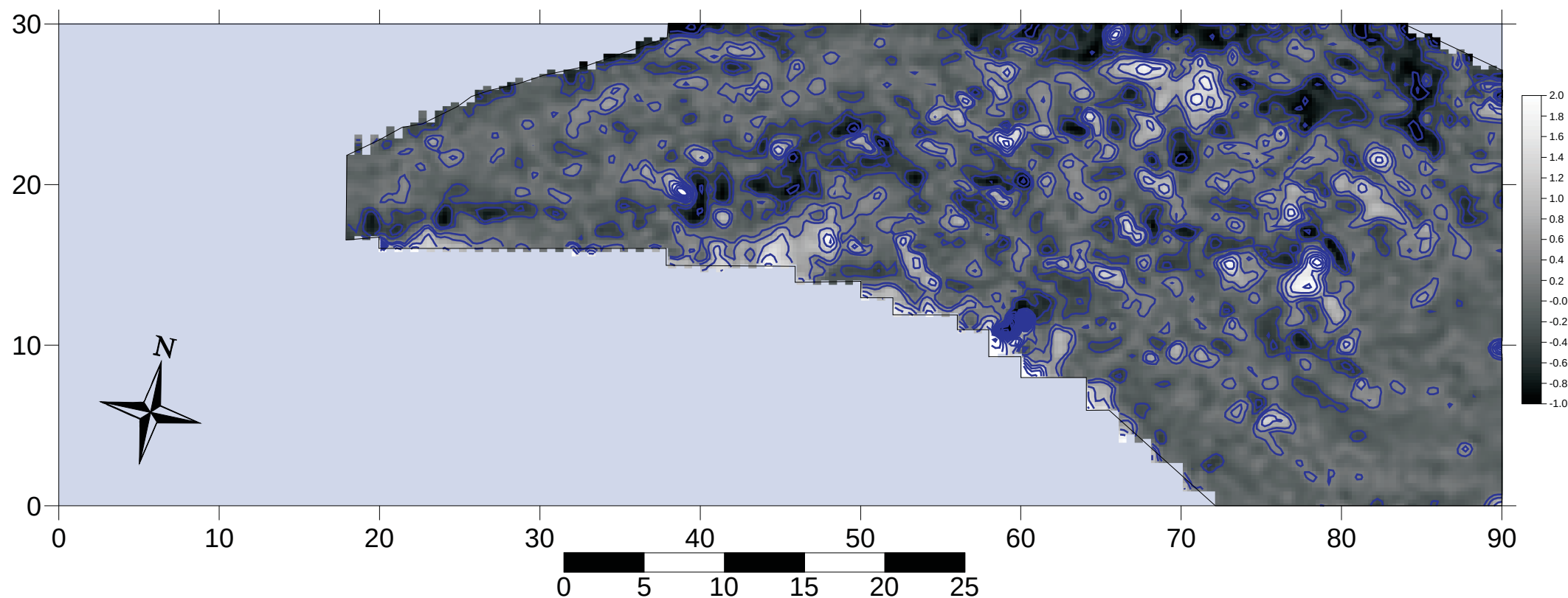
Campanya 2010

Gràfic 17

Prospecció magnètica

Camp 3. Mapa magnètic amb isolínies

Ubicació de l'àrea representada





Jaciment arqueològic Puig Ciutat (Oristà-Torre d'Oristà)

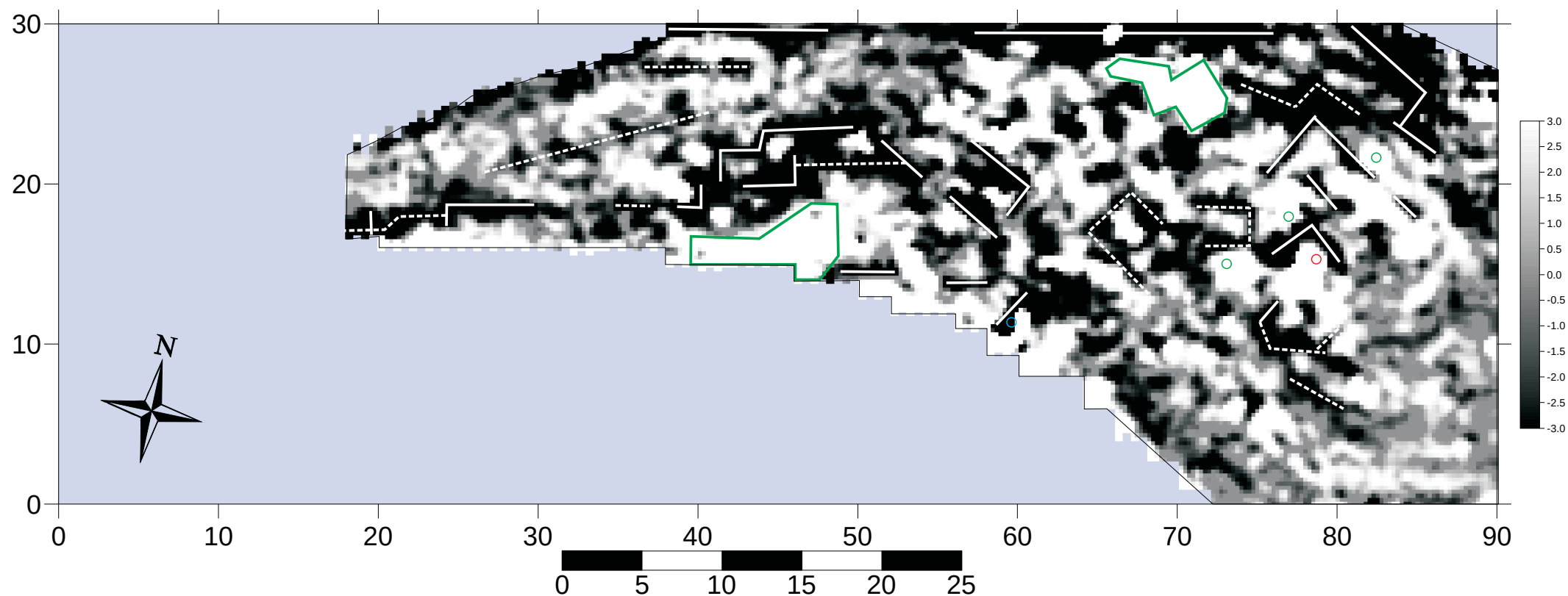
Campanya 2010

Gràfic 18

Prospecció magnètica

Camp 3. Compressió de dades i interpretació

Ubicació de l'àrea representada





Jaciment arqueològic Puig Ciutat (Oristà-Torre d'Oristà)

Campanya 2010

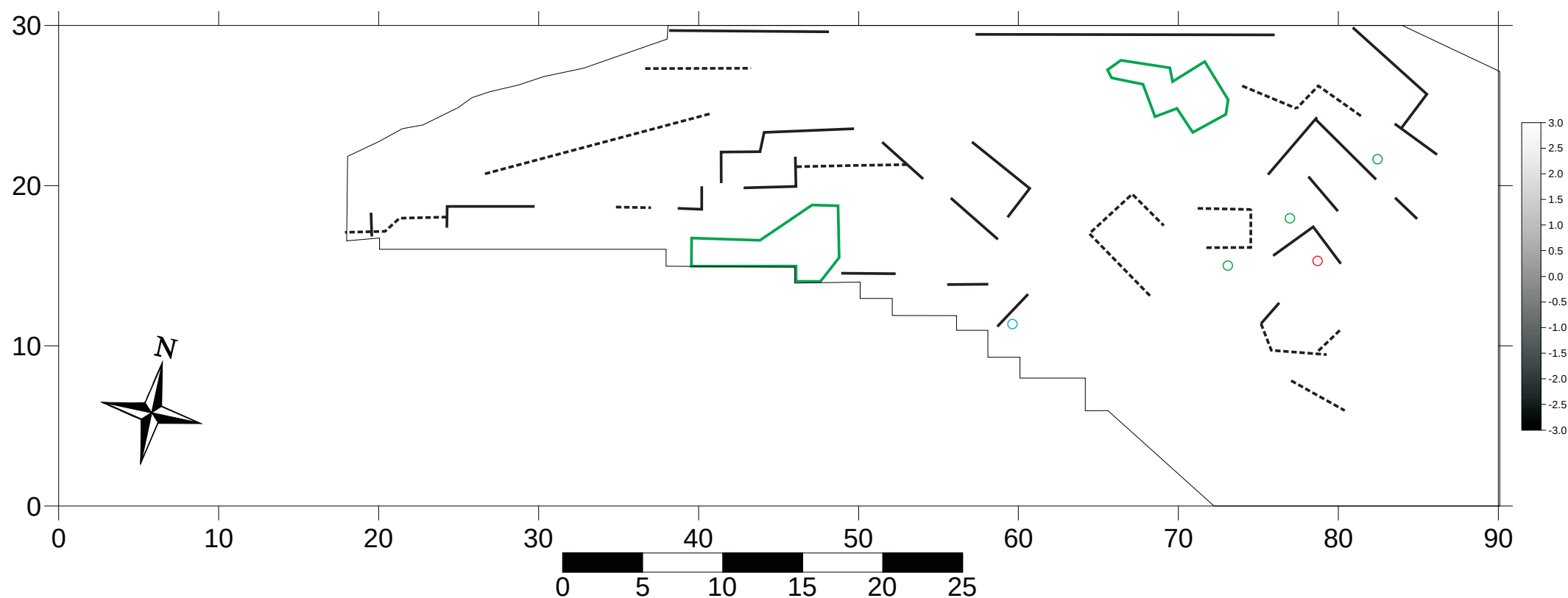
Gràfic 19

Prospecció magnètica

Camp 3. Esquema interpretatiu

- Estructura interpretada
- - - Estructura dubtosa
- Zona anòmla de polaritat -
- Zona anòmla de polaritat +
- Element fèrric
- Combustió
- Possible sitja

Ubicació de l'àrea representada





Jaciment arqueològic Puig Ciutat (Oristà-Torre d'Oristà)

Campanya 2010

Gràfic 20

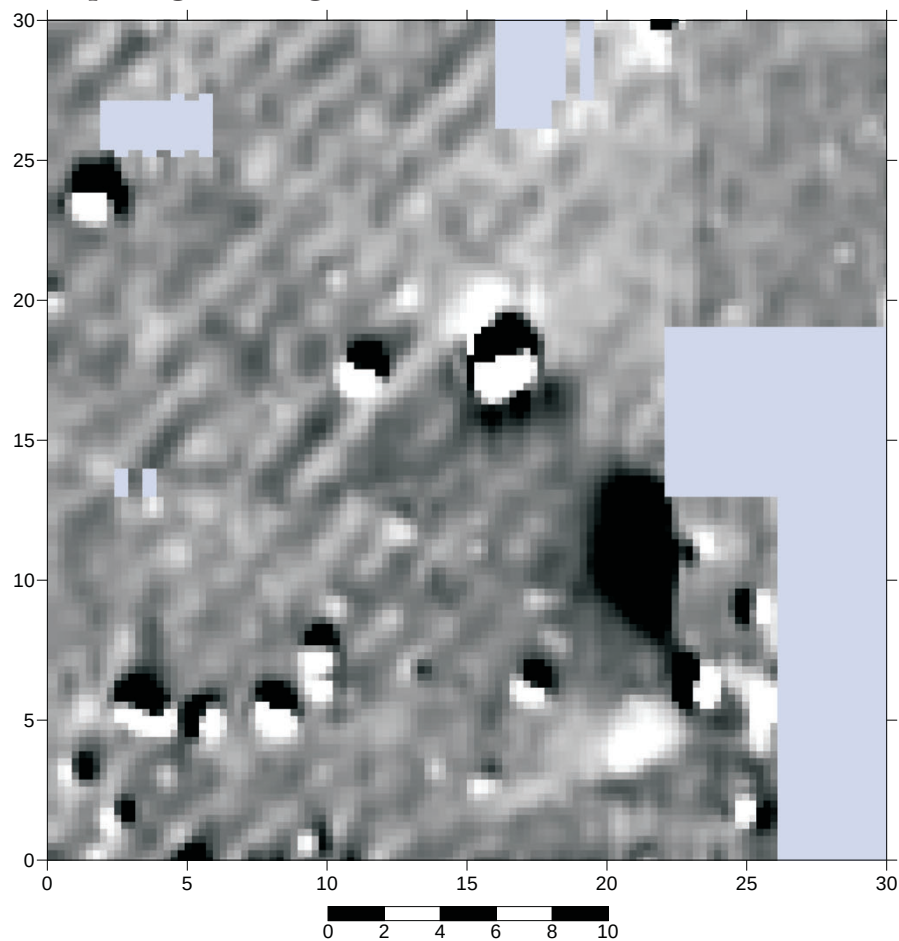
Prospecció magnètica

Grid bosc 7. Mapes magnètiques

Ubicació de l'àrea representada

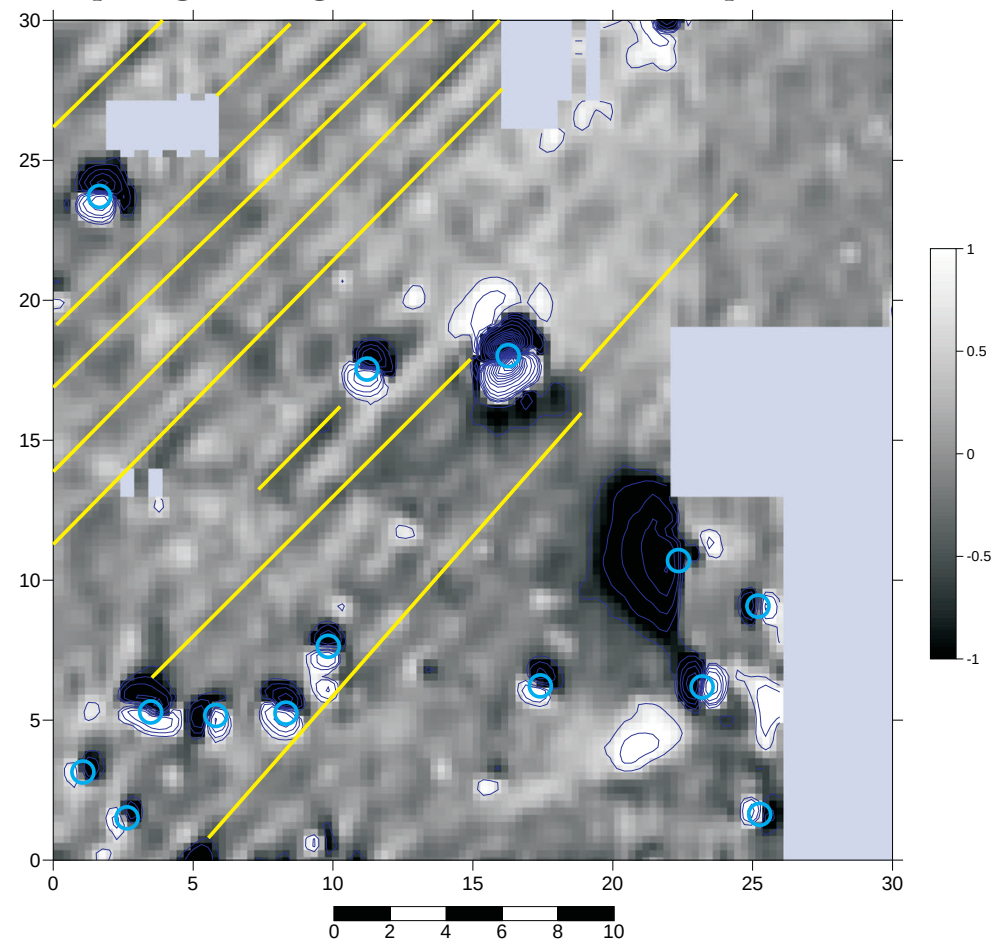


Mapa magnètic del grid bosc 2



- Línies de cultiu
- Element fèrric

Mapa magnètic del grid bosc 2 amb isolínies i interpretació





Jaciment arqueològic Puig Ciutat (Oristà-Torre d'Oristà)
Campanya 2010
Gràfic 21
Mapes magnètics sobre imatge aèria

Ubicació de l'àrea representada





Jaciment arqueològic Puig Ciutat (Oristà-Torre d'Oristà)

Campanya 2010

Gràfic 22

Esquemes interpretatius sobre topogràfic

Ubicació de l'àrea representada



Appendix F

List of delivered files

+—CH3 _EL-MEDOL

— +—01 _RAW _DATA

—GPR

MEE ____001.DZT

...

MEE ____501.DZT

+—02 _PROCESSED _DATA

+—GPR

+—SURFACE

E _Face.xyz

High-moisture-contents.xyz

N _Face.xyz

O _Face.xyz

S _Face.xyz

–VOLUMES

E _Volumes.xyz

N _Volumes.xyz

O _Volumes.xyz

S _Volumes.xyz

Volumes.xyz

–TLS

3D _Surgace-model _1x1cm.xyz

Cracks-and-protrusions.xyz

+—03 _DOCUMENTATION

20130924 _SOT _El-Medol-Needle _Graphical-report.pdf

20130924 _SOT _El-Medol-Needle _report.pdf

20150815 _SOT _El-Medol _video.mp4

20150816 _SOT _El-Medol-Needle _Graphical-report.pdf

20150816 _SOT _El-Medol-Needle _report.pdf

–04 _MODEL

ELMEDOL _Integrated-3D-Model.bin

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+—GPR

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info _all _rev.dat

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PED ____253.DZT

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+—MAGNETIC

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pedb _2.dat

pedb _2.hdr

pedb _3.dat

pedb _3.hdr

pedb _4.dat

pedb _4.hdr

pedb _5.dat

pedb _5.hdr

pedb _6.dat

pedb _6.hdr

ped _1.dat

ped _1.hdr

ped _2.dat

ped _2.hdr

ped _3.dat

ped _3.hdr

ped _4.dat

ped _4.hdr

ped _5.dat

ped _5.hdr

ped _6.dat

ped _6.hdr

ped _7.dat

ped _7.hdr

ped _8.dat

ped _8.hdr

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Surface _Sampling.dat

+—02 _PROCESSED _DATA

+—GPR

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PED_GPR_filt_7_079_087.dat

PED_GPR_filt_8_085_095.dat

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PED_GPR_filt_res_6_071_079.dat

PED_GPR_filt_res_7_079_087.dat

PED_GPR_filt_res_8_085_095.dat

+—GPS

GPS.txt

+—MAGNETIC

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—SURFACE _SAMPLING

Ped _CCW _trend01.dat

Ped _LHTS-mt _trend01.dat

Ped _LHTS-pt _trend01.dat

Ped _Modern _trend01.dat

Ped _T-WP _trend01.dat

Ped _TOTAL _trend01.dat

+—03 _DOCUMENTATION

20120215 _SOT _La-Mina _Graphical-report.pdf

20120215 _SOT _La-Mina _report.pdf

20120215 _SOT _La-Mina _video.wmv

20150816 _SOT _La-Mina _Graphical-report.pdf

20150816 _SOT _La-Mina _report.pdf

20150930 _SOT _La-Mina _video.mp4

—04 _GIS

La _Mina.qgs

+—RASTERS

+—GEOFISICS

+—GPR

Ped _GPR _5 _064 _072.tif

—MAG

PED _P4N _UTM.tif

PED _P4N _UTM.tif.aux.xml

+—OF

PNOA _89HU30 _0453 _extract.tif

PNOA _89HU30 _0453 _extract.xml

—SURFACE _SAMPLING

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Ped _LHTS-mt _trend01.tif

Ped _LHTS-pt _trend01.tif

Ped _Modern _trend01.tif

Ped _T-W _P _trend01.tif

Ped _Total _trend01.tif

—VECTORS

+—AREAS

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Covered _Areas.prj

Covered _Areas.qpj

Covered _Areas.shp

Covered _Areas.shx

+—INTERP

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Ped _GPR _interpretation.qpj

Ped _GPR _interpretation.shp

Ped _GPR _interpretation.shx

Ped _GPR _zones.dbf

Ped _GPR _zones.prj

Ped _GPR _zones.qpj

Ped _GPR _zones.shp

Ped _GPR _zones.shx

Ped _mag _interp _lineas.dbf

Ped _mag _interp _lineas.prj

Ped _mag _interp _lineas.qpj

Ped _mag _interp _lineas.shp

Ped _mag _interp _lineas.shx

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Ped _mag _interp _puntos.shp

Ped _mag _interp _puntos.shx

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Topography _contour-lines.qpj

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Topography _contour-lines.shx

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GPS _points.shp

GPS _points.shx

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Ped _Surface _sampling.shp

Ped _Surface _sampling.shx

—CH5 _PUIG-CIUTAT

+—01 _RAW _DATA

+—EMI

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PC _1prp _ec.csv

PC _1prp _ms.csv

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TAB10100.dt

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TAC20034.dt

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TAC40034.dt

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30juny _2.hdr

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dia4 _2.dat

dia4 _2.hdr

dia4 _3.dat

dia4 _3.hdr

dia4 _4.dat

dia4 _4.hdr

dia4 _5.dat

dia4 _5.hdr

dia4 _6.dat

dia4 _6.hdr

dia4 _7.dat

dia4 _7.hdr

dia4 _8.dat

dia4 _8.hdr

+—02 _PROCESSED _DATA

+—EMI

PC _EMI _EC _HCP _krig.grd

PC _EMI _EC _PRP _krig.grd

PC _EMI _MS _HCP _krig.grd

PC _EMI _MS _PRP _krig.grd

+—GPR

+—HORIZONS

Z _01.xyz

Z _02.xyz

Z _03.xyz

Z _04.xyz

Z _05.xyz

Z _06.xyz

Z _bedrock.xyz

–SLICES

Slice _200 _04-05.dat

Slice _200 _05-06.dat

Slice _600 _01-02.dat

Slice _600 _02-03.dat

Slice _600 _03-04.dat

Slice _IZ _160.dat

Slice _IZ _170.dat

Slice _IZ _180.dat

Slice _IZ _190.dat

Slice _IZ _200.dat

Slice _IZ _210.dat

Slice _IZ _220.dat

–MAGNETIC

PC _mag.grd

+—03 _DOCUMENTATION

2010 _Puig-Ciutat _informe.pdf

2011 _Puig-Ciutat _informe.pdf

2011 _Puig-Ciutat _memoria-grafica.pdf

2011 _Puig-Ciutat _video.wmv

2012 _Puig-Ciutat _informe.pdf

2015 _Puig-Ciutat _video.mp4

—04 _GIS

PC _GIS.qgs

+—RASTERS

+—AERIAL _PHOTOGRAPHS

1956-57VA _PC.tiff

Orto2010-25c _PC.tiff

—GEOPHYSICS

+—EMI

00 _PC _EMI _EC _HCP _krigv02.tif

00 _PC _EMI _EC _HCP _krigv02.tif.aux.xml

00 _PC _EMI _EC _HCP _res-large _filtv02.tif

00 _PC _EMI _EC _HCP _res-large _filtv02.tif.aux.xml

00 _PC _EMI _EC _PRP _krigv03 _lpf.tif

00 _PC _EMI _EC _PRP _krigv03 _lpf.tif.aux.xml

00 _PC _EMI _EC _PRP _res-large _filt.tif

00 _PC _EMI _EC _PRP _res-large _filt.tif.aux.xml

00 _PC _EMI _MS _HCP _krigv02.tif

00 _PC _EMI _MS _HCP _krigv02.tif.aux.xml 00 _PC _EMI _MS _HCP _res-large
_filt.tif

00 _PC _EMI _MS _HCP _res-large _filt.tif.aux.xml

00 _PC _EMI _MS _PRP _krigv04.tif

00 _PC _EMI _MS _PRP _krigv04.tif.aux.xml

00 _PC _EMI _MS _PRP _res-large _filt.tif

00 _PC _EMI _MS _PRP _res-large _filt.tif.aux.xml

+—GPR

Slice _200 _04-05.tif

Slice _200 _04-05.tif.aux.xml

Slice _200 _05-06.tif

Slice _200 _05-06.tif.aux.xml

Slice _600 _01-02.tif

Slice _600 _01-02.tif.aux.xml

Slice _600 _02-03.tif

Slice _600 _02-03.tif.aux.xml

Slice _600 _03-04.tif

Slice _600 _03-04.tif.aux.xml

Slice _IZ _160.tif

Slice _IZ _160.tif.aux.xml

Slice _IZ _170.tif

Slice _IZ _170.tif.aux.xml

Slice _IZ _180.tif

Slice _IZ _180.tif.aux.xml

Slice _IZ _190.tif

Slice _IZ _190.tif.aux.xml

Slice _IZ _200.tif

Slice _IZ _200.tif.aux.xml

Slice _IZ _210.tif

Slice _IZ _210.tif.aux.xml

Slice _IZ _220.tif

Slice _IZ _220.tif.aux.xml

Z _Bedrock.tif

Z _Bedrock.tif.aux.xml

–MAGNETIC

PC _Mag.tiff

PC _Mag.tiff.aux.xml

–VECTORS

+—AREAS

PC _ARQ _SUPI.dbf

PC _ARQ _SUPI.prj

PC _ARQ _SUPI.qml

PC _ARQ _SUPI.qpj

PC _ARQ _SUPI.shp

PC _ARQ _SUPI.shx

PC _geophysics _areas.dbf

PC _geophysics _areas.prj

PC _geophysics _areas.qpj

PC _geophysics _areas.shp

PC _geophysics _areas.shx

PC _Zones _clean.dbf

PC _Zones _clean.prj

PC _Zones _clean.qml

PC _Zones _clean.shp

PC _Zones _clean.shx

+—CONTOURS

PC _ICC _MDT _contours _50cm.dbf

PC _ICC _MDT _contours _50cm.prj

PC _ICC _MDT _contours _50cm.qpj

PC _ICC _MDT _contours _50cm.shp

PC _ICC _MDT _contours _50cm.shx

PC _Mag _contours _02nT.dbf

PC _Mag _contours _02nT.prj

PC _Mag _contours _02nT.shp

PC _Mag _contours _02nT.shx

+—EXCAVATIONS

PC _Det.dbf

PC _Det.prj

PC _Det.qpj

PC _Det.shp

PC _Det.shx

PC _OD.dbf

PC _OD.prj

PC _OD.qpj

PC _OD.shp

PC _OD.shx

PC _P.dbf

PC _P.prj

PC _P.qpj

PC _P.shp

PC _P.shx

+—INTERPRETATION

PC _synth _polygons.dbf

PC _synth _polygons.prj

PC _synth _polygons.qpj

PC _synth _polygons.shp

PC _synth _polygons.shx

+—EMI

PC _EMI _polygons.dbf

PC _EMI _polygons.prj

PC _EMI _polygons.qpj

PC _EMI _polygons.shp

PC _EMI _polygons.shx

+—GPR

PC _GPR _lines.dbf

PC _GPR _lines.prj

PC _GPR _lines.qpj

PC _GPR _lines.shp

PC _GPR _lines.shx

PC _GPR _polygons.dbf

PC _GPR _polygons.prj

PC _GPR _polygons.qpj

PC _GPR _polygons.shp

PC _GPR _polygons.shx

–MAG

PC _Mag _lines.dbf

PC _Mag _lines.prj

PC _Mag _lines.qpj

PC _Mag _lines.shp

PC _Mag _lines.shx

PC _Mag _points.dbf

PC _Mag _points.prj

PC _Mag _points.qpj

PC _Mag _points.shp

PC _Mag _points.shx

PC _Mag _polygons.dbf

PC _Mag _polygons.prj

PC _Mag _polygons.qpj

PC _Mag _polygons.shp

PC _Mag _polygons.shx

–REFERENCES

Topographic _Bases.dbf

Topographic _Bases.prj

Topographic _Bases.qpj

Topographic _Bases.shp

Topographic _Bases.shx