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Geophysical prospection
in the Roman city of Conimbriga
(Condeixa-a-Nova, District of Coimbra, Portugal)

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1. Abstract

In summer of 2022, the Berlin-based company cmp in cooperation with SOT Prospecció Arqueològica, Barcelona (Spain), realized the first large-scale geophysical prospection campaign in the Roman city of Conimbriga (Condeixa-a-Nova, District of Coimbra, Portugal). Conimbriga has been a classified National Monument since 1910 and is one of the most important archaeological sites in Portugal. The site was first settled in the Iron Age and later occupied by the Romans in the 1st century BC. After destruction in the 5th century BC, only low settlement activity is documented, until the place was completely abandoned and used for agricultural purposes and as a quarry. Archaeological research of the site began in the 19th century and has continued to the present day. Excavations have revealed a wealth of information about the town, including large parts of its layout, monumental buildings, and artefacts. So far, the geophysical prospection was used only on small sections of the site, starting already in the 1960s, when first magnetic and electric surveys were carried out. The campaign of 2022 was the first large-scale application of both magnetic and georadar methods in Conimbriga. During a 5-day campaign, an area of 8 hectares was covered with magnetic measurements using the cmp 7-probe fluxgate gradiometer array combined with a GNSS-RTK positioning system. At the same time, an area of 1.5 hectares was investigated by use of the IRIS HI-MOD (IDS) system equipped with five 600 MHz antennas, also combined with a GNSS-RTK system. In addition, several soil samples were taken in order to determine their magnetic susceptibility and the electrical conductivity. The most important result of the survey campaign is the understanding that the geological and archaeological conditions in Conimbriga are extremely challenging for both, magnetic and GPR prospection. Low contrasts in magnetic susceptibility and high clay content of the soil result in noisy and diffuse geophysical data. Moreover, geological and surface conditions change throughout the site. The areas first studied were located in the Vale Norte (North valley) where remains of Roman houses were localized. To the east of the already known amphitheatre other building remains, and a complex stratigraphy, were identified. They could be related to another theatre, which is suspected to be there. Subsequently, the area inside the late-imperial city walls was investigated. The magnetic data set covers almost the entire accessible area to both sides of the forum and the southern baths. An area of about 9,000 m², located in the eastern part of the city was covered with both, magnetic and GPR measurements. Despite the limitations, this large-scale data set allowed to identify monumental building complexes in all parts of the intramural area and to distinguish city quarters and ancient infrastructure. It has to be stated that the presented interpretation of the geophysical data is a first attempt to translate the diffuse geophysical data into archaeological information. It is based primarily on the geophysical data itself and the available a-priori information. Certainty about the reliability of this interpretation can be gained by verifying the proposed interpretations through targeted archaeological excavations by a discussion on the plausibility of the interpretation. The report ends with considerations for planning future geophysical prospection projects in and around Conimbriga.

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3. Objective and area of investigation

On behalf of the Museu Monográfico de Conimbriga – Museu Nacional and funded by the DGPC (Direção-Geral do Património Cultural) the Berlin-based company cmp in cooperation with SOT Prospecció Arqueològica, Barcelona (Spain) carried out a large-scale geophysical prospection in the Roman city of Conimbriga in summer of 2022. This was the first time in decades of research and archaeological excavations that most of the accessible intramural part of the Roman city of Conimbriga and parts of the Vale Norte had been surveyed using geophysical methods.

The objective of the recent investigation was the large-scale investigation of building complexes within the city limits, as well as the detailed investigation of already known buildings in the area of the Vale Norte. Magnetic measurements were realized using the cmp multi-sensor system carrying 7 Fluxgate gradiometer probes, while the GPR measurements were carried out by means of the Fast-Wave system (IDS) equipped with five 600-MHz antennae. In addition, 8 samples, taken from recently opened excavation trenches, were subjected to susceptibility and electrical conductivity measurements to be able to draw conclusions about outcomes to be expected in future investigations.

The locations of the researched areas are shown in Figure 1. General data of the geophysical prospection is listed in Table 1.

Survey area	Conimbriga
Prospection methods	Magnetic and prospection, sampling for susceptibility measurements
Date of fieldwork	July – August 2022
Field operators	cmp: Cornelius Meyer, Margherita Carletti, SOT: Roger Sala, Pedro Rodríguez Simón, Anna Morales Isaac
Country / Region / District / Municipality	Portugal / Centro / Coimbra / Condeixa-a-Nova
Locations	Intramural area and Vale Norte
Topographic measurements	cmp and SOT
Coordinate system	ETRS89 UTM Zone 29N (EPSG: 25829)

Table 1: General data of the geophysical prospection campaign in Conimbriga in 2022

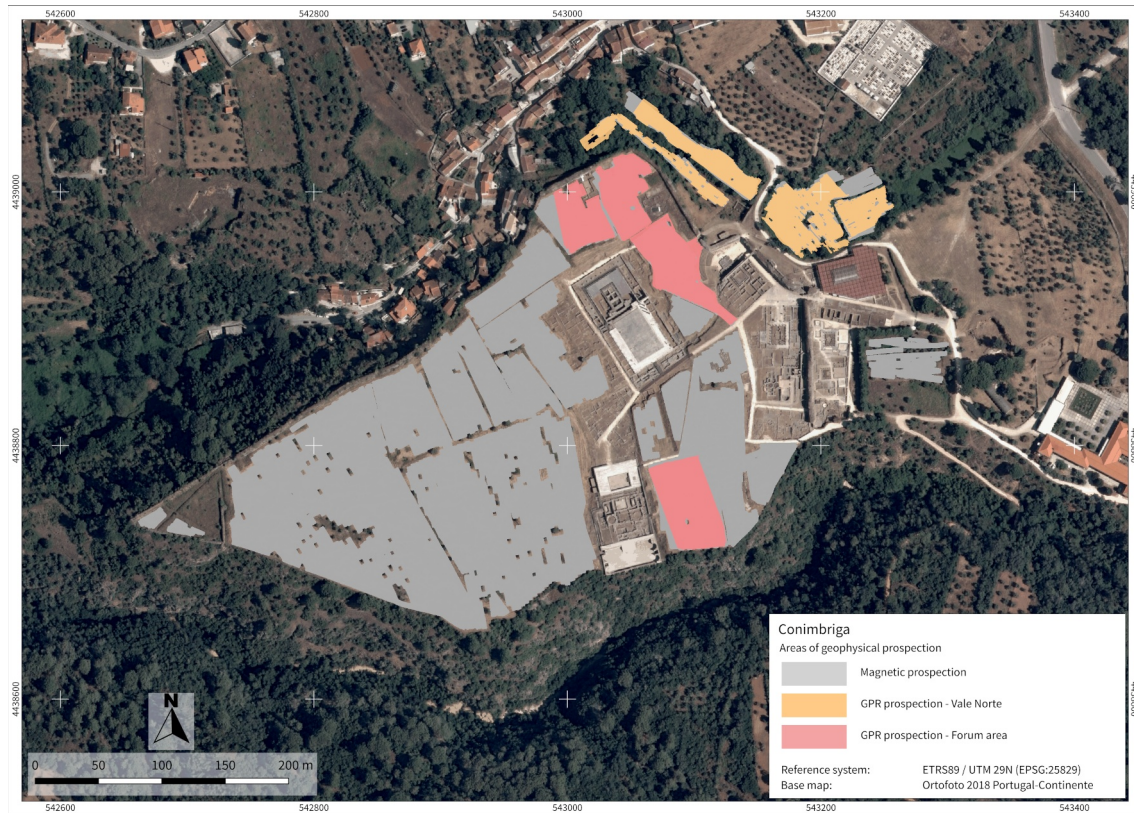


Figure 1: Areas of geophysical prospection in Conimbriga, campaign of 2022

4. Natural and archaeological context

4.1. *Geology and geomorphology*

The archaeological site of Conimbriga is located outside the modern town of Condeixa-a-Nova, to the south of the local district of Condeixa-a-Velha (Province of Coimbra). It is situated on an EW running ridge above the valley of the Rio do Mouros. The uppermost layers are formed by quaternary calcareous tufa. The larger region is characterized by a complex geology, with sedimentary rocks from the Jurassic and Cretaceous periods, as well as granites and schists from the Paleozoic era. Moreover, a variety of mineral deposits is found there, including iron, copper, and gold. The surroundings of Conimbriga are known for its karst formations, which are formed by the dissolution of limestone and dolomite rocks (Cunha, 1990). Prevailing soil types in the area are Fluvisols, Podzols, Cambisols, Luvisols and Leptosols.

4.2. *Archaeological research history*

The site of Conimbriga was first settled in the Iron Age and was later occupied by the Romans in the 1st century BC. During the 3rd century AD, the still existing city walls were erected. In the 5th century AD, the city was destroyed and abandoned. The site was again inhabited in the Early Middle Ages, firstly under Visigoth later Muslim rule.

Archaeological research of the site began in the 19th century and has continued to the present day. Excavations have revealed a wealth of information about the town, including large parts of its layout, monumental buildings, and artefacts.

Between 1964 and 1971, the focus of several Franco–Portuguese excavation campaigns was on the monumental buildings in the central part of the site. Later, in the 1980s, the pre–Roman occupation of the site was studied by Ana Margarida Arruda. During the last three decades, archaeological intervention has been reduced to small-scale targeted investigations, focusing on the post–Roman occupation phases.

Regarding the expectations of geophysical prospection, it should be noted that the presence of material dating to Late Antiquity and Early Medieval periods, as well as the observed transformations at buildings structures such as the late-imperial city wall and the *forum*, indicate the existence of complex layers of multiple construction phases. Moreover, the debris deposits of large-scale excavations, especially from the large-excavations in the 1960s, pose additional challenges in the geophysical data interpretation. For a detailed summary of the archaeological research history, see also Ruivo and Correia, 2017.

In the past decades, there have been repeated attempts to use geophysical prospection in Conimbriga. However, these were limited to small partial areas. The first magnetic measurements were carried out by M. Aitken already in 1964. Three zones were investigated using a Proton magnetometer, resulting in ambiguous magnetic data (Tite and Alldred, 1965). Another example is from 2019, when an area of less than 1,000 m² was covered with GPR measurements, located between the southern baths and the *forum* area. However, the data obtained did not allow any meaningful archaeological interpretation due to the limited surface area.

5. Methodology, measuring parameters and data processing

5.1. *Principles of the magnetic prospection*

Magnetic anomalies are caused by changes in the magnetic properties of the soil. The intensity of the magnetic anomalies is determined by the contrast between the different magnetic susceptibilities of objects or layers and the surrounding uninfluenced soil, as well as by their volume and depth. Two types of magnetisation can be observed during magnetic measurements: the induced and the remanent magnetisation.

The induced magnetisation is ascribed to the effect that the elementary magnets of a specific matter are enhanced by external magnetic fields (e.g. the Earth's magnetic field) and, consequently, partly align with it. The propensity for this alignment and the enhancement's strength are determined and described by the magnetic susceptibility. In soils, the highest magnetic susceptibility values are observed at ferromagnetic or ferrimagnetic minerals like the iron oxides magnetite and maghaemite. These minerals occur ubiquitously in the soil, forming microscopically small grains. There are several possibilities to explain their origin and concentration in soils:

- Heating: In soils with rich organic content and in reducing conditions, iron oxides of low magnetisation can be transformed into magnetite and maghaemite under the influence of fire (Le Borgne, 1955).
- Microbial mediation: Microbes populating rich organic deposits can change the soil conditions sufficiently to favour the conversion of weakly magnetised iron oxides into more magnetic forms (Linford, 2004).
- Magnetotactic bacteria: These bacteria are able to produce intracellular crystalline magnetite which allows them to navigate using the Earth's magnetic field. These magnetite crystals remain in the soil after the death of the bacteria (Fassbinder et al, 1990).
- Pedogenetic origin: The magnetic susceptibility can increase during soil formation processes in which organic material is absent (Maher and Taylor, 1988).

While induced magnetisation requires an external magnetic field for its development, remanent magnetisation permanently remains in a material after its creation. The most important type of magnetic remanence is caused by the heating of a material over its specific Curie temperature. In this process, the elementary magnets become mobile and align with the external Earth's magnetic field. During the subsequent cooling, the alignment of the magnets is conserved and, consequently, the burnt material becomes a strong magnet. Since the Curie temperature of typical soil components is between 600 and 700°C, fireplaces, kilns, layers of burned daub, accumulations of pottery and other burned materials can be detected based on this effect (Schmidt, 2009).

In addition, other types of remanent magnetisation can occur in soils. For example, small grains of magnetic minerals tend to align with the external magnetic field during sedimentary processes, producing the so-called detrital or depositional remanent magnetisation (DRM). This effect can

also be observed in anthropological deposits, and thus remanent magnetisation can be registered in the filling materials of human-made pits or ditches (Fassbinder, 2015).

Another important magnetic phenomenon is the diamagnetism. Structures mainly composed of diamagnetic materials, including quartz and calcite, cause noticeable negative anomalies. Diamagnetic materials literally repel the external magnetic field and, thus, form a strong magnetic field in the opposite direction, which results in an anomaly field with negative values. Due to this effect, not only buried constructions of limestone and quartzite, but also infill composed of sand and calcareous sediments, can be identified in the magnetic data as negative anomalies of the magnetic gradient.

5.2. *Technical data of the magnetic prospection*

For the magnetic measurements at the site of Conimbriga, an array of seven Förster fluxgate gradiometer probes was used (Figure 2). The seven probes were mounted on a light cart, which was moved by two operators by hand.



Figure 2: Magnetic gradiometer array cmp carrying seven Förster fluxgate gradiometer probes in Conimbriga (photo: Margherita Carletti)

The Förster FEREX CON650 fluxgate gradiometer probes register the vertical gradient of the vertical component of the Earth's magnetic field with an accuracy of 0.2 nT (Nanotesla). The measured gradient (the difference between two vertically arranged sensors in the gradiometer probe) is insensitive to the typically large fluctuations of the Earth's magnetic field and is determined only by the magnetisation of local subsurface objects. The technical details concerning the measurements are specified in Table 2.

Method	Magnetic prospection
System	cmp multi-probe array
Sensors	Förster Fluxgate Gradiometer FEREX CON650 (vertical separation: 65 cm)
Data logger	LEA D2 with 10 channels
Measurement category	Vertical gradient in nT
Configuration	7 sensors, mounted on cart
Resolution	0.5 m profile distance, max. 0.1 m point distance
Topographic measurement	2 GNSS receivers STONEX S900A and SC600A in RTK mode
Data positioning	Relative and absolute error: 0.02 m
Processing and filters	Ealdec and Ealmat, decoding program including offset and drift correction
Data format	ASCII, GeoTiff
Image resolution	0.25 m x 0.25 m

Table 2: Technical parameters of the magnetic prospection

5.3. *Principles of GPR prospection*

The Ground–Penetrating Radar (GPR) is a geophysical survey method based on the emission, propagation through the ground and reception of electromagnetic pulses with a known frequency, duration and intensity. Variations in both the pulse travel time and the amplitudes of the electromagnetic waves provide information about the position, depth, and specific properties of buried objects and layers. The spherical resolution and depth of penetration depend on the GPR antenna’s frequency and the electromagnetic properties of the ground. A rule of thumb is that the higher the frequency, the better the spherical resolution, but with diminishing capacity with increasing depth of penetration.

The Ground Penetrating Radar extensive survey method, also called time–slicing, consists of covering a given area with single GPR lines with a known position, followed by further integration of all that 2D data in a 3D data set. This methodology allows the presentation of amplitude maps in 3D (x, y, z) and, consequently, an easier representation of buried features.

The propagation of electromagnetic waves is basically determined by the soil properties. The main factor is the water content in the soil. Water has a very high dielectric permittivity (ϵ), and thus causes strong attenuation of electromagnetic waves. Consequently, dry ground offers more favourable conditions for GPR measurements compared to saturated soils. However, extremely dry soils tend to offer poor data quality. Another important factor comes from clay minerals. Penetration depth and resolution of GPR measurements in clayey soils are very poor in most cases because crystallized water is present embedded in the clay minerals.

Moreover, the results of GPR data are dependent on the material properties of the objects to be localized. The image generated by the GPR measurements becomes clearer and of higher quality when the contrast between the electromagnetic properties of the targets and the surrounding sediments increases. This is due to the high reflectivity of electromagnetic waves at the boundaries of distinct layers.

In Conimbriga we used the IDS Fast-Wave GPR system with five 600-MHz antennae (Figure 3). The system set-up was established to collect swaths composed by five simultaneous GPR profiles in a 0.2-m spacing, and an in-line resolution of 0.027 m (or nearly 37 scans per meter). The time-window was set to 60 nanoseconds, and the velocity of propagation was estimated using the hyperbola fitting method (Conyers and Goodman, 1997) resulting in an average value of 0.11 m/ns. The technical parameters concerning the GPR investigation are specified in Table 3.



Figure 3: GPR measurements with IDS HI-MOD system in the Vale Norte (photo: Pedro Rodríguez Simón)

Method	GPR prospection		
System	Fast-Wave (IDS)		
Sensors	TR600 (IDS)		
Data logger	Panasonic CF-19		
Measurement category	Amplitudes (SI)		
Configuration	5 parallel antennas separated by intervals of 0.2 m		
	600 MHz	60 ns	512 samples per trace
Resolution	0.20 m between profiles; 0.03 m between traces		
Data positioning	GNSS RTK system, Leica GS15/GS16, base/rover		
Topographic measurement	SOT		
Processing and filters	De-wow filter, background removal, band-pass and gain filtering, time slicing		
Data format	ASCII, GeoTiff, grd		
Image resolution	0.1 m x 0.1 m		

Table 3: Technical parameters of the GPR prospection

5.4. *GPR data processing*

The raw data was processed using GPR-Slice software in three steps: data conversion to the native GPR-Slice format, correction of system and environmental noises, and finally, the creation of a time-slice sequence.

Once the entire data set was converted to the software format, a de-wow algorithm was applied to correct the phase deviation of the data with depth. The second step was the application of a background removal filter, followed by a combined application of a manual gain curve and a band-pass filter, using a low-cut of 900 MHz, and a high-cut of 300 MHz.

After the creation of the time-slice sequence, it was analysed by comparing the detected reflection amplitude variations in time-slice views with GPR profiles obtained in the same positions.

An additional format was created by converting the reflective alterations in each time-slice into vectorial polygons, in order to create a simplified visualization of reflective elements according to their depth. That format was produced by blanking the time-slice values below a given threshold, that was established manually, and converting the resulting views into vectorial files using QGIS software. The function of these views is to show the strongest reflective features, expressing the depth of these features according to a colour scale.

5.5. *Magnetic susceptibility and electrical conductivity measurements*

Soil samples were investigated in order to get additional information that helps to evaluate the results of the magnetic and GPR measurements. Magnetic susceptibility is a measure of the degree to which a material can be magnetized in response to an external magnetic field. The presence of material with high values of magnetic susceptibility, such as soils containing magnetite or maghaemite, guarantees a sufficient contrast of magnetic gradient measurements at archaeological sites.

The electrical conductivity σ of a matter has an influence on the quality of georadar data. Materials with high electric conductivity show a high attenuation of electromagnetic waves, which limits the penetration depth. For the intensity of reflection signals, the contrast of electric conductivity and dielectric permittivity ϵ is decisive. If the different soil materials have only a small bandwidth in these parameters, this will result in poor unambiguity and interpretability of the GPR data.

To determine the magnetic susceptibility, the four loose material samples were measured with the Bartington MS3 meter and the MS2B dual frequency sensor. Prior to measurement, the samples were dried in an oven at 30 °C for 120 minutes. After cooling to room temperature, two subsamples of each sample were transferred to cylinders of a 15-ml volume. Measurements were carried out at room temperature (approx. 21 °C) with low and high frequency, respectively. For quality assurance, each of the 8 subsamples was measured threefold.

The electrical conductivity of the four unconsolidated rock samples was measured using a Hanna Instruments HI98304 DiST4 EC tester (measuring range 0 to 20 mS/cm, resolution 0.01 mS/cm, accuracy: +/- 2 % of measuring range). Before the measurements, the samples were dried in a

drying oven at 30 °C for 60 minutes. For the measurements, 5 g of the sample material per sample were weighed and mixed with 50 ml of distilled water. The samples were then mixed in a rotator for 120 minutes and then measured three times each.

5.6. *Positioning and presentation of the geophysical data*

The data positioning for the GPR survey was realised by means of differential GPS, using two Leica GS15/GS16 GNSS receivers in RTK mode (Real-Time Kinematic) to achieve a relative accuracy of 2 cm. In order to increase the precision of the positioning, a connection to the National Network of GNSS Permanent Stations (RENEP) was established via GSM. This way, the absolute accuracy reached values of less than ± 5 cm. The magnetic data were located by use of another GNSS-RTK system. In order to correct the position errors, a fix point at the city wall was measured on every field day and compared with the data from the corrected coordinates of the GPR survey. The resulting differences were used to correct the magnetic data positions. The coordinate system used during the geophysical measurements was WGS84 UTM 29N (EPSG: 32629). Subsequently, the data was reprojected to the reference system ETRS89 UTM Zone 29N (EPSG: 25829).

6. Results of the geophysical prospection and their archaeological interpretation

6.1. General information on the geophysical prospection

The geophysical measurements were carried out in the Vale Norte and inside the late-imperial city wall. Initially the magnetic prospection was conducted in the accessible areas of the Vale Norte. Almost all areas could be covered with magnetic measurements. Only a small sector at the amphitheatre was impossible to survey due to dense trees. Subsequently, the GPR measurements were carried out in the Vale Norte. The magnetic survey of the intramural areas was started at the eastern section of the late imperial city wall and continued towards the west. Fences, food paths, and open excavations restricted the investigated surface. Data gaps are due to trees, the edges of the terraces, and impassable debris dumps. Most of the area was liberated from high vegetation. The GPR survey in the intramural parts were realized to the northeast of the *forum* and to the east of the southern baths. The location of the survey areas was determined after analysing the magnetic data. In addition, a small area east of the late imperial city wall was investigated by magnetic measurements. Due to irregularities of the terrain and dense olive trees, only a part of the squared area was covered with measurements. More information on the survey and the conditions found in the investigated areas is listed in Table 4.

Site	Conimbriga	
Archaeological context	Protohistoric, Roman and Late Antiquity site	
Geology	Quaternary calcareous tufa	
Soil	Alluvial and anthropogenic soils	
Surface	Vale Norte: Mostly rough	
	Intramural area: Mostly even in eastern part, mostly rough in western part	
Above ground archaeological features	Ruins of Conimbriga, open excavations	
Vegetation	Grass, shrubs and trees	
Land use	Archaeological park, private orchards in Vale Norte	
Weather	Sunny, max. 24°C	
Sources of disturbance	Scrap metal, wire fences, iron posts, installations of archaeological park	
Investigated area	Vale Norte	Magnetics: 7,250 m ²
		GPR: 6,188 m ²
	Intramural area (<i>Forum</i> and western part)	Magnetics: 73,200 m ²
		GPR: 9,040 m ²

Table 4: Geophysical prospection in Conimbriga, general information

6.2. Magnetic data and interpretation

For interpretation, the magnetic data images were thoroughly examined for anomalies that might indicate historical features. Motivation and discussion concerning the results are concisely postulated below. The depicted and described interpretation presented in this report, is the outcome of a subjective approach that takes both the historical context as well as the environmental conditions under consideration, that by no means aims to claim exhaustiveness. It is rather a cautious proposition, serving as a base for further archaeological research. Needless to

say, the precarious nature of any interpretation has to be taken into account, since the reading of magnetic results can ever be subject to new or evolving hypotheses and knowledge.

The classification of the magnetic anomalies is based on their intensity, polarisation, and shape. In addition, context and a-priori information also play a role. Thus, several classes were introduced with corresponding causal physical structures. The specific characteristics of the anomalies, the related archaeological structures, and the colour scheme, as used in the interpretation maps, are set out in Table 5.

Colour	Magnetic anomaly type	Intensity	Type of magnetisation	Related structures
	Circular and oval positive anomalies	+3 to +12 nT	Induced and remanent	Fillings of pits, cultural layers; fillings may contain burnt material
	Linear positive anomalies	+3 to +12 nT	Induced and remanent	Organically enriched fillings of ditches, fillings may contain burnt material and construction debris
	Dipole anomalies of moderate to high values	± 9 to ± 24 nT	Predominantly remanent	Remains of ovens and other fireplaces, accumulations of burnt material
	Linear anomalies of varying polarisation and intensity	-2 to -10 nT	Diamagnetism	Remains of foundations and walls of limestone
	Zones of anomalies of varying polarisation and intensity	± 3 to ± 15 nT	Induced and remanent	Accumulations of construction debris
	Linear cluster of positive, negative and dipole anomalies of low intensity	± 3 to ± 10 nT	Induced and remanent	Street, path, pavements
	Linear cluster of dipole anomalies of high intensity	$> \pm 20$ nT	Induced and remanent	Aqueduct, sewerage
	Elongated, positive anomaly with high intensity	$> \pm 12$ nT	Induced and remanent	Backfilled cistern
	Large-scale anomalies of different polarisation with low intensity	± 3 to ± 15 nT	Induced and remanent	Geomorphological feature, backfilled water course
	Clearly defined dipole anomalies	$> \pm 30$ nT	Induced	Scrap metal and other ferromagnetic sources of modern origin

Table 5: Colour scheme of magnetic data interpretation

The overall display of the magnetic survey in Conimbriga is found on maps no. 2202-101 to 2202-103 with greyscale values of ± 12 nT, ± 8 nT, and ± 4 nT. The Vale Norte section is shown on maps 2202-104 to 2202-106 with the same greyscale dynamics.

The overall map of the interpretation is shown on map no. 2202–301. Map no. 2202–302 shows the same without the anomalies of presumably modern origin. Maps 2202–303 to 2202–308 zoom in on detailed maps of the forum area, the western part of the Roman city, and the Vale Norte.

Finally, map no. 2202–309 shows an attempt to distinguish between large building complexes and urban districts. Suspected monumental structures are marked with an 'L' and a number, while areas where small buildings or empty zones are more likely to be found are marked only with a number. A detailed discussion of the results of the interpretation follows in the sections containing the results of the georadar measurements. The unit numbers used in the text all refer to map no. 2209–309.

6.3. *GPR data and interpretation*

The results of the GPR survey showed that the soil conditions are different between Vale Norte and the intramural area. Both areas exhibit significant attenuation of the electromagnetic waves. However, the velocity of the electromagnetic waves is different: in the Vale Norte, the wave velocity was determined to be 0.085 m/ns, while in the intramural area it was about 0.1 m/ns. The difference can be explained by a higher clay content and a higher humidity of the sediments in the Vale Norte compared to the drier sediments in the intramural area. Since the soil around the Forum is mainly composed of anthropogenic sediments and ancient debris, it is assumed that the clay content is lower than in the sediments of the Vale Norte. Therefore, the maximum depth of investigation is greater in the intramural area than in the Vale Norte.

Specific processing parameters of the data result from the different electromagnetic wave propagation conditions: The time slice sequence from Vale Norte consists of 16 overlapping slices, each 0.18 m thick, between depths of 0 and 1.44 m. In the Forum area, 18 overlapping time slices, each 0.19 m thick, were calculated. They extend from the surface to a maximum depth of 1.91 m.

Nine of the eighteen time-slices of the data set from the forum area are presented on the maps no. 2202–201 to 2202–109. They show the spatial distribution of the electromagnetic reflectivity to a maximum depth of 1.81 m. A selection of eight horizontal sections obtained from the Vale Norte data set is shown on the maps 2202–211 to 2202–218. The time-slices show the electromagnetic reflectivity to a maximum depth of 1.35 m.

For the presentation of the first interpretation step, the vectorial maps, three or four depth levels were combined in one map. The increasing depth is indicated by a colour scheme starting from yellow for shallow features to dark blue for the deepest depth level. The vectorial maps of the *forum* data set are presented in maps no. 2202–401 to 2202–406, while the corresponding presentations of the Vale Norte data are shown on maps no. 2202–411 to 2202–415.

On the basis of the vector maps, simplified archaeological interpretation maps were produced in which the reflectivity anomalies were assigned to archaeological structures according to the interpretation scheme shown in the map legends. These simplified representations can be found on map no. 2202–501 for the Forum area and on map no. 2202–502 for the Vale Norte.

Linear features with medium to high reflection amplitudes are related to the remains of walls and water pipelines or channels. More diffuse zones of moderately increased reflectivity can be attributed to street pavements or accumulations of debris. Cavities can be identified by strong reflections in different depths, indicating the boundary between soil or rock and air.

6.4. *Soil samples: Determination of magnetic susceptibility and electrical conductivity*

The soil samples were taken from the western and northern profiles of an open archaeological excavation trench at different depths. All samples come from anthropogenically affected layers. The trench is located 40 m towards the northeast of the southern baths (N4438811, E543060). The preparation of the samples and the measurements were carried out by Dr. Steffen Schneider from ENRECO (Osnabrück, Germany).

Sample ID	Sample type	Depth [cm]	Electrical conductivity σ [mS/m]	Mass susceptibility χ [10 ⁻⁶ m ³ kg ⁻¹] LF – low frequency	Mass susceptibility χ [10 ⁻⁶ m ³ kg ⁻¹] HF – high frequency
Con1 W	Loose soil sample, dry	40	0.11	1.29	1.16
Con2 W	Loose soil sample, dry	100	0.09	1.02	0.92
Con3 N	Loose soil sample, dry	40	0.07	1.55	1.39
Con4 N	Loose soil sample, dry	100	0.08	1.18	1.06

Table 6: Results of the magnetic susceptibility measurements

The results of the susceptibility and conductivity measurements show a high reproducibility. The data show that the soil material has a relatively low electrical conductivity, on the one hand, due to the physical properties of its mineral components and, on the other hand, due to the low water saturation of the soil. This safeguards favourable penetration conditions for electromagnetic waves. However, it is expected that the conductivity will show low variability over the entire survey area, which may contribute to the difficulty of interpreting the georadar data.

The measured magnetic susceptibility values are in the lower range of those expected in soils on archaeological sites. It is typical that the magnetic susceptibility decreases with increasing depth. The low susceptibility values are most probably due to the source material of the soil, the calcareous tufa. Its main mineral component calcite is a diamagnetic mineral with very low negative susceptibility values. The low positive susceptibility, indicating a paramagnetic behaviour of the soil, probably comes from paramagnetic mineral components of the specific tufa in Conimbriga and anthropogenic or biogenic soil components with paramagnetic or ferrimagnetic properties. Even though this is a very small number of samples, the data show that low contrasts are to be expected in the magnetic mapping of the gradient. However, high contrasts of the magnetic gradient are to be assumed in the presence of fired material due to its thermoremanence.

6.5. Summarised interpretation: Vale Norte

The survey in the Vale Norte comprised magnetic and GPR measurements on the accessible and mainly flat parts. Partly the irregular surface impeded to gain interpretable GPR data. The archaeological interpretation of the Vale Norte data set is ambiguous, since the terrain is characterised by backfills and layers of construction debris created from antiquity to modern times. Parts of the area are affected by recent archaeological excavations, i. e. the zone to the north of the *Casa dos Repuxos*.

Based on the magnetic and GPR data, a larger building complex is expected to the north of the *Casa dos Repuxos*. Besides several wall sections, the GPR data indicate the presence of a cavity located under a paved floor to the north of the complex (L9 in map 2202–309 and Figure 4).

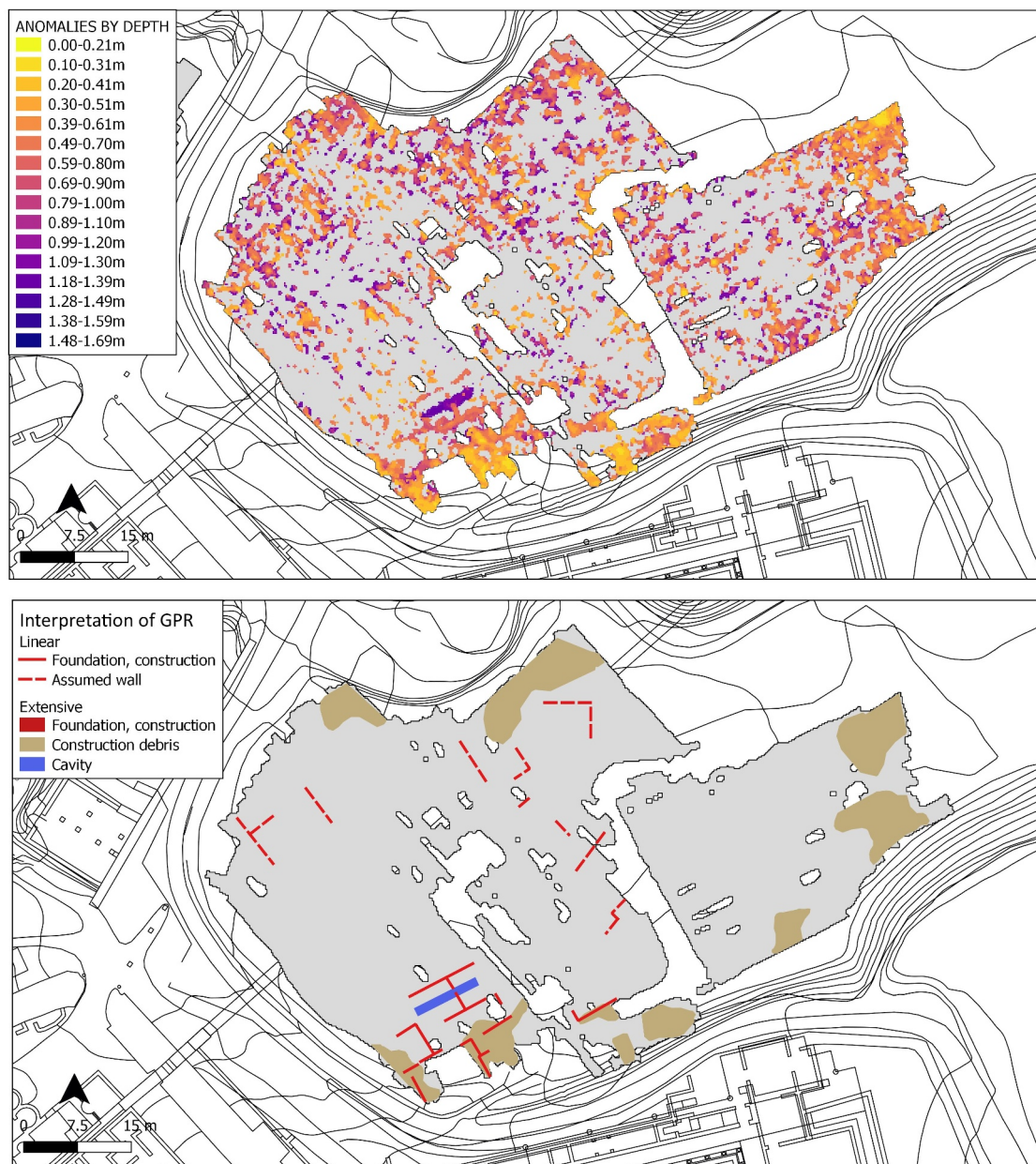


Figure 4: Overview of the GPR data interpretation in the eastern part of the Vale Norte

To the north of the building complex, the magnetic data show further anomalies with a negative magnetic gradient. These point to larger limestone blocks and pavements. Some nearly rectangular anomalies with extensions of 2 m x 2 m and negative values of the gradient could represent the remains of pillars supporting the aqueduct, which is still visible at the late-imperial city wall.

The EW running features in the centre of the eastern survey area could show a street pavement. However, it is possible that under the pavement is a gallery in continuation of the visible ditch further east and the outlet under the modern road at its western limit.

The northern and eastern parts of the area to the east of the modern road are characterised by a variety of anomalies indicating a debris layer and the remains of buildings (16). However, an unambiguous reconstruction of ground plans is not possible. The rough surface, the modern contamination, and the small dimensions of the accessible areas are the main reasons for the difficulties in interpreting GPR and magnetic data.

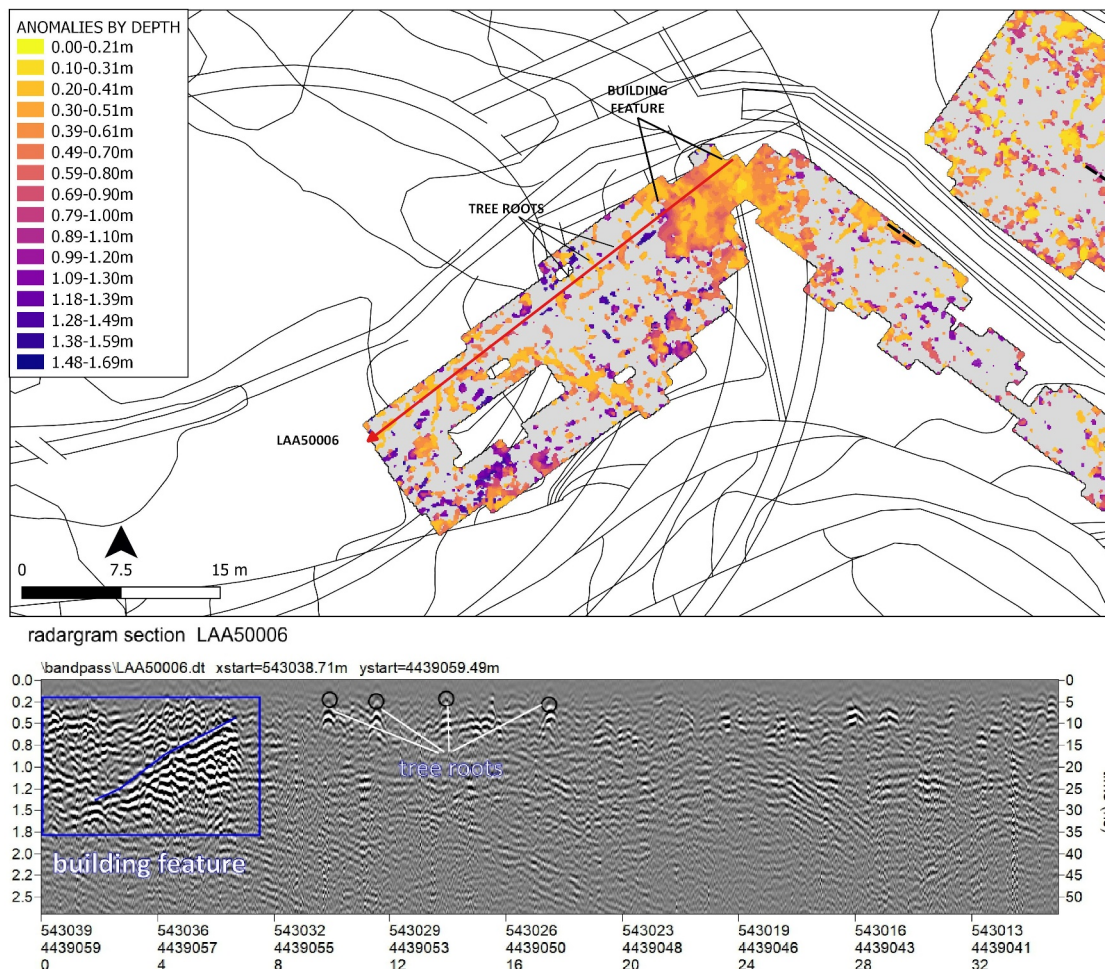


Figure 5: Details of the GPR data interpretation in the surroundings of the amphitheatre

The area between the amphitheatre and the modern road was investigated along two, about 120 m long strips in the NW–SE direction. At the northwestern corner, the remains of the amphitheatre's *cavea* can be identified in the magnetic and GPR data (L10). The GPR profiles

clearly show the inclination of the *cavea* (Figure 5). The dense vegetation and the uneven ground made it impossible to extend the measurements further to the west.

The eastern parts of the two surveyed strips show GPR anomalies indicating the presence of building remains (L1). Complex layers can be expected along both sides of the street or sewage system. The location at the deepest part of the terrain suggests thick debris layers, but there are indications of the remains of buildings, probably related to the street and sewer. Since no clear ground plans can be identified, it is likely, that the fragmented anomalies reflect various construction phases of the ancient town. The depth of the identified features is between 0.5 m and 1.5 m, approximately. It cannot be excluded that other features still exist in greater depth, however, due to the inhomogeneity of the spoil and its clay content, the penetration depth of the GPR measurements is limited to about 1.5 m.

Some 2 to 3 m wide negative linear anomalies are observed in the magnetic data, suggesting some massive foundations in the area where another ancient theatre is suspected (L1). Magnetic and GPR data are broadly consistent in this area, but there is no clear evidence of a theatre building. The zone between L1 and L10 (32) shows a few anomalies, suggesting an open space. However, the effects of modern interventions and a thick cover of sediment may conceal or obscure any evidence of ancient buildings in the ground.

6.6. *Summarised interpretation: East to the forum and the southern baths*

In the forum area, three zones were covered with both magnetic and GPR measurements. Area CNBRF1 is located between the forum and the eastern late-imperial city wall. Area CNBRF2 covers the northeastern corner of the intramural area, bordering to the southern flank of the amphitheatre. Finally, area CNBRF3 is situated on the eastern side of the southern baths. The GPR areas sum up to a total surface of 9,040 m², the magnetic measurements were carried out on a larger area, i.e. on 21,500 m².

The area to the east of the forum is characterised by a high density of both magnetic and GPR anomalies, indicating a great variety of architectural remains in the ground. The data suggest an area of small-scale buildings crossed by a paved street in the EW direction (17). The orientation of the detected building remains differ from the orientation of the *forum*. Rather, they are consistent with the orientation of the pre-Roman structures uncovered around the perimeter and under the forum. GPR data and magnetic data are broadly consistent. The GPR data shows that the foundations can be found at depths of 30 cm and below. However, some features can only be identified in one of the data sets. This is most probably due to the superposition of various construction phases and the existence of large debris layers. Additionally, the clear recognition of structures is made difficult by the low contrast in both magnetic and GPR data.

At the eastern limits of the GPR area, linear and highly reflective features are detected at 60 cm depth. They can be associated with a pipe or building conduit. At a depth of 90 cm it crosses the known aqueduct leading to the *forum*.

In the southern part of the areas, both data sets show less consistent structures, indicating heterogeneous fillings or extensive debris layers near the surface (19). Only in the direct neighbourhood of the forum some isolated linear anomalies point to further building remains (18). A circular dipole anomaly with a diameter of about 3 m could indicate the remains of an oven, found at the southern edge of the area, only 10 m outside the *forum*. An investigation of archaeological or construction activity in the area in recent decades would be useful to distinguish the archaeological remains from more recent elements in the data.

A similar situation is observed to the north and northeast of the forum (area CNBRF2). The GPR time slice sequence offers a convulsive response from shallow depths, indicating heterogeneous composition of soils. At shallow layers, weak linear features are detected, but in most cases, they show no precise geometries, and are blurred by amorphous anomalies. This is interpreted as product of an irregular conservation status of the building features, and a stratigraphic context dominated by heterogeneous fillings. Despite the noisy response, a detailed analysis of the time-slice sequence allows for recognition of parts of building groups showing a diversity of orientation patterns (15).

The magnetic data support these assumptions. Besides the irregularly distributed building remains, a continuation towards the west of the paved street, identified further east (17) is observed. In addition, a rectangular street junction is found at the southern edge of the surveyed area. The consistency of the features, derived from magnetic and GPR data is lower here, suggesting a complex stratigraphy with different construction phases and pronounced debris layers.

To the north of the EW running street, the magnetic data point to a 20 m x 20 m large ground plan, which could belong to a kind of monumental building (L2). The magnetic anomalies are very weak and show only fragments of foundations. The GPR data provides no evidence. It is therefore assumed that his remains are at greater depths, probably over 1 m.

A highly reflective anomaly group, observed at the extreme northeastern corner of the grid, is associated with a part of the city wall (to the north of 15). The space between the amphitheatre and the building complex L2 shows diffuse reflective anomalies, related to minor building units (31). However, the magnetic data do not allow for a more detailed interpretation, since the effects of modern deposits mask any information on ancient structures.

The third GPR grid was surveyed in an area sloping to the south, where notable magnetic anomalies are observed to the east of the southern baths. While the magnetic data indicate the presence of another WE-oriented building complex surrounded by a rectangular street grid (L3), the GPR data are dominated by complex near-surface reflections of high amplitudes. This point to a heterogeneous composition of the topsoil layers, probably due to flattened spoil deposits from 20th century archaeological excavations.

The GPR time-slices reveal the presence of linear features from 30 to 90 cm depth, possibly corresponding to wall remains, mostly in ENE-WSW orientation. The assumed building remains are fragmented and accompanied by debris accumulations. It is likely that the features, observed in

the GPR data, partly overlay the building remains identified in the magnetic data (L3). In the space between the southern baths and complex L3, GPR and magnetic data are more consistent, suggesting a less complex stratigraphy (13). Towards the southern limit and the city wall, the GPR and magnetic data show rather diffuse signals pointing to complex debris layers.

In the magnetic data, the strongest anomalies are observed in the central part of the assumed building complex L3. Besides massive foundations several dipole anomalies of medium intensity point to accumulations of burned material, probably the remains of ovens or a heating system. The surrounding areas are characterised by weak and fragmented anomalies, most likely attributable to small-scale building (*insulae*), partly divided by streets (11, 12 and 13). Several circular positive and dipole anomalies with medium intensities show deep fillings and accumulations of burnt material inside these buildings, indicating backfilled cisterns and domestic fireplaces. Close to the city wall, the magnetic data lacks significant anomalies that could indicate empty spaces of the ancient city or thick layers of sediment and debris that obscure deeper features (35 and 36).

6.7. *Interpretation of magnetic data: Western part of Conimbriga*

Almost the entire area located to the west of the forum and the southern baths was covered with magnetic measurements. The surveyed field has a surface area of more than 5 hectares. The manifold structures, derived from the data, are discussed starting in the east and the north. In general, the character of the magnetic data change from the east to the west. While, the data in the east show a low variability with only few strong anomalies, the western part reveals a greater bandwidth, from areas of low magnetic contrast to large-scale anomalies with high intensity.

The area to the west of the forum reveals a continuation of the regular building patterns already discovered. The data show the remains of foundations, a the NNW–SSE running street and several indications of domestic fireplaces (21). The orientation of the buildings changes in the space between the northwestern corner of the forum and the late-imperial city wall (14).

Further west, on the most elevated part of the intramural city, a zone of transition can be assumed (22). In its eastern part, the continuation of the regular building grid is observed, including fireplaces and backfilled cisterns. Further west and northwest, the orientation of walls changes, and two larger building complexes are identified (L4 with a surface of about 1,000 m², and L5, covering more than 1,500 m²). The orientation of their longitudinal axes is NW–SE. Both complexes also show anomalies that indicate paved floors. At the northwestern flank of L5, there are indications of an apsis-like building closure. The fact that no significant anomalies are found in the space between L4 and L5, indicating open spaces (33 and 34), supports the assumption of a monumental complex at the northern centre of the intramural area of Conimbriga.

Further south, along the western flank of the southern baths, diffuse patterns of magnetic anomalies are visible. Some features indicate a continuation of the regular grid given by the outline of the baths. Other anomalies, pointing to streets and foundations differ in orientation (23).

In the northern part of the Area 23, several strong linear dipole anomalies are observed. These linear features could be related to ancient water pipelines or sewers. In addition, a continuation of the NE–SW running axis, discovered to the north of the baths, can be recognized. The clear identification of house complexes and street grids is made difficult, since the sloped terrain is scattered with limestone blocks, debris deposits, and small ditches.

The Area 23 can also be attributed as a transition zone between two larger city quarters. Its southwestern limit is marked by a wide, slightly negative anomaly band of 4 to 5 m width, indicating a major street in the WNW–ESE direction. At its southwestern side (24), the data show a more regular orientation of the building remains, including a parallel street in a distance of 19 m from the main street, separating 23 and 24.

To the west of L5, another large quarter can be delimited (28). It covers an area of almost 1 hectare. The main axes are east-west oriented. However, a predominant orientation of building remains cannot be observed. Some of the anomalies also run EW and NS, respectively, but others have different directions. On the one hand, this could reflect different construction phases, on the other hand, the presence of debris deposits on the surface, of early modern or recent terrain modifications for agricultural purposes, and of various trees complicate the interpretation of the weak and blurry magnetic anomalies.

At the southern limit of 25, another striking linear anomaly in the EW direction and pronounced dipole characteristics is observed. It is supposed, that this feature reflects the continuation of the water conduit, located further east (between 22 and 23). The structures identified on the southern side of the lineament are similar to the ones located in areas 23 and 28.

Starting from the supposedly densely built-up city quarters, a different picture emerges when looking at the western tip of the plateau: the data give reason to expect to find the remains of monumental buildings there. Even though, the anomalies are very noisy and difficult to decipher, two spots stand out. At the northwestern corner of the plateau, linear negative and circular positive anomalies allow to delimit an about 2,000 m² plot with massive foundations and deep fillings indicate a 40 to 50 m long, and 25 m wide ground-plan of an at least two-aisled monumental building (L6). In its interior, preserved pavements and large accumulations of burned material can be expected. The extension and intensities of the positive and dipole anomalies rather suggest the presence of debris of a catastrophic fire than simple fireplaces or heating remains. Close to its northern front, there are indications of a backfilled cistern.

The complex is in a spatial connection with another EW-oriented building feature (L8). Its reconstruction based on the magnetic data is more difficult, since the northern part is covered by an impassable debris dump. Between L6 and L8 an area with small-scaled building remains is recognised (27). According to rough estimates, the monumental building occupied an area of 40 by 30 m, and shows similar anomaly patterns as found at L6. At its northern front, the striking linear dipole anomaly bends towards the south and is probably connected with the complex. Further east, an adjacent EW building complex can be identified (L7). It extends along an EW axis of about 80 m and is about 18 m wide. In its surroundings, further foundations including an apsis-like construction and large debris layers, are visible.

Along the southern city wall, the anomaly patterns are even more difficult to decipher. The main reason for this could be the presence of extensive debris layers at the foot of the slightly sloped terrain. To the south of L8 a row of single limestone blocks can be assumed, but no clear building remains are visible (29). Further east, a larger section of a street and some minor building remains with a NW–SE orientation can be expected. The southernmost tip of the terrain is probably characterized by massive debris accumulations on top of a filled ditch or natural terrain depression (30).

Magnetic measurements on the westernmost part of the plateau have been limited to two small areas due to open trenches and spoil heaps from archaeological excavations. The small grid sizes do not allow detailed and contextual interpretation. The data indicate the presence of other human activity remnants including foundations, fills and accumulations of burnt material.

6.8. *Interpretation of magnetic data: Assumed eastern forum*

At the end of the survey campaign, an area of 2,000 m² was investigated outside the late-imperial city walls. It was a slightly elevated but very undulating site covered with old olive trees. Due to the rough terrain and the trees, only half of the 4,000 m² area could be surveyed, under which the remains of another forum are thought to lie (20).

The limited area and modern contamination limit the interpretation of the magnetic data. Although the data give some indication of building remains and rubble deposits, a full interpretation is not possible. In particular, the southern part of the site has been heavily modified in modern times, and much of the ancient structure may have been destroyed.

7. Summary

The geophysical survey campaign in the Roman city of Conimbriga provided a plethora of results serving as a useful base for further archaeological excavations and non-invasive investigations of the Roman city and its surroundings. The following conclusions can be drawn:

- The geological and archaeological conditions of Conimbriga resulted to be challenging for both, magnetic and GPR prospection.
- Magnetic prospection: The calcareous tufa and the weathering soil are characterized by low magnetic susceptibility, causing a weakly paramagnetic behaviour of soil and construction material. Thus, the contrast of building structures and surrounding soil is low in magnetic data, too. Second, the presence of extensive debris layers combined with modern terrain interventions results in noisy data that does not allow for unambiguous interpretation in most areas. The strongest magnetic anomalies in Conimbriga are observed on materials with remanent magnetization, which in most cases is related to thermoremanence caused by heating of the material.
- GPR prospection: In general, the GPR data are characterized by a limited penetration depth between 1.5 and 1.9 m (at an antenna frequency of 600 MHz) and diffuse to noisy reflection signals. The main reason for this is again the geological base: The weathering soil has a high clay content which contributes to the attenuation of the waves and limits the penetration depth. Moreover, the contrast of the electromagnetic properties between the limestone, the tufa and the surrounding soil is not sufficiently high for clear reflection signals to delimit foundation remains, debris layers, and other archaeological structures.
- Despite these limitations, the attempt to cover large areas helped to obtain useful results. In particular, the comparison between the geophysical data from the smaller grids in the Vale Norte and the large-scale prospection in the intramural area show, that only large-scale geophysical surveys will provide satisfying results.
- Results in the Vale Norte: The combination of magnetic and GPR data revealed that larger buildings with complex stratigraphy can be expected to the north of the *Casa de Repuxos*. In addition, the survey provided indications of complex construction remains in the area of the suspected theatre, located to the east of the amphitheatre. The significance of the data was limited by the small dimensions of the surveyed grids and the partially rough surface conditions. Moreover, along the topographically deepest part of the valley, a very complex, multi-phased stratigraphy has to be expected.
- Intramural area and second *forum*: Inside the late-imperial city walls, the magnetic data show wide variations. While the eastern part is characterised by low contrasts of the archaeological features and a severe modern contamination (caused by modern installations and the archaeological excavation of the past 100 years), the data of the western part show a greater variety of different anomaly types and thus, allows to delimit monumental building complexes, city districts and infrastructure installations.

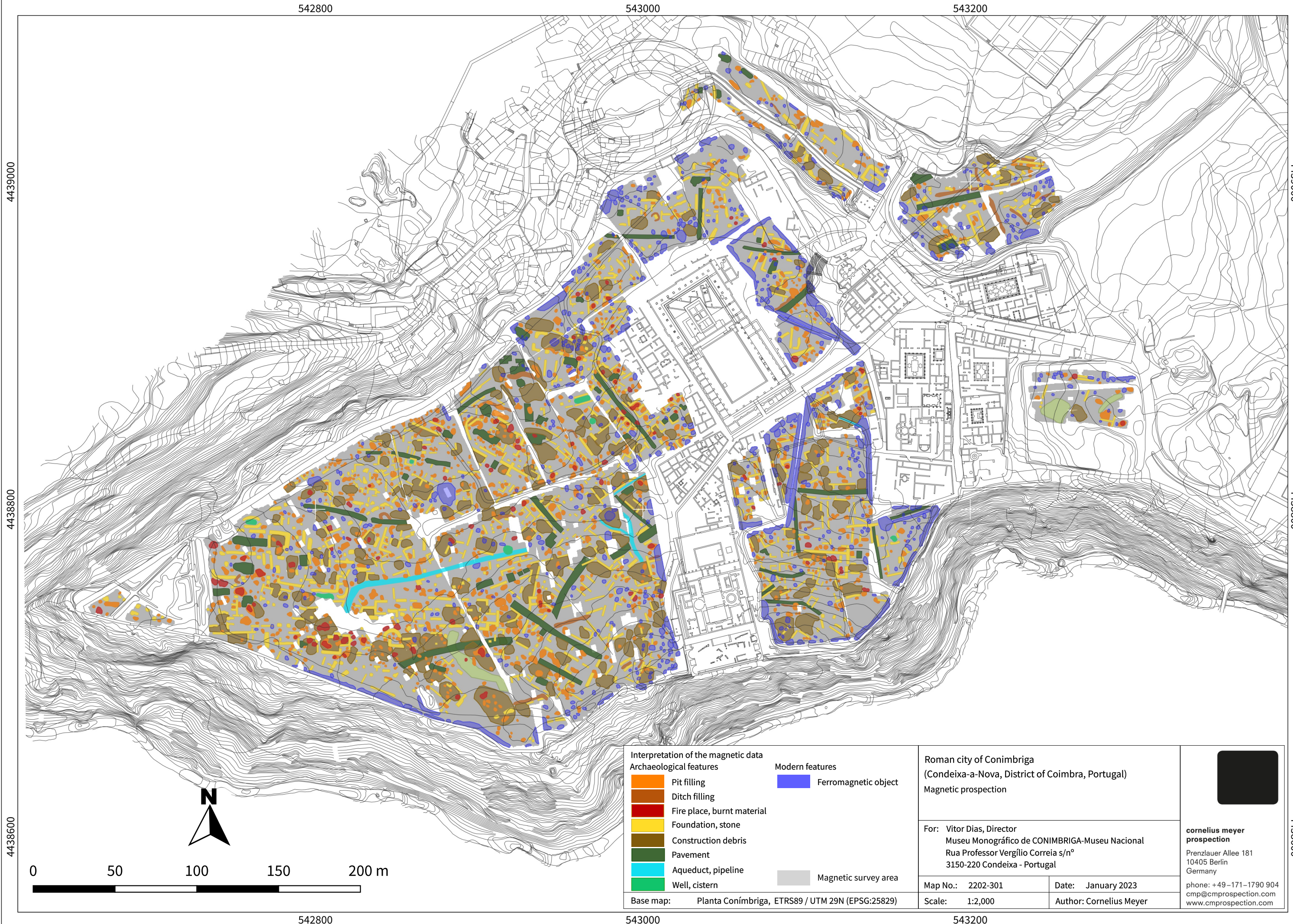
Nevertheless, all magnetic data are noisy and lack of consistency, challenging the archaeological interpretation. The areas, where magnetic and GPR surveys were combined (east of the forum and the southern baths), show no consistency throughout the surveyed areas. This can be explained with complex stratigraphy and different focuses of the two methods. It is assumed, that the GPR data rather show more shallow features (between 30 cm and 100 cm), while the magnetic data can give at least rough outlines of preserved structures in depths greater than 100 cm.

- It is important to note that the present interpretation is only a first draft for the representation of the actual archaeological situation. It is based primarily on the geophysical data itself and the available a-priori information. Greater certainty about the reliability of this interpretation can be gained by verifying the proposed interpretations through targeted archaeological excavations and other archaeological methods. Of course, a discussion on the plausibility of the interpretation should be part of the archaeological toolbox.
- For future geophysical prospection campaigns for the investigation of the surroundings of Conimbriga the following workflow is proposed: Firstly, a thorough analysis of the data presented here and the resulting new archaeological questions is recommended. Based on the new insights in combination with existing questions, areas of interest should be selected. All available information on these areas should be collected and analysed, including the surface and vegetation conditions. Based on this, the methodology should be selected with the consideration that the larger the area covered, the better the results.
- In addition to the extensive coverage of areas outside the late imperial city walls, it may also be useful to apply different georadar methods to selected areas. In order to improve the performance of future GPR surveys, it would be useful to test a wider range of antenna frequencies that allow better penetration and result in less influence from heterogeneous topsoil in the data. This can be done by systematic testing using antennas at different frequencies or by using a stepped-frequency system that allows focusing on selective frequency ranges.

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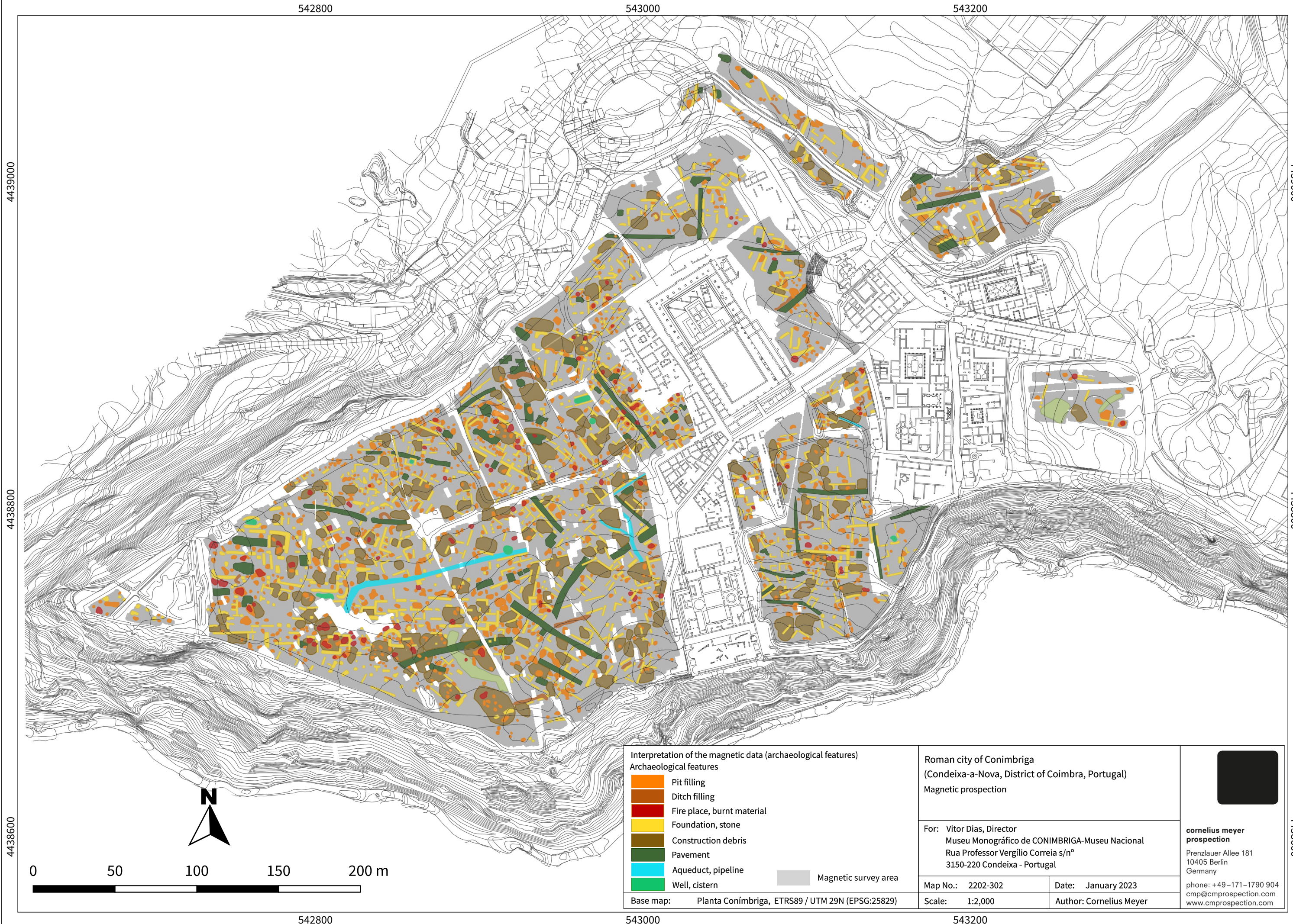
Berlin, 15 February 2023



Interpretation of the magnetic data	
Archaeological features	
	Pit filling
	Ditch filling
	Fire place, burnt material
	Foundation, stone
	Construction debris
	Pavement
	Aqueduct, pipeline
	Well, cistern
Modern features	
	Ferromagnetic object
	Magnetic survey area
Base map: Planta Conímbriga, ETRS89 / UTM 29N (EPSG:25829)	

Roman city of Conimbriga (Condeixa-a-Nova, District of Coimbra, Portugal)	
Magnetic prospection	
For: Vitor Dias, Director Museu Monográfico de CONIMBRIGA-Museu Nacional Rua Professor Vergílio Correia s/nº 3150-220 Condeixa - Portugal	
Map No.: 2202-301	Date: January 2023
Scale: 1:2,000	Author: Cornelius Meyer

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Interpretation of the magnetic data (archaeological features)

Archaeological features

- Pit filling
- Ditch filling
- Fire place, burnt material
- Foundation, stone
- Construction debris
- Pavement
- Aqueduct, pipeline
- Well, cistern

Magnetic survey area

Base map: Planta Conímbriga, ETRS89 / UTM 29N (EPSG:25829)

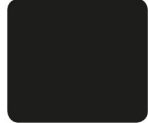
Roman city of Conimbriga
(Condeixa-a-Nova, District of Coimbra, Portugal)

Magnetic prospection

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Map No.: 2202-302 Date: January 2023

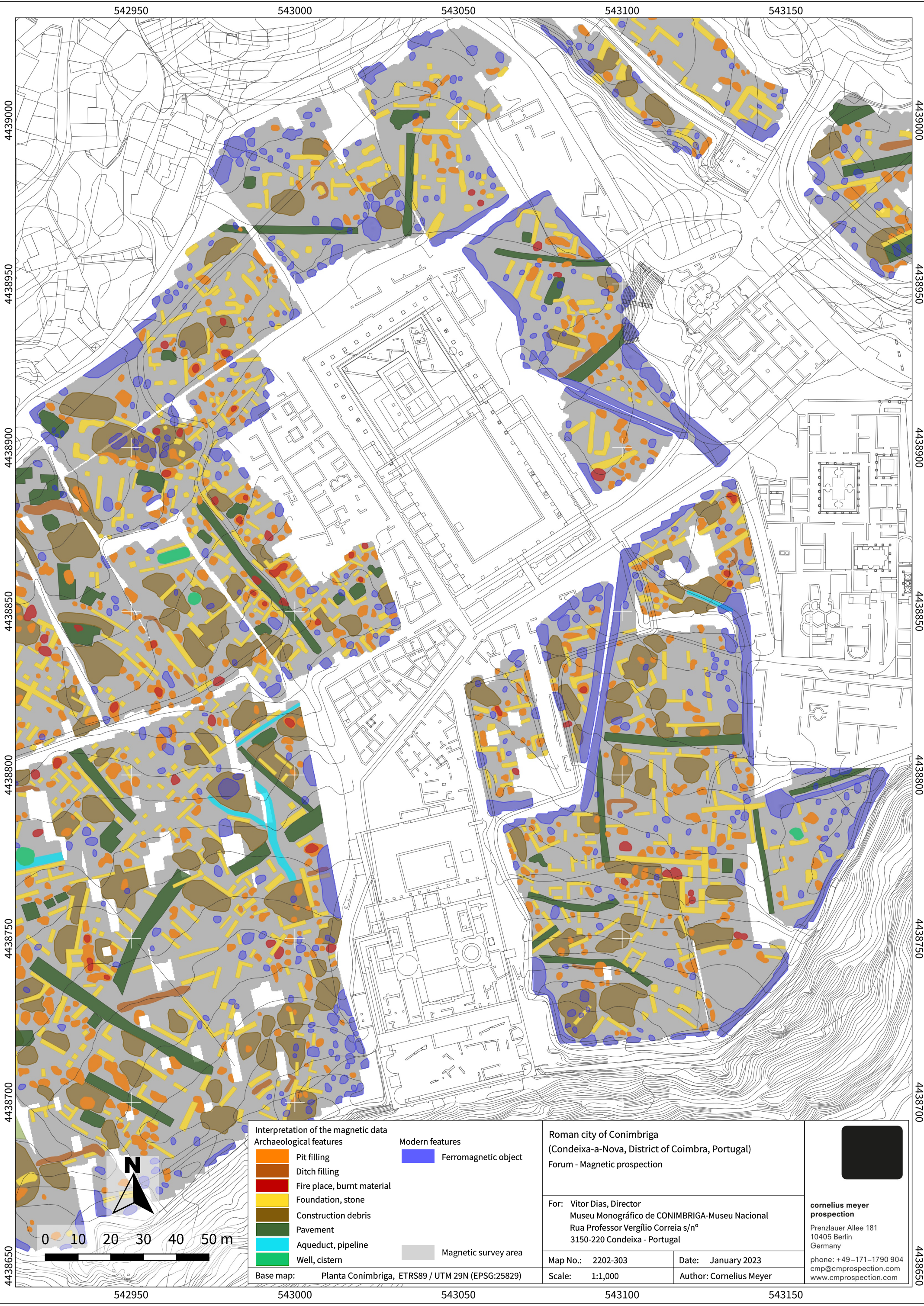
Scale: 1:2,000 Author: Cornelius Meyer



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Interpretation of the magnetic data

Archaeological features

- Pit filling
- Ditch filling
- Fire place, burnt material
- Foundation, stone
- Construction debris
- Pavement
- Aqueduct, pipeline
- Well, cistern

Modern features

- Ferromagnetic object

Magnetic survey area

Base map: Planta Conímbriga, ETRS89 / UTM 29N (EPSG:25829)

Roman city of Conimbriga
(Condeixa-a-Nova, District of Coimbra, Portugal)
Forum - Magnetic prospecting

For: Vitor Dias, Director
Museu Monográfico de CONIMBRIGA-Museu Nacional
Rua Professor Vergílio Correia s/nº
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Map No.: 2202-303

Scale: 1:1,000

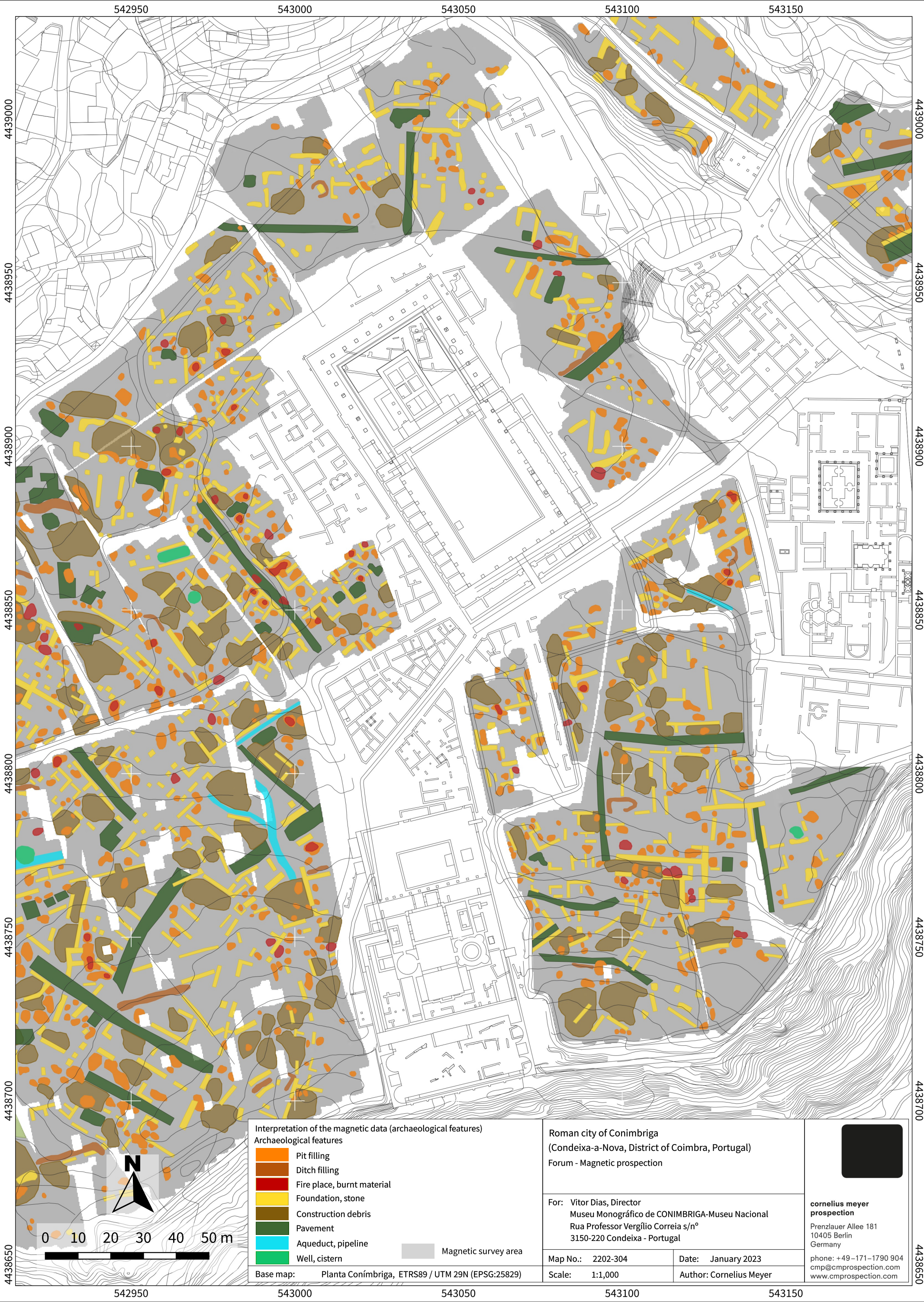
Date: January 2023

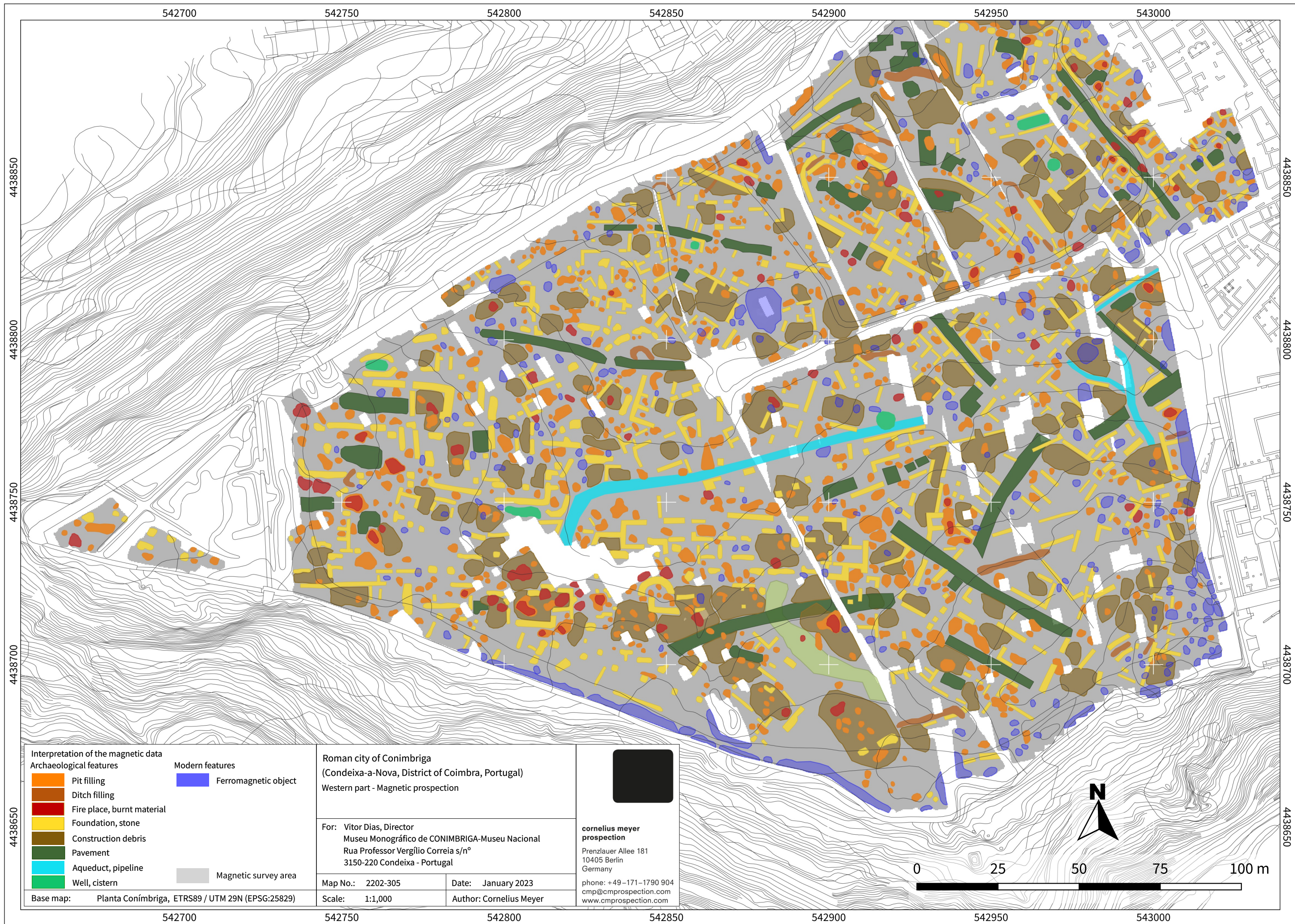
Author: Cornelius Meyer

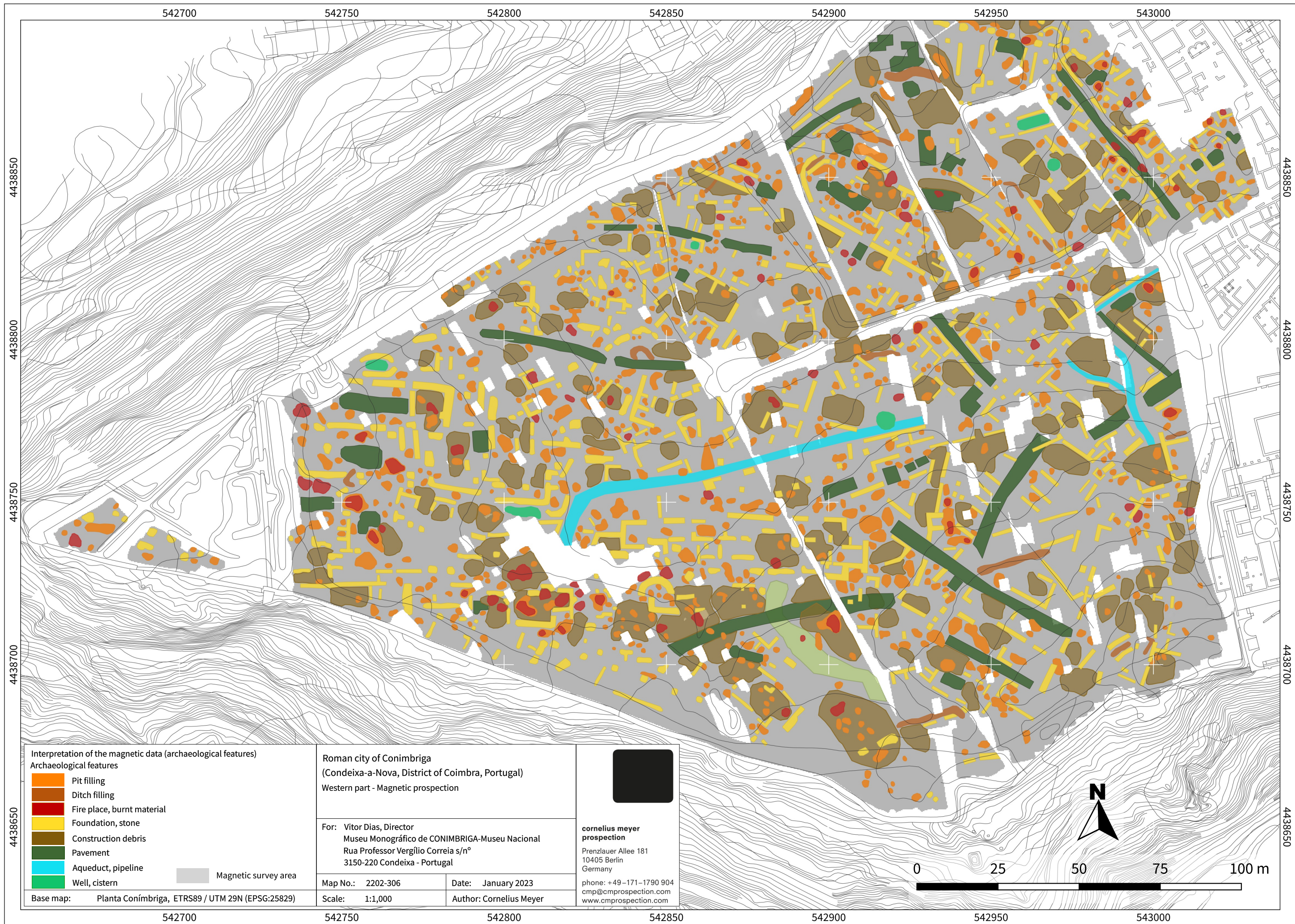
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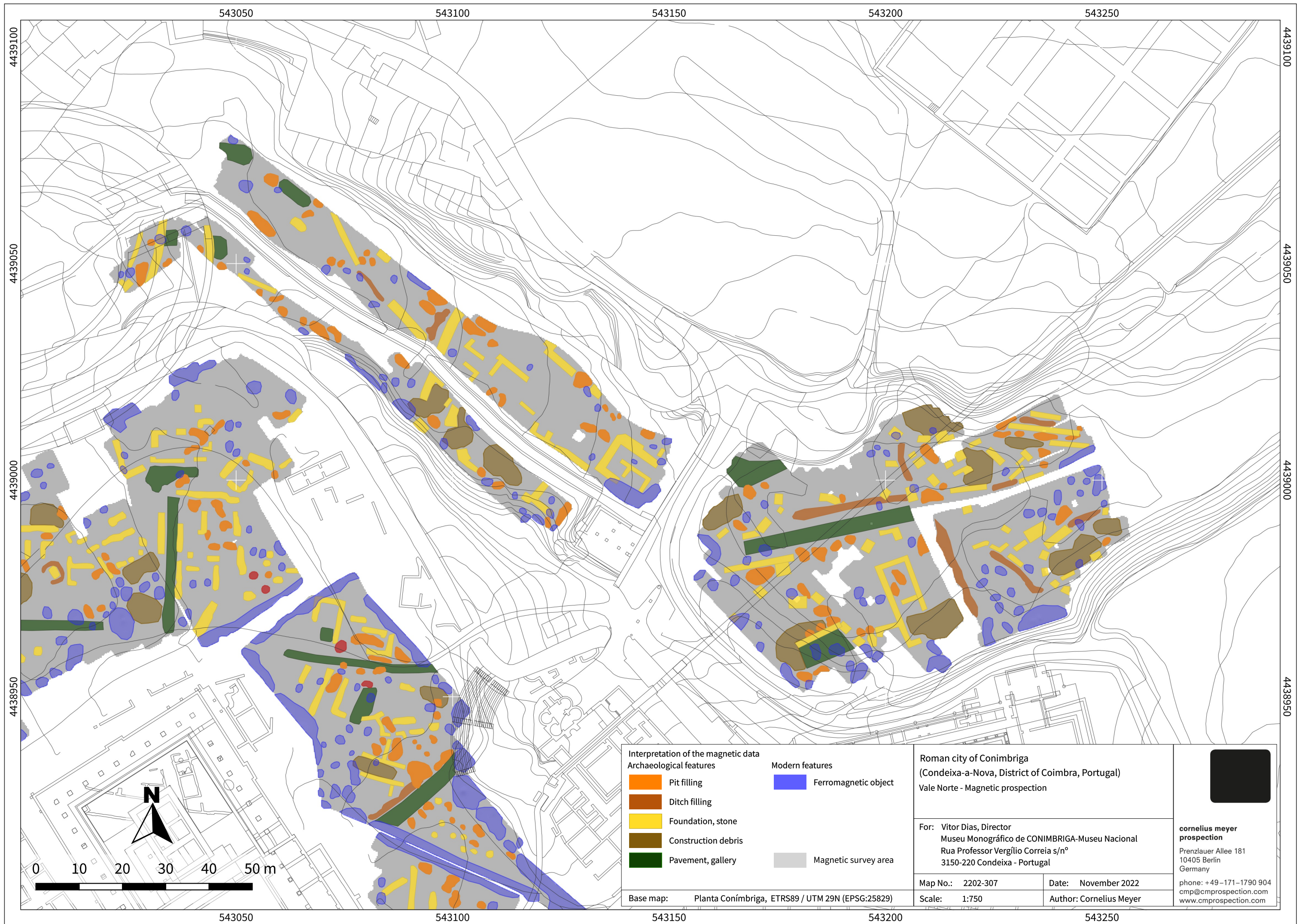
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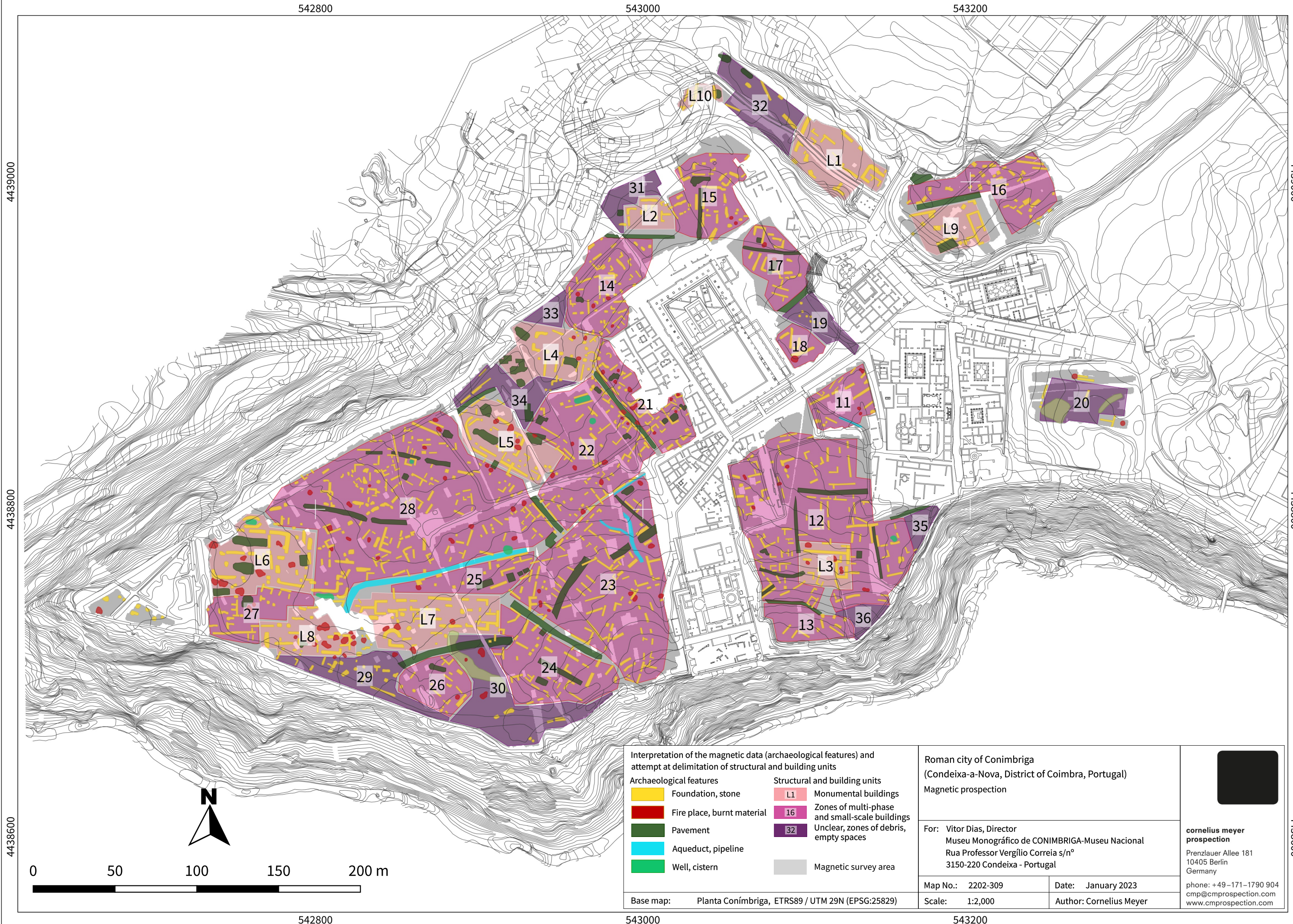












Interpretation of the magnetic data (archaeological features) and attempt at delimitation of structural and building units

Archaeological features

- Foundation, stone
- Fire place, burnt material
- Pavement
- Aqueduct, pipeline
- Well, cistern

Structural and building units

- L1: Monumental buildings
- L6: Zones of multi-phase and small-scale buildings
- L10: Unclear, zones of debris, empty spaces
- Magnetic survey area

Base map: Planta Conímbriga, ETRS89 / UTM 29N (EPSG:25829)

Roman city of Conimbriga
(Condeixa-a-Nova, District of Coimbra, Portugal)
Magnetic prospection

For: Vitor Dias, Director
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Map No.: 2202-309
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