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Zagreb, 3rd – 4th December 2020

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Project MagIstra – magnetic mapping of archaeological structures in soils on flysch: case studies from Slovenian Istria

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The main goal of the research project "MagIstra" was to assess the potential of the magnetic method in identifying and determining the type of archaeological remains in the soil sequence on the soft carbonate rocks (Eocene flysch bedrock). For this purpose, magnetic contrast between the individual archaeological remains and the medium in which they are located was evaluated. Furthermore, all the anthropogenic and natural factors affecting the magnetic measurements in the researched environment were carefully analysed. The investigation was conducted in the late spring of 2021, on four selected case study archaeological sites from different archaeological periods in the interior of Slovenian Istria. Precise surveys with a high-resolution magnetometer were combined with the topsoil magnetic susceptibility survey. The results were supplemented and compared with the results of the earth resistance survey for a better evaluation of magnetic anomalies and to determine the possibility of the magnetometer to recognize the weakly magnetic dry-stone walls built of sandstone. The geophysical surveys were followed by ten test pits to assess the accuracy of the results and to determine the magnetic properties of the natural and archaeological materials. Research has shown that weakly magnetic soils on sandstone bedrock that are equally weakly magnetic are ideal natural conditions for detecting a variety of archaeological remains, especially those with thermoremanent magnetization (burned layers, ceramic accumulations, daub). As a result of a detailed analysis of the magnetic anomalies and the magnetic susceptibility data, we were also able to gain a better understanding of the specific conditions required to detect magnetic anomalies caused by the induced magnetization of sandstone structures. In addition to improving our knowledge of the magnetic field survey's efficiency in this environment, the study also enabled us to interpret the results of the magnetic survey in a more effective way.

Keywords: *magnetic method, Flysch, magnetic susceptibility, archaeology, archaeogeophysics, Slovenian Istria*

Introduction

Although integrated non-invasive research has been efficiently applied on archaeological sites throughout Slovenia (Slapšak and Grosman 2010; Mušič et al. 2015), Slovenian Istria remains largely unexplored when it comes to the use of geophysical methods. Geophysical research was mainly carried out as part of the protective archaeological research in the urban areas of the coastal zone (in the cities of Koper, Izola, and Piran), where ground penetrating radar was used as the most efficient geophysical method (Maselli and Monti 1994; Car 2005; Mušič 2011). Until now, only the Roman coastal villa in the Bay of San Simon has been the subject of more detailed

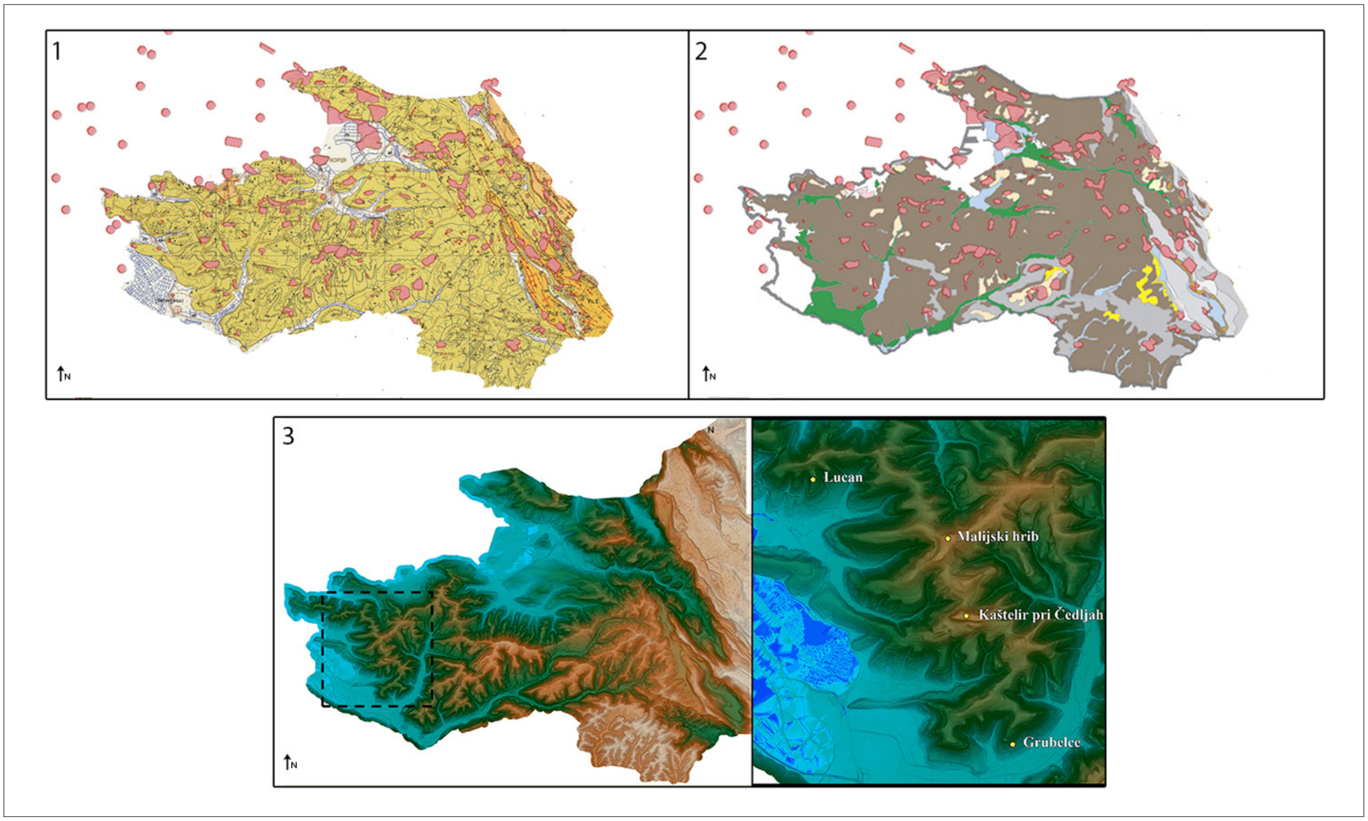

Figure 1. Slovenian Istria. Protected areas of registered archaeological sites (marked in red) on basic geological map 1: 100,000 (map adapted after Plesničar 1970 (1), and map of soils 1: 250,000 (map adapted after Grčman et. al 2015) (2). Studied archaeological sites on a digital elevation model (DEM) (map produced by the author. Raw data: https://gis.arso.gov.si/) (3).

geophysical studies in Slovenian Istria. Numerous geophysical methods have been used successfully over the past decades at the famous site, with excavations and/or chore drilling backing up the results. (Lapajne and Kelhar 1970; Mušič 2006; Groh and Sedlemayer 2017). The wider area of Izola being an exception in terms of geopedological features, since this part is a smaller outcrop of foraminifera limestone bedrock, covered with brown carbonate soil, the results in this work are not directly comparable and not so relevant to the present research. The results nevertheless contribute significantly to the archaeo-geophysical interpretation of various archaeological features and materials found on site. The interior of Slovenian Istria however, where remains of lowland and highland settlement systems are recorded, often with continuous habitation from different archaeological periods ranging from the Copper Age to the Middle Ages, remains completely un-investigated with the use of geophysical methods (Fig 1. 1 and 2). A systematic assessment of a geophysical method in a geo-pedological environment of Slovenian Istria is conducted for the first time in this study.

Each of the geophysical methods is sensitive to different physical parameters of the soil and the buried archaeological structures. A comprehensive interpretation of the archaeological sites usually requires the implementation of a multi-method approach, state-of-the-art in current archaeogeophysics (Piro et al. 2000; Piro 2009; Fassbinder 2011). Nonetheless, in this study, the magnetic method is used as the primary one among all of the geophysical methods, due to its accurate and rapid inspection capability of larger areas, and its ability to identify all types of archaeological remains under ideal conditions (Aspinall et al. 2008; Smekalova et al. 2008; Fassbinder 2015). Numerous surveys that use the magnetic method as the primary method at archaeological sites elsewhere in Slovenia show positive results in the recognition of various types of archaeological remains (Mušič 1999; Mušič et al. 2015; Medarić et al. 2016). However, solutions from one natural environment are often not directly transferable to another. For maximum survey efficiency, with a faster and more archaeologically effective interpretation of the measured data, a precise verification of the results, analysis of individual

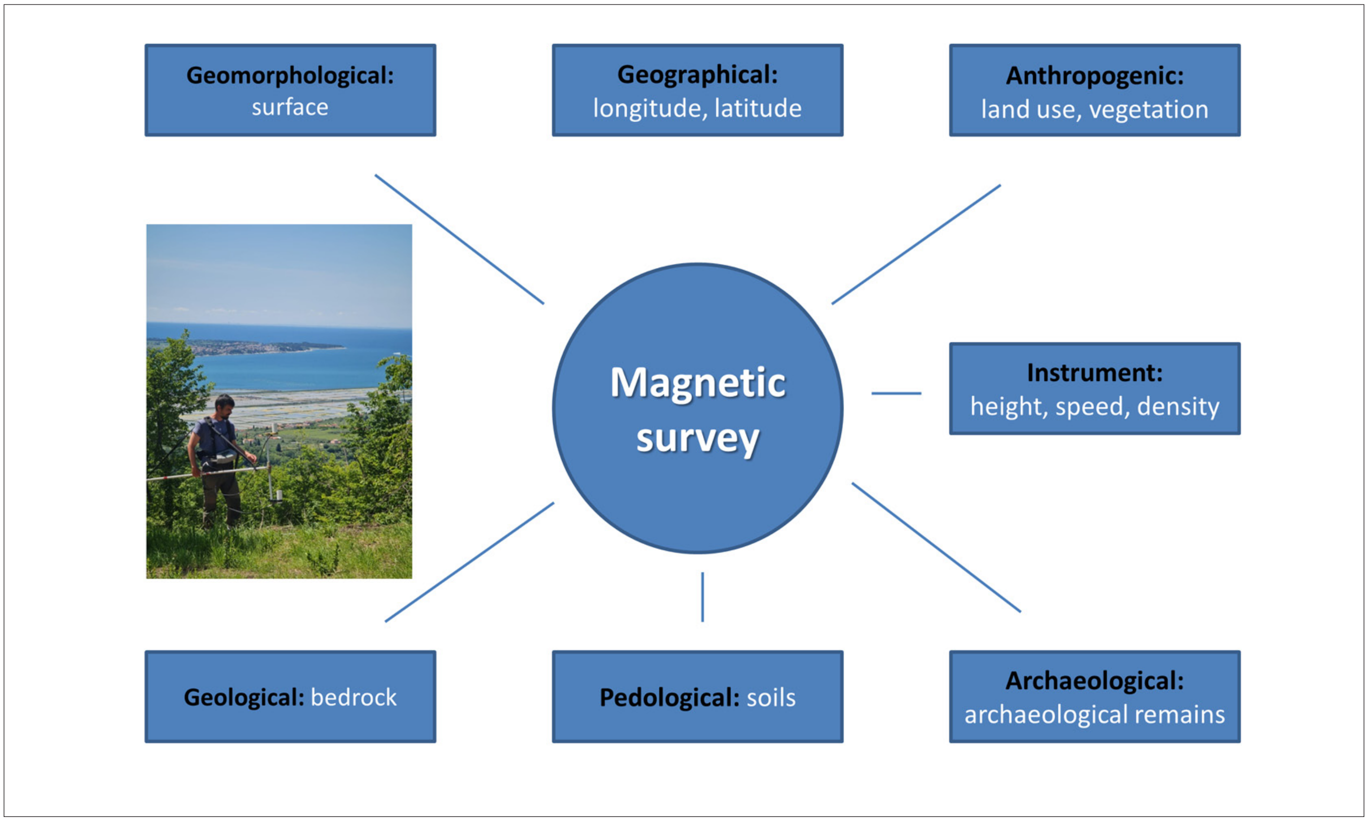

Figure 2. Factors influencing magnetometer survey evaluated in the research project (Photo by: Aleks Kunst).

factors that influence the measurements within specific natural conditions, and adaptation of the results to the goals of the research have to be conducted.

This project aimed at analysing the basic conditions specific to the geo-pedological environment of Slovenian Istria (sols on Eocene flysch bedrock). Detailed evaluation of the effectiveness of the magnetometer survey for identification and determination of the type and physical properties of archaeological remains was carried out in late spring 2021, at four typologically and chronologically different archaeological sites: multi-periodic hill-fort of Kaštelir near Čedlje (Late Bronze Age, Iron Age, Roman Age, Middle ages), hill-fort Malijski hrib (Iron Age, Early Roman period), villa rustica at Grubelce near Dragonja (Roman period) and the site of possible remains of villa rustica or a small medieval village at Lucan (Roman period, Middle Ages) (Fig. 1 and 3). The sites were selected not only for their typological and chronological diversity, but also for their geo-pedological, geographical, and anthropogenic context.

Methodology

Applied fieldwork methodology, on all the archaeological sites consisted of detailed and dense magnetic surveys with a highly sensitive optically pumped magnetometer and surveys of topsoil magnetic susceptibility, carried out at the exact same areas. Due to the limited depth reach of the susceptibility field instrument and the fact that it measures only the component produced by magnetic induction, we were able to complement the magnetic measurements by separating the properties of anomalies caused by susceptibility contrasts from those caused by magnetic remanence. A comparison of magnetic results and resistivity results was carried out on specially selected areas to determine if the magnetometer was capable of detecting the expected weak differences in magnetic properties between drywall remnants constructed from sandstone and soil.

We also analyzed the apparent magnetic susceptibility of soil and typical buried archaeological structures found on-site, or during the test pitting, to determine if there was enough magnetic contrast between them to conduct a magnetometer survey. A catalogue of individual values of apparent magnetic susceptibility measurements on samples of natural and archaeological materials was produced. Together with magnetograms of magnetic anomalies of various archaeological structures, this provided a valuable data set for assisting with future magnetometer surveys in Slovenian Istria.

Other than that, anthropogenic and natural influences, variables, and noises that were faced while conducting magnetic measurements on archaeological sites in the area were also carefully analysed. Variables that affect the identification of the individual anomalies such as the physical properties (shape and size) of the target archaeological structures, the degree of their preservation, and the depth in which they are buried were evaluated. Other influences related to the surface (relief, overgrowth, and anthropogenic influences), choice of the instrument, the way of conducting measurements (e.g. sensors height, data acquisition speed, and density of measurements), and the influence of the operator on the measurements themselves were checked (Fig. 2). The selected areas were re-measured with different densities, heights, and sensitivity levels. By carefully analysing and understanding all the unwanted information (characterized as noise), we were exploring the possibilities to reduce it, or even eliminate it completely. An efficient data capture strategy and a set of advanced processing procedures for the effective solving of specific problems which could arise in the studied environment will be developed.

Magnetometer survey

Magnetometry is one of the most widely used geophysical methods for an accurate and rapid inspection of extensive archaeological areas. Magnetometers detect small local variations in the magnetic flux density in the Earth's magnetic field, due to differences in the magnetic susceptibility of the material below the surface (Clark 1990). Under optimal conditions, sensitive instruments enable the recognition of anomalies resulting from the archaeological remains of various magnetizations (Fassbinder 2015). Magnetometers most successfully identify archaeological remains with thermoremanent magnetization (TRM), which is formed during the cooling of fired materials over its specific Curie temperature (the average Curie temperature of soil components is around 650°C). In this process, elementary particles - magnetic domains align with the external Earth's magnetic field and the burnt material becomes a strong magnet. Thermoremanent magnetisation (TRM) is characteristic mainly for fired clay, fireplaces, ceramic architectural elements, pottery kilns, metallurgical workshops, etc. Strong magnetic anomalies are also produced by larger iron objects, which, however, cannot be reliably defined as archaeological objects, as their magnetic effect is no different from pieces of modern iron.

With sensitive instruments, it is also possible to recognize extremely weak anomalies, which are the result of induced magnetization. This is the effect, when 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. Induced magnetization is specific for instance, for the remains of walls and various forms of buried structures, such as ditches, pits, clusters of pits, and also simple communications and more compact floor surfaces (Le Borgne 1955; Tite and Mullins 1971).

The magnetic data were obtained with the Geometrics G-858 high-sensitivity caesium vapour magnetometer, which enables a resolution of 0, 1 – 0, 2 nT with a reading speed of 0, 2 s. For the analysis, the values of the vertical gradient of the total magnetic field, with the sensors deployed at a fixed distance of 70 cm between each other, were used. Parallel magnetic profiles were measured in a "zigzag" pattern with an interval of 50cm, and with readings along the profiles of 15 cm. The lower sensor was raised at a constant height of 30 cm from the surface.

Magnetic susceptibility survey

Magnetic susceptibility is a measure of the degree to which a substance can be magnetized and it is defined as the ratio of the induced magnetization to the inducing field. Magnetic susceptibility has been well established in geophysical prospecting in archaeology as an independent prospecting technique (Dalan and Banerjee 1998; Dalan 2007). The method has been in use on archaeological sites in Slovenia non solely as an archaeological prospection survey (Mušič 1997; Mušič 1999; Mušič et al. 2014), but also for predicting the success of magnetometer and as an aid for quantitative analysis of magnetic data with the creation of direct magnetic models (Medarić et al 2011; Medarić et al 2016).

The physical parameter expressed as a volume-specific magnetic susceptibility (SI measurement system) (k') was measured with a field instrument (Satisgeo KM-7), with

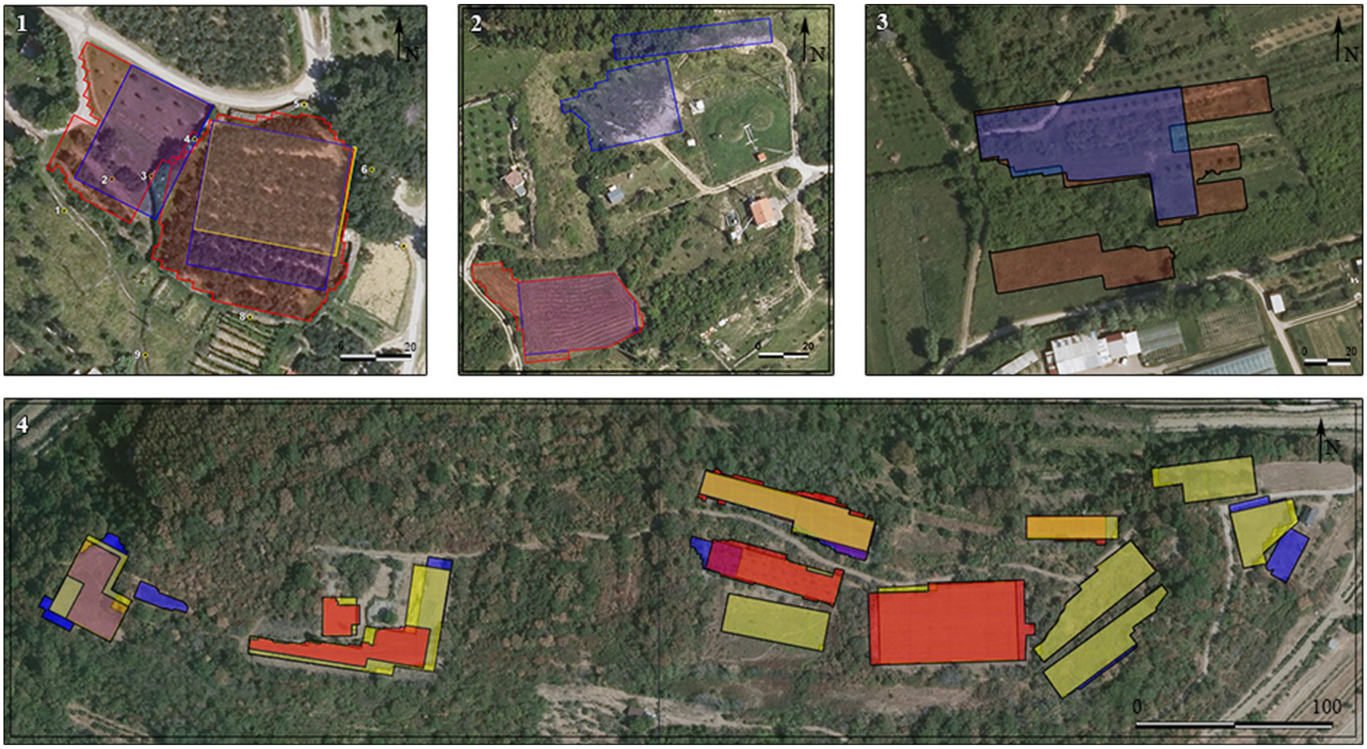

Figure 3. Location of surveyed areas (magnetometer - blue; earth resistance survey - red; topsoil magnetic susceptibility mapping - yellow). 1. Lucan. 2. Malijski hrib; 3. Grubelce near Dragonja, 4. Kaštelir near Čedlje.

a sensitivity of 0,001 x 10-3 SI units. Topsoil susceptibility surveys were performed within the grids of various sizes in a “zigzag” pattern at 2m intervals along parallel transects set 2 meters apart. Since the value of the magnetic susceptibility depends on the size and shape of the object, during the calibration, the measuring coil was applied to an absolutely smooth surface. The samples have been measured several times to obtain the mean value. To minimize the influence of environmental factors such as non-soil inclusions and moisture content, which affects the bulk density, during the measurements of the magnetic properties of the soil, it was made sure that all the samples had equal mass and were dry.

Earth resistance survey

A Geoscan RM85 earth resistance meter with a twin probe array was used for the resistivity survey - a configuration commonly used for archaeological work. For the mapping of the values of apparent electrical resistance, a pair of movable and a pair of static electrodes is used, where the depth range is determined by the distance between the mobile electrodes. The depth range at the distance of 0, 5 m between the electrodes and with the optimum humidity of the soil is 0, 75 m (Clark 1990). In addition to the distance between the moving electrodes, the depth reach is mainly affected by the moisture of the terrain. Measurements performed in the same place will not necessarily give the same results as the moisture conditions at the site change with time.

During the measurements, the static electrodes were placed at a distance of 0, 75 m. A resistivity survey was performed within the individual grids of 20 × 20 meters, by taking readings every 1m by 1m. Most of the electrical resistance measurements on each site were performed under similar conditions so that the soil moisture and thus the depth range and contrast of the results were uniform.

Results

Presented below are some results of the study of individual influences, variables, and noises encountered during the magnetic survey on archaeological sites on Eocene flysch in Slovenian Istria:

Impact of the Bedrock

The largest share (approximately 75%) of the Slovenian Istria is covered by geologically fairly uniform bedrock from the middle Eocene (Istrian Flysch), which predominantly consists of successive sequences of marl and sandstone (Pleničar 1970) (Fig. 1. 1). Magnetic susceptibility samples on the bedrock of sandstone were taken at the archaeological sites during test pitting and on exposed bedrock in their immediate vicinity (Fig. 4). The bedrock shows low mean MS values ranging from 0, 036 × 10^{-3} to 0, 130 × 10^{-3}, with only a few individual values exceeding 0, 2 × 10^{-3} (Table 1). The low and sometimes negative MS values can be attributed to high levels of Quartz (SiO2) (range: 28, 26 % - 49,1 %) and Calcite (CaO) (range: 21, 53 % – 35, 89 %) and low level (1,61 % - 2,47%) of Iron oxides Fe2O3 found in sandstones in the Triest-Koper segment of the Flysch belt (Mikes et al. 2006).

The low magnetic susceptibility of the bedrock had lesser or almost no effect on magnetic measurements in terms of “background noise” and is a favorable environment for the detection of archaeological remains with the magnetometer. No significant overlapping and concealing weaker anomalies representing archaeological structures was recognizable on the magnetograms.

Impact of soil

The relatively uniform Istrian flysch bedrock has also a rather unambiguous connection with the soil. The largest part of the region is covered with eutric brown soil (eutric cambisol). On all four investigated archaeological sites, variations of the same type of soil are present (Repe 2012) (Fig. 1. 2).

Readings on soil samples were taken in the immediate vicinity of archaeological locations on natural soils without anthropogenic disturbance, from the topsoil on the archaeological sites and especially during the test pitting (Figs 5 and 6). Mean MS values from undisturbed soil samples are similar, but slightly higher compare, to the values of sandstone bedrock, and are ranging from 0, 057 × 10^{-3} SI to 0, 138 × 10^{-3}, with individual values over 0, 2 × 10^{-3} but not exceeding 0, 3 × 10^{-3} SI. The low magnetic properties of soil sequences found on sites can be also attributed to the diamagnetic minerals. Analysis of physical and chemical properties previously done on soil samples in Slovenian Istria show that typical soil on Flysch consists of 51% quartz (SiO2), while still relatively low level of Iron oxides Fe2O3 is represented (4, 28 %) (Prus and Grčman 2019).

Since the soils on Flysch are the results of the weathering of the same low magnetic rocks, there is no sharp boundary between the physical properties and magnetic susceptibility of soil and bedrock. A predominantly uniform and isotropic medium without many rock inclusions is also a favorable environment for the detection of any type of anthropogenic contribution to the magnetic susceptibility levels in the soils. The weakly magnetic soils had low magnetic background variations and only minor irregularities, considered as surface noise (e.g. plowing). Both types of noises were easily distinguished on the magnetometer results.

Archaeological site	MS values for bedrock (sandstone) (× 10^{-3} SI units) lowest / mean / highest / standard deviation
Malijski hrib	-0, 181 / 0, 112 / 0, 276 / 0, 116
Kaštelir pri Čedljah	0, 072 / 0, 130 / 0, 207 / 0, 038
Lucan	-0, 033 / 0, 036 / 0, 130 / 0, 050
Grubelce pri Dragonji	0, 003 / 0, 094 / 0, 214 / 0, 057

Table 1. Magnetic susceptibility values of the bedrock, on researched archaeological sites.

Archaeological site	MS values for variants of eutric brown soil ($\times 10^{-3}$ SI) lowest / mean / highest / standard deviation
Malijski hrib	-0,045 / 0,086 / 0, 215/ 0, 060
Kaštelir near Čedlje	0, 029 / 0, 138 / 0, 288 / 0, 063
Grubelce near Dragonja	0, 003 / 0, 057 / 0, 205 / 0, 04
Lucan	0, 040 / 0, 113 / 0, 237 / 0, 041

Table 2. Magnetic susceptibility of the undisturbed soils, measured in the vicinity of individual archaeological site.

Figure 4. Magnetic susceptibility measurements performed on exposed bedrock, south of archaeological Kaštelir near Čedlje (left) and on Malijski hrib (right).

Magnetic properties of the archaeological remains

At surveyed sites, all architectural remains found during previous excavations were made of locally extracted sandstone. (Boltin-Tome 1967; Sakara Sućević et al. 2012.). The mean value of MS for dry-stone rubble remains taken during test pitting on Lucan and Kaštelir near Čedlje is 0, 12 × 10^{-3} (Table 1; Figs 6 and 9) (Medarić and Vinazza 2022). The values of MS do not deviate much from the values of the bedrock (Table 1) or natural soil (Table 2). Consequently, architectural remains from sandstone have a weak contrast in the magnetiza-

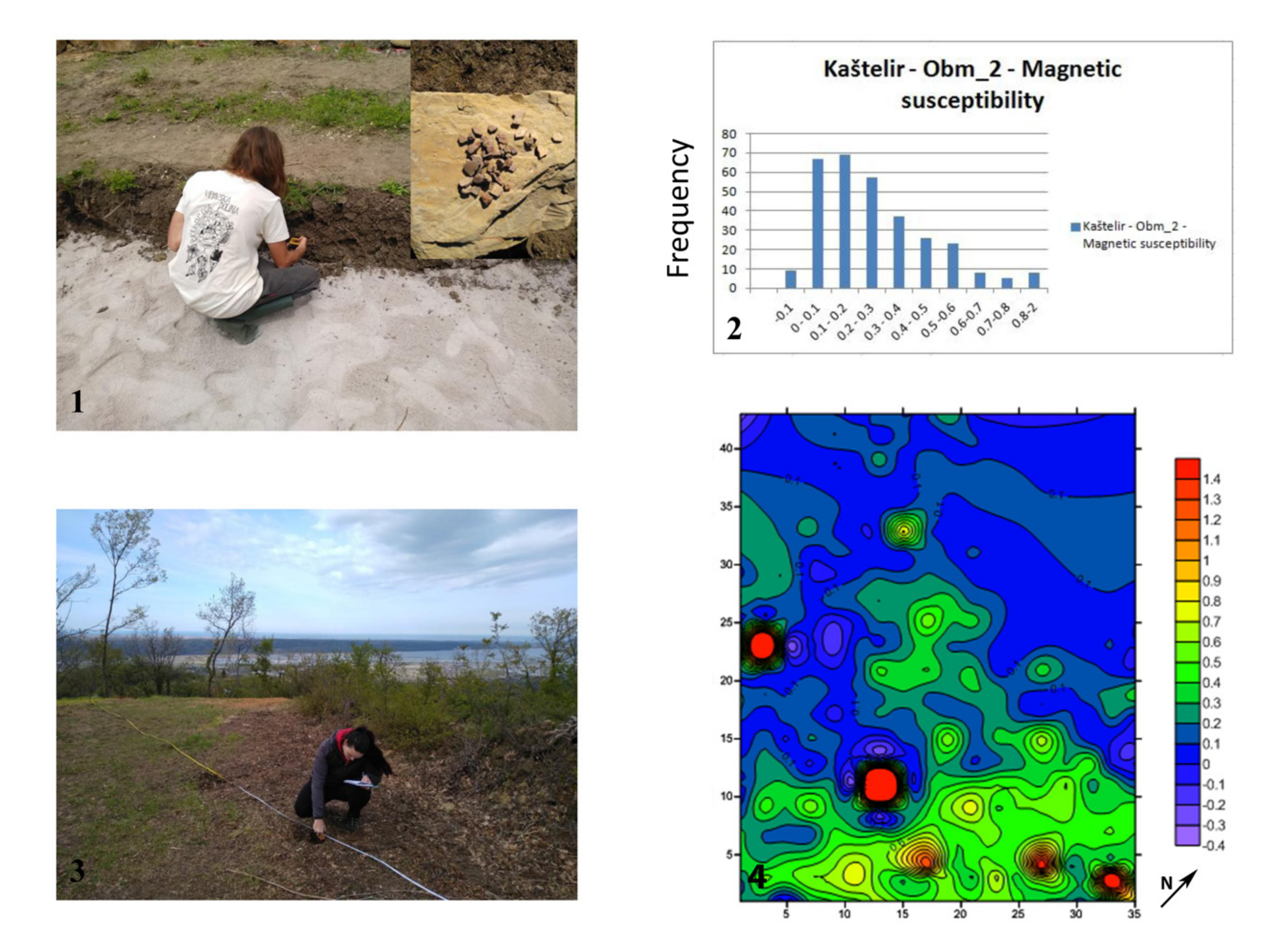

Figure 5. Kaštelir near Čedlje. Measurements of volume magnetic susceptibility conducted in a soil profile (1). Histogram of frequency distribution for collected magnetic susceptibility data (2). Topsoil magnetic susceptibility mapping (3). Magnetic susceptibility map (4). Areas of magnetically enhanced topsoil (values above $0, 3 \times 10^{-3}$ are emphasized in green and red). The accumulation of ceramic remains and daub was found here during construction work dig.

tion against the natural soils (see Tables 1 and 2) and are not easily detectable on the magnetograms. However, on all of the surveyed archaeological sites, past human activities left a permanent and considerably higher magnetic imprint on the soil, which in some cases enabled the stone walls to be more clearly identifiable on magnetic maps. The sandstone structures are more evident on the magnetic maps from the multi-periodic site of Kaštelir near Čedlje, where the accumulation of the ceramics and other burned material is considerably higher due to long occupation, burning processes and the destruction of the settlement during recent cultivation (Figs 6 and 9). On all of the researched sites, sandstone structures (bedrock, rubble, walls) are recognizable on magnetograms as negative and weakly positive anomalies ranging between -1, 5, and 1, 5 nT/m.

An example of magnetic detection of sandstone structures (bedrock or rubble) is shown in figure 6. The sandstones in this case produced negative and weakly positive gradients between -1 and 0, 7 nT. In the northern and northeastern parts, the higher magnetic gradients of 1, 7 - 2 nT well highlight the edges of the structure. In addition to supporting and contributing to the magnetometer survey results, resistance mapping helps define the shape and edges of buried sandstone structures. The resistivity values over sandstones are in this case relatively high (30 - 50 ohm/m) and are enhanced by surrounded relatively low resistivity values (20 - 28 ohm/m) caused by deeper soil and therefore higher moisture content. These deeper soil "pockets," which are evident on both methods, can store archaeological remains that have either been undisturbed by industrial agriculture or pre-

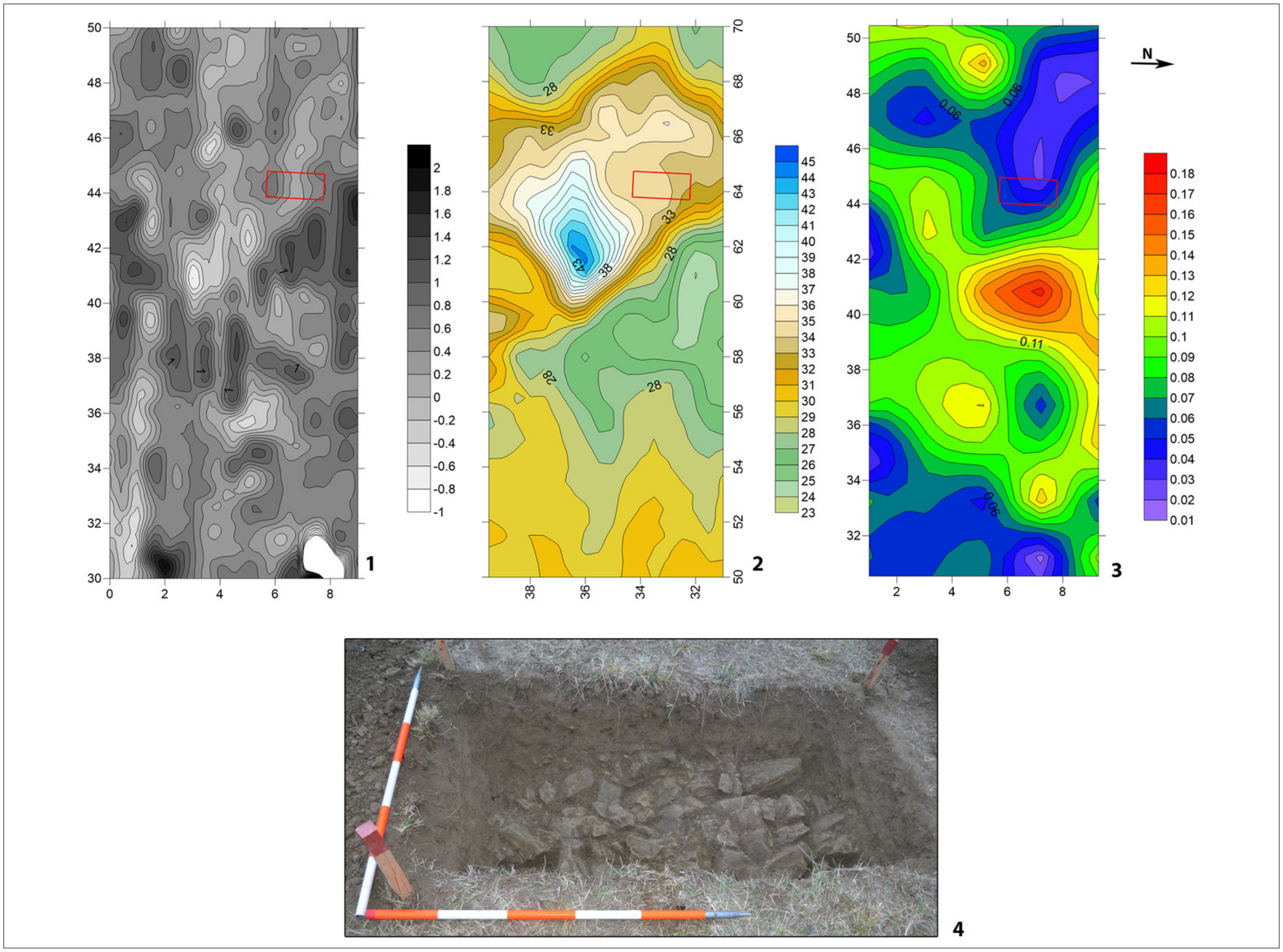

Figure 6. Kaštelir near Čedlje. The possibility of detecting sandstone structures with different geophysical methods. Researched area (10 x 20 m), with the location of test pit 1 x 2 m (marked in red): magnetometer survey (1); earth resistance survey (2), topsoil magnetic susceptibility survey (3) and test pit results (4) (photo by: M. Vinazza, 2022).

sent areas of accumulated archaeological material. This situation was commonly observed in the results in all four locations (see also results on Fig. 9). Although the susceptibility instrument cannot reach the possible in situ archaeological layers, the redisposition of remains through plowing may cause magnetic enhancement of the soil near the surface which can be detectable also with this method. On the topsoil magnetic susceptibility map (Fig. 6.3) also the edges of the sandstone structure can be sensed.

A typical soil background value for each site was estimated based on measurements taken from the surface and during the test pitting. The susceptibility measurements results from the surface and test pitting, at the site Kaštelir near Čedlje have a mean value of 0, 18 × 10^{-3} SI and a standard deviation of 0, 23 × 10^{-3} SI (Medarić and Vinazza 2022). Taking into account the variability, we can suggest that the MS of the soil higher than 0, 25 × 10^{-3} SI, can represent archaeological remains. The materials found in the filling of pits, ditches, and natural features (ceramics, burned clays, slags, and daub remains) can be detected by magnetometers of a high sensitivity. These types of structures produced positive magnetic gradients ranging from 2 to 10 nT/m (Fig. 7)

At the site Grubelce near Sečovlje (roman villa), areas of building debris with TRM such as tegulae, bricks, and imbrexes were successfully mapped with the magnetometer. The structures were well recognizable on magnetograms and produced positive magnetic gradients ranging from 5 nT/m to 20 nT/m.

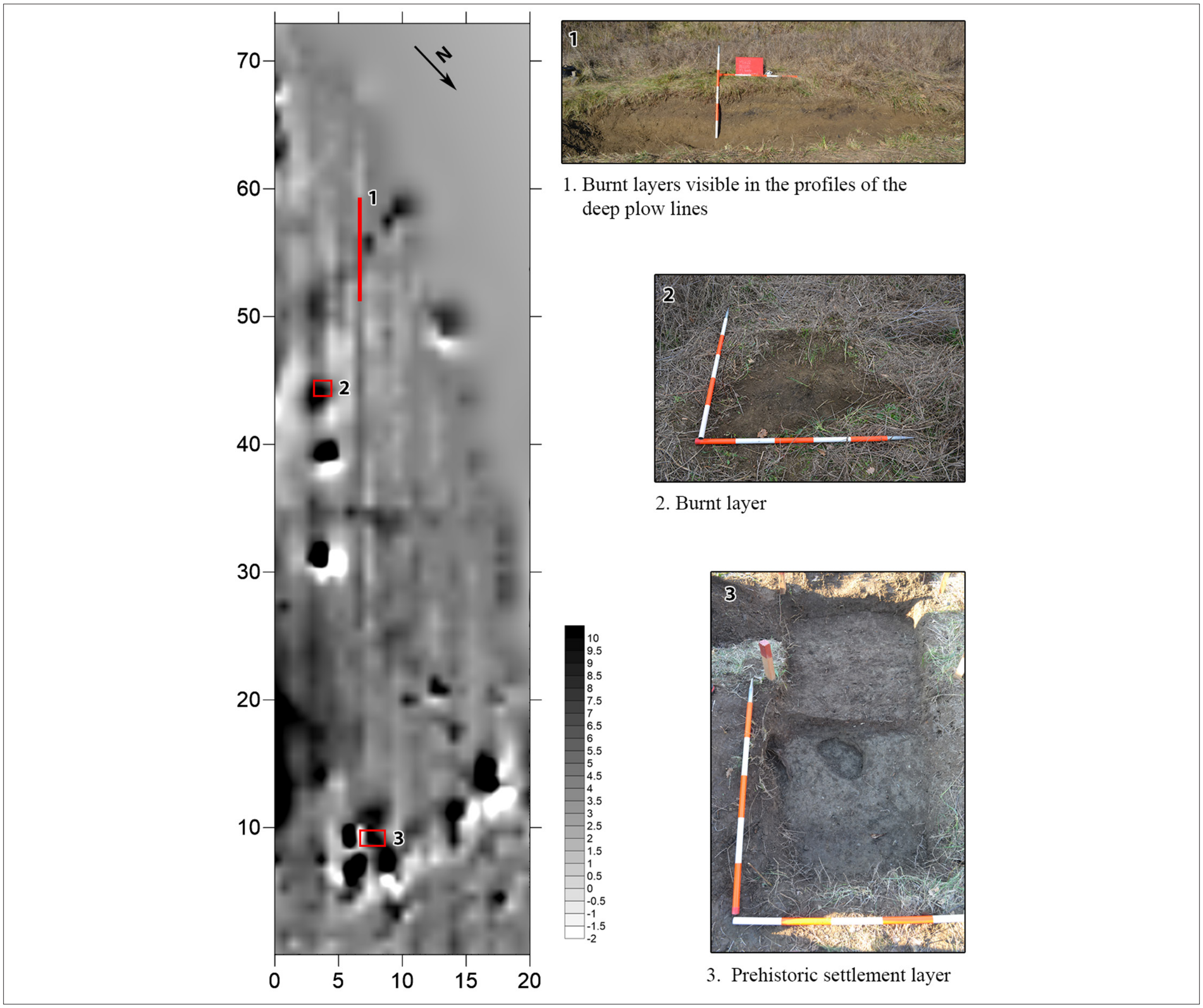

Figure 7. Kaštelir near Čedlje. Area 5. Test pits confirmed in situ archaeological remains (burnt and settlement layers). The structures are clearly visible on the magnetic map as positive gradients with values ranging from 2 to 10 nT/m (left) (photos by: M. Vinazza, 2022).

Archaeological Structure	**MS values (x 10^{-3} SI) for archaeological structures lowest / mean / highest /standard deviation**	**Assessment of recognition capabilities for ideal responses of archaeological structures in soil sequeces on flysch: poor / moderate / good / excellent**
Walls (sandstone)	-0, 169 / 0, 12 / 0, 289 /	moderate
Pits / ditches	0, 25 / 0, 34 / 0, 50 / 0, 70	good
Imbrex / Tegulae	0, 82 / 3, 29 / 1, 71 / 1, 03	Excellent
Daub	1, 16 / 7, 65 / 20, 54 / 5.95	Excellent
Roman brick	7, 83 / 9, 05 / 10, 83 /1, 83	Excellent
Slag	32 / 91, 5 / 54 / 11, 2	Excellent

Table 3. Values of magnetic susceptibility and assessment of magnetometer recognition capabilities of individual archaeological structures.

The soil thickness and the depth of the buried archaeological structures

In vertical gradient mode, with a survey height of 35 cm above ground level, the depth range of the magnetometer surveys is approximately 1 m - to the tops of buried structures (Scollar et al. 1990). Although, when estimating depth, the variation in size, shape, and magnetization of buried archaeological structures has to be considered. During the test pitting from Kaštelir near Čedlje and Lucan, archaeological structures recognized on the magnetograms were buried at shallow depths (between 20 and 50 cm) (Medarić and Vinazza 2022). The depth ranges are comparable to the results from previous excavations on the surveyed sites (Boltin-Tome 1958; 1967; Sakara Sučević et al. 2012, Tomaž and Sakara Sučević 2017).

The shallow depths, on which the archaeological remains are buried on the archaeological sites in soils on Flysch, represent another favorable condition for mapping and identifying the type of archaeological structures (Figs 6 and 7). However, the archaeological structures in shallow soil are consequently more exposed to devastating anthropogenic factors, mostly agricultural, such as plowing and terracing. Archaeological layers during vineyard plowing can be heavily mixed or in some cases completely destroyed all the way to the bedrock. Nonetheless, for the detection of the destroyed sites and defining their boundaries, a dense magnetic susceptibility survey of the topsoil was applied with great success on Kaštelir near Čedlje (Fig. 5).

External influences - geomorphic and anthropogenic factors (vegetation, land use, infrastructure)

Archaeological sites located in the area are currently used as agricultural land. The most typical commercial agricultural practices are olive groves, orchards, and vineyards. Due to the strong erosion processes, typical for Flysch in Slovenian Istria, people constructed terraces and built dry-stone boundary walls between the arable lands (see Fig. 3). Both constructions are significant obstacles to a successful implementation of the magnetic survey. On top of that, archaeological sites are mostly inaccessible due to overgrowth. Altogether they represent a limiting factor since they prevent extensive magnetic surveys, which would enable us to get a more holistic view of the researched sites.

Olive groves and orchards with densely planted trees are a demanding polygon for successful magnetic surveys. During the magnetic measurements in the olive groves on the sites of Lucan and Kaštelir near Čedlje, the trees had an impact on the position noise resulting in an error in the accuracy of acquiring the magnetic data. Moving in the direction of the set profiles was aggravated, with the trees affecting the changes in the sensor's height and survey speed. This type of small inconsistencies can significantly contribute to producing erroneous measured data and a faulty final interpretation. Measurement errors such as the positional and speed noise were reduced by placing the grids and measuring profiles parallel to the direction of the tree rows and by repeating the inappropriate measurements.

There were no recognizable anomalies of roots on the magnetograms apart from the influence of individual tree trunks. However weak enhancement of susceptibility is visible in the direction of olive tree rows supposable due to the hoeing of the olive trees. This effect of mixing the higher magnetic soil with the topsoil is even more evident in the magnetic results where the measurements were taken in profiles 1 m apart.

The effect of conducting measurements in a lavender field was also evaluated. Measurements were taken before and after the lavender field was felled – consequently on different heights (Fig. 8). The reduced quality of resolution details was expected since the strength of magnetic anomalies is decreasing inversely with the distance of the sensors from the source of anomalies. However, this small "experiment", showed that the magnetometers can be efficient in similar situations and emphasizes the importance of conducting the measurements with a sensor on a lower height (approx. 25 – 30 cm above the surface). In this way, all the weaker magnetic gradients and anomalies caused by smaller archaeological remains can be mapped more efficiency.

The magnetic survey in the vineyards was completely inhibited as the buried weights made from concrete and metal wires supporting the vines produced unwanted noise which had a significant effect on the results. Modern features such as metal fences, pipelines, power lines, and antennas posed similar problems on the site of Malijski hrib, where most of the areas were unsuitable for the magnetic survey (see Fig. 2).

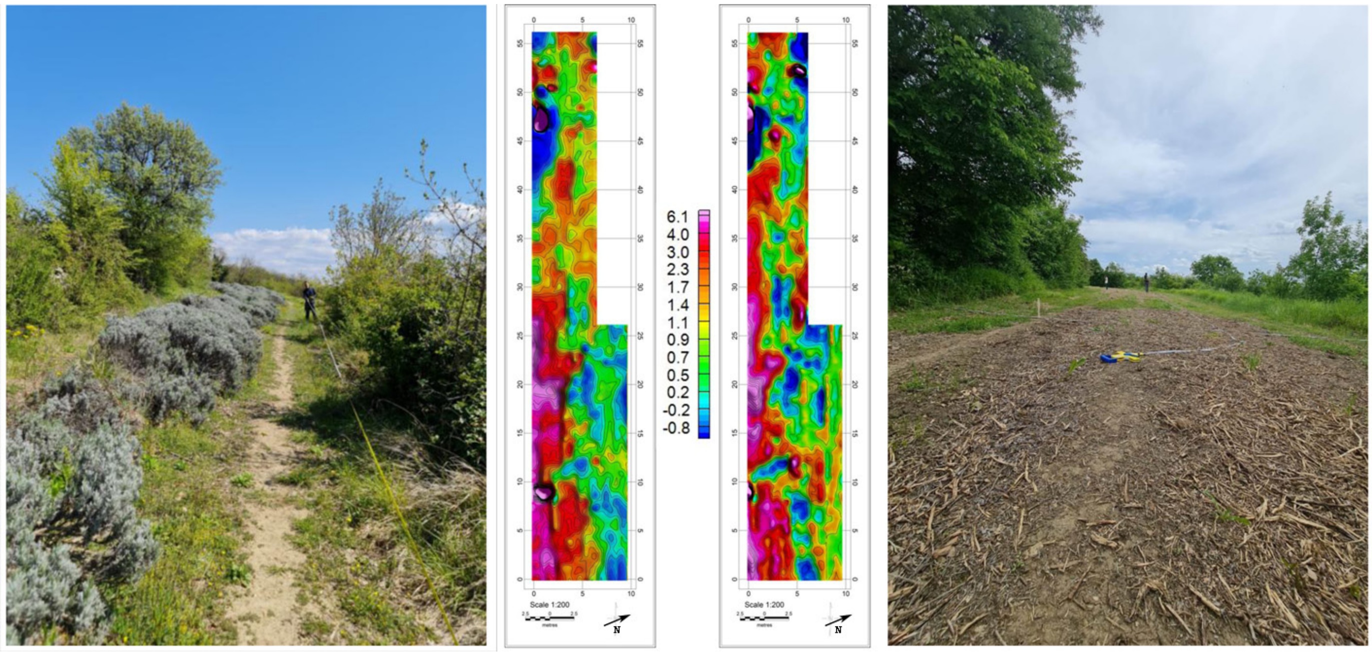

Figure 8. Kaštelir near Čedlje. The effect of vegetation on magnetometer readings. Surveyed area before (left) and after (right) the lavender was felled. Higher magnetic gradients (2 – 10 nT) seen in the southern–southeastern edge are suggesting an accumulation of archaeological material and possible in situ archaeological remains. Excavations conducted by previous researchers here support the interpretation of magnetometer data (see Sakara Sučević et al. 2012).

Influence of the instrument / conducting measurements

Due to the expected low values of magnetic susceptibility, a high-resolution magnetometer was used, which enabled the successful detection of weak anomalies of archaeological structures with induced magnetization. In such magnetically quiet environments, with extremely low magnetic contrasts, lines that run in the direction of measurements often stand out on the raw magnetic data. High-resolution sensors detected the smallest technically flawed measurement procedures, such as changes in measurement speed, differences in the position of sensors in two opposite directions, and sometimes also the magnetic effect of the operator. It became evident that the choice of the instrument is an important factor for a successful magnetic survey in this environment. In addition to the sensitivity of the instrument, instrument performance in noise correction, due to the choice of measurement direction and even using the instrument on a cart has to be considered.

The effect of conducting measurements (such as sensors height, data acquisition speed, and measurement density) was also evaluated in the study. As shown in Figure 9 an example of the magnetic gradient observed with a different spacing between the profiles 0, 5 m (Fig. 9. 1a - 1c) and 1m (Fig. 9. 1d - 1f) is presented. The total number of the readings recorded per each 15 m profile also

Factors	Bedrock	Soil	Anthropogenic	Targeted structures	Depth	Instrument/ Operator
Influence: Low/ Medium/ High	Low	Low	High	Medium / Varies	Low	High
Suitability	Favourable	Favourable	Unfavourable	Mostly favourable	Favourable	Favourable

Table 4. Influence levels of various natural and anthropogenic factors affecting magnetic surveys on soils on Flysch.

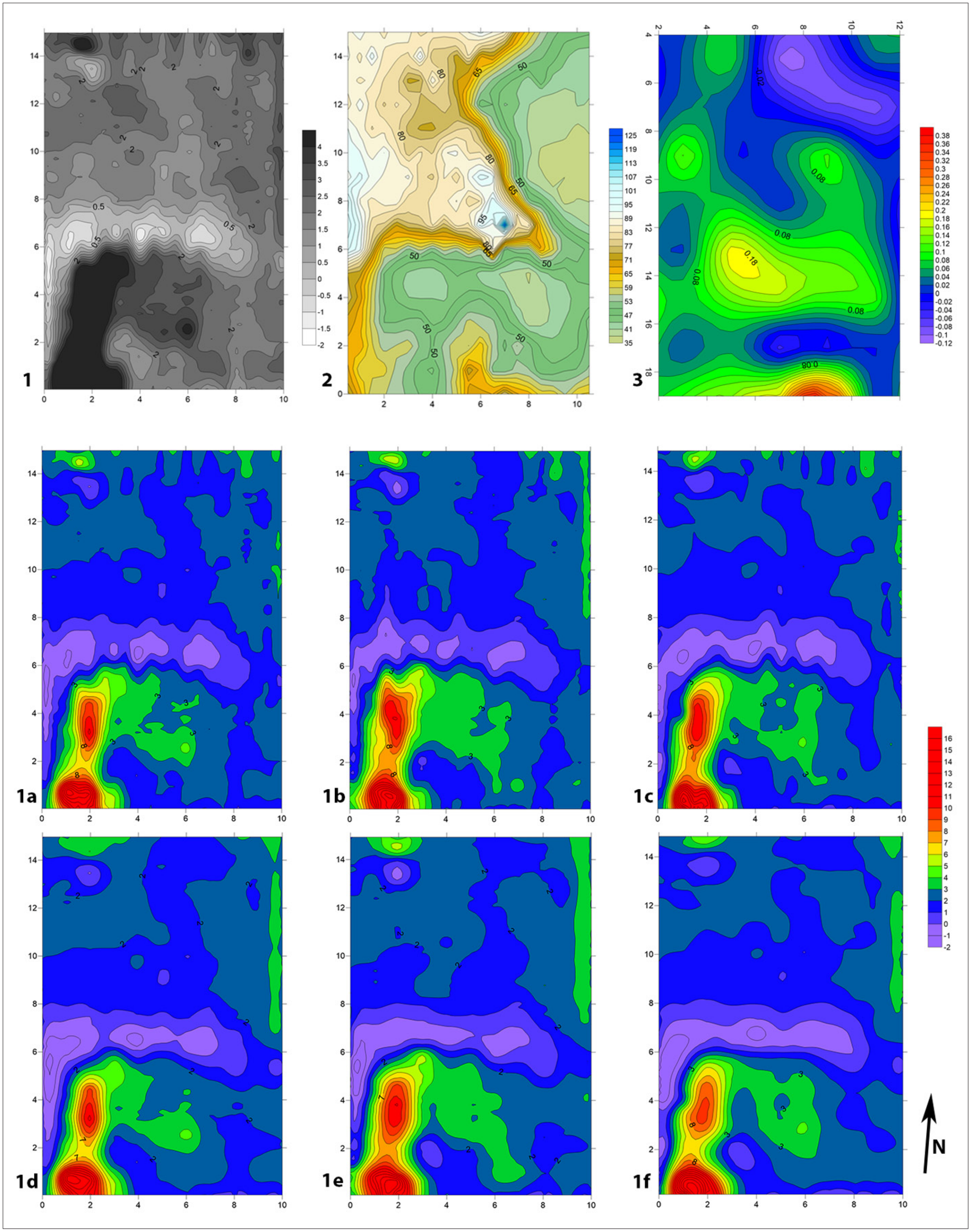

Figure 9. Kaštelir near Čedlje. The comparison of geophysical results obtained over a 10 x 15 m area: magnetometer survey (1), earth resistance survey (2), and topsoil magnetic susceptibility survey (3). Magnetometer survey results obtained with different data acquisition settings: 225 (1a), 115 (1b), and 45 (1c) readings recorded per 15 m profile, with 0, 5 m between profiles, and 225 (1d), 115 (1e), and 45 (1f) readings recorded with 1m between profiles. Although in all the magnetometer maps all three types of anomalies are well identifiable, the denser readings (higher resolution) are crucial for detecting more in details the shapes of buried structures

varied: 225 (Fig. 9. 1a and 1d), 115 (Fig. 9. 1b and 1e), and 45 (Fig. 9. 1c and 1f). Three types of anomalies can be identified in the studied area (including some that may be indicative of archaeological remains): negative and positive anomalies (-1, 5 to 1, 5 nT) marked in purple and blue are caused by weakly magnetic or non-magnetic materials (sandstone bedrock or rubble), positive anomalies from 2 to 6 nT marked in green are possibly due to accumulation of the human habitation (repeated heating of the soil as well as accumulation of organic debris, etc.) with two local high-intensive anomalies (6 – 15 nT) marked in yellow and red possibly in - situ archaeological structures due to the burning.

Conclusion

In the research, it has been demonstrated that magnetic methods can be efficiently used to identify and interpret a wide range of archaeological remains buried in the soil sequence on the Istrian flysch. Conditions related to bedrock and soil (thickness, uniformity, and low magnetic susceptibility background) are favorable since they do not significantly affect measurements. Negative impacts on magnetic research are mostly anthropogenic. Obstacles such as terraces and walls between cultivated areas, as well as overgrowth or, more often, cultivated orchards and olive groves greatly impede, and in some cases, prevent the magnetometer survey. Similarly, the measurements have been hampered by the influence of modern elements typically found in the area, such as metal fences in vineyards, but also common noise as pipes, power lines, and erected antennas. Nevertheless, under optimal conditions, in areas without external noise and major interventions or land use, the magnetometers successfully identified various types of archaeological remains, such as ditches, pits, floors, burnt houses, and walls. The identification of locally formed sandstone walls is strongly related to magnetic enhancement due to human activities in the past, as a higher magnetic background is required for their unequivocal detection. Successful distinguishing between natural and artificial sandstone structures and more effective positioning of the magnetic anomalies produced by the walls using only the magnetic method still presents a considerable challenge. However, the study gave us a much better understanding of the ranges of magnetic data values of possible sandstone remnants. Some percentage of the final result of successful magnetometer research in soils on Flysch can be attributed to the resolution of the instrument and the consistency of control over the optimal course of measurements. Therefore, magnetic data of the best possible quality should be obtained when conducting measurements. Cesium magnetometer surveys have proven to be effective in identifying subtle and low-contrast magnetic anomalies, making them a suitable choice for effective surveying. Both magnetometer surveys and especially topsoil magnetic susceptibility surveys have also proven to be very good in complementing other geophysical methods resulting in situations where there is no architecture, especially in areas where archaeological sites have been destroyed by agriculture.

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