Geophysical prospecting in Slovenia: an overview with some observatons related to the natural environment

Branko MUŠIČ

Izvleček

Desetletje geofizikalnih raziskav za potrebe arheologije na Oddelku za arheologijo Univerze v Ljubljani je dalo vrsto koristnih informacij tako za akademske arheološke analize kot tudi za zaščito arheološke kulturne dediščine pred gradbenimi posegi v prostor. Sodelovanje z arheološko stroko ocenjujem kot konstruktivno tudi zaradi izdatne pomoči pri pridobivanju povratnih informacij o rezultatih arheoloških izkopavanj in drugih arheo-loških virov, kar je preraslo v skupno načrtovanje raziskav za prihodnost. Uspešnost sodelovanja nazorno ilustrira že baza podatkov, ki obsega preko 150 lokacij doma in v tujini, kar predstavlja dober potencial tudi za vključevanje v teoretične diskurze o potencialu uporabne geofizike v arheologiji. Po mojem je eden od temeljnih problemov arheološke prospekcije še vedno ocena ustreznosti posameznih tehnik v odvisnosti od naravnih danosti in tipa arheoloških ostalin. To je zelo ambiciozna tema, ki jo odpiram s tem članko m. Veliko problemov bo seveda tudi s tem prispevkom ostalo nerešenih, rešitve, ki jih po-nujam, so rezultat lastnih izkušenj in jih zato utemeljujem samo na podatkih, do katerih sem prišel sam. Razmišljanja o tej temi ilustriram z rezultati izbranih raziskav, ki zadovoljivo opišejo možnosti geofizikalne prospekcije za detekcijo nekaterih značil-nih tipov ostalin v konkretnih naravnih okoljih. Večina teh raz-iskav je bila že objavljena v arheološki strokovni literaturi zato se v tem članku omejujem le na tiste podatke, ki z različnih gledišč prispevajo k pojasnjevanju ocene potenciala geofizikal-ne prospekcije pri različnih delovnih pogojih. Rezultati geofizikalnih raziskav na prazgodovinskih najdiščih so kljub razmeroma velikemu številu raziskav, ki so bile opravljene v okviru arheološke prospekcije predvsem na trasah, predvidenih za gradnjo avtocest, še brez uporabnih zaključkov, zato razlagam predvsem ugotovitve, do katerih sem prišel z raziskavami na antičnih najdiščih v različnih naravnih okoljih.

Abstract

Decade of geophysical investigations for archaeological purposes at the Department of Archaeology, the University of Ljubljana, have produced a series of useful information for academic archaeological analyses as well as for the protection of the archaeological cultural heritage from construction intervention. It is my opinion that cooperation with the archaeological profession is constructive as it substantially contributes to the attainment of reflective information on the results of archaeological excavations and other archaeological sources, all of which have augmented into a combined research plan for the future. The success of this cooperation is clearly illustrated already by the database including more than 150 locations at home and abroad, also presenting good potential for being incorporated in theoretic discussions concerning the potential of applied geophysics in archaeology. One of the main problems with archaeological prospecting is still the evaluation of the suitability of individual techniques with regard to the various natural environments and the types of archaeological remains. This is a rather ambitious theme that I am opening to discussion with this article. Numerous problems will obviously remain unsolved even with the publishing of this article; the solutions that I am presenting are the result of my own experience and I thus ground them on my own data exclusively. I shall illustrate my thoughts on this theme with the results of select investigations which satisfactorily describe the possibilities provided by geophysical prospecting for the detection of certain characteristic types of archaeological remains in diverse natural environments. The majority of these investigations have already been published in the archaeological literature, for this reason I have limited the scope of this article to those data that contribute, from various points of view, to the clarification of the potential of geophysical prospecting under diverse working conditions. The results from geophysical investigations on prehistoric sites are still lacking of any applicable conclusions, despite the relatively large number of investigations that were carried out within the framework of archaeological prospecting primarily along the routes anticipated for the construction of highways; for this reason I shall for the most part present the research determinations attained through investigations on Roman sites in various natural environments.

INTRODUCTION

The first geophysical prospecting on an archaeological site in Slovenia was executed by Eng. Franc Miklič (IGGG, Ljubljana) in 1969 at Dolge njive in Vrhnika (Mikl Curk 1970, 39-40). Andy Waters from the University in Bradford commenced systematic geophysical prospecting in 1986 on the initiative of dr. Božidar Slapšak (see Waters 1989, 74-77). Doctorate students at the same University, Cris Gaffney and Vincent Gaffney, continued his work in the years 1988 and 1989. In 1990, the then Secretariat for Science and Technology granted the Department of Archaeology at the Faculty of Philosophy, University of Ljubljana, the means to purchase geophysical equipment (a Resistance meter Geoscan RM15 and Fluxgate gradiometer Geoscan FM36, Geoscan Research, Bradford, UK). Due to other ongoing research projects requiring geophysical equipment, we collaborated with other Institutes that also enabled research with a field instrument for measuring the apparent magnetic susceptibility (a Kappameter KT-5; the Administration of Culture, Republic of Slovenia), a proton magnetometer for measuring the total magnetic field (a Geometrics G 819; IGGG Ljubljana and a GemSystem GSM19; the Faculty for Electrotechnics, University of Ljubljana), and georadar measurements (using a GSSI SIR 3; MIC d. o. o., Ljubljana).

The research strategy, from the outset of independent geophysical prospecting at the Department of Archaeology in 1990, was primarily directed towards collecting data on anomalies in physical fields resulting from archaeological remains that are situated in various natural environments. We avoided selecting -economic- and -noneconomic- archaeological sites based upon their anticipated archaeological potential, their level of conservation, their natural features and the presumed detectability of archaeological remains under their respective conditions. Consequently, the general concept that has been grounded on these principles currently enables a comprehensive evaluation of the suitability of various geophysical techniques for the detection of particular types of archaeological remains situated in various natural environments on the basis of a relatively extensive database (more than 150 locations here and abroad).

The more significant primary objectives of geophysical prospecting can be summarized as follows:

To determine the correspondence between various geophysical techniques for the detection of particular types of archaeological remains situated in various natural environments, where the division of Slovenia into regional systems is used to determine the geological/pedological foundations. These regional systems can be classified as the functions of basic geology, relief, climatic conditions and the hydrosphere. The result of these factors are the soil and pedosequences, which are defined as soil sequences that appear in the same or similar foundation (Stritar 1990, 51). Pedosequences generally correspond to the boundaries of regional systems and define them in a geographic sense and, furthermore, dictate their present-day agricultural purpose. Natural and anthropogenic components of the regional system influence each in themselves, as well as on the whole, upon the potential of archaeological prospecting.

One of the basic principles of geophysical prospecting is to apply a variety of geophysical techniques at the same archaeological site, wherever possible, irrelevant of the estimated detectability of the anticipated archaeological remains. Current applications include magnetometry using a fluxgate gradiometer and a proton magnetometer, measuring the magnetic susceptibility, the apparent resistivity and self potentials, as well as georadar measurements. Such an approach procures more data, which consequently enables a better interpretation (e.g. *the principle of anomaly associations in the physical field*).

To determine the -critical- or -border- values of the multitudinous anomalies measured in the physical expanse. It is an empirical or statistically determined value which represents the lower limit of a -significant- anomaly characteristic for a particular type of archaeological remain in an established archaeological context and natural environment. Basically, it is a matter of distinguishing the signal to noise ratio; to do so, the value span, which is a result of noise, must first be established. These so-called -critical- values can, in an archaeological context, also determine the boundaries between varying activity areas which, for instance, C. Carr (1982) first defined for the resistivity method.

To employ an approach similar to combining multi-channel satellite shots into a composite picture, replacing the satellite shots with a data series from archaeological prospecting. The conjunction of various geophysical data as well as geophysical data together with data from archaeological field survey is thus enabled (see i.e. *unsupervised classification*; Ladefoged et al. 1995, 471-481).

Concerning the stance of geophysical prospecting in archaeology, I generally agree with the evaluation of Boucher (1996, 139): -It would appear that there is an underlying philosophy of archaeological prospection being primarily a locational or evaluation tool and its increased use in pre-planning permission determinations has firmly chanelled it in this direction-. The same author continues and ascertains that the possibilities for instating geophysical methods into the entire specter of archaeological analyses should be considered more frequently and more earnestly. The author's well-intentioned and illustrative assertion, which probably expresses the general conviction on geophysical prospecting in the field of archaeology, nevertheless overlooks select significant investigations that were rendered on archaeological materials and were aimed at comprehending the results from geophysical prospecting (see i.e. Carr 1982). I believe that laboratory analyses of a relatively small number of soil samples also contribute to improved archaeological interpretational evidence, especially as concerns 'activity areas'. Accordingly, further analyses are then carried out upon samples exclusively from regions that were determined, on the basis of previous geophysical prospecting, as potential centers of particular activities in the archaeological past. Geophysical prospecting thus incorporates granulometrical analyses, X - ray analyses, differential thermal analyses and laboratory measurements of the magnetic susceptibility.

THE DATABASE FOR GEOPHYSICAL PROSPECTING

This article presents a review of the current stance of geophysical prospecting in the region of Slovenia in view of the evaluated potential of individual geophysical techniques subject to the natural characteristics and the type of archaeological remains. The Department of Archaeology has, in addition to the above mentioned investigations carried out in Slovenia within the framework of various international projects, completed geophysical prospecting at numerous archaeological sites abroad (they are omitted due to their divergence from the concept of this article).

Owing to the relatively large amount of geophysical prospecting performed since 1990 the creation of a suitable database was considered a prerequisite for the successful execution of the primary goal, which I deem to be the determination of the suitability of various geophysical techniques for archaeological prospecting subject to the type of archaeological remain and the natural characteristics. The whole database comprises more than 150 geophysical investigations on archaeological sites in Slovenia and abroad. In the *Table 1* are included some sites which are ilustrative for mentioned goals.

Information cited in the literature may be helpful to some degree when determining the potential of geophysical techniques, although it is insufficient for a more precise evaluation. The most evident limitation is that predominantly results from -successful- geophysical investigations are cited in the literature, that is, the majority of cases were executed on recognized archaeological sites with well preserved archaeological remains and various other favorable natural characteristics. Noticeably fewer publications are more research oriented and deal with the effectiveness of geophysical techniques under various working conditions (see Bevan 1996a; 1996b and 1996c). An extensive investigation was organized in which numerous various techniques were tested, for example, within the region of the Selinunte archaeological park, Sicily (Finetti 1992, 83-232). Publications concerning geophysical investigations that failed to produce the anticipated results are even more seldom (see i.e. Nishimura et al. 1991, 757-765).

Much attention has been dedicated to national archaeological databases, in the past few years, that also incorporate results from geophysical investigations (see i.e. Linford, Cottrell 1994, 133-134; http://www.eng-h.gov.uk/). This could be an indication that archaeological prospecting, and consequently also geophysical investigations, have sufficiently asserted themselves throughout the academic world serving for archaeological settlement analyses, as well as for the everyday conservation of the cultural heritage. These types of databases are usually quite specific and with a strongly accentuated goal to record and document anomalies in the physical fields resulting from various archaeological features; they tend to follow the recognized trend of persuading archaeologists in the effectiveness and almost infallibility of these sorts of investigations that are based upon modern electronics and computer technology. Newer databases are created in program packages that serve as tools for examining extensive databases for geographic information systems (i.e. *ArcView, Esri*). The primary advantage of these databases is that they enable a link between the textual part of the database and the graphic foundations composed of georeferential information on geophysical investigations and aerial photography (see i.e. Doneus, Neubauer 1998, 29-56). I also chose this type of open database structure as it enables the combination of diverse types of information concerning archaeology, archaeological prospecting and the natural environment.

The trends in geophysical investigations in archaeology indicate that the phase of -filtering- so-called -raw- values has, having experienced its culmination at the end of the 1980's and the beginning of the 1990's, finally expired. At that time, such an extensive selection of investigations was not yet available considering that they only came into full swing with the development of microcomputers. Initially the trend was to present and process the data in the foreground with the intention of emphasizing the significant anomalies in the physical fields, which result from the presence of archaeological structures against the various noise in the background. The aim was to substitute the missing values, which were the aftereffect of optimizing field work so as to accelerate the process of data collection. Various modification masks that were used for digital image enhancement prior to this were usually applied. A later research trend can best be illustrated on the example of magnetometry. Research evolved in the direction of the development of better instruments with greater resolution and highly accelerated data collection capabilities (see i.e. Becker 1995, 217-228), as well as the development of program and machine equipment enabling enormous amounts of data to be processed. This still speaks in favor of investing in magnetometers with a higher resolution, which due to their being robust (see Doneus, Neubauer 1998, 32), are useful only up to the first physical obstacle - with some instruments, this could already be a small step in the field (i.e. the demarcation of a lot) - and useful only on entirely flat surfaces - which is irrelevant throughout most of Slovenia. Furthermore, the high resolution factor of instruments is pronounced exclusively in magnetically -quiet- areas. Consequently, there have been numerous articles published during the past few years discussing the results of magnetometric investigations on so-called Neolithic rings (see i.e. Eder-Hinterleitner, Neubauer, Melichar 1996, 185-197; Kuzma et al. 1996, 71-79; Becker 1995, 222; Doneus, Neubauer 1998, 42-47). These rings, in terms of geophysical prospecting, manifest themselves as negative topographic anomalies, or rather ditches, that were filled with upper horizons of soil over time and are usually more magnetic than horizons lying further below (Clark 1990). This explains the weak contrast in the magnetic susceptibility between ditches and the medium through which they cut, which is usually clay, a homogeneous composition. This weak anomaly in the Earth's magnetic field can nevertheless be measured using a Cesium gradiometer which has a resolution of at least 0.1 nT/m, while newer versions have a factor of even 0.01 nT (1pT). Many of these Neolithic rings are also visible already from aerial photographs. The difference between a Cesium magnetometer and a more inexpensive one, such as a fluxgate gradiometer, becomes negligible on -regular- and, as far as magnetic characteristics are concerned, heterogeneous sites where the background is quite variable. This could be illustrated by H. Becker's investigations in the Troy region, where the advantages of a Cesium magnetometer are demonstrated; yet I believe that the results fail to sufficiently substantiate this assertion. Practically equivalent results were obtained with the Geoscan FM36 fluxgate gradiometer, which is simpler to use and also considerably more inexpensive.

Bevan (Geosight, USA) chose a different approach to geophysical prospecting in archaeology. His prospecting results are cited in three unpublished reports (Bevan 1996a; 1996b and 1996c). Relying on the basis of numerous investigations at very diverse sites, he was the first to provide an evaluation of the suitability of various geophysical techniques subject to the natural characteristics and the types of archaeological remains. Only recently have proposals recommending appropriate solutions for regulating databases for geophysical prospecting begun to be published (Linford, Cottrell 1994a, 71-72; 1994b, 133-134; Doneus, Neubauer 1998, 29-56). Due to the enormous amounts of data, they should be linked in such a manner that immediate access to information, essential for either academic settlement analyses or for the protection and conservation of the archaeological cultural heritage, is enabled.

While establishing the database for geophysical prospecting, the fundamental principles of the English Heritage Geophysical Survey Database (SDB), proposed by the Ancient Monuments Laboratory (//www.eng-h.gov.uk/) in 1994, were taken into consideration. As the national database for archaeological sites (ARKAS) (Tecco-Hvala1992, 62-63) is a project underway for many years already at the Institute of Archaeology, Scientific Research Center of Slovenian Academy of Sciences and Arts, the particularities of this database were also considered while creating the one for geophysical prospecting. The database is intended to provide an organized register of archaeological sites according to the established criteria for organizing archaeological databases while taking into consideration the specifics of geophysical investigations. The register includes all sites upon which prospecting was executed between the years 1990 and 1998. A description of the geographic location of the site, the use of surface area and the chronological determination are attributes that are recorded applying the same procedure as used at ZRC SAZU in managing the archaeological database (ARKAS;//www.zrc-sazu.si/aspweb/ARCAS-normal.htm/); the database structure is presented in the article by S. Tecco-Hvala (1992, 62-63). The remaining information fields are selected and organized in such a way so as to enable an evaluation of the potential of geophysical investigations for determining the various types of archaeological remains in diverse natural surroundings. I used the division of Slovenia into regional systems (pedosequences) as established by Stritar (1990, 29-30) for describing the natural surroundings. This division, despite certain doubts regarding the precision in the classification of natural surroundings, seems the most suitable solution for describing the potential of geophysical prospecting methods in various natural environments. The practicability of this division is seen especially in that it substantiates pedosequences on the basis of their basic geological foundation, while at the same time it also takes into consideration the essential geographic determinants which, together with the pedological composition, dictate the current purpose of the surface area. The quotient of success and consequently also the evaluation of the suitability of geophysical investigations was determined relevant to corroborative archaeological excavations. The estimated suitability of individual prospecting techniques were recorded for those sites not yet excavated, based upon comparisons with similar archaeological sites wherever justification by excavation was possible.

Unrestricted accessibility to such a database which primarily enables access to all prospecting information, including numerical files that contain -raw- values of field measurements, represents, in my opinion, a constituent part of a database that is to serve as a register for geophysical investigations. Immediate access to data matrices is thus enabled and consequently data processing is delayed, as are reinterpretations of results or the incorporation of data matrices in expert, or hybrid systems, and neuron networks. A relatively frequent situation presents different teams at the same archaeological site collaborating at various intervals in the geophysical investigations and applying diverse geophysical techniques. This is also the main reason that M. Dabas and I prepared the framework for a database of geophysical investigations also at the Mont Beuvray (France) archaeological site (1997, 199-210); F. Laudrin set up the register in the program *File Maker* (*Centre archéologique européen du Mont Beuvray*).

AN EVALUATION OF THE SUITABILITY OF GEOPHYSICAL TECHNIQUES

Ideally, selection of the most suitable geophysical techniques is dictated only by the targeted archaeological objects that we wish to locate. In reality, the targeted archaeological objects account for only a larger or smaller part in determining the most appropriate geophysical techniques. Correspondingly, an anomaly in the physical field, resulting from the presence of a targeted archaeological object, is termed a *signal*, while all other irregularities in the physical fields, resulting from various other factors, are termed *noise*. The most suitable selection is not evidenced by the geophysical technique when the anticipated amplitude of the signal is the greatest, but rather when the ratio of the signal versus noise is the greatest. This is termed the *signal to noise ratio*.

Geophysical investigations are generally executed in a field for which we know, at least approximately, of its archaeological potential as regards the type of archaeological remain that can be detected using geophysical techniques. The targeted objects are commonly various elements of a settlement structure (walls, ruination layers, refuse pits, postholes, ditches, various trade workshops, hearths and stratigraphic sequences manifesting traces of anthropogenic activity, etc.). Better results are usually attained in the instance that the anticipated type of archaeological remain is at least approximately known. The physical parameters, of which the greatest difference is between the archaeological object and the plot of ground upon which it is situated, are determined contingent upon the data concerning the archaeological and natural surroundings. The most effective strategy for geophysical prospecting is then selected on the basis of the evaluated -contrast- of particular physical parameters (e.g. resistivity/conductivity, the magnetic susceptibility and the permittivity, as well as the magnetic permeability) for a particular type of archaeological remain, the noise from the surroundings, the surface condition, as well as the geological and pedological composition of the terrain.

My own presentation evaluating the effectiveness of geophysical techniques is essentially only a slightly altered and supplemented variation of that proposed by B. Bevan (1996a) for presenting his own investigations. These results are not published, however they are in essence accessible to the wider public. The principal determinant, in my opinion, for the small number of such investigations in this field is the strong tendency toward specialization in only one geophysical technique. Numerous articles have been published by various authors in which the results from several geophysical techniques, or rather instruments, applied at the same site are presented, yet these publications discuss the results of each of the techniques independent of the results of any other technique; comparative studies, generating a detailed review of the potential of these various techniques at different sites, are lacking (see i.e. Finetti 1992, 83-232).

The information presented in *Table 1*, assessment data for my evaluation of the suitability of geophysical prospecting techniques, is in many ways imperfect as regards a naturalistic and tech-

Location	X, GK	Y, GK	Site	Targets	Pedosequences	Prospections	Excavations
Ajdna nad Potoki	5433471	5142254	altitude, fortified	walls	PHC	GR**	Yes*
Ajdovski Gradec pri B.B.	5420416	5126649	altitude, fortified	furnaces?, slag dumps, walls	PHC	TPA**, FG***, AMS*, GR**, DEM****	Yes*
Ajdovščina	5415068	5083083	lowland	walls, pits	FGS	TPA**, FG*	Yes
Ajdovščina - Nemškarica	5413400	5083010	lowland	walls	FGS/PCL	TPA***, FG*	No
Ajdovščina nad Rodikom	5421658	5053830	altitude, fortified	forge, slag dumps, walls	PNC	TPA**, FG****, PM****, AMS****, DEM****	Yes, Yes*
Bovec	5388576	5132897	lowland	walls, road	PGS	TPA***, GR****	Yes
Buče - Groblje	5545636	5107251	lowland, villa	walls, ditches	PSC	TPA****, FG****	Yes*
Cvinger pri Meniški Vasi	5503954	5068053	altitude, iron-smelting	furnaces, slag dumps	PHC	FG****, AMS****, SP**, DEM***	Yes*
Čatež ob Savi	5547205	5083120	lowland, villa	walls, ditches?	PCL	TPA****, FG****	Yes**
Črnomelj - Okljuk	5515000	5047500	lowland, vicus?	walls	FGS/PCL	TPA***, FG**	No
Črnomelj - Sv. Peter	5515454	5047355	church	walls, vault	urban	GR****	Yes*
Dolnja Prekopa	5530269	5080164	lowland, fortified	ditches, fireplace?, forge?	FGS/PCL	TPA**, FG***, DEM****	No
Dragomelj	5469201	5106887	lowland	post holes, fireplace, ditches	FGS/PCL	TPA*, FG*	Yes
Dragomelj	5469273	5106919	lowland	post holes, fireplaces, ditches	FGS/PCL	TPA*, FG**	Yes
Dragomelj	5469331	5107110	lowland	post holes, fireplaces, ditches?	FGS/PCL	TPA*, FG**	Yes
Dvorce pri Čatežu	5547921	5082479	lowland	graves	PCL	TPA**, FG**	Yes
Gračišče - Zabavska varda	5410288	5040968	altitude, house	walls, bricks	PHC	TPA***, FG****	Yes*
Groblje pri Bučah	5511731	5072717	lowland, villa	walls, bricks, ditches	PHC	TPA***, FG***	Yes*, Yes**
Ivančna Gorica	5485291	5087731	lowland	road	PCL	GR****	Yes
Ivančna Gorica	5485243	5087819	lowland	post holes, fireplaces, ditches	FGS	TPA*, FG*	Yes
Ivančna Gorica	5485291	5087707	lowland	post holes, fireplaces, ditches	FGS/PCL	FG**	Yes
Ivančna Gorica	5485599	5087946	lowland	road	PCL	TPA****, FG**	Yes
Ivančna Gorica	5485470	5087962	lowland	road	FGS/PCL	TPA**, GR****	Yes
Kamnik - Mali grad	5470426	5120119	altitude, fortified	ditches, walls	PHC	TPA**	Yes
Kostenjevica na Krki	5532923	5078293	lowland, fortified	walls?, kilns	PCL	TPA**	Yes*
Krtina	5473176	5111755	lowland	post holes, fireplaces, ditches	PCL	TPA*	Yes
Krtina	5473200	5111882	lowland	post holes, fire places, ditches	PCL	TPA*	No
Laško - Sv. Martin	5518518	5112411	church	walls, vault	urban	GR***	No
Ljubljana	5461662	5100492	lowland, fortified	walls	urban	TPA****	No
Ljubljana - Stožice	5462899	5104865	lowland	walls, ditches	FGS	TPA*, FG**	Yes
Log pri Vipavi	5417780	5080587	lowland	post holes, fireplaces	PCL	TPA*, FG*	Yes
Logatec	5440181	5086223	lowland, settlement	walls	urban	TPA**	No
Mačkovec pri Dvoru	5497555	5074606	altitude, villa	walls	PHC	GR*	No
Maribor	5547899	5156350	lowand	ditches, walls	FGS/PCL	TPA**, FG***	No
Maribor	5547701	5156087	lowland	ditches, walls	FGS/PCL	TPA*, FG*	No
Maribor	5547648	5155948	lowland	ditches, walls	FGS/PCL	TPA*, FG**	No
Ogulin	5519922	5035521	lowland	walls?, ditches	PHC	TPA**	No
Ogulin	5520061	5035418	lowland	walls?	PHC	TPA**	No
Podrečje	5471002	5111549	lowland	ditches, fireplaces, post holes	FGS/PCL	FG**	No
Ptuj	5566199	5141892	lowland	walls	FGS	TPA**, FG*	Yes*
Pusti Gradac	5515980	5041609	lowland, church	walls?, pavement	PCL	GR****	No
Rogaška Slatina - Sv. Križ	5549652	5120424	church	walls	urban	GR****	Yes*
Rogovila	5486083	5087801	lowland	graves	PCL	GR**	Yes
Rogoza	5551907	5151741	lowland, settlement	post holes, ditches, fireplaces	FGS	TPA**, FG*	Yes
Slivnica	5550995	5148523	lowland	post holes, fireplaces, ditches	FGS	TPA**, FG***	Yes
Spodnje Bitnje	5449092	5118302	lowland, villa	walls, ditches	FGS	TPA**	Yes
Spodnje Hoče	5550251	5150937	lowland	walls, ditches	FGS	TPA**, FG*	Yes
Središče ob Dravi	5597108	5138777	lowland, villa	walls, ditches	FGS/PCL	TPA***	Yes*
Stična	5485241	5090342	lowland, monastery	walls, pavement	FGS	GR***	Yes*
Šentpavel pri Domžalah	5469342	5107805	lowland, villa	walls	FGS	TPA**	Yes
Škocjan	5421885	5058402	altitude, fortified	terraces, ditchesi, walls, bricks	PHC	TPA*, FG**, DEM***	No
Škocjan	5421983	5058377	altitude, fortified	terase, jarki, zidovi, opeka	PHC	TPA*, FG***, DEM***,	No
Špitalič	5553121	5129512	lowland, house	walls	FGS	TPA***	No
Tolmin - Na Doru	5402815	5115994	altitude	walls?, ditches	PHC	TPA*, FG**	No
Velike Malence	5544654	5082646	lowland, villa	walls, bricks, enclosure	PCL/PHC	TPA****, FG***, PM**, AMS**	Yes
Velike Malence	5544581	5082693	lowland, villa	walls, ditches	PCL/FGS	TPA****, FG**	No
Vransko - Ilovca	5496835	5121804	lowland, tilery	kilns, bricks, walls	FGS	TPA*, FG****	Yes
Vrhpolje pri Šentvidu	5486286	5088360	lowland, burrow	graves	PCL	GR***	No
Žička kartuzija	5530611	5129808	monestery	walls	urban	GR***	No

Table 1: The table presents some of the archaeological sites upon which geophysical prospecting was executed.
Tab. 1: Preglednica nekaterih arheoloških najdišč na katerih smo opravili geofizikalne raziskave.

nical approach. For instance, the division of the natural environment into regional systems, or pedosequences, as proposed by A. Stritar (1990, 29-30), was applied for describing the natural environment. This division nevertheless corresponds perfectly to select more general determinations that were attained during my investigations on the various geological foundations (e.g. the signal to noise ratio is approximately the same on particular pedosequences with the same type of archaeological remains). There is essentially no simple manner in which all the various factors that inevitably influence upon geophysical prospecting can be considered.

← **LEGEND / LEGENDA** (*Table 1 / Tab. 1*)

Prospecting / prospekcija
- The effectiveness of prospecting with regard to the archaeological object discovered: / uspešnost prospekcije glede na odkrite arheološke objekte: **** - very effective / zelo uspešno, * - ineffective / neuspešno

Magnetometry / magnetometrija
- FG - a fluxgate gradiometer / pretočni gradiometer (Fluxgate gradiometer Geoscan FM36)
- PM - a proton magnetometer / protonski magnetometer (Gem System GSM 19) in (Geometrics G816)

Resistivity / električna upornost
- TPA - twin probes array / metoda elektrodnih dvojčkov (Resistance meter Geoscan RM15)
- SP - self potentials / lastni potenciali

Magnetic susceptibility / magnetna susceptibilnost
- AMS - the apparent magnetic susceptibility / navidezna magnetna susceptibilnost (Kappameter KT-5)

Georadar
- GR - georadar GSSI SIR 3 (500 MHz antenna / 500 MHz antena)

Survey
- DEM - digital elevation model / digitalni model reliefa

Excavations / izkopavanja
- YES - archaeological excavations / arheološka izkopavanja
- YES* - informations concerning older excavations / podatki o starejših izkopavanjih
- YES**- construction pit / gradbena jama - delovišče
- NO - no subsurface information / nobenih podpovršinskih podatkov

Pedosequences / pedosekvence
- PGS - pedosequences on gravel and sand / pedosekvenca na produ in pesku
- PCL - pedosequences on clay and loam / pedosekvenca na glinah in Ilovicah
- PSC - pedosequences on soft carbonaceous rock / pedosekvenca na mehkih karbonatnih kamninah
- PHC - pedosequences on hard carbonaceous rock / pedosekvenca na trdih karbonatnih kamninah
- PNC - pedosequences on noncarbonaceous rock / pedosekvenca na nekarbonatnih kamninah

EXAMPLES OF GEOPHYSICAL PROSPECTING

To illustrate the suitability of geophysical techniques in various natural environments, classified subject to their diverse pedosequences or regional systems, I selected investigations on archaeological sites that were well researched using geophysical methods and on which the results satisfactorily describe the potential of the particular method in its respective natural circumstances. At the same time, my aim was to incorporate as many diverse natural environments and types of archaeological remains as possible.

The majority of the article is devoted to Late Roman hill-top settlements which are often situated where prehistoric hillforts previously existed. This type of archaeological site is quite common in Slovenia and will thus represent a frequent target of research using archaeological prospecting methods. The work conditions are extremely demanding as concerns geophysical investigations, therefor I believe it is entirely justified that I present my own experiences on these types of archaeological sites in the forefront.

The only geophysical prospecting within a prehistoric fortification that I know of, although very extensive, was executed in southern England (Payne 1996, 163-184); already simple magnetometry investigations procured substantial insight into the organization of the settlement. I was unable to rely on these data during my own investigations of prehistoric fortifications and Late Roman hill-top settlements as the natural conditions are entirely different here. Prehistoric fortifications in southern England are primarily situated on level plateaus that are overgrown with grass and raised only a few meters above extensive flat lands. These are considered incomparably better conditions for geophysical prospecting than on any of the somewhat similar archaeological sites in Slovenia, where unlevel terrain, dense vegetation, the occasional thick layer of Late Roman ruins or just slight prehistoric archaeological cultural horizons are regularly encountered. All these factors indeed bear serious limitations for most types of geophysical prospecting techniques. The actual absence of archaeological publications concerning geophysical investigations on these types of archaeological sites is also an indirect indication of this. The results of geophysical investigations at other archaeological sites were selected so as to illustrate certain particularities in the regional systems of which we should be mindful while planning prospecting. The archaeological sites discussed

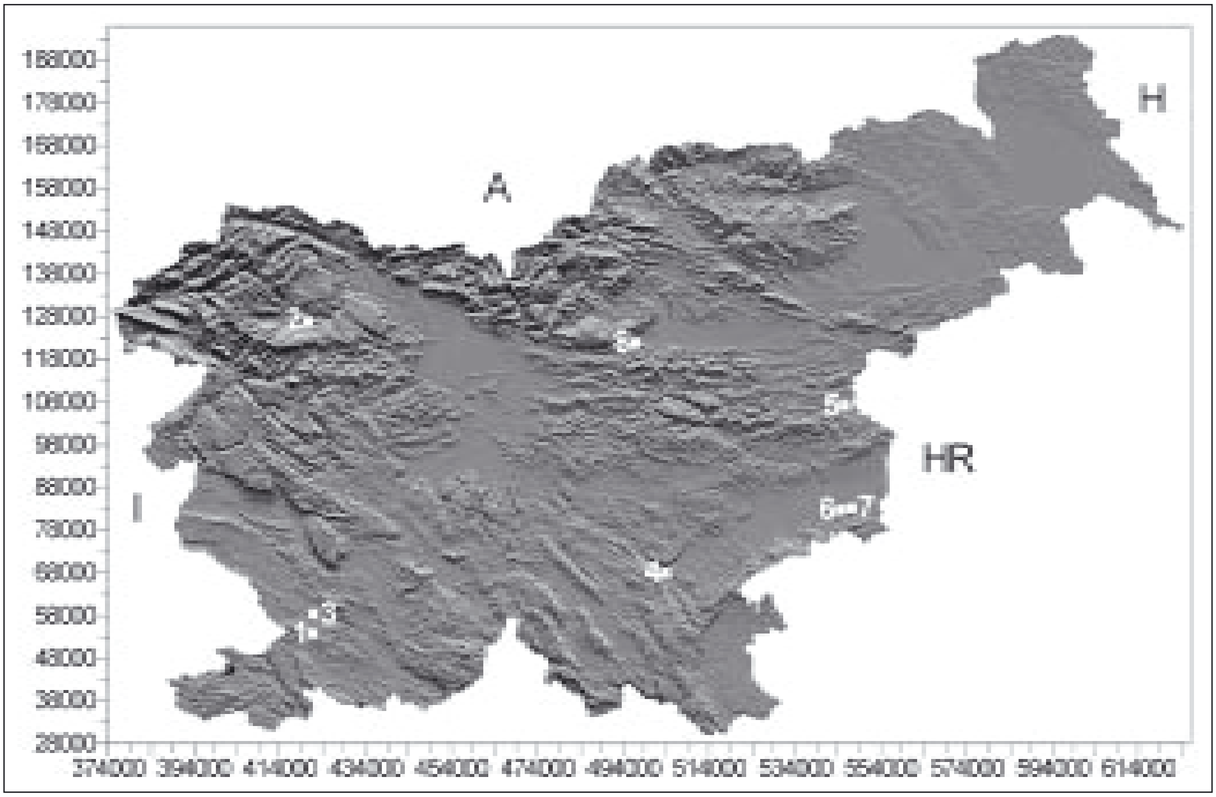


Fig. 1: Location map of archaeological sites in different natural environments (pedosequences), which were geophysicaly surveyed.
Sl. 1: Položajna skica arheoloških najdišč v različnih naravnih okoljih (krajinskih sistemih), ki smo ih raziskali z geofizikalno metodo.

in the article (*fig. 1*) are sorted according to their geologic-pedologic foundation:

Pedosequences on noncarbonaceous rock
- Ajdovščina above Rodik (1)

Pedosequences on hard carbonaceous rock
- Ajdovski gradec near Bohinjska Bistrica (2)
- Škocjan (3)
- Cvinger near Meniška vas (4)

Pedosequences on soft carbonaceous rock
- Groblje near Buče (5)

Pedosequences on clay and loam
- Grafendorf (Austria)
- Velike Malence (6)
- Čatež along the Sava (7)

Pedosequences on gravel and sand
- Ilovca near Vransko (8)

PEDOSEQUENCES ON NONCARBONACEOUS ROCK

Ajdovščina above Rodik (*Fig. 2*)

The site at Ajdovščina above Rodik (Marchesetti 1903; Slapšak 1978; 1985 and 1988) (*Fig. 2*), situated on pedosequences on noncarbonaceous rock (flysch) (see: Orehek 1972; Orehek, Silvester 1964 and 1967), serves well to illustrate the strategy for archaeological prospecting on prehistoric and Late Roman settlements. The research project was initiated and led by Slapšak (Department of Archaeology, University of Ljubljana) (see Mušič, Slapšak 1998; Mušič et al. 1995; and Mušič, Slapšak, Perko 1999). I shall use this site to clarify the potential of archaeological prospecting (*Fig. 3*) on Late Roman hill-top settlements, which represent an extremely complex problem, at least as far as geophysical research is concerned. The reasons for this are numerous and they differ from site to site. The natural conditions, ranging from moderate to very unlevel terrain with dense vegetation and a very inconstant thickness of ground and/or archaeological cultural horizon, are on the one hand, the most significant. While on the other hand, the surface and therefore also the archaeological remains are often covered with a layer of Late Roman ruins. These are the essential factors that expressly influence upon the reduction of the signal to noise ratio and which consequently lower the detectability of archaeological remains for almost all

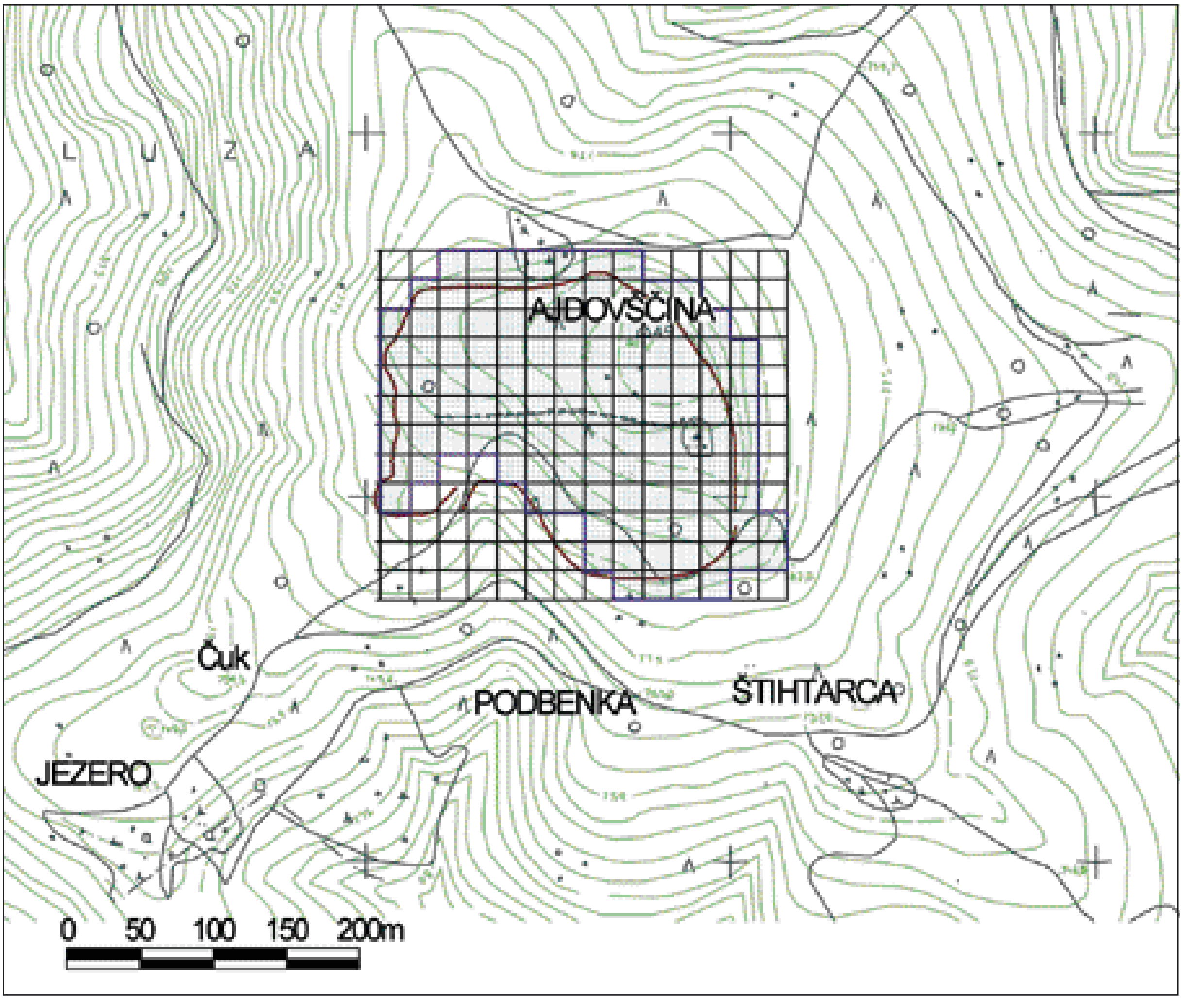


Fig. 2: Ajdovščina above Rodik. Pedosequences on noncarbonaceous rock. A topographic sketch of the investigated area. The prehistoric rampart is delineated and the system of quadrants measures 20 x 20 m. The quadrants were used as the geodetic zero reference point for determining the x and y coordinates, optional variables in archaeological prospecting.
Sl. 2: Ajdovščina nad Rodikom. Pedosekvenca na nekarbonatnih kamninah. Položajna skica raziskane površine. Linija prazgodovinskega nasipa in mreža kvadrantov 20 x 20 m. Kvadrante smo uporabljali kot geodetska izhodišča za določitev koordinat x in y poljubne spremenljivke pri arheološki prospekciji.

geophysical techniques, some of which are almost even entirely disenabled (e.g. the resistivity). As it is in the interest of the science of archaeology to investigate the range of geophysical methods also under these circumstances, I chose to carry out a detailed analysis of the individual geophysical techniques applied at select sites in Slovenia. In the continuation I shall present the results from certain so-called hill-top sites situated in diverse regional systems (=pedosequences).

In addition to Ajdovščina above Rodik, situated on pedosequences of noncarbonaceous rock, the prehistoric and Roman settlement at Škocjan, the prehistoric and Late Roman settlement at Ajdovski gradec near Bohinjska Bistrica and the prehistoric settlement at Cvinger near Meniška vas all serve to exemplify the potential of geophysical prospecting techniques on such archaeological sites, the majority of which in Slovenia are situated on pedosequences of hard carbonaceous rock (limestone, dolomite).

Digital Elevation Model

On the basis of measurements of the relative differences in the heights above sea level, derived from a reference point with absolute Gauss-Krueger coordinates, a precise topographic map of the site and a Digital Elevation Model (DEM) were created; the small relative differences in the above sea level heights significant for archaeological interpretation

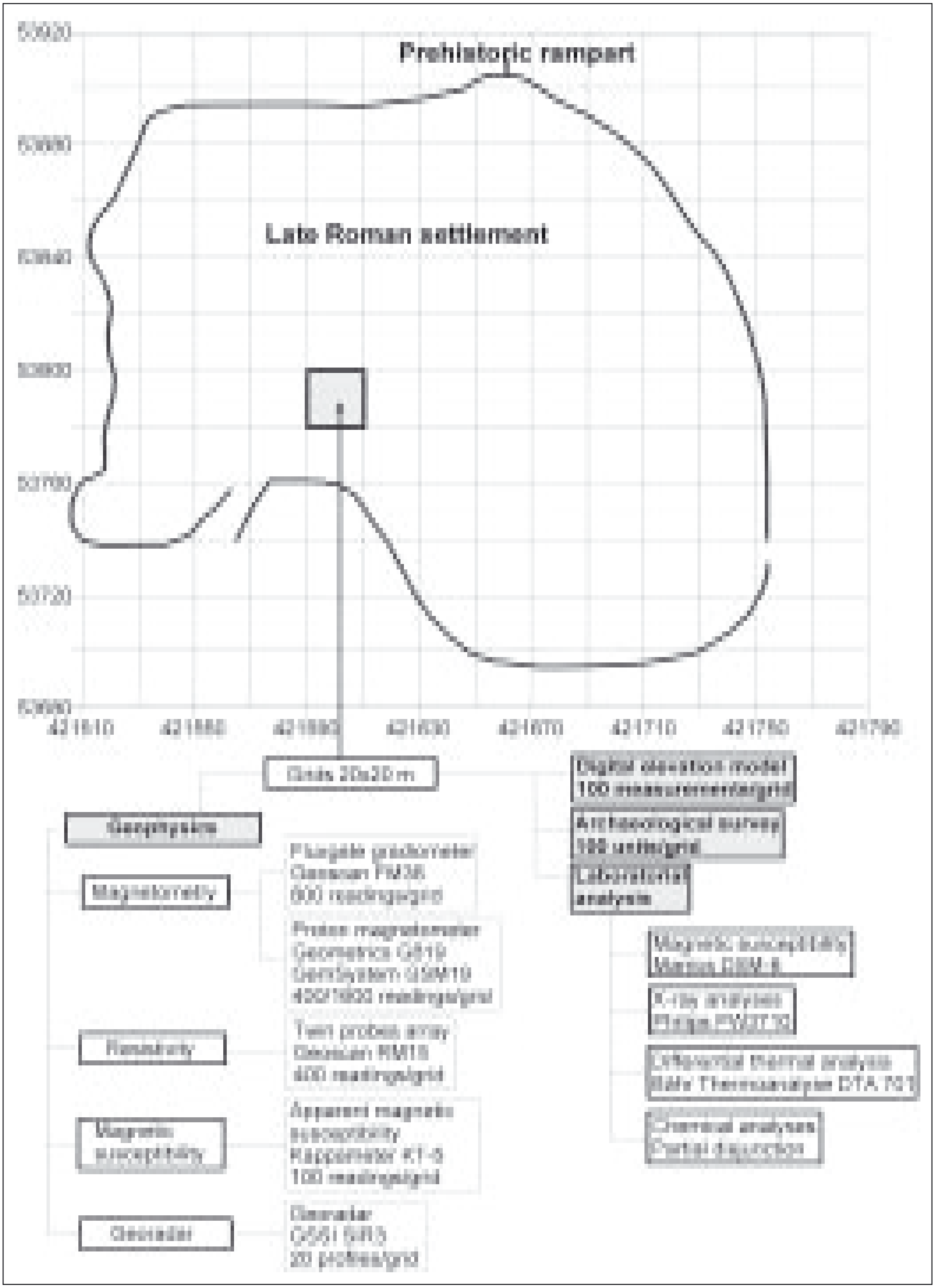


Fig. 3: Ajdovščina above Rodik. A schematic depiction of the applied prospecting techniques and the laboratory analyses of soil samples.
Sl. 3: Ajdovščina nad Rodikom. Shematični prikaz uporabljenih prospekcijskih tehnik in laboratorijskih analiz vzorcev tal.

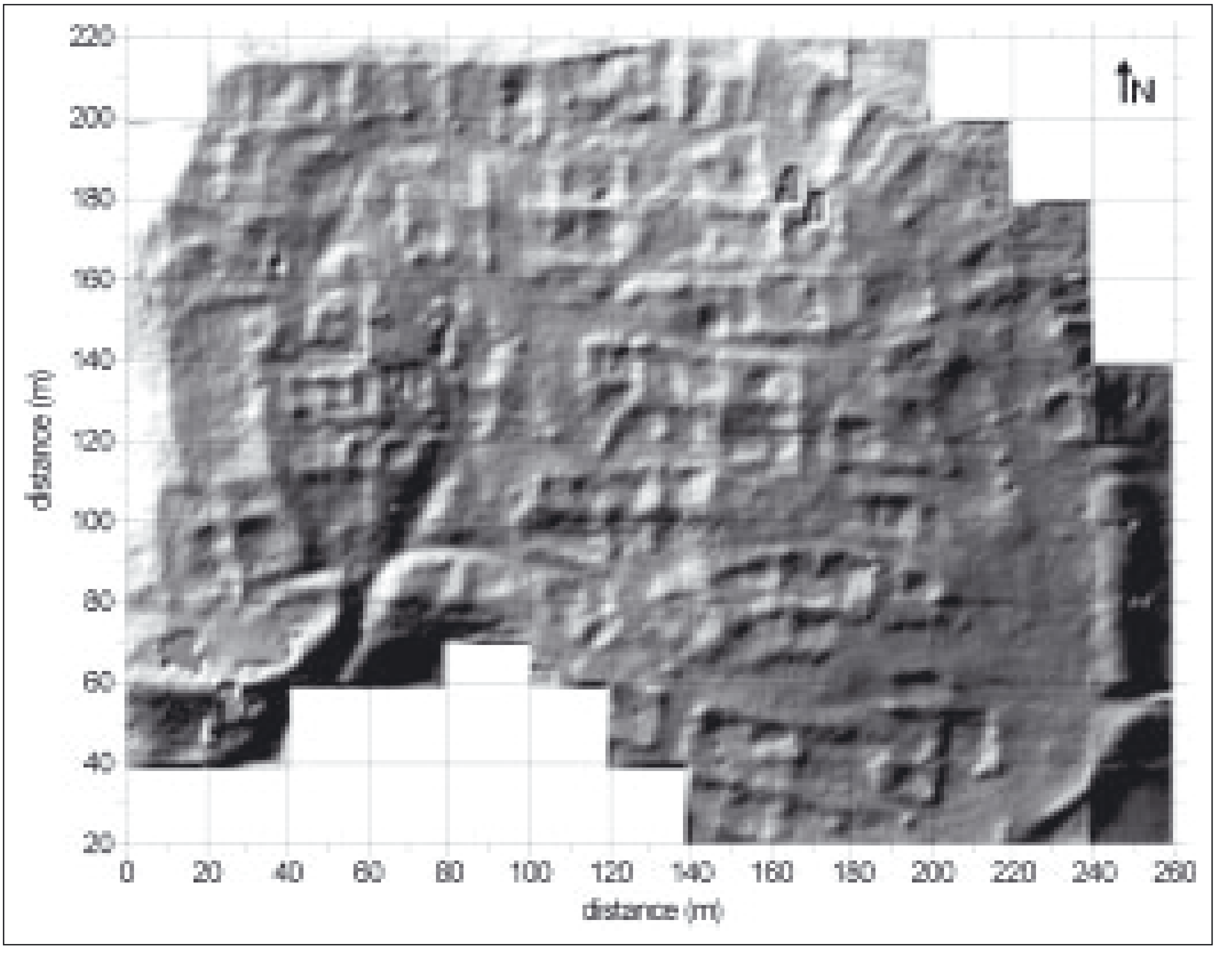


Fig. 4: Ajdovščina above Rodik. Pedosequences on noncarbonaceous rock. A Digital Elevation Model with analytical hill shading. Positive topographic anomalies are the result of Late Roman architectural debris. The course of the prehistoric rampart is also clearly discernible.

Sl. 4: Ajdovščina nad Rodikom. Pedosekvenca na nekarbonatnih kamninah. Digitalni model reliefa je prikazan z osenčenostjo (*analytical hill shading*). Pozitivne topografske anomalije so posledica ruševinskih grobelj poznoantičnih stavb. Dobro viden je tudi potek prazgodovinskega obzidja.

can be illustrated applying analytical hill shading (*Fig. 4*). The above sea level heights were measured with a precision of 1 cm at 1 m intervals between the measuring points. A total of 44,400 points were measured for the DEM (a surface area of 44,400 m^2). -Raw- data was interjected in both directions applying bicubic interpolation (Davis 1986, 204-207) and measurements were thus simulated at 0.5 m. Positive topographic anomalies visible on the DEM are the result of debris above the Late Roman architectural remains. The remains of the prehistoric rampart that surrounds the Late Roman settlements are also just as evident.

Resistivity method

The resistivity method using twin probes (Resistance meter RM15, Geoscan Research, Bradford) was applied for the purpose of geoelectric mapping (*Fig. 10*) with a distance of 0.5 m between the mobile electrodes (C_1P_1). The resolution between the Geoscan RM15 measuring instrument is 0.5 Ohm.m. At a distance of 0.5 m between the mobile electrodes the effective depth reaches 1 - 1.5 m under favorable conditions of ground humidity; this is sufficient, in view of the data on archaeological remains at numerous Roman sites, for a precise delimitation of highly resistive architectural remains. This is also sufficient under favorable natural conditions for areas of various purposes which are within a complex of buildings, or rather in their direct vicinity, and whose apparent resistivity can also be lower than the background value (ditches and caves). The smallest alterations that were registered in the apparent specific electric resistivity totaled approximately 5 % of the value of the measured background. The alterations were

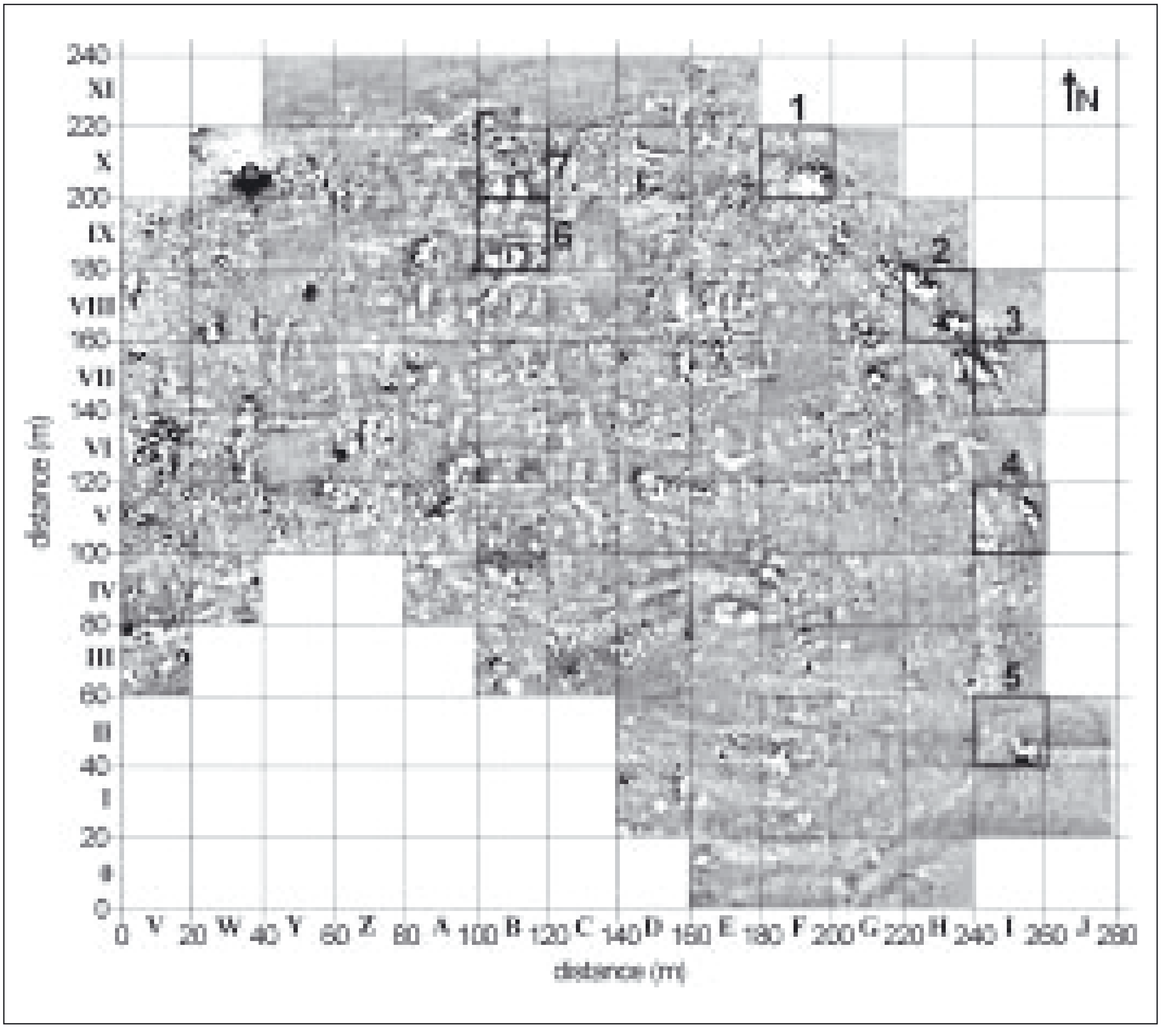


Fig. 5: Ajdovščina above Rodik. Pedosequences on noncarbonaceous rock. Magnetometry using a fluxgate gradiometer (Fluxgate gradiometer FM36). The surfaces upon which high thermoremanent magnetization from trade workshops was discovered are designated. These surfaces were investigated using a proton magnetometer (Geometrics G819 in GemSystem GSM19).
Sl. 5: Ajdovščina nad Rodikom. Pedosekvenca na nekarbonatnih kamninah. Magnetometrija s pretočnim gradiometrom (Fluxgate gradiometer FM36). Označene so površine, na katerih smo ugotovili močno termoremanentno magnetizacijo (železarskih?) obrtnih delavnic. Te smo raziskali tudi s protonskim magnetometrom (Geometrics G819 in GemSystem GSM19).

measured in a grid with 1 m between profiles and with the same distance between measuring points. A total of 36,400 m^2 was measured using the resistivity method. The matrix of -raw- values was condensed using bicubic interpolation (see Davis 1973, 204-207) and the readings at 0.5 m intervals were thus simulated.

Magnetometry

Magnetometry was executed using a fluxgate gradiometer (Geoscan FM36, Geoscan Research, Bradford). This instrument is used to measure changes in the gradient of the vertical component of the Earth's magnetic field (dZ/dz, nT/m) (*Fig. 5* and *6*) with regard to the zero reference point. Only one reference point was applied for all measurements. Any errors that could occur during the repeated transfer of the zero reference point to a new location were thus avoided and consequently a unified background measurement of the entire settlement was also secured. The distance between the measuring points in the direction of the profile (west-east) was 0.5 m, and 1 m between the profiles (north-south). The total number of measurements of the vertical gradient of the magnetic field was 95,200 (a surface area of 47,600 m^2). Theoretically, this instrument could be used to measure magnetic anomalies above

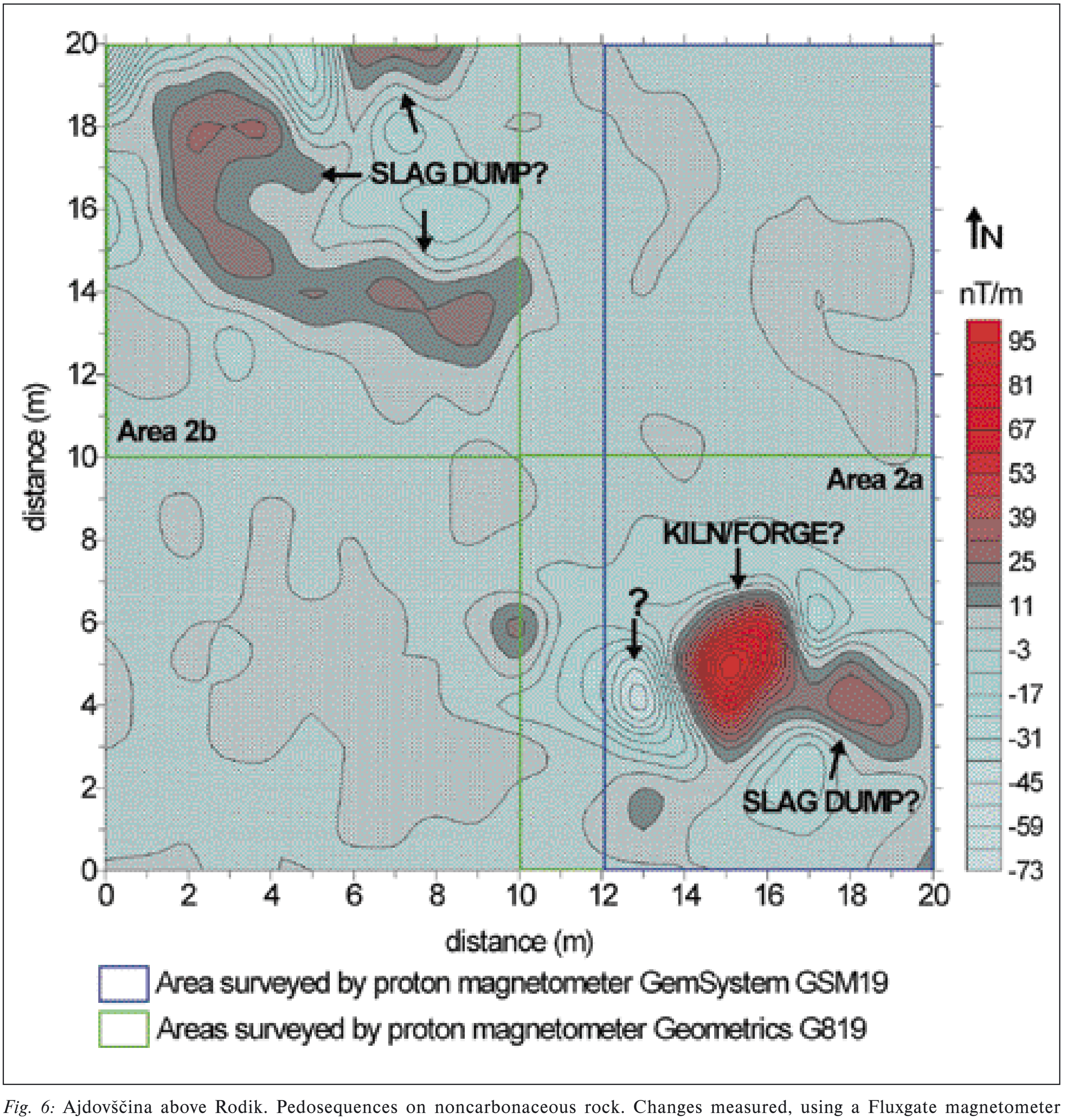


Fig. 6: Ajdovščina above Rodik. Pedosequences on noncarbonaceous rock. Changes measured, using a Fluxgate magnetometer FM36*,* in the gradient of the vertical component of the magnetic field in area 2, where strong magnetic anomalies were detected due to the thermoremanent magnetization from the ironworks forge (Area 2a) and the depositing of metallurgic refuse products (Area 2b). The distance between measuring points is 0.5 m, the distance between profiles is 1 m (n = 800, m = 3.71, s = 13.71, min = -85.45, max = 102.30).

Sl. 6: Ajdovščina nad Rodikom. Pedosekvenca na nekarbonatnih kaminah. Spremembe gradienta vertikalne komponente magnetnega polja, izmerjene s pretočnim gradiometrom (Fluxgate magnetometer FM36) na območju 2, kjer so bile ugotovljene močne magnetne anomalije zaradi termoremanentne magnetizacije kovaške peči (območje 2a) in deponije odpadnih produktov metalurgije (območje 2b). Razdalja med merilnimi točkami je 0,5 m, razdalja med profili je 1 m (n = 800, m = 3,71, s = 13,71, min = -85,45, max = 102,30).

archaeological objects such as ferromagnetic iron artifacts and ferrimagnetic ceramic objects (e.g. firing kilns for pottery, metallurgic iron-smelting furnaces, bricks, tiles, etc.) (Heathcote, Aspinall 1981, 61-70; Papamarinopoulos, Tsokas, Williams 1985, 483-490; 1986, 111-112). Areas with thermoremanent magnetization (*Fig. 5*) were investigated also using the Geometrics GSM 819 in GemSystem GSM19 proton magnetometers (*Fig. 7* and *8*). The distance between measuring points was the same in both directions, that is 1 m and 0.5 m respectively.

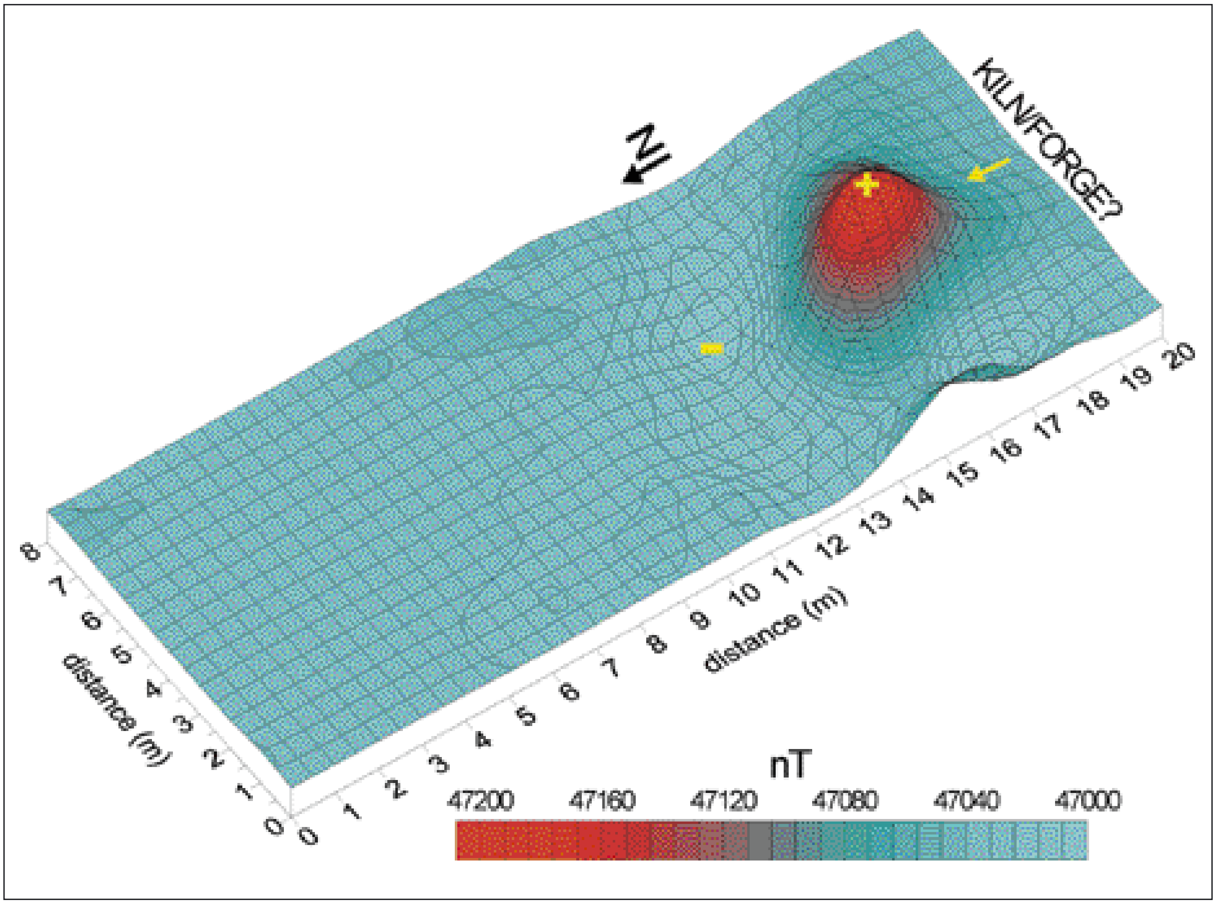
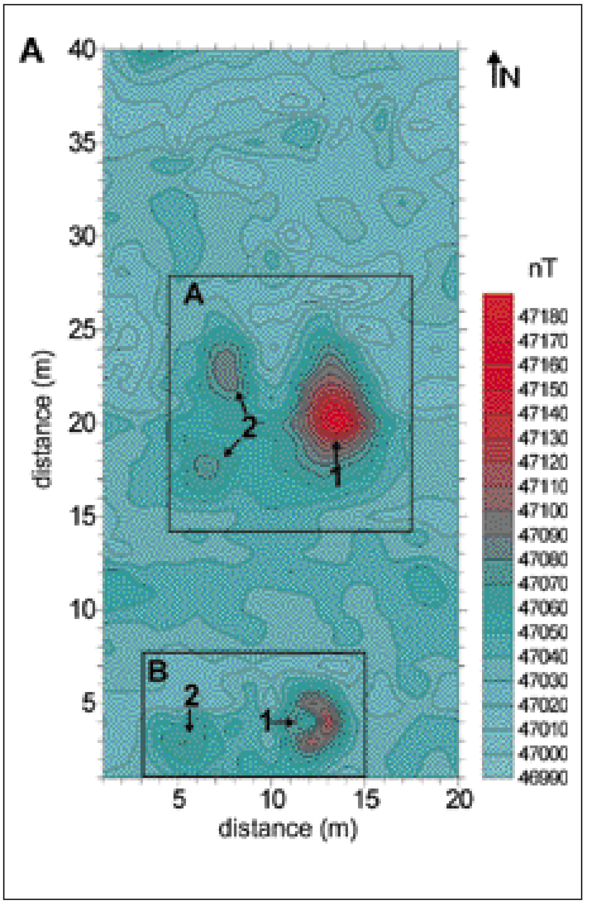


Fig. 7: Ajdovščina above Rodik. Pedosequences on noncarbonaceous rock. The total magnetic field lying above the ironworks furnace in area 2a (see *Fig. 6*) measured using a proton magnetometer (GemSystem GSM19). The sensors are 0.6 m high, the distance between the measuring points is 1 m, the equidistance is 8 nT (n = 160, m = 47041, s = 31, min = 46957, max = 47206).
Sl. 7: Ajdovščina nad Rodikom. Pedosekvenca na nekarbonatnih kamninah. Totalno magnetno polje nad železarsko pečjo na območju 2a (glej *sl.6*) izmerjeno s protonskim magnetometrom (GemSystem GSM19). Višina senzorja je 0,6 m, razdalja med meritvami je 1 m, ekvidistanca je 8 nT (n = 160, m = 47041, s = 31, min = 46957, max = 47206).

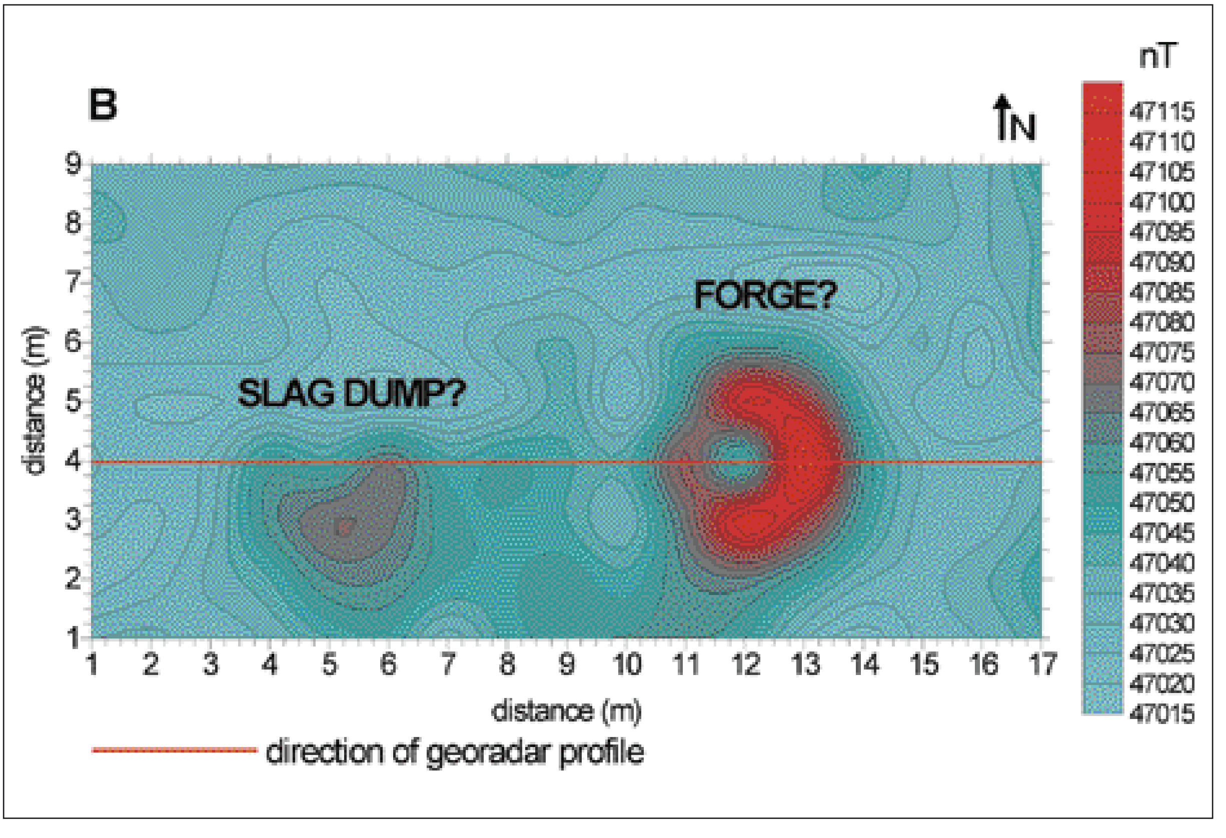
Magnetic Susceptibility

The apparent magnetic susceptibility was measured using a Kappameter KT-5 field instrument (Geofyzika, Brno). This instrument is used to measure the susceptibility of the ground up to approximately 3 cm. The variableness of the magnetic susceptibility, which is largely the result of the conversion of weakly magnetized iron minerals into more magnetic forms due to raised temperatures from the use of fire, is measured in this way. The magnetic susceptibility is otherwise only a physical property that is defined as a quotient between the measured intensity of magnetization and the inducing magnetic field, which is the Earth's magnetic field in this instance. Consequently, among methods of magnetic measurement, measuring the magnetic susceptibility is considered equivalent to magnetometry. Measurements of the magnetic susceptibility of the various materials that are searched for during magnetic prospecting usually serve merely as a significant source of information on the magnetic characteristics of the target objects and the media in which they exist. Measurements of the magnetic susceptibility on the surface have been established as an independent prospecting method in geophysical prospecting for archaeology (see Mušič, Orengo 1998; Mušič, Slapšak, Perko 1999). The distance between the measuring points was the same in both directions (2 m). This relatively large distance between measuring points was chosen so as to save precious survey time. Initially, the plan was to use data concerning the range of values for the magnetic susceptibility on the surface of the settlement only as a piece of information on the magnetic characteristics of the materials present on the settlement and then to apply it in the interpretation of the magnetometry. While processing the data, I soon discovered that the level of correlation between the results



from the intensive field survey (the number of pottery fragments or slag per surface unit; 4 m^2) and the magnetic susceptibility was unexpectedly high (*Fig. 11*). For the purpose of researching the correlation between the concentration of material surface finds and the susceptibility of the ground, the measurements were extended to an incomparably larger part of the settlement surface than initially anticipated and the entire surface that was investigated during the intensive field survey was measured (*Fig. 12*). A surface area of 22,800 m^2 was measured using the Kappameter KT-5, with a total of 5700 measurements.

Fig. 8: Ajdovščina above Rodik. Pedosequences on noncarbonaceous rock. High thermoremanent magnetization (A: 1 - a blacksmith's furnace?, 2 - deposit of metallurgic refuse products?) above the structures of metallurgic workshops were detected in areas 6 and 7 (*Fig. 5*) using a GemSystem GSM19 proton magnetometer, as well as a detail of thermoremanent magnetization from the forge in area 6 (B).
Sl. 8: Ajdovščina nad Rodikom. Pedosekvenca na nekarbonatnih kamninah. S protonskim magnetometrom GemSystem GSM19 smo ugotovili močno termoremnanentno magnetizacijo nad objekti metalurških delavnic (A: 1 - kovaške peči?, 2 - deponije odpadnih produktov metalurgije) na območju 6 in 7 (*Sl. 5*) in detajl termoremanentne magnetizacije peči na območju 6 (B).



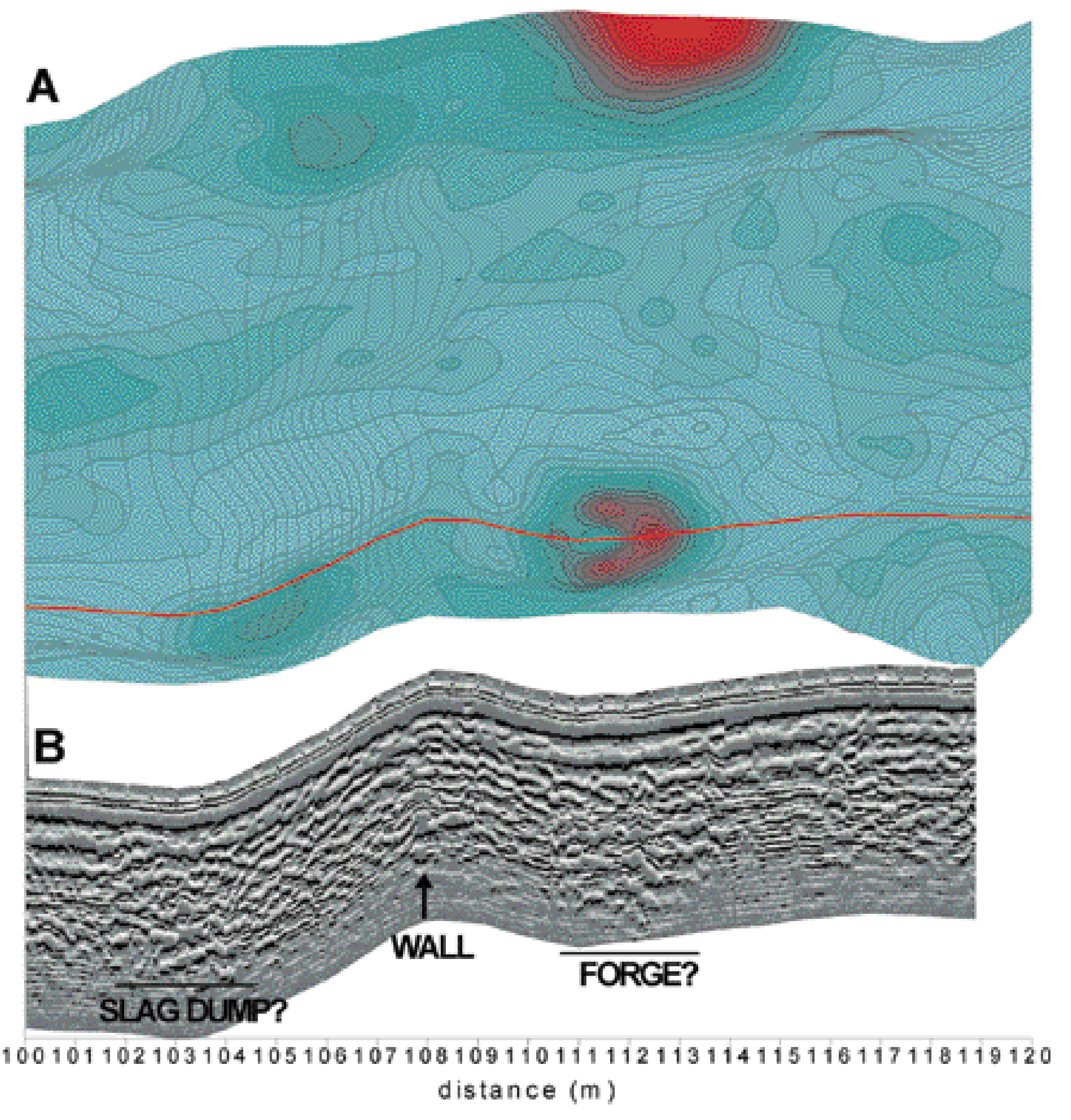


Fig. 9: Ajdovščina above Rodik. Pedosequences on noncarbonaceous rock. Radar reflections from slag deposits, a wall under the heap of ruins and from the blacksmith's forge are visible on the georadar profile (GSSI SIR 3, 500 MHz antenna) running across area B (*Fig. 8:* B). Distinct reflections were measured within the vicinity of the furnace and deposits, and a very strong reflection from under the debris is indicative of a well preserved wall.
Sl. 9: Ajdovščina nad Rodikom. Pedosekvenca na nekarbonatnih kamninah. Na georadarskem profilu (GSSI SIR 3, 500 MHz antena), ki poteka čez območje B (*Sl. 8:* B), vidimo radarske odboje od deponije žlindre, zidu pod ruševinsko grobljo in odboje od kovaške peči. Na območju peči in deponije so bili izmerjeni izraziti odboji; zelo izrazit odboj pod ruševinsko grobljo kaže položaj dobro ohranjenega zidu.

Georadar

The GSSI SIR3 served as the main measuring instrument for georadar research. All measurements were carried out using a monostatic antenna with a central frequency of 500 MHz. The situation and direction of the profiles was the same as for the other geophysical techniques. The distance between the parallel profiles measured was 1 m. The situation and level of preservation of the walls of Late

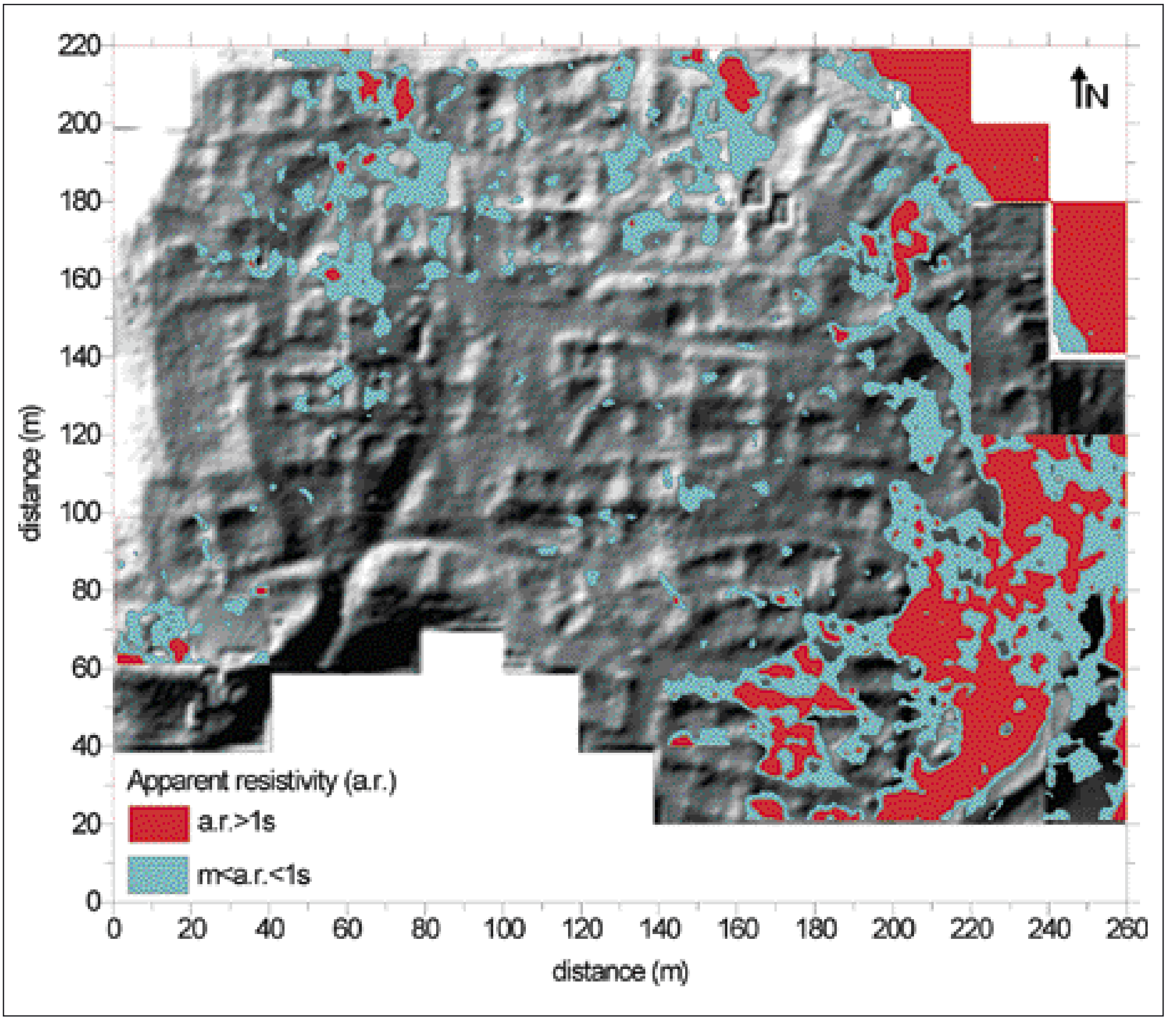


Fig. 10: Ajdovščina above Rodik. Pedosequences on noncarbonaceous rock. The interpreted values of the apparent resistivity (m - mean value, s - standard deviation) in the Digital Elevation Model.
Sl. 10: Ajdovščina nad Rodikom. Pedosekvenca na nekarbonatnih kamninah. Interpretirane vrednosti navidezne električne upornosti (m - srednja vrednost, s - standardni odklon) na digitalnem modelu reliefa.

Roman architectural remains under the heap of ruins was determined using georadar techniques. Objects with thermoremanent magnetization were detected in numerous places and, on the basis of magnetometry, magnetic susceptibility and field survey, I believe them to be the remains of some sort of industrial activity (ironworks?) (*Fig. 9*).

Archaeological Field Survey

Each collecting unit within the intensive field survey measured 4 m^2 (2 x 2 m). The majority of surface finds are Roman pottery fragments (tiles, bricks, pottery ware) (for a more precise explanation see Vidrih Perko1997, 341-358) and various types of metallurgical refuse products (from ironworks). The surface finds were divided into pottery fragments (pottery, brick, tiles) and metallurgical refuse products. The distribution of these two types of finds were used in addition to the results from geophysical research to classify the various activity areas dating to the Late Roman period (see Mušič, Slapšak 1998, 81-93; Mušič, Slapšak, Perko 1999, 132-146).

In addition to the -standard- prospecting techniques mentioned above, with which the activity areas were classified, geochemical prospecting (see Mušič et al. 1995), granulometrical analyses, differential thermal analyses, X - ray analyses and laboratory measurements of the magnetic susceptibility (see Dimc, Mušič, Osredkar 1994

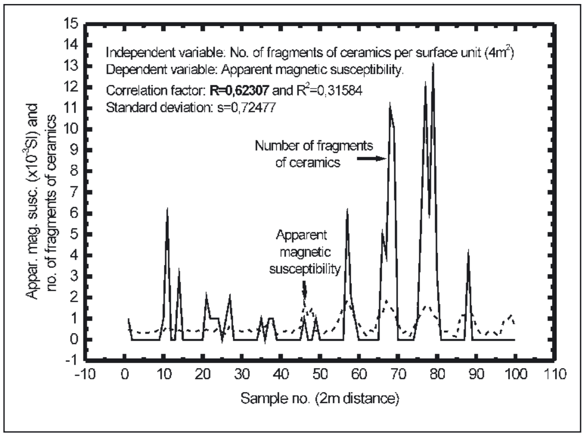


Fig. 11: Ajdovščina above Rodik (quadrant FX). A diagram depicting the number of pottery fragments in a 2 x 2 m collecting unit and the values of the apparent magnetic susceptibility in the center of each collecting unit using a Kappameter KT-5 instrument.
Sl. 11: Ajdovščina nad Rodikom (Kvadrant FX). Diagram števila kosov keramike na zbiralno enoto 2 x 2 m in vrednosti navidezne magnetne susceptibilnosti v centru vsake zbiralne enote, izmerjene z instrumentom Kappameter KT-5.

and Dimc, Mušič 1996) on small samples were tested at Ajdovščina above Rodik for additional information on the function of these areas. A full discussion of these results would extend beyond the purpose of this article, thus I shall only present select results in brief.

Prospecting Results

A very high positive gradient in Area 2 (*Fig. 5; 6* and *7*) indicates a strong thermoremanent magnetization in the south-eastern corner of the area; this section can be interpreted, in an archaeological context, a kiln or forge. Thermoremanent magnetization is the result of the conversion of weakly magnetized iron minerals into more magnetic forms at high temperatures. Based on the shape of the anomaly, my inference is that it is a well preserved structure with a narrowing, or rather framework, made either of brick or fired stones. It is also possible that the entire inside is filled with a block of material with high magnetic susceptibility. A smaller area with much higher values than the background (10-30 nT/m) is connected with the forge on its eastern side, although the values are still much lower than in the area of the forge (up to 100 nT/m). My deduction is that the area is for industrial activity refuse products with high magnetic susceptibility. The lower values were measured due to the smaller pieces, or rather the diversely oriented magnetic dipoles, of which the magnetic effect basically equalizes itself and thus outwardly results with a smaller vector sum. Both magnetic anomalies are interpreted as a consequence of the same industrial activity. A very irregularly shaped magnetic anomaly of the same intensity as the anomaly by the forge, determined as the effect of refuse products resulting from industrial activity, was detected in the north-western corner of area 2. Similarly, it would seem that this anomaly is also indicative of the same effect from depositing industrial activity refuse products with high magnetic susceptibility.

Similar to the application with the fluxgate gradiometer (Geoscan FM36) (*Fig. 6*), a proton magnetometer (GemSystem GSM19) was used to measure a high amplitude (200 nT) anomaly at the same location, only confirming the initial determinations (*Fig. 7*). A low extreme of the same magnetic anomaly (-) was also measured north-west of the anomaly (+) probe. This one was directed approximately 10° east of the geographic North. A strong positive declination indicates that thermoremanent magnetization definitely predominates over the induced magnetization and it is probably directed towards the magnetic field from the Late Roman period when the trade ceased to function and the furnace finally cooled down. This shape of anomaly is indicative of a strong dipole characteristic, resulting from the thermoremanent magnetization of a well preserved structure still standing in its original location.

The magnetic anomalies in areas 6 and 7 (*Fig. 5* and *8*) were also investigated using the GemSystem GSM19 proton magnetometer. Similar to the application with the fluxgate gradiometer (*Fig. 5*), an area with high thermoremanent magnetization, probably representing the remains of industrial workshops in-situ (blacksmith's workshop?) (*Fig. 8A:* 1), was also detected using the proton magnetometer, as well as somewhat weaker magnetic anomalies probably resulting from the depositing of metallurgic refuse products (*sl.8A*: 2). An almost identical situation was already discovered prior to this in area 2 (*Fig. 5* and *6*). The lower magnetic anomalies could be the result of diversely oriented smaller magnetic dipoles, these could be pieces of slag in this instance. Better results were achieved using the proton magnetometer GemSystem GSM 19, primarily as concerns the geometry of the structure with thermoremanent magnetization in area B (*Fig. 8B*) showing a distinct semicircular cut in the ground plan.

The example set at Ajdovščina above Rodik has demonstrated that the georadar method is by far the most effective for detecting walls under thick

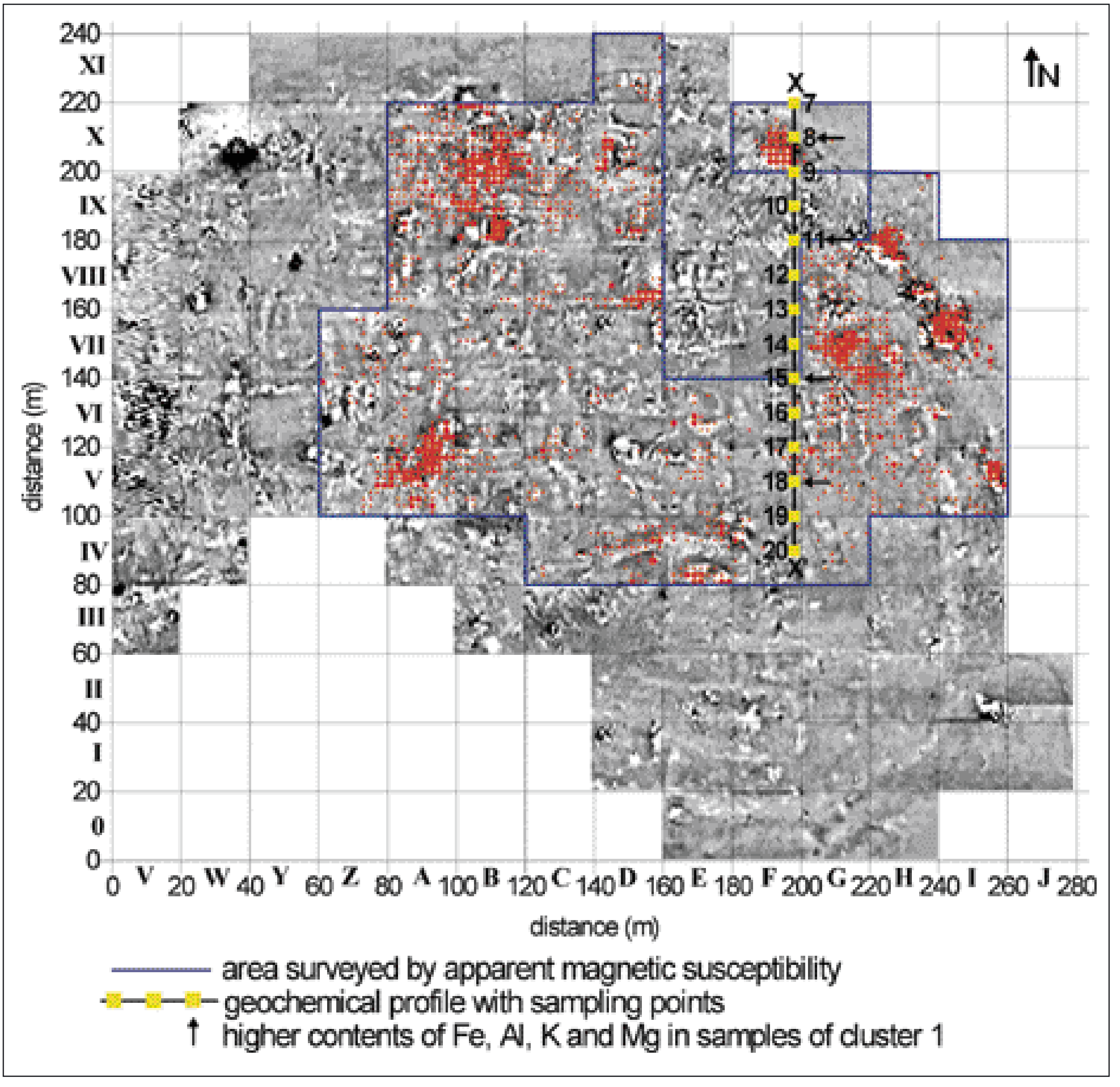


Fig. 12: Ajdovščina above Rodik. The values of the apparent magnetic susceptibility higher than the so-called critical, or border values, which amount to 0.6 x 10^{-3} SI, are presented. The high susceptibility values correspond well with the high gradients of the magnetic field.
Sl. 12: Ajdovščina nad Rodikom. Prikazane so vrednosti navidezne magnetne susceptibilnosti, višje od t. i. kritične oz. mejne vrednosti, ki v tem primeru znaša 0,6 x 10^{-3} SI. Visoke vrednosti susceptibilnosti se dobro ujemajo z visokimi gradienti magnetnega polja.

Ajdovščina above Rodik Ajdovščina nad Rodikom	Brkini
n = 14	n = 8
m = 2,43	m = 2,96
s^2 = 0,14	s^2 = 2,73
s = 0,37	s = 1,65
min = 1,94	min = 1
max = 3,29	max = 5,6
sim = 1,41	sim = 0,30
spl = 0,62	spl = -0,58

layers of ruins (*Fig. 9*). This method was also applied to detect structures with high thermoremanent magnetization, all interpreted as the remains of industrial workshops (ironworks?) and deposits of metallurgic refuse products on the basis of magnetometry. Explicit radar reflections were perceived from all these structures. All these determinations are significant for evaluating the potential of geophysical techniques at Late Roman settlements, where the architectural remains are covered with thick layers of ruins. Perhaps the most important determination from georadar investigations for the purpose of researching the urbanistic design of such settlements and their architectural heritage, is that the walls are not always situated directly beneath the higher part of heap of ruins. Consequently,

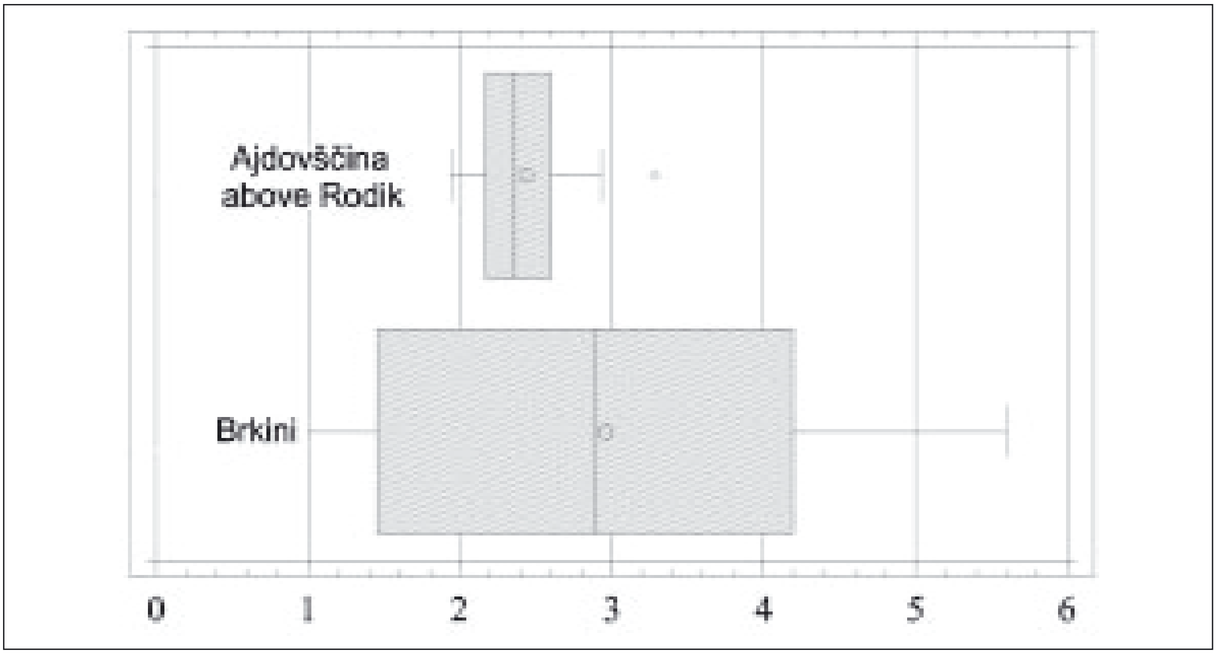


Fig. 13: Ajdovščina above Rodik. A statistical comparison of the mean values of the iron content in seven samples of natural soil from Brkini flysch (m = 2.96 %) - among which a sample collected in the direct vicinity of the settlement was also included - with 14 soil samples from within the settlement (m = 2.43 %), established that, at a confidence level of 95 %, there are no statistically characteristic differences between the medial values of iron content. The same result was attained applying the Kolmogorov-Smirnov test, which compares the distribution of both samples, and the Mann-Whitney W test, which compares the medians of both samples. Only the standard deviations differentiate as concerns their statistical characteristics, although I attributed this to the number of samples, especially in the comparative group of the chemical composition of the natural background, where only eight samples were available for statistical processing.
Sl. 13: Ajdovščina nad Rodikom. S statističnim primerjanjem srednjih vrednosti vsebnosti železa v 7 vzorcih naravnih tal na brkinskem flišu (m = 2,96 %), ki smo jim dodali še vzorec, ki je bil pobran v neposredni bližini naselbine in vsebnosti v 14 vzorcih tal na naselbini (m = 2,43 %), sem ugotovil, da na nivoju zaupanja 95 % med grupama vzorcev ni statistično značilnih razlik med srednjima vrednostma vsebnosti železa. Enak rezultat sem dobil tudi s Kolmogorov-Smirnovim testom, ki primerja distribuciji obeh vzorcev, in Mann-Whitneyevim W testom, ki primerja mediani obeh vzorcev. Statistično značilno se razlikujeta edino standardna odklona, vendar to pripisujem številu vzorcev, še posebej v primerjalni grupi kemične sestave naravnega ozadja, kjer sem imel za statistično obdelavo na razpolago skupaj le 8 vzorcev.

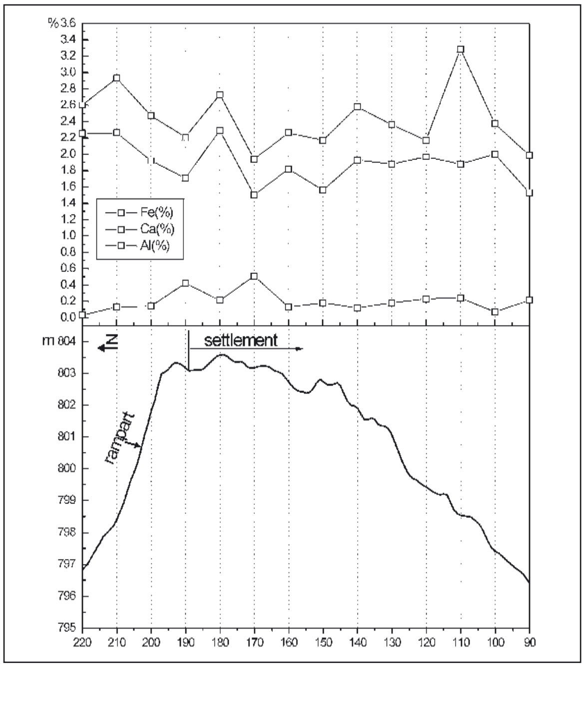


Fig. 14: Ajdovščina above Rodik. Pedosequences on noncarbonaceous rock. The profile from which soil samples for chemical analyses (*Fig. 12;* x = 180, y = 220-90) were taken begins outside the settlement before the defensive rampart, it crosses the rampart and the Late Roman architectural debris and continues deep into the heart of the settlement of the so-called empty space, where anomalies which could correspond to archaeological structures or perhaps to certain settlement activities failed to be determined using other prospecting techniques. The differences in height are somewhat emphasized.
Sl. 14: Ajdovščina nad Rodikom. Pedosekvenca na nekarbonatnih kamninah. Profil, v katerem smo vzorčevali tla za kemično analizo (*sl. 12;* x = 180, y = 220-90), se začne zunaj naselbine pod obrambnim nasipom, prečka nasip in ruševinske groblje kasnoantičnih arhitekturnih ostalin tik ob nasipu in se nadaljuje globoko v notranjost naselbine v t. i. prazen prostor, kjer z ostalimi prospekcijskimi metodami nismo ugotovili anomalij, ki bi jih lahko povezali z arheološkimi objekti oz. predpostavili določene naselbinske aktivnosti. Višinske razlike so nekoliko poudarjene.

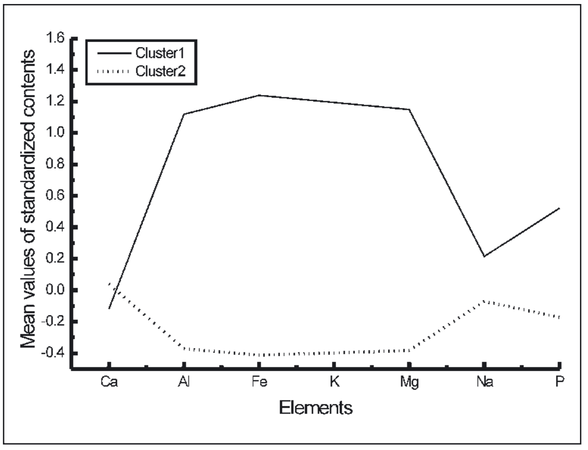


Fig. 15: Ajdovščina above Rodik. Pedosequences on noncarbonaceous rock. K-mean cluster analysis of the content of 7 elements in the geochemical profile at Ajdovščina above Rodik (*Fig. 12*). This statistical method was applied so as to group the samples, on the basis of their standardized contents (%) of the stated elements, into two classes. Class 1 incorporates samples with higher contents of Al, Fe, Mg, Na and P, as well as lower values of Ca. I consider these samples to be chemical anomalies at the site, resulting due to contamination from industrial activity (ironworks?). All other samples are attributed to class 2, which I define as the geochemical background of the settlement.

Sl. 15: Ajdovščina nad Rodikom. Pedosekvenca na nekarbonatnih kamninah. K-mean clustrska analiza vsebnosti 7 prvin v geokemičnem profilu na Ajdovščini nad Rodikom (*sl. 12*). S to statistično metodo sem vzorce na podlagi standardiziranih vsebnosti (%) navedenih prvin grupiral v 2 razreda na podlagi podobnih kemijskih značilnosti vzorcev. V razred 1 sodijo vzorci, ki imajo višje vsebnosti Al, Fe, K, Mg, Na in P ter nižje vrednosti Ca. Zaradi tega štejem te vzorce za kemično anomalijo na najdišču, ki je posledica kontaminacije zaradi obrtne dejavnosti (železarstvo?). Vsi ostali vzorci sodijo v razred 2, ki ga razlagam kot geokemično ozadje naselbine.

a microrelief of the surface does not provide a sufficient basis for drawing a precise ground plan from (*Fig. 4*), but rather the walls must be located using georadar measurements.

The corrected values of the apparent resistivity were divided into two classes on the basis of the statistic parameters. The first class includes those between the medial value and the standard deviation of 1, while the second class includes all values higher than the standard deviation of 1. The correlation between the hip of ruins and the high values of the apparent resistivity is weak, or rather much lower than anticipated (*Fig. 10*). Topographic anomalies, which are the result of debris and the apparent specific resistivity that is higher than the medial value, correspond only in select places in the southeastern area. Exclusively a negative correlation between the topography and the apparent resistivity was determined on all other parts of the settlement. These results enable us to conclude that all the measured values of the apparent resistivity of the debris are, quite surprisingly, lower than the mean value.

A high level of correlation between the magnetometry (Fluxgate gradiometer FM36) and the magnetic susceptibility (Kappameter KT-5) (*Fig. 12*) as well as between the magnetic susceptibility and the field survey (*Fig. 11*) was determined throughout the entire settlement. Laboratory measurements (for a more detailed explanation see Dimc, Mušič, Osredkar 1994, 225-230; Mušič, Slapšak 1998, 81-93; Mušič, Slapšak, Perko 1999, 132-146) ascertained that the raised values of susceptibility of the top, approximately 3 cm thick horizon of soil, resulted from contamination with ceramic and/or metallurgic dust (ironworks?), most likely the result of decaying fragments of pottery and slag on the settlement surface.

As no intervention other than pasturage occurred on the settlement from the Late Roman period until today, the suitability of geochemical analyses for detecting regions and their respective purposes in the archaeological past could be checked (see Mušič et al. 1995). Samples were taken from one profile (*Fig. 12*), which based on the result from prospecting techniques, incorporated an area serving various purposes during the Late Roman period. Sampling was carried out under the direction of S. Pirc and N. Zupančič (NTF, Department of Geology). The profile begins at the northern end of the settlement, beyond the settlement under the prehistoric and Late Roman rampart, it traverses the strong magnetic anomaly with the thermoremanent type of magnetization on the outer part of the prehistoric rampart, running over the wall it continues deep into the heart of the settlement, where it crosses the debris as well as the apparently -empty- parts of the settlement. We were interested in determining whether there is a statistically characteristic difference in the chemical composition of the natural soil on the flysch rock of the Brkini hills and the settlement floor. This difference could be the result of intensive industrial activity (ironworks?) during the Late Roman period. The results of the chemical analyses from the geochemical map of the Brkini hills in Istria were applied for this purpose (Zupančič 1990). The content of Fe in the soil of the Brkini flysch was compared statistically with that in the samples collected from the geochemical profile (*Fig. 13*). No statistically characteristic differences were demonstrated in the content of iron within and beyond the settlement. This result is likely the consequence of high oscillation in the iron content in the soil of the Brkini flysch. A larger

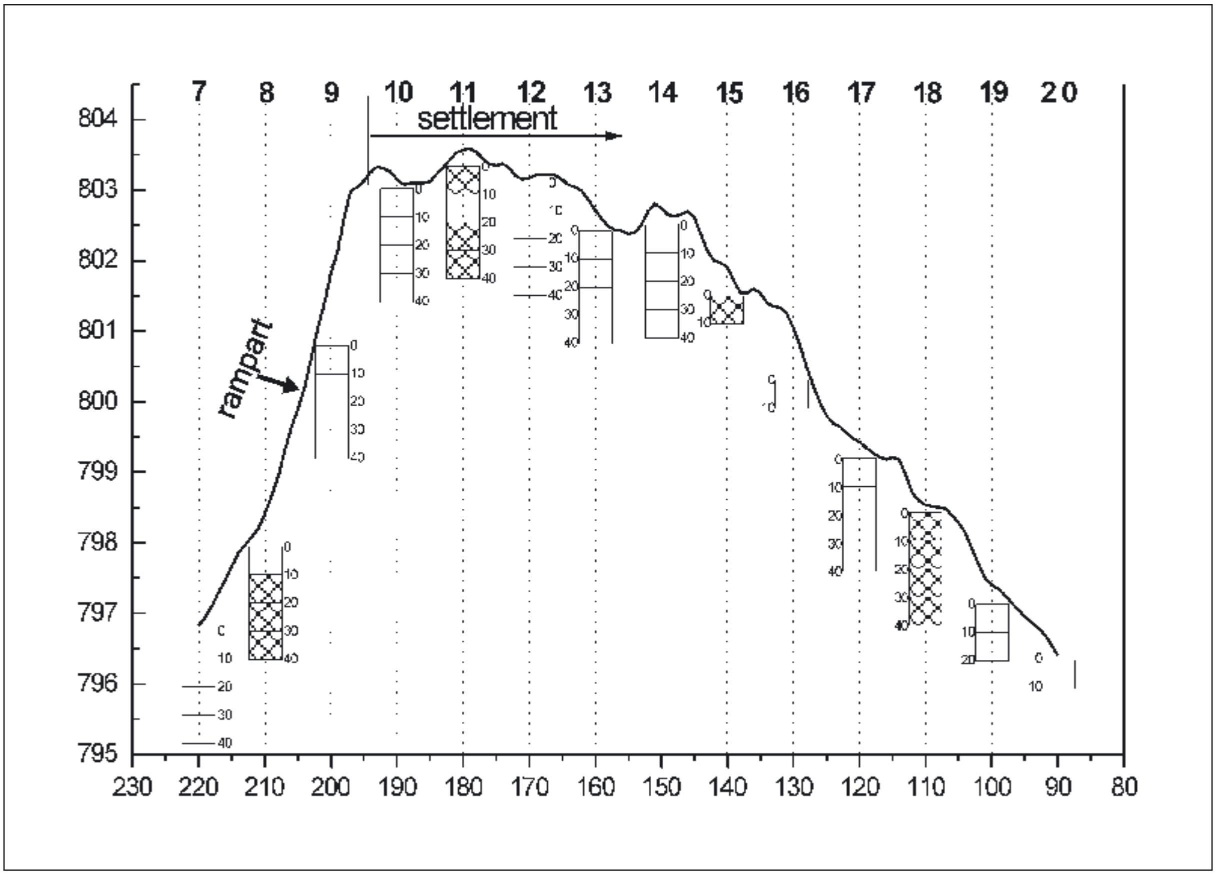


Fig. 16: Ajdovščina above Rodik. Pedosequences on noncarbonaceous rock. An illustration of the samples grouped into two classes, based on their sample points (*Fig. 12*). Class 1, for which higher contents of Fe, Al, K and Mg are characteristic, includes 11 samples (hatched squares); class 2, for which lower contents of these elements and only somewhat higher contents of Ca are characteristic, includes 33 samples. Class 1 represents a geochemical anomaly, while the measured contents of elements in the samples attributed to class 2 represent the background of the settlement. Only slightly higher contents of Ca were determined in class 2, which could perhaps be the result of fragments of Late Roman mortar in the soil.
Sl. 16: Ajdovščina nad Rodikom. Pedosekvenca na nekarbonatnih kamninah. Prikaz grupiranja vzorcev v dva razreda glede na vzorčne točke (*sl. 12*). V razred 1 za katerega so značilne višje vsebnosti Fe, Al, K in Mg, sodi 11 vzorcev (šrafirani kvadratki), v razred 2, za keterega so značilne nizke vsebnosti teh prvin in le nekoliko višje vsebnosti Ca, je skupaj 33. Razred 1 predstavlja geokemično anomalijo, medtem ko predstavljajo izmerjene vsebnosti prvin v vzorcih razreda 2 geokemično ozadje na naselbini. V razredu 2 so bile ugotovljene le nekoliko višje vrednosti Ca, kar je lahko posledica drobcev kasnoantične malte v tleh.

number of samples from the direct vicinity of the settlement should be tested for a more reliable interpretation in determining the content of iron in the natural background. Small differences in the content of certain elements are present within the settlement (*Fig. 14*). The chemically anomalous region was defined by applying the K-mean cluster analysis, through which all samples were grouped into two classes (*Fig. 15*). One class designates the background, the other designates the anomaly. Higher content of iron was determined in the area of thermoremanent magnetization on the rampart, above the heap of ruins, as well as within the settlement, where distinctive anomalies failed to be determined using other prospecting techniques (*Fig. 16*).

PEDOSEQUENCES ON HARD CARBONACEOUS ROCK

Ajdovski gradec near Bohinjska Bistrica (*Fig. 17*)

Pieces of iron slag, or various ironworks refuse products, were discovered in almost all trenches during Schmid's archaeological excavations in 1936 (see Gabrovec 1966). Schmid also discovered small ditches, which he interpreted as the remains of a smeltery, in two trenches in houses II and III on the eastern side of the settlement. On the basis of these data, I chose magnetometry as the most suitable geophysical method for detecting industrial zones with metallurgic activity (*Fig. 18*).

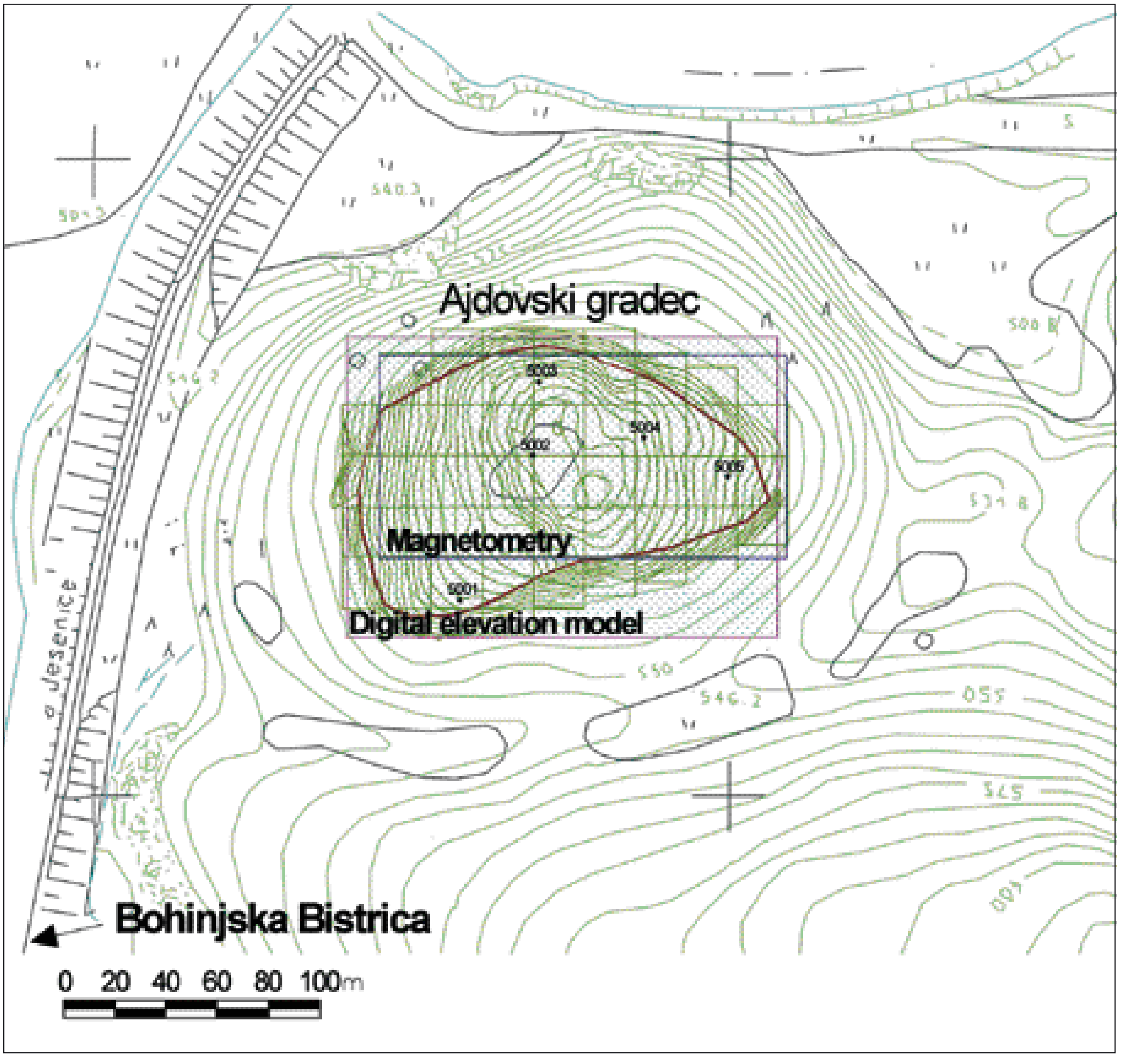


Fig. 17: Ajdovski Gradec near Bohinjska Bistrica. Pedosequences on hard carbonaceous rock. A topographic map of the surface upon which the DEM was created for mapping minor topographic diversity resulting from various surface use in the archaeological past, and magnetometry for mapping anomalies in the vertical gradient of the magnetic field, probably the consequence of thermoremanent magnetization of iron-smelting refuse products.
Sl. 17: Ajdovski gradec pri Bohinjski Bistrici. Pedosekvenca na trdih karbonatnih kamninah. Položajna skica površine, na kateri smo izdelali digitalni model reliefa za kartiranje majhnih topografskih razlik, ki so lahko posledica namembnosti prostora tudi v arheološki preteklosti, in magnetometrijo za kartiranje anomalij v vertikalnem gradientu magnetnega polja, ki so najverjetneje rezultat termoremanentne magnetizacije odpadnih produktov železarstva.

The anticipated thickness of the soil is rather small and the terrain is quite unlevel as the settlement is situated atop a hill with pedosequences on hard carbonaceous rock (limestone). Measuring the microrelief is one of the most effective prospecting techniques in these conditions. A microrelief, or rather a Digital Elevation Model, is really only a precise topographic map; although due to its testimonial value in archaeological interpretation, I consider it a prospecting technique. Interpretation of archaeological remains is based on observing small topographic differences in the formation of the surface at a settlement (*Fig. 19* and *20*).

The measured values of the vertical gradient of the magnetic field (Geoscan FM36) were between -30 nT/m in +40 nT/m. The values of the magnetic susceptibility of the bedrock and the pedologic horizons at the archaeological site must be known for an interpretation of the magnetic anomalies that result from induced magnetization. The mean

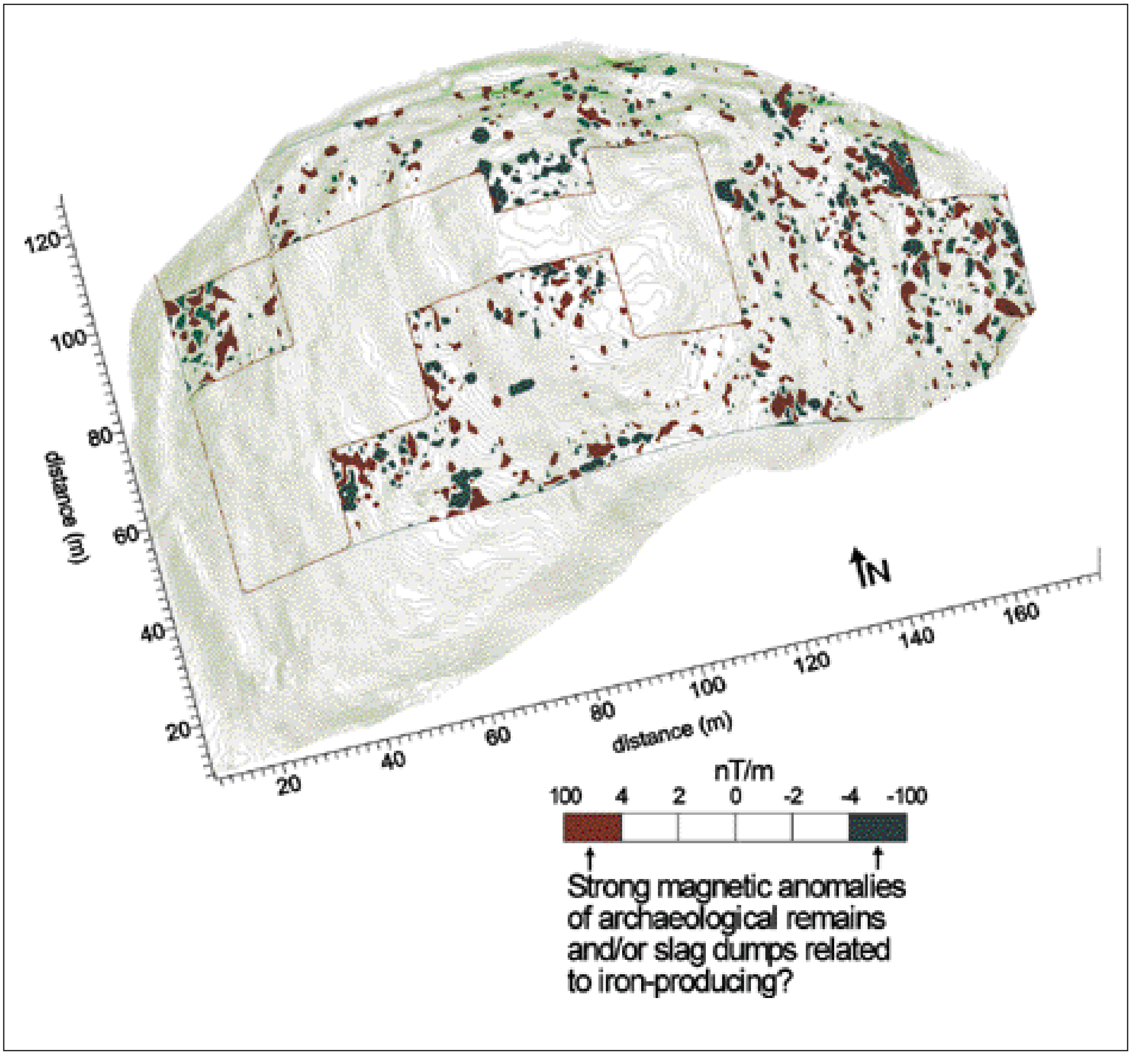


Fig. 18: Ajdovski Gradec near Bohinjska Bistrica. The Digital Elevation Model (the equidistance between contour lines is 0.15 m) and magnetometry. Stronger magnetic anomalies, most likely resulting from industrial ironworks activity during the Late Roman period, are depicted.
*Sl. 18: A*jdovski gradec pri Bohinjski Bistrici. Digitalni model reliefa (ekvidistanca med izohipsami je 0,15 m) in magnetometrija. Prikazane so močnejše magnetne anomalije, ki so najverjetneje posledica obrtnih železarskih dejavnosti v pozni antiki.

value of the apparent magnetic susceptibility (Kappameter KT-5) of limestone is 0.018 x 10^{-3}SI for 22 measurements. The mean value for the same number of measurements of noncontaminated soil samples is 0.12 x 10^{-3}SI. This means that the ground is 6 times more magnetic than the limestone geologic foundation. Such a contrast in the magnetic susceptibility can, in addition to the unlevel morphology of the terrain and the low lying limestone geologic foundation, cause relatively strong magnetic anomalies of a similar size as the amplitude of induced magnetization on archaeological structures.

Figure 18 depicts the negative gradients in blue and the positive gradients in red. The positive gradients designated in red are more important for determining metallurgic activity. It is evident in all figures that the red fields are very irregular shapes and approximately equally distributed throughout the entire investigated area. High positive gradients are not present solely on the terraces but also along the less inclined slopes on the eastern side of the settlement. I am of the opinion that they are magnetic anomalies resulting from the combination of all the magnetic fields in the archaeological cultural layers, as well as magnetic anomalies resulting from

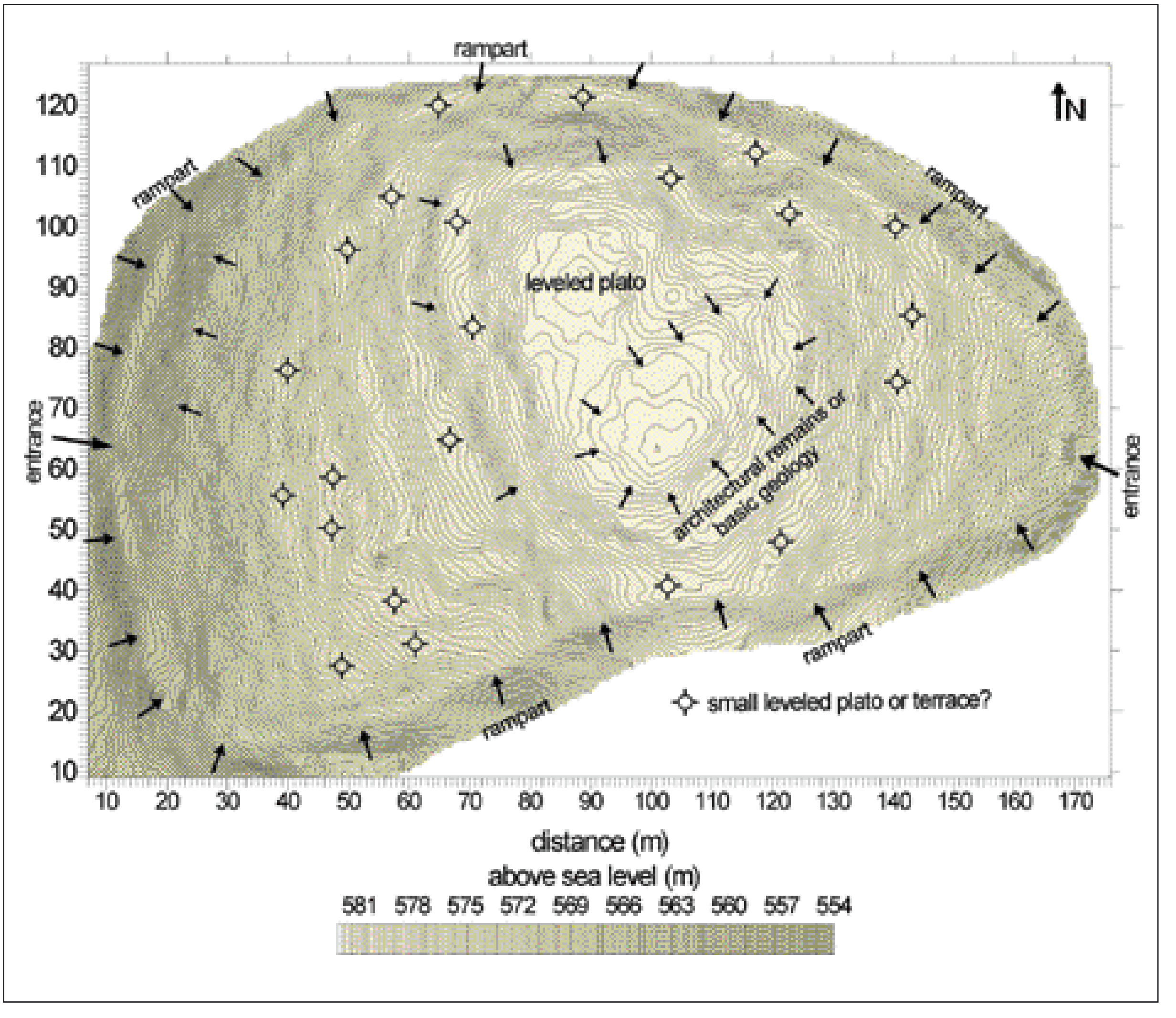


Fig. 19: Ajdovski Gradec near Bohinjska Bistrica. An interpretation of the morphologic features of the site.
Sl. 19: Ajdovski gradec pri Bohinjski Bistrici. Interpretacija morfoloških oblik na najdišču.

natural factors. As we are primarily interested in the strong thermoremanent type of magnetization, in the instance of metallurgic activity, I chose to display the distribution of only positive gradients, those higher than +5 nT/m. The number of anomalous regions reduced greatly in this instance, although they are still numerous. As the magnetic anomalies are strong, they are probably a thermoremanent type of magnetization resulting from metallurgic refuse products or from some smaller structures that incorporate the thermoremanent type of magnetization (refuse products - pieces of slag). Almost all strong magnetic anomalies are situated along the outer edge of the leveled surfaces, or terraces. This corresponds with the postulation that the leveled surfaces, or smaller terraces, are suitable for habitation as well as for preserving the archaeological cultural layers; however, we cannot exclude the possibility that we are dealing with the topographic effect of a folding terrace slope, and thus the limestone could be near the surface or even exposed.

The purpose of measuring the microrelief is to enable a depiction of even the smallest morphologic unit upon an archaeological site, thus permitting a determination of the archaeological remains on the basis of the surface configuration. The larger archaeological remains, such as ramparts, ditches, communication ways and terraces, represent the target objects for measuring the microrelief. Mapping the differences in height could be, in this respect, considered an independent prospecting method used for determining the archaeological morphologic shape of a site. At the same time, this type of map also serves as a precise topographic map for all other geophysical methods; for example, it is used for recognizing

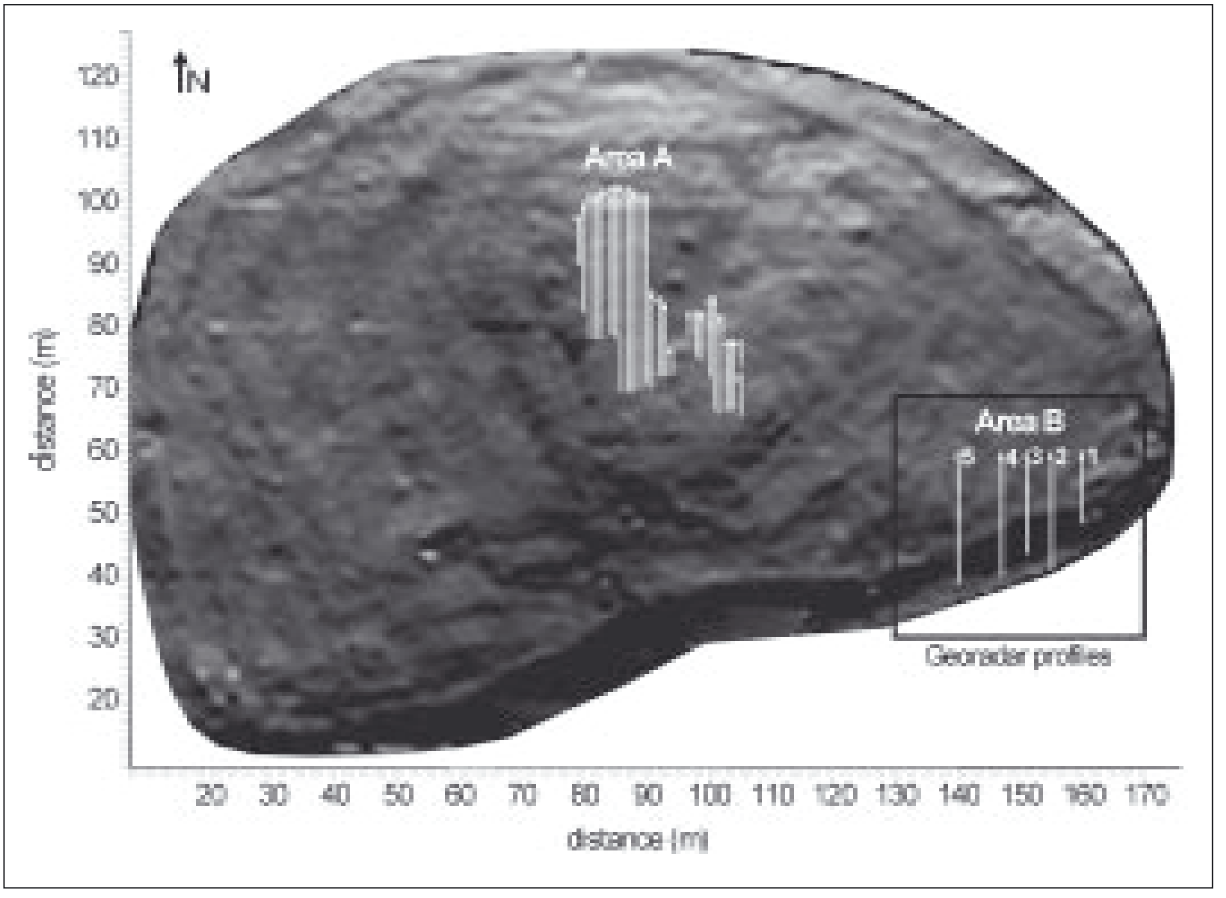


Fig. 20: Ajdovski Gradec near Bohinjska Bistrica. Pedosequences on hard carbonaceous rock. The Digital Elevation Model showing analytical hill shading and the positions of georadar profiles in area A, which covers the flat plateau atop the settlement and area B, where the profiles traverse the prehistoric rampart.
Sl. 20: Ajdovski Gradec pri Bohinjski Bistrici. Pedosekvenca na trdih karbonatnih kamninah. Digitalni model reliefa *(analytical hill shading*) in položaj georadarskih profilov na območju A, ki zajema ravni plato na vrhu naselbine in na območju B, kjer potekajo profili prečno čez prazgodovinski obrambni nasip.

magnetic anomalies resulting from the so-called -topographic effect- (see Mušič, Orengo 1998, 178-179, Fig. 16).

Topographic features that are significant for archaeological interpretation are designated on *Fig. 19*. I classify the following characteristic morphologic forms:

Distinct positive topographic forms representing the remains of a prehistoric and/or Late Roman rampart can be traced around the settlement. It is a closed rampart that runs around the outer edge of the settlement directly along the line where the natural terrain turns into a steep slope facing outwards. The rampart is discontinued only along the eastern and western part (*Fig. 19*: the western and eastern entrance into the settlement). These discontinuations are situated right at today's entrance into the settlement, although the topography of the terrain indicates that communications in prehistory and/or the Late Roman period ran along the same direction and through the entrances situated just as they are today. The rampart divides into two, such that the inner part extends parallel with the outer one along the northwestern segment.

Throughout the settlement smaller and larger segments were leveled; I have termed these segments as -terraces-. Some of the terraces were probably naturally leveled, while some of them were probably man-made. The purpose terraces served within the settlement is unclear, although most likely they were meant to level the karstic limestone geologic foundation so as to gain housing surface. It is less likely that the terraces were used for agricultural cultivation purposes. Furthermore, thicker archaeological cultural layers can be anticipated along the -terraces-. It can be concluded on the basis of the above mentioned that the leveled surfaces, or terraces, are important indications of archaeological cultural layers.

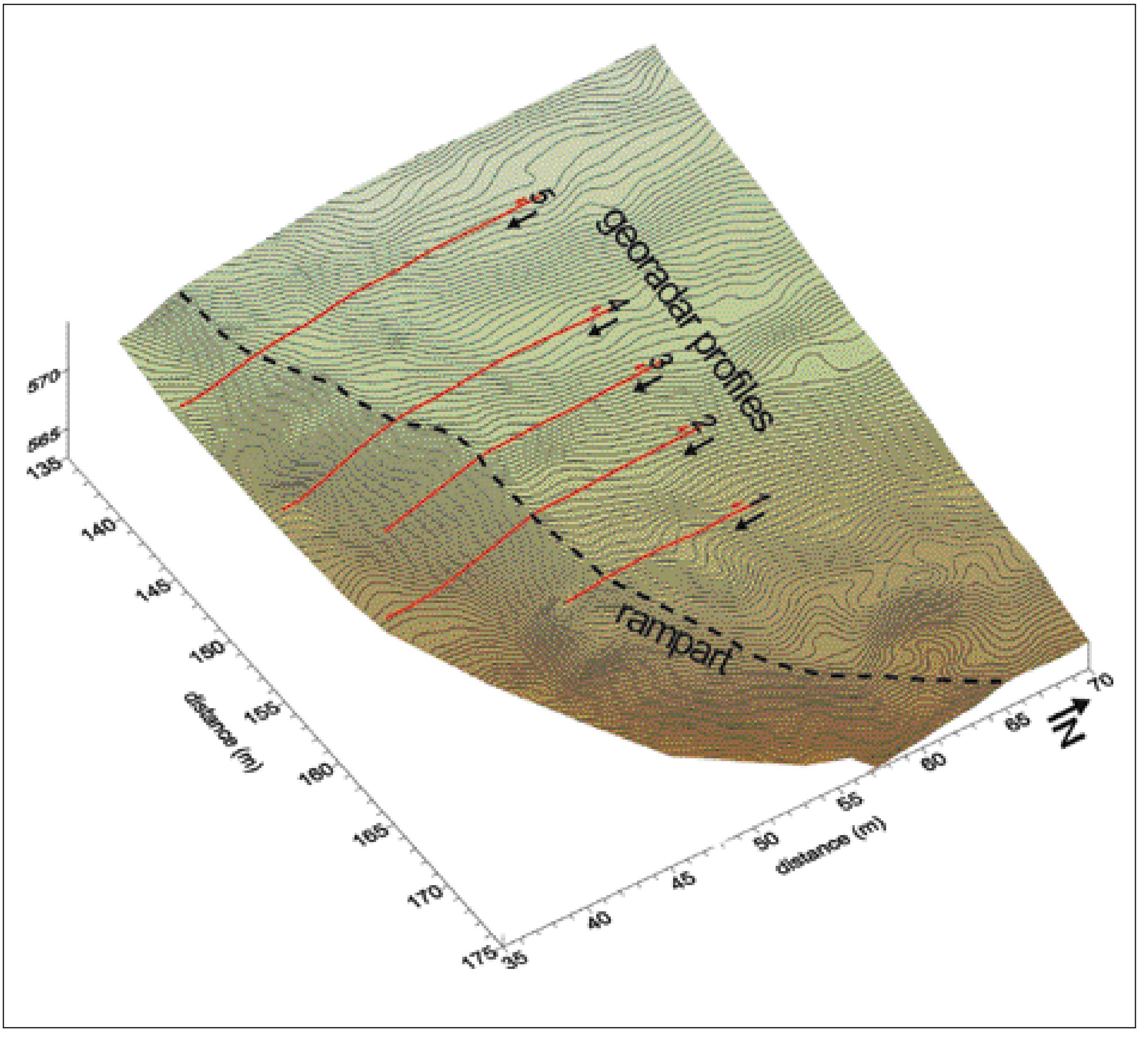


Fig.21: Ajdovski Gradec near Bohinjska Bistrica. Pedosequences on hard carbonaceous rock. Georadar profiles traversing the rampart in area B.
Sl. 21: Ajdovski gradec pri Bohinjski Bistrici. Pedosekvenca na trdih karbonatnih kamninah. Georadarski profili čez obrambni nasip na območju B.

An almost entirely leveled plateau is situated atop the settlement and marked off by a steep slope on the western side and a gentle slope along the eastern side. Architectural remains are presumably situated on the plateau, or in the near vicinity. The Digital Elevation Model is almost completely flat in the northern part of the plateau where there is currently a clearing. The southern part is overgrown with thick vegetation and it is morphologically quite unlevel. The map of the microrelief reveals forms similar to architectural remains (*Fig. 19:* architectural remains/basic geology). It should be emphasized that conclusions based solely on the morphology of the terrain can be misleading.

A Digital Elevation Model must first be created for these types of topographically unlevel sites to enable execution of the georadar method. Only in this manner, corresponding to the surface shapes, can the georadar image be interpreted. One of the most evident morphological forms on almost all prehistoric hillforts is the rampart (*Fig. 19; 20* and *21*). As we wish to evaluate the potential of georadar investigations for detecting remains such as prehistoric ramparts, we traversed a segment of the rampart along the southeastern side of the settlement with a few profiles (*Fig. 20* and *21*). Distinct radar reflections in the shape of a hyperbola were determined along the edge of the plateau where the terrain falls into a steep slope;

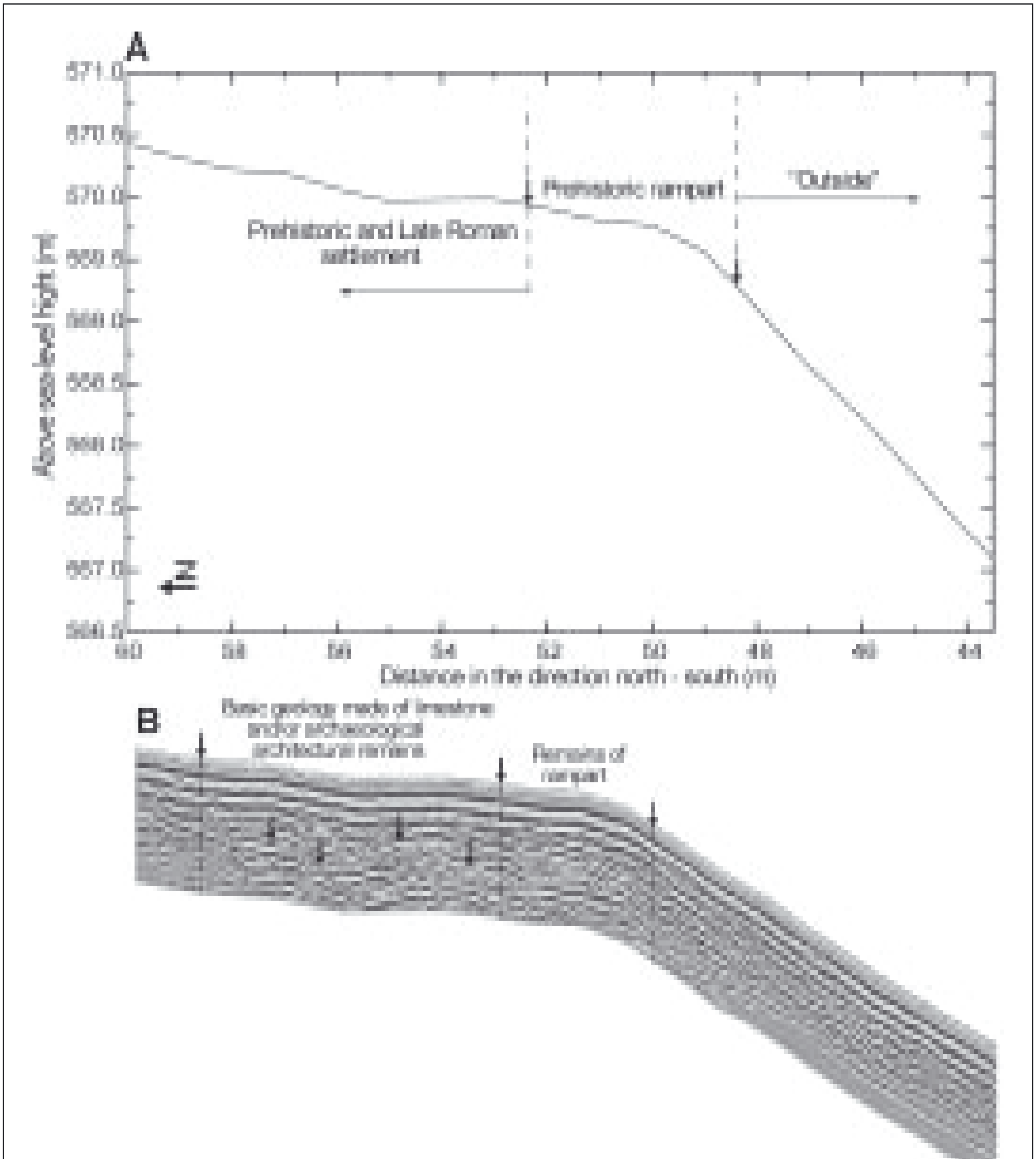


Fig. 22: Ajdovski Gradec near Bohinjska Bistrica. Pedosequences on hard carbonaceous rock. The microrelief in the direction of georadar profile no. 3 in area B (A) (*Fig. 20* and *21*) and radar reflections in the direction of the same profile (B).
Sl. 22: Ajdovski Gradec pri Bohinjski Bistrici. Pedosekvenca na trdih karbonatnih kamninah. Mikrorelief v smeri georadarskega profila 3 na območju B (A) (*sl. 20* in *21*) in radarski odboji v smeri istega profila (B).

they could be the result of a large mass of rock material corresponding to the rampart or perhaps they are reflections from the karstic limestone foundation. The same shapes also continue into the settlement (*Fig. 22*).

Škocjan (*Fig. 23*)

The suitability of geophysical prospecting was tested at the prehistoric hillfort at Škocjan (*Fig. 23*) so as to evaluate the archaeological poten-

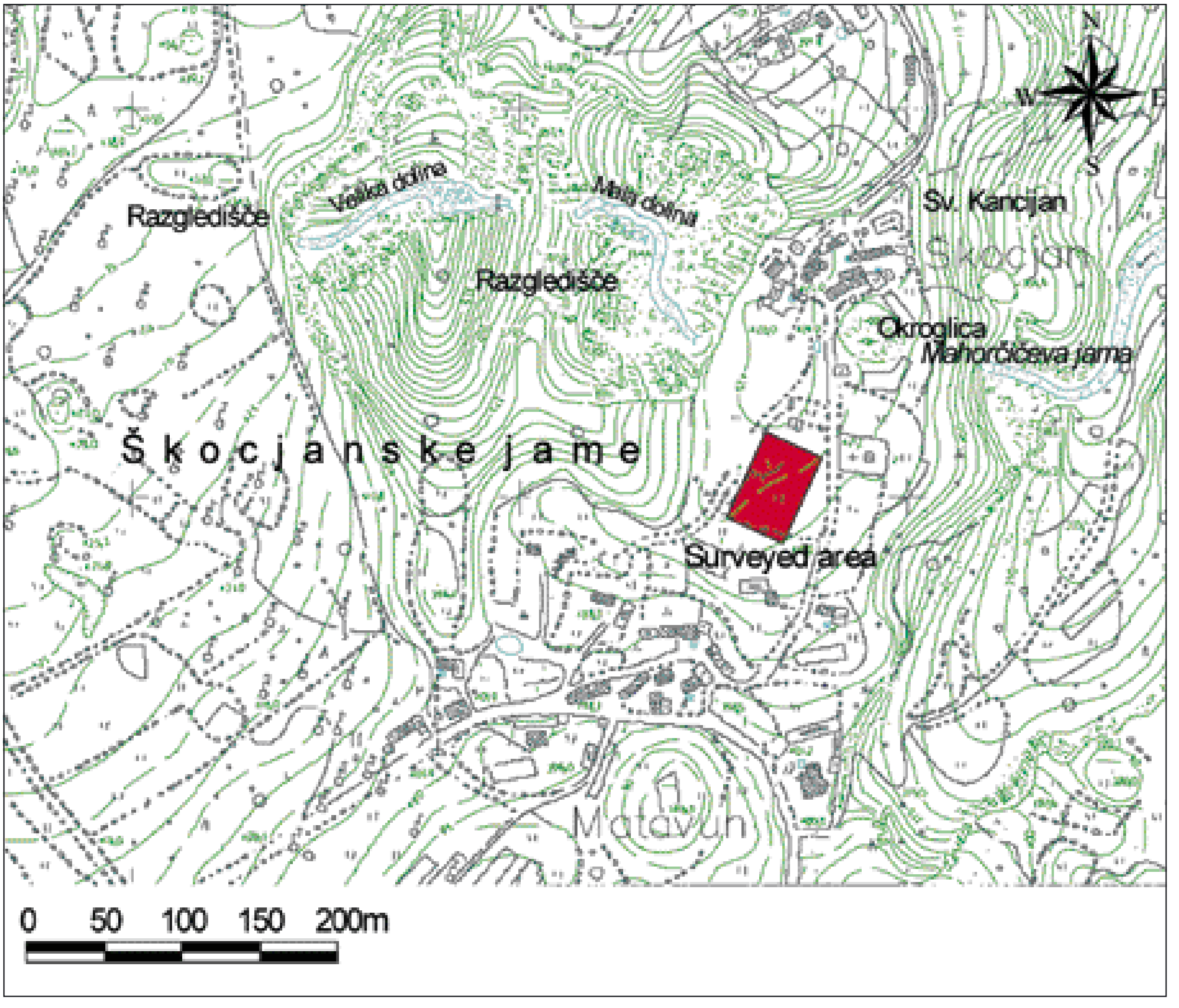
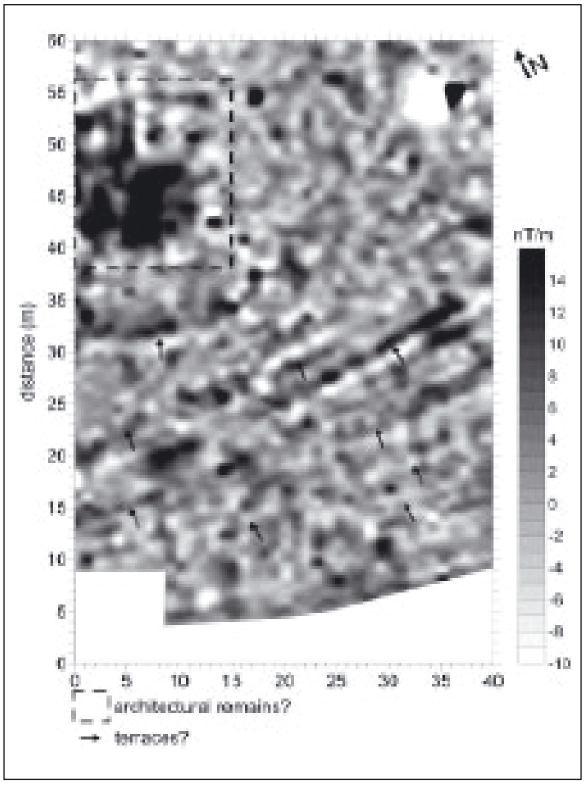


Fig. 23: Škocjan. Pedosequences on hard carbonaceous rock. Location map of investigated area.
Sl 23: Škocjan. Pedosekvenca na trdih karbonatnih kamninah. Položajna skica raziskane površine.

tial of this type of site situated upon a karstic geologic foundation. The resistivity method was applied using the Twin Probes (Geoscan RM15) instrument, as well as magnetometry using the Fluxgate gradiometer FM36 (*Fig. 24*). Due to the variable morphology of the terrain, a microrelief was mapped upon which the results from the magnetometry were also displayed (*Fig. 25*), so as to correct the so-called -topographic effect- resulting from the combined effect of the contrast in the magnetic susceptibility between the weak magnetic limestone geologic foundation and the strong magnetic underground variegation and the configuration of the surface. No data directly applicable for archaeological interpretation was attained using the resistivity method. Nonetheless, these data are indirectly significant as they enable us to determine, in addition to the microrelief, the changes in the morphology of the karstic bedrock under the surface, which were furthermore applied in the interpretation of the magnetometry.

Certain data was attained in this manner, which we consider significant for evaluating the potential of geophysical investigations on prehistoric hillforts throughout the Karst region. Transverse linear anomalies from the vertical gradient of the magnetic field, which are at least partly the result of terracing in the past, are evident on the magnetogram (*Fig. 24*) in the lower half of the diagram. Very distinct positive magnetic anomalies were detected up and to the left, most likely the consequence of thermoremanent magnetization of bricks.

Transverse linear anomalies are partly the result of the -topographic effect- in places of greater level differences, which can be clearly seen in the diagram showing the microrelief as well as the



magnetometry (*Fig. 25*). This could be indicative of natural forms or of sub-recent terracing. In addition to these magnetic anomalies, numerous other linear anomalies which cannot be connected to the configuration of the surface or the bedrock are evident in Figure 24. These lines could be the result of terracing in the archaeological past. Strong magnetic anomalies (*Fig. 24* and *25*) (architectural remains?), most likely resulting from thermoremanent magnetization of bricks, were measured on entirely level ground with relatively lower values of apparent electric resistivity than other parts of the terrain; consequently, the -topographic effect- can be eliminated in this instance.

Fig. 24: Škocjan. Pedosequences on hard carbonaceous rock. Linear anomalies, visible on the lower half of the magnetogram, are probably the result of terraces, at least in part. Very strong positive magnetic anomalies, most likely the result of thermoremanent magnetization of bricks, were also measured in the upper left hand corner (architectural remains?).
Sl. 24: Škocjan. Pedosekvenca na trdih karbonatnih kamninah. Linearne anomalije v spodnjem delu slike so verjetno vsaj deloma rezultat terasiranja v arheološki preteklosti. Močna termoremanentna magnetizacija levo zgoraj je posledica arhitekturnih ostalin iz opeke (arhitekturne ostaline?).

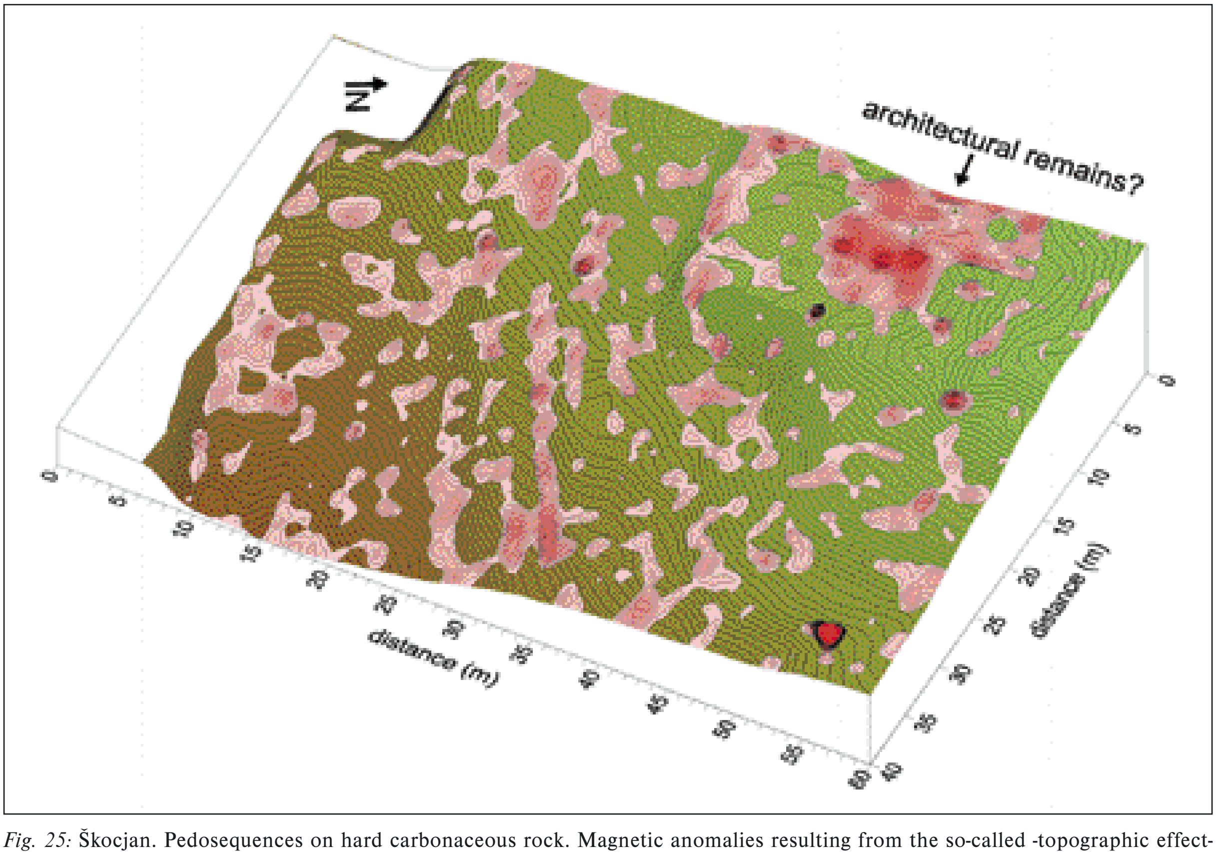


Fig. 25: Škocjan. Pedosequences on hard carbonaceous rock. Magnetic anomalies resulting from the so-called -topographic effect- can be discerned on the combined depiction of magnetometry and the Digital Elevation Model.
Sl. 25: Škocjan. Pedosekvenca na trdih karbonatnih kamninah. Na kombiniranem prikazu magnetometrije in digitalnega modela reliefa lahko izločimo magnetne anomalije, ki so posledica t.i. -topografskega efekta-.

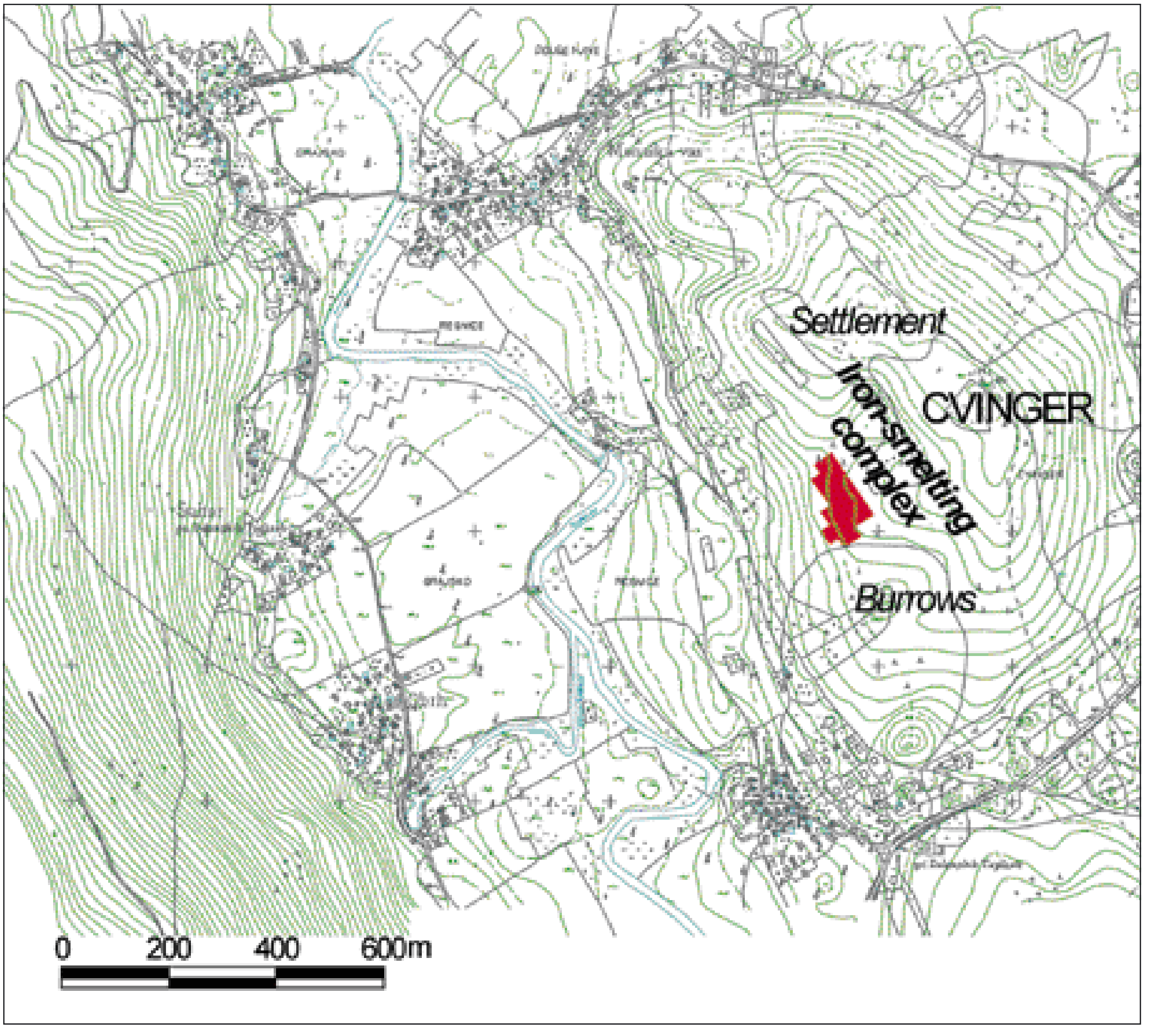


Fig. 26: Cvinger near Meniška vas. Pedosequences on hard carbonaceous rock. The surface area of the ironworks smelting complex that was investigated using geophysical prospecting methods is demarcated.
Sl. 26: Cvinger pri Meniški vasi. Pedosekvenca na trdih karbonatnih kamninah. Označena je površina železarskega talilnega kompleksa, ki smo ga raziskali z geofizikalno metodo.

Cvinger near Meniška vas (*Fig. 26*)

As the results from geophysical prospecting on Cvinger near Meniška vas (*Fig. 26*) have already been presented in detail elsewhere (Mušič, Orengo 1998, 157-186), only select determinations important for evaluating the potential of magnetometry and the magnetic susceptibility for detecting prehistoric ironworks industrial zones, or rather an ironworks smeltery complex with a primitive smelting furnace for extensive attainment of iron or the karstic bedrock, shall be summarized in this article. The primary characteristic of such industrial zones are metallurgic refuse products in the shape of blocks of underground slag found in larger and smaller underground pits (see: Smekalova, Voss, Abrahamsen 1993, 83-103).

We succeeded in delimiting the prehistoric ironworks smeltery complex (*Fig. 27*) using geophysical investigations. Based on the size of the entire industrial zone and the number of blocks of underground slag, the hypothesis concerning the smeltery furnaces used for extensive ironworks metallurgic processes was thus indirectly confirmed. These furnaces were constructed to be used only once.

It was also determined that the three-dimensional magnetic modeling method is useful at such archaeological sites for a precise quantitative interpretation. I used the Magpoly (USGS) computer

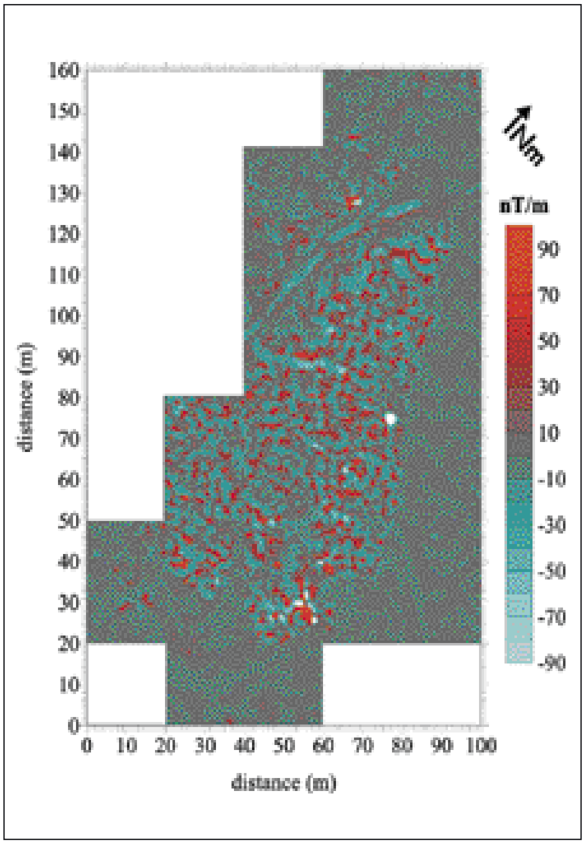


Fig. 27: Cvinger near Meniška vas. A map of magnetic anomalies (the vertical gradient of the density of the magnetic field - dZ/dz) for the entire investigated area. The highest gradients were determined in those areas where Iron Age remains of smelting furnaces (blocks of underground slag), representing structures with strong induced/thermoremanent magnetization, lay shallowly under the surface. This magnetization is manifested by an explicit bipolar characteristic in the measured magnetic anomalies (red: strong positive gradients; blue: strong negative gradients). The boundary lines to the industrial zone are also clearly visible.
Sl. 27: Cvinger pri Meniški vasi. Karta magnetnih anomalij (vertikalni gradient gostote magnetnega polja -dZ/dz) za celotno raziskano površino. Najvišji gradienti so bili ugotovljeni na mestih, kjer so plitvo pod površino ostanki železnodobnih talilnih peči (bloki talne žlindre), ki predstavljajo objekte z močno inducirano/termoremanentno magnetizacijo. Ta se odraža v izrazito bipolarnem značaju izmerjenih magnetnih anomalij (rdeče: močni pozitivni gradienti; modro: močni negativni gradienti). Lepo so vidne tudi meje industrijske cone.

program for modeling the remains of the smeltery furnaces, which are objects with thermoremanent magnetization and which have the characteristic of strong magnetic dipoles due to their thermic history. I decided that a low, upright cylinder presented the most appropriate geometric model for cavities filled with blocks of underground slag. The graphic procedure recommended by Telford and colleagues (1990, 87) can be applied to determine their depths.

The determination that the ironworks smeltery complex could be delimited also by mapping the apparent magnetic susceptibility using even less sophisticated instruments than for instance a Kappameter KT-5 was also significant.

As concerns magnetometry prospecting at similar sites in the Dolenjska region, it is also important that this so-called -topographic effect- does not affect the magnetometry results while carrying out prospecting at ironworks smeltery complexes.

PEDOSEQUENCES ON SOFT CARBONACEOUS ROCK

Groblje near Buče (*Fig. 28*)

The results from geophysical investigations at the site of the Roman villa at Groblje near Buče, where A. Vogrin (1990), ZVNKD Celje (the Institute for the Protection of the Natural and Cultural Heritage, Celje), conducted rescue excavations, are published in numerous articles (Mušič 1994, 9-19; 1994-1995, 59-72; 1996, 83-137). I have limited this article to emphasizing select facts important for evaluating the suitability of geophysical investigations on pedosequences of soft carbonaceous rock. Roman walls of a provincial villa, preserved only in part and discovered during excavations are consequential for an evaluation of the potential of geophysical investigations. Only the foundations, constructed using local stone (Miocene sandstone, sandy marl and limestone conglomerates), were relatively well preserved. They are situated at a depth of 40 cm on the northern side, and somewhat deeper (up to 70 cm) on the southern side. The width of the walls, or rather the foundations, is approximately equal throughout measuring 60 cm.

The ground on soft carbonaceous rock (marl) is relatively thick and lacking of a thickly grained stony structure due to the rapid rate of decay. Consequently, pedosequences on soft carbonaceous rock can be treated as a homogeneous and isotropic medium as concerns geophysical investigations. The results from geoelectric mapping and magnetometry precisely confirm this. To a large degree only the foundations of the wall, lying up to 70 cm deep, are preserved, nonetheless the results from geoelectric mapping are quite clear (*Fig. 29*); likewise are also the magnetometry results (see Mušič 1994; 1996 and 1997). This is somewhat surprising as the architectural remains are built of local stone, usually indicative of a weak contrast

Fig. 28: Groblje near Buče. Pedosequences on soft carbonaceous rock. Location map of the investigated area.
Sl. 28: Groblje pri Bučah. Pedosekvenca na mehkih karbonatnih kamninah. Položajna skica raziskane površine.

with the ground, a consequence of the same types of stone decaying.

PEDOSEQUENCES ON CLAYS AND LOAM

Grafendorf (Austria)

As mentioned already introductorily, one of the guiding fundamentals of geophysical prospecting research is the application of as many diverse geophysical techniques at the same archaeological site as possible. To portray the complementarity of georadar investigations, magnetometry and geoelectric mapping only one of the geophysical profiles was used for the Roman archaeological site at Grafendorf in Austria (*Fig. 30* and *31*), as the research will be published in full elsewhere. I allowed myself this one exception as archaeological excavations have already been carried out there to confirm this type of interpretative procedure. The aim was to suitably illustrate this segment of geophysical investigations as it will serve as a guiding principle in planning future archaeological prospecting. E. Pochmarski from the Department of Archaeology, University of Graz, conducted the archaeological project at the Grafendorf site. I divided the geophysical profile into several parts such that they clarify the archaeological context of the anomalies in the physical fields (*Fig. 31*). I am thus introducing the concept of *anomaly associations in the physical fields* which I substantiate on the basis of the general -geophysical image- of the region. This approach enables interpretations founded on anomalies in various physical fields at the same point (e.g. a wall) or within a region (e.g. ruins).

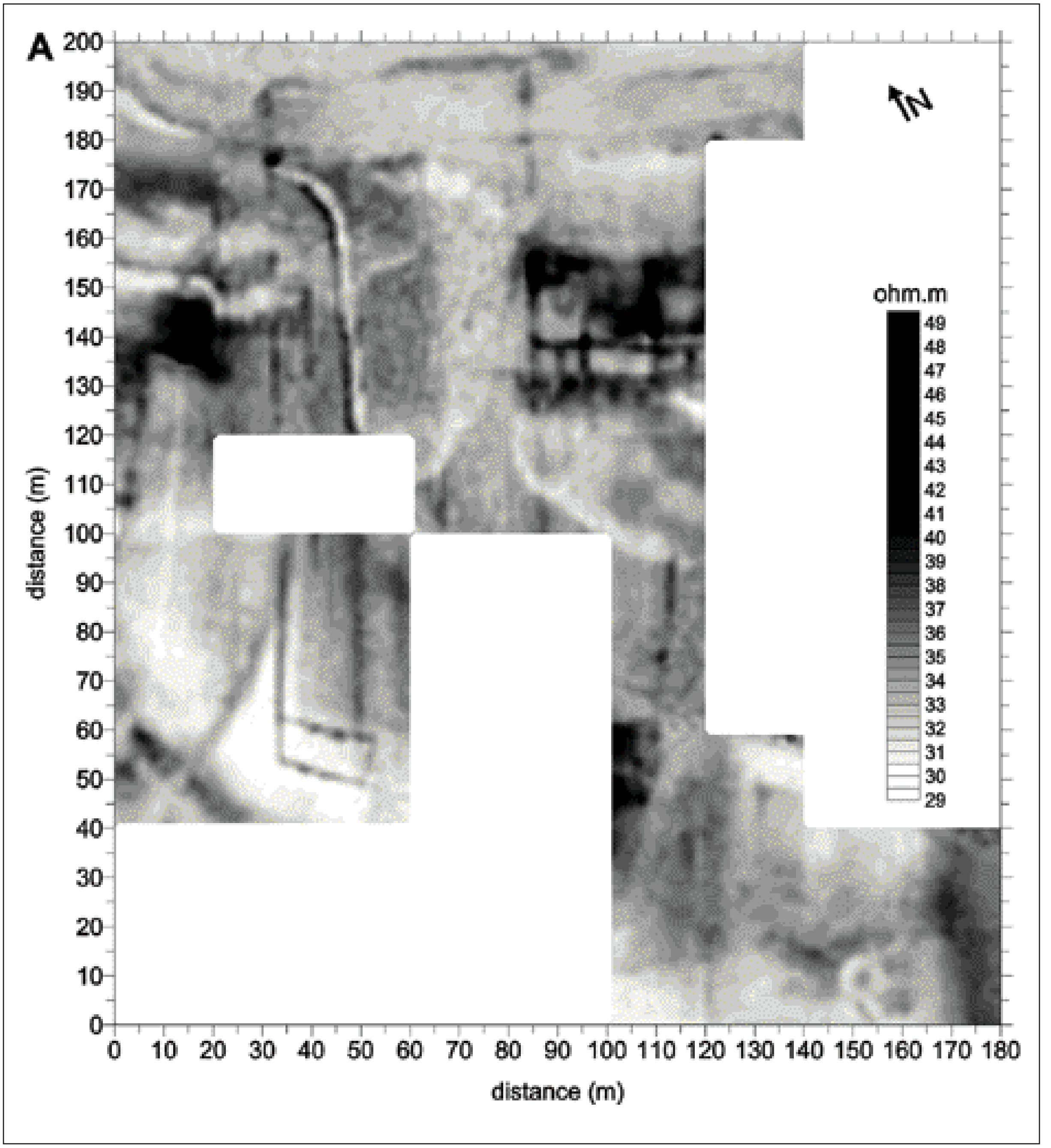
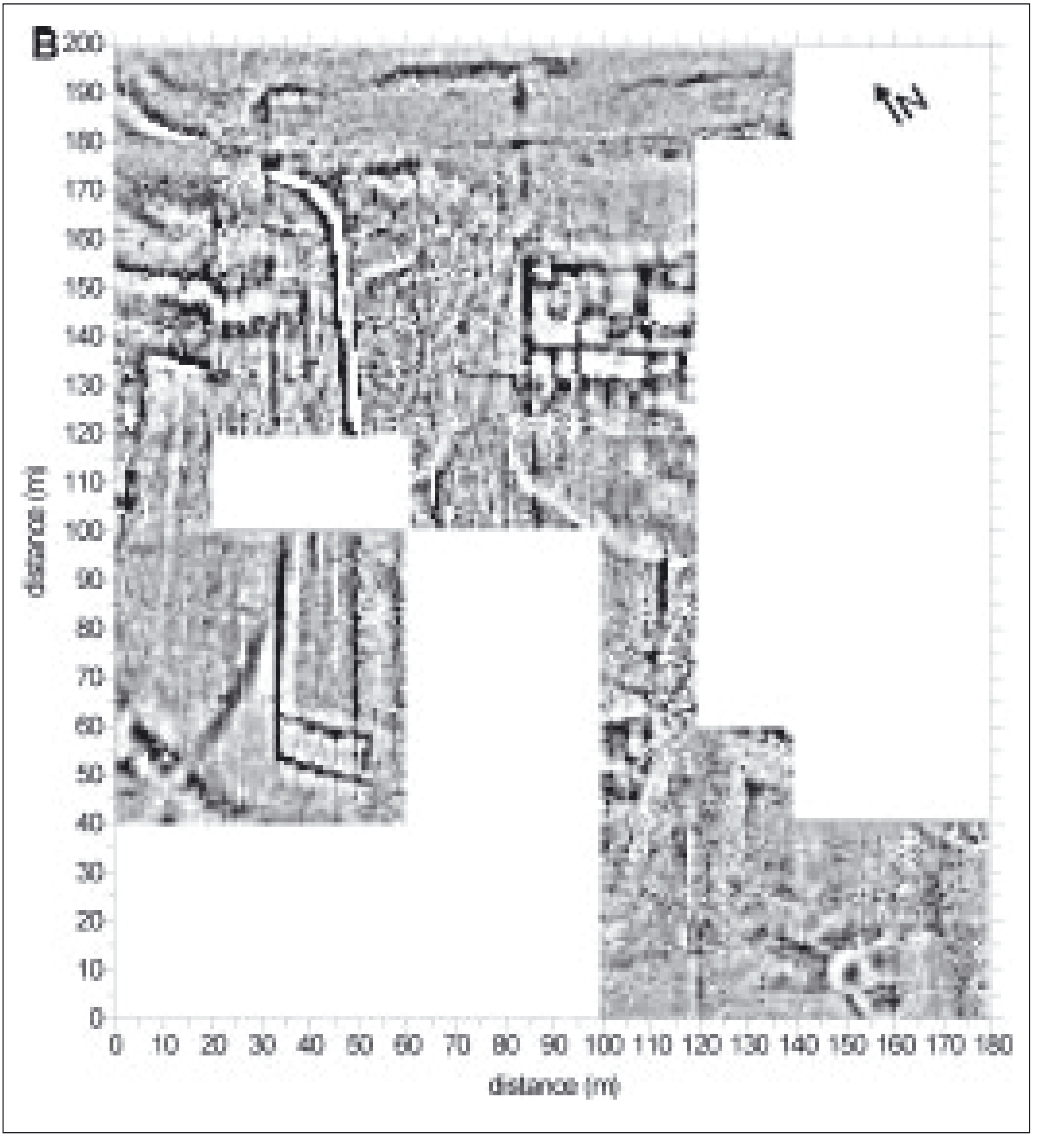


Fig. 29: Groblje near Buče. Pedosequences on soft carbonaceous rock. Geoelectric mapping with the Twin probes array (Geoscan RM15). An illustration of the values of the apparent resistivity with gray tones (A). The darker shades represent higher values (walls, ruins, paved or well built surfaces etc.). Long wave anomalies of the resistivity resulting from the geologic foundation, varying soil consistency and the ruination layers, were removed with the application of a high pass filter. Linear anomalies from the high resistivity of walls (B) are more distinctly visible.

Sl. 29: Groblje pri Bučah. Pedosekvenca na mehkih karbonatnih kamninah. Geoelektrično kartiranje z metodo elektrodnih dvojčkov (Twin probes, Geoscan RM15). Prikaz vrednosti navidezne električne upornosti s sivimi toni (A). Temnejši odtenki predstavljajo višje vrednosti (zidovi, ruševine, tlakovane ali dobro utrjene površine itd.). S filtriranjem nizkofrekvenčnih anomalij (*high pass filter*) smo odstranili dolgovalovne anomalije električne upornosti zaradi geološke podlage, različne konsistence zemljišča in ruševinskih plasti. Bolje so vidne linijske anomalije visoke upornosti nad zidovi (B).

The border between areas 1 and 2 represents the edge of the archaeological site in its strictest meaning, or rather the limit to which the Roman architectural remains extend.



Area 1 (from 0 to 7 m). This area is situated beyond the boundary of the archaeological site. Only weak reflections from the direct horizontal reflector are visible on the radar shot. I believe these reflections are the result of the soil stratification due to contemporary use of the ground for agricultural purposes (the border of arable land) and for natural pedogenetic factors.

Area 2 (from 7 to 12.5 m). A very well-defined reflection between 9.5 and 10 m is the result of a shallow lying wall. Two highly resistive anomalies and negative gradients of the vertical component of the magnetic field were also measured in this same place. The positioning of the prods on both anomalies correspond precisely with the well-defined radar signal. Otherwise, the highly resistive anomalies extend from 6.5 to 12.5 m. The values are somewhat lower than those above the wall, however they are still higher than the background measurements. It most likely represents the echo of the layer of ruins in the direct vicinity of this wall. In view of the negative gradient of the magnetic field, I believe that it is a stone wall with low magnetic susceptibility. The material

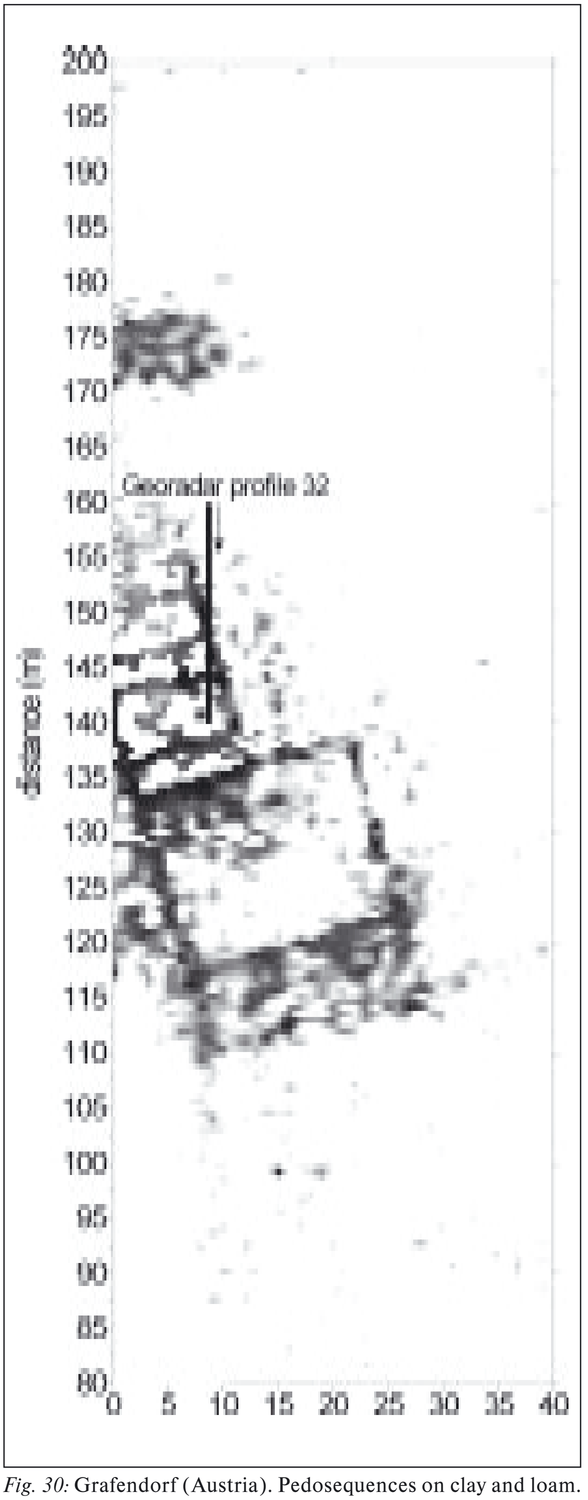


Fig. 30: Grafendorf (Austria). Pedosequences on clay and loam. Composite image of resistivity and magnetometry. Direction of georadar profile 32 is also marked.
Sl. 30: Grafendorf (Avstrija). Pedosekvence na glinah in Ilovicah. Kompozitna slika upornosti in magnetometrije. Označena je tudi smer georadarskega profila 32.

ruins are the result of the wall collapsing. Weak reflections of an irregular shape are also visible on the georadar profile at the same distance as the resistive anomalies were determined resulting from the ruins; this confirms the supposition that it is chaotic, stony ruination material.

Area 3 (from 12.5 to 20 m). Reflections were detected on the georadar profile in the layer that toned (from 12.5 to 17 m), as well as reflections in the irregular layers (from 17 to 20 m). The values of electric resistivity in these places are slightly higher than in the background. Very high positive gradients of the vertical component of the magnetic field above the layer that tones indicate ruination layers with high magnetic susceptibility, characteristic of ceramic objects. The archaeological context of magnetic anomalies is suggestive of a layer of tiles. A weak radar reflection representing the echo of a poorly preserved partition wall was also measured in the same area. A weak, highly resistive anomaly and a well-defined negative gradient of a magnetic field were measured here. On the basis of these data I determined the existence of a partition wall built of stone with low magnetic susceptibility. A negative gradient of the vertical component of the magnetic field was measured above the reflections from the irregular layers, thus indicating that the layer is most likely stone ruins.

Velike Malence (*Fig. 32*)

A Roman archaeological site is situated north-east of Velike Malence, or rather in the direct vicinity of the St. Martin church (*Fig. 32*). Excavations conducted by P. Petru (Petru 1970-1971), geoelectric mapping carried out in 1986 by Andy Waters from the University of Bradford, UK, as well as other types of archaeological data attained from field surveys and probe excavations, have all contributed to the knowledge that relatively well preserved Roman architectural remains lie beneath the surface. Extensive rescue excavations were carried out by Ph. Mason and U. Bavec in 1993, which enabled a comparison between the results from geophysical investigations and the discovered architectural remains on at least a smaller part of the research area (see Mušič 1996, 106-112).

Determinations influential upon the evaluation of the potential of geophysical investigations on pedosequences of clays and loam can be summed up as follows:

The results from the resistivity method are very good under certain conditions (*Fig. 33:* A). Numerous linear, highly resistive anomalies due to walls and/or foundations, ruination layers and stone enclosures can be traced (see Mušič 1996, 112-113).

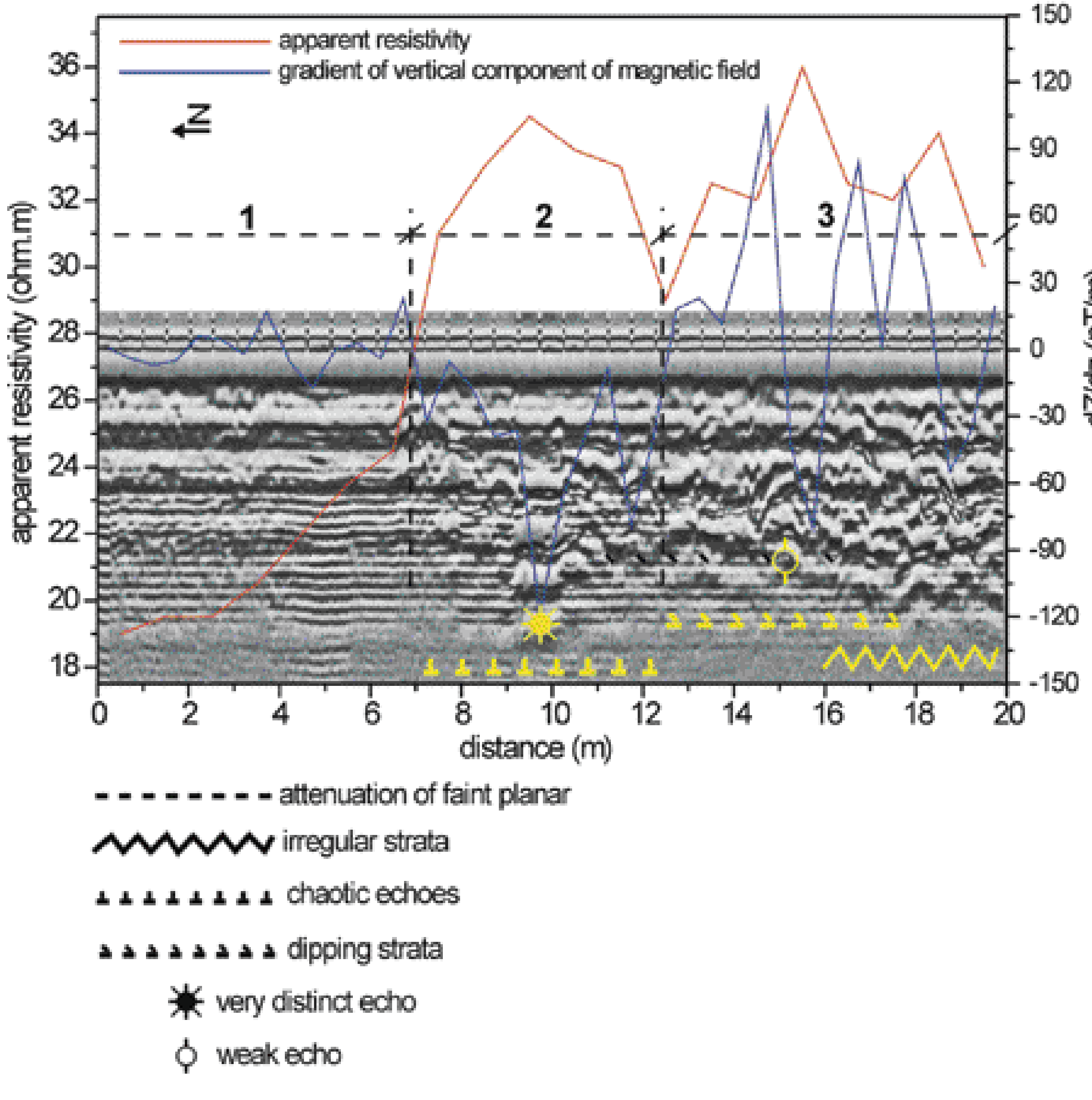


Fig. 31: Grafendorf (Austria). Pedosequences on clay and loam. Geophysical profile no. 32 within the area of the Roman architectural remains. Radar reflections are portrayed in gray tones, as well as the vertical gradient of the magnetic field (the blue curve) and the apparent specific resistivity (the red curve).

Sl. 31: Grafendorf (Avstrija). Pedosekvenca na glinah in Ilovicah. Geofizikalni profil 32 na območju antičnih arhitekturnih ostalin. Prikazani so radarski odboji v sivih odtenkih, vertikalni gradient magnetnega polja (modra krivulja) in navidezna specifična upornost (rdeča krivulja). Pedosekvenca na glinah in Ilovicah.

The magnetometry results obtained using the Fluxgate gradiometer FM36 instrument were generally less distinct than from geoelectric mapping. This is due to the small contrast in the magnetic susceptibility between the walls and the soil in which they are situated. Entirely the same can be said of the measurements of the total magnetic field using the proton magnetometer (Geometrics G819). Nevertheless, lines with weak negative gradients of the vertical gradient of the magnetic field, resulting from the lower susceptibility of the walls, can still be traced (*Fig. 33:* B). In addition to the low magnetic anomalies which are the result of the difference in the induced magnetization, a few more areas with strong thermoremanent magnetization characteristic of brick are also evident on *Figure 33:* B (see Mušič 1996, 111-115).

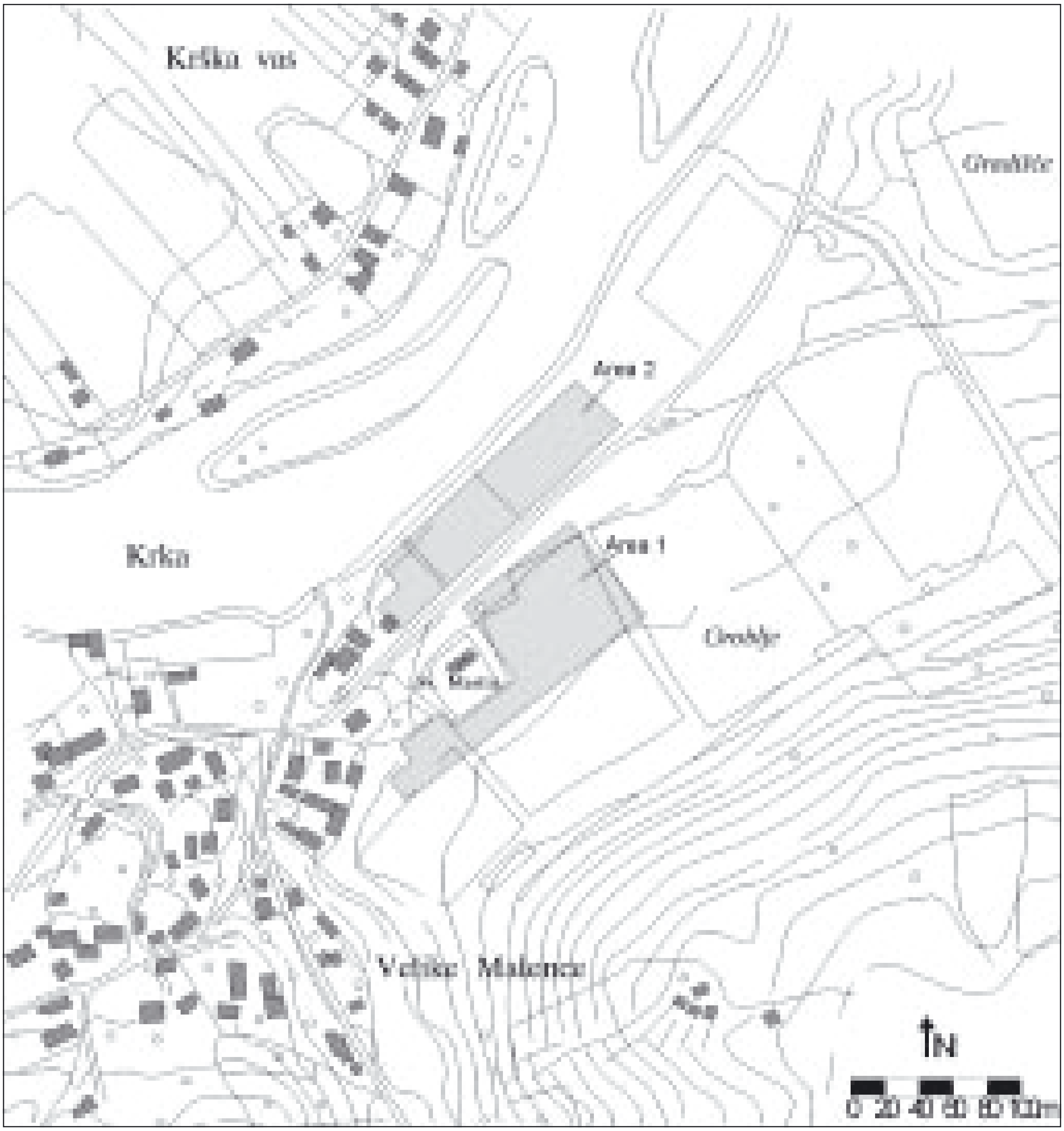


Fig. 32: Velike Malence. Pedosequences on clays and loam. A diagram of the investigated area.
Sl. 32: Velike Malence. Pedosekvenca na glinah in Ilovicah. Položajna skica raziskane površine.

Čatež along the Sava (*Fig. 34*)

This site, similar to the Roman site at Velike Malence, is situated on pedosequences of clays and loam; good results were thus anticipated primarily using the resistivity method. The architectural remains of a Roman structure were successfully delimited applying this method (*Fig. 35:* A). The strong contrast between the apparent resistivity is the result of an essentially clay foundation which is humid and very conducive, and the well preserved architectural remains are situated directly beneath the surface and they represent a medium with very high resistivity. A flat anomaly with high values of resistivity is located within the architectural structure (*Fig. 35:* A); with no distinct configuration, it could perhaps be the effect of the ruination layers of ceramic tiles or a hypocaust. Two thin lines were discerned on the southern and eastern side, their resistivity values

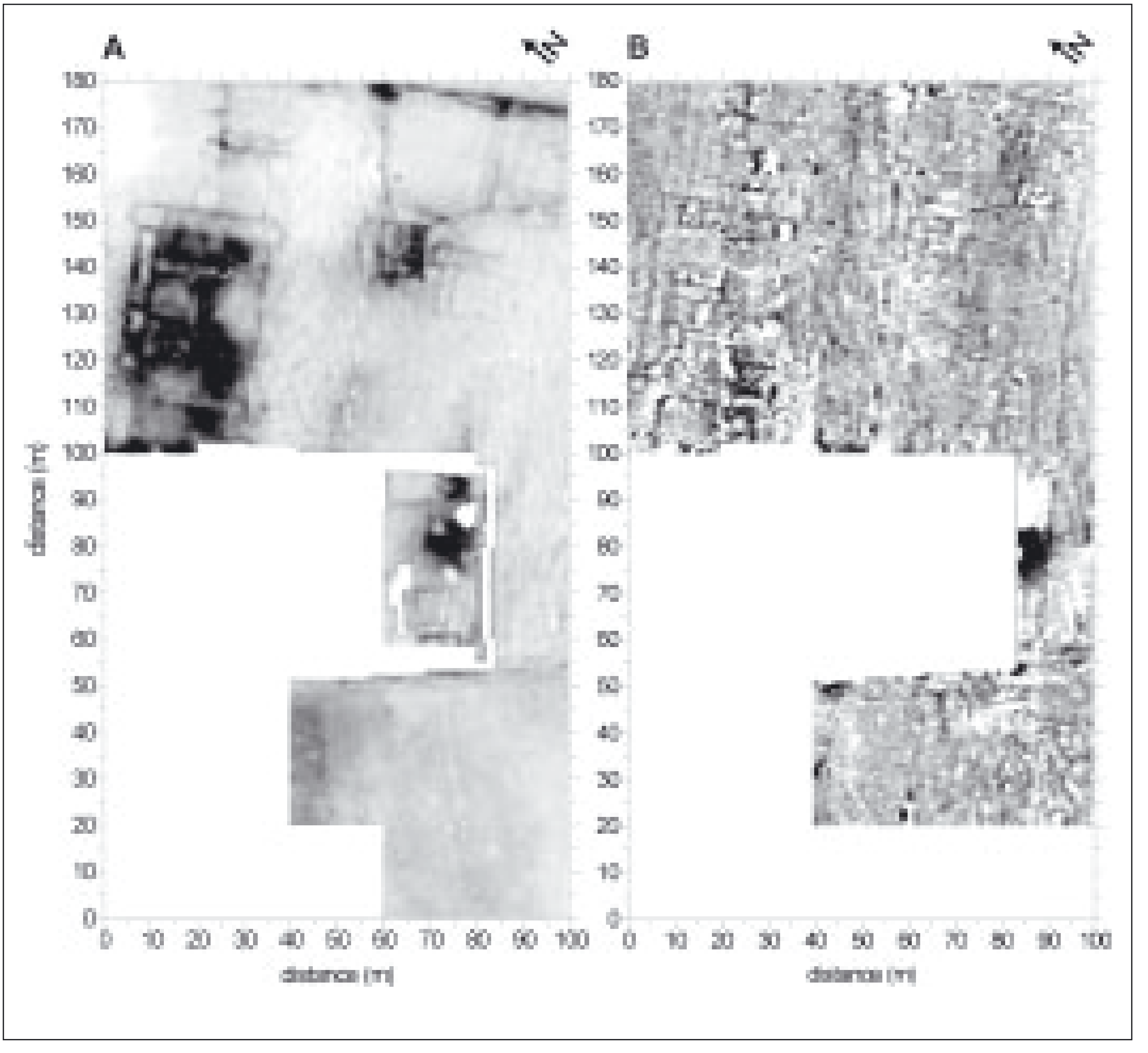


Fig. 33: Velike Malence. Pedosequences on clays and loam. The values of the apparent resistivity are shown in gray tones (A). The darker shades represent the higher values, measured above the walls or ruination layers. An illustration of the changes in the vertical gradient of the magnetic field is presented with gray tones (B).
Sl. 33: Velike Malence. Pedosekvenca na glinah in Ilovicah. Vrednosti navidezne električne upornosti so prikazane s sivimi toni (A). Temnejši odtenki predstavljajo višje vrednosti, izmerjene nad zidovi oz. ruševinskimi plastmi. Prikaz sprememb v vertikalnem gradientu magnetnega polja je prikazan s sivimi toni (B).

were somewhat higher than the background (*Fig. 35:* A). They could represent contemporary architectural remains (wall) or perhaps modern ditches with infrastructures within.

Here the magnetometry results present clearly visible linear anomalies on the eastern and northern side of the structure (*Fig. 35:* B). Weak negative gradients were measured in the direction of both lines, which means that the magnetic susceptibility is somewhat lower than the background in these areas. Consequently, the magnetometry in these areas can be interpreted similar to that applying geoelectric mapping. Architectural remains (walls) with lower magnetic susceptibility than the background are a possibility. Similar results were also attained during magnetometric investigations at other archaeological sites in the vicinity (e.g. Velike Malence; Mušič 1996, 105-120). The highest positive gradients of the magnetic field were measured within the structure (*Fig. 35:* B and *Fig. 36*), which is indicative of a thermoremanent type of magnetization of bricks (roofing tiles?). The negative gradients follow in lines, indicating the directions of the stone walls (*Fig. 35:* B and *Fig. 36*).

Fig. 34: Čatež along the Sava. Pedosequences on clays and loam. A diagram of the area investigated with a magnetogram of the vertical gradient of the magnetic field (Fluxgate gradiometer FM36).
Sl. 34: Čatež ob Savi. Pedosekvenca na glinah in Ilovicah. Položajna skica raziskane površine z magnetogramom vertikalnega gradienta magnetnega polja (Fluxgate gradiometer FM36).

PEDOSEQUENCES ON GRAVEL AND SAND

Ilovca near Vransko (*Fig. 37*)

The archaeological data significant for evaluating the results from geophysical investigations are summarized according to I. Lazar's publication (1997, 159-164), where she presents the results from archaeological excavations carried out in 1995. The time span of this Roman archaeological site, ranging from the end of the 1st through the entire 2nd century and to the first quarter of the 3rd, was determined on the basis of material finds and Roman coins. Fifty percent of the coins discovered are attributed to the second half of the 2nd century. This is considered evidence substantiating that the height of activity in this area was during this time. The author continues and claims that the archaeological layers were destroyed by floods to the extent that the stratigraphy of the cultural layers could not be reconstructed precisely. Along the southern side of the excavated area the walls of limestone and pebbles were extremely well preserved. Limestone quarry stones were red on the inside, the effect of being exposed to high temperatures. Two brick kilns were discovered during excavations of the central part.

Kiln 1 - The western kiln (*Fig. 39:* W) was better preserved. It was constructed using bricks with square and rectangular cross-sections. Only two of the original five brick vaults were preserved. The space was filled with fragments (ceramic?) of various forms. The channel was built from large pieces of brick with rectangular cross-sections and inverted tiles. Stamps of the *Legio II Italica* were discovered on the bricks used for the construction of the kiln.

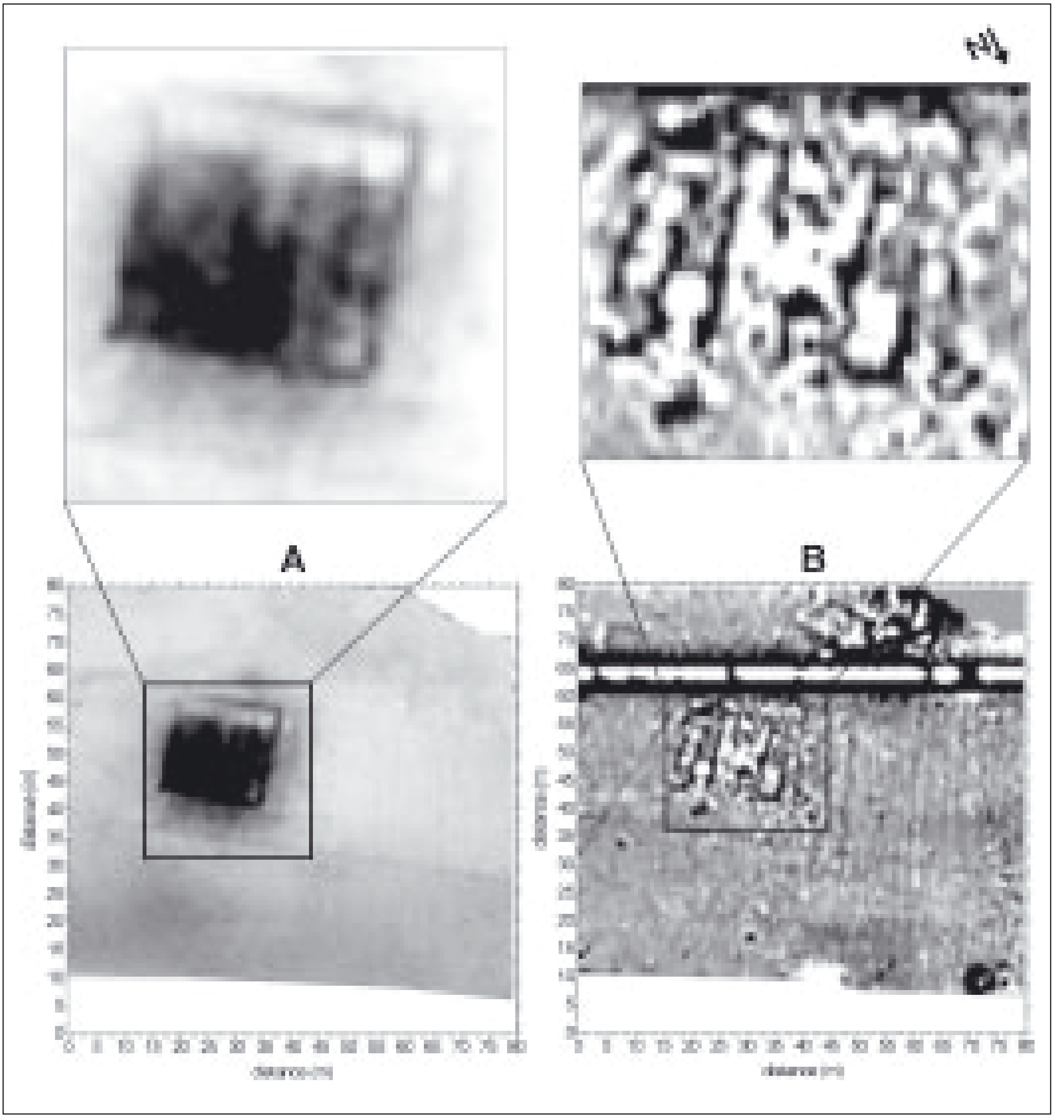


Fig. 35: Čatež along the Sava. Pedosequences on clays and loam. A comparison between geoelectric mapping (A) and magnetometry (B).
Sl. 35: Čatež ob Savi. Pedosekvenca na glinah in Ilovicah. Primerjava geoelektričnega kartiranja (A) in magnetometrije (B).

Kiln 2 - The eastern kiln (*Fig. 39:* E) was situated somewhat higher than the western one and was thus also more exposed to destruction due to cultivation. The brick vaults of the kiln were entirely destroyed. On the basis of the foundations it was determined that the kiln was constructed with seven vaults. The channel and the central part of the kiln was filled with various pieces of brick. The construction was otherwise quite similar to that of the adjacent kiln.

The walls enclosing the kilns were 100 cm wide and preserved to a height of 70-90 cm. All four corners conclude in a circular shape.

To a large degree, only the location of the gravel fill was determined using the Twin probes resistivity method. The range of values of the apparent resistivity of the natural background is so wide on this type of pedosequence that it incorporates all types of archaeological remains. Consequently, only characteristic shapes of anomalies can serve

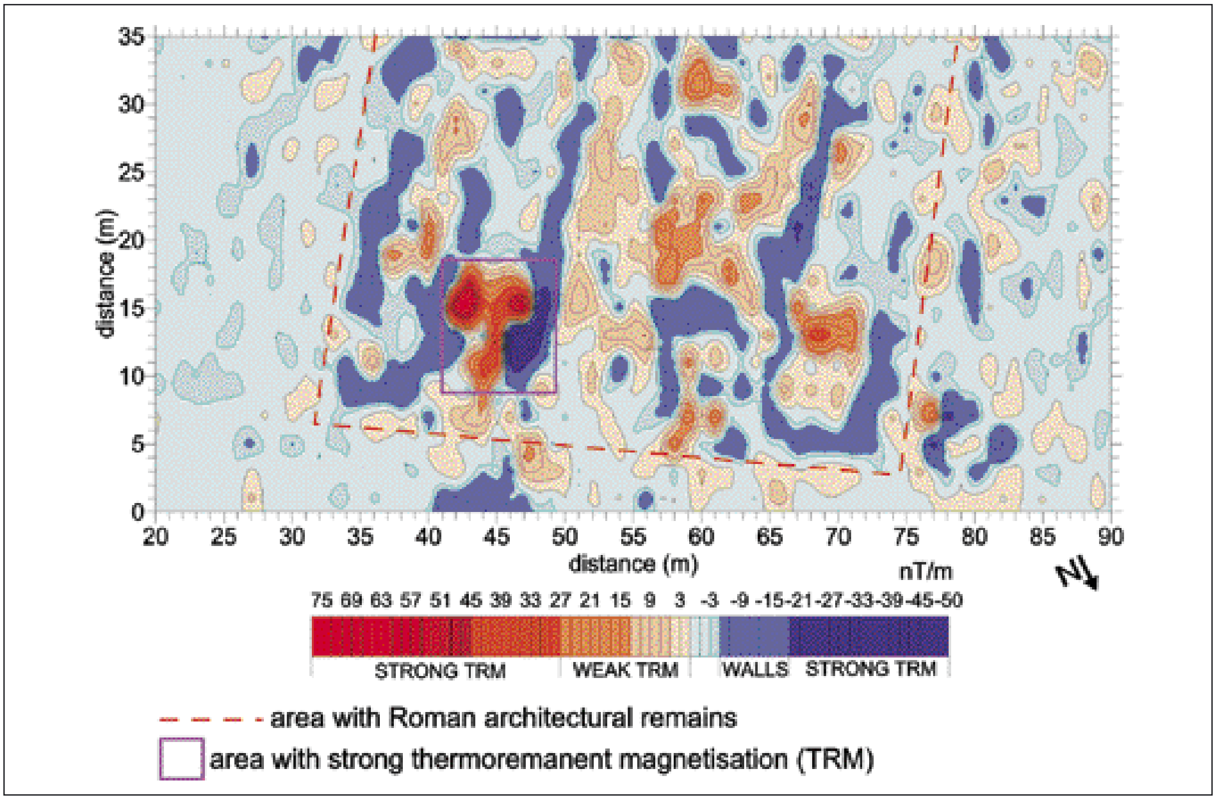
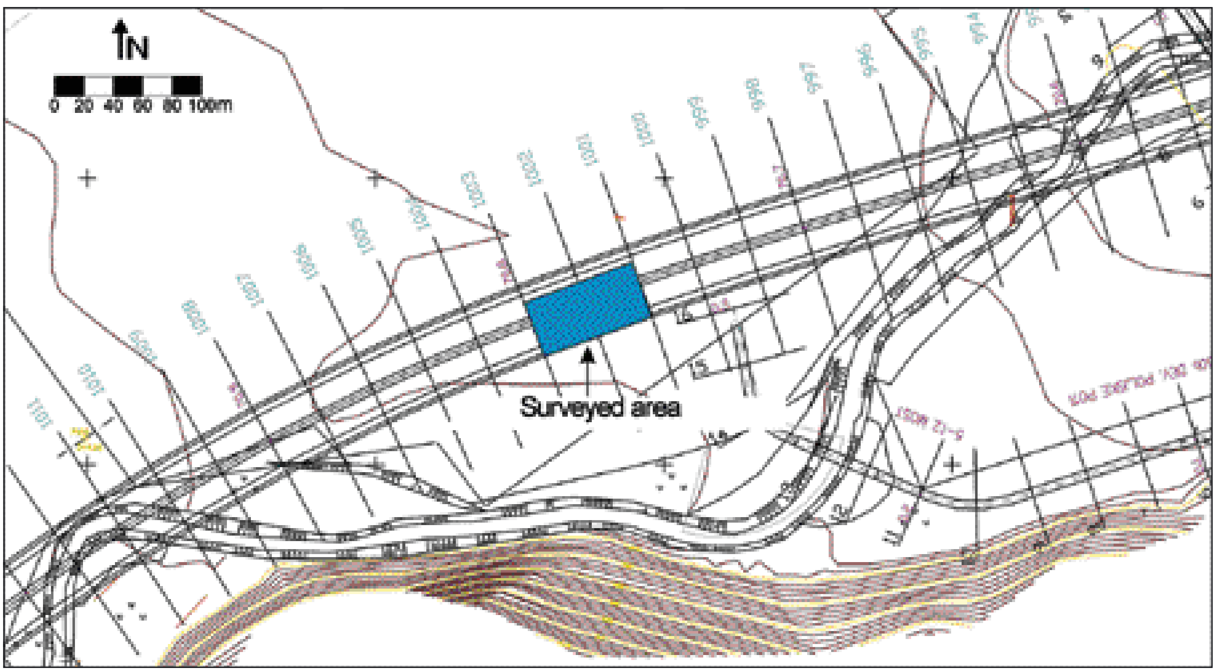


Fig. 36: Čatež along the Sava. Pedosequences on clays and loam. The gradient of the vertical component of the magnetic field (Geoscan FM36) within the area of the Roman architectural remain (n = 4200, m = -0.8 nT/m, s = 5.9 nT/m, min = -48 nT/m, max = +75 nT/m).
Sl. 36: Čatež ob Savi. Pedosekvenca na glinah in Ilovicah. Gradient vertikalne komponente magnetnega polja (*Geoscan FM36*) na območju antičnih arhitekturnih ostalin (n = 4200, m = -0,8 nT/m, s = 5,9 nT/m, min = -48 nT/m, max = +75 nT/m).



Sl. 37: Ilovca pri Vranskem. Peosekvenca na produ in pesku. Geodetski načrt avtocestnega odseka pri Vranskem z vrisanim izsekom površine, kjer smo z magnetometrijo odkrili antično opekarsko peč.
Fig. 37: Ilovca near Vransko. Pedosequences on gravel and sand. The geodetic map of the highway segment near Vransko including the investigated area where a Roman brick-kiln was discovered using magnetometry.

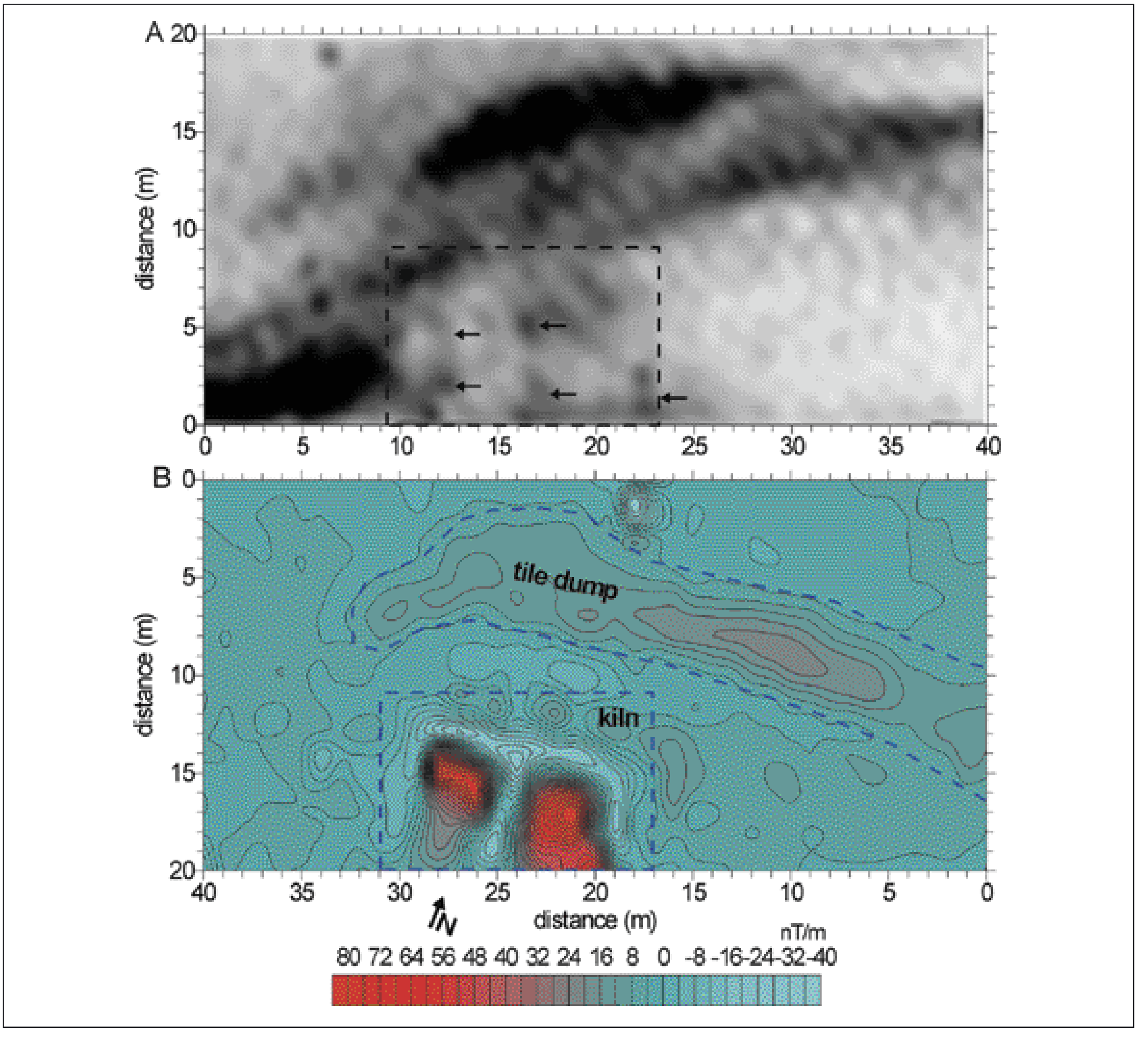


Fig. 38: Ilovca near Vransko. Pedosequences on gravel and sand. The result from geoelectric mapping (upper) with which only weak positive resistivity anomalies were determined above the brick kiln. Strong thermoremanent magnetization of the brick kiln with magnetic dipoles in the same direction (*in situ*) and numerous weaker thermoremanent magnetization above the deposit of refuse brick products with magnetic dipoles oriented in different directions (below).
Sl. 38: Ilovca pri Vranskem. Pedosekvenca na produ in pesku. Rezultat geoelektričnega kartiranja (zgoraj) s katerim smo ugotovili le nekaj šibkih pozitivnih upornosnih anomali nad opekarsko pečjo. Močna termoremanentna magnetizacija opekarske peči z magnetnimi dipoli v isti smeri (*in situ*) in veliko šibkejša termoremanentna magnetizacija nad deponijo odpadnih opekarskih izdelkov z različno orientiranimi magnetnimi dipoli (spodaj).

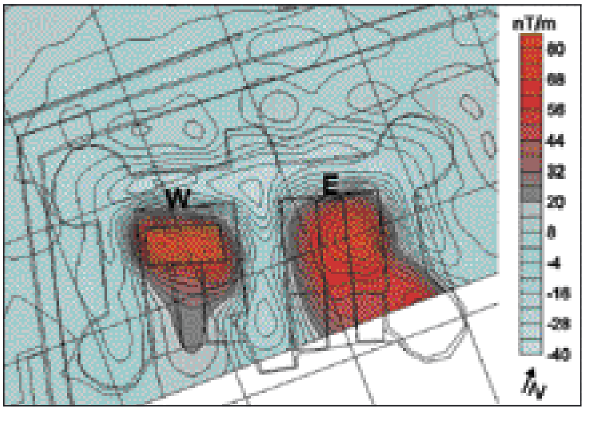


Fig. 39: Ilovca near Vransko. Pedosequences on gravel and sand. Magnetic anomalies above the architectural remains of the Roman brick kiln. Prepared according to the documentation from archaeological excavations (I. Lazar).
Sl. 39: Ilovca pri Vranskem. Pedosekvenca na produ in pesku. Magnetne anomalije nad arhitekturnimi ostalinami antične opekarske peči. Prirejeno po dokumentaciji arheoloških izkopavanj (I. Lazar).

as a foundation for their determination. In this instance, highly resistive anomalies, undoubtedly resulting from the architectural remains of the Roman kilns (*Fig. 38:* A), were measured only in

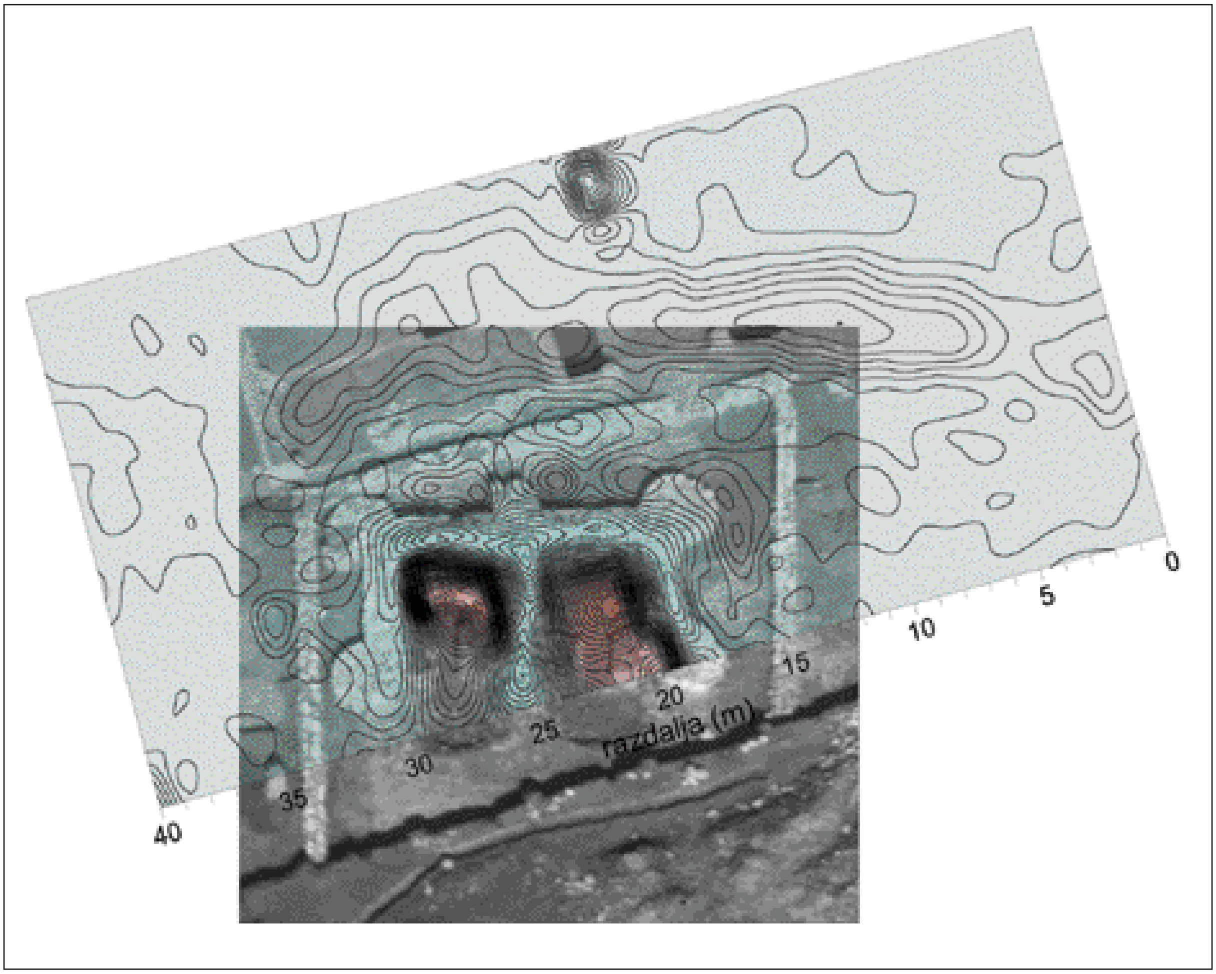


Fig. 40: Ilovca near Vransko. Pedosequences on gravel and sand. The area of the archaeological excavation and an aerial photography of the brick kiln (photo: S. Olić), as well as the magnetic anomalies above the brick kiln.
Sl. 40: Ilovca pri Vranskem. Pedosekvenca na produ in pesku. Arheološko izkopno polje in zračni posnetek opekarske peči (foto: S. Olić) in magnetne anomalije nad opekarsko pečjo.

select areas. All other highly resistive anomalies were entirely the result of natural causes.

Strong positive gradients of the vertical component of the magnetic field were measured above the clay architectural elements within the two-part brick kilns (*Fig. 38:* B; *39; 40; 41* and *42*) with high magnetic susceptibility and a thermoremanent type of magnetization. The highest amplitude of positive gradients of the magnetic field above the kiln is 82 nT/m (*Fig. 42*). The walls are built of pebbles with very low magnetic susceptibility. The lowest amplitude of the gradient of the magnetic field above the stone walls is -30 nT/m. A preserved, or rather -frozen-, remanent magnetization dating to when the kiln cooled down the last time is present within the architectural elements of the interior of the kiln. I estimate the declination (D) in the thermoremanent magnetization of the kiln to be -2°. A declination evaluated in this manner is of course quite superficial and cannot be regarded in terms of magnetic dating. The magnetic anomaly is a vector sum of the induced and remanent magnetization, where the direction of the remanent magnetism could be different from that when the kiln was still functioning due to the viscidity of magnetization. I have cited this example as a point of interest, as the above mentioned manner of determining the declination of thermoremanent magnetization corresponds to the data Marton (1998, 74) cited for the second half of the 2nd and first half of the 3rd centuries.

A relatively strong magnetic anomaly (min = -26 nT/m, max = +23 nT/m) was measured north of the brick kiln in a zone approximately 5 m wide and more than 10 m long (*Fig. 38*). A refuse pit filled with fragments of brick was discovered during archaeological excavations. A smaller natural depression was supposedly filled with brick,

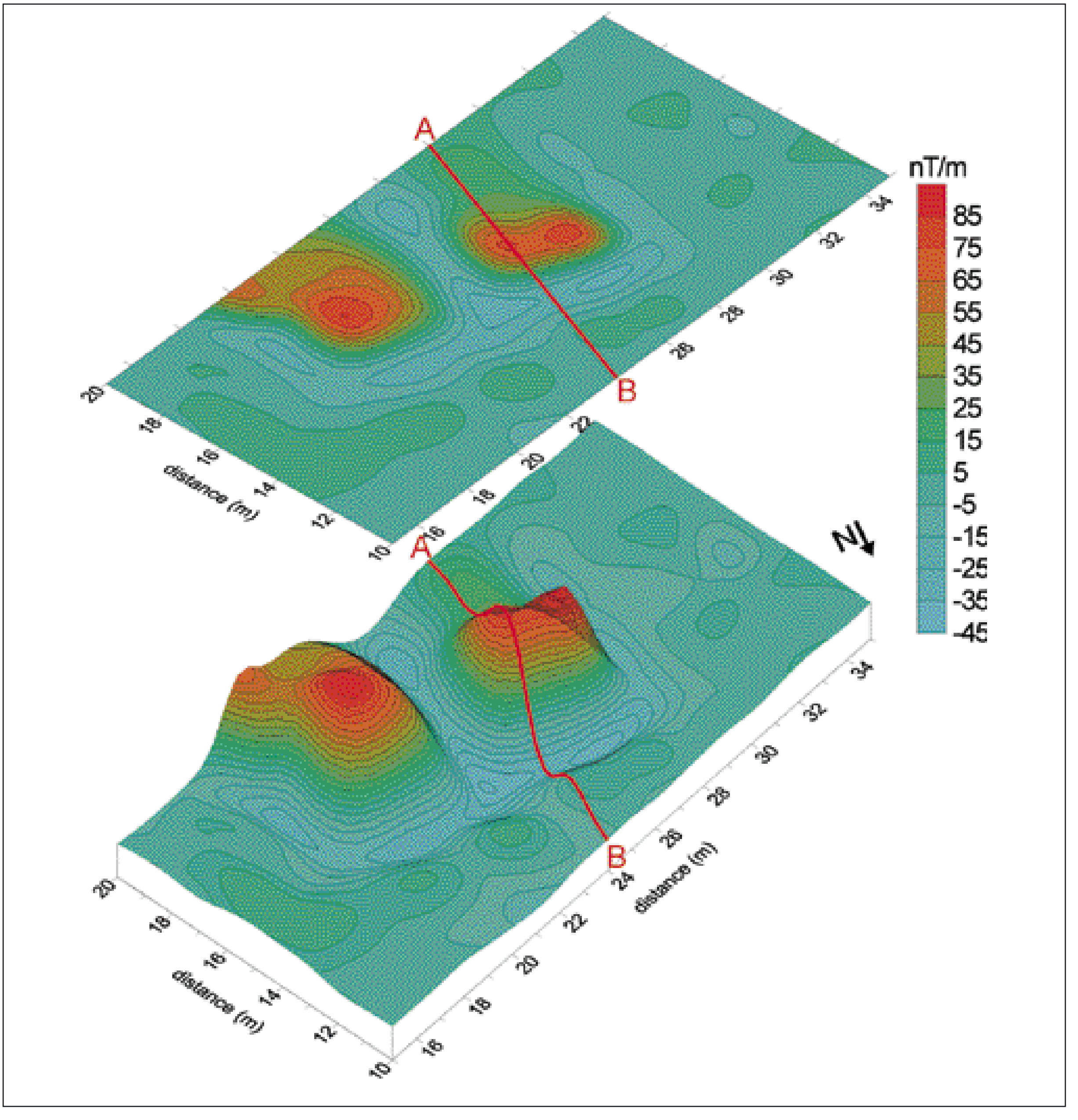


Fig. 41: Ilovca near Vransko. Pedosequences on gravel and sand. A three-dimensional depiction of the effect of thermoremanent magnetization of the Roman brick kiln.
Sl. 41: Ilovca pri Vranskem. Pedosekvenca na produ in pesku. Tridimenzionalni prikaz učinka termoremanentne magnetizacije antične opekarske peči.

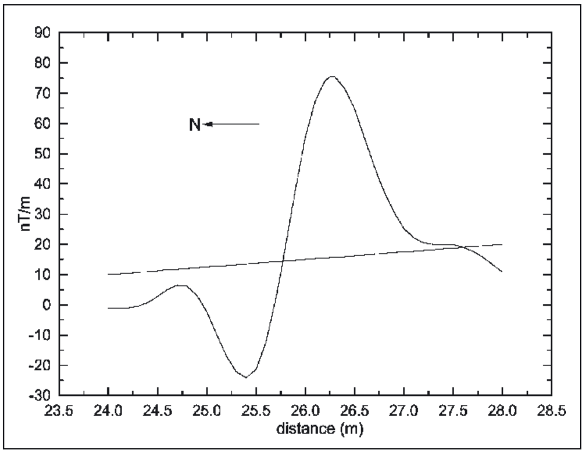


Fig. 42: Ilovca near Vransko. Pedosequences on gravel and sand. The vertical gradient of the magnetic field above the eastern part of the Roman brick kiln in the direction of the profile A-B (*Fig. 41*).
Sl. 42: Ilovca pri Vranskem. Pedosekvenca na produ in pesku. Vertikalni gradient magnetnega polja nad vzhodnim blokom antične opekarske peči v smeri profila A-B (*sl. 41*).

presumably to level the ground. Considering that it is a deposit of discarded ceramic artifacts, an appropriate interpretation of this structure, in an archaeological context, is as a refuse pit. The depth of the refuse pit in the western profile is 90 cm at most, with a width of 350 cm.

CONCLUSION

The determination that good results for geophysical investigations can be expected only in the instance that various geophysical techniques are applied at each individual archaeological site, as well as diverse types of instruments functioning on the basis of different physical principles, is incontestable. I am thus introducing the concept of *anomaly associations in the physical fields*, which enable a more precise interpretation of the -points- of targeted objects (e.g. a wall) as well as of surfaces that represent a region serving a particular purpose in the archaeological past (e.g. ruination layers incorporating a layer of tiles = the inside of a house).

I consider the classification of the natural environment into regional system (=pedosequences), first established by Stritar (1990), the most appropriate also for describing the suitability of geophysical investigations subject to the natural circumstances.

Pedosequences on soft carbonaceous rock (marl) (Groblje near Buče) and pedosequences on clays and loam (Čatež along the Sava) are the most suitable for geophysical investigations. Both these types are relatively homogeneous and isotropic mediums. The soil is deep and lacks any thick stony aggregate. The detectability of archaeological remains is very good for all used geophysical techniques.

Pedosequences on noncarbonaceous rock in Slovenia are still, as of yet, poorly investigated. Only one site was researched on flysch stone presenting excellent results from geophysical prospecting (Ajdovščina above Rodik). Results attained on acidulous magmatic rock at similar archaeological sites abroad (Mont Beuvray, France) were less favorable. The resistivity method produced the worst results on these types of pedosequences. This is partly due to the thick layer of Roman ruins and partly the consequence of thick decaying layers with magmatic rock-disintegration. Magnetometry and apparent magnetic susceptibility proved the most useful for detecting industrial workshops (e.g. ironworks) in such surroundings with low susceptibility of the geologic and pedologic background. As architectural remains are usually made of the same stone as the basic geology, the contrast in the magnetic susceptibility is too small to detect individual walls. I believe that the georadar method provides the only prospecting method capable of detecting architectural remains under these types of circumstances.

I base my evaluation of geophysical investigations on pedosequences of hard carbonaceous rock on hill-top settlements that are situated on karstic limestone foundations (Ajdovski gradec near Bohinjska Bistrica, Škocjan, Cvinger near Meniška vas). Due to the large contrast in the magnetic susceptibility between the limestone geologic foundation and the various soils rich with iron minerals, as well as the unlevel topography of the karstic geologic foundation, the so-called -topographic effect- should not be neglected. Geoelectric mapping similar to that on pedosequences of gravel and sand is also used here for determining geologic forms. Magnetometry serves well in these circumstances primarily for detecting objects within industrial workshops with a thermoremanent type of magnetization (e.g. kilns and smelting furnaces) (Cvinger near Meniška vas), smaller deposits of metallurgic refuse products (Ajdovski gradec near Bohinjska Bistrica), architectural remains made of brick and traces of terracing (Škocjan).

The most unfavorable environment for geophysical investigations is on pedosequences of gravel and sand (Ilovca near Vransko). The rapid alternation of sandbanks in such an environment elicits an exceedingly wide range, and also extremely variable, of apparent resistivity. Consequently, the use of the resistivity method is very limited. Better results are usually attained in such environments using magnetometry and georadar. The results from geoelectric mapping are indirectly useful as they serve well for demarcating changes in the geologic foundation; this data is often significant for distinguishing geologic and archaeological information on magnetograms and radar diagrams.

BECKER, H. 1995, From nanotesla to picotesla - a new window for magnetic prospecting in archaeology. - *Archaeological prospection* 2/4, 217-228.

BEVAN, B. W. 1996a, *Geophysical exploration for archaeology. Volume A: Archaeological question and answers*. - Geosight technical report 4.

BEVAN, B. W. 1996b, *Geophysical Exploration for Archaeology. Volume B: Introduction to geophysical exploration*. - Geosight Technical Report 4.

BEVAN, B. W. 1996c, *Geophysical Exploration for Archaeology. Volume C: Detailed survey procedures*. - Geosight Technical Report 4.

BINTLIFF, J., C. GAFFNEY, A. WATTERS, B. DAVIES and A. SNODGRASS, 1990, Trace metal accumulation in soils on and around ancient settlements in Greece. - In: *Man's role in the shaping of the eastern Mediterranean landscape*, 159-172.

BOUCHER, A. R. 1996, Archaeological feedback in geophysics. - *Archaeological prospection* 3/3, 129-140.

CARR, C. 1982, *Handbook on soil resistivity surveying*. - Center for American Archaeology press (research series, volume 2), Evanston.

CLARK, A. 1990, *Seeing beneath the soil (Prospecting methods in Archaeology)*. - London.

DABAS, M. and B. MUŠIČ 1997, Bilan des prospections géophysiques. - In: *Rapport annuel d'activite scientifique 1997,* 199-210, Centre archéologique européen du Mont Beuvray.

DAVIS, J. C. 1973, *Statistics and data analysis in geology*. - New York.

DIMC, F. and B. MUŠIČ 1996, Usklajevanje metod za karakterizacijo arheoloških materialov z meritvami magnetne susceptibilnosti (Harmonization of the characterization methods for archaeological materials with magnetic susceptibility measurements). - In: *Kovine, zlitine, tehnologije (Metals, Alloys, Technologies)* 30/1-2, 111-115, Ljubljana.

DIMC, F., B. MUŠIČ and R. OSREDKAR 1994, Magnetic susceptibility measurements as a quantitative support for characterization of archaeological materials. - *Rudarsko-metalurški zbornik* 41, 225-230.

DONEUS, M. and W. NEUBAUER 1998, 2D combination of prospection data. - *Archaeological Prospection* 5/1, 29-56.

EDER-HINTERLEITNER, A., W. NEUBAUER and P. MELICHAR 1996, Restoring magnetic anomalies. - *Archaeological prospection* 3/4, 185-197.

FINETTI, I. R. 1992, Monograph on the geophysical exploration of the Selinunte archaeological park. - *Bolletino di geofisica, teorica ed applicata* 34, 83-232.

GABROVEC, S. 1966, Latensko obdobje na Gorenjskem. - *Arh. vest.* 17, 243-262.

GABROVEC, S. 1975, Ajdovski gradec. - In: *ANSl*, 164, Ljubljana.

HEATHCOTE, C. and A. ASPINALL 1981, Some aspects of the use of fluxgate magnetometers (gradiometers) in geophysical prospection in archaeology. - *Revue d'Archéométrie* 5, 61-70.

KUZMA, I., J. HANZELYOVÁ, J. RAJTÁR and J. TIRPÁK 1996, New results in aerial archaeology in Slovakia: experience with reconnaissance, geophysical measurement and follow-up excavations. - *Archaeological prospection* 3/2, 71-80.

LADEFOGED, T. N., S. M. McLACHLAN, S. C. L. ROSS, P. J. SHEPPARD and D. G. SUTTON 1995, GIS-based image enhancement of conductivity and magnetic susceptibility data from Ureturituri Pa and Fort Resolution, New Zealand. - *American Antiquity* 60, 3, 471-481.

LAZAR, I. 1997, The Roman tile factory at Vransko near Celeia (Noricum). Part one: excavation report. - *Acta Rei Cret. Rom. Faut.* 35, 159-164.

LEBEN, A. 1975, Škocjan. - In: *ANSl*, 132, Ljubljana.

LINFORD, P. and P. COTTRELL 1994a, The English heritage geophysical survey database (short report). - *Archaeological prospection* 1/1, 71-72.

LINFORD, P. and P. COTTRELL 1994b, The English heritage geophysical survey database: an update (short report). - *Archaeological prospection* 1/2, 133-134.

MARCHESETTI, C. 1903, *I castellieri preistorici di Trieste e della Regione Giulia*. - Trieste.

MARTON, P. 1998, Magnetic directional data for Hungary and their application for archaeomagnetic dating. - In: Kolto, L. and L. Bartosiewicz (eds.), *Archaeometrical research in Hungary* 2, 71-74.

MIKL CURK, I. 1970, Zapažanja ob orientacijskem raziskovanju arheološkega terena na Vrhniki z merjenjem specifične upornosti tal. - *Var. spom.* 13-14, 39-40.

MUŠIČ, B. 1993, Odkrivanje arheoloških ostalin pred gradbenimi posegi v prostor z nedestruktivnimi metodami. - In: *Cestarski dnevi'93. Zbornik kratkih vsebin referatov,* 189-191.

MUŠIČ, B. 1994, Geophysikalische Untersuchungen und archäologische Denkmalpflege. - *Arch. Austr.* 78, 9-19.

MUŠIČ, B. 1994-1995, Geofizika in varovanje arheološke dediščine. - *Var. spom.* 36, 59-72.

MUŠIČ, B. 1996, Geofizikalne raziskave antičnega podeželja Slovenije. - In: *Rimsko podeželje / Roman countryside*, Razprave FF, 83-137, Ljubljana.

MUŠIČ, B. 1997, Magnetic susceptibility measurements in dolinas. - *Annales* 10, 37-42.

MUŠIČ, B. and F. DIMC 1994, Magnetna susceptibilnost kot kvantitativni kriterij za razvrščanje arheoloških materialov. - *Arheo* 16, 37-44.

MUŠIČ, B. and L. ORENGO 1998, Magnetometrične raziskave železnodobnega talilnega kompleksa na Cvingerju pri Meniški vasi. - *Arh. vest.* 49, 157-180.

MUŠIČ, B. and B. SLAPŠAK 1998, GIS in on-site analysis: Rodik, Slovenia. Cost action G2: Paysages antiques et structures rurales. - In: *The use of geographic information systems in the study of ancient landscapes and features related to ancient land use*, 81-93.

MUŠIČ, B., B. SLAPŠAK and V. PERKO 1999, The Roman site of Rodik: surface distributions and geophysical prospections. - In: *Extracting meaning from ploughsoil assemblages*, Populus project (Siena colloquium), 132-146.

MUŠIČ, B., B. SLAPŠAK, S. PIRC, N. ZUPANČIČ, F. DIMC and L. TROJAR 1995, On-site prospection in Slovenia: the case of Rodik. - *Archaeological Computing Newsletter* 43, 6-15.

NISHIMURA, Y. and H. KAMAI 1991, A study on the application of geophysical prospection. - In: *Archaeometry '90*, 757-763.

OREHEK, S. 1972, Eocenski fliš Pivške kotline in Brkinov. - In: *VII Kongres geologa SFRJ* 2, 253-270.

OREHEK, S. and M. SILVESTER 1964, *Poročilo o sedimentno petrografski preiskavi eocenskega fliša - list Ilirska Bistrica,* 11 p. - Ljubljana (Typed report. Archive of Geološki zavod, Ljubljana).

OREHEK, S. and M. SILVESTER 1967, *Sedimentno petrografske preiskave eocenskega fliša - list Ilirska Bistrica* 51, 52, 24 p. - Ljubljana (Typed report. Archive of Geološki zavod, Ljubljana).

PAPAMARINOPOULOS, P., G. N. TSOKAS and H. WILLIAMS 1985, Magnetic and electric measurements on the island of Lesbos and the detection of buried ancient relics. - *Geoexploration* 23, 483-490.

PAPAMARINOPOULOS, P., G. N. TSOKAS and H. WILLIAMS 1986, Electric resistance and resistivity measurements and magnetic mapping of the archaeological relics on the castle of Mytilene. - *Bolletino Geofisica Teorica ed Applicata* 28, 111-112.

PAYNE, A. 1996, The use of magnetic prospection in the exploration of iron age hillfort interiors in Southern England. - *Archaeological prospection* 3/4, 163-196.

PETRU, P. 1970-1971, Sondi pri Sv. Martinu v Malencah. - *Arh. vest.* 21-22, 163-166.

SCHURR, M. R. 1997, Using the concept of the learning curve to increase the productivity of geophysical surveys. - *Archaeological prospection* 4/2, 69-83.

SLAPŠAK, B. 1978, Rodik - Ajdovščina. - *Arh. vest.* 29, 546-547.
SLAPŠAK, B. 1985, Ajdovščina nad Rodikom. - *Arh. preg.* 26, 135-136.
SLAPŠAK, B. 1988, Defining the economic space of a typical Iron Age hillfort: Rodik, Yugoslavia, a case study. - In: Bintliff, J., D. Davidson and E. Grant (eds.), *Conceptual issues in environmental archaeology,* 95-107.
SMEKALOVA, T., O. VOSS, and N. ABRAHAMSEN 1993, Magnetic investigation of iron-smelting centres at Snorup, Denmark. - *Archaeologia Polona* 31, 83-103.
STRITAR, A. 1990, *Krajina. Krajinski sistemi. Raba in varstvo tal v Sloveniji.* - Ljubjana.
TECCO HVALA, S. 1992, Kataster arheoloških najdišč Slovenije ali zgodba o nastanku neke računalniške baze podat-kov (prvi del). - *Arheo* 15, 62-64.
TELFORD, W. M., L. P. GELDART and R. E. SHERIFF 1990, *Applied geophysics.* - Cambridge.
TURK, P. 1994-1995, Škocjan. - *Var. spom.* 37, 306.
VALIČ, A. 1997, Arheološki drobci vojaških prvin pozne rim-ske dobe na Gorenjskem. - *Arh. vest.* 48, 261-268.
VIDRIH PERKO, V. 1997, Rimskodobna keramika z Ajdovščine pri Rodiku. - *Arh. vest.* 48, 341-358.
VOGRIN, A. 1990, *Situacija arheoloških izkopanin; arheološko najdišče Buče - Groblje. Manuskriptna karta v merilu 1:200.* - Archive of ZVNKD, Celje.
WATERS, A. 1989, Merjenje specifične upornosti tal v arheološkem terenskem pregledu na področju Slovenije. - *Arheo* 9, 74-77.
ZUPANČIČ, N. 1990, *Geokemične lastnosti tal v Istri in Slovenskem primorju glede na matično kamnino.* - Master thesis, Ljubljana.

Geofizikalna prospekcija v Sloveniji: pregled raziskav z nekaterimi ugotovitvami glede naravnega okolja

UVOD

Prve geofizikalne raziskave na arheološkem najdišču v Sloveniji je opravil Franc Miklič (Geološki zavod Ljubljana) leta 1969 na Dolgih njivah na Vrhniki. (Mikl Curk 1970, 39-40). Sistematične geofizikalne raziskave je na pobudo Božidarja Slapšaka začel leta 1986 Andy Waters z Univerze v Bradfordu (glej: Waters 1989, 74-77). Njegovo delo sta v letih 1988 in 1989 nadaljevala takrat doktorska kandidata na isti univerzi Cris Gaffney in Vincent Gaffney. Leta 1990 je Oddelek za arheologijo Filozofske fakultete Univerze v Ljubljani preko tedanjega Sekretariata za znanost in tehnologijo pridobil sredstva za nakup geofizikalne opreme (Resistance meter Geoscan RM15 in Fluxgate gradiometer Geoscan FM36; Geoscan Research, Bradford, Anglija). Zaradi potreb nekaterih raziskovalnih projektov smo glede geofizikalne opreme sodelovali tudi z drugimi institucijami, s čimer smo omogočili še raziskave z merilcem navidezne magnetne susceptibilnosti (Kappameter KT-5; Uprava za kulturo RS), meritvami totalnega magnetnega polja s protonskim magnetometrom (Geometrics GSM 819; IGGG Ljubljana in GemSystem GSM19; Fakulteta za elektrotehniko, Univerza v Ljubljani) in georadarskimi meritvami (GSSI SIR 3; MIC d. o. o., Ljubljana).

Od začetka samostojnega uvajanja geofizikalnih raziskav na Oddelku za arheologijo smo strategijo raziskav usmerjali predvsem v zbiranje podatkov o anomalijah v fizikalniih poljih, ki so posledica arheoloških ostalin in ki jih je najti v različnih naravnih okoljih. Izogibali smo se selekciji arheoloških najdišč na -ekonomična- in -neekonomična- glede na predvideni arheološki potencial, stopnjo ohranjenosti ostalin, naravne danosti in predpostavljeno detektibilnost arheoloških ostalin pri teh pogojih. Splošni koncept, ki smo ga gradili na takšnih načelih, nam danes omogoča na podlagi razmeroma obsežne baze podatkov (čez 150 lokacij doma in v tujini) splošno oceno ustreznosti več geofizikalnih tehnik za detekcijo določenih tipov arheoloških ostalin v različnih naravnih okoljih. Pomembnejša izhodišča, ki usmerjajo geofizikalne raziskave:

Ugotavljanje ustreznosti različnih geofizikalnih tehnik za detekcijo določenih tipov arheoloških ostalin v različnih na-ravnih okoljih, pri čemer uporabljamo za opredeljevanje geološko-pedološke osnove razdelitev Slovenije na krajinske sisteme (glej Stritar 1990). Te lahko opredelimo kot funkcijo litološke podlage, reliefa, klimatskih razmer in hidrosfere. Rezultat vseh naštetih dejavnikov so tla in pedosekvence, ki so definirane kot združbe tal, ki se pojavljajo na isti ali podobni matični osnovi (ibid., 51). V geografskem smislu pedosekvence, ki praviloma ustrezajo mejam krajinskih sistemov, opredeljujejo ta sistem in hkrati narekujejo njegovo sodobno kmetijsko namembnost. Naravne in antropogene komponente krajinskega sistema vplivajo vsaka zase in vse skupaj na potencial arheološke prospekcije.

Eno od bistvenih načel geofizikalne prospekcije je, da neglede na ocenjeno detektibilnost pričakovanih arheoloških osta-lin, kjer koli je to mogoče, na istem arheološkem najdišču uporabimo več različnih geofizikalnih tehnik. Trenutno uporabljamo magnetometrijo s pretočnim gradiometrom in protonskim magnetometrom, meritve magnetne susceptibilnosti, navidezne električne upornosti in lastnih potencialov ter georadarske meritve. Takšen pristop zagotavlja več podatkov, ki omogočajo bolj izpovedno interpretacijo (t. i. *načelo združbe anomalij v fizikalnih poljih*).

Opredeljevanje -kritičnih- oz. mejnih vrednosti amplitud anomalij merjenih fizikalnih veličin. Gre za empirično ali statistično določene vrednosti, ki opredelijo spodnjo mejo -pomenljive- anomalije, ki je značilna za določen tip arheoloških ostalin v konkretnem arheološkem kontekstu in naravnem okolju. V bistvu gre za ločevanje signala in šuma (*signal to noice ratio*) pri čemer moramo najprej določiti razpon vrednosti, ki so posledica šuma. Te t. i. -kritične- vrednosti lahko v arheološkem kontekstu opredeljujejo tudi meje med območji različnih aktivnosti *(activity areas, use areas*), ki jih je za geoelektrično upornostno metodo prvi definiral Carr (1982).

Uporaba pristopa, podobnega sestavljanju večkanalnih satelitskih posnetkov v kompozitno sliko, pri čemer namesto satelitskih posnetkov uporabimo podatkovne nize arheološke prospekcije. Tak pristop omogoča združevanje različnih geofizikalnih podatkov kot tudi geofizikalnih podatkov in podatkov iz arheološkega terenskega pregleda (glej npr. Ladefoged et al. 1995, 471-481; Mušič, Slapšak 1998, 81-93).

V splošnem se strinjam z oceno položaja geofizikalnih raziskav v arheologiji kot ga je opredelil Boucher (1996, 139). Očitno je, da obstaja v ozadju filozofija arheološke prospekcije, ki jo avtor opredeljuje kot orodje za lociranje ali ovrednotenje, njena razširjena uporaba v začetnih fazah načrtovanja arheoloških raziskav pa jo je ves čas vodila v tej smeri. Isti avtor nadalje ugotavlja, da bi morali možnosti umeščanja geofizikalnih metod v celotni spekter arheoloških analiz obravnavati bolj pogosto in bolj resno. V tej sicer dobronamerni in ilustrativni izjavi, ki verjetno odraža splošno videnje geofizikalnih raziskav v arheo-loški stroki, je avtor spregledal nekatere pomembne raziskave, ki so bile narejene na arheoloških materialih in so imele za cilj razumevanje rezultatov geofizikalnih raziskav (glej Carr 1982). Po mojem mnenju lahko z laboratorijskimi analizami relativno majhnega števila vzorcev tal prispevamo tudi k arheološko izpovednejši interpretaciji predvsem na nivoju *use areas oz. activity areas*. V ta namen vzamemo vzorce za nadaljnje analize izključno na območjih, ki smo jih predhodno na podlagi geofizikalne raziskave opredelili kot potencialne centre določenih aktivnosti v arheološki preteklosti. V ta namen uporabljamo sejalno analizo, rentgensko difraktometrično metodo, diferenčno termično analizo in laboratorijske meritve magnetne susceptibilnosti.

BAZA PODATKOV GEOFIZIKALNIH RAZISKAV

Članek predstavlja pregled dosedanjih geofizikalnih raziskav na območju Slovenije v luči ocene potenciala posameznih geofizikalnih tehnik v odvisnosti od naravnih danosti in tipa arheoloških ostalin. V članku sem zajel samo lokacije, ki so ilustrativne za oceno potenciala geofizikalnih tehnik (*tab. 1*). Sicer je vseh lokacij, kjer smo izvajali geofizikalne raziskave preko 150. Omeniti velja, da je Oddelek za arheologijo Filozofske fakultete Univerze v Ljubljani poleg navedenih raziskav v Sloveniji v okviru različnih mednarodnih projektov izvajal geofizikalno prospekcijo tudi na številnih arheoloških najdiščih v tujini (Jugoslavija, Hrvaška, Avstrija in Francija), ki pa sem jih zaradi koncepta članka v preglednici izpustil.

Glede na razmeroma veliko število geofizikalnih prospekcij je bilo kreiranje ustrezne baze podatkov eden od potrebnih pogojev za uspešno delo na temeljnem zastavljenem cilju. Pri ugotavljanju potenciala geofizikalnih tehnik se lahko do neke mere opremo na podatke iz literature, vendar za natančnejšo oceno samo to ne zadošča. Najočitnejša omejitev je ta, da se v literaturi navajajo v glavnem rezultati -uspešnih- geofizikalnih raziskav, ker so bile v večini primerov izvedene na znanih arheoloških najdiščih z dobro ohranjenimi arheološkimi ostalinami in pri ugodnih naravnih danostih. Veliko manj je objav, ki imajo za cilj bolj študijsko usmerjene raziskave, ki obravnavajo učinkovitost geofizikalnih tehnik pri različnih pogojih dela literature (glej: Bevan 1996a; 1996b in 1996c). Obsežno raz-iskavo, pri kateri so testirali veliko različnih tehnik so organizirali na primer na območju arheološkega parka Selinunte na Siciliji (Finetti 1992, 83-232). Še redkejše pa so objave, kjer so obravnavani rezultati geofizikalnih raziskav, ki niso dale pričakovanih rezultatov (glej npr. Nishimura, Kamai 1991, 757-765).

Sicer se tudi v svetu v zadnjih letih posveča precej pozornosti nacionalnim arheološkim bazam podatkov, ki vključujejo tudi rezultate geofizikalnih raziskav (glej npr. Linford, Cottrell 1994a, 71-72; 1994b, 133-134; http://www.eng-h.gov.uk/). To lahko razumemo kot dejstvo, da se je močno uveljavila arheološka prospekcija in z njo tudi geofizikalne raziskave tako v akademskem okolju za potrebe arheoloških prostorskih analiz kakor tudi pri vsakodnevnem varovanju arheološke kulturne dediščine. Takšne baze so praviloma ozko usmerjene, z močno poudarjenim ciljem evidentirati in dokumentirati anomalije v fizikalnih poljih, ki so posledica različnih arheoloških objektov, s prepoznavnim trendom prepričevati arheologe o uspeš-nosti in skorajda nezmotljivosti takšnih raziskav, ki temeljijo na sodobni elektroniki in računalniški tehnologiji. Novejše baze so izdelane v programskih paketih, ki služijo kot pregledovalniki obsežnih baz podatkov za geografske informacijske sisteme (npr. ArcView, Esri). Bistvena prednost teh baz podatkov je, da omogočajo povezavo med tekstovnimi deli baze in grafičnimi podlagami z georeferenciranimi podatki geofizikalnih raziskav in zračno fotografijo (glej npr. Doneus, Neubauer 1998, 29-56). Tudi sam sem se odločil za takšno odprto strukturo baze, ker omogoča združevanje najrazličnejših podatkov o arheologiji, arheološki prospekciji in naravnem okolju.

Trendi geofizkalnih raziskav v arheologiji kažejo, da je faza -filtriranja- t. i. -surovih- vrednosti, ki je doživela svoj višek ob koncu 80-ih in v začetku 90-ih let, dokončno minila. Takrat še ni bilo na razpolago tako obsežnega nabora raziskav, ker so te doživele pravi razmah šele v novejšem času, ker je oboje pogojeval razvoj mikroračunalnikov. V začetku je bil torej v ospredju trend prikazovanja in procesiranja podatkov s ciljem ojačati pomenljive anomalije v fizikalnih poljih, ki so posledica prisotnosti arheoloških objektov, proti različnim šumom ozadja (*signal to noice ratio*). Na ta način so želeli nadomestiti manjkajoče vrednosti, kar je bilo posledica optimizacije terenskega dela zaradi počasnega zajemanja podatkov. V ta namen so največ uporabljali razne modifikacije mask (obteženi filtri srednjih vrednosti: Carr 1982, 582), ki so jih pred tem uporabljali za digitalno procesiranje slik (*image enhancement*). Kasnejši trend raziskav lahko najbolje ilustriram na primeru magnetometrije. Raziskave so šle v smeri razvoja boljših instrumentov z boljšo ločljivostjo in veliko hitrostjo zajemanja podatkov (glej npr. Becker 1995, 217-228) ter vzporednega razvoja programske in strojne opreme, ki omogoča procesiranje ogromne količine podatkov. Še vedno se želi dokazati ustreznost vlaganja v mag-netometre z visoko ločljivostjo, ki so zaradi robustnosti (glej npr. Doneus, Neubauer 1998, 32) uporabni le do prve fizične ovire, ki je lahko pri nekaterih instrumentih že manjša stopnica na terenu (npr. parcelna meja), ali pa so uporabni le na povsem ravnih površinah, kar pa na večjem delu Slovenije ne pride v poštev. Poleg tega pride dobra ločljivost instrumentov do izraza izkljčno na magnetno zelo -tihih- območjih. Zaradi tega se v literaturi zadnja leta kar vrstijo članki, ki obravnavajo rezultate magnetometričnih raziskav na t. i. neolitskih krogih (glej npr. Eder-Hinterleitner, Neubauer, Melichar 1996, 185-197; Kuzma et al. 1996, 71-79; Becker 1995, 222; Doneus, Neubauer 1998, 42-47). S stališča geofizikalnih raziskav gre za negativne topografske anomalije oz. jarke, ki so bili čez čas zapolnjeni z vrhnjimi horizonti tal in ki so praviloma bolj magnetni od globlje ležečih horizontov (Clark 1990). To je razlog za šibek kontrast v magnetni susceptibilnosti med jarki in medijem, v katerem se ti nahajajo; medij je običajno glina, ki je homogene sestave. To sicer šibko anomalijo v Zemljinem magnetnem polju lahko izmerimo s cezijevimi gradiometri, ki imajo ločljivost vsaj 0,1 nT/m, novejše izvedbe tudi 0,01 nT (1pT). Poleg tega je veliko teh neolitskih krogov vidnih že iz aeroposnetkov. Na -običajnih- najdiščih in tudi kar se tiče magnetnih lastnosti heterogenih najdišč, kjer je ozadje zelo spremenljivo, postane razlika med cezijevimi magnetometri in veliko cenejšimi, npr. pretočnimi gradiometri zanemarljiva. To trditev lahko ilustriram z raziskavami Beckerja na območju Troje, kjer sicer dokazuje prednosti cezijevega magnetometra, vendar rezultati po mojem mnenju tega ne potrjujejo v zadostni meri. Praktično enake rezultate so dobili tudi s pretočnim gradiometrom Geoscan FM36, ki je preprostejši za uporabo in hkrati tudi veliko cenejši.

Za drugačen pristop pri geofizikalnih raziskavah v arheologiji se je odločil Bevan (Geosight, ZDA). Rezultate raziskav podaja v treh neobjavljenih poročilih (Bevan 1996a; 1996b in 1996c). Na podlagi številnih raziskav na najrazličnejših najdiščih je prvi ocenil ustreznost različnih geofizikalnih tehnik glede na odvisnost od naravnih danosti in tip arheoloških ostalin. Šele v zadnjih letih pa se pojavljajo v strokovni literaturi tudi objave, ki predlagajo ustrezne rešitve pri urejanju baz podat-kov geofizikalnih raziskav (Linford, Cottrell 1994a, 71-72; 1994b, 133-134; Doneus, Neubauer 1998, 29-56). Zaradi ogromnih količin podatkov se zdi nujno povezati jih na način, ki omogoča trenuten dostop do informacije, ki je potrebna za akademske prostorske analize ali zaščito in varovanje arheološke kulturne dediščine.

Pri sestavljanju preglednice geofizikalnih raziskav sem upošteval osnovna načela Britanskega zavoda za spomeniško *varstvo (English Heritage Geophysical Survey database, SDB*), ki jo je leta 1994 predlagal *Ancient monuments laboratory (//www.eng-h.gov.uk/)*. Ker na Inštitutu za arheologijo ZRC SAZU že več let poteka projekt nacionalne baze arheoloških najdišč (ARKAS) (Tecco-Hvala 1992, 62,63), sem upošteval tudi nekatere posebnosti te baze, ki omogočajo združevanje. Preglednica je urejen seznam arheoloških najdišč po uveljavlje-nih kriterijih arheoloških baz in upoštevanimi specifičnostmi geofizikalnih raziskav. Za opis geografske lokacije najdišča, rabe površine in datacije sem uporabil postopek, ki ga uporabljajo na ZRC SAZU pri urejanju arheološke baze podatkov (ARKAS; //www.zrc-sazu.si/aspweb/ARCAS-normal.htm/); struktura baze je opisana v članku Tecco-Hvala (1992, 62-63). Ostala polja so izbrana in urejena tako, da je tabela uporabna tudi za ugotavljanje ocene potenciala geofizikalnih raziskav pri odkrivanju različnih tipov arheoloških ostalin v različnih naravnih okoljih. Za opisovanje naravnega okolja sem uporabil razdelitev ozemlja Slovenija na krajinske sisteme (združbe tal, pedosekvence), ki jo utemeljuje Stritar (1990, 29-30). Ta razdelitev se mi zdi kljub nekaterim pomislekom glede natančnosti opredeljevanja naravnega okolja najustreznejša rešitev za opisovanje potenciala geofizikalnih raziskav v različnih naravnih okoljih. Uporabnost te razdelitve vidim predvsem v tem, da utemeljuje združbe tal (pedosekvence) glede na litološko podlago in hkrati upošteva tudi bistvene geografske determinante, ki pa skupaj s pedološko sestavo narekujejo sodobno namembnost površin. Količnik uspešnosti in s tem ocenjene ustreznosti geofizikalnih raziskav sem ocenjeval glede na potditve z arheološkimi izkopavanji. Kjer izkopavanj še ni bilo, sem podal ocene ustreznosti posameznih prospekcijskih tehnik na podlagi primerjave s podobnimi arheološkimi najdišči, kjer je bila možna preverba z izkopavanji.

Eden od temeljev baze podatkov geofizikalnih raziskav je po mojem mnenju odprtost takšne baze, ki v največji meri omogoča dostop do vseh podatkov o prospekciji vključno z numeričnimi datotekami, ki vsebujejo t. i. -surove- vrednosti, izmerjene na terenu. S tem omogočimo takojšen dostop do podatkovnih matrik in kasnejše procesiranje podatkov, reinterpretacijo rezultatov ali vključevanje podatkovnih matrik v ekspertne oz. hibridne sisteme in nevronske mreže. Razmeroma pogosta je situacija, kjer je to pri vsakdanjem delu neobhodno, ko na istem arheološkem najdišču sodelujejo pri geofizikalnih raziskavah različne ekipe v različnih obdobjih in z različnimi geofizikalnimi tehnikami. To je bil tudi glavni razlog, da sva z Dabasom (1997, 199-210) pripravila ogrodje baze podatkov geofizikalnih raziskav tudi na arheološkem najdišču Mont Beuvray (Francja), ki jo je v programu File Maker postavil Fabrice Laudrin (*Centre archéologique européen du Mont Beuvray*).

OCENA USTREZNOSTI GEOFIZIKALNIH TEHNIK

V idealnih razmerah narekujejo izbiro najustreznejše geofizikalne tehnike samo ciljni arheološki objekti, ki jih želimo locirati. Dejansko je tako, da pri geofizikalni prospekciji ciljni arheološki objekti prispevajo le večji ali manjši del pri odločit-vi o najustreznejši geofizikalni tehniki. V tem kontekstu imenujemo anomalije v fizikalnih poljih, ki so posledica prisotnosti ciljnih arheoloških objektov *signal*, vse ostale nepravilnosti v fizikalnih poljih, ki so posledica številnih drugih faktorjev, pa imenijemo *šum*. Najustreznejše izbire ne predstavlja geofizikalna tehnika, pri kateri je pričakovana amplituda signala največja, temveč tista, pri kateri je največje razmerje signala proti šumu.

Geofizikalne raziskave običajno izvajamo na terenu, za katerega vsaj približno vemo, kakšen je njegov arheološki potencial kar se tiče tipa arheoloških ostalin, ki jih lahko zaznamo z geofizikalnimi tehnikami. Ciljni objekti so običajno različni elementi naselbinske strukture (zidovi, ruševinske plasti, odpadne jame, stojke, jarki, razne obrtne delavnice, kurišča in stratigrafske sekvence z znaki antropogene dejavnosti itd.). Boljše rezultate praviloma dobimo, ko vsaj približno vemo, kakšen tip arheo-loških ostalin pričakujemo. Na osnovi podatkov o arheologiji in naravnem okolju izločimo fizikalne parametre, pri katerih je največja razlika med arheološkimi objekti in zemljiščem, v katerem so. Na podlagi ocene -kontrasta- nekaterih fizikalnih parametrov (npr. specifična električna upornost oz. prevodnost, magnetna susceptibilnost in dielektrična konstanta ter magnetna permeabilnost) za določen tip arheoloških ostalin šumov iz okolja, stanja površja in geološke ter pedološke sestave terena se odločimo za najprimernejšo strategijo geofizikalnih raziskav.

Oceno ustreznosti geofizikalnih tehnik podajam na način, ki je v bistvu samo nekoliko prirejena in dopolnjena različica predlog, ki jih je izdelal Bevan (1996a) za predstavitev rezultatov svoje raziskave. Ti rezultati niso bili objavljeni, so pa načeloma dostopni širši javnosti. Po moji oceni je bistveni razlog za majhno število tovrstnih raziskav močen trend specializacije na eno samo geofizikalno tehniko. Napisanih je bilo sicer veliko člankov različnih avtorjev, kjer podajajo rezultate različnih geofizikalnih tehnik oz. instrumentov na istem arheološkem najdišču, vendar so v takšnih publikacijah rezultati vsake od tehnik razlagani neodvisno od rezultatov ostalih, manjkajo pa primerjalne študije, ki bi podale natančen pregled tega potenciala na različnih najdiščih (glej npr. Finetti 1992, 83-232).

Podatki v pregledni (*tab. 1*), ki jih uporabljam za oceno ustreznosti geofizikalne prospekcije, so z naravoslovno-tehničnega stališča v marsičem nepopolni. Za opis naravnih danosti sem uporabil npr. razdelitev naravnega okolja na krajinske sisteme oz. pedosekvence, kot jo predlaga Stritar (1990, 29-30). Ta razdelitev sicer ustreza nakaterim splošnim ugotovitvam, do katerih sem prišel pri svojih raziskavah na različnih geoloških podlagah (npr. razmerje signal/šum je na določeni pedosekvenci za enak tip arheoloških ostalin približno enako). Enostavne poti za upoštevanje vseh različnih dejavnikov, ki tako ali drugače vplivajo na geofizikalne raziskave, ni.

PRIMERI GEOFIZIKALNIH RAZISKAV

Za ilustracijo ustreznosti geofizikalnih tehnik v različnih naravnih okoljih, ki jih opredeljujem z različnimi pedosekvencami oz. krajinskimi sistemi, sem izbral nekaj raziskav na arheoloških najdiščih, ki so bila dobro raziskana z geofizikalno metodo, rezultati pa zadovoljivo opišejo potencial metode v konkretnih danostih. Hkrati sem želel zajeti čim več različnih naravnih okolij in hkrati tudi več različnih tipov arheoloških ostalin.

V članku sem največ prostora namenil kasnoantičnim višinskim naselbinam, ki so običajno na mestu prazgodovinskih gradišč. Ta tip arheoloških najdišč je v Sloveniji zelo pogost in bo zato v prihodnosti verjetno še večkrat predmet raziskav z arheološko prospekcijo. S stališča geofizikalnih raziskav gre za izredno zahtevne pogoje dela in mislim, da povsem upravičeno postavljam v ospredje svoje izkušnje na tovrstnih arheo-loških najdiščih.

Edina meni znana, vendar zelo obsežna geofizikalna raziskava notranjosti prazgodovinskih gradišč je bila narejena na prostoru južne Anglijie (Payne 1996, 163-184), kjer so dobili že samo z magnetometrično raziskavo zelo dober vpogled v organiziranost naselbin. Pri svojih raziskavah prazgodovisnkih gradišč in kasnoantičnih višinskih utrdb se na te podatke nisem mogel opirati, ker gre v tem primeru za povsem drugačne naravne danosti. Prazgodovinska gradišča v južni Angliji so v glavnem nad obsežno ravnino le nekaj metrov dvignjeni povsem ravni platoji, porasli s travo. To so neprimerno boljši pogoji za geofizikalne raziskave, kot so na domala vseh podobnih arheoloških najdiščih v Sloveniji, kjer se praviloma srečujemo z razgibnim reliefom, gosto vegetacijo, ponekod debelimi ruševinskimi plastmi kasnoantičnih objektov ali samo s tankimi prazgodovinskimi arheološkimi kulturnimi horizonti. Vsi ti dejavniki predstavljajo resno omejitev za večino geofizikalnih tehnik. Da je temu res tako, posredno dokazuje tudi popolna odsotnost objav o geofizikalnih raziskavah na tovrstnih arheoloških najdiščih v strokovni literaturi. Rezultate geofizikalnih raziskav na ostalih arheoloških najdiščih sem izbral tako, da najbolje ilustrirajo nekatere posebnosti krajinskega sistema, na katere moramo biti pozorni pri načrtovanju prospekcije. Arheološka najdišča, ki jih obravnavam v članku (*sl. 1*), so razvrščena glede na geološko-pedološko podlago:

Pedosekvenca na nekarbonatnih kamninah
- Ajdovščina nad Rodikom (1)

Pedosekvenca na trdih karbonatnih kamninah
- Ajdovski gradec pri Bohinjski Bistrici (2)
- Škocjan (3)
- Cvinger pri Meniški vasi (4)

Pedosekvenca na mehkih karbonatnih kamninah
- Groblje pri Bučah (5)

Pedosekvenca na glinah in Ilovcah
- Grafendorf (Avstrija)
- Velike Malence (6)
- Čatež ob Savi (7)

Pedosekvenca na produ in pesku
- Ilovca pri Vranskem (8)

PEDOSEKVENCA NA NEKARBONATNIH KAMNINAH

Ajdovščina nad Rodikom (*sl. 2*)

Strategijo arheološke prospekcije na prazgodovinskih in kasnoantičnih naselbinah podajam na primeru Ajdovščine nad Rodikom (Marchesetti 1903; Slapšak 1978; 1985 in 1988) (*sl. 2*), ki je na pedosekvenci na nekarbonatnih kamninah (fliš; Orehek 1972; Orehek, Silvester 1964 in 1967). Raziskovalni projekt je nastal na pobudo B. Slapšaka (Oddelek za arheologijo Univerze v Ljubljani) (glej Mušič, Slapšak 1998; Mušič et al. 1995; Mušič, Slapšak, Perko 1999). Na tem primeru razlagam potencial arheološke prospekcije na kasnoantičnih višinskih utrdbah (*sl. 3*), ki predstavljajo, vsaj kar se tiče geofizikalnih raziskav izredno kompleksen problem. Razlogov za to je več in se razlikujejo tudi od najdišča do najdišča. Najpomembnejše so na eni strani naravne danosti, ki se kažejo kot zmerno do zelo topografsko razgibane površine z gosto vegetacijo, z zelo spremenljivo debelino tal in/ali arheoloških kulturnih horizontov. Na drugi strani je površina pogosto prekrita z ruševinskimi grobljami kasnoantičnih arhitekturnih ostalin in s tem tudi arheološke ostaline. To so bistveni dejavniki, ki izrazito vplivajo na znižanje razmerja signal/šum in s tem slabše detektibilnosti arheoloških ostalin za skoraj vse geofizikalne tehnike, nekatere pa so pri takšnih pogojih skoraj popolnoma onemogočene (npr. geoelektična upornostna metoda).

Ker je v interesu arheološke vede, da se razišče domet geofizikalne metode tudi pri takšnih pogojih, sem se odločil za podrobno analizo posameznih geofizikalnih tehnik na nekaterih najdiščih v Sloveniji. V nadaljevanju podajam rezultate na nekaterih t. i. višinskih najdiščih v različnih krajinskih sistemih (=pedosekvencah).

Poleg Ajdovščine nad Rodikom, ki je na pedosekvenci na nekarbonatnih kamninah, uporabljam za ilustracijo potenciala geofizikalnih tehnik na takšnih arheoloških najdiščih, ki so v Sloveniji v večini primerov na pedosekvenci na trdih karbonatnih kamninah (apnenci, dolomiti), še prazgodovinsko in antično najdišče na Škocjanu, prazgodovinsko in kasnoantično naselbino na Ajdovskem gradcu pri Bohinjski Bistrici in prazgodovinsko naselbino na Cvingerju pri Meniški vasi.

Digitalni model reliefa

Na podlagi meritev relativnih razlik v nadmorski višini, ki izhajajo iz referenčne točke z absolutnimi Gauss-Kruegerjevimi koordinatami, smo izdelali natančno topografsko karto najdišča in digitalni model reliefa (DMR), kjer so majhne relativne razlike v nadmorski višini, ki so pomenljive za arheološko interpretacijo, lahko prikazane z različno osenčenostjo (*sl. 4*). Nadmorske višine so bile merjene z natančnostjo 1 cm v razdalji 1 m med merilnimi točkami. Na ta način smo izmerili za DMR 44.400 točk (površina 44.400 m^2). -Surove- podatke smo interpolirali v obeh smereh s polinomi tretje stopnje (*bicubic interpolation*) (Davis 1973, 204-207) in tako simulirali meritve na 0,5 m. Pozitivne topografske anomalije v mikroreliefu so rezultat ruševinskih grobelj nad kasnoantičnimi arhitekturnimi ostalinami. Dobro je vidna tudi linija prazgodovinskega obrambnega obzidja, ki obdaja kasnoantično naselbino.

Geoelektrično kartiranje

Za geoelektrično kartiranje (*sl. 10*) smo uporabili geoelektrično upornostno metodo elektrodnih dvojčkov (MED) (Twin probes, Resistance meter RM15, Geoscan Research, Bradford) z razdaljo 0,5 m med premičnima elektrodama (C_1P_1). Resolucija merilnega instrumenta Geoscan RM15 je 0,5 ohm.m. Pri razdalji 0,5 m med premičnima elektrodama je pri ugodnih pogojih vlažnosti zemljišča efektivna globina dosega 1 - 1,5 m, kar glede na podatke o arheoloških ostalinah na števil-nih antičnih najdiščih zadošča za natančno zamejitev visoko-upornostnih arhitekturnih ostalin in pri ugodnih naravnih danostih tudi zamejitev območij različne namembnosti znotraj kompleksa zgradb ali njihove neposredne okolice, katerih navidez-na električna upornost je lahko tudi nižja od vrednosti ozadja (jarki in jame). Najmanjše spremembe navidezne specifične električne upornosti, ki smo jih registrirali, znašajo cca. 5 % vrednosti ozadja meritev. Spremembe smo merili v pravilni mreži z razdaljo 1 m med profili in enako razdaljo med merilnimi točkami. Z geoelektrično upornostno metodo smo premerili 36.400 m^2. Matriko -surovih- vrednosti smo zgostili z bikubično interpolacijo (glej Davis 1973, 204-207) in tako simulirali odčitke na 0,5 m.

Magnetometrija

Magnetometrijo smo izvajali s pretočnim gradiometrom (PG) (Fluxgate gradiometer Geoscan FM36, Geoscan Research, Bradford*)*. S tem instrumentom merimo spremembe gradienta vertikalne komponente Zemljinega magnetnega polja (dZ/dz, nT/m) (*sl. 5* in *6*) glede na ničelno referenčno točko. Za vse meritve smo uporabili le eno referenčno točko. S tem smo se izognili morebitnim napakam pri večkratnem prenašanju ničelne točke na novo pozicijo in zagotovili enotno ozadje meritev za celo naselbino. Razdalja med merilnimi točkami v smeri profilov (zahod-vzhod) je bila 0,5 m, med profili (sever-jug) pa 1 m. Skupno število vseh meritev vertikalnega gradienta magnetnega polja je 95.200 (površina 47.600 m^2). Teoretično lahko s tem instrumentom merimo magnetne anomalije nad arheološkimi objekti, kot so npr. feromagnetni železni predmeti in ferimagnetni keramični objekti (npr. žgalne peči za keramiko, metalurške talilne peči, opeka, strešniki itd.) (Heathcote, Aspinall 1981, 61-70; Papamarinopoulos, Tsokas, Williams 1985, 483-490; 1986, 111-112). Območja s termoremanentno magnetizacijo (*sl. 5*) smo raziskali tudi s protonskima magnetometroma Geometrics GSM 819 in GemSystem GSM19 (*sl. 7* in *8*). Razdalja med merilnimi točkami je bila v obeh smereh enaka, in sicer 1 m oz. 0,5 m.

Magnetna susceptibilnost

Navidezno magnetno susceptibilnost smo merili s terenskim instrumentom Kappameter KT-5 (Geofyzika, Brno). S tem instrumentom merimo susceptibilnost zemljišča samo do globine približno 3 cm. Na ta način ugotavljamo spremenljivost magnetne susceptibilnosti, ki je v glavnem posledica spremembe šibko magnetnih železovih mineralov v bolj magnetne oblike pri povišani temperaturi zaradi uporabe ognja. Magnetna susceptibilnost je sicer samo fizikalna veličina, ki je definirana kot količnik med izmerjeno intenziteto magnetizacije in inducirajočim magnetnim poljem, ki je v tem primeru Zemljino magnetno polje. Glede na to sodijo meritve magnetne susceptibilnosti enako kot magnetometrija med magnetne metode. Meritve magnetne susceptibilnosti različnih materialov, ki jih iščemo pri magnetni prospekciji, služijo običajno le kot pomemben vir informacij o magnetnih lastnostih ciljnih objektov in medija, v katerem se nahajajo. Meritve magnetne susceptibilnosti na površju so se pri geofizikalni prospekciji v arheologiji uveljavile kot samostojna prospekcijska tehnika (glej npr. Mušič, Slapšak 1998; Mušič, Slapšak, Perko 1999). Razdalja med merilnimi točkami je bila v obeh smereh enaka (2 m). Za takšno (razmeroma veliko) razdaljo med merilnimi točkami smo se odločili zaradi prihranka pri terenskem času. Prvotno smo namreč nameravali uporabiti podatke o razponu vrednosti magnetne susceptibilnosti na površini naselbine le kot podatek o magnetnih lastnostih materialov, ki se pojavljajo na naselbini in to uporabiti pri interpretaciji magnetometrije. Pri sprotni obdelavi podatkov sem kmalu ugotovil, da je stopnja korelacije med rezultati intenzivnega terenskega pregleda (število drobcev keramike oz. žlindre na enoto površine; 4 m^2) in magnetno susceptibilnostjo nepričakovano visoka (*sl. 11*). Zaradi opazovanja korelacije med koncentracijo površinskih najdb in susceptibilnostjo tal smo meritve razširili na večjo površino kot je bilo prvotno predvideno (*sl. 12*). Velikost površine, premerjene z instrumentom Kappameter KT-5, je 22.800 m^2, vseh meritev pa je bilo 5.700.

Georadar

Pri georadarski raziskavi smo uporabili za glavno merilno enoto instrument GSSI SIR3. Vse meritve smo opravili z monostatično anteno s centralno frekvenco 500 MHz. Položaj in smer profilov sta enaka kot pri drugih geofizikalnih tehnikah. Razdalja med vzporednimi profili je bila 1 m. Z georadarskimi raziskavami smo ugotavljali položaj in stopnjo ohranjenosti zidov kasnoantičnih arhitekturnih ostalin pod ruševinskimi grobljami in na več mestih detektirali objekte s termoremanentno magnetizacijo, ki sem jih na podlagi magnetometrije, magnetne susceptibilnosti in terenskega pregleda opredelil kot ostaline, povezane z obrtno dejavnostjo (železarstvo?) (*sl. 9*).

Arheološki terenski pregled

Velikost zbiralne enote pri intenzivnem terenskem pregledu je bila 4 m^2 (2 x 2 m). Večino površinskih najdb predstavljajo drobci antične keramike (strešniki, opeka, lončenina) (za natančo razlago glej Vidrih Perko 1997, 341-358) in različni tipi odpadnih produktov metalurgije (železarstvo). Površinske najdbe smo razdelili v keramične odlomke (lončenina, opeka, strešniki) in odpadne produkte metalurgije. Razširjenost teh dveh tipov najdb smo poleg rezultatov geofizikalnih raziskav uporabili za opredeljevanje območij različnih aktivnosti (*activity areas*, *use areas*) v kasni antiki (glej Mušič, Slapšak 1998, 81-93; Mušič, Slapšak, Perko 1999, 132-146).

Poleg navedenih -standardnih- prospekcijskih tehnik s katerimi smo opredelili območja različnih aktivnosti (*activity areas*), smo na Ajdovščini nad Rodikom testirali tudi uporabo geokemične prospekcije (glej Mušič et al. 1995), sejalno analizo, di-ferenčno termično analizo, rentgensko difraktometrično metodo in laboratorijske meritve magnetne susceptibilnosti (glej Dimc, Mušič, Osredkar 1994, 225-230; Dimc, Mušič 1996, 11-115) na majhnih vzorcih za dodatne informacije o funkciji teh območij. Diskusija o teh rezultatih presega namen tega članka, zato nekatere pomembnejše rezultate predstavljam le na krat-ko.

Rezultati prospekcije

Zelo visok pozitivni gradient na območju 2 (*sl. 5; 6* in *7*) kaže na močno termoremanentno magnetizacijo v jugovzhodnem vogalu območja, ki jo lahko v arheološkem kontekstu interpretiramo kot žgalno oz. talilno peč ali kovaško ognjišče. Termoremanentna magnetizacija je posledica konverzije šibkomagnetnih železovih mineralov v bolj magnetne oblike pri viso-kih temperaturah. Glede na pravilno obliko anomalije sklepam, da gre za dobro ohranjen objekt z ostenjem oz. ogrodjem iz keramike (opeka) ali žganih kamnov. Možno je tudi, da je vsa notranjost zapolnjena z enim blokom materiala z visoko magnetno susceptibilnostjo. S pečjo (kovaškim ognjiščem) je na vzhodni strani povezano manjše območje precej višjih vrednosti od ozadja (10-30 nT/m), vendar veliko nižjih kot na območju peči (do 100 nT/m). Sklepam, da gre za odpadne produkte obrtne dejavnosti z visoko magnetno susceptibilnostjo. Nižje vrednosti so bile izmerjene zato, ker gre za manjše kose oz. različno orientirane magnetne dipole, katerih magnetni učinek se zaradi tega v veliki meri izniči in rezultira navzven v manjšo vektorsko vsoto. Obe magnetni anomaliji interpretiram kot posledico iste obrtne dejavnosti. V severozahodnem vogalu območja 2 je bila ugotovljena magnetna anomalija zelo nepravil-nih oblik in enake intenzitete kot anomalija ob peči, ki sem jo opredelil kot rezultat odpadnih produktov obrtne dejavnosti. Sklepam, da gre tudi tukaj za enak učinek deponije odpadnih produktov z visoko magnetno susceptibilnostjo.

Podobno kot s pretočnim gradiometom (*Geoscan FM36*) (*sl. 6*) smo tudi s protonskim magnetometrom (*GemSystem GSM19*) izmerili na isti lokaciji anomalijo z visoko amplitudo (200 nT), kar prve ugotovitve samo potrjuje (*sl. 7*). Severozahodno od pika anomalije (+) je bil izmerjen tudi nižji ekstrem iste magnetne anomalije (-). Pri tem moram opozoriti na to, da je ta usmerjen za približno 10^{o} od smeri geografskega severa proti vzhodu. Močna pozitivna deklinacija kaže na to, da termoremanentna magnetizacija močno prevladuje nad inducirano magnetizacijo in je najverjetneje usmerjena v smeri magnetnega polja v kasni antiki, ko so prenehali z obrtjo in se je peč zadnjič ohladila. Takšna oblika anomalije kaže na močan dipolni značaj, ki je posledica tremoremanentne magnetizacije dobro ohranjenega objekta ostalinam, ki je seveda še vedno na prvotnem mestu.

S protonskim magnetometrom GemSystem GSM19 smo dodatno raziskali še magnetne anomalije na območjih 6 in 7 (*sl. 5* in *8*). Podobno kot s pretočnim gradiometrom (*sl. 5*) smo tudi s protonskim magnetometrom ugotovili območja z močno termoremanentno magnetizacijo, ki najverjetneje pred-stavljajo ostaline obrtnih delavnic *in-situ* (kovačije?) (*sl. 8A*: 1), in nekoliko šibkejše magnetne anomalije, ki so najverjetneje rezultat deponije odpadnih produktov metalurgije (*sl. 8A*: 2). Skoraj popolnoma identično situacijo smo pred tem ugotovili že na območju 2 (*sl. 5* in *6*). Nižje magnetne anomalije so lahko posledica različno orientiranih manjših magnetnih dipolov, ki so v tem primeru lahko kosi žlindre. S protonskim magnetometrom GemSystem GSM 19 smo dobili boljši rezultat predvsem glede geometrije objekta s termoremanentno magnetizacijo na območju B (*sl. 8B*), ki kaže v tlorisu jasen polkrožni presek.

Kot se je izkazalo na primeru Ajdovščine nad Rodikom, je za detekcijo zidov pod debelimi ruševinskimi grobljami daleč najbolj učinkovita georadarska metoda (*sl. 9*). Poleg tega smo to metodo uporabili tudi za dokazovanje objektov z močno termoremanentno magnetizacijo, ki sem jih na osnovi magnetometrije interpretiral kot ostaline obrtnih delavnic (železarstvo?) in deponije odpadnih produktov metalurgije. Od vseh teh objektov smo dobili zelo jasne radarske odboje. Vse te ugotovitve so seveda zelo pomembne za oceno potenciala geofizikalnih tehnik na kasnoantičnih naselbinah, kjer so arhitekturne ostaline prekrite z debelimi plastmi ruševinskih grobelj. Za proučevanje urbanistične zasnove takšnih naselbin in njihove stavbne dediščine je morda najbolj pomembna ugotovitev georadarskih raziskav ta, da zidovi niso vedno pod vrhom groblje. To pomeni, da ne moremo izrisati natančnega tlorisa hiše le na podlagi mikroreliefa ruševinskih grobelj (*sl. 4*), temveč moramo položaj zidov locirati z georadarskimi meritvami.

Korigirane vrednosti navidezne električne upornosti sem glede na statistične parametre razdelil v dva razreda. V prvi razred sodijo tiste med srednjo vrednostjo in 1 standardnim odklonom, v drugi razred pa vse vrednosti, ki so višje od 1 standardnega odklona. Korelacija med ruševinskimi grobljami in visokimi vrednostmi navidezne specifične upornosti je slaba oz. vsaj veliko nižja od pričakovane (*sl. 10*). Samo na jugovzhodnem območju se na nakaj mestih ujemajo topografske anomalije, ki so posledica ruševinskih grobelj in navidezna specifična upornost, ki je višja od srednje vrednosti. Na vsem preostalem delu naselbine je ugotovljena izključno negativna korelacija med topografijo in navidezno električno upornostjo. Na podlagi teh rezultatov lahko zaključimo, da so domala vse izmerjene vrednosti navidezne specifične upornosti na ruševinskih grobljah nižje od srednje vrednosti, kar je pravzaprav presenetljiv rezultat.

Na območju cele naselbine smo ugotovili visoko stopnjo korelacije med magnetometrijo (Fluxgate gradiometer FM36) in magnetno susceptibilnosjo (Kappameter KT-5) (*sl. 12*) ter magnetno susceptibilnostjo in terenskim pregledom (*sl. 11*). Z laboratorijskimi meritvami (za natančnejšo razlago glej Dimc, Mušič, Osredkar 1994, 225-230; Mušič, Slapšak 1998, 81-93; Mušič, Slapšak, Perko 1999, 132-146) je bilo ugotovljeno, da so povišane vrednosti susceptibilnosti vrhnjega približno 2 cm debelega horizonta tal posledica kontaminacije s keramičnim in/ali metalurškim prahom (železarstvo?), ki je najverjetneje rezultat mehanskega razpadanja kosov keramike in žlindre na površini naselbine.

Ker na naselbini razen pašništva od kasne antike do danes ni bilo nobenih posegov, smo lahko preverjali tudi ustreznost geokemične analize za detekcijo območij različne namembnosti v arheološki preteklosti (glej Mušič et al. 1995). Vzorčevali smo en profil (*sl. 12*), ki glede na rezultate ostalih prospekcijskih tehnik zajema območja z različno namembnostjo v kasni antiki. Vzorčevanje je potekalo pod vodstvom dr. Simona Pirca in dr. Nine Zupančič (NTF, Oddelek za geologijo). Profil se začne na severni strani najdišča, zunaj naselbine pod prazgodovinskim in kasnoantičnim obzidjem, prečka močno magnetno anomalijo s termoremanentnim tipom magnetizacije na zunanjem delu prazgodovinskega nasipa, gre čez obzidje in se nadaljuje globoko v notranjost naselbine, kjer prečka ruševinske groblje in tudi navidezno -prazne- dele naselbine. Zanimalo nas je ali obstaja statistično značilna razlika v kemični sestavi naravnih tal na flišnih kamninah Brkinov in tlemi na naselbini. Ta razlika bi bila lahko posledica intenzivne obrtne dejavnosti (železarastvo?) v kasni antiki. V ta namen sem uporabil rezultate kemične analize z geokemične karte Brkinov in Istre (Zupančič 1990). Statistično sem primerjal vsebnosti železa v tleh na Brkinskem flišu in v vzorcih, ki so bili pobrani v geokemičnem profilu (*sl. 12*). Statistični testi kažejo, da ni statistično značilne razlike v vsebnosti železa na naselbini in zunaj nje. Ta rezultat je najverjetneje posledica močne oscilacije vsebnosti železa v tleh na Brkinskem flišu. Za zanesljivejšo interpretacijo bi morali uporabiti za ugotavljanje vsebnosti železa v naravnem ozadju večje število vzorcev iz neposredne bližine naselbine. Znotraj naselbine obstajajo majhne razlike v vsebnosti nekaterih elementov (*sl. 14*). Kemično anomalna območja sem določil s K-mean clustrsko analizo, s katero sem grupiral vse vzorce v 2 razreda (*sl. 15*). En razred pomeni ozadje, drugi pa anomalijo. Višja vsebnost železa je bila ugotovljena na mestu termoremanentne magnetizacije na obrambnem nasipu, na ruševinski groblji tik ob nasipu kakor tudi na nekaj mestih v notranjosti naselbine, kjer z drugimi prospekcijskimi tehnikami nismo ugotovili izrazitejših odstopanj (*sl. 16*).

PEDOSEKVENCA NA TRDIH KARBONATNIH KAMNINAH

Ajdovski gradec pri Bohinjski Bistrici (*sl. 17*)

Pri Schmidovih arheoloških izkopavanjih leta 1936 (glej Gabrovec 1966) so bili v skoraj vseh sondah tudi kosi železne žlindre oz. raznih odpadnih produktov železarstva. V dveh sondah na vzhodni strani naselbine je Schmid v hišah II in III odkril tudi manjše jame, ki jih je razlagal kot ostanke topilnic. Zaradi teh podatkov sem se odločil za magnetometrijo kot najustreznejšo geofizikalno metodo za detekcijo obrtnih con z metalurško aktivnostjo (*sl. 18*). Ker je najdišče na vrhu hriba s pedosekvenco na trdih karbonatnih kamninah (apnenci), je pričakovana debelina tal majhna, topografska razgibanost terena pa razmeroma velika. V takšnih razmerah je mikrorelief ena od najučinovitejših prospekcijskih tehnik. Mikrorelief oz. digitalni model reliefa je sicer samo natančen topografski načrt, ki pa ga zaradi izpovednosti pri arheološki interpretaciji uvrščam med prospekcijske tehnike. Interpretacija arheoloških osta-lin temelji na opazovanju majhnih topografskih razlik v oblikovanosti površja na naselbini (*sl. 19* in *20*).

Izmerjene vrednosti vertikalnega gradienta magnetnega polja (Geoscan FM36) so bile med -30 nT/m in +40 nT/m. Za interpretacijo magnetnih anomalij, ki so posledica inducirane magnetizacije, je potrebno poznati vrednosti magnetne susceptibilnosti trdne geološke podlage in pedoloških različkov na arheološkem najdišču. Srednja vrednost navidezne magnetne susceptibilnosti (Kappameter KT-5) apnenca za 22 meritev je 0,018 x 10^{-3}SI. Srednja vrednost za isto število meritev nekontaminiranih vzorcev tal pa je 0,12 x 10^{-3}SI. To pomeni, da so tla 6 krat bolj magnetna od apnenčeve geološke podlage. Takšen kontrast v magnetni susceptibilnosti lahko poleg razgibane morfologije terena in plitvoležeče apnenčeve geološke podlage povzroči razmeroma močne magnetne anomalije, ki so lahko podobnega velikostnega reda kot so amplitude inducirane magnetizacije arheoloških objektov.

Na *sl. 18* so prikazani negativni gradienti z modro, pozitivni gradienti pa z rdečo barvo. Za ugotavljanje metalurških aktivno-sti so pomembnejši pozitivni gradienti, ki so označeni z rdečo barvo. Na vseh slikah vidimo, da so rdeča polja zelo nepravil-nih oblik in približno enakomerno distribuirana po celotni raziskani površini. Visoki pozitivni gradienti se ne pojavljajo samo na terasah, temveč tudi na pobočjih z manjšimi nakloni na vzhod-ni strani najdišča. Sam sem mnenja, da gre za magnetne anomalije, ki so vsota magnetnih polj arheoloških kulturnih plasti in magnetnih anomalij, ki so posledica naravnih dejavnikov. Ker nas pri metalurških aktivnostih zanima predvsem močen termoremanentni tip magnetizacije, sem se odločil, da prikažem le distribucijo pozitivnih gradientov in sicer tistih, ki so višji od +5 nT/m. V tem primeru so se anomalna območja zelo skrčila, vendar so še vedno zelo številna. Ker gre za razmeroma močne magnetne anomalije, sklepam, da gre za termoremanentni tip magnetizacije odpadnih produktov metalurgije oz. manjših objektov, ki vsebujejo termoremanentni tip magentizacije (odpadni produkti-kosi žlindre). Skoraj vse močne magnetne anomalije so na zunanjem robu izravnanih površin oz. teras. To sicer ustreza predpostavki, da so izravnane površine oz. manjše terase primeren prostor za bivanje kot tudi za ohranjanje arheoloških kulturnih plasti vendar ne moremo izključiti možnosti, da gre za topografski učinek pregiba pobočja terase, kjer je lahko apnenec blizu površja ali celo izdanja.

Namen izdelave mikroreliefa je prikazati tudi najmanjše morfološke enote na arheološkem najdišču, kar nam omogoča, da na osnovi oblikovanosti površja sklepamo na arheološke ostaline. Pri mikroreliefu so ciljni objekti večje arheološke ostaline, kot so razne naselbinske strukture (obrambna obzidja oz. nasipi, ruševinske groblje arhitekturnih ostalin, jarki, komunikacije, terase). V tem kontekstu lahko razumemo kartiranje višinskih razlik kot neodvisno prospekcijsko metodo, ki jo uporabimo za kartiranje arheoloških morfoloških oblik na najdišču. Hkrati nam takšna karta služi kot natančen topografski načrt za vse ostale geofizikalne metode, in ga hkrati uporabimo npr. tudi za prepoznavanje magnetnih anomalij, ki so posledica t. i. -topografskega efekta- (glej npr. Mušič, Orengo 1998, 178-179, sl. 16).

Topografske oblike, ki so pomembne za arheološko interpretacijo, so označene na *sl. 19*. Ugotovil sem naslednje značil-ne morfološke oblike:

Okoli naselbine lahko sledimo izraziti pozitivni topografski obliki, ki predstavlja ostaline prazgodovinskega in/ali kasnoantičnega obzidja. Gre za sklenjen nasip, ki poteka po zunanjem robu naselbine natančno po liniji, kjer se naravni teren proti zunanji strani prevesi v strmo pobočje. Obzidje oz. nasip je prekinjen edino na vzhodnem in zahodnem delu (*sl. 19*: zahod-ni in vzhodni prehod v naselbino). Ti prekinitvi sta na mestu današnjih prehodov v naselbino, vendar lahko glede na topografijo terena sklepamo, da je komunikacija potekala v enaki smeri s prehodi na istih mestih tudi v prazgodovini oz. kasni antiki. Na severozahodnem delu se obzidje razcepi v dva kraka tako, da notranji krak poteka vzporedno z zunanjim.

Povsod po naselbini so manjše ali večje izravnave, ki jih imenujem -terase-. Verjetno gre deloma za naravne izravnave, deloma pa za umetne oz. arheološke terase. Namen terasiranja na naselbini ni povsem jasen, vendar gre najverjetneje za izravnave zakrasele apnenčeve geološke podlage, s čimer so pridobili bivalne površine za hiše. Manj verjetno je, da bi te terase uporabljali kot kmetijske obdelovalne površine. Poleg tega lahko na -terasah- pričakujemo debelejše arheološke kulturne plasti. Na osnovi povedanega lahko zaključim, da so zravnane površine oz. terase pomembne indikacije za arheološke kulturne plasti.

Na vrhu naselbine je skoraj povsem izravnan plato, ki je na zahodni strani zamejen s strmim pobočjem, na vzhodni strani pa se teren spušča polagoma. Na platoju oz. v neposredni bližini naj bi bile arhitekturne ostaline. Severni del platoja, kjer je danes jasa, je na digitalnem modelu reliefa skoraj povsem raven. Južni del je poraščen z gosto vegetacijo in je morfološko veliko bolj razgiban. Na tem delu se na izrisih mikroreliefa kaže oblika, ki spominja na arhitekturne ostaline (*sl. 19*: arhitekturne ostaline/geološka podlaga). Ob tem moramo povedati, da so takšni zaključki samo na podlagi morfologije terena lahko tudi zavajajoči.

Tudi za georadarsko metodo je potrebno na takšnih topografsko razgibanih najdiščih predhodno izdelati digitalni model reliefa. Le na ta način lahko interpretiramo georadarski posnetek v odvisnosti od površinskih oblik. Ena od takšnih izrazitih morfoloških oblik na praktično vseh prazgodovinskih gradiščih je obrambni nasip (*sl. 19, 20* in *21*). Ker smo želeli podati oceno potenciala georadarskih raziskav za odkrivanje ostalin na liniji prazgodovinskega obzidja, smo z nekaj profili prečkali del nasipa na jugovzhodni strani naselbine (*sl. 20* in *21*). Na robu platoja, kjer se teren prevesi v strmo pobočje, smo ugotovili izrazite radarske odboje v obliki hiperbol, ki so lahko posledica večjega kamninskega materiala, ki pripada obzidju, ali pa gre za odboje od zakrasele apnenčeve podlage. Iste oblike se nadaljujejo tudi v notranjost naselbine (*sl. 22*).

Škocjan (*sl. 23*)

V vasi Škocjan je bilo prazgodovinsko gradišče, ki je merilo v obsegu 950 m in je bilo na edini položni strani obdano z obzidjem. Na površini kaštelirja so našli obilo glinastih posod, ki kažejo podobnost s keramiko pozne bronaste dobe ter ozko etnično in kulturno povezavo med prebivalci istrskih kaštelirjev in prebivalstvom Benečije. Manjša sondiranja na območju gradišča je vodil tudi Neumann, in sicer na mestu, kjer se teren strmo prevesi proti udorni Mali dolini pod Škocjanom. Izkopal je skeletne človeške grobove s pridatki iz železne dobe (Leben 1975, 132). Pri zaščitnih izkopavanjih na območju gradišča v letu 1996 so poleg dokazov o poselitvi v starejšem delu pozne bronaste dobe in v starejši železni dobi pridobili tudi podatke o rimskodobnih ostalinah. Ohranjen je zid, grajen z obdelanimi kamni (dve legi kamnov), vezanimi z malto (Turk 1994-1995, 306).

Na tem arheološkem najdišču smo preverjali ustreznost geofizikalne prospekcije za oceno arheološkega potenciala na zakraseli geološki podlagi. Uporabili smo geoelektrično upornostno metodo elektrodnih dvojčkov (Twin probes, Geoscan RM15) in magnetometrijo s pretočnim gradiometrom (Fluxgate gradiometer FM36). Zaradi variabilne morfologije terena smo izdelali mikrorelief, na katerega smo položili rezultate magnetometrije (*sl. 24*), da smo lahko korigirali t. i. -topografski efekt- zaradi kombiniranega učinka kontrasta v magnetni susceptibilnosti med šibko magnetno apnenčevo geološko podlago in močno magnetnimi talnimi različki ter oblikovanosti površja (*sl. 25*). Z geoelektrično upornostno metodo nismo dobili podatkov, ki bi bili neposredno uporabni za arheološko interpretacijo. So pa ti podatki pomembni posredno, ker nam omogočajo poleg mikroreliefa ugotoviti spremembe v morfologiji zakrasele geološke podlage pod površjem, kar sem uporabil pri interpretaciji magnetometrije.

S takšnim pristopom smo prišli do nekaterih podatkov, ki so po mojem mnenju pomembni za oceno potenciala geofizikalnih raziskav na prazgodovinskih gradiščih na Krasu. Na magnetogramu (*sl. 24*) so v spodnji polovici slike vidne prečne linearne anomalije vertikalnega gradienta magnetnega polja, ki so vsaj deloma najverjetneje posledica terasiranja v preteklosti. Levo zgoraj so bile izmerjene zelo izrazite pozitivne magnetne anomalije, ki so najverjetneje posledica termoremanentne magnetizacije opeke.

Prečne linearne anomalije so deloma posledica -topografskega efekta- na mestih večjih nivojskih razlik, kar se lepo vidi na sliki, kjer sta hkrati prikazana mikrorelief in magnetometrija (*sl. 25*). Lahko gre za naravne oblike ali subrecentno terasiranje. Poleg teh magnetnih anomalij so na *sl. 24* vidne še številne druge linijske anomalije, ki jih ne moremo povezati z oblikovanostjo površja ali geološko podlago. Te linije so lahko posledica terasiranja v arheološki preteklosti. Močna magnetna anomalija (*sl. 24* in *25*) (arhitekturne ostaline?), ki je najver-jetneje posledica termoremanentne magnetizacije opeke, je bi-la izmerjena na povsem ravnem terenu z relativno nižjimi vred-nostmi navidezne električne upornosti kot na drugih delih tere-na, kar pomeni, da lahko učinek topografije v tem primeru iz-ključimo

Cvinger pri Meniški vasi (*sl. 26*)

Ker so bili rezultati geofizikalne prospekcije na Cvingerju pri Meniški vasi (*sl. 26*) že podrobneje predstavljeni na drugem mestu (Mušič, Orengo 1998, 157-186), v tem članku povzemam samo nekatere ugotovitve, ki so pomembne za ugotav-ljanje potenciala magnetometrije in magnetne susceptibilnosti za detekcijo prazgodovinskih železarskih obrtnih con oz. železarskih talilnih kompleksov s primitivnimi plavži za ekstenzivni način pridobivanja železa na zakraseli geološki podlagi. Glavna značilnost takšnih obrtnih con so odpadni produkti metalurgije v obliki blokov talne žlindre, ki zapolnjujejo večje ali manjše jame v tleh (glej Smekalova, Voss, Abrahamsen 1993, 83-103).

Z geofizikalnimi raziskavami smo uspeli zamejiti prazgodovinski železarski talilni kompleks (*sl. 27*). Glede na velikost celotne industrijske cone in število blokov talne žlindre smo posredno podprli tezo o talilnih pečeh, ki so jih uporabljali pri ekstenzivnih železarskih metalurških procesih. To so bile peči za enkratno uporabo.

Ugotovili smo, da je tudi na takšnih arheoloških najdiščih mogoče za natančno kvantitativno interpretacijo koristno uporabiti metodo tridimenzionalnega magnetnega modeliranja. Za modeliranje ostankov talilnih peči, ki so objekti s termoremanentno magnetizacijo in imajo zaradi termične zgodovine značaj močnih magnetnih dipolov, sem uporabil računalniški program Mag-poly (USGS). Ugotovil sem, da je nizek pokončni valj naj-ustreznejši geometrijski model za jame, zapolnjene z bloki talne žlindre. Za določanje njihove globine lahko uporabimo grafični postopek kot ga predlaga Telford s sodelavci (1990, 87).

Pomembna je tudi ugotovitev, da lahko s kartiranjem navidezne magnetne susceptibilnosti tudi z uporabo preprostejših instrumentov, kot je npr. Kappameter KT-5, zamejimo železarske talilne komplekse.

Za magnetometrične prospekcije na podobnih najdiščih na Dolenjskem je pomembno tudi to, da t. i. -topografski efekt- ne vpliva bistveno na rezultate magnetometrije pri prospekciji na železarskih talilnih kompleksih.

PEDOSEKVENCA NA MEHKIH KARBONATNIH KAMNINAH

Groblje pri Bučah (*sl. 28*)

Rezultati geofizikalnih raziskav na lokaciji rimske vile na Grobljah pri Bučah, kjer je leta 1990 Alenka Vogrin (1990), ZVNKD Celje, vodila zaščitna izkopavanja, so objavljeni na več mestih (Mušič 1994, 9-19; 1994-1995, 59-72; 1996, 83-137). V tem članku sem se omejil na poudarke nekaterih dejstev, ki so pomembna za oceno ustreznosti geofizikalnih raziskav na pedosekvenci na mehkih karbonatnih kamninah. Za oceno potenciala geofizikalnih raziskav v takšnih pogojih je pomembno, da so pri izkopavanjih odkrili zidove antične podeželske vile, ki so ohranjeni le še mestoma; sorazmerno dobro so ohranjeni le temelji, ki so zgrajeni iz lokalnih kamnin (miocenski peščenjaki, peščeni laporji in kremenovi konglomerati). Na severni strani ležijo na globini 40 cm, na južni pa nekoliko globlje (do 70 cm). Debelina zidov oz. temeljev je povsod približno enaka in znaša 60 cm.

Tla na mehkih karbonatnih kamninah (laporji) so zaradi hitrega preperevanja razmeroma debela in brez debelozrnatega kamninskega skeleta. Zaradi tega lahko pedosekvence na mehkih karbonatnih kamninah s stališča geofizikalnih raziskav obravnavamo kot homogen in izotropen medij. Rezultati geoelektričnega kartiranja in magnetometrije to v največji meri potrjujejo. Ne glede na to, da so v glavnem ohranjeni le temelji zidov, ki ležijo do 70 cm globoko, so rezultati geoelektričnega kartiranja zelo jasni *(sl. 29*), enako velja tudi za magnetometrijo (glej Mušič 1994; 1996 in 1997), kar je nekoliko presenetljivo, ker so arhitekturne ostaline zgrajene iz lokalnih kamnin, kar običajno pomeni le šibek kontrast proti tlem, ki so posledica preperevanja teh istih kamnin.

PEDOSEKVENCA NA GLINAH IN ILOVCAH

Grafendorf (Avstrija)

Uvodoma sem povedal, da je eno od osnovnih vodil geofizikalnih raziskav uporaba čim več različnih geofizikalnih tehnik na istem arheološkem najdišču. Za prikaz komplementarnosti georadarske raziskave, magnetometrije in geoelektričnega kartiranja sem uporabil samo enega od geofizikalnih profilov na antičnem arheološkem najdišču pri Grafendorfu v Avstriji (*sl. 30* in *31*), ker bo raziskava v celoti objavljena na drugem mestu. To izjemo sem si dovolil, ker so bila tam že opravljena arheološka izkopavanja, ki so takšen interpretativni postopek potrdila. Na ta način sem želel pomenu ustrezno ilustrirati segment geofizikalnih raziskav, ki bo pomembno vodilo pri načrtovanju arheološke prospekcije v prihodnosti. Vodja arheološkega projekta na najdišču pri Grafendorfu je prof. dr. Erwin Pochmarski z Arheološkega odelka na Univerzi v Grazu. Geofizikalne profile sem razdelil na posamezna območja tako, da razlagajo arheološki kontekst anomalij v fizikalnih poljih (*sl. 31*). S tem uvajam *koncept združbe anomalij v fizikalnih poljih*, ki jih utemeljujem na podlagi splošne -geofizikalne podobe-območja. Takšen pristop omogoča interpretacijo na podlagi anomalij v različnih fizikalnih poljih na isti točki (npr. zid) ali na nekem območju (npr. ruševine).

Meja med območjema 1 in 2 (*sl. 31*) predstavlja mejo arheološkega najdišča v ožjem pomenu oz. rob, do katerega segajo antične arhitekturne ostaline.

Območje 1 (od 0 do 7 m). To območje se nahaja zunaj ožjega arheološkega najdišča. Na radarskem posnetku so vidni le šibki odboji od ravnega horizontalnega reflektorja. Sklepam, da gre za odboje, ki so posledica stratifikacije tal zaradi sodobne kmetijske namembnosti površin (meja ornice) in naravnih pedogenetskih dejavnikov.

Območje 2 (od 7 do 12,5 m). Zelo izrazit odboj med 9,5 do 10 m je posledica plitvo ležečega zidu. Na istem mestu sta bili izmerjeni tudi visokoupornostna anomalija in negativni gradient vertikalne komponente magnetnega polja. Položaja pikov obeh anomalij natančno ustrezata izrazitemu radarskemu signalu. Visokoupornostna anomalija sega od 6,5 do 12,5 m. Vrednosti so nekoliko nižje kot neposredno nad zidom, vendar še vedno precej višje od ozadja meritev. Najverjetneje gre za odziv ruševinskih plasti v neposredni okolici zidu. Glede na negativni gradient magnetnega polja sklepam, da gre za kamniti zid z nizko magnetno susceptibilnostjo. Ruševinski material je posledica destrukcije istega kamnitega zidu. Na istem mestu, kjer je bila ugotovljena upornostna anomalija, ki je posledica ruševin, so tudi na georadarskem profilu vidni šibki odboji nepravilnih oblik, ki potrjujejo domnevo, da gre za kaotičen kamninski ruševinski material.

Območje 3 (od 12,5 do 20 m). Na georadarskem profilu so bili ugotovljeni odboji od plasti, ki tone (od 12,5 do 17 m), in odboji od nepravilnih plasti (od 17 do 20 m). Vrednosti električne upornosti na teh mestih so višje od ozadja, vendar neizrazite. Zelo visoki pozitivni gradienti vertikalne komponente magnetne-ga polja nad plastjo, ki tone, kažejo na to, da gre za plasti ruševinskega materiala z visoko magnetno susceptibiolnostjo, ki je značilna za keramične objekte. Glede na arheološki kontekst magnetnih anomalij sklepam, da gre za ruševinsko plast s strešniki. Na istem območju je bil izmerjen tudi šibek radarski odboj, ki predstavlja odziv slabo ohranjenega pregradnega zidu. Na tem mestu je bila izmerjena šibka visokoupornostna anomalija in izrazit negativni gradient magnetnega polja. Na podlagi teh podatkov sklepam, da gre za tanek pregradni zid, zgrajen iz kamnine, z nizko magnetno susceptibilnostjo. Nad odboji od nepravilnih plasti je bil izmerjen negativni gradient vertikalne komponente magnetnega polja, kar pomeni, da ta plast najverjetneje predstavlja kamninski ruševinski material.

Velike Malence (*sl. 32*)

Severovzhodno od Velikih Malenc oz. v neposredni okolici cerkve sv. Martina je že dalj časa znano antično arheološko najdišče (*sl. 32*). Na podlagi izkopavanj Petra Petruja (Petru 1970-1971) in geoelektričnega kartiranja iz leta 1986, ki ga je opravil Andy Waters z Univerze v Bradfordu, Velika Britanija, ter drugih arheoloških informacij, ki izhajajo iz površinskih terenskih pregledov in testnih sondiranj je znano, da so pod površjem razmeroma dobro ohranjene antične arhitekturne ostaline. Leta 1993 so bila opravljena obsežna zaščitna izkopavanja pod vodstvom dr. Philipa Masona in Uroša Bavca, zato smo lahko vsaj na manjšem delu raziskane površine primerjali rezultate geofizikalnih raziskav z odkritimi arhitekturnimi ostalinami (glej Mušič 1996, 106-112).

Ugotovitve, pomembne za oceno potenciala geofizikalnih raziskav na pedosekvenci na glinah in Ilovcah, lahko strnem v nekaj točk:

Rezultati geolektrične upornostne metode v danih pogojih so zelo dobri (*sl. 33:* A). Sledimo lahko številnim linijskim visokoupornostnim anomalijam, ki so posledica zidov in/ali temeljev, ruševinskih plasti in kamnitih ograd (glej Mušič 1996, 112-113). Deloma so bili rezultati geofizikalnih raziskav potrjeni z arheološkimi izkopavanji (glej Mušič 1996, 112-113).

Rezultati magnetometrije s pretočnim *gradiometrom (*Fluxgate gradiometer FM36) so v splošnem manj jasni od geoelektričnega kartiranja. To je posledica majhnega kontrasta v magnetni susceptibilnosti med zidovi in zemljiščem, v katerem so. Povsem enako velja tudi za meritve totalnega magnetnega polja s protonskim magnetometrom (Geometrics G819). Kljub temu lahko sledimo linijam s šibkimi negativnimi gradienti vertikalnega gradienta magnetnega polja, ki so posledica nižje susceptibilnosti zidov (*sl. 33:* B). Poleg šibkih magnetnih anomalij, ki so posledica razlik v inducirani magnetizaciji, pa je na *sl. 33:* B vidnih še nekaj območij z močno termoremanentno magnetizacijo, ki je značilna za opeko (glej tudi Mušič 1996, 111-115).

Čatež ob Savi (*sl. 34*)

Podobno kot antično najdišče pri Velikih Malencah se tudi to nahaja na pedosekvenci na glinah in Ilovcah, zato smo pričakovali dobre rezultate predvsem z geoelektrično upornostno metodo. S to metodo smo uspešno zamejili arhitekturne ostaline antičnega objekta (*sl. 35:* A). Dober kontrast v navidezni električni upornosti je rezultat pretežno glinene osnove, ki je vlažna in dobro električno prevodna, ter arhitekturnih ostalin, ki so dobro ohranjene, so plitvo pod površjem in predstavljajo medij z zelo visoko električno upornostjo. V notranjosti objekta je ploskovna anomalija visokih vrednosti električ-ne upornosti (*sl. 35:* A) brez jasne strukturiranosti, kar je lahko učinek ruševinskih plasti keramičnih strešnikov ali hypocausta. Na južni in vzhodni strani sta bili ugotovljeni tanki liniji, katerih električna upornost je le nekoliko višja od ozadja. Lahko gre za istodobne arhitekturne ostaline (zid) ali novodobne jarke z infrastrukturnimi objekti.

Na tem mestu sta na rezultatih magnetometrije dobro vidni linearni anomaliji na vzhodni in severni strani objekta (*sl. 35:* B). V smeri obeh linij so bili izmerjeni šibki negativni gradienti, kar pomeni, da je na teh mestih magnetna susceptibilnost nekoliko nižja od ozadja. S tem lahko tudi magnetometrijo na teh mestih interpretiramo podobno kot geoelektrično kartiranje. Lahko gre za arhitekturne ostaline (zidove), katerih magnetna susceptibilnost je nižja od ozadja. Podobno je bilo ugotovljeno pri magnetometričnih raziskavah tudi na drugih arheoloških najdiščih v bližini (npr. Velike Malence, Mušič 1996, 105-120). Najvišji pozitivni gradienti magnetnega polja so bili izmerjeni v notranjosti objekta (*sl. 35*: B in *sl. 36*), kar kaže na to, da gre za termoremanentni tip magnetizacije opeke (strešniki?). Negativni gradienti potekajo v linijah, ki nakazujejo smeri kamnitih zidov (*sl. 36*).

PEDOSEKVENCA NA PRODU IN PESKU

Ilovca pri Vranskem (*sl. 37*)

Arheološke podatke, ki so pomembni za ovrednotenje rezultatov geofizikalne raziskave povzemam po objavi Irene Lazar (1997, 159-164), kjer podaja rezultate arheoloških izkopavanj iz leta 1995. Z drobnimi najdbami med katerimi so tudi rimski novci so ugotovili časovni razpon tega antičnega arheološkega najdišča, ki sega od konca 1. st. skozi celo 2. st. do prve četrti-ne 3. st. 50 % najdenih kovancev sodi v drugo polovico 2. st. To razlagajo kot dokaz, da je bil v tem obdobju tudi višek aktivnosti na tem območju. Avtorica nadalje piše, da so bile zaradi poplavljanja Bolske arheološke plasti uničene do te mere, da ni bilo mogoče natančno rekonstruirati stratigrafskih odnosov kulturnih plasti. Na južni strani izkopnega polja so bili zidovi iz apnenca in prodnikov izjemno dobro ohranjeni. Apnenčevi lomljenci so bili na notranji strani rdeče barve, kar pomeni, da so bili izpostavljeni visokim temperaturam. Z izkopavanji centralnega dela so ugotovili dve opekarski peči.

Peč 1 - zahodna peč (*sl. 39:* W) je bila bolje ohranjena. Zgrajena je bila iz opeke kvadratnih in pravokotnih presekov. Od petih originalnih opečnih obokov sta bila ohranjena le dva. Prostor je bil zapolnjen s fragmenti (keramičnimi?) različnih oblik. Kanal v peči je bil zgrajen iz velikih kosov opeke pravokotnih presekov in obrnjenih strešnikov. Na opekah, ki so jih uporabili za gradnjo peči, so odkrili pečate *legio II Italica*.

Peč 2 - vzhodna peč (*sl. 39:* E) je nekoliko višje glede na zahodno peč in je bila zato bolj izpostavljena uničevanju pri oranju. Keramični oboki peči so bili popolnoma uničeni. Na podlagi temeljev je bilo mogoče ugotoviti, da je bila peč zgrajena iz sedmih obokov. Kanal kurišča in centralni del peči je bil do vrha zapolnjen z različnimi kosi opeke. Sicer je bila konstrukcija podobna kot pri sosednji peči.

Zidovi, ki obdajajo peč so debeli 100 cm in so ohranjeni do višine 70-90 cm. Vsi štirje vogali se zaključujejo v krožno obliko.

Z geoelektrično upornostno metodo elektrodnih dvojčkov smo ugotovili v glavnem le položaj prodnih zasipov. Razpon vrednosti navidezne električne upornosti naravnega ozadja je na tej pedosekvenci tako širok, da zajema tudi vse tipe arheoloških ostalin. Zaradi tega lahko te ugotovimo le na podlagi pravilnih oblik anomalj. Pri tem so bile le na nekaj mestih izmerjene visokoupornosne anomalije, ki so nedvomno posledica arhitekturnih ostalin antične peči (*sl. 38:* A). Vse ostale visokoupornosne anomalije so povsem naravnega izvora.

Močni pozitivni gradienti vertikalne komponente magnetnega polja so bili izmerjeni nad keramičnimi arhitekturnimi elementi v notranjosti dvodelne opekarske peči (*sl. 38:* B; *39; 40; 41* in *42*) z visoko magnetno susceptibilnostjo in termoremanentnim tipom magnetizacije. Najvišja amplituda pozitivnega gradienta magnetnega polja nad pečjo znaša 82 nT/m (*sl. 42*). Zidovi so zgrajeni iz prodnikov z zelo nizko magnetno susceptibilnostjo. Najnižja amplituda gradenta magnetnega polja nad kamnitimi zidovi je -30 nT/m.

V arhitekturnih elementih notranjosti peči, ki so iz opeke, je ohranjena oz. -zamrznjena- remanentna magnetizacija iz časa, ko se je peč zadnjič ohladila. Deklinacijo (D) termoremanen-tne magnetizacije peči ocenjujem na približno -2°. Smer sem določil tako, da sem povezal točki najvišjega in najnižjega gradienta remanentne magnetizacije zahodnega bloka opekarske peči in odčital odklon od geografskega severa. Tako ocenjena deklinacija je seveda zelo površna in je ne moremo resno upoštevati v smislu magnetne datacije. Magnetna anomalija je vektorska vsota inducirane in remanentne magnetizacije, pri čemer je tudi smer remanentnega magnetizma zaradi viskozne magnetizacije lahko drugačna, kot je bila v času delovanja peči. Ta primer navajam predvsem kot zanimivost, ker je takšna deklinacija na Madžarskem značilna za drugo polovico 2. st. in prvo polovico 3 st. (Marton 1998, 74).

Severno od opekarske peči smo izmerili v pasu, širokem približno 5 m in dolgem več 10 m (*sl. 38*), razmeroma močno magnetno anomalijo (min = -26 nT/m, max = +23 nT/m). Izkopavanja so odkrila, da gre za naravni jarek oz. depresijo, ki je bila uporabljena kot odpadna jama. Jarek je bil zapolnjen z odlomki odpadnih kosov opeke, ki so bili očitno izpostavljeni previsokim temperaturam. Večina keramičnih odlomkov v odpadni jami je bila nasičena z vodo in v fazi intenzivnega razpadanja. Globina odpadne jame v zahodnem profilu je največ 90 cm, širina pa 350 cm.

ZAKLJUČKI

Nesporna je ugotovitev, da lahko pričakujemo dobre rezultate geofizikalnih raziskav le v primeru, ko na istem arheološkem najdišču uporabljamo več različnih geofizikalnih tehnik in tudi več različnih izvedb instrumentov, ki delujejo na drugačnih fizikalnih principih. Na tej osnovi vpeljujem koncept združb anomalij v fizikalnih poljih, ki omogočajo natančnejšo interpretacijo -točkovnih- ciljnih objektov (npr. zid), kot tudi površin, ki predstavljajo območja z določeno namembnostjo v arheološki preteklosti (npr. ruševinske plasti s plastjo strešnikov = notranjost hiše).

Ocenjujem, da je razdelitev naravnega okolja na krajinske sisteme (=pedosekvence), kar je prvi utemeljil Stritar (1990), najustreznejša delitev tudi za opisovanje ustreznosti geofizikalnih raziskav v odvisnosti od naravnih danosti.

Za geofizikalne raziskave so najugodnejše pedosekvence na mehkih karbonatnih kamninah (laporji) (Groblje pri Bučah) in pedosekvence na glinah in ilovcah (Čatež ob Savi). Pri obeh gre za precej homogen in izotropen medij. Tla so globoka in brez debelega kamninskega skeleta. Detektibilnost arheoloških ostalin je zelo dobra za vse uporabljene geofizikalne tehnike.

Pedosekvence na nekarbonatnih kamninah v Sloveniji zaenkrat še niso zadostno raziskane. Raziskali smo le eno najdišče na flišnih kamninah, kjer so bili rezultati geofizikalne prospekcije zelo dobri (Ajdovščina nad Rodikom). Rezultati, ki smo jih dobili na kislih magmatskih kamninah (rioliti) na podobnih arheoloških najdiščih v tujini (Mont Beuvray, Francija) so bili slabši. Na teh pedosekvencah smo dobili najslabše rezultate z geoelektrično upornostno metodo. To razlagam deloma kot posledico debelih plasti antičnih ruševinskih grobelj in deloma kot posledico debelih preperinskih plasti s kamninskim skeletom na magmatskih kamninah. Magnetometrija in navidezna magnetna susceptibilnost sta se izkazali v takšnih okoljih z nizko susceptibilnostjo geološke in pedološke podlage kot zelo uporabni za detekcijo obrtnih delavnic (npr. železarstvo). Ker so arhitekturne ostaline praviloma iz kamnin geološke po-dlage, je kontrast v magnetni susceptibilnosti premajhen, da bi lahko zaznali posamezne zidove. Po mojem mnenju je georadar edina metoda, s katero lahko uspešno detektiramo arhitekturne ostaline pri takšnih pogojih.

Oceno ustreznosti geofizikalnih raziskav na pedosekvenci na trdih karbonatnih kamnninah utemeljujem na višinskih najdiščih, ki so na zakraseli apnenčevi podlagi (Ajdovski gradec pri Bohinjski Bistrici, gradišče na Škocjanu, Cvinger pri Meniški vasi). Zaradi velikega kontrasta v magnetni susceptibilnosti med apnenčevo geološko podlago in z železovimi mine-rali bogatimi talnimi različki ter razgibano zakraselo geološko podlage moramo upoštevati t. i. -topografski efekt-. Geoelektrično kartiranje podobno kot na pedosekvencah na produ in pesku tudi tukaj uporabljamo za ugotavljanje geoloških oblik. V takšnih okoljih z magnetometrijo učinkovito odkrivamo pred-vsem objekte obrtnih delavnic s termoremanentnim tipom magnetizacije (npr. peči in plavži) (Cvinger pri Meniški vasi), manjše deponije odpadnih produktov metalurgije (Ajdovski gradec pri Bohinjski Bistrici), arhitekturne ostaline iz opeke in sledove terasiranja (gradišče na Škocjanu).

Za geofizikalne raziskave so najbolj neugodno okolje pedosekvence na produ in pesku (Ilovca pri Vranskem). V teh okoljih je zaradi hitrega menjavanja prodnih zasipov npr. razpon navidezne specifične upornosti izredno širok in tudi izredno spremenljiv. Zaradi tega je uporabnost geoelektrične upornostne metode zelo omejena. Praviloma dobimo v takšnih okojih boljše rezultate z magnetometrijo in georadarjem. Rezultati geoelektričnega kartiranja so uporabni posredno, ker služijo za kartiranje sprememb v geološki podlagi, kar je pogosto pomembno za ločevanje geološke in arheološke informacije na magentogramih in radarskih izpisih.

Mag. Branko Mušič
Oddelek za arheologijo
Filozofske fakultete
Univerze v Ljubljani
Zavetiška 5
SI-1000 Ljubljana