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REVIEW ARTICLE

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Images of the invisible-prospection methods for the documentation of threatened archaeological sites

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Abstract To understand the development of prehistoric cultural and economic activities, archaeologists try to obtain as much relevant information as possible. For this purpose, large numbers of similar sites must be identified, usually by non-destructive prospection methods such as aerial photography and geophysical prospection. Aerial archaeology is most effective in locating sites and the use of digital photogrammetry provides maps with high accuracy. For geophysical prospection mainly geomagnetic and geoelectrical methods or the ground-penetrating radar method are used. Near-surface measurements of the respective contrasts within physical properties of the archaeological structures and the surrounding material allows detailed mapping of the inner structures of the sites investigated. Applying specially developed wheeled instrumentation, high-resolution magnetic surveys can be carried out in a standard raster of 0.125×0.5 m covering up to 5 ha per day. Measurements of ground resistivity or radar surveys in a raster of 0.5 or 0.5×0.05 m, respectively, are used to gain information on archaeological structures and on the main stratigraphic sequence of sites covering up to 0.5 ha per day. Data on intensities of the Earth's magnetic field, apparent resistivities of the ground or amplitudinal information of radar reflections are processed using a digital image processing technique to visualize the otherwise invisible archaeological structures or monuments buried in the ground. Archaeological interpretation, in the sense of detecting, mapping and describing the archaeological structures, is done using GIS technology by combining all relevant prospection data. As most of the Middle European archaeological heritage is under a massive threat of destruction, dramatically accelerated by intensive agriculture or industrial transformation of the landscape, the prospection techniques presented here represent an approach towards an efficient documentation of the disappearing remains of our ancestors.

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Introduction

Archaeologists are often asked: How do you know where to excavate? Archaeological intuition or inspiration together with trial trenches might have been the basis of Schliemann's success at Troy or Carter's discovery of Tut-ank-amun's grave. Nowadays, to obtain as much relevant information as possible prior to any cost-effective and time-consuming excavation, archaeologists may choose from a wide range of prospection methods developed during the past few decades (Linington 1970; Hesse 1973; Aitken 1974; Scollar 1975; Becker 1978) for exploring the landscape for earlier human activity. The techniques for detecting and mapping invisible archaeological structures were initially derived from explorative geophysical prospecting or conventional aerial survey, before becoming a separate archaeological discipline (Weymouth 1986; Clark 1990; Neubauer 1990; Scollar et al. 1990; Becker et al. 1996; Fassbinder and Irlinger 1999). The adopted methods are applied all over the world by a few specialized teams. The geophysical location and identification of archaeological structures and monuments is a fascinating field, opening up completely new possibilities for future archaeological research. With the most sophisticated systems, a laptop computer using image processing in the field is capable of revealing the structure of an archaeological monument to the archaeologist's eyes just 10 min after finishing the fieldwork. The following techniques of data processing, modelling, combination with additional data and archaeological interpretation, depict the remains and give an insight into the living space of our ancestors which is easily understandable by both experts and the general public.

Threatened cultural heritage

Most of our archaeological heritage is hidden beneath the surface. There are two kinds of remains left by man: those small objects once lost or thrown away and those which are vestiges of buildings, fortifications, rural or industrial installations, roads and so on; generally known as archaeological structures. The latter represent archaeological sites suitable for being prospected by aerial or geophysical surveys (Scollar et al. 1990). When such archaeological structures are built, for instance in the case of a settlement, the natural soil layers are disturbed by digging holes, foundations, ditches or pits. At the beginning of the Neolithic, man began to disturb nature significantly for the first time; land was cleared in forest and bush for agriculture, houses were built, pits were dug for storage, for extracting clay, for waste disposal or for burials; ditches and banks were constructed for fortification. Throughout history, men have produced different structures that after their decay remain as disturbances of the soil strata or incorporations of either surface or foreign material into the subsoil, and these form the main part of our Middle European archaeological heritage.

Archaeological sites as settlements usually cover 1–20 ha (Fig. 1) and are mainly recovered by accident during modern earthworks due to building activities or consolidation of farmland, or are detected from the air. The aerial evidence for nearly all these sites shows a dramatically increasing rate of destruction. The buried heritage is removed centimetre by centimetre by different kinds of erosive processes. In areas under intensive agricultural use, the erosive processes are accelerated by ploughing with heavy machines (Gerstner 1996). Slice by slice it is worn away by the plough, turned over and exposed on the surface for final destruction. Our observations, for example at Asparn (Fig. 1) have shown slices up to 2 cm thick annually cut away by the plough. On intensively cultivated loess soils, the combination of precipitation, topographic situation, inappropriate crop rotations and soil-specific erosive potential may cause a loss of soil cover of up to 3 cm per year. The Middle and Central European sites documenting the last 7,500 years of human occupation are under threat of being lost in just a few decades. Although the threat of irreversible destruction of the major part of the Continental heritage is well known within the archaeological community, the immense speed and scale of the destruction process may not register with the next generation of archaeologists until it is too late, and will probably not even touch the public consciousness.

Locating and mapping archaeological sites

The recognition that the hidden archaeological remains must be identified, interpreted and protected economically was and still is a major stimulus to the development of non-destructive archaeological prospection methods (Pollard 1994). Aerial archaeology, systematically applied since the late 1920s, is the most effective method for locating archaeological sites or monuments. The high viewpoint allows the perception of archaeological structures visible due to their specific physical properties as soil marks, moisture marks or crop marks. In

Fig. 1 Aerial photograph (Freigabenr. 13086/30-1-6/82) and digital image representation of the magnetic survey of the multiphase site Asparn a.d. Zaya, Lower Austria. The *central area* is fortified by an oval and a trapezoidal ditch system. The fortified site is dated to the Early Neolithic (5200–4950 BC) and spreads over 20 ha. In the north-east another settlement from the 2nd–3rd century was recovered by the magnetic survey. The site has already suffered serious destruction by erosive processes visible as *the light areas* in the aerial photograph. The soil horizon sequence in this area is Ap–C parent loess, indicating the complete loss of soil cover

the case of still existing above-surface irregularities, they clearly appear as shadow marks in the morning or evening sun; thermal properties may produce frost or snow marks. Most European aerial archives store thousands of photographs, documenting the detected sites. However, if aerial photographs are used solely for site localization, a good deal of the photograph's information is wasted. By applying analytical and digital photogrammetry (Scollar et al. 1990; Becker 1996b; Doneus 1996) the existing aerial photographs can thus be further analysed to produce precise maps of the visible features or to create rectified photo maps (orthophotos). Three-dimensional descriptions of the archaeological features as well as of the terrain under investigation are digitized from vertical stereo-pairs or from digitally rectified oblique photographs. Using these techniques, aerial archaeology is not only able to search landscapes for sites, but also to map the visible inner structures of an archaeological site with high accuracy to at least 0.25 m (Doneus 1995; Doneus and Neubauer 1997).

More detailed mapping of the inner structures of the located sites is the domain of geophysical prospecting, the use of non-destructive magnetic, electrical, electromagnetic, seismic, thermal, gravimetric or radiometric methods, all specially adapted for archaeological use. The detection of archaeological structures by these highly ingenious techniques is based on the near-surface measurement of contrasts in the properties of the materials forming the respective archaeological structures and those of their surrounding environment (e.g. a wall in humic soil). The experience and developments of the last 40 years have proved magnetic and electrical methods, and more recently ground-penetrating radar, to be the most suitable for standard archaeological applications (Clark 1990; Neubauer 1990; Scollar et al. 1990; Becker et al. 1996; Conyers and Goodman 1997) whereas the other methods mentioned may provide important additional information on specific problems. The ground measurements are normally taken by automatic and wheeled devices in specific configurations in a raster of 0.5 m or less. The registered magnetic intensities or apparent resistivities of the investigated subsurface are visualized and processed as digital images (Becker 1984; Scollar et al. 1990; Becker et al. 1996; Neubauer et al. 1996) making the otherwise invisible structures 'visible' again.

Archaeological magnetometry is the best established and most widely used geophysical prospection technique (Clark 1990; Neubauer 1990; Scollar et al. 1990; Becker et al. 1996), based upon a passive measurement of the intensity of the Earth's magnetic field. Its beginning dates back to 1958 (Aitken 1958) and it has been under rapid and continuous development during the last 40 years, now offering the possibility of rapid coverage of extended archaeological sites with resolution down to 0.5×0.125 m and with pico Tesla sensitivity (Becker 1995; Neubauer et al. 1996, 2001). The instrumentation available at the Bayerisches Landesamt für Denkmalpflege and the University of Vienna based on optically pumped caesium magnetometers (Scollar et al. 1990) allows high resolution measurements and interpretations in the sense of effective and accurate mapping of archaeologically relevant structures ranging up to 5 ha daily.

Magnetic properties of archaeological structures

Magnetic locating of archaeological structures is achieved by precise mapping of local anomalies in the Earth's magnetic field with high-resolution field magnetometers (Scollar et al. 1990). The anomalous intensities produced by archaeological structures, such as refilled fortification ditches, storage pits, and postholes of wooden prehistoric houses, typically range over around 0.1–10 nT for earthen features once dug into the subsoil. These relatively slight deviations from the main field intensity of about 48,000 nT in our latitude are due to according magnetization contrasts between the archaeological structure and the undisturbed subsoil. Fireplaces, hearths or kilns may produce stronger anomalies (e.g. up to 100 nT) for strongly magnetized pottery kilns due to thermoremanence. The iron compounds initially present in the clay used for the construction of the kiln have randomly oriented magnetic domains, producing little net effect. With burning, demagnetization occurs at the Curie point and on cooling the iron oxides in the baked clay are remagnetized, ending up in a permanent magnetization aligned with the geomagnetic field at the time of the firing. Stones and soils can also acquire a thermoremanent magnetization if their magnetic mineral content is reasonably high and the net effect has not been randomized by later disturbances.

Remanent magnetization is just one source of the magnetic detectability of archaeological features. The other is the effect of induced magnetization due to magnetically susceptible materials. It was first shown by Le Borgne (1955, 1965) that topsoils have higher magnetic susceptibility than subsoils, and that on archaeological sites susceptibility is markedly enhanced. The susceptibility of soils is dependent on the content of iron compounds, mainly ferrimagnetic magnetite (Fe_3O_4), maghaemite (γ-Fe_2O_3) and haematite (α-Fe_2O_3). Based on Le Borgne's work and further investigations by Mullins (1974) and Graham et al. (1976), the hypothesis was introduced to archaeological literature that enhanced susceptibility on anthropogenic-influenced soils is mainly due to firing and subsequent conversion of weakly magnetic haematite by reduction to magnetite and following oxidation to maghaemite. Another incompletely explained theory suggests an influence of fermentation processes on the conversion of weak to stronger magnetic minerals subsequently dispersed on the topsoil of archaeological sites. Thus, as any archaeological structure once dug into the subsoil is normally refilled with topsoil of higher magnetic susceptibility it produces an induced positive magnetic signal. On the other hand, any structures made from weakly or non-magnetic material, such as walls, floors, streets or roads, situated in high susceptibility topsoils, are detectable as slight negative anomalies.

Surveying Early and Middle Neolithic sites in Bavaria and Austria on low susceptibility loessic soils showed the traces of wooden palisades and even single postholes with intensities of 0.1–0.3 nT; anomalies only prospectable with the highest resolution magnetometers. Investigating excavated structures showed ferrimagnetic iron compounds, especially magnetite of small grain size and of biogenic origin (Fassbinder et al. 1990; Fassbinder and Stanjek 1993). As shown by Fassbinder, these are fossils of magnetotactic bacteria in different states of preservation (Fassbinder 1994). These magnetotactic bacteria are thought to find their environment during the decay of materials (e.g. wood), thus after marking the former posts with magnetic crystals once intracellularly aligned in chains, forming the so-called magnetosomes used by the bacteria for orientation in the Earth's magnetic field. These crystals, mainly magnetite, are of very high susceptibility, especially as very small grains have only one magnetic domain. Such single-domain magnetite may be the most important source for the enhanced magnetization of the traces of wooden posts or beams. Dispersion of these grains may be the source of the enhanced susceptibility of the archaeological site itself (Fassbinder and Stanjek 1996).

Magnetic prospecting

Preliminary work in the 1980s using portable proton-magnetometers on sites that were mainly situated in loess with low susceptibilities (about $20 \cdot 10^{-5}$ SI) showed that sensitivities of 1 nT and a spatial resolution of 1 m is suitable for producing a magnetic overview of a site (Becker 1979; Neubauer 1990). Nevertheless, excavations of prospected sites showed that it is not possible to detect small features with weak anomalies (0.1–0.5 nT) as these are masked by the traces of wooden palisades or postholes using such instrumentation (Trnka 1991). Because of the rapid and extensive destruction of the sites, commonly covering many hectares, both apparatus and techniques had to be developed so that precise high-resolution measurements could be carried out in an appropriate timescale. Austrian archaeology took the chance to utilize the high sensitivity of the first portable caesium gradiometer delivered in Europe, formerly used for locating a new magnetic observatory (Melichar 1990). Similar optically pumped alkali vapour magnetometers (Scollar et al. 1990) at the Bayerisches Landesamt für Denkmalpflege at Munich showed the necessity of automated wheeled devices for prospecting the Middle European archaeological remains (Becker 1996a).

The Archeo Prospections magnetic scanning systems developed and used in Austria for more than 10 years are mounted on two completely non-magnetic wooden handcarts (Neubauer 1990; Neubauer et al. 1996). The latest caesium magnetometer system (MEP7xx series developed by Picodas), in use since 1997 and originally designed for aeromagnetics, was specially modified for archaeological purposes (Neubauer et al. 2001). The main cart (Fig. 2) carries the caesium sensors which are fixed for gradiometer array at different heights (e.g. 0.5 and 3.0 m) above the surface. To compensate for the Earth magnetic field's time-dependent variations, which may be several nT per minute, the difference in the magnetic

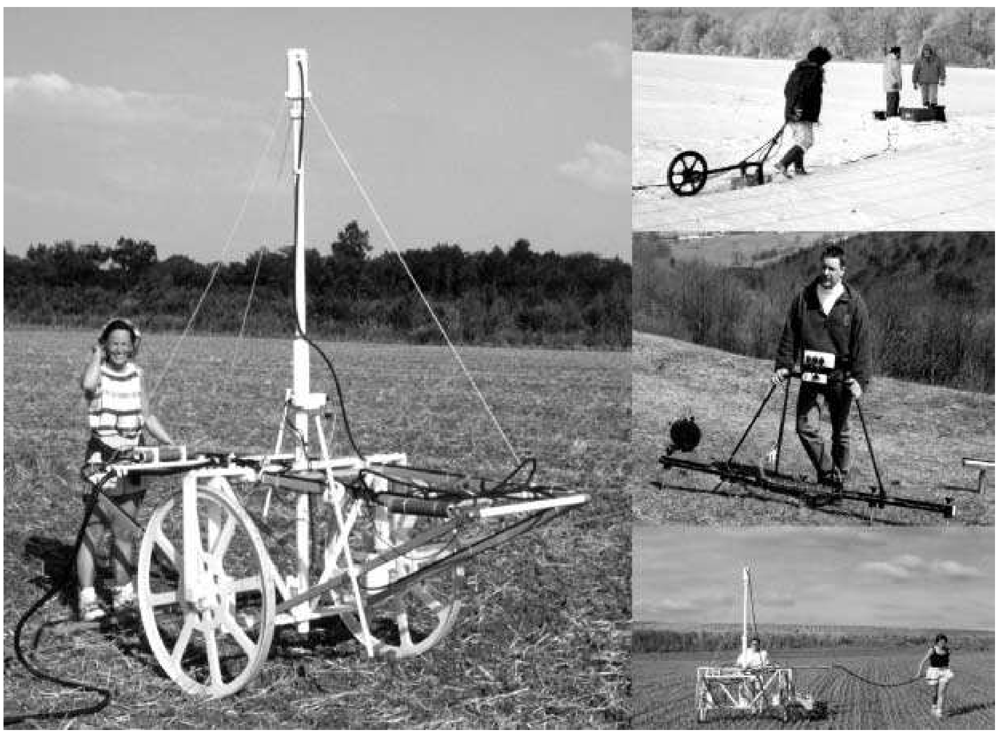


Fig. 2 *Left, bottom right* Archeo Prospections multisensor caesium gradiometer developed for archaeological prospection with 1 pico Tesla sensitivity. Three or four sensors may be used in parallel mounted in the wheel's axis 0.5 m apart at constant sensor height above surface; thus the changing of the cart's balance during driving has no effect on the sensor position. A telescope pole in the centre allows variable gradiometer arrays by positioning the reference sensor up to 3 m above ground. *Top right* Ground-penetrating radar device used for archaeological prospection in winter 1998 in the Roman town Carnuntum. The transmitting and the receiving antennae are mounted in the wooden sledge and are pulled along the surface. The wheel behind is used for distance measuring. *Middle right* RM15 resistivity meter in multiprobe array as used for archaeological prospection

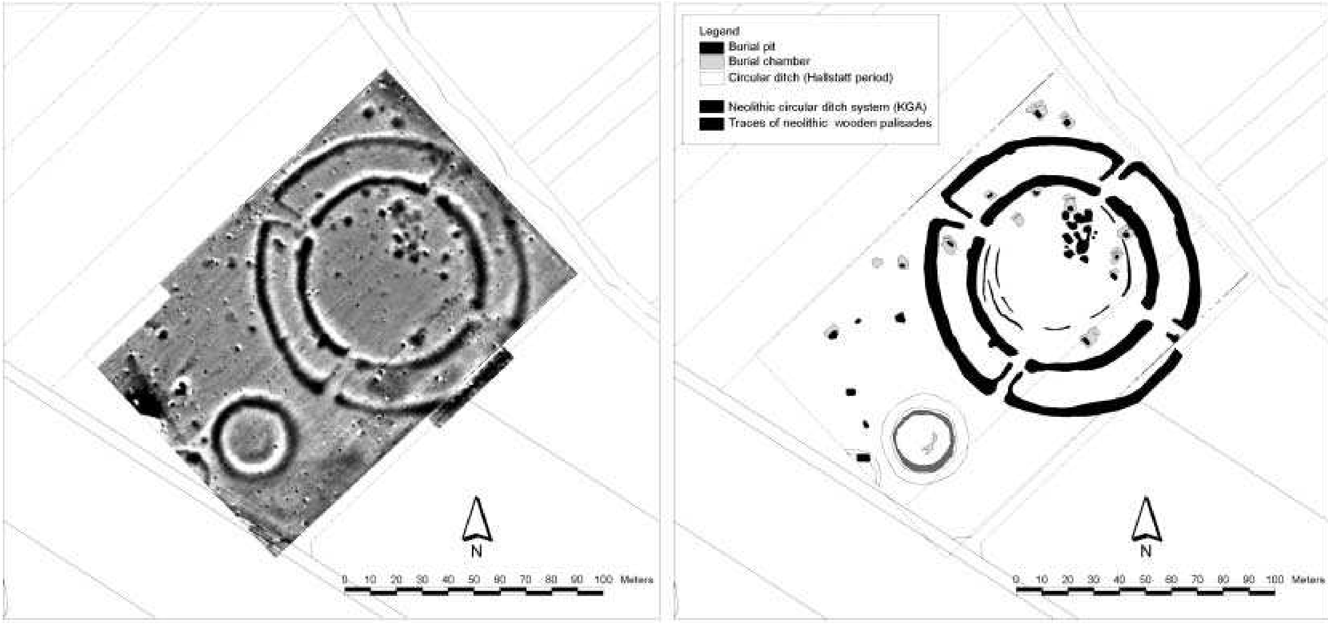


Fig. 3 Magnetogram and archaeological interpretation map of the multiphase site at Kleinrötz, Lower Austria. The double ditch system is dated to the Middle Neolithic (4800–4500 BC) and shows traces of three concentric wooden palisades in the interior. The small circular ditch once enclosed a burial dated by surface finds to the Hallstatt period (800–600 BC). The burial was protected by a mound which has already been completely destroyed by ploughing. The early Iron Age cemetery was discovered by the magnetic survey as the Middle Neolithic circular ditch system was detected by aerial archaeology

field's total intensity between the two sensor positions (e.g. 2.5 m gradient) is measured with a sensitivity of 0.001 nT at a sampling rate of 0.1 s. As the magnetic signal decreases by the third power of distance, the lower sensors register a stronger signal from near-surface archaeological structures than the reference sensor above. One of the wheels is used for optoelectronic distance measuring. All parts of the sensor cart are constructed of either plastic or wood and special care has to be taken with regard to possible magnetic contamination of personnel due to zippers, rivets, jewellery, watches, belts, bras, credit cards or even a cigarette lighter in the pocket. Each operator has to be tested to ensure an undisturbed survey because even invisible wire netting inside the plastic soles of boots may produce inevitable anomalies up to 3 nT. The sensor-carrying cart is connected to the processing unit, the data-recording unit and the power supply carried by the second cart 20–30 m away. The binary data files store the various data channels (sensor readouts, distance pulses and time) in 0.1 s units each representing one measured rectangle. For further processing, the binary data files stored in time mode are resampled on a regular grid of 0.125×0.5 m, ultra-high resolution in geophysical terms. The resulting binary data files of the single rectangles are assembled using an image composer developed for caesium magnetometry (Neubauer et al. 1996). During data processing, automatic data correction such as despiking, correction of subgrid or line shifts is optionally applied (Eder-Hinterleitner et al. 1996b). The data are interpolated on to a regular grid of 0.125 m and converted into a 256-level greyscale image for display on high-resolution screens. The produced digital image representation or magnetogram is displayed using standard image processing software on a laptop in the field straight after finishing the survey. This kind of non-standard data representation in geophysical terms provides an easy and comprehensive reception of contrasting physical properties of the subsurface, making archaeological sites such as Kleinrötz visible (Fig. 3).

The site north of Vienna was discovered by aerial archaeology and is a so-called Kreisgrabenanlage (KGA), one of the oldest known Middle European monumental sites. The nature of the Middle Neolithic KGA phenomenon is still under discussion by archaeologists, palaeoastronomers and the prospectors involved. KGAs generally consist of more or less concentric circular ditches with at least two entrances, implying a communal area isolated inside wooden palisades. They have no obvious defensive function and some meeting-place or ritual role is likely (Petrasch 1990; Trnka 1991; Becker 1996c; Podborský 1999), but it is still too early for a serious hypothesis on the KGA phenomenon. Magnetic prospecting is one of the most important methods for collecting more facts on the KGA (Becker 1990b; Melichar and Neubauer 1993; Neubauer et al. 1997). The magnetogram of Kleinrötz (Fig. 3) reveals the monument in all its details. The double-ditch system measures 105 m in diameter with four entrances, and two or three concentric traces of wooden palisades are visible. The ditches are 5 m wide and, as known from similar excavated monuments, V-shaped up to 4 m deep. Near this monument a smaller circular structure 35 m in diameter was detected, belonging to an Early Iron Age (Hallstatt period) burial.

The deceased was buried in a chamber surrounded by stones and covered by a mound with a circular bordering ditch. As the once impressing burial mound is flattened by agricultural use and has disappeared from the surface, the last remains of the cemetery are still visible in the magnetogram: another burial mound surrounded by a ditch lies nearby and dug-in rectangular chambers with burials can be made out all over the site (Fig. 3).

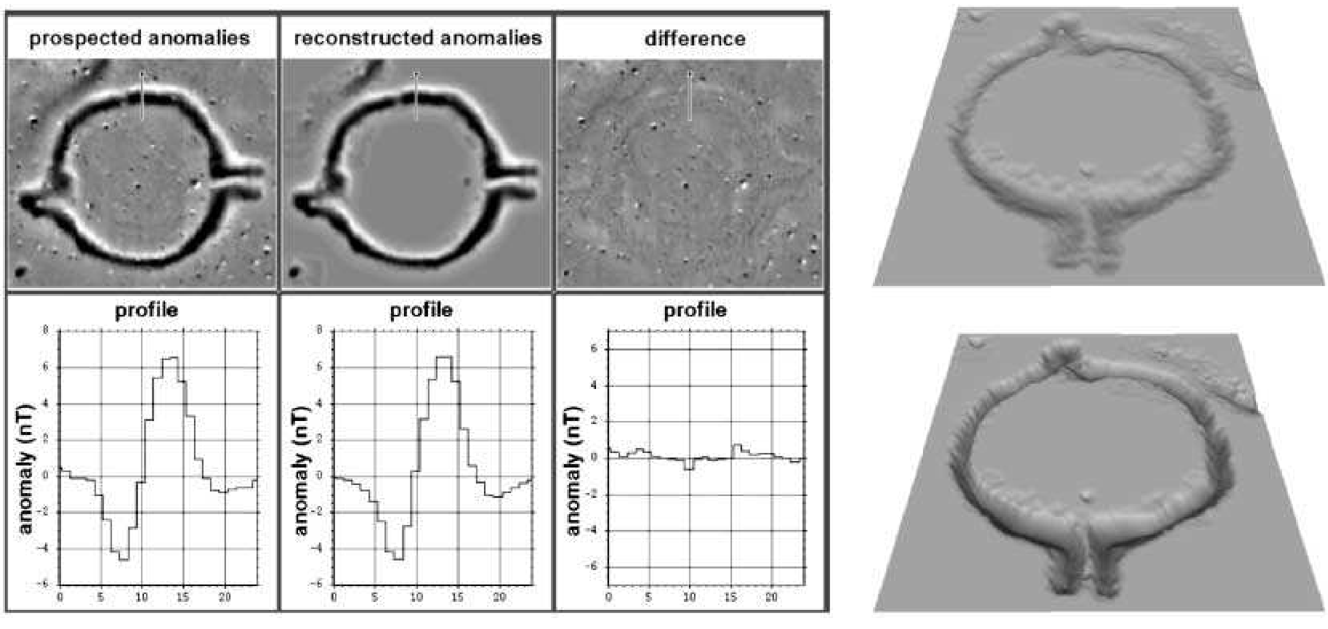
3D-magnetic modelling and reconstruction

The monument at Schletz (Fig. 4), known by aerial archaeology, is another KGA with only one single ditch. Two excavation campaigns in 1985 and 1986 dated this monument to the Early Middle Neolithic (MBK Ia; 4930–4470 BC) but could not determine the exact shape of the monument nor the number of entrances (Trnka 1991). Only magnetic prospection carried out 10 years later was able to answer these questions. Magnetic prospection of such a KGA or of any other archaeological ditch produces not only evidence on the shape and the width of the ditches but can also be used to estimate their depth. An automatic reconstruction of this depth information for the whole prospected area in a high spatial resolution of at least 0.5 m in the horizontal plane and 0.1 m in the vertical could be used for detailed interpretation as well as for comprehensive 3D visualizations (Neubauer and Eder-Hinterleitner 1997). For reconstructing ditches, a magnetic subsurface model has to be built, corresponding to the measured magnetic anomalies.

The developed method (Eder-Hinterleitner et al. 1996a) inverts the idea of simulating magnetic anomalies caused by archaeological structures of arbitrary shape by a three-dimensional array of dipole sources (Scollar 1969). The subsurface is magnetically modelled by various types of homogeneous dipole sources of equal size arranged in a 3D regular grid. The different types of dipoles represent the different magnetic properties of the layers forming the archaeological structure and the undisturbed subsoil. The problem of reconstruction is to determine the distribution of the various dipole sources of the subsurface model to minimize the differences between the modelled magnetic anomalies and the measured data. This optimization problem is solved using an iterative random search algorithm called leaped annealing (Eder-Hinterleitner 1994), derived from simulated annealing (Kirkpatrick et al. 1983; Romeo and Santigiovanni-Vincentelli 1991). Although the optimization problem has a huge solution space, leaped annealing is fast enough to find good solutions using the computational power of conventional workstations within a few hours by dividing the problem into subproblems which are solved in parallel.

After magnetic prospecting of the Schletz KGA in 1995, a reconstruction with a simple four-layer magnetic subsurface model was derived (Eder-Hinterleitner and Neubauer 2001). Each dipole source represents a cube of 0.5 m and has specific magnetic susceptibility according to the four layers (topsoil, subsoil, topsoil over ditch,

Fig. 4 The magnetogram of the site at Schletz, Lower Austria, shows a single circular ditch 44 m in diameter and with two entrances. The entrances, two 14 m long earthen bridges, are formed by the ditch, turning at a right angle at this point. In the interior a palisade and a row of single postholes arranged concentrically are detectable. The inner palisade encloses an area of 550 m^2. The monument is dated to the Middle Neolithic (4800–4500 BC) has already suffered massive destruction by erosion and by the consolidation of farmland some years ago. *Left* Comparison of the anomalies reconstructed by magnetic modelling and the prospected anomalies. *Right* 3D visualization of the ditch interface reconstructed by magnetic modelling. *Top* The situation without the high susceptibility top layer. This might have been the stage of refilling in the Bronze Age (about 2000–1500 BC) as indicated by finds. *At the bottom,* the ditch without the filling as it might have looked in the Neolithic



ditch-filling) each assumed to be homogeneous. The whole subsurface beneath the prospected area is modelled with these dipole sources. Although the filling of the ditch shows remanent magnetization, only induced magnetism is considered in the model. It is assumed that the field vector of the ditch anomaly has the same direction as the field vector of the Earth's magnetic field and therefore the remanent magnetization of the ditch is modelled by a higher magnetic susceptibility. The reconstruction method starts with a classification of the preprocessed data. The probability for each data value to actually originate from modern sources, such as ferrous litter on the surface, is computed and integrated into the optimization problem. This classification is necessary, because these disturbing anomalies may be much stronger than the anomalies of the archaeologically relevant structures. Data points with probabilities of 1, e.g. marking iron litter, are not considered for modelling. The first step in reconstruction is used to determine the course of the ditch and a rough estimation of its depth. Preliminary information about the expected shape can be integrated during the second step when the structures detected in the first step and a modelling of the expected typical V-shape of the ditch section are used to reconstruct the position, depth and shape on a increased depth resolution of 0.1 m.

Because there were no magnetic analyses of the sediments carried out in the prior excavations at Schletz, their magnetic properties had to be estimated. The result of the first reconstruction was already useful but still not completely satisfactory. The reconstructed depth at the location of the excavation in 1986 was not deep enough while other locations were reconstructed unrealistically deep. The conclusion was that the magnetic properties of the several layers of the ditch filling varied very strongly due to the complicated refilling processes and that the simple model that we used was not realistic enough for the whole monument. More information about the magnetic properties of the ditch filling had to be included and therefore we decided to carry out another excavation to get samples of the filling. Susceptibility measurements and sediment analysis of the uncovered layers of the filling showed the clayey uppermost layer to be the main magnetic structure, accumulated by eroded Neolithic topsoil washed into the final slight depression of the already almost refilled ditch. The thickness and the magnetization of the upper magnetic layer, strongly influenced by the refilling process of the ditch in the past and by the present state of preservation of the monument, is decisive for the strength of the magnetic anomaly due to its higher magnetization and its shorter distance to the measuring sensors.

To modify the subsurface model, a new ditch filling layer with high magnetic susceptibility is added which can vary in thickness independently of the depth of the reconstructed ditch. For the new model, again built with dipole sources, the ditch filling was split into two different layers; the lower magnetic layer with a low and constant magnetic susceptibility and the upper magnetic layer with a higher magnetic susceptibility. Thus the modelled susceptibility of the upper magnetic layer is not constant. It is actually modelled by giving the layer a maximum possible depth and a minimum susceptibility. The susceptibility of the upper magnetic layer is then increased by twice as much again within the thickness of the layer. This model is able to adapt to different refilling and preservation conditions occurring in a circular ditch on hilly topography. The resulting optimized subsurface model is used for 2D and 3D visualization of the ditch, representing the reconstructed interface between ditch filling and subsoil (Fig. 4). The reconstructed ditches can be intersected with the digital terrain model and mapped including the reconstruction of palisades based on excavation results. An animation of this scenario provides new and spectacular insights into a KGA (Doneus and Neubauer 1997; Doneus et al. 1997) and might be a helpful tool in exploring the monument. The visualization of the upper layer represents the state of the monument before final refilling by slow erosive processes. As the interface marking these two sediment zones is archaeologically relevant, its three-dimensional visualization is of archaeological interest. The reconstructed thickness of the upper layer may also be an indicator for the state of preservation of the monument (Eder-Hinterleitner and Neubauer 2001).

Electrical properties of archaeological structures

Electrical locating of archaeological structures is mainly done by mapping contrasts in apparent resistivity of the subsurface (Clark 1990). The electrical conductivity or its inverse the resistivity of the ground is electrolytic, based on the displacement of ions in interstitial water. It is therefore dependent on the presence of water and dissolved salts. Being dependent on the mobility of ions, their size, soil porosity and temperature are equally of paramount importance. As a consequence, climatic factors, especially rainfall and temperature, play a fundamental role for variation of the resistivity of the uppermost soil layers (Scollar et al. 1990). The apparent resis-tivities of a specific volume of various soil and rock materials show large differences and variations. Clayey or humic layers are normally of low resistivity (10–100 Ωm) whereas stones, sand or gravel show high resistivities of 100–1,000 Ωm. Because of corresponding contrasts, resistivity measurements are an important tool for locating stony archaeological structures as walls, floors or roads as well as refilled ditches or pits dug into bedrock. Weak contrasts are developed by pits or ditches dug into loess or sand and refilled with similar materials and these are normally not prospectable by resistivity mapping.

Resistivity mapping

For resistivity mapping, electrodes or probes have to be inserted a few centimeters into the ground and the appar-

Fig. 5 Aerial photograph (Freigabenr. 13088/15-1.4-99) of the civil town of the Roman Carnuntum combined with the digital image representations of the resistivity mapping (*left*) and the magnetic surveys (*right*) outlining the town's layout. The large building complex visible in the resistivity mapping could be identified as to be the southern part of the forum sought for over 100 years and discovered by prospection in 1996. The monumental buildings are facing to the open square of the forum. The already excavated monumental bath visible in the aerial photograph is situated north of the forum

ent resistivity of a specific subsurface volume is measured. To overcome the contact resistance, four electrode configurations are in use (Scollar 1959; Atkinson 1963; Scollar et al. 1990). An alternating current is passed through two electrodes (C_1, C_2) and the resulting potential gradient in the ground is sampled between two others (P_1, P_2). The apparent resistance, the ratio of applied current and measured potential difference, is normally measured in a 0.5- or 1-m grid with various electrode configurations (Wenner, Double Dipole, Square) and with different instrumentation. Specially developed systems for archaeological applications are the RM15 resistivity meters from Geoscan (Fig. 2) working with a twin electrode configuration (Clark 1990). Two pairs (C, P) of current and potential electrodes are separated at least 30 times their individual spacing of 0.5 or 1 m. As one of the two pairs is placed in fixed position, the other pair, mounted on a frame, is moved over the grid. The depth of investigation depends on the probes' separation, thus enlarging the inter-probe separation gives higher penetration depth. The systems are fully automated and connected to a data-logger. Specific multiplexers allow switching of multi-probe arrays on the frame for speeding up the survey and working with different penetration depths at the same time (Walker 2000).

A typical application, resistivity surveying at Carnuntum, a well-known Roman town east of Vienna, yielded a detailed insight into the town's layout (Fig. 5) (Neubauer and Eder-Hinterleitner 1998). The street plan is irregular, forming blocks of various shapes and sizes. A main street enters the town from the south after passing one of the town's gates. The various blocks, or insulae, are divided by streets and pathways. They show different states of preservation. An extremely large building complex giving onto an open square dominates the digital image. Its dimensions and the symmetrical layout indicate that it is a typical communal building of the civil town. The square is 50 m wide, the full length is still unknown but 45 m is already uncovered. This insula with the open square might end in front of the main road, the 'decumanus maximus' opposite the already excavated monumental bath. The eastern and western sides of the open square are formed by halls. The now recovered square with monumental buildings to the north and the south might be the 'forum' so far undiscovered and sought for over 100 years. It was further investigated by a detailed ground-penetrating radar survey (Neubauer et al. 1998).

Ground-penetrating radar survey

The ground-penetrating radar (GPR) method is based on the transmission of high-frequency (100–1,000 MHz) electromagnetic radio pulses into the ground (Lorra 1996; Conyers and Goodman 1997). A pulse of radar energy is transmitted from an antenna placed on the ground. On its way through the subsurface, portions of the resulting wave of electromagnetic energy are reflected by layer interfaces, buried bodies or objects, while the rest is propagating downward. By measuring the time elapsed between transmission, reflection and reception back at a receiving radar antenna on the surface, the shape of interfaces and the location of buried archaeological structures can be surveyed. The propagation velocity of radar waves in the ground and the reflectivity depend on various factors, the most important being the electrical properties of the materials passed through. Reflections occur at interfaces of archaeological structures or layers with contrasting physical properties and are recorded as the two-way travel time and the amplitude and wavelength of the reflected radar waves derived from the transmitted pulses. The data are normally collected in 0.05 m steps along lines separated by 0.5 m or less and

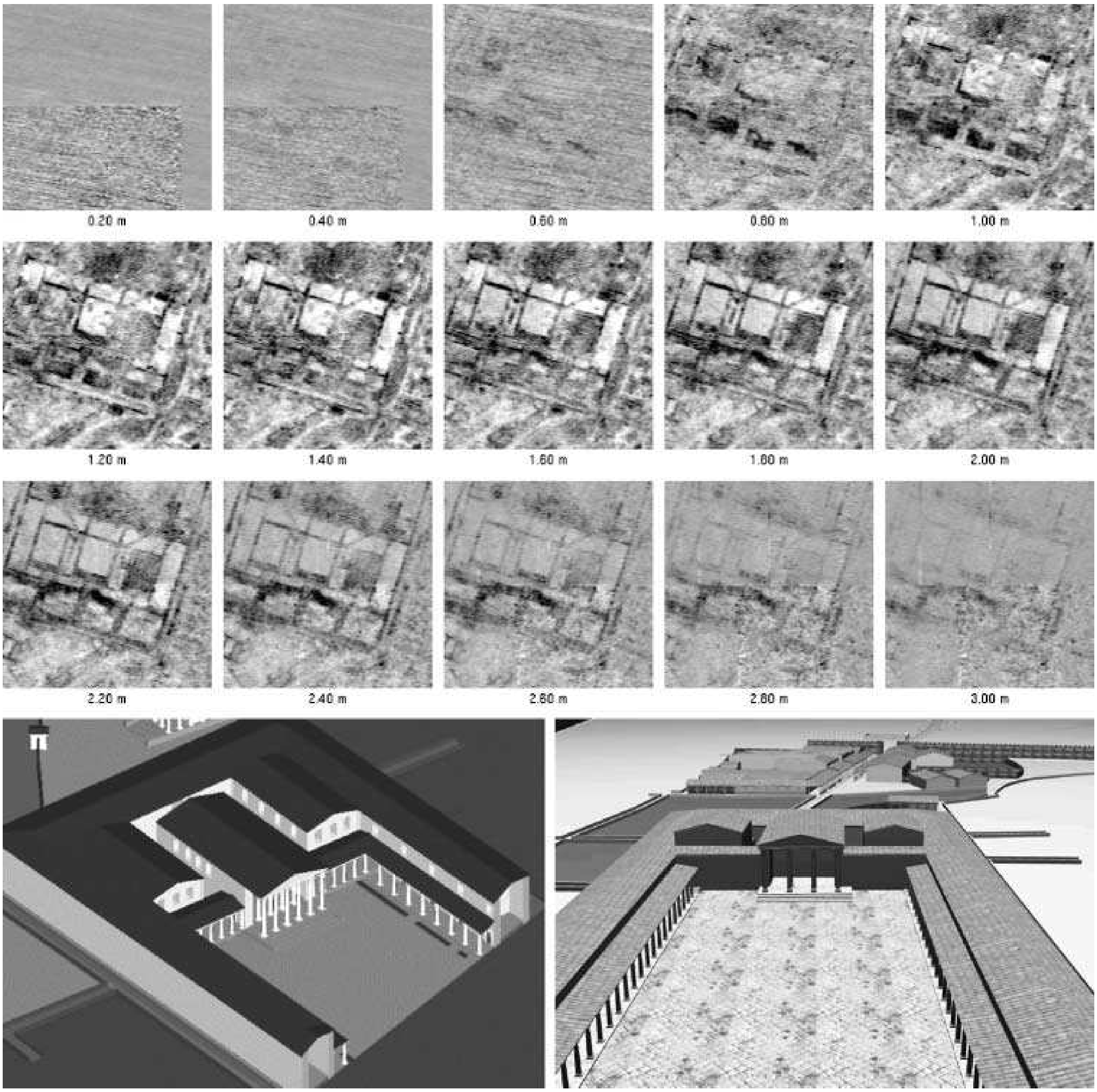


Fig. 6 *Top* Depth slices of the ground-penetrating radar data of the southern part of the forum of the civil town of Carnuntum. The images show the summarized amplitudinal information of the reflected radar waves for slices 20 cm thick. *Bottom* Virtual reconstruction of the forum and the so far prospected part of the civil town based on the archaeological interpretation of the combined prospection data

recorded on a laptop field computer as the sender and receiver antennas are being pulled along the surface (Fig. 2). Thus two-dimensional vertical radar sections are collected, which are arranged in a 3D-data block for further processing and visualization.

The monumental building complex at the forum of Carnuntum was surveyed using a 450-MHz antenna, which was a good compromise as spatial resolution was about 10 cm and investigation depth was 2–3 m, both depending mainly on the wavelength (Neubauer et al. 1998). For visualization of GPR reflection data we used horizontal time-slices (Goodman et al. 1995; Malagodi et al. 1996; Nishimura and Goodman 2000). Such a time-slice is created by summarizing (or averaging) the reflected energy of the radar waves over a time window at any discrete reading of the measurement grid. The 3D-data block of summarized amplitudes thus created can be sliced in horizontal, vertical or any desired direction and thickness. The slices are processed and visualized as digital images representing amplitude anomaly maps used for subsequent archaeological interpretation. If the propagation velocity of the radar wave is known, the measured reflection time is used to derive depth. The sequence of amplitude anomaly maps outlines the location and the three-dimensional shape of the archaeological structures in the subsurface (Fig. 6). For easier understanding of the information content of the data block, the series of images can be animated or viewed using virtual reality techniques.

Considering the results of the GPR survey, the large building complex with symmetrical layout covering an area of over 3,000 m^2 with walls of up to 1.5 m thickness gives the possibility to deduce a 3D interpretation model (Fig. 6). The northern part of the building could be reached from the lower open square of the forum by a monumental staircase and shows three large halls of 150 m^2. One of these halls has an 'apsis', the corresponding room to the east is equipped with hypocausts, probably being the 'curia', the meeting hall of the city council. In the southern part small rooms partly constructed with cellars are flanked by corridors. These were reached by two staircases and a 'porticus' from the south. The halls lining the forum with a porticus each, presumably housed shops (tabernae) with cellars. Below the floor level of the building two channels/drains leading to the river Danube were traced. Beside these important features, information about depth of foundations, filling layers and plastering, as well as the height of the remaining walls and the position of wall debris and the penetration depth of modern ploughs, could be documented and used for virtual reconstruction of the prospected part of the Roman town (Fig. 6). Further prospection of the civil town as well as the analysis of the town's layout in comparison with excavated structures from similar sites will certainly recover more hitherto unknown details.

Conclusions and outlook

Since magnetics, resistivity mapping and GPR are based on different physical properties, they provide complementary information on the archaeological structures. An integrated prospection approach combining various methods will overcome the limitations of the individual methods and will produce relevant results in most archaeological contexts. A resistivity survey, as at Carnuntum, points out walls or floors, and in general any stony features. An additional magnetic survey adds important information on pits, ditches, wooden structures, robbed out walls, walls built of bricks, tiles from roofs or on hypocausts, the typical Roman floor heating. GPR surveys provide high-resolution depth information and the main stratification. To visualize the information contents of various surveys in one single image the respective images are mathematically combined (Neubauer and Eder-Hinterleitner 1998). Digital image combination facilitates correlation of the various data sets and offers new insights for the interpretation process. The combination of geophysical data with results from aerial archaeology will provide detailed geophysical windows within an aerial overview of the whole site and the landscape (Figs. 1, 5), thus giving a comprehensive impression of a monument (Becker 1990a, 1996b; Doneus and Neubauer 1998). The combined images can reveal new clues to a site's interpretation. With the overview and detailed information at hand, the site is more easily understandable and contexts become clearer.

The various methods of visualization and data treatment aim to present the raw data in various images ready for archaeological interpretation. Any image might be seen as a georeferenced informative layer bearing geographical and archaeological information. By interactively outlining the archaeologically relevant anomalies using GIS technology, archaeologists are provided with an accurate map (Fig. 3) of the respective site (Neubauer et al. 1996; Gaffney et al. 2000). The archaeological structures are drawn on different thematic layers and each feature is described in an attributable database, allowing further archaeological analysis, such as intrasite spatial analysis. Archaeological interpretation in terms of detecting, precise mapping and describing archaeologically relevant features is a dynamic process based on mental comparison of the detected features with known structures driven by archaeological feedback.

To document the rapid destruction of the various archaeological sites detected by aerial archaeology, periodic geophysical remeasurements are planned. Non-invasive repeated surveys and inverse modelling permit estimation of the threat of destruction and the time left to undertake archaeological rescue excavations, to document at least the better preserved areas. Excavations are always coupled with an irreversible destruction of the investigated archaeological structure. It is also the most expensive method for evaluation of archaeological data. Therefore it is necessary to try to build and appropriately visualize a model of a monument including all relevant and known information prior to any excavation. However, the development and use of the best and most sensitive instruments for geophysical prospection is of little use when the methods of interpretation are not fully developed (Scollar 1969). The rapid development of computer hardware and software brings the possibility of 3D visualization and interpretation of aerial evidence closer. Geophysical prospection data offer the possibility of reconstruction by inverse modelling. There is still a lot of work to be done developing archaeological interpretation tools based on GIS technology for exploiting all the details provided by prospection. The interpretation of archaeological prospection data in its best sense must be seen as a dynamic process and, in contrast to excavation, is a repeatable and non-destructive evaluation of archaeological information. These buried remains comprise the library of the unwritten history of mankind. But, as already pointed out, one book after another is in danger of being lost. The rapid and efficient prospection methods presented so far would be able to document at least some examples. However, the final decisions in archaeological research policy regarding a wider application of high-resolution geophysical prospection to document threatened monuments still have to be made. It is hoped this will happen before it is too late for the majority of our unique Middle European archaeological sites.

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