Chapter 23

Applications of Ground-Penetrating Radar, Magnetic and Electrical Mapping, and Electromagnetic Induction Methods in Archaeological Investigations

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Introduction

The Geophysical Service of the Archaeological Division of the State Antiquities Department in Baden-Wuerttemberg, Germany, employs various geophysical methods for surveying archaeological sites: magnetic mapping, electrical mapping, electromagnetic induction (EMI), and ground-penetrating radar (GPR). These techniques are used not only for preparation of excavations but also, and mainly, for the documentation of sites, which, hopefully, will remain untouched and thus be preserved for the future.

In 10 years of experience on more than 480 field campaigns in rural settings, the magnetic method is the one most frequently used. Also, it is the only method not prohibitively affected by weather conditions. The magnetic maps thereby produced help the archaeologist organize his excavation in advance and therefore save time and money. In cases where contrasts in the magnetic properties of the soil and the embedded archaeological structures are small, electrical mapping methods can, in many cases, provide a logical and viable alternative to magnetic mapping; despite the fact that this method can be extremely sensitive to changes in humidity and soil moisture content. Because of the very shallow depth of most archaeological investigations, mostly not more than 0.5 m, electrical contrasts often disappear within two hours of a rainfall event. In urban areas, EMI and GPR are the methods generally selected to detect and map subsurface historical structures, although the two methods are also suitable for investigations in rural areas.

In practice one is often confronted with the limitations of a specific method and site-specific constraints. This problem is frequently solved by combining different methods. Moreover, this combination, particularly when the methods are complementary, often provides more and better information on the archaeological features than would be attainable if only one method were used.

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Equipment, Methods, and Field Procedures

Magnetic mapping

Magnetic surveys are conducted using a Geoscan FM36 fluxgate gradiometer. Sample and traverse intervals of 0.25 m are used during magnetic surveys to achieve better and more unique results for small spatial-extent anomalies. Surveying one 20- × 5-m grid (1600 readings) takes about 10 to 15 minutes time, depending on the quality and smoothness of the soil-surface (grass, or freshly plowed soil).

Electrical mapping

The Geoscan RM15 resistivity system, with a pole-pole array, is mainly used for electrical mapping. With this array, taking measurements is much easier and more effective than it is, for example, using a Wenner array. This is especially the case at sites with “hard” ground conditions, which slow down electric mapping, especially when operating with Wenner arrays. The sample and traverse interval is chosen to be 0.5 m. Two experimental investigations at different places with sample and traverse intervals of 0.25 m did not significantly improve the subsurface definition. On the other hand, intervals of 1.0 m or greater are in most cases not suitable for archaeological mapping. A current of 1 mA is sufficient for electrical mapping with electrode intervals of the order of 0.5 m. Under normal conditions, surveying one 20- × 20-m grid (1600 readings) takes about 70 minutes. The same grid can take as long as two hours on hard ground conditions, especially in semi-arid areas.

Electromagnetic induction

The Geonic EM38 is used for most of the EMI studies, and the results presented here are achieved with this instrument. It is possible to operate with the EM38 in two modes: horizontal and vertical dipole orientations, with depth of penetration being approximately 0.75 and 1.50 m, respectively. The best results are obtained using the horizontal mode. With the EM38 the conductivity and the susceptibility of the soil can be estimated. Generally, surveys with the EM38 indicate that there is a good correlation between successful magnetic and successful electromagnetic investigations. A correlation between unsuccessful magnetic mapping but successful electric mapping and successful electromagnetic mapping, however, seems to be poor. A sample and traverse interval of about 0.50 m with the EM38, produces good results for most archaeological studies. One 20- × 20-m grid (1600 readings) can be mapped in 20 minutes under good ground conditions (grass, smooth plains).

Ground-penetrating radar

In all of our GPR studies to date, the SIR-2 system from GSSI was used with antennas with center frequencies of 200, 500, 900, and 1500 MHz. Initially, GPR profiling was conducted using profile intervals of about 1 m, as suggested in the literature (for example Mellett, 1995). It soon became clear that this interval was too large to obtain good results in archaeological mapping, so the distance between adjacent profiles was reduced to 0.5 m. Moreover, on testing the GPR system in the center of a town, it was noted that the quality of GPR surveys can be significantly enhanced if an orthogonal arrangement of the profiles is used. The use of a survey wheel is obligatory to be able to carry out profiling with high positioning accuracy.

Data processing

GPR data are processed using the program REFLEX (Sandmeier, 2002). In most cases little processing is required. GPR profiles are generally corrected for time zero drift. After background removal, the data sets are migrated using the velocity derived from diffraction hyperbolas. If necessary, static correction is applied to the processed profiles. Finally, time slices are calculated.

The data from magnetic, electrical, and EMI surveys are processed by a custom package for processing and digital image manipulation. The routines in this package are based mainly on routines published in various digital image-processing handbooks (Russ, 1998; Klette and Zamperoni, 1992). Several specific operations on the data, such as cubic spline interpolations, are made using Mathematica 4.1 for Linux (Wolfram, 1999).

Cubic spline interpolations also can be essential in adaptation and adjustment of adjacent data sets to each other. Each data set consists of 1600 values; recorded, for example, by electrical mapping, within 60 to 75 minutes. In some areas, this period of time can be long enough for significant, nonlinear changes in the humidity in the ground. This in turn means that adjacent grids do not fit together without doing this kind of adjustment.

Choosing the best method(s)

To be able to work as effectively as possible, it is advisable to visit the area to be investigated prior to any mapping or profiling and to obtain information not only on the geology, but also on the historical and present land use. For example, gathering such information as whether remains of metallic objects in the soil are to be expected, which can complicate magnetic mapping. Moreover, it is important to acquire any information on the kind of archaeological structures that might be expected beneath the soil surface. In most cases, it is possible to estimate whether magnetic contrasts are large enough for effective magnetic mapping, or whether electrical mapping is preferable.

If GPR is considered, one should have information on the kind and size of the archaeological structure expected, in order to use the most suitable antenna. Based on field walking or surface surveys, archaeologists can often provide this sort of information. In cases where such information is lacking, it was found that profiling with 500-MHz and with 200-MHz antennas is sufficient in most cases.

Experience has shown that archaeological structures made from wood are best investigated with magnetic surveys. With electric methods as well with GPR there are not sufficient contrasts between any kind of soil and the remains of wooden structures. Trenches, however, are best detected in magnetic and electrical surveys. In most cases, it is difficult to get any positive results for these structures with GPR. However, if the soil is frozen, these structures appear in the results of GPR profiling very clearly.

If no information at all can be provided by archaeologists, magnetic mapping is the preferred method with which to begin geophysical investigations. If these results are poor, GPR or electrical mapping would be the next choice.

Field Examples

Magnetic mapping and GPR profiling of a Roman fort

The Roman fort Rainau-Buch, Germany, is an archaeological treasure that must be preserved. Because of this, extensive geophysical investigations were undertaken for a thorough documentation of this fort and of the Roman village next to it. In the aerial photograph shown in Figure 1, only the main building of this fort is visible from the air. The existence and location of this building was already known approximately from excavations done by the Limes Commission in the end of the 19th century (Herzog, 1898). The building was constructed of sandstone, with the surrounding soil being sandy clay. GPR profiling was employed using antenna frequency of 500 MHz. To provide

Figure 1. Roman fort Rainau-Buch, Germany. (A) indicates the main building of the fort, the only archaeological structure which can be seen from the air.

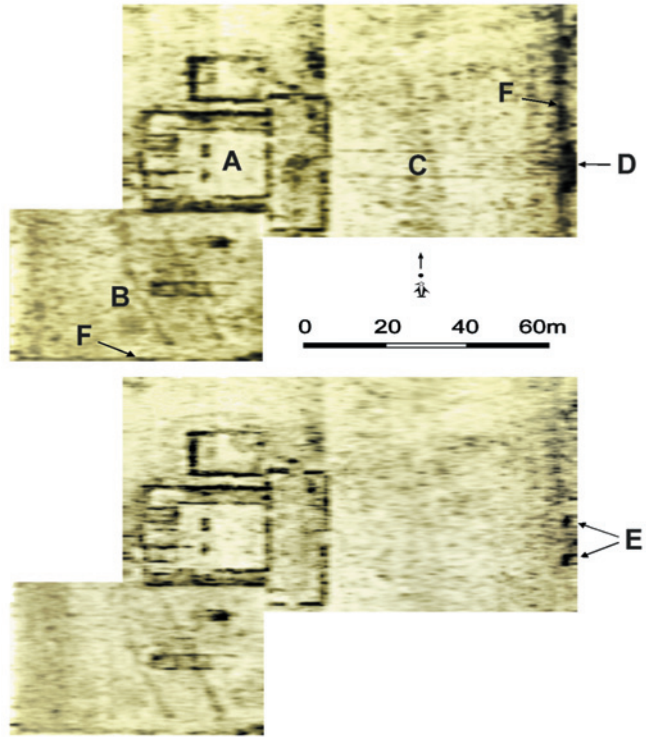

Figure 2. Results of a GPR survey of a Roman military building. Top: Structures in a depth of about 0.30 m; bottom: Structures in a depth of about 0.50 m.

detailed horizontal resolution of the subsurface structures, 0.05 m to 0.50 m steps were used for the survey. Near-surface velocities were calculated from several different hyperbolic events in the GPR record, with mean value of 0.08 m/ns. Two time slices, corresponding to a depth of about 0.30 m (Figure 2, top) and of about 0.50 m, respectively (Figure 2, bottom), contain the ground-plan of the main building (A) and of another building (B) to the south of it. Moreover, the limits to the main road (C) within the fort are visible. This road connects the main entrance (D) with the great hall of the main building. As far as the GPR measurements are concerned, there seem to be no archaeological structures next to this road, except the foundations of two towers (E) next to the main entrance and one side of the road (F), which runs around the inner side of the fort.

Using magnetic mapping, with a sample and traverse interval of about 0.25 m, various structures within the Roman fort and parts of the Roman village can be detected (Figure 3). Small, bright, more or less round, linear-oriented anomalies can be seen in the northern small building (A), next to the main building (B). These magnetic anomalies are typical for wooden pillar bases. The bright magnetic anomalies, covering the floor of the northern rooms (C) of the main building, indicate the location of fired clay-tiles. In addition to the structures recorded by GPR, nearly all other anomalies within the fort are wooden barracks (D), which consist of single rooms of about 4.5 × 5 m, with fireplaces in each room. The fort was surrounded with four trenches (E), which display an unusual form in front of the main entrance (F). GPR profiling of these trenches (Figure 4) was done in winter at about –5°C air temperature. The uppermost part of the soil was frozen. After two days of rain and a temperature increase to +6°C, a repetition of the GPR survey on the same site no longer indicated the trench. A repetition of this survey on the same place no longer indicated any trench.

In Figure 3, streets (G), houses (H) and cellars (J) (only some of which are labeled in this figure for reasons of clarity) are obviously not arranged in a rectangle, which would be typical for Roman construction, but in a circuit around the fort. The more or less parallel anomalies (K) mark structures that are typical for field systems of the medieval period. Finally, two parallel lines (L) in the map suggest that magnetic mapping has detected the main road to the fort.

Numerical combination of magnetic, electrical, and EMI data: The Hethitic town of Kerkenes

The Hethitic town Kerkenes is situated near Yozgat, Central Anatolia, Turkey. Known to the scientific world since the beginning of the 20th century, it is now subject to intensive archaeological investigations. The magnetic survey referred to in this section was designed and inaugurated by Dr. Lewis Somers, Geoscan Research, USA. He used sample intervals of 0.5 m and traverse intervals of 1.0 m.

In 2001 experimental field work took place, carrying out electrical and EMI mapping of selected places, using sample and traverse intervals of 0.5 m. The results discussed here are of an area of 100 × 100 m. Its location is marked (A) in Figure 5. In the background, remains of the city wall are marked (B). Kerkenes Mountain is a granitic batholyth, and the houses are built mainly of this material.

The results of magnetic, EMI, and electrical mapping are presented in Figure 6a-c, with different numerical combinations shown in Figure 6d-f. A 20- × 20-m grid is copied into each subfigure to make it easier to compare to one another the distinctive structures which the various methods produced. The magnetic map clearly delineates rectangular structures that belong to several houses of the Hethitic town. For reasons of clarity, only one house, consisting of several rooms, is marked (A) in Figure 6a. Anomalies at (B) indicate significant influence of the geology and (C) specifies a waterhole. The magnetic map gives a good impression on the city map of Kerkenes, although in some areas the influence of geological structures is strong.

Before proceeding with the mapping shown in Figure 6b some testing was done using EM38 at various sites within the Kerkenes town. Contrary to the findings of Clark (1996), for work in semiarid areas, who found that the EM38 gave the best results working in a vertical mode,

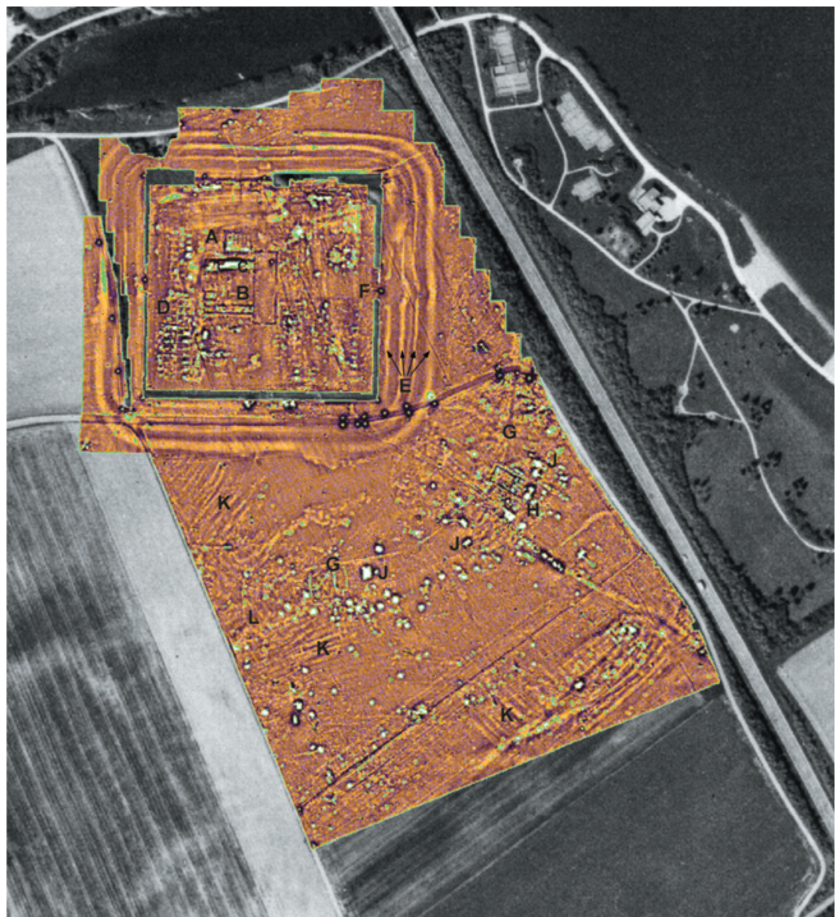

Figure 3. Magnetic map of the complete Roman fort Rainau-Buch and of a part of the Roman village surrounding the fort. Traverse and sample intervals were 0.25 m.

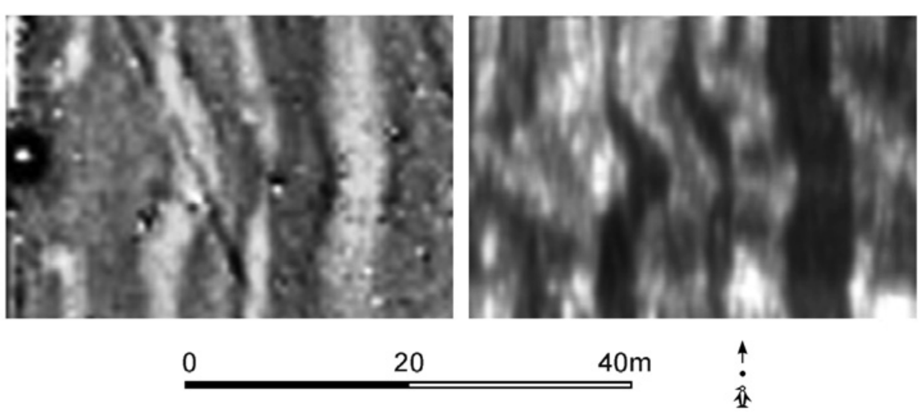

Figure 4. Comparison between the magnetic map (left) and GPR profiling (right) of a small area next to the main entrance. The depth of this time slice is about 0.5 m.

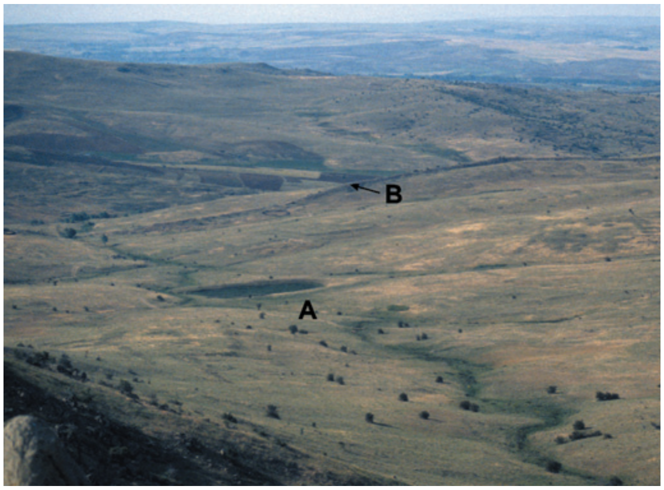

Figure 5. Kerkenes Dag, Turkey. (A) indicates the position of geophysical investigations; (B) one part of the ancient town wall.

it was found at Kerkenes that the opposite was the case. Archaeological structures were best delineated operating in a horizontal mode, which means that the depth of mapping was limited to about 0.75 m. Compared with the magnetic map the buildings are more clearly defined, especially in the southern part of the mapped area. On the other hand, some archaeological structures (D) that the magnetic map shows remain invisible for the EM38. One reason for this discrepancy might be that additional materials and not just granite were used to build the houses (Summers, pers. communication 2001). Thus, different temperatures would have been reached when the houses burned down.

Archaeological features are most clearly delineated with electrical mapping (Figure 6c). A track (E), often used by a Landrover is visible in this map because of the compression of the topsoil. An area of high humidity (F) due to a small river results in a reduction of contrasts in resistivity. Compared to magnetic and EMI mapping, houses,

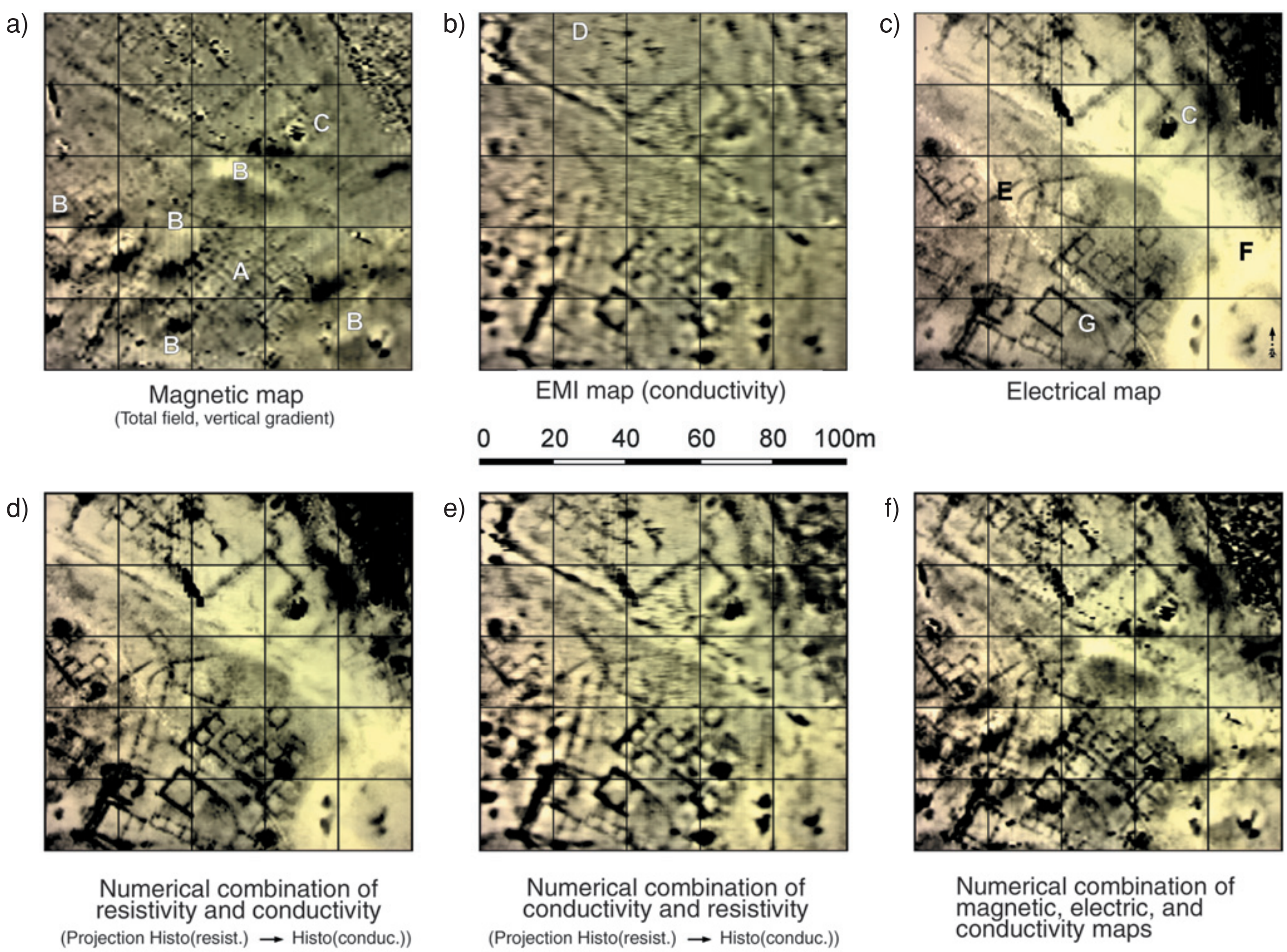

Figure 6. (a): Magnetic map (total field, vertical gradient), (b): EMI map (conductivity), (c): Electrical map, and numerical combinations of them (d-f) demonstrate digital enhancements of archaeological structures.

streets, water-channels and floors (G) are well defined in this map. The feature (C) marks a waterhole and the dark area next to it specifies an area where the bedrock reaches the depth of mapping and the surface. Comparing the same areas in magnetic, electric and EMI maps (Figure 6a-c) it can be seen that anomalies are present in each of these maps or at least in one of them [for example (D)]. To overcome the individual limits of magnetic, electrical, and EMI mapping, we tried a numeric combination of these maps. All the data are normalized and gaussian fits to the three histograms were computed. The resistivity data set was transformed to fit the histogram of the conductivity data set. The two normalized data sets were then multiplied with each other. The result of this transformation is presented in Figure 6d. As a result, archaeological features are enhanced to a certain extent and the disturbing, unwanted influence of the wet area is slightly reduced. If the conductivity data set is transformed so that the distribution of the data fits the histogram of the resistivity data set and a multiplication is performed once more on these two data sets, the result, as shown in Figure 6e, is a map on which the influence of the wet area is reduced to a minimum. For a combination of the results of all three methods, weighting factors were introduced because of the significant influence of the underlying geology, especially on the magnetic data. For this representation it was found that a weighting factor of 0.2 for the magnetic data gives the best result (Figure 6f). If this magnetic weighting factor is reduced, there will be no significant influence of the magnetic data on the final result, as far as archaeological features are concerned.

Conclusions

The combination of suitable geophysical methods can provide the archaeological community with very detailed information on the man-made structures beneath the soil, especially for documentation of nonthreatened archaeological structures, which should remain untouched and thus be preserved for the future. The decision as to which geophysical methods are most effective depends on the site itself, and on the kinds of structures that are expected (remains of walls, trenches, wooden structures, etc.). If no information is available, magnetic mapping should be the first choice. If these results are poor, electrical mapping or GPR profiling should be considered. Magnetic mapping is good for wooden structures, trenches, and also for stones, if there is a magnetic contrast between the stone of an archaeological structure and the soil in which it is embedded (limestone in a calcareous area wouldn't work). Electrical mapping is the preferred method if stone structures are to be investigated, and good results are also achieved for trenches. Wooden structures are invisible for electrical mapping as well as for GPR profiling. GPR is excellent for stone and can achieve good results when profiling for trenches in good conditions. Trenches are best seen by GPR if the top soil is frozen. Moreover GPR is the best choice for work in urban situations and for the localization of cavities. EMI is good for stone containing magnetic components and for burnt features (fired tiles, hypocaust, etc.) and can be good for trenches if the contrast in susceptibility of the material in the trench differs significantly from the soil. But EM38 is not suitable for small archaeological artifacts because of it's low spatial resolution.

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References

Clark, A., 1996, Seeing beneath the soil. Prospecting methods in archaeology: Reprinted by Routledge, 2000.

Herzog, R., 1898, Das Kastell Buch: Der Obergermanisch-raetische Limes des Roemerreiches, *im* Auftrage der Reichs-Limes-Kommission, O. Von Sarwey, E. Fabricius, and F. Hettner, eds., Verlag Otto Petters, **67**, 1–16

Klette, R., and P. Zamperoni, 1992, Handbuch der Operatoren für die Bildverarbeitung: Vieweg.

Mellett, J. S., 1995, Ground penetrating radar applications in engineering, environmental management, and geology: Journal of Applied Geophysics, **33**, 157–166.

Russ, J. C., 1998, The image processing handbook: CRC Press.

Sandmeier, K. J., 2002, REFLEXW, Version 2.5. Windows 9x/2000/NT-program for the processing of seismic, accoustic or electromagnetic reflection, refraction and transmission data: Instruction manual.

Wolfram, S., 1999, Mathematica: A system for doing mathematics by computer: Cambridge University Press.