Archaeological prospecting – state of the art
A literature review

Kjell Persson

Archaeological Research Laboratory, Stockholm University, SE-106 91 Stockholm, Sweden (kjell.persson@arklab.su.se)

This work comprises a literature review of geophysical and geochemical prospecting in archaeology and focuses on phosphate analysis, EM measurements with slingram devices, resistivity mapping, Ground Penetrating Radar and magnetometric surveys. A literature study resulted in 89 papers, which have been clustered structurally on the basis of the prospecting methods and types of archaeological features considered.

Keywords: geophysical, geochemical, prospecting, magnetometer, radar, electromagnetic

Background

Urban and regional planning for changed or extended land-use sometimes comes into conflict with legal or ethical restrictions concerning the protection of archaeological remains. Permission for moving or destroying such remains after scientific excavation and documentation can be given if needed for progress in society, but the law concerning ancient remains in Sweden forces contractors to add an archaeological excavation budget to the total construction budget and vast sums are invested annually in rescue excavations. Traditional archaeological excavations are expensive and time-consuming, and society can gain a lot by including non-destructive geophysical and geochemical prospecting in the planning in order to detect invisible subsurface archaeological structures. Geochemical and geophysical prospecting techniques are aimed in the first place at finding places with anomalous chemical and physical soil properties. Then, since some anomalies are caused by human activities and some by natural geological variations, it is important to gather detailed information on the local bedrock and soil properties in order to differentiate between the two. The anthropogenic anomalies can sometimes be of lower amplitude than the natural ones and only the geometry and exposure can adequately recognize them. Seasonal variations in some parameters must also be considered, and the study of historical maps can be used to differentiate between recent or historical features and archaeological features. The resulting surveys can give guidance for carefully targeted, limited excavations, which can provide as much and sometimes even more information than traditional test trenches and at a lower cost. Geophysical and geochemical methods have developed a great deal recently and automatic sampling in digital form has dramatically increased sampling density and accuracy, especially in geophysical surveys.

Objectives

The main objective of this literature review is to summarize and analyse the present state of the art with regard to the applications of geophysical and geochemical methods to archaeological investigations, in order to reach a recommendation for the optimal combination of methods to be used in Swedish archaeology.

A comprehensive literature search was made covering a number of global literature and journal databases:
- GeoRef 1785–2002 (American Geological Institute)
- GEOBASE™ 1980–2002 (Elsevier Science Ltd)
- GeoArchive 1974–2002 (Geosystems)
- Pascal 1973–2002 (INIST/CNRS)
- SciSearch 1990–2002 (Inst for Sci Info)

- Ei Compendex 1970–2002 (Engineering Info. Inc)
- NTIS 1964–2002 (US Dept. of Com.)
- INSPEC 1983–2002 (Institution of Electrical Engineers)
- Enviroline® 1975–2002 (CIS Inc.)

The following search keywords were used in various combinations: archaeology / geology / geophysical / geochemical / electromagnetic / slingram / metal detector / VLF / GPR / Ground Penetrating Radar / magnetometer / magnetic / gradiometer / cemetery / grave / burial / settlement / artifact / phosphate / phosphorus.

To keep the number of references at a reasonable level, some methods had to be excluded.

The search resulted in 166 references, some of which were not relevant, while others, such as papers about resistivity methods in archaeology, were added in the course of this work, so that the final reference list consisted of 89 items.

Methods

All kinds of land use have an impact on soil properties such as bulk density, weathering, particle redistribution and magnetic, electric and chemical properties. Activities such as firing, drainage, ploughing, digging, manuring, cultivation and grassing can be traced by means of geophysical and geochemical explorations.

The most common geochemical method in archaeology is:
- Soil phosphate analysis

while the geophysical methods available are:
- electric (resistivity, SP, IP)
- magnetic (magnetometer, gradiometer)
- electromagnetic (EM, GPR)
- aerial photo and thermal infrared imagery
- gravimetric
- acoustic (reflection and refraction seismic)

This work has been limited to methods applicable to site prospecting: Ground Penetrating Radar (GPR), resistivity, magnetometer/gradiometer, EM measurements (electric and magnetic components) and phosphate mapping.

Resistivity

Resistivity mapping as a geophysical method has been known since the early twentieth century. It was already being used by Richard Atkinson as an archaeological prospecting method in 1946 and is the most common

electrical surveying method employed in archaeology (Atkinson 1946, 1952, 1953, 1963).

Resistance is given by Ohm's law, R= V/I, where R is the resistance in ohms, V is the potential difference in volts and I is the electric current in amperes. Resistivity, or specific resistance, as a material property, is expressed in ohm-metres (Ω-m). In a resistivity survey an electric current is generated between two current electrodes in the ground and the resulting potential difference is measured between two potential electrodes. By varying the distance between the electrodes and moving the midpoint of the electrode configuration, variations in ground resistivity are obtained that can be mapped horizontally and vertically, whereupon deviations from an expected homogeneous material can provide information on subsurface inhomogeneities (Clark 1990; Kearey & Brooks 1984).

Variations in resistivity and the extent and geometry of anomalies can be used to deduce the possible presence of archaeological structures such as cultural layers, stone walls, ditches, graves etc, provided the natural variations are known.

Recent developments include multi-electrode systems with a large number of electrodes attached to long prefabricated cables (50–100 m). A control unit alternately chooses which are current and which are potential electrodes according to a specific schedule, which gives greater variation in electrode distances and hence variations in depth and accuracy. Resistivity data can be modelled and presented as 2 D resistivity transects or, if parallel lines are used, in 3 D resistivity models of the ground using a method called resistivity tomography (Dahlin 2001b).

Conductivity

EM measurement with slingram devices uses a transmitting coil to induce a current in the ground. The primary electromagnetic field together with induced secondary fields in the ground then induce currents in a receiving coil and any disturbance of the primary field can be used to calculate either the electrical conductivity or the magnetic susceptibility of the soil, which makes the slingram a two-in-one instrument. Soil water content and conductive metals are the principal factors influencing conductivity and iron/magnetite content that influencing magnetic susceptibility. The reciprocal of resistivity is conductivity, measured in milli-siemens per metre, mS/m. The magnetic component is recorded as ppt (parts per thousand) for the ratio of the secondary to the primary magnetic field. It can then be used to calculate the magnetic sus-

ceptibility, the unit of which is κ, a dimensionless material property (Clark 1990).

Electrical conductivity surveys make it possible to detect the extent of cultural layers and the presence of metals and of linear structures such as roads, walls and ditches. The magnetic component can detect iron objects and magnetic minerals such as magnetite, and it can therefore be useful for identifying stonewalls and hearths.

Magnetometry

All material is magnetic at the atomic level, because of the spinning of electrons in orbits around the atomic nucleus. There are different forms of magnetism depending on whether the magnetic fields of the electrons coincide or oppose each other. Maximum reinforcement of the magnetic fields occurs in ferromagnetic materials such as iron, cobalt and nickel, and once acquired, the magnetization is permanent or remanent, while anti-ferromagnetic materials have magnetic fields in opposite directions that completely balance each other out, so that no magnetization is recordable. Ferrimagnetic materials, such as magnetite and maghaemite, are slightly less magnetic than ferromagnetic material because of some opposing fields, and they have some permanent magnetization, although it is greatly increased by an external magnetizing field (Clark 1990; Kearey & Brooks 1984).

Magnetic minerals received their magnetization when the magma cooled to below the Curie point for iron (approximately 700°C) and they picked up the alignment of the current earth's magnetic field at the time of cooling. The particles have since been redistributed by weathering and erosion, however, so that different particles in the soil may have random magnetic alignments, which often balance out each other. Firing directly on the ground is an efficient way of achieving magnetic enhancement, because the weakly magnetic iron oxide haematite is converted to the more magnetic oxide magnetite. When heated to above the Curie point, all oxides become demagnetized, but the minerals will be remagnetized when the soil subsequently cools, and will assume the same magnetic alignment as the current terrestrial magnetic field. The magnetic fields of the individual particles will then coincide and the place can be recorded by means of magnetic mapping (Clark 1990).

GPR

A radar control unit sends out electromagnetic pulses into the ground using a transmitting antenna and measures the time required for the reflected waves to reach a receiving antenna. The frequency is proportional to the inverse of the wavelength, and a low frequency means low resolution, although depth penetration will increase. The electromagnetic wave will reflect and refract when it reaches a new layer with different physical properties. The amplitudes of the reflected waves can give information on the properties of the bordering zone. The attenuation of the radar wave is related to the conductivity of the ground. When the GPR antennae are moved along the survey lines, the reflected signals can be plotted as functions of travel time and the distance moved. The variations in the reflected signals that can be seen in the radar profiles can then be evaluated in order to distinguish between natural geological variations and artefacts. Computer modelling programs can interpolate between parallel profiles and produce 3D models of the ground (Conyers & Goodman 1997).

Acoustic methods

Seismic refraction methods are seldom used in archaeological prospecting, since they work best for mapping undisturbed horizontal layers that have velocities that increase with depth and are difficult to use in cases of human cultural disturbance. Some seismic refraction results have been reported recently, however (Karastathis et al. 2001)

Seismic reflection methods (e.g. sonar methods) are often used in marine prospecting to detect shipwrecks buried in sediment (Edgerton 1972) and they can also be used to detect cavities in homogeneous rock masses (Dolphin 1981).

Phosphate analysis

Soil phosphate mapping is the most widely used chemical method involved in archaeological site prospecting, because phosphate is so readily fixed to soil particles after the decomposition of organic material. Other nutrients are more easily leached and are therefore not suitable. Most organic material contains phosphorus, and when a body or plant dies and decomposes, the dissolved phosphates will become fixed to soil particles and increase the soil phosphate content at that point, which can be traced by phosphate mapping up to thousands of years later. Archaeological features such as waste deposits, dung heaps, stables, graves and settlement shorelines can be detected in this way (O. Arrhenius 1931, 1935, 1950; Bethell & Màté 1989), and phosphate analysis has also been used to

detect the walls dividing rooms and to deduce the functions of rooms (Middleton & Price 1996).

Intra-site analysis of phosphate in combination with other chemical compounds using ICP (inductively coupled plasma) spectrometry has been successfully employed in a soil sample classification context to distinguish between natural and anthropogenic soils (Linderholm & Lundberg 1994).

Research history

Geophysical prospecting in archaeology was mentioned as early as 1895, by an English officer, Lieutenant-General August Pitt Rivers, who used a hammer to sound for subsurface features (Pitt Rivers 1898). Aerial photography similarly began to be used as an archaeological tool in England, when Lieutenant P. H. Sharpe took a photo of Stonehenge from a balloon in 1906, and continued with photographs taken from aeroplanes by O.G.S. Crawford (1928a, 1928b).

An equipotential method (similar to resistivity) was developed by the Swedish geophysicist Hans Lundberg, who together with Helmut de Terra detected the remains of a very early human skeleton, Tepexpan Man, in a survey in Mexico in 1947 (De Terra 1947).

Electrical resistivity measurements were developed for archaeological purposes by Richard Atkinson in the late 1940's (Atkinson 1946, 1952, 1953, 1963). It was already known in the nineteenth century that burned clay was weakly magnetic, and magnetic mapping with a magnetometer was used for the first time to locate buried kilns in the 1950's (Aitken et al. 1958).

Measurements of ground electrical conductivity with a slingram were developed in Sweden in the 1940's for mineral prospecting. The method uses the induction of currents in the ground without electrodes and is hence a non-destructive method that is well suited for archaeological purposes (Frohlich & Lancaster 1986; Deletie et al. 1988; Persson 1998).

Radar systems were developed during the 1930's for military use, and the first ground penetrating radar surveys were performed to measure the depth of glaciers. After almost thirty years, in the late1950's, the method also came into use for mapping subsoil structures and features, and the system became commercially available and was used in archaeology in the 1970's (Bevan & Kenyon 1975).

The use of geophysical methods in archaeological fieldwork is certainly increasing. First of all, they provide a non-destructive, fast and cost-effective means of choosing the optimal location for excavation in order to obtain maximal information on earlier land use. These methods have also developed greatly in recent times due to computer and software development, and it is now possible to present both two and three-dimensional models of the results graphically at high degrees of accuracy, which improves interpretation.

Geochemical prospecting with phosphate analysis for archaeological purposes was already reported in 1911 (Russell 1957) but was first described and systematically used to locate prehistoric settlements by Olof Arrhenius (1931). In the late 1930's Walter Lorch used a field spot test method to reconstruct settlement geography over large areas and to differentiate types of settlements by reference to the patterns of phosphate anomalies (Lorch 1940), and some work was done on a smaller scale in the 1950's to examine soil silhouettes at burial sites (Solecki 1951; Johnson 1956; Biek 1957). In the 1960's Cook and Heizer tried to quantify the amounts of phosphates present in order to draw conclusions about settlements, and they also maintained that phosphate should not be considered in isolation from other aspects of the environmental depositions (Cook & Heizer 1965). Lorch's spot test was further developed by Gundlach (1961), and the first step towards integrating phosphate mapping with other forms of analysis for the planning of an excavation was made in Britain by Paul Craddock (1984), who also used phosphate analysis as an interpretation tool at excavated features. In Norway, Donald Provan (1973) used phosphate in multi-element analysis to detect anthropogenic changes in the soil. Tests also showed that phosphate enrichments could be used to detect totally decomposed bodies (Barker et al. 1975; Hudson 1974), and in North America phosphate analysis, together with magnesium and calcium, was used along with magnetometric mapping at Munsungun Lake in Maine (Konrad et al. 1983). In Sweden Birgit Arrhenius (1990) used phosphate analysis together with trace element analysis, and an improved field test kit was developed in Stockholm in the 1990's that used standardized test strips, which are possible to combine with other test strips for multi-element field analysis (Persson 1996, 1997). Intra-site prospecting by means of multi-element analysis has been used recently to detect the dividing walls of rooms, for instance, and to deduce room functions (Linderholm & Lundberg 1994; Middleton & Price 1996; Isaksson 2000).

Discussion

Altogether 28 papers out of the 89 considered in this investigation were about GPR surveys, 13 about resis-

tivity, 14 about magnetometry, 31 about phosphate mapping and 12 about EM measurements with slingram devices. There was also a literature review (Wynn 1986) and a bibliography (De Vore 2004). Altogether 46 papers reported on the use of multi-method surveys (Table 1).

Sixteen papers reported on the combined use of two geophysical properties. Among others:

Pattantyus described geophysical results obtained in Hungary for archaeological purposes using magnetic and electric methods, leading to the discovery of medieval houses, the ruins of a Roman brick building and pits of a Copper Age settlement by magnetic methods, for instance. He also defined the plan of a Roman fortress and the exact location of a 50.000-year-old flint mine by means of resistivity surveys. A 3D model of mine trenches constructed from these surveys proved to correspond very well to the shape of the trench as excavated later (Pattantyus 1986).

Bruce Bevan described two techniques for locating unmarked graves when all known grave markers have been lost. All the sites considered were in U.S.A. and not older than the 17th century. He found GPR to be especially suitable, on account of its capability for estimating the depth and shape of buried objects. Soil conductivity surveys performed using electromagnetic induction methods were also able to detect disturbed soil in the graves (Bevan 1991).

Rinita Dalan used two instruments, Geonics EM-31 and EM-38, to locate and define a number of buried archaeological features at the Cahokia Mounds State Historic Site in Illinois, U.S.A. She detected a wooden stockage (the Central Palisade), delineated a number of levelled earthen mounds and succeeded in mapping a broad, flat area, known as the Central Plaza. She emphasizes the usefulness of EM surveys to detect terrain modified by earth-moving (Dalan 1991).

Ladefoged, McLachlan, Ross, Sheppard and Sutton used GIS to display, analyse and interpret geophysical data from conductivity and magnetic susceptibility surveys conducted with a Geonics EM-38 instrument at two sites in northern New Zealand, one a pre-European Maori fortification and the other a late nineteenth-century European fortification (Ladefoged et al. 1995).

Thomas Sträng used a combination of magnetic and resistivity surveys in his exploration of the fortress of Lindholmen in Scania, Sweden. He was able to detect the central tower, one gate tower and the inner wall by magnetic mapping, and the magnetic measurements also made it possible to determine the depth of a wall. His calculations were confirmed by the later excavations. He also used a multi-electrode system for resistivity profiling and was able to detect the extent of the northern wall (Sträng 1995).

Dabas, Camerlynck and Freixas used GPR and resistivity measurements to map the floor of the cathedral of Girona in northern Spain. An electrostatic quadrupole was towed continuously to produce a resistivity map that showed anomalies corresponding to known graves and one obvious anomaly that appeared to relate to foundations of former buildings. A set of parallel 450-MHz GPR profiles were used to produce time slices. One time slice at a depth of 0.9 m showed anomalies corresponding to the resistivity anomalies. Their conclusion is that the combination of two physical properties improved the confidence of the deduction that a previous building was located on the site of the present cathedral in Girona (Dabas et al. 2000).

Susanne Lorra, Stefan Kroll and Dirk Thomsen of the University of Kiel used magnetic mapping and a GPR survey in attempts to detect unknown archaeological remains and guide an ongoing excavation project at the Uppåkra site in Scania, Sweden.

Magnetic mapping with a gradiometer was used to detect a recent metal cable, crop marks and some dipole anomalies arising from metal finds or hearths. The result of the magnetic mapping was then used to guide the choice of areas for a GPR survey. 120 MHz and 500 MHz antennas were used to produce 3D time slices by interpolating between parallel profiles, which makes it possible to show structures at different depths in a top view.

In one area a linear, right-

Table 1. Review of methods and combinations of methods.

Method	Number of papers
GPR	28
Resistivity	13
Equipotential	1
Magnetometry	14
Phosphate	31
EM measurements	12
Combination of two geophysical methods	16
Combination of three or more geophysical methods	10
Combination of phosphate analysis and one or more geophysical methods	6
Multichemical analysis	14

angled structure was detected at a depth of 1.3–1.5 m. After every area the authors present an exemplary list of the most obvious anomalies with alternative interpretations, and they finally recommend a grid size of not larger than 0.4 × 0.1 m for magnetic mapping and a frequency of 100–300 MHz for GPR surveys, with 0.5 m between the profiles for 3D mapping purposes (Lorra et al. 2001).

Katarina Frost, Kristina Jonsson and Kjell Persson described the use of a Geonics EM-38 instrument and GPR to detect subsurface structures in the kitchen garden of Strömsholm Castle, Middle Sweden. The use of GPR on clay has often been discussed and questioned, and this survey was performed during a very hot, dry summer on postglacial clay, giving a penetration of 4 metres with a 250 MHz antenna, whereas the slingram measurement did not detect as many contrasts as expected because of the low water content. The slingram was able to detect possible stone-filled ditches as the water inlet and outlet of a dam, and also some larger structures most probably showing the extent of the former garden. The radar anomalies coincided well with gravel paths in an old map of the baroque garden and were subsequently confirmed by excavation (Frost & Jonsson 2002).

Ten papers report the use of three or more geophysical properties. Among others:

Arlsan et al. (1999) used magnetic, electrical and GPR methods in S. Agata at the northern end of Lake Como in Northern Italy and excavated the sites of significant anomalies given by two or three of these geophysical methods. A deposit of large pebbles was interpreted as having been caused by the development of fluvial channels between Roman and Low-Medieval times, while a structure detected under fluvial deposits by all three methods proved to be a large medieval edifice, identified as the church of S. Stefano, which was abandoned in 1444. The church was built on an older structure, an apse with a single aisle, interpreted as an early Christian church.

David Nobes (1999) used a combination of electromagnetic, magnetometric and GPR techniques to survey a Maori family burial site at Oaru Urupa, New Zealand. The location of some older graves was not known, sometimes through loss of the marker stones and sometimes through absence of any oral record. The knowledge that Maori graves traditionally faced east made it possible to identify anomalies despite the disturbing presence of metal fencing. EM in-phase response, magnetic gradient and GPR proved to be a useful combination. It was noted, however, that 450 MHz antennae gave limited depth penetration in the

GPR survey, so that signal ringing was obtained only in the surface clay. The 200 MHz antennae also gave signal ringing, but anomalous features could be detected below.

Altogether the methods enabled unmarked graves to be located, using marked graves for calibration. The locations were consistent with elements of the oral history of the site.

Domenico Patella and Paolo Mauriello (1999) used gravity, magnetic, self-potential (SP), electrical and magnetotelluric methods to map the Mount Vesuvius area in Italy. The gravity survey results were used to produce a 3D tomographic image, the magnetic result from an aeromagnetic survey together with results from drilling to model the inside of Mount Vesuvius, a seismic NW-SE profile together with data on 40 local earthquakes to produce a 2D tomographic model, the SP results to produce horizontal 2D slices, dipole-dipole geo-electric profiling to produce a N–S and a W–E vertical 2D tomographic image over Vesuvius and magnetotelluric profiling to produce a 11 km N–S 2D profile and a 5 km W–E 2D profile.

Finally they performed a risk analysis using all the data to model a pyroclastic flow simulating the eruptive scenario of Vesuvius according to its internal structure and dynamics. As a result, they suggest the placement of artificial barriers close to the eruptive vent to guide the pyroclastic flow away from the cultural heritage. Their conclusion is that integrated geophysical surveying and modelling can contribute to the protection of historical structures in active volcanic areas.

Sambuelli et al. (1999) conducted a multi-method geophysical survey at a Roman archaeological site in the S. Secondo valley between Dorzano and Salussola in Biella, Italy, where test excavations had previously discovered the apse of a church. Magnetic gradient measurements were able to detect an area with interesting anomalies, and resistivity tomography and GPR profiles were then run along selected lines to examine the vertical distribution of the anomalous bodies. They mention especially the 500 MHz GPR survey processed in time slices as having given good results. The whole structure of the apse was clearly outlined.

Persson and Olofsson (2004) describe the use of electromagnetic, magnetic and GPR methods to detect the inner structures of two burial mounds in Old Uppsala, Sweden. Some anomalies in the Eastern Mound were recorded using a combination of methods, with slingram (EM 31 and EM 38), GPR (200 and 500 MHz) and the magnetic gradiometer all identifying an area with a minor depression, inter-

preted as a possible older grave under the mound. The slingram devices and gradiometer also indicated linear structures running from SW and SE to the top of the mound, which were interpreted as possible rows of subsurface boulders. Both slingrams and GPR methods pointed to an old excavation tunnel. The GPR survey at The Thing Mound showed reflections with the typical pattern of glaciofluvial deposits indicative of upstream bedding. The Mound is interpreted as having been part of a former esker with a levelled top, and had probably once been prepared for use as a burial site. The conclusion is that a combination of several independent methods enhances the probability that anomalies may be detected and improves their interpretation.

Six papers report a combination of phosphate analysis with one or more geophysical parameter. Among others:

Konrad et al. (1983) used magnetometric mapping and soil analysis for pH, Mg, P and Ca at a Palaeo-Indian site at Munsungun Lake Thoroughfare, Main, USA. Concentrations of Mg pointed to probable hearths and correlated well with anomalies determined independently by the magnetic survey. Excavation of the anomalies provided evidence of hearths and other cultural artefacts, and also features resulting from fallen trees and drainage variation. Concentrations of P and Ca were used to define and delimit areas of activity. The authors' conclusion was that soil chemical analysis can be used both as a means of locating areas of interest and for the pre-excavation differentiation of habitation sites from limited areas of specialized activity.

Kjell Persson (1998) describes a multi-method prospecting programme undertaken in an attempt to locate settlements connected with the famous boat-grave cemetery in Vendel, Sweden. The site is located on an esker consisting of layered gravel and sand, and a combination of phosphate analysis, magnetic gradiometer, electromagnetic mapping (Geonics EM 31, 38) and GPR profiling detected a former subsurface terrace with a house thirty metres long from the Late Migration Period. A well-preserved bronze-casting furnace dated to the 16th century was also found. Since the thermoluminescence method dates the last heating, this furnace may have been used for casting Vendel's first church bell when the church was built there in the late 13th century.

A combination of archive and map studies with electromagnetic and soil phosphate mapping, followed by test coring and a GPR survey is recommended.

Multichemical analyses are reported in fourteen papers. Among others:

M.A. Griffith (1980, 1981) performed a pedological investigation and analysed magnesium, calcium, potassium, sodium, phosphorus, carbonates, pH and organic carbon in soil samples from a Huron Indian village dating from the 1600's at the Benson site, located 90 km northeast of Toronto, Canada. Three off-site soil profiles (podzols) were sampled and analysed for comparative purposes. The amounts of magnesium and organic and inorganic phosphorus in particular were sufficiently different to be useful in distinguishing formerly occupied soils from off-site soils.

The use of statistical discriminant analysis made it possible to rank the chemical attributes of the soil materials as to their usefulness in discriminating between settlement features such as middens, pits, longhouses, hearths, posts and former pathways. The middens and some pits were so rich in most elements that they overshadowed the amounts found in other features. Soils from the former paths could be distinguished from those of the pits, posts and longhouses in terms of their exchangeable magnesium levels, while organic and inorganic phosphorus levels differed statistically between the soils from paths, pits and houses. Dolomite, exchangeable calcium and potassium levels were sufficiently different statistically to distinguish between soils from paths or walking tracks from those of posts.

Exchangeable magnesium was found to be the most useful chemical compound to distinguish between settlement features, followed in rank order by organic phosphorus, dolomite, inorganic phosphorus and calcite, exchangeable calcium, potassium, pH and organic carbon.

Some papers describe GPR surveys that have yielded good results in dry soils, while others describe low penetration of ½ m to 1 m in moist clays.

Kloehn et al. (2000) conducted a GPR survey to determine the origin of the Western Prairie Mound Group in central Wisconsin, U.S.A. The mounds have historically been interpreted as Pre-Columbian Native American burial mounds, but they are located in an area with similar natural landforms. Two of the mounds were selected for a GPR survey with 200, 225 and 450 MHz antennae. The radar signals were able to penetrate down to 4–5 m and the reflection patterns were interpreted as indicative of typical sandy, aeolian geomorphological units, so that the mounds were deemed to be the result of natural rather than cultural processes.

Ben Sternberg and James McGill (1995) used GPR to detect near-surface archaeological finds in southern Arizona. Previous GPR surveys in the region had met

with limited success. Surveys with 500 MHz antennae showed that the radar signals were penetrating less than 1 m into the soils of the southern Arizona basins. Further surveys at lower frequencies (80 MHz) increased the penetration depth only to slightly more than 1 m and the resulting resolution became too low for archaeological targets.

They then used a frequency of 500 MHz to gather high-resolution information from the upper metre of the ground. The soil properties were an average of 79% sand, 10% silt and 11% clay down to 3 m. Water content was 5% down to 3 m and a DC resistivity of 15.7 Ω-m was measured. The surveys were able to image buried plaster, adobe walls, roasting pits, canals, trash pits, plastered floors and artefacts such as pot sherds and knives.

Basile et al. (2000) used GPR in an urban area in Lecce, Italy, at the site of a Franciscan friary built in 1432 that had been transformed into a military barracks in 1861 and finally destroyed in 1971. It was situated just outside the 16th-century Carlo V Castle and a 2nd-century Roman Amphitheatre. The investigation was aimed at examining whether there were also remnants of other structures such as tombs of Roman or Messapic age (6th–8th centuries).

The ground consisted of fine-grained, wet Miocenic calcarenite and the penetration was less than one metre with 500 MHz antennae and about 1 metre with 100 MHz antennae. The survey did not succeed in detecting the walls of the friary because they were built of the same material as the surrounding bedrock, but it did detect a barrel-vault cavity at a depth of 0.65 m which was confirmed by later excavation. A time-slice method was used to map the shape and extent of the vault.

The problems of limited penetration can sometimes be solved by filtering with background removal, bandpass and especially time gain filters, for instance, to amplify the late reflections. In Sweden and Norway we have succeeded in detecting reflections at penetration depths of 3 to 4 m in clays using 250 MHz RAMAC GPR (Persson 2002a, 2002b, 2002c, 2002d, 2002e, 2003c; Damstuen 2003). The depth penetration is probably affected by the percentage of clay minerals, and especially the water content.

Successful EM measurements with slingram devices have been reported in arid or semi-arid environments. The contrast in water content between the buried structures and the surrounding matrix is essential for detection purposes, and even in arid and semi-arid areas subsurface cultural layers can contain enough water to contrast with the totally dry surroundings.

On the other hand, subtle differences in water content between structures in non-arid areas can be difficult to detect in dry seasons.

Frohlich & Lancaster (1986) used a Geonics EM-31 device in the Middle East and investigated its response to changing environmental and climatic conditions, while Aaltonen (2001) investigated seasonal variations in resistivity due to soil moisture and weather factors. Since slingram and resistivity measurements are dependent on water content, they respond to climatic changes. Since attenuation in a GPR survey is correlated with electrical conductivity, GPR also responds to climatic changes. If a site has to be mapped at different times, a reference line that comprises all the soil types present at the site can be used for correlation purposes under changing climatic conditions.

The methods also seem to be of varying usefulness for different types of archaeological remains.

Prospecting for subsurface church remains with GPR has been reported in ten papers (Alkarp & Price 2003; Arlsan et al. 1999; Sambuelli et al. 1999; Dabas et al. 2000; Pérez-Gracia et al. 2000; Persson 2002a, 2003a, 2003b, 2003d; Anund et al. 2003), and similar attempts with magnetic surveys in two papers (Arlsan et al. 1999; Sambuelli et al. 1999), with resistivity surveys in two papers (Arlsan et al. 1999; Dabas et al. 2000) and with slingram in two papers (Persson 2002a, 2003d). Correspondingly, prospecting for building structures and stone walls with GPR has been reported in seven papers (Sternberg & McGill 1995; Persson & Olofsson 1995, Persson 1998; Baker et al. 1997; Basile et al. 2000; Pérez-Gracia et al. 2000; Whiting et al. 2001), with magnetic surveys in four papers (Pattantyus 1986; Persson & Olofson 1995; Persson 1998; Lopez-Loera et al. 2000), with a resistivity survey in one paper (Pattantyus 1986) and with slingram in four papers (Dalan 1991; Ladefoged et al. 1995; Persson & Olofsson 1995, Persson 1998). The detection of graves with GPR has been reported in five papers (Bevan 1991; Nobes 1999; Kloehn et al. 2000; Whiting et al. 2001; Persson & Olofsson 2004) and with slingram in three papers (Froehlich-Gugler & Gex 1996; Nobes 1999; Persson & Olofsson 2004), and prospecting for cultural layers with GPR is reported in four papers (Persson & Olofsson 1995, 2004; Persson 1998; da Silva et al. 2001), with magnetic mapping in one paper (Herwanger et al. 2000), with slingram in four papers (Dalan 1991; Persson & Olofsson 1995, 2004; Persson 1998) and with chemical analysis in 24 papers (O. Arrhenius 1931, 1935, 1950; Lorch 1940; Solecki 1951; Johnsson 1956; Biek

1957; Cook & Heizer 1965; Provan 1971, 1973; Hudson 1974; Barker et al. 1975; Griffith 1980, 1981; Konrad et al. 1983; Craddock 1984; B. Arrhenius 1990; Linderholm & Lundberg 1994; Persson & Olofsson 1995; Persson 1998; Middleton & Price 1996; Isaksson 2000; Isaksson et al 2002; Hjulström & Isaksson 2004).

Conclusions

Swedish archaeology has a long tradition of geo-chemical prospecting, i.e. phosphate mapping (Arrhenius 1931, 1935), but only sporadic use has been made of geophysical prospecting. Mostly one single method has been used, e.g. resistivity, magneto-metry or GPR, although a few investigations have been reported in which combined surveys methods have been employed (Sträng 1995; Persson 1998; Dahlin 2001a; Grassi 2001; Lorra et al. 2001; Mercer & Schmidt 2001; Persson & Olofsson 2004).

Each method is able to detect anomalies in the actual parameter studied, but if no obvious geometrical pattern is visible, any interpretation will be hazardous. Every attempt to combine this with another, independent parameter will increase the interpretation possibilities. Even different instrument configurations can add information about the cause of the anomalies. If conductivity and/or resistivity surveys detect linear and right-angled structures, for instance, a magneto-metric survey may detect point anomalies inside and outside these structures and phosphate mapping may detect increased values just outside the structure, making the interpretation of a building with walls, indoor and outdoor hearths and a waste heap outside more reliable than it would have been on the basis of only one of these parameters.

The information gathered here from the literature and the author's own experience of the usefulness of different prospecting methods can be summarized as shown in Table 2. The structures in the table can differ

a lot in reality, of course, which can affect the choice of methods. It is assumed in this table that mounds have a height of more than one metre. Otherwise some of the methods suggested for graves should be chosen.

The optimal combination of methods depends on the features expected. Based on the present results, we can recommend for objective, unbiased site prospecting a combination of
- phosphate mapping
- slingram/magnetic/resistivity surveys, alternatively or in combination
- GPR

English language revision by Malcolm Hicks.

References

Aaltonen, J. 2001. *Ground Monitoring using Resistivity Measurements in Glaciated Terrains.* Doctoral thesis. Royal Institute of Technology, Stockholm.

Aitken, M.J., Webster, G., Rees, A. 1958. Magnetic prospecting. *Antiquity* 32, pp. 270–271.

Alkarp, M., Price, N. 2003. *Georadarundersökning vid Gamla Uppsala kyrka*, Dept. of Archaeology, Uppsala University.

Anund, J., Jonsson, K., Persson, K. 2003. *Arbogas urbanisering och tidiga kyrkor, Etapp 1: Helge Svens kapell. Rep. Kulturmiljö-avdelningen rapport A 2003:A38*, Västmanlands läns museum, Västerås.

Arlsan, E., Biela, G., Boniolo, G., Caporusso, D., de Franco, R., Lozej, A., Veronese, L. 1999. Geophysical investigations of the Olonium Roman site (Northern Como Lake). *Journal of Applied Geophysics* 41 (2–3), pp. 169–188.

Arrhenius, B. 1990. Fosfat och spårämnesanalyser som hjälpmedel vid bebyggelseanalys. *Bebyggelsehistorisk tidskrift* 19, pp. 63–77.

Arrhenius, O. 1931. Die Bodenanalyse im dienst der Archäologie. *Zeitschrift für Pflanzenernährung, Düngung und Bodenkunde* Teil B, 10 Jahrgang, pp. 427–439.

Arrhenius, O. 1935. Markundersökning och arkeologi. *Fornvännen* 30, pp. 59–62.

Arrhenius, O. 1950. Förhistorisk bebyggelse antydd genom kemisk analys. *Fornvännen* 45, pp.59–62.

Atkinson, R.J.C. 1946. *Field Archaeology.* London.

Atkinson, R.J.C. 1952. *Methodes électriques de prospection en archéologie.* Paris.

Atkinson, R.J.C. 1953. *Field Archaeology.* London.

Atkinson, R.J.C. 1963. *Resistivity surveying in archaeology.* London.

Baker, J.A., Anderson, N.L., Pilles, P.J. 1997. Ground-penetrating

Table 2. Usefulness of site prospecting methods for various archaeological features, graded as X - 'possible', XX - 'good' or XXX - 'very good'.

	Slingram	Magnetometer	Resistivity	Radar	Phosphate
Cultural layers	XX	XX	XX	XX	XXX
Graves	XX	XX	X	XX	XX
Mounds	X	XX	X	XXX	X
House structures/stone walls	XX	XX	XXX	XXX	XX
Hearths	XXX	XXX	XX	X	X

radar surveying in support of archaeological site investigations. *Computers & Geosciences* 23, pp. 1093–1099.

Barker, H., Hughes, M.J., Oddy, W.A., Werner, A.E. 1975. Report on phosphate analysis carried out in connection with the cenotaph problem. In *The Sutton Hoo Ship Burial*, ed. RIS Bruce-Milford, pp. 550–572. London.

Basile, V., Carrozzo, M.T., Negri, S., Nuzzo, L., Quarta, T., Villani, A.V. 2000. A ground-penetrating radar survey for archaeological investigations in an urban area (Lecce, Italy). *Journal of Applied Geophysics* 44 (1), pp. 15–32.

Bethell, P., Màté, I. 1989. The use of soil phosphate analysis in archaeology; a critique. In *Scientific analysis in archaeology*, ed. J Henderson, pp. 1–29. Oxford: Oxford University Committee for Archaeology Monograph.

Bevan, B.W. 1991. The search for graves. *Geophysics* 56, pp. 1310–1319.

Bevan, B.W., Kenyon, J. 1975. Ground penetrating radar for historical archaeology. *MASCA Newsletter* 11, pp. 2–7.

Biek, L. 1957. The Great Barrow at Bishop's Waltham, Hampshire. *Proceedings of the Prehistic Society* 23, pp. 137–166.

Clark, A. 1990. *Seeing beneath the soil, prospecting methods in archaeology.* London.

Conyers, L.B., Goodman, D. 1997. *Ground Penetrating Radar: An Introduction for Archaeologists.* London.

Cook, S.F., Heizer, R.F. 1965. Studies on the chemical analysis of archaeological sites. In *University of California Publications in Archaeology.*

Craddock, P.T. 1984. Soil phosphate survey. Cat's Water, 1973–1977. In *Excavation at Fengate, Peterborough, England: The fourth Report*, ed. F Pryor.

Crawford, O.G.S. 1928a. *Air Survey and Archaeology.* London.

Crawford, O.G.S. 1928b. *Wessex from the Air.* Oxford.

da Silva Cezar, G., da Rocha, P.L.F., Buarque, A., da Costa, A. 2001. Two Brazilian archaeological sites investigated by GPR: Serrano and Morro Grande. *Journal of Applied Geophysics* 47 (3–4), pp. 227–240.

Dabas, M., Camerlynck, C., Frexias i Camps, P. 2000. Simultaneous use of electrostatic quadrupole and GPR in urban context; investigation of the basement of the Cathedral of Girona (Catalunya, Spain). *Geophysics* 65, no 2, pp. 526–532.

Dahlin, T. 2001a. Resistivity survey at Stora Uppåkra, Sweden. In *Uppåkra, Centrum i analys och rapport*, pp. 59–64. Lund.

Dahlin, T. 2001b. The development of electrical imaging techniques,. *Computers and Geosciences* 27(9), pp. 1019–1029.

Dalan, R.A. 1991. Defining archaeological features with electromagnetic surveys at the Cahokia Mounds State Historic Site. *Geophysics* 56, no 8, pp. 1280–1287.

Damstuen, L. 2003. *Rapport: Hagearkeologisk undersökelse av dammene i landskapsparken på Bogstad Gård, Oslo; Unpublished*, Oslo.

De Terra, H. 1947. "Preliminary note on the discovery of fossil man at Tepexpan in the Valley of Mexico." *American Antiquity* 1, pp. 40–43.

De Vore, S. L. 2004. Selected Bibliography of Remote Sensing/ Geophysical Techniques for Cultural Resource Management. Current Archaeological Prospection Advances for Non-destructive Investigations in the 21st Century, workbook compiled by Steven L. De Vore, National Park Service, Lincoln, Nebraska. United States.

Deletie, P., Lemoine, Y., Montlucon, J., Lakshman, I. 1988. *Discovery of two unknown pyramids at Saqqarah (Egypt) by a multimethod geophysical survey.* Presented at SEG Annual Meeting, Anaheim.

Dolphin, L.T. 1981. *Geophysical methods for archaeological surveys in Israel. Stanford Research International, Menlo Park, California.*

Edgerton, H.E. 1972. Underwater archaeology – Sonar surveys in Greece. *MASCA Newsletter 9*, p. 3.

Froehlich-Gugler, A.I.M, Gex, P. 1996. Electromagnetic survey of a Celtic tumulus. *Journal of Applied Geophysics* 35, pp. 15–25.

Frohlich, B., Lancaster, W.J. 1986. Electromagnetic surveying in current Middle Eastern archaeology. *Geophysics* 51, pp. 1414–1425.

Frost, K., Jonsson, K. 2002. *Köksträdgården vid Strömsholms slott. Rep. Rapport 2002:A53*, Västmanlands läns museum.

Grassi, R. 2001. Geofysiska mätningarna vid Uppåkra. In *Uppåkra, Centrum i analys och rapport*, pp. 79–86. Lund.

Griffith, M.A. 1980. A pedological investigation of an archaeological site in Ontario, Canada, I: An examination of the soils in and adjacent to a former village. *Geoderma* 24, pp. 327–336.

Griffith, M.A. 1981. A pedological investigation of an archaeological site in Ontario, Canada, II: Use of chemical data to discriminate features of the Benson site. *Geoderma* 25, pp. 27–34.

Gundlach, H. 1961. Tüpfelmethode auf Phosphat, angewandt in prähistorischer Forschung (als Feldmethode). *Mikrochima Acta* 5, pp. 735–737.

Herwanger, J., Maurer, H., Green, A.G., Leckebusch, J. 2000. 3-D inversions of magnetic gradiometer data in archaeological prospecting; possibilities and limitations. *Geophysics* 65, no 3, pp. 849–860.

Hjulström, B., Isaksson, S. 2004. *Arkeologiska Undersökningar vid Tuna 2:1, Alsike sn, Uppsala kn, 2003. Grävrapport för VT 2003 & HT 2003; Unpublished*, The Archaeological Research Laboratory, Stockholm University.

Hudson, G.E. 1974. *The Determination of Trace Elements in Saxon Human Remains*, London.

Isaksson, S. 2000. *Food and Rank in Early Medieval Time. (Theses and Papers in Scientific Archaeology 3).* Stockholm.

Isaksson, S., Arrhenius, B., Karlsson, Ö. 2002. *Långhus på liden, Arkeologiska boplatsundersökningar vid Vendels kyrka 1994–1998 och 2001–2002; Unpublished*, The Archaeological Research Laboratory, Stockholm University.

Johnson, A.H. 1956. Examination of soil from Corrimony chambered cairn. *Proceedings of the Society of Antiquaries of Scotland* 88, pp. 200–207.

Karastathis, V.K., Papamarinopoulus, S., Jones, R.E. 2001. 2-D velocity structure of the buried ancient canal of Xerxes: an application of seismic methods in archaeology. *Journal of Applied Geophysics* 47, pp. 29–43.

Kearey, P., Brooks, M. 1984. *An Introduction to Geophysical Exploration.* Oxford.

Kloehn, N.B., Junck, M.B., Jol, H.M., Running, G.L., Greek, W., Caldwell, K. 2000. *GPR investigations of the West Prairie Mound Group, central Wisconsin, U.S.A.; are they burial mounds or natural landforms?* Presented at GPR 2000, the Eighth international conference on Ground penetrating radar, Gold Coast, Queensland, Australia.

Konrad, A.V., Bonnichsen, R., Clay, V. 1983. Soil Chemical Identification of Ten Thousand Years of Prehistoric Human Activity Areas at the Munsungun Lake Thoroughfare, Maine. *Journal of Archaeological Science* 10, pp. 13–28.

Ladefoged, T.N., McLachlan, S.M., Ross, S.C.L., Sheppard, P.J., Sutton, D.G. 1995. GIS-Based Image Enhancement of Conductivity and Magnetic Susceptibility data from Ureturuturi Pa and Fort Resolution, New Zealand. *American Antiquity* 60 (3), pp. 471–481.

Linderholm, J., Lundberg, E. 1994. Chemical characterization of various archaeological soil samples using main and trace elements determined by inductively coupled plasma atomic emission spectrometry. *Journal of Archaeological Science* 21, pp. 303–314.

Lopez-Loera, H., Urrutia-Fucgauchi, J., Comparan-Elizondo, J.L., Castilo-Torres, R., Ponce-Juarez, R., Jarquin-Pacheco, A.M., Martinez-Vargas, E. 2000. Magnetic study of archaeological structures in La Campana, Colima, western Mesoamerica. *Journal of Applied Geophysics* 43 (1), pp. 101–116.

Lorch, W. 1940. Die siedlungsgeographische Phosphatmethode. *Die Naturwissenschaften* 28, pp. 633–640.

Lorra, S., Kroll, S., Thomsen, D. 2001. Geophysical Investigations at the Uppåkra Site (Sweden). In *Uppåkra, Centrum i analys och rapport*, pp. 41–58. Lund.

Mercer, E., Schmidt, A. 2001. A magnetometer survey of an Iron Age settlement site at Uppåkra, Skåne, Sweden. In *Uppåkra, Centrum i analys och rapport*, pp. 65–78. Lund.

Middleton, W., Price, D. 1996. Identification of Activity Areas by Multi-element Characterization of Sediments from Modern and Archaeological House Floors Using Inductively Coupled Plasma-atomic Emission Spectroscopy. *Journal of Archeological Science* 23, pp. 673–687.

Nobes, D.C. 1999. Geophysical surveys of burial sites: a case study of the Oaro Urupa. *Geophysics* 64 (2), pp. 357–367.

Patella, D., Mauriello, P. 1999. The geophysical contribution to the safeguard of historical sites in active volcanic areas. *Journal of Applied Geophysics* 41 (2–3), pp. 241–258.

Pattantyus, A.M. 1986. Geophysical results in archaeology in Hungary. *Geophysics* 51, pp. 561–567.

Pérez-Gracia, V., Canas, J.A., Pujades, L.G., Clapés, J., Caselles, O., Garcia, F., Osorio, R. 2000. GPR survey to confirm the location of ancient structures under the Valencian Cathedral (Spain). *Journal of Applied Geophysics* 43 (2–4), pp. 167–174.

Persson, K. 1996. Phosphate Test Strips; A new equipment for direct soil-phosphate field analysis. *Journal of Nordic Archaeological Science* 9, pp. 57–60.

Persson, K. 1997. Soil Phosphate Analysis: A new technique for measurement in the field using a test strip. *Archaeometry* 39, pp. 441–443.

Persson, K. 1998. Archaeological Prospection. *Laborativ Arkeologi* 10/11, pp. 17–26.

Persson, K. 2002a. *Geofysisk prospektering, Arboga;* Unpublished report, The Archaeological Research Laboratory, Stockholm University.

Persson, K. 2002b. Geofysisk prospektering i köksträdgården, Strömsholms slott; In Frost, K., Jonsson, K. Köksträdgården vid Strömsholms slott, Trädgårdsarkeologisk förundersökning. ed. C Svensson. Västerås: Kulturmiljöavdelningen Rapport 2002:A53, Västmanlands Läns Museum.

Persson, K. 2002c. *Prospektering i Kungliga Vetenskapsakademins trädgård;* Unpublished report, The Archaeological Research Laboratory, Stockholm University.

Persson, K. 2002d. *Rapport, Geofysisk prospektering, Martebo myr, Gotland;* Unpublished report, The Archaeological Research Laboratory, Stockholm University.

Persson, K. 2002e. *Geophysical and Geochemical prospecting at Grönsöö 2000–2002,* Unpublished report, The Archaeological Research Laboratory, Stockholm University.

Persson, K. 2003a. *Rapport, Geofysisk prospektering, Sala silvergruva;* Unpublished report, The Archaeological Research Laboratory, Stockholm University.

Persson, K. 2003b. *Geofysisk Prospektering med georadar vid G:a Uppsala kyrka, 3D-modellering,* Unpublished report, The Archaeological Research Laboratory, Stockholm University, Stockholm.

Persson, K. 2003c. *Geophysical Prospection with GPR, Ground Penetrating Radar,at Bogstad Gård,* Unpublished report, The Archaeological Research Laboratory, Stockholm University, Stockholm.

Persson, K. 2003d. *Geofysisk prospektering med georadar vid S:t Nicolaus och S:t Olofs kyrkor, Sigtuna, 3D-modellering,* Unpublished report, The Archaeological Research Laboratory, Stockholm University.

Persson, K., Olofsson, B. 1995. Kan modern teknik avslöja var båtgravfolket bodde? *Populär Arkeologi* 1, pp. 12–13.

Persson, K., Olofsson, B. 2004. Inside a mound:applied geophysics in archaeological prospecting at the Kings' Mounds, Gamla Uppsala, Sweden. *Journal of Archaeological Science* 31, pp. 551–562.

Pitt-Rivers, A. *Excavations in Cranborne Chase* Vol. I (- vol. IV). Printed Privately, 1887, 1888, 1892 and 1898.

Provan, D. 1971. Soil phosphate analysis as a tool in archaeolgy. *Norwegian Archaeological Review* 4, pp. 37–50.

Provan, D. 1973. The soils of an iron age farm site. *Norwegian Archaeological Review* 6, pp. 30–41.

Russel, E.J. 1957. *The World of the Soil.* London.

Sambuelli, L., Socco, L.V., Brecciaroli, L. 1999. Acquisition and processing of electric, magnetic and GPR data on a Roman site (Victimulae, Salussola, Biella). *Journal of Applied Geophysics* 41 (2–3), pp. 293–312.

Solecki, R.S. 1951. Notes on soil analysis and archaeology. *American Antiquity* 16, pp. 254–256.

Sternberg, B.K., McGill, J.W. 1995. Archaeological studies in southern Arizona using ground penetrating radar. *Journal of Applied Geophysics* 33:, pp.209–225.

Sträng, T. 1995. *Lindholmen och geofysiska mätningar. Lindholmen – Medeltida riksborg i Skåne,* Lund studies in medieval archaeology, ed. Mogren, M. & Wienberg, J.

Whiting, B.M., McFarland, D.P., Hackenberger, S. 2001. Three-dimensional GPR study of a prehistoric site in Barbados, West Indies. *Journal of Applied Geophysics* 47 (3–4), pp. 217–226.

Wynn, J.C. 1986. Archaeological Prospection: An introduction to the special issue. *Geophysics* 51, pp. 533–537.