INTEGRATED GEOPHYSICAL-GEOCHEMICAL METHODS FOR ARCHAEOLOGICAL PROSPECTING

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Integrated Geophysical-Geochemical Methods For Archaeological Prospecting
LIST OF PAPERS

The thesis is based on following papers


PREFACE AND ACKNOWLEDGEMENTS

This thesis was produced at the Department of Land and Water Resources Engineering, Royal Institute of Technology, Stockholm during the years 2002-2005. The thesis consists of a summary together with five papers. Field measurements were performed during many years in different projects. The most important pilot projects were SIV (Svealand in Vendel and Viking periods) in Vendel parish, Uppland, Sweden and another at the Eastern Mound in Old Uppsala, Uppland, Sweden. Both projects were led by Professor Birgit Arrhenius at the Archaeological Research Laboratory, Stockholm University.

I want especially to thank my supervisors Dr Bo Olofsson and Associate Professor Herbert Henkel at the Department of Land and Water Resources Engineering, Royal Institute of Technology in Stockholm and Professor Birgit Arrhenius at the Archaeological Research Laboratory, Stockholm University.

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Slingram measurements were carried out by the author with a Geonics EM 38 from the Archaeological Research Laboratory. Slingram measurements with Geonics EM 31 and gradiometer survey in the SIV project were carried out by Civ. Eng. Leif Eriksson, Geological Survey of Sweden and at the Eastern Mound by the author. GPR measurements were carried out in the SIV project by a group from the Department of Land and Water Resources Engineering at the Royal Institute of Technology, Stockholm led by Dr Bo Olofsson. GPR measurements at the Kings Mounds were carried out by Dr Bo Olofsson, Dr Jaana Aaltonen, Mälà Geoscience and the author. The VLF measurements in Vendel were carried out by the author. Thank you all!

Finally I want to thank my wife Leena and my children Maria, Tomas and Staffan for their patience and support.

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ABSTRACT

A great number of field measurements with different methods and instruments were conducted in attempts to develop a method for an optimal combination of various geochemical and geophysical methods in archaeological prospecting. The research presented in this thesis focuses on a study of how different anthropogenic changes in the ground can be detected by geochemical and geophysical mapping and how the results can be presented.

A six-year pilot project, Svealand in Vendel and Viking periods (SIV), was the beginning of this work in which EM- measurements, gradiometer and GPR surveys together with phosphate mapping succeeded in detecting settlements, mainly from the Iron Age. During the project, a new field kit for soil phosphate analysis was also developed and patented.

Another major project was the examination of the Kings’ Mounds in Old Uppsala where a multi method survey including two different slingrams, three different types of GPR equipments and two different gradiometers was used for detecting structures inside the mounds. The Thing Mound was interpreted not to be a burial mound. The layers indicated by the GPR survey are most probably natural glaciofluvial layers. At the Eastern Mound the measurements detected an excavation tunnel from 1846-47, some known old brick furnaces from the time of building of the church, the original esker surface and the central cairn. The survey also detected two linear structures from the mounds base to the top and a depression under the mound in the old esker. The linear structures were interpreted as possible boulder rows and the depression as a possible older burial preceding the construction of the mound.

Other surveys with slingram and GPR were used to detect subsurface features at historical gardens and historical glass works. A number of surveys to detect older church remnants were also carried out. In a project at Arethousa, Greek Macedonia, slingram measurements pointed out possible subsurface stonewalls and a possible hearth, which were confirmed later by excavations. At Old Uppsala, Sweden a GPR survey was successfully used for detecting the older cathedral under the present church.

The overall results led to a recommended concept of combined methods for archaeological prospecting, especially in northern Europe. Slingram measurements of both electrical and magnetic components combined with phosphate mapping and GPR surveys proved to be useful methods for such prospecting.

Keywords: geophysical, geochemical, prospecting, archaeology, electric, magnetometric

BACKGROUND

The placement of trenches at archaeological excavations has traditionally been chosen based on topography, exposure and reported findings. However, most archaeological remains are hidden beneath the ground surface and are not possible to detect solely through ocular inspection. Further more, some hidden structures are not even visible through excavation and can only be detected by chemical or physical analysis. Increased soil-phosphate content is sometimes not visible if soil layers do not differ in colour. A fossil sediment-covered ground surface is not always possible to detect by ocular inspection during excavation but it can be detected through magnetic susceptibility measurements or through radar reflections. Such a surface has decreased susceptibility due to weathering, oxidation and transportation of iron minerals down the profile. An old pit may not be visible if it is re-
filled with the same material as the surrounding matrix while it still may be detectable through radar reflections or magnetic mapping, for instance. Excavations are destructive and expensive and therefore it is desirable to find non-destructive methods that can detect subsurface structures and minimize both excavated area and cost. Geophysical and geochemical methods offer such possibilities. Different methods to chemically and physically locate prehistoric houses, settlements, graves and other features have long been used in archaeological prospecting. Some of them, for instance phosphate analysis, have been carried out by archaeologists on the basis of the archaeological hypothesis that human activities can change the phosphate content in the ground. That method has often produced good results. Geophysical methods have been widely used in other countries, often in geological environments that significantly differ from the conditions prevailing in the Nordic countries. There are several reasons why combinations of geophysical indirect methods have not always been included in archaeological investigations in Scandinavia. These include working traditions, a huge natural variation in physical and chemical properties of soils and rock and hence difficulty in interpreting complex measurements. Therefore, surveys have often been carried out by non-archaeological specialists, sometimes based on archaeological hypotheses but often without adaptation of methods and instruments to archaeological needs. There is an urgent need for both methodological development of the indirect investigation methods adapted to Swedish geology with its variation in soils and soil humidity and a spread of knowledge about these methods and the benefits of multi-method surveys within Swedish archaeology. An important development is hence to integrate different geophysical and geochemical prospecting methods with each other and with other archaeological methods.

Geochemical prospecting, mainly phosphate mapping, has an old tradition in Sweden since Olof Arrhenius first described it (Arrhenius 1931). However, geophysical prospecting is seldom used in Sweden and most reported surveys are carried out with one single method. Multi-methods with combination of two or more geophysical methods have only been applied in a few projects in Sweden (Sträng 1995, Dahlin 2001, Grassi, 2001, Lorra et al 2001, Mercer & Schmidt 2001), while multi-instrument methods are much more used in other countries. During the work with this thesis a number of multi method surveys have been carried out at The Archaeological Research Laboratory, Stockholm University (Isaksson 2000, Isaksson et al 2002, Persson 1998, Hjulström & Isaksson 2004).

The methods used in these surveys are geochemical (mainly phosphate analysis) and geophysical (mainly gradiometer, slingram and ground penetrating radar, GPR).

HYPOTHESIS

When humans use a piece of land for living, grazing or cultivation, soil chemical and physical properties are changed because of, for instance increased weathering due to wear, changes in soil compaction, nutrient decreases due to harvesting and grazing and nutrient increases due to fertilizing and waste deposition. Archaeological prospecting comprises methods, which can be used for detection of such places with anomalous chemical and physical properties compared to the undisturbed surroundings. To be able to interpret survey data and differ between anthropogenic and geological anomalies, it is important to document natural seasonal and local variations in chemical and physical soil properties and known history of land-use at the site. Anomalies that cannot be explained geologically or historically can then be selected for further surveys or test coring and finally for excavation.
The main hypotheses investigated in this thesis were:

- The chemical and physical anomalies created by earlier land-use can be separated from natural variations based on the signature of the changes, despite single properties possibly can be within the range of natural variation.
- A scientific and structural system for selecting the most favourable combinations of various geophysical and geochemical methods increase the efficiency of archaeological prospecting in various geological conditions.

**OBJECTIVES**

The major objective of the research was to develop a method for an efficient combination of various geochemical and geophysical methods in archaeological prospecting.

The specific target for the work presented in this thesis was to study how different anthropogenic changes in the ground could be detected by geochemical and geophysical mapping and how the results can be presented.

The investigations concentrated on some specific methods and were mainly carried out at Iron Age settlements and burials in South Central Sweden because of access to sites and instruments. The work focused on:

- Phosphate mapping
- Electromagnetic (EM) measurements with slingram
- Gradiometer magnetic measurements
- Ground Penetrating Radar (GPR) measurements
- 2D and 3D modelling in Geographical Information Systems (GIS) and Computer Aided Design (CAD) programmes

**RESEARCH METHODS**

**Literature studies**

A comprehensive literature search was carried out in a number of global literature and journal databases:

- GeoRef 1785-2002 (American Geological Institute)
- GEOBASE(TM) 1980-2002 (Elsevier Science Ltd)
- GeoArchive 1974-2002 (Geosystems)
- Pascal 1973-2002 (INIST/CNRS)
- Ei Compendex 1970-2002 (Engineering Info. Inc)
- NTIS 1964-2002 (US Dept. of Com.)
- INSPEC 1983-2002 (Institution of Electrical Engineers)
- Enviroyline(R) 1975-2002 (CIS Inc.)

The search was carried out using the search keywords: archaeology / geology / geophysical / geochemical / electromagnetic / slingram / metal detector / VLF / GPR / Ground Penetrating Radar / magnetometer / magnetic / gradiometer / cemetery / grave / burial / settlement / artifact / phosphate / phosphorus

The search resulted in 168 references. Some of the references were not relevant, while some, such as articles about resistivity methods, were added during this work. The reference list now consists of 89 items.

Paper I describes the results of the literature studies.

**Field work**

Field measurements were carried out during several years at many investigations in Sweden, Norway, Greece and Zimbabwe. An important pilot investigation was the six-year project SIV (Svealand in Vendel and Viking Periods) in which a number of methods in searching for Iron Age settlements were tested in Vendel parish, northern Uppland, Sweden. The results
are presented in Paper II. Another major project was the investigation of the Kings’ Mounds in Old Uppsala, Uppland, Sweden, in which the experiences of earlier tests were used to design the investigation of a 6-metre high mound. The results are presented in Paper V.

Projects and conferences
During this work I performed prospecting surveys at many different places searching for settlements and graves from the Stone Age, Bronze Age and Iron Age, foundation walls from medieval churches and remains of historical gardens. The locations of the sites included in this thesis are presented in Fig. 1.

The results were presented at two seminars at Grönsöö Castle:
‘Non-destructive Archaeological Methods in Historic Parks’ on August 30th 2001’ and a seminar on garden archaeology on October 9th 2002

a seminar in Old Uppsala: ‘The East Mound in Old Uppsala, Plans for New Investigations’ on June 5th. 2003,
an workshop in Oklahoma, USA: ‘Current Archaeological Prospecting Advances

Fig. 1. Map of Scandinavia showing the main investigation sites included in this thesis.
Prospecting Methods

Geochemical prospecting in archaeology with phosphate analysis was reported as early as 1911 (Russell, 1957) but was first described and systematically used to locate prehistoric settlements by Olof Arrhenius (1931). In late 1930's Walter Lorch used a field spot test method to reconstruct settlement geography over large areas and also to differentiate types of settlements by the patterns of phosphate anomalies (Lorch 1940). In the 1950's some work was done at a smaller scale to examine soil silhouettes at burial sites (Solecki 1951, Johnson 1956, Biek 1957). In the 1960's Cook and Heizer (1965) tried to quantify the amounts of phosphates in the ground in order to draw conclusions about settlements in California and Mexico. They also warned that phosphate should not be considered isolated from other elements in the environmental depositions. A development of Lorch's spot test was made by Gundlach (1961). The first step to integrate phosphate mapping with other analyses in the planning of an excavation was made in Britain by Paul Craddock, who also used phosphate analysis at excavated features as an interpretation tool (Craddock 1984). In Norway, Donald Provan used phosphate in multi-element analysis to detect anthropogenic changes in the soil (Provan 1973). Tests have also shown that phosphate enrichments can be used to detect totally decomposed bodies (Hudson 1974, Barker et al 1975, Keeley et al, 1977). In North America phosphate analysis was used together with analyses of magnesium and calcium and magnetometric mapping at Munsungun Lake in Maine (Konrad et al, 1983). In the 1990's, an improved field test kit for soil phosphate analysis was developed in Stockholm using standardized test strips, which can be combined with other test strips for multi-element field analysis (Persson 1997).

Phosphate analysis

Phosphorus (P) is a naturally occurring element found in all living organisms as well as in water and soils. It is found in soils in three different fractions, the organic, the inorganic and the soil solution.

P is an essential element for plant growth and plants can derive it from soils mostly in the orthophosphate form from the soil solution. Crops are dependent on the ability of the organic and inorganic fractions to deliver more phosphorus to the soil solution fraction. Before uptake, the organic fraction must be converted to a plant-available inorganic form via soil biological activity, a process known as mineralization.

In natural soils there is an equilibrium between these fractions, but the equilibrium can be changed by anthropogenic actions such as fertilizing, cropping, grazing and deposition of organic waste (Bethell & Máté, 1989, Ivarsson 1989). Soil phosphate mapping can detect places with anomalous soil phosphate content. The analysis is carried out in three steps. Extraction of phosphorus from the soil with an acid or alkali gives a soluble orthophosphate. Adding a reagent and a reducer forms a complex coloured solution, in which the colour intensity is proportional to the concentration of phosphorus. The intensity can be measured in a spectrophotometer or by optical comparison. Most archaeological methods use weak acids to extract plant available phosphorus. At the Archaeological Research Laboratory the PMB-method (Phosphate Molybdenum Blue) is used. After extraction with 2 % citric acid the orthophosphate ions react with molybdenum to form a phosphomolybdate complex that can be reduced with hydroquinone to develop a blue colour. The new field method, Merck Reflectoquant phosphate test strips
(Fig. 2), which is presented in Paper III, uses 0.2 M sulphuric acid to get a fast extraction (Persson 1997).

An anomaly is defined as a deviation from the natural variations and it can be of natural origin such as fallen trees or dead animals or caused by human activities. One important objective during interpretation is to differ between natural and anthropogenic anomalies. Archaeological and historical features that can be detected by phosphate mapping include waste-deposits, dung heaps, stables, graves and settlement shorelines. Phosphate analysis has also been used to detect room-dividing walls and to interpret room functions (Middleton & Price 1996).

Fig. 2. Merck Reflectoquant System with photometer and test-strips.

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 as an archaeological prospecting tool started in England when Lieutenant P.H. Sharpe took a photo of Stonehenge from a balloon in 1906. It continued in England with photos from airplanes by O.G.S. Crawford (Crawford 1928 a,b). Richard Atkinson developed electrical resistivity measurements in archaeology in the late 1940’s (Atkinson 1946, 1952, 1953, 1963). The fact that burned clay was weakly magnetic was known already in the nineteenth century and in the 1950’s magnetic mapping with a magnetometer was used for the first time to locate buried kilns (Aitken et al 1958).

Measurements of ground electrical conductivity with slinagram were developed in Sweden in the 1940’s for mineral prospecting. The method uses induction of currencies in the ground without electrodes and is hence a non-destructive method well suited for archaeology (Frolich & 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 (GPR) surveys were performed to measure the depth of glaciers. After almost thirty years in the late 1950’s, the method also came into use for mapping sub-soil structures and features and in the 1970’s the system was commercially available and also used in archaeology (Bevan & Kenyon 1975).

The use of geophysical prospecting is growing particularly rapidly within archaeological fieldwork. First of all the methods provide a non-destructive, fast and cost-effective examination, which make it possible to choose the optimal location for excavation to obtain maximum information on earlier land-use. The methods have also improved considerably lately due to computer and software development and it is now possible to graphically present both two- and three-dimensional models of the results with high accuracy, which improves interpretation.

Electric measurements

The electric direct current (DC) method for resistivity measurements gives the distribution of the electrical or potential gradient of a direct current. Electrical resistance of the ground is almost entirely dependent on the water content. Buried features and earlier diggings affect the distribution and therefore resistivity mapping can be used to detect such archaeological remains. Electrodes are used to introduce a current to the ground and to map
the potential distribution. There are different types of electrode configurations and the Twin Electrode configuration has been developed specially for archaeology (Clark 1990).

**Electromagnetic measurements**

Electromagnetic wave propagation in the ground and the interactions between the electric and magnetic fields can give information about soil characteristics.

Electrical properties come from the interaction between electrical fields and charged particles, mainly electrons.

Electrical conduction depends on charge motion and electrical polarization (dielectrical permittivity), which come from charge separation over a distance.

Magnetic polarization (permeability or susceptibility) depends on electron spin and motion in atomic orbits.

Electrical and magnetic processes are coupled. Accelerating electrons generate electromagnetic radiation (Smith 1997). Moving charges (currents) generate magnetic fields and time varying magnetic fields cause charges to move. The velocity of electromagnetic wave propagation is the reciprocal of the square root of the product of permittivity and electromagnetic permeability. The velocity in low loss, non-magnetic materials is approximately the speed of light in vacuum divided by the square root of the relative dielectric permittivity. The four fundamental vector field quantities in electromagnetics are the electric field intensity, \( \mathbf{E} \), the magnetic flux density, \( \mathbf{B} \), the electric flux density, \( \mathbf{D} \) and the magnetic field intensity, \( \mathbf{H} \). These quantities are related to each other by Maxwell’s equations:

\[
\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \\
\nabla \times \mathbf{H} = i + \frac{\partial \mathbf{D}}{\partial t} \\
\n\nabla \cdot \mathbf{B} = 0 \\
\n\nabla \cdot \mathbf{D} = \varrho_c
\]

and the constitutive relationships

\[
\mathbf{D} = \varepsilon \mathbf{E} \\
\mathbf{B} = \mu \mathbf{H}
\]

\( i = \sigma \mathbf{E} \)

where

\( i \) = the electric current density

\( \varrho_c \) = the electric charge density

\( \varepsilon \) = the dielectric permittivity

\( \mu \) = the magnetic permeability

\( \sigma \) = the electric conductivity

\( \nabla \) = nabla vector operator

\( \nabla \cdot \) = divergence operator

\( \nabla \times \) = curl operator (rotation)

**Equations 1. Maxwell's equations and the constitutive relationships**

In the regime of high frequency (\( f > 10 \text{ MHz} \)) and low conductivity, the propagation of the EM field depends mainly on the dielectric permittivity and the magnetic permeability of the rock. Propagating fields of this type are used in ground-penetrating radar.

At low frequencies (\( f < 100 \text{ Hz} \)) the displacement currents are much smaller than the conduction currents (\( \mu \varepsilon \omega^2 \ll i \sigma \omega ; \omega = \text{angular frequency} \)), because \( \varepsilon \) for most rocks is small, and the conductivity, \( \sigma \) for favourable targets in EM surveys is usually >10\(^2\) S/m.

In a vacuum, the electric and magnetic fields propagate at the speed of light (Balanis 1989, Smith 1997). In different soil layers they propagate with lower speed and are scattered by changes of electric and magnetic properties.

The electric and magnetic fields propagate in a straight line until they reach a change in electric or magnetic properties. At the boundary zone between two layers with different properties part of the wave is reflected and the rest is diffracted. This is repeated at the next boundary zone as long as there is wave energy left.

The amplitude of the reflected wave is determined by the Fresnel reflection coefficient, the angles by Snell’s law and a polarization change by the Mueller matrix (phase matrix). Even antenna pattern and distance from the antenna have an effect on the amplitude.
**Slingram**

Slingram instruments consist of one transmitting and one receiving coil. A transmitted alternating electromagnetic primary field with a frequency of approx. 10-50 kHz applied to the ground surface induces secondary fields in the ground. By measuring the total electromagnetic field the variations in physical properties in the soil can be mapped and anomalies caused by anthropogenic activities can be separated from the natural variations.

Measurements of the magnetic component of the total magnetic field in phase with the transmitted field is used to calculate soil magnetic susceptibility using the output unit parts per thousand (ppt) for the ratio of second to primary field, and of the electrical component 90° out of phase to calculate soil electrical conductivity using the output unit millisiemens per metre (mS/m). Consequently a slingram can be a two-in-one instrument.

Depth sensitivity is ruled by frequency and distance between transmitting and receiving coils. Instruments from Geonics EM-series use fixed frequency and coil distance. A survey with both EM-38 (1m long, Fig. 3) and EM-31 (4m long) improves the interpretation due to different depth sensitivities. Other EM-instruments with variable frequencies are available, which allow variations in depth sensitivity with the same instrument.


**Very Low Frequency, VLF**

The VLF method uses electromagnetic waves in the low frequency band of 15-25 kHz generated by radio transmitters normally used for long-range communications and navigational systems. At large distance from the transmitter the wave is planar and horizontal. When the wave passes over a conductor, induced edgy currents cause secondary electromagnetic fields and the primary field is tilted. By mapping this tilt with a hand-held VLF-receiver anomalous conductors can be detected. The output expresses the rate of secondary to primary field in %.

![Fig. 3. Geonics slingram EM 38 (photo Jonas Förare).](image)

VLF is rarely used in archaeology. The method is more suitable for detecting large structures and the accuracy is not sufficient for detailed prospecting. It has, however, been used to find buried pyramids (Deletie et al. 1988).

**Ground Penetrating Radar, GPR**

A GPR system consists of antennae, a control unit and a display (Fig. 6). The GPR technique is based on transmitting electromagnetic pulses from a dipole antenna into the ground and measuring the time until the reflected waves reach a receiver antenna. The velocity of the radar wave through the material is ruled by the equation:

$$\sqrt{\varepsilon} = \frac{c}{V}$$

\(\varepsilon\) = relative dielectric permittivity
\(c\) = speed of light (≈300,000 km/s)
\(V\) = velocity of the radar energy as it passes through a material

*Equation 2. Relative dielectric permittivity and radar velocity relationship*
Usually frequencies between 200 and 500 MHz are used in archaeological investigations. Since the frequency is proportional to the inverse of the wavelength, a low frequency used implies a low resolution, although the depth penetration increases. Amplitude of the reflected wave can give information about the difference between the properties of two adjacent layers. Increasing difference between the dielectric permittivity of adjacent layers in the soil profile gives increasing amplitude of the reflection. The magnitude is defined in equation 3, if the relative dielectric permittivity (RDP) of the materials in two layers is known (Conyers & Goodman 1997):

\[
R = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}}
\]

\( R \) = coefficient of reflectivity at a buried surface

\( \varepsilon_1 \) = RDP of the overlying material

\( \varepsilon_2 \) = RDP of the underlying material

**Equation 3. The coefficient of reflectivity at an interface between materials of different relative dielectric permittivity (RDP) and their relationship (Reynolds 1997)**

The attenuation of the radar wave is related to the magnetic permeability and electrical conductivity of the ground. Most soils are only slightly magnetic but iron-rich soils transmit radar energy poorly. More often soils can be conductive because of saltwater and high clay content, which cause attenuation. When the GPR antennae are moved along survey lines, the reflected signals are plotted versus travel time and distance moved. The variations in the reflected signals in the radargrams can then be evaluated in order to separate artefacts from natural geological variations, which requires good knowledge of geology. The GPR technique is most suitable for detecting layer stratigraphy and subsurface point objects. A point object is presented in the graph as a hyperbola because of spread of the radar wave, which is defined by equation 4 (Fig. 4):

\[
A = \frac{\lambda^2}{4} + \frac{D}{\sqrt{\varepsilon_r} + 1}
\]

\( A \) = approx. long dimension radius of footprint

\( \lambda \) = center frequency wavelength of radar energy

\( D \) = depth from ground surface to reflection surface

\( \varepsilon_r \) = average relative dielectric permittivity of material from ground surface to depth D

**Fig. 4. Equation 4 defining the elliptical footprint caused by the spread of the micro-waves. (Modified from Conyers & Goodman 1997).**

Even before the antennae reach the point right above the object some waves cause reflections because of this spread. These reflections are in the graph marked under the position of the antennae at that time and at a position deeper than the actual depth of the object, because the inclined distance to the object is longer than the vertical distance when the antennae are positioned right above the point object. As the antennae approach the object the distance become shorter and the reflections received from the point object forms a conical curve, a hyperbola pointing upwards (Fig. 5). The form of the hyperbola can be used to calculate the depth of the buried object. The shape of the hyperbolae depends on the velocity of the soil.
A narrow hyperbola means low velocity material and an open hyperbola high velocity material. In most GPR-processing computer programs a hyperbola fitting process is available. Fitting a synthetic hyperbola with known dielectric permittivity to a well-defined hyperbola in the actual profile gives the dielectric permittivity of the media in which the microwaves travel. The velocity of the microwaves in that medium is given by equation 2, and a conversion of the two-way travel time to the depth in metres from the ground surface to the object is possible.

Traditional radar techniques produce vertical profiles showing natural layers and anomalies caused by eventual anthropogenic structures such as diggings, stonewalls and cultural layers. It is not easy in the individual profiles to interpret reflections with low amplitudes. A new technique involving measurements of parallel profiles and computer interpolation produces 3D models of the ground layers.

When studying the pattern of reflection anomalies in a top view it is possible to detect even the low amplitude anomalies if the geometry of patterns makes them visible. By separating reflections with different travel times, it is possible to study changes in structures in the top view at different depths and produce so called time slices or depth slices. This is a digital, non-destructive ‘excavation’ and the first geophysical method that allows high-resolution study of structures at specific depths without influences from overlying or underlying layers (Conyers & Goodman 1997).

**Magnetometric measurements**

All materials are magnetic at an atomic scale. Every atom acts like a dipole due to spin of electrons orbiting 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 magnetization once acquired can be permanent or remanent. In anti-ferromagnetic material magnetic fields of opposite directions completely balance out each other and no magnetization is recordable. There are various intermediate states. In canted anti-ferromagnetic material such as haematite there is a small residual magnetization due to misalignment of anti-parallel magnetic moments. Ferrimagnetic materials, such as magnetite and maghaemite, have a clear magnetization but are slightly less magnetic than ferromagnetic materials because of some opposing fields. Canted anti-ferromagnetic
and ferrimagnetic materials have some permanent magnetization but that is greatly increased by an external magnetizing field and they have a high magnetic susceptibility or ability to become magnetized. Paramagnetic material has net magnetic moments, which are aligned in the presence of an applied magnetic field. Such induced magnetism disappears when the external field is removed (Kearey & Brooks 1984, Clark 1990).

The Earth's magnetic field is caused by rotation and convection in the liquid outer core around the solid inner. The axis of the magnetic poles is not aligned parallel to the Earth's rotational axis and therefore the magnetic and geographic poles do not coincide. The angle between the magnetic axis and the rotational axis varies over time. The movement of the magnetic pole is referred to as secular variation in the pole.

The angle of incidence of the Earth's magnetic field with the Earth surface varies from 90 degrees at the Earth's magnetic south pole (pointing upwards) to zero degrees at the magnetic equator and back to 90 degrees at the Earth's magnetic north pole (pointing downwards). The intensity of the Earth's magnetic field also varies from pole to pole with a maximum at the magnetic poles and diminishes uniformly towards the magnetic equator.

The unit of magnetic flux density is T, tesla but the SI sub-unit nanotesla (nT = 10^-9 T) is normally used. The flux varies from ca 70000 nT at the South Pole down to approx. 30000 nT at the equator and back to approx. 60000 nT at the North Pole (Nordling & Österman 1987).

The most common magnetic rock mineral are magnetite and pyrrhotite. Mafic igneous rocks (basic) are often highly magnetic due to high magnetite content and felsic igneous rocks (acid) are less magnetic.

By measuring the magnetic field with sensitive magnetometers, variations in the magnetite content in soil and bedrock can be mapped. Anthropogenic activities can have redistributed the magnetite and also changed other chemical compounds with iron into magnetite and therefore the mapping can be used to reveal a pattern of anthropogenic activities.

Magnetic minerals received their magnetization when the magma first 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. Furthermore, when heated to above the Curie point, all oxides become demagnetized, but the minerals are remagnetized when the soil subsequently cools, and assume the same magnetic alignment as the current terrestrial magnetic field. The magnetic fields of the individual particles then coincide and the place can be recorded by means of magnetic mapping (Clark 1990).

Magnetic prospecting is probably the most used method in archaeology so far and a lot of very good results with high accuracy are reported. Modern portable gradiometers are very easy to operate and produce maps with high accuracy for the upper few metres of the ground (Fig. 7). They measure the vertical gradient of the magnetic field in nT/m as the difference of field measurements from two sensors about one metre apart.

Features suitable for this method are for instance fortresses, defensive walls, gates, pits, trenches, ditches and hearths (Becker & Fassbinder, 2001, Mercer & Schmidt, 2001).
Fig. 7. Bartington gradiometer Grad 601.

Sampling
In all methods, sampling density depends on expected size of the features searched and on the instrument resolution and coverage. Along the survey lines very dense sampling is possible, especially with GPR and gradiometric methods. It is desirable to get as good coverage as possible even between lines but sometimes compromises must be accepted due to working time and cost.

Slingram measures a volume defined by the coil design. Geonics EM-series transmit a magnetic field with vertical focus with a maximal depth sensitivity of 1.5 metres and approx. 0.75 metres sensitivity to both sides, which means that a survey with line spacing and measurement density of not more than one metre is accepted to get full coverage. When searching for large and especially elongated features a less dense grid can be accepted.

GPR antennae transmit a cone formed radar beam with an elliptical footprint increasing with depth and also depending on the soil relative dielectric permittivity. The long axis of the ellipse is directed in the walking direction, but there is also a spread to the sides. Hence the coverage increase with depth and is also dependent on the relative dielectric permittivity of the soil. In single profile surveying, the accuracy and coverage are only defined by the sampling distance. In multi line sampling for 3D modelling, a distance not exceeding 0.5 metres between survey lines is recommended in order to get acceptable coverage between lines.

Gradiometers measure only the magnetic field passing through the sensors and there is no other way to get an acceptable coverage than to keep a short distance between survey lines. Along survey lines very dense sampling is possible, while between lines 0.5 metres or a maximum of 1 metre is recommended.

Modelling
Only two decades ago, analogue geophysical instruments were used for sampling in lines along tape measures. Measurements were recorded by writing or perhaps by tape-recorders. Consequently the number of readings was limited, as were both access to, and need of, advanced computer modelling programmes.

When digital sampling became available the sampling frequency could be increased drastically and the number of data to interpret became difficult to handle. Computer programmes were then developed for data treatment, statistical analysis and graphic presentation in various diagrams and maps. The displayed grid density can now be digitally increased by statistical interpolation with, for instance the Kriging method (Cressie 1990), and results can be presented as 2D contour maps or as 3D surfaces (Paper IV). Computer programmes make it possible to edit and filter to search for any anomalous patterns, which improves the interpretation.
Fig. 8. Model of present Björkö Island, Lake Mälaren, Middle Sweden (top) and of Björkö in the Viking Period (bottom). Ground surface triangulated from topographic data and rendered in MicroStation CAD. Water table raised in bottom picture to sea level of the Viking Age. From Paper IV.

Digital Terrain Modelling (DTM) makes it possible to construct a terrain model from topographic data by triangulation. This triangulated net can be manipulated in the computer and by e.g. exaggerating the height, the visibility of terraces may be improved. It is also possible to use hill shading, to attach a texture to the surface and to place a water table at various levels to simulate shoreline displacements as in Fig. 8.

2D contour maps of geophysical and geochemical data can be wrapped on 3D terrain models and the distribution of geophysical and geochemical parameters with geometry, location and exposure of the anomalies can be studied at the real topographic variations of the ground surface, which improves the interpretation.

Geophysical data can also be used to construct 3D-models of the anomalous source body and hence visualize the extent of potential source structures (Eder-Hinterleitner et al. 1995, Conyers & Goodman 1997).

In the present research, modelling in 2D and 3D and the use of Geographical Information System (GIS) to produce overlays of topographic data, earlier research data and prospecting survey data, proved to be of great value and great importance as an interpretation tool.
RESULTS

Settlements:

Vendel

Within the project Svealand in Vendel and Viking Periods (SIV), geophysical and geo-chemical prospecting was carried out in attempts to find settlements connected to the famous boat graves excavated in the 1880’s (Stolpe & Arne 1912). The project is described in Papers II and IV.

Fig. 9. Vendel church with the two survey areas in rectangles, excavation trenches marked in dotted lines and two GPR-lines.
Southwest of the churchyard stonewall in Vendel (Fig. 9) an early phosphate mapping had detected an anomaly with increased phosphate. Surveys at Area 1 with slingrams (EM 31 and EM 38), gradiometer and GPR all showed anomalies at the same location and the excavation revealed the remains of a very well preserved bronze-casting furnace with a bell pit (Fig. 10). The furnace was dated using the thermo-luminescence method to the 16th century, which is the last time the furnace was heated, but it is possible that it was in use for a long time before that date (Anund 2001).

Fig. 10. Survey Area 1 at Vendel church (Fig. 9) with excavation trench and some revealed features together with results from EM 38 as contour map (grid density 1 m), EM 31, Gradiometer, GPR and test coring with symbols. Photo of the excavated furnace (photo Kjell Persson).
South of Vendel church

GPR profiles south of the church from the stonewall down the slope (Fig. 9) showed a horizontal subsurface layer interpreted as a former ground surface on a terrace with possible accumulated cultural layers (Figs. 11 and 12). Slingram surveys and phosphate mapping also indicated anomalies (Fig. 13). Recent earth moving had levelled and smoothed the slope, but previous topographic measurements made it possible to reconstruct the former ground surface with a terrace (Fig. 14).

Excavations revealed a terrace with remains of cultural layers from Stone Age to historical time. Preserved postholes from two gable posts, seven roof supporting posts from a 30-metre long residential building and postholes and a wall line from a farm building were also found (Figs. 11 and 15). Both buildings were dated to the Late Migration Period - Vendel Period and thus contemporary with the boat graves, which were dated to 550 AD -1000 AD. (Persson & Olofsson 1995, Persson 1998, Isaksson 2000, Isaksson et al 2002.).

Fig. 11. Radargram and excavation results along profile GPR 1 south of Vendel church (Fig. 9). Frequency 200 MHz.
Fig. 12. Interpretations from radargrams GPR 1 and GPR 2 at Vendel church (Fig. 9). Modified from Persson & Olofsson 1995.

Fig. 13. EM-38 readings with magnetic component in ppt (parts per thousand) and soil phosphorus distribution in Survey Area 2 at Vendel church (Fig. 9). 1P= 10 ppm P₂O₅. Grid density in both surveys 1 m.
Fig. 14. Digital Terrain Model of the Vendel church area before levelling and planning in 1960’s with excavated terrace at black arrow (from Paper IV).

Fig 15. Excavation results from Area 2 at Vendel church (see trench placement in Fig. 9).
Medieval churches

Arethousa

As part of an archaeological project led by Dr Arja Karivieri, the Finnish Institute at Athens, slingram measurements of both magnetic and electric components were carried out 1999-2000 in Arethousa, Greek Macedonia in attempts to detect subsurface walls of an already partly discovered Christian Church from the 5th century (Fig 16). Phosphate mapping combined with slingram survey (EM 38) was also used in attempts to detect settlements from the same time on a terrace close to the church. Based on a slingram survey at the church, linear structures were indicated north and west of the already excavated walls. Subsequent excavations revealed another stone-wall coinciding with the linear anomalies in the measurements. The northern aisle within this wall and the previous was in fact used for wine production. In the western room treading floors for wine production were excavated and an outlet pipe to an adjacent room, where pithos vessels for wine storing were still intact under the floor. A well-preserved hearth was also found, coinciding with a strong magnetic anomaly (Karivieri 2003).

Fig. 16. Plan from July 1999 of the excavated part of the church in Arethousa, Greek Macedonia, and contour maps of the distribution of soil magnetic component in ppt (parts per thousand). Grid density 1m. Photos of a reused marble grave relief from AD 300 (bottom left, photo Arja Karivieri), the new found stone wall (bottom middle, photo Kjell Persson), and the excavated new aisle with treading floors and the pithos vessels in the background and hearth in front (bottom right, photo Arja Karivieri).
**Old Uppsala church**

The first cathedral in Old Uppsala was built in the 12th century and was destroyed by fire in the 13th century. A new cathedral was then built in the present Uppsala and a smaller church in Old Uppsala. Earlier research and excavations had detected remains of stone-walls at a few places from the first cathedral in Old Uppsala. In July 2003, a GPR survey (500 MHz) was carried out within the Project for Non-destructive Archaeology in Old Uppsala in attempts to detect the extent of preserved subsurface stonewalls of the old cathedral and any other features (Fig. 17). The project was led by Neil Price and Magnus Alkarp, Uppsala University. A new method was tested using a RAMAC GPR, 500 MHz, for scanning of two areas, north and south of the recent church, respectively.

Parallel survey lines every 0.5 m were used in two modelling programmes, Easy3D, from Malå Geoscience (Figs. 18-19) and GPR-Slice Imaging Software developed by Dean Goodman, Geophysical Archaeometry Laboratory, California (Figs. 20-21) to interpolate between the measured radar profiles and create three-dimensional blocks of the ground and time/depth slices. On screen top-, side- and front views can be seen together with the 3D block. When a ruler in the front view is moved downwards, the top view changes and shows the reflection pattern at different depths in time slices. The changes can be presented in a slideshow as a virtual excavation in a realistic way. Both north and south of the present church a preserved subsurface structure from the first cathedral was seen at 0.25–1.50 metres (Alkarp & Price 2003)

![Fig. 17. Old Uppsala church in black with the extent of the old cathedral interpreted from earlier research in grey. Survey Areas 1 and 2 in black rectangles.](image-url)
Fig. 18. Radar results processed in Easy 3D from Area 1 with top view at 0.5 m depth, side view, front view and 3D-model. Reflection pattern confirms earlier interpretations. Sampling interval 0.03 m along lines, 0.5 m between lines.

Fig. 19. Radar results processed in Easy 3D from Area 2 at Old Uppsala church with top view at 0.4 m depth, side view, front view and a 3D-model. Reflection pattern confirms earlier interpretations. Sampling interval 0.03 m along lines, 0.5 m between lines.
Fig. 20. Time slices processed by Dean Goodman in GPR-Slice Imaging Software from Area 1 and Area 2. Sampling interval 0.03 m along lines, 0.5 m between lines.

Fig. 21. 3D-model with top view of Area 1 and 2 at Old Uppsala church at 0.55 m depth processed by Dean Goodman in GPR-Slice Imaging Software. Sampling interval 0.03 m along lines, 0.5 m between lines.
Historical gardens

In attempts to develop and evaluate geophysical and geochemical prospecting as a tool in restoration of historical gardens, slingram mapping with EM 38 of both magnetic susceptibility and electric conductivity, GPR profiling and phosphate mapping were conducted at three different gardens, Strömsholms castle (EM, GPR), Grönsöö castle in middle Sweden (EM, GPR, phosphate) and Bogstad gård in Oslo, Norway (GPR) (Fig. 1). The objectives were to detect possible subsurface remains of gravel-walks, stonewalls, water dams and channels, cultivation beds or other features.

**Strömsholm**

From June to September 2002 a comprehensive geophysical slingram survey with EM 38 and a GPR survey (250 MHz) during six days was carried out at the former kitchen garden of Strömsholm castle in south central Sweden (Fig.1) in a project led by Katarina Frost, the Swedish University of Agricultural Sciences, Uppsala. The objectives were to examine whether geophysical measurements of soil properties could detect subsurface structures from earlier land use at the kitchen garden and be a non destructive tool in park conservation.

Excavations showed that structures like gravel walks, drainage ditches, plant pits and dam remnants were best detected by GPR surveys (Figs. 22 and 25). The GPR anomalies showed good correlation with features in an older map (Fig. 26). Some features were detected by slingram surveys (Fig. 24), but maybe because the field had been ploughed and surveys were performed in a very dry summer, most indications by the slingram were diffuse (Frost & Jonsson, 2002).

![Fig. 22. The kitchen garden at Strömsholm castle with survey areas in dotted rectangles (top left) and radar lines with interpretations in Area 1 (top right) with an example from radargram profile 9 (bottom). Sampling interval 0.03m](image-url)
For many decades, the Swedish Land Survey (Lantmäteriet) has produced aerial photographs covering the whole country. Not so many years ago, out-prints of requested photos were delivered by mail and were not possible to edit. Now a database with digital photographs is available on the Internet, which provides a very good, fast and cost-effective physical prospecting method.

Within the Strömsholm castle project, the raw aerial photograph over the kitchen garden was downloaded. Not many features were visible that were not visible also in the field. After a change of grey scales and filtering, much more information became available, like features interpreted as a dam inlet and outlet, the borders of different earlier gardens and possible gravel walks. (Fig. 23).

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*Fig. 23. Air photo of the kitchen garden at Strömsholms castle. Raw photo left and filtered photo right.*
Fig. 24. Distribution of magnetic component as parts per thousand (ppt) and electric conductivity (mS/m) in Area 1 at Strömsholm castle. Grid density 1m. Photos of stone features found in trench. Photo Kristina Jonsson (left) and Margaretha Larsson (right).
Fig. 25. Stone filled ditch for dam drainage (top, photo Kristina Jonsson) and radargram profile II, (bottom) at the kitchen garden of Strömsholm castle. Sampling interval 0.03m

Fig. 26. Overlay showing the good correlation of radar anomalies marked with black rectangles and a system of gravel walks on an older map of the kitchen garden. Illustration Kristina Jonsson.
Grönsöö

From 2000 to 2003, geophysical surveys were conducted at Grönsöö castle, south central Sweden (Fig. 1) in attempts to detect subsurface features from earlier stages of the castle garden. At the house garden the survey included phosphate mapping, slingram measurements of both magnetic and electric components and radar profiling (Fig. 27). The project was led by Torbjörn Sunesson and Sophia Normman, Swedish University of Agricultural Sciences (SLU) in Uppsala. The phosphate mapping did not show any anomaly pattern. Both slingram and GPR surveys indicated house foundations from known buildings and a right-angled structure just north of the road (Figs. 28, 29). The structure is interpreted as a possible block row with more organic soil within the structure than outside causing the observed increased electric conductivity and decreased radar penetration. A multi-folded radar survey in March 2004 was then used to produce a 3D-model of the ground at the same right-angled structure (Fig. 29).

Fig. 27. The house garden at Grönsöö castle with radar lines and interpretations. Area for slingram survey in solid line and area for 3D-modelling in dotted line.
Fig. 28. Slingram results and interpretations from the house garden at Grönsöö castle, magnetic susceptibility in parts per thousand (ppt), left and electric conductivity in millisiemens per metre (mS/m), right. Grid density 1m

Fig. 29. 3D model of Area 1 at Grönsöö house garden, processed in Easy3D with the right-angled structure at 0.4 m depth marked with white dotted line. Sampling interval 0.03 m along lines, 0.5 m between lines. Frequency 500 MHz
**Bogstad gård**

In September 2003, a field survey with GPR (Ground Penetrating Radar) was carried out with 250 MHz antennae at the garden of Bogstad Gård, Oslo, Norway (Figs. 1 and 30). The purpose was to see whether the survey could detect any subsurface features and be of assistance in the restoration plans for three older dams. The project was led by Anne Kaurin, Landskapsfabrikken, Oslo. Excavations revealed a wooden construction (Fig. 33) that was detected as hyperbolas in two parallel profiles (Fig. 31). Other hyperbolas can be a result from similar wooden constructions.

The concentration of hyperbolas between ponds 2 and 3 was interpreted as being caused by stone concentrations (Fig. 31). Some stones were still visible above ground surface. Excavations later also confirmed that interpretation (Fig. 34). An important result of the survey was the detection of the pond bottom outline based on layer reflections (Fig. 32) (Damstuen 2003).

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*Fig. 30. Survey area at Bogstad gård, Oslo, with the three ponds in red and radar area grids 1-5.*
Fig. 31. Radargrams from Bogstad gård, Oslo, showing Pond 1 with interpretations. Sampling interval 0.03 m

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Fig. 32. Interpretation of pond bottom outline of Pond 3 at Bogstad gård, Oslo, with one radargram example. Sampling interval 0.03 m
Fig. 33. Wooden construction, approx. 1 m height, in Pond 1 at Bogstad gård, Oslo (photo Anne Kaurin).

Fig. 34. Stone concentration between Pond 1 and Pond 2 at Bogstad gård, Oslo (photo Anne Kaurin).
Glassworks
Slingram measurements with Genonics EM38 for detecting any remains of furnaces and buildings at historical glassworks were tested at Bryggholmen island in Lake Mälaren (Fig. 1), where it is known from written sources that the glass-works of King Johan III was situated between 1580 and 1640. A lot of glass fragments can still be found in the area. In September 2002, a slingram survey was conducted at the presumed location of the furnace in a project led by Lars G. Henricsson.

On the northern side of the main building some rectangular anomalies indicated possible remains of a building and a point anomaly was interpreted as being caused by a possible furnace.
Later excavations partly confirmed this interpretation and stone rows from house foundations were found together with a cooking furnace (Fig. 35).

Fig. 35. Distribution of soil magnetic component in parts per thousand (ppt) from Bryggholmen (left). Grid density 1 m. Excavation result in drawing (top right) and in photo (bottom right) (photo Lars G. Henricsson).
Mounds
The choice of geophysical methods for mapping of subsurface mound structures depends on the height of the mound. When the height exceeds the depth sensitivity of the actual instrument it may not be possible to detect e.g. a central cairn. However, it is valuable to map the outer layers of the mound down to the maximum depth sensitivity of that instrument. The use of different instruments or instrument configurations sometimes makes it possible to determine the depth to the cause of anomalies (Paper V). A GPR survey with a low frequency is probably the best suited method to visualize the inner structure of a mound. The King’s Mounds of Uppsala were mapped during the present work with 50, 200 and 250 MHz antennae with penetrations of approx. 15, 10 and 7m respectively (Figs. 36 - 38).

Fig. 36. Radar profile from the Eastern Mound, Old Uppsala measured with 50 MHz antennae (Modified from Persson 2004b). Sampling distance 0.2 m

Fig. 37. Radar profile from the Eastern Mound, Old Uppsala measured with 200 MHz antennae (Paper V). Sampling distance 0.5 m
In Old Uppsala, combinations of GPR profiles and 2D electromagnetic and gradiometric contour maps displayed with 3D topographic models provided a good picture of the inner structure of the mounds. This made it possible to interpret the placement of the central cairn, an older possible grave under the Eastern mound, an earlier excavation tunnel and two potential rows of boulders from the mounds base to the top (Paper V). The middle mound also had linear structures from base to top and anomalies interpreted as being caused by houses and cultural layers at the base of the mound. The contour maps can be presented in 3D, together with the topographic model (Fig. 39).
The GPR survey at the Thing Mound in Old Uppsala made it possible to state that the mound had not been used as a burial mound. The inner structure showed a pattern of typical glaciofluvial, backstream beddings. A plausible interpretation of the reflection pattern is that the top was levelled by man and probably prepared to become a burial mound (Fig. 40). Similar results have been reported from a GPR survey in Wisconsin by Kloehn et al. (2000). They investigated some mounds that had been protected as Pre Columbian Native American burial mounds. Similar natural eolian deposits surrounded the mounds. The GPR survey showed an inner structure of typical eolian deposits and the mounds were interpreted as being of geological origin (Fig. 41).

Fig. 40. GPR profile of the Thing Mound at Old Uppsala showing the typical reflection pattern of glaciofluvial backstream beddings. Previous geological structure interpreted as flattened on top. From Paper V. Time-depth conversion by assigning average velocity for dry sand.
DISCUSSION

All prospecting involves planning - field measurements - data processing/modelling and interpretation.

Planning
The planning consists of literature, archive and map studies but also the choice of methods, instruments, instrument configurations and sampling strategy.

Field measurements
The sampling density is usually determined by the size of the expected subsurface features. A distance between measurements of not more than half the smallest dimension of expected features is recommended. It is desirable to choose the same sampling density in both X- and Y-directions. Today's geophysical digital equipments make very dense sampling down to every centimetre possible along the survey line and it is not practically possible or necessary to use the same density between lines. Both GPR and slingram methods have a spread of the electromagnetic fields and hence they have certain coverage also to the sides. To produce an acceptable coverage of a survey area, a distance of 0.5 - 1m between survey lines is recommended. A normal sampling density for phosphate mapping is 5m but sometimes the method is used to detect room-dividing walls and then of course a denser grid of at least one metre is needed.

In our slingram surveys with Geonics EM-38 a sampling distance of 1m along survey lines was used because of the expected size of any features.

Profiling with GPR is normally a single line method with a sampling distance of 2-5 cm along the line. When a GPR survey is used to construct three-dimensional models of the subsurface structure not more than 0.5 m is recommended between survey lines.

Data processing/modelling
Data processing and modelling aim to search for and visualize anomalous structures and to present results in graphs or maps.
Negative values observed with an EM-38 (or other EM devices) are a result of numerous factors and are generally observed over metallic bodies (less than the intercoil spacing) or elongated targets of sufficient contrast (resistivity). Another complicating factor is that the response varies in polarity to such a target depending on the height/depth between the object and the instrument. Generally these negative values are explained by a phenomenon known as ‘current gathering’ (McNeill 1990). In order to simplify the interpretation for archaeological prospecting, the use of the nominal value only is recommended, which in the graph gives a zero value/colour at undisturbed conditions and higher values/colours at anomalies. Otherwise, two different colours are needed to differ between negative and positive values.

**Interpretation**

An archaeological interpretation process is always in three steps:

- Noting measurement anomalies
- Differentiating between natural and anthropogenic anomalies
- Identifying and describing possible features causing the anthropogenic anomalies.

The interpretation should be restricted to terms of pattern descriptions such as 'linear structures', 'right-angled structures' etc and terms like 'house' and 'building' should not be used. Terms like 'possible house' can be used if different methods indicate for instance right-angled structures together with phosphate enrichment just outside, and maybe a road to the structure. Identifying and describing the possible features should always be done together with the archaeologists.

Accessibility to equipment and cost conditions had an effect on the choice of methods selected for the different archaeological sites in this research. Other scholars in their surveys may have used other combinations with good results.

Soil phosphate mapping was already a well-known method in Sweden, but in these surveys a combination of phosphate mapping with one or more physical surveys was used in attempts to improve the conditions for successful archaeological interpretation.

A new field kit for on-site phosphate analysis, developed and patented by the author (Paper III), made interactive field prospecting possible, including phosphate mapping and various geophysical properties.

The first tests in Vendel with a VLF survey showed that the instrument used (Geonics EM-16) did not have sufficient spatial resolution for the actual purpose and no more VLF measurements were carried out. The instrument is more suitable for detecting elongated conductors and showed no reaction to smaller features found at later excavations.

EM measurements in Vendel with slingrags (Geonics EM 31 and EM 38) proved to be more useful and EM 38 in particular became a regularly used method in the following surveys (Paper II).

DC resistivity measurements have been shown by others to be useful for archaeological prospecting and are an alternative to conductivity measurements with slingram (Atkinson 1963, Dahlin 2001).

Screening measurements with an analogue Vallon fluxgate gradiometer were successfully used in both Vendel and Old Uppsala (Papers II, V) and a digital Bartington gradiometer was tested at the smaller mounds in Old Uppsala.

Profiling with GPR was a success already at the first attempt in Vendel (Paper II). The method has great pedagogic value since the results presented as radargrams are very reminiscent of the ordinary layer profiles that archaeologists are used to. In 3D CAD programmes, it is possible to present the subsurface layers in place along the GPR lines, which together with the spatial distribution of other geophysical soil properties and the phosphate content enhances the interpretation possibilities.
In Old Uppsala, a new method to produce digital 3D blocks of the ground by interpolation between parallel profiles was used. On screen top-, front- and side views of the area are interactively displayed together with a 3D block. When a ruler in e.g. the front view is moved downwards, the top view changes and shows the actual reflection pattern at different depths. The method is very reminiscent of archaeological excavations and it is the first geophysical method to allow study of the physical properties at a certain depth without influence from layers above or below. This method is most suitable for remains with regular linear and right-angled patterns such as stonewalls and house grounds. It will most certainly come to more frequent use in future studies of urban settlements, medieval churches, castles, historical gardens etc.

As seen in Table 1, the optimal combination of methods depends on the expected features. Based on the results of this research a combination of

- Phosphate mapping
- Slingram/magnetic/resistivity survey alternatively or combined
- GPR

...can be recommended for archaeological prospecting.

*Table 1. The usefulness of different prospecting methods on various archaeological features graded as X - 'possible', XX - 'good' to XXX - 'very good'*

<table>
<thead>
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<th>Expected archaeological features</th>
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<th>Gradiometer</th>
<th>Resistivity</th>
<th>GPR</th>
<th>Phosphate</th>
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**Conclusions**

During the work for this thesis, combinations of a number of geophysical methods and phosphate analysis were used for detection of different kinds of prehistoric subsurface structures and artefacts.

Such combinations of different independent methods proved to enhance the possibility of selecting the areas for further investigations during archaeological prospecting and finally of choosing the optimal trench location for excavation. The combinations also proved to enhance the potential for correct archaeological interpretation of the excavated findings and features.

The use of GIS based 2D and 3D modelling to analyze and present the result has proved to be of great pedagogical value and also to be an important tool for interpretation.

A new field kit for phosphate analysis has been developed and patented.

Further important results of this research were also the new knowledge obtained of the inner structure of the Kings’ Mounds in Old Uppsala, Sweden and in particular the revelation of
the glaciofluvial inner structure of the Thing Mound, which showed that it had never been used as a burial mound.

The experiences obtained from some years of different surveys within the research for this thesis led to a recommended concept of combined geophysical and geochemical prospecting methods.

FUTURE RESEARCH

Future research should deal with the development of a systematic prospecting model using a combination of geophysical and geochemical methods for various artefacts, different geological environments and seasonal changes in weather conditions.

A method for a combination of anomalies from different measurements using a structural, statistical approach should also be developed.
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