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MAGNETIC SURVEYING in ARCHAEOLOGY

**More than 10 years of using
the Overhauser GSM-19 gradiometer**



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PART 1 Principles of magnetic surveying

Preface *In this book we have collected information about magnetic prospecting of archaeological sites. We have based most of our examples on the use of the Overhauser magnetometer-gradiometer GEM-19WG from GEM Systems. Our aim has not been to give a full explanation of neither the physical principles of the method nor of the magnetometers; rather, we have collected references from books and articles where the reader can find detailed information. We have concentrated mostly on practical aspects of magnetic survey for the investigation of archaeological sites situated in different geographical and geological conditions. Therefore, we have submitted as many examples from our field work as possible.*



INTRODUCTION

Geophysical methods for the investigation of features under the earth were developed initially for studying geological structures, but during recent years they have become more and more important for archaeological prospecting. Since Atkinson's application of electrical resistivity in 1946, archaeologists have increasingly employed classical geophysical methods which have resulted in successful investigations of many cultural resources (Weymouth, 1986). Improved geophysical instruments and application methods, together with computer data treatment and interpretation have, in many cases, allowed study and measurement of subsurface contrasts attributable to historic and prehistoric human-related activities through extreme precision and high speed, thereby avoiding any destruction. Therefore, one could say that geophysical methods allow a non-invasive identification of buried archaeological features.

The use of proton magnetometers in the early 1950s is often considered the first important application of a geophysical methods in an archaeological investigation (Heimmer, De Vore, 1995, p. 3). Magnetometer surveys are among the most effective and universal among the geophysical methods used for archaeology because many archaeological objects have distinctive magnetic properties which allow one to distinguish them on the surface of the site by the specific magnetic anomalies they create.



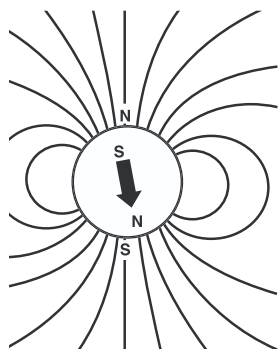


Martin Aitken using the prototype proton magnetometer. The detector bottle is supported on a tripod in the background. (Adapted after Clark, 1990, p. 17).



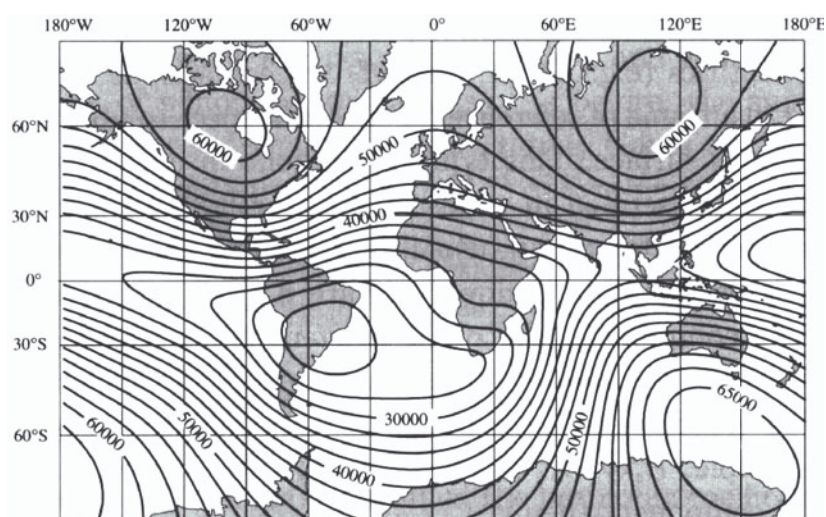
Schematic presentation of the Earth's magnetic field.

THE METHOD of MAGNETIC SURVEYING

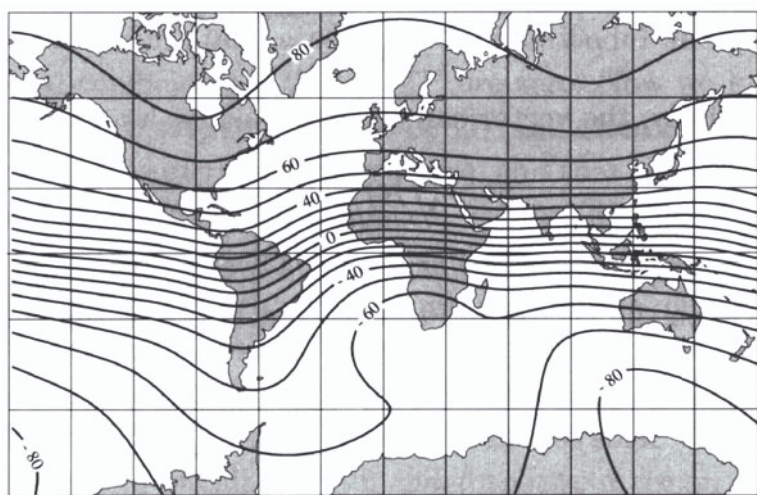


The Earth's magnetic field

Magnetic fields exist around us. We can not see or feel them, but we can measure them with sensitive instruments called magnetometers. The Earth's magnetic field is approximately the same as would be produced by a large bar magnet near the Earth's center, oriented with the positive end towards the North pole and inclined at an angle of 10° to the axis of rotation. The field, or flux lines of the Earth exhibit the usual pattern common to a small magnet. They are vertical near the poles and horizontal near the equator (Breiner, 1973).



The total intensity of the earth's magnetic field.



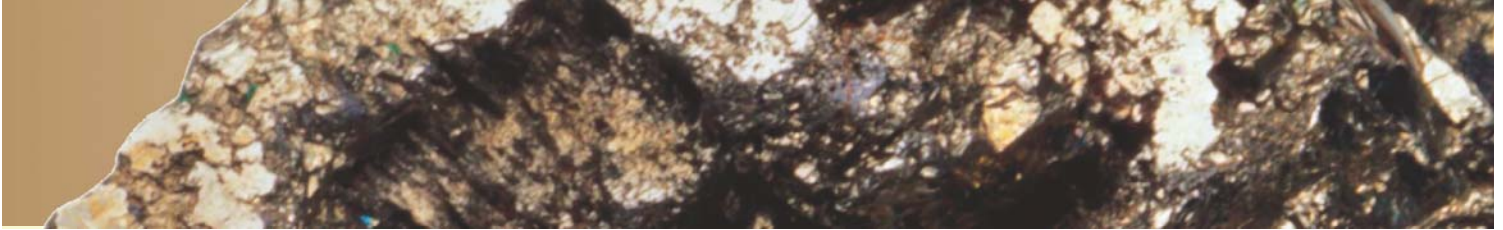
The geomagnetic inclination in degrees from the horizontal.

In favourable conditions magnetic prospecting is the most effective, fast, and absolutely non-destructive method for the investigation of archaeological sites; the information one can obtain by magnetic prospecting is close to that which is revealed during actual archaeological excavations.

Iron constitutes about 6% of the Earth's crust. Most of it is dispersed through soils, clays and rocks as chemical compounds which are magnetically very weak. Man's activities in the past (especially the use of fire for heating, cooking, production and industry) have changed these compounds into more magnetic forms, creating special patterns of anomalies in the Earth's magnetic field, detectable with sensitive instruments - magnetometers.

The method of magnetic survey is a passive geophysical technique based on the detection of contrasts in the magnetic properties of different materials. In the event that such contrasts do not exist, magnetic prospecting will not be useful. To do magnetic prospecting, one simply measures the Earth's magnetic field with a small measurement spacing and very close to the surface.

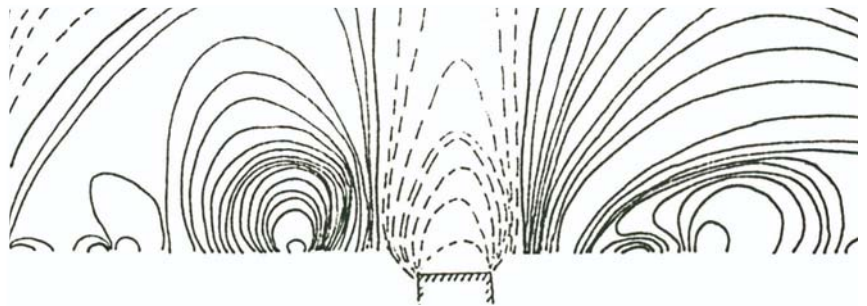
The intensity of the Earth's field is three times as great in the polar region (approximately 70,000 nT) as in the equatorial region (25,000 nT). Elsewhere on the Earth, the global magnetic field parameters are between these limits. For example, the inclination and total magnetic field intensity for Denmark is 69° and 48,000 nT respectively.



Magnetic anomalies

If the Earth were composed of uniform material, the magnetic lines of force would be evenly distributed between the poles; in a small area the lines would be parallel. However, since various materials have different magnetic susceptibilities due to their composition, the Earth's magnetic lines of force are distorted. The local disturbances of the global magnetic field are called magnetic anomalies (Breiner, 1973).

The anomalies from archaeological objects or naturally occurring rocks and minerals are due chiefly to the presence of the most common magnetic mineral, magnetite, $\text{FeO} \cdot \text{Fe}_2\text{O}_3$, or its related minerals. All rocks contain some magnetite, ranging from very small fractions of a percent to several percent.



Observed vertical distribution of the total field lines of flux at the Hellenistic settlement Generalscoey, Crimea.

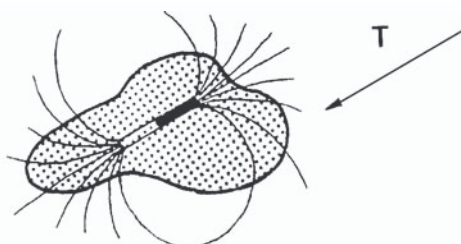
	Magnetic Susceptibility, SI									
	0,000001	0,00001	0,0001	0,001	0,01	0,1	1	10	100	
	Percent of Magnetite by Volume 0,1% 0,5% 1% 5% 20% 100%									
Metallic Iron										IRON
Magnetic Minerals				HEMATITE	IRON SLAG		MAGNETITE			
Igneous Rocks					BASALT					
					FIRED CLAY					
					GRANITE					
					HEATED SOILS					
					GABBRO					
					DIORITE					
Metamorphic Rocks					QUARSITE					
					SANDSTONE					
					TOPSOILS					
					SUBSOILS					
					MARBLE					
Segimentary Rocks					CHALK					
					LIMESTONE					
					SAND					

THE METHOD of MAGNETIC SURVEYING

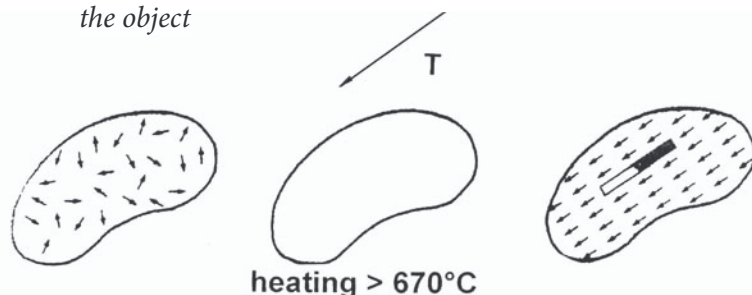
Magnetic anomalies within the Earth's magnetic field are caused either by induced or remanent magnetism.

Induced magnetism simply denotes that an item within the earth's magnetic field becomes magnetized by the action of the Earth's magnetic field on it.

Induced magnetization of the object.



Remanent magnetization of the object



high temperatures, small regions, called domains, reorient themselves, which upon cooling tend to align themselves more or less in the direction of the contemporary Earth's magnetic field and are thus parallel to each other, creating a net magnetization fixed with respect to the object (Heimmer, De Vore, 1995, p. 12).

Both kinds of magnetism are very important in archaeology. The induced magnetisation is directly proportional to the intensity of the ambient field and to the ability of the material to enhance the local field – a property called magnetic susceptibility, χ (or κ). Magnetic susceptibility is the ease with which a substance is magnetized by the Earth's magnetic field (Heimmer, De Vore, 1995, p. 12)

The variations in magnetic susceptibility between topsoil, subsoil and rocks (topsoil is normally more magnetic than subsoil) affect the Earth's field locally, making it possible to detect ditches, pits and other silted-up features which were excavated in ancient times and then silted or backfilled with topsoil. They will produce a positive magnetic signal. Conversely, less magnetic material introduced into the topsoil, including many kinds of masonry – for example, limestone walls – can be detectable by a subtractive effect which gives a negative signal.

The remanent magnetization is related to the effect of heating, whether naturally heated as in the case of igneous rocks, or artificially heated, as in the case of baked clay, pottery, and other man-made objects found in archaeological sites. This remanent magnetization can be as much as ten or more times greater than the induced magnetization.

Archaeological objects such as kilns, furnaces, slag blocks, and fire places, possess rather strong remanent magnetization. If they are still in situ, one can date them by measuring the direction of their magnetization or by analysis of magnetic anomalies over them.

Thermoremanent magnetism is acquired while clay is in the process of cooling down and remains 'frozen-in' once the clay is cold. The figure on the right demonstrates the thermoremanent magnetization of a big clay vessel – a Medieval pithos from Crimea.

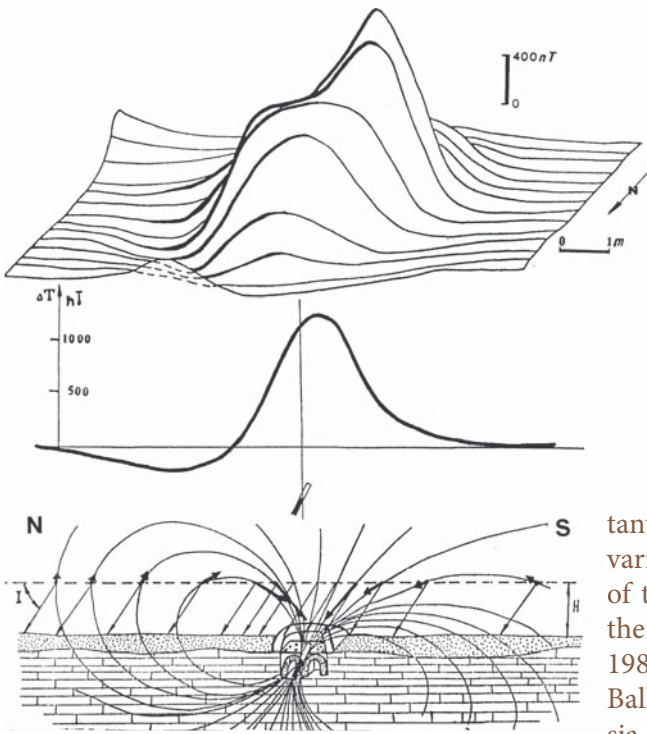


Measuring magnetic susceptibility of backfill in Neolithic flint mines filling in Hov, Jutland, Denmark with help of the Russian instrument PIMV-1M

Remanent magnetism means the magnetism that an object has in the absence of a magnetic field. During heating, particularly at



*A bread oven.
Dakhleh Oasis,
Egypt.*



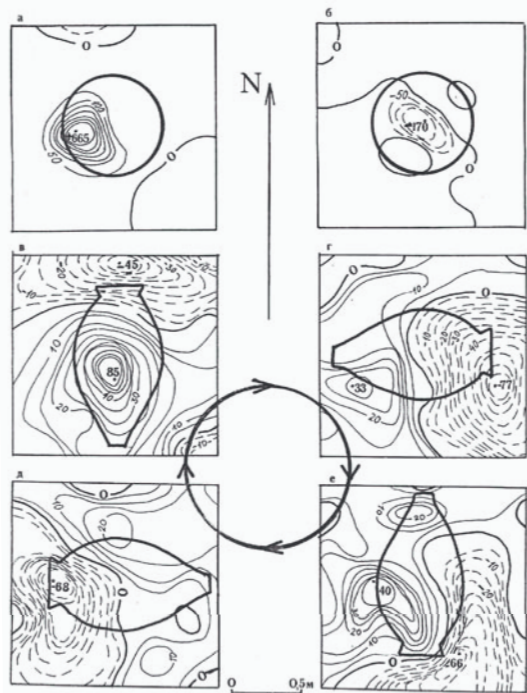
The scheme of the creation of the magnetic anomaly over a kiln.

For archaeomagnetic dating it is important to know the master curve of the secular variations of the declination and inclination of the Earth's magnetic field. It is known for the United Kingdom (Clark, Tarling, Noël, 1988), Italy, Bulgaria (Kovacheva, 1969), Balkans (Kovacheva, Vejovich, 1977), Russia (Бурлацкая, 1965), Southwest and North America (Watanabe, DuBois, 1965), Arkansas (Wolfman, 1979), and the Ukraine (Загний, Русаков, 1982); it was transformed from the British curve for the conditions of Denmark by N. Abrahamsen (Abrahamsen, 1996).

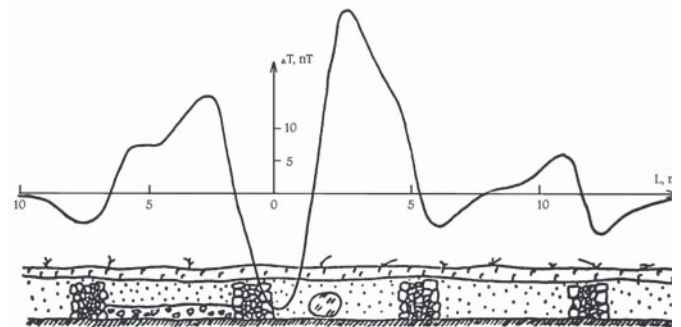
Thus, negative and positive magnetic anomalies over different archaeological structures can cause complicated patterns that are rich in information.

Utilizing sensitive instruments, the Earth's magnetic field can be measured with great precision, with an accuracy of one nanotesla (nT), or one tenth of nT. In Northern Europe, the Earth's magnetic field is approximately 50,000 nT. Archaeological earthen structures typically show local magnetic anomalies in the range of 1-20 nT; more rare fired structures show 10-1,000 nT; quite rare ferrous archaeological objects - including iron-smelting slag blocks show 20-2,000 nT.

Typical magnetic anomalies of common archaeological features.

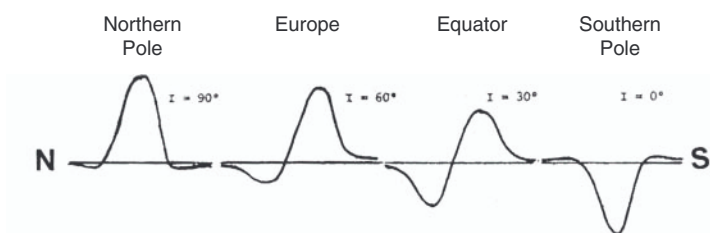


The magnetic field, measured over a big Medieval pithos with different rotations of the pithos: above left - on the mouth; above right - on the bottom; four maps below - on the side.

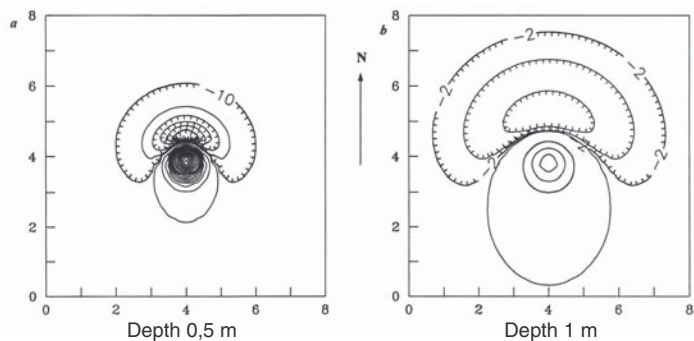


THE METHOD of MAGNETIC SURVEYING

Briefly, it is necessary to notice some properties of local anomalies from archaeological objects. The asymmetrical nature of the total magnetic field anomalies is primarily a consequence of the usually-inclined direction of the Earth's magnetic field. The anomaly over the same dipole has a different shape in different areas of the Earth: near the poles, in middle latitudes, and at the equator (see the upper figure, below). Another significant characteristic of a magnetic anomaly is its variation with the distance between the magnetometer and the source: the deeper the source, the broader the anomaly, as shown in the lower figure.



Different shapes of a dipole anomaly at different areas of the Earth.



Depth dependence.

Field procedure of magnetic surveying

In the initial stage of an investigation, so-called “free search” is carried out to determine the boundaries of the site and to locate isolated magnetized objects. At this stage, the operator measures the magnetic field with the help of a proton or Overhauser magnetometer without using a regular grid. Instead, the operator meanders while measuring at spacings of about 1-1.5 m, and marking the anomalies with small flags which may sometimes be magne-

tized objects. This method of “free search” is characterized by a high speed (covering typically 3-4 hectares per day).

The method of detailed magnetic surveying of archaeological sites is one of measuring the Earth's magnetic field point by point with a small step (not more than half a meter), close to the surface; the measurements are plotted on a magnetic map.

A coordinate system is set on the site for data collecting. Usually, if there are no obstacles, these plots are 40 m (or 20 m) wide and as long as is necessary to cover the area of those parts of the site. Two plastic measuring tapes are put on opposite sides of the grid and 40-m strings with meter marks stretched between the meter marks on the tapes. One can also use small wooden sticks on the opposite sides of the grid.

Our main survey instrument is an Overhauser magnetometer GSM-19WG. The measurements are made along straight and parallel lines (strings with meter marks); the space between the lines is 0.5 m. The magnetometer is operated in so-called “walking mode,” measuring every 0.2 second, and thus the distance between the measurements along the lines is not more than 0.2-0.3 meter. The height of the mapping sensor above the surface of the ground is usually about 0.2-0.4 meter.

If the archaeological site is large, it is necessary to continuously monitor the daily variations of the Earth's magnetic field. A second magnetometer of the same type (GEM Systems) is used to monitor temporal changes of the magnetic field. Its sensor was installed at a base (reference) point in a zone of a more or less “normal” magnetic field, while the other (working) magnetometer is moved about the site. Using special computer programs, the signals from both sensors are used for the removal of daily (temporal) variations of the Earth's magnetic field. Before 2005 we used a 50-meter long cable to connect the two sensors of a gradiometer and then subtracted the daily variations of the Earth's magnetic field.

The data are stored in the memory of the magnetometer; after the survey they are transmitted to a portable computer. Different pre-

sentations of the magnetic data can be prepared with help of the Surfer software (Golden, Colorado): most useful are coloured contour maps and grey-scale maps. On the contour maps the positive anomalies are marked with blue colour, the negative ones - with red colour. On the grey-scale maps the positive anomalies are marked with dark colour, the negative ones - with light colour. The contour interval could be 2, 5 or more nanotesla (nT).



Preliminary observation of the data in the field. Gødsvang, SW Jutland.

Stages of magnetic surveying



Surveying by "free search". Holsted, central Jutland, Denmark.



Collecting maps of big areas of iron smelting sites in SW Jutland.

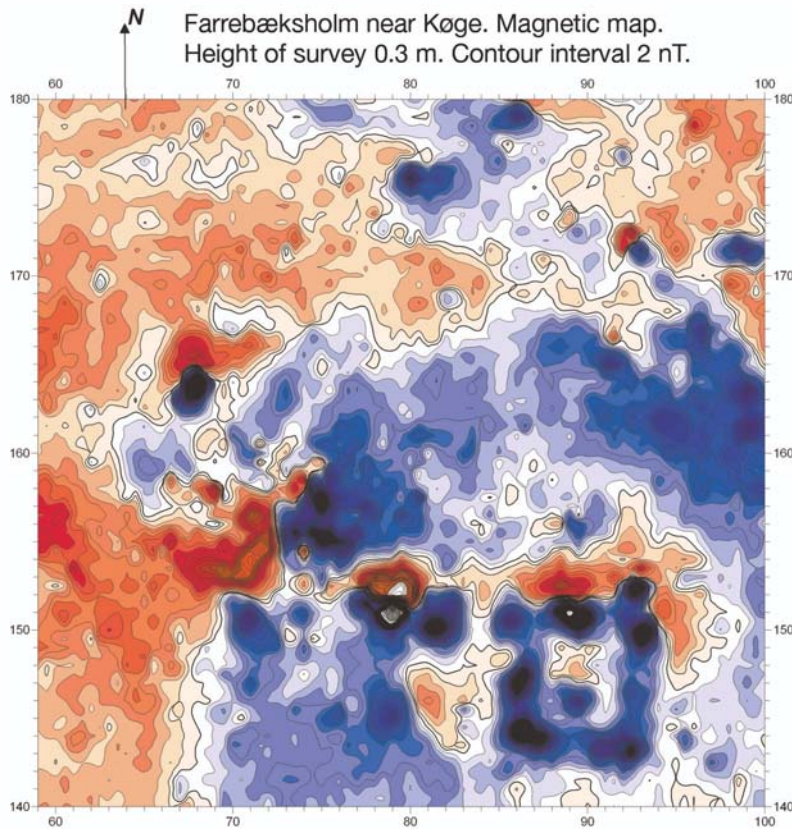


Detailed measurement using a grid. Neolithic flint mines in Hov, Thy.



Checking magnetic anomalies with excavations. Neolithic flint mines at Hov, Thy.

THE METHOD of MAGNETIC SURVEYING



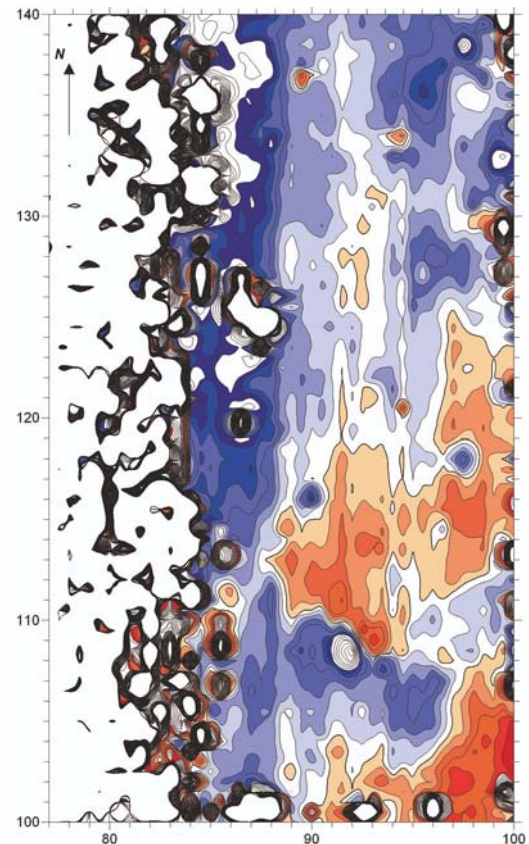
Limitations

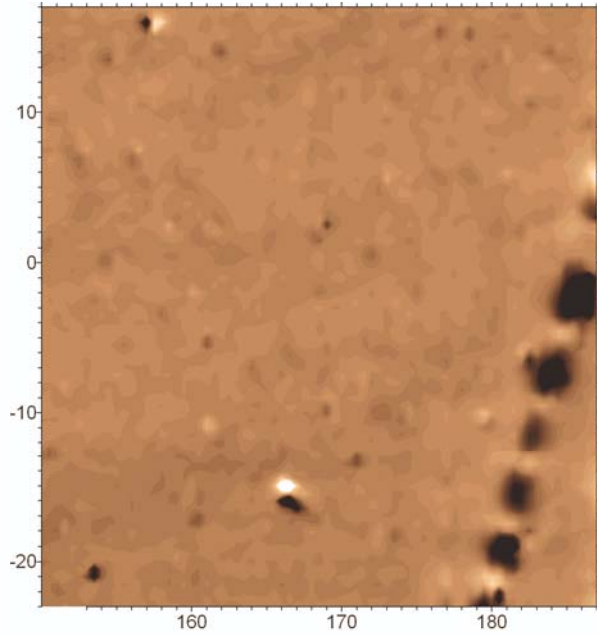
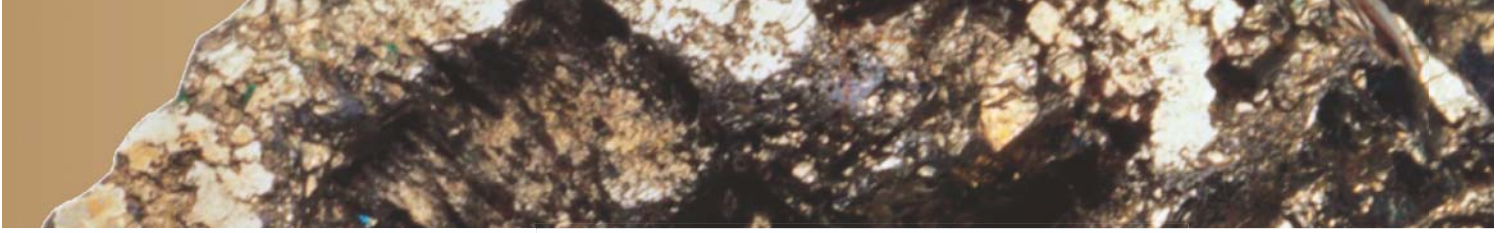
Since the magnetic method, like other geophysical methods, is by nature indirect, the geophysicist can interpret data in the form of anomalies. Causes of an anomaly can be suggested or speculated upon; however, only excavations can verify the source of an anomaly.

All geophysical techniques are subjected to noise. Noise is nothing more than false signals in the geophysical measurements. These false signals can be caused by cultural features: buildings, fences, electric power lines, small modern metal objects on the surface of a site, pipe lines, and natural features: magnetic (granite etc.) bedrock, solar storms, and lightning. Sources of noise should be identified prior to any magnetic field work, as geophysical surveys can be planned to eliminate or diminish the noise (Breiner, 1973).

Magnetic survey on a site north-west of Ejby, south of Køge, Denmark. Below, left: The area of magnetic survey was to the east of the castle mound.

Below, right: Magnetic map near the electric power line and below it. The readings are completely false below the electric wires. Above: The magnetic map of the site, which was measured after the electric current was switched off. The contours of a building are very clear.

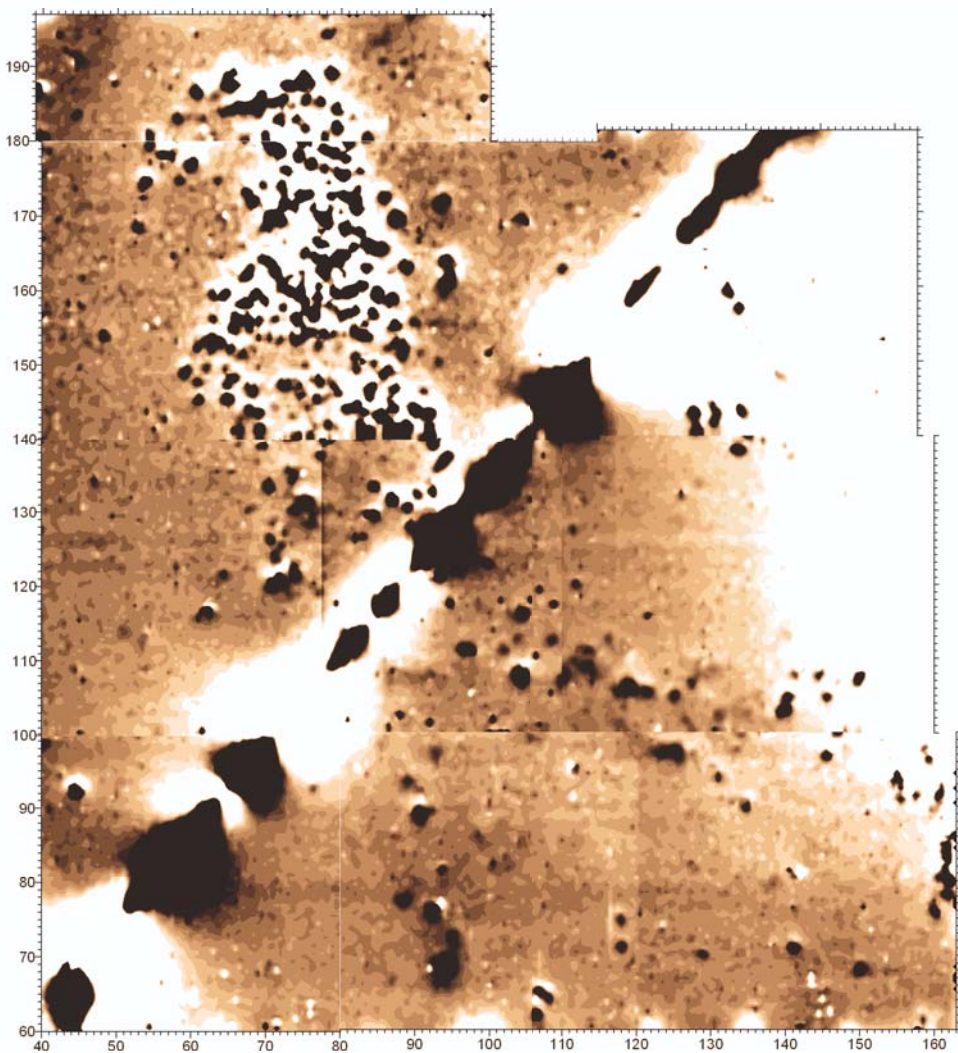
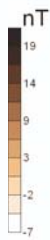




*Iron smelting site
Yderik in SW
Jutland.*

*Above: magnetic
anomaly over
an underground
electric cable.*

*Below: Magnetic
map over a gas
pipe line and a
big cluster of slag
blocks.*



MAGNETOMETERS



A special pattern of anomalies of the Earth's magnetic field is created at archaeological site which are detectable with sensitive instruments - magnetometers. For our archaeological prospecting we have used:

- two Overhauser gradiometers GSM-19WG of GEM Systems Inc. (Canada, Ontario) as main instruments;
- caesium magnetometers MM-60, M-33 and PKM-1 (Russia, St.Petersburg, "Geologorazvedka");
- a proton magnetometer MMP-203 (Russia, St.Petersburg, "Geologorazvedka").

From right to left: Bruce W. Bevan with MMP-60, Olfert Voss, Tatyana Smekalova with GSM-19WG and M-33 on the iron-smelting site Snorup in SW Jutland, 1996.

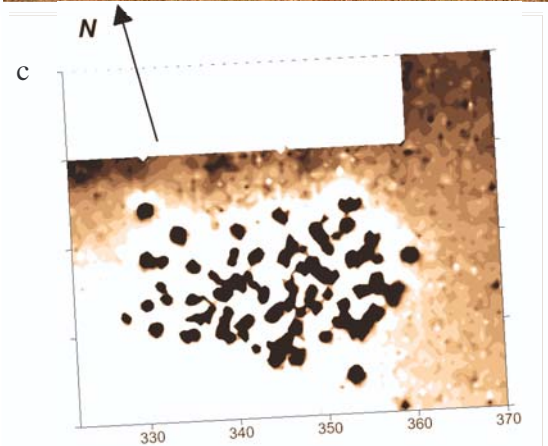
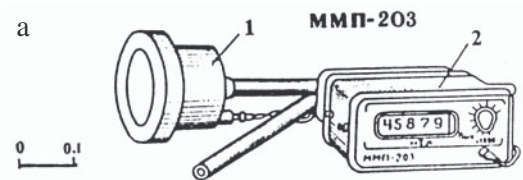
A proton precession magnetometer is one of the most common types of portable magnetometers used today for archaeological purposes. It is so named because it utilises the precession of the spinning protons or nuclei of the hydrogen atom in a sample of hydrocarbon fluid (water, kerosene, alcohol, etc.) to measure the total intensity of the magnetic field. The spinning protons, which behave as small magnetic dipoles, are temporarily polarised by the application of a strong magnetic field generated by a current in a coil of wire. When the current is removed, the spin of protons causes them to precess around the direction of the ambient or Earth's magnetic field. The precessing protons then generate a small signal in the same coil used to polarise them, the frequency of this signal is precisely proportional to the total intensity of the magnetic field which can be measured with a precision of 1 nT.



Proton gradiometer G-856AG of the firm Geometrics, California, USA.

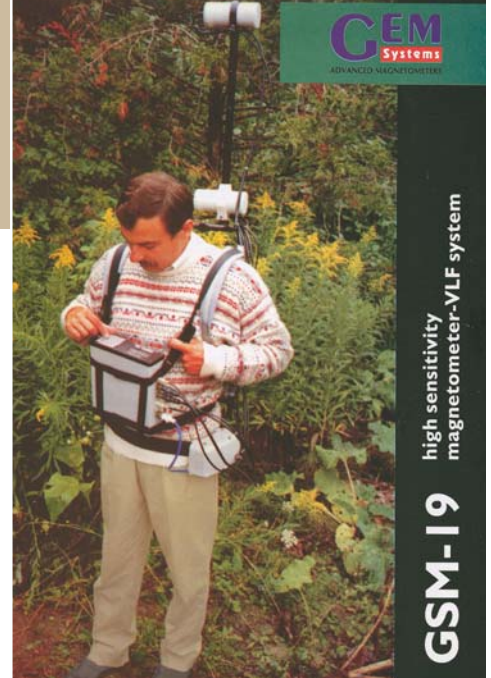
The principle upon which it is based is so elegant and simple that it retains its importance many decades after the development of other methods (Scolar, Tabbagh, Hesse, Herzog, 1990, p. 450-456). Proton magnetometers have two serious disadvantages. First, erroneous observations may occur where gradients of 300-1,000 nT per m are encountered. Also, due to a finite measurement time, approximately three seconds, they are quite slow.

Therefore, in the last few years, proton instruments have been largely displaced by new, much more rapid magnetometers. We mostly use proton magnetometer MMP-203 for the preliminary "free search" investigation of an area.



a - A proton magnetometer MMP-203, Russia. Sensitivity 1 nT ; cycle time 3 s
 b - Method of "free search" with help of a proton magnetometer MMP-203. The iron smelting site Gødsvang in SW Jutland, Denmark.

The anomalies from ancient slag blocks are marked with white flags.
 c - The detail magnetic map, obtained later on this plot with help of Overhauser gradiometer GSM-19WG. The dark dots are strong positive anomalies of slag blocks. The numbers on the drawing are in meters.



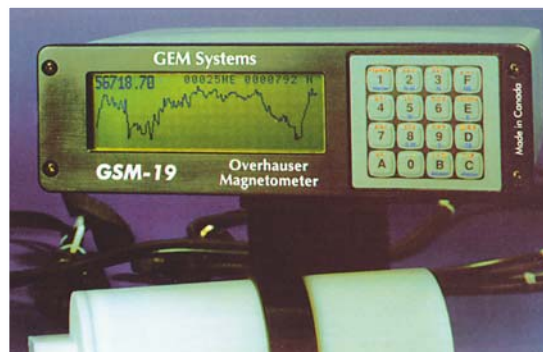
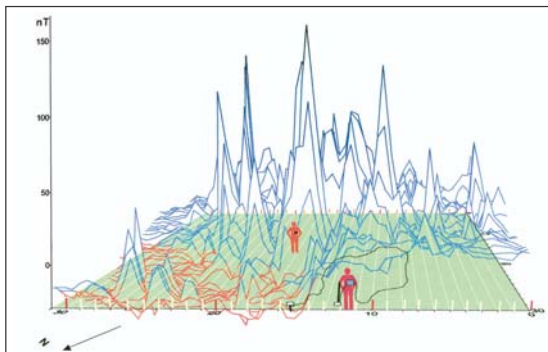
The Overhauser magnetometer is a variation of the proton-precession magnetometer.

In the proton magnetometer, the polarization is caused by briefly applying a strong field. The Overhauser magnetometer uses free radicals dissolved in a liquid to raise its apparent susceptibility by pumping with a radio frequency. There is a dipole coupling between the proton spins of a liquid and the electron spins of a free radical dissolved in it. Because of the very great increase of polarization (by a factor of up to 4000 or 5000), very small amounts of fluid can be used, which makes the sensors quite small and therefore also highly resistant to gradients. Sensitivities of the order of 0.01 nT are readily obtained in practice (Scollar, Tabbagh, Hesse, Herzog, 1990, p. 450-456).

The main instrument that we use for archaeological prospecting is an Overhauser

gradiometer GSM-19 from Gem Systems Inc. (Ontario, Canada). It permits measuring magnetic fields at rates as high as 5 readings per second with a storage capacity of about 32 Mbytes. The sensitivity is from 0.02 nT to 0.015 nT/ $\sqrt{\text{Hz}}$ with 10,000 nT/m gradient tolerance. The spacing between two sensors in such a gradiometer can be changed and the sensor height can be set at any value. One sensor may be used as a base station to provide a correction for the temporal change in the Earth's field, and can be connected to the console by a long cable (we have a 50 meter long cable).

GSM-19WG for magnetic gradient surveying (vertical mode shown).



GSM-19 console with magnetic sensor and standard real-time graphic display.



Glarborg, Zealand, Denmark. 2001. Above: Scheme of magnetic survey with one gradiometer GSM-19 (one sensor is on the base point to control temporal variations; it is connected to the console with a 50 m long cable). Graphs of the measured magnetic field are shown. Below: At work with the magnetic survey. One operator is collecting magnetic data, the other one is measuring GPS coordinates of the plot.



Synchronization of the GSM-19 magnetometer with the base station. The sensor and the console of the reference magnetometer are in a special foil covering for protection from temperature changes.



Magnetic survey on a barrow in Zealand, Denmark.

MAGNETOMETERS



Caesium magnetometer PKM-1, "Geologorazvedka", St. Petersburg, Russia



Caesium magnetometers are highly sensitive types of instruments, their resolution is about 0.01 nT.

Their operating principle is more complex than that of the proton magnetometer. They operate at the atomic rather than nuclear level. A lamp is used for polarization. When monochromatic light passes through a magnetic field in an appropriate material, there is an interaction between the spins of the substance and electromagnetic properties of the light. In contemporary instruments, caesium 133 is used.

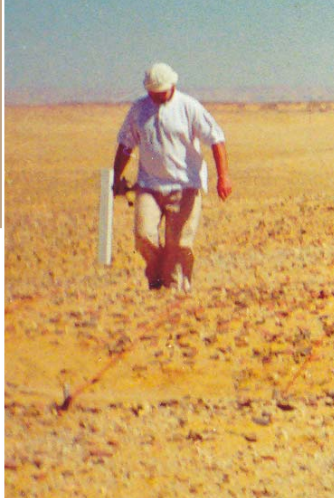
The sensor is a glass cell containing metallic caesium. It is heated slightly to vaporise the material. The circular polarised pumping light excites electrons in the caesium atoms to a more energetic state. The electrons quickly fall back to their original energy level, but they are continuously re-excited. The magnetic vectors of the atoms precess around the external field, and their moments lock onto one of the rotating components of the field from the coil around a glass cell. This 'depumps' the spins and increases the transparency of the cell, with a maximum at resonance, which occurs at a frequency proportional to the total magnetic field intensity (Scollar, Tabbagh, Hesse, Herzog, 1990, p. 466-469). The sensitivity of caesium magnetometers derives from their high precession frequencies, which is important for recording small signals. Another advantage of a caesium magnetometer - high gradient tolerance makes it useful in measuring strongly magnetised archaeological objects at a very shallow depth.

The Russian caesium magnetometer PKM-1 was used for surveying in bushy areas, where it is not possible to make continuous measurements, or where there are some obstacles, like near the excavations in Dakhleh Oasis, Egypt in 2005.

Fluxgate gradiometer. The sensor consists of two similar parallel strips of an alloy of high magnetic permeability called Mumetal.

They are driven in and out of magnetic saturation by the solenoid effect of an alternating 'drive current' in the coils that are wound around them. Every time they come out of saturation, an external field can enter them, causing an electrical pulse in the detector coil proportional to the field strength. The drive coils of the two strips are switched in opposite directions - so that the drive current has no net magnetic effect (Scollar, Tabbagh, Hesse, Herzog, 1990, p. 456-466).

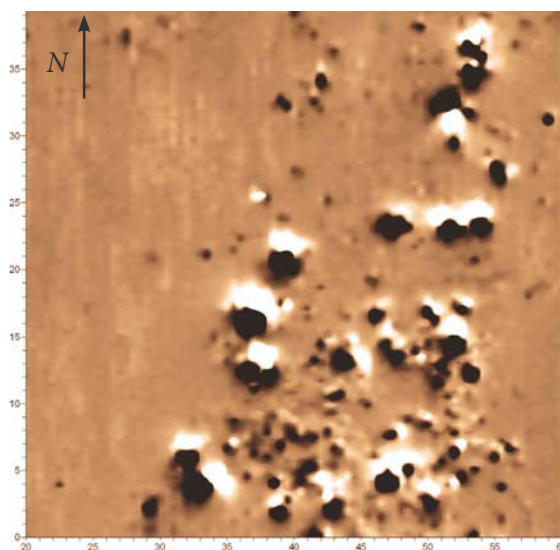
The Geoscan fluxgate instruments have a noise level of about 0.1 nT, which makes surveys in areas of weak magnetic contrasts readily achievable. There are additional advantages of compactness and relative cheapness. Therefore, the fluxgate gradiometer with its closely-spaced direction-responsive detectors has become 'the workhorse - and the racehorse' - of British archaeological prospecting (Clark, 1996, p. 69)



The Polish archaeologist and geophysicist Dr. Tomasz Herbich is doing a magnetic survey in Dakhleh Oasis in Egypt with Geoscan fluxgate gradiometer FM-36.



Nydam Bog (Denmark). Magnetic survey with help of two fluxgate magnetometers done by a team from York, 2005.



Nydam Bog (Denmark). Magnetic map, measured on part of the bog with help of the GSM-19WG. The black and white dots are positive-and-negative anomalies over iron objects, 2005.



Nydam Bog (Denmark). Magnetic survey with Overhauser GSM-19WG, 2005.

The use of magnetic prospecting in Denmark



Niels Abrahamsen and Olfert Voss in Kalø, August 2005.

A considerable part of our work is connected with investigations of archaeological sites in Denmark. Magnetic methods have been used in Danish archaeology in two different ways: first, for archaeomagnetic dating, and second, for magnetic surveying. Olfert Voss and Niels Abrahamsen carried out the first magnetic survey in Denmark in 1965 on the Roman Age iron-smelting site of Drenghsted in southern Jutland; this immediately showed the effectiveness of this method for searching for slag-blocks (Abrahamsen, 1965).

Other archaeological features that create strong anomalies, and therefore are prospective targets for magnetic survey, are pottery kilns. Several of them were investigated with magnetometers in the field and were also ar-

chaeomagnetically dated (Abrahamsen et al., 1982; Abrahamsen et al., 1991). Good results were obtained by geomagnetic field measurements over a reconstructed Bidstrup brick kiln (Hansen et al., 1980). Many important investigations, which could clear up the nature of magnetism in different kinds of archaeological material along with age determinations, have been carried out at the Geophysical laboratory of Aarhus University by Niels Abrahamsen, Niels Breiner and their colleagues and students (Abrahamsen & Breiner, 1990, 1993; Abrahamsen, et al, 1998). Since 1992, systematic magnetic surveys have been carried out in south-west Jutland by the authors, mostly on Roman Age iron-smelting production centers. Several promising magnetic surveys have also been done on other archaeological sites.

For the conditions in Denmark, especially in south-west Jutland, where almost all the land is cultivated, the only parts of archaeological sites still preserved are those which were underground in ancient times: all kinds of pits (garbage pits, pit-houses, postholes), wells, ditches, and also slag-blocks, etc. The usefulness of magnetic surveys on archaeological sites in Denmark is mostly due to the combination of two conditions. First, the contrast of the magnetic properties of the archaeological material and the surrounding matter (almost nonmagnetic sand) is large (see Table below), and, second, the noise level is rather low.

	Magnetic susceptibility χ , ISO $\times 10^{-5}$	Remanent magnetic moment per mass unit, J_n , Am ² /kg	Q - ratio $Q = J_n/J$
Blocks of slag (Snorup, SW Jutland, 200-600 AD)	50 ÷ 1700	5 ÷ 114 •10	5 ÷ 212
Bog iron ore from Jutland	0.5 ÷ 0.3		
Fired bog iron ore from Jutland	2 ÷ 10		
Tile kiln (Veldbæk near Esbjerg in SW Jutland, ca 1790 AD) (N. Abrahamsen, U. Jacobsen, V. Mejdahl, U. Mejdahl, 1998)	10 ÷ 3,000		3.6 ÷ 25
Bricks from tile kiln (Kalø, first half of 1300 A.D.) (N. Abrahamsen, N. Breiner, 1991)	500 ÷ 1,000	5.4 •10	
Filling of household pits and post holes (Snorup, Krarup, SW Jutland, 200-600 AD)	1.2 ÷ 2.6		
Filling of a pit house (Krarup, SW Jutland, 200-600 AD)	6.5		
Filling of the well (Snorup)	3		
Topsoil over the cluster of slag blocks (Snorup)	3 ÷ 5		
Topsoil outside the cluster of slag blocks (Snorup)	0.35 ÷ 2		
Dark soil from one of the ridges of a Medieval field (Snorup)	0.9		
Sand close to the ridges of Medieval field (Snorup)	0.3		
Sand (Snorup)	0.1 ÷ 0.7		

Magnetic properties of features from archaeological sites in Denmark.

PART 2 Results





Early Dynastic sites in the DAKHLEH OASIS in EGYPT



*'Ain el-Gezzareen.
Magnetic survey. 1999.*



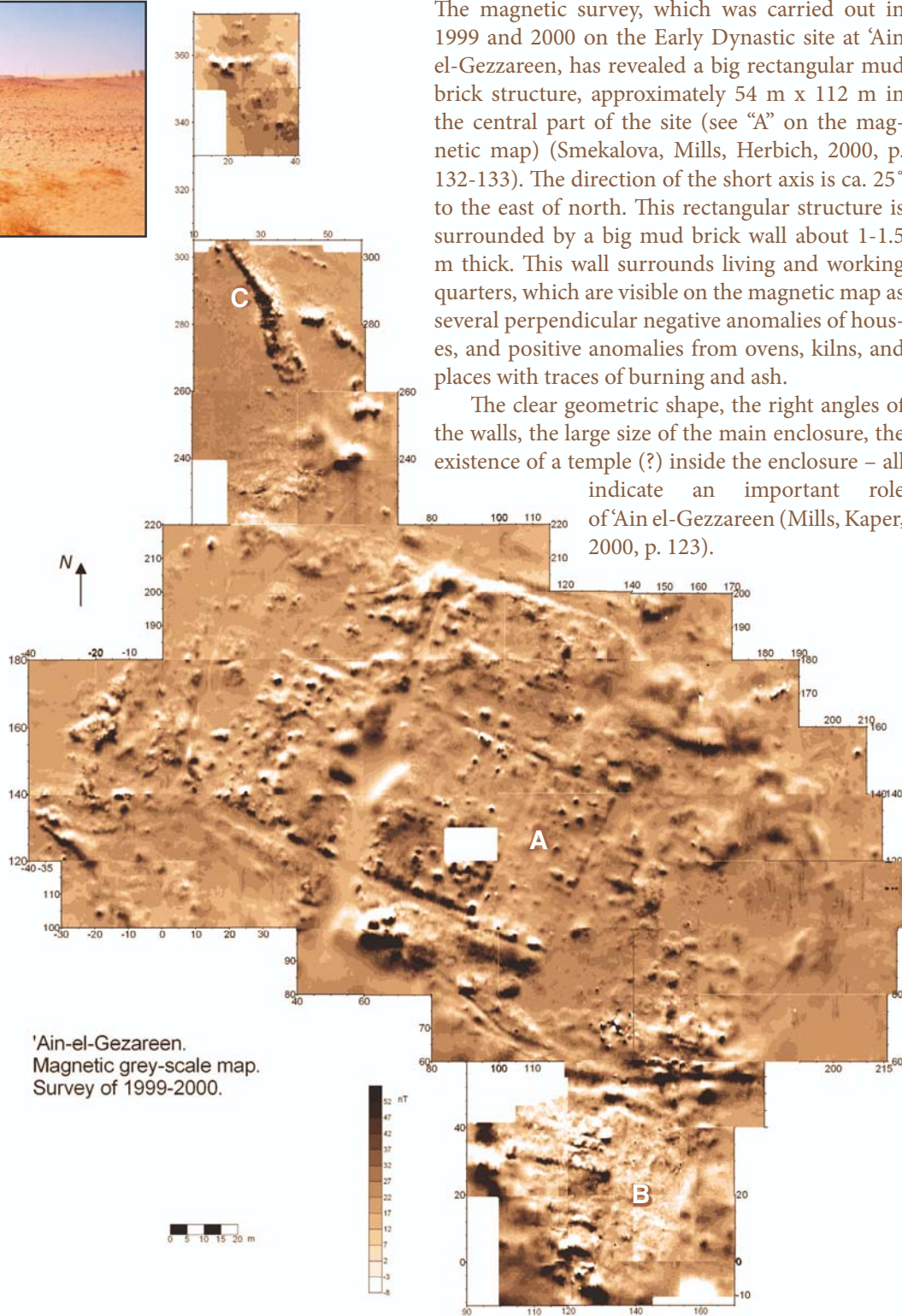
*Green fields in the
Dakhleh Oasis.*



*Anthony Mills and
Tatyana Smekalova
on Amheida, 2005.*



*Explaining principles
and results of a mag-
netic survey, 2005.*



The magnetic survey, which was carried out in 1999 and 2000 on the Early Dynastic site at 'Ain el-Gezzareen, has revealed a big rectangular mud brick structure, approximately 54 m x 112 m in the central part of the site (see "A" on the magnetic map) (Smekalova, Mills, Herbich, 2000, p. 132-133). The direction of the short axis is ca. 25° to the east of north. This rectangular structure is surrounded by a big mud brick wall about 1-1.5 m thick. This wall surrounds living and working quarters, which are visible on the magnetic map as several perpendicular negative anomalies of houses, and positive anomalies from ovens, kilns, and places with traces of burning and ash.

The clear geometric shape, the right angles of the walls, the large size of the main enclosure, the existence of a temple (?) inside the enclosure – all indicate an important role of 'Ain el-Gezzareen (Mills, Kaper, 2000, p. 123).

It is very interesting that there is another rectangular structure, almost of the same size (54 m), with a south-north direction as the main enclosure to the south-east of it (see "B" on the magnetic map). It seems that it has a continuation to the south.

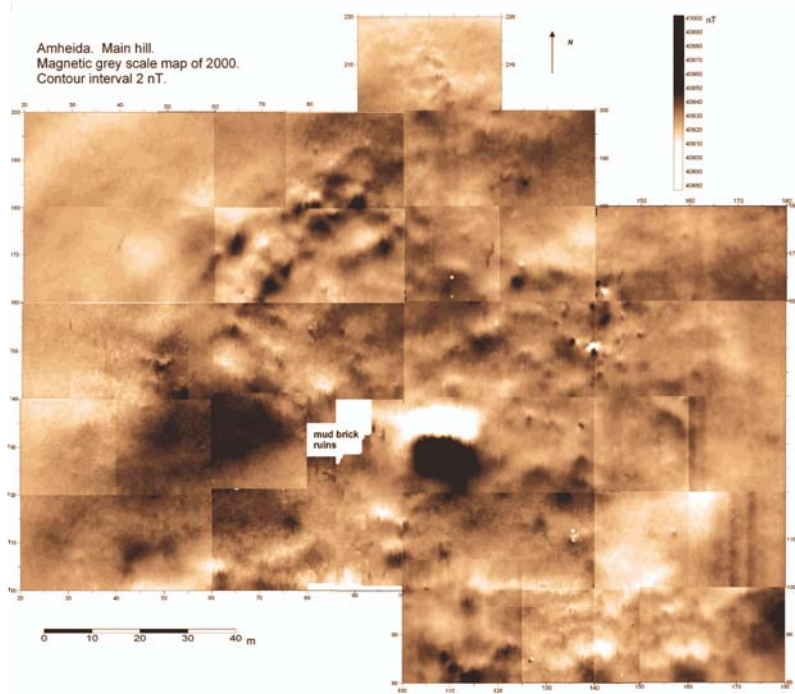
Strong and long positive anomalies, which were probably created by long ditches, the inner parts of which were subjected to a fire (perhaps a row of cooking pits), are situated at the northern part of the site (see "C" on the magnetic map and p. 24).



The most surprising fact is that the magnetic survey in 2000 has revealed a rectangular structure on the neighboring site, Amheida, which has almost the same dimensions and orientation of the walls as the main enclosure on 'Ain el-Gezzareen. The size of the possible enclosure in Amheida is approx. 108 m × 56 m. The orientation of the short axis of this structure is about 37 degrees to the east from north.



Lecture about magnetic survey at the American institute in Dakhleh Oasis.



This rectangular structure at Amheida is a predecessor of the Roman town of Trimithis, the ruins of which cover the Early Dynasty site. The breadth of the magnetic anomalies indicates that the sources are quite deep, at least they are deeper than on 'Ain el-Gezzareen. As is known, material of earlier periods has been found at the Amheida site, but there were no pre-Roman structures revealed there. Perhaps by now we have found the traces of an earlier layer at the Amheida site? It is supposed that the area of the main (or Temple) hill on Amheida was occupied by several temples, which succeeded each other. The possible "enclosure" on Amheida could contain a temple as was the case on the site of 'Ain el-Gezzareen.

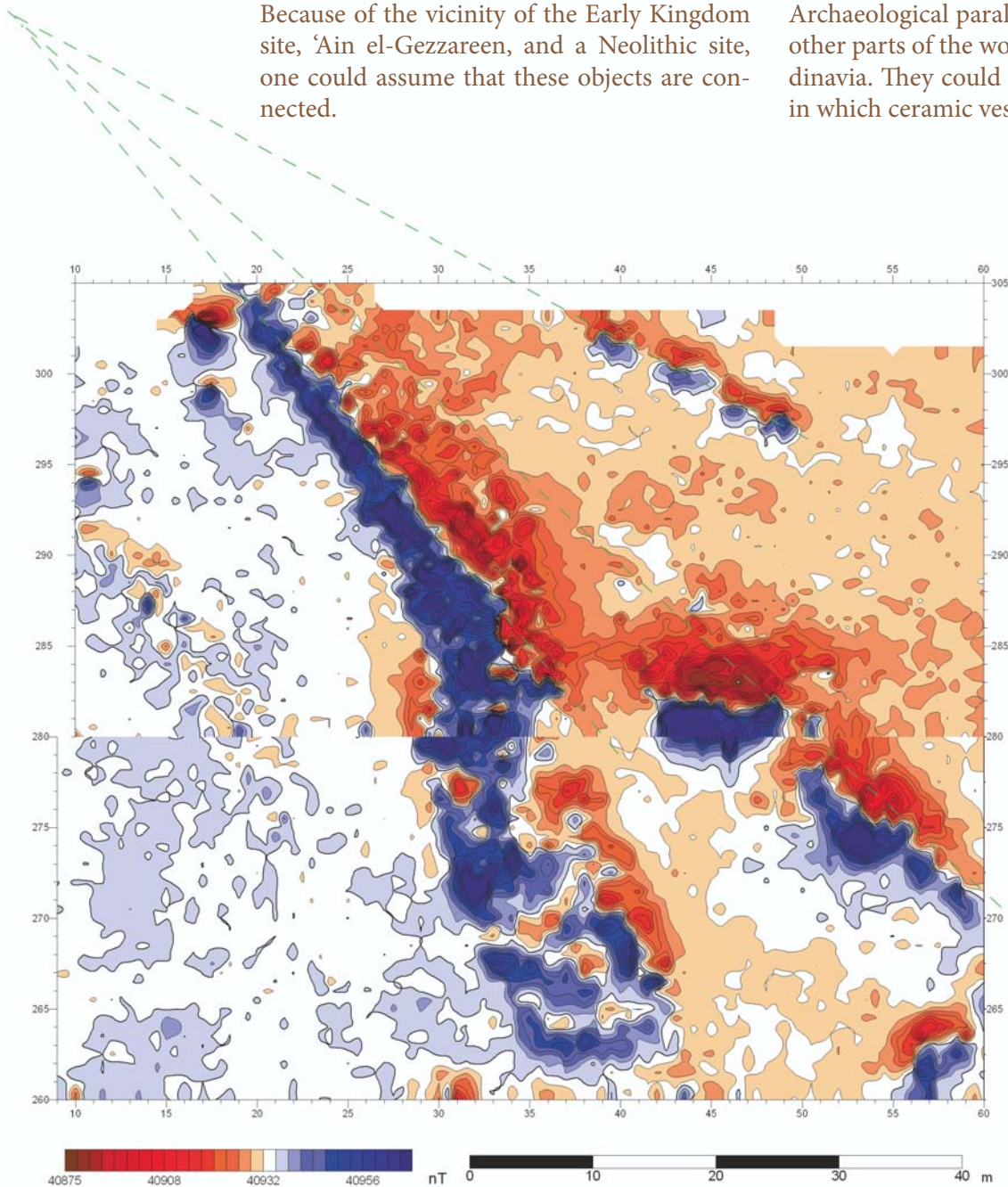
It was necessary to prepare a large amount of bread on the site for the ancient travelers to go through the desert and also for the workers and slaves who served the governor. Therefore, there are many ovens for baking bread inside the enclosures both in 'Ain el-Gezzareen and in Amheida.



'Ain el-Gezzareen – an Old Kingdom Site in DAKHLEH OASIS, EGYPT

During the magnetic survey of the site in 2000, strange long, positive anomalies were revealed at the northern part of the site, outside the Main Enclosure (see structure “C” on page 22). They are rather strong disturbances of the magnetic field, and there are no visible signs of the structures on the surface. It seems that the linear structures have the same “meeting point,” as is shown by dashed lines of green in the figure below. This “meeting point” could be a water spring or another important object. Because of the vicinity of the Early Kingdom site, 'Ain el-Gezzareen, and a Neolithic site, one could assume that these objects are connected.

The first explanation of these features could be that they had a connection to water springs, the traces of which are visible on the plateau in the form of black minerals – tuffs, originated from natural water fountains. If so, the long objects could be water channels that were specially fired in antiquity to improve the waterproof properties of the clay. The other explanation could be that they are rows of cooking pits, or ditches for preparing a kind of ritual food for the people from the sites. Archaeological parallels are known to exist in other parts of the world, for example, in Scandinavia. They could also be rows of fireplaces in which ceramic vessels were fired.



'Ain el Gezzareen.
Magnetic map of the
northern part
of the site.
Long anomalies
over fired structures.
Contour
interval 3 nT.

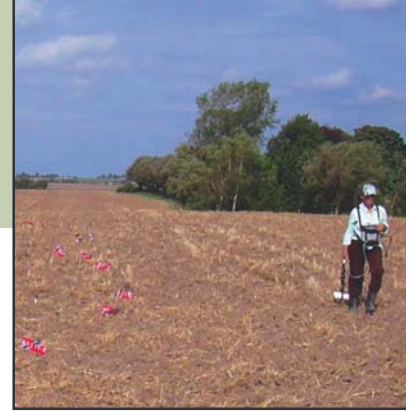
Bronze Age cooking pits on the ISLAND of FYN, DENMARK

Rows of cooking pits and long ditches, filled with fired stones, are known from Scandinavia in the Late Bronze Age (ca. 1000 BC) (Henriksen, 2005).

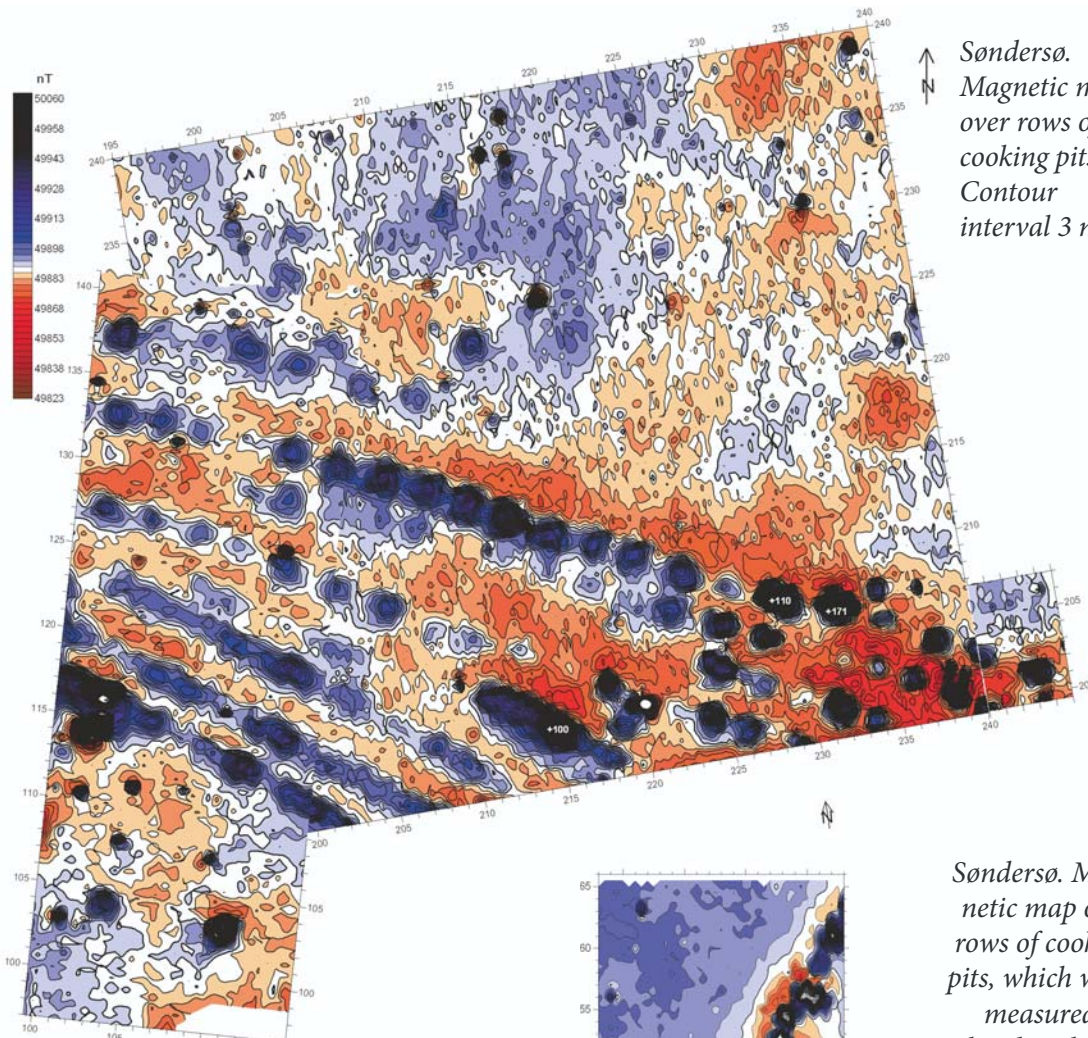
In 2005, we surveyed similar archaeological features at the site, Søndersø, north west of Odense on the island of Fyn in Denmark (see magnetic maps below). Rows of cooking pits have also been found and investigated by magnetometers in another part of Denmark - near Holstebro in Jutland (see the corresponding magnetic map below).

Such archaeological objects produce very characteristic magnetic anomalies: a strong positive anomaly directly over cooking pits

and a distinctive negative anomaly to the north of the positive one. Both Egyptian and Danish archaeological features create similar magnetic anomalies (compare the maps below and on the previous page) in spite of the geographical and chronological differences. One might presume that the rows of anomalies on the site 'Ain el-Gezzareen in Egypt could also be cooking pits.

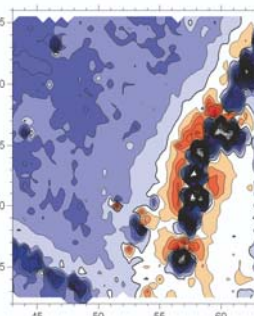


Søndersø. Photo showing detailed magnetic surveying above the rows of cooking pits. One can see the small flags which mark the anomalies over the cooking pits. The anomalies have been revealed by the method of "free search" during the initial stage of the investigation of the site.

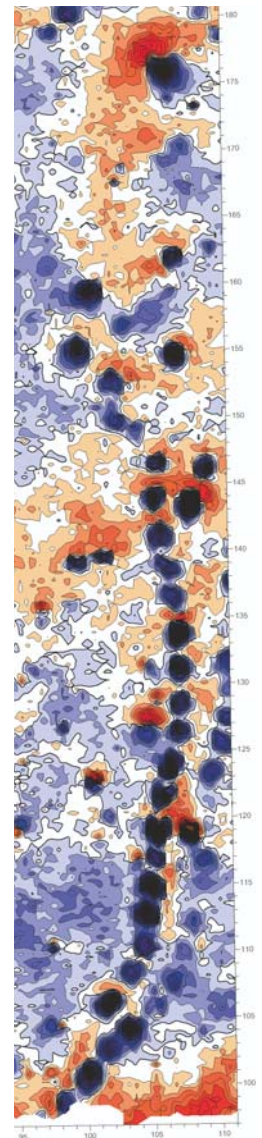


Søndersø. Magnetic map over rows of cooking pits. Contour interval 3 nT.

Holstebro. Magnetic map over rows of cooking pits. Contour interval 3 nT.



Søndersø. Magnetic map over rows of cooking pits, which were measured on the plot, shown above, right. Contour interval 3 nT.



Hov. Neolithic flint mines

in **NORTHERN JUTLAND**



In the Neolithic and Early Bronze Ages, flint was the main material for tools and weapons. For ancient people, it was very important to find good flint for making their tools. Flint is usually deposited in certain layers in chalk. The ancient people had to dig deep shafts to reach the layers containing flint.

The dating of the shafts for flint mines in Hov, Northern Jutland, Denmark is 2500-2000 BC. They were excavated in 1957-58 by Prof. C.J. Becker for the Danish National Museum. The flint mines have shafts 8 meters deep and 4 meters wide, with side corridors up to 5 meters long.

For the magnetic survey it is important to know that these shafts were backfilled with a mixture of soil and chalk pieces. In some shafts there were also pit dwellings, often with fireplaces for the ancient miners.

While chalk is absolutely nonmagnetic, soil and fireplaces are slightly magnetic. This creates a magnetic contrast which is enough for observing weak positive anomalies over flint mines. The magnetic survey of 1999-2003 was carried out on an area of more than 2 hectares. A whole set of weak local anomalies, with values from 10 to 60 nT, has been revealed. Trial excavations in the area with probable flint mines confirm the supposition about the location of shafts.

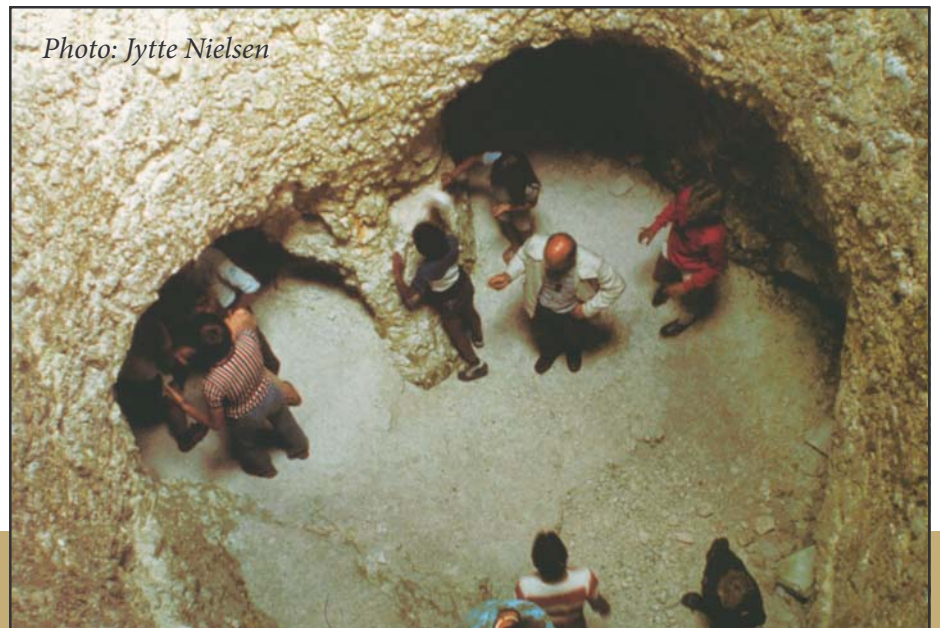
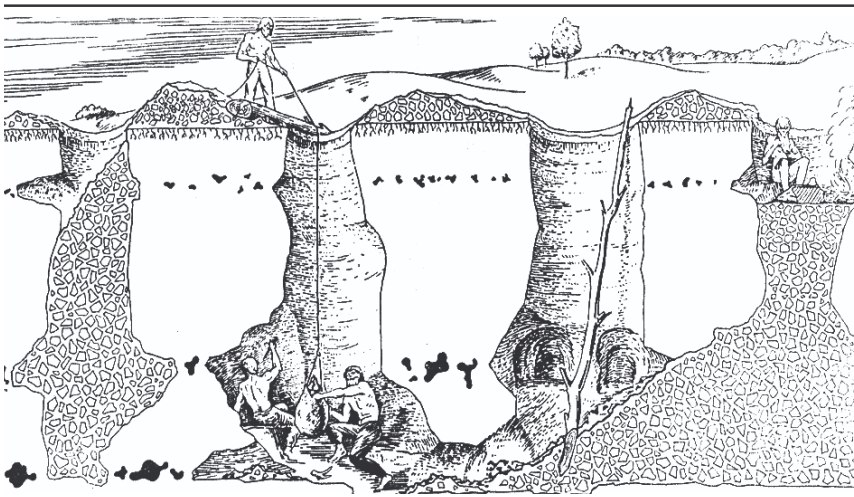


Photo: Jytte Nielsen



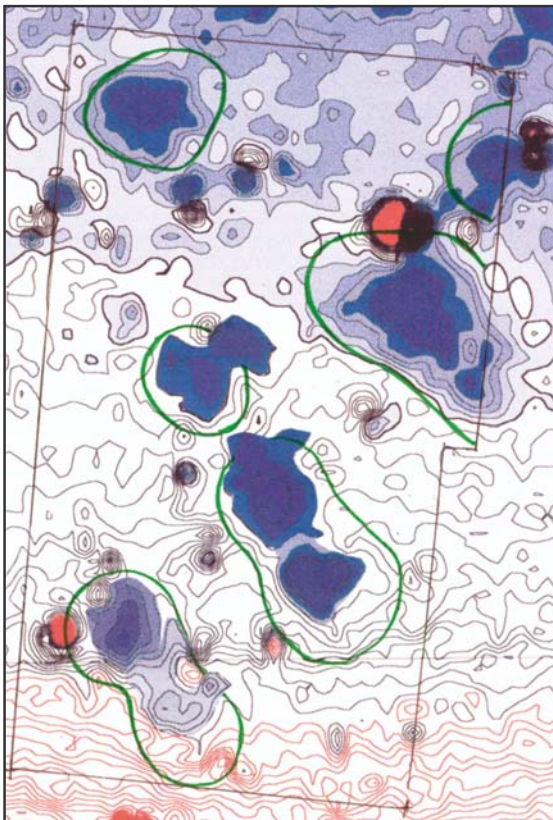
Photo of the area. The upper layer of soil was removed in 2000 to check the anomalies of the magnetic field, shown on the magnetic map (below). Photo: Jens Henrik Bech.



Hov, Thy. Magnetic surveying on the western part of the site. The reference sensor is covered with a plastic pack against rain. 2002.



Hov. The south-western part of the site. Magnetic surveying. 2001.



Hov. 2000. Part of the magnetic map with positive local anomalies from flint mines. The area which was opened is shown; the contours of flint mines are marked with green lines.

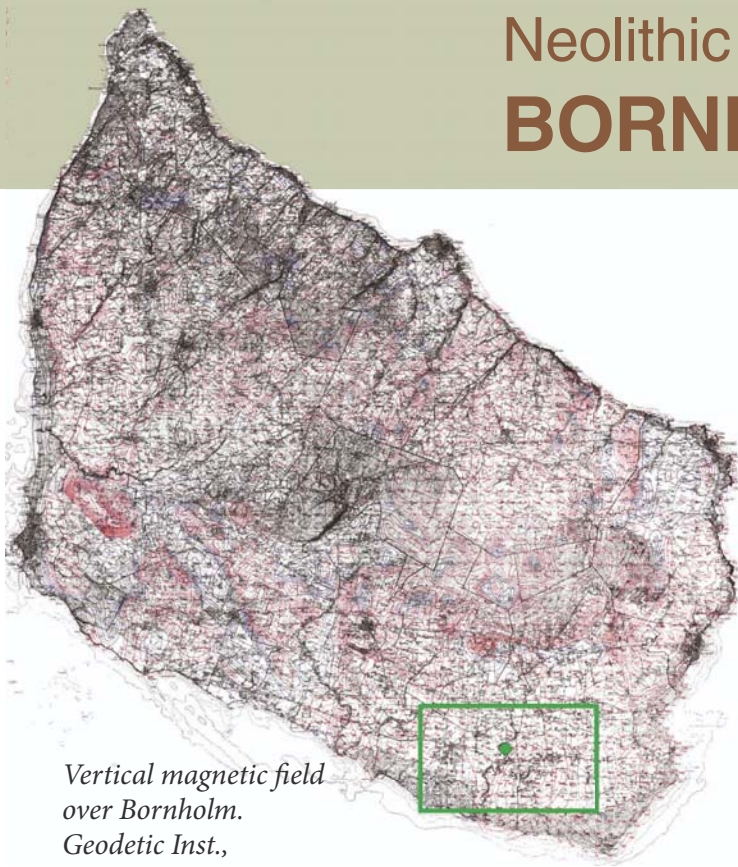


Hov. The eastern part of the site. A moment of the magnetic surveying. 2003.



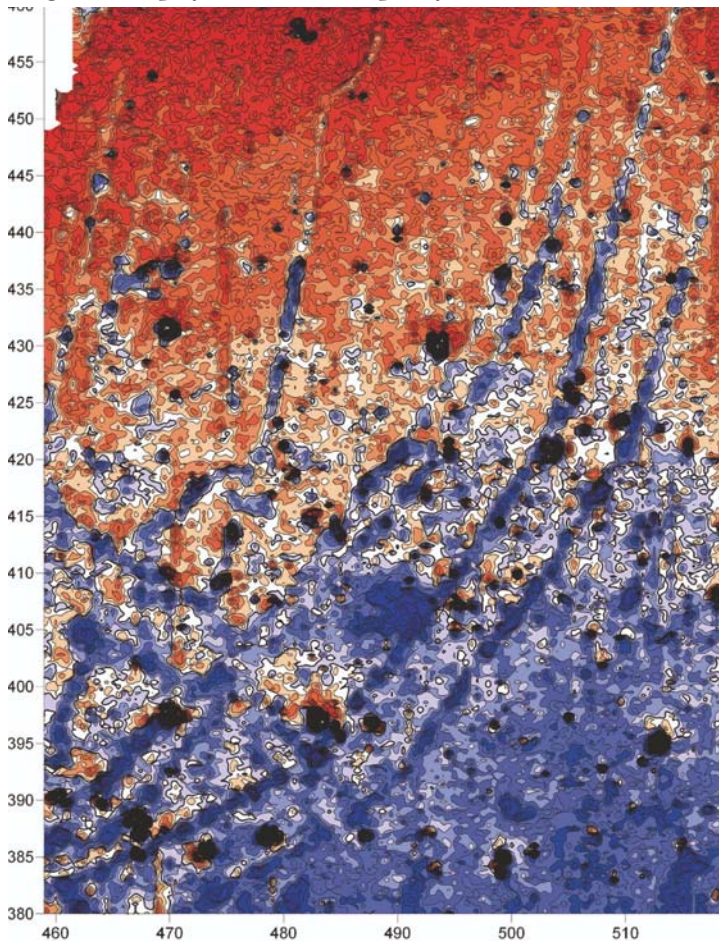
Hov. After the working day of magnetic surveying. 2003.

Neolithic palisades at Rispebjerg, BORNHOLM, DENMARK

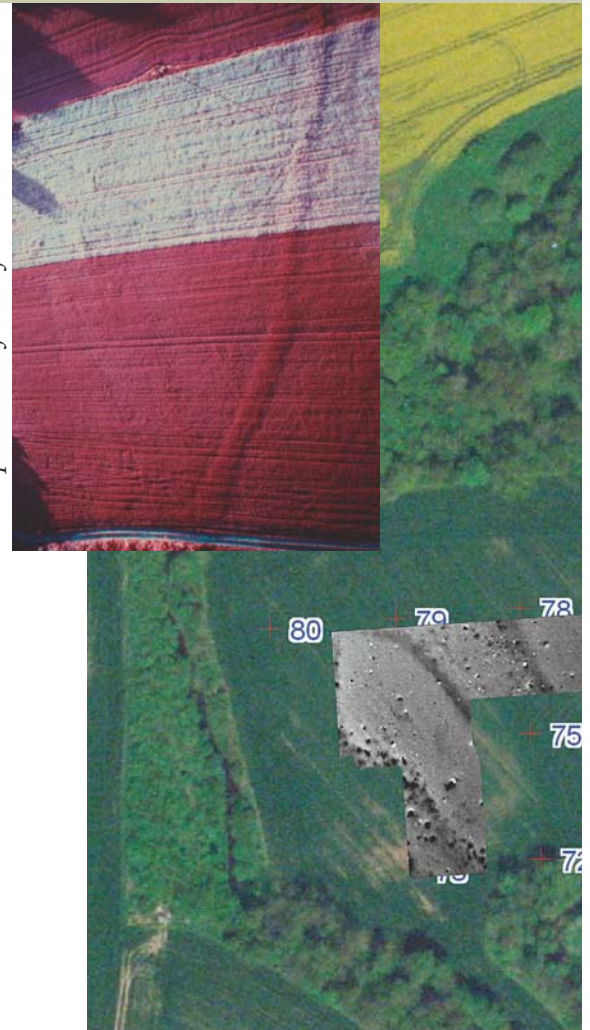


Vertical magnetic field over Bornholm. Geodetic Inst., Copenhagen, 1984.

Magnetic map of the south-east part of the site.



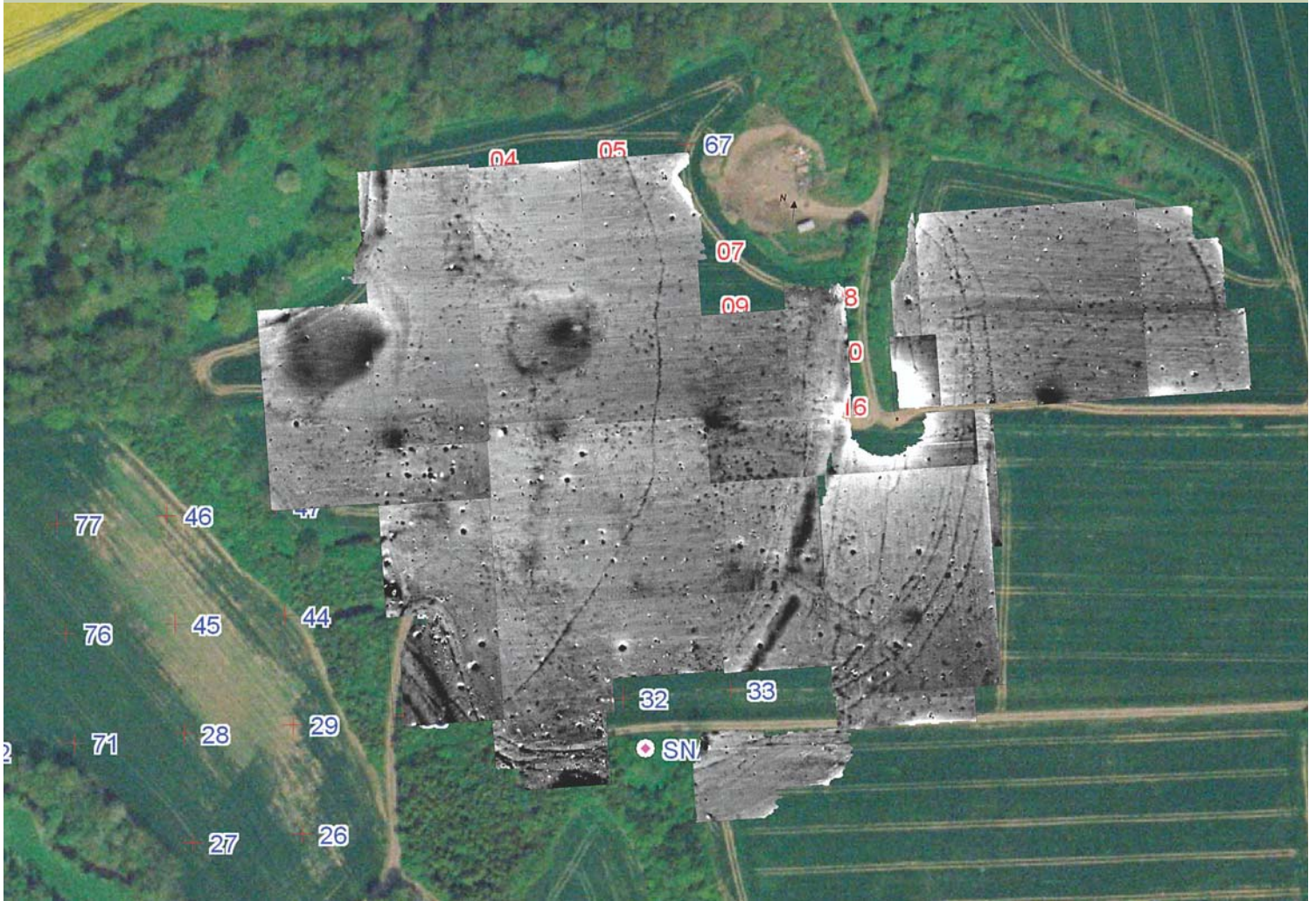
Aerial photo in infrared filter.



The air photos from the Migration Period fortification Rispebjerg on the Baltic island Bornholm revealed a wide ditch about 200 meters from the fort.

The only thing that is now visible at the site is the fort itself and a gravel pit where archaeologist from the Bornholm Museum in 1995 found traces of palisades and Neolithic pottery from the Late Funnel Beaker Culture, 2900-2700 BC.

During two weeks in the spring of 2007 a magnetic survey was carried out here covering 4 ha. It revealed the outline of some palisade ditches and several circular features, 8-10 meters in diameter that consists of 8-10



big postholes (woodhenges). They have been compared to the English woodhenges and are found all over the site.

Two circular areas about 40 meters in diameter contain a more magnetic material and excavations will one day identify what this is.

In the eastern part of the area traces of several entrances to the site can be seen. This part of the magnetic map will be of great help to the archaeologists when they are going to excavate.

With the magnetic map, the archaeologist can plan how the excavation can be organized in order to obtain the best possible documentation because he can decide where he has to

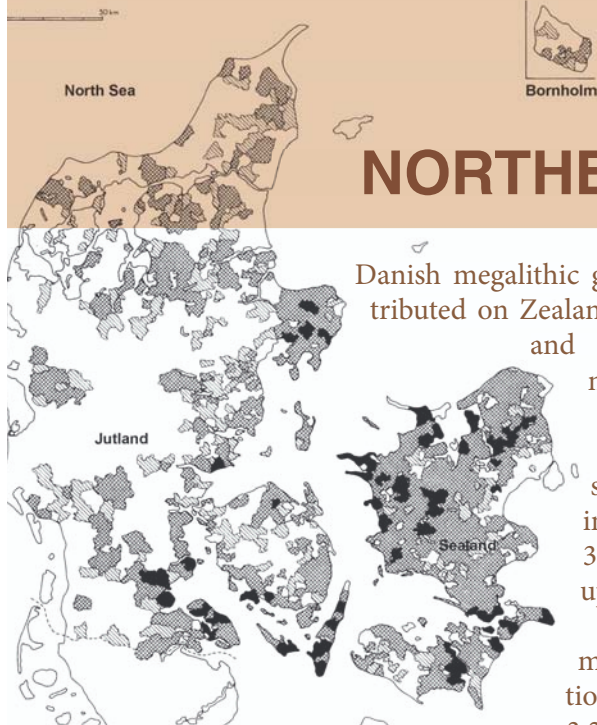
uncover the topsoil and where the sections should be put.

It seems that there is another entrance in the middle of the east side, but here the magnetic survey have been completely overshadowed within a diameter of 40 meters by the strong magnetic field around an electric pylon of steel that have destroyed the possibilities to register the weak magnetic signals that are produced by the palisades.

The pylons of wood for the electric wires show up as dark spots that within a distance of 60 meters can be followed from east to west.

Magnetic grey scale map. The background is an aerial photo. The latest measurements were made in November 2007.

Stone Age megalithic graves in NORTHERN ZEALAND, DENMARK



Danish megalithic graves are widely distributed on Zealand, Fyn, other islands, and in the eastern and northern areas of Jutland. Altogether there are about 700 preserved passage graves in Denmark and some 380 in Sweden (Skaarup, 1993).

Danish barrows with megalithic constructions date from 3,500 – 3,200 B.C.; the charac-

teristic feature of their burial chambers is their construction with large granite stones; these are covered by a large capstone that can be visible above the surrounding mound.

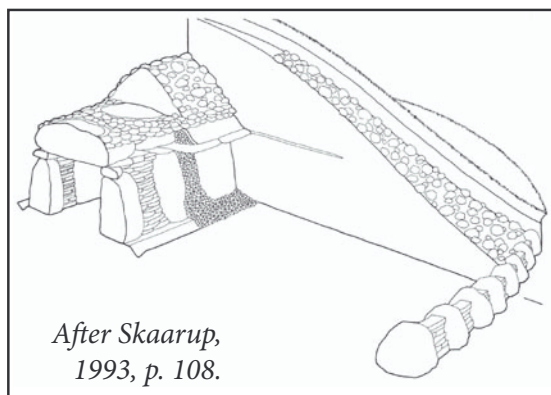
enclosure of curbstones is circular in a one-grave mound, or rectangular in long barrows with several burials. The tombs of passage graves are roofed entirely with earth, so they look like ordinary burial mounds. For the magnetic survey, it is important to know that the main construction material for these passage graves is granite. Granite is a rather magnetic intrusive rock; it contains up to a few per cent magnetite – magnetic iron oxide. The magnetic susceptibility (χ or κ) of granite could vary from 10 to 1,000 x 10⁻⁵ ISO (compared with χ for topsoil in Denmark: from 0.3 to 2 x 10⁻⁵ ISO). Granite also acquired a considerable remanent magnetisation when it was formed. Therefore, each granite boulder is like a small magnet that has its own positive and negative magnetic poles. Such objects are called magnetic dipoles. Therefore, each granite stone creates an anomaly which is similar to the magnetic anomaly of a dipole. The main feature of the dipole anomaly is the presence of both positive and negative parts. In general, the shape and value of the magnetic anomaly over a granite boulder is dependent on the orientation of the dipole with respect to the direction of the Earth's magnetic field.

If the orientation of the dipole (at the latitude of Denmark), is coincides with the direction of the Earth's magnetic field, the anomaly over it would have a large positive part slightly to the south of the center of the object and a weaker negative part immediately to the north of the maximum.

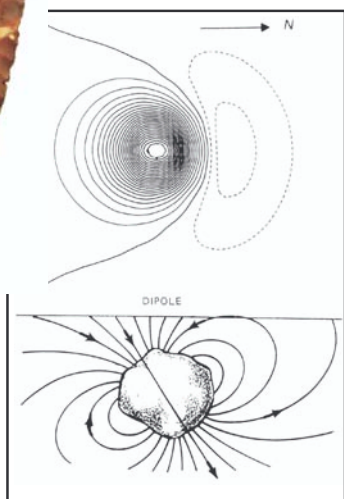
The magnetic field over barrows with megalithic graves is a superposition of many different dipole anomalies from granite boulders; these have different sizes and they are situated at differing depths below the sensor.

In 1997 the magnetic field over a half-excavated Stone Age barrow in Vedsted (Vedsted parish, registration number sb.153) was measured with help from Mogens Schou Jørgensen.

The magnetic map was very informative: the central chamber, the passage and each stone of the circular enclosure caused strong anomalies, up to several hundred nanotesla (20-800 nT).



Dipole anomaly over a granite boulder.



teristic feature of their burial chambers is their construction with large granite stones; these are covered by a large capstone that can be visible above the surrounding mound.

An enclosure of massive stones was raised around the base of the mound. Another characteristic feature is that the barrow has a stone-built passage (Skaarup, 1993). Sometimes, there can be two passage graves in the same mound (Dehn, Hansen, 1999). The





The magnetic map revealed invisible stones in the northern part of the barrow; these have not been excavated. (Compare the magnetic map with the excavation plan).

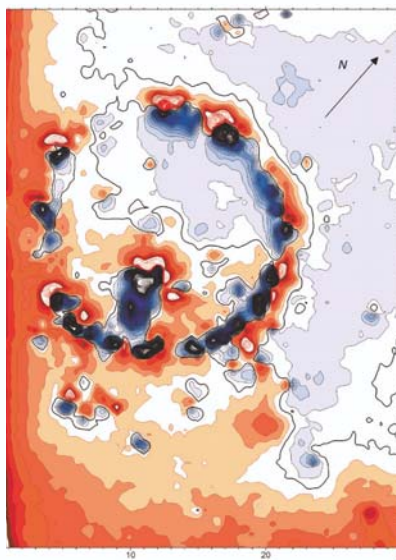
Keeping this positive experience in mind, the magnetic survey of another Stone Age barrow at Jægerspris (Dråby parish, registration number sb. 155) in northern Zealand was done in September 2000. This barrow was partly excavated more than 250 years ago because of the archaeological interest of one of the Danish kings.

On the resulting magnetic map, it is possible to see that the excavated passage and a chamber create very strong magnetic anomalies (up to 750 nT). These anomalies are on a vertical line on the magnetic map midway between the left and right sides of the map. However, the most interesting thing is that there is symmetrically another group of anomalies 7 m to the southwest of this chamber. (Smekalova, Voss, 2001).

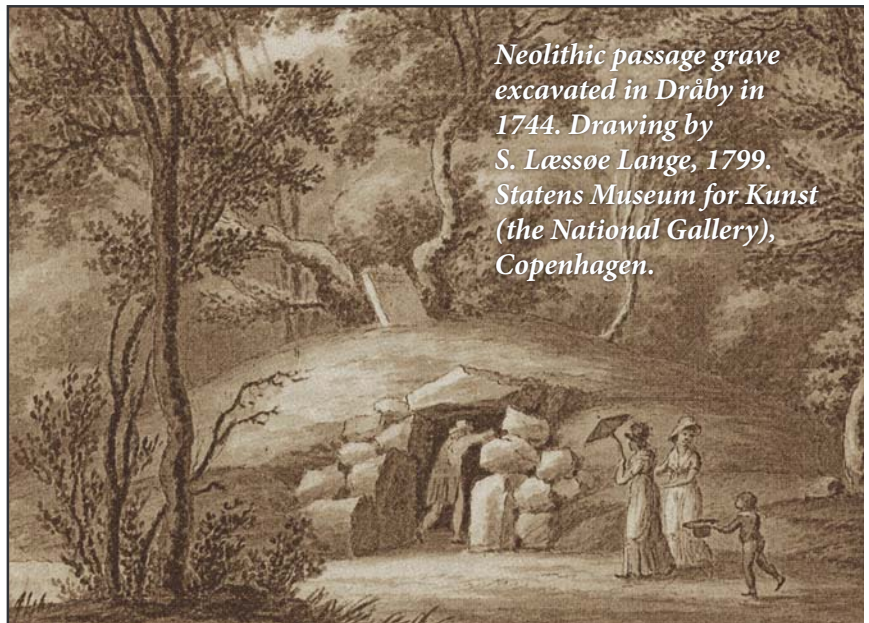
One could interpret these anomalies as another corridor, almost parallel to the first one, and another chamber, which is situated side-by-side with the excavated one. There is also a circular wall of smaller stones which surround the two chambers and corridors. Some stones are missing in the northern part of the circle. There are also smaller structures to the north of both chambers and also between them. It is difficult to identify these structures; each could be just one large stone (Smekalova et al. 2005).

Magnetic surveys appear to be very efficient for the investigation of Danish barrows. It was possible to create a detailed picture of their inner construction, even though they are covered with earth. It is necessary to note that the success of the magnetic survey over the barrows was determined by the fact that the mounds were shallow. If, for example, the barrows were one or two meters higher, the magnetic field over them would change considerably.

But in favourable conditions, magnetic surveys open the possibility for seeing if there are stone constructions inside barrows, and in this way, distinguish Stone, Bronze and Iron Age barrows. This is because Bronze Age bar-

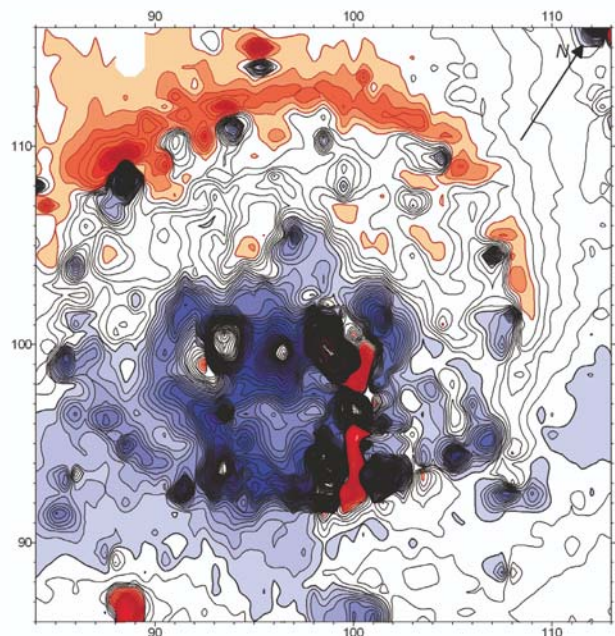


Magnetic map and excavation plan of a megalithic grave in Vedsted. Contour interval 5 nT.



Neolithic passage grave excavated in Dråby in 1744. Drawing by S. Læssøe Lange, 1799. Statens Museum for Kunst (the National Gallery), Copenhagen.

rows have much smaller stones in their construction than the Stone Age ones, and Iron age barrows are only of wooden construction, which is nonmagnetic. Magnetic survey seems to be a powerful method for the investigation of barrows; these are protected in Denmark and cannot now be excavated.



Magnetic map of the megalithic grave in Dråby. Contour interval 5 nT.

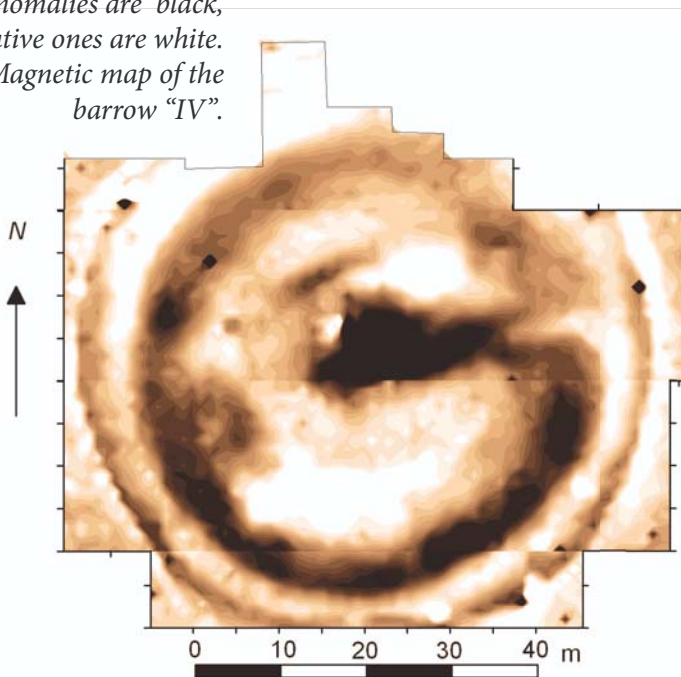


Scythian barrows in **THE CRIMEA**



Ak-Kaja. One of the biggest Scythian barrows - "IV". It was excavated after the magnetic survey had been carried out in 1996. Its height is 10 m and its diameter is 60 m.

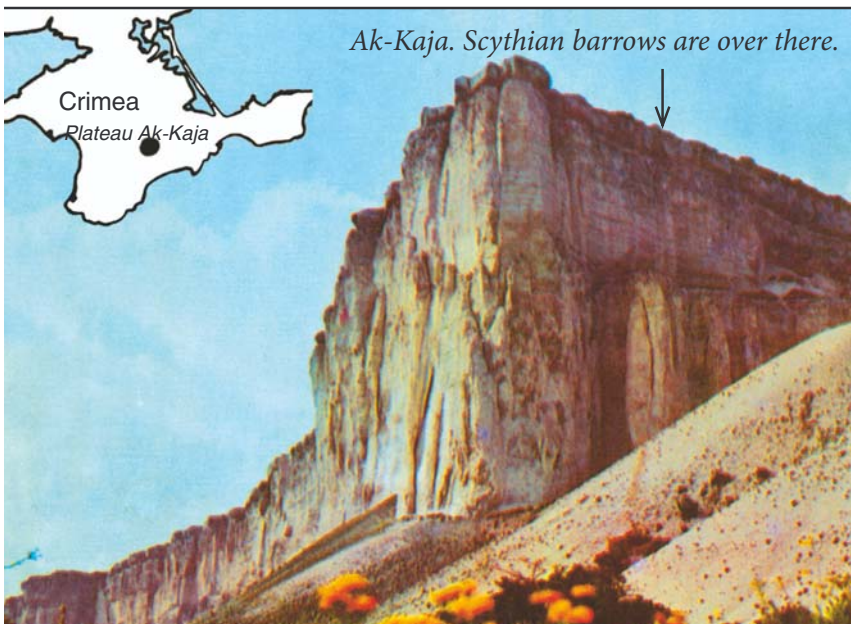
Positive anomalies are black,
negative ones are white.
Magnetic map of the
barrow "IV".



A magnetic survey with an Overhauser gradiometer from Gem Systems was carried out in 1996 at the plateau Ak-Kaja, north of the town of Belogorsk in central Crimea at the northern part of the Black Sea. There are very high cliffs on this plateau, a very attractive natural phenomenon, where all Russian "cowboy" films were shot. Scythian governors chose this area in the 4th century BC as an ancestral cemetery. Archaeologically, this region is almost unexplored, but there are enormous numbers of barrows. In this region, periodic alternations exist between larger (about 10 m in height) and smaller barrows (Smekalova et al. 2005).

The building material for the internal construction of the barrows is limestone; this is practically nonmagnetic, while the soil in these regions has a significant magnetic susceptibility. This makes it possible to reveal stone structures by their negative anomalies on magnetic maps. A circle with a negative anomaly and a diameter of 50 m surrounds each of three large barrows; the circular walls inside the barrows

Barrow "IV". After the excavation. The depth of the chamber is 17 m below the top of the barrow, or 7 m from the surface level.





Barrow "IV"

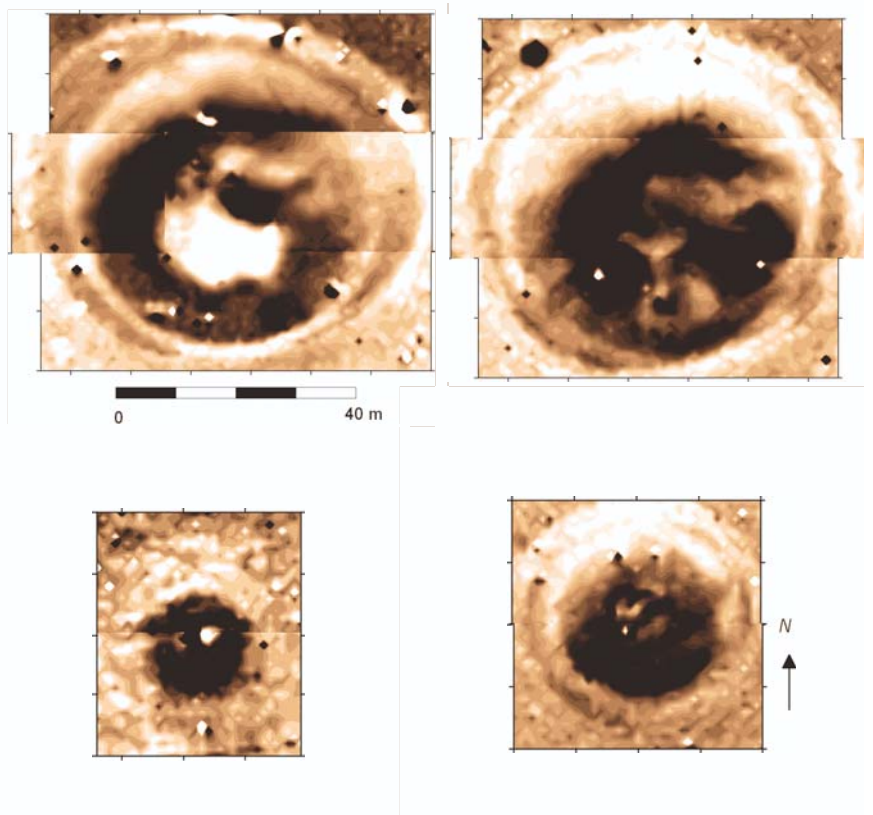
cause this anomaly. In each barrow a long negative anomaly (up to -20 nT) that starts at the eastern side of a cromlech and leads toward the center of the barrow is an indication of a corridor (dromos).



Ak-Kaja. Scythian barrows.

Ak-Kaja. Barrows I and II. Magnetic map. The inner white circle shows the limestone wall.

The dromoses start from the East side (light color). White or dark areas in the center correspond to the chambers, which are either partly destroyed, or completely destroyed and filled with soil that is more magnetic than limestone.



Two smaller barrows (I/1 and V) with their surface covered with small and medium-sized stones. The magnetic field over these barrows is considerably different from the ones mentioned before. There are no traces of a cromlech or a central burial. A positive anomaly occupied all the middle part of the barrow.

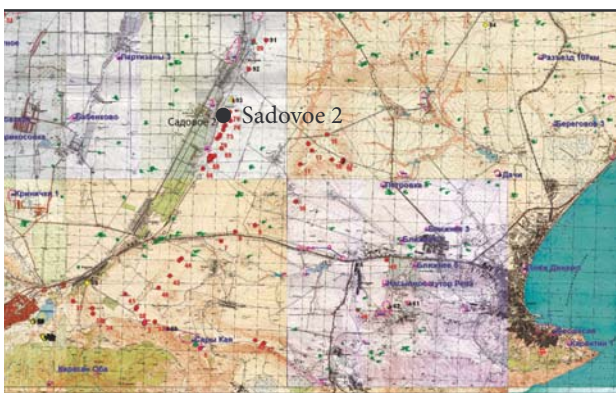


Transporting the gradiometer GSM-19WG to a site in the Crimea.

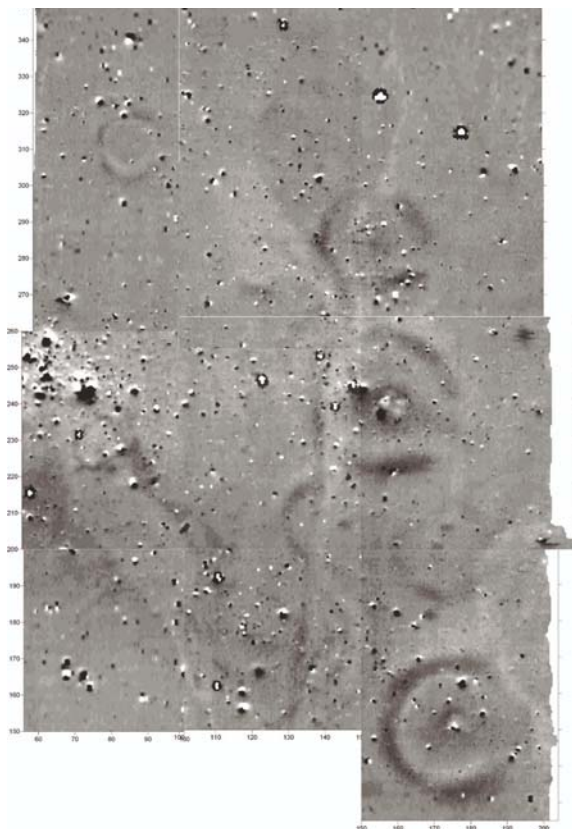
Barrows on the western borders of the Bosphorus in **THE CRIMEA, UKRAINE**



*Relief map of the Kertch peninsula.
The barrows are shown with black circles.*



Part of archaeological map near Sadovoe 2.



*Magnetic grey scale map of the group
of barrows near Sadovoe 2.*

Thousands of the barrows are situated in the steppes of Crimea. On the composite map the kurgans found on the 19th century one-verst and 1:25,000 map are shown with black circles. Remarkable on the latter is a lengthy row of kurgans or some local elevations following each other closely. This row extends from the north-eastern outskirts of the town of Staryj Krym along the Čuruk-Su River, then turns abruptly to the east near v. Novopokrovka and runs along the Parpač Ridge to the Uzunlar Rampart. Here the row splits in two, one branch of it running to Nymphaion, the other to Cape Ak-Burun. The barrows, which are situated in such long row, probably, mark the ancient traditional roads and tracks of nomads (see the map with barrows, marked as dots).

The last big river to the west of Kertch peninsular is the Čuruk-Su River. To the east from it there is a plain, almost without water, especially at the southern-western part of the peninsular, until the Kertch strait. Therefore, there are not only a lot of barrows, but also many settlements of the 5th-3rd cent. BC along the high eastern bank of the Čuruk-Su River.

One of the groups of barrows, situated near the settlement Sadovoe 2 has been surveyed in 2007 with two Canadian Overhauser magnetometers GSM-19WG, while the third one (proton magnetometer MMPG-1, St. Petersburg, Russia) served as a base point. There are very clear patterns of the barrows visible on the magnetic map. Each barrow is surrounded with a circular positive anomaly, which corresponds to a ring ditch, created during the construction of the barrow. There is an interruption of the circle at the eastern side, that indicates the entrance into the barrow. Some local positive anomalies are possibly created by the burials inside the barrows.

Semibratnee fortified site on the KUBAN' RIVER IN SOUTHERN RUSSIA

The Semibratnee fortified site is situated on the middle flow of the Kuban' River, approximately 28 km north-east of the town Anapa (Ancient Greek city Gorgippia). Based on the results of the excavations at the northern part of the site, it is possible to date the site at the time from the end of 6th cent. B.C. to the 1st cent. A.D. In this period the river Kuban' was close to the site. The city was surrounded by big fortification walls and ditches, including the part, which was adjacent to the river.

Magnetic survey has been carried out in 2006 in the southern, most elevated area, where the recent excavations have taken place and on the western field (in 2007).

The most interesting result was obtained on the western field. On the magnetic map of the western field there are two long positive anomalies (in average 40 nT in the amplitude), which are meeting each other in an angle of 90° (see the magnetic map to the right). There are two very strong positive magnetic anomalies and also two interruptions in the long anomalies in the western and southern-eastern parts of these linear structure.

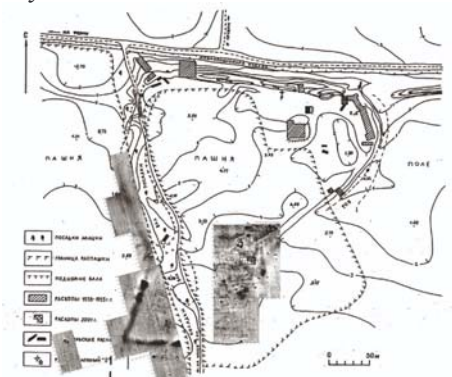
If the magnetic map is put on the aerial photo of 1970, it become clear, that the two long anomalies correspond very precisely to the south-western border of the southern rectangular part of the site. The source of the anomaly is, probably, a city wall. It is rather unusual, that it gives positive magnetic anomaly. It can tell us, that the wall was probably built of a clay material, which was subjected to fire afterwards either occasionally, or specially to harden the clay "body" of the wall. It is not excluded, that the foundation of the wall was built of stone.

Two big positive anomalies, situated along the line of the supposed city wall, were probably two towers, which have been destroyed by strong fire. These "towers" defended two "gates" in the city wall.

It is possible to see rectangular negative anomalies inside the southern part of the fortified site, in some distance from the wall. One could interpret them as the rests of quite big buildings.

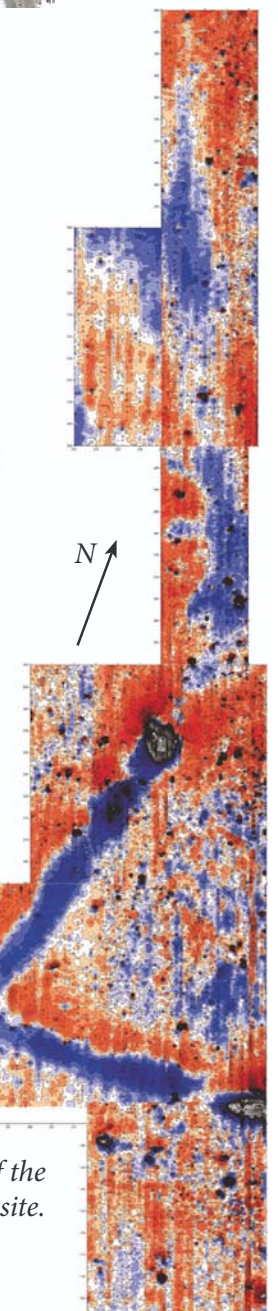
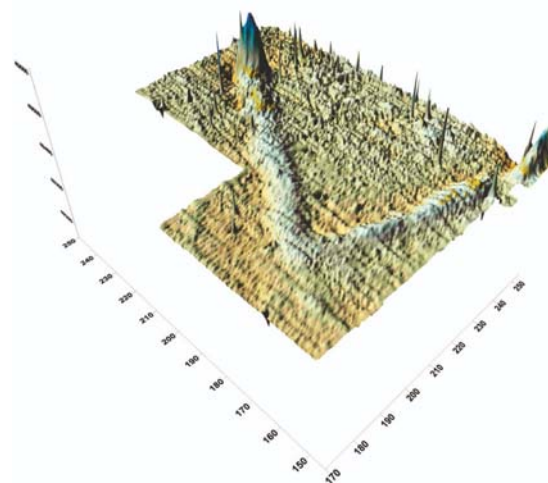


Plan of the site and magnetic maps of 2006-2007.



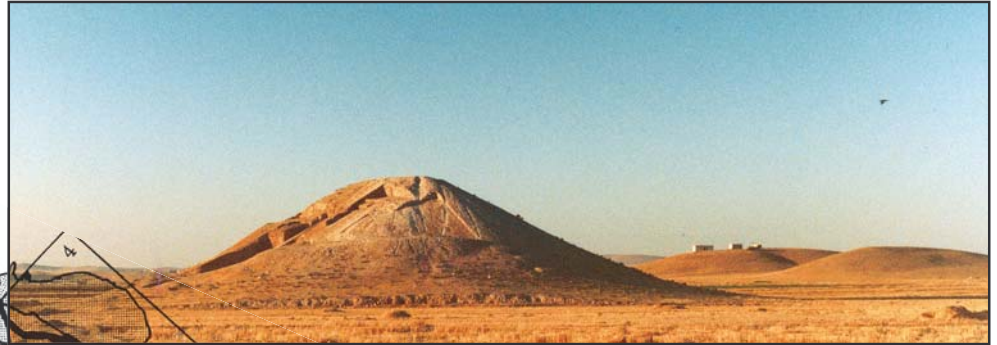
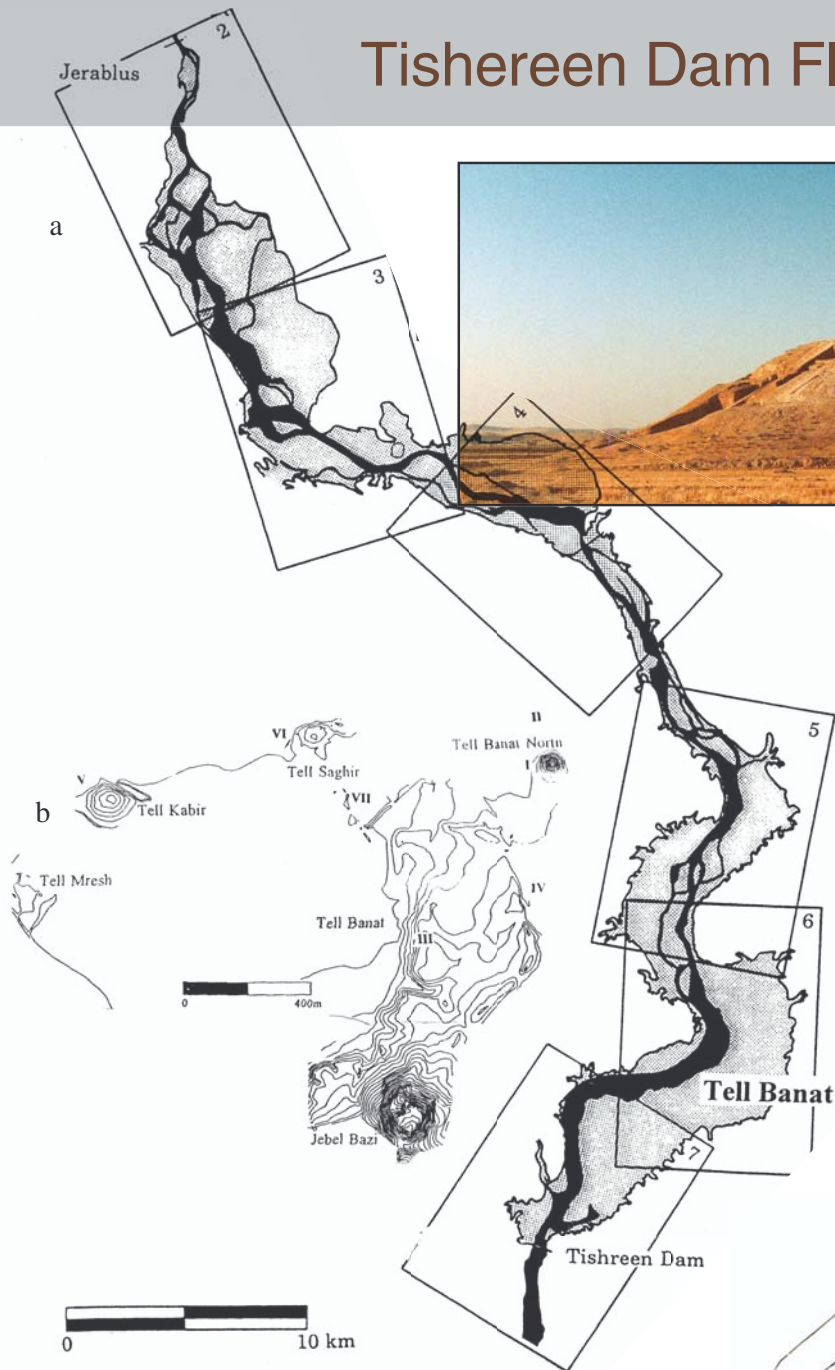
Aerial photo and magnetic grey scale map.

Three dimensional magnetic map.



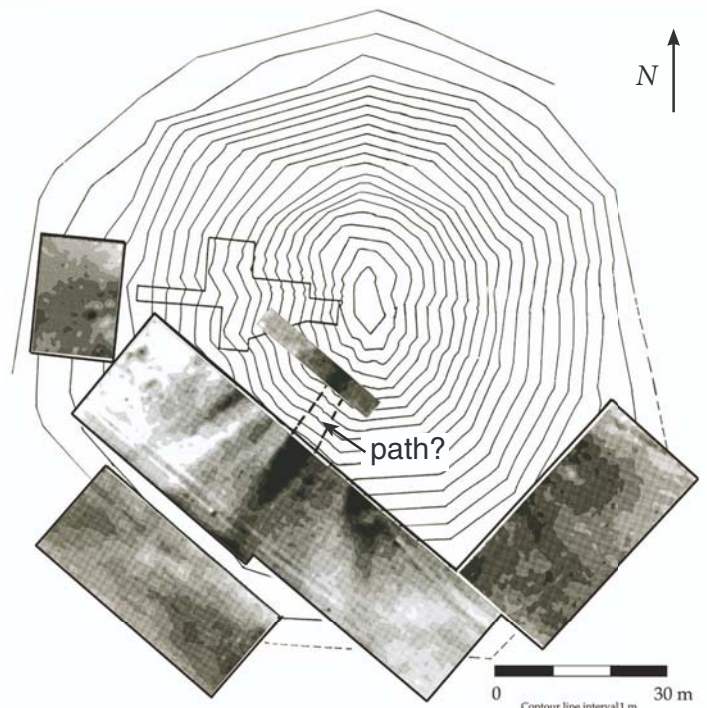
Magnetic contour map of the western part of the site.

Tell Banat at the Euphrates River. Tishereen Dam Flood Zone. SYRIA.



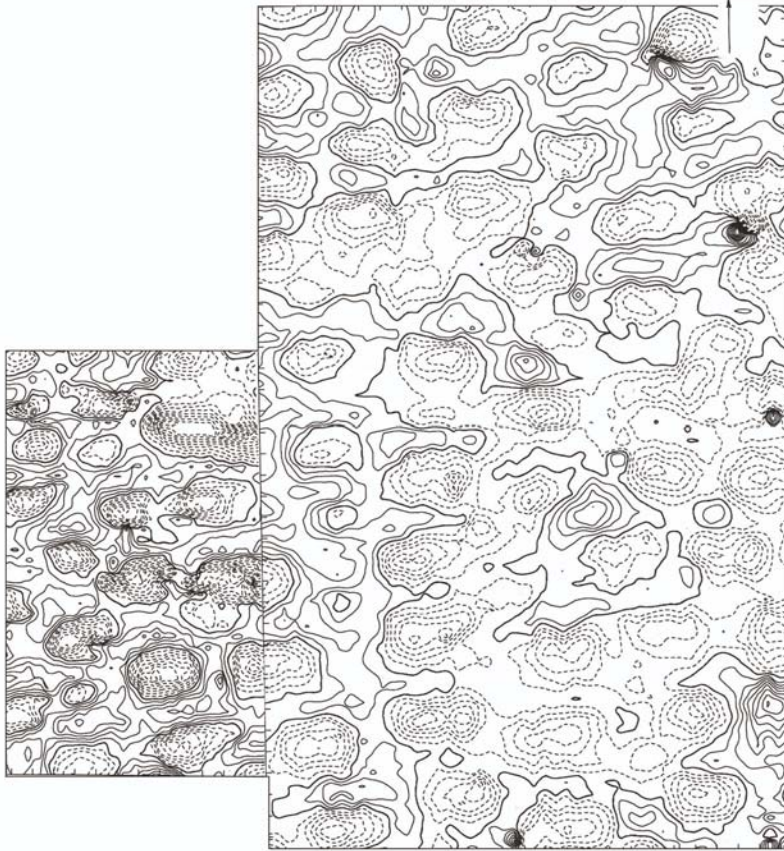
A big project for archaeological investigations in Syria along the Euphrates River was carried out during the 1990s before the Tishereen Dam was constructed. Large areas of the valley were flooded afterwards.

The clay “pyramid”, which is called The White Monument, has been investigated with the help of an electromagnetic conductivity meter EM31 by B. Bevan and with gradiometer GSM-19WG by T. Smekalova in 1997. Some of the results of the magnetic survey are presented here. There are several positive (dark) anomalies on the south-west part of the mound (see below). They could serve as evidence about the manner of the monument’s construction. The central long positive anomaly could be a path into the “pyramid” (?). It is not possible to check by excavation because the area is now flooded.

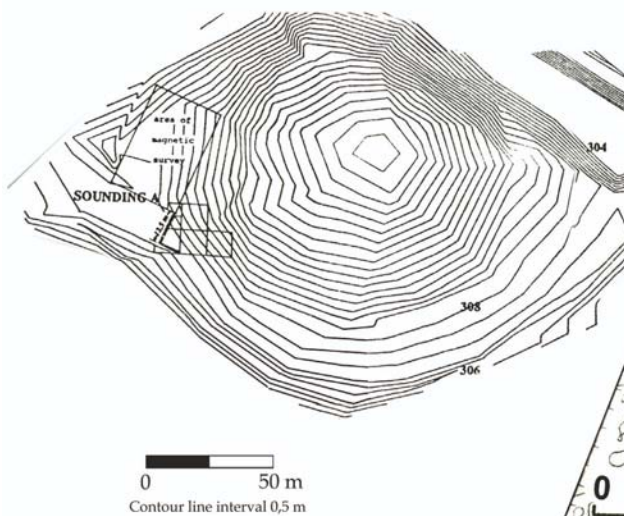


a) A map of the Tishereen Dam flood zone.
b) Location of the Bronze Age “pyramid” Tell Banat North and Roman Age site Tell Kabir.

Tell Banat North. Bronze Age. Magnetic map of the SW part of the White Monument. The dark area is a positive anomaly, possibly created by a path into the monument(?).



Syria. Tell Banat.
Muslim cemetery.
Magnetic map. Contour interval 5 nT.
A series of negative anomalies (dash lines)
are from stone graves.

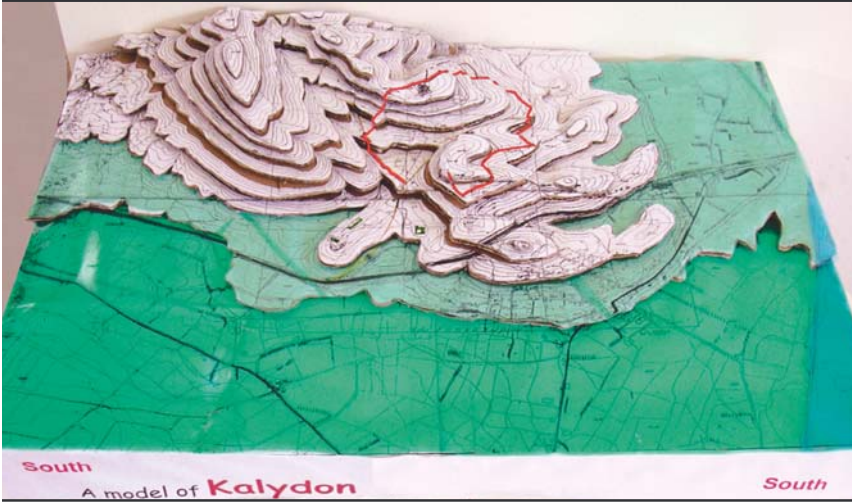


Syria. Tell Banat.
Tell Kabir. Roman Age settlement.
Magnetic map showing a negative anomaly
(dashed lines) from a wall and positive
anomaly (solid lines) from a big kiln (?).
Contour interval -2; +5 nT.

There is clear evidence of a Roman house on hill, Tell Kabir. There is a long and broad negative anomaly caused by a limestone wall, and a big local positive anomaly possibly from a kiln.



Kalydon. Aetolia. GREECE

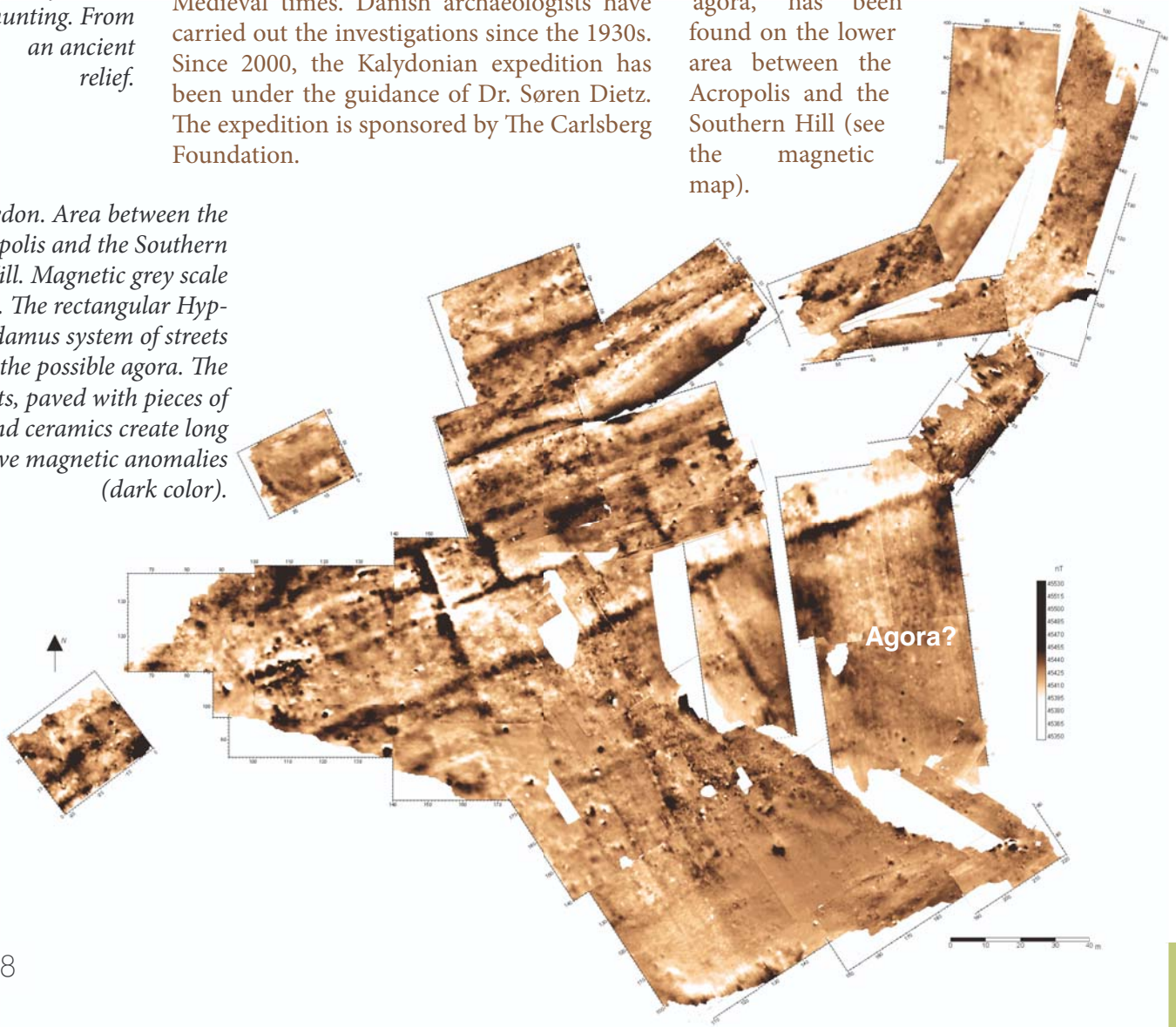


Magnetic surveys in 2001-2003 were been carried out on a large area of ancient Kalydon. A radial planning system of “Lower town” streets, a temple and a smithy on the Acropolis, pottery kilns, and cemeteries outside the city walls have all been revealed. The most interesting result is that the rectangular Hypodamus planning system and a town square, ‘agora,’ has been found on the lower area between the Acropolis and the Southern Hill (see the magnetic map).

Left: A model of Kalydon by T. Smekalova. Right: Kalydonian hunting. From an ancient relief.

The ancient town of Kalydon is known in connection with the myth about Kalydonian hunting which existed in Archaic, Classical, Hellenistic, and, probably, in Roman and early Medieval times. Danish archaeologists have carried out the investigations since the 1930s. Since 2000, the Kalydonian expedition has been under the guidance of Dr. Søren Dietz. The expedition is sponsored by The Carlsberg Foundation.

Kalydon. Area between the Acropolis and the Southern Hill. Magnetic grey scale map. The rectangular Hypodamus system of streets and the possible agora. The streets, paved with pieces of tile and ceramics create long positive magnetic anomalies (dark color).



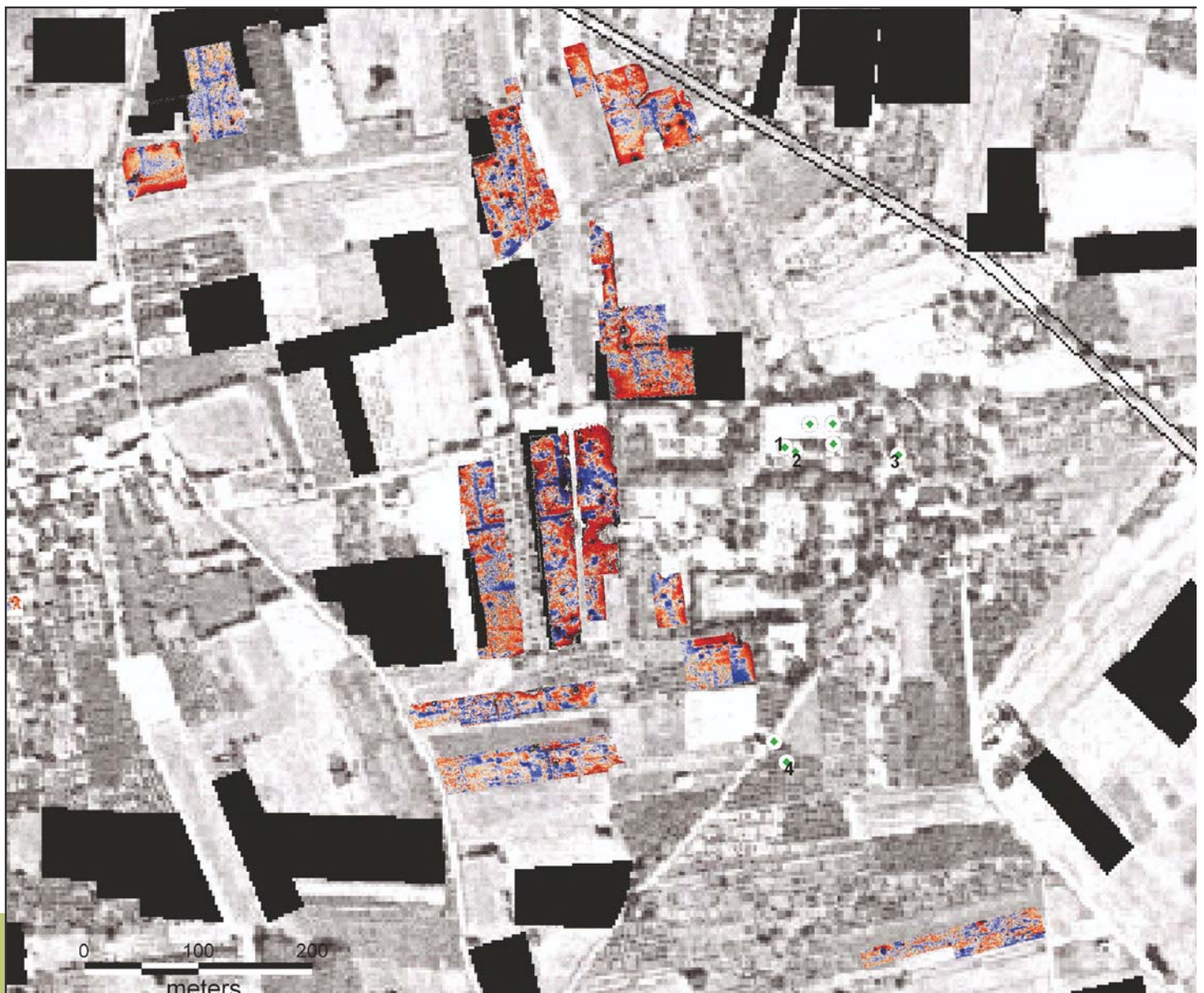
Tegea on Peloponnesus. GREECE

Magnetic surveys on the site of ancient Tegea in Arcadia on the Peloponnesus have been carried out in 2004-2005 under the guidance of Dr. Knut Ødegård (the Norwegian Institute in Athens). One of the most important reasons for the success of the magnetic survey of ancient Tegea is that the streets were paved with pieces of ceramic tile, potsherds, and slag. All these materials are very magnetic: therefore, the streets create positive anomalies with amplitudes of 10-100 nT, depending on the amount of the covering material and the magnetic properties of the surrounding matter. This fact opens the possibility for revealing the plan of the whole city by magnetic mapping. The streets could be traced in different fields, even with some interruptions where there are obstacles like modern houses or fences. There



is quite a large contrast of magnetic properties between the non-magnetic limestone and marble walls, and the soil. Therefore, it is possible to see the negative anomalies from the walls.

Air photograph with magnetic maps of the center of ancient Tegea. The long blue anomalies show the buried streets of the town which are paved with tile and ceramic fragments. It is possible to reveal the rectangular planning system of the streets, which are dated back to late Archaic and Classical times. The dimensions of the rectangular quadrants are about 75 m x 25 m.



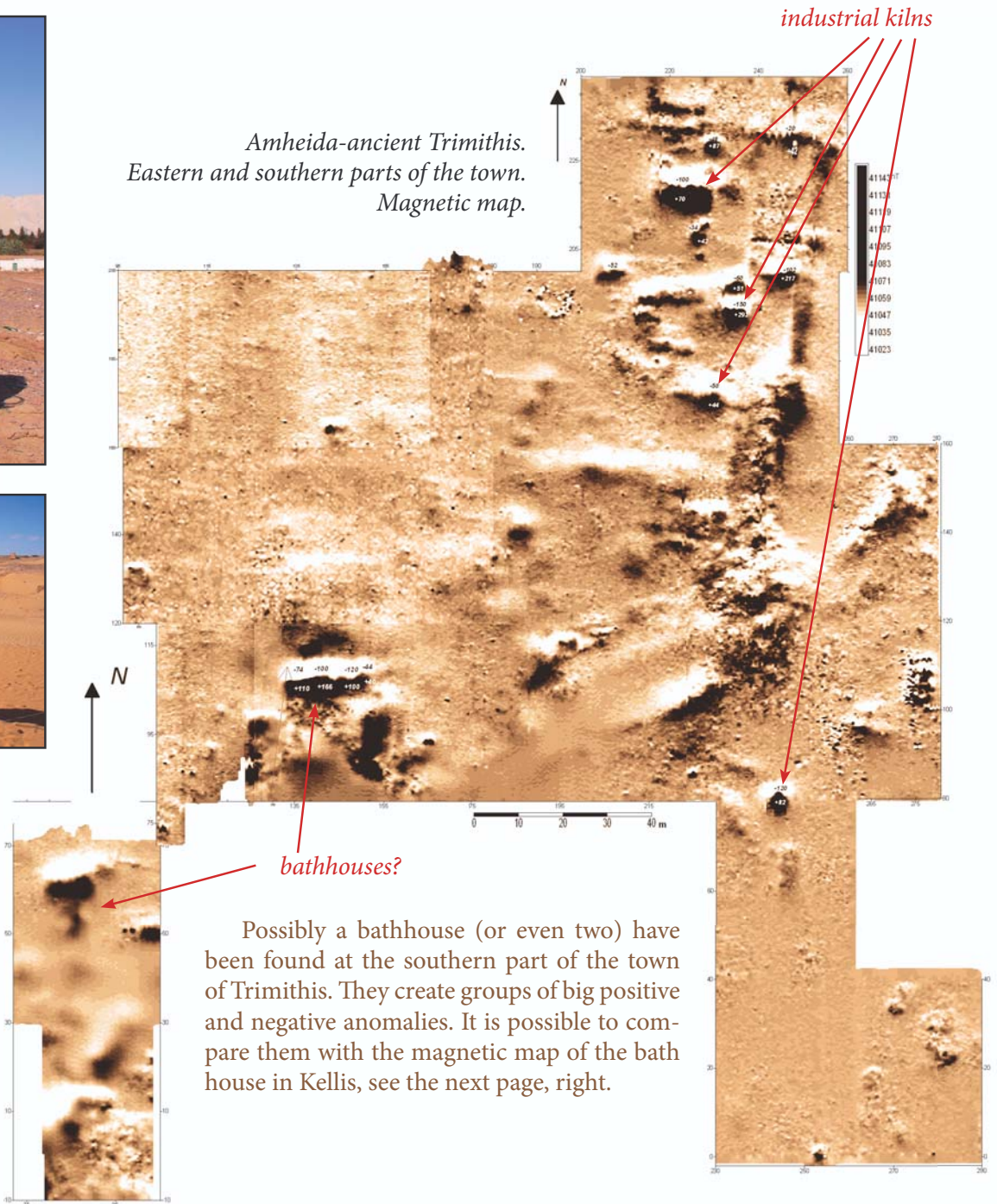
The Roman towns Trimithis and Kellis in the **DAKHLEH OASIS, EGYPT**



There is a large industrial quarter in the eastern part of the town of Trimithis. The industrial area is bounded by four streets, which are visible on the magnetic map as long positive (dark) anomalies. There are at least seven or eight industrial furnaces or kilns situated within the industrial quarter. Heaps of slag debris and ash were deposited at the ends of streets, at the eastern side of the site.

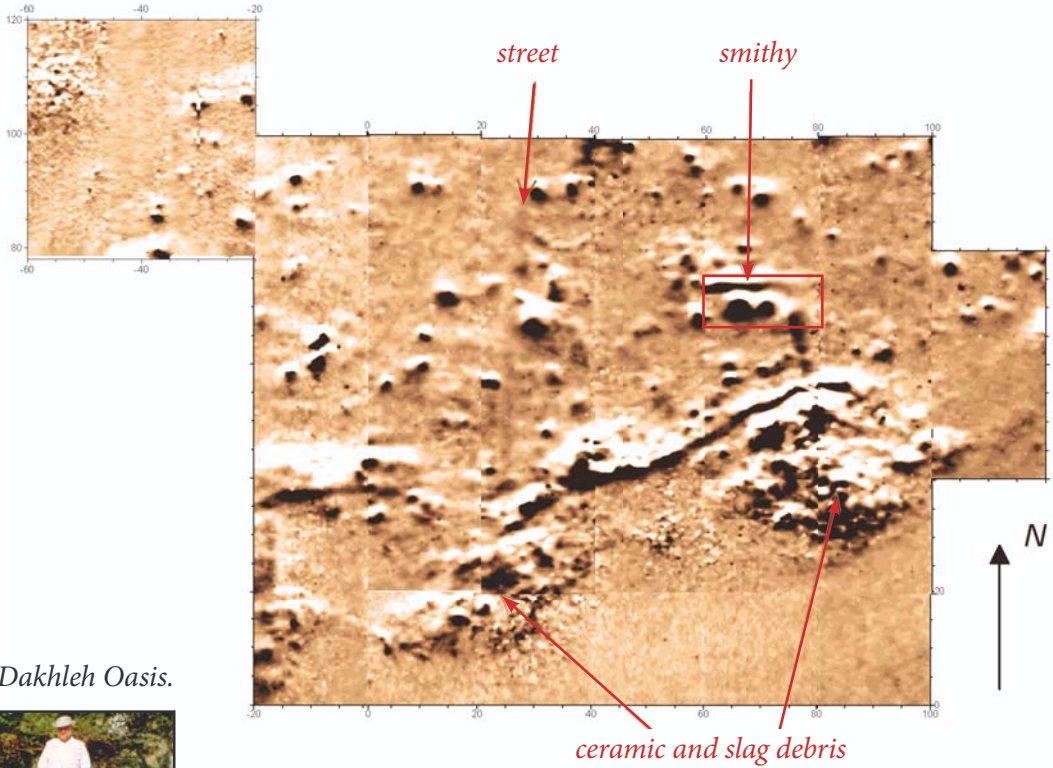


*Amheida-ancient Trimithis.
Eastern and southern parts of the town.
Magnetic map.*

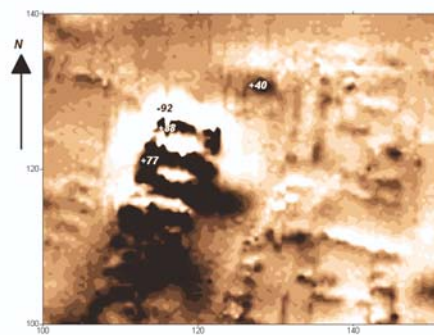




Ismant el-Kharab - the Roman town Kellis. Magnetic map of 1998 and 2005. Dark areas mean strongly magnetized objects. They are mostly kilns or furnaces. There are large areas, filled with ceramic debris and slags, which are reflected in the magnetic field as complex anomalies. The marked area was excavated in January 2000. There was a smithy with two kilns in two rooms.



Modern pottery workshop in Dakhleh Oasis.



Ismant el-Kharab - the ancient Kellis. Bath house. Magnetic map.





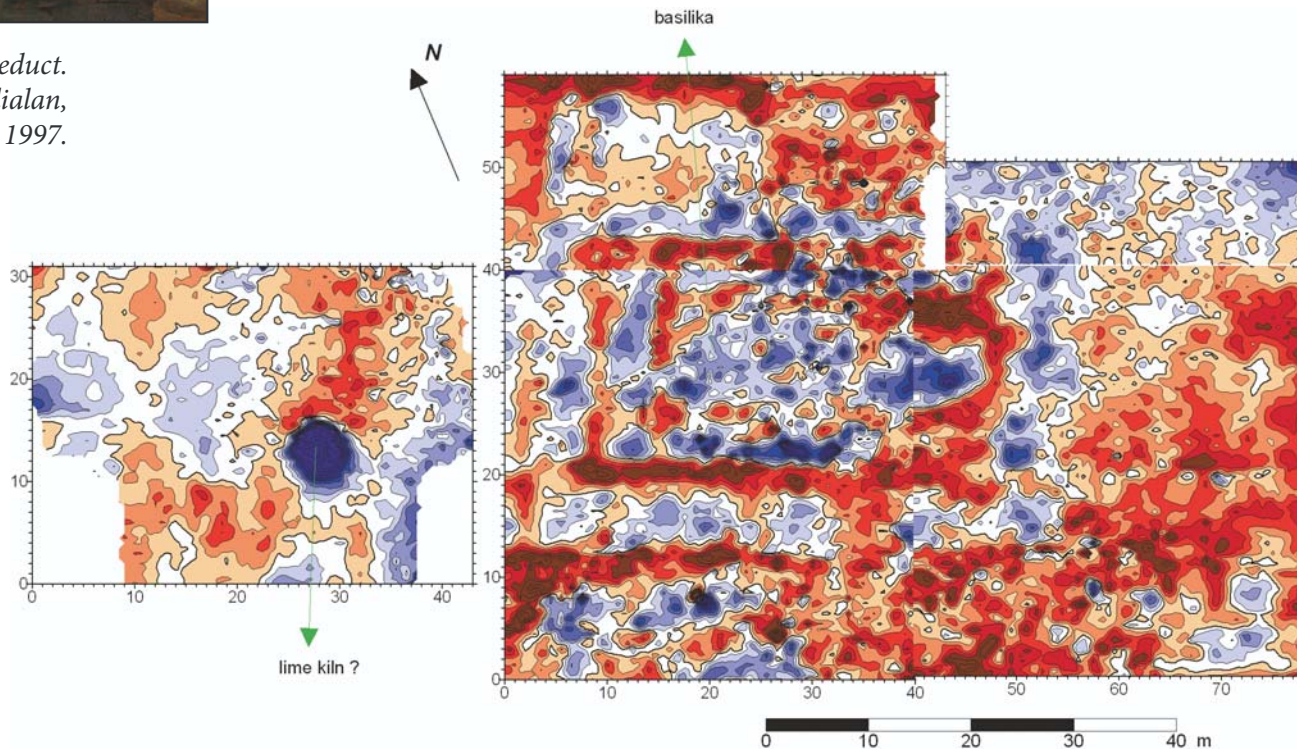
Roman aqueduct.
After Taşlıalan,
1997.

Antioch - the Roman capital of Pisidia and a Biblical town

The ancient town of Antioch was the capital of Roman Pisidia, the area deep within the southern part of Asia Minor.

The Pisidian Antioch is well known as a biblical town because of the travels of St. Paul. The Pisid-

ian Antioch had been scientifically discovered during the first third of the 19th century, and the excavations on the acropolis started by the beginning of the 20th century. Magnetic surveys on the acropolis of the Pisidian Antioch site were carried out in June 2001.



The St. Paul basilica. After Taşlıalan, 1997.

The most interesting results have been obtained in the area between the Roman baths and nymphaeum. It was presumed that the palestra (the building for physical training) was situated to the east of the Roman baths (Mitchell, Wealkens, 1998, p. 199). But as magnetic surveys showed, there was a basilica there, a very clear plan which was revealed on the magnetic map. It is possible that the basilica was built on the foundation of the palestra. The nave of the basilica was divided

into three parts. The size of the church is about 25 m × 50 m (together with the central apse, 10 m in diameter). It has two external enclosures: 47 m × 57 m and 57 m × 57 m. The plan of this church is similar to the plan of the large basilica of St. Paul, which was excavated at the lower town, but this one is larger (70 m × 25 m).

Magnetic surveys have been carried out also in the area above the Roman baths.

A very strong local magnetic anomaly was found there, the source of which was interpreted as a big tile or lime kiln. It has two parallel channels, the dimensions of which are approx. 4 m × 4 m. The remainders of another kiln are visible at the edge of excavations nearby. It is possible that both kilns were built in early medieval times for producing construction materials for the basilica.

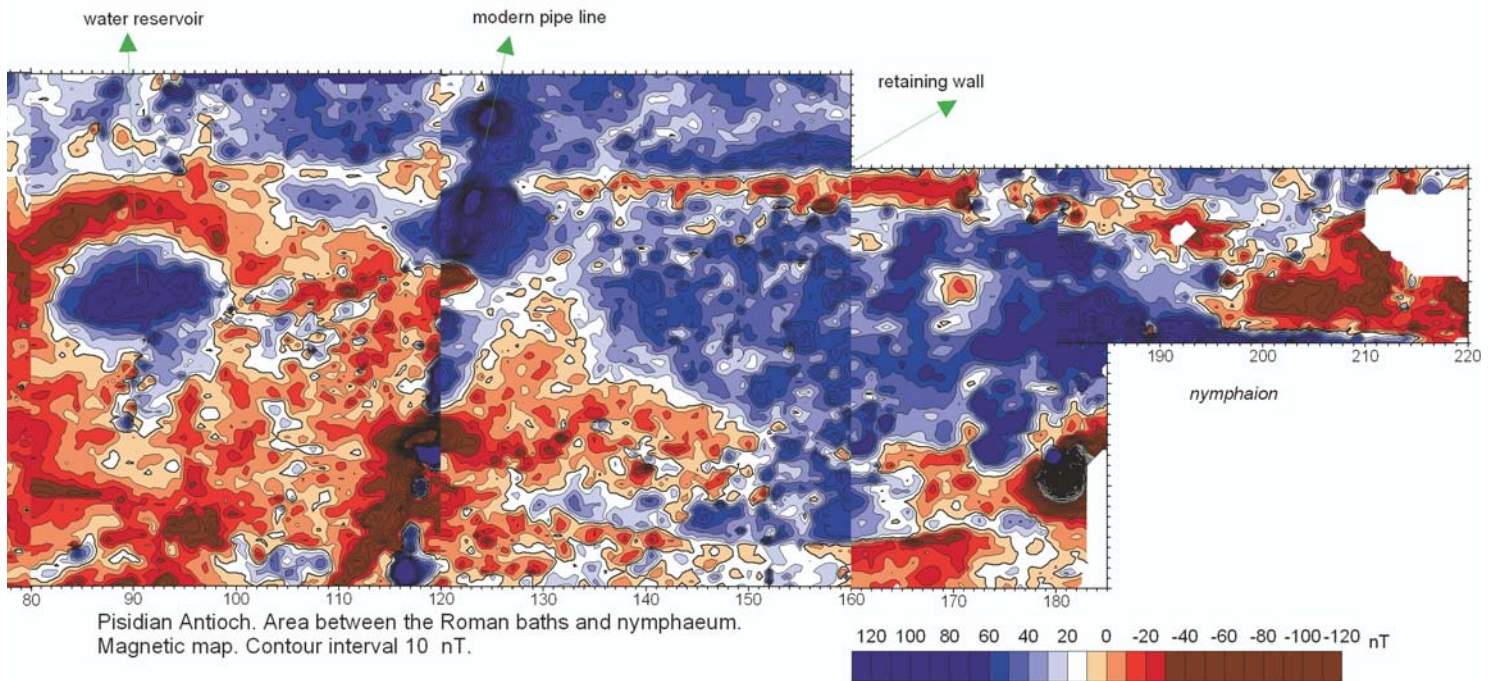
Another interesting object which was revealed in the area is a complex, connected to the city's water supply. It consists of a big water reservoir, surrounded with walls built of limestone blocks. One can see a ceramic water pipe line with a length of more than 10 m, which starts from at the southern side of the water reservoir. Each section of this pipe line exhibits a positive-negative magnetic signal because it had been magnetized during heating in a pottery kiln.

The area from this big water complex to the nymphaeum was artificially leveled, and for this purpose the long retaining wall (90 m long) was erected at the beginning of the natural slope at the northern part of the plot.

The earthen leveling of the area was done purposely in order to have the same horizontal surface for collecting water from the aqueduct and for supplying the ancient city with water.



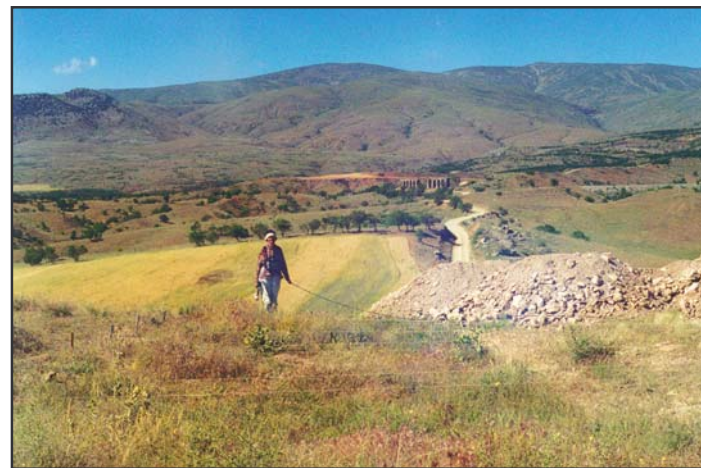
Street in the Pisidian Antioch. After Taşlıalan, 1997.



Roman aqueduct. After Taşlıalan, 1997.



Magnetic survey in the area east of the Roman Baths.

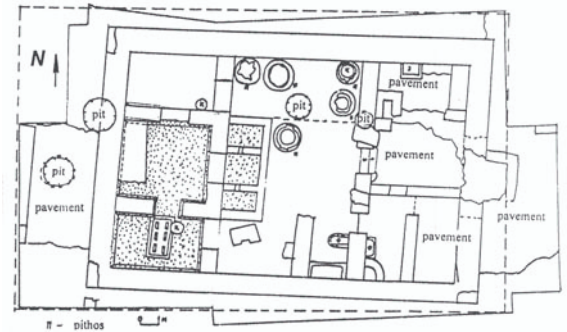
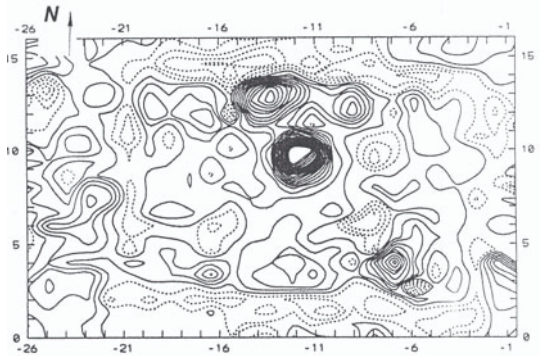
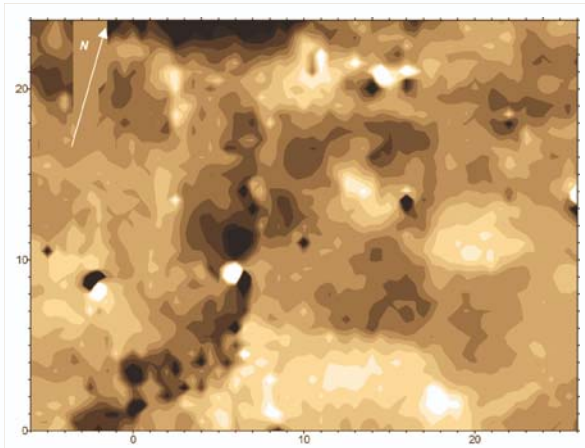


Greek villas in the CRIMEA



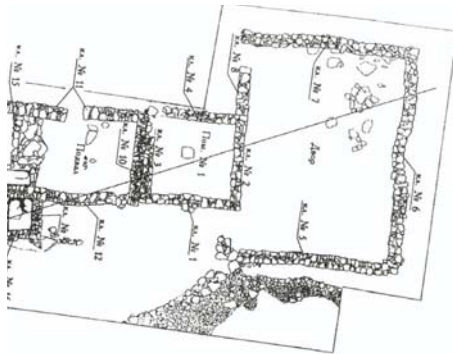
Nonmagnetic limestone walls from ancient Greek and Roman villas create clear negative anomalies, because they are situated in slightly magnetic soil. The contents of the rooms (large ceramic vessels, pits, ovens, cisterns and earth) produce positive anomalies. In Crimea, in the territory of the Ancient Greek Bosporan Kingdom on the coast of the Sea of Azov, more than 15 settlements and farmsteads have been investigated with the help of a magnetometer during the years 1992-2005.

Magnetic map of the farmstead Pustunnuj Beger 2. Contour interval 2 nT. The contours of a rectangular limestone building are visible.



Magnetic map of the central part of a Hellenistic vineyard, Cormorant Rock. Contour interval 2 nT. Negative anomalies (dashed lines) correspond to nonmagnetic limestone walls; positive anomalies (solid lines) - to pithoi and pits inside the building.

The results of excavations of the farmstead Pustunnuj Bereg 2 (after Ломтатдзе Г.А., Масленников А.А., 2003).



Crimean Azov sea coast near Pustunnuj Bereg 2.



Golden Bosporan coin from the 4th century BC. The ear of wheat below the legs of the griffin symbolizes the richness of wheat in the Bosporus.

The Roman villa Petropigi in MACEDONIA, GREECE

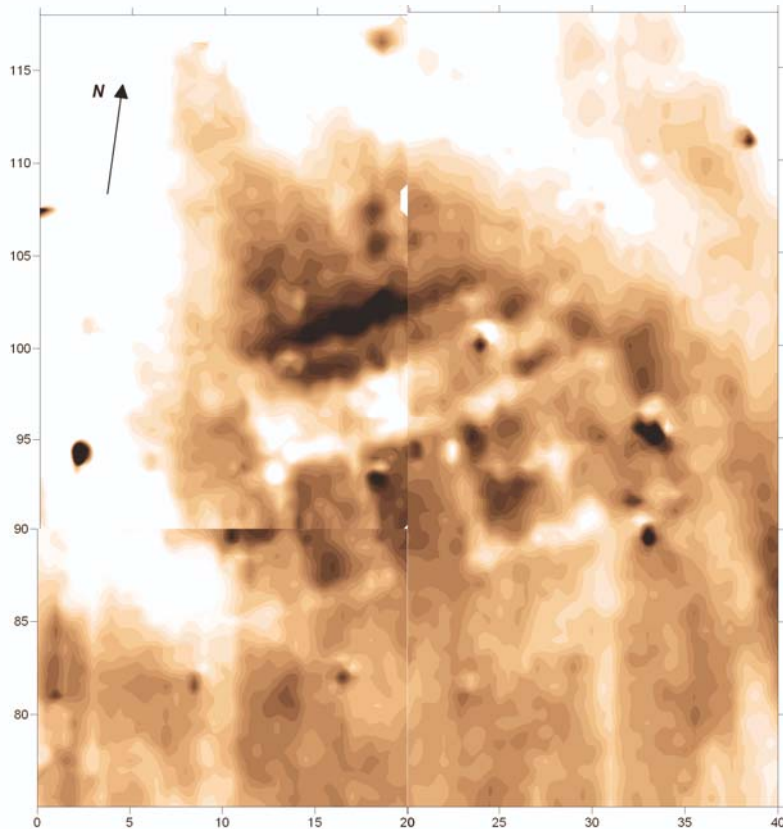
A big building is clearly visible on the magnetic grey scale map at the northern part of the plot (see magnetic map). This is a stone construction of about 25 m x 25 m. The outer and inner walls of this building are visible on the magnetic map as negative anomalies (white color). There are many small magnetic objects in the interior of the building. Some of them correspond to ovens inside the rooms, whilst others are caused by pits, filled with material that is more magnetic (pieces of ceramics, ashes, etc.), than the surrounding soil or rock.



*Magnetic survey
in Petropigi,
Macedonia.*



There are also smaller local magnetic anomalies, which could have been created by big ceramic vessels (pithoi, amphorae). Because of the material which was found on the surface, it is possible to date the building to the late Roman times.



*Magnetic grey scale map of the Roman villa in Petropigi, in Macedonia, on the coast just opposite the island of Thasos.
Contour interval 2 nT.*



Recording the remains of ancient metallurgy

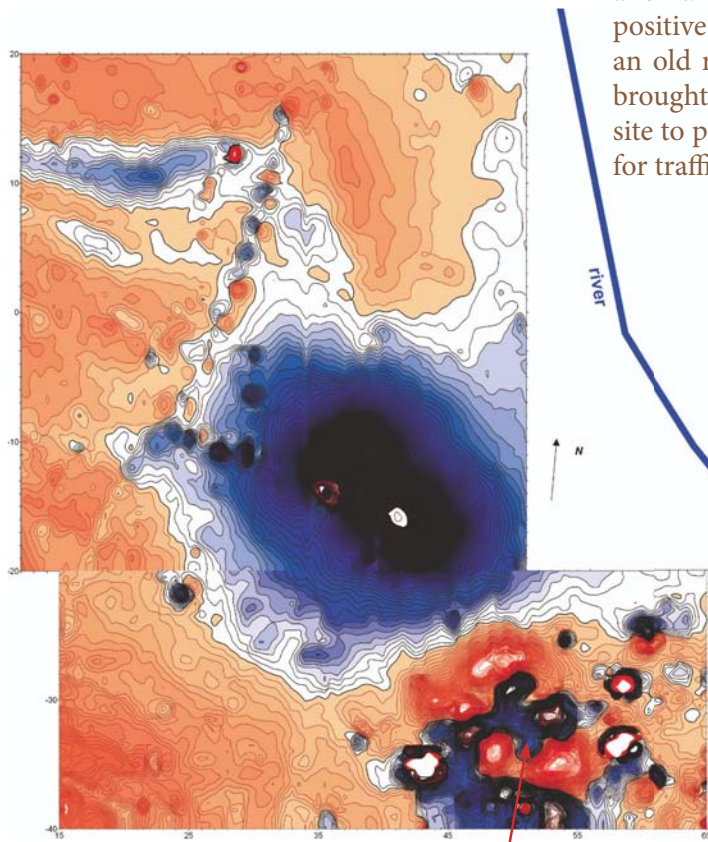
Kupferberg in 1650.

Magnetic surveys have been used for the investigation of medieval copper smelting sites in an area to the north-east of Kupferberg in the German province of Bavaria. The copper smelting slag is extremely magnetic there; the other remains of the copper production are also very magnetic : fragments of clay shafts, roasted ore, pits filled with fired soil, ashes, etc. Therefore, the magnetometer could easily record strong magnetic anomalies at the copper extracting sites.

A copper-smelting site is reflected in the magnetic map as a group of very strong anomalies. There is also a strong and wide positive anomaly, which could be produced by geological structures (a body of magnetic ore), situated in a depth of about 10 m to the north of the copper-smelting site. A long line of narrow positive-negative anomalies, which could be a road, or part of a pipeline (?) is seen to the north of the big "geological" anomaly.

The magnetic survey also revealed a long anomalous zone, consisting of many local positive anomalies. It could be interpreted as an old road covered with slag that had been brought from a neighbouring copper-smelting site to pave a surface of the road, improving it for traffic.

Schallerhöferhütte. Magnetic map. Contour interval 20 nT.

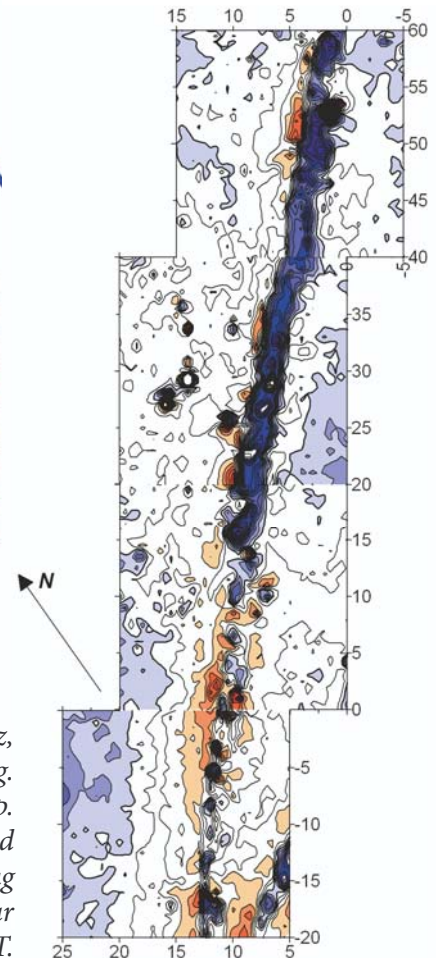


Representatives of local authorities, sponsors and participants of the expedition, on one of the copper-smelting sites near Kupferberg.



Remains of a copper-smelting site.

Alte Schmoltz, near Kupferberg. Magnetic map. Over an old road covered with slag pieces. Contour interval 3 nT.





Since 1986, excavations have been carried out each year at the late prehistoric ironworking settlement at Crawcwellt, in north-west Wales, Great Britain by Peter and Susan Crew. The site is over 300 m above sea level and the terrain is now rough grazing with frequent areas of peat bog. The area has never been plowed, leaving archeological sites in good condition. There are remains of furnaces and smithing hearths, outside of which are heaps of iron-working slags. (Crew, Smealova, Bevan, 2003).

A high resolution magnetometer survey has been carried out on four prehistoric furnaces and a medieval furnace, producing detailed maps of their magnetic signals. Through mathematical modeling of these maps using magnetic dipoles, it was possible to estimate the direction of the total magnetisation.



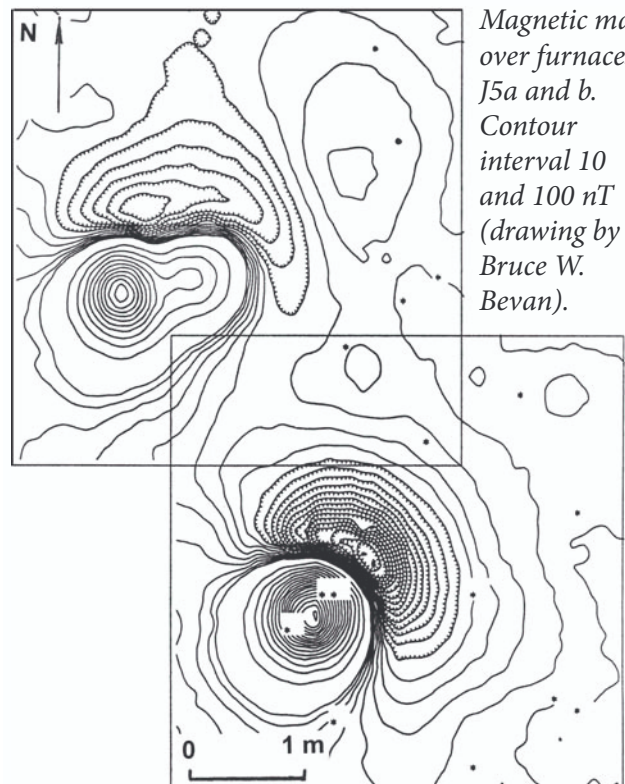
Surveys were carried out on 5 cm and 10 cm grids.



Crawcwellt J5a. Photo of two neighboring furnaces. Photo: P. Crew.



Crawcwellt J5b. Photo of the furnace. Photo: P. Crew.



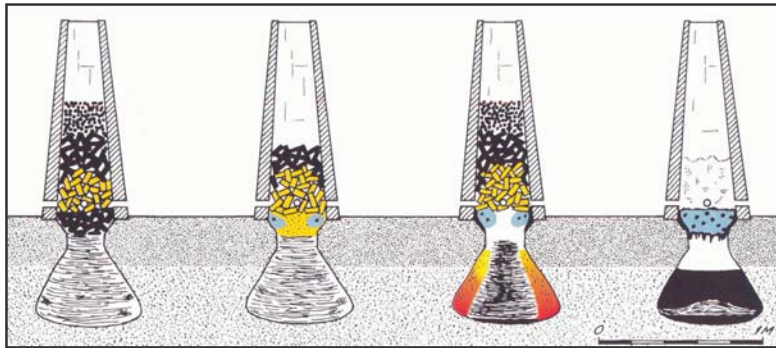
Magnetic map over furnaces J5a and b. Contour interval 10 and 100 nT (drawing by Bruce W. Bevan).

Iron smelting sites with slag blocks in SW JUTLAND

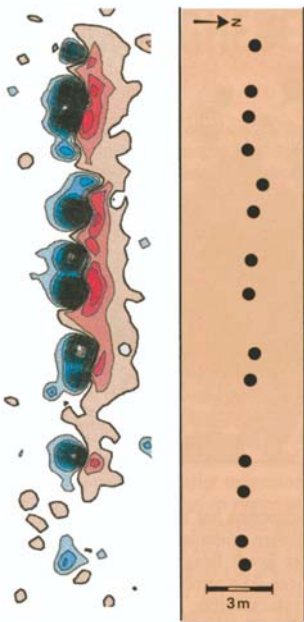


During each smelt the slag ran down into the underlying pit where it solidifies and forms a slag block.

Iron smelting furnaces with clay shafts and underlying slag-pits were widely distributed throughout the western part of Jutland between the 2nd-6th centuries AD. 120 smelting sites from this period have now been located. Furnaces of this type are well known throughout a large area of Europe from the end of the first millennium B.C. to the first half of the first millennium A.D.



Bruce Bevan and Sergej Smekalov are measuring the magnetic properties of slag blocks from SW Jutland, 2004.



Those blocks that have been well preserved have an average weight of almost 200 kg. In southwest Jutland the top of the block was generally 30-35 cm below the surface, with the bottom of the pit 50 to 70 cm below the surface.

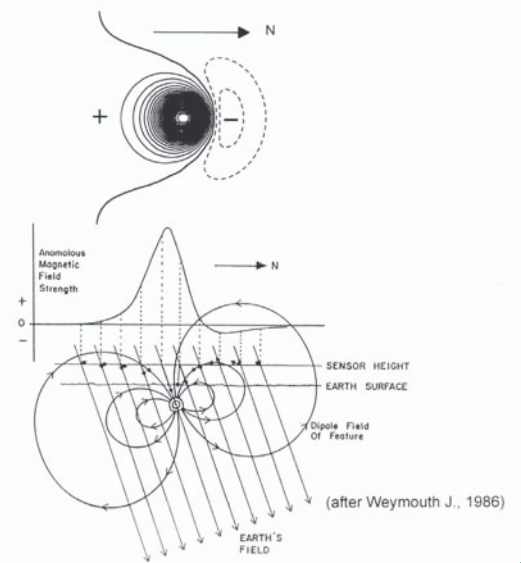
A physical-archaeological model, proposed by Niels Abrahamsen (1965) in the form of a point dipole (or a magnetized sphere), is an excellent magnetic simulation of the real slag-pit.

Slag blocks represent near ideal objects for magnetic prospecting because they are large magnetic masses, buried in very shallow pits, which produce strong magnetic anomalies of several hundred nanotesla, and in some cases, even several thousand nanotesla.

Each slag pit is a result of a single smelt. When the number and weight of the slag blocks are determined, it is possible to determine the total volume of iron production. The magnetic survey also reveals

Left: Magnetic anomalies, measured in 1992 over a row of slags in Snorup and the results of their excavation in 1993 following the magnetic survey.

Magnetic dipole anomaly



(after Weymouth J., 1986)

the position of the slag pits; the relationship between the production and the living areas; and also the organisation of the smelting process.



An excursion to the Snorup site for the participants of the Sandbjerg Conference on Prehistoric and Medieval Direct Iron Smelting in Scandinavia and Europe (September, 1999).

Snorup is the biggest iron production site in south-west Jutland. Map of the iron production site and the Iron Age village. Red dots on the air photograph are slag pits, revealed by excavations and by magnetic survey.

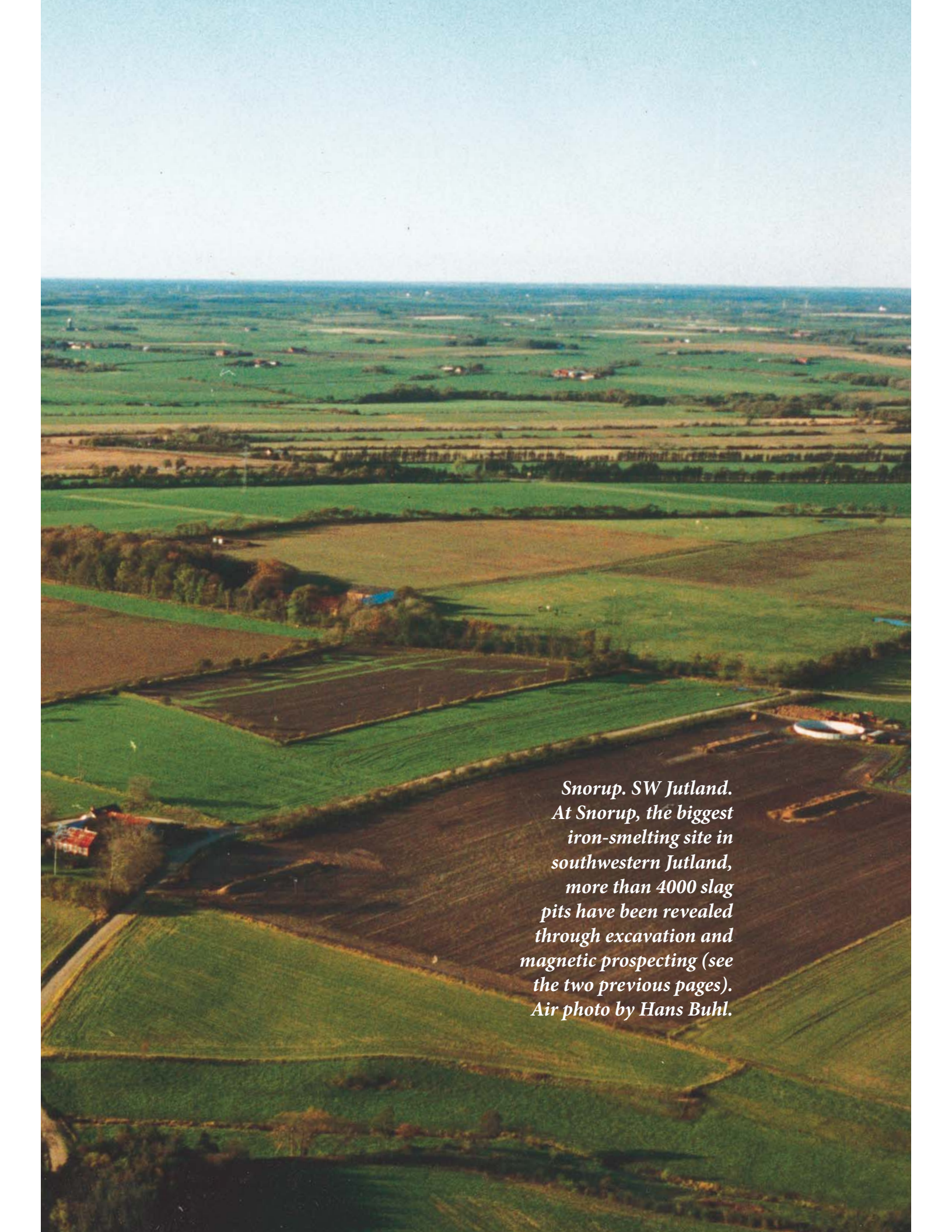


Far left: Olfert Voss presents the excavated row of slag blocks. Left: the explanation of the use of the GSM-19 gradiometer for magnetic surveys on ancient iron smelting sites. 18th of September, 1999.



Snorup. The excavated row of slag blocks.





*Snorup. SW Jutland.
At Snorup, the biggest
iron-smelting site in
southwestern Jutland,
more than 4000 slag
pits have been revealed
through excavation and
magnetic prospecting (see
the two previous pages).
Air photo by Hans Buhl.*



To get a better understanding of the organisation of the iron production in this region, it was decided to try to locate and survey as many iron smelting sites as possible within an area of 10 km x 8 km around Snorup.

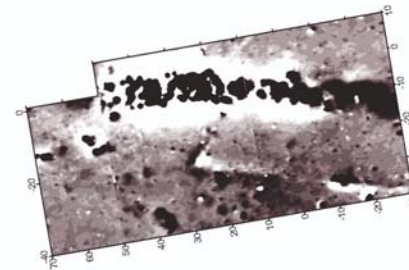
This work is still ongoing with the surveys not yet completed. However, 7 new sites have been found: Krarup and Yderik (1000 slag pits resp.), Gødsvang (>1000 slags), Hodde (>1000 slags),

Horne (>300 slags), Krarup East (ca. 100 slags), Hindsig (ca. 70 slags).

In 1975, part of an Iron Age settlement had been excavated in Hessel because the traces of long houses had been spotted on an aerial photo (see to the left). In 2000, a big cluster of slag blocks was found by a magnetic survey close to the excavated houses (see magnetic

map above), these blocks must have had a connection to the village. A trial trench revealed quite a thick cultural layer around the slag pits that still contained a

great deal of information about the construction of the furnaces and the organization of iron production. This is a very rare case, where the cultural layer around the slag pits has survived.



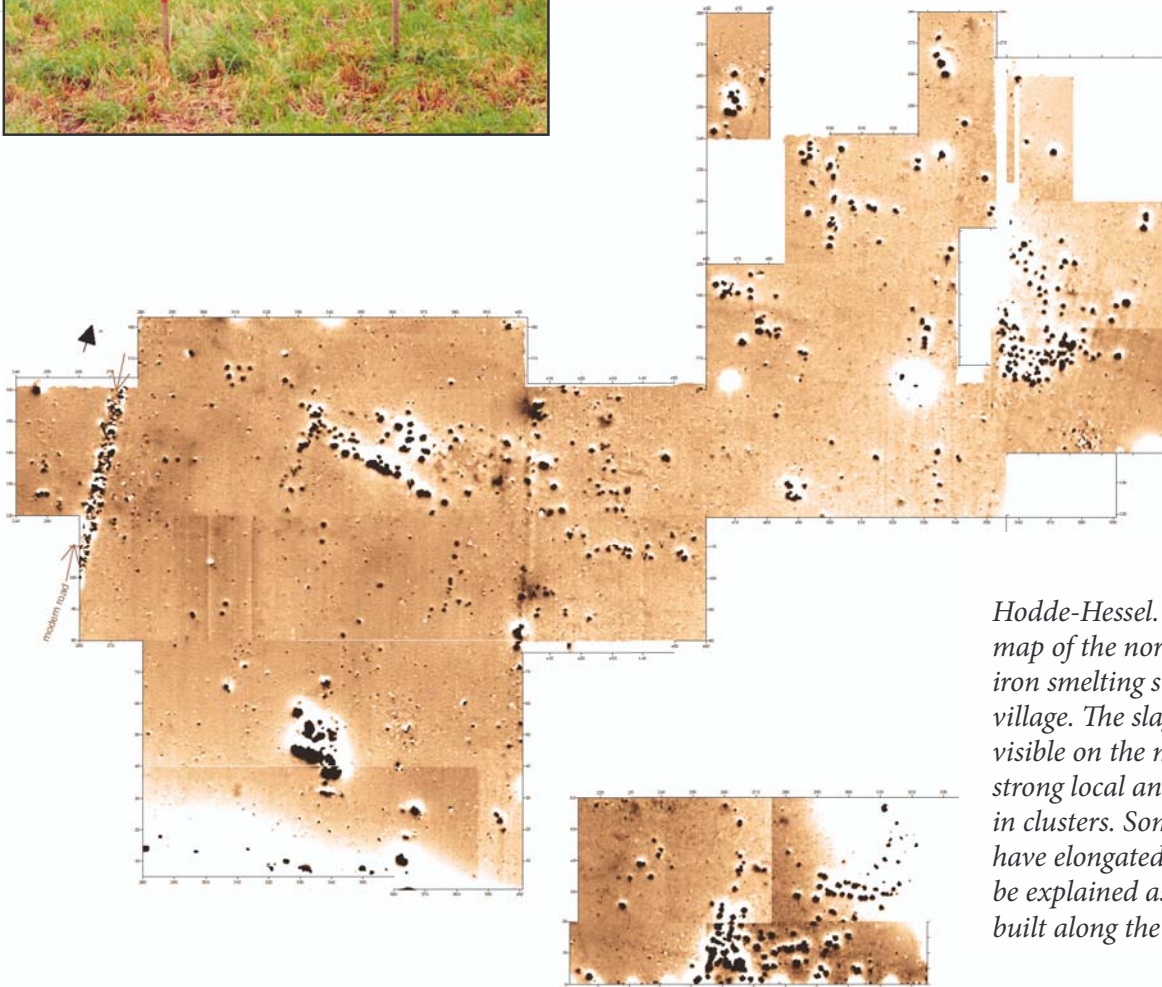
Air photo of the Hessel site by Hans Buhl, 1975. The position of the area of the magnetic survey is shown by yellow dashed lines. Situated within the yellow dashed lines is the magnetic grey scale map of the big cluster of slag blocks in Hessel.

SOUTHWEST JUTLAND – a large area for producing iron in the late Roman Iron Age



Normally, the clay shafts are completely destroyed by ploughing. We still have only scant evidence about the construction of the clay shaft. This could be an explanation why so many experiments with iron production have been unsuccessful. Therefore, it is very important to carry out detailed and careful excavations of this cluster of slag blocks in Hessel.

Iron smelting sites are often close to rivers and streams. From the wet areas around them, the ancient people collected bog iron ore which was necessary for the iron smelting.



Hodde-Hessel. Magnetic grey scale map of the northern part of the iron smelting site, and an Iron Age village. The slag blocks, which are visible on the magnetic map as strong local anomalies, are grouped in clusters. Sometimes the clusters have elongated shapes, which might be explained as rows of furnaces built along the fences of the farm.



GØDSVANG – a large iron-smelting site from the Late Roman Age with Medieval strip fields

Magnetic maps contain rich information not only about iron smelting sites but also about other archaeological objects. Thus, beside the groups of strong local anomalies from the clusters of slag blocks, it is possible to see the traces of Medieval strip fields in the area around Gødsvang. These are reflected in the magnetic map as very weak but regular, parallel positive anomalies. They are caused by the magnetic filling of the ditches between each field which served as boundaries. These ditches were gradually filled with topsoil, which is more magnetic than subsoil. It is interesting to see that the system of medieval fields has a north-

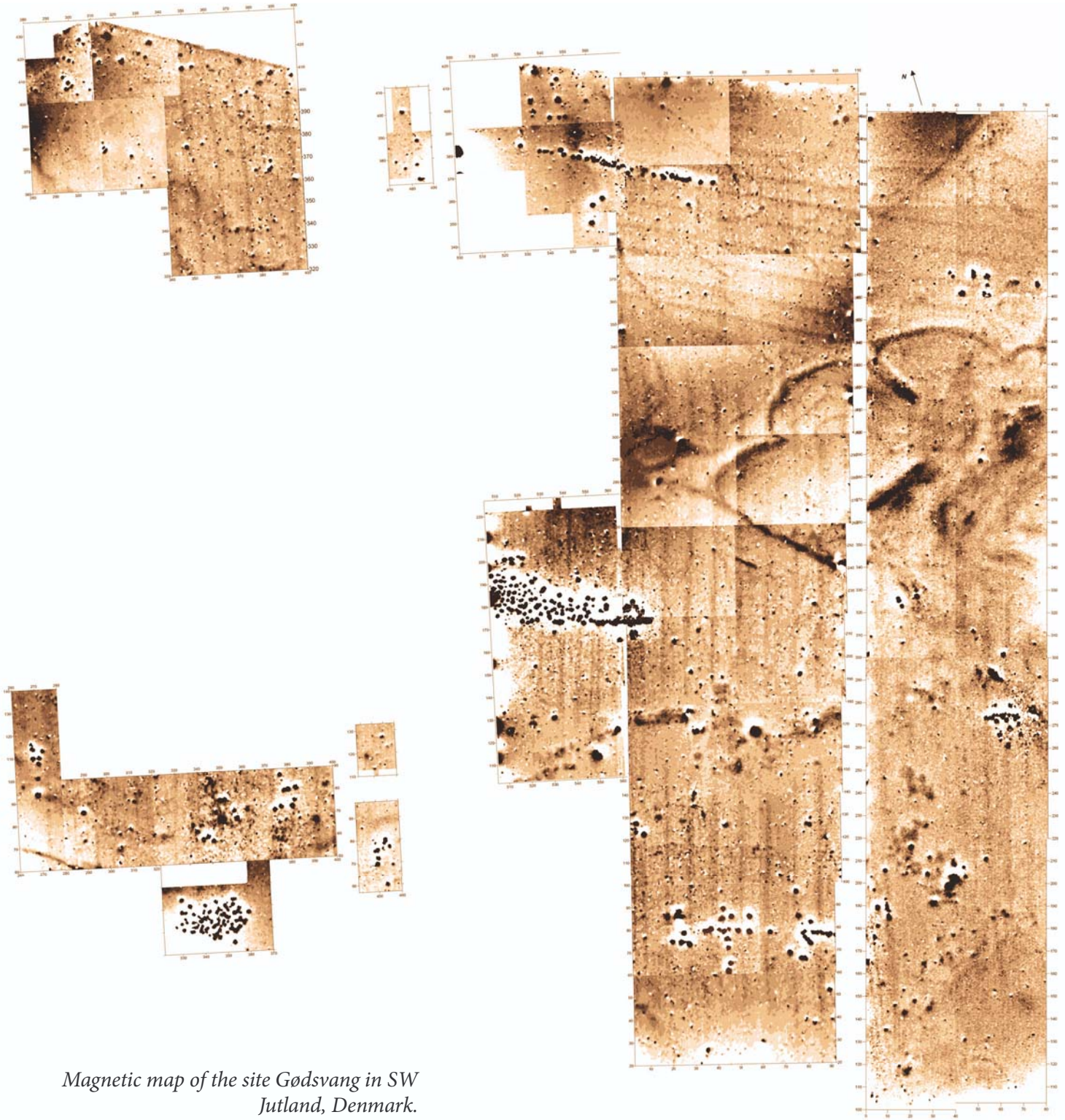


Air photo of Gødsvang by Olfert Voss.

south direction in the southern part of the site and an east-west orientation in the northern part. On other sites – in Snorup, Yderik and elsewhere in Jutland – we have observed the same weak positive magnetic anomalies from Medieval fields.

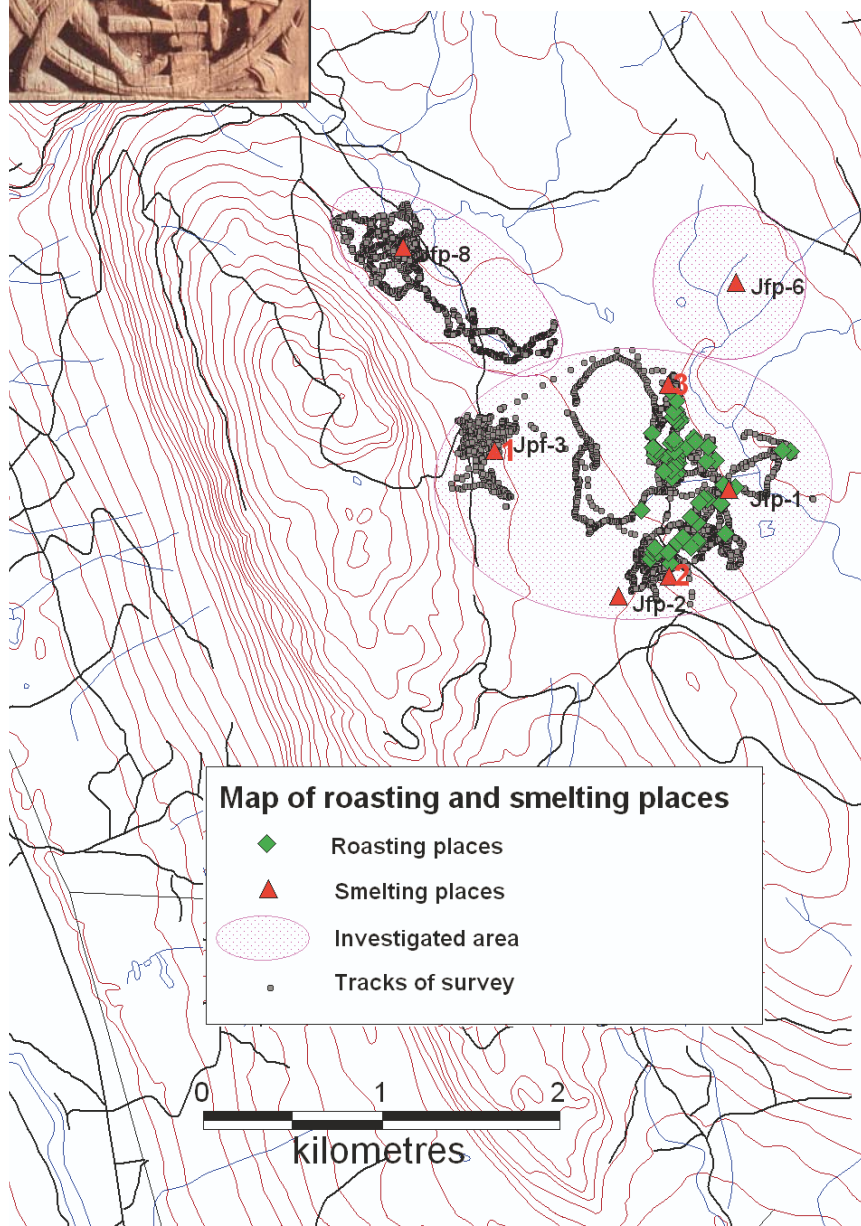
Iron Age long houses could be revealed by weak positive anomalies from the magnetic material in big postholes, and also from the magnetic material of the fireplaces. We recorded such anomalies in Krarup, Gødsvang, Snorup, and other Iron Age settlements. Pit houses also give us rather weak local positive anomalies.





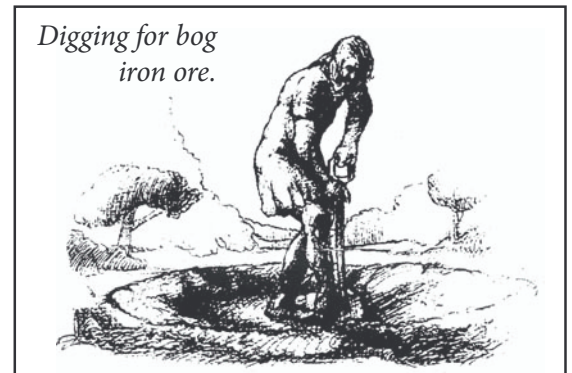
*Magnetic map of the site Gødsvang in SW
Jutland, Denmark.
Positive anomalies are dark and negative
anomalies are white.*

Iron production in EARLY MEDIEVAL NORWAY

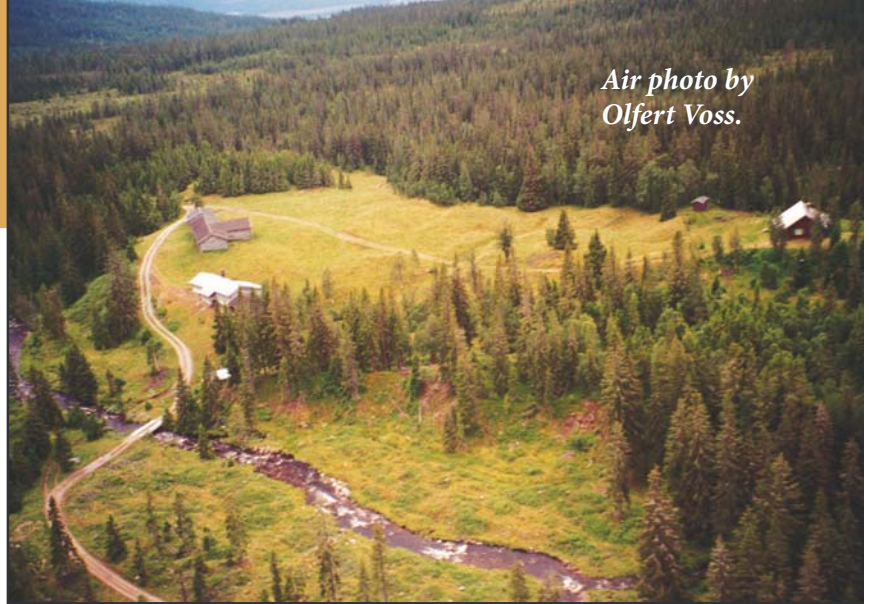


One of the biggest projects in Norwegian archaeology has been devoted to the investigation of a large area (228 square kilometers) of wooded land near the town of Rena where there are also extensive bogs. The bulk of the archaeological monuments are from the Early Medieval period (c. 1000-1300 AD) and are related to the process of iron extraction. To investigate such a big area and reveal as many archaeological objects as possible, a special methodology has been developed which was a combination of the use of GPS (Geographical Positioning System) and magnetometry. Magnetic surveys have been used in the field in Gråfjell during five seasons. They proved to be a very effective field method for finding the remains of archaeological monuments relating to all stages of iron production: from the roasting of bog iron ore to iron extraction and treatment. Magnetic surveys helped to reveal those objects that could not be seen on the surface. In this way, six new smelting sites have been found in the areas where visual archaeological surveys had previously been carried out. But the most important results of magnetic surveys in the area were in revealing places where ancient people roasted bog iron ore. These places are not visible on the surface and the only way to find them is to walk in the woods with a magnetometer, “free walking”, constantly measuring the magnetic field. When strong magnetic anomalies were found, they were checked with a small digging tool and a handheld magnet, and the GPS co-ordinates of such roasting places were recorded. The map of the location of the places for roasting bog iron ore gives important information about the organization of iron production in antiquity.

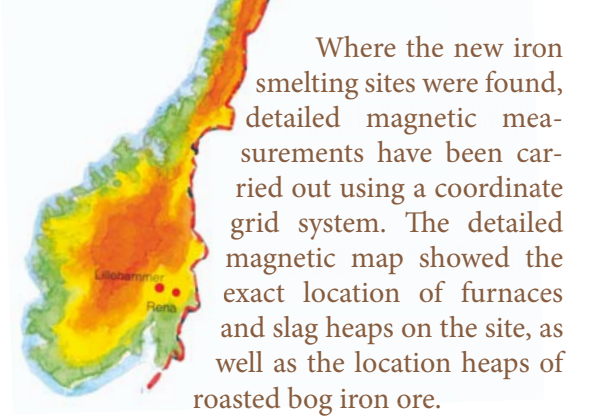
Cross section of the excavated heap of roasted bog iron ore. Photo: Bernt Rundberget.



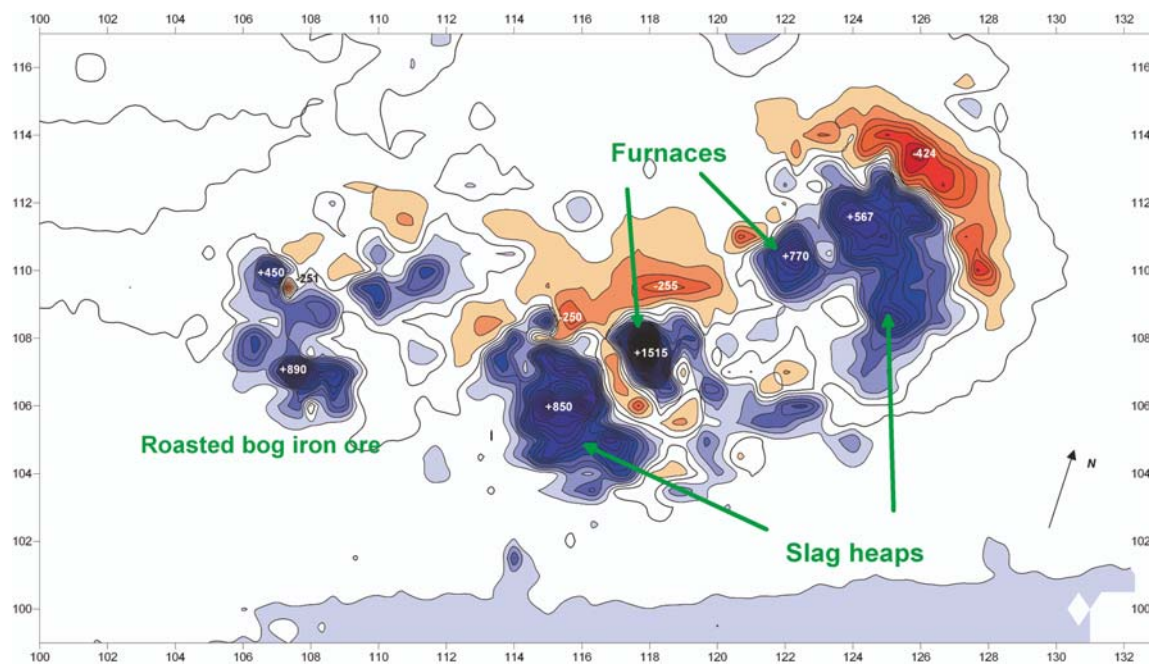
Air photo by Olfert Voss.



Where the new iron smelting sites were found, detailed magnetic measurements have been carried out using a coordinate grid system. The detailed magnetic map showed the exact location of furnaces and slag heaps on the site, as well as the location heaps of roasted bog iron ore.



Magnetic map of a new iron smelting site #240S, found with the help of the magnetometer. There were two furnaces and two slag heaps on this site. Contour interval 50 nT.



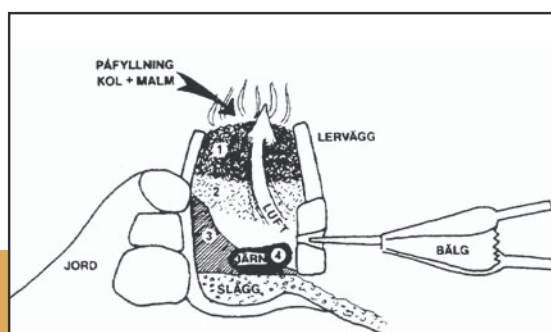
The process of iron extracting.



Detail magnetic survey using a co-ordinate grid.



Explanation of the process of iron extracting.



Lejre - an important Viking Age center

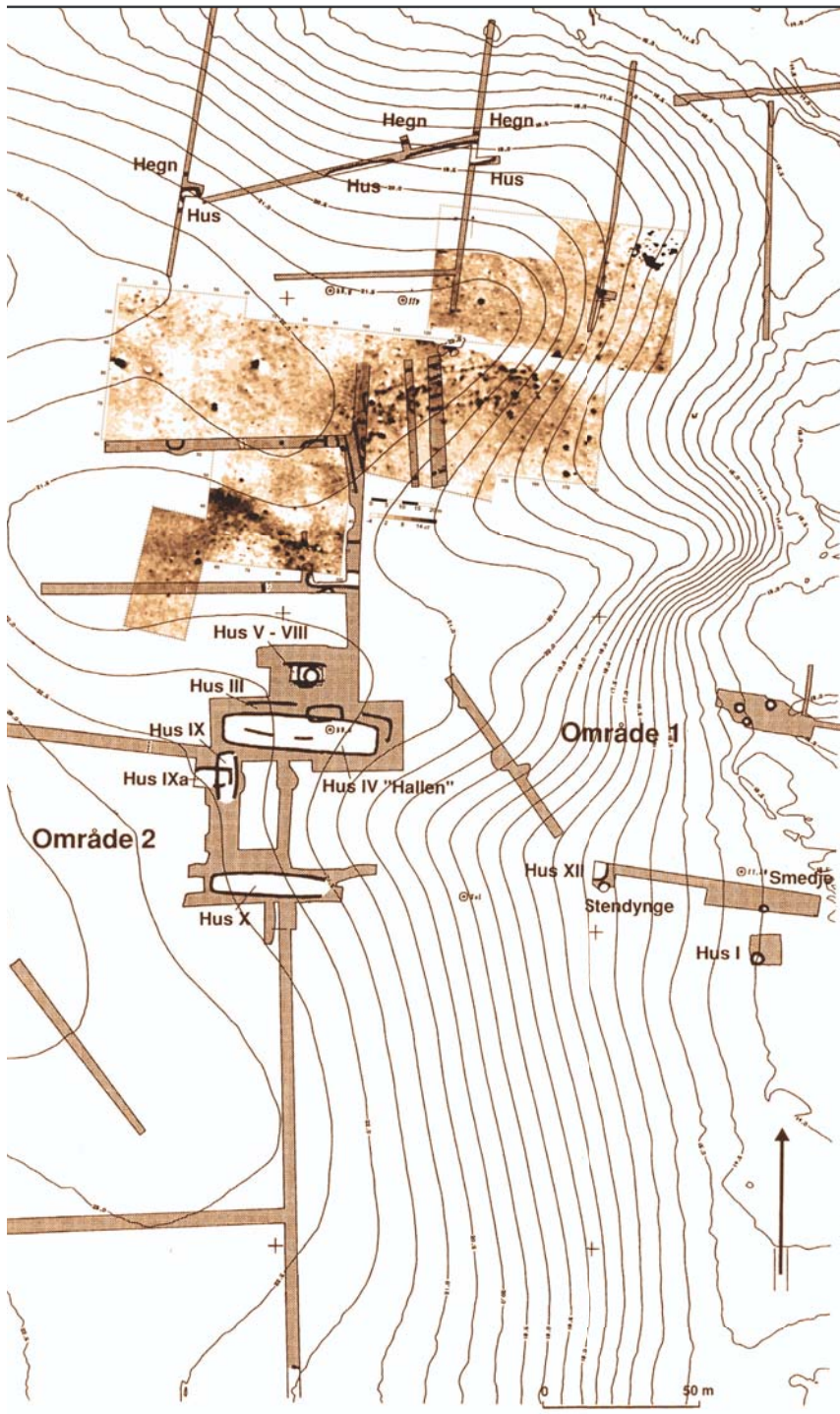
in ZEALAND, DENMARK



The Viking Age is the last period of Danish prehistory. Its beginning is somewhere in the 8th century. Lejre, situated in central Zealand, was an important center in the Viking Age.

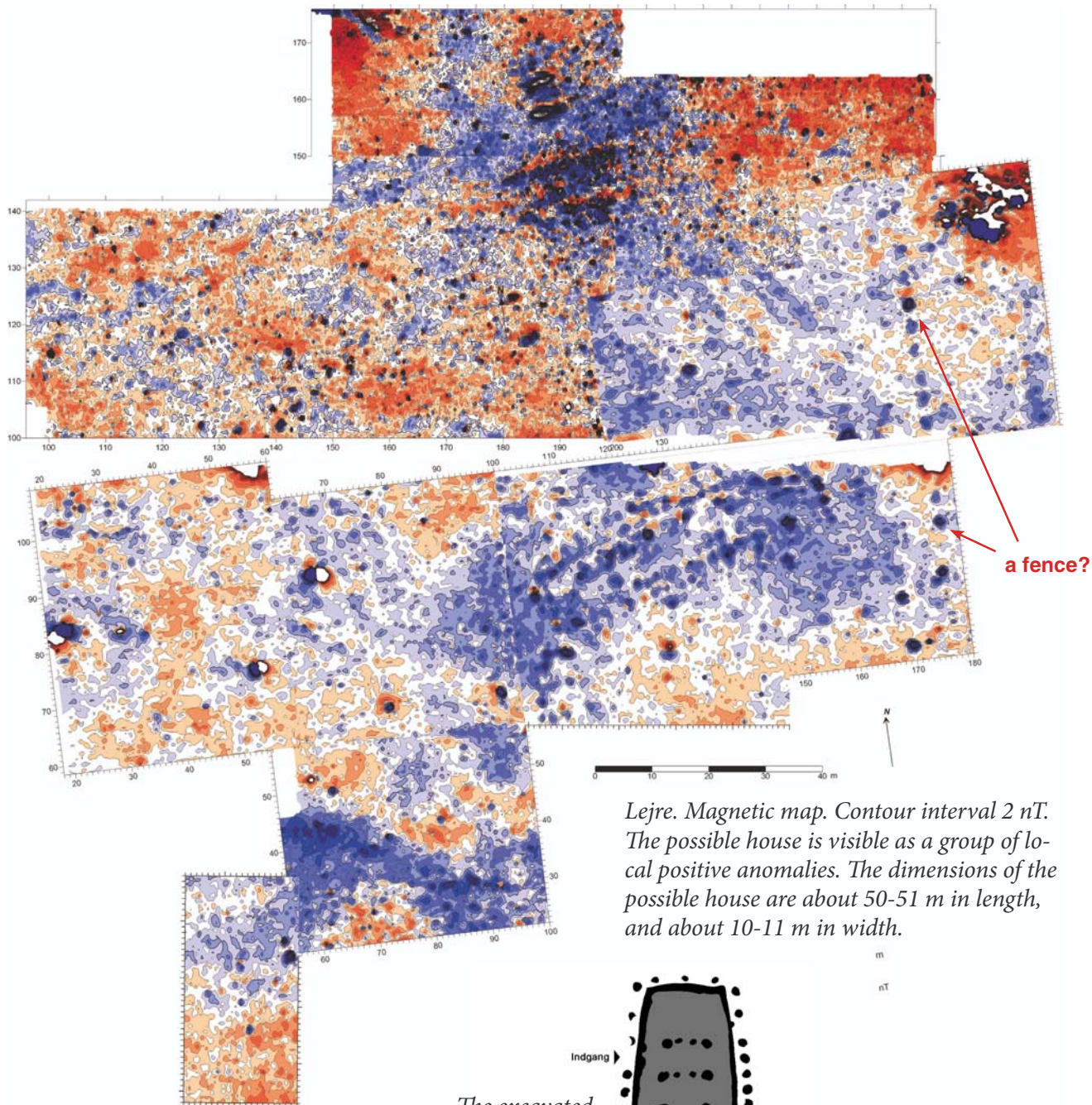
The most important result of the excavations was the revealing of the big house which is called "House IV" or "Hallen." Its dimensions of 48.5 m long by 11.5 m wide probably allowed for the gathering of many people and was like a Viking "palace" (T. Christensen, 1991). The walls of the house are represented by a ditch which is surrounded by a row of big post holes. There are two rows of holes inside the house for the posts which were supporting the roof. A fireplace is situated in the Western part of the house, closer to its center. A storage box was found at the southeast corner of the building. There are four entrances to the house: two on each side.

The object of the magnetic survey was to try to reveal other archaeological objects in the area north of the big house, "Hallen." The magnetic survey revealed two clear structures. The first one is the anomaly showing an oblong shape in the middle of the investigated area. This structure can be interpreted as a big long house, or rather two or more phases of the walls of possible 'houses,' which existed in the same place for quite a long period of time. The possible house is about 50-51 m long, and about 10-11 m wide, and that is almost the same as the House IV or "Hallen". The walls of the 'houses' are reflected in the magnetic field as a series of local positive anomalies, situated side-by-side with each other and forming curved linear structures. Some of the local anomalies are rather strong, and in such cases, there could be stones in the postholes.



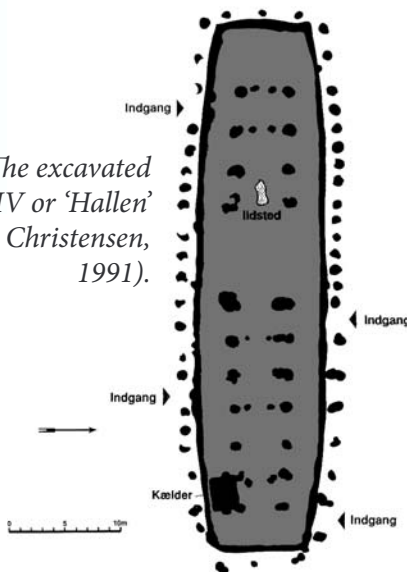
A map combining the excavations in Lejre with the magnetic map.



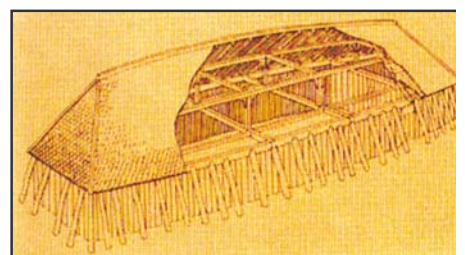


Lejre. Magnetic map. Contour interval 2 nT. The possible house is visible as a group of local positive anomalies. The dimensions of the possible house are about 50-51 m in length, and about 10-11 m in width.

The excavated House IV or 'Hallen' (After T. Christensen, 1991).



A model of a long house from the Viking Age (after Stig Jensen, 1991, p. 67).



The other prominent feature is a row of local positive anomalies which show a straight-linear structure, and could be a type of fence (?) consisting of postholes and/or stones. This structure could be in association with a pile of stones in the northeast corner of the plot.



VIKING AGE SITES

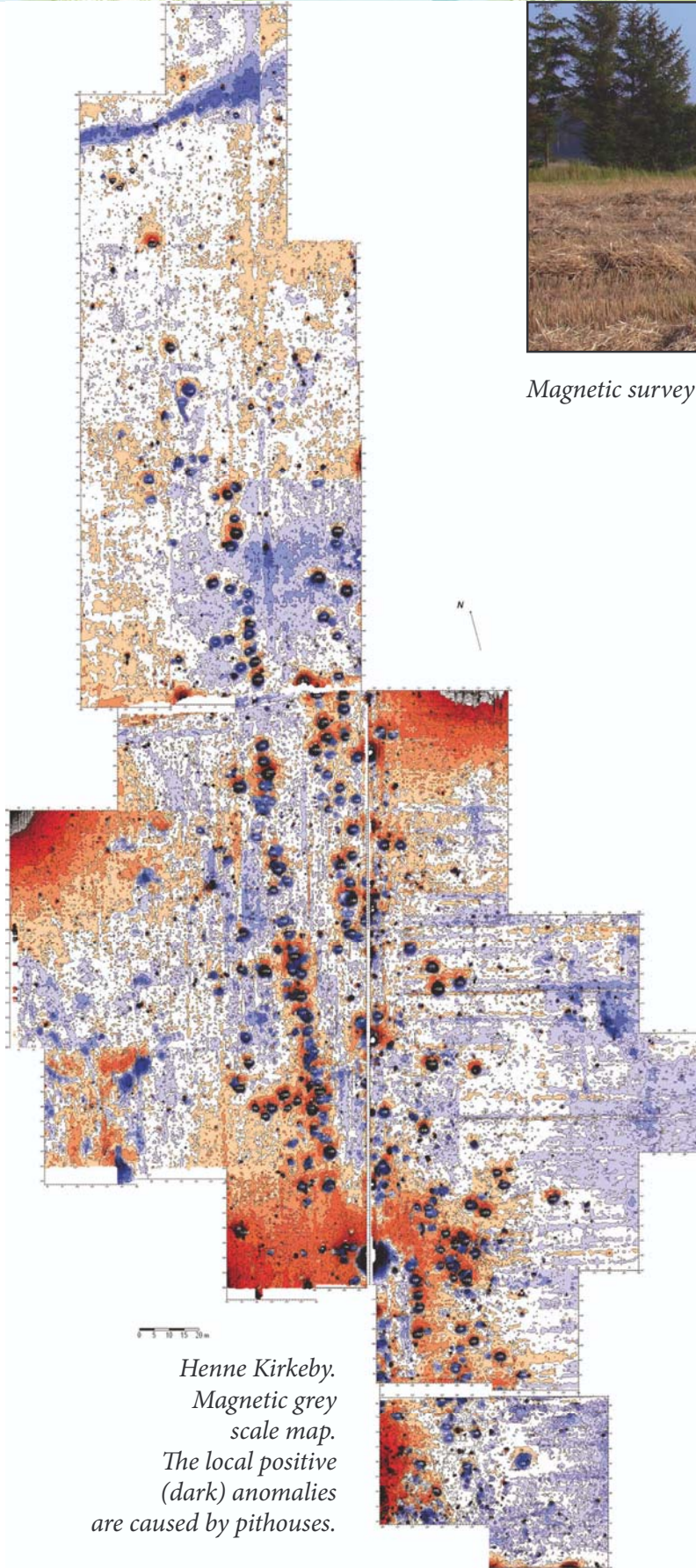
Henne Kirkeby



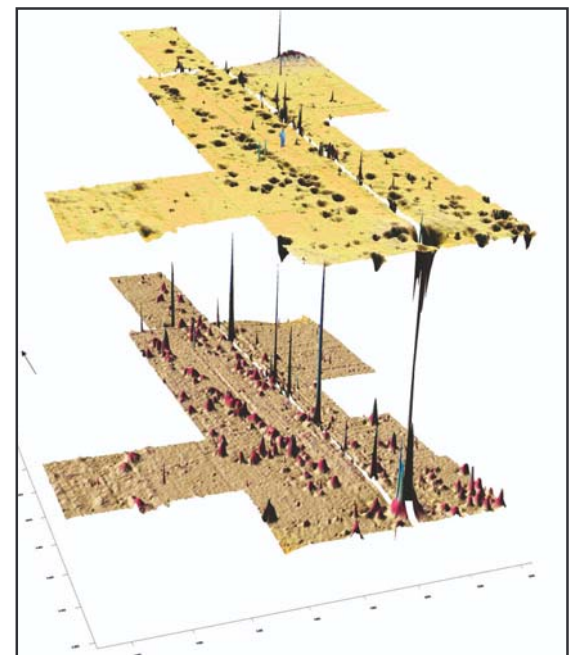
Magnetic survey on the site Henne Kirkeby.

Magnetic surveys proved to be a very effective method for locating Viking Age pithouses, which are rather numerous in the settlements around western Jutland. In 2004 and 2005, three such settlements were surveyed: Henne Kirkeby, Nørre Farup and Snæum Kirke. All these sites are situated in areas close to the sea, and on the banks of rivers or fjords so they had easy access to the sea. It is also interesting that these settlements are situated close to churches, which are younger than the settlements.

In Henne Kirkeby, the magnetic survey revealed more than 200 pithouses, which are situated on both sides of the more than 360 meters long “street” (Frandsen L., 2005).



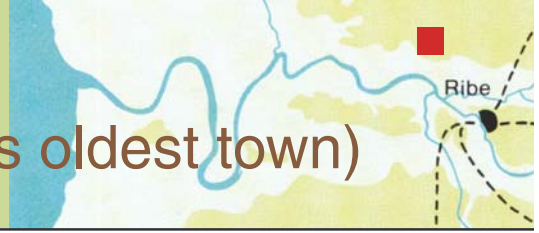
*Henne Kirkeby.
Magnetic grey
scale map.
The local positive
(dark) anomalies
are caused by pithouses.*



Henne Kirkeby. Magnetic perspective map.

WITH PITHOUSES

Nørre Farup (near Ribe, Denmark's oldest town)

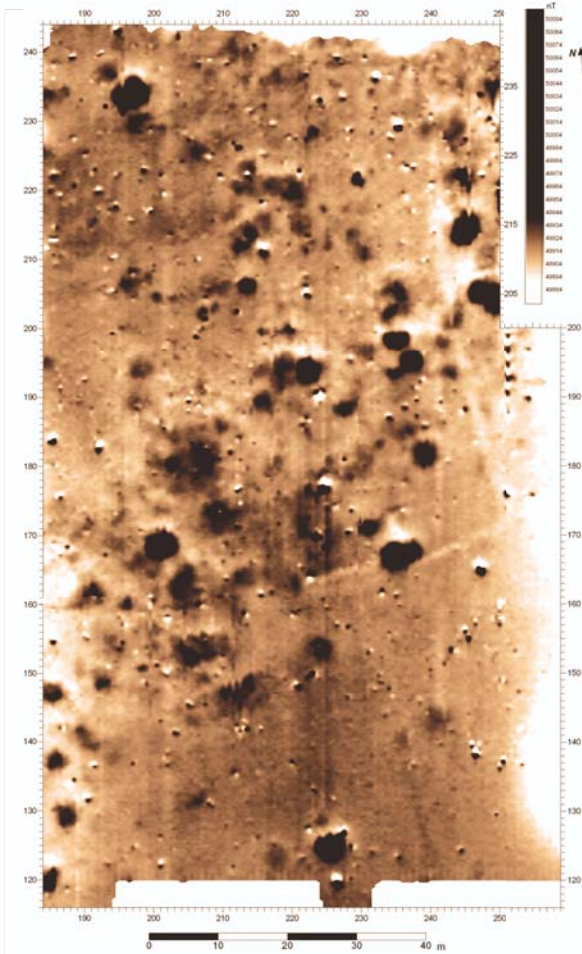


The magnetic survey of these settlements revealed strong local anomalies from different pithouses, many of which were workshops. Depending on the character of the workshop, the magnetic signals of the pithouses could be weaker (for weaving workshops), or stronger (for smithies, or foundries).

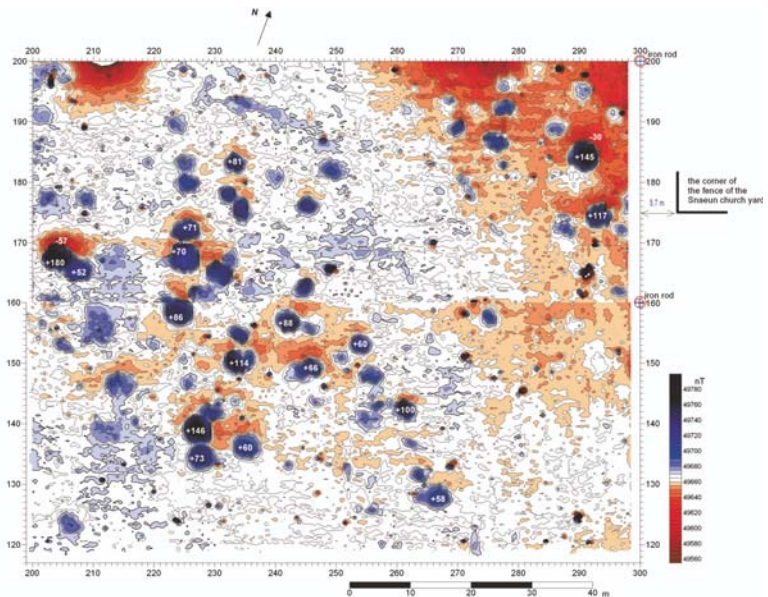


Magnetic surveying is a very effective method in revealing the plan of Viking Age settlements, determining the exact position of each pithouse or workshop, and complementing the air photos taken of the settlements.

Nørre Farup (near Ribe).



Nørre Farup. Magnetic grey scale map. The dark local anomalies are caused by pithouses.



Sneum Kirke. Magnetic map. Contour interval 5 nT. Pithouses created positive anomalies (blue color) of different values – ranging from 20 to 180 nT.

Sneum Kirke



Location of the Viking Age settlement near Sneum Kirke.

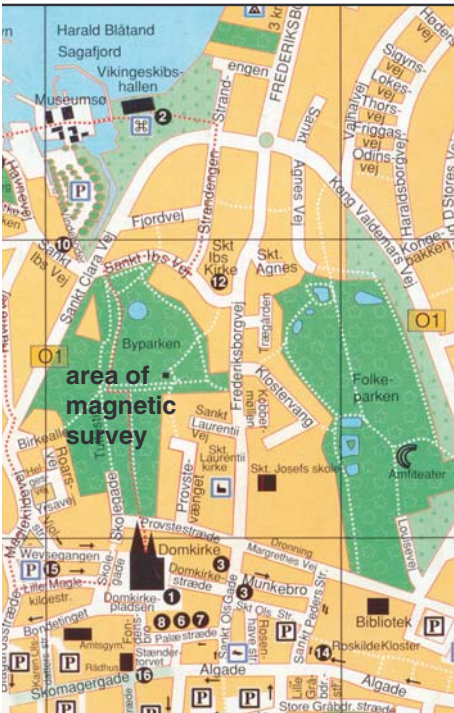


Air photograph of Sneum Kirke (Esbjerg Museum).

Magnetometer surveys in Danish Medieval archaeology



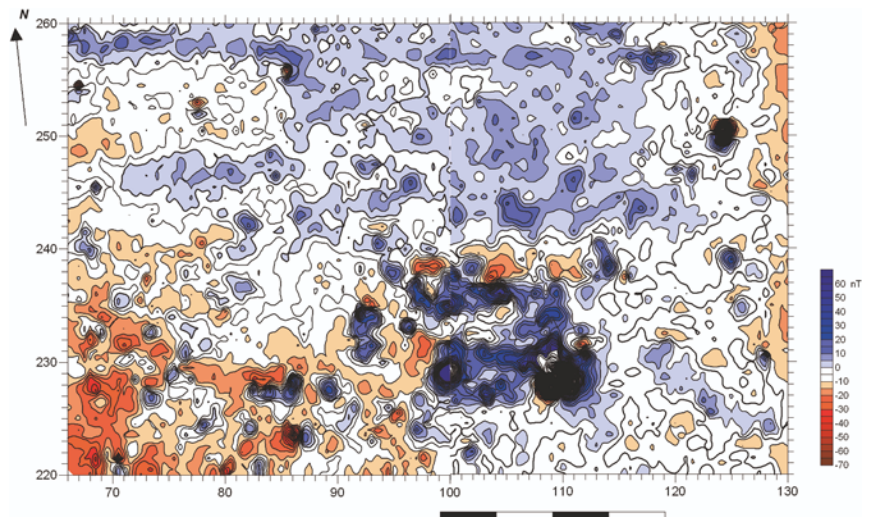
The area north of Roskilde Cathedral.



The magnetic survey has been carried out on quite a big part of Provstevænget, south of Byparken.

Important results have been obtained in the field, Provstevænget, north of the Roskilde Cathedral. According to Resen's map of the 1670's, there was a wide street that divided into two streets somewhere at the middle of the plot, just north of the Skt. Hans' churchyard. As the results of the magnetic survey in 2003 showed, an important build-

ing is situated at a distance of 35 meters north of the Skt. Hans' Church. This is a rectangular building (10 m x 12 m), the walls of which were built of bricks, probably on a stone or brick foundation. It is possible that the building had a cellar. An interesting iron object is situated in the southeast corner of the building; and it could be connected to the brick building. The building had heavy walls, and one can see certain similarities in architecture and building materials to the tower on Nebbe Castle (see next page).

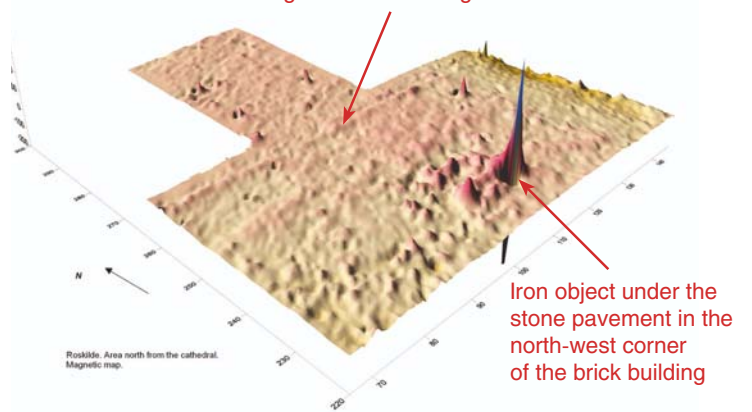


Roskilde. An area north of the cathedral. Magnetic map. Contour interval 5 nT.

There is a long positive anomaly which crosses the whole plot of the magnetic survey in an east-west direction. It is possible that this is a wall which could have a connection to the rectangular brick building mentioned above.



Results of the excavations in 2004 showing the rectangular brick building with a cellar.



Iron object under the stone pavement in the north-west corner of the brick building

Magnetic perspective map of the area north of Skt. Hans' Church.

Nebbe Castle

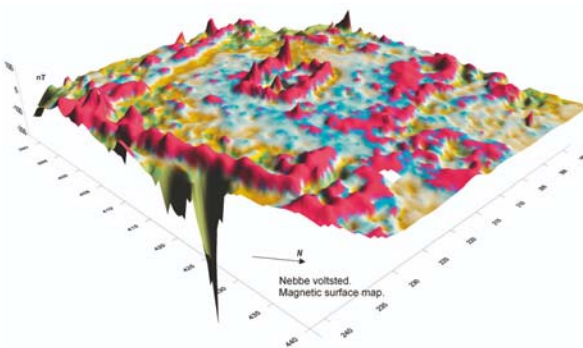
Nebbe Castle is situated north-west of Roskilde near Herslev on the spit between Kattinge Bay and Store Kattinge Lake. Magnetic surveys revealed a square enclosure and a rectangular tower in the middle of the southernmost hill. It is the central part of the site that was defended. The tower is approximately 11.5 x 8 m. It had thick brick walls, possibly with stone foundations and a cellar. There are several very strongly magnetized objects inside the tower that may be big stones or iron objects. The enclosure has a square shape and measures approximately 40 x 42 m. It consists of a double brick wall. The distance between the inner and the outer walls is about 4 m. The coastal part of the enclosure (eastern side) was built of stronger material (stones and bricks). There is quite a large positive anomaly in the valley between the two hills, which may be interpreted as a bridge, the supports of which were constructed from stones and bricks.

On the next hill, one can see other anomalies, probably from the traces of the wooden constructions further to the north of the bridge. An interesting structure is situated at the most northern part of the plot of the magnetic survey. It has a strong positive magnetic signal that forms a right angle.

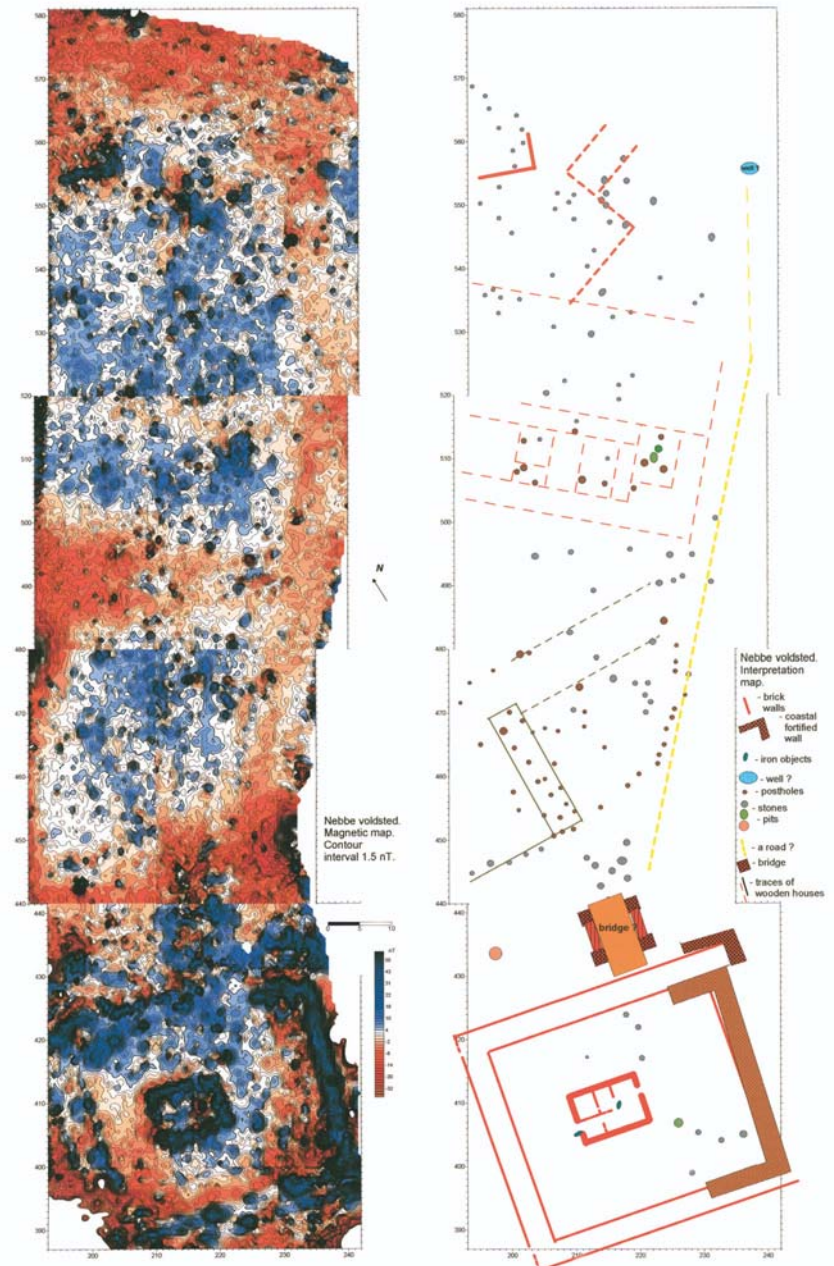
The tower and enclosure could be reconstructed somewhat in the same way as was done for the castle Falsterbohus in Skåne by A. Ödman, 2002, p. 56.



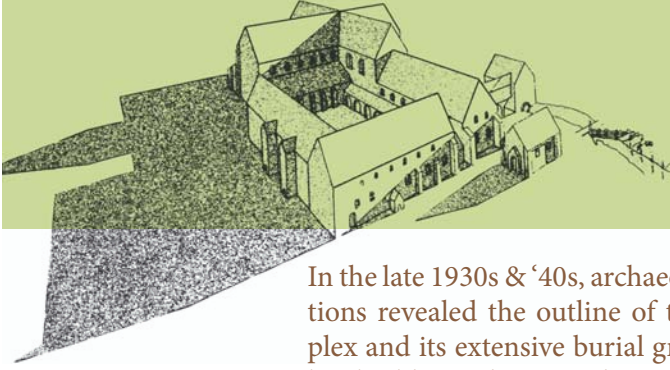
The site Nebbe Castle consists of three low hills. Magnetic surveying has been carried out on all of them (view from the north).



Magnetic perspective map of the Nebbe Castle.



Æbelholt - one of Denmark's largest Augustinian abbeys

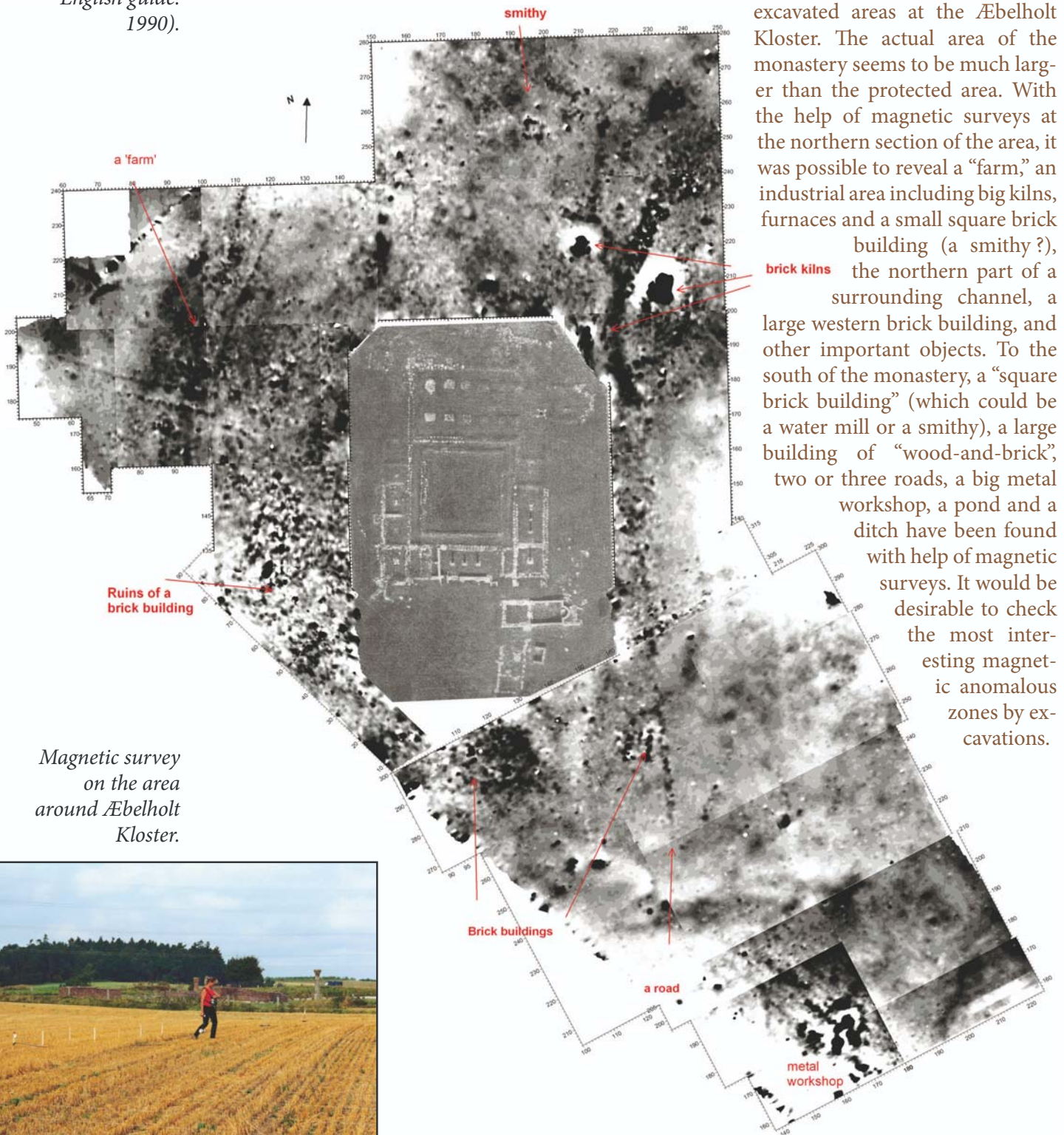


Reconstruction of the Æbelholt Kloster (From Æbelholt Abbey and Museum. English guide. 1990).

In the late 1930s & '40s, archaeological excavations revealed the outline of the abbey complex and its extensive burial grounds. The abbey buildings, dating to the 13th-14th century, were constructed in red brick on a foundation of large granite boulders. They follow the traditional four-winged plan, where the high church building forms the north wing, so as not to take light from the other wings.

Today, Æbelholt Abbey (Kloster) is situated in the middle of ploughed fields, and it was possible “to protect what is known while the unknown is destroyed slowly and steadily by cultivation.” (H.K. Kristensen, 2001, p. 8, 16). The results of magnetic surveys can be used for protecting the wider area around the abbey.

During two seasons (2002 and 2003) magnetic surveys have been carried out on non-excavated areas at the Æbelholt Kloster. The actual area of the monastery seems to be much larger than the protected area. With the help of magnetic surveys at the northern section of the area, it was possible to reveal a “farm,” an industrial area including big kilns, furnaces and a small square brick building (a smithy?), the northern part of a surrounding channel, a large western brick building, and other important objects. To the south of the monastery, a “square brick building” (which could be a water mill or a smithy), a large building of “wood-and-brick”, two or three roads, a big metal workshop, a pond and a ditch have been found with help of magnetic surveys. It would be desirable to check the most interesting magnetic anomalous zones by excavations.



Magnetic survey on the area around Æbelholt Kloster.



Moesgård. Smed Back – “Smithy Hill”

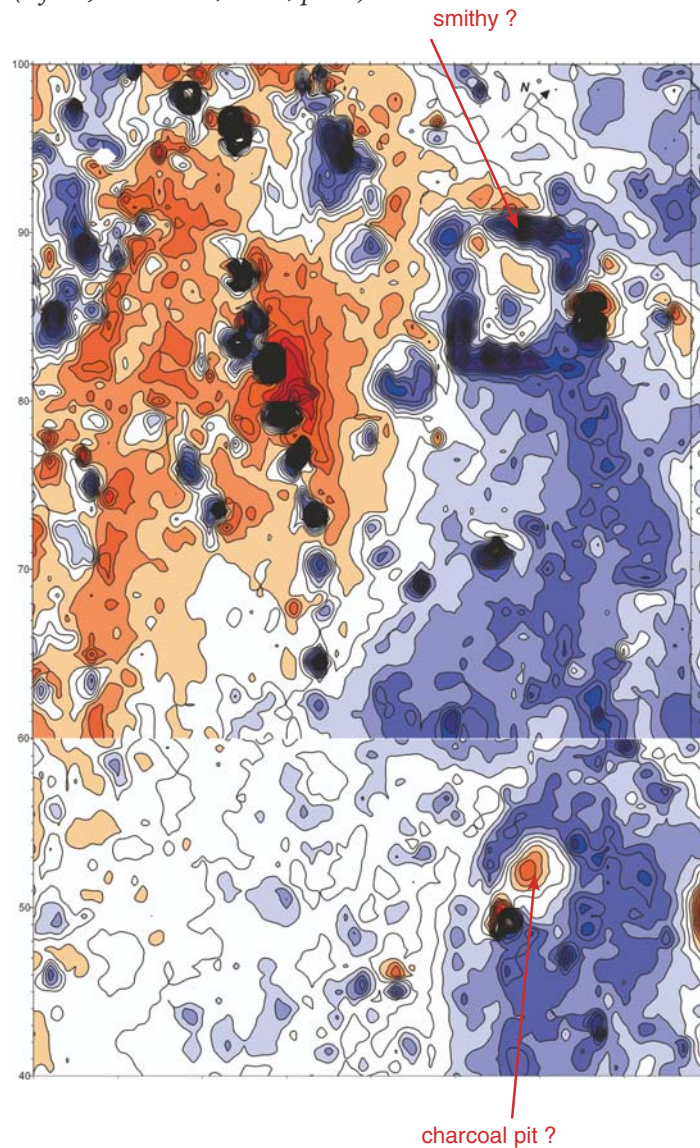
The history of Gammel Moesgård dates back to the 1300s. On the map of 1783, the hill opposite Gammel Moesgård is called “Smed Back”, which means “Smith Hill”. The magnetic survey of 2001 (see magnetic map below) revealed a rectangular building with the outer dimensions 7 m × 10 m, which can be interpreted as the old smithy. This building has only one room, in the middle of which is a positive magnetic anomaly - possible traces of a forge and a concentration of hammer scale from an anvil. The walls of this building are reflected in the magnetic field with very clear and rather strong positive anomalies (up to 70 nT).

The entrance to the “smithy” is through the southwest wall. Outside the building there are three pits filled with magnetic material (ashes or slag), that could be waste from the “smithy.” There is an iron object lying outside, close to the back wall that could be a hidden anvil (?).

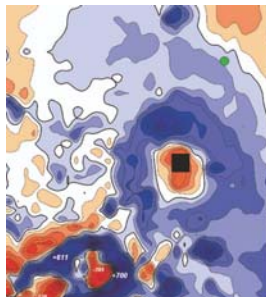
There is a row of some small, rather magnetic, objects which could be granite stones or pieces of slags, placed along the old road which is not visible on the surface. There is a local negative anomaly to the south of the “smithy,” which could be interpreted as a charcoal pit. We had similar anomalies over charcoal pits in Tyin, Norway.



Part of the map of Gammel Moesgård, 1783, near Århus. (After J.B. Skriver, 2001, p. 10).



Magnetic map of a charcoal pit in Tyin. Contour interval 50 nT.



Magnetic map of Smed Back. Contour interval 5 nT.

Mountainous Crimea.

Byzantine and Medieval pottery kilns.



Pottery kilns create extremely strong magnetic anomalies, from 150 to 8000 nT, because they are a big mass of hard-fired clay, which is a ferromagnetic material. Therefore, magnetic prospecting is a very effective method for revealing and investigating pottery production centers where ceramic vessels, tiles, and bricks were fired. With the help of a magnetic survey, it is possible to determine the exact location of a pottery kiln, its dimensions, the orientation of the opening, and, sometimes, even its inner structure (Смекалова et al. 2000).

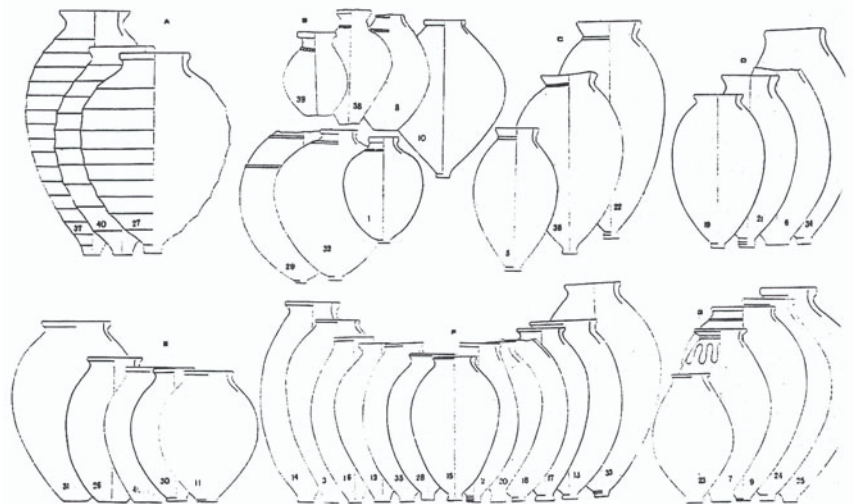
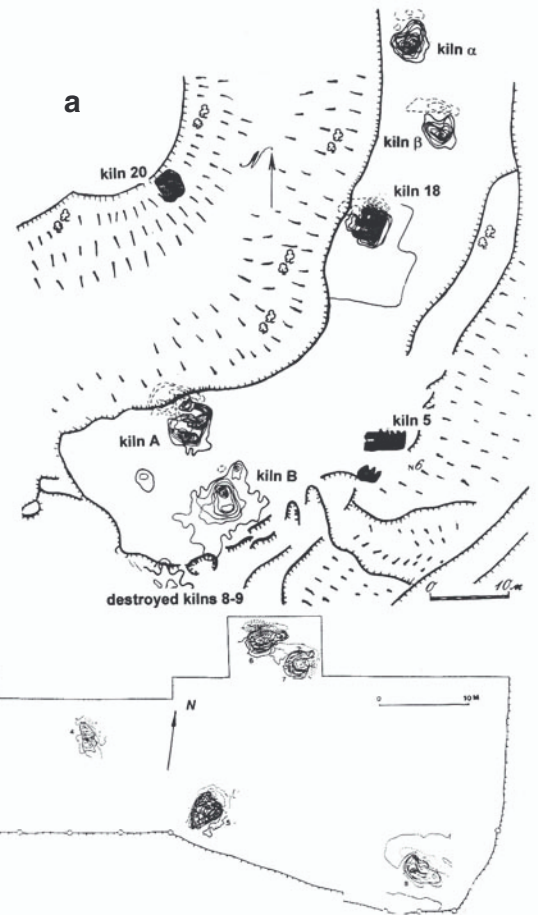


Location of the pottery production centers in mountainous Crimea.

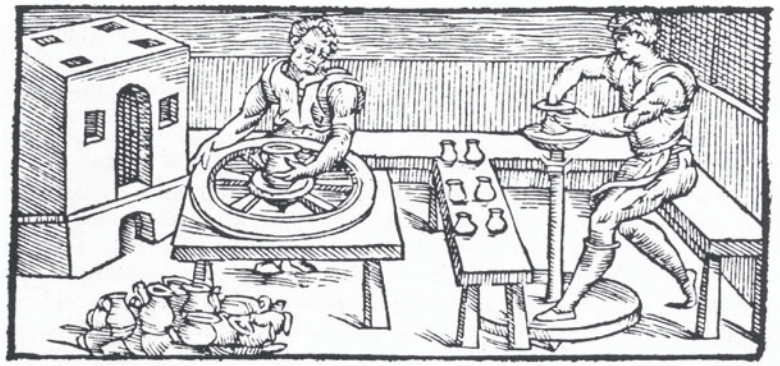
South-eastern Crimea. Pottery production centers from the 8th-10th century AD.

a) Choban-Khule, where five big anomalies have been revealed. The kilns "A" and №18 have been excavated after magnetic survey.

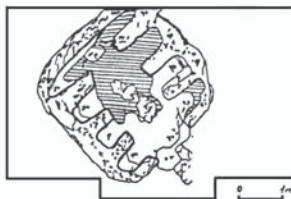
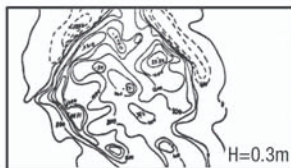
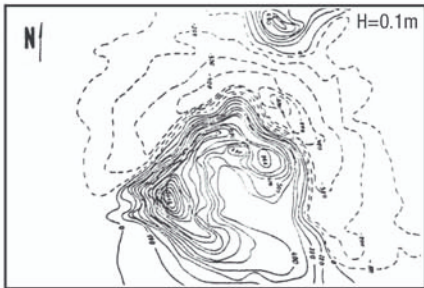
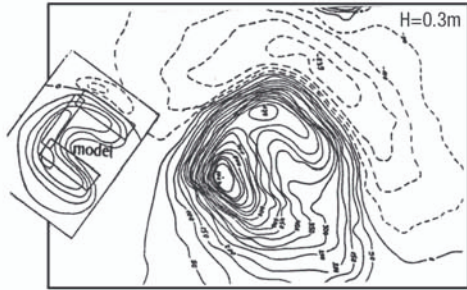
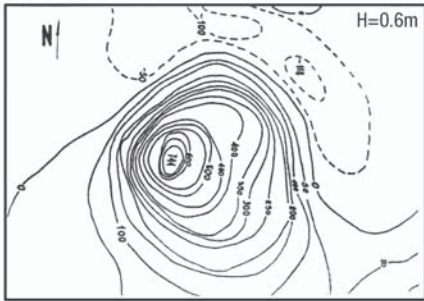
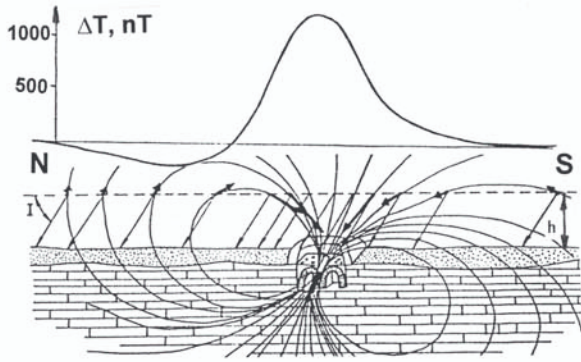
b) Alushta. Pottery production center with eight big kilns. Kiln №1 has been excavated (see magnetic maps and plan of the excavations on the next page).



Collection of the pithoi from Alushta. 8th-10th century AD.



Alushta. Pottery production center. Magnetic maps of the kiln №1, which were measured at different heights: at 0.6, 0.3, 0.1 m above the surface, -0.3 m (after top soil has been removed). At the bottom: plan of the excavation of the kiln №1.



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