GEM Systems
ADVANCED MAGNETOMETERS

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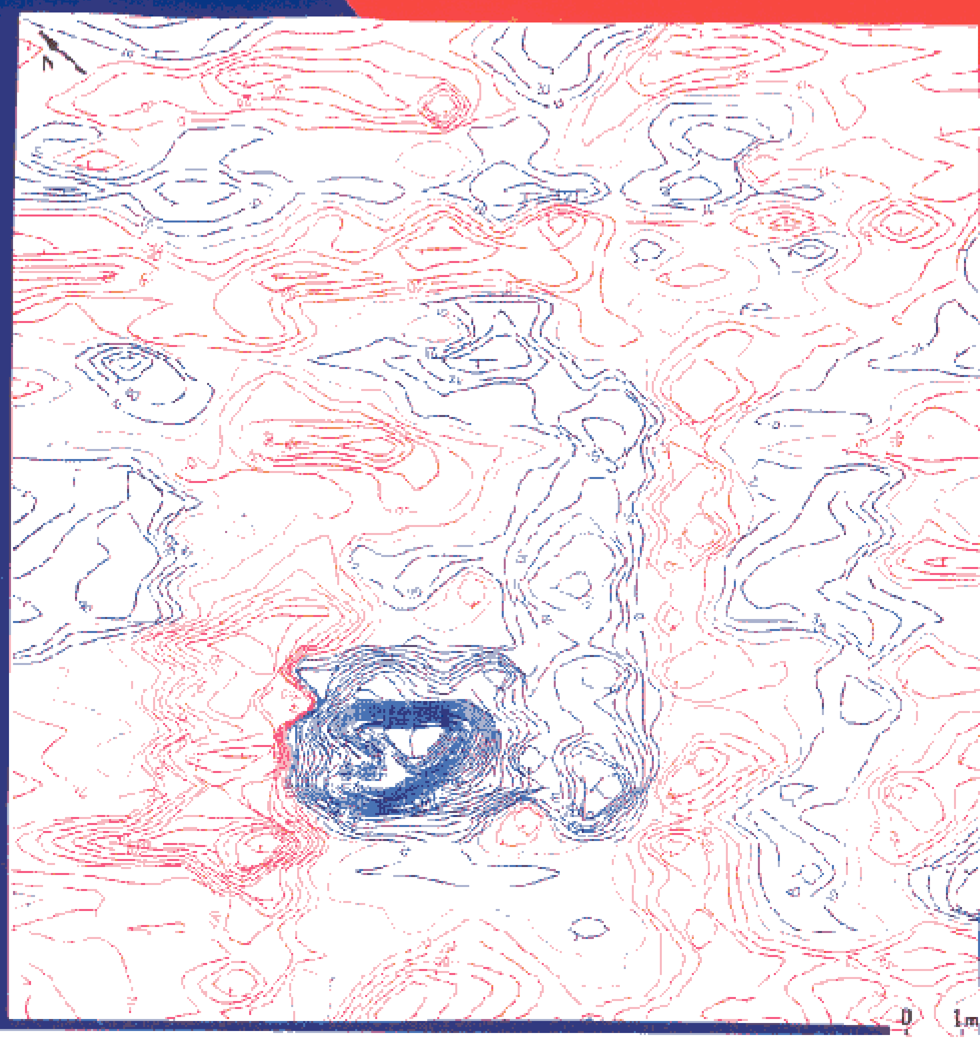
MAGNETIC PROSPECTING IN ARCHAEOLOGY



Advancing Overhauser, Potassium and Proton Precession Magnetometer Technologies for More than 2 Decades - "Our World is Magnetic!"

Magnetic survey on the archaeological sites.

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ABSTRACT

Magnetometer survey is one of the most effective and universal among the other geophysical methods for archaeological application, because many of archaeological objects could be distinguishon the surface of the site by specific magnetic anomalies they create.

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

Man's activities in the past (especially using of fire for heating, cooking, production and industry) have changed magnetic properties of clay, stones and earth, therefore the **anomalies in the Earth's magnetic field appear**, detectable with sensitive instruments - magnetometers.

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 at the ancient time and then silted or backfilled with topsoil. They will produce a positive magnetic signal; conversely, less magnetic material introducing into topsoil, including many kinds of masonry, for example, limestone walls, can be detectable by a subtractive effect which gives a negative signal.

Archaeological earthen structures typically show local magnetic anomalies in the range of 1-20 nT, more rare fired structures - 10-1,000 nT, quite rare ferrous archaeological objects including iron-smelting slag blocks - 20-2,000 nT. Limestone walls, situated in soil could give negative magnetic anomalies of the values of about 2-12 nT.

One could conclude, that magnetometry is **passive** geophysical technique based on responses from natural conditions, on the detection of **contrasts** in the different magnetic properties of materials. In the event that such contrasts do not exist, magnetic prospecting will not be useful.

For the archaeological prospecting we use the following magnetometers:
- an Overhauser gradiometer GSM-19WG of GEM systems Inc. (Canada, Ontario) as a main instrument;
- a cesium magnetometer MM-60 (Russia, St. Petersburg);
- a proton magnetometer MMP-203 (Russia, St. Petersburg).

Magnetic survey on the archaeological sites was carried out by our group since 1978 every field season in Armenia, Denmark, Egypt, Estonia, Germany, Greece, Norway, Russia, Sweden (Skåne), Syria, Turkey, Ukraine (Crimea), Wales.

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Acnowlegements.

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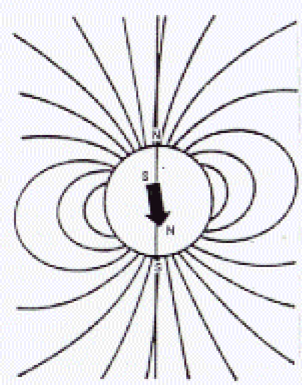
Introduction

Geophysical methods were developed initially for the studying of geological structures under the earth, but during recent years geophysical survey became more and more important for the revealing and investigations of archaeological objects.

Magnetometer survey is one of the most effective and universal among the other geophysical methods for archaeological application, because many of archaeological objects have distinctive and individual magnetic properties, which allow to distinguish them on the surface of the site by specific magnetic anomalies they create.

The Earth magnetic field

The Earth magnetic field is approximately the same as would be produced by a large bar magnet near earth's centre oriented with the positive end towards the North pole and inclined at an angle of 10° to the axes of rotation. The field, or flux, lines of the earth exhibit the usual pattern common to a small magnet.



The direction of the Earth field is vertical at the north and south magnetic poles, and horizontal at the magnetic equator. This is important for the interpretation of magnetic anomalies. The *intensity* of the Earth field is twice as large in the polar region (approximately 60,000 nT) as in the equator region (30,000 nT). The inclination and total magnetic field intensity for Denmark is 69° and 48,000 nT respectively.

It must be understood that the bar magnet is hypothetical. The core of the earth is a hot liquid under high pressure, and the most likely cause of the 99 per cent of the earth's magnetic field is the magnetic effects associated with electric currents in this liquid core.

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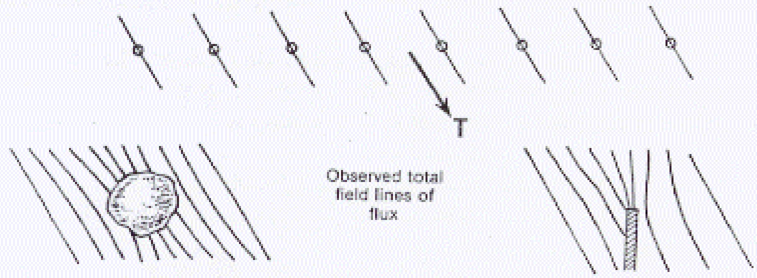
Magnetic anomalies

If the earth were composed of **uniform material**, the magnetic lines of force would be evenly distributed between the poles and at the small area would be parallel. However, since various materials in the earth have different magnetic susceptibilities due to their composition, the earth's magnetic lines of force are distorted.

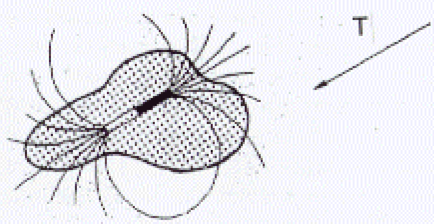


The local disturbances of the global magnetic field are called magnetic **anomalies**.

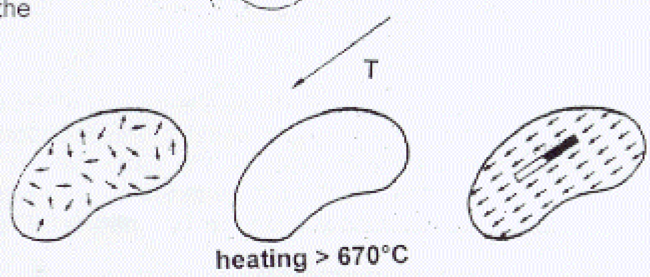
Iron constitutes about **6 %** of the Earth's crust. Most of it is dispersed through soils, clays and rocks as chemical compounds which are very weakly magnetic. **Man's activities in the past** (especially using of fire for heating, cooking, production and industry) have changed this compounds into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

The anomalies from archaeological objects or naturally occurring rocks and minerals are due chiefly to the presence of the most common magnetic mineral, **magnetite**, or its related minerals. All rocks contain some magnetite from very small fractions of per cent to several per cent.

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.



Remanent magnetism simply denotes the magnetism that an object has in the absence of a magnetic field.



Both kinds of magnetism are very important in archaeology.

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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: $I_i = \text{æ} T$.

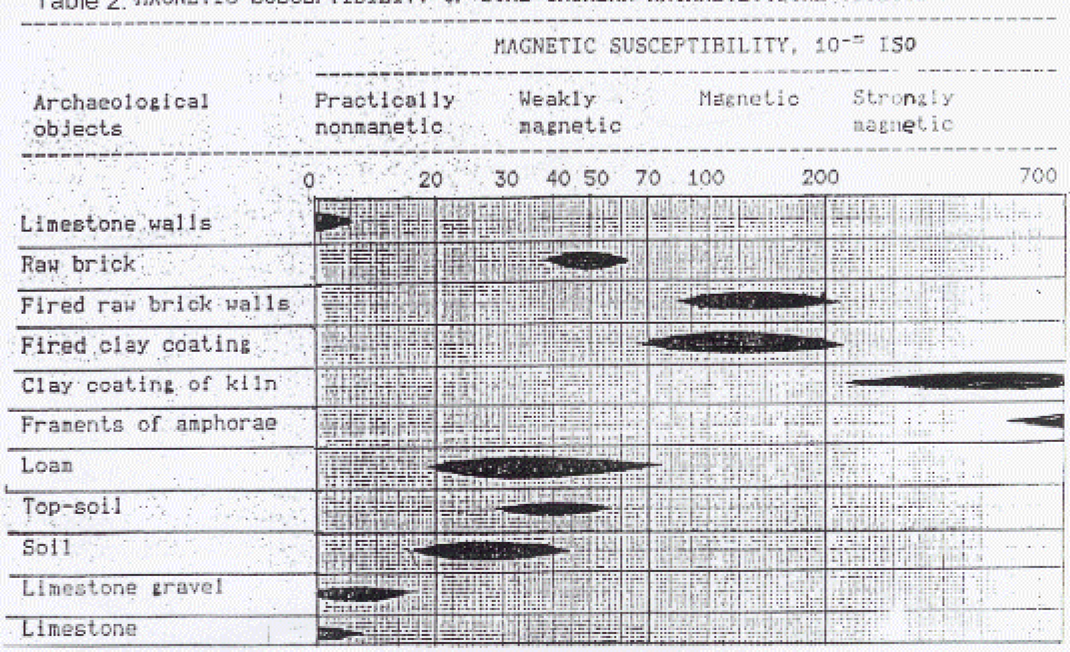
Typical susceptibilities of rocks are given below, but may vary by an order of magnitude or more in most cases:

Table 1. Typical magnetic susceptibilities of rocks.

Rocks	Magnetic susceptibility, æ 10^{-5} ISO
altered ultrabasic rocks (pyroxenite, dunite, serpentinite and others)	100 to 10,000
basalt	100 to 1,000
granite	10 to 1,000
grabbo	100
andesite	100
shale	10 to 100
shist and other metamorphic rocks	1 to 100
most sedimentary rocks	1 to 10
limestone and chert	1

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 at the ancient time and then silted or backfilled with topsoil. They will produce a positive magnetic signal; conversely, less magnetic material introducing into topsoil, including many kinds of masonry, for example, limestone walls, can be detectable by a subtractive effect which gives a negative signal.

Table 2. MAGNETIC SUSCEPTIBILITY OF SOME CRIMEAN ARCHAEOLOGICAL OBJECTS



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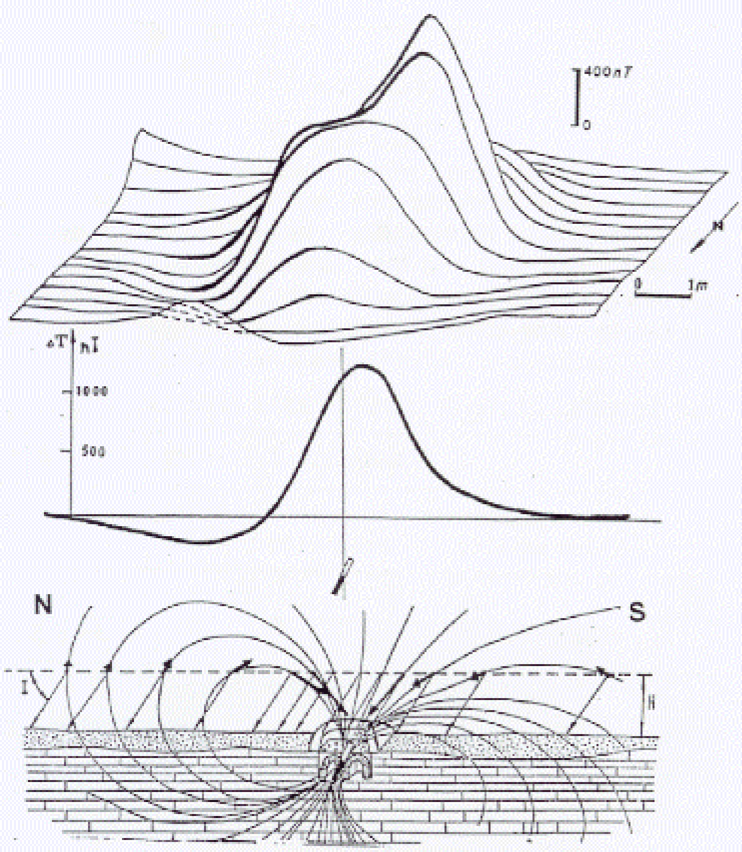
The **remanent magnetization** are related to the effect of heating, whether naturally heated, as in case of igeneous rocks, or artificially heated, as in the case of baked clay, pottery, and other man-made objects found in archaeological sites.

> *During heating, particularly at 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 thus parallel to each other, thus creating a net magnetization fixed with respect to the object (see the last figure on the previous page). This remanent magnetization can be as much as 10 or more times greater than the induced magtnetization.*

Archaeological objects like kilns, furnaces, slag blocks, fire places and other objects, possess rather strong remanent magnetisation. If they are situated still in situ, that allows to date them measuring the direction of their magnetisation in samples or by analysis of magnetic anomalies over them.



For archaeomagnetic dating it is important to know the master curve of the secular variations of the declination and inclination of the Earth magnetic field. It is known for United Kingdom, Italy, Greece, Ukraine; it was transformed from the British curve for the conditions of Denmark by N.Abrahamsen.

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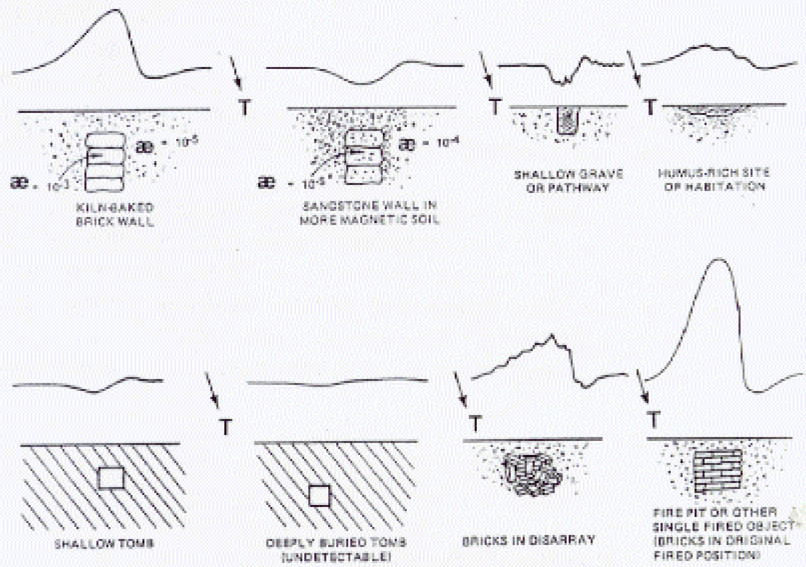
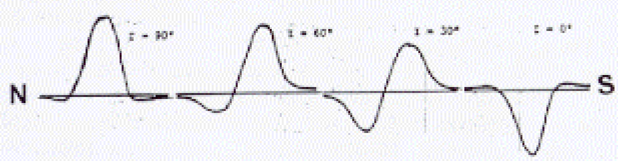
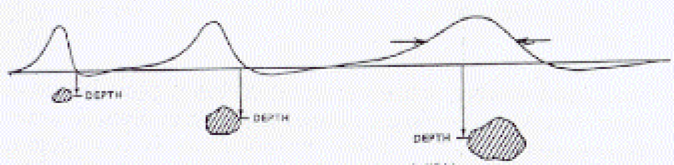
Thus, one could have a quite complicated and reach in information picture on the archaeological site as a combination of some negative and positive magnetic anomalies over different archaeological structures.



Utilising sensitive instruments, the earth's magnetic field can be measured with great **precision**, with the accuracies of one nT. Earth's magnetic field is approximately 50,000 nanoTesla (nT). Archaeological earthen structures typically show local magnetic anomalies in the range of 1-20 nT, more rare fired structures - 10-1,000 nT, quite rare ferrous archaeological objects including iron-smelting slag blocks - 20-2,000 nT.

*It is necessary just briefly notice some properties of the local anomalies from archaeological objects. **Assymetry** of the anomaly due to the direction of the field lines. **Depth dependance**. – the deeper the source, the broader the anomaly.*





Effect of Depth on Anomaly Width

One could conclude, that magnetometry is **passive** geophysical technique based on responses from natural conditions, on the detection of **contrasts** in the different magnetic properties of materials. In the event that such contrasts do not exist, magnetic prospecting will not be useful.

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Limitations

Since magnetic method, as other geophysical methods, is indirect by nature, the geophysicist can only **interpret data in the form of anomalies**. Anomalies can not be interpret as being archaeological objects. Causes of an anomaly can be suggested or speculated, however the only verification of an anomalous condition is by visual observation (excavation).

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 a surface of a site, pipe lines) and **natural features** (magnetic (granite etc.) bedrock, solar storms, lightning). Sources of noise should be identified prior to any magnetic field work, as geophysical surveys can be planned to eliminate or diminish noise.

Magnetometers

For the archaeological prospecting we use:
- an Overhauser gradiometer GSM-19WG of GEM systems Inc. (Canada, Ontario) as a main instrument;
- a cesium magnetometer MM-60 (Russia, St.Petersburg);
- a proton magnetometer MMP-203 (Russia, St.Petersburg).

One of the most common type of portable magnetometers in use today for archaeological purposes are the **proton magnetometers** of free precission.

It is so named because it utilises the precession of spinning protons or nuclei of the hydrogen atom in a sample of hydrocarbon fluid (water, kerosene, alcohol, etc.) to measure the total field intensity. The spinning protones, which behave as small magnetic dipoles, are temporarily polarised by application of a uniform 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 about the direction of the ambient or earth's magnetic field. The processing protons then generate a small signal in the same coil using to polarise them, and the frequency of this signal is precisely proportional to the total magnetic field intensity, which can be measured with a precision of 1nT.

The proton magnetometers have two serious disadvantages. First, erroneous observations may occur where gradients of 300-1000 nT per m are encounted. Also, due to a finite measurement period of time, approximately three seconds, it is quite slow.

Therefore for the last years proton instruments have been largely displaced by new, much more rapid ones.

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

In the proton magnetometer the polarisation is raised by applying a strong field for a time. The Overhauser magnetometer uses a free radicals dissolved in a liquid to raise its the apparent susceptibility by pumping with a radio frequency. There is 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 polarisation (by a factor of up to 4000 or 5000), very small amount of fluid can be used, which makes the sondes quite small and therefore also highly resistant to gradients. Sensitivities of the order of 0.01 nT are readily obtained in practice.

The main instrument, which we normaly use for the archaeological prospecting is an Overhauser gradiometer GSM-19WG of GEM systems Inc. (Canada, Ontario). It allows to measure magnetic field at rates as high as 2 readings-per-second with

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storage capacity for gradiometer mode of about 30,000 measurements (almost enough for one working day). The spacing between two sensors in such a gradiometer can be changed and the sensor height can be settled at any value. One sensor may be used as a base station and provide a correction for the temporal change in the earth's field. It is possible to survey up to 0.5 ha per day with a step of 0.5 x 0.5 meters with the gradiometer GSM-19WG (if the co-ordinate system is prepared).

The **cesium** (or optically pumped) magnetometers are highly sensitive type of instrument, their high resolution is about 0.01 nT.

The principle is more complex than that of the proton magnetometer. It operates at the atomic rather than nuclear level. There is a lamp using for polarisation. When monochromatic light passes through a magnetic field in an appropriate material, there is interaction between the spins of the substance and electromagnetic properties of the light. In contemporary instruments caesium 133 is used. The sensor is 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 moment locks 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 the frequency, proportional to the total magnetic field intensity.

The sensitivity of the caesium magnetometers derives from its high precession frequencies, which is important for recording small signals. Another advantage of caesium magnetometer - high gradient tolerance makes it useful in measuring of strongly magnetised archaeological objects in a very shallow depth. Thus, Russian caesium magnetometer MM-60 was used for precise measurements on a minimum height over separate slag blocks on the iron-smelting sites in south-west Jutland with aim of dating them. The speed of survey is very high, because it produces an effectively continuos signal. This instrument is direction-sensitive, and needs to be maintained within 5 degrees in direction, to keep the orientation error within 0.1 nT, but it could be improved by combining tree such a dual cells, as it was done in MM-60.

A sensor of **fluxgate gradiometer** 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 wound round them. Every time they come out of saturation, external field can enter them, causing an electrical pulse in the detector coil proportional to the field strength. The drive coils of the two stripes are switched in opposite directions - so that the drive current has no net magnetic effect .

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

Note: Please see other related documents that provide case histories.