The Application of Magnetic Methods for Dutch Archaeological Resource Management

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3 The principles of the application of magnetic methods for archaeological prospection focused on The Netherlands

3.1 Introduction

This chapter investigates the principles that underlie the application of magnetic methods in archaeological prospection. Archaeological features can magnetically be mapped if they differ, in a magnetic sense, from the matrix that they are embedded in. This magnetic contrast is either of an induced or of a remanent nature. In order to explain the difference between induced and remanent magnetic anomalies, this chapter starts with listing the different types of magnetism. Then, magnetic susceptibility will be introduced and the way that the soil magnetic susceptibility is defined by the iron compounds that are contained in the soil. A focus shift to the archaeological component of soil magnetism will occur in paragraph 3.5, where the different pathways for the enhancement of soil magnetic susceptibility are discussed. If archaeological deposits are magnetically enhanced, induced magnetic anomalies may occur that can, under certain circumstances, be measured on the surface, whereas other processes may give rise to remanent magnetic anomalies. Paragraph 3.9 is concerned with the interpretation of these anomalies based on their shape, size and orientation.

In the soil, dynamic processes are taking place that can cause changes in the type and in the amount of the iron oxides that are contained in the soil, and with it in the magnetic susceptibility of the soil. The most important of these soil processes are discussed in paragraph 3.10.

3.2 Different types of magnetism

On an atomic level, magnetism is caused by the motion of electrons. In the traditional atomic model, electrons orbit the atomic nucleus, while spinning around their own axis. As electrons have an electric charge, the movement of the electrons creates a magnetic moment.

Diamagnetism is caused by the orbiting motion of the electron. All materials display magnetic behavior in the presence of an applied magnetic field. Diamagnetism is a slight repulsive reaction that all matter has when it is subjected to a magnetic field; it obtains a small magnetic moment opposite to the direction of the applied field. Diamagnetism is the most common type of magnetism, but it is usually very weak and of the opposite sign to other types of magnetism, thus in the total magnetic moment it is often overshadowed by these other types of magnetism. The magnetic susceptibility of diamagnetic materials is weakly negative. Two of the main soil components are diamagnetic, i.e. quartz and water. Diamagnetic material can be recognized because of its linear dependency between an applied field and the magnetization of the material.

All the other types of magnetism are caused by the motion of electron spin. In *ferromagnetic* materials, for example, all electron spins are aligned in the same direction and interact with each other, thus creating a net magnetic moment. Ferromagnetic materials, most noticeably iron, are usually very crystalline and have a high magnetic susceptibility. They can posses a magnetic moment without an applied field, a property which is known as magnetic remanence.

In *antiferromagnetic* materials all the electron spins are aligned in two opposite directions. The resulting net magnetic moment is zero. Antiferromagnetic materials, e.g. chromium, have a small positive magnetic susceptibility. Spin-canting, i.e. a small rotation of the spin directions, causes the two spin directions not to be perfectly opposite, this results in a weak magnetic moment, hematite is an example of a spin-canted mineral.

In *ferrimagnetic* materials, the electron spins are aligned like in antiferromagnetic material in opposite directions, but the two directions of magnetization have a different magnitude, which results in a net magnetic moment. This type of magnetism is similar to antiferromagnetism, but with a two-third rather than half of the spins aligning in one direction. Magnetite and maghemite are ferrimagnetic minerals that have a high magnetic susceptibility and lack a linear dependency to temperature increase. Ferro- and ferrimagnetic materials can obtain a magnetic remanence at room temperature, which is important for archaeological prospection, but above a certain temperature T_C (Curie temperature) these materials will display paramagnetic behavior. The Curie temperature of magnetite and maghemite, the most important ferrimagnetic iron oxides in the soil, is much higher than room temperature (magnetite $T_C = 577$ °C, maghemite $T_C = 547$-713 °C). Antiferromagnetic materials will become paramagnetic above the Néel temperature (T_N), e.g. for goethite 127 °C, and for lepidocrocite -196 °C. In *paramagnetic* materials, like aluminium, the spin of the unpaired electrons is randomly oriented, causing a number of magnetic moments in random directions with no net magnetic moment. Under the influence of an applied field, however, all these magnetic moments align to one direction. The magnetic susceptibility of paramagnetic materials is weakly positive, and there is a linear dependency between the applied field and the resulting magnetic moment in the material. Paramagnetism is inversely proportional to temperature. Lepidocrocite and ferrihydrite are paramagnetic at room temperature.

3.3 Magnetic susceptibility

Magnetic susceptibility is a measure for the ease with which a material can be magnetized in an applied field.

$\kappa = J / H$
where κ is volume magnetic susceptibility
J is magnetic moment of the material
H is the intensity of magnetization (i.e. the magnetic moment per volume)

mass magnetic susceptibility
$\chi = \kappa / \rho$
where ρ is the density of the material

Every material has a different magnetic reaction to the application of an external magnetic field, and for soils this is no different. Soil magnetic susceptibility mainly depends on the mixture of iron compounds that is present in the matrix, further, it is influenced by the grain size, grain shape and the concentration of magnetic minerals in the soil. The most common soil iron oxides and their magnetic susceptibilities are listed in Table 1 and discussed in paragraph 3.4.

Table 1 Properties of the most common iron oxides in Dutch soils. After Cornell & Schwertmann (2003).

iron oxide		magnetic susceptibility x 10^{-8} m^3/kg	
magnetite	Fe_3O_4	50000[1], 56500[2], 20000-110000[3]	ferromagnetic
maghemite	γ Fe_2O_3	40000[1], 26000[2], 40000-50000[3]	ferromagnetic
hematite	α Fe_2O_3	60[1], 40[2], 10-760[3]	spin-canted antiferromagnetic
goethite	α FeOOH	70[1,2], 26-280[3]	antiferromagnetic
lepidocrocite	γ FeOOH	70[1,2], 40-70[3]	paramagnetic*
ferrihydrite	$5Fe_2O_3 \cdot 9H_2O$	40[2]	paramagnetic*

Data from: [1] Thompson & Oldfield (1986), [2] Maher (1998), [3] Hunt (1995); * At room temperature (> Néel temperature).

For archaeological purposes it is important to realize at this point that all deposits, natural or anthropogenic, contain a specific combination of iron compounds, giving rise to a specific magnetic susceptibility. Every deposit is unique, and is likely to have a magnetic susceptibility that is different from the deposits surrounding it. However, archaeological deposits and topsoil material often have an increased magnetic susceptibility compared to the undisturbed subsoil. The reason for this enhancement is the topic of paragraph 3.5.

3.4 Soil iron oxides

In this section the iron oxides that are typical for temperate climate zones are summarised, using data from Taylor (1980), Weston (1999), Cornell and Schwertmann (2003) and Hansel *et al.* (2005). The chemical formula, colour and possible formation pathways of each iron oxide are briefly discussed, in addition to a description of well documented formation and transformation processes. However, the (trans)formation of iron in the soil is a complex process, which depends on many variables, including climate, soil pH, organic matter content and redox status of the soil. More advanced processes, not discussed here, are also possible and are best understood in the laboratory.
In some cases the chemical formula for the iron oxides is the same (for example for hematite and maghemite) but the crystal structure is different, this is indicated with a prefix of α for the hexagonal and γ for the cubic crystal structure.

Goethite α FeOOH Goethite is the most common iron oxide in cool to temperate humid climates, where it usually coexists with lepidocrocite and ferrihydrite. It is yellowish brow in colour (7.5 to 10 YR). It can be formed from solid Fe(II) compounds like iron-carbonates or iron-sulphides, or reduced from Fe(III) by microbial action. Alternatively it can be transformed from ferrihydrite, or from ferric hydroxide ($Fe(OH)_3$), which is a precursor to the more crystalline iron oxides, and can be formed after the water logging of a soil.

Hematite α Fe_2O_3 Hematite is the second most common soil iron oxide, it mainly occurs in warmer to subtropical / tropical climates. It has a distinctively red colour (5YR to 10R). Hematite and goethite are closely related and can coexist, formation of either of the two iron oxides depends on temperature and drainage. Ferrihydrite, for example, can transform to goethite, but also to hematite in warmer and drier climatic conditions where the formation of hematite is preferred over the formation of goethite. In gley soils ferrihydrite may be the precursor of hematite.

Lepidocrocite γ FeOOH Lepidocrocite has been identified in different climatic zones, but not in calcareous soils. It is a very common iron oxide, usually orange in colour (5YR to 7.5YR). It is formed in seasonally wetting and drying (reductomorphic) environments, for example in iron pans. It can be transformed from ferrihydrite, or from magnetite after dissolution and consequent oxidation.

Ferrihydrite $5Fe_2O_3•9H_2O$ $5Fe_2O_3•9H_2O$ is a possible formula for ferrihydrite, but other formulas have been proposed. Ferrihydrite is a hydrated ferric oxide, which can only be found in young (Holocene) deposits where its transformation to goethite or hematite has been impeded or delayed, or where circumstances are detrimental to the formation of more crystalline iron oxides like goethite. These are environments where there is sufficient Fe(II) oxidation in the presence of organic matter and silicate. Ferrihydrite occurs in gley soils, on the oxidizing / reducing boundary of the soil and in the B-horizon of podzol soils.

Magnetite Fe_3O_4 Lithogenic magnetite occurs commonly in the coarse fraction of the soil. The abundance of magnetite in the topsoil when compared to the subsoil suggests a pedogenic formation (see § 3.5). Magnetite is a reduced iron oxide, which may oxidize to form maghemite, turning in colour from black to brown. In an oxidizing environment, magnetite will usually oxidize partly, the resultant iron oxide will belong to the magnetite / maghemite series, but will neither be purely maghemite, nor purely magnetite. Magnetite can be formed trough the reduction of hematite and goethite, or the reaction of ferrihydrite with Fe(II).

Maghemite γ Fe_2O_3 Maghemite is found mainly in tropical and subtropical regions, with localized deposits in temperate regions. The iron oxide occurs in concretions, or can be dispersed through the soil. It can be formed through the oxidation of magnetite, or the dehydration of lepidocrocite at a temperature of ~250 ºC. Taylor (1980) has synthesized maghemite from green rust during laboratory experiments, in a process that approximated the oxidation of a gley soil.

The iron mineralogy of the oxidizing part of calcareous estuarine, fluvial and marine deposits in Dutch subsoils is expected to be dominated by ferrihydrite and goethite, the former of which can, over time, transform into the latter. These two dominant iron compounds have a very low magnetic susceptibility (Table 1). Hematite, on the other hand, is unlikely to be formed from ferrihydrite in our climatic zone, except possibly in gley soils. In topsoils the non-ferrimagnetic compounds are expected to be mixed with ferrimagnetic, and thus high magnetic susceptibility iron oxides of the magnetite / maghemite series. The main contribution to the magnetic susceptibility of the deposits will come from these ferrimagnetic minerals.

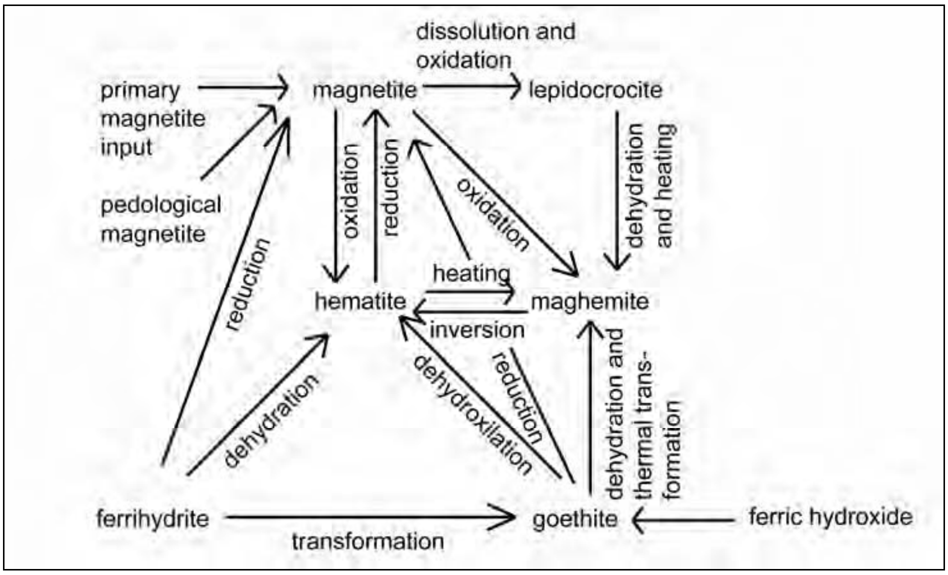

Figure 6 Schematic representation of a number of important transformation processes between the most common soil iron oxides in the Dutch soil.

In non-calcareous deposits, lepidocrocite is likely to be present along side ferrihydrite and goethite. Here too, the main contribution to the soils magnetic susceptibility comes from the ferrimagnetic iron compounds of the magnetite / maghemite series. The soil is a complex dynamic system, and changes in for example hydrological circumstances or the soil chemistry have an impact on its iron mineralogy. The magnetic susceptibility of the soil most noticeably influenced when non-ferrimagnetic iron minerals transform to ferrimagnetic minerals, or the other way around. A number of relevant transformation processes between the iron oxides that are discussed here is illustrated in Figure 6.

3.5 Enhancement of magnetic susceptibility

Le Borgne was the first to notice that usually, topsoil material has a higher magnetic susceptibility than the subsoil (Le Borgne 1955). This, he found, is caused by a concentration of ferrimagnetic minerals, mainly in the clay fraction of the topsoil. He proposed two principles of magnetic susceptibility enhancement, ‘fermentation’ (a term that was later replaced by ‘pedological processes’) and burning, both of which rely on the reduction and subsequent oxidation of non-ferrimagnetic iron oxides in the soil in order to form ferrimagnetic minerals of the magnetite - maghemite series. The most quoted example is:

$$\text{hematite} \xrightarrow{\text{reduction}} \text{magnetite} \xrightarrow{\text{oxidation}} \text{maghemite}$$

Because of the predicted lack of hematite in the Dutch soils, this reaction may be of lesser importance to this study. Probably more relevant is the thermal alteration of for example lepidocrocite to maghemite to hematite (Dearing *et al.* 2001); see Figure 6.

Pedological processes Weston calls the term fermentation ‘something of a misnomer’, all of the processes that cause magnetic susceptibility enhancement in the soil, apart from burning, can in his opinion be described as pedological and edaphic (soil biological) processes (Weston 2002). Long after Le Borgne, indeed an example of purely pedological enhancement was published in a paper by Maher and Taylor, on the discovery of the formation of magnetite in soils that were known not to have any primary magnetite input (Maher & Taylor 1988). There is no reason to assume that this pedological neoformation of magnetite would be preferential either to archaeological deposits or to the matrix surrounding these deposits, which leaves this type of magnetic susceptibility enhancement of no direct relevance to archaeological prospection.

Edaphic processes Edaphic processes can be divided into the intracellular and extracellular bacterial formation of magnetite on the one hand, and the bacterially mediated processes that result in the formation of ferrimagnetic iron compounds on the other hand. In the early 1990s, Fassbinder & Stanjek (1993) are critical about the trend in archaeological prospection to explain the enhanced magnetic susceptibility of topsoils solely by heating processes and the subsequent formation of magnetite or maghemite. Not all archaeological sites, however, they argue, have burning episodes. In their research, the authors have found magnetite in an unburned post, and in their paper they show that this magnetite probably is bacterially formed. The soil bacteria that are likely to be responsible are magnetotactic bacteria, which produce intracellular magnetite in chains (Fassbinder *et al*. 1990).
Extracellular bacterial formation of magnetite has been shown to occur in anaerobic sediments (Lovley *et al*. 1987). The microorganism GS-15 (now renamed Geobacter metallireducens; Lovley *et al*. 1993) can reduce amorphic iron to magnetite during the oxidation of organic matter. Both intracellular and extracellular magnetite forming bacteria need organic matter as a nutrient. Differences in soil organic matter content may lead to the preferential formation of bacterial magnetite in organic deposits, and may in this respect be important for the magnetic differentiation between archaeological and non-archaeological deposits.
Dearing *et al*. (1996, 2001) argue that most of the topsoil enhancement in the temperate climate of England has to be attributed to the bacterially mediated formation of magnetite (or maghemite after oxidation) from ferrihydrite. According to the authors, low concentrations of secondary ferrimagnetic minerals can be explained either by the lack of an Fe supply for the formation of ferrihydrite, or by non favourable conditions for the iron reducing bacteria, or by post formation processes. The optimal conditions for iron reducing bacteria, they observed, is a wet but free-draining soils containing micropores, for example a silty loam. Ferrihydrite is the key mineral in this process. For The Netherlands it is important to note the grain size dependency for this type of magnetic susceptibility enhancement.

Heating Heating may not be the only principle that causes the magnetic susceptibility enhancement of the soil, it is however the most important for archaeological prospection. The basic underlying chemical process for the enhancement is that non-ferrimagnetic iron oxides in the soil-like antiferromagnetic hematite and goethite- that are exposed to high temperatures under reducing circumstances will convert directly into ferrimagnetic maghemite, or to maghemite through a magnetite phase. The reducing circumstances are created through the combustion of organic matter that is present in the soil. This obviously is a simplification of the process. As Weston has shown in his laboratory experiments, it is not simply heating that causes magnetic susceptibility enhancement, but there is a temperature bracket in which enhancement can occur, if other conditions, the presence of organic matter and a fine grain size for the onset of reducing circumstances, have been met (Weston 2002). If soil is heated to temperatures that are too low to ignite organic matter (and create reducing circumstances), iron oxides may dehydrate or dehydroxylate rather than be turned into ferrimagnetic iron oxides, but if the soil is heated to very high temperatures, the magnetic susceptibility may decrease (Weston 2004). This has been further investigated by Maki *et al.* (2006) who encountered archaeological hearths that produced a negative magnetic anomaly during a magnetometer survey. In a laboratory reconstruction they found the primary (lithogenic) magnetite oxidized to maghemite at high temperatures, followed by an inversion to hematite. That the other conditions, the presence of organic matter and a fine grain size, are important as well has also been shown in laboratory experiments (Weston 2004).

The coarse mineral soils that lack organic matter and lack a finer soil fraction reached a lower total magnetic susceptibility than finer soils or soils with more organic material. The coarser the material, the higher the temperature needed to obtain the maximum susceptibility in the medium.
Moreover, Weston (2004) has found in his experiments that the waterlogging of soil can prevent magnetic susceptibility enhancement during heating. His explanation is that on the one hand the heat cannot penetrate sufficiently into the soil if it is waterlogged, on the other hand it is difficult to obtain higher temperatures.

3.6 Magnetic susceptibility in The Netherlands

In England, a large topsoil magnetic susceptibility survey has been conducted that covered the whole land surface in approximately 1200 samples (Dearing *et al.* 1996, 2001). In The Netherlands there is no such national database in which values of the soil magnetic susceptibility are stored. During this study, however, topsoil samples were collected on a series of locations, the data of which is digested in Table 2. This very limited amount of samples has been used to create a map with topsoil magnetic susceptibility (Fig. 7). An impression of the variation in the magnetic susceptibilities in subsoil samples is given in Table 3.

Table 2 The magnetic susceptibility of the topsoil samples that were collected during this study. N is the number of samples.

site	N	range x 10^{-8} m^3/kg	mean x 10^{-8} m^3/kg
Aarle Rixtel	1	-	30.3
Beugen Zuid	13	19.87 - 39.58	30.02
Borgharen	4	33.85 - 44.79	40
Breda	5	0.92 - 16.17	10.46
Broekpolder	22	8.18 - 21.90	16.25
Deil	3	7.48 - 11.96	9.64
Den Dolder	3	6.36 - 9.38	7.7
Geldermalsen	3	8.92 - 9.25	9.1
Harnaschpolder	21	8.65 - 58.85	19.17
Heeten	21	13.12 - 39.19	22.43
Limmen	5	12.86 - 18.90	16.19
Meerssen	3	32.78 - 39.48	36.42
Midsland aan zee	1	-	0.76
Oostelbeers	1	-	12.81
Oostrum	4	8.88 - 14.61	11.21
Poeldijk	2	14.81-17.32	16.07
Raalte	1	-	8.53
Smokkelhoek	2	6.64 - 6.68	6.66
Stede Broec	3	10.16 - 31.10	18.25
Steenbergen	1	-	30.05
Stroe	3	1.11 - 1.31	1.22
Swalmen	2	36.82 - 55.98	46.4
Uitgeest	1	-	11.32
Vleuten	1	-	16.32
Wervershoof	3	7.85 - 8.80	8.23
Wijk bij Duurstede	3	129.73 - 240.48	178.03
Zaltbommel	5	16.70 - 27.97	20.29

Figure 7 does not pretend to provide an overview of Dutch topsoil magnetic susceptibility like its English counterparts does. It has been solely displayed because it seems to show a meaningful trend that may be important for the following chapters. Most strikingly, in the province of Limburg the topsoil magnetic susceptibility is elevated. This magnetically enhanced area possibly coincides with the extent of the presence of loess in the soil matrix. The area of enhancement is larger than the loess region, a phenomenon that may be caused by the transportation of loess sediment along the river Meuse. Elevated magnetic susceptibility of the soil can also been seen in the eastern part of The Netherlands. The two sample locations that cause the anomaly are metal working sites, however, and this type of high temperature activity can be expected to have caused an elevated soil magnetic susceptibility.

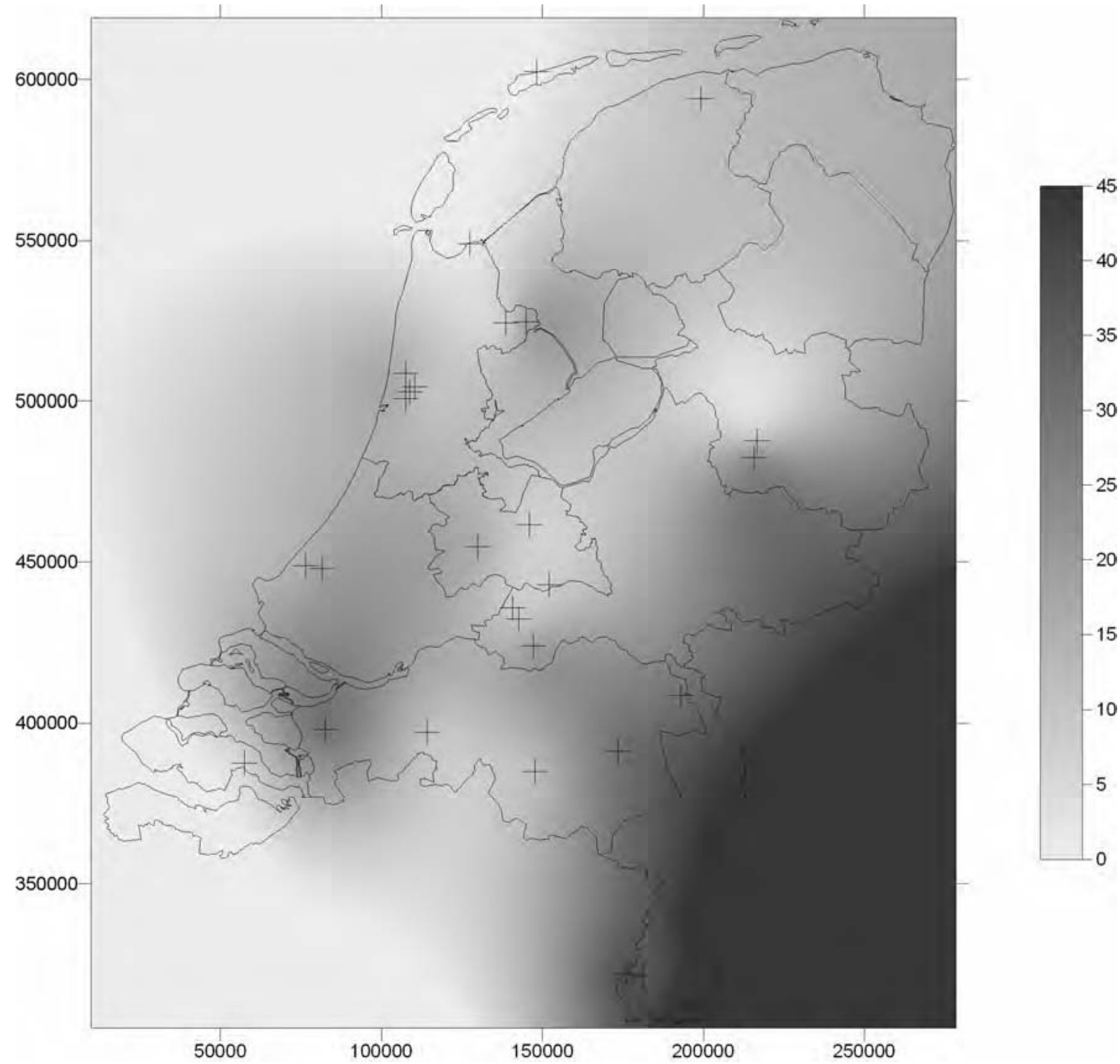

Figure 7 Topsoil magnetic susceptibility in The Netherlands from samples in this study, scale 8 x 10^{-8} m^3/kg. Crosses indicate the sample locations. Data has been gridded using the minimum curvature routine, which gives the smoothest possible surface and is more suitable for small and scattered datasets than other interpolation methods like for example Kriging.

On the other end of the spectrum, very low topsoil magnetic susceptibilities are recorded in Midsland and Den Dolder, both soils are coarse mineral soils, a quality that has been related to low magnetic susceptibility in paragraph 3.5. On the Brabant pleistocene sand plateau and in the fluvial area in the center of The Netherlands, magnetic susceptibility is usually relatively low and homogeneous. These observations will be further elaborated in Chapters 5 and 6.

To add some detail, typical ‘magnetic susceptibility sections’ for the four prevalent Dutch geogenetic environments are displayed in Figure 8. As was discussed in paragraph 3.5, topsoil magnetic susceptibility is usually higher than in the layers underneath, a phenomenon that is observed in these sections. Exceptions are the estuarine examples of Smokkelhoek and Oostrum; both of these sections contain high magnetic susceptibility layers in the subsoil, and have relatively low magnetic susceptibility topsoils. The processes that underlie this phenomenon will be discussed in Chapter 5. Except for a high magnetic susceptibility topsoil, the other profiles have in common that their magnetic susceptibility decreases with depth. This may be linked to the general lack of organic matter at greater depth, which is needed for the bacterial or thermal enhancement of soil magnetic susceptibility. The Stroe profile is no exception; the two top layers are interpreted to be a recent addition and not part of the developed soil. The third layer is the actual high magnetic susceptibility topsoil layer.

Table 3 The magnetic susceptibility of the subsoil samples that were collected during this study. N is the number of samples. It must be noted that samples were taken across the whole undisturbed soil section. Different material properties have not been taken into account.

site	N	range x 10^{-8} m^3/kg	mean x 10^{-8} m^3/kg
Beugen Zuid	14	0.77 - 18.74	4.80
Borgharen	6	5.65 - 11.81	10.45
Breda	5	0.12 - 1.02	0.44
Broekpolder	26	2.98 - 9.80	5.25
Deil	3	4.06 - 5.04	4.71
Den Dolder	8	0.53 - 3.52	2.23
Geldermalsen	4	1.41 - 6.98	4.07
Harnaschpolder	32	0.48 - 11.09	6.66
Heeten	21	4.48 - 108.51	23.84
Limmen	5	6.02 - 8.15	6.74
Meerssen	3	14.67 - 20.97	18.63
Oostrum	6	9.5 - 21.47	16.51
Poeldijk	5	0.73 - 24.79	9.66
Raalte	4	0.68 - 56.48	19.56
Smokkelhoek	44	-0.8 - 177.33	24.11
Stede Broec	6	3.05 - 6.02	4.34
Stroe	4	0.95 - 2.12	1.3
Swalmen	2	0 - 1.72	0.86
Uitgeest	4	1.74 - 5.32	3.13
Wervershoof	4	2.78 - 7.00	4.97
Wijk bij Duurstede	2	9.28 - 12.81	11.04
Zaltbommel	5	4.18 - 13.73	7.96

For archaeological prospection purposes, the two characteristics that were discussed, i.e. a high magnetic susceptibility topsoil and a decreasing magnetic susceptibility down profile, are of vital importance for a potential magnetic differentiation of the feature fill and the undisturbed matrix, and subsequently for the formation of induced magnetic anomalies. Negative archaeological features can get a positive magnetic expression if they are filled with a higher magnetic susceptibility fill. This is more easily obtained in a situation where topsoil and surface material have higher magnetic susceptibilities than the subsoil. The greater the differentiation between topsoil and subsoil was in the past, the more likely it is that archaeological features now cause an induced magnetic anomaly. Based on the presented data, there are hints as to where the application of magnetic methods for archaeological prospection in The Netherlands may have more or less potential. In the south eastern loess area and in the Meuse valley, for example, topsoil magnetic susceptibility is high, and differences between topsoil and subsoil are large, whereas in the northern areas the two layers seem to be far less differentiated. Based on this limited information, the loess area seems to have more potential for the use of magnetic methods in archaeological prospection than the marine clay areas. The aeolian deposits in the southern and eastern part of The Netherlands seem to be well differentiated, but the current situation, where plaggensoils have been added since the prehistory, is unlikely to correspond to the situation at which these soils may have been inhabited in the prehistory.

The relation between the high magnetic susceptibility fill of archaeological features and magnetic anomalies is the topic of the following paragraphs.

3.7 Induced magnetization

Induced magnetization is the magnetic moment that occurs in a material under the influence of an external magnetic field. It has a linear dependency on both the magnetic susceptibility of the material and on the applied magnetic field:

$$J_i = \kappa H$$

where J_i is the induced magnetization, κ is the mass magnetic susceptibility and H is the field strength of the applied magnetic field. The direction of magnetization is usually identical to the direction of the applied field.

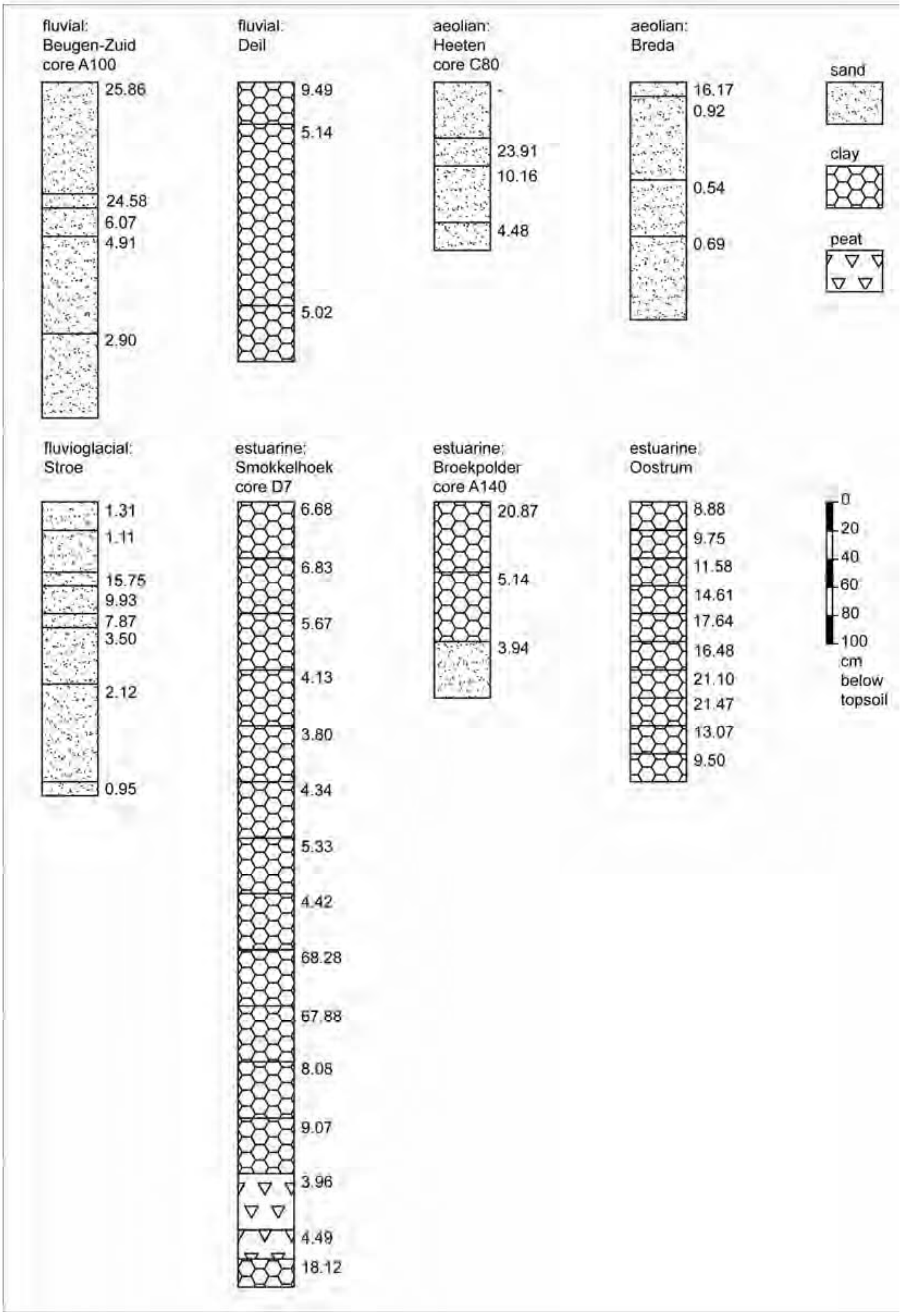

Figure 8 The magnetic susceptibility of eight typical soil profiles. Values on the right hand side of the cores represent the magnetic susceptibility x 10^{-8} m^3/kg. For matters of clarity the soil descriptions have been simplified to the three main classes of sand, clay and peat. Detailed soil descriptions of these profiles can be found in Appendix III.

The soil matrix, the object of archaeological magnetic prospection, is continuously magnetized by the earth's magnetic field. Differences in soil magnetic susceptibility, under the influence of the earth's magnetic field, are the cause of differences in induced magnetization in the soil.

3.8 Remanent magnetization

Some objects or materials can be magnetized without the application of an external magnetic field, this is called remanent magnetization. An example are ferromagnetic materials, like iron. In the case of objects, the direction of magnetization is along the easy axis of magnetization in the object.
Most relevant for archaeological prospection is *thermoremanence*, the remanent magnetization that an object or feature can obtain after is has been heated to high temperatures. The transition of non-ferrimagnetic minerals into ferrimagnetic minerals causes the magnetic susceptibility of the material to increase, but these ferrimagnetic minerals can also carry a remanent magnetization in zero external field. In the heating process the direction of the magnetic particles is disturbed, on cooling the (newly formed) magnetic particles will align along the direction of ambient magnetic field. *In situ*, the direction of magnetization will be approximately parallel to the direction of the earth's magnetic field on cooling. Measurements of this direction, in combination with knowledge about the past declination and inclination of the earth's magnetic field, can be used for magnetic dating. *Ex situ*, the magnetic moment of thermoremanent objects or features can have any direction. Examples of thermoremanent objects are bricks, tiles, and igneous rocks, features that have obtained a thermoremanent magnetization are, for example, hearths and kilns.
There can be other reasons than heating and cooling why magnetic particles align themselves in one preferred direction. In a material that carries no magnetic remanence, but that does contain an amount of ferrimagnetic minerals, a mechanical shock may cause the magnetic minerals to align in one predominant direction (this is named *shock or shear remanent magnetization*). It has been suggested that mud bricks, which are made in moulds from which they are removed by hitting the ground with force, carry this type of remanent magnetization (Kattenberg 1999).

Chemical remanent magnetization is laid down during the formation of magnetic minerals that grow in one predominant magnetic direction. *Detrital remanent magnetization* is a post-formation process that is caused by magnetic particles which lay themselves down in one magnetic direction after having been in suspension. These two types of remanent magnetization may not be relevant for the magnetic detection of archaeological features, but magnetic anomalies that are caused by chemical or detrital remanent magnetization may be encountered during a magnetometer survey for archaeological purposes.

3.9 Magnetic anomalies

Variations in both induced and remanent magnetization in the soil influence the total ambient magnetic field, which is the combination of the earth's magnetic field and other magnetic moments that are present near the earth's surface. In a magnetometer survey, anomalies in the total ambient field may be meaningful for objects or features that are buried underneath the surface. Magnetometer instruments are constructed to measure (one of the components) of the ambient field (see paragraph 4.3.1). The main contribution will, in almost all cases, come from the earth's magnetic field, followed by any remanent and induced magnetizations.

3.9.1 Direction of magnetization

In most cases, the magnetic responses of features with an induced or a remanent magnetization can not be distinguished, because their direction of magnetization is similar. Features with a thermoremanent magnetization that have remained in the position where they cooled, will have a magnetization in the direction of the ambient field at that moment, which is mainly dominated by the earth's magnetic field.

The direction of the earth's magnetic field has changed through archaeological time, but on an archaeological timescale not so drastically that this shift in orientation can be seen in the magnetic anomalies that are mapped in a magnetometer survey. Magnetic anomalies that are caused by the induced magnetization of archaeological feature fills with a magnetic susceptibility contrast are also magnetized in the direction of the earth's magnetic field, and cannot be distinguished from the anomalies that stem from a remanent magnetization. Objects with a remanent magnetization like pieces of brick or metal, however, may have any direction of magnetization and can, because of their direction, be easily distinguished in the results of a magnetometer survey.

The size, shape and orientation of the magnetic anomaly that are caused by objects or features which either have an induced or a remanent magnetization can be used for the interpretation of magnetometer data, which is discussed in the next paragraph.

3.9.2 Size and shape

The size of a magnetic anomaly depends on the strength of the remanent or induced magnetic contrast, the volume of the object or feature causing the anomaly, and the depth at which it is buried.

The properties of a feature or object causing a magnetic anomaly can be modeled through inversion based on its magnetic response, for example in the program MAG3D[15]. This software assumes that the anomalies that it analyzes are caused by magnetic susceptibility distributions in the soil, and induced magnetization under the influence of the earth's magnetic field. A program for the inversion of metal objects is UXOLab[16], which was developed for the analysis of the magnetic response of unexploded ordinance. In reverse fashion, an anomaly can be forward modeled by defining a set of relevant variables, magnetic susceptibility contrast, volume and depth of burial of an object or feature. In this study the program Modeller[17] was used. Only magnetic susceptibility contrasts have been investigated, anomalies that were caused by magnetic remanence have not been modeled in this study.

In Figure 9a, a typical induced magnetic anomaly, a pit, buried at 0.25 meter depth, has been displayed as a magnetometer response at Dutch latitudes if traversed from north to south. The response is parabolic, with its peak slightly off-set to the south of the causative object and a negative dip to the north side of the peak. In Figure 9b the same pit is buried at greater depth, between 0.75 and 1.25 meter. Because of the greater distance between the feature and the magnetometer, the response is much weaker, but in size it is actually wider. The peak and the dip are less pronounced. In Figure 9c a smaller pit is modeled, that is buried at the same depth as the pit in a. Because of the decrease in volume, the response is weaker and narrower than that of the original pit in Figure 9a.

Figure 10 is an example of the geometry of the peak and trough of a magnetic anomaly in a 2D view, this is the type of display that is the most commonly used graphical way to display magnetometer data. The data is a section of the survey that was carried out on the metal working site of Heeten Hordelman. Because the site was excavated after the magnetometer survey, anomaly A is known to represent a rubbish pit. The geometry of the magnetic anomaly, a peak with a relatively small halo shaped trough on its north side, is a typical example of induced magnetization. Object or feature B, on the other hand, was not recorded during the excavation. It consists of a central trough with a circle of higher values surrounding it, which is, because of its orientation, indicative for remanent magnetization. The anomaly was possibly caused by a piece of metal in the topsoil. Two small anomalies marked with C in Figure 10, are clear peak-and-trough anomalies. Because of their east-west orientation, the features can be interpreted as having a remanent magnetization. If the objects causing the anomalies would have been turned by 90 degrees anti-clockwise, the anomalies could have been misinterpreted as features with an induced magnetization.

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[15] MAG3D; A Program Library for Forward Modelling and Inversion of Magnetic Data over 3D Structures. Developed under the consortium research project Joint/Cooperative Inversion of Geophysical and Geological Data (JACI), UBC-Geophysical Inversion Facility, Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, British Columbia.

[16] UXOLab is a software package for analyzing magnetic and electromagnetic data for the purpose of detection and discrimination of unexploded ordnance (UXO).

[17] Modeller version 2.11, © Nic Sheen 1995.

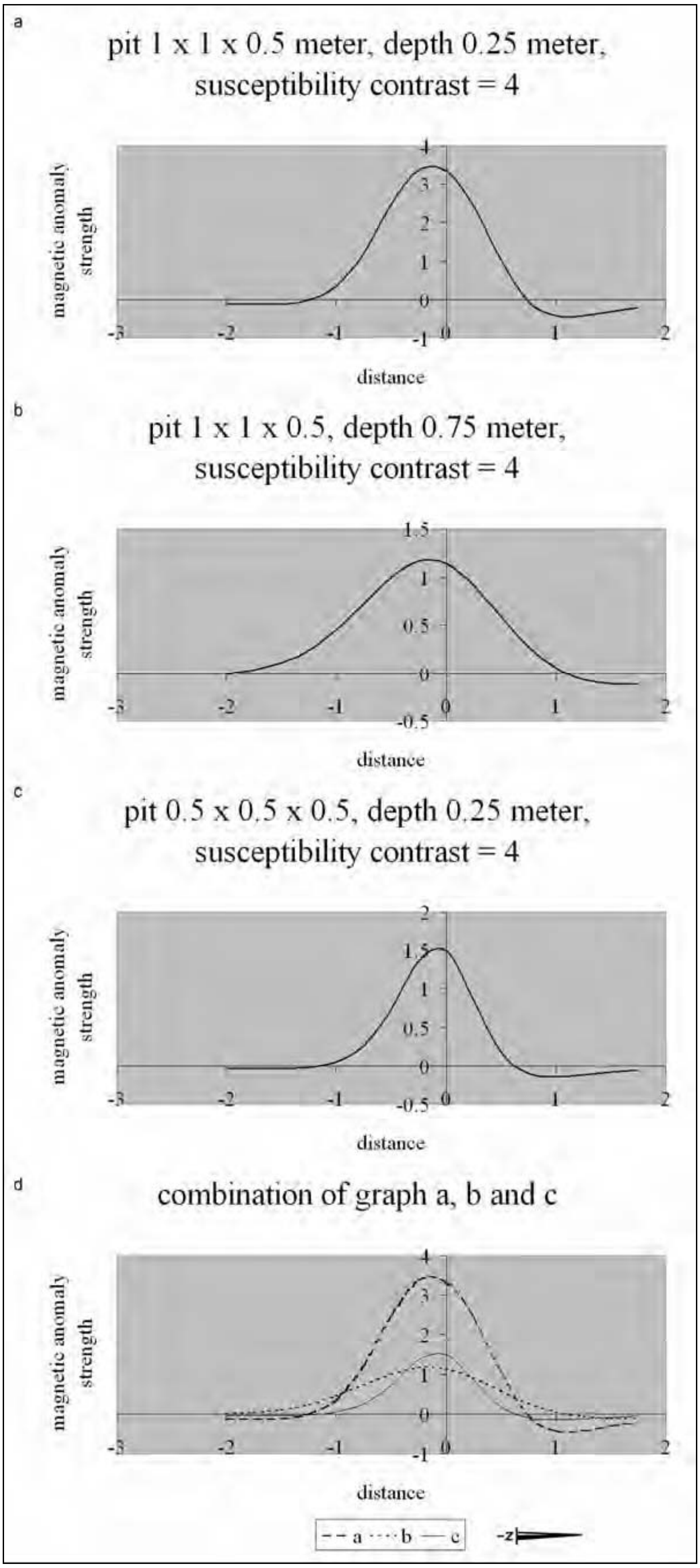

Figure 9 Modeled gradiometer responses (vertical component). North is pointing to the right.
a: typical archaeological pit with a high magnetic susceptibility fill; b: the same pit as in (a) buried at a greater depth; c: a smaller pit buried at the same depth as (a); d: a combination of graph (a), (b) and (c). Deeper burial of the same object (compare (a) and (b)) causes a weaker and broader magnetic anomaly. Shrinking the object (compare (a) and (c)) causes a weaker and narrower anomaly. Note the negative trough is located on the north side of the anomaly.

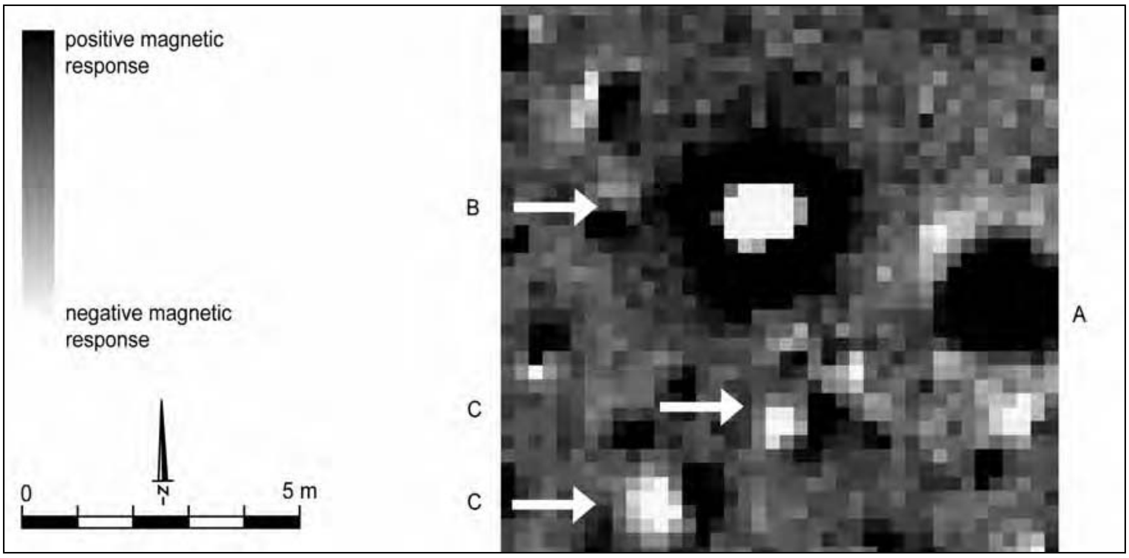

Figure 10 An example of the response of magnetized objects or features in a magnetometer survey in a 2D display. Anomaly A represents the response of a rubbish pit with a high magnetic susceptibility fill. The positive peak and the slight negative halo on its north side are typical features of an induced magnetization. Anomaly B has a central trough surrounded by a positive halo, an indication of a remanent magnetization. The anomalies marked with C have a clear peak with a trough to the west. Because of this orientation they can be identified as remanent magnetic objects or features, if the trough has been oriented to the north, than the features could have been misinterpreted as being caused by induced magnetization.

A 3D view of Figure 10 can be seen in Figure 11.

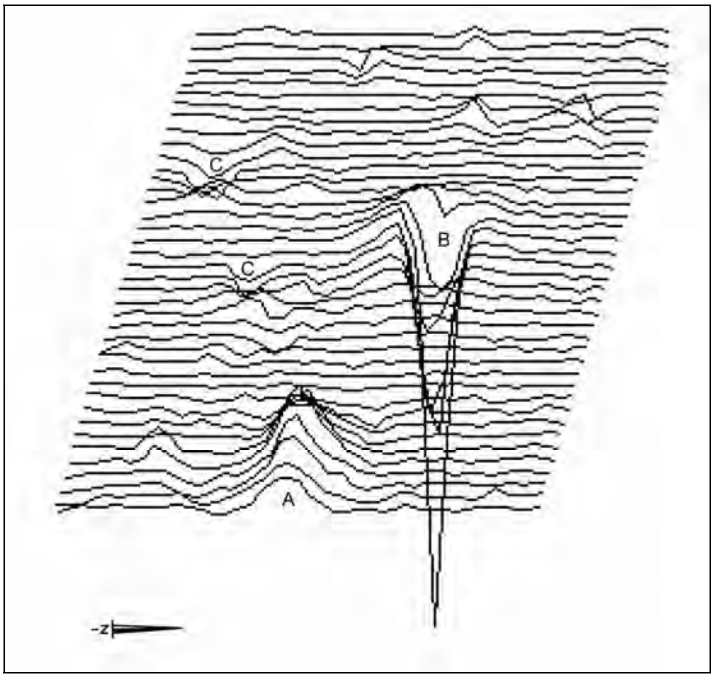

Figure 11 Trace plot of the data of Figure 10, looking west. The pit anomaly (A) is located on the foreground. Note the sharp trough in anomaly B.

3.10 Post depositional processes

Remanent magnetization in an object or feature is usually firmly preserved in the material, but mechanical processes can break up and change the direction of their magnetic moment.

A remanently magnetized object with one predominant direction of magnetization, e.g. a kiln, can desintegrate into pieces that each still have a remanent magnetic moment, but all in a different direction. Chemical and detrital magnetization in sediments may be destructed if the soil material is agitated for example by flowing water.

Magnetic susceptibility, and therefore induced magnetization, on the other hand, is much easier affected by post depositional processes. The processes that are most likely to influence the magnetic susceptibility of a soil are wetting and drying, because these processes can lead to the transformation or the movement of iron oxides (Fig. 6) in the soil.

If a soil is continuously *waterlogged* for a long period of time, iron oxides can be reduced to hydrated iron hydroxides (Weston 2002). Further reduction will change iron in the ferric form (FeIII) to a ferrous form (FeII), which is accompanied by a soil colour change from red, yellow and brown to blue and grey. The ferrous iron is likely to be redistributed or leached from the soil profile. During long lasting waterlogging episodes, even ferrimagnetic minerals can dissolve, and they may be removed from the soil profile (or be transformed into ferric hydroxides; Weston 2002), causing a drop in soil magnetic susceptibility. The sequence of the solubility of iron oxides is ferrihydrite > lepidocrocite > maghemite > goethite > hematite, but the latter two iron oxides may be in reverse order (Cornel & Schwertmann 2003). Goethite and hematite are the most stable iron oxides, and are the end product of many transformation routes (see also Fig. 6). Transformations of the soil iron oxides caused by water-logging will influence the magnetic susceptibility of the soil. Changes in the iron mineralogy that may occur under the influence of sea water logging are discussed in Chapter 5.

During the process of *gleying* Fe(III) is dissolved under long lasting reducing conditions and relocated to a higher level, to the zone in which the groundwater fluctuates, causing the typical iron staining. Mullins noticed that gleyed horizons have unusually low susceptibilities, which, he states, is caused by the dissolution (and movement) of ferrimagnetic maghemite under reducing circumstances (Mullins 1977). The oxidation of redeposited iron can possibly lead to the formation of a number of different iron oxides, most noticeably ferrihydrite, but, according to laboratory experiments (Taylor 1980) also for example hematite and maghemite.

The process of *leaching* occurs, for example, during podzolisation. Iron is leached from the upper part of the soil and redeposited at a lower level, in the case of a podzol in an ‘iron pan’ in the form of (antiferromagnetic) lepidocrocite. Weston has seen that subdued magnetic susceptibilities occur in coarse mineral soils, especially in those soils that have a high water table, suggesting leaching of iron oxides to be the cause. In order to find out if this was the case, he set up two leaching experiments:

- leaching with H_2SO_4, mimicking leaching by acid rain;
- leaching with EDTA, mimicking leaching by plants and soil biota.

The experiment showed coarse (sandy) soils are more easily leached of iron than finer soils or soils with a high organic matter content, and only very acidic conditions can mobilize iron (Weston 1999). Moreover, there was no noticeable influence on the magnetic susceptibility of previously ignited samples. The enhanced magnetic susceptibility in both clay and sand samples appeared to be more resistant to leaching than the in the non-ignited samples (Weston 2004).

3.11 Conclusion

In this chapter the principles behind magnetic prospection in archaeology have been set out. The most important points, which are needed to understand the following chapters, are summarized here.

Magnetic susceptibility

- The magnetic susceptibility of a soil is mainly determined by the amount and type of soil iron oxides, in The Netherlands magnetite, maghemite, lepidocrocite, goethite, hematite and ferrihydrite are expected to be the most common iron oxides.
- Every (soil) material has a different magnetic susceptibility.
- Topsoil usually has an enhanced magnetic susceptibility compared to the undisturbed subsoil, this also appears to be the case in samples from The Netherlands.

- Archaeological deposits often have an enhanced magnetic susceptibility.
- Magnetic susceptibility enhancement can be caused by heating (but is impeded by waterlogging during heating) or by bacterial action, both processes depend on the presence of organic matter.
- The magnetic susceptibility of finer soil fractions is more easily enhanced than coarser fractions, in the Dutch soil samples coarse samples appear to have a lower magnetic susceptibility than the finer samples.

Magnetic anomalies

- Magnetic susceptibility differentiation between the topsoil and the subsoil is a favorable circumstance for the formation of magnetic anomalies, in The Netherlands this differentiation appears to be best in the loess area and Meuse valley.
- Differences in magnetic susceptibility lead to induced magnetic anomalies.
- Remanent magnetic anomalies can be caused by heating or other processes.
- Magnetic anomalies can be interpreted based on their shape, size and orientation.

Post depositional processes

- Prolonged water logging, severe leaching and gleying can cause the dissolution and movement of iron, and will usually lead to a change in soil magnetic susceptibility.