The Application of Magnetic Methods for Dutch Archaeological Resource Management

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Citation for published version (APA):
Kattenberg, A. E. (2008). The Application of Magnetic Methods for Dutch Archaeological Resource Management Amsterdam: Amsterdam Institute for Geo and Bioarchaeology, Vrije Universiteit

8 Discussion

This discussion will start with the critical observation of the methodology that was used during the research that is reported on here, including site selection and instrument choice.
The second section considers the factors that facilitate and hamper the formation and preservation of enhanced soil magnetic susceptibility in The Netherlands, which is of critical importance for the formation of induced magnetic anomalies. The topic will be discussed in conjunction with the results of the investigations that have been carried out on estuarine, wind blown and fluvial soils.
Finally, the discussion will focus on the possibilities of magnetically mapping certain archaeological features and objects, unrelated to the geological environment in which they are embedded.

8.1 Methodology

Chapter 4 discussed how, during the research, the methodology regarding site selection had diverted from the original research plan. Rather than investigating three large areas which included one or more archaeological sites, as was originally proposed, a larger number of smaller areas was investigated. Hence the research has concentrated on groups of individual sites rather than on the archaeological landscape. The shift in the site selection process was made after magnetometer surveys had taken place in the first two larger research areas, where results were disappointing. It was thought that a larger diversity of sites was needed in order to investigate the differences between magnetic contrasts in different areas and to understand the lack of contrast that was observed in the first two areas, Broekpolder and Harnaschpolder. On hindsight, the choice of these two sites, both on estuarine deposits, was unfortunate. Very few archaeologically relevant magnetic anomalies could be recognized in the datasets, but this lack of a magnetic contrast in archaeological deposits was observed on estuarine soils in general. In areas with another geological background the magnetic response was different, and in the Meuse valley, for example, investigating a larger area around an archaeological site would have probably proved worthwhile. Whether of not any of the elements that make up the (man-made) landscape can be detected magnetically in the areas where there is an on-site magnetic contrast remains a topic of further research.
The larger number of sites that was thus surveyed and otherwise investigated, allowed for a better overall interpretation of magnetic responses related to the different geological backgrounds in The Netherlands. Moreover, the new approach to site selection secured a much better ground truthing of the data. Using a small dataset like this (31 sites, two of which outside of The Netherlands), however, it remains difficult to generalize, but the geological approach has appeared to be useful to discuss similarities in magnetic susceptibility and magnetic response between the sites. Apart from the geological background, there are two other factors that may correlate to the presence of a magnetic contrast and the potential for a successful magnetometer survey; the age of the archaeological deposits and the type of archaeological site, which will be discussed in a later section of this discussion.
The single type of magnetometer that was used during this research is the fluxgate gradiometer. The choice for a gradiometer as opposed to a total field magnetometer is obvious when the generally small magnetic variations that are caused by archaeological features are considered. As was discussed in Chapter 4, although the fluxgate gradiometer remains the magnetometer which is most used in archaeological prospection, other types, like the caesium vapour magnetometer are increasingly deployed. For a number of surveys that were conducted within the framework of this study, it is expected that the use of a more sensitive magnetometer, for example a caesium vapour instrument, would have yielded better results.

This is only the case, however, on sites where a magnetic contrast was present in the first place, like in Limmen and Beugen. Sites that lack this contrast, or sites on which the features have both a positive and a negative contrast to the subsoil (see for example Fig. 32) would obviously not necessarily benefit from the use of a more sensitive magnetometer.
Investigations into the iron mineralogy of estuarine deposits by means of Curie balance and IRM measurements, although not included in the original research plan, proved to be very important for understanding both geological and archaeological magnetic contrasts. If these magnetic measurements would have been part of the original research plan, a more systematic sampling strategy could have been applied and sites on wind blown and fluvial geologies could also have been investigated.

8.2 Contrasts in magnetic susceptibility

This thesis has mainly been concerned with magnetic susceptibility contrasts within the three geogenetic environments that were defined at the start of this study: estuarine, wind blown and fluvial. Different contrasts, for example between topsoil and subsoil, or between archaeological deposits and the subsoil, could be observed in these environments and in order to investigate the relation between the background geology and the possibilities for the magnetic mapping of archaeological features, the variables that influence the formation and preservation of magnetic contrasts will now be discussed.

Organic matter
The importance of the presence of organic matter for the enhancement of the soil magnetic susceptibility was discussed in Chapter 3. In the process of the transformation of non-ferrimagnetic compounds to ferrimagnetic iron oxides by heating, organic matter is needed to create reducing circumstances. For bacterial magnetic enhancement, the presence of organic material is important for two reasons; it acts as a nutrient for the bacteria, and it can facilitate reduction as a source of electrons. In the Netherlands, the magnetic susceptibility of topsoil material is generally enhanced. There are no sources for primary magnetite from a parent material. If the industrial fall out of ferrimagnetic particles is discounted, and there is no reason to believe that all topsoil enhancement can be attributed to this fall out (see Dearing *et al*. 1996), especially not below the surface level, than the observed enhancement is likely to be caused or facilitated by bacteria. If enhancement is so strongly related to the presence of organic matter, it can be expected that the fill of archaeological features, which usually have a higher organic matter content than the matrix that they are embedded in, is enhanced as well. Either because the 'archaeological' topsoil was already enhanced, and has collected in the fill, or because of the post depositional bacterial enhancement of the archaeological deposit. In a number of the case studies this appeared to be the case, in Meerssen for example, topsoil and feature fill magnetic susceptibilities are very similar. On other sites, samples from archaeological feature fills had higher susceptibilities than the topsoil, for example in Borgharen. In many of the case studies it was observed, however, that although the topsoil magnetic susceptibility on the archaeological site was enhanced when compared to the subsoil, in the archaeological features this enhancement could not be seen, or was less prominent.
The formation of (ferrimagnetic) iron sulphides (for example in Smokkelhoek, Harnaschpolder and Spalding) appears to be linked to deposits which are rich in organic matter, suggesting a bacterial origin. In this study geological features in which these iron sulphides had been formed sometimes caused magnetic anomalies in the magnetometer data. In theory, the preferential formation of iron sulphides could also occur in archaeological deposits, provided that they have a higher organic matter content and that they are subject to sea or brackish waterlogged conditions. An example of preferential formation in organically rich archaeological deposits is the greigite which was encountered in the postholes of the ‘seahenge’ monument (Linford 2006). During this study, the magnetic anomaly caused by the deep well deposits in Limmen may have been caused by the presence of iron sulphides in the deposits, but this remains speculative. Further research is needed to confirm the preferential formation of iron sulphides in archaeological deposits. Moreover, it may be difficult to distinguish the archaeological signal from the geological signal if iron sulphides are formed in both types of deposit.

Particle size
Detailed investigations into the relation between magnetic susceptibility and grain size in archaeological deposits have been conducted by Weston (2002, 2004). He concludes from his experiments that finer soil fractions (clay and silt) are more easily enhanced, and that this enhancement is more difficult to undo by post depositional processes than in coarser material. Coarse soils without organic matter or a finer soil fraction can more easily be flushed of iron. Dearing *et al*. (1996, 2001) have suggested that ferrihydrite may be an important precursor of magnetite in English soils. Magnetite can be formed through bacterial reduction, during short periods with anaerobic conditions. This is best achieved in soils which have a large micropore volume on the one hand, but are free-draining on the other hand, identified as silty loams, clayey loams and silty clays, again the finer soil fractions. The lack of magnetic susceptibility enhancement in the fills of archaeological features on coarse sandy soils was also observed in this study, whereas the largest magnetic susceptibility contrasts occurred in silt, in clay and in sand and clay and sand and silt mixtures. An exception is the site of Limmen, were magnetic contrasts existed in dune sand, which has a smaller particle size than the cover sands in the eastern and southern part of the country.

Soil pH
If a soil is very acidic, the soil pH can influence the magnetic susceptibility of a deposit, whereas other pH values have very limited influence on the susceptibility (Weston 1999). In an acidic environment, iron is more easily mobilized and can be flushed from or translocated within the deposit. In Broekpolder, the effect of an acidic top layer could be seen to have resulted in a low magnetic susceptibility topsoil. Another example is the formation of podzols on for example the cover sands, where iron is flushed from the upper horizons and moved to a lower soil layer, the B-horizon. Although the iron is concentrated in this horizon, it is present as paramagnetic ferrihydrite. For this reason, magnetic susceptibility samples that were taken from a podzol in Den Dolder showed no enhancement for the B-horizon. The presence of a podzol soil is an indication of (past) acidic circumstances and the movement of iron within the soil profile. This process of podzolization will also affect any archaeological deposits, and will change their magnetic susceptibility. If calcareous material is present in a deposit, it can form a buffer for acidity, for example the shells in the estuarine soils. Focusing on the areas that have been studied, cover sands and Meuse valley deposits are non-calcareous, and more prone to magnetic susceptibility changes due to the loss of iron.

Post depositional processes
One of the post depositional processes that may affect the magnetic susceptibility of a deposit, podzolization, is discussed above. In a podzol iron is moved down the soil profile, but dissolution of iron can also occur in less well drained soils. Gleying is the dissolution and oxidation of iron due to the oscillating groundwater table. This does usually not affect archaeological levels, as these often occur above the groundwater table, but if it does, the magnetic susceptibility of the gleyed deposits will change. Mullins (1977) has suggested that a low magnetic susceptibility in gleyed soil layers is due to the dissolution of maghemite, but more generally, as a result of gleying, the iron oxide forms will have changed, and with it the soil magnetic susceptibility. Iron oxides may also change during waterlogging, but the conditions will have to be long lasting and severe. A post depositional process that has received a lot of attention in this study is the so called sea waterlogging. During this process, soil iron oxides may dissolve to form iron sulphides. Again, the changes in the iron mineralogy affect the magnetic susceptibility of the soil. A complicating factor for magnetic prospection is the high magnetic susceptibility of certain iron sulphides, most noticeably greigite, bodies of which can cause magnetic anomalies that are much stronger than archaeologically caused anomalies. The iron sulphides that were observed in the field occurred in conjunction with organic matter, which would favour the interpretation of the iron sulphides as being bacterially mediated.

8.3 Estuarine and marine deposits

The influence of the above factors on soil magnetic susceptibility, could be illustrated well on the sites of Broekpolder and Harnaschpolder, where more detailed magnetic measurements were conducted.

Organic matter content did not appear to bear a relationship to the soil magnetic susceptibility, archaeological feature fills, which were high in organic matter when compared to the matrix, did generally not have a magnetic contrast. This was found to be the result of several post depositional processes. One of these processes could be identified on both sites; gleying. During gleying, iron is mobilized and moved up in the profile, thus creating depleted and enriched areas. In such cases, fractional conversion values cannot be used to pinpoint 'archaeological enhancement', although they may be used to identify gleying in the profile, as was shown in Chapter 5. The present gley horizon may generally be visually identifiable, but evidence of past gleying may be much harder to define. In Broekpolder and Harnaschpolder the presence of oxidized magnetite (maghemite) and hematite in the subsoil provided additional proof for gleying. For archaeological prospection purposes, any magnetic contrast between the archaeological deposits and the matrix can generally be expected to have ceased in areas where gleying has occurred above the archaeological level.
It is assumed that the influence of leaching could be seen in the data from Broekpolder, where the acidic upper part of the soil profile appears to be partly flushed of iron. Leaching, like gleying, translocates iron in the soil profile, and changes the iron distribution in the soil. It is interesting to note that neither gleying nor leaching could be observed in the soil magnetic susceptibility, as values were low, but homogeneous.
Extremely acidic soil conditions can occur during the oxidation of a Potential Acid Sulphate Soil into an Actual Acid Sulphate Soil. It can be assumed that this acidity too affects the iron mineralogy of the soil. Non-oxidized iron sulphides in the subsoil occur in marine and estuarine deposits in The Netherlands. On the one hand their presence causes large magnetic anomalies of a geological nature, often correlated to the presence of organic material in the subsoil. These anomalies can hamper the interpretation of magnetometer data which is collected for archaeological purposes. On the other hand, the preferential formation of iron sulphides may occur in archaeological deposits if their fill contains more organic material than the matrix that they are embedded in. If ferrimagnetic iron sulphides are present, archaeological feature fills may cause a magnetic anomaly. This hypothetical scenario needs to be tested on archaeological sites which are brackish or sea waterlogged.

8.4 Wind blown deposits

The largest extend of superficial wind blown deposits in The Netherlands are the cover sands in the eastern and southern part of the country. There is generally a magnetic susceptibility contrast between the topsoil and the subsoil, which coincides with the boundary between subsoil deposits without much organic material content, and topsoil deposits which contain much more organic matter. The argument of the bacterial enhancement of the topsoil layer in the presence of organic matter could be valid for these deposits.
Magnetic susceptibility contrasts between the fills of archaeological features and the matrix, however, could not be observed on archaeological sites on cover sands. Feature fills in this type of soil usually contain more organic matter than the surrounding matrix, a similar situation to the estuarine deposits. In this case, however, it is more difficult to determine if the magnetic susceptibility contrast has never existed or if it has existed but has been undone. The first reason is that detailed magnetic mineral investigations have not taken place, which makes it more difficult to reconstruct the magnetic history of a site. Moreover, many of the topsoil deposits in the cover sand area are man made, for which reason it is more difficult than in the case of the estuarine deposits to compare the present topsoil to the archaeological topsoil.
One post depositional process can be visually identified, without magnetic measurements, and that is visible in much of the cover sand area is podzolisation. This process occurs readily because of the acidic nature of the soil environment and the coarse nature of the sand, which makes the soil prone to the leaching of iron. Leaching has possibly affected magnetic contrasts on archaeological sites on which podzolisation has taken place. This process may for example have caused the lack of or limited observed magnetic contrasts on the sites of Breda and Den Dolder. In Heeten, large magnetic susceptibility variations were observed within the lower soil layers of the podzol; the B-, BC- and C-horizon.

For the B- and BC-horizon these variations are likely to be specific for this site, because of the high temperature activities that have taken place, which may have caused local enhancement of the deeper soil layers. The observed C-horizon susceptibility variations, however, appear to be more general, and could be related to the presence of red sand. Where red sand occurs, distinguishing natural magnetic variations from the variations that are caused by archaeological features may be cumbersome.
The influence of masking on the magnetic prospection of archaeological features is mentioned here, although it may occur in any of the geogenetic environments, because it is most relevant for plaggen soils. The presence of a masking layer will increase the distance between the archaeological feature and the magnetometer, which will result in the decrease of the magnetic anomaly strength. The influence of a masking layer on the resulting magnetic signal at the surface can easily be modeled.
In contrast to the problems that were encountered on cover sands, the other two groups of wind blown deposits in The Netherlands, loess deposits and inland dunes, appeared to be far more suitable for magnetic prospection. On each of these geologies, only one archaeological site was investigated within the framework of this study. On these two sites, magnetic contrasts could be identified between the undisturbed matrix and the archaeological feature fills, and a number of archaeological features could be magnetically detected at the surface. More research is needed to assess the factors that have caused and preserved magnetic contrasts on these sites. The particle sizes of the coastal dune (fine sand) and loess (mainly silt) deposits when compared to the cover sands (coarse sands) may play an important role.

8.5 Fluvial deposits

In fluvial deposits, particle size mixtures that favour the formation and preservation of magnetic contrasts (often containing clay and silt) predominate. In the Meuse valley, clear magnetic contrasts could be observed that resulted in the magnetic detection of archaeological features at the surface. In the central river area, the observations were more mixed, as certain features have a magnetic contrast to the undisturbed matrix, whereas others do not. More detailed investigations are needed in order to understand the formation, preservation and possibly deletion of magnetic contrasts in these deposits.

8.6 Magnetic anomalies unrelated to the geological environment

Thermoremanent magnetic anomalies are formed by in situ heating of the soil, and include kilns, hearths and furnaces, of which only furnaces were mapped in this study. It is important to realize that the detectability of these features does not depend on the type of matrix that they are embedded in. The same applies to remanent magnetic objects, like bricks and metal working debris. In this study the difference in magnetometer response between walls or foundations (e.g. Valkenisse) on the one hand, and scatters of brick or pits filled with pieces of brick or pottery (e.g. Meerssen) could be clearly observed.
Natural stone building material can have a magnetic remanence, this is the case in for example basalt and granite. The building material that was investigated in this study, limestone, did not have a magnetic remanence. Due to the very low magnetic susceptibility of the limestone, however, it is expected to cause a negative magnetic anomaly in most matrices.