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# Archaeological Prospection of the Dutch Perimarine Landscape by Means of Magnetic Methods

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ABSTRACT Fluxgate gradiometer surveys on two sites in the coastal plains of The Netherlands showed unexpected results. On the one hand, archaeological features, identified by coring or test trenching, were undetectable owing to a lack of sufficient magnetic contrast between the infill of the archaeological structures and the surrounding natural (salt marsh) sediments. This lack of contrast was shown to be caused by the iron mineralogy and not by iron deficiency of the soil. On the other hand, geological features, interpreted as anoxic shallow creek fills, showed with surprising clarity. Analysis of black-stained deposits underlying the features identified pyrite and associated iron sulphide minerals as the cause for the magnetic anomalies. The complex iron sulphide/oxide mineralogy of salt marsh environments, coupled with geological history of the sites with multiple marine inundations, indicate that detection and interpretation of magnetic anomalies in the coastal zone of The Netherlands requires both thorough knowledge of the geology and further research into the geochemistry of these deposits.


*Key words:* magnetometry; magnetic susceptibility; iron sulphides; salt marsh; marine transgression; geoarchaeology

## Introduction

Magnetic variations in hard rock geology are known to hamper magnetometer surveys carried out for archaeological purposes (e.g. Clark, 1996), but less attention has been paid to the magnetic response of geological structures in unconsolidated sediments (for an example see Weston, 2001). If geological magnetic variations are as large as or larger than archaeologically caused variations, the latter may not be distinguishable from the natural. Smaller scale geological features thus cause a greater problem than broad geological variations. Long wavelength or gradual geological changes can be filtered out by post-processing software, or by using the magnetometer in a gradiometer configuration. Short wavelength, abrupt geological changes, however, can have magnetic characteristics very similar to buried archaeological features, which makes it difficult to separate the two.

The geological subsoil of the western part of The Netherlands consists entirely of unconsolidated Quaternary sediments. As the coastal plains occupy a considerable part of the Dutch landscape (Figure 1) and parts of this landscape have been inhabited continuously since neolithic times, it is important to understand the magnetic characteristics of the marine and the perimarine

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Figure 1. The extent of marine sediments in The Netherlands (shaded) and the location of Harnaschpolder (H) and Smokkelhoek (S). Adapted from Berendsen (1997).

(salt marsh) deposits. In the current study several known sites dating from various archaeological periods have been investigated. This paper reports on preliminary findings.

The results of magnetometer surveys on two of these sites, Harnaschpolder and Smokkelhoek (labelled H and S respectively in Figure 1) present several problems that may be typical of this specific geological setting. Given the widespread occurrence and the significance of perimarine sediments as a geological substrate in The Netherlands, it is necessary to investigate these problems.

The aim of this paper therefore is to:

(i) identify the possible reasons for the lack of magnetic contrast that was expected between the fill of archaeological features and the undisturbed matrix on the sites discussed;
(ii) discuss the (geological) origin of the magnetic anomalies encountered in Harnaschpolder and Smokkelhoek.

The paper starts with an overview of the geological development of the perimarine landscape of The Netherlands, and the archaeology of the sites discussed. This is followed by the methodology and the results of the magnetometer survey and the magnetic susceptibility sampling in Harnaschpolder and Smokkelhoek.

## Archaeology and geology

The Holocene development of the Dutch coastal plains is characterized by an alternation of clastic deposition under marine or supratidal environments, and peat formation. In general, the sequence consists of a layer of basal peat overlying Weichselian coversands, followed by two major phases of clastic sediments, respectively termed Calais and Dunkirk deposits. These deposits are separated by the so-called Holland peat. Recently a new lithostratigraphic nomenclature has been introduced (De Mulder *et al.*, 2003). However, the now obsolete Calais and Dunkirk terminology is still being used frequently, and to aid reference to older literature, this paper will refer to the 'old' terminology.

The area of Harnaschpolder (Figure 1, H) has been occupied since the neolithic period. Although the Harnaschpolder was inhabited almost continuously, the landscape changed dramatically between the different periods, resulting in a layered archaeological landscape. In the neolithic period, settlements were located on dunes along the coast; these were high points in a landscape dominated by wetlands. After the neolithic period, marine influence increased, and the landscape was covered with silts and sands (Calais phase). The tidal flats of this period gradually developed into tidal marshes. As the marine influence diminished, vegetation eventually returned, resulting in the growth of a layer of fen peat (Holland peat). At the start of the Iron Age, the peat blanket had locally reached a thickness of several metres. The next phase of marine transgressions occurred from the Iron Age to late medieval times. These Dunkirk transgressions partly eroded the peat before covering it with another layer of silts and sands. In this new tidal marsh, Iron Age and Roman Period people would inhabit and farm the raised sandy beds of former tidal creeks. Medieval occupation consisted of dwelling mounds constructed in the areas where the peat had not been eroded away. A last phase of marine transgressions, in the late Middle Ages, covered the already layered archaeological landscape with another thin layer of marine sediment.

At Smokkelhoek (Figure 1, S) the site was first inhabited in the Roman Period. At this time the

 

Holland peat was still being formed. Marine influence increased from the late Roman Period, and transgressions of the Dunkirk phase continued to take place until as late as the 1950s. These transgressions were more severe in this area than in the Harnaschpolder, and a layer of sediment with a thickness of a few metres in places was deposited on top of the peat, again eroding it in places. In the Middle Ages people inhabited the drier parts of the landscape, for example, the former tidal creeks, just as in the Roman Period in Harnaschpolder. Large-scale peat extraction became an important industry. Pits were dug through the layer of Dunkirk sediment in order to reach the peat, which was either used as a fuel, or as a source of salt. By digging into the peat, traces of Roman occupation were erased as well. After the peat extraction, the pits were not backfilled, but left open to be filled in with the sediments of later marine transgressions.

All through the archaeological periods discussed here, houses would have been timber built; stone masonry was not used because it simply was not available, and brick was only introduced in the late Middle Ages. The archaeological record thus mainly consists of in-filled pits and ditches, and of post holes. The fill of the archaeological features generally has a different colour and a different texture compared with the surrounding matrix. On both sites the Roman and Medieval features are contained within the first metre of the matrix. Lacking bedrock and gravels, any magnetic anomaly caused by archaeological features would have to be either the result of differences in soil magnetic susceptibility, or, for features such as hearths and kilns, would have to be of a thermoremanent nature. On the other hand, magnetic anomalies that are caused by changes in geology may be due to differences in magnetic susceptibility, or differences in natural remanent magnetization (NRM).

## Methodology

Magnetometer surveys were carried out at both Harnaschpolder and Smokkelhoek. A Geoscan FM36 Fluxgate Gradiometer was used at a spatial resolution of $0.5 \times 1.0$ metre, and an instrument resolution of 0.1 nT.

Soil samples for magnetic susceptibility measurements were taken by hand-auger. For the top metre a 7 cm Dutch (screw) auger was used and a 3 cm gouge auger for samples deeper than a metre. Soil profiles were described and the remainder of the cores discarded after sampling. Archaeological features in excavation were sampled by pushing sample tubes into the exposed section. These small plastic lidded tubes were also used for storing and transporting the samples. The soil samples were not dried in order to prevent any chemical changes by oxidation, but frozen and measured within 14 days from sampling, using an Agico KLY-2 Kappabridge in the palaeomagnetic laboratory of the Universiteit van Utrecht. The weakly diamagnetic contribution of the sample tubes (ca. $-10 \times 10^{-8}\,\mathrm{m^3\,kg^{-1}}$) was taken into account. A heat-treatment was carried out on a selection of samples from Harnaschpolder in order to obtain fractional conversion values. This set of samples was air-dried, and the samples were crushed with a porcelain mortar and pestle. The magnetic susceptibility of the samples before and after the treatment was measured on an AC magnetic susceptibility bridge in the Department of Archaeological Sciences at the University of Bradford, UK. One gram of plain flour was added to each sample and the samples were placed into porcelain crucibles and covered with a porcelain lid. A Carbolite electric muffle kiln was used and the procedure as described by Clark (1996) was followed. All magnetic susceptibility values are mass specific and expressed as $\mathrm{m^3\,kg^{-1}}$ throughout the paper.

## Results

The most striking magnetic anomalies that were encountered at Harnaschpolder (Figure 2) are two bands of positive anomalies with a smaller negative component, more or less at right angles to each other. Between these two bands smaller linear positive anomalies can be seen. Test trenches that were excavated prior to the magnetometer survey overcut these magnetic anomalies, but no apparent relationship was found between the archaeological features that were excavated and the anomalies. In fact, none

 

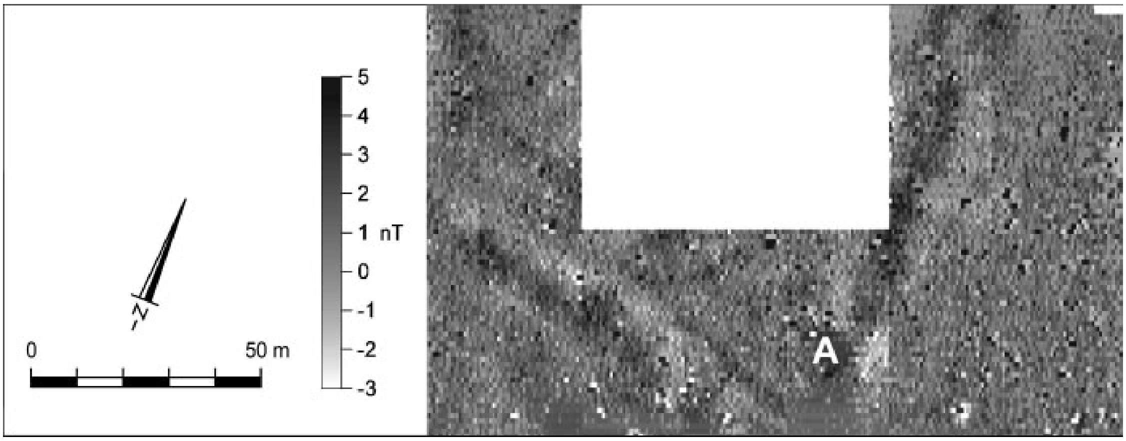


Figure 2. Result of the gradiometer survey at Harnaschpolder with the location of core A.

of the archaeological features that were encountered in the test trenches could be identified by the gradiometer survey.

In de Smokkelhoek (Figure 3) linear and curved positive anomalies occurred in pairs. In the northwestern corner of the area surveyed features seem to be overcutting each other. The only unpaired anomaly, running north–south in the eastern part of the survey, could be identified as a track also visible on the 1832 map of the area. Patches of noise correlate to the field boundaries on the same map and are probably caused by the material in the in-filled ditches. In the centre of the eastern block of survey, faint linear negative anomalies indicate the presence of rims of peat in the subsoil. These are the bands that were left during the peat extraction.

In neither of the sites could any magnetic response of archaeological features be identified. Test trenching (in Harnaschpolder) and hand-augering (in Smokkelhoek) had, however, positively identified archaeological features in the areas surveyed. Soil samples were taken from two excavations directly to the north and the south of the surveyed area in Harnaschpolder. Samples were taken from pits, ditches and a post hole from the Roman Period, as well as from the undisturbed silts and the topsoil. Magnetic susceptibility measurements (Table 1) show that generally the values are very low. There is very little difference between the magnetic susceptibility of the fill of the Roman Period features and the natural material they are embedded in. Values for the topsoil, on the other hand, are higher, and less consistent. In order to assess if the sediments are capable of acquiring higher magnetic susceptibilities, samples were taken at Harnaschpolder for an investigation into the fractional conversion. Sixteen samples were taken using a hand auger so that all sedimentary layers in the profile were represented. Fractional conversion values were calculated as $\chi/\chi_{\max} \times 100\%$, and range from 0.31% to 6.08% with an average of 3.36%. This indicates that the low magnetic susceptibility values encountered are not caused by a lack of Fe; the magnetic susceptibility thus has to be related to the type of iron compounds present in the soil.

Based on their morphology, the large, short wavelength magnetic anomalies encountered in both Harnaschpolder and Smokkelhoek could be identified as geological structures. Their appearance, in particular the ‘loop’ in the Smokkelhoek data, suggests a geological origin, for instance small creeks or gullies. They are most likely to be associated with either one of the two major marine transgression phases.

A transect of borings was carried out at both sites in order to identify the features causing the magnetic anomaly. Each of the cores was sampled for magnetic susceptibility measurements in the laboratory. The stratigraphy of the top 4 m can be simplified to four layers; the silts of the Calais phase at the lower part of the sequence are overlain by Holland peat. The peat, in turn, is covered by the silts and sands of the Dunkirk transgression phase, and in these silts a topsoil has developed. It must be noted

 

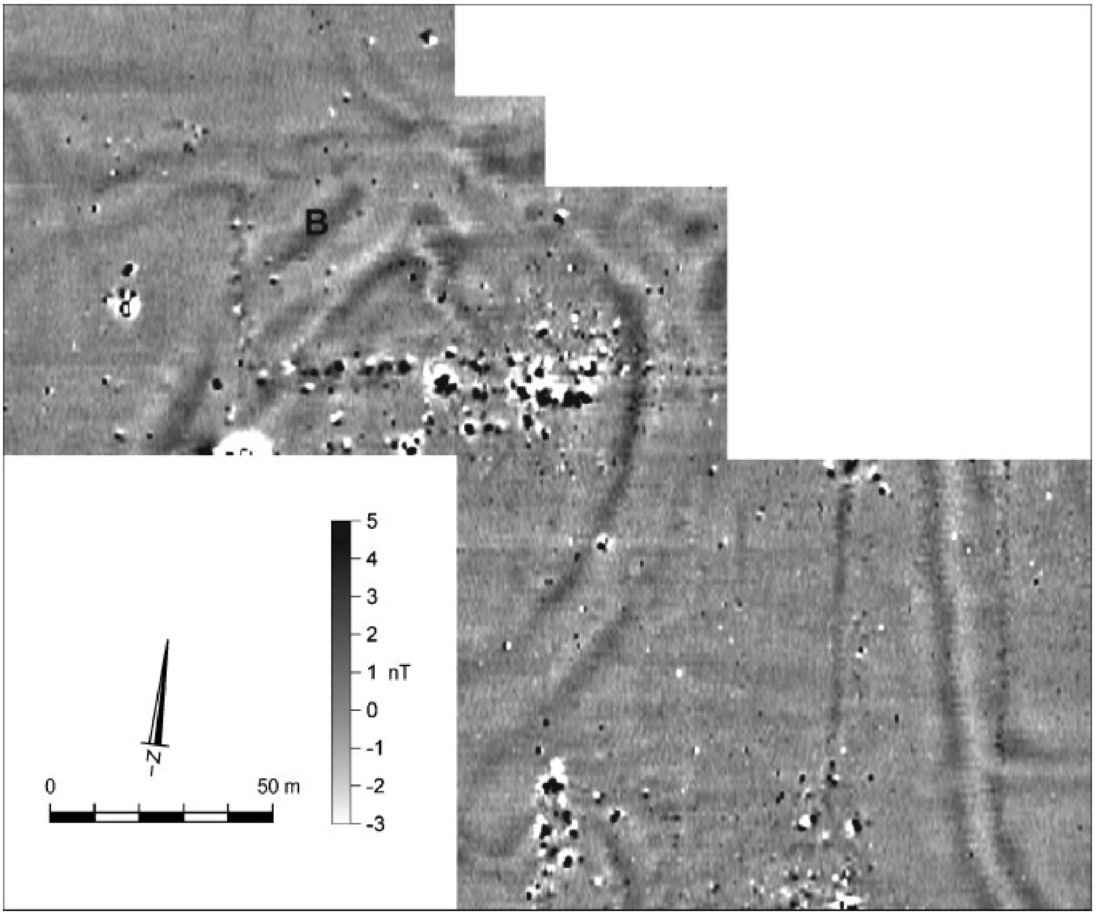


Figure 3. Result of the gradiometer survey at Smokkelhoek with the location of core B.

Table 1. Magnetic susceptibility of soil samples from Harnaschpolder excavations: *N* is the number of samples; SD the standard deviation from the mean magnetic susceptibility

| | *N* | Mean magnetic susceptibility $\times 10^{-8}$ m$^3$ kg$^{-1}$ | SD $\times 10^{-8}$ m$^3$ kg$^{-1}$ | Range $\times 10^{-8}$ m$^3$ kg$^{-1}$ |
|---|---|---|---|---|
| Topsoil | 7 | 31.74 | 17.57 | 13.81–58.85 |
| Archaeological features | 12 | 10.47 | 1.65 | 7.73–12.89 |
| Undisturbed (C) | 6 | 9.63 | 1.54 | 7.61–11.09 |
| All samples | 25 | 16.22 | 13.29 | 7.61–58.85 |

that grey silts with black staining occur locally in sediments of the Calais phase at both sites.

Measurements of the magnetic susceptibility of the sediments in the laboratory showed that the stained Calais silts were at least partly responsible for the magnetic anomalies in the gradiometer survey. A possible contribution of any chemical or detrital remanent magnetism to the anomalies has not been investigated in this study. Table 2 presents the data of two cores, A and B, their location relative to the magnetic anomalies is indicated on Figures 2 and 3. Magnetic susceptibility values of the topsoil and the Dunkirk silts are generally very low. The lack of any clastic material in the peat explains the near-zero magnetic susceptibility values. One slightly

Table 2. Magnetic susceptibility of samples from core A (Harnaschpolder) and core B (Smokkelhoek)

| Core | Depth (cm) | Material | Mass magnetic susceptibility $\times 10^{-8}$ m$^3$ kg$^{-1}$ | Sediment oxidized (O)/reduced (R) |
|---|---|---|---|---|
| A | | | | |
| | 10 | Silt | 13.98 | O |
| | 55 | Silt + Fe | 8.93 | O |
| | 155 | Silty sand + Fe | 7.09 | O |
| | 175 | Silt | 4.64 | R |
| | 210 | Sand | 5.16 | R |
| | 280 | Peat | 0.99 | R |
| | 310 | Silt | 5.30 | R |
| | 315 | Silt | 199.56 | R |
| | 319 | Silt | 980.82 | R |
| B | | | | |
| | 0 | Silty clay | 6.6 | O |
| | 60 | Silty clay + Fe | 5.9 | O |
| | 120 | Peat | 0.9 | O |
| | 140 | Silty clay + humus | 5.0 | R |
| | 180 | Peat | −0.5 | R |
| | 220 | Silty clay | 58.9 | R |
| | 240 | Silty clay | 177.3 | R |
| | 300 | Silty clay | 35.2 | R |

Table 3. Magnetic susceptibility of subsamples from core A (Harnaschpolder) before and after air-drying

| Core | Depth (cm) | Material | Mass magnetic susceptibility before air-drying $\times 10^{-8}$ m$^3$ kg$^{-1}$ | Mass magnetic susceptibility after air-drying $\times 10^{-8}$ m$^3$ kg$^{-1}$ |
|---|---|---|---|---|
| A | | | | |
| | 310 | Silt | 6.02 | 6.02 |
| | 315 | Silt | 200.40 | 30.04 |
| | 319 | Silt | 981.34 | 40.79 |

negative value was caused by the presence of (diamagnetic) water in the samples, which were not dried prior to the measurements. The magnetic susceptibility of the grey layer with black stains in the Calais silts in these two cores is five to 100 times higher than the susceptibility of the Dunkirk silts. This is, however, a local phenomenon. Away from the magnetic anomalies, silts of the Calais phase have susceptibility figures similar to the Dunkirk silts. Microscopic inspection of the black stained soil showed that it contains pyrite crystals. The crystals are concentrated in and around macrofossils present in the soil. The samples were not investigated further, and only the presence of non-framboidal pyrite crystals was confirmed.

Three subsamples of the Harnaschpolder core were measured before and after air-drying (Table 3). The upper sample (310 cm) has the lowest magnetic susceptibility of the three samples, and its susceptibility does not change upon oxidation. The magnetic susceptibility of the two lower samples (315 and 320 cm), however, decreased considerably after air drying. Oxidation of the samples apparently causes changes in the iron mineralogy that are reflected in the magnetic susceptibility of the samples.

## Discussion

The fluxgate gradiometer surveys in Harnaschpolder and Smokkelhoek failed to identify any archaeological features. The data on the magnetic susceptibility of the archaeological features in Harnaschpolder, however limited in the number of samples, suggests that the magnetic contrast between the fill of the archaeological features and the matrix in which they are embedded is negligible. In general the values are very low compared with, for example, values found in the UK (e.g. Dearing *et al*., 1996). A heating experiment, however, showed that the soils could be enhanced magnetically. This indicates that it is not the lack of Fe that suppresses the magnetic susceptibility in Harnaschpolder. Topsoil samples do have a higher magnetic susceptibility, as would be expected, but the values of the samples are not very consistent. This could be due to the presence of inclusions (the samples were not dried and not sieved), or to the fallout from industrial activities in the vicinity of the Harnaschpolder.

Thus, archaeological features were not and possibly could not have been detected in the gradiometer survey in Harnaschpolder. The reason why can only be speculated upon in this stage of the research, and further investigations are required to shed light on the processes explaining this phenomenon. The following section will list some of the possible reasons for the lack of magnetic contrast in Harnaschpolder. These reasons can be split into two groups: either the magnetic contrast between the archaeological features and the natural matrix has never existed, or the contrast did exist but has been reduced over time.

Into the first group falls the impediment of magnetic susceptibility enhancement by waterlogging, and the lack of vertical differentiation of the young soil. According to Weston (2002), waterlogging of a soil can prevent the enhancement of the magnetic susceptibility by heating. Linford and Canti (2001) came to similar conclusions in their experiments. Enhancement of a waterlogged clay soil was achieved by kindling a fire for 1 day and 4 days. The enhancement is concentrated in the top 4 cm of the soil, but causes a clear magnetic anomaly.

The lack of vertical differentiation is common in young sediments. Soil formation processes are hampered by waterlogging of the soil, and because of ongoing marine transgression, the formation of a well-defined A horizon is prevented. In the surroundings of Harnaschpolder, but not in the Harnaschpolder excavations, a vegetation level associated with the Roman Period habitation has been found locally. The appearance of the fill of the archaeological features on the Harnaschpolder excavations suggests that a topsoil with organic material has been present here, but post-Roman marine transgressions have probably eroded or reworked this layer. With the topsoil, the magnetic susceptibility variations contained in it would have been taken away, but this erosion should not have affected the fill of the archaeological features. The contrast between the fill of the archaeological features and the matrix they are embedded in is, however, very small. If the magnetic contrast was larger once, is it possible that it was reduced?

Long-term waterlogging of the soil could reduce or possibly even delete a magnetic enhancement; by continuous waterlogging, ferrimagnetic iron oxides will dissolve, and they can eventually flush out of the soil profile (Thompson and Oldfield, 1986). Short-term waterlogging can cause iron compounds to change into either the ferrimagnetic maghemite, or to the non-ferrimagnetic green rusts or ferric or ferrous hydroxides upon oxidation (Weston, 2002). Fractional conversion values indicate that the soils of Harnaschpolder were not flushed of Fe, but chemical changes induced by waterlogging may have changed the magnetic contrast.

In sharp contrast to the lack of magnetic contrast between the fill of the archaeological features and the undisturbed matrix, strong features of a natural origin were detected in the magnetometer survey. In a magnetometer survey, induced and remanent magnetism cannot be distinguished from one another, and magnetic anomalies may be caused by either of the two, or a combination of both types of magnetization. Although a possible contribution of chemical or detrital remanence was not investigated, it can be inferred from the data that the magnetic anomalies that were encountered in both Harnaschpolder and Smokkelhoek were at least partly caused by bodies of highly magnetic material in the sediments of the Calais phase. Based on their black colour or staining and their geomorphological expression, these deposits are interpreted as anoxic shallow creek fills, in which stagnant water provided continuous reducing conditions. High magnetic susceptibility values also have been recorded just over or under the black layer. Pyrite was visually identified in these layers with the aid of a microscope. Pyrite, however, is paramagnetic, and its magnetic susceptibility of $30 \times 10^{-8}\,m^3\,kg^{-1}$ cannot explain the magnetic anomalies encountered in Smokkelhoek and Harnaschpolder, and other minerals must be responsible.

Although a full discussion falls outside the scope of this paper, a short review of iron sulphide formation and degradation is required to understand the phenomena encountered in this study. It is known that sedimentary iron sulphides occur in marine and perimarine environments (e.g. Luther *et al*., 1982; Rabenhorst, 1990). The formation of these sulphides requires a source of ferrous iron (Fe(II)), a source of sulphur and a reducing environment. Fe (II) is present in sea water, but studies into the cycling of iron in salt marshes suggest that crystalline Fe (III) minerals from the sediment can be dissolved by organic ligands, which makes them available for the formation of iron sulphides (Luther and Kostka, 1992; Kostka and Luther, 1995). Sulphates are abundant in sea water, and they can be reduced by sulphate-reducing bacteria in the process of decomposition of organic matter. Thus iron sulphides can be formed in a reducing estuarine environment in the presence of organic matter. The end product could be one of the monosulphides mackinawite ($FeS_{0.9}$) or greigite ($Fe_3S_4$), pyrrhotite (ca. $Fe_7S_8$), or in fact pyrite ($FeS_2$). Pyrite and mackinawite are paramagnetic, pyrrhotite and greigite, however, are ferrimagnetic, and the presence of either of these two iron sulphides, or a combination, could be responsible for the magnetic anomalies in Harnaschpolder and Smokkelhoek. Greigite oxidizes rapidly on exposure in air, and the data in Table 3 may indeed indicate the presence of greigite in the waterlogged sediment.

In order to fully understand the occurrence of iron minerals in perimarine sedimentary sequences it is essential to know the depositional and the post-depositional processes involved. For both sites, post-depositional processes can de separated into two phases. First, as part of the geological development of the landscape, a phase of drying out and oxidation takes place. After cessation of the marine influence the environment gradually becomes fresher. Lowering local groundwater levels and increasing vegetation lead to better aeration of the soil, oxidizing the iron sulphides to goethite ($\alpha$-FeOOH) or haematite ($\alpha$-$Fe_2O_3$), both paramagnetic minerals, or to ferrimagnetic magnetite ($Fe_3O_4$) (Luther *et al*., 1982). These newly formed iron compounds also occur in the now oxidized zone with archaeological features, and their distribution does not necessarily bear a relation to the distribution of iron compounds before the marine transgression.

The second phase consists in both cases of renewed marine inundation of the landscape. Despite the abundant literature on the subject of sulphide formation, it is as yet unclear what the potential effect of saline waterlogging on the existing iron mineralogy of the soil is. Neo-formation of (primary) iron sulphides is likely to take place, but it can be envisaged that at least part of the iron oxide present will be reduced to sulphides again.

In addition to the high magnetic susceptibility values already identified in this preliminary study, NRM may also have contributed to the magnetic anomalies identified. Evidence for the co-occurrence of high magnetic susceptibility and high NRM has been found in a freshwater environment by Ellis and Brown (1998). It is conceivable that processes similar to those postulated by Ellis and Brown have operated on the sites in the current study as well, but unfortunately the distinction between induced and remanent magnetism cannot be made from magnetometer survey data. Without further study therefore the contribution of NRM remains uncertain.

## Conclusion

This paper has shown that perimarine (salt marsh) or estuarine sediments pose several difficulties in the interpretation of magnetometer surveys carried out for archaeological purposes. Archaeological features may be indistinct or invisible, whereas geological structures may show with unexpected clarity. The reason for the lack of magnetic contrast between archaeological deposits and the undisturbed soil matrix is the topic of further research. Knowledge of the type of iron minerals present at the sites under investigation can lead to the understanding of the processes that hamper the creation of a contrast, or delete an existing contrast in magnetic susceptibility.

Magnetic mineral investigation will also have to clarify whether it is indeed greigite or pyrrothite, or a combination of the two iron sulphide compounds, that is causing the magnetic anomalies encountered on the two sites discussed in this paper. The topic of the possible magnetic remanence of the sediments will also be addressed in further studies.

Marine transgressions can have a great influence on the iron mineralogy of the soil. It is likely that this would have affected iron oxides in the fills of archaeological features. Further research will be carried out on selected samples, in order to reconstruct the magnetic history of the investigated sites.

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