The Application of Magnetic Methods for Dutch Archaeological Resource Management

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6 Wind blown and fluvial deposits

6.1 Wind blown sands

The eastern and southeastern parts of The Netherlands are characterized by the superficial occurrence of Pleistocene aeolian, fluvial and glacial deposits. This section is concerned with the wind-blown sands, which include Late Pleistocene cover sands and Holocene inland dunes. The cover sands constitute approximately 40% of the superficial deposits and are found predominantly on the higher grounds. They were formed in the Weichselian Late Pleniglacial and Late Glacial and have been dated between circa 16,000 and 11,500 BP.

Based on the relief and the underlying deposits, the cover sand area can be divided into the north, the central, the eastern and southern cover sand area.

The cover sands of the *northern sandy area* overlie deposits from the Saalien ice age, extensive boulder clay deposits, which have been pushed up by the land ice in the southern part of the area. The Weichselien cover sand relief follows the Saalien relief, which makes it more pronounced than in the southern cover sand area. A rising ground water table has facilitated the peat formation in the Holocene, starting in the lower parts of the landscapes and in the river valleys, and continuing to include the higher parts. The excavation of peat as a fuel started around 1600, causing the Weichselien cover sand to surface once again in many places. The northern sandy area has not been investigated in this study because of the relative lack of intrusive archaeological investigations taking place, which were needed for the ground truthing of the magnetic data.

The *central sandy area*, of which the site of Den Dolder is an example, is dominated by high ice pushed ridges from the Saalien ice age. The material of these terminal moraines consists of reworked coarse river deposits. The Weichselien cover sands occur in the lower parts of the landscape and on the slopes of these ice pushed ridges. Extensive areas of drifting sand with inland dunes have formed in those areas that lacked sufficient vegetation. A similar situation occurs in the *eastern cover sand area*, but here the ice pushed ridges from the Saalien ice age are lower than in the central area. In this region the sites of Heeten and Raalte have been investigated for this study.

The *southern cover sand area* is the only sandy area that has not been covered by land ice during the glacial periods. The resulting relief of the cover sands is minimal, and consists of low cover sand ridges and shallow valleys. As a whole, the southern Pleistocene sand area dips from the southeast to the northwest. East of the river Meuse, the cover sands are deposited on top of the Pleistocene river terraces. The area is drained by rivers that flow through the valleys that were shaped earlier, during the glacial period. The southern cover sand area is represented by two sites, Breda and Slabroek.

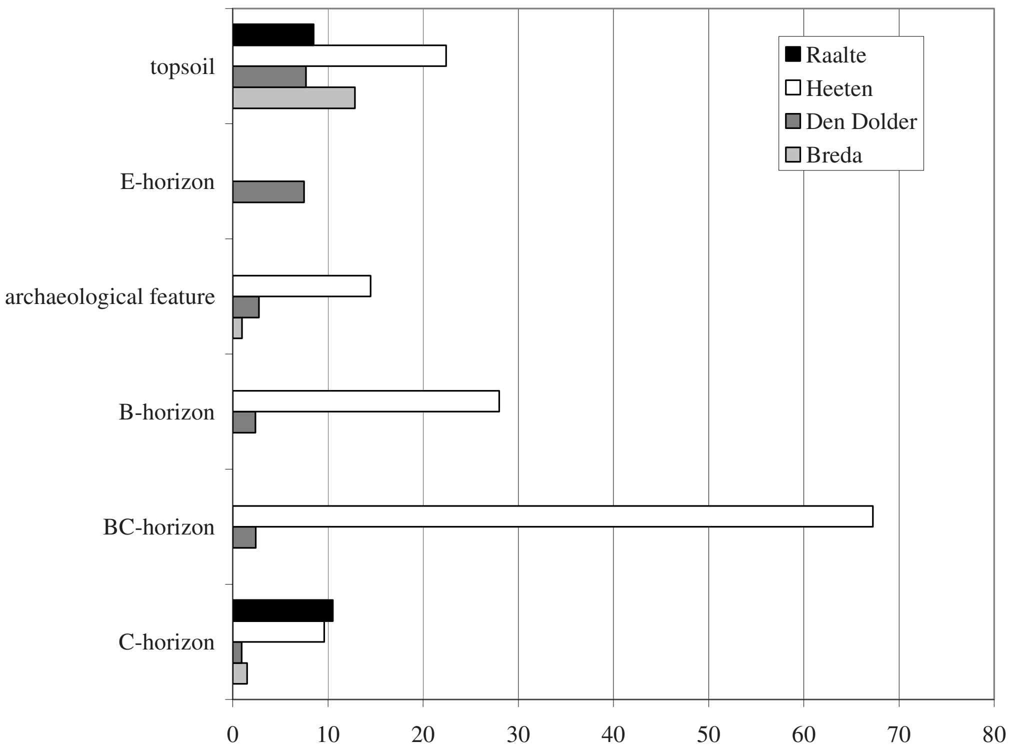
Inland dunes are derived from the finer fraction of the Weichselien cover sands, which makes these blown out deposits younger than the parent material that they originate from. The cover sands, and the inland dune material, is non calcareous. *Coastal dunes* have a fine texture and are calcareous south of the breach in the dune row at Bergen, and non calcareous to the north of it. During this study, no archaeological sites have been investigated on inland dunes, whereas coastal dunes are represented by the site of Limmen.

Soil formation on sandy soils can lead to the development of *podzols*. The type of podzol that has been formed depends mainly on the hydrological situation, and on topography. Starting in the Prehistory, human impact changed the landscape. On the higher grounds the fertility of the sandy soils was insufficient to grow crops, but the topsoil could be excavated to be used elsewhere as plaggen. These plaggen were added to the medium high and lower sandy soils. This way, fertile plaggen soils were constructed, a process that probably started in the Iron Age.

The excavation of plaggen contributed to the instability of the higher grounds by making the higher parts of the landscape prone to wind erosion. This erosion is one of the causes of the formation of inland dune areas.
Because of the age of the cover sands, most of the archaeological remains in the sandy areas can be expected on or just underneath the current land surface. Only Paleolithic archaeological sites are stratigraphically located underneath the cover sands. Moreover, Mesolithic and Neolithic archaeological remains are more likely to be covered by redeposited cover sand material (e.g. drifting sands) than younger archaeological remains. The sites that are included in this study are all of a younger age.

6.1.1 Magnetic susceptibility of the cover sands

Soil samples for magnetic susceptibility measurements were taken at the sites of Raalte, Heeten, Breda and Den Dolder (Fig 31). The samples were initially collected to investigate magnetic susceptibility contrasts on the individual archaeological sites. They do also give an insight, however, to the range of magnetic susceptibility values that may be expected on wind blown sands. The mean values for the soil horizons that were encountered at these sites and for the fill of the archaeological features that were sampled are displayed in Figure 31. Details about the individual sites can be found in Appendix I.
For magnetometer surveys to successfully detect archaeological features, the fill of these features needs to have a different, usually enhanced magnetic susceptibility (see Chapter 3). A high magnetic susceptibility topsoil is an indication of the potential magnetic susceptibility enhancement of the soil.



	C-horizon	BC-horizon	B-horizon	archaeological feature	E-horizon	topsoil
Raalte	10.53 (N=2)	-	-	-	-	8.53 (N=1)
Heeten	9.6 (N=7)	67.25 (N=4)	27.99 (N=7)	14.48 (N=7)		22.43 (N=21)
Den Dolder	0.94 (N=2)	2.42 (N=2)	2.4 (N=2)[1]	2.77 (N=16)	7.48 (N=2)[2]	7.7 (N=3)
Breda	1.51 (N=4)	-	-	0.99 (N=4)	-	12.85 (N=4)

[1] only the samples from the wind blown sand have been included; [2] horizon has been partly mixed with topsoil material by ploughing.

Figure 31 A comparison of the magnetic susceptibility through the soil profile on wind blown sand sites. The value that is displayed is the mean value of the magnetic susceptibility of a number of N samples.

The topsoil samples from Breda and Den Dolder are higher in magnetic susceptibility than the subsoil samples. If features are (partly) filled with topsoil material, and the magnetic susceptibility of the soil profile decreases with depth, the archaeological features can cause a magnetic anomaly. In the soil profile of Den Dolder a magnetic susceptibility decrease with depth can be seen, but the enhancement of magnetic susceptibility of the archaeological feature fills is minimal. The samples from Breda show that a magnetic susceptibility contrast exists between the topsoil - a plaggen soil - and the subsoil, but the archaeological feature fills are not enhanced.
For Raalte and Heeten, the magnetic susceptibility of the soil layers does not appear to decrease with depth. At the Raalte site very few samples have been collected, but the magnetic susceptibility of the subsoil is greater than the topsoil susceptibility. In Heeten, which was sampled much more intensively, both by hand auger and from excavation trenches, the magnetic susceptibility of the B- and the BC-horizon surpasses the topsoil susceptibility, whereas the archaeological features actually have a lower magnetic susceptibility than the topsoil. As a result, the magnetic susceptibility contrast between the archaeological features and the B- and the BC-horizon which they are cut into is negative. The contrast between the fill of the archaeological features and the undisturbed subsoil, however, will be positive. The complexity of this situation is illustrated in Figure 32. There are both positive and negative magnetic contrasts within the same archaeological feature. The shape, size and sign of the resulting magnetic anomaly that is caused by the feature depends on the amount of contrast and the volume of each of the components, and it is not possible to predict from magnetic susceptibility samples only if these contrasts will cause a detectable magnetic anomaly.

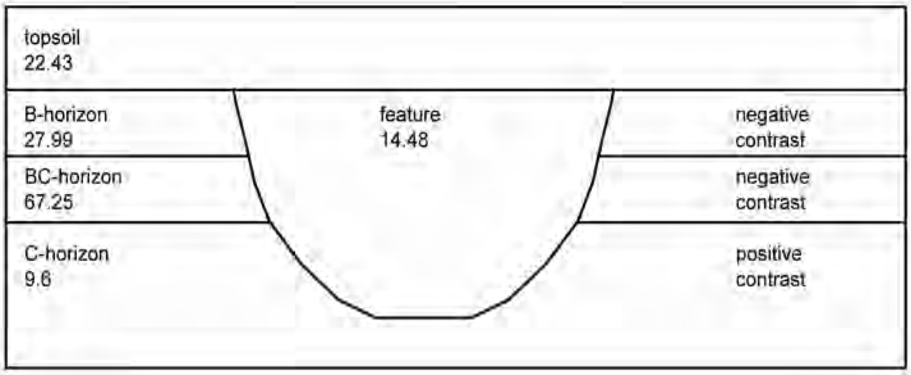


Figure 32 An example of the change of sign in magnetic contrasts for features with a homogeneous fill in a magnetically layered subsoil.

The presence of high magnetic susceptibility subsoil layers can cause problems for the magnetic detection of archaeological features for two reasons, because of the sign reversal of the contrast, as was discussed above, and because of the variability of magnetic susceptibility, which will be discussed below (§ 6.1.5). At this point it is interesting to look into possible causes for the observed lack of magnetic susceptibility enhancement in archaeological feature fills on sandy soil and for the presence of high magnetic susceptibility subsoil layers in Raalte and Heeten.

Why do the archaeological features on sandy soil lack a magnetic susceptibility enhancement?
Difficulties with magnetic prospection on coarse mineral sand have been encountered and investigated by Weston (Weston 1999). Because of the lack of any detectable magnetic contrast that he encountered on the archaeological site of Easingwold, United Kingdom, where in subsequent excavations indications of intense heating on the site were encountered. Laboratory experiments were conducted in order to explain why these high temperature features, or indeed any of the features, could not be detected magnetically. It was found that texture played an important role in the acquisition and the conservation of magnetic susceptibility enhancement (Weston 2004).
Sandy soils achieve their maximum magnetic susceptibility at higher temperatures than finer textured soils. There are two factors that suppress the level of enhancement, staged heating, particularly in sandy soils, and heating under waterlogged conditions in mineral soils.

Heating to lower temperatures will cause any organic matter present to combust, any goethite (the main iron oxide in under temperate humid conditions) will convert into hematite, but a lack of further organic material will prevent the reducing circumstances that would be necessary for the further conversion into magnetite / maghemite.
Experiments on leaching showed that sandy soils are more prone to the loss of iron than fine textured soils, except when they have been ignited, in that case the Fe present in the matrix is more resistant to leaching.

Why do high magnetic susceptibility subsoil layers occur in Raalte and Heeten but not in Breda and Den Dolder?
There is a marked difference between the magnetic susceptibilities from Den Dolder and Breda on the one hand, and Raalte and Heeten on the other. These differences may be caused by the site function, the former two being settlement, burial, and off-site sites, and the latter two being iron production sites. It is possible that a magnetic susceptibility enhancement of the undisturbed soil layers has occurred because of the repeated high temperature activities that have taken place on the soil surface. An indication that this process has taken place is the magnetic enhancement of the B- and BC-horizon. There horizons contain much iron, but as was seen in Chapter 3, the iron oxides usually occur as ferrihydrites, with a low magnetic susceptibility. Transformation through dehydroxylation can change ferrihydryte into hematite or via goethite into maghemite, resulting in a higher magnetic susceptibility.

6.1.2 Magnetic anomalies in the cover sands
Very few magnetic anomalies that were mapped on the sandy soil sites can be attributed to archaeological features. In Breda and Slabroek, no archaeologically relevant interpretation could be made of the magnetometer data (see Appendix I, 6 and 20). In Heeten, a late Roman Period metal production site, two types of archaeological features had a magnetic response; furnaces and large rubbish pits. In Den Dolder and Raalte no magnetometer surveys were carried out.
The results of the magnetometer surveys in Heeten and a comparison with the excavation data are displayed in Figure 33. The furnaces, marked with a star, cause strong, irregular magnetic anomalies. The positive and negative component of the magnetic anomaly are oriented randomly, which is an indication that the anomaly is caused by remanent magnetism. The shape and size of this type of anomaly is independent of the type of geology that is surveyed. Further details about the furnaces can be found in § 7.4. The anomalies that are caused by rubbish pits are shown with arrows in the magnetic plot. They consist of a positive anomaly with a small negative component. It is likely that these anomalies are caused by induced magnetization in features with a magnetic susceptibility contrast between the fill of the feature and the matrix. It is remarkable that the furnaces and these two pits are the only apparent archaeological features in the magnetometer data. As was discussed above, the fills of the archaeological features that were sampled for magnetic susceptibility measurements had a lower magnetic susceptibility than the matrix they were embedded in, but there are no negative anomalies that reflect the presence of archaeological features in the data. The anomalies may have been 'cancelled out' because of differences in magnetic susceptibility in the subsoil, as was illustrated in Figure 32.
If the non-archaeological soil is assumed to be a homogeneous medium, however, whether or not a feature can be detected in a magnetometer survey depends on the strength of the magnetic contrast, the volume of the archaeological feature and the depth of burial. A combination of these three variables may explain lack of detectable magnetic anomalies in terms of strength and size, but the visual detection of the anomalies may also have been hampered by the variability of the magnetic susceptibility within the soil layers, either in the topsoil or subsoil. In the following paragraphs both masking (increase of depth) and variability are discussed.

6.1.3 Masking
Masking takes place when the archaeological record is covered by a later deposition of soil material. In the sandy area, there are two main types of masking material, plaggen and wind blown sand deposits (inland dunes).

If the post archaeological deposit is assumed to be a homogeneous layer, the only influence of the addition of such a layer on a magnetometer survey is that the distance between the archaeological record and the surface is increased. Any magnetic anomalies are further away from the magnetometer, resulting in a weaker anomaly strength (see § 3.9.2). Figure 34 shows an example of the decrease of the anomaly strength with distance to the magnetometer.

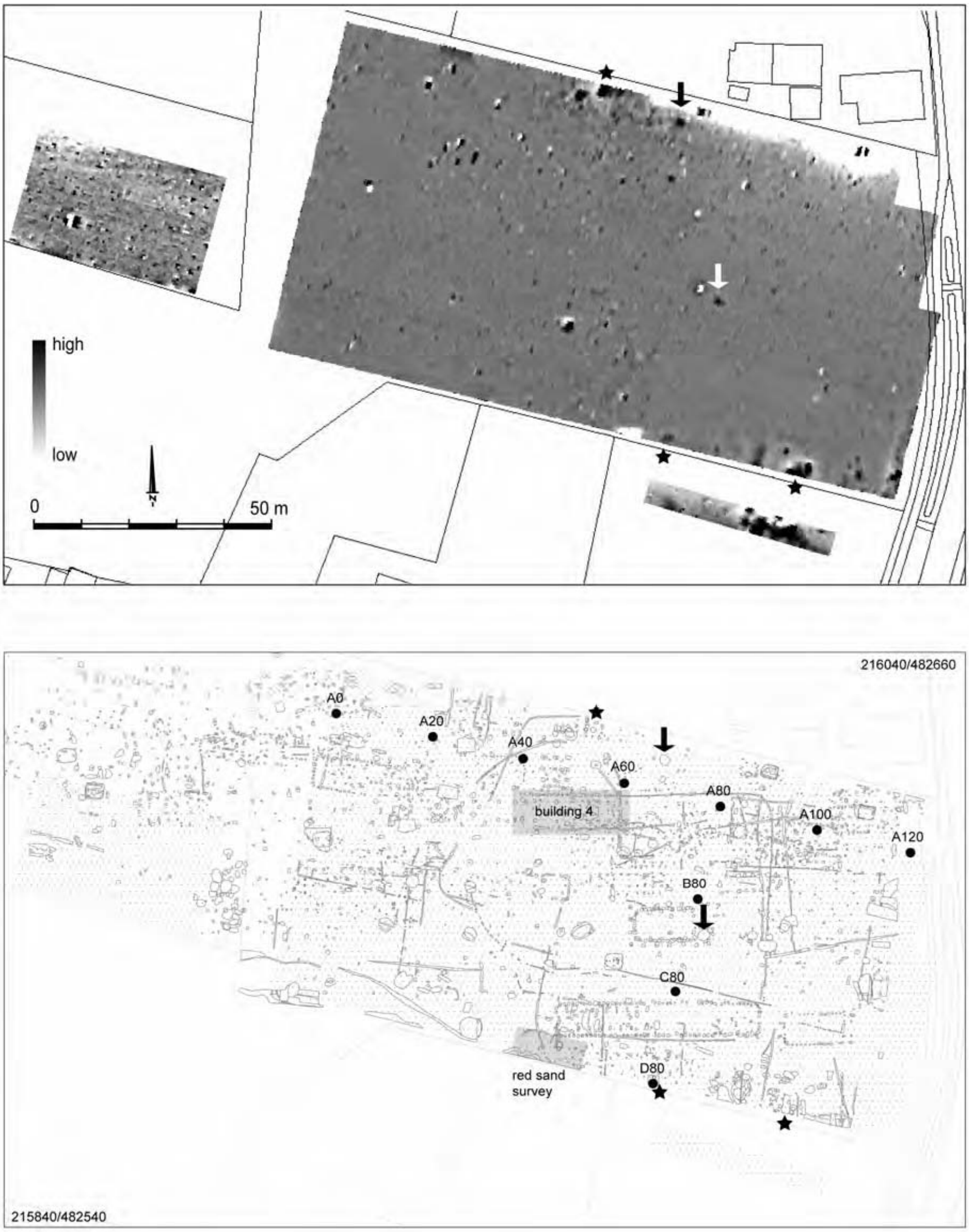


Figure 33 The results of the magnetometer survey (top) and the excavations (bottom) in Heeten. Furnaces that were detected magnetically are indicated with a star, two rubbish pits that have caused a magnetic anomaly with an arrow.

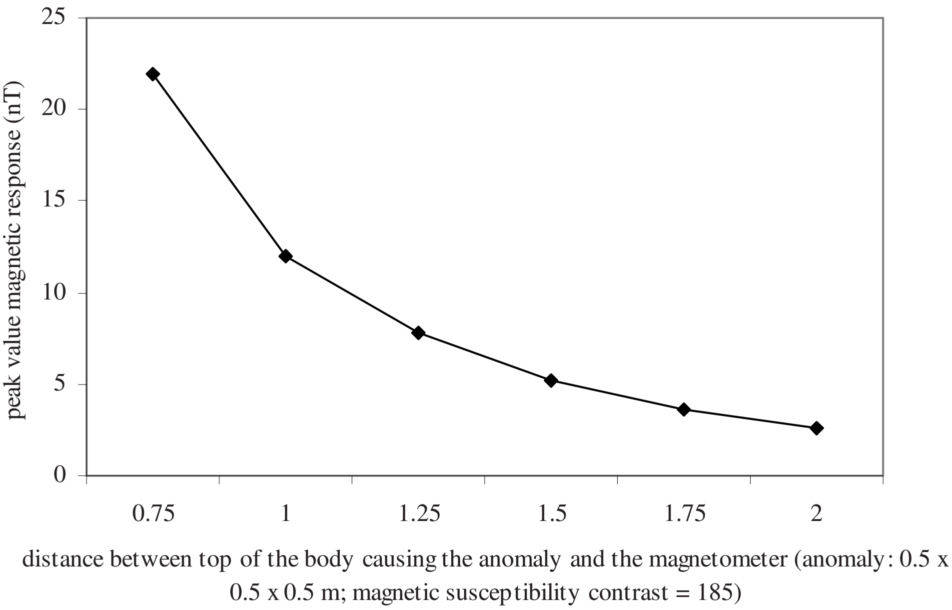


Figure 34 The peak value strength of the magnetic anomaly decreases when the distance between the object and the magnetometer is increased.

6.1.4 Variability

The deposits masking the archaeological layers are rarely magnetically homogeneous. The material that makes up a plaggen soil, for example, has often been mixed with household waste. Inclusions like brick and small metal objects cause remanent magnetic variations that do not reflect the archaeological record. Moreover, variations in the magnetic susceptibility within the post archaeological layer can cause induced magnetic anomalies that may resemble archaeologically caused anomalies. If this remanent or induced magnetic variation is expressed at the surface in a similar way as the magnetic variation that is caused by an archaeological feature, an archaeological magnetic anomaly may be present, but it may not be recognized as such. The variation in magnetic susceptibility values that were measured in Heeten are displayed in Figure 35.

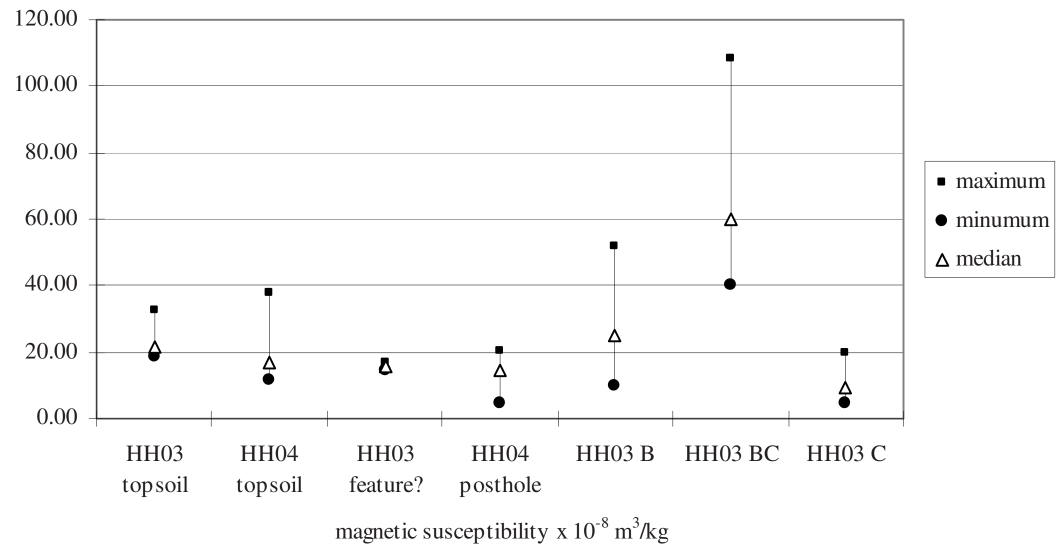


Figure 35 Minimum, maximum and median magnetic susceptibility for the topsoil, B-, BC- and C-horizon and that archaeological features that were sampled. HH03 samples were collected in the 2003 season by hand auger, HH04 samples have been taken directly from the excavation in 2004.

It is clear from the data that in Heeten there is a contrast between for example the median magnetic susceptibility of the archaeological features and the B- and BC-horizon, but the variations within the B- and BC-horizon are much larger. The variation in these subsoil layers may cause non-archaeological magnetic anomalies. The magnetic susceptibility variation in the plaggen soil (topsoil), however, is smaller, but may still cause anomalies because the magnetometer reading is more influenced by the topsoil layer than the archaeological layer.
Any possible magnetic susceptibility variation in the C-horizon in Heeten is not reflected by the samples that are displayed in Figure 35, that were taken by hand auger before the excavation. During the excavation in Raalte another possible cause of magnetic variation was encountered as the C-horizon appeared to have obtained an orange-red colour in places (Fig. 36), the colouring occurs in patches. During the excavation in Heeten the red sand was encountered here as well. This hydrological phenomena is known to occur on sandy soils in the central and eastern sandy area; Bakker & Rogaar (1993) have explained it to be caused by the local abundance of hematite and magnetite in the soil matrix. The bright orange-red colour of the sand supports the explanation of the presence of hematite. The authors suggest that these iron minerals have been transported through effluent seepage.

Figure 36 Excavation trench in Raalte. Patches of red sand (grey in picture) can be seen in the foreground. Darker patches in the background are archaeological features.

The results of initial, limited magnetic susceptibility measurements that were carried out within the framework of this study, suggested that the red sand at Raalte had a higher magnetic susceptibility than the 'non coloured', yellow sand (Appendix I, 19). A more detailed investigation into the magnetic susceptibility of the patches of red sand could be conducted at Heeten Hordelman, where similar red sand patches had come to light during the excavations. An area that included red sand, non coloured sand and archaeological features was sampled for magnetic susceptibility measurements. The samples were taken in a one meter grid from the bottom of the excavation trench (top of the C-horizon). The results of the measurements have been displayed as a plan in Figure 37. In the western half of the survey, the archaeological features have enhanced magnetic susceptibilities, in the eastern half the red sand area can also be defined by higher magnetic susceptibility values. The magnetic susceptibility in the fills of the archaeological features in this example is higher than the red sand for two of the archaeological features, similar for two others and lower for the fifth feature. It has to be kept in mind that the plot only represents the superficial magnetic susceptibility values of the top of the C-horizon.

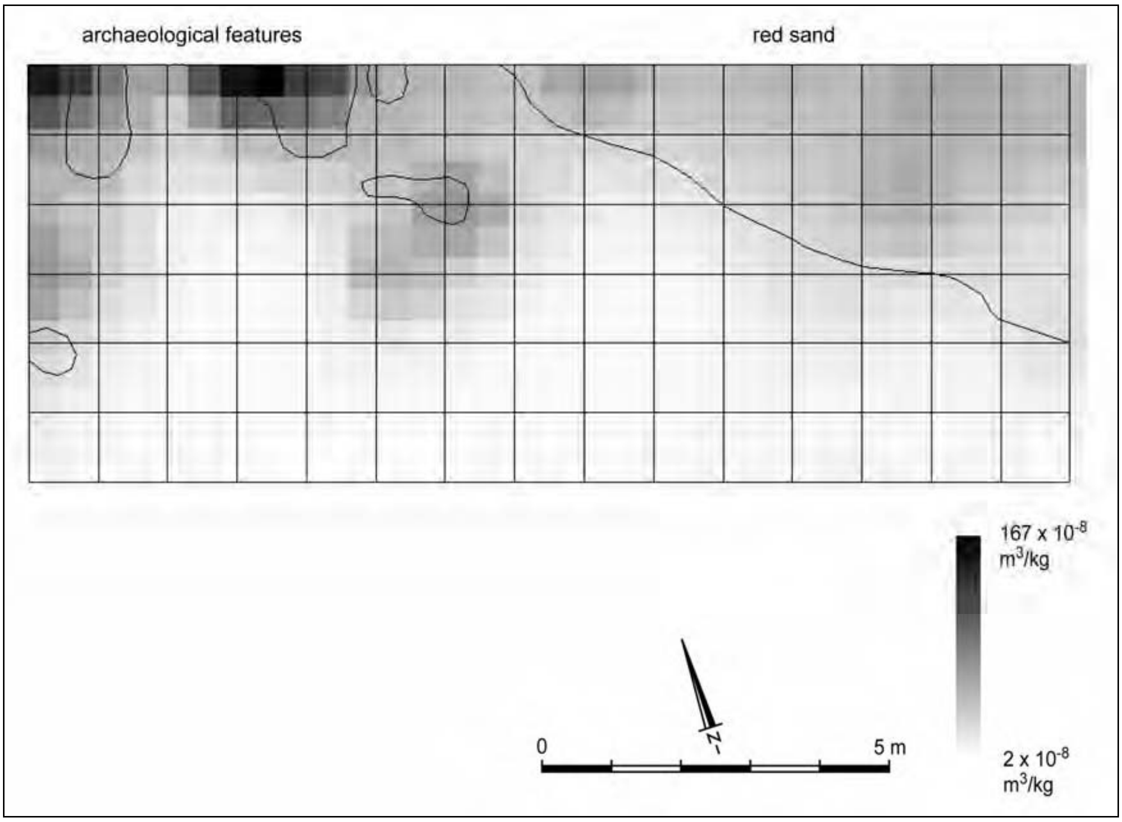


Figure 37 Magnetic susceptibility survey in an excavation trench in Heeten. See the plan in Figure 33 for the location of this survey. Soil samples were collected at the grid intersections and measured for magnetic susceptibility in the laboratory. Five archaeological features are included in the western half of the grid, the red sand patch is located in the eastern half. Both the archaeological features and the red sand have an enhanced magnetic susceptibility.

The strength of the magnetic anomalies that may be caused depends not only on the magnetic susceptibility contrast, but also on the volume of the bodies that cause them. It is clear to see, however, that the range of magnetic susceptibility values of the archaeological feature fills and the red sand is similar. This may cause problems with false positives, and it may also make magnetic anomalies that are caused by induced magnetization of archaeological features less easy to define.

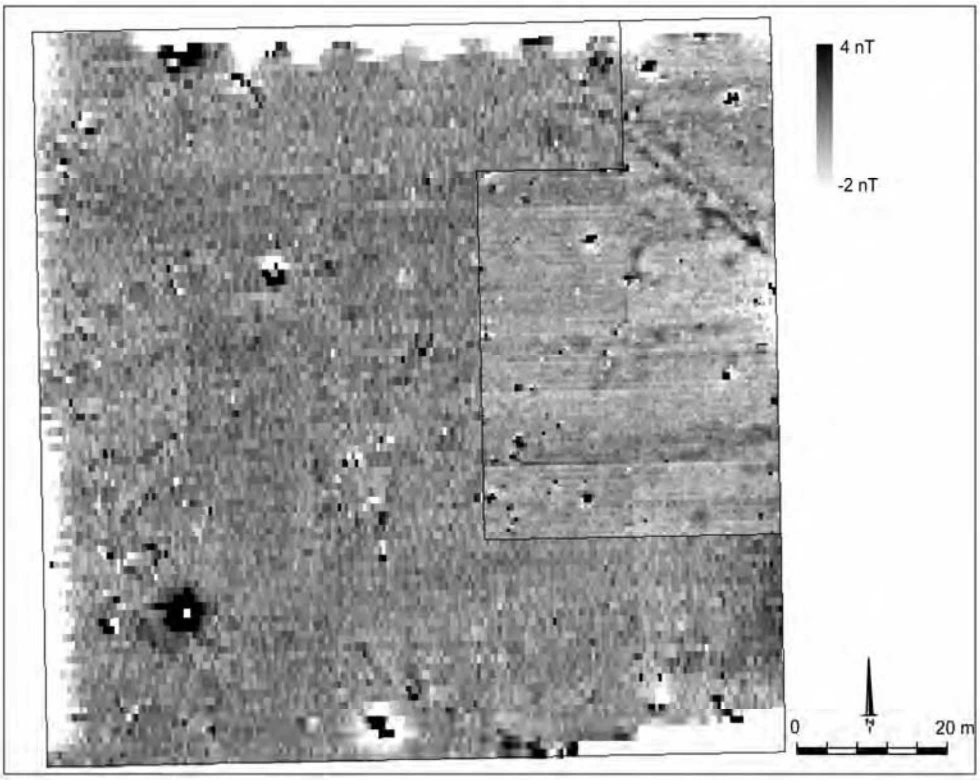
6.1.5 Magnetic susceptibility of coastal dunes

At the excavation of the Medieval settlement of Limmen, samples could be collected from natural and archaeological contexts in coastal dune sands. It can be observed that there is a clear differentiation in magnetic susceptibility between the topsoil, the subsoil and archaeological features (Table 16). The magnetic susceptibility of the undisturbed matrix is low, and comparable to the susceptibility of marine clastic sediments. The archaeological features generally have a positive magnetic contrast compared to the matrix that they are embedded in and they can be expected to cause positive magnetic anomalies. The magnetic susceptibility of the topsoil is higher than the subsoil susceptibility and varies in the same range as the values for the archaeological features, which could cause problems with masking and variability (see § 6.1.3 and § 6.1.4).

Table 16 The results of the magnetic susceptibility measurements on the samples taken from the excavation at Limmen. All values x 10^{-8} m^3/kg. N is the number of samples. For details see Appendix I, 12.

	maximum	minumum	median	mean	N
topsoil	18.90	11.43	14.72	15.15	7
archaeological feature	84.13	4.84	13.39	17.15	42
undisturbed	8.15	4.68	6.06	6.31	9

One set of features proved to have a much higher magnetic susceptibility, in the fill of two ditches that defined the course of the Medieval road, values over 200 x 10^{-8} m^3/kg were measured. The reason for this enhancement is unknown.



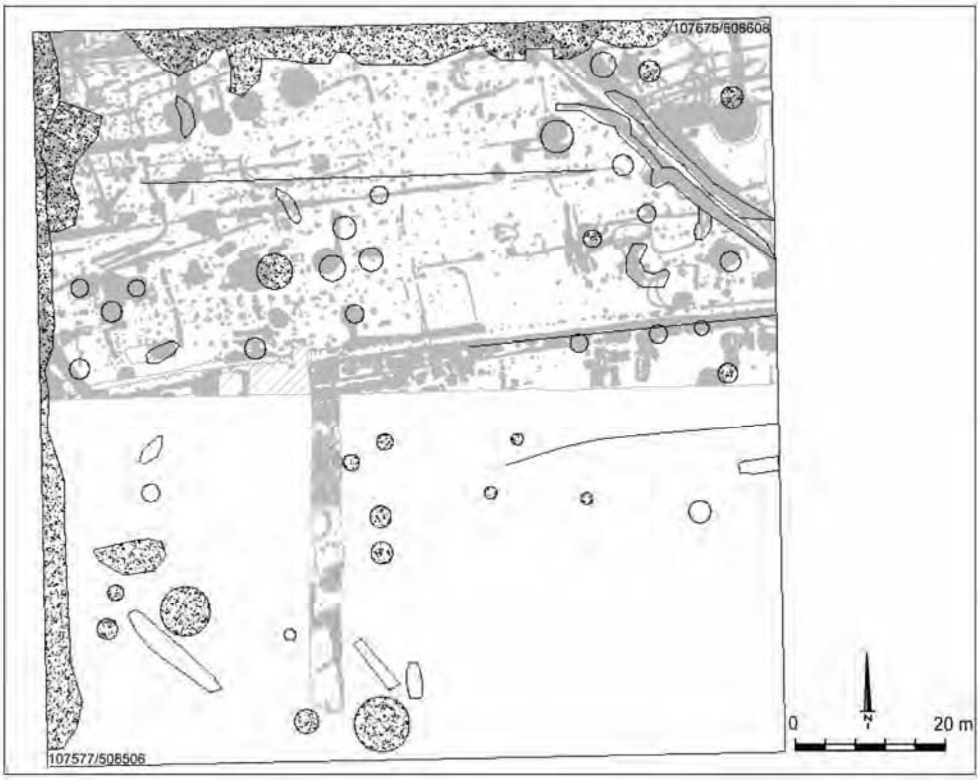


Figure 38 The results of the magnetometer survey at Limmen (top) and the interpretation diagram in black (bottom) as an overlay over the results of the excavation (grey). Magnetic anomalies that have been caused by metal objects have been hatched in the interpretation diagram.

6.1.6 Magnetic anomalies in coastal dunes

The difference in response between the generally slightly enhanced archaeological features and the strongly enhanced road side ditches in the magnetometer survey can be seen in Figure 38 and 39. The ditches show clearly as parallel linear anomalies, whereas most of the other archaeological features do not cause a detectable magnetic anomaly. Most of the anomalies that were mapped, on the other hand, represent archaeological features, almost all of which are wells. It is not clear which part of the well or well fill causes the magnetic anomaly. Most of the wells that were detected are constructed with plaggen, rich in organic material, the presence of which is a prerequisite for the enhancement of magnetic susceptibility. The primary fill of the wells is usually also high in organic material content, whereas the secondary fill usually is not, samples from the upper fill of one of the wells confirmed that these non organic deposits had a low magnetic susceptibility (see Appendix I, 12 for details). It is likely that the anomalies that are caused by the wells must be attributed to a combination of the high magnetic susceptibility construction material or primary fill and the large volume of the high magnetic susceptibility body, if compared to for example a pit or a ditch on the same settlement site.
General conclusions about the possibilities for magnetic prospection on coastal dunes can not be made as only one archaeological site has been surveyed on this geological background. For this one site, however, a general pattern of magnetic enhancement of the fill of archaeological features could be seen. Some of these features caused anomalies that were detectable with the instrument that was used. The use of a more sensitive instrument would probably have mapped more anomalies that were related to the archaeological record.

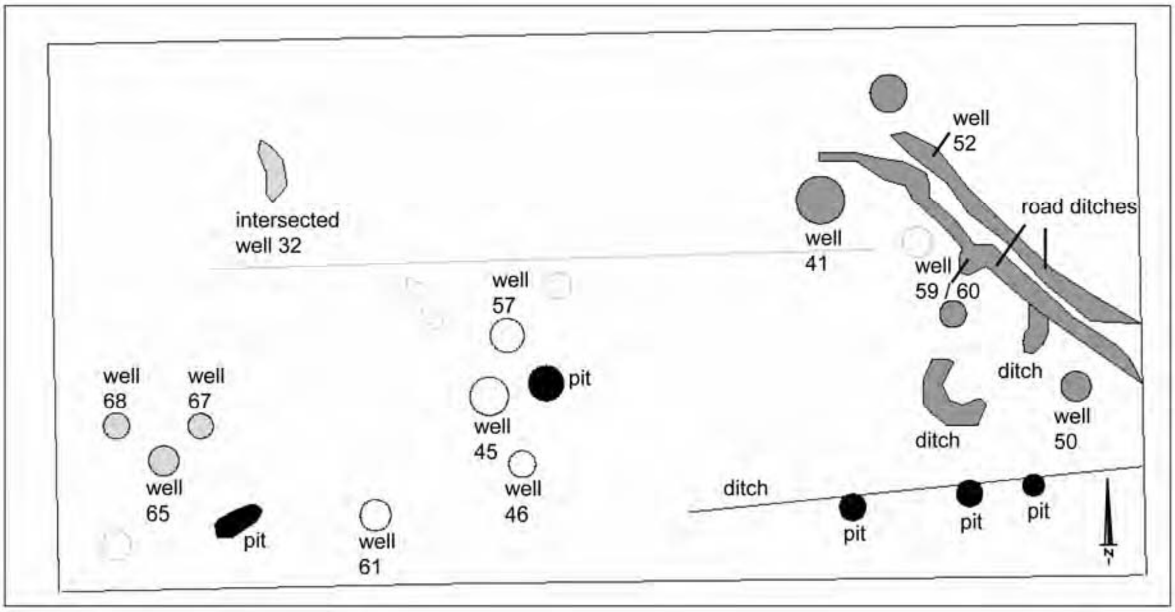


Figure 39 A summary of the non-remanent magnetic anomalies that were identified and their relation to the archaeological record. Only the northern (excavated) half of the interpretation diagram in Figure 38 is shown. Anomalies that did not prove to be caused by an archaeological feature: grey line (no fill); early period (800-1000 AD): black line (no fill); middle period (1000-1150 AD): light grey fill; late period (1150-1250 AD): dark grey fill; post settlement: black fill. See Appendix I, 12 for details.

6.2 Loess

Like the cover sands, the superficial deposits of *loess* in the southeast of the country have been deposited around 10.000 BC, the late-Weichsel period. They cover an older (Saalien) loess deposit. The Dutch loess area lies at the northwestern edge of the much larger Belgian-Germanic loess region. The relief in the Dutch loess deposits is mainly determined by the underlying terraces of the river Meuse and by the tectonic breaks in the area. Only one archaeological site has been investigated on loess in this study, a Roman villa in Meerssen.

6.2.1 *Magnetic susceptibility*

The limited amount of work that has been done on loess shows promising results. A selection of the results of the measurement of magnetic susceptibility samples that were collected during the excavation of the Roman villa at Meersen is shown in Figure 40. Although limited in number, the samples show a clear magnetic contrast between the undisturbed matrix and the fill of the archaeo-logical features. A similar contrast can be seen between the undisturbed matrix and the samples that were collected from the fill of a modern ditch, these samples have magnetic susceptibilities of 29.2 and 30.67 x 10^{-8} m^3/kg (not displayed in Fig. 40).

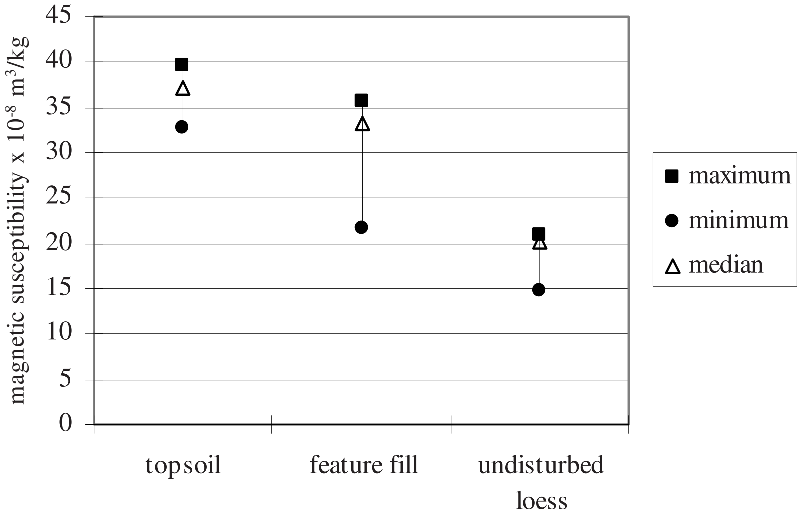


Figure 40 The minimum, maximum and medial magnetic susceptibility of samples from Meerssen. Note the limited number of samples: topsoil N = 3, feature fill N = 4, undisturbed loess N = 3.

6.2.2 *Magnetic anomalies*

The magnetic contrast that was observed in the samples is a prerequisite for the formation of induced magnetic anomalies. Nevertheless, when the interpretation of the magnetometer survey at Meerssen is compared to the results of the trial trenches (Fig. 41), only very few of the archaeological features have given a magnetic response. These include remanent magnetic features and two anomalies that are likely to be caused by buried limestone walls, anomalies which are not caused by magnetic susceptibility enhancement. Two pits and a modern ditch are represented by induced magnetic anomalies. It is interesting to speculate why these features do and the remaining features do not cause detectable magnetic anomalies. The fill of the modern ditch has a magnetic susceptibility comparable to the feature fills that were sampled in trench 1 (the western trench), the ditch has a greater volume and causes an anomaly, whereas the much smaller pits do not. During the trial trenching it was observed that the top level of the archaeological remains had been destroyed, for example, the foundation trenches were the only remnants of the Roman building. The shape and size of a magnetic anomaly is influenced by the amount of magnetic contrast and the volume of the body causing the anomaly. The way the anomaly is recorded also depends on the distance between the body and the magnetometer.

Based on the limited evidence that was collected, there appears to be a magnetic contrast between the fill of the features and the loess matrix that they are embedded in. It is likely that magnetic anomalies have been caused by the archaeological features, but most of these could not be mapped at the surface in the magnetometer survey. The combination of the amount of magnetic contrast, the volume of the features and the depth of burial has been detrimental to the detection of the anomalies at surface level. Magnetic mapping at less damaged sites on loess geology would probably be more successful. It is possible that a more sensitive magnetometer would have mapped a greater amount of archaeologically relevant anomalies.

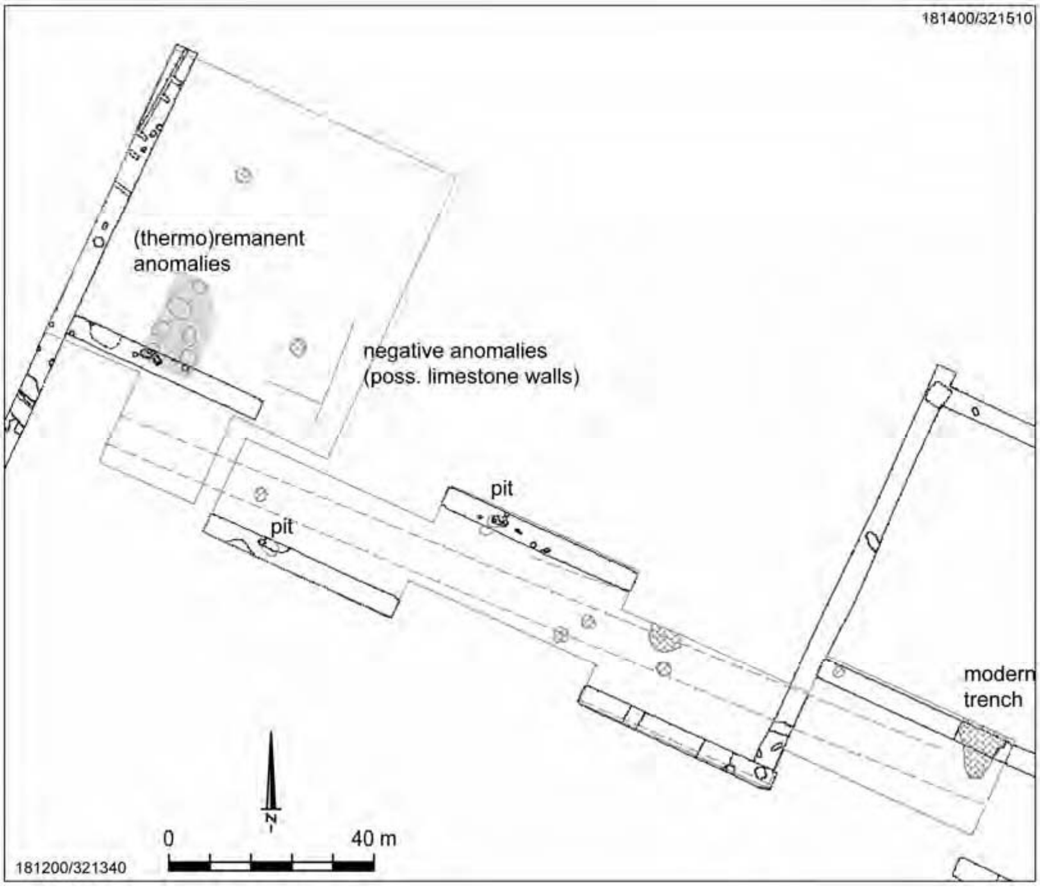


Figure 41 The interpretation of the results of the magnetometer survey (in grey) combined with the trial trench results (in black) at the Meerssen Roman villa site. For more details of the survey and the magnetometer data refer to Appendix I, 13.

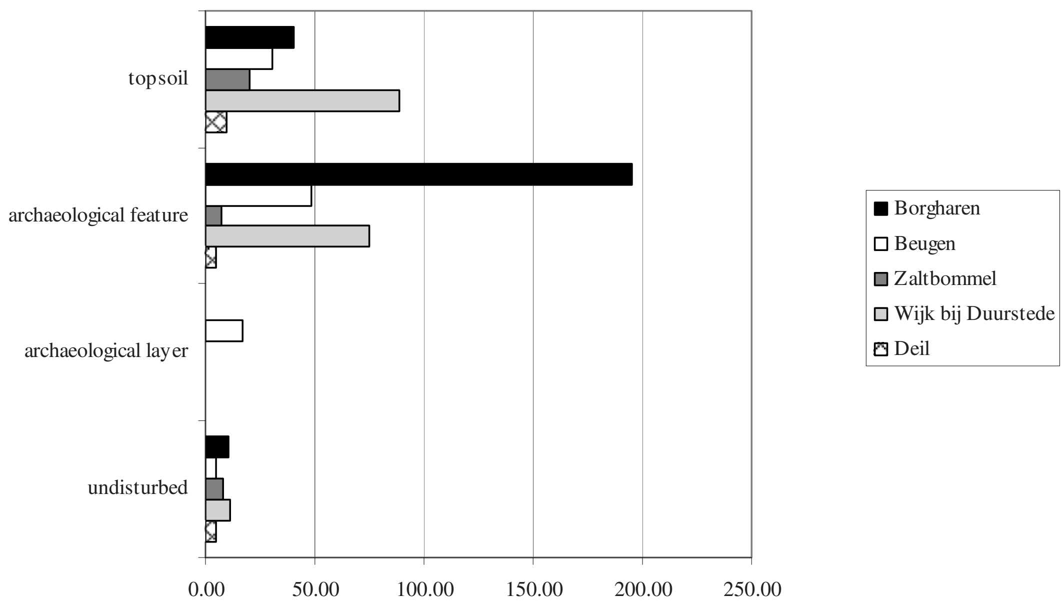
6.3 Fluvial deposits

The extent of the river area in The Netherlands is defined by the presence of Pleistocene and Holocene deposits of the rivers Rhine and the Meuse. It consists of a *central river area*, west of the line Arnhem-Nijmegen, *the valley of the river IJssel*, and the *valley of the river Meuse* in the southern part of the country. West of the line Utrecht-Den Bosch lies the *perimarine* part of the river area.
In the *central river area* Holocene deposits overlay Pleistocene deposits. Geomorphologically the area is dominated by natural levees of a calcareous nature, with coarse material in the subsoil, and by backswamps, which, because of their slow sedimentation rate, consist of material of a fine soil fraction, clay and silt. Four archaeological sites were investigated in the central river area in the course of this study; Deil, Meteren, Wijk bij Duurstede and Zaltbommel. The soil material on these sites is calcareous clayey silt and silty clay.
In the *IJssel valley* the Holocene deposits are much thinner than in the central river area. The IJssel valley has not been represented by any archaeological sites in this research. Neither has the *perimarine* area, in this westernmost part of the river area. Here, the sedimentation of the rivers and peat formation has depended largely on sea level changes.
In the *Meuse valley* the Holocene deposits are concentrated in the river valley, whereas the higher terraces that surround the valley have been deposited in the Pleistocene era. The Meuse deposits are and have been non-calcareous. Two archaeological sites were investigated in the Meuse valley; Beugen en Borgharen. In a previous study (Anderson, not published) a magnetometer survey was conducted in Gennep, also in the Meuse valley.

6.3.1 *Magnetic susceptibility*

In Figure 42 the mean magnetic susceptibility of the soil samples that were collected on sites on fluvial geology is compared. The first observation that can made is that the values for the undisturbed subsoil are all low, and topsoil values are much higher. A good magnetic susceptibility contrast between topsoil and subsoil can be an indication of the suitability of a site for a magnetometer survey, because it is an indication that the sediment can be magnetically enhanced. Moreover, if a topsoil with an enhanced magnetic susceptibility is present now, it may also have existed during past habitation. Negative archaeological features can be (partly) filled with topsoil material, the topsoil-subsoil contrast is extended to the feature fill-subsoil contrast, a contrast which may result in induced magnetic anomalies under the influence of the earth's magnetic field.

The topsoil-subsoil contrast gives an indication of a possible magnetic contrast between the fill of archaeological features and the subsoil. Looking at the magnetic susceptibility of the samples from archaeological features it is clear that this contrast is indeed present in three out of the five sites that have been investigated on fluvial geology in this study. In Borgharen and Beugen the magnetic susceptibility of the feature fills is actually higher than the topsoil values. This is illustrated in Figure 43, which displays a section through an archaeological layer or feature in Beugen. One of the features in Borgharen (feature 253 in trench 11, see Appendix I, 7 for details) has a magnetic contrast with the matrix surrounding it of 182-15 = 167 x 10^{-8} m^3/kg. A pit that measures 0.5 x 0.5 x 0.5 meter and is buried at a depth of 0.5 meter would give a magnetic anomaly with a peak of 12.4 nT, which would be easily recognized in the results of the fluxgate gradiometer that was used during this project. Based on the magnetic susceptibility measurements, both of the sites that have been investigated in the Meuse valley have a good potential for a magnetometer survey.



	undisturbed	archaeological layer	archaeological feature	topsoil
central river area				
Deil	4.7 (N=3)	-	4.6 (N=2)	9.6 (N=3)
Wijk bij Duurstede	11.0 (N=2)	-	75.0 (N=3)	88.7 (N=3)
Zaltbommel	8.0 (N=5)	-	7.3 (N=12)[1]	20.3 (N=5)
Meuse valley				
Beugen[2]	4.44 (N=12)	16.74 (N=8)	48.58 (N=9)	30.64 (N=12)
Borgharen	10.5 (N=6)	-	195.2 (N=3)[3]	40.0 (N=4)

[1] the anomalous sample with a magnetic susceptibility of 119.5 x 10^{-8} m^3/kg has been excluded; [2] samples from the prehistoric site only; [3] samples from high temperature features have been excluded.

Figure 42 A comparison of the magnetic susceptibility of the subsoil, archaeological layer and archaeological feature fills and the topsoil on fluvial sites. The value that is displayed is the mean value of the magnetic susceptibility x 10^{-8} m^3/kg of a number of N samples.

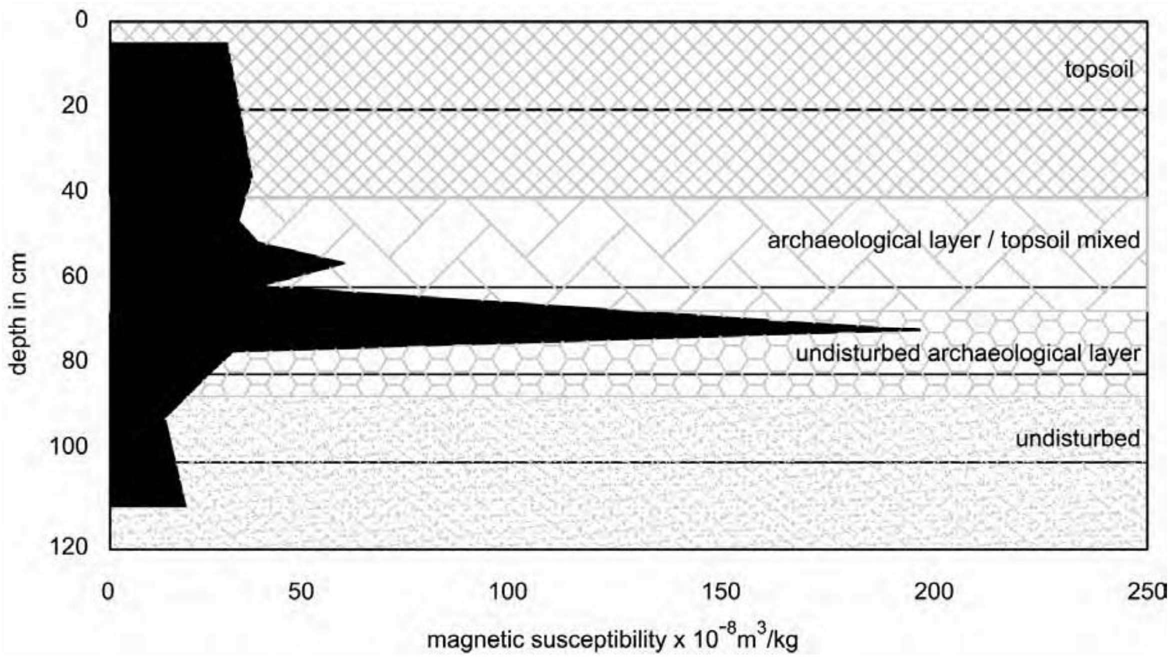


Figure 43 The downcore magnetic susceptibility of feature X1 of the Beugen-Zuid survey. Samples have been taken by hand auger (see Appendix III for full data). High magnetic susceptibility values are associated with the undisturbed archaeological level, the archaeological deposits that were plough damaged have medium high magnetic susceptibility values.

In Wijk bij Duurstede the samples show a good contrast between the fill of archaeological features and the matrix that they are embedded in, but topsoil samples have an even higher magnetic susceptibility. Based on the magnetic susceptibility contrast this site may be suitable for a magnetometer survey. In Zaltbommel and Deil no such contrast could be observed in the samples that were collected here, which makes it less likely that these sites in the Central river area can be mapped magnetically.

6.3.2 Magnetic anomalies

For the Meuse valley sites of Beugen en Borgharen, the contrast that could already be observed in the magnetic susceptibility samples (§ 6.3.1) is reflected in the results of the magnetometer surveys on these sites. In Figure 44 the results of the survey in Beugen and in Figure 45 of the survey in Borgharen are displayed.

On both archaeological sites, part of the archaeological features present in the subsoil caused a magnetic anomaly that could be detected in the fluxgate gradiometer survey. In Beugen, pits and ditches could be magnetically detected. Looking at the feature density in the areas that were excavated around the magnetometer survey, it is unlikely that all archaeological features that are present have been magnetically mapped. Further intrusive investigations can possibly clarify why certain features do and others do not cause a detectable magnetic anomaly. In Borgharen, archaeological features from different periods are interpreted to have caused a magnetic anomaly, building remains from the Roman Period, early Medieval graves and a number of pits of undetermined age. Another interesting aspect of this survey is the clear plough marks in the magnetometer data, these are an indication of the contrast that exists between the topsoil and the undisturbed subsoil.

A dataset that has not been displayed was collected by Anderson in Gennep (Anderson, not published). A small Fluxgate gradiometer (FM18) survey of 20 x 40 meter was conducted over part of a $4^{th}/5^{th}$ century settlement on sandy Meuse deposits. The results of the magnetometer survey showed a number of linear and non-linear anomalies, which could - in the excavation after the survey- be interpreted as three ditches, two rubbish pits and a furnace. There were two false positives in the data, but an overall good correlation between the archaeological record that was excavated and the results of the magnetometer survey.

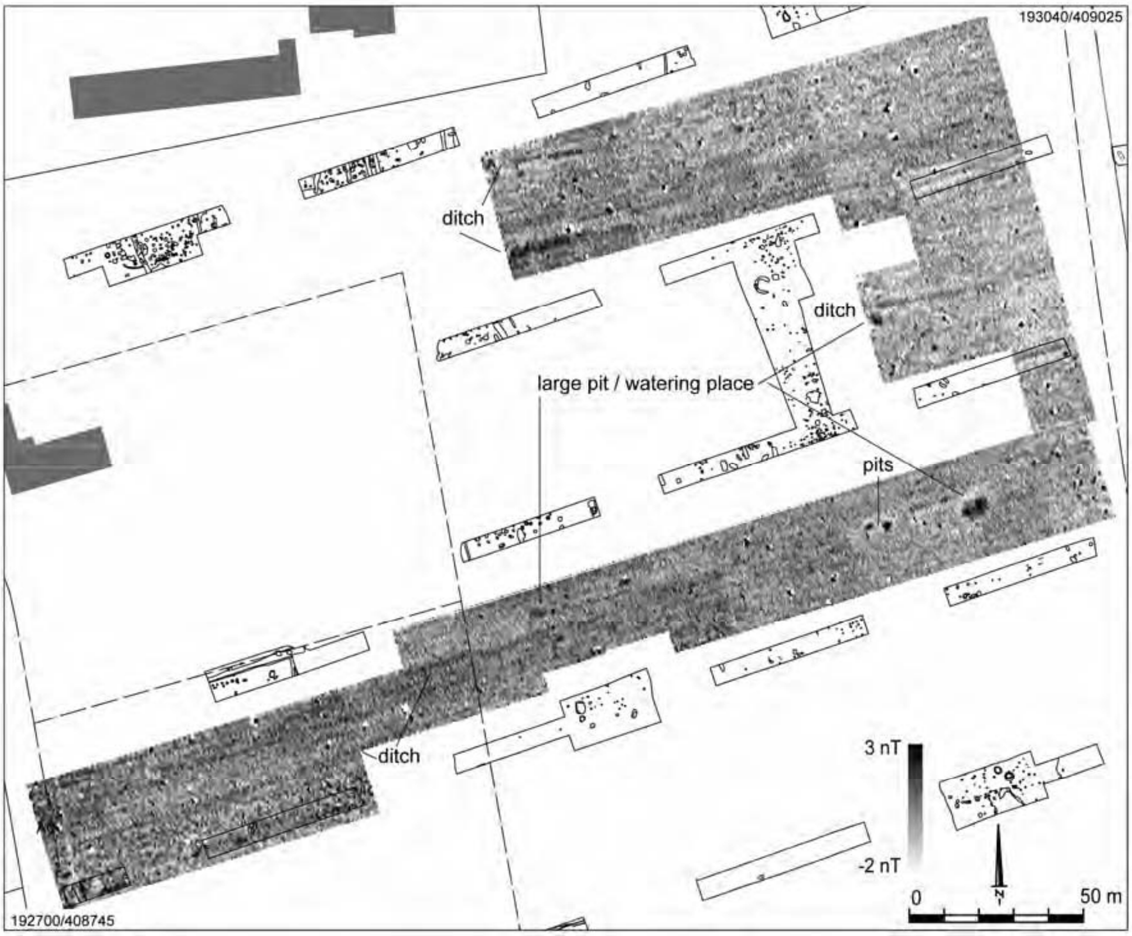


Figure 44 The results of the magnetometer survey in Beugen with the interpretation of the magnetic anomalies. For details see Appendix I, 2.

In the Meuse valley, the contrast that was observed in the magnetic susceptibility samples translated into detectable magnetic anomalies in the results of the magnetometer survey. Based on the lack of contrast in samples from two of the Central river area sites, Deil and Zaltbommel, it was expected that a magnetometer survey conducted here would be less successful in mapping archaeological features. In Zaltbommel none of the archaeological features that were excavated after the magnetometer survey could be mapped. A second magnetometer survey in the Central river area was conducted on the archaeological site of Meteren, prior to its excavation. On this Iron Age / Roman period settlement site there was a relatively large variation in the recorded magnetic dataset (see Appendix I, 14). Most of the anomalies could be attributed to post-Medieval ditches, although there is some indication that the location of the houses that were excavated show in the magnetometer data as positive anomalies, possibly caused by patches of enhanced magnetic susceptibility soil.

6.4 Conclusions

Cover sands, general

- Subsoil magnetic susceptibilities are generally low. Topsoil deposits (plaggen soil) have a higher magnetic susceptibility, but the plaggen soil is not the original topsoil. The fill of archaeological features is not enhanced and has little magnetic contrast to the surrounding matrix.
- Magnetometer surveys do not show any archaeologically relevant induced magnetic anomalies.
- Problems with the magnetic detection of archaeological features on coarse mineral soils have also been reported elsewhere, and are confirmed by the results in this study.

- The presence of a plaggen soil increases the distance between the archaeological features and the magnetometer (masking), which results in a weaker signal.
- Magnetic susceptibility variations in red sand and in plaggen soils and remanent magnetic inclusions in plaggen soils can cause false positives and can hamper the interpretation of magnetometer data.

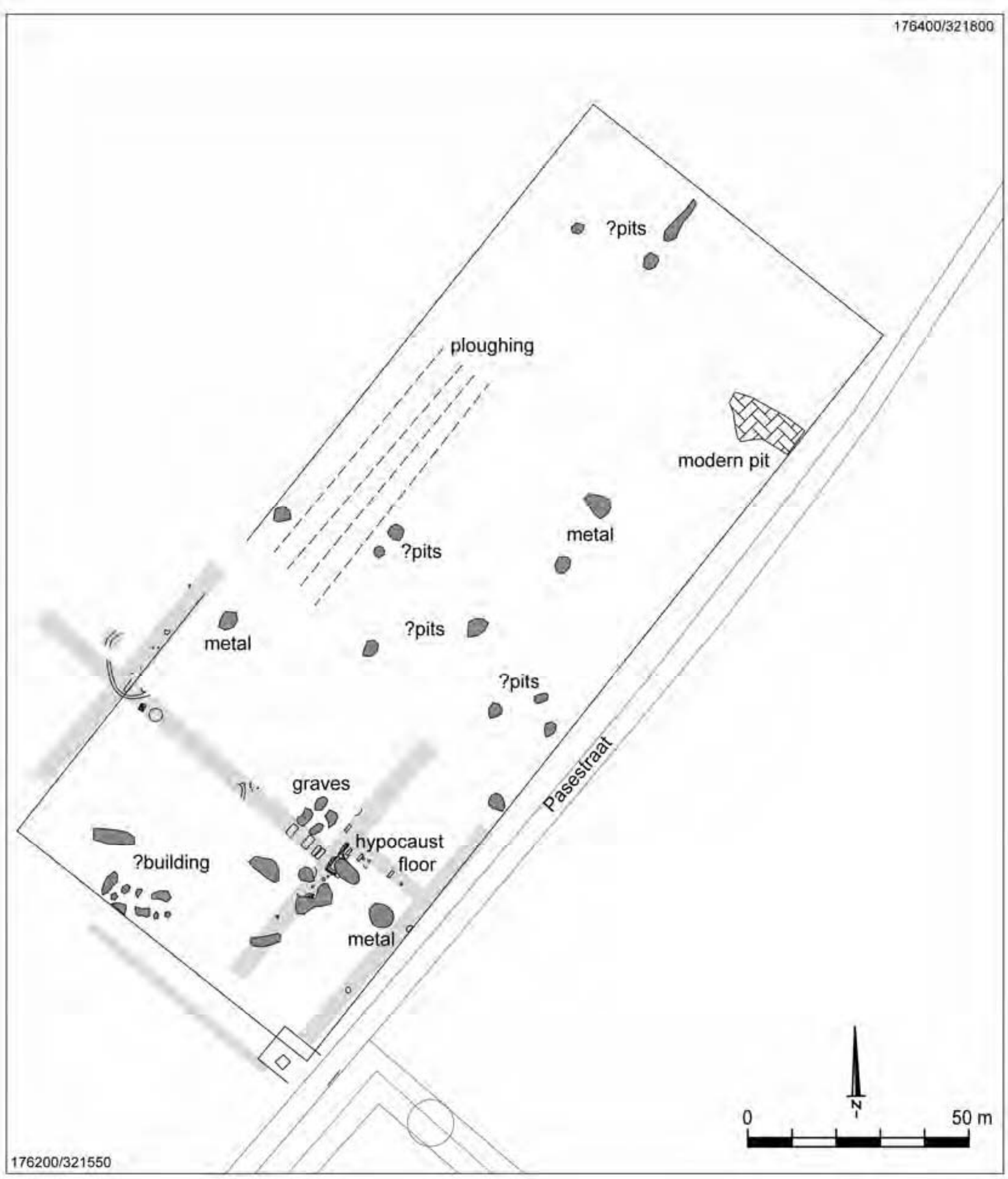


Figure 45 The interpretation diagram of the magnetometer survey in Borgharen; see Appendix I, 7 for the data and more details.

Cover sands, metal working

- On the metal working site of Heeten, high magnetic susceptibility subsoil layers are encountered, which are probably related to the high temperature activities on the site. Variations in these layers can cause false positives and hamper the interpretation of magnetometer data. Archaeological feature fills have a negative magnetic contrast to the surrounding matrix.
- Magnetometer surveys could not map these negative contrast features A number of positive anomalies, however, all of the furnaces and a number of pits, could be mapped.

Coastal dunes

- Topsoil magnetic susceptibility is enhanced and there is a clear magnetic contrast between the fill of archaeological features and the undisturbed matrix.
- A multitude of archaeological features could be mapped in the magnetometer survey, with only a few false positives.

Loess

- Topsoil magnetic susceptibility is enhanced and there is a clear magnetic contrast between the fill of archaeological features and the undisturbed matrix.
- A magnetometer survey on a Roman villa site mapped a number of remanent and induced magnetic anomalies that were related to the archaeological record. A greater number of features, however, could not be mapped, which was probably due to the damaged nature of the site.

Fluvial deposits, Central river area

- Topsoil magnetic susceptibility is enhanced, but there is no magnetic contrast between the fill of the archaeological features and the undisturbed subsoil on two of the three sites.
- Magnetometer surveys generally did not reflect the archaeological record, although some post-Medieval features could be mapped.

Fluvial deposits, Meuse valley

- Topsoil magnetic susceptibility is enhanced and there is a clear magnetic contrast between the fill of archaeological features and the undisturbed matrix.
- Part of the archaeological features could be mapped in a magnetometer survey.