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RESEARCH ARTICLE

Classification of buried soils, cultural, and colluvial deposits in the Viking town Hedeby

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Abstract

Objective classification of settlement deposits is a prerequisite for understanding human-environment interactions at habitation sites. This paper presents a novel approach combining a relatively fine-scale sampling strategy, a multimethod geoarchaeological investigation of cores and multivariate statistics to aid in the classification and interpretation of complex and intricately stratified archaeological deposits. Heterogeneous settlement deposits, buried soils, colluvial, fluvial, and fluvioglacial sediments from cores retrieved in the Viking settlement Hedeby were investigated using six cost-effectively measurable geoecological parameters: loss on ignition at 550°C, magnetic susceptibility, contents of stones, artifacts, bones, and charcoal with wood. Principal component analysis allowed identifying variables that would sufficiently describe data and cluster analysis enabled the classification of the materials. As a result, 13 classes were distinguished with a detailed and reliable differentiation of materials of natural and cultural genesis. Based on spatial distribution patterns of the classes, hypotheses regarding land use in the adjacent areas were made: Waste disposal in the valley of Hedeby-brook and metallurgic activities north of it. This approach is valuable for coring-based research at settlements, in particular at tightly managed heritage sites, and for surveys to identify potential excavation sites, whereas the set of variables must be adjusted according to local conditions.

KEYWORDS

classification, cultural layers, Hedeby, multivariate statistics, soil horizons, Viking Age

1 | INTRODUCTION

In a complex interplay with natural processes, settlement activities cause a multifaceted transformation of landscapes, including soil cover (McNeill & Winiwarter, 2006; Schultze, 2014; Yakimov, Kaidalov, Sechko, Pustovoytov, & Kuzyakov, 2012). As a result, cultural layers and a whole range of other settlement deposits are formed related to waste dumping, formation of pit fills and so forth (e.g. Goldberg & Macphail, 2006). These various settlement deposits, as they form under the influence of settlement activities, record processes and conditions to which they were exposed during the occupation and thus represent valuable archives of human economic activities and human-landscape interactions in general (Alexandrovskiy, Dolgikh, & Alexandrovskaya, 2012; Bronnikova, Zazovskaya, & Bobrov, 2003; Goldberg & Macphail, 2006; Milek & Roberts, 2013). Due to the extreme heterogeneity of such settlement deposits and not always a straightforward identification in the field, their objective classification is often complicated (Golyeva, Zazovskaia, & Turova, 2016; Hamerow,

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2006). As it is the case for archaeosediments of various earthworks (e.g. Sherwood & Kidder, 2011), settlement deposits also lack standardized soil/sediment descriptions. Due to the absence of standardized geoarchaeological approaches for the classification of settlement deposits, methods of soil science and sedimentology, which are not adapted to geoarchaeological needs, are usually applied (Golyeva et al., 2016). This issue is of particular importance at protected archaeological monument sites, where standard excavation possibilities are limited, and coring or augering represent the only sampling methods. In contrast to the interpretation of cores, scientists investigating settlement deposits in excavation profiles are usually able to directly identify a cultural layer or a waste dump as such due to the fabric of the material, orientation of artifacts, bedding and so forth (Karkanas & Goldberg, 2018). In cores, a differentiation between various settlement deposits and natural materials is often problematic.

Moreover, coring only generates point information; thus the understanding of the spatial relationships between the deposits in different cores is frequently complicated. Therefore, it is necessary to employ a reproducible approach for the classification of such materials based on objective criteria. The choice of the criteria for the differentiation of settlement deposits depends on the nature and size of the site and the type of questions raised (e.g. Goldberg & Macphail, 2008; Karkanas & Goldberg, 2018). The following geoecological parameters, which are indicative of different settlement activities, are usually used in geoarchaeological studies of cultural layers at (former) habitation sites: Contents of stones, bones, artifacts, charcoal, and wood (e.g. Alexandrovskiy et al., 2012; Milek & Roberts, 2013), organic matter content (e.g. Holliday, 2004), magnetic susceptibility (e.g. Dalan & Banerjee, 1998; Jeleńska et al., 2008), grain size distribution (e.g. Blott & Pye, 2001), and contents of chemical elements (e.g. Wilson, Davidson, & Cresser, 2008). Even though statistical analyses of some of these characteristics have often been applied for former settlements (Dirix et al., 2013; Entwistle, Abrahams, & Dodgshon, 2000), in such studies surface sampling was carried out with the aim to group elements with similar spatial enrichment patterns and distinguish functional areas rather than for cores or deep profiles. In this study, hierarchical cluster analysis was applied for cores as it represents an agglomerative method designed to classify samples of different natures without any a priori information regarding the number and composition of the resulting classes (Legendre & Legendre, 2006; Templ, Filzmoser, & Reimann, 2008).

Also, it has to be noted that even though there is a number of important publications devoted to the interpretation of borehole/coring data and interpolation of this information to construct deposit models and model buried surfaces (e.g. Bates, Bates, & Whittaker, 2007; Carey, Howard, Corcoram, Knight, & Heathcote, 2017), these studies mostly focused on major stratigraphic units (Quaternary deposits, surfaces of archaeological deposits, etc.) of clear genesis without detailed investigation of cultural layers and other intricately stratified deposits at settlements. Hence, the question of the classification of these units has not been relevant in these studies. Although this paper does not explicitly aim to perform any sort of deposit modeling (in this case the coring strategy must have been different), it intends to develop an approach for an objective classification of deposits in cores, which could serve, among other things, as an assisting tool to enable correlation of stratigraphies in cores and to solve other geoarchaeological tasks. The novelty of this approach is not in the application of individual techniques but in the combined methodology coupled with statistical data analysis that would enable a structured and cost-effective investigation of heterogeneous settlement deposits in cores. Therefore, the goal of this study is to develop an approach for a classification of settlement deposits and other soil and sediment materials based on their numeric parameters using the example of the Viking town Hedeby.

2 | STUDY AREA

The area of investigation is located in the undulating young moraine landscape in the southern part of the Jutland peninsula (Figure 1), approximately 2.5 km south of the city of Schleswig, which belongs to the region of Schleswig-Holstein in Northern Germany. This landscape unit was formed during the Weichselian cold period (115,000–11,560 BP) (Fränzle, 1988, 2004; Stephan, 2003). Late Pleistocene deposits in the area are represented by tills of ground and end moraines, fluvioglacial sand, and, in some landscape positions, varved sediments of proglacial lakes underlying the fluvioglacial sand (Geologischer Dienst Schleswig-Holstein, 2012). Due to the high degree of landscape heterogeneity in terms of topography, parent material, and land use, a complex mosaic of soils is found in the young moraine landscape unit (Burbaum, 2008; Fränzle, 2004; Jones, Montanarella, & Jones, 2005). Luvisols dominate in decalcified glacial till, whereas Cambisols are common on coarser sandy materials. In outwash plains inside the outer Weichselian glacier margins, they are associated with Gleysols and Gleyic Cambisols. In undulating landscapes, Stagnosols are found on slopes, Colluvisols at footslopes and hydromorphic soils (Gleysols, Histosols, etc.) in depressions. In fluvioglacial sands and in eolian sand deposits Podzols have formed since the Neolithic period.

The region of Schleswig-Holstein lies within the Cfb maritime temperate climate class according to the Köppen–Geiger climate classification system (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006). This climate class is described as a fully humid climate with warm summers. Near the study site (weather station in Schleswig), the mean annual precipitation is 896 mm and the mean annual temperature is +8.3°C, according to the German Weather Service.

The study site, the former Viking town Hedeby (54°29′ 27.77′′ N, 9°33′ 54.42′′ E), occupies an area of approximately 26 ha inside the defense rampart, the so-called semicircular wall. It is situated on a relatively smooth slope falling eastward towards the Haddebyer Noor lake, which formerly represented the western end of the 42 km long inlet, Schlei, connecting it with the Baltic Sea. Strategically, Hedeby was founded at the narrowest part of the Jutland peninsula to connect the trade routes of the Baltic Sea and the North Sea (Schietzel, 2014). A small brook, named Hedeby-brook, enters the settlement through an opening in the semicircular wall in the western part of the town and flows into Haddebyer Noor.

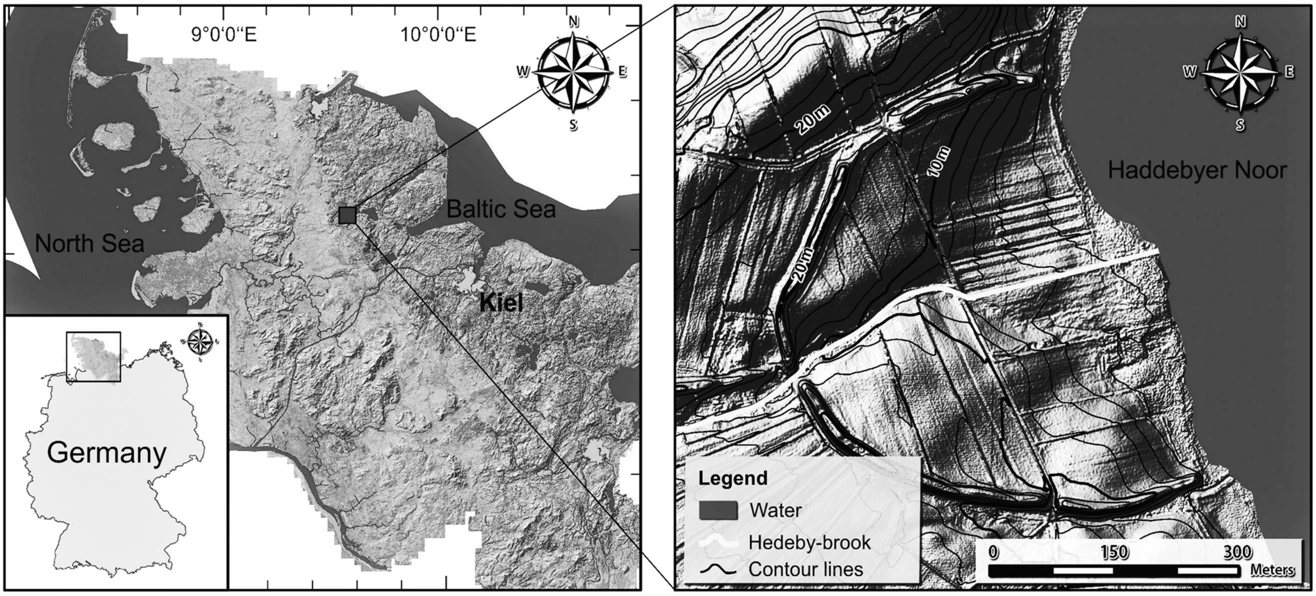


FIGURE 1 Location of the study area

Hedeby is known from written records from AD 804 (e.g. Kalmring, 2010) and developed in the 9th century as a leading emporium and proto-town of the Danish kingdom until its final destruction in AD 1066 (Hilberg, 2009). After the complete abandonment of Hedeby in the second half of the 11th century, agricultural land use was practiced on the territory of the former town in late-medieval and modern times. For this reason, cultural layers on slopes and watersheds have been disturbed by plowing, while in accumulative landscape positions, for instance, at the brook, they were buried by the colluvium of cultural layers. No other settlement activities took place on the territory of Hedeby, and as a result, the stratigraphy of settlement deposits was not disturbed, and no overprinting with younger settlement signals occurred, which makes Hedeby an optimal site for geoarchaeological investigations. At present, Hedeby is part of a nature reserve, and existing fields on its territory are used as permanent grasslands for extensive grazing and hay production. In 2018, Hedeby together with the Danevirke defense system was declared a UNESCO world heritage site.

Archaeological research that has an over 100-year-long history in Hedeby has provided important information about the economic activities in the town, the lifestyle of its inhabitants and the architecture of their dwellings (e.g. Lüdtke, 2013; Schietzel, 2014; Schultze, 2008a; Westphal, 2006). Even though there has been a hypothesis regarding the layout of the town with three nuclei at small streams (Jankuhn, 1963), until now there is no consensus whether the three excavated settlement areas do form settlement nuclei or whether they formed one settlement stretching along the shore (Hilberg, 2009). It is known, however, based on archaeological excavations and geophysical surveys that there was a large cemetery in the southern part of the town, some workshops in the northwestern part, a large harbor area with wooden piers and a large wooden platform in the eastern part and the main road along the shore of Haddebyer Noor (reviewed in detail by Carnap-Bornheim, Grupe, Hilberg, & Schultze, 2013; Hilberg, 2008, 2009; Schietzel, 2014). Scarce information regarding the topographic situation is available in the works of Schultze (2008b) and Kalmring (2010) but both of them focused on the area at the eastern margin of the settlement. The area at Hedeby-brook in the western half of the settlement, as mentioned previously, has not been investigated archaeologically nor geophysically.

3 | METHODS

3.1 | Field methods

Due to the protected status of Hedeby, excavations were not possible, and sampling had to be carried out by coring. Coring sites were selected in the valley of Hedeby-brook, avoiding locations of previous archaeological excavations and anomalies revealed by geophysical surveys; these data were kindly provided by the Archaeological State Office of Schleswig-Holstein. Two coring systems were applied for sampling: Universal gouge corers of Pürckhauer type, which includes 1 m long steel augers of ca. 1.6 cm inner diameter and additional metal rods for extension, and the Vibracore system, which includes closed steel percussion corers of 6.3 cm diameter and steel extension rods with PVC inner liners with 5 cm outer diameter inserted with a handheld impact hammer (jackhammer 23 kg). Ten cores were retrieved in the central part of the settlement along the Hedeby-brook, and five cores were sampled in the southern part of the settlement to investigate buried soils (Figure 2). Of the five additional cores, one was taken through the semicircular wall in the southwestern part of the settlement and four cores were taken in the southern part of the settlement. In all five additional cores, buried soil horizons were identified and analyzed selectively. The Pleistocene basis of the sequences was reached in all cores resulting in the depths of the cores varying from 2 to 7 m.

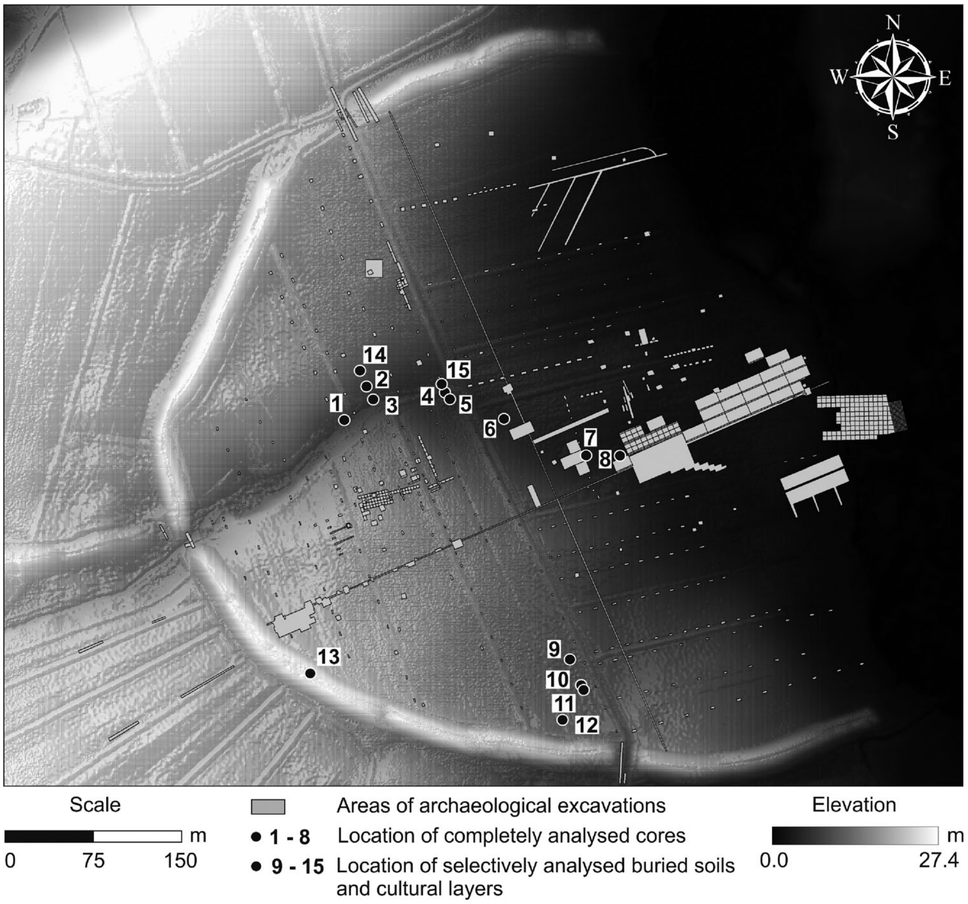


FIGURE 2 Digital elevation model of Hedeby with location of coring sites and areas of archaeological excavations (data source: Archaeological State Office Schleswig-Holstein)

All cores were documented in photographs. Soils were described in the field following the FAO soil description guidelines (FAO, 2006) documenting soil moist color (Munsell, 2000), texture by a finger test, and composition (presence of organic remains, bioturbation features, coarse fragments etc.). Cultural layers and other settlement deposits were distinguished and described in the field based on their morphological properties, texture, and composition with special attention given to the presence of inclusions such as artifacts, bones, charcoal, and woody remains.

3.2 | Laboratory methods

Eight cores at Hedeby-brook (coring points 1–8) were sampled continuously with a total number of 253 samples taken from stratigraphic units so that the maximum thickness of a sample did not exceed 10 cm. The samples were taken in the individual sediments and soil horizons, and sampling ended at the borders of sediments and soil horizons, meaning no mixed samples were taken. The number of samples per core varied from 29 to 46, and the number of layers in one core often exceeded 20. In two cores at the slopes of the brook valley (coring points 14 and 15), 12 samples of cultural layers that formed in situ were selected and analyzed. From the five cores in the southern part of the settlement (coring points 9–13), a selective sampling of soil horizons was performed, resulting in 22 samples.

For all 287 samples taken for laboratory analysis, a set of six geoecological parameters was determined: Content of stones >2 mm diameter, contents of artifacts, bones, and charcoal with wood (CH/wood) as well as loss on ignition (LOI) and magnetic susceptibility (MS). From those 287 samples, grain size distribution, and multi-element composition were measured additionally for 99 samples from cores 2, 4, and 5 for testing classification results. For a small selection of materials, pH was determined.

Before the analyses, samples were dried for 72 hr at 40°C and sieved through a sieve with a 2 mm mesh size. During sample preparation, the separation of the following components was performed: Fine grain size fraction (<2 mm), coarse grain size fraction (>2 mm), artifacts, bones, and charcoal/wood. All these components were weighed, and the respective weight percentages were calculated.

In the laboratory, pH was measured in a 1:5 suspension (air-dried soil: 1 M KCl) by a pH meter WTW pH 330i, SenTix 41. LOI was determined as a measure of organic matter content by combustion at 550°C for 2 hours. For grain size distribution analysis, samples were step-wise treated with 35% hydrogen peroxide for the destruction of organic matter and, if necessary, with 0.5 M sodium acetate buffer solution for removal of carbonate. After the destruction of the cementing agents, the samples were treated with sodium pyrophosphate to prevent coagulation of soil and sediment particles and left for overhead shaking overnight. The measurement was performed by laser diffraction spectrometry on Mastersizer 2000 particle size analyzer, developed by Malvern Instruments. The fraction size limits correspond to international standards. Volume-specific magnetic susceptibility was measured at low frequency (0.465 kHz) using a Bartington Instruments MS2 meter. The calibration of the instrument was performed using a 1% Fe_3O_4 calibration sample. Using the samples' bulk density data, the mass-specific magnetic susceptibility was calculated.

To homogenize samples for multielement analysis they were powdered for 1 minute in an agate mill. The measurement was performed by X-ray fluorescence with an XL3t 900-series GOLDD+ instrument by Thermo Scientific Niton Analyzers in the mining mode with Cu and Zn filters for 300 s. A helium purge was activated for improved detection of light elements. Elements with a measurement error <10% were considered. Radiocarbon dating (^{14}C-AMS) was performed on four samples: A charcoal fragment with determined tree taxa (1), hazelnut shells (2), and a charred seed (1) originating from the units of interest in sampled cores (Table 1). The samples were dated in two laboratories: Leibniz-Laboratory for Radiometric Dating and Stable Isotope Research at the University of Kiel, Germany, and The National Laboratory for ^{14}C Dating at the Norwegian University of Science and Technology, Trondheim, Norway. The ^{14}C-AMS dating results were calibrated using the program OxCal V4.2 (Bronk Ramsey, 2009) and IntCal 13 calibration set (Reimer et al., 2013).

3.3 | Statistical methods

To classify heterogeneous habitation deposits, soil horizons, colluvial layers, and other materials based on objective criteria, multivariate methods of statistical analysis were applied. Distribution normality was tested by the Shapiro–Wilk test. Even though principal component analysis and cluster analysis do not strictly require normally distributed data, before the analysis the data were transformed following a Box-Cox transformation to reduce the effects of nonnormal distributions and to enhance the robustness of the results. Also, the data were standardized to minimize the effects of the differing scales of the variables.

To understand the factors of data variability, principal component analysis was performed based on a correlation matrix. The appropriate number of principal components was determined by the assessment of the respective eigenvalues of the principal components. The classification of samples was carried out by means of the hierarchical cluster analysis with the Ward's method as the amalgamation rule and squared Euclidean distances as a distance measure. As input data for cluster analysis, the scores of the principal components with eigenvalues above 1 were used instead of the raw values of the variables. This is a widely applied procedure in geochemical-environmental studies to reduce the dimensionality and noise of the data while attempting to preserve the relationships present in the original data (Cañellas-Boltà et al., 2012; Shine, Ika, & Ford, 1995). The statistical significance of the differences among obtained clusters was tested by the nonparametric Kruskal–Wallis test and the post hoc Mann–Whitney test with the Bonferroni correction to reveal the exact differences among the clusters. All statistical analyses were performed using software Statistica v. 12.0.

4 | RESULTS

4.1 | Description of soils and settlement deposits

Deposits present in the obtained cores at the brook (coring points 1–8) are heterogeneous and of different genesis. The summary of descriptions of cores 1–8 is provided in appendix. At the Pleistocene base of the stratigraphic sequences reached by coring, fluvioglacial sand (C_{sand}), and clastic varve deposits (C_{varved}) were found. In the central part of the Hedeby-brook valley, a layer of late Pleistocene gravel (*Gravel*) and an anthropogenic stone deposit ($Gravel_{cult}$) is located at the border between the late Pleistocene and Holocene deposits. Late Pleistocene gravel layers are dominated by rounded flints of varying sizes embedded in coarse and medium sand. In contrast, anthropogenic stone deposits are characterized by 4–5 cm large stones of heterogeneous rock composition (flint, gneiss, granite, sandstone, and quartzite) embedded in a finer-grained humic sediment matrix of varying grain size from silty loam to sand.

At coring points 9–13 in the southern part of the settlement, buried Holocene soil horizons were identified in the upper part of late Pleistocene deposits. Soil horizons were completely preserved when they were buried under sediments without a preceding surface disturbance, for instance, under the deposits of the semicircular wall in

TABLE 1 Results of radiocarbon dating

Lab number	Sample/material	Point nr./depth (cm)	Radiocarbon age	Calibrated age (2σ range)	δ^{13}C (‰)
KIA50328	Spelt barley seed (*Hordeum vulgare*)	2/187	940 ± 25 BP 980 ± 25 BP	1080–1155 cal AD (61.2%) 1020–1055 cal AD (34.2%)	−20.53 ± 0.11 −20.07 ± 0.10
KIA50329	Hazelnut shell fragment (*Corylus*)	2/355	1105 ± 25 BP 1130 ± 25 BP	890–977 cal AD (95.4%)	−26.15 ± 0.09 −27.61 ± 0.22
Tra11347	Hazelnut shell (*Corylus*)	6/293	1130 ± 15 BP	883–975 cal AD (95.4%)	−26.9 ± 1.6
KIA50333	Charcoal fragment (*Salix*)	7/376.5	1100 ± 25 BP	885–995 cal AD (95.4%)	−26.01 ± 0.23

the southwestern part of the settlement (coring point 13). There, a complete buried profile of a Cambisol with initial podzolization features was discovered. The Ab horizon is very dark brown in the upper part and dark greyish brown in the lower part. It is dominated by medium sand with bleached sand grains present. The underlying Bb horizon has a dark yellowish-brown color and is also dominated by medium sand. The parent material of this soil is represented by pale yellow fluvioglacial sand; however, such conditions of preservation of a complete soil profile were rather unique. At two coring points (9 and 10), Ab is present, but in the upper part it is mixed with the overlying cultural layer. At other points, only remnants of a Bw horizon of a Cambisol are preserved. They were identified at two coring points (11 and 12). At point 12, Bw is buried under a cultural layer, whereas at point 11 it is overlain by the colluvium of the semicircular wall.

However, soil horizons are usually absent, and, in most cases, cultural layers are located directly above Pleistocene deposits. Well-stratified cultural layers (Y_{cult}) that formed in situ were identified at upper and lower slope positions at the Hedeby-brook (coring points 14 and 15), but are absent at transition slope segments. Cultural deposits in the brook valley are generally rich in artifacts, bones, charcoal, and wood. Artifacts include various pottery shards of different sizes (0.5–4.5 cm) clearly identifiable as such, metallurgic slag fragments, which were identified due to a high specific weight and a typical porous structure, well-preserved leather pieces and small burnt loam fragments, which were recognized based on their texture and reddish color.

In the central part of the settlement near the thalweg of the brook and at other sites with waterlogged conditions (coring points 1–8), cultural layers rich in organic matter ($Y_{cult,org}$) and organic-rich layers with abundant woody remains (H_{wood}) were identified. There, they are followed by peat layers (*H*), which are free of artifacts or any other indications of settlement activities. On top of the peat at the brook, or above cultural layers at other parts of the settlement, colluvium consisting of reworked cultural layers (M_{cult}) was discovered. The upper part of the colluvium of reworked cultural layers and the cultural layers at the surface are homogeneous and nearly free of artifacts ($M_{cult\text{-}hom}$).

Sediments that were directly deposited by humans, such as the archaeosediments of the semicircular wall or material of hedgerows were also distinguished. The materials of the semicircular wall were identified in the coring point 13 as in situ wall deposits and in the coring point 12 as colluvium of the wall material at its footslope.

Various kinds of mineral interlayers free of any artifacts, bones, wood or charcoal, were identified in the stratigraphy of Hedeby deposits such as gravel, sand layers dominated by different sand fractions, loamy layers as well as colluviual layers of unclear origin (*M*). Also, layers representing mixtures of different materials (*Mix:…*) were frequently found which could not be identified based on morphology alone.

4.2 | Geoecological properties

From the eight cores that were continuously sampled and analyzed in the laboratory, measurement results of core 2 are provided here, as this core is representative of the stratigraphic sequences in the brook valley. The sediment sequences in other cores are in general similar: Pleistocene deposits are followed by different cultural layers or cultural layers alternating with fluvial deposits near the brook bed, peat, and colluvium of reworked cultural layers (Appendix).

A complete set of geoecological parameters was determined for core 2, located approximately 6 m north of the modern thalweg of Hedeby-brook. This core was continuously sampled to a depth of 380 cm resulting in 45 samples (Figure 3). The differentiation of stratigraphic units shown in Figure 3 is based on the visual examination of the core. The border between Holocene and Pleistocene sediments in this core is located at a depth of 360 cm. Pleistocene silty sand with a natural gravel layer on top represents the late Pleistocene basis of the sequence. Stones comprising the gravel layer are mostly flints. As expected, these deposits are characterized by very low LOI values at 550°C, very low MS values, and very low phosphorus (P) and lead (Pb) values. Above the gravel layer, heterogeneous settlement deposits were found. The cultural layer directly above the gravel at 333–360 cm depth is characterized by a relatively high LOI value and by the presence of charcoal and abundant wood fragments. The first increase in the contents of P and Pb is present in this unit. Above this layer, at a depth of 297–333 cm, a sand layer 36 cm thick without any anthropogenic inclusions is present. Most finds of charcoal/wood, bones, and artifacts are concentrated higher in the profile in the heterogeneous settlement deposits between 180 and 300 cm depth. The lower part of these deposits at 220–300 cm represents alternating layers of sand and cultural material with a low organic matter content and also low MS value but with a relatively high concentration of charcoal/wood. The upper part (180–220 cm depth) has a relatively high LOI (up to 20%) and rather low MS with the only relatively high values at 200–220 cm depth, where also the highest artifact concentration was determined. The content of Pb in this part reaches its highest value of the core at 426 ppm. The settlement deposits are followed by a peat layer at a depth of 150–180 cm, with the highest LOI content in the sequence reaching 55.5%. The peat layer is free of any artifacts, bones or charcoal/wood finds. As expected, MS of the peat material is also very low. Above the peat layer, colluvium of reworked cultural layers was identified. This layer is quite homogeneous in terms of LOI and Pb content. The highest values of MS for this core were measured in this layer reaching 160.7 $10^{-8} m^3 kg^{-1}$. The homogenous colluvium of reworked cultural layers has properties very similar to the underlying layer with only small artifacts (burnt clay fragments, metal objects) representing anthropogenic inclusions.

4.3 | Age of materials

Radiocarbon dating was performed for samples in cores 2, 6, and 7 (Table 1). Hazelnut shell fragments at points 2 and 6 and a charcoal fragment at point 7 were sampled at the bases of cultural deposits, near the border to the underlying Pleistocene material. All these samples were dated into the period of intensive settlement activities in the Viking Age.

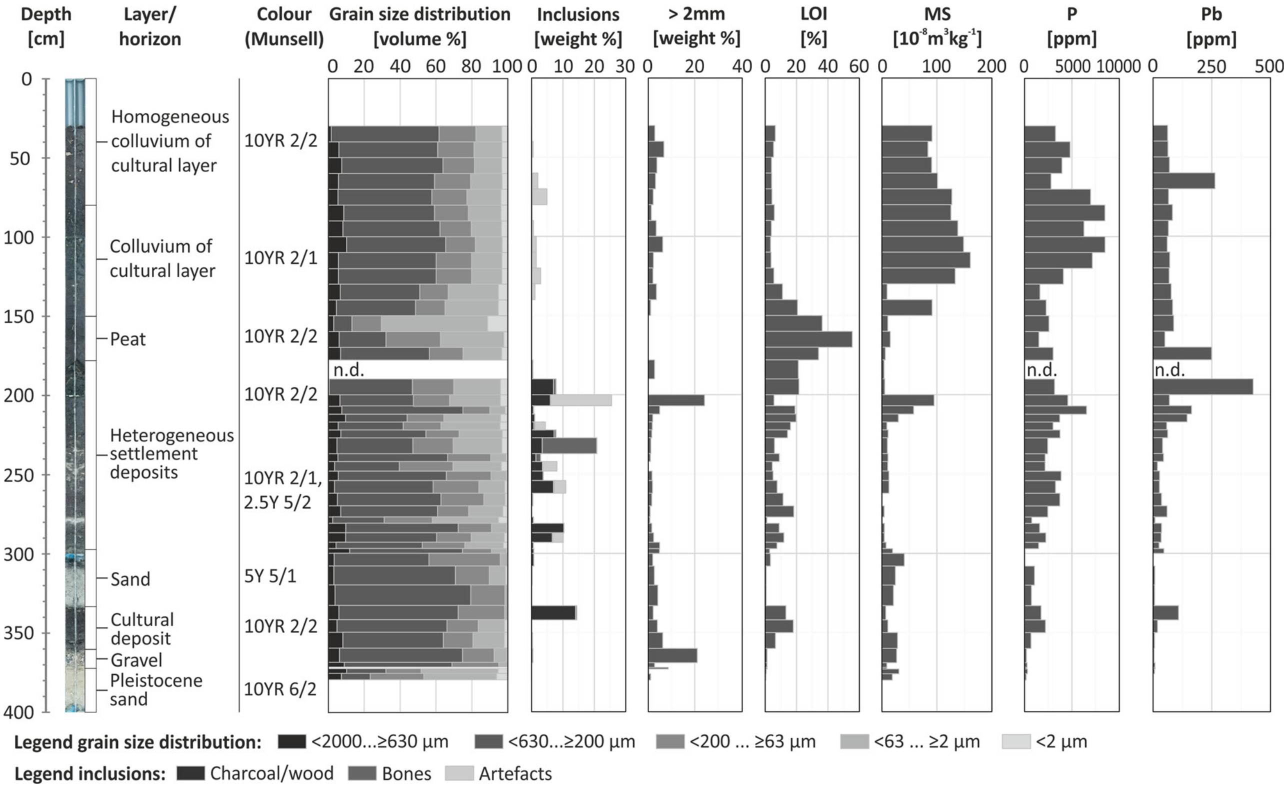


FIGURE 3 Geoecological properties of deposits in core 2. LOI, loss on ignition; MS, magnetic susceptibility [Color figure can be viewed at wileyonlinelibrary.com]

Therefore, it is confirmed that the cultural layers in the sequences formed during the settlement period in the Viking Age. The age of a charred spelt barley seed that was found in the cultural organic material directly underlying the peat layer at point 2 falls into the end of the Viking Age. Therefore, the formation of peat above the cultural layers corresponds to the period after the abandonment of the settlement in the second half of the 11th century.

4.4 | Statistical analyses

As for any classification, criteria for the differentiation of objects must be determined first. Therefore, to find out whether the set of six geoecological variables, which were determined for all samples, would sufficiently describe the data, a principal component analysis was performed (Figure 4).

Three principal components (PC) were able to explain 75.58% of the total variance (Table 2), although the third component had an eigenvalue slightly below 1. The projection of variables on the plane of PC 1 and PC 2 in Figure 4 and factor loadings in Table 3 illustrate factor-variable correlations and thus depict the meaning of the principal components. PC 1 accounts for 31.81% of the total variance and is associated with stones, bones, artifacts, and MS. Therefore, PC 1 reflects an anthropogenic signature in the samples and is thus associated with mineral cultural layers. PC 2 explains 27.44% of the total variance and is strongly related to CH/wood, bones, and LOI. Therefore PC 2 is associated with an anthropogenic organic signature in the samples and thus describes organic cultural layers. PC 3 has only a weak correlation with the parameters considered

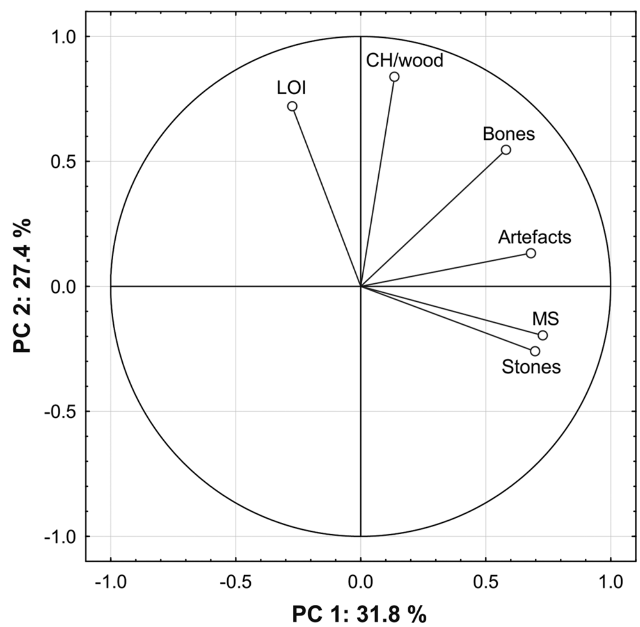


FIGURE 4 Projection of variables on the plane of principal components PC 1 and PC 2. The percentages indicate the share of the variance explained by the respective principal component. CH/wood, charcoal/wood; LOI, loss on ignition; MS, magnetic susceptibility

TABLE 2 Eigenvalues and accounted variance of the principal components

Value number	Eigenvalue	Variance, %	Cumulative variance, %
1	1.91	31.81	31.81
2	1.65	27.44	59.25
3	0.98	16.33	75.58
4	0.54	9.04	84.62
5	0.49	8.22	92.84
6	0.43	7.16	100

(Table 3) and probably indicates natural mineral materials. Based on the results of the principal component analysis it was concluded that the six parameters selected (stones, CH/wood, bones, artifacts, LOI, and MS) sufficiently explain the variance of the data. They can, therefore, be used for further analysis steps as indicators for the cultural genesis of the materials.

In the next step, hierarchical cluster analysis was carried out. Instead of the values of the six variables that were selected as classification criteria, the factor scores of PC 1–3 resulting from principal component analysis were used. A vertical dendrogram illustrating the results of clusterization is shown in Figure 5. To obtain meaningful clusters reflecting the heterogeneity of natural and cultural deposits at Hedeby, the amalgamation schedule of clustering was analyzed. It suggested a differentiation of 9–16 clusters. After comparing the composition of clusters with the morphological properties and, if known, the genesis of materials, a relative linkage distance of 8.2% was selected, at which 15 meaningful clusters were obtained.

According to the results of the significance difference test provided in Table 4, all but two of the clusters (8 and 9) differ in at least one of the analyzed parameters, whereas most of them differ in three or more parameters. Therefore, the clusters obtained can be considered as significantly different (Table 4).

Based on the descriptive statistics of the clusters (Figure 6), several groups of clusters can be distinguished. The ranking of the levels of the parameters was performed based on the division of the whole range of median values of the parameters into percentile intervals (Table 5). For median values of a corresponding parameter below the 20th percentile the level of the parameter was interpreted as very low (or absent in case of inclusions). The same was done for median values between the 20th and the 40th percentile, between the 40th and 60th percentile, between the 60th and the 80th percentile and above the 80th percentile, these intervals were ranked as low, moderate, high and very high levels of the corresponding parameters. These ranking intervals are used in the following for the description of the materials of different genesis in Hedeby.

TABLE 3 Factor-variable correlations (factor loadings)

Variable	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6
Stones	**0.70**	−0.26	**0.43**	0.30	0.40	0.10
CH/wood	0.14	**0.84**	0.25	0.00	0.10	−0.45
Bones	**0.58**	**0.55**	0.35	−0.13	−0.35	0.32
Artifacts	**0.68**	0.13	**−0.52**	−0.41	0.27	0.03
LOI	−0.27	**0.72**	**−0.41**	0.38	0.16	0.26
MS	**0.73**	−0.20	**−0.41**	0.35	−0.32	−0.20

Abbreviations: CH/wood, charcoal/wood; LOI, loss on ignition; MS, magnetic susceptibility.
Note: Bold values indicate correlations significant at $p < .05$.

Clusters 1–3 can be considered as one group as they are characterized by the absence of any anthropogenic inclusions and a low to moderate MS for all three clusters, whereas contents of stones and organic matter are varying. Samples in cluster 2 are characterized by low and very low values of all parameters considered, whereas cluster 3 is described by a very high gravel content and moderate value of MS. Cluster 1 is distinguished from the other two clusters by an elevated value of LOI and a relatively high value of the upper quartile of MS.

The next group is composed of clusters 4–6, which, similar to the clusters 1–3, also have a low to moderate MS and no bones or artifacts, but in contrast, slightly elevated contents of charcoal and wood. Clusters 4 and 5 are very similar to each other with only MS indicating a significant difference. Cluster 6 can be distinguished from the others due to the very high organic matter content (highest among all clusters).

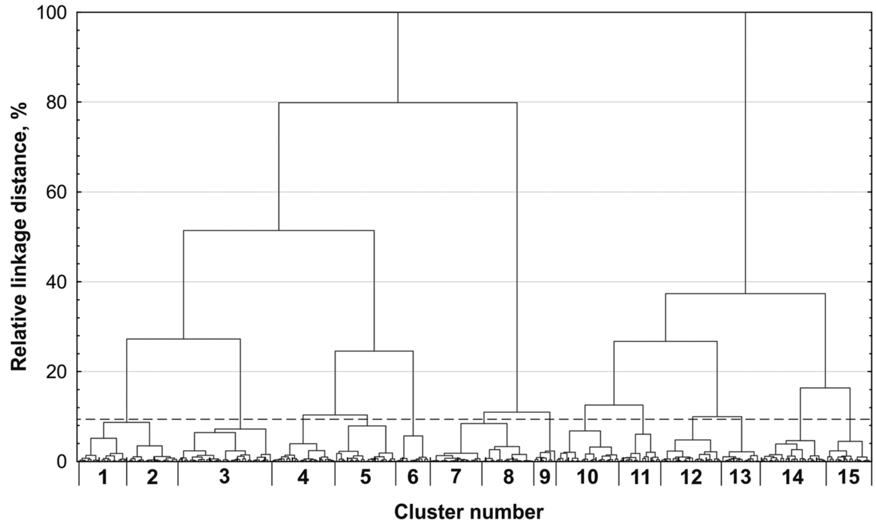
Clusters 7–10 and 14 form another distinct group. The characteristic feature of these clusters is a very low to moderate organic matter content, presence of artifacts in different quantities, and a high to very high magnetic susceptibility. Clusters 7 and 8 do not contain any bones or charcoal/wood with stone content and LOI varying in similar ranges. However, cluster 8 has a very high artifact content and a very high MS. Materials in cluster 10 have high contents of stones, charcoal/wood, and artifacts and a very high bone content and MS. Clusters 9 and 14 are very coarse with 18.7–20.8% of stones and both have high values of MS. Cluster 9 is rather small and is characterized by the presence of a low amount of artifacts, whereas cluster 14 is distinguished by moderate quantities of bones and artifacts. Although post hoc tests did not show any significant differences between clusters 8 and 9, it can be seen in Figure 6 that the content of stones and MS values indicate that these two clusters are composed of different materials.

Clusters 11–13 are characterized by a relatively high organic matter content, a high to very high charcoal/wood content and low/very low MS. Content of bones varies from zero, in cluster 11, to relatively high, from 0.5% to 0.7%, in clusters 12 and 13, although cluster 11 has very high contents of artifacts and wood remains. Cluster 12 differs from cluster 13 most importantly in the higher content of stones and slightly higher MS as well as artifact content (no artifacts in cluster 13).

Cluster 15 has intermediate properties with low to moderate values of anthropogenic parameters. It is similar to the cluster group 4–6, but it is characterized by slightly elevated contents of stones and bones and somewhat higher MS.

According to the properties of the obtained clusters, they can be grouped into five large groups of materials: natural mineral (clusters 2 and 3), natural organic-rich (cluster 6), intermediate (clusters 1, 4, 5, and 15), cultural mineral (clusters 7–10 and 14) and cultural organic-

FIGURE 5 Dendrogram obtained by the hierarchical cluster analysis using Ward's method with 15 clusters distinguished at relative linkage distance 8.2% marked with a dashed line



rich (clusters 11–13) materials. These material groups are characterized by considerably different properties, which are summarized in Table 6. The highest stone content is typical for cultural mineral materials as well as for natural mineral materials since gravel layers are included in this group. Natural organic-rich materials are stone-free. There is no charcoal and wood in natural mineral and cultural mineral materials, whereas cultural organic-rich deposits have the highest contents of charcoal/wood and bones. The highest artifact contents were measured in cultural mineral deposits. LOI varies in wide ranges among material types considered. The lowest organic matter content was identified in natural mineral materials, whereas cultural mineral and intermediate layers had intermediate values. Elevated content was found in organic-rich cultural layers and was highest in natural organic-rich materials. MS, as expected, distinguishes cultural mineral deposits. For a small number of samples, pH was measured. Neutral to slightly alkaline conditions describe natural mineral deposits since most of them include Pleistocene deposits. Cultural mineral and intermediate materials have a slightly acidic to neutral pH, whereas natural organic-rich and cultural organic-rich materials are characterized by the lowest pH values of 5.1.

4.5 | Classification results

Based on the results of multivariate statistical analysis and by the analysis of the composition of the clusters, a classification of

TABLE 4 Results of the post hoc Mann–Whitney test with a Bonferroni correction

Cluster	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1															
2	l														
3	sl	s													
4	w	swl	wl												
5	wm	wlm	swlm	m											
6	sl	sl	sl	sl	sl										
7	a	alm	salm	wa	wam	salm									
8	am	salm	alm	wam	wam	salm	am								
9	al	sam	a	a	wam	salm	l								
10	swbam	swbalm	wbalm	bam	bam	sbalm	wba	wb	b						
11	wa	wal	swal	a	am	sal	w	wlm	wl	m					
12	swb	swbl	wbl	b	sbm	sbl	swb	wbam	wbl	am	sa				
13	wb	wbl	swbl	b	bm	sb	wbam	wbalm	wbalm	alm	a	s			
14	swbal	swbam	wbam	sbalm	swbalm	sbalm	swbl	sbl	b	l	swlm	walm	swalm		
15	swbl	sb	wb	bl	swblm	sblm	swbal	balm	ba	alm	swal	wl	swl	a	

Note: Letter codes in cells represent significant differences ($p < .05$) in parameters: s, stones; w, charcoal/wood; b, bones; a, artifacts; l, loss on ignition; m, magnetic susceptibility.

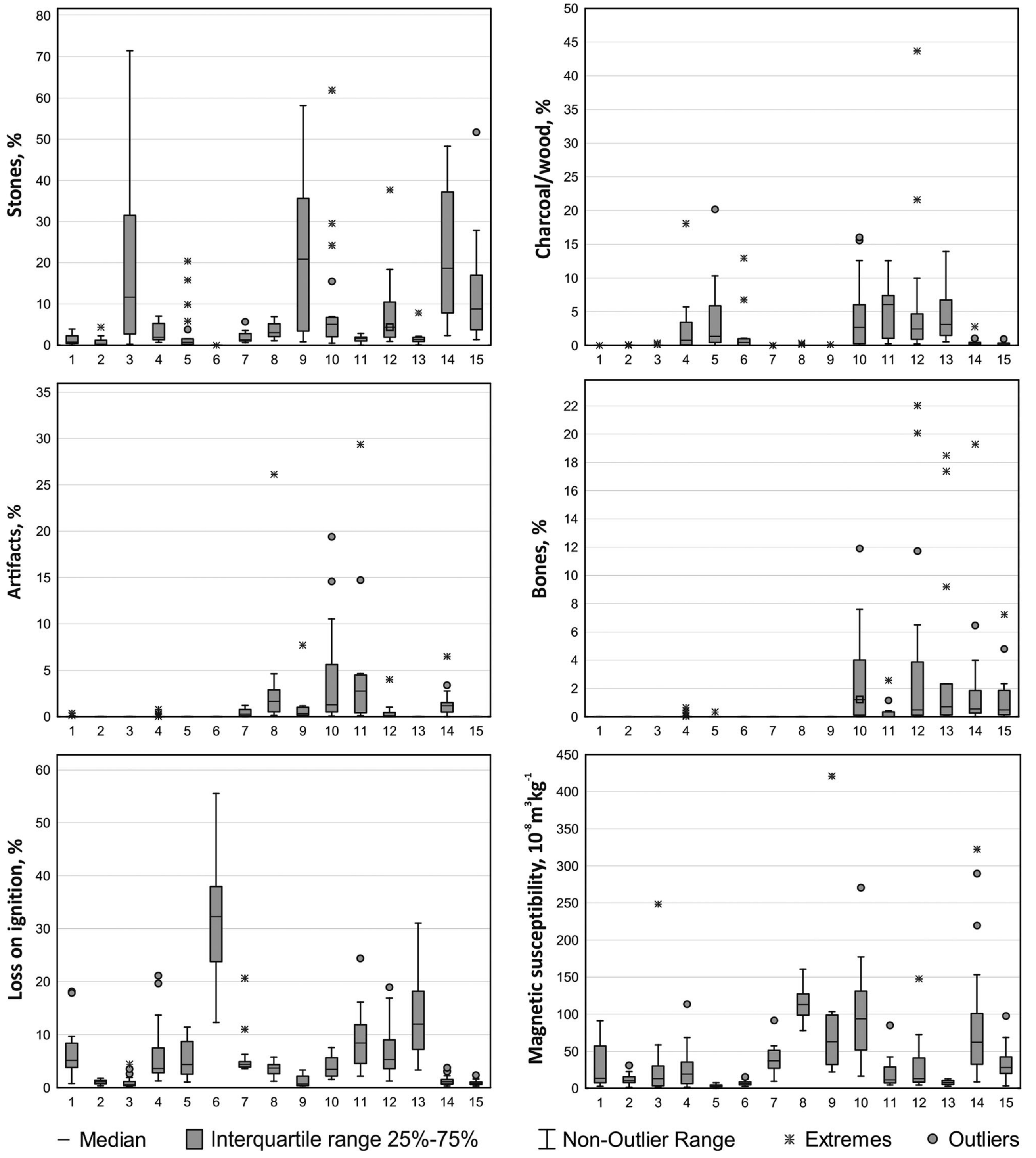


FIGURE 6 Box and whisker plots of the geoecological properties for the 15 clusters obtained at linkage distance 8.2% (cluster numbers are indicated in the horizontal axes)

heterogeneous materials of different genesis in Hedeby was developed (Figure 7). Within the main types of sediments natural, cultural, and intermediate (Table 6), 13 classes of materials can be distinguished based on the content of stones and organic matter as well as the presence and level of anthropogenic characteristics indicated by the contents of artifacts, bones, and charcoal/wood and enhanced MS.

4.5.1 | Natural materials

Materials with different organic matter and stone content represent natural deposits at the investigated sites of Hedeby. Such sediments do not contain any features of human activities: No bones, artifacts, and no or minimal quantities of charcoal/wood. Three classes of natural materials can be distinguished.

TABLE 5 Descriptive statistics of the 15 clusters with the ranking of parameters' levels according to median values: Very low/absent (med <20th percentile), low (med 20th–40th percentile), moderate (med 40th–60th percentile), high (60th–80th percentile), very high (med >80th percentile)[†]

Cluster (N)	Stones, %			CH/wood, %			Bones, %			Artefacts, %			LOI, %			MS, $10^{-8}m^3kg^{-1}$		
	Q25	Med	Q75	Q25	Med	Q75	Q25	Med	Q75	Q25	Med	Q75	Q25	**Med**	Q75	Q25	Med	Q75
1 (18)	0.4	**0.8**	2.3	0.0	**0.0**	0.0	0.0	**0.0**	0.0	0.0	**0.0**	0.0	3.8	**5.1**	8.4	7.4	**13.7**	57.1
2 (18)	0.2	**0.3**	1.2	0.0	**0.0**	0.0	0.0	**0.0**	0.0	0.0	**0.0**	0.0	0.7	**1.1**	1.4	7.5	**10.1**	15.7
3 (34)	2.7	**11.6**	31.5	0.0	**0.0**	0.0	0.0	**0.0**	0.0	0.0	**0.0**	0.0	0.4	**0.6**	1.1	3.3	**13.4**	30.1
4 (23)	1.3	**1.9**	5.2	0.1	**0.8**	3.4	0.0	**0.0**	0.0	0.0	**0.0**	0.0	2.8	**3.6**	7.5	6.4	**19.4**	35.3
5 (22)	0.2	**0.7**	1.5	0.4	**1.3**	5.9	0.0	**0.0**	0.0	0.0	**0.0**	0.0	2.5	**4.4**	8.7	2.0	**3.0**	4.5
6 (12)	0.0	**0.0**	0.0	0.0	**0.4**	1.0	0.0	**0.0**	0.0	0.0	**0.0**	0.0	23.8	**32.2**	37.9	4.6	**5.4**	8.6
7 (19)	1.0	**1.3**	2.8	0.0	**0.0**	0.0	0.0	**0.0**	0.0	0.1	**0.3**	0.8	3.9	**4.5**	4.9	27.2	**37.2**	51.2
8 (19)	2.1	**3.0**	5.1	0.0	**0.0**	0.0	0.0	**0.0**	0.0	0.5	**1.7**	2.9	2.6	**3.7**	4.3	98.6	**113.3**	127.1
9 (8)	3.4	**20.8**	35.6	0.0	**0.0**	0.0	0.0	**0.0**	0.0	0.2	**0.3**	1.0	0.4	**0.7**	2.2	32.1	**62.9**	98.8
10 (23)	2.0	**5.0**	6.7	0.3	**2.7**	6.0	0.1	**1.2**	4.0	0.5	**1.3**	5.6	2.2	**3.4**	5.6	51.6	**93.5**	131.0
11 (15)	1.0	**1.7**	2.0	1.0	**6.0**	7.4	0.0	**0.0**	0.3	0.4	**2.7**	4.5	4.5	**8.4**	11.9	7.2	**11.7**	28.7
12 (22)	1.9	**4.3**	10.4	0.9	**2.4**	4.7	0.1	**0.5**	3.9	0.0	**0.1**	0.4	3.6	**5.2**	9.0	8.4	**13.2**	40.9
13 (14)	0.9	**1.4**	1.9	1.5	**3.1**	6.7	0.1	**0.7**	2.3	0.0	**0.0**	0.0	7.2	**12.0**	18.2	5.2	**7.6**	10.7
14 (24)	7.8	**18.7**	37.1	0.1	**0.2**	0.5	0.3	**0.5**	1.8	0.5	**1.1**	1.5	0.7	**1.1**	1.6	32.5	**62.1**	100.9
15 (16)	3.7	**8.8**	17.0	0.0	**0.2**	0.4	0.1	**0.5**	1.9	0.0	**0.0**	0.0	0.6	**0.8**	1.1	20.1	**27.7**	42.5

[†]The filling of median columns reflects the parameters' levels: Very low/absent, white; low, light gray; moderate, gray; high, dark gray; very high, very dark gray.

The first class includes fine-grained Pleistocene deposits, mineral interlayers without any anthropogenic characteristics and buried soil horizons with low values of all parameters considered. Nearly all of the additional 22 samples of buried soil horizons from the southern part of the settlement fell into this class apart from B horizons from coring points 10 and 12, where they were in direct contact with cultural layers. The second class contains coarser mineral sediments including natural gravel layers and coarse-grained interlayers, as well as Pleistocene deposits with high stone content. The third class of natural materials is formed by natural peat layers with a high organic matter content and the presence of minimal quantities of charcoal/wood. MS varies in these three classes of natural materials from very low in peat (Med = 5.4 $10^{-8}m^3kg^{-1}$) to moderate in the gravelly layers (Med = 13.4 $10^{-8}m^3kg^{-1}$). Thus, these MS values can be considered as a natural background signal in Hedeby.

4.5.2 | Materials with intermediate properties

Among sediments with intermediate properties, no organic matter-rich deposits were found. Materials with different stone contents and with weak anthropogenic characteristics were distinguished yielding three classes of sediments. The first class with elevated LOI and MS is formed by the upper parts of the redeposited cultural layers exposed at the modern land surface. These materials were plowed in late medieval and modern times and, currently, they are involved in soil formation. Although no artifacts, bones, or charcoal/wood are present in these deposits, their MS is higher than in natural deposits and thus indicates a cultural origin of the material. The second class of sediments with intermediate properties comprises different sandy deposits with presence of wood and plant remains. MS varies in this class in the range of natural materials. The third class is formed by stone-enriched materials with weak anthropogenic characteristics. This class of materials is represented by sandy deposits with stones, very low organic matter content and with the presence of a small number of bones and very low quantities of charcoal and wood remains. Slightly elevated MS suggests low levels of magnetic enhancement in comparison to the natural materials.

4.5.3 | Cultural materials

Cultural materials compose the third type of sediment in Hedeby, which is divided into seven classes that form two large groups based on the content of organic matter. The first group includes mineral cultural deposits with low to moderate levels of organic matter content. The first class in this group is formed by nearly stone-free mineral cultural deposits with very high levels of anthropogenic characteristics. These are typical cultural layers. The second class of mineral cultural deposits is formed by the colluvium of reworked cultural layers with very high levels of anthropogenic characteristics (artifacts and MS). The third group is formed by the plowed colluvium of reworked cultural layers, for which only high MS reflects the cultural origin. Within mineral cultural materials, stone-rich deposits with moderate and strong anthropogenic characteristics form another distinct class. These are cultural stone layers, which were identified at the bases of the sequences, and coarse to gravelly cultural materials.

The second group of cultural materials includes cultural deposits with a high content of organic matter. These layers are not

TABLE 6 Properties of the material types

Cluster group	Clusters	N	Stones, %			CH/wood, %			Bones, %			Artifacts, %			LOI, %			MS, $10^{-8} m^3 kg^{-1}$			pH
			Q25	Med	Q75	Q25	Med	Q75	Q25	Med	Q75	Q25	Med	Q75	Q25	Med	Q75	Q25	Med	Q75	Med
Natural mineral	2, 3	52	0.4	3.4	27.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.7	1.2	5.7	12.0	22.6	7.1
Natural organic-rich	6	12	0.0	0.0	0.0	0.0	0.4	1.0	0.0	0.0	0.0	0.0	0.0	0.0	23.8	32.2	37.9	4.6	5.4	8.6	5.1
Intermediate	1, 4, 5, 15	79	0.7	1.9	5.3	0.0	0.3	1.3	0.0	0.0	0.0	0.0	0.0	0.0	1.2	3.6	6.5	3.5	9.3	29.4	5.9
Cultural mineral	7–10, 14	93	2.1	4.1	12.0	0.0	0.0	0.4	0.0	0.0	0.6	0.3	0.9	1.7	1.4	3.1	4.4	37.8	76.0	115.6	5.8
Cultural organic-rich	11–13	51	1.3	1.9	3.7	1.3	3.4	6.7	0.0	0.2	2.3	0.0	0.1	0.8	4.5	7.7	13.2	7.2	10.5	22.5	5.1

dominated by organic material but have significantly higher LOI values (median 5.2–12%) than the mineral cultural layers. They contain a small number of stones and have a low MS due to high organic matter levels and other diamagnetic materials (bones and/or wood). These layers are marked by very high CH/wood content and in some cases, with a very high artifact or bone content.

4.6 | Effects of additional variables on classification results

To test the robustness of the obtained classification results, the statistical analyses were repeated for a selection of 99 samples out of 287 samples that were analyzed previously, with the only difference that additional variables were involved in the analysis. For these 99 samples that originate from cores 2, 4, and 5, contents of elements and grain size fractions were used, in addition to the set of six parameters that were analyzed previously in the same statistical procedure. Hence, 20 variables were analyzed, including the set of 6 parameters that were used initially. Principal component analysis of 20 variables yielded five principal components with eigenvalues above 1, explaining 77.21% of the total variance. PC 1 and PC 2 accounted for 53.72% of the total variance (Figure 8). According to factor-variable correlations (Table 7), PC 1 is associated with the grain size indicators with the strongest positive correlations with the sum of silt and clay, Al, Rb, Sr, and strongest negative correlations with medium sand and Si. PC 2 shows an association with the anthropogenic characteristics: Strongest correlations with Pb, P, CH/wood, MS, artifacts, and bones. Among additional variables, only P and Pb are associated with the anthropogenic characteristics indicated by MS, artifacts, and bones.

Following the same procedure, cluster analysis was performed and provided 15 clusters at a relative linkage distance of 15.0%. The composition and properties of these new clusters were compared with the results of the primary clusterization, which was based on the six geoecological parameters. Figure 9 depicts the differences between the initial and new classifications. The type of natural organic-rich materials is not represented, as in the data set of 99 samples it consisted only of a few units. In the initial classification, 28.3% of samples were classified as natural, 18.2% as intermediate, 35.4% as cultural mineral, and 18.2% as cultural organic-rich materials. In the classification of the same set of samples with 20 parameters, 21.2% of samples were classified as natural, 5.1% as intermediate, 49.5% as cultural mineral, and 24.2% as cultural organic-rich. The changes between the initial and new classifications are described below.

For 71.4% of samples of natural materials the results of the initial classification were confirmed by the new classification; however, this group of materials became smaller (Figure 9). Indeed, 28.6% of natural samples were reclassified as intermediate or cultural materials, whereas only 4.8% of the newly formed type of natural materials came from the cultural mineral layers.

The strongest change was observed within the type of materials with intermediate properties, all of them were reclassified with

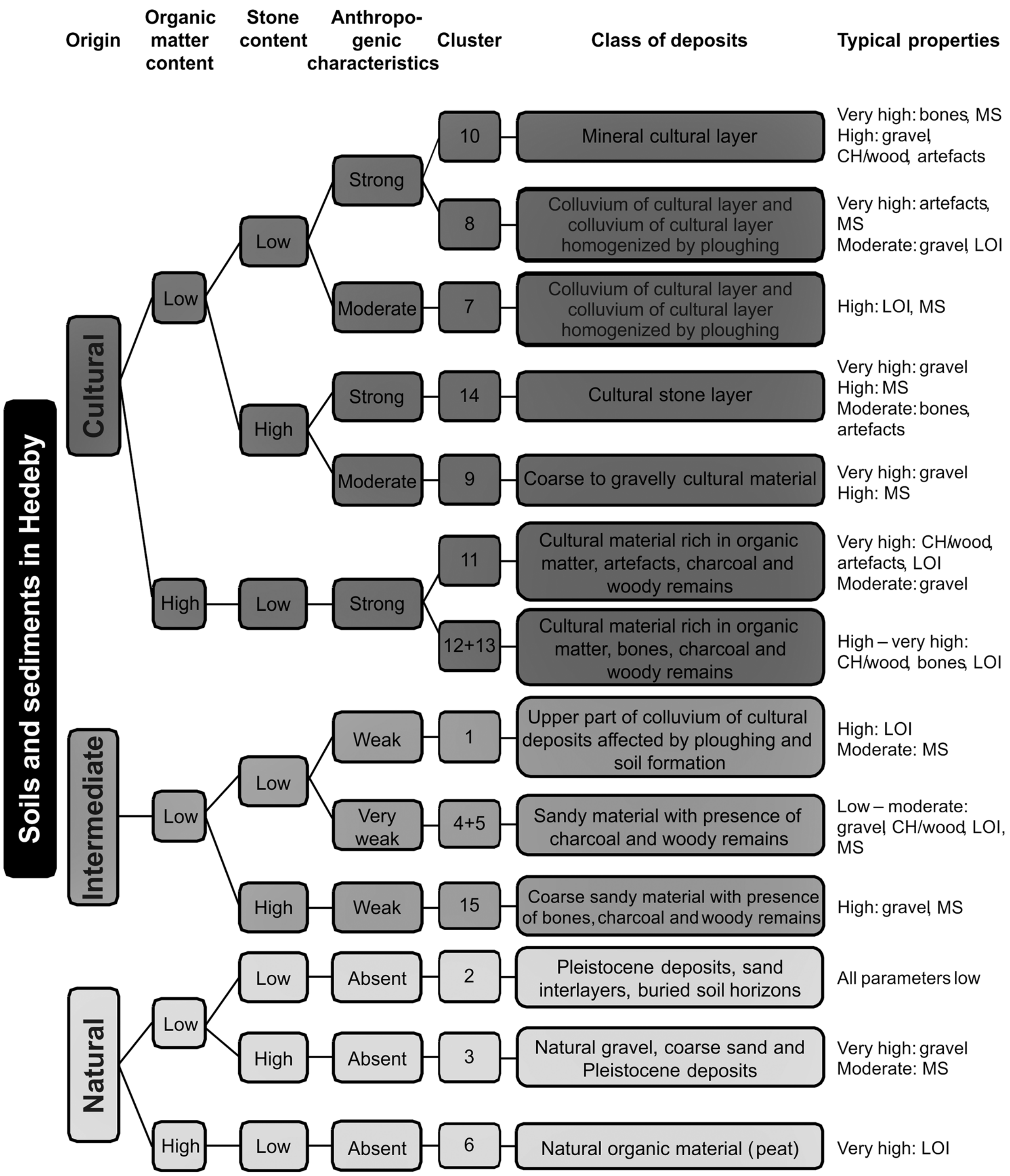


FIGURE 7 Classification of soils and sediments in Hedeby based on the results of cluster analysis

additional parameters: 83.3% as cultural mineral layers and 16.7% as cultural organic-rich materials. At the same time, five other samples were classified as intermediate materials in the new classification: 20% from materials previously classified as natural, 60% from the cultural mineral, and 20% from cultural organic-rich materials.

The groups of cultural materials (both mineral and organic-rich) increased in size, mostly due to the reclassification of natural and intermediate materials. Nevertheless, the agreement of both classifications for cultural materials is high: 74.3% of cultural mineral samples and 61.1% of cultural organic-rich samples were classified in the same way.

Therefore, it can be concluded that even though the classification based on the small set of six parameters works quite well for the majority of materials, the application of the advanced set of parameters significantly increases the recognition of human-altered soils and deposits with signatures of cultural enrichment "unseen" by the small set. Incorporating elemental and grain size data resulted in 34.7% more of the samples being identified as mineral cultural and 33.3% as organic-rich cultural, rather than inaccurately categorized as natural or intermediate, and vice versa for natural materials.

4.7 | Application of the classification results

The results of classifications with the small and large sets of parameters are presented in Figure 10 to visualize the results of

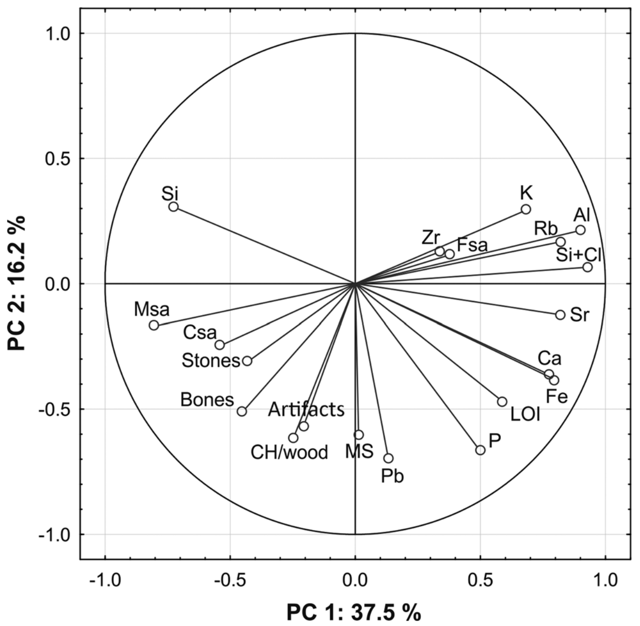


FIGURE 8 Projection of variables on the plane of principal components 1 and 2 (Si+Cl, sum of silt and clay; Fsa, fine sand; Msa, medium sand; Csa, coarse sand; CH/wood, charcoal/wood; LOI, loss on ignition; MS, magnetic susceptibility). The percentages indicate the share of the variance explained by the respective principal component

TABLE 7 Factor-variable correlations

Variable	PC 1	PC 2	PC 3	PC 4	PC 5
Stones	**−0.43**	−0.31	**−0.54**	**−0.42**	−0.06
CH/wood	−0.25	**−0.62**	0.39	−0.36	−0.19
Bones	**−0.45**	**−0.52**	0.04	**−0.43**	−0.08
Artifacts	−0.21	**−0.57**	−0.11	**0.41**	−0.09
LOI	**0.59**	**−0.47**	**0.44**	−0.01	0.07
MS	0.01	**−0.59**	**−0.46**	0.35	−0.20
CSa	**−0.55**	−0.25	**−0.60**	−0.30	0.01
Msa	**−0.81**	−0.17	0.07	0.25	0.23
Fsa	0.38	0.12	**0.49**	0.01	**−0.61**
Si+Cl	**0.92**	0.07	0.07	0.03	0.02
Zr	0.33	0.13	−0.29	0.02	**−0.68**
Sr	**0.81**	−0.13	−0.18	−0.37	0.08
Rb	**0.81**	0.17	−0.28	0.09	0.19
Pb	0.13	**−0.70**	0.01	**0.41**	−0.13
Fe	**0.79**	−0.38	−0.26	0.13	−0.01
Ca	**0.77**	−0.36	0.04	−0.40	−0.05
K	**0.68**	0.30	−0.32	0.08	−0.11
P	**0.50**	**−0.67**	0.09	0.26	0.24
Si	**−0.74**	0.32	−0.14	0.31	−0.25
Al	**0.90**	0.22	−0.22	0.05	0.09

Abbreviations: Csa, coarse sand; CH/wood, charcoal/wood; Fsa, fine sand; LOI, loss on ignition; Msa, medium sand; MS, magnetic susceptibility; Si+Cl, sum of silt and clay.
Note: Bold values indicate correlations significant at $p < .05$.

the described classification approach in comparison to a visual assessment of the same core. The classifications were applied to core 2, which was described previously in detail. Natural Pleistocene sandy deposits at the base of the sequence, which were also identified by a visual examination, were confirmed as such by both classifications. The gravel layer, which was classified as intermediate material by a small set of variables, was corrected to be a natural deposit. The organic-rich material, which could neither be clearly classified visually nor by the small set of variables, was identified as a cultural organic-rich deposit due to the elevated contents of Pb and P present in the expanded

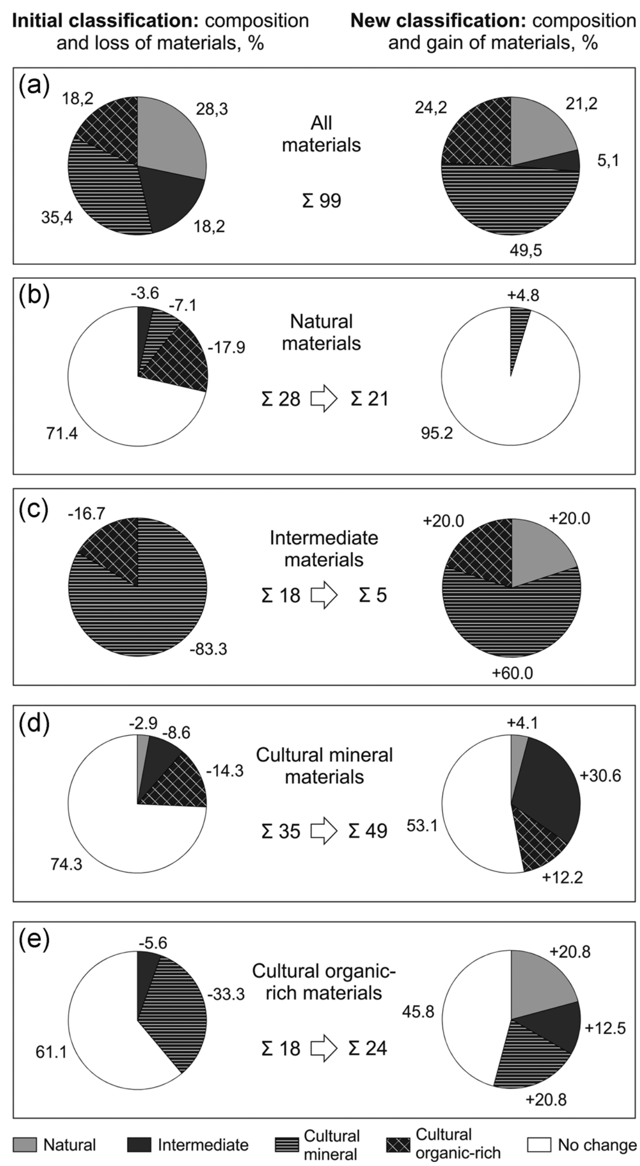


FIGURE 9 Comparison of the initial classification based on 6 parameters and the new classification based on 20 parameters. (a) Proportions of material types in both classifications. (b) Loss and gain of samples within the type of natural materials. (c) Loss and gain of samples within the type of intermediate materials. (d) Loss and gain within the type of cultural mineral materials. (e) Loss and gain within the type of cultural organic-rich materials

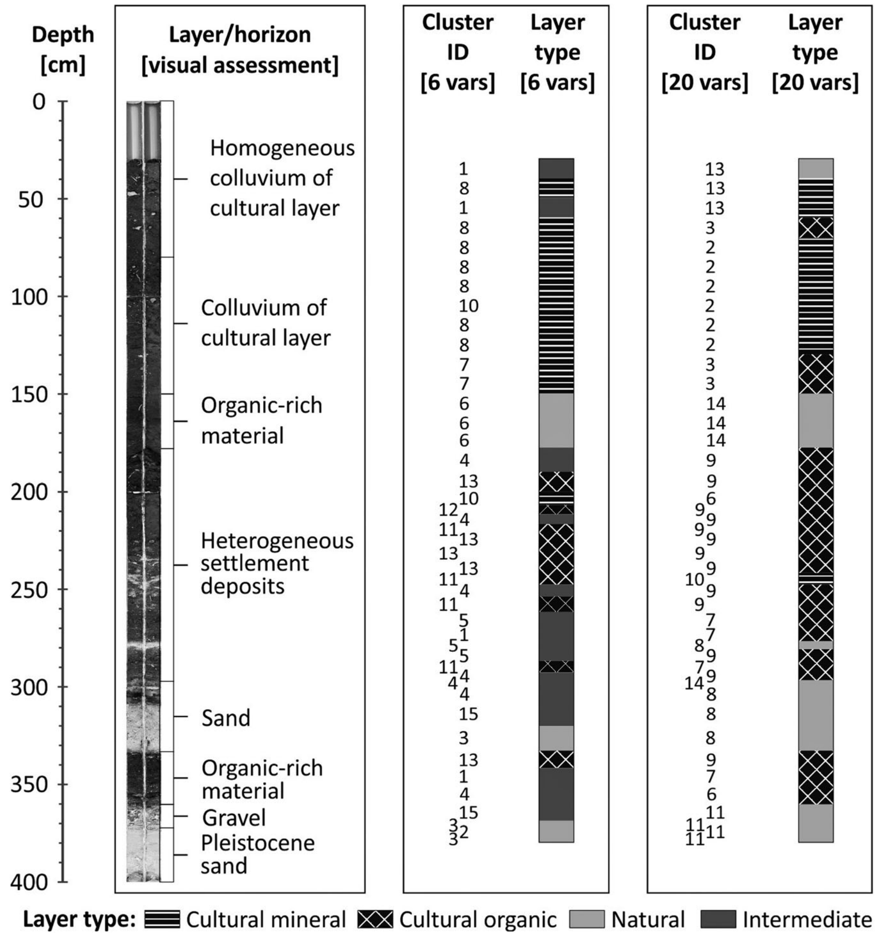


FIGURE 10 Application of the classification results for the core 2

set of variables. Sand at 300–335 cm depth, which was initially described as a sterile deposit, was confirmed to be a natural deposit. Importantly, it was possible to differentiate the next stratigraphic unit "heterogeneous settlement deposits" into subunits. Although both classifications agree on the mostly cultural organic-rich character of the materials, the initial classification revealed the presence of three sublayers of unclear origin. The extended classification revealed that one of such sublayers is a natural sand layer (perhaps of fluvial origin), whereas the other ones were reclassified as cultural organic-rich and cultural mineral materials. The IDs of the clusters in this unit also show that some differentiation is observed within the type of cultural organic materials. According to the classification based on six variables, two types of organic cultural deposits are present within this unit: Those rich in organic matter, CH/wood, and bones and those rich in organic matter, CH/wood, and artifacts. A layer of mineral cultural material was found at a depth of 210 cm. When compared to the expanded classification, three types of cultural organic-rich subunits are also present; however, they differ in terms of the content of stones, organic matter and CH/wood. The size of bones and artifacts present in this heterogeneous unit does not correspond to the relatively fine-grained embedding material in terms of depositional environment if fluvial or colluvial processes would be considered. Also, the artifacts and bones are well preserved and do not show any features suggesting fluvial transport. These considerations allow concluding that these organic-rich deposits in the valley of the brook represent waste deposits, which based on different clusters were dominated by waste from metal workshops (slags and pottery) or from households (bones and pottery).

Organic-rich material at 150 cm was identified as a natural peat layer, whereas the colluvium of the cultural layer was, as expected, classified as cultural material. The extended classification pointed out the presence of organic-enriched subunits within the colluvium, probably indicating changes in the hydrological situation. Interestingly, the uppermost part of the homogenous colluvium of cultural layer was classified as natural material by the extended classification, most probably because of weathering and soil formation.

Therefore, the clusters identified by the statistical analyses mostly show coherence and overlap with the visually identifiable strata in the core. More important, the relatively high-resolution sampling demonstrated that the principal component analysis combined with the clustering method helps to identify variability and internal stratigraphy within the stratigraphic units.

5 | DISCUSSION

5.1 | Set of parameters and classification as an approach

The classification approach presented in this study is based on six geoecological parameters, which were selected based on the existing knowledge of the characteristics of settlement deposits. Principal component analysis confirmed that this set of parameters, including contents of stones, artifacts, bones, and charcoal/wood as well as LOI at 550°C and MS, is a justifiable basis for the classification of materials in Hedeby. As a result of the clusterization performed in this study, 15 meaningful clusters were obtained, which were significantly different from each other in at least one parameter, with only one exception.

It is known that high numbers of artifacts, bones, and stones are characteristic of habitation deposits (Alexandrovskaya & Panova, 2003; Alexandrovskiy et al., 2012) and thus can be used for distinguishing cultural deposits from natural ones. Since these inclusions are separated during sample preparation for lab analyses, it is reasonable to include this information in quantitative terms for material classification. In this context, questions of preservation of artifacts and bones must be taken into account. Since artifacts in Hedeby are dominated by pottery shards, burnt loam, and metal slags—rather stable components against diagenesis—bone preservation is the most important issue. As it was shown by Milek and Roberts (2013), artifact and bone distributions should be used with a control of pH to account for possible under- or overrepresentation of some materials in comparison with others. In our study, pH varied in a range from 4.5 in cultural organic deposits to 7.7 in partly calcareous Pleistocene sediments. In organic-rich cultural layers, pH values were lower than in cultural mineral layers, which may have caused less favorable conditions for bone preservation in organic-rich deposits. Nevertheless, bones were also present in these slightly more acidic conditions, although in smaller amounts. Importantly, water stagnation conditions were observed in organic-rich cultural layers with lower pH. Even though bones and teeth are preserved better in alkaline soil conditions (Kibblewhite, Tóth, & Hermann, 2015), bones might persist in slightly acidic conditions at low redox potential levels in wet and waterlogged conditions, although some degradation features may occur (Retallack, 1984). Therefore, the effects of pH on bone preservation in the investigated cores probably did not reach critical levels due to the anoxic conditions. Nevertheless, it cannot be excluded that organic-rich cultural layers initially contained more bones during the settlement period.

Low values of the anthropogenic characteristics (artifacts, bones, charcoal/wood, and MS) were indicative of natural deposits and soil horizons. The measurement of organic matter content enabled further differentiation of natural deposits and soil horizons as well as cultural layers. MS and artifact content best described cultural mineral materials, whereby MS allowed revealing cultural materials and colluvium of reworked cultural layers if they were free of artifacts or other anthropogenic inclusions. High MS values were obviously associated with the presence of pottery fragments, burnt loam construction materials, and, most significantly, metal slags. High values of bone and charcoal/wood contents combined with organic matter content characterized cultural organic-rich materials. 18.2% of samples with intermediate properties could not be further classified using the six parameters. Thus, statistical analyses with additional variables were performed to test the robustness of the classification and to find out whether the reason for the large group of intermediate materials was the lack of information provided by the six parameters or whether these materials had such character.

The difference in classification results acquired by the application of the advanced set of parameters demonstrated that the results of classification are strongly dependent on the set of parameters used for the differentiation. Application of additional parameters showed, on the one hand, a good agreement of the initial classification with a more detailed one and, on the other hand, it allowed a better differentiation of intermediate materials, for which the genesis could not be initially determined. Unambiguously natural and cultural materials were classified in a similar way when applying additional parameters. The most significant changes occurred in intermediate and to a lower extent in natural samples; they were reclassified as cultural materials. This apparently took place since many samples that were initially classified as natural or intermediate, were free of archaeological finds and had a relatively low MS, but contents of Pb and P revealed their anthropogenic origin as cultural materials.

Among chemical elements, only P and Pb fell into the group of variables that describe cultural materials. Elemental data thus enhanced and even changed the interpretation of the genesis of some materials in Hedeby. Although contents of Pb and P seem to be most indicative of cultural deposits in Hedeby due to the performed settlement activities, at other sites, other parameters must be considered. However, the use of principal component analysis in the first step enables a correct and objective choice of variables. Since element measurements were performed in this study by a portable X-ray fluorescence device, with only powdering as a sample preparation procedure, the analytical time required for the inclusion of elemental data would not increase significantly. A more time-consuming procedure is the determination of grain size distribution, although, in the case of Hedeby, the increase in interpretative power provided by grain size data in terms of cultural versus natural genesis of materials is not as apparent. Cultural deposits are characterized by various grain size distributions so that no relevant information could be extracted from these data. However, in studies, where depositional processes are of interest, grain size data might provide valuable information.

5.2 | Classes of materials and their spatial patterns in Hedeby

The type of natural sediments resulting from the classification is quite homogeneous as it includes deposits that formed before settlement activities or natural materials that were translocated during the Viking settlement period, for example, fluvial sediments deposited by the brook.

Natural deposits were found in all investigated cores (coring points 1–15). Undisturbed buried soil horizons in Hedeby are rare but all of those that were intact were classified as natural materials. Soil A horizons were usually not found since they were truncated by erosion or incorporated into the cultural layers (J. Wendt, Christian-Albrechts-University of Kiel, unpublished results), whereas B horizons in most cases were often preserved and lay in contact with cultural layers. For this reason, the material of B horizons in 25% of the cases was classified as intermediate.

Figure 11 depicts spatial patterns in the distribution of some clusters among the investigated cores. Intermediate materials (clusters 1, 4, 5, and 15) are stronger associated with cores retrieved nearer to the thalweg of the brook (particularly cores 6 and 8, but also 2 and 3), whereas 80% of materials classified as intermediate are restricted to these cores. Thus, it can be assumed that these deposits represent fluvial sediments of the brook, which were initially natural in their properties, but which became postdepositionally enriched in anthropogenic characteristics due to their deposition within the settlement.

Due to the absence of younger settlement activities in Hedeby, Viking Age cultural layers are well preserved in accumulative landscape positions at the brook. The geomorphological conditions, hydrologic regime, and land use are the main factors affecting the preservation of cultural layers (Baltakov, 2008). Thus, the type of cultural deposits represents materials that formed during the settlement period (mineral and organic-rich cultural layers). Cultural organic-rich deposits with high contents of bones and artifacts (clusters 11, 12, and 13, Figure 11) are present in all cores but are particularly abundant in cores 1, 2, and 4 in the western part of the settlement. Mineral cultural layers with very high levels of anthropogenic characteristics (clusters 10 and 14) are dominating in cores 4, 5 and 7, indicating the presence of features most probably related to metalworking (very high MS values). Due to the properties of the embedding material and well-preserved state of bones and artifacts, it can be concluded that these inclusions were not transported by water but were deposited there by humans. Therefore, these cultural deposits with abundant bones and artifacts probably represent waste materials deposited in the brook valley originating from both domestic (bones and pottery) and economic activities (slags and pottery). This agrees with findings in the eastern part of Hedeby, which suggested the deposition of wastes in the brook in the late settlement period (Jankuhn, 1943; Kalmring, 2010).

Two classes of colluvium of reworked cultural layers were distinguished: 7 (moderate anthropogenic characteristics) and 8 (strong anthropogenic characteristics). Because the colluvial material originates from cultural layers upslope in the catchment, its properties reflect the properties of these cultural layers before erosion. Colluvium of reworked cultural layers in cluster 8 was characterized by a high MS of the same magnitude as the cultural layers of clusters 10 and 14 but no bones and wood and a lower content of artifacts

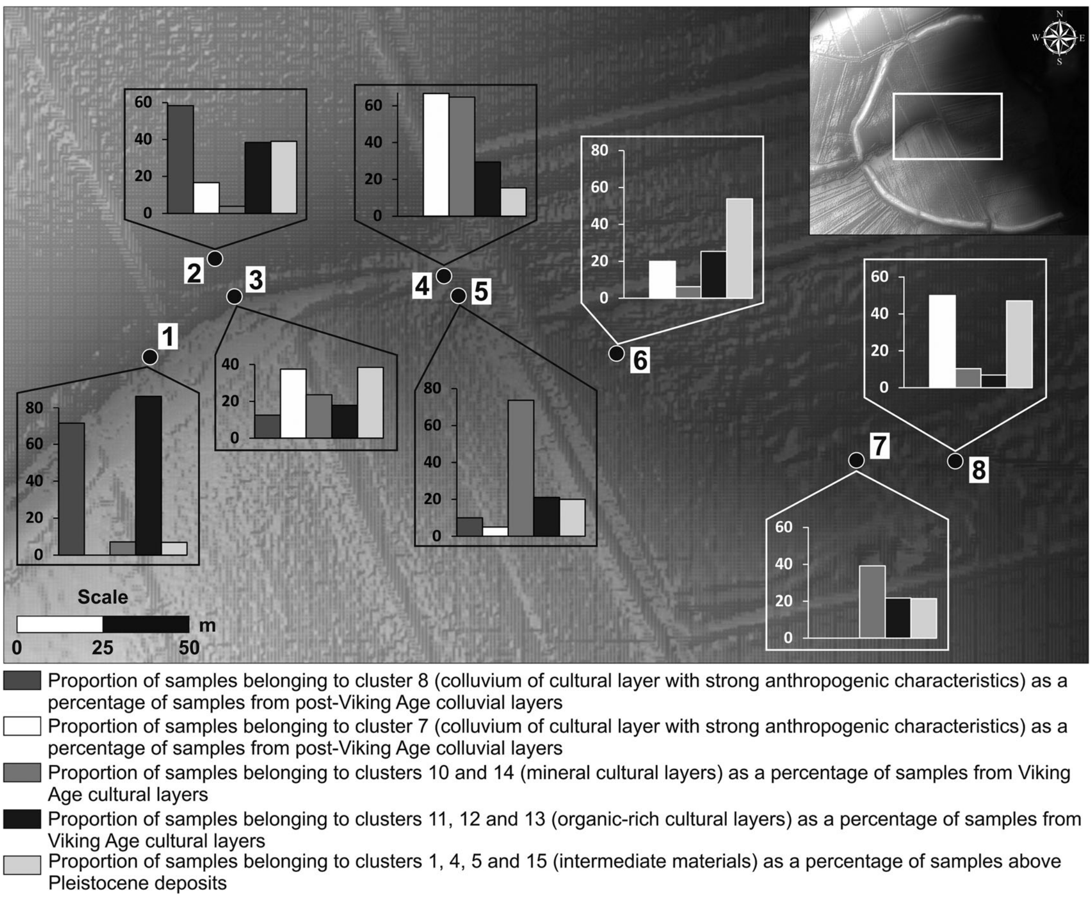


FIGURE 11 Spatial patterning of clusters among the cores

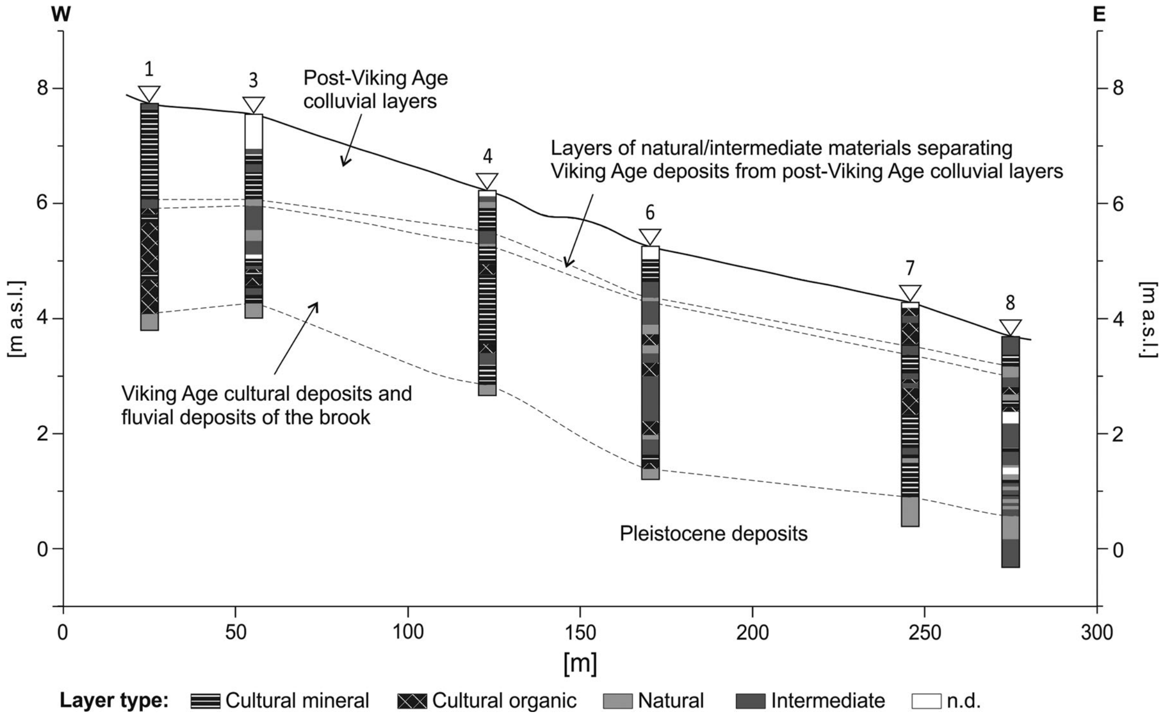


FIGURE 12 Longitudinal profile of the cores along Hedeby-brook with major stratigraphic units

were found in the colluvium. Cluster 8 is clearly restricted to the northwestern part of the study area (Figure 11), whereas cluster 7 is dominating in the central and eastern part of the study area implying the absence of cultural layers with high MS in the vicinity of those coring sites. The measured values of MS in cluster 8 correspond to MS values obtained in other studies of habitation deposits of urban and protourban settlements in the region (Macphail, Cruise, Engelmark, & Linderholm, 2000). Such high MS together with the spatial distribution of cluster 8 points at the presence of workshops of smiths in the northwestern part of the settlement that has been previously suggested by geophysical surveys using Fluxgate- and Cesium-magnetometer and ground-penetrating radar (Hilberg, 2009).

Interestingly, colluvium of reworked cultural layers and cultural layers themselves near the modern land surface were classified as intermediate materials. This occurred due to the homogenization of their upper parts by long-term plowing and quasi absence of artifacts. Moreover, these layers are involved in recent soil formation, which caused the classification of the plowed colluvium of reworked cultural layers exposed at the land surface as natural material in the initial classification based on six parameters. According to Sycheva (2006) such cultural layers are a subject to postdepositional transformation, and in case of a pedogenic transformation, they overtake the properties of the soil being formed. The results of research by Golyeva, Chichagova, and Bondareva (2016) even show that cultural layers of ancient settlements transform into zonal soils over time, regardless of their geographic location. Hence, the results of this study clearly show the beginning of the “erasing” of the cultural signature by soil formation in the material, which was initially a cultural layer.

For six cores near the thalweg of the Hedeby-brook, a longitudinal profile with major stratigraphic units was constructed (Figure 12). The results of the classification aided in the connection of some units in individual cores; however, heterogeneous cultural deposits were not possible to correlate with these large distances between the cores. The basis of the sequences was easily identifiable as the natural Pleistocene deposits, followed either by Viking Age cultural deposits (cores 1, 4, 6, and 7) or fluvial deposits of the brook alternating with cultural layers (cores 3 and 8). Interestingly, for both groups of the cores, Viking Age deposits are separated from the colluvium of the cultural layer above by layers of natural and intermediate origin (peat or sand layers depending on the hydrological conditions). This probably illustrates the period of low human activity on the territory of the former town after the abandonment of the settlement and before agricultural land use started in high medieval times.

6 | CONCLUSIONS

The novel approach presented in this paper combines a relatively fine-scale sampling strategy, a multimethod geoarchaeological investigation of cores and multivariate statistics to aid in the classification and interpretation of large, complex, and intricately stratified archaeological deposits at former settlements. It was demonstrated that it is possible to reliably distinguish materials of natural and cultural genesis using a small set of rapidly and cost-effectively measurable parameters, whereas an extended set of parameters allows a more precise and accurate classification. Based on the case study at the internationally significant Viking Age town Hedeby, the proposed approach enabled the classification of heterogeneous settlement deposits, colluvial sediments, and soil horizons providing new archaeological information about this prominent settlement.

For the first time, the complex stratigraphy of various deposits at Hedeby-brook was described based on objective criteria developed through the detailed geoarchaeological investigation of cores. Intensive settlement activities have considerably altered natural soils and sediments in Hedeby, which led to the formation of a wide range of heterogeneous settlement deposits. Together with soils, they were classified based on a multivariate statistical analysis of a set of geoecological parameters by principal component analysis and cluster analysis. An objective and reliable differentiation between natural and cultural deposits (a key task of most archaeological investigations) could be performed. Diverse cultural deposits were further distinguished in terms of organic matter content, stone content, and level of anthropogenic characteristics. Based on that, some hypotheses regarding land use in the adjacent areas were made. It was suggested that the area at Hedeby-brook was used for the disposal of wastes from different sources, whereas the area north of the brook was confirmed to be associated with metalworking.

The approach developed for the classification of various settlement deposits is applicable to other settlements—only the set of parameters needs to be adapted to local conditions. Because the classification approach is based on simple and cost-effective measurements on cores, it can be used in the first research step after field surveys to identify habitation sites and function areas within them, to select sites where detailed investigations are necessary, and to develop a correct and reproducible stratigraphy. Areas that are of interest for larger-scale excavations may be found and justified based on objective criteria. Moreover, the methods presented allow important archaeological information to be gathered fast and with minor disturbances compared to full-scale excavations, particularly in wetland areas and where archaeological remains are covered with thick colluvial or alluvial sediments. Materials with intermediate properties can be investigated in a more goal-oriented manner using this classification approach. The set of parameters describes only current properties of the materials without considering the genesis and diagenesis of the sediments, thus a detailed analysis of the composition and properties of the clusters must be carried out. Therefore, this classification approach should not be considered as an “automated” procedure of classification but as a support tool when large numbers of cores and samples are to be analyzed, particularly at such complex study sites as former settlements.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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APPENDIX

SUMMARY OF DESCRIPTIONS OF CORES 1–8 WITH RESULTS OF CLUSTER ANALYSIS

Layer ID	Depth	Colour	Texture	Clusters	Comments
Core 1					
$M_{cult\text{-}hom}$	0–91	10YR 2/2	Silty MSa & FSa	1, 9, 8, 8, 8, 8, 8	Contains a few stones (2–4 cm) at 23, 50, and 61 cm; a yellowish aggregate of burnt material and relatively large charcoal (ca. 1 cm) at 85 cm
$M_{cult\text{-}hom}$(ch)	91–100	10YR 2/1	Silty FSa & MSa	8	Similar to the layer above but darker and somewhat finer (less Msa)
Sand(h)	100–139	10 YR 3/1, 2/1	MSa	8, 8, 10	Hom. dark brown sand material
M_{cult}	139–190	10YR 2/1	Silty MSa & FSa	8, 10, 8, 4	Relatively hom. material rich in OM and with presence of a small amount of charred material. Contains a stone (more than 5 cm diam.) that was destroyed during drilling at 143 cm, at the same place—a pottery fragment; a slag; a small flint splitter at 172 cm and a small stone at 196 cm
$Y_{cult,org}$	190–300	10YR 2/1	Silty MSa & FSa	11, 9, 12, 12, 12, 13, 12, 11	Contains bones at 235, 240, 260, and 278 cm, a relatively large stone 4 cm and some wood remains in whole layer
Y_{cult}	300–313	10YR 2/2	Silty MSa & FSa	14	
$Y_{cult,org}$	313–372	10YR 3/1, 4/2	Silty FSa & MSa	12, 12, 11, 11, 13	Het. material, partly an alternation of H and sand layers. Contains a bone at 366 cm and a large burnt fragment (4–5 cm) of construction material at XX cm; charcoal in dark parts.
Gravel	372–390	10YR 5/3, 4/3	MSa, CSa, stones	3, 3	Not similar to gravel at other valley bottom parts. Nearly no OM, matrix is Csa—brook bed? The stones are mostly subrounded.
C_{varved}	390–400	10YR 5/6	FSa, sandy loam	3	Alternation of fine sand and loam layers
Core 2					
$M_{cult\text{-}hom}$	0–80	10YR 2/2	Silty MSa & FSa	1, 8, 1, 8, 8	Contains a few stones (0.5–3 cm) at 47, 58, 65 cm, brick fragment at 67 cm
M_{cult}	80–150	10YR 2/1	Silty MSa & FSa	8, 8, 10, 8, 8, 7	Similar to the layer above but darker (especially in the lower part). Contains a large burnt clay piece (1 cm) at 84 cm and a few stones (~2 cm) at 81 and 93 cm
H	150–178	10YR 2/2	Organic	6, 6, 6	A typical peat layer, very homogeneous, nearly purely organic; most plant remains are decomposed
$Y_{cult,org}$	178–297	10YR 2/2, 2/1, 2.5Y 5/2, 5/1	Organic, sand: MSa, Fsa	4, 13, 10, 12, 4, 11, 13, 13, 13, 11, 4, 11, 5, 1, 5, 5, 11, 4	A very het. layer dominated by organic material and in some parts plant remains, at some places layering is recognizable. At 240–259 cm disturbed layers of light greyish sand are present. Contains large bone fragments (>3 cm) at 227 and 232 cm, wood fragments (a large one >5 cm at 179–186 cm) and charcoal
Grey sand	297–333	5Y 5/1	MSa - CSa	4, 4, 15, 3	Weakly sorted grey sand. Contains stones (1 cm) at 112 and 114 cm

(Continues)

$Y_{cult,org}$	333–360	10YR 2/2	Het.	13, 1, 4	A het. OM-rich layer with abundant wood fragments. Contains a charcoal at 338 cm
Gravel	360–369	nd	MSa, FSa, stones	15	A het. layer of gravel and coarse sand. At the transition to the lower layer a prominent thin layer of coarse sand is located. Contains a large (>5 cm) flint at 155 cm
C_{sand}	369–400	10YR 6/2	MSa	3, 3, 2, 3	Part of Pleistocene filling of the valley; light grey sand with some finer material in the upper part
Core 3					
$M_{cult\text{-}hom}$	0–100	10YR 2/2	Silty MSa & FSa	1, 8, 9, 4	Hom. layer, rich in OM but dominated by mineral material. Contains a large flat stone fragment (5 cm) at 82 cm with sharp edges; a white burnt flint (3 cm) at 78 cm
M_{cult}	100–147	10YR 3/1	Silty MSa & FSa	7, 10, 7, 7	The material is very similar to the one above with a slightly higher sand content. Contains a root of an aquatic plant; single charcoal fragments are present, a relatively large pottery fragment at 124 cm
H	147–158	10YR 2/2	Organic	6	Mostly OM with single quartz grains. Fine peat with only some undecomposed plant remains present.
Sand+M(h) (layered)	158–242	10YR 3/1, 4/1, 5/1	MSa & FSa	4, 5, 5, 5, 3, 5, 15	Alternating layers of pale light grey sand and OM-rich finer-grained layers. Contains abundant wood pieces, plant remains, and large charcoal fragments
Y_{cult}	242–262	10YR 2/2	Het.	13, 10	Upper part of the het. settlement deposits, rich in OM with plant/wood remains and charcoal. Lower part is more het. and in general coarser—with presence of Csa. Contains a bone at 257 cm
Sand	262–267	10YR 5/1	FSa & MSa	4	Light grey sand, hom. well-sorted. Contains a charcoal at ca. 265 cm
$Y_{cult,org}$	267–273	10YR 2/1		12	Het. layer dominated by OM and undecomposed wood/plant remains. Contains a bone at 268 cm
Y_{cult}	273–300	10YR 3/2 10YR 5/1 10YR 2/2	MSa with CSa	14, 12, 14	A very het. layer dominated by light grey Msa with presence of Csa. Contains a whitish, most probably burnt sharp-edged stone at 278 cm and a bone at 276 cm, charcoal. Lower part is more hom., dominated by brownish sand with a relatively high OM content. Contains charcoal, bone at 298 cm
Sand	300–311	10YR 4/2	Msa	15	A quite hom. layer. Contains small burnt clay piece
$Gavel_{cult}$	311–326	10YR 3/2–3/1	MSa, CSa, stones	14, 9	Matrix dominated by Csa with presence of small and large stones. In the lower part: Large stones (4–5 cm or more). In general, stones are both sharp-edged and rounded. Embedding material is dark grey Msa, Csa. In some parts, presence of charred material is possible
Gravel	326–343	10YR 3/2–3/1	CSa, MSa, stones	3, 3	
C_{varved}	343–351	5Y 4/1	alternating	2	
Core 4					
$M_{cult\text{-}hom}$	0–70	10YR 3/1	Silty Fsa	1, 3, 7, 7, 7, 7	
Mix: $M_{cult\text{-}hom}$+Sand	70–108	10YR 4/2, 5/2–8/2, 5YR 4/6–6/6	MSa & FSa	1, 1, 3, 10	Abundant oxidation spots
$Gravel_{cult}$	108–124	10YR 3/1 (fine fraction)	Gravel with Fsa & Si	14	A few relatively large stones (5 cm) are present in this layer
$Y_{cult,org}$	124–145	10YR 3/1, 4/1, 7/2–7/3	MSa with Si	10, 11, 11, 12, 12, 12	Lower part contains Csa. Contains a brick fragment at the border with the lower layer
Y_{cult}	145–247	10YR 3/1	Sand+Si with Csa and pebbles	10, 10, 10, 10, 10	Contains pottery and leather pieces at 150 and 185 cm, bone at 160 cm, abundant charred material, wild boar tooth at 235

(Continues)

		10YR 2/1	Fsa, Si		
		10YR 4/1	Msa, Fsa, Si		
Gravel$_{cult}$	247–264	10YR 2/1	Fsa, Si	10	Contains abundant pebbles, bone at 250 cm, wood pieces at 265 cm
Y$_{cult,org}$	264–280	10YR 2/1	Het.	12	
Gravel$_{cult?}$	280–300	nd	Msa, Csa	15	
Y$_{cult}$	300–334	10YR 4/2–4/3	Msa, Csa	14, 14	
Gravel	334–340	10YR 4/2	Msa, Csa	3	Most probably the brook bed, lower part contains a wild boar tooth
Sand	340–352	10YR 3/1	Fsa, Msa, Si	2, 2	
		10YR 5/1	Fsa, Si		
Core 5					
M$_{cult\text{-}hom}$	0–70	10YR 2/2	Silty Fsa	1, 8, 7, 7, 7, 7, 7	Contains a wood fragment at 26 cm.
M$_{cult\text{-}hom}$+Sand	70–118	10YR 7/2, 3/2, 5YR 4/6	Fsa, Msa	1, 4, 1	A mixture of the cultural layer with sand material with oxidation spots
Sand+Y$_{cult}$ (layered)	118–130	10YR 2/2, 7/2	Fsa, Msa	2, 7, 4	
Y$_{cult,org}$	130–140	10YR 2/1	Silty Fsa	11	Contains a stone at 143 cm, charcoal fragment at 157 cm
Gravel$_{cult}$	140–150	10YR 2/1	Silty FSa, MSa, stones	12	
Y$_{cult,org}$	150–165	10YR 2/2	Silty FSa, MSa	11	
Y$_{cult}$	165–176	10YR 7/2	Fsa, Msa, Si	14, 14	
		10YR 7/2, 3/1			
Y$_{cult,org}$	176–200	10YR 2/2	Fsa+Si	12, 4	
Gravel$_{cult}$+Y$_{cult}$	200–250	10YR 7/2, 2/2–2/1	Fsa, Si	14, 10, 10	Contains stones, bones, and charcoal at 210 cm; a bone fragment at 230 cm, stones at 235 cm, wood pieces at 247 cm
Y$_{cult}$	250–264	10YR 4/1	Fsa, Si	14	Contains a bone fragment at 257 cm
Gravel$_{cult}$	264–276	10YR 3/1–4/1	Fsa, Si	14	Contains pottery at 263 cm, stones at 270 cm
Y$_{cult}$	276–288	10YR 5/2, 2/1	Fsa, Msa	10	Contains bone fragment at 280 cm, burnt clay piece at 285 cm
Gravel$_{cult}$	288–300	10YR 6/2–5/2	Upper: Fsa, Msa, lower: Msa, Csa	14	Contains bone fragment at 320 cm, flint at 333 cm, burnt clay at 358 cm, bone at 367 cm
Y$_{cult}$	300–323	10YR 4/1	CSa, MSa	14	
Gravel$_{cult}$	323–386	nd	MSa, CSa, stones	14, 14	
M	386–398	10YR 3/2	Msa, Csa	2	Colluvial material of unclear origin
Core 6					
M$_{cult\text{-}hom}$	0–61	10YR 2/2	Fsa, Msa, Si	7, 7	Contains abundant roots in the upper part, a brick piece at 31 cm and a large stone (4 cm) at 45 cm
Mix: M(h) +Sand	61–83		MSa & FSa	1	
H	83–94	10 YR 2/2–2/1		1, 6	Nearly purely organic layer. Contains charcoal in the lower part
Mix: Sand+H	91–135	10 YR 7/2, 2/2	MSa & FSa	5, 5, 5	Dominated by H material with presence of charcoal. Contains some wood remains

(Continues)

H	135–183,5	10 YR 2/2–2/1	Organic	6, 6, 11,6	Peat with presence of some wood (root?) material in the upper part and a fine-grained dark mineral material with a high OM content and some relatively large wood pieces in the lower part
Mix: H+Sand +H_{wood}	183,5–324	Extremely het.	Extremely het.	5, 13, 5, 4, 4, 5, 5, 12	Alternation of coarse sandy (partly gravelly) and organic-rich layers. Contains a very large (width 5 cm, length 10 cm) wood piece embedded at 185–195 cm and a smaller (3–4 cm) wood piece at 295 cm, numerous undecomposed wood remains, stones (ca. 2 cm) at 268, 276, 289 cm, some charcoal
Sand	324–331	Brown	MSa	3	Mostly light-colored Msa with some brown organic spots
Mix: H+Sand	331–357	10 YR 2/1–2/2, 7/2	MSa & FSa	5, 15, 5	Dark brown layer of OM and sand with presence of a large (3–4 cm) wood piece and with very abundant wood remains, and a large charcoal piece
Y_{cult}	357–382	5Y 4/2	Fsa/Msa	14, 12	Not hom. but obviously finer than sand material above and below. Contains a pottery piece at 358 cm and small wood remains at 380 cm
Gravel	382–400	10YR 2/2, 5/1	Csa and gravel	3, 3, 3	Stones ca. 5 cm embedded in coarse sand and dark brown organic-rich material
Core 7					
$Y_{cult,org}$	0–74	10YR 2/2	Fsa, Si+Msa	13, 4, 13, 13, 11	Peaty layer consisting of nearly pure organic material with plant remains and with single sand grains. Contains partly decomposed wood remains in the lower part
Y_{cult}+Sand (layered)	74–126	10 YR 2/1–2/2, 7/2	Silty Fsa, MSa, sand - MSa	10, 4, 10, 10	Very dark greyish brown muddy material and organic material dominated by decomposed plant/wood remains alternating with light grey sand layers
$Y_{cult,org}$+Sand	126–152	10 YR 2/1–2/2, 5/1	Het., sand - MSa	4, 11, 15	Loose layer of mostly partly decomposed wood remains with presence of light grey sand
H_{wood}+Gravel	152–200	10YR 2/2, 2/1, 5/6	Extremely het.	12, 12, 12, 12	Very “turbulent” layer dominated by organic material (mostly undecomposed) and gravel. Numerous large wood pieces are present at 153, 176 cm, large broken flints at 166 cm, large bone pieces at 153 and 194–200 cm
Y_{cult}+Sand (layered)	200–278	10 YR 2/1–2/2, 7/2	Msa/Csa	14, 10, 10, 14, 4, 15, 14	Het. mixture of sandy and organic material forming a few alternating layers. Contains small stones at 220–235 cm and 250–270 cm
Sand+M(h) (layered)	278–286	10YR 4/1	MSa & Csa	3	Presence of small stones
$Y_{cult?}$	286–300	10YR 2/2	Msa/Csa & gravel	14	
Sand+Y_{cult} (layered)	300–348	10YR 4/3	Het.	9, 9, 9	Contains single stones in the whole layer and a wood piece/root at 313 cm
Gravel	348–355	nd	CSa, MSa	3	Mostly sandy layer but with presence of a relatively large amount of gravel
Sand	355–389	10YR 6/4	MSa, CSa	3, 3, 3	Same material as at 300–348 cm but a bit lighter in colour; in the upper part, dominated by dark brown sand, in the lower part by light brown sand. Contains a flint (2–3 cm) with sharp edges at 366–367 cm, root remains at 384 cm
Gravel	389–396	nd	Gravel+CSa	3	
C_{varved}	396–400	5Y 5/2	Loamy sand	3	
Core 8					
$M_{cult\text{-}hom}$	0–52	10YR 3/1, 2/2	Msa, Fsa+(Si)	1, 4, 7, 7	Relatively hom. layer, quite rich in organic matter. The upper 19–20 cm of this layer, modern Ah with recent organic matter formation and accumulation. Contains a few charcoal pieces (largest 0.6–0.7 cm) at 23 cm, few small charcoal pieces at 35 cm, burnt clay fragments at 32, 46 and 47 cm, some stones, vivianite formations throughout the layer

(Continues)

H	52–70	10YR 2/1	Organic	6	Hom. peat layer consisting of nearly pure organic matter (decomposed plant remains)
Mix: Sand+H	70–87	5Y 5/1, 10YR 2/1–2/2	Msa (sand)	4, 4, 5	A mixture of in situ formed peat and redeposited sand (m.p. deposition during peat formation). Contains some undecomposed plant/wood remains.
Mix: H_{wood}+Sand	87–130	10YR 2/1–2/2, 5Y 5/1	Msa	12, 2, 14, 12	The upper part of this layer is dominated by H material (hom., almost no sand); the mid-part of the layer is a chaotic mix dominated mostly by H_{wood} followed by relatively hom. sandy material, quite rich in organic matter, mostly MSa with some small stones. The lowest sublayer is H_{wood} with a high OM content and some undecomposed wood. Contains abundant fragments of undecomposed wood, stones, burnt flint throughout the sublayers and small wood and bone fragments at 110 cm, 117–121 cm, and 126 cm
Mix: H+Sand +H_{wood}	130–223	10YR 2/1–2/2, 5Y 5/1	Msa, Csa (sand)	5, 15, 15, 15, 14, 15, 15	Het. layer in the upper part dominated by H (almost purely organic), in the central part: A disturbance filled by sand is present; in the lower part: H_{wood}, at some places very thin (2 mm) layering is distinguishable. Contains undecomposed wood fragments, a large bone (sheep or goat) piece at 177 cm, another bone piece at 180 cm, group of thin and flat bones at 200 cm, wood piece at 185 cm
Gravel	223–227	nd	CSa	3	Sandy layer with a very high content of gravel with rounded edges (from 0.2 to 2.5–3 cm). At the border with the underlying layer a stone with sharp edges is located
Wood piece	227–238				
Sand	238–248	2.5Y 5/1, 6/3	Fsa/Msa	3	A layer of well-sorted Fsa/Msa with prominent fine layering (1–2 mm). Some microlayers are composed of pure mineral sand, some sand with OM.
Mix: Sand+M (h)+Gravel (layered)	248–311	10YR 4/2–3/2	Fsa/Msa & Msa	9, 4, 2, 15, 10, 5, 2, 5, 3, 5	Alternation of: het. layers rich in OM and sandy finely layered deposits (mostly MSa) consisting of thin (2 mm–1 cm) layers of pure sand and sand with a high OM content. Contains: OM-layers—rounded stones (2–3 cm) as well as stones (flint) with sharp edges at 284–260 cm, undecomposed wood remains at 254–260, hazelnut shell at 272 cm, charcoal present; sandy layers: Some charcoal pieces, largest at 261 cm
Mix: Sand +Gravel	311–341	10YR 4/1	MSa & CSa	3, 3	Het. layer dominated by pale sand material (Msa and Csa) with presence of OM at some places, becomes coarser with depth. Contains abundant stones particularly in the lower part (1–2 cm up to 3–4 cm), both rounded and sharp, undecomposed wood/root fragment at 115–117 cm
Sand	341–372	10YR 5/3	Msa+(Csa)	3, 15, 15	Quite well-sorted light brown sand material with presence of Csa and single stones (1 cm), becomes coarser with depth. Contains bone fragments at 346, 353, and 372 cm
C_{sand}	372–400	2.5Y 6/2	MSa–CSa	15, 15	Poorly sorted sand material that contains some OM (light greyish brown). Contains abundant small stones (1–2 cm) in the whole layer

Abbreviations: (ch), with presence of charred material; (h), with presence of humic material; CSa, coarse sand, FSa, fine sand, Het., heterogeneous, hom., homogeneous, MSa, medium sand, OM, organic matter; Si, silt.