

# LANDSCAPE DEVELOPMENT AND SOIL TRANSFORMATION IN THE FORMER VIKING SETTLEMENT HEDEBY

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**Svetlana Khamnueva**

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Dekanin: Prof. Dr. Natascha Oppelt

Erster Gutachter: Prof. Dr. Hans-Rudolf Bork

Zweiter Gutachter: Prof. Dr. Ingmar Unkel

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## Abstract

Geoarchives at former settlements – namely buried soils and cultural layers – contain valuable information about human-landscape interactions in the past. Understanding these relationships is particularly important owing to the current problems of soil and landscape degradation. Due to the complex interplay of natural and anthropogenic processes responsible for the formation of the geoarchives, environmental conditions and human activities can be reconstructed based on their properties. Abandoned early urban settlements represent precious objects for geoarchaeological research since the processes of deep soil and landscape transformation in result of the transition from the rural to the urban life can be traced there.

In Northern Europe it was the Viking Age, when the first proto-towns appeared. The Danish emporium of Hedeby, which is known from written records since 804 AD, was a major international trading centre in the Viking Age until its final destruction in 1066 AD. Although abundant archaeological data regarding the lifestyle of the inhabitants and economy of the town are available, only very scarce information about local soil and landscape transformation exists. This research aimed to fill this gap by a detailed analysis and classification of the heterogeneous soils and settlement deposits of Hedeby and by an integrative investigation of the development of the geomorphologic situation in the central part of the settlement.

The heterogeneous soils and settlement deposits were classified using a new approach, developed in this research, which is based on multivariate statistical analysis of the geo-ecological characteristics of the soils and sediments. Natural and cultural deposits as well as materials with transitional properties were distinguished. Cultural and natural deposits could be further classified based on their specific features. The developed approach is reliable, reproducible and well applicable to other settlements. It can be used in the first research step to select sites where detailed investigations are necessary. Particularly for protected sites where only drillings are possible, this approach may significantly help to improve the understanding of the variety of sediments in cores, to provide a reliable stratigraphy and to prepare a solid and reproducible basis for further research steps.

Using the results of the classification, a correct correlation of the cores in the central part of Hedeby could be done, which was essential for the construction of the general stratigraphy of the sediments at the Hedeby-brook. There, a large valley-like structure created by humans in the Viking Age was discovered. The results of dating, geomorphological, geo-ecological and micromorphological investigations allowed reconstructing the main phases of local landscape transformation before, during and after settlement activities. Some theses for the initial purpose behind this elaborate landscape-engineering project were suggested including water management and extraction of material for different settlement activities. The structure undoubtedly played a major role in the organization and functioning of the town; moreover, it divided the whole western part of the town into a northern and a southern district, which required the erection of special constructions to enable a direct access from the northern to the southern district and vice versa. The buried anthropogenic valley-like structure in the central part of Hedeby has no analogies at other Viking Age sites. Its interpretation is essential for our understanding of the settlement patterns in the Viking Age.

The outcome of this research can be relevant for investigations at other sites regardless their spatial or temporal constraints. The findings emphasize the importance of interdisciplinary research at archaeological sites with an effective involvement of natural scientists.

## Zusammenfassung

Geoarchive in ehemaligen Siedlungen mit begrabenen Böden und Kulturschichten enthalten wertvolle Informationen zu den Mensch-Umwelt-Interaktionen in der Vergangenheit. Umfassende Kenntnisse zu diesen Wechselwirkungen sind erforderlich, um die Probleme der rezenten Boden- und Landschaftsdegradation verstehen zu können. Basierend auf den in Geoarchiven bis heute erhaltenen Relikten der komplexen Interaktionen von natürlichen und anthropogenen Prozessen können Umweltbedingungen und Aktivitäten von Menschen mit Hilfe der Materialeigenschaften rekonstruiert werden. Aufgegebene frühe städtische Siedlungen sind bedeutende geoarchäologische Untersuchungsobjekte, da in ihnen die Prozesse tiefgreifender Boden- und Landschaftstransformationen als Resultat des Übergangs von ländlichem zu städtischem Leben noch heute identifiziert werden können.

In Nordeuropa bildeten sich die ersten Proto-Städte in der Wikingerzeit. Der Seehandelsplatz Haithabu, der aus schriftlichen Quellen seit 804 n. Chr. bekannt ist, war bis zu seiner Zerstörung im Jahr 1066 n. Chr. das bedeutendste internationale Handelszentrum in Nordeuropa in der Wikingerzeit. Obgleich vielfältige Daten zum Leben der Bewohner und zu der ökonomischen Situation der Stadt durch intensive archäologische Forschung gewonnen werden konnten, liegen nur wenige Informationen zur Boden- und Landschaftstransformation vor. Die vorliegende Dissertation verfolgt das Ziel, diese Lücke über eine detaillierte Analyse und Klassifikation der heterogenen Böden und siedlungsbedingten Ablagerungen sowie durch eine integrative Untersuchung der Entwicklung des Reliefs im zentralen Bereich der Siedlung zu schließen.

Die heterogenen Böden und siedlungsbedingten Ablagerungen Haithabus werden mit einem neuen Ansatz klassifiziert. Er nutzt multivariate Statistikmethoden für eine fundierte geoökologische Charakterisierung der Böden und Sedimente. Unterschieden werden natürliche und anthropogene Sedimente sowie Ablagerungen mit Übergangseigenschaften. Die natürlichen und die anthropogenen Sedimente konnten auf der Grundlage bestimmter Merkmale weiter differenziert werden. Der entwickelte Ansatz ist zuverlässig, reproduzierbar und auch auf andere Siedlungen übertragbar. Er kann in einem ersten Arbeitsschritt genutzt werden, um Standorte zu identifizieren, an denen detaillierte Forschungsarbeiten notwendig und lohnend sind. Besonders an geschützten Standorten, an denen nur gebohrt und nicht gegraben werden darf, hilft die entwickelte Methode, die Vielfalt der in Bohrkernen vorgefundenen Sedimente besser zu verstehen und kausal zu verknüpfen. Sie ermöglicht die Erstellung einer verlässlichen Stratigraphie und ist eine solide und reproduzierbare Basis für die weiteren Arbeitsschritte.

Mit den Resultaten der entwickelten Sedimentklassifikation konnten die Bohrkern im zentralen Bereich von Haithabu korreliert werden – ein essentieller Schritt für die Erstellung einer generellen Stratigraphie für alle Sedimente im Tal des Haithabu-Baches. Dort wurde eine große talartige Struktur entdeckt, die Menschen in der Wikingerzeit angelegt hatten. Die Ergebnisse von Datierungen, geomorphologischen, geoökologischen und mikromorphologischen Untersuchungen erlauben eine verlässliche Rekonstruktion der Hauptphasen der Landschaftstransformation vor, während und nach den wikingerzeitlichen Siedlungsaktivitäten.

Einige Thesen zu den Gründen der arbeitsintensiven Anlage der talartigen Struktur werden vorgeschlagen, darunter ein Wassermanagement und die gezielte Entnahme von Material für unterschiedliche Siedlungsaktivitäten. Die Struktur hatte unzweifelhaft eine große Bedeutung für die Organisation und die Funktionen der Stadt. Sie teilte den Westen der Stadt in einen nördlichen und einen südlichen Bereich. Damit wurde die Errichtung spezieller Konstruktionen erforderlich, die einen direkten Zugang zwischen beiden Stadtteilen ermöglichte. Die anthropogene talartige Struktur im zentralen Bereich von Haithabu besitzt keine Analogien in anderen Wikingersiedlungen. Ihre Interpretation ist essentiell für das Verständnis der Siedlungsstrukturen der Wikingerzeit. Die Forschungsergebnisse können relevant sein für Untersuchungen an anderen Orten, unabhängig von den räumlichen und zeitlichen Rahmenbedingungen. Sie verdeutlichen die Bedeutung interdisziplinärer Forschung an archäologischen Standorten und die Notwendigkeit der effektiven Einbeziehung von NaturwissenschaftlerInnen.



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## List of abbreviations

a. s. l.	above sea level
c:f ratio	coarse material : fine material ratio
CH	charcoal
FOV	field of view
GSD	grain size distribution
LOI	loss on ignition
LOD	limit of detection
MS	magnetic susceptibility
OIL	oblique incident light
OM	organic matter
PCA	principal component analysis
PPL	plain polarized light
ppm	parts per million
XPL	crossed polarized light
XRF	x-ray fluorescence

# 1. INTRODUCTION

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## 1.1. RELEVANCE OF THE RESEARCH

Human settlements represent complex natural-anthropogenic systems with their own principles of organization and functioning. In the context of human-landscape interactions, most complex, concentrated and intensive processes of landscape alteration by humans characterize settlements. Understanding the complexity of processes of geomorphological and pedo- and lithological transformations is not only of bare interest for the reconstruction of ancient societies' relationships with their environments, but it is of crucial importance for a correct and objective interpretation and the modelling of present and future landscape processes. During the last decades, a better understanding of the long-term human-environment interactions has been earning a growing concern due to the progressing landscape degradation and climate change.

In a complex interplay with natural processes, human settlement activities cause a deep landscape transformation including an alteration of the terrain and soil cover. In result of these transformations, entirely new types of soils and sediments are formed, which acquire their own specific features and evolution pathways. These soils and cultural layers, as they form under the influence of settlement activities, record processes and conditions to which they were exposed and thus represent valuable archives of human-landscape interactions in settlements.

The first proto-urban settlements are particularly interesting as the transition from a rural to a new urban life can be traced at these sites. Depending on the region, the first transition to urban settlements took place on a broad time scale. In Northern Europe it was the early Medieval Age, regionally referred to as the Viking Age, when the first proto-towns appeared. According to the present state of knowledge, Hedeby was one of the first truly urban settlements and the largest town in Northern Europe in the period between the 9<sup>th</sup> and the 11<sup>th</sup> century. The very special development, the abundance of archaeological knowledge and the fact that, unlike most other contemporary sites, the settlement was completely abandoned at the precise end of the Viking Age, make Hedeby an outstanding object for geoarchaeological research.

Intensive archaeological investigations in Hedeby have provided very detailed and valuable insights into the organization of the settlement as well as the mode of life and the economic activities of its inhabitants. However, as far as landscape development in Hedeby and in the nearest vicinity of the town is concerned, a large gap is present until today. The unique geoarchives of Hedeby that have preserved information, which is not available from archaeological, historical or other sources, have not been yet investigated in detail. Undoubtedly, the knowledge about how humans interacted with the landscape and to which extent they altered

it would not only provide new information about the unique Viking town, but it would also contribute to our understanding of ancient societies and long-term human-environment interactions in general. This thesis addresses these questions and attempts to fill existing gaps of knowledge about landscape development at Hedeby.

## **1.2. AIMS AND OBJECTIVES**

Based on the gaps of knowledge indicated in the previous section and undoubted relevance of such studies, this thesis aims to investigate soil and landscape transformation in the former Viking town Hedeby before, during and after settlement activities. In order to achieve this goal, the research seeks to accomplish two main aims:

- (1) Analyze, compare and classify soils, natural deposits, cultural layers and archaeosediments in Hedeby in the context of settlement activities;
- (2) Investigate the geomorphologic situation in the central part of the settlement at the Hedeby-brook and reconstruct the local landscape transformation since the onset of the settlement activities by the Vikings.

These aims will be achieved by accomplishment of the following objectives:

- Detailed description of soils and sediments in Hedeby based on a set of objective and easily determinable characteristics;
- Elaboration of a classification of soils and sediments in Hedeby based on statistical analysis of the geochemical characteristics determined;
- Comparison of classified soils, natural and anthropogenic sediments in Hedeby;
- Construction of a stratigraphy of deposits in the vicinity of Hedeby-brook;
- Reconstruction of the main phases of geomorphologic transformation of the area at Hedeby-brook;
- Interpretation of the obtained results in the context of human-landscape interactions in Hedeby.

## **1.3. THESIS OUTLINE**

The thesis contains seven chapters including an introduction, the geographic setting of the study area, state of the art, methodology, findings of the research, their discussion, conclusions, and references to the literature cited as well as appendices. The following section provides an outline and a brief description of the content of each chapter.

Relevance of the research, its aims and objectives are provided in the introduction in chapter 1. The general geographic setting of the research area is explained in chapter 2 with sections devoted to the location of the research area, landscape development, quaternary deposits and soils of the region, climate as well as vegetation and land use. In chapter 3, a literature review is given covering three main topics. First, the state of the art in the field of former settlement studies is reviewed discussing site formation processes, main questions addressed as well as potentials of such studies for reconstructing long-term human-landscape interactions. Secondly, geoarchives present in former settlements are reviewed, together with methods used for their analysis and interpretation of the signals. Thirdly, the history of archaeological research in Hedeby is summarized, and an overview of the history, structure and development of Hedeby is provided. The research design and the methodology are described in chapter 4 with attention given to the selection of the drilling sites, field and laboratory methods. In chapter 5 the results of the investigations are provided. They consist of two main parts with two corresponding sections. The first section is devoted to the analysis of soils and sediments in Hedeby, their properties, statistical characterization and resulting classification. The second section considers the geomorphologic changes in the central part of the settlement at Hedeby-brook. The subsections of this section are focusing on the three drilling transects across the brook and a longitudinal profile. Stratigraphy and properties of the deposits in cores are described, results of a micromorphological examination of a selection of samples are provided. In chapter 6 the results concerning the two main fields of research (soils/sediments and geomorphology) are discussed, and an interpretation of the obtained results is performed. In chapter 7, conclusions based on the conducted investigations are drawn. Lastly, references to the literature cited and appendices are provided.

## 2. GEOGRAPHIC SETTING OF THE RESEARCH AREA

This chapter provides an overview of the geographic setting of the research area in terms of its location, landscape development, quaternary deposits and soils, climate as well as vegetation and land use.

### 2.1. LOCATION OF THE RESEARCH AREA

Investigation area is located in the region Schleswig-Holstein, northern Germany, in the south of the Jutland peninsula between the Baltic and the North Sea. The study site, the former Viking settlement Hedeby, is situated in the eastern part of Schleswig-Holstein (Figure 1) approximately 3 km south of the city of Schleswig ( $54^{\circ} 29' 27.77''$  N,  $9^{\circ} 33' 54.42''$  E).

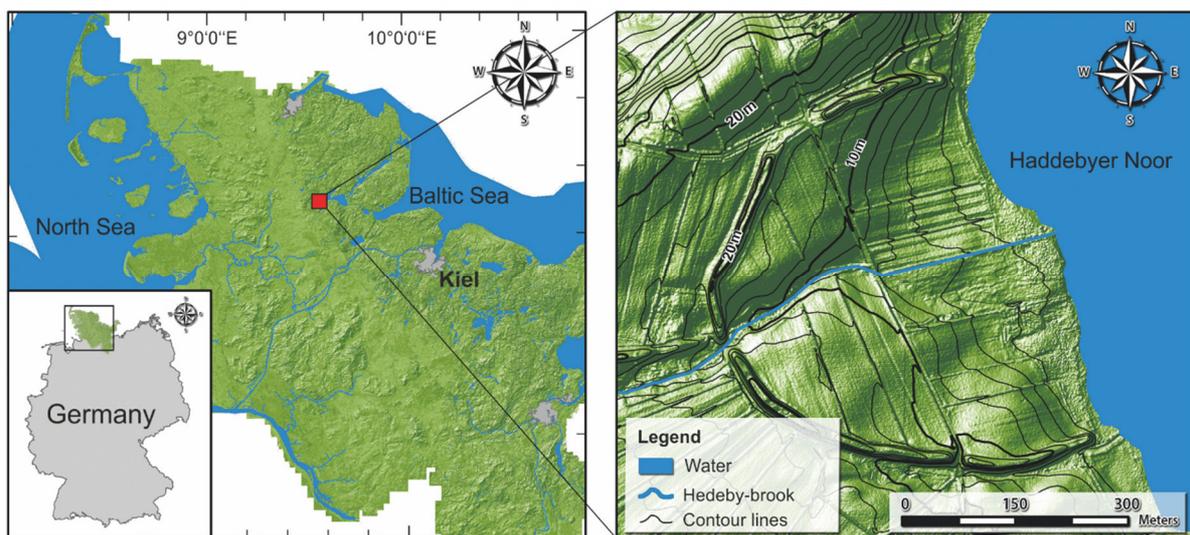


Figure 1. Location of the study area.

Hedeby, occupying an area of 26 ha inside the half-circle wall (Figure 2), lies west of the Haddebyer Noor, which represents the western end of the 42 km long inlet Schlei, which connects it with the Baltic Sea. The river Treene, which flows into the river Eider and then to the North Sea, is situated 15 km west of Hedeby. Hedeby was founded at this important strategic location, which was most convenient for connecting the trade routes of the Baltic Sea and the North Sea.

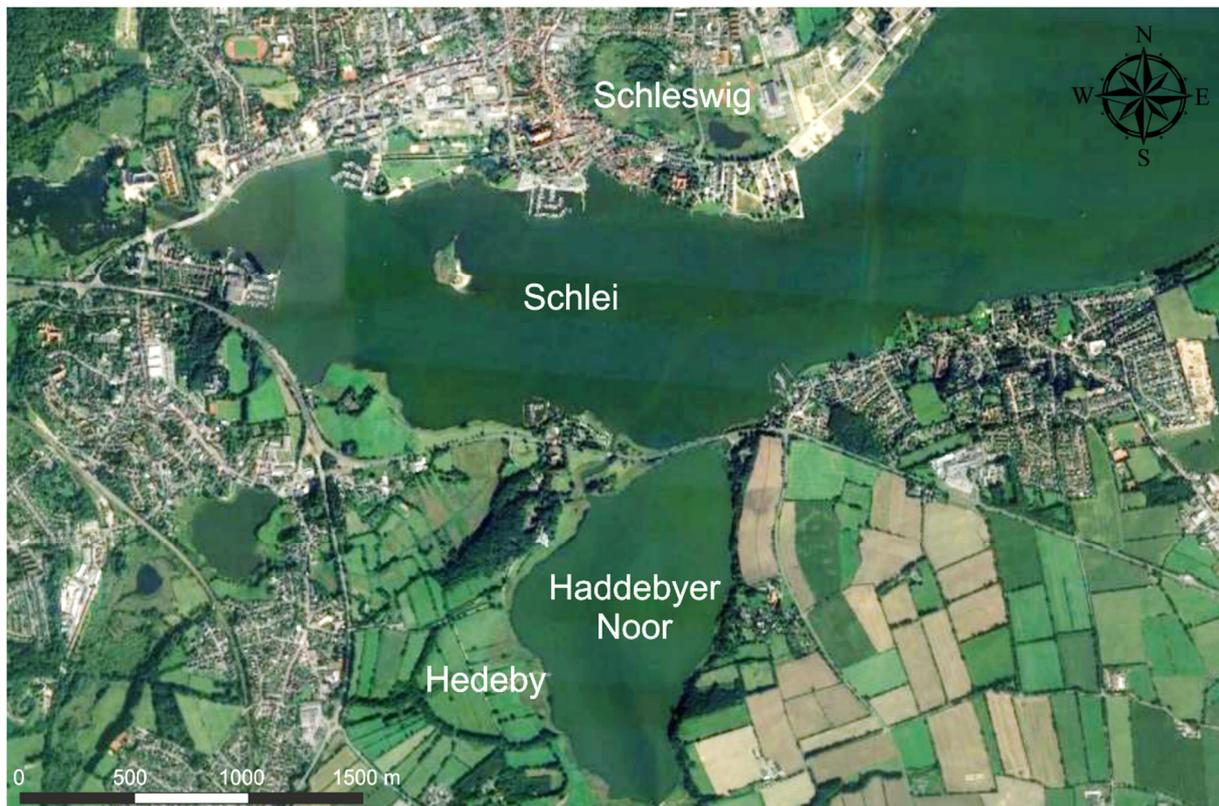


Figure 2. Aerial image of the study site Hedeby and its surrounding.

## 2.2. LANDSCAPE DEVELOPMENT OF THE REGION

The major landforms of Schleswig-Holstein were formed and reworked in glacial periods of the mid and late Pleistocene and in Holocene (Fränzle, 1988; Stephan, 2003). In the younger part of the last glacial period, the Weichselian (115,000 – 11,560 BP), a large ice sheet covered northern Europe and reached the eastern part of Schleswig-Holstein (Figure 3). During the younger part of the Saalian glacial period (300,000 – 126,000 BP) the ice sheet nearly completely covered Northern Germany. Geomorphological processes during these last two glacial periods and the Holocene have had the strongest impact on the formation of the modern landscapes of northern Germany (Stephan, 2003). Based on the morphology and the sediments, four northwest-southeast oriented major units can be distinguished in Schleswig-Holstein (Figure 4).

In the most western part of the region at the North Sea coast, the youngest unit Marsh (*Marsch*) is located. Due to similar processes, the intertidal zone (*Watt*), North Sea islands and the marsh foreland are part of this unit. The geologic origin of these landscape types is related to the ongoing postglacial processes such as sea level rise and sedimentation of tidal and organic sediments. The shoreline has been permanently changing due to the sea level rise, sedimentation and erosion of marine sediments.

Further east, the High Geest (*Hohe Geest*) unit is located. It represents an old moraine landscape that was formed during the Saalian glaciation. The topography of this area is slightly undulating

with elevations reaching 80 m a. s. l. in some areas. However, in comparison with the young moraine landscape in the east, it has a more smooth relief. This is related to the periglacial processes during the Weichselian glacial period. These processes include solifluction and repeated erosion processes during warmer and wet periods. Slope steepness in these areas usually lies below 5° (Fränzle, 2004).

As a result of glacier melting large outwash sand plains (sandurs) have formed. This unit is named Foregeest (*Vorgeest*) and it represents a transition from the old moraine landscape in the west to the young moraine landscape in the east of Schleswig-Holstein. The outwash plains are flat with a slight inclination from east to west. The thickness of sandur sands varies from a few meters up to tens of meters, in some areas composing only a thin cover of older geologic formations.



Figure 3. Extent of the Weichselian / Würm glaciation in Europe. 1 : 40,000,000 (Michael, 2015).

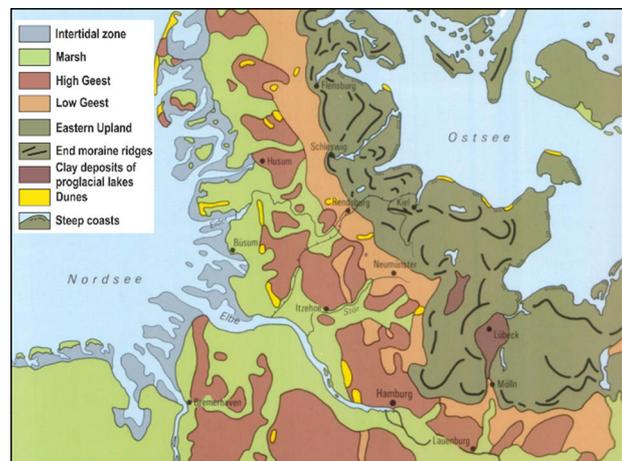


Figure 4. Landscape types of Northern Germany (Schmidtke and Lammers, 2004).

The glacier of the Weichselian glacial stage produced the largest unit in Schleswig-Holstein – a young moraine landscape, regionally referred to as the Eastern Upland (*östliches Hügelland*). The landscape is undulating and includes distinct former glacier margins, sandurs, hills and closed hollows (e.g. lakes, dead ice kettle holes). On the one hand, the highest elevation in Northern German flatland can be found here (167 m a. s. l. at Bungsberg); on the other hand, the steepest natural slopes of the region are also located in this young moraine landscape (Burbaum, 2008). This distinctive relief formed due to various glacial-geological processes, most important being the effects of dead ice melting and the “pushing” action of a glacier during the alternating phases of glacier advancing and melting during the Weichselian (Fränzle, 1988). However, there are also large areas of plains and depressions due to the abrading processes caused by a glacier. Depressions are often filled with melting water sand, peat or mud. It has to be noted that in some parts of the young moraine landscape the effects of Weichselian glaciation were rather weak and

the landscape present today was mostly formed in the Saalian or even Elsterian glacial periods (Stephan, 2003).

The investigation area is located in the undulating young moraine landscape close to the transition to the sandur landscape. Hedeby lies on a relatively smooth slope falling towards the Haddebyer Noor with a small brook dissecting the Viking settlement into two parts. At present, the lower part of the former settlement lies near the sea level, whereas in the upper part elevations of 14 – 15 m a. s. l. are reached. The geomorphologic development of the area and sea level dynamics are closely linked with the evolution of the Baltic Sea since the last glacial period.

The Baltic Sea is today a semi-enclosed intra-continental sea of the Atlantic Ocean that developed since the younger Dryas period (around 11,000 BP). During the postglacial period due to ice melting and glacial isostatic adjustment, it went through a few development stages (Kostecki, 2014): freshwater lake (Baltic ice lake), brackish sea (Yoldia stage), brackish/freshwater lake (Ancylus lake), brackish/salt water sea (Littorina Sea) (Figure 5). Nowadays the process of isostatic adjustment continues. It causes a regression in the region of the Fennoscandian Shield and a transgression at the southern coast of the Baltic Sea with a rate of approximately 1 mm per year in the study area (Kalmring, 2010).

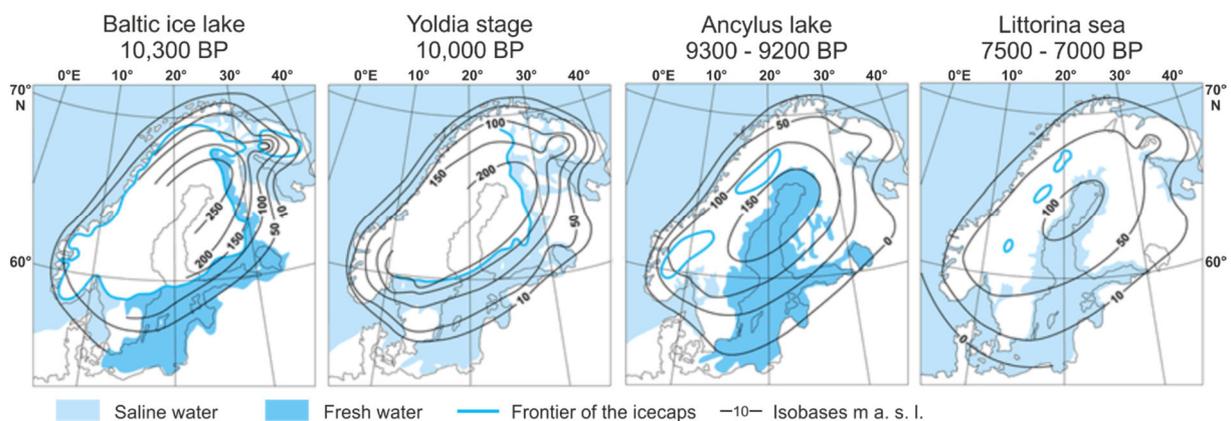


Figure 5. Postglacial development stages of the Baltic Sea (modified after Ehlers, 1996).

The Schlei is a narrow, 42 km long inlet of the Baltic Sea that ends in the direct proximity of Hedeby, where it is connected with two lakes: Haddebyer Noor and Selker Noor. Together with the Flensburg, Eckernförde and Kiel bays, it represents one of the characteristic features of the western Baltic Sea coast. Unlike the other bays mentioned, the Schlei did not represent a glacier tongue of a late phase of the Weichselian glaciation. It developed due to subglacial glacio-fluvial erosion and represented a tunnel valley (Kalmring, 2010). The content of salt in the Schlei decreases from northeast to southwest. In the most north-eastern part at the entrance to the Baltic Sea it equals 12 – 22 ‰ depending on the current conditions of the sea and in the inland south-western parts it is below 5 ‰ (Dries and Adelung, 1982).

### 2.3. QUATERNARY DEPOSITS AND SOILS

Due to the occurrence of glacial, glacio-fluvial and other processes in Pleistocene and Holocene, various geologic deposits have formed in the region (Geologischer Dienst Schleswig-Holstein, 2012). Until now there is no evidence for early Pleistocene glacial deposits older than of Elsterian glacial stage near the surface; probably they were eroded during Elsterian glaciation (Stephan, 2003). In the intertidal zone and marshland, parent material of soils is mostly represented by younger Holocene marine deposits (Fränze, 2004). Semi-aquatic and subaquatic soils affected by tides such as Gleyic Tidalic Fluvisols are dominating (Jones, 2005). They often contain thionic and salic soil material. In marshlands, soils develop from (peri)marine sediments. In young marshes, Gleysols and Gleyic Fluvisols are present, they are often Calcaric and Eutric. In old marshes, Gleyic Stagnosols and Gleysols, less Fluvisols are present. On dunes, there are Regosols and Arenosols, in depressions Histosols.

The old moraine landscape of the High Geest is comprised of ground, terminal and lateral moraine deposits and fluvio-glacial sand of the Saalian glaciation, which were strongly altered by processes during the Weichselian glaciation (Fränze, 2004). Also, fluvio-glacial and aeolian sediments of the Weichselian period are present. These parent materials define soil formation in the Holocene. In well-drained areas with sandy terminal and lateral moraines, Cambisols represent the main soil type; sometimes they are transitional to Podzols. On thick sandy deposits, especially aeolian sand, podzolization processes are dominating and Podzols are formed. In areas, where loamy deposits are closer to the surface, Luvisol formation takes place. Stagnosols and Gleysols as well as Histosols represent intrazonal and azonal soils.

In the Foregeest, the main parent material is outwash sand. In the eastern, somewhat more elevated part of the landscape, sand deposits are relatively coarse, heterogeneous in terms of mineral composition and rich in weatherable minerals. Here Cambisols are dominating (Jones, 2005). Aeolian sand is particularly poor in easily weatherable silicates. Therefore in these areas (and in the west overlying finer and well-sorted fluvio-glacial sandy deposits), podzolization processes are dominating. Podzolization was even more facilitated during the Middle Ages and early Modern Times when heath vegetation dominated and since the end of the 19<sup>th</sup> century when wide areas were afforested with coniferous tree species. In depressions, bogs and mires Histosols are present. In dryer areas such as dunes, Regosols and Arenosols are developing. In areas close to the ground water table, often a thin cover with aeolian sand is present. In the beginning of the Holocene, Podzols were developing there. Due to the sea level rise during the Holocene, Podzols transformed there into Gleyic Podzols and Gleysols.

The Eastern Upland landscape was formed by the Weichselian glacier, which brought fresh material from Scandinavia and reworked it together with the deposits present in the area since

the other glaciations (Burbaum, 2008). Poorly sorted glacial till with and without carbonates is the most widely spread glacial deposit on the land surface, followed by glacial sand and fluvio-glacial sand. Also, glacio-lacustrine sediments are present in form of silts, clays and fine sands.

In the vicinity of the study site Hedeby, late Pleistocene deposits are represented by tills of ground and end moraines, usually free of calcium carbonate today in the upper part due to leaching in humid climate conditions during Holocene. Also, better sorted fluvio-glacial sand is present; it often covers till deposits. In some landscape positions, varved sediments of proglacial lakes are found under fluvio-glacial sand. Three to five kilometres southwest of Hedeby a transition to the old moraine landscape starts with outwash sand plains (sandurs). Figure 6 illustrates the distribution of quaternary deposits at the study area.

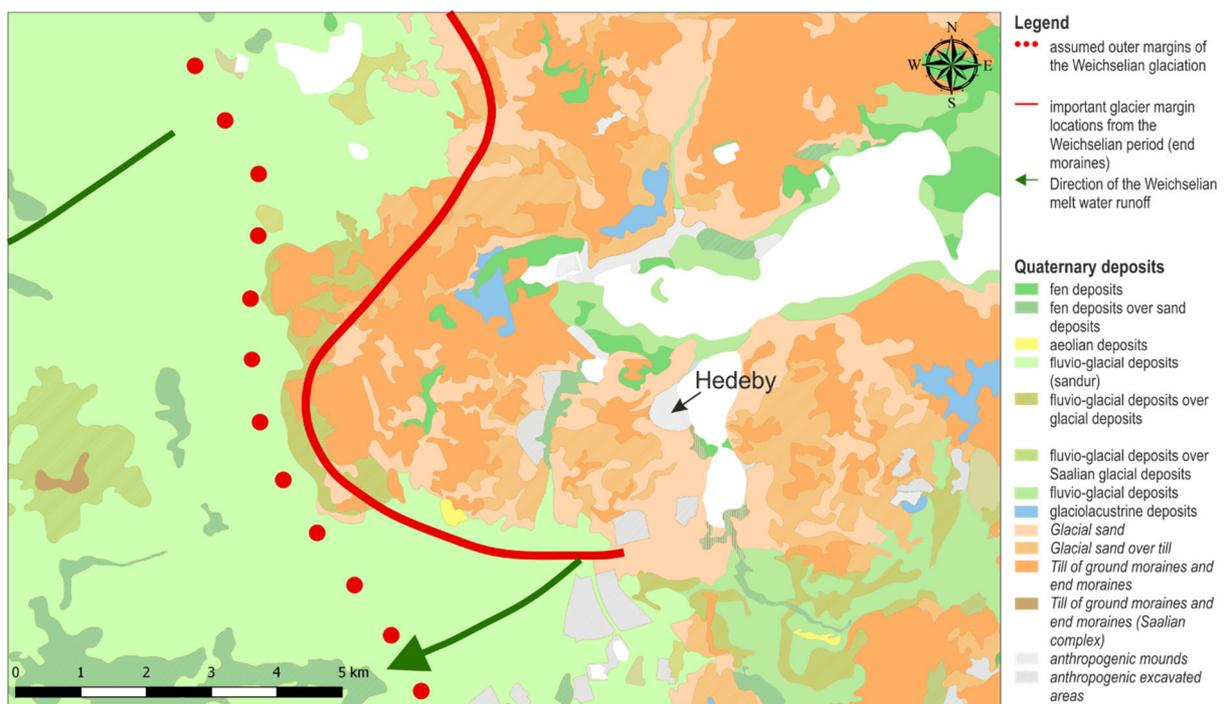


Figure 6. Quaternary deposits in the investigation area (modified after GÜK 1: 250,000, Landesamt für Landwirtschaft, Umwelt und ländliche Räume Schleswig-Holstein).

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 Eastern Upland unit (Burbaum, 2008; Fränzle, 2004; Jones, 2005). The distribution of the main soil types in the study area is shown in Figure 7. Luvisols dominate in decalcified glacial till, while Cambisols are common on coarser sandy materials. In outwash plains inside the outer Weichselian glacier margins (inland sandurs) 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 fluvio-glacial sands and in aeolian sand deposits Podzols have formed.

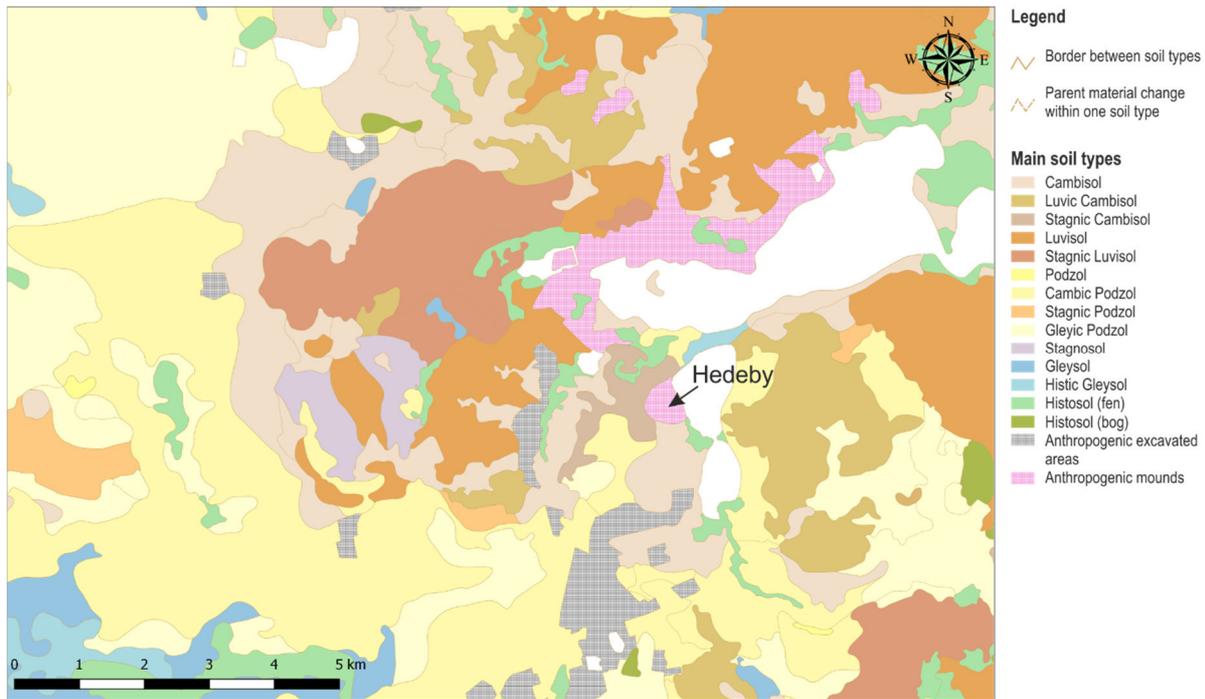


Figure 7. Soil types in the investigation area (modified after BÜK 1 : 250,000 Landesamt für Landwirtschaft, Umwelt und ländliche Räume Schleswig-Holstein).

## 2.4. CLIMATE

The region Schleswig-Holstein lies within the Cfb maritime temperate climate class according to the Köppen-Geiger climate classification system (Kottek *et al.*, 2006). This climate class is described as a fully humid climate with warm summers. The western part of Schleswig-Holstein is characterised by high precipitation with maxima in summers and high wind frequencies, while frost and snow days are rare. The mean temperature in January equals  $+0.5 - +1.0$  °C and around  $+16$  °C in July with an annual precipitation between 850 mm at the coast and 750 mm further inland.

The central and eastern parts of Schleswig-Holstein are transitional to the humid subcontinental climate region. The Geest area (old moraine and sandur landscapes) is characterized by the highest precipitation in Schleswig-Holstein; it varies between 800 and 900 mm with a mean temperature of  $0 - +0.5$  °C in January and  $+15.5 - +16.5$  °C in July. Further east in the Schleswig-Holstein Uplands, the degree of continentality increases with slightly lower winter temperatures and slightly higher summer temperatures:  $-0.5$  °C in January and up to  $+17.5$  °C in July in south-eastern Schleswig-Holstein. The mean annual precipitation in this landscape type has a weak decreasing trend from west to east due to dominating western winds and equals ca. 800 mm in the transition to Foregeest and around 550 mm on Fehmarn. For the study site (weather station in Schleswig), the mean annual precipitation lies at 896 mm and the mean annual temperature equals  $+8.3$  °C according to the German Weather Service (Figure 8).

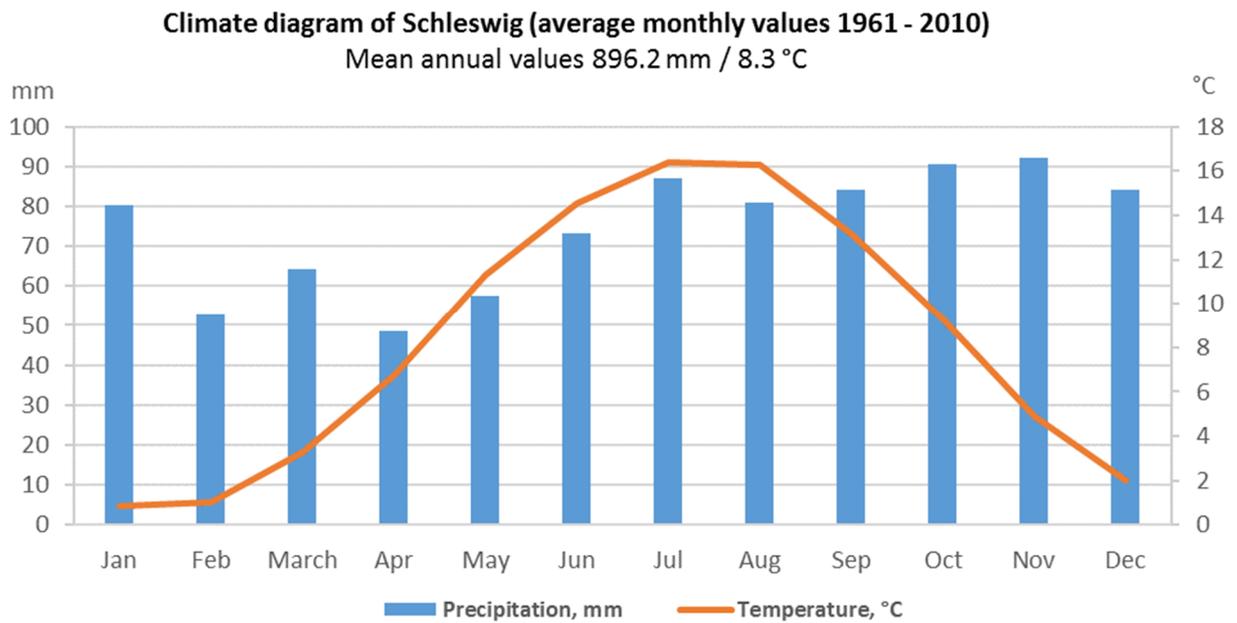


Figure 8. Climate diagram of the weather station Schleswig Wewa, 50-year-average (source: German Weather Service).

## 2.5. VEGETATION AND LAND USE

Modern vegetation in Schleswig-Holstein mostly reflects the postglacial landscape development and is determined by environmental factors such as topography, soils, climate and land use (Dierßen, 2004). Today, the landscapes of Schleswig-Holstein are strongly dominated by agricultural ecosystems that are occupying over 70 % of the total area (Statistisches Amt für Hamburg und Schleswig-Holstein, 2016). Thus, the vegetation is strongly dependent on the human impact. Without any human influence most sites in Schleswig-Holstein would have been covered by a woodland with a domination of beech (*Fagus sylvatica*) and oak (*Quercus robur*) (Dierßen, 2004). At present, forests cover only approximately 11 % of the state (Bundesministerium für Ernährung und Landwirtschaft, 2016).

In small areas suitable for the growth of tree species and without strong effects of human activities, a west-east gradient can be observed, which mostly reflects the change in edaphic conditions (Dierßen, 2004). In the marsh landscape, where soil conditions are too wet for beech trees, ash (*Fraxinus excelsior*) and alder (*Alnus glutinosa*) are dominating as well as wych elm (*Ulmus glabra*), pedunculate oak (*Quercus robur*) and willow (*Salix alba*, *S. cinerea*, *S. caprea*). Depending on the drainage conditions, marsh landscapes are used as grasslands or agricultural fields.

On oligotrophic sites of the High Geest and in the sandur plains, hairgrass (*Deschampsia flexuosa*) – beech communities are dominating, while in wetter conditions these communities are replaced with oak-birch forests. In the large lowland valley systems (Eider, Treene, Sorge and Stör river

systems) that cross the Geest, alder-ash and alder forest mires are present. In bogs and mires, birch and oak-birch communities are found in oligotrophic conditions and ash forest mires in eutrophic conditions. Today, these wet landscapes are mostly deforested, drained and transformed into mire grasslands.

In the Eastern Upland, vegetation is represented by a complex pattern due to heterogeneous edaphic conditions. Bedstraw (*Galium odoratum*) – beech forests are dominating on Luvisols, while hairgrass-beech and milletgrass-beech are dominating on leached hill tops, inner sandurs and end moraines. Alder-ash forests and alder-beech forests are common in less drained landscape positions. In the landscapes of the Eastern Upland agricultural fields are dominating in well-drained areas and grasslands in areas with a high ground water table.

The area of Hedeby was also used agriculturally until the last decades of the 20<sup>th</sup> century. Then the former town area was acquired by the Federal State of Schleswig-Holstein and a grassland was established without the application of fertilizers (Carnap-Bornheim *et al.*, 2013). The road Kirchweg (“chirch road”) that crosses Hedeby at present from north-west to south-east is a recent road and does not reflect an element of the settlement structure in the Viking Age. The old Kirchweg that in some parts approximately corresponded to the main street of Hedeby lied in the eastern part of the settlement. The modern Kirchweg was established at its current position at the end of the 18<sup>th</sup> century due to the agrarian reformation in order to enable an easy access to the fields on both sides of it (Schietzel, 2014). The eastern hedgerow marking the road and field boundaries was removed in the 1960s to allow heavy machines that were used in archaeological excavations to enter the area.

## 3. STATE OF THE ART

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### 3.1. FORMER SETTLEMENTS: PROCESSES AND FEATURES

The relationship between humans and landscapes has undergone significant changes since the first breakthrough in human evolution – the ability to control fire. Thousands of years later the second major shift in human-landscape interactions occurred – the domestication of plants and animals and herewith the establishment of agriculture as the main means of living (Wilson, 2011). It is well known that agriculture triggered the first massive human-induced landscape transformation processes like deforestation, soil erosion, land degradation, soil depletion or in some cases enrichment, for instance, due to manuring. The third milestone in cultural landscape development is related to the emergence of urban settlements (McNeill and Winiwarter, 2006). Many scientists agree that among culturally affected and transformed areas, the urban environment can be considered as most extreme (Antrop, 2000; Heimdahl, 2005; McNeill and Winiwarter, 2006; Wilson, 2011). With the emergence of the first towns, the fluxes of matter and energy in landscapes have been strongly altered with soil nutrients never returning to the landscapes where they were systematically drawn from. On the contrary, either the nutrients stayed within urban settlements in the form of materials or human bodies, or they were carried away by runoff on the land surface and percolation to the ground-water or they landed in habitation deposits of the settlements. Antrop (2000) distinguishes different kinds of pressures on the landscape in urban settlements: housing and settlement, land as a production space, networks of infrastructure, recreation, and landscape fragmentation.

At present, urban soils are mainly studied to assess the modern state of urban systems (Lehmann and Stahr, 2007). Therefore, the investigation of urban soils and cultural layers of former settlements can provide insights into the state and development of those settlements in the past. In order to understand and reconstruct cultural landscape development and the formation of cultural layers, particularly at such complex sites as urban settlements, a wide range of site formation processes and resulting features have to be taken into account. Site formation processes are thought to be fundamental to the interpretation of most former settlements (Canti and Huisman, 2015).

#### 3.1.1. SITE FORMATION IN SETTLEMENTS

Site formation processes in settlements can be broadly divided into natural and anthropogenic processes of deposition and modification, and postdepositional diagenetic processes (Goldberg and Macphail, 2008). On the time scale, site formation processes include those that take place before, during and after occupation (Canti and Huisman, 2015). Natural site formation processes

are well known for natural landscapes and modern geological environments (French, 2003). They include colluvial, alluvial, aeolian and lacustrine processes. Cultural layers and other archaeosediments in settlements form due to more complex site formation processes than natural ones since their triggers represent a potentially infinite variety of anthropogenic activities (Goldberg and Macphail, 2008). Moreover, humans often modified and reworked already existing deposits and features thus causing overprinting of different records and making it more complicated to distinguish and interpret individual strata and events.

The same is the case for postdepositional diagenetic transformations, which can be caused by a variety of natural and human-associated processes (French, 2003). Soil formation may take place at an abandoned habitation site or in certain areas of a functioning settlement with various deposits representing parent material for the new soil formation cycle be it a filling of a pit, a cultural layer or a previously formed soil (Alexandrovskaya and Panova, 2003). Bacterial breakdown as well as chemical processes of material transformation play an important role in the transformation of certain soil or sediment components and geochemical properties of materials, particularly due to changes in land use or geomorphologic conditions (Goldberg and Macphail, 2008; Oonk *et al.*, 2009). Such post-depositional pedogenic processes as the enrichment of organic matter, podzolisation, leaching and gleying can strongly influence the distribution of elements in the soil (Wilson *et al.*, 2008). Another important postdepositional process that may considerably alter or disturb the original stratigraphy and properties of sediments is bioturbation. The effects of this processes are known but often underestimated (Goldberg and Macphail, 2008). Among human-induced postdepositional processes agriculture and changes in the drainage system or other types of an archaeological site re-use should be mentioned (French, 2003).

Taking into account the postdepositional diagenetic processes is essential for the correct interpretation of the stratigraphy and its formation (Weiner, 2010). Different components of soils, archaeosediments and cultural layers react differently to diagenetic processes. An extremely good preservation of organic remains in archaeosediments may be the case when an iron pan forms that maintains strong reduction conditions and a high moisture level (Breuning-Madsen *et al.*, 2001). Alexandrovskiy *et al.* (2012) showed in their study of the cultural layers of Moscow that properties of cultural layers were quite stable and were not “erased” by postdepositional pedogenesis.

Most progress in the last twenty years of geoarchaeological research has been done in the investigation of site formation processes in cave sediments (Canti and Huisman, 2015). It was shown that in palaeolithic caves natural site formation might be dominant over anthropogenic ones. Complex site formation processes as well as the preservation state of different types of materials composing the mound of the famous Neolithic site Silbury Hill was investigated (Canti

*et al.*, 2004). The effects of fire on soils and sediments, probably one of the most common site formation processes, have been in detail reviewed by Canti and Huisman (2015). Taphonomy and preservation of archaeological materials such as wood, bone, metal and glass as well as site degradation problems are reviewed and discussed by e.g. Canti and Huisman (2015) and Weiner (2010).

### **3.1.2 BURIED SOILS AND CULTURAL LAYERS AS GEOARCHIVES IN FORMER SETTLEMENTS**

The concept of soil memory is well established in soil science (Targulian and Goryachkin, 2004). Soils are believed to have a capacity to store the information about environmental factors and pedogenic processes that have been acting upon them during a period of pedogenesis. Soils possess a palimpsest-wise memory meaning that new records overprint the existing records stored by soils (Targulian and Goryachkin, 2004). This concept is well applicable to soils and cultural layers of cultural landscapes and settlements with a difference that soils of cultural landscapes contain records of both natural processes and human activities (McNeill and Winiwarter, 2006). Therefore, soils, cultural layers and various archaeosediments of former settlements contain valuable environmental records of palaeoenvironmental conditions, landscape transformation and human-landscape interactions (Yakimov *et al.*, 2012), which are often not available from archaeological or other sources.

Original soils that were exposed at the surface before a human impact and settlement activities are usually disturbed by these activities and incorporated into the cultural layers. Entwistle *et al.* (2000) pointed out that human habitation significantly alters soil physical, biological and chemical properties. Moreover, since profiles of urban soils are formed by a continuous input of materials, they contain a detailed record of the events of the economic development of a city (Alexandrovskaia and Alexandrovskiy, 2000). Due to the formation of cultural layers in settlements partial or complete removal and / or the turbation of original soils often takes place (Bronnikova *et al.*, 2003; Devos *et al.*, 2013a). But often original soils stay preserved due to their burial under archaeological sediments such as e.g. burial mounds or fortifications with only minor post-burial changes e.g. compaction (French, 2003). Due to their isolation from further pedogenic processes through the termination of the exchange of matter and energy to a large extent after burial, the records of formation of these soils stay mostly conserved and can thus be used for environment reconstructions before and in the early phases of occupation (Yakimov *et al.*, 2012). Buried soils often allow the reconstruction of pre-settlement environmental conditions (French, 2003) or landscape changes in the early occupation phases. Often, a ploughing layer is found underlying the cultural layers (Alexandrovskaia and Panova, 2003; Alexandrovskiy *et al.*, 2012), pointing at agricultural land use before the onset of the settlement activities.

If present, buried soils are often investigated in the framework of studies of cultural layers and other archaeosediments as reference material or natural background. Palaeosols buried under cultural layers of Russian cities have been investigated (Alexandrovskaia and Panova, 2003; Alexandrovskiy *et al.*, 2012; Bronnikova *et al.*, 2003) as well as soils underlying a fortification rampart from 4<sup>th</sup>-6<sup>th</sup> centuries at a settlement of Ust-Utyak in Western Siberia (Yakimov *et al.*, 2012).

Cultural layers themselves represent geoarchives with various records. In literature, different terms are used for the description of cultural layers: cultural layers (Alexandrovskaia and Panova, 2003), habitation or occupation deposits (Bronnikova *et al.*, 2003; Milek and Roberts, 2013), urbosediments or urban habitation deposits (Alexandrovskiy *et al.*, 2012).

Human settlement activities disregarding their location or age have always left their traces on a land surface – on the one hand, as material objects, food and domestic waste, remains of houses and production activities; on the other hand, as results of the modification of vegetation cover, topsoil horizons or exposed parent materials (Goldberg and Macphail, 2006). With time, anthropogenic cultural remains get involved in different material turnover processes and are incorporated into soil and/or lithological material. In result, a qualitatively new type of sediment is formed – a cultural layer, which has its own morphology, physical and geochemical properties, its own functioning dynamics, its own development and evolution (Sycheva, 2006). Due to these various processes involved into the formation of cultural layers, they represent simultaneously a soil, a sediment and a habitation deposit (Alexandrovskaia and Panova, 2003). Such a complexity of processes that form cultural layers, on the one hand, makes it difficult to decode the information that they contain correctly. Since cultural layers form during certain historic-natural period, they carry information not only about material culture of a particular society or group of humans, but they also record environmental conditions (including climate) and events occurring during their formation (Sycheva, 2006; Sycheva and Uzyanov, 2006). Therefore, cultural layers also reflect the impacts of human activities on the surrounding landscape as well as effects of a changing environment on human life. All this makes cultural layers one of the main study objects in geoarchaeology (Goldberg and Macphail, 2006). Two components of the cultural layer can be distinguished: a natural component (pedo-lithological material) and an anthropogenic component (inclusions and indirect traces of human activities) (Sycheva, 2006). While the anthropogenic component is given a lot of attention by archaeologists, the natural pedogenic component is less well understood and the valuable information that it stores is often not taken into consideration and interpretation.

Along with cultural layers, different other types of sediments can be found in former settlements. They include colluvial, alluvial and aeolian sediments that form a complex system together with

cultural layers. Also, different types of anthropogenic sediments can be found in settlements including not only cultural layers, but also such materials as pit fillings, burial mound sediments, fortification structures materials etc. (Alexandrovskaya and Panova, 2003). Different types of anthropogenic deposits have been distinguished (Figure 9).

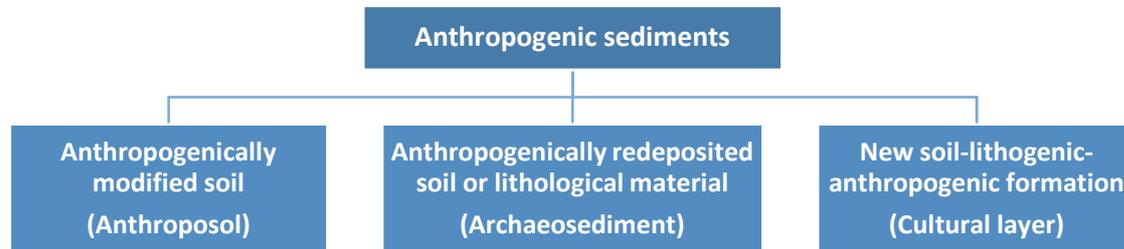


Figure 9. Scheme of anthropogenic sediment types (after Sycheva, 2006).

The first type of anthropogenic sediments in fact represents an anthropogenic soil, which has a thickness comparable to the thickness of the original soil horizons. Soil profiles are often well preserved and modified only the upper part. It is still under discussion whether garden soils should fall into this type of materials. The second type of anthropogenic sediments includes redeposited soil or lithic material that are dominated by the natural substrate and may or may not contain anthropogenic components. This group includes usually thick relatively homogenous sediments such as fortification sediments, burial mounds, dams etc. The third type of anthropogenic sediments includes the cultural layers that form *in situ* due to a strong transformation of soil-lithic material due to human habitation. These layers have their own spatial and temporal borders, functioning regime and history of development. Complex cultural layers of rural and urban settlements as well as tells belong to this group. Within cultural layers sterile interlayers due to material deposition by alluvial or aeolian processes or even soil horizons may be found due to stable periods when the cultural sediment accumulation rate is lower than the soil formation rate.

Often, a differentiation between organo-mineral and peat-like organic-rich cultural layers is done (Alexandrovskaya and Panova, 2003; Alexandrovskiy *et al.*, 2012). In organic-rich layers remains of straw (manure), wooden chips and other plant remains are often found (Alexandrovskaya and Panova, 2003; Alexandrovskiy *et al.*, 2012) as well as other inclusions such as stone debris, various artefacts, wooden pavements, and logs (Alexandrovskiy *et al.*, 2012). Such organic-rich cultural layers are usually water-saturated and found in depressions and buried valleys, whereas they alternate in flat interfluvial plots in which organic matter is absent (Alexandrovskiy *et al.*, 2012). Alexandrovskiy *et al.* (2012) concluded that in humid conditions of the forest zone of Russia organic-rich cultural layers are dominating, while in the steppe zone mineral material is dominating in the cultural layers. This is due to bioclimatic conditions and the availability of initial

construction materials: more wood and plant material in the forest zone and more loam, clay and lime in the steppe.

In many settlements there is a general trend that younger stratigraphic units are thinner and more distinctly stratified than older units, which are often composed of a thick (20 – 70 cm), dark, homogeneous material rich in organic matter (Heimdahl, 2005). Internationally such material has been called “dark earth”. According to the definition of Macphail *et al.* (2003), dark earths are dark, humus-rich, homogeneous occupation deposits that usually separate Roman from Early Medieval and Medieval strata in towns. The formation of dark earth is the result of a complex interplay of human actions and non-anthropogenic phenomena (Devos *et al.*, 2013b; Macphail, 2010). Models of dark earth formation were discussed by Macphail *et al.* (2003). Sycheva (2006) stated that the older cultural layers, the simpler is their stratigraphy and the smaller is the content of the anthropogenic components in them. Cultural layers of proto-urban settlements of the early medieval period represent the first complex cultural layers.

### **3.1.3. PROPERTIES OF GEOARCHIVES AS BASIS FOR RECONSTRUCTIONS**

There is a variety of methods from several disciplines applied at geoarchaeological studies of former settlements. Their choice for a particular site depends on the nature and size of the site and the types of questions raised (Goldberg and Macphail, 2008). However, the best understanding of a site can be achieved by a thorough investigation of the geomorphologic setting of the study area, its landscape position, rock and soil types present. Further analytical work should be carried out in close cooperation with archaeologists (Heimdahl, 2005). Bronnikova *et al.* (2003) conducted an interdisciplinary study by independently applying and correlating soil data, sediment lithology, pollen analysis and analysis of siliceous biomorphs to reconstruct the local landscape for the periods before, during and after settlement activities in the early medieval pre-urban centre Gnezdovo in Russia. The results of the study suggested that the area of the settlement and its vicinity were strongly deforested due to extensive habitation and agricultural activities. Pastures and arable land with a great variety of crops grown (wheat, buckwheat, hemp and others) were widespread in the area.

In numerous studies, different properties of cultural layers were studied and attempts to find out typical properties of cultural layers have been made. Alexandrovskaya and Panova (2003) and Alexandrovskiy *et al.* (2012), who investigated cultural layers of ancient towns in European Russia, stated that cultural layers are characterized by high alkalinity, stratification, evident traces of different technological impacts, and a high content of stones and artefacts. Cultural layers of the (pre-)urban centres in the temperate zone usually have a neutral pH (Bronnikova *et al.*, 2003), while the pH of buried and natural soils in the surroundings is acidic.

### ***Organic matter content***

Cultural layers represented sinks in landscapes for many substances, particularly organic matter. According to Alexandrovskaya and Alexandrovskiy (2000) the cultural layers of the Earth might contain about 6 % of the total reserves of carbon in the pedosphere. Relatively high contents of organic matter were determined in many studies of cultural layers due to the accumulation of organic residues resulting from various human activities. Therefore, the variability of organic matter content may be used for the identification of occupation zones or even activity areas within sites (Holliday, 2004). The organic matter content measurement by loss on ignition at 550 °C of floor deposits in a Viking Age house on Iceland (Milek and Roberts, 2013) helped to identify parts of the house that received the greatest inputs of organic material, while loss on ignition at 950 °C confirmed the presence of ash and showed its spatial distribution in the house. However, it has to be noted that in former arable soils a depletion of organic matter may occur instead of accumulation (Entwistle *et al.*, 2000) since cultivation and regular cropping extracts organic material and often enhances the rate of organic matter decomposition.

When interpreting organic matter contents in buried soils or sediments, diagenetic processes have to be taken into account because after burial the organic matter content can decline due to oxidation (Holliday, 2004). According to Gubin (1984) soils buried in medieval ages lost about 50 % of their organic matter, whereas in light-textured material losses can reach 70 %. Therefore, based on the content of organic matter determined for an A horizon of a buried palaeosol, the initial organic matter content before burial can be reconstructed.

### ***Multi-element analysis***

During the last decades a large number of multi-element analyses of soils and sediments in former habitation sites have emerged, indicating their great potential in the identification of use-of-space patterns (Abrahams *et al.*, 2010; Gauss *et al.*, 2013). The interpretation of element distributions in geoarchaeological contexts has to be done with caution due to the complexity of the site use history and the effects of postdepositional pedogenic processes (Wilson *et al.*, 2008). The occupation of an area is associated with many human activities that tend to enrich soil in certain elements (e.g. P and K) and deplete in other parameters (e.g. organic matter content). Wilson *et al.* (2008) in their investigation of element concentration from abandoned farms from different regions on the British Isles, proved that despite the differences in geological backgrounds, there were similarities in element concentration patterns across areas of a similar function.

Entwistle *et al.* (2000) performed multi-element soil analysis and investigated the spatial variability of soil properties to distinguish land use types and settlement features inside of a former habitation site in the township of Greaulin (Trotternish peninsula, Isle of Skye). Surface

soils on-site and off-site were sampled and “enrichment factors” were calculated as ratios of the concentration of the on-site sample by the mean off-site value. In this research, K, Rb, Th, Cs and Sr were found to be most useful in distinguishing areas influenced by human activities from those that were not, whereas P was a less reliable indicator due to possible different sources of its enrichment.

Phosphorus is the traditionally investigated element as indicator for human activities (Holliday and Gartner, 2007) as it forms phosphates, which are stable and generally immobile in soils (Holliday, 2004). The most frequently used model relates enrichment of P as a result of disposal of domestic waste, excrements and organic decay (Entwistle *et al.*, 2000; Gauss *et al.*, 2013). Together with K, Ca and Mg, P also has elevated concentrations in ashes. Entwistle *et al.* (2000) explained enrichments of K, Rb and P in locations of suspected hearths by inputs of organic material in areas associated with food preparation and cooking activity. In general, food production areas contain elevated contents of P and Ca (Middleton, 2004). Gauss *et al.* (2013) found strong positive correlations between P, Sr and Ca, which are most importantly accumulated through a disposal of organic materials, wastes and excrements. Nitrogen, also representing an important component of organic wastes like human and animal excrements, is subject to rapid decomposition and thus usually does not persist long in archaeological sediments (Holliday, 2004). Strong enrichment in P in relation to natural soils in the surroundings was observed for cultural layers of Moscow (Alexandrovskaya and Panova, 2003).

A wide range of elements have been found in cultural layers including those that are usually considered pollutants like heavy metals (Alexandrovskaya and Panova, 2003; Bullock and Gregory, 1991). According to Wilson *et al.* (2008), Ca, Zn and Pb represent anthropogenic element signatures that are relatively resistant and may persist in soil for relatively long time periods. Wells *et al.* (2000) suggested that relatively high concentration levels of heavy metals have come from workshops, craft, or ceremonial activities with enrichments in Fe, Cu and Hg. They are most probably associated with wall paints. Similarly, the distribution of heavy metals, particularly Cu, Fe and Sn (in some studies also Zn), was useful in the identification of potential metal workshops (Alexandrovskaya and Alexandrovskiy, 2000; Gauss *et al.*, 2013). Also, in early medieval cultural layers of Moscow elevated concentrations of Cu, Zn and As, which were used e.g. for the depilation during the tanning process. Habitation deposits of the 17<sup>th</sup> to 19<sup>th</sup> centuries contain very high concentrations of Pb, Cu and As, exceeding 1000-fold levels in comparison to natural soils. Cu was used for domestic and horticultural pest control and as a ductile metal (Alexandrovskaya and Panova, 2003). Pb was used in Moscow in the 15<sup>th</sup> to 20<sup>th</sup> centuries for making household utensils and also for pipes and roof covering; Pb-based paints were widely used from the 15<sup>th</sup> century on (Alexandrovskaya and Alexandrovskiy, 2000). Also, Cu and Zn are reported to be enriched in sites

where an accumulation of refuse and excreta took place (Bintliff *et al.*, 1990; Dirix *et al.*, 2013); this was, however, not the case in the study of Entwistle *et al.* (2000).

In areas thought to be formerly cultivated, high enrichments in levels of Ca and Sr were measured (Entwistle *et al.*, 2000). The authors explain this with possible additions of shell-sand, bone and fish refuse as manure. Also, enrichments of Ca and Sr were observed for closed spaces of human occupation, most likely due to the use of lime as construction material (Middleton, 2004). In general, Ca due to its association with bones and limestone processing has been often used as an archaeological indicator of human activity (Holliday, 2004).

Based on microelement composition of bone tissues recovered from burials in Moscow (Alexandrovskaya and Panova, 2003) causes of death could be reconstructed. Bones of highborn women in Moscow contained much higher concentrations of Pb, Cu and Hg than bones of women from the town, probably indicating living conditions of the highborn women, who used white lead and other toxic elements as medication and cosmetics. The wide variety of records that can be acquired from bone material is presented by Weiner (2010).

In order to analyse and interpret complex patterns of vertical and lateral element distributions and in account for geologic backgrounds, advanced statistical methods have been applied (Dirix *et al.*, 2013; Entwistle *et al.*, 2000; Gauss *et al.*, 2013; Oonk *et al.*, 2009; Wilson *et al.*, 2008). In recent years, multi-element analysis with portable XRF (pXRF) devices have become more common. Several publications prove the reliability of results obtained with pXRF in comparison to other methods (Gauss *et al.*, 2013; Hayes, 2013), partially in case of a proper sample preparation involving drying and homogenization. Dreibrodt *et al.* (2017) obtained results of satisfactory quality in a quantitative comparison of measurements by p-ed-XRF and wd-XRF devices.

### ***Palaeoecological analysis***

Palaeoecological studies have become an important part of geoarchaeological research at occupation sites. Siliceous bioturbates (phytoliths, diatoms, sponge spicule etc.) may deliver important information about the hydrologic regime and vegetation type (Bronnikova *et al.*, 2003). Layers with an elevated density of diatoms in floodplain soil-sedimentary sections indicate periods of increased wetness. At the same time, an increased density of both diatoms and sponges can be conditioned by their influx with waters of spring floods. Phytoliths are often used as an archaeobotanical proxy as they do not need to be waterlogged or charred to be preserved (Devos *et al.*, 2013a). Pollen spectra are commonly used for the reconstruction of vegetation, climate, landscape openness and landscape changes caused by human activities (Ryabogina and Yakimov, 2010), mostly on a regional level (French, 2003) and usually based on geoarchives of lake

sediments (Dörfler *et al.*, 2012). The potentials of archaeobotanical studies to reconstruct plant economy in northern and north-western Europe in Neolithic were presented by Kirleis *et al.* (2012).

### ***Magnetic susceptibility***

Magnetic susceptibility has become a commonly applied method in palaeoenvironmental research as a palaeo-rainfall proxy (Alekseeva *et al.*, 2007; Maher *et al.*, 1994; Maher *et al.*, 2003). In recent years, the study of magnetic properties of soils and sediments has become an important tool for the scientific investigation of archaeological sites (Schmidt, 2007) – based on the idea that if past human habitation has led to enhanced levels of magnetic susceptibility in the soils, magnetic measurements can be used for their detection. The application of magnetic susceptibility method allows identifying past human activities in the landscape, such as burning. Under high temperatures, antiferromagnetic minerals (e. g. goethite and hematite) transform into ferrimagnetic minerals like magnetite or maghemite, depending on different conditions such as temperature, content of organic matter and iron compounds etc. (Jeleńska *et al.*, 2008). Jordanova *et al.* (2001) used magnetic susceptibility as a measure of the intensity of firing of archaeological sediments and objects. In this research, a collection of archaeological samples of burnt clay of different origin was analysed in order to determine factors, which may have affected their enhancement. It was found out that the firing temperature and duration of burning are important conditions defining the degree of magnetic enhancement. Thus burnt soils have the lowest values of magnetic susceptibility, whereas bricks had the highest values. Combined with chemical analyses, magnetic susceptibility can be also useful in distinguishing cultural layers formed in urban and rural environments (Macphail *et al.*, 2000).

A comprehensive review on solving archaeological problems using techniques of soil magnetism was made by Dalan and Banerjee (1998). Their case study at Cahokia Mounds in Illinois (USA) serves as an example of how soil magnetic techniques can be effective tools for the identification of anthropogenically modified soils and for tracing the movement of soils over a site due to cultural processes. Besides, magnetic methods allowed determining layering and structure of the mound as well as defining the source of materials used for the infilling of off-mound areas.

Archaeological ash deposits were studied by magnetic methods with the aim to identify and quantify fuel types used in prehistory. Magnetic susceptibility measured by Bartington MS2 meter discriminated well between different fuel types (Peters *et al.*, 2002). Hounslow and Chepstow-Lusty (2002), that have investigated the remains of a Roman bathhouse in Albania, have also reported that the magnetic properties of the archaeological deposits are strongly related to the charcoal content that is probably a reflection of ash content. In a Viking Age house in Iceland, magnetic susceptibility confirmed *in situ* burning in the central hearth (Milek and Roberts, 2013).

Magnetic susceptibility was measured to aid the interpretation of soil and sediment history at a site occupied since the Neolithic in Ashcombe Bottom, UK (Allen, 2005).

In the research of Lubos *et al.* (2013) magnetic susceptibility, on the one hand, allowed distinguishing the layers of different age and, on the other hand, it enabled the identification of different sectors of the settlement. Background parent materials were characterized by low MS signals, while layers with soil formation features had higher magnetic susceptibility, and layers with the evidence of human impact in the past in the area i.e. fire or metallurgic activities were characterized by the highest values. This was confirmed by the correlation of magnetic susceptibility with the artefact content.

### *Micromorphological analysis*

The micromorphological analysis of soils and sediments in archaeological contexts has become an essential analytical method in geoarchaeology (Courty *et al.*, 1989; French, 2003; Goldberg and Macphail, 2008). In contrast to bulk soil or sediment analysis, micromorphological investigations are carried out on thin sections that represent intact replica of the soil or sediment. They provide unique information about the internal arrangement and relationships of the soil or sediment constituents (French, 2003). Detailed micromorphological analysis of soils and sediments in archaeological contexts can provide concrete information about activity areas, land use, construction materials etc., and the nature of post-depositional effects on the soil or sediment matrix (Devos *et al.*, 2013b).

Among pedogenic processes, many of the main soil forming processes such as gleying, leaching, illuviation, acidification, podsolization as well as colluvial, alluvial or aeolian inputs of material are detectable in thin sections (French, 2003). The morphology of textural pedofeatures (e.g. clay coatings) can indicate changes in vegetation e.g. from an undisturbed woodland to arable land (Devos *et al.*, 2013a). According to French (2003), colluvial materials are usually easily recognizable as heterogeneous and poorly sorted sets of additions to a soil matrix with a disoriented juxtaposition of partially mixed but different fabrics. Alluvial material, on the contrary, tends to clog the entire fine groundmass and pore space with fine, homogeneous material. In thin sections, alluvium is recognized by very abundant intercalations of silty clay throughout the whole fabric. Micromorphological features of soils and regoliths are extensively described and reviewed in detail by Stoops *et al.* (2010).

Also, land use types like arable agriculture and manuring can be identified in buried soils by micromorphological evidence (Devos *et al.*, 2013a; French, 2003). French (2003) reported that the identification of plough marks not visible macroscopically could be done by micromorphology,

while the survival of indicators of past ploughing is determined by how fast and effective was the burial of the soil after the last ploughing episode.

Human occupation leaves various traces of human activities that can be identified by micromorphological observations (Courty *et al.*, 1989):

- burning features reflected in changes of the soil or sediment matrix and the presence of ash layers;
- different types of organic refuse like coprolites and inorganic plant remains like phytoliths;
- construction materials such as mud bricks, daub, turves etc.;
- mineral artefacts such as flints, ceramics, slags;
- activity surfaces and floors.

In the multi-method geoarchaeological research of floor deposits in a Viking Age house, micromorphological analysis had the greatest interpretative power (Milek and Roberts, 2013). It helped to distinguish activity areas within the house by the possibility to identify walking surfaces; identify and quantify different types of organic matter (e.g. dung excrements, phytoliths, charred and uncharred wood and plant remains). Soils and cultural sediments at another Viking Age site of Quoygrew, Westray, Orkney (Scotland, UK), were investigated by Simpson *et al.* (2005) using micromorphological and bulk physico-chemical soil analysis methods to reconstruct landscape and land use changes in the transition period from the Viking Age to the high Medieval period. Environmental conditions and human activities of Burchtsite in early medieval Antwerp (Belgium) were reconstructed by Devos *et al.* (2013b) based on a soil micromorphological study combined with phytolith and grain size analysis of dark earth layers. Also, Devos *et al.* (2013a) carried out an integrated study of two dark earth units in Brussels applying micromorphology and phytolith studies. Various human activities, land use changes and natural processes were shown to be involved into the formation of dark earths, which has been confirmed in a large number of other studies (Heimdahl, 2005; Macphail *et al.*, 2003).

### **3.1.4. LAND SURFACE TRANSFORMATION**

The terrain is an important factor of the environment that significantly determines human activities in different ways (Schultze, 2014). The transformation of land surface takes place due to both human activities and natural processes as for instance accumulation of cultural layers and sea level change (Schultze, 2014) as well as intended landscape engineering practices and others. Human activities related to land cover changes, most importantly deforestation, enable soil erosion processes that lead to considerable geomorphological changes (Bork and Lang, 2003). The complexity of such combinations of processes make land surface reconstructions difficult.

The study of ancient settlements in the East European Upland by Sycheva (1993) shows that settlements of different age were restricted to different geomorphologic landscape situations, probably due to the fluctuations of the water regime. One of the main conditions for the foundation of settlements seems to be the proximity to the source of fresh water. Cultural layers and associated sediment redistribution processes in a settlement have a levelling effect on the topography (Alexandrovskaya and Alexandrovskiy, 2000). The thickness of urban occupational deposits depends on local topographical features and thus has a levelling effect on the topography, since they tend to fill depressions (Heimdahl, 2005). In such large cities as Moscow, the thickness of cultural layers reaches 20 m in some depressions (Alexandrovskaya and Panova, 2003), although most probably, no separation has been made in this case between the *in situ* cultural layer and its colluvium.

### **3.2. HEDEBY: A PROTO-TOWN IN THE NORDIC WORLD**

Viking Age stands for the early medieval period in Northern Europe and covers the period traditionally set from the first raid of Scandinavians in Lindisfarne, England in 793 AD to the battle at Stamford Bridge in 1066 AD, where the Vikings were defeated (Brink and Price, 2008). The Viking Age is a period of significant political, economic and social transformations in Europe, when first urbanization processes started in Northern Europe (Helle, 2003). Intensive trade activities mark this period with multiple trading centres established in the region (Figure 10). Along with such contemporary trading sites as Birka, Kaupang and Ribe (Olausson, 2002), Hedeby represents one of the first proto-towns where the transition from a rural settlement to a new urban form of life took place for the first time in the region (Wiechmann, 2007). According to the definition of an urban settlement given by Heimdahl (2005), being “a densely and permanently populated area that is environmentally characterized by trade, craft and / or industry” Hedeby can be considered an urban settlement, a town.

Hedeby was a large settlement with an area of approximately 26 ha (Hilberg, 2007) and one of the major international trading centres in Northern Europe in the Viking Age (Winroth, 2012). According to Winroth (2012), the Swedish town of Birka was the only Scandinavian trade town in early medieval period to compete with Hedeby in size and importance. The rapid development of Hedeby to the emporium (Hilberg, 2009) is largely due to its key geographic position at the intersection of the east-west and north-south transport and trading routes. The direct access to the Baltic Sea via its ca. 40 km long inlet Schlei and its proximity to the river Treene, which flows via river Eider into the North Sea, were crucial for seafaring. Also, Hedeby was terrestrially accessible via the Hærcvejen (Heerweg), a route which was of importance for the Frankish and German kingdoms' access to the Baltic Sea (Hilberg, 2009).

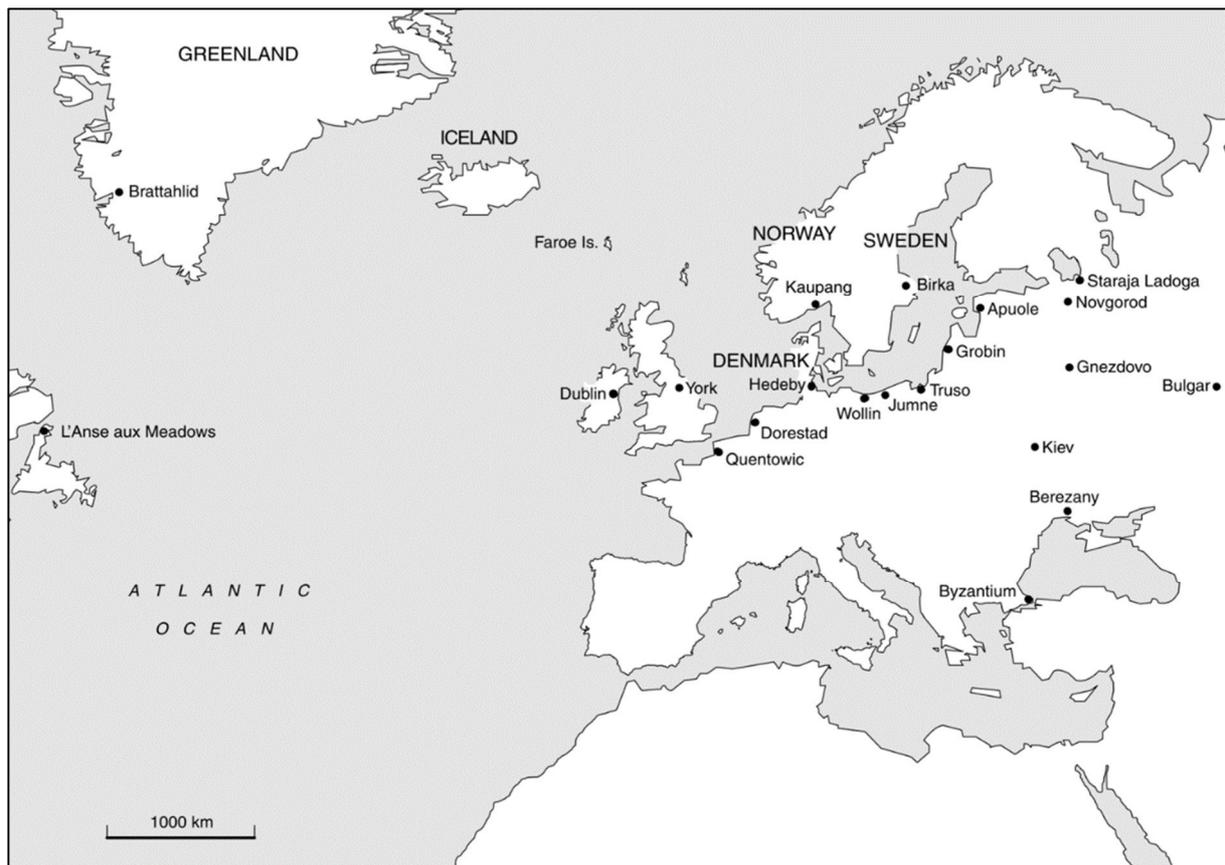


Figure 10. Main sites of the Viking world (Brink and Price, 2008).

Hedeby represents an excellent object for a geoarchaeological investigation of the human-landscape interactions in early urban contexts (Behre, 1983; Hilberg, 2007). After the abandonment of the settlement at the end of the Viking Age, no other occupation took place on the territory of the former town until today. Thus, no overprinting with younger signatures occurred. Only very few comparable early medieval trading centres in Europe are characterized by similar conditions of record preservation (Hilberg, 2007).

### 3.2.1. ARCHAEOLOGICAL RESEARCH: RESULTS AND GAPS

Over hundreds of years after destruction and abandonment of Hedeby, the knowledge about its historical meaning and exact location went lost (Hilberg, 2008). The area surrounded by the semi-circular rampart was interpreted by historians as a medieval military camp (Schietzel, 2014), probably owing to the use of the defence structures as late as in the German-Danish war in the 19<sup>th</sup> century. This changed in the end of the 19<sup>th</sup> century as the Danish archaeologist Sophus Müller from the National Museum of Copenhagen discovered finds in this area that could not be related with a military camp, e.g. pottery sherds, spindle whorls and loom weights (Schietzel, 2014). He supposed that this place could be the early medieval settlement mentioned in written sources and in runic inscriptions on stones in the surrounding. This hypothesis initialized more than 100 years

of excavations and archaeological research in Hedeby. Figure 11 illustrates the extent of archaeological excavations carried out from 1900 until 2010.

In 1900 and in the following years until 1915 and once again in 1921 workers of the Museum für Vaterländische Altertümer in Kiel performed archaeological investigations inside and outside the semi-circular defence wall, which revealed deposits and wooden remains of the former town (Hilberg, 2009). In this period, 500 to 700 graves from a large cemetery inside the wall were excavated. One of the main findings of this initial period of excavations was the impressive boat chamber grave, which was fully analysed in 1976 (Müller-Wille, 1976). In 1913, a team of Friedrich Knorr has excavated the area in the western opening of the half-circle wall, where Hedeby-brook enters the settlement. Results of this work were later summarized by Jankuhn (1937b).

The next large scale excavations took place starting in 1930 led by Herbert Jankuhn, who excavated trial trenches that crossed the settlement from east to west (ca. 530 m length) and from north to south (ca. 585 m length). They represented reference axes for the following excavations until 1969 (Hilberg, 2009). Starting from 1935, Jankuhn concentrated his excavations on the low-lying areas near the coastline with an up to 2 m thick stratigraphy and well-preserved wooden remains (Jankuhn, 1937a, 1943). Although this research was interrupted by the Second World War, in later works Jankuhn (1943) made important statements about house types that he found in this low-lying area. Also, Jankuhn (1937b, 1938) investigated the stratigraphy and composition of the northern segment of the half-circle wall and the eastern end of the connection wall.

The next great step towards a better understanding of the settlement structure was done by systematic archaeological investigations performed by Kurt Schietzel starting in 1963. The results of this research are summarized by Schietzel (2014).

In the last years, new investigations have taken place. Geophysical methods were applied to evaluate the archaeological character of the areas inside and outside of the half-circle wall (Carnap-Bornheim *et al.*, 2013). A large-scale geophysical prospection to assess the extent and intensity of settlement activities was undertaken in 2002 when a total area of ca. 29 ha inside and outside the wall was analysed using Fluxgate- and Caesium-magnetometer and ground-penetrating radar (Hilberg, 2009). Due to these investigations such important settlement elements as the main street, workshop areas, sunken buildings etc. could be identified (Figure 11) (Carnap-Bornheim *et al.*, 2013; Hilberg, 2009). Locations of metal processing sites in the north-western corner of the settlement revealed by the geomagnetic surveys agreed with numerous finds of iron slags made by Kurt Schietzel in the same area (Hilberg, 2009; Schietzel, 2014). From 2005 until 2010, an area nearby the workshop quarter was excavated (Hilberg, 2007; Hilberg *et al.*, 2012) indicating planned and dense building activities there during the 10<sup>th</sup> and 11<sup>th</sup> centuries.

Special attention was given to the harbour of Hedeby since it played a major role in the functioning and development of the settlement (Carnap-Bornheim *et al.*, 2013). Underwater research started in 1953 reaching its maximum in the intensive harbour excavations in 1979 and 1980 by K. Schietzel (Hilberg, 2008) delivering new information about the functioning of this key element of the trading centre. Kalmring (2010) reworked and summarized results of these excavations. Most recent research includes 3D marine seismic investigations of the harbour, which allowed acquiring information about the material below the sea-floor (Mueller *et al.*, 2013).



Figure 11. Simplified interpretation of magnetic anomalies in Hedeby (Hilberg, 2009).

Arents and Eisenschmidt (2010) have analysed remnants of ca. 1350 graves that were found in different excavations since the beginning of the 20<sup>th</sup> century for instance by Herbert Jankuhn (1986), Heiko Steuer (1984) and others including the impressive boat-chamber grave (Müller-

Wille, 1976). The main questions addressed were related to the demographic, social and ethnic structure of the settlement population.

Schultze (2008b) used a geographic information system combined with a database to process archaeological and dendrochronological data from settlement excavations in order to develop a methodology for the structural analysis of the settlement. A number of works were devoted to the investigation of different buildings and house types in Hedeby (Schultze, 2008a, 2014). Due to waterlogged conditions, vast amounts of wooden remains of different origin were recovered. This material was analysed by Westphal (2006).

An important contribution to the knowledge about Hedeby life mode and its environment was an extensive investigation of plant remains (fruits, seeds, wood, pollen and other macrofossils) by Karl-Ernst Behre (1983). On the one hand, this research aimed to reconstruct the food economy of the settlement by attempting to distinguish imported food resources from those that were cultivated locally. On the other hand, the results of this palaeobotanical analysis allowed reconstructing the vegetation in Hedeby and its surroundings during the Viking Age.

In total ca. 5 % of the area inside the half circle wall has been excavated by archaeologists, although only a small part has been analysed and published (Carnap-Bornheim *et al.*, 2013; Hilberg, 2009). Hedeby belongs to the archaeologically best investigated Viking Age sites (Carnap-Bornheim *et al.*, 2013; Hilberg *et al.*, 2012), but until now only very limited knowledge about the local landscape transformation exists. One of the main research gaps is the area at Hedeby-brook, which was investigated only in the eastern part of the town, although it represented one of the main axes of the settlement and played the key role in organization and functioning of the settlement (Schietzel, 2014). Geophysical surveys did not consider the brook area in the western part because of a difficult access probably caused by vegetation and topography (Neubauer *et al.*, 2003). All the information about the brook morphology in the Viking Age is based solely on investigations carried out in the area at the reconstructed houses in the central part of the town, while the situation in the area upstream in the western part of the settlement is completely unknown.

### **3.2.2. HISTORY OF DEVELOPMENT**

Although Hedeby was most probably already founded before the beginning of the 9<sup>th</sup> century (Schietzel, 2014), the first written record, in which the town is mentioned, dates back to 804 AD (Kalmring 2010) when Danish king Göttrik collected his army and fleet in the area of a small harbour settlement Hedeby. According to the Royal Frankish Annals, around 808 AD, king Göttrik destroyed a rival Slavic trading centre Reric that was located at the southern coast of the Baltic Sea, and launched Hedeby as a trade centre. Based on the rapid growth of the population after these events it is supposed that the merchants of Reric liable to taxes were resettled to Hedeby

(Radtke, 2009). These processes seem to have significantly contributed to the rapid development of the small harbour settlement into the proto-urban trade centre.

The first systematic construction activities were proven since 811 AD (Schietzel, 2014) and in 850 AD the first Christian church was constructed. In 948 AD Hedeby became a bishopric, while Christians and pagans inhabited the town also in the later settlement phases (Winroth, 2012). Politically Hedeby belonged nearly the whole duration of its existence to the Danish crown. Only in the period from 934 until 983 AD it was under German rule.

By the 10<sup>th</sup> century Hedeby has become a proto-urban settlement and developed to the international trading centre connecting the Frankish-Frisian trading network of the North Sea region with the Scandinavian region and Slavic Baltic Sea (Hilberg, 2009). This can be clearly seen in numerous findings (Schietzel, 2014). Based on the analysis of archaeological material by Jankuhn (1937b) it is widely accepted that the period of maximum development of Hedeby was the second half of the 9<sup>th</sup> and the first half of the 10<sup>th</sup> centuries. In the archaeological find material, the significance of emporium Hedeby in the exchange between the West (North Sea: Frankish-Frisian realm, Anglo-Saxons, Norway) and the East (Baltic basin, Russia and Caliphate) is clearly visible (Hilberg, 2009). Hedeby was one of the trade towns, through which the Scandinavian elite was able to acquire luxury and exotic goods (Winroth, 2012). Many trade articles were found in Hedeby: foreign jewellery, Arab coins, amber, bars of iron, lead, silver, and brass, mercury, silk, glass, pottery, cornelian, and rock crystal. Many of these products originated further south in Europe, but some are of Asian origin, like some semiprecious stones, some of the silk, and the Arab coins. As an international trading centre Hedeby also had developed own handcraft activities with processing of metal, wood and antlers as well as glass melting and leather treatment being most important (Behre, 1983). In the second half of the 10<sup>th</sup> century Hedeby was incorporated into the defensive system of Danevirke as indicated by the connection wall that was constructed after 968 AD (Stefansdottir and Malück, 2014).

Based on archaeological findings, it seems that in the 11<sup>th</sup> century the town lost its international importance and started to decline, the reasons remain unclear until today. The last proven construction activities date to 1020 AD (Hilberg, 2008). However, there is also evidence that speaks against a clear decline. All the shipwrecks that were found at Hedeby are from late Viking age. For instance, the largest wreck number 3 belonged to a large cargo ship that was built in 1025 and had an estimated loading capacity of 60 tons (Hilberg, 2007). Also, recent investigations with metal detectors revealed 166 Viking Age coins attributed to the 10<sup>th</sup> and 11<sup>th</sup> centuries suggesting that there was probably still a substantial settlement activity in Hedeby in the first half of the 11<sup>th</sup> century (Carnap-Bornheim *et al.*, 2013).

In 1050 AD, Hedeby was plundered by the troops of the Norwegian King Harald Hardrada and in 1066 it was destroyed by a west Slavic army. By the end of the 11<sup>th</sup> century, Hedeby was completely abandoned and the town of Schleswig three kilometres away from Hedeby at the northern shore of the Schlei overtook its functions. The first proven construction activities in Schleswig are dated to 1071 AD (Schietzel, 2014).

### **3.2.3. SETTLEMENT STRUCTURE AND LIFE OF INHABITANTS**

The landscape at Hedeby has changed significantly since the Viking Age. Particularly the topography (Schultze, 2014) and the vegetation (Behre, 1983) have undergone strong alterations due to both human activities and natural processes. In the Viking Age, the landscape surrounding Hedeby was prevailed by woodland and became more open during the settlement period (Behre, 1983). The forests were dominated by mixed woodland with beech or oak dominating, depending on the local soil conditions. Heathlands developed in this period due to forest clearing and grazing. As Haddebyer Noor provided the direct connection to the Baltic Sea and Hedeby-brook carried freshwater, these two landscape elements must have played a decisive role in the selection of the settlement location (Schietzel, 2014).

Before the half-circle wall was constructed in the middle (Stefansdottir and Malück, 2014) or second half (Behre, 1983; Hilberg, 2009) of the 10<sup>th</sup> century, the settlement probably stretched along the shore of Haddebyer Noor following the main street (Hilberg, 2008; Steuer, 1974). In the southern part of the town the street crossed the Hedeby-brook with a small bridge that was dendro-dated to 819 AD (Schietzel, 2014). Streets or roads running parallel to the waterfront are characteristic of early medieval trading centres (Callmer, 2007; Clarke and Ambrosiani, 1991). The main street of Hedeby can be recognized in the magnetogram as a linear structure following the entire shoreline of Haddebyer Noor for ca. 530 m with workshop houses on both sides (Hilberg, 2009). Several streets running from the large harbour to the inner areas of the settlement also apparently crossed it.

The harbour facilities were of prime importance for the development and functioning of the town. Their extension and complexity point at the raised significance of Hedeby in a naval trading system (Kalmring, 2006). The harbour structures are presumed to be situated along the entire shoreline enclosed by the southern and northern ends of the half-circle wall (Stefansdottir and Malück, 2014). Based on archaeological findings a successive expansion of the harbour can be recognized for the period between the end of the first one third of the 9<sup>th</sup> century and the first half of the 11<sup>th</sup> century. Moreover, the harbour with its port facilities was not only meeting the needs of seafaring but also served as a market place and thus represented the economic centre of the settlement (Kalmring, 2010). The absence of a special open market place or a square in Hedeby corresponds to the situation in other towns at the western coast of the Baltic Sea in the Viking Age

(Kalmring 2010). A large wooden U-shaped platform of nearly 1500 m<sup>2</sup> surface area in the harbour was interpreted as the main place of market transactions (Figure 12), which is supported by numerous coins and trade goods (that must have fallen down during trading activities) found in its vicinity.

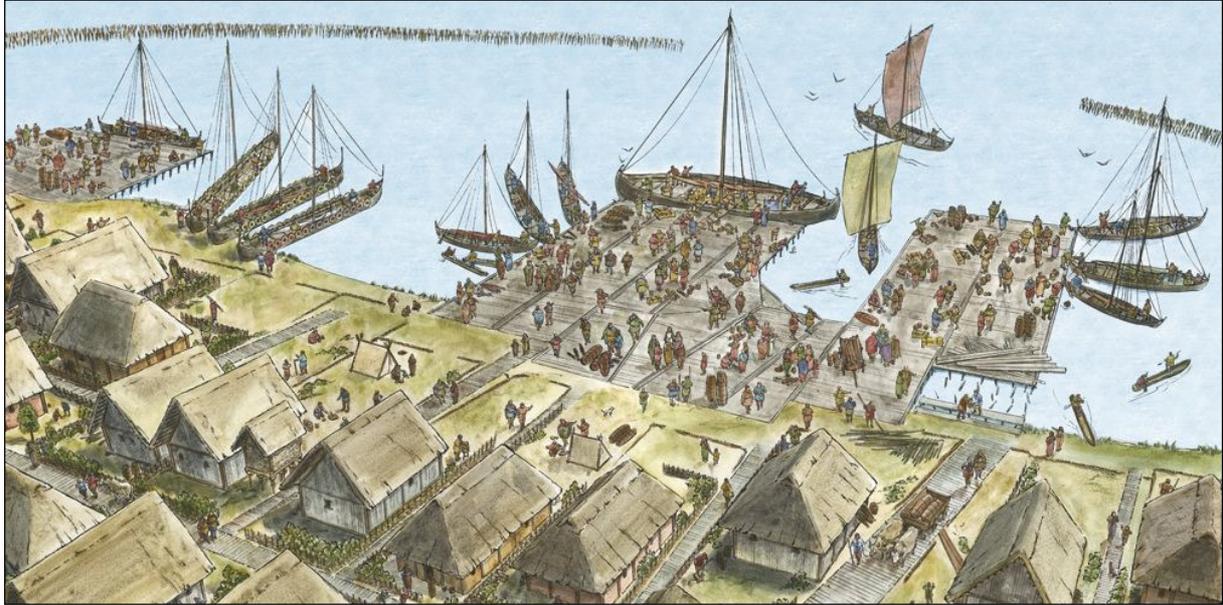


Figure 12. Reconstruction of the harbour of Hedeby (© Wikinger Museum Haithabu).

Some 30 meters south of the platform, Hedeby-brook used to discharge into Haddebyer Noor. It is supposed that in the beginning of the settlement activities Hedeby-brook had a stronger undulating morphology and represented a narrow natural gully. In the early settlement phases, the brook was not fixed and the houses were located nearly directly at it. In this period the brook was mostly used for freshwater supply of people and animals and as the source of process water for washing and other purposes (Schietzel, 2014). Later the brook was fixed by wood posts and had wooden structures above the water stream. Afterwards the wooden structures were removed and installed again (Jankuhn, 1938), which points at the change of the use of the brook and its water resources a few times during settlement activities. Schietzel (2014) found wooden structures at the brook that were built perpendicularly into the shore embankment and reached into the water. These structures had inclined wooden boards that were interpreted as washboards. There is also evidence that wastewater and surface runoff were discharged into the brook by artificial ditches with periods when the brook was even used as a gutter (Schietzel, 2014). In result, the quality of drinking water of the brook diminished and led to the silting up of the water body, which would explain the construction of wells in later periods of the settlement activities (more than 30 wells were found). The original course of the brook turned southeast at the location of the modern road Kirchweg, but in the 1880s it was relocated and straightened (Kalmring, 2010).

A workshop area of iron smiths must have been located in the north-western corner inside the half-circle wall north of the brook (Jankuhn, 1938; Schietzel, 1981). Due to the alignment of the workshop buildings with an east-west-oriented road that runs towards the rampart, they seem to belong to the younger phases of Hedeby in the 10<sup>th</sup> to 11<sup>th</sup> centuries (Hilberg, 2009; Hilberg *et al.*, 2012). It has to be mentioned that the available archaeological evidence speaks against iron smelting in Hedeby. The abundant iron objects were most probably produced out of raw iron material (bloom formed into transportable bars) that was imported from southern Sweden or they represent objects imported as ready high-quality goods, first of all weapons (Westphalen, 1989). Also, it is supposed that antler working took place in this area since high amounts of production waste were found here (Ulbricht, 1978).

According to Behre (1983), Hedeby was not only a place of trade and handicraft, but agriculture and collecting of fruits and nuts were important substantial settlement activities too. A lot of information about the vegetable diet of Hedeby's inhabitants originated from this study. Cereals (mostly barley, rye and oat) were the most important vegetable food in Hedeby. Also, to a limited extent, people of Hedeby cultivated fruit like damsons and peach, whereas up to 20 % of the human nutritional requirements (without meat and fish) were fulfilled by fruits and nuts such as wild cherry, apple, blackberry, raspberry, wild strawberry, elder, hazelnuts, beechnuts, hops, acorns and others that were collected in forests nearby. Although agricultural farming was practiced, probably at the margins of the settlement or in its direct vicinity, no precise conclusions could be made whether this production would have been sufficient for the settlement, or whether it had to be supplemented from the neighbourhood. An import of cereals from distant sources was excluded, as all the weeds contained in the cereal samples belonged to the species native in the vicinity of Hedeby. Only the import of luxury food like walnuts and wine was proven. Behre (1983) concluded that, as at other early medieval settlements, the food for Hedeby must have been grown in the respective surrounding. Randsborg (1980) estimated an area of about 600 km<sup>2</sup> necessary to support Hedeby with food supplies by comparing it to Anglo-Saxon sites of the late 9<sup>th</sup> century.

Among domestic animals, pigs and cattle were the most important ones, followed by sheep and goats. They account for 45.0 %, 38.9 % and 14.3 % of mammal bone finds, respectively (Schietzel, 2014). While pigs were used for meat production, cattle was also intensively used for milk production as well as for the transport and work in the field as indicated by the features of their joints. The percentage of wild animal bones is very low and equals 0.61 %. Domestic chickens (57.9 %), wild birds (23.3 %) and domestic geese (18.9 %) dominate the bird bones.

Since the early phases of archaeological excavations in Hedeby, houses were one of the main research interests. As indicated by geomagnetic survey, Hedeby was a densely built settlement (Kalmring, 2010). In the low-lying areas separate plots each containing a main house, an

outbuilding and a well were found (Jankuhn, 1943). Most of the houses were non-uniform and varied considerably in size and construction; however one common feature was present – the absence of inner posts (Schietzel, 1981). Schultze (2014) was able to distinguish the main construction elements of the houses as well as the main house types including frame-constructed houses, houses with palisade walls and log houses. One of the best-preserved houses (“Haus 1”) was investigated in very high detail and showed a structure typical for contemporary Viking Age sites in northern Europe (Schultze, 2014).

Cemeteries occupied the south-western part of the settlement. A disturbance of the burials by younger settlement structures points at a change in the land use in this area (Hilberg, 2009). Based on discovered burials in the south-western part of the town within the half-circle and in a large area south of it, Steuer (1984) estimated the average population size of Hedeby with 1000 inhabitants during the 250 years of occupation. Rapid population growth took place starting from ca. 900 AD and particularly in the first half of the 10<sup>th</sup> century. In the same research, burial types served as a basis for reconstruction of the ethnic composition of Hedeby in different periods. Since Hedeby lies in the border area of Danes, Saxons, Frisians and Slavs (Hilberg, 2009), a rather international ethnic composition was expected. According to Steuer (1984), in the 10<sup>th</sup> century the population was strongly dominated by Saxons (ca. 30 %) and Danes (ca. 30 %), followed by Slavs and Swedes. However, this attempt to combine the different ethnicities known from written records with the different known grave types in Hedeby has been strongly rejected (Hilberg, 2009). Particularly, an interpretation of the lack of grave goods in the 9<sup>th</sup> and 10<sup>th</sup> centuries as a reflection of a Frisian-Saxon population was strongly criticized. Nevertheless, a noteworthy conclusion was made by Steuer (1984) stating that a special “Hedeby population” had formed by the end of the 10<sup>th</sup> century, which made a reliable reconstruction of the ethnic origin from then on impossible.

It has to be noted that a so-called “southern settlement” with older settlement structures was found south of the half-circle wall (Steuer, 1974). However, the question of whether this demonstrates social, functional or mainly chronological differences has still not been answered (Carnap-Bornheim *et al.*, 2013). It is known that the southern settlement was abandoned during the second half of the 9<sup>th</sup> century and the area was then used for burials (Hilberg, 2009).

## 4. METHODOLOGY

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### 4.1. FIELD METHODS

Hedeby, as a historical and archaeological monument, has been designated a protected area status. For this reason, excavations can take place there only under special conditions. Therefore, in this research drillings represented the main method of sampling. Prior to the execution of drillings, results of former archaeological excavations and geomagnetic surveys were analysed in order to avoid sites of former excavations and geomagnetic anomalies. The field work was carried out in favourable conditions during the field seasons in the period May 2012 – October 2016.

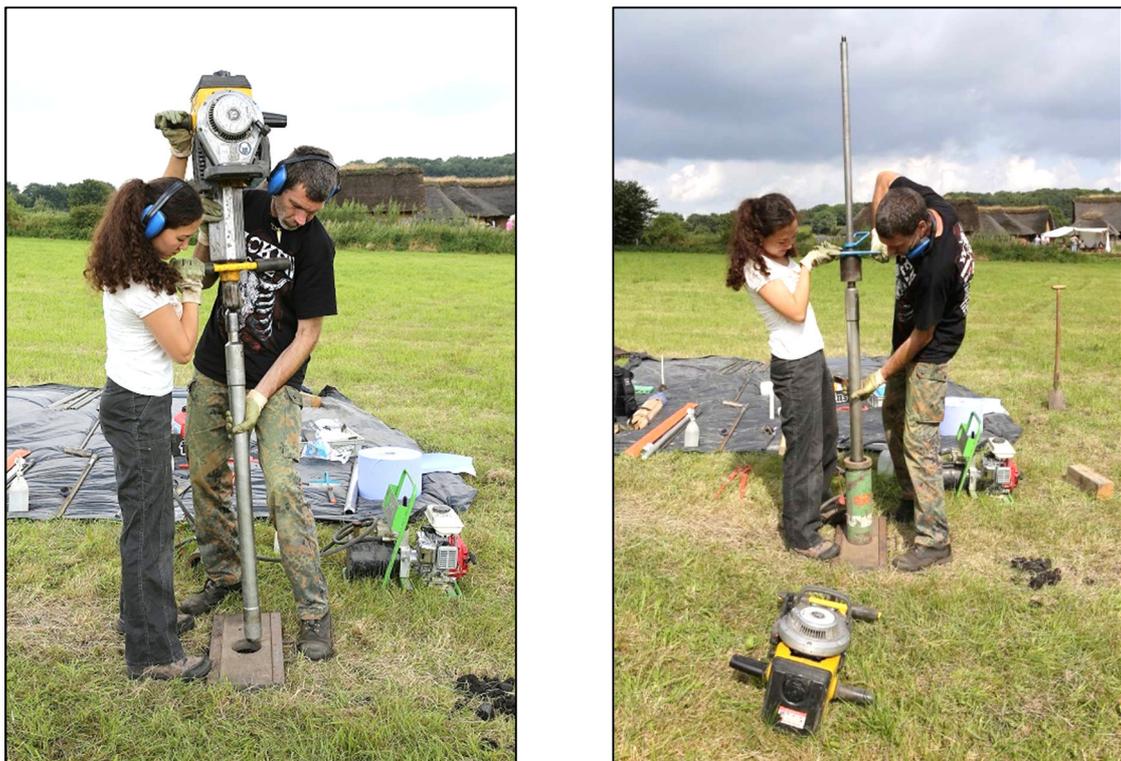


Figure 13. Drilling in Hedeby with the Vibracore system (photos Hans-Rudolf Bork).

The preliminary sondage of the study area as well as shallow drillings at elevated landscape positions, where no ground water effects on core retrieval were present, drillings by universal gauge augers of Pürckhauer type were performed. Pürckhauer coring system includes 1 m long steel augers of ca. 1.6 cm inner diameter with additional metal rods for the extension. The auger is inserted into the ground by a 4 kg nylon hammer and withdrawn by a lever ball clump mechanism. Key advantages of the Pürckhauer system are the simple handling, high speed and low costs. Limitations are the small core diameter, the risk of contamination by upper soil/sediment layers and a partial loss of material during recovery. 124 drillings of 1 to 4 m depth were performed by the Pürckhauer system. Therefore, in areas, where soil and sediment sampling

was necessary or if water saturation level would not allow an undisturbed Pürckhauer sampling, an alternative percussion method, the Vibracore method, was applied.

The Vibracore system provides the opportunity of accurate sampling with respect to depth and a higher sampling density due to the larger core diameter. The Vibracore system includes closed steel percussion coring augers (63 mm diameter) with steel extension rods and PVC inner liners with 50 mm outer diameter. The plastic tubes are placed into the steel augers and attached to a handheld impact hammer (jackhammer 23 kg), which inserts the augers into the ground. For the withdrawal of the augers, hydraulic pulling equipment (8 t pulling force) with a bull clump is applied. 54 drillings were performed by the Vibracore system. The depth of the drillings varied between 2 and 5 m, in single cases a depth of 10 m was reached. After the retrieval of the tubes filled with sediments from the augers, the tubes were cut on the long sides into two halves using a vibration saw.

All cores were documented in photographs. Soils and sediments were described in the field following the FAO soil description guidelines (Guidelines for soil description, 2006) with a determination of soil and sediment colour of moist samples using the Munsell soil colour chart (Munsell, 2000). Soil terminology follows World Reference Base for Soil Resources (World reference base for soil resources, 2014).

The geographical positions and altitudes of the cored sites were determined with a differential geographic positioning system (DGPS), in which the reference station was located with a precise reference to an official survey point with known coordinates. The coordinate system WGS84 was used.

## **4.2. LABORATORY METHODS**

### **4.2.1. SAMPLE PREPARATION**

Halves of the cores were sampled, while the other halves were kept undisturbed for reference. Prior to the analyses samples were dried for a few days at 40 °C and sieved through a sieve with a 2 mm mesh size. During the sample preparation the separation of the following components was performed:

- fine grain-size fraction (< 2 mm),
- coarse grain-size fraction (> 2 mm),
- artefacts,
- bones,
- charcoal/wood (not always possible to separate qualitatively) and

- other plant remains.

All these fractions were weighed and respective percentages were calculated.

#### 4.2.2. GEO-ECOLOGICAL ANALYSES

Laboratory measurements included

- determination of loss on ignition,
- C/N ratio,
- pH-value,
- magnetic susceptibility,
- grain size distribution,
- multi-element analysis and
- micromorphological analysis.

The pH is a quantitative measure of soil and sediment acidity based on its hydrogen ion concentration. It helps not only to differentiate soil chemical state but also hints at the preservation conditions for natural materials and artefacts, bones etc. within the deposit (Weiner, 2010). The pH value was determined in a 1 : 5 suspension (air-dried soil : 1 M KCl) by a pH meter WTW pH 330i, SenTix 41 consisting of a glass electrode and a reference calomel half-cell instrument.

Loss on ignition represents a measure of organic matter content as it is based on the assumption that organic material is combusted at the temperature 550 °C. Porcelain crucibles were cleaned and dried at 105 °C until constant weight was reached. Samples of approximately 3 g mass were sequentially heated in a drying chamber at 105 °C overnight and in a muffle furnace at 550 °C for 2 hours. The weight of the samples was recorded after each step. The loss of weight between the heating procedures at 105 °C and 550 °C is the loss on ignition, which is calculated as weight percentage.

For the measurement of the C/N ratio, macroscopically visible plant residues were removed and the material was ground to a powder for 30 seconds in an agate vibratory disk mill. The measurement was performed by spontaneous combustion with subsequent chromatographic separation using an Euro EA – CHNSO Element Analyser.

Two methods were used to measure the grain size distribution for different cores: the sieving and sedimentation method and the laser diffraction method. For both methods, the fine grain-size fraction (3-20 g depending on the method) was step-wise treated with 35 % hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) for the destruction of organic matter and, if necessary, with 0.5 M sodium acetate buffer

solution for removal of carbonate. In case of sedimentation analysis, after the destruction of the cementing agents, the samples were treated with ultrasound to prevent coagulation of soil and sediment particles. The next step included the separation of sand fractions by wet sieving using sieves with 63  $\mu\text{m}$ , 200  $\mu\text{m}$  and 630  $\mu\text{m}$  mesh size. Silt and clay were separated in the effluent water by sedimentation in Atterberg cylinders. In case of the laser diffraction method, when the cementing agents were removed, 10 ml of distilled water and 0.5 ml of tetrasodium pyrophosphate ( $\text{Na}_4\text{P}_2\text{O}_7$ ) were added and the samples were left for 6 hours of overhead shaking. After this final preparation step, the samples were analysed on the Mastersizer 2000 particle size analyser in the laboratory of the Geographical Institute of Kiel University. This instrument has a measuring range from 0.02  $\mu\text{m}$  to 2000  $\mu\text{m}$ , which results in 70 classes of grain sizes. The measurement error of the instrument was very low in all grain-size fractions and thus was not further considered (standard deviations are 0.002% in clay, 0.03% in silt and 0.1% in sand fractions).

For the magnetic susceptibility measurement, dry material from the fine < 2 mm fraction was placed into 10 ml plastic cylinders (3 replications). The tubes were weighed and measured at low (0.465 kHz) and high (4.65 kHz) frequency using a Bartington Instruments MS2 meter. The calibration of the instrument was performed using 1%  $\text{Fe}_3\text{O}_4$  calibration sample.

Multi-element analysis was done by a X-ray fluorescence with an XL3t 900-series GOLDD+ instrument by Thermo Scientific Niton Analyzers. A powder < 60  $\mu\text{m}$  prepared in an agate vibratory disk mill was used for the analysis. Samples were transferred into plastic tubes that were covered with a thin film of 4  $\mu\text{m}$  thickness. The measurements were performed for 300 seconds in the mining mode under standardized conditions in a lead-mantled measurement chamber and helium-flotation in the detector unit of the device to enhance quantitative measurement of light elements.

#### **4.2.3. MICROMORPHOLOGICAL ANALYSIS**

Thin sections with a size of 12  $\times$  3.5 cm were prepared from undisturbed materials of interest in the cores obtained by the Vibracore method. In each case, one of the halves of the cores in plastic tubes was cut across providing a half-tube-core fragment of 12 cm length. Afterwards the sample was wrapped, sealed and sent to a laboratory for the preparation of thin sections. In the laboratory, after drying, the samples were transferred into labelled containers, which were then placed into excicators and impregnated in vacuum with a two-component epoxy resin Araldite 2020. After the impregnation had been completed, the containers were removed and impregnated blocks were cut to the size of 2  $\times$  10 cm. Consequently, the blocks were polished and mounted onto the glass slides (3.5  $\times$  12 cm). These mounted sediment slices were then ground and polished to a thickness of 25  $\mu\text{m}$  and finally covered with a coverslip. The orientation of each sample was

engraved on each slide, as was the sample ID number. Thin sections were described at 25× to 400× magnification (with an additional magnification up to 1000×) under a polarization microscope using the terminology and guidelines of Stoops (2003) and Courty *et al.* (1989).

#### **4.2.4. DATING METHODS**

Radiocarbon dating ( $^{14}\text{C}$ -AMS) was performed on nine samples: charcoal fragments with determined tree taxa (5), hazelnut shells (2) and charred seeds (2). 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  $^{14}\text{C}$  Dating at the Norwegian University of Science and Technology, Trondheim, Norway. The  $^{14}\text{C}$ -AMS dating results were calibrated using the program OxCal V4.2 (Bronk Ramsey, 2009) and IntCal 13 calibration set (Reimer *et al.*, 2013). Cultural layers could be often dated archaeologically based on the presence of pottery and other artefacts.

#### **4.3. SOFTWARE**

Geographic information was managed in ArcGIS v. 10.3. Statistical analysis was performed using software Statistica v. 12.0 and R-3.4.2. Graphs and figures were made or modified using MS Office 2016 tools as well as RStudio 1.0.136 and CorelDraw X7.

## 5. RESULTS

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### 5.1. SOILS AND SEDIMENTS IN HEDEBY: PROPERTIES AND CLASSIFICATION

In this chapter, soils, cultural layers and other settlement deposits and archaeosediments in Hedeby are described. Furthermore, an approach for their classification based on objective criteria and their statistical analysis is presented.

#### 5.1.1. SOILS AND SEDIMENTS IN HEDEBY

The information on soils and sediments at Hedeby was deduced from 178 drillings performed inside and outside the half-circle wall. In order to obtain information on the diverse types of sediments, different landscape positions and settlement areas were covered by these drillings with the main focus made on the areas adjacent to the Hedeby-brook. 116 drillings were performed in a small dry valley in the southern part of the settlement, 51 drillings were made along and across Hedeby-brook, 10 drillings were made outside the settlement north of the half circle wall as well as one drilling through the half-circle wall (Figure 14).

Soils and sediments present at Hedeby are heterogeneous and of different origin. Depending on the location, they include different natural sediments and soil horizons as well as sediments, which were affected by humans, and cultural layers. In order to standardize and to unify the descriptions of the layers in the cores and to enable further interpretation, a field classification scheme for sediments and horizons was developed and applied in Hedeby based on morphological properties. The classification includes 44 classes of sediments that were grouped into 7 types. For further simplification, 11 additional descriptors combinable with all types of sediments were introduced. Below, the categories of layers, horizons and structures are described. The summarized field classification is provided in appendix 1. The principles of international soil horizon designation of the World Reference Base (2014) were applied for the classification of soil horizons and modified for the designation of other sediment types. It has to be noted that often the genesis of materials could not be determined in the field; such layers were designated based namely on their (micro-)morphological properties.

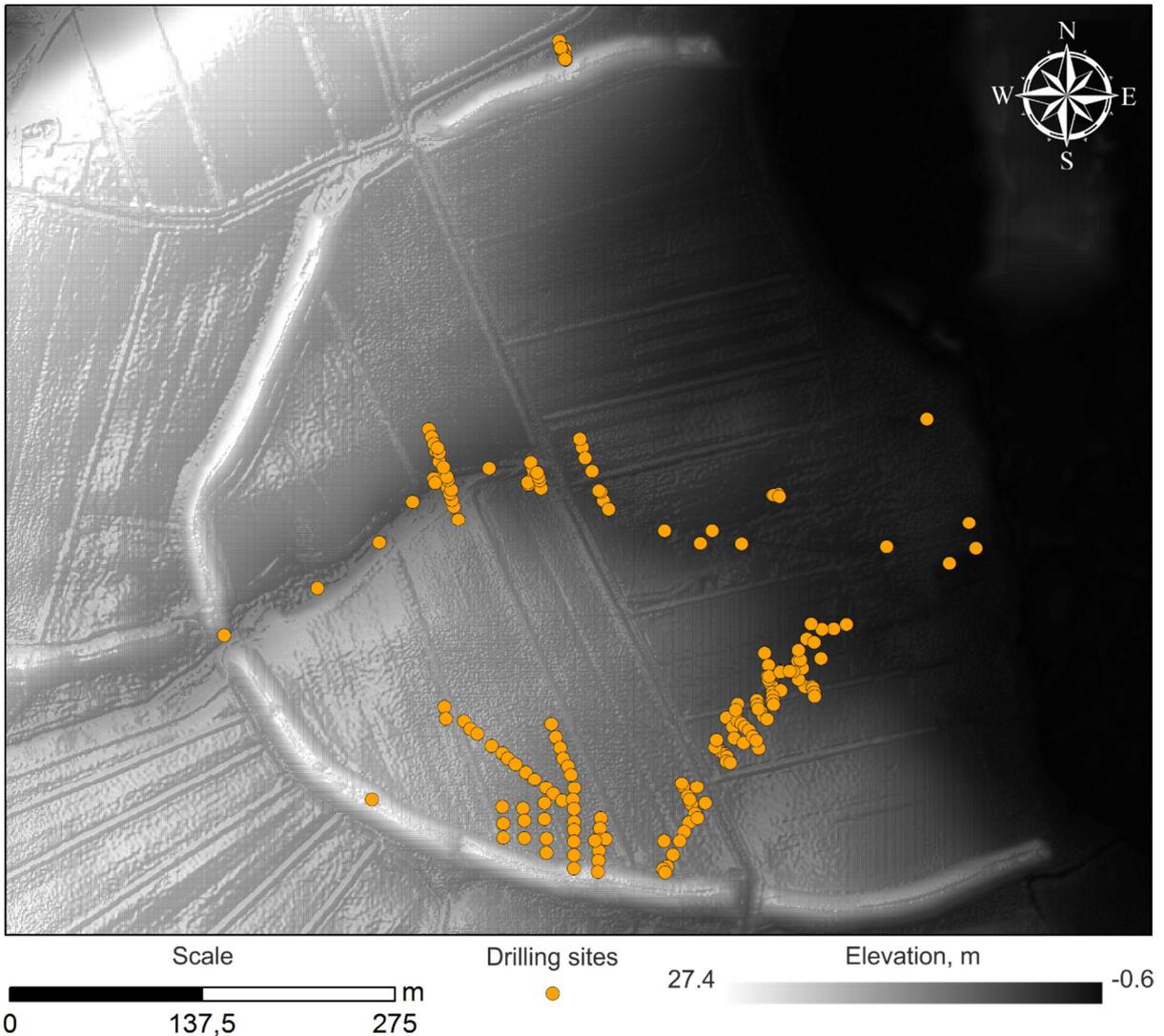


Figure 14. Digital elevation model of Hedeby with location of drilling sites.

## 1. Pleistocene deposits

Different glacial, fluvio-glacial, fluvial and limnic sediments deposited during the last glacial period (Weichselian) represent the Pleistocene deposits in the study area. The oldest deposit reached by the drillings is glacial till material ( $C_{\text{till}}$ ) with typical properties: unstructured, massive material of varying grain size with a high bulk density, the presence of stones and a high content of carbonates. Clastic varves ( $C_{\text{layered}}$ ) consisting of thin alternating layers of sand and silty-clayey material were found at sequences bases in the central part of the settlement. Most commonly, Pleistocene fluvio-glacial sand ( $C_{\text{sand}}$ ) was found, but also Pleistocene deposits dominated by silt ( $C_{\text{silt}}$ ) or clay ( $C_{\text{clay}}$ ) were identified.

## 2. Soil horizons

Buried soil horizons of different degrees of preservation were identified in some areas inside of the settlement. Humic horizons (Ahb) were usually absent, disturbed or incorporated into the overlying cultural or colluvial layers. Only rarely, as for instance under the half-circle wall

material, a nearly complete buried profile of a soil was found that has developed during the Holocene. Soil B horizons were more often preserved and such types of B horizons as Bwb (weathered horizon), Bwhb (weathered horizon with features of organic matter accumulation), Btb (with clayey bands, sometimes with small quantities of iron oxides) could be distinguished. Parent material for soil formation in the area is Pleistocene fluvio-glacial sand ( $C_{sand}$ ). Figure 15 shows an example of a buried soil with preserved A and B horizons with features of eluviation in the upper part of the A horizon. Suffixes b, e, h, s, t, w, p, commonly applied in the World Reference Base, were used for describing the features of soil horizons (see appendix 1).

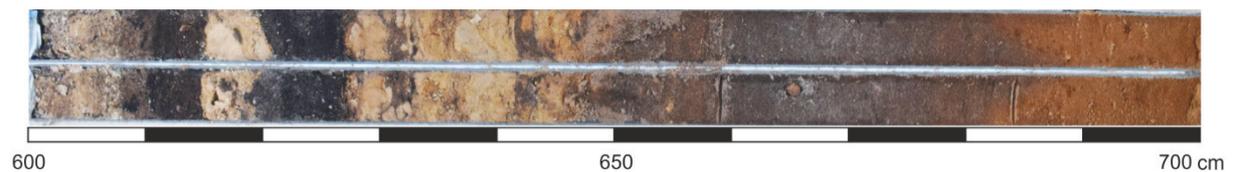


Figure 15. Soil buried under the half-circle wall in the western part of the settlement (p. 1401); starting at ca. 660 cm horizons AEb, Bshb, Bwb (increased brightness for a better recognition of stratigraphic units).

At a few sites, humic horizons were identified in colluvial layers (AhM), while ploughing horizons (Ap) formed within sediments at the exposed surface due to the agricultural land use in high medieval and modern times.

### 3. Mineral deposits

Various kinds of mineral, often sterile, interlayers were identified in the stratigraphy of Hedeby sediments such as gravel, sand layers dominated by different sand fractions, silt and clay layers. The thickness of such layers was usually between 10 and 30 cm. In one drilling point at Hedeby-brook, a redeposited pond sediment dominated by fine sand and silt was identified and designated as L standing for a limnic sediment.

### 4. Organic horizons

Layers rich in organic material are widely spread in Hedeby. In depressions, valleys and near the shoreline of the Haddebyer Noor, peat layers of different degrees of plant remains decomposition were identified; they were designated as H. Depending on the degree of plant remains decomposition suffixes “a” (highly decomposed) or “e” (moderately decomposed) were added: Ha and He respectively (Figure 16). In case of presence of a large amount of wood remains and domination of organic matter in the matrix a designation  $H_{wood}$  was used. Also, a litter layer O, dominated by undecomposed plant remains (e.g. leaves), was identified in some areas.

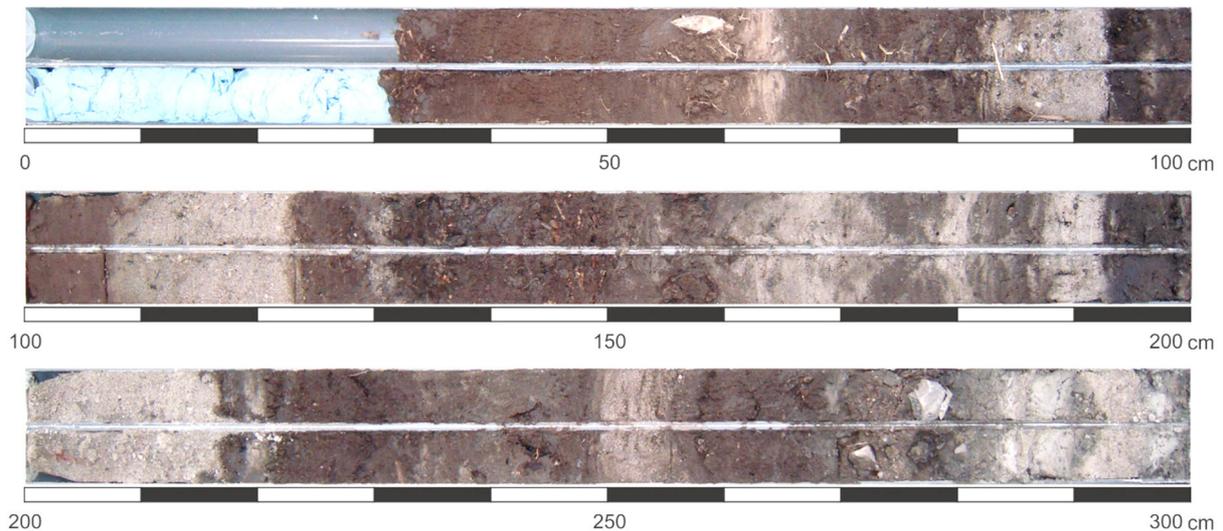


Figure 16. Alternation of organic matter-rich material (He and Ha) and sand layers in the central part of the valley at Hedeby brook (p. 409) (increased brightness for a better recognition of stratigraphic units).

## 5. Cultural layers and anthropogenically affected sediments

Sediments that were directly deposited by humans such as the archaeosediments of the defence wall or material of hedgerows, pit fillings were designated as Y with additional indexes corresponding with the use of the sediment (wall, knick etc.). Heterogeneous, usually dark coloured sediments with presence of artefacts, bones and/or charcoal and woody remains were designated as cultural deposits ( $Y_{\text{cult}}$ ) (Figure 17). In case of a high organic matter content these layers were named  $Y_{\text{cult,org}}$ .

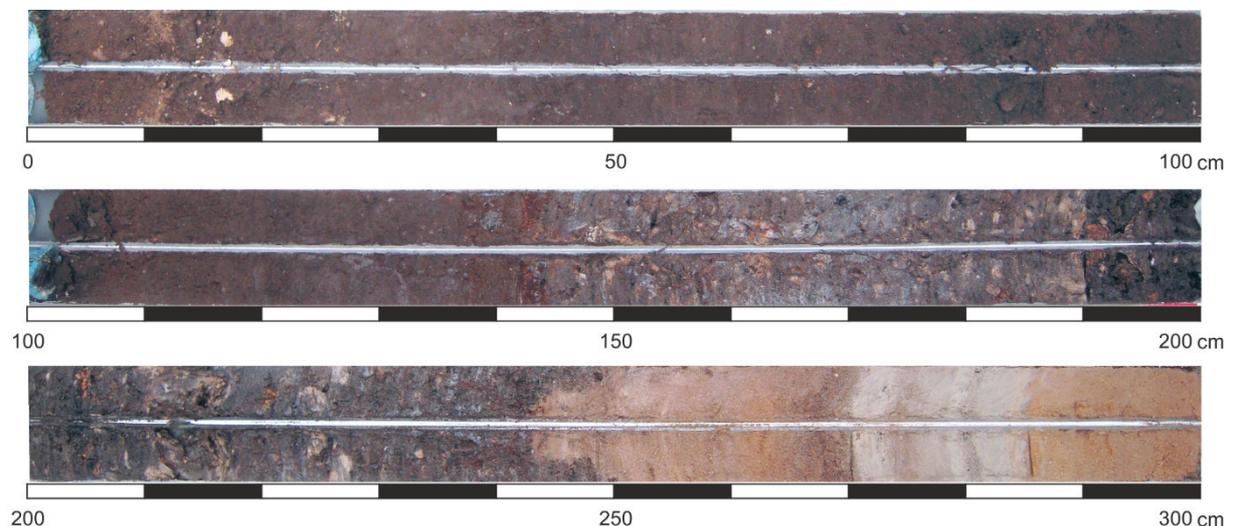


Figure 17. Cultural layer  $Y_{\text{cult}}$  (145-244 cm) in the central part of the settlement (p. 406) (increased brightness for a better recognition of stratigraphic units).

The upper part of cultural deposits that is homogeneous due to the former agricultural land use and ploughing after abandonment of the settlement and nearly free of artefacts was designated  $Y_{\text{cult-hom}}$ . As often the case in former settlements, dark coloured layers enriched with charcoal and charred material were identified ( $Y_{\text{ch}}$ ). At a few locations (mostly at the half-circle wall) a light

grey layer of ash at different depths was identified, it was designated as  $Y_{ash}$ . At locations with good preservation conditions, layers with abundant wood remains but dominated by mineral material were identified. They were designated  $Y_{wood}$ . In the cores near the Hedeby-brook, a cultural stone deposit rich in artefacts and bones was identified, it was designated  $Gravel_{cult}$ .

## 6. Re-deposited (colluvial) layers

At sites with material accumulation, colluvial layers that contain materials from different sources were distinguished. Colluvial layers from unclear sources were designated as M. In case of presence of a relatively large amount of organic matter (morphologically) a designation  $M_h$  was given.  $M_{cult}$  represents colluvium with material from cultural layers – dark-coloured, with small artefact fragments but more homogeneous in comparison with the *in situ* cultural layer (Figure 18). Due to the agricultural land use in high medieval and modern times, the upper part of this cultural colluvial layer was homogenized by ploughing and was thus designated as  $M_{cult-hom}$ .  $M_{wall}$  represents colluvium of the half-circle wall material. Often, heterogeneous colluvial layers with a prominent alteration of sublayers of different materials were found, they were designated as  $M_{layered}$ . If the source soil horizon for colluvium could be determined, designations MAh and MBw were applied representing colluvium of A and B horizons respectively.

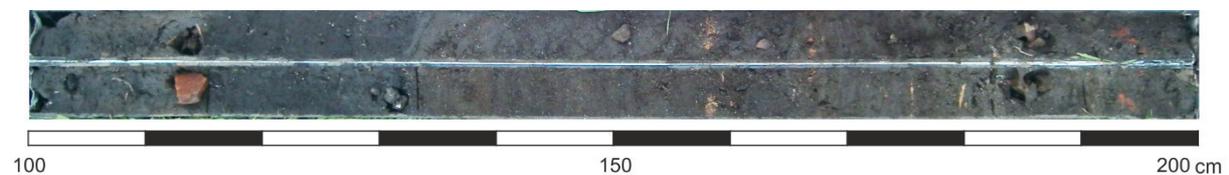


Figure 18. Colluvium of the cultural layer  $M_{cult}$  (100-133 cm) underlain by peaty material in the central part of the settlement at the Hedeby brook (p. 120) (increased brightness for a better recognition of stratigraphic units).

## 7. Disturbance structures and mixed layers

An undifferentiated class of disturbances that could not be classified was distinguished and designated as  $Y_y$ . Examples of such units represent presumed crotowinas, post hole fillings etc. Often layers representing mixtures of different materials were found. In order to keep the number of stratigraphic units reasonable, such layers were designated as Mix: X+Y+..., with X and Y representing the components of the mixtures.

Certain features could be observed for different types of layers, for instance such as the presence of charred material, the presence of pedogenic oxidation and reduction features. So that each layer with an additional feature did not form a separate class, additional indexes combinable with any of the above classes were introduced (see appendix 1).

### 5.1.2. SPATIAL DISTRIBUTION AND STRATIGRAPHY OF SOILS AND SEDIMENTS

Due to the intensive and diverse settlement activities as well as the agricultural land use in late medieval and modern times, nearly all types of layers and horizons, described above, were present in different parts of Hedeby. However, depending mainly on geomorphological conditions, some tendencies can be pointed out.

Buried soil horizons were well preserved when they were buried under sediments without surface disturbance, for instance, under the half-circle wall in the western part of the settlement. However, such conditions were rather unique. Usually, only fragments of B horizons were preserved. They were identified at two drilling sites at the Hedeby-brook and at 56 drilling sites in the small dry valley in the southern part of the settlement.

Cultural layers that formed *in situ* were identified in all parts of Hedeby. In the valleys they were preserved at upper and lower slope positions, while at transit slope segments they were eroded. In the central part of the settlement at the Hedeby-brook and at other sites in waterlogged conditions cultural layers very rich in organic matter were identified.

In the two valleys, different colluvial layers of different age were found, too. One type represented colluvium of the cultural layer, while another included homogeneous brown material – eroded topsoil and B horizon material. In the deeper parts of the valley at the Hedeby-brook as well as in areas close to the Haddebyer Noor peat and peat-like layers were identified. They were differing in their degree of plant material decomposition and sometimes included artefacts.

Half-circle wall material, besides drillings through the wall, was identified as colluvium at the foot of the wall in the southern part of Hedeby. In a depression west of the half-circle wall, very fine pond sediments were identified. Such sediments, but redeposited, were also found in a few cores inside the settlement at the Hedeby-brook.

Stratigraphy of soils and sediments is also non-uniform and depends on local conditions. Therefore, a generalized scheme describing different possibilities was elaborated (Figure 19). Mixtures of layers and disturbance structures are not reflected in this scheme.

The basis of the stratigraphic sequences reached by drillings was usually represented by fluvio-glacial sand ( $C_{\text{sand}}$ ). It was often underlain by loamy Pleistocene sediments ( $C_{\text{clay}}$ ), clastic varve deposits ( $C_{\text{layered}}$ ) or glacial till ( $C_{\text{till}}$ ). However, it has to be noted, that  $C_{\text{clay}}$ ,  $C_{\text{layered}}$  and  $C_{\text{till}}$  were mostly found at sites where deeper drillings were performed. Thus at other sites, where shallower drillings were made, such deposits probably were not reached. At some sites, features of Holocene soil formation and corresponding soil horizons were identified in the upper part of Pleistocene deposits. Usually, it was a Bwb horizon, which, in exceptional preservation conditions, was overlain by the humic horizon Ahb. This soil profile was buried either by the half-circle wall

material ( $Y_{wall}$ ) or by cultural layers ( $Y_{cult}$  or  $Y_{cult,org}$ ). In cases when soil profile was truncated and only a B horizon was present, it was covered directly by the cultural layers ( $Y_{cult}$  or  $Y_{cult,org}$ ) or by a colluvial layer M, and on eroded slopes it was lying directly under the ploughed part of the cultural layer ( $Y_{cult-hom}$ ) or its colluvium ( $M_{cult-hom}$ ).

In the valley of Hedeby-brook – except peat – soil horizons were not found and Pleistocene deposits were overlain directly by Holocene sediments. In the central part of the Hedeby-brook valley, a layer of Pleistocene gravel (Gravel) or an anthropogenic stone deposit ( $Gravel_{cult}$ ) represented the border between the Pleistocene and Holocene deposits. The next stratigraphic unit was represented by cultural sediments of anthropogenic origin ( $Y_{cult}$ ), often rich in organic matter ( $Y_{cult,org}$ ). In the brook valley, these cultural deposits were followed by a peat horizon (Ha) and then by the colluvium of the reworked cultural layer  $M_{cult}$  or by the ploughed cultural colluvium layer  $M_{cult-hom}$ . A peat layer was also identified in the fen area near the Haddebyer Noor, where it was lying directly above Pleistocene deposits or above natural gravel layers.

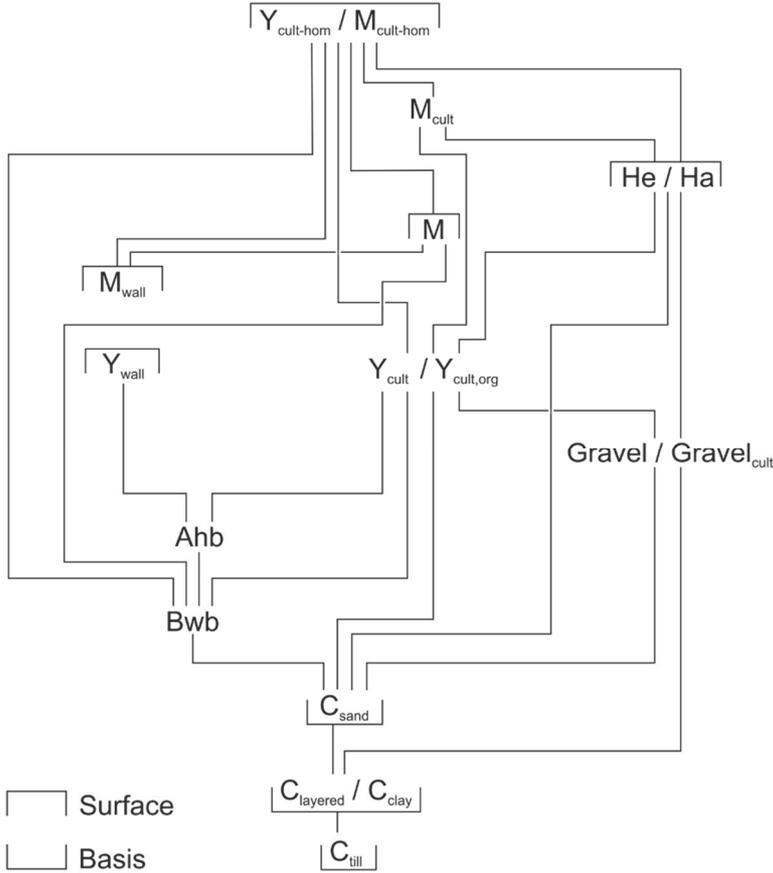


Figure 19. Generalized scheme of the most typical stratigraphic sequences in Hedeby.

**5.1.3. GEO-ECOLOGICAL PROPERTIES AND STATISTICAL ANALYSIS**

The amount of samples taken per core varied from 29 to 46, while the number of layers in one core often exceeded 20. For all the samples from the cores that were analysed in the laboratory (A1, A2, 198, 270, 300, 311, 441, 442) the following properties were determined:

- content of the coarse fraction (> 2 mm);
- contents of artefacts, bones and charcoal with wood;
- loss on ignition;
- magnetic susceptibility.

For cores A1, A2, 198 and 441 grain size distribution by the sieving method (without separation of silt and clay) was measured, while for cores 198 and 441 also laser diffraction for grain size analysis was carried out. Additionally, for cores A1, A2, 198 and 270 multi-element analysis by XRF was performed. Elements with measurement error < 10 % were considered. For a small selection of materials at points A1, 198, 441 and 442, pH in 1 M KCl was measured. These results are presented in section 5.2. of the Results chapter.

The stratigraphy in the cores is complex; sometimes the connection of layers and thus determination of their genesis by visual investigation was not reliable. Even for cores located only 1 – 2 meters away from each other, problems of connection of individual layers occasionally occurred. In order to account for the high spatial heterogeneity of the materials and to classify them based on objective criteria, multivariate methods of statistical analysis were applied. Depending on the number of variables to be analysed, the sample consisted of 99 to 287 observations. In these analyses, calculations were performed based on lab measurements only – disregarding the spatial location of cores and depth of corresponding layers.

All variables show distributions significantly ( $p < 0.05$ ) different from the normal distribution law that was tested with the Shapiro-Wilk method. Therefore, in further analyses nonparametric methods were applied. In the first step, a Spearman correlation test was run in order to assess correlations between the variables and better understand factors of data variation (Table 1).

The strongest correlations were obtained for some of the elements that are caused by the local geologic conditions and the specific geochemical situation. The relation of element contents with grain size distribution can be well seen in strong positive correlations of K, Rb, and Al with the sum of silt and clay and negative correlations for all these elements with medium and coarse sand fractions. These elements are also characterized by absent or negative correlations with anthropogenic parameters bones, artefacts and MS, but by positive correlations with P.

Elements Ca, Sr and Fe also correlate positively with fine grain size indicators and P; additionally, they show strong positive correlations with the organic matter content. Ca and Sr also correlate positively to C/N, while Fe correlates with MS and Pb.

Table 1. Correlation table based on nonparametric Spearman rank correlation coefficient for variables analysed. Correlations significant at  $p < 0.05$  are marked with a black font; strong correlations ( $|r_s| \geq 0.60$ ) are marked with a dark blue (strong negative) and a dark red (strong positive) filling and moderate correlations ( $0.30 \leq |r_s| < 0.60$ ) are marked with a light blue (negative) and a light red (positive) filling.

Variable	Gravel	CH/ wood	Bones	Art.	LOI	MS	C/N	Csa	Msa	Fsa	Si+Cl	Zr	Sr	Rb	Pb	Fe	Ca	K	P	Si	
Gravel																					
CH/wood	-0.02																				
Bones	0.28	0.42																			
Art.	0.22	0.10	0.27																		
LOI	-0.31	0.41	0.08	0.03																	
MS	0.33	-0.15	0.19	0.44	-0.14																
C/N	-0.12	0.57	0.21	0.03	0.43	-0.09															
Csa	0.75	0.08	0.39	0.26	-0.39	0.37	-0.12														
Msa	0.21	0.15	0.26	0.27	-0.32	-0.02	-0.27	0.33													
Fsa	-0.32	0.18	-0.08	-0.16	0.12	-0.16	0.30	-0.40	-0.51												
Si+Cl	-0.40	-0.26	-0.34	-0.14	0.60	0.00	0.18	-0.52	-0.73	0.15											
Zr	0.08	-0.21	0.00	-0.10	-0.27	0.10	-0.10	-0.09	-0.17	0.18	0.16										
Sr	-0.23	0.00	-0.15	0.09	0.53	0.07	0.36	-0.20	-0.65	0.24	0.57	-0.02									
Rb	-0.35	-0.34	-0.44	0.01	0.19	0.03	-0.03	-0.44	-0.59	0.15	0.65	0.25	0.65								
Pb	-0.13	0.19	0.07	0.36	0.38	0.37	-0.02	-0.03	-0.04	0.01	0.12	0.10	0.23	0.26							
Fe	-0.19	-0.15	-0.17	0.17	0.62	0.35	0.17	-0.15	-0.51	0.14	0.62	-0.01	0.75	0.52	0.42						
Ca	-0.20	0.22	0.01	0.15	0.67	0.10	0.57	-0.16	-0.57	0.29	0.56	-0.05	0.85	0.43	0.30	0.73					
K	-0.29	-0.09	-0.27	0.16	0.24	0.10	0.18	-0.36	-0.50	0.27	0.44	0.10	0.67	0.72	0.18	0.48	0.44				
P	-0.20	0.13	-0.02	0.27	0.68	0.22	0.24	-0.24	-0.36	0.18	0.46	-0.23	0.57	0.43	0.57	0.66	0.66	0.28			
Si	0.21	0.04	0.17	0.15	-0.68	-0.03	-0.35	0.30	0.61	-0.23	-0.70	0.01	-0.67	-0.49	-0.20	-0.70	-0.81	-0.13	-0.59		
Al	-0.40	-0.39	-0.52	-0.14	0.24	0.00	-0.01	-0.50	-0.69	0.31	0.73	0.34	0.68	0.83	0.07	0.62	0.44	0.72	0.40	-0.54	

CH/wood: charcoal and/or wood; Art.: artefacts; LOI: loss on ignition; MS: magnetic susceptibility; Csa: coarse sand; Msa: medium sand; Fsa: fine sand; Si+Cl: sum of silt and clay

Pb correlates strongly with P and moderately with anthropogenic parameters artefacts, MS as well as LOI, Rb, Fe and Ca. P correlates positively with fine material indicators (sum of silt and clay, Rb, Al) as well as with LOI, Ca, Fe, Sr, Pb and artefacts. Interestingly, there is no correlation between P and the content of bones. LOI correlates positively with the sum of silt and clay, Fe, Sr, Ca, P and negatively with Si. Variables indicating human activities (charcoal/wood, bones, artefacts, MS) show only weak to moderate correlations between each other. A moderate-strong correlation was observed between MS and artefacts ( $r_s = 0.44$ ) and between bones and CH/wood ( $r_s = 0.42$ ). Also, a strong correlation was found between CH/wood and C/N.

The purpose of the next analysis step was to investigate interrelations between the variables and determine a representative set of variables that would explain the variability of the data. In order to achieve this goal cluster analysis and principal component analysis were applied. Prior to the analyses the data were transformed following a Box-Cox transformation to reduce the effects of non-normal distributions. Then the data were standardized to minimize the effects of strongly differing values of the variables (subtraction of the mean and division by the standard deviation).

In cluster analysis, Ward's method was used as the amalgamation rule with Euclidean distances as a distance measure. Figure 20a shows that two large distinct clusters can be distinguished at the relative linkage distance  $D_{link}/D_{max}$  80 %. The first cluster consists of variables describing the natural component of the materials with such elements like K, Rb, Ca, Sr, Fe, Al and Zr as well as C/N ratio and content of fine material (fine sand and the sum of silt and clay). The second cluster is associated with variables indicating anthropogenic signatures. At the relative linkage distance 50 % the anthropogenic cluster can be divided into two parts. The first cluster groups Pb, P, LOI with MS and artefacts, while the second cluster contains variables describing coarseness of materials (coarse sand and gravel), Si, bones and CH/wood. Therefore, from the set of elements measured, only P and Pb fall into the group of variables that describe anthropogenic features. Following the same rules of clusterization, the analysis of the six variables available for all samples was carried out. Figure 20b illustrates that one cluster is dominated by organic cultural variables (LOI, bones, CH/wood), whereas MS and artefacts associate with gravel forming a group of mineral cultural variables. At relative distance 60 % organic matter content separates from CH/wood and bones, and gravel from MS and artefacts.

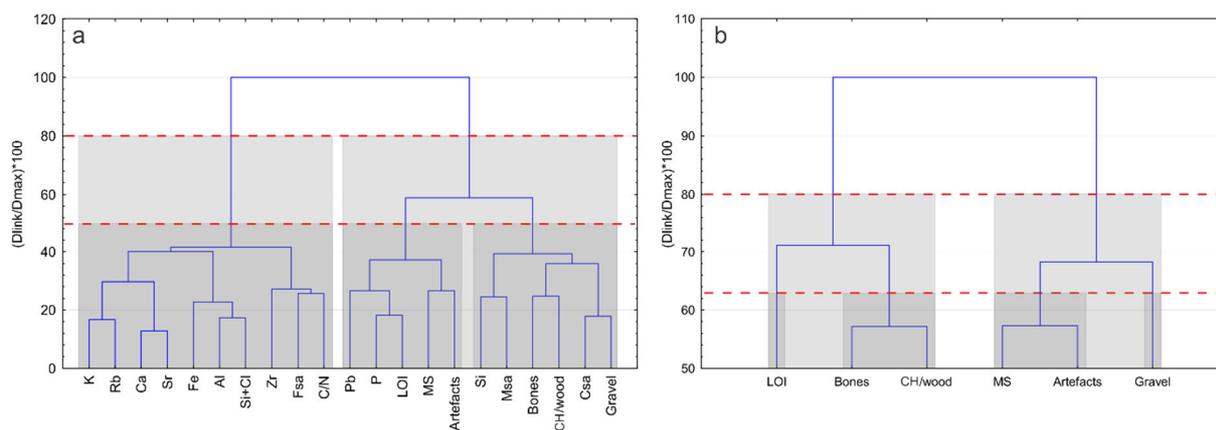


Figure 20. Dendrograms obtained by the hierarchical cluster analysis of the variables. A: all variables, N=99; B: set of six variables, N=287.

Principal component analysis was performed in the next step to determine the factors of data variance. The analysis was based on a correlation matrix due to the difference in units of the variables analysed. Based on the Kaiser-Guttman criterion only components with eigenvalues larger than 1 were interpreted (Legendre and Legendre, 2006). Different combinations of variables were tested to produce best representation of total variance and meaningful principal components. The best PCA results were obtained when the following set of variables was considered: contents of stones, bones, artefacts, CH/wood, LOI, MS, coarse sand, sum of silt and clay, Pb, P). Four factors were necessary to explain 73.1 % of total variance, while the first two components were most meaningful. However, these data were simultaneously available for only four cores out of eight.

Somewhat different results were obtained when a smaller number of variables was taken for PCA – those available for all eight cores and well indicating anthropogenic signatures as shown by clusterization of the variables in the previous step. These results can be also considered as satisfactory since three components were able to explain 75.6 % of the total variance (Table 2), although the third component had an eigenvalue slightly below 1.

Table 2. Eigenvalues of the correlation matrix.

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	100.00

Factor-variable correlations in Table 3 and the projection of variables on the factor plane in Figure 21 illustrate the meaning of the principal components. The first principal component is associated with gravel, bones, artefacts and MS – an anthropogenic signature; the second with CH/wood, bones and LOI – an organic anthropogenic signature, while the third component probably

indicates natural mineral materials (negative correlation with artefacts, MS, LOI and positive with gravel). Since these data are available for all samples, they will be further used for cluster analysis.

Table 3. Factor-variable correlations (factor loadings), based on correlations.

Variable	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
Gravel	<b>0.70</b>	-0.26	<b>0.43</b>	0.30	0.40	0.10
CH/wood	0.14	<b>0.84</b>	0.25	0.00	0.10	-0.45
Bones	<b>0.58</b>	<b>0.55</b>	0.35	-0.13	-0.35	0.32
Artefacts	<b>0.68</b>	0.13	<b>-0.52</b>	-0.41	0.27	0.03
LOI	-0.27	<b>0.72</b>	<b>-0.41</b>	0.38	0.16	0.26
MS	<b>0.73</b>	-0.20	<b>-0.41</b>	0.35	-0.32	-0.20

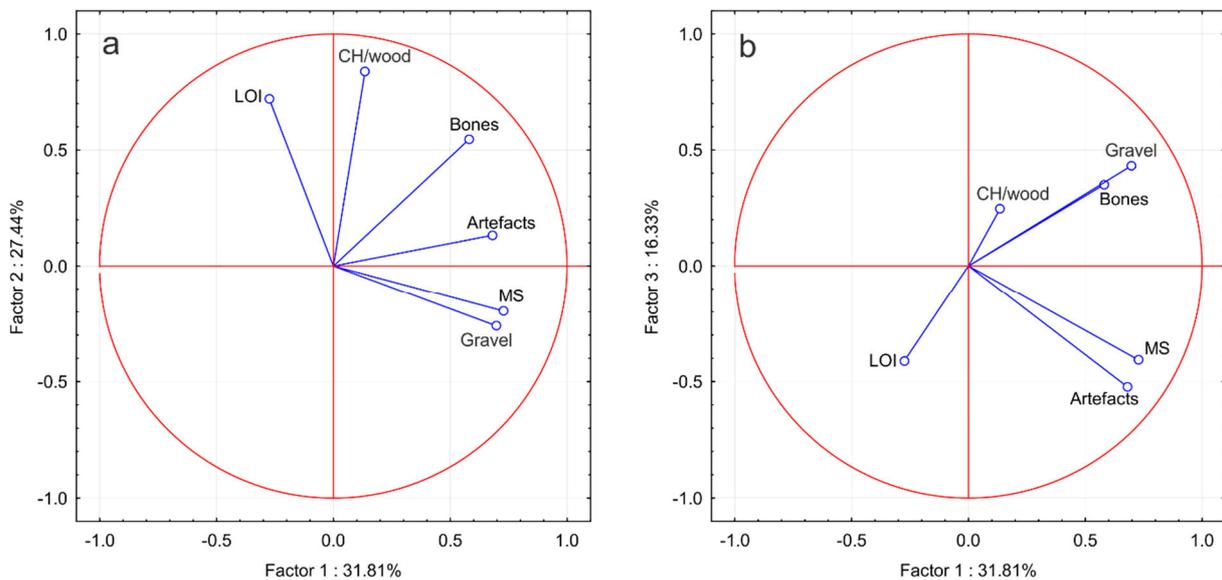


Figure 21. Projection of variables on the factor plane. A: component 1 vs. component 2; B: component 2 vs. component 3.

Based on results of PCA hierarchical cluster analysis was performed with the aim to classify the materials from the cores. In the analysis, factor scores were used instead of original values of the variables in order to reduce noise effects. During test-analysis using the original values of the variables less distinct clusters were obtained. In the same manner as it was done for clusterization of the variables, Ward's method was used as the amalgamation rule with Euclidean distances as a distance measure. A horizontal dendrogram representing results of clusterization is shown in Figure 22. Two large clusters can be distinguished at relative linkage distance 90 % and three large clusters at linkage distance 60 %. Materials with essentially different properties form these groups. However, such clustering is not detailed enough to classify cultural materials. For this reason, a linkage distance of ca. 8.2 % was selected, at which 15 clusters can be obtained. The composition of the clusters is provided in appendix 2.

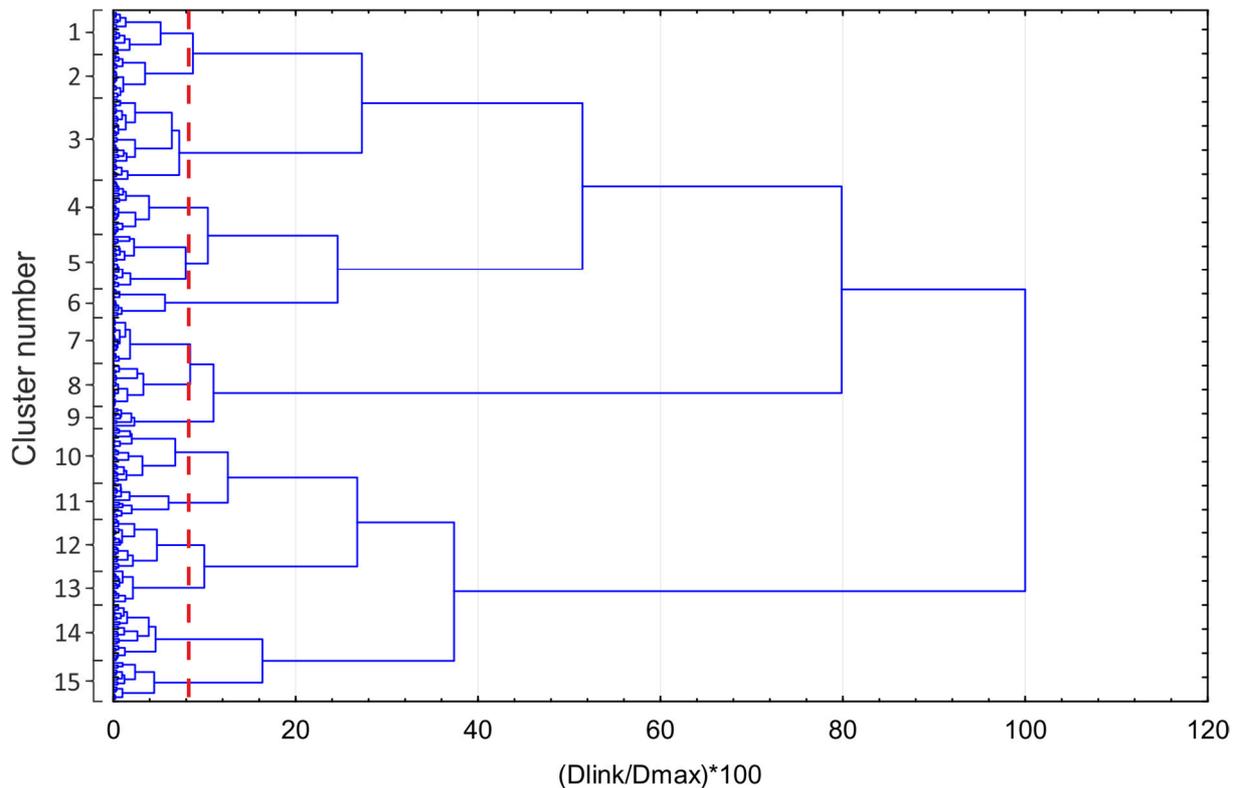


Figure 22. Dendrogram obtained by the hierarchical cluster analysis using Ward's method and clusters distinguished at relative linkage distance 8.2 %.

Table 4 and Figure 23 illustrate descriptive statistics of the clusters obtained at linkage distance 8.2 %. Several groups of clusters can be distinguished. Clusters 1 – 3 can be considered as one group as they are characterized by the absence of any anthropogenic features and a low MS for all three clusters, while contents of stones and organic matter are varying. Clusters 1 and 2 are very similar with a significant difference in organic matter content. Layers in cluster 3 are marked through a lower organic matter content and a high content of stones. It has to be pointed out that cluster 1 is characterized by an elevated MS (see Q75 in Table 4). The next group is composed of the clusters 4 – 6 (which as the clusters 1 – 3) also have a low MS and no bones or artefacts, but moderate to relatively high amounts of charcoal and wood distinguish them. These are fine sediments with very low to low content of stones. Clusters 5 and 6 have a very low MS and cluster 6 can be distinguished from the others due to the very high content of organic matter (highest among all clusters).

Clusters 7 – 10 and 14 form one separate group. The common feature of these clusters is presence up to a very high content of artefacts and a moderate to very high magnetic susceptibility. Clusters 7 and 8 are very similar in terms of content of stones, bones and organic matter; they differ in MS and artefact content. Cluster 8 has a significantly higher MS and a higher content of artefacts. Materials in cluster 10 are coarser in comparison to clusters 7 and 8 and have high to very high contents of charcoal/wood, bones, artefacts and a high MS, which varies in a wider range. Clusters

9 and 14 are very coarse with 18.7 – 20.8 % of stones and have moderate values of MS. Cluster 14 has a somewhat higher content of artefacts and bones.

Clusters 11-13 form another distinct group. They are characterized by a relatively high organic matter content, a high to very high content of charcoal/wood and low MS. Content of bones varies from zero in cluster 11 to relatively high in clusters 12 and 13, although cluster 11 has a very high content of artefacts and wood remains. Cluster 12 differs from cluster 13 most importantly in the higher content of the coarse fraction and slightly higher MS as well as artefact content (no artefacts in cluster 13). Cluster 15 has transitional 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 gravel and bones and somewhat higher MS.

Table 4. Descriptive statistics of the clusters obtained at linkage distance 8.2%.

Cluster	N	Gravel, %			CH/wood, %			Bones, %			Artefacts, %			LOI, %			MS, 10 <sup>-8</sup> m <sup>3</sup> kg <sup>-1</sup>		
		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	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	0.7	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	0.4	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

Box and whisker plots in Figure 23 visualize the differences described above and clearly show the difference between clusters of natural and cultural materials.

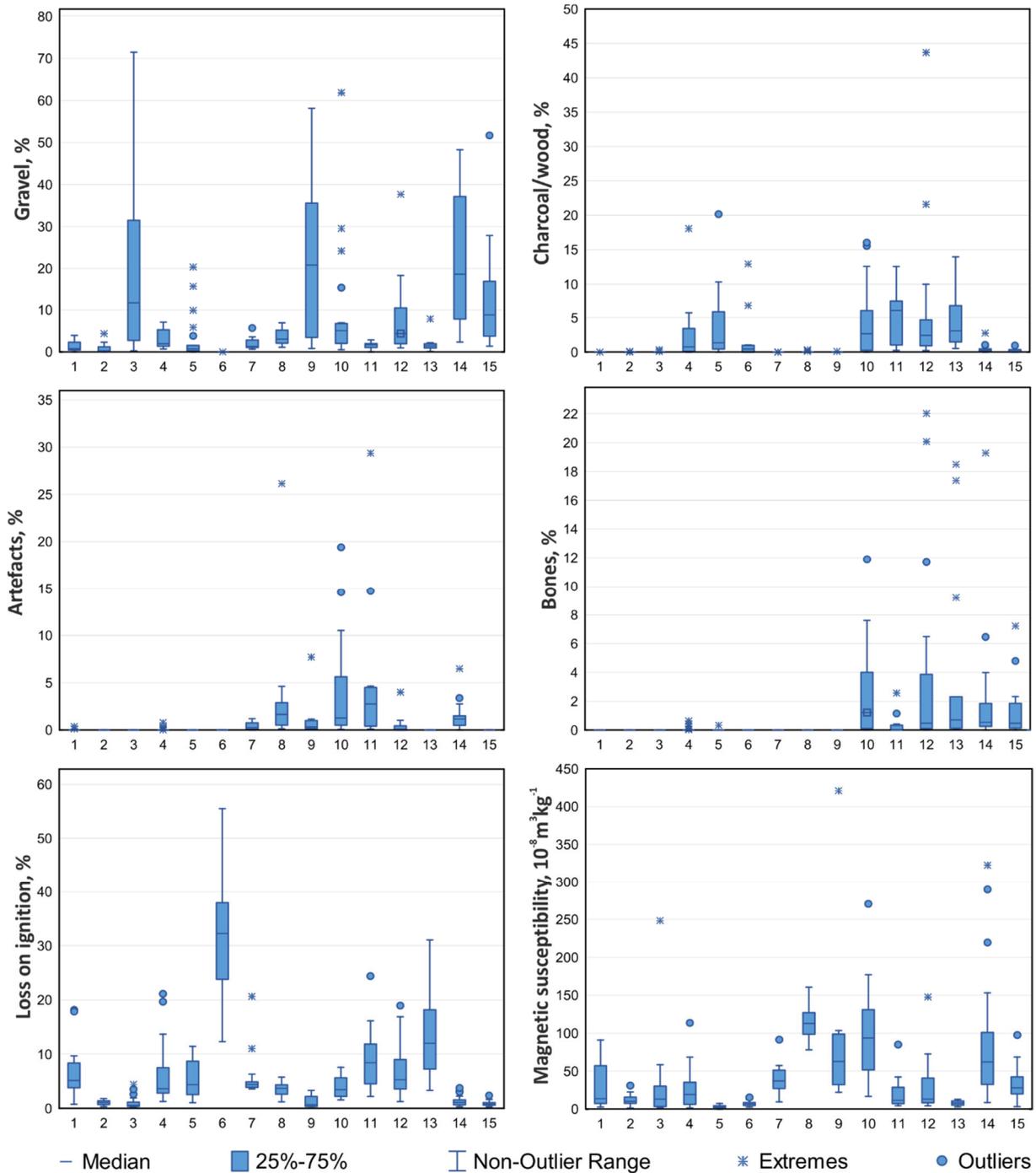


Figure 23. Box and whisker plots for the obtained clusters.

A one-way Anova test was performed in order to assess the significance of the differences among the clusters based on the variables analysed. This test was preferred to the nonparametric Kruskal Wallis test due to its higher statistical power. Kruskal Wallis test, while comparing mean ranks, might lose important information. For the Anova test, data were transformed to reduce the effects of high skewness and asymmetry. Due to the differing N in clusters from 8 to 34, Tukey Honestly Significant Difference (HSD) test modified for unequal sample size was selected. Table 7 presents a summary of the post hoc Tukey HSD test for unequal sample sizes. Full results of the test can be found in appendix 3. It can be seen that all clusters differ in at least one of the analysed parameters,

while most of them differ in three or more parameters. Some of the neighbouring clusters differ in only one parameter. Strongest differences are found between natural and cultural materials. Therefore, the clusters obtained can be considered as significantly different.

All clusters are composed of samples from different cores indicating the absence of strong local patterns. Cluster 1 is mostly composed of materials from the uppermost parts of cultural colluvial deposits (redeposited cultural layers), which were ploughed and have been involved into soil formation since abandonment of the settlement. The properties of these materials correspond rather to natural deposits, but the high value of Q75 of magnetic susceptibility indicates a cultural origin of the material. Therefore, this cluster can be referred to as colluvium of cultural material with transitional properties. Cluster 2 is strongly dominated by buried soil horizons, sterile mineral interlayers with presence of Pleistocene deposits from different drilling sites. The properties and composition of this cluster indicate that these are fine-grained natural deposits. Cluster 3 includes Pleistocene gravel layers that were found at the bases of the sequences and coarse sandy deposits that were found at the bases and embedded in Holocene deposits, but their origin is probably Pleistocene material. Thus, cluster 3 groups coarse-grained natural deposits. Cluster 4 contains different sandy deposits with presence of wood, while cluster 5, being very similar to cluster 4 in terms of its properties, is dominated by mixed layers with sand and woody/organic remains as dominating components. Therefore, clusters 4 and 5 contain materials with transitional properties. Cluster 6 has grouped all the peat layers found in different cores and thus stands for natural peat material.

Table 5. Results of the post hoc Tukey HSD test for unequal sample sizes.

Cluster	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1															
2	l														
3	gl	g													
4	w	gwl	gwl												
5	wm	wlm	gwl	m											
6	gwl	gwl	gwl	gl	gwl										
7	a	alm	galm	wa	wam	gwalm									
8	am	galm	galm	wam	wam	gwalm	m								
9	gal	gam	am	walm	gwalm	galm	gl	l							
10	gwbam	gwbalm	wbalm	bam	gbam	gbalm	wb	wb	wbl						
11	wba	wbal	gwbalm	ba	bam	gwbalm	wb	wblm	gwbalm	gblm					
12	gwba	gwbalm	wbal	ba	gbam	gwbalm	wba	wbam	wbal	am	gba				
13	wbl	wbl	gwbl	bl	bl	gwbl	wbam	wbalm	gwbalm	alm	ba	a			
14	gwbalm	gwbalm	wbam	gbalm	gwbalm	gbalm	gwbl	gwbl	b	gl	gwbalm	gwalm	galm		
15	gwbl	gwb	wb	bl	gwbalm	Gblm	gwbalm	wbalm	ba	alm	gwbalm	wal	glm	a	

Letter codes in cells represent significant differences ( $p < 0.05$ ) in parameters: g (gravel), w (CH/wood), b (bones), a (artefacts), l (LOI), m (MS). Dark red filling indicates differences in 6 parameters, red in 5, light red in 4, light blue in 3, blue in 2, dark blue in 1.

Cluster 7 is relatively homogenous and composed of colluvium of cultural layers homogenised by ploughing, but not involved into modern soil formation. Cluster 8, having properties very similar

to cluster 7, contains mostly colluvium of cultural material, which was not affected by ploughing. Clusters 7 and 8 include colluvium of cultural material.

Cluster 9 is rather small and consists of different coarse-grained deposits from sandy layers and cultural colluvium to gravel layers with moderate anthropogenic features. Cluster 10 contains fine-grained cultural deposits with very strong anthropogenic features that were identified as  $Y_{cult}$  using the field classification. Cluster 11 contains cultural deposits  $Y_{cult,ch}$ ,  $Y_{cult,org}$  and  $He_{wood}$  rich in OM and wood remains with artefacts but without bones. Clusters 12 and 13 are also cultural deposits rich in OM and wood remains ( $Y_{cult,ch}$ ,  $Y_{cult,org}$ ,  $He_{wood}$ ) with bones but with absent or a very low content of artefacts. Therefore, clusters 11 – 13 are cultural materials with strong anthropogenic features and a high organic matter content. Cluster 14 is dominated by gravel and coarse sandy deposits with a high artefact content and moderate content of bones; it represents cultural coarse deposits and cultural gravel with strong anthropogenic features. Cluster 15 is characterized by coarse sand and gravel material from lower parts of the sequences with only a low amount of bones and wood remains; it can be considered as relatively coarse deposits with transitional properties.

It has to be noted that in the clusters described above no difference between *in situ* cultural layers and redeposited cultural material could be made. Thus, in order to test the stability of clusters and to check whether *in situ* cultural layers would form a separate group, a selection of cultural layers formed *in situ* that were easily identifiable morphologically were added to the existing data base and the analysis was performed once more. As a result, added samples distributed in the existing clusters without forming a separate cluster and without strong effects on the clusterization acquired in the previous step. Based on the descriptive statistics of the clusters and analysis of their composition, a summarized description of the clusters was elaborated (Table 6).

Additionally for the three cores (101 samples), for which also grain size distribution and XRF analyses were carried out, PCA and cluster analysis were performed following the same procedure but using contents of Pb, P, coarse sand and fine fraction in addition to the six parameters used previously. In this case four principal components were able to explain 78.1 % of total variance, the fourth PC had an eigenvalue slightly below 1. It was possible to distinguish 14 clusters at  $D_{link}/D_{max}$  12.6 %. The comparison of the clusterization results allows stating that the agreement with the primary general clusterization is quite good; unambiguously natural and cultural materials were classified in a similar way when applying additional parameters. A difference could be observed within the group of materials with transitional properties. Some of them could be classified as natural materials, some of them were re-classified as rather cultural materials. But in some cases an aggregation of clusters took place. A considerably smaller group

of transitional materials was obtained when using additional data. In order to proceed with their classification a more detailed geochemical analysis would be necessary.

Table 6. Description of the clusters.

Type	Cluster nr.	Cluster meaning
Natural	2	Fine-grained natural mineral materials (sterile sandy interlayers and Pleistocene deposits) and soil horizons
	3	Coarse-grained natural mineral material including coarse sand and gravel
	6	Natural organic material (peat)
Transitional	1	Homogenized colluvium of cultural deposits affected by ploughing and soil formation – weak anthropogenic features
	4+5	Comparatively fine-grained mineral material with presence of charcoal and woody remains – very weak anthropogenic features
	15	Comparatively coarse-grained mineral material with presence of bones and wood remains – very weak anthropogenic features
Mineral cultural	7+8	Colluvium of cultural material and colluvium of cultural material that was homogenized by ploughing with moderate to strong anthropogenic features
	9+14	Coarse to gravelly cultural mineral material with moderate to strong anthropogenic features
	10	Mineral cultural layer with very strong anthropogenic features
Organic cultural	11	Cultural material rich in organic matter and woody remains and with artefacts
	12+13	Cultural material rich in organic matter and woody remains and with bones

#### 5.1.4. CLASSIFICATION

Based on the elaborated approach, a classification of heterogeneous materials of different genesis in Hedeby was elaborated (Figure 24). The classification contains three large types of sediments: natural, transitional and cultural. Within these three types of sediments, 13 classes of soil horizons and sediment layers can be distinguished based on the organic matter content and texture as well as the presence of anthropogenic features (presence of artefacts and bones, elevated content of charcoal/wood and enhanced magnetic susceptibility).

Fine- and coarse-grained materials with different organic matter contents represent natural deposits at Hedeby. Such sediments do not contain any features of human activities: no bones, artefacts and no or only very small amounts of charcoal/wood. Three classes of natural materials can be distinguished. The first class includes Pleistocene deposits, sterile mineral interlayers and buried soil horizons with a fine texture and low values of all parameters. The second class contains coarse mineral sediments including natural gravel layers and coarse sterile interlayers as well as coarse Pleistocene deposits. The main features of this sediment class are high gravel contents and low values of all other parameters. The third class of natural materials is formed by peat with a

high organic matter content, presence of a very small amount of charcoal/wood remains and low values of stone, artefact and bone contents and magnetic susceptibility.

Among sediments with transitional properties no organic matter-rich deposits were found, but also fine and coarse materials with very weak to weak anthropogenic features were distinguished yielding three classes of sediments. The first class, coarse materials with weak anthropogenic features, is represented by coarse sandy materials with a very low organic matter content and with presence of a small amount of bones and a very low quantity of charcoal and wood remains. Slightly elevated MS suggests low levels of magnetic enhancement. The second class of sediments is relatively fine sandy material with a moderate organic matter content and a moderate to high content of charcoal and wood. MS varies in this class of sediments from very low to low and lies in the range of natural materials. A separate class is formed within the sediments with transitional properties by the upper parts of the colluvial cultural layers exposed at the modern surface and involved into soil formation and formerly ploughing. A somewhat higher value of the upper quartile of MS indicates the cultural origin of this material, whereas other parameters vary in the natural ranges.

Cultural materials compose the third type of sediments 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 moderate levels of organic matter content. The first class in this group is relatively fine mineral cultural deposit  $Y_{\text{cult}}$  with very high levels of anthropogenic features. These are typical cultural layers. The second group of fine mineral cultural deposits is formed by the colluvium of cultural material  $M_{\text{cult}}$  with high levels of anthropogenic features and the third group is formed by the ploughed colluvium of the cultural material  $M_{\text{cult-hom}}$ , for which only MS reflects the cultural origin. Another prominent class within mineral cultural materials is cultural gravel. High levels of MS and artefacts and moderate content of bones characterize this class. The second group includes cultural deposits with a high content of organic matter. These layers are not dominated by organic material but have significantly higher LOI values (median 5.2 – 12 %) than the mineral cultural layers. They are relatively fine-grained and have a low and very low MS due to the large amount of OM 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 artefact and bone content. Some of the layers can be probably interpreted as waste deposits.

Therefore, the type of natural sediments represents deposits that formed before settlement activities or natural materials that were translocated during the Viking settlement period, e.g. fluvial sediments. Transitional sediments represent mostly natural materials that were indirectly affected by settlement activities. In case of colluvium of cultural deposits involved into ploughing and soil formation, the transition has a reversed character – from cultural to rather natural. The

type of cultural deposits represents materials that formed during the settlement period (mineral and organic cultural layers) as well as redeposited cultural material (colluvium) that was not influenced by soil formation and thus preserved its cultural features.

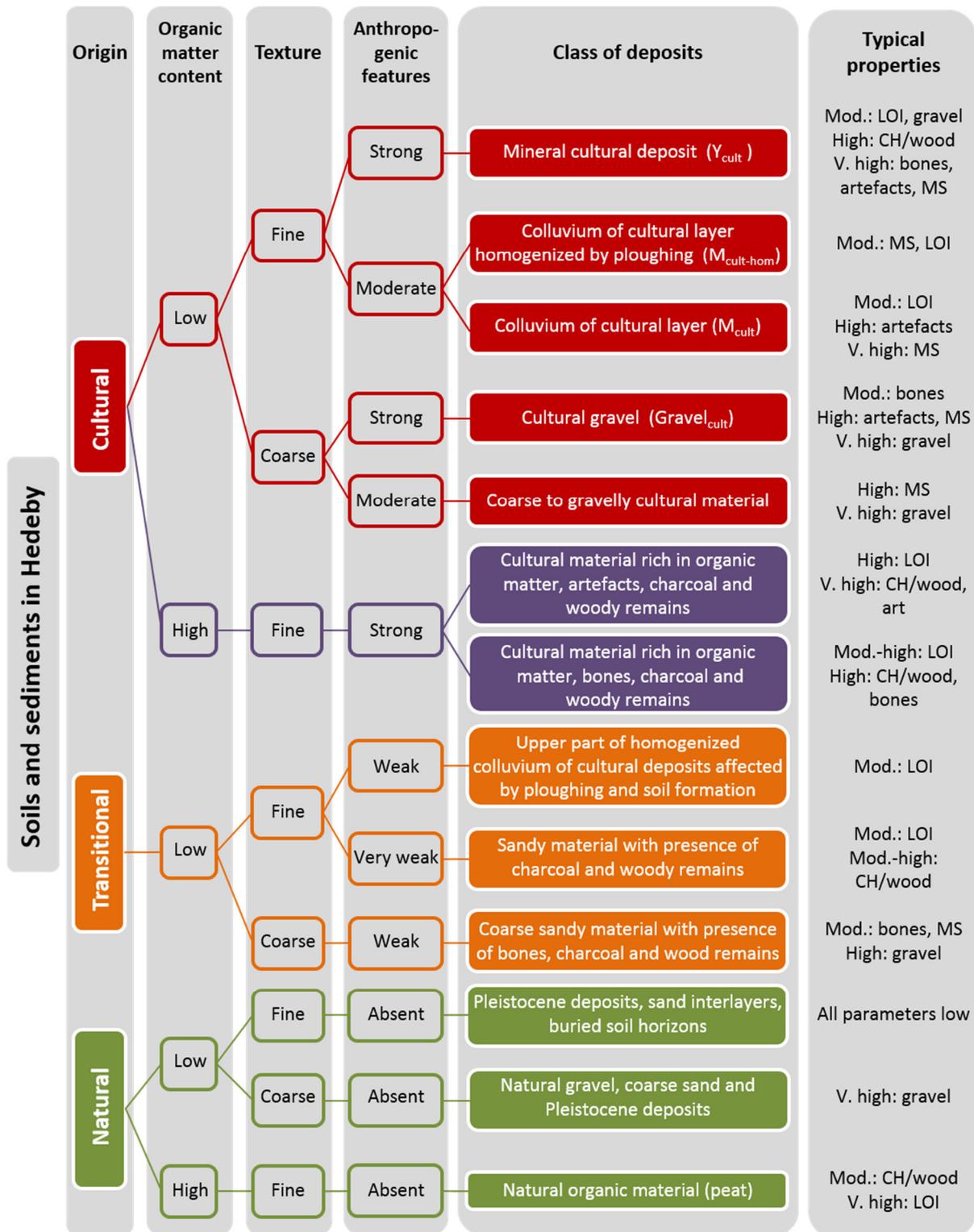


Figure 24. Classification of soils and sediments in Hedeby based on results of cluster analysis.

## 5.2. GEOMORPHOLOGICAL CHANGES AT THE HEDEBY-BROOK

In order to investigate geomorphologic features and local landscape development at the Hedeby-brook, drillings across and along its former course were performed composing three transects and one longitudinal profile. The drilling transects were executed in the western and central part of Hedeby. Transect 1 is located 70 m west of the road Kirchweg, whereas transect 2 is situated in a flat recent depression approximately 10 m west of the road and drillings of transect 3 were performed 20 m east of the road (Figure 25).

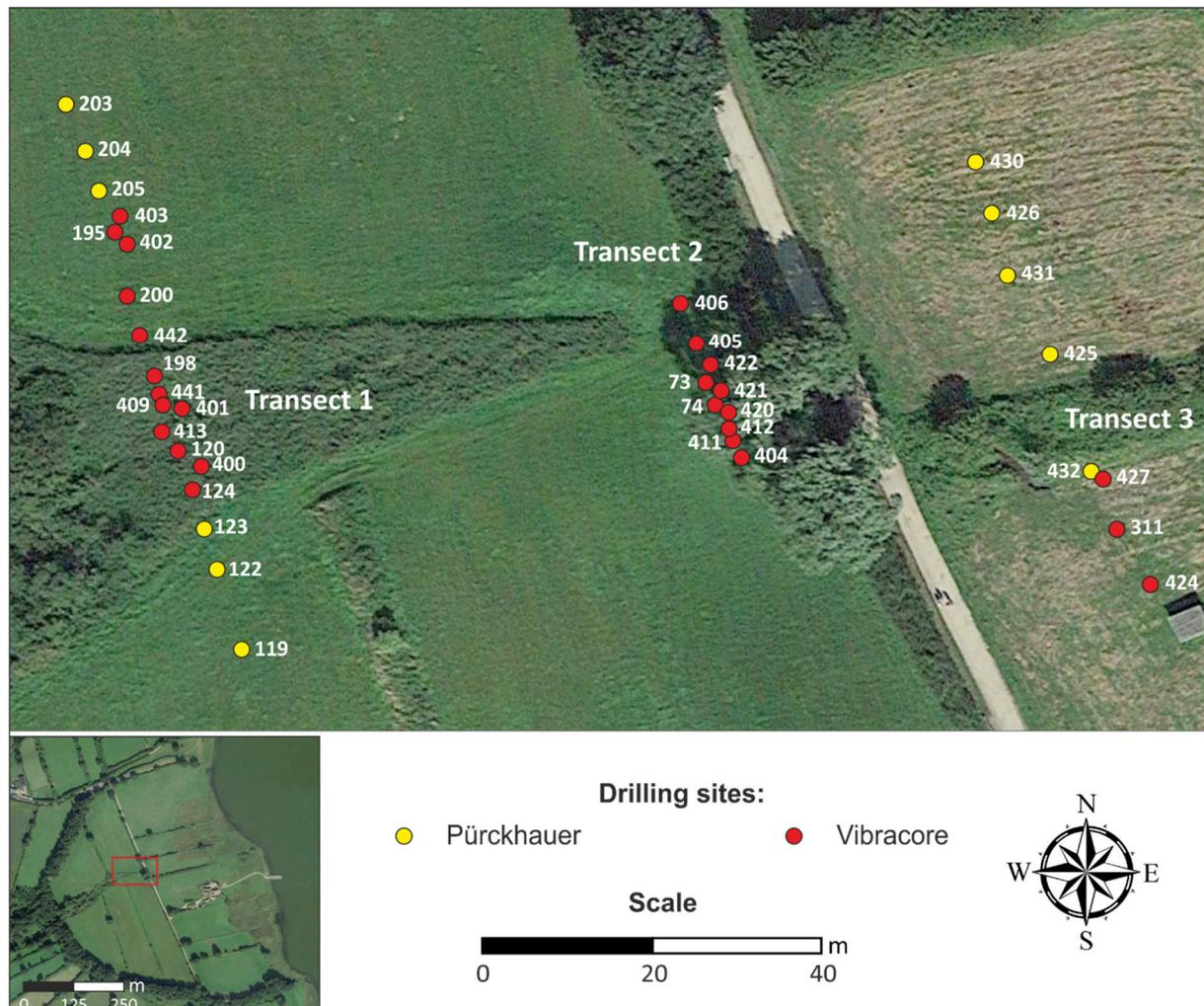


Figure 25. Location of the transects across the Hedeby-brook.

### 5.2.1. DESCRIPTION OF TRANSECT 1

Transect 1 consists of 19 drilling cores: six Pürckhauer drillings on the higher slope positions in the northern and southern parts of the transect and 13 Vibracore drillings downslope and in the central part of the transect at the brook. A schematic overview of the central part of the drilling transect with the corresponding photographs of the extracted cores is shown in Figure 26. On the slopes, the distance between individual drillings is approximately five meters, while in the central part near the brook the distance equals 1 – 2 m. The border between Holocene and Pleistocene

sediments lies at 0.5 – 1 m depth on the slopes and at nearly four meters depth in the central part at the brook. This implies the presence of a buried structure with a width of ca. 30 m on the modern land surface and with a depth of up to 3.5 – 4 m in the central part of the valley. This underground structure has two asymmetric slopes and a nearly horizontal basis.

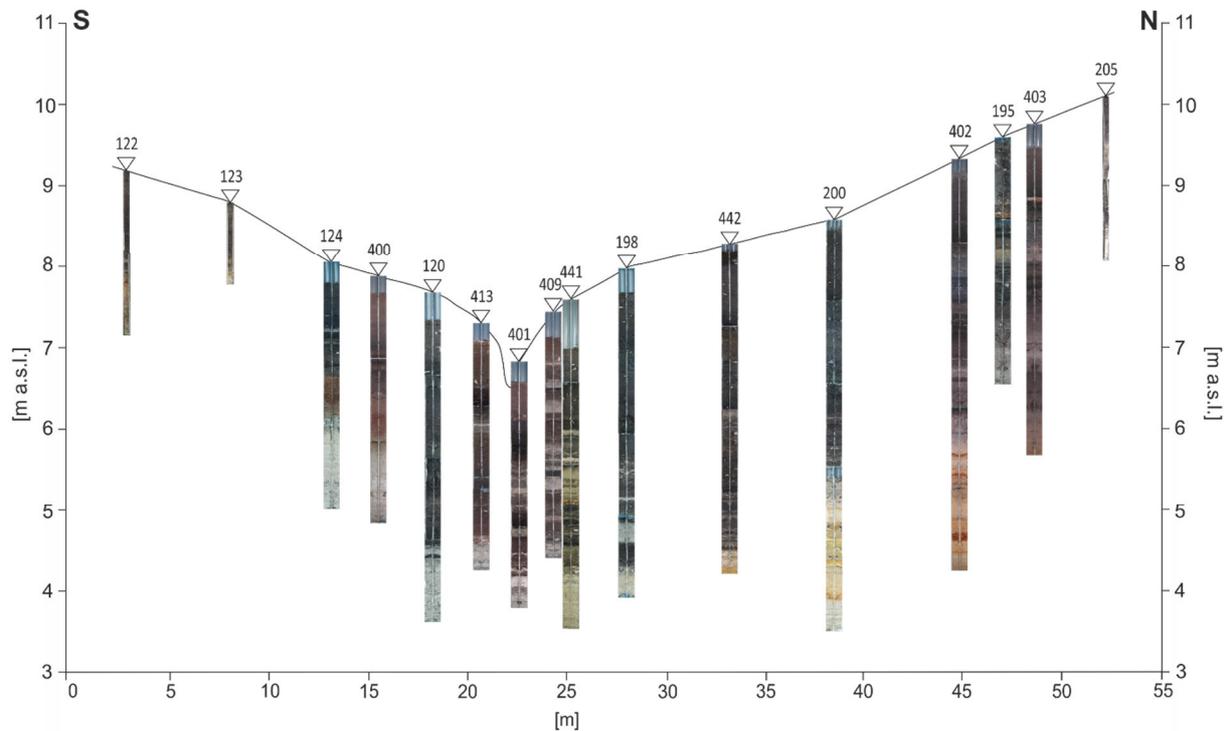


Figure 26. Photographs of drilling cores retrieved in transect 1.

### *Individual cores*

The sediments in the cores are heterogeneous and the number of layers distinguished reaches 20 in the single cores, while the number of samples taken was up to 45 per core. Three cores from this transect were analysed in the laboratory: 198, 441 and 442. The same parameters that were applied for the classification of soils and sediments in Hedeby were determined. Additionally, XRF measurements were performed for core 198 and micromorphological investigations of cultural layers and other deposits in cores 400 and 402 were carried out.

Drilling point 198 is located in the central part of transect 1, approximately six meters north of the modern course of Hedeby-brook. The border between Holocene and Pleistocene sediments in this core is located at a depth of 360 cm. A Pleistocene silty sand with a natural gravel layer on top represents the Pleistocene basis of the sequence. Stones comprising the gravel layer are mostly flints. As expected, these deposits are characterized by a very low organic matter (OM) content and magnetic susceptibility (MS) and a relatively high C/N ratio (Figure 27). Above the gravel layer, a heterogeneous filling of the structure was found. A layer lying directly above the gravel layer  $Y_{cult,org}+Ha_{wood}$  (333 – 360 cm depth) is characterized by a relatively high OM content and the

presence of charcoal and abundant wood fragments. Above this layer at 297 – 333 cm depth a sterile sand layer of 36 cm thickness without any anthropogenic features is located. Most finds of charcoal/wood, bones and artefacts are concentrated higher in the profile in the cultural layers between 180 and 300 cm depth. The lower part of the cultural filling (220 – 300 cm depth) represents alternating layers of sand and  $Y_{cult}$  with a low OM content and also low MS but with relatively high concentration of charcoal/wood. The upper part (180 – 220 cm depth) has a relatively high OM content (up to 20 %) and rather low MS with the only relatively high values at 200 – 220 cm depth, where also the largest artefact concentration was determined. The cultural filling of the structure is followed by a peat layer at a depth 150 – 180 cm with the highest OM content in the sequence reaching 55.5 %. The peat layer is free of any artefacts, bones or charcoal/wood finds. As expected, MS of the peat material is very low, too. Above the peat layer, colluvium of cultural layer  $M_{cult}$  was identified. This layer is quite homogeneous in terms of OM content and C/N ratio. The highest values of magnetic susceptibility for this core were measured in this layer reaching  $160.7 \cdot 10^{-8} m^3 kg^{-1}$ .  $M_{cult-hom}$  has properties very similar to  $M_{cult}$  with only small modern-time artefacts (brick fragments, metal objects) representing anthropogenic inclusions.

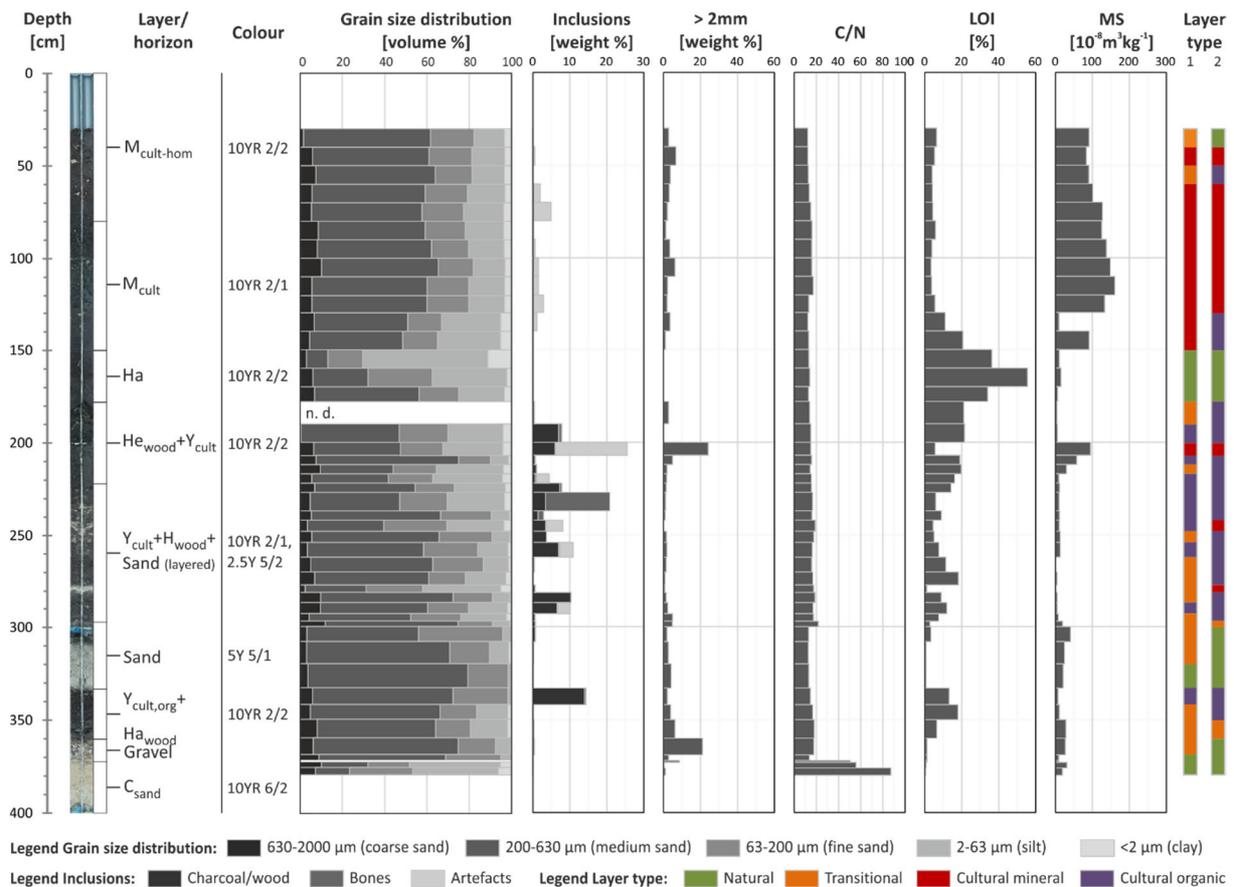


Figure 27. Geo-ecological properties of the sediments of core 198. Layer type column 1: clusters obtained with 6 parameters, layer type column 2: clusters obtained with 10 parameters.

Additionally, XRF measurements were performed for the core 198. Here, elements with a measurement error < 10 % and with relevance to the research questions and study site conditions were selected for analysis: P, Ca, Zn and Pb. The profile distribution of the selected elements is illustrated in Figure 28. The elements show different distribution patterns throughout the profile. Pleistocene deposits are characterized by very low values of P, Zn and Pb, while the content of Ca is highest in the Pleistocene silty sand. The first Holocene layer  $Y_{cult,org}$  shows somewhat elevated concentrations of P, Pb and Zn, whereas in the sterile sand layer above it all elements are present in concentrations typical for natural deposits. Cultural layers in depths between 180 and 300 cm contain large amounts of the elements considered. Based on the distribution of P, also two parts can be distinguished: a lower part (that has a low to moderate content of OM) with a P content between 1500 and 4000 ppm and an upper part (that has a relatively high OM content) with a P content between 3000 and 6500 ppm. Similar trends can be seen in the distribution of Pb and Zn. In peat, smaller amounts of P are present, while in the overlying  $M_{cult}$  very high values above 6000 ppm are common. In the uppermost part, which was ploughed, a lower P content is observed. In the distribution of Pb no differences can be seen above a depth of 200 cm. The high peak in Pb and Zn distributions at 60 – 70 cm depth is probably related to the presence of modern artefacts.

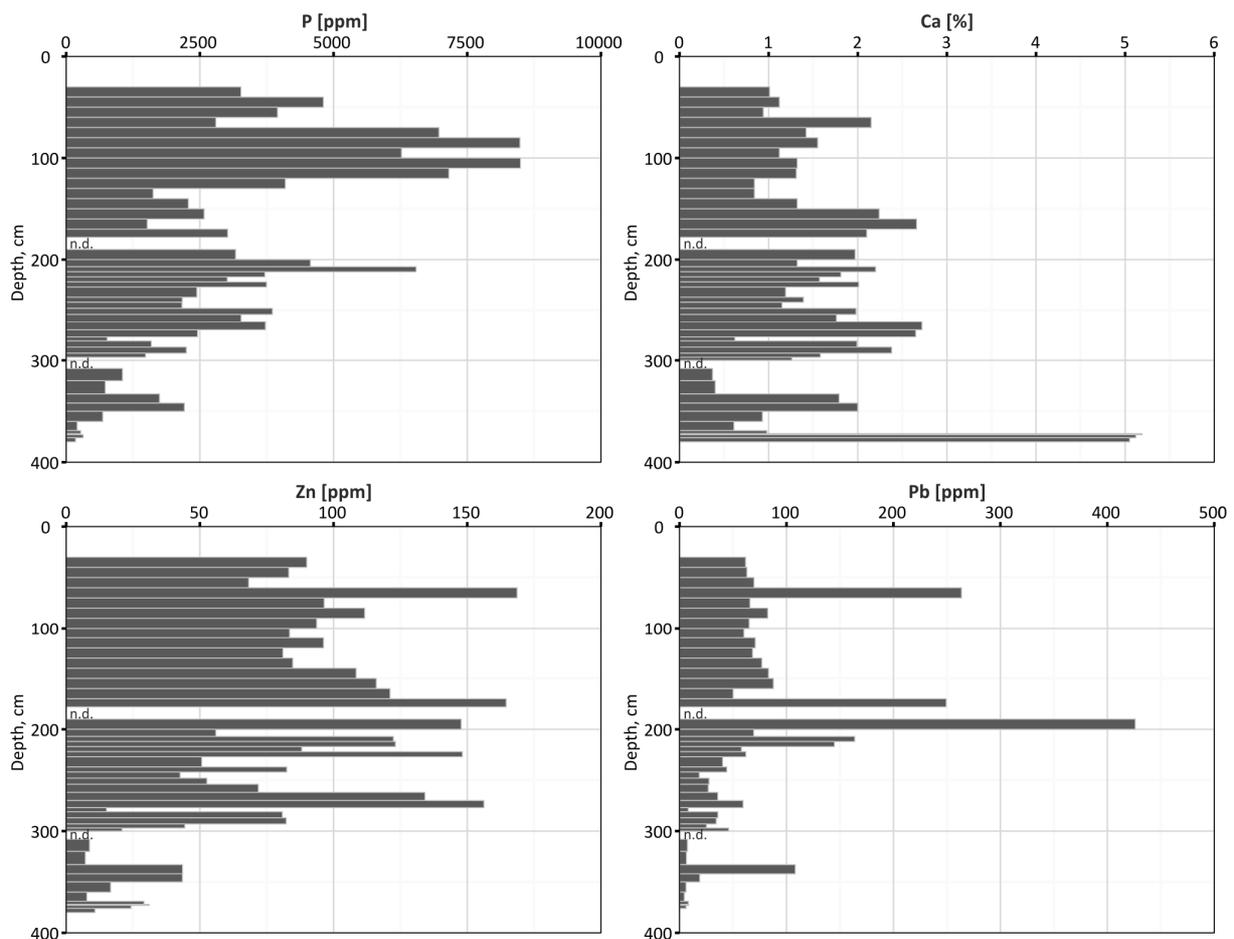


Figure 28. Profile distribution of the selected elements in the drilling core 198.

The developed classification that was described in the previous chapter was applied here to reveal the distribution of the obtained layer types in the individual cores. The results of the sediment classification are depicted in the layer type column in Figure 27. For the sake of a better visualisation, the samples were separated into four main groups: natural and transitional materials as well as cultural mineral and cultural organic deposits. In addition to the main classification results based on 6 parameters (layer type 1 in Figure 27), a refinement of the classification was performed using additionally contents of P and Pb, and coarse sand and the sum of silt and clay content (layer type 2 in Figure 27). The results of this classification correspond well to the morphological and geo-ecological properties and to the primary layer division. The uppermost part of  $M_{\text{cult-hom}}$  layer exposed at the modern surface was classified as a transitional or natural material. Pleistocene material, sterile sand layer and peat materials were classified in both cases as natural materials. It can be seen that by applying additional parameters most of the transitional materials could be reclassified. Therefore, the stratigraphy of core 198 can be summarized into nine stratigraphic units:

<b>IX</b>	0-80 cm	Ploughed colluvium of the cultural layer
<b>VIII</b>	80-150 cm	Colluvium of the reworked cultural layer
<b>VII</b>	150-178 cm	Peat layer
<b>VI</b>	178-222 cm	OM-rich cultural filling with a high content of charcoal/wood and artefacts
<b>V</b>	222-297 cm	Heterogeneous cultural filling with interlayers of sand
<b>IV</b>	297-333 cm	Sterile sand layer
<b>III</b>	333-360 cm	OM-rich cultural layer with wood and charcoal
<b>II</b>	360-372 cm	Pleistocene gravel
<b>I</b>	372-400 cm	Silty sand Pleistocene deposit

The next core analysed is at drilling point 442, located on the same slope five meters north of point 198. Clastic varved sediments represent Pleistocene deposits here with a gravel layer on top of them. Flints represent coarse fragments in the gravel layer. As it is the case at point 198, these Pleistocene deposits contain no anthropogenic features and have a low OM content and a low MS. They correspond to the stratigraphic units I and II in point 198. Both deposits were classified as natural materials based on the obtained classification (Figure 29). A thick heterogeneous filling, representing an alternation of light brown sandy layers with dark-coloured cultural layers, is located above gravel at 300 – 370 cm depth. The sandy sublayers have a low OM content (1.3 – 3.9 %) and small amounts of wood and charcoal, while dark sublayers have a higher OM content (5.6 – 8.1 %) and contain artefacts, some bones and larger amounts of charcoal/wood. This deposit corresponds to the stratigraphic unit V in point 198. The next deposit is OM-rich cultural filling  $Y_{\text{cult,org}}$  (215 – 300 cm depth) with a high content of bones and charcoal/wood in the whole layer and with occasional presence of artefacts. MS is low in this deposit, whereas OM content varies in a wide range between 4 and 30 %. This deposit is comparable to deposit VI in point 198. In the layers above, no charcoal/wood and bones are present, while artefacts are quite abundant. A

sediment package with a thickness of 100 cm located at a depth 100 to 200 cm below the land surface is a colluvium  $M_{cult}$  that consists of reworked material of the cultural layer mixed with sand in the upper part. It can be noted that MS and the content of OM in  $M_{cult}$  decrease slightly up the profile. On the contrary, in the uppermost part of the sequence  $M_{cult-hom}$ , the distribution of these two parameters is more uniform: OM content varies from 2.5 % to 3.6 %, MS from  $91 \cdot 10^{-8}m^3kg^{-1}$  to  $123 \cdot 10^{-8}m^3kg^{-1}$ . These sediments correspond to the units VIII and IX in point 198, respectively. As it was the case at point 198, the uppermost part of  $M_{cult-hom}$  exposed at the surface was classified as transitional material. Therefore, in relation to the stratigraphy in point 198, the following stratigraphic units can be distinguished in core 442:

<b>IX</b>	0-100 cm	Ploughed colluvium of the cultural layer
<b>VIII</b>	100-215 cm	Colluvium of the reworked cultural layer
<b>VI</b>	215-300 cm	OM-rich cultural filling with a high content of charcoal/wood and bones
<b>V</b>	300-372 cm	Heterogeneous cultural filling with interlayers of sand
<b>II</b>	372-391 cm	Pleistocene gravel
<b>I</b>	391-400 cm	Varved Pleistocene deposit

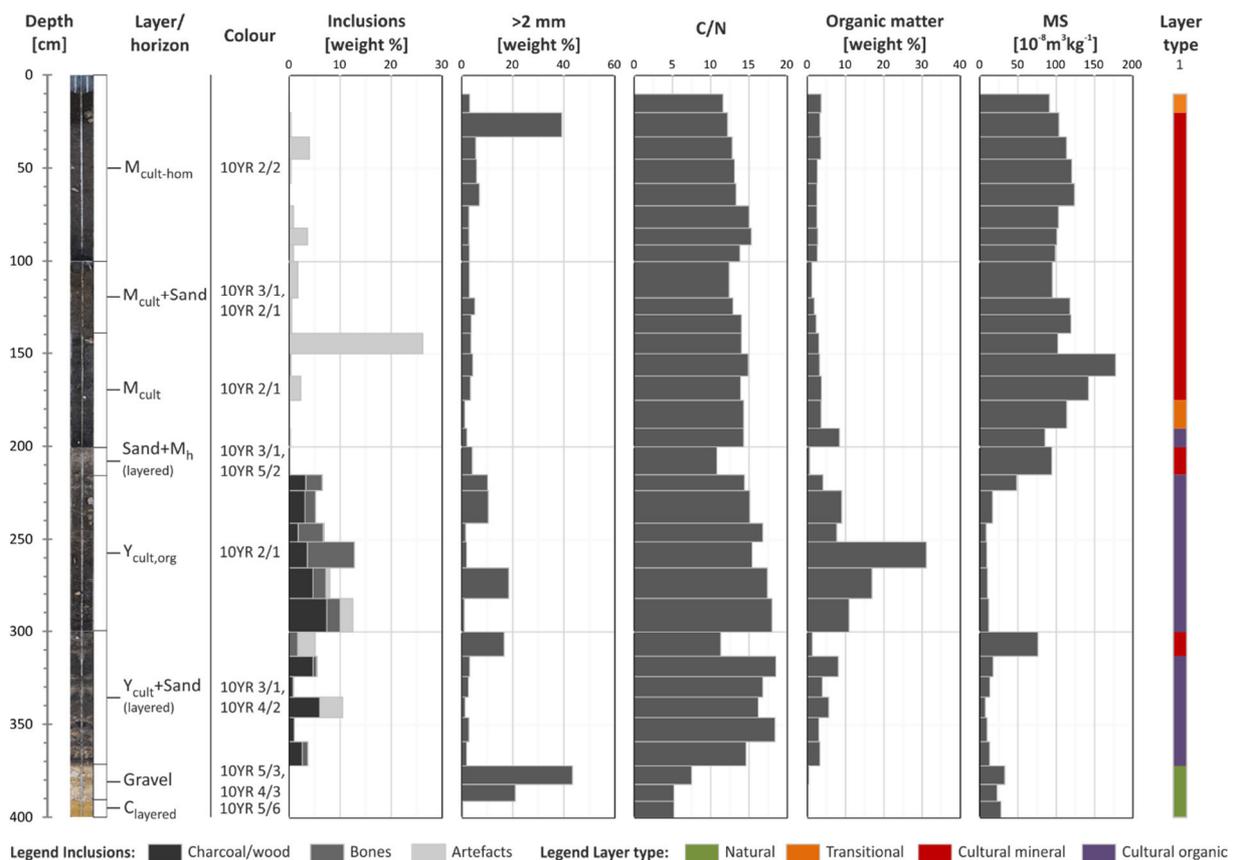
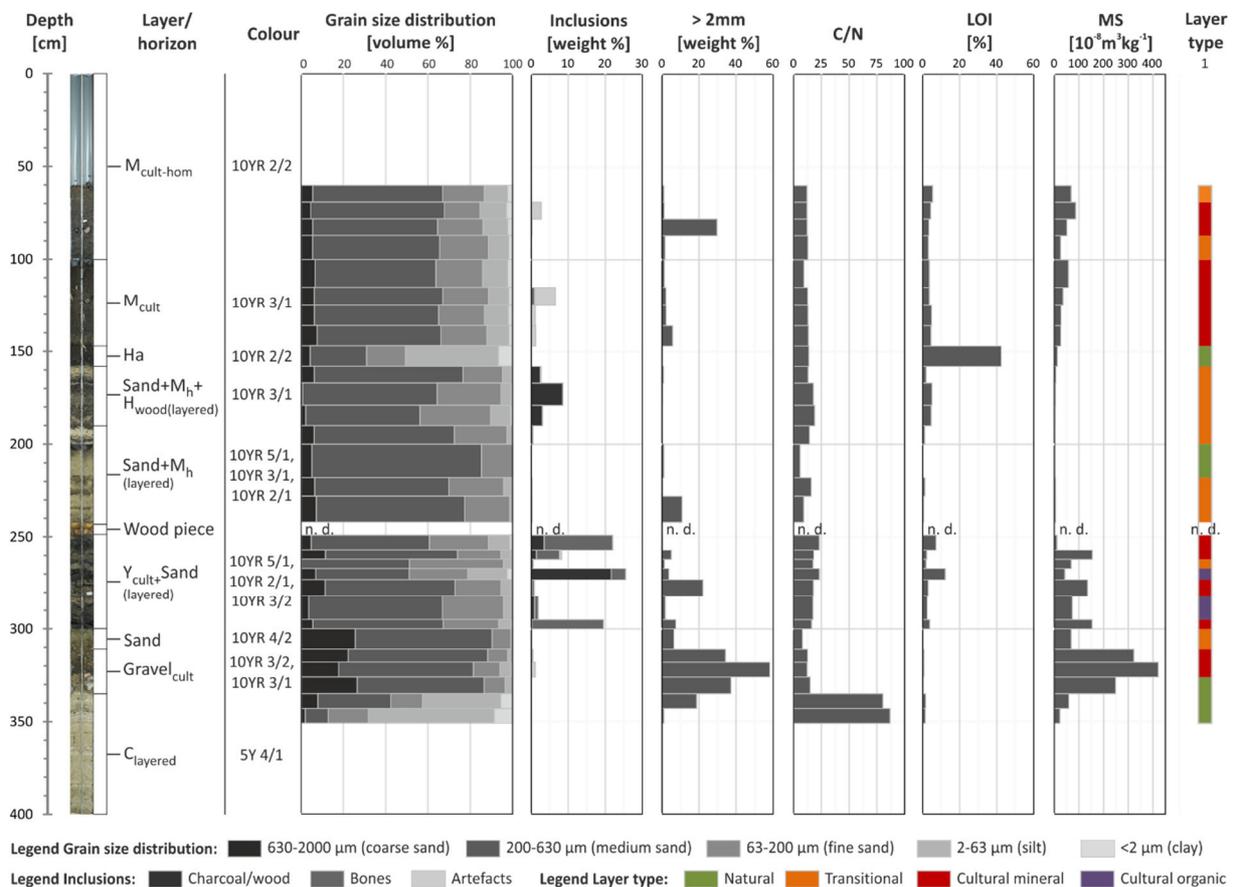


Figure 29. Geo-ecological properties of the sediments of core 442. Layer type column 1: clusters obtained with 6 parameters.

The third core investigated at the drilling site 441 is located 2.5 m south of point 198 close to the Hedeby-brook. The basis of the stratigraphic sequence in point 441 also starts with the varved Pleistocene sediment  $C_{layered}$  that was unequivocally classified as a natural deposit (Figure 30).

Further up the profile at a depth of 311 – 335 cm a gravel layer is located, which, unlike the gravel layers in points 198 and 442, has a clear anthropogenic signature expressed in the presence of a small amount of artefacts in the mid-part of the layer as well as in extremely high values of MS in the whole layer reaching  $421 \cdot 10^{-8} \text{m}^3 \text{kg}^{-1}$ . Unlike natural gravel layers at previous points, rock fragments include not only flints but also granite. Above  $\text{Gravel}_{\text{cult}}$ , a sterile sand layer that was found in point 198 as unit IV is also present. Probably, because of a somewhat higher MS, this layer was classified as a deposit with transitional properties. This is probably related to the presence of the gravel below with the high MS. Further up the profile at a depth of 250 – 300 cm, again a layered deposit  $\text{Y}_{\text{cult}} + \text{Sand}_{\text{(layered)}}$  was found, which represents alternating cultural and sandy layers that was also the case in the two drillings points discussed previously (unit V). The alternation can be well seen in the distribution of artefacts, charcoal/wood and MS in this deposit.



**Figure 30. Geo-ecological properties of the sediments of core 441. Layer type column 1: clusters obtained with 6 parameters.**

In the two previous points, deposit V was overlain by the OM-rich cultural layer (VI); however, in this point another structure is present, presumably a small filled gully. This structure starts at a depth of 160 cm and finishes at 250 cm below recent the land surface. Characteristic for the gully filling is the alternation of dark-coloured material with sand layers, which was designated  $\text{Sand} + \text{H}_{\text{(layered)}}$ . It has to be mentioned that the content of OM, also in the dark-coloured H-sublayers, is relatively low (below 5.5 %). Also, artefacts and bones are not present in the deposit

and MS is very low having values that are usually found in reduced environments. Only in the upper part of the deposit quite abundant wood/charcoal fragments were identified. The next unit in the sequence is the thin peat layer Ha with an OM content of 42.4 % without any anthropogenic/cultural features. The following deposit is the same as the one found at points 198 and 442 and represents the colluvium of the cultural layer, which was affected by ploughing in the upper part. However, it should be noted that here MS is somewhat lower and varies in the range 25 – 86  $10^{-8}m^3kg^{-1}$ , whereas OM content varies in the range 3.1 – 5.5 %. Therefore, the following stratigraphy can be suggested for core 441 (\* indicates a difference in the unit properties in comparison to the previous cores):

<b>IX</b>	0-100 cm	Ploughed colluvium of the cultural layer
<b>VIII</b>	100-147 cm	Colluvium of the reworked cultural layer
<b>VII</b>	147-158 cm	Peat layer
<b>Gully</b>	158-249 cm	Gully filling
<b>V</b>	249-300 cm	Heterogeneous cultural filling with interlayers of sand
<b>IV</b>	300-311 cm	Sterile sand layer
<b>II*</b>	311-335 cm	Cultural gravel
<b>I</b>	335-400 cm	Varved Pleistocene deposit

Based on the results of geo-ecological analyses, the results of sediment classification and morphological properties of the materials, a scheme of stratigraphy in the cores of transect 1 can be suggested (Figure 31).

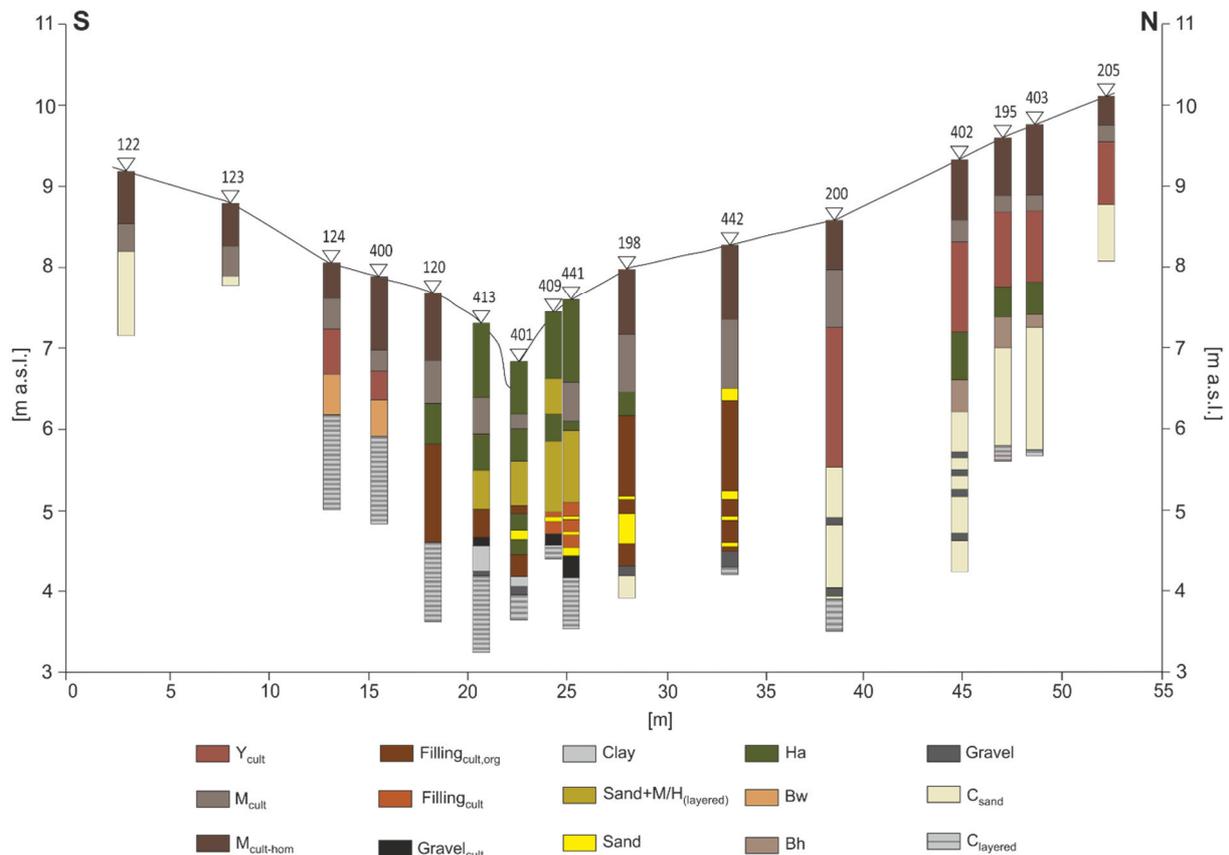


Figure 31. Scheme of stratigraphic sequences in the sediment cores of transect 1.

The filling of the structure was found at drilling points in the central part of the transect: from point 120 in the south to point 442 in the north. On the slopes (points 124, 120 and 200, 402, 195, 403, 205), *in situ* cultural layers were identified. For simplicity of the graph, the heterogeneous cultural materials (mineral and organic) comprising the filling of the structure were aggregated and designated as Filling<sub>cult</sub> or Filling<sub>cult,org</sub>, respectively.

**Micromorphological investigations**

For micromorphological analysis, one core on the southern slope and one core on the northern slope outside of the structure filling were selected in transect 1. They contain *in situ* cultural layers and buried soil horizons. The aim of the analysis was to investigate micromorphologic properties of the *in situ* cultural layers on both slopes of the structure and to substantiate the identification of buried soil horizons. Table 7 shows the locations, at which the materials were sampled, and the sedimentary context for the thin sections.

Table 7. Sampling of materials for micromorphological analysis from deposits in transect 1.

Drilling site	Sampling depth, cm	Material sampled/context
400	142-152	Transition from the OM-rich cultural layer (Y <sub>cult,org</sub> ) to a colluvial deposit (M) underneath
400	166-176	Buried soil horizon (Bwb)
402	134-144	Transition from the colluvium of the cultural layer (M <sub>cult</sub> ) to the charred cultural layer (Y <sub>cult,ch</sub> )
402	184-194	Cultural layer (Y <sub>cult</sub> ) with a sublayer of charred material (Y <sub>cult,ch</sub> )
402	235-245	Peat-like material with a loose weathered stone (Ha)

The core at drilling point 400 is located on the southern slope of the structure. It contains colluvium of the cultural layer in the upper part of the profile with an organic cultural layer underneath. Further down the profile a homogeneous deposit, presumably a colluvial layer is situated. A remnant of the buried soil underlies the colluvium. Figure 32 shows photographs of the core with marked locations of materials sampled for thin section preparation.

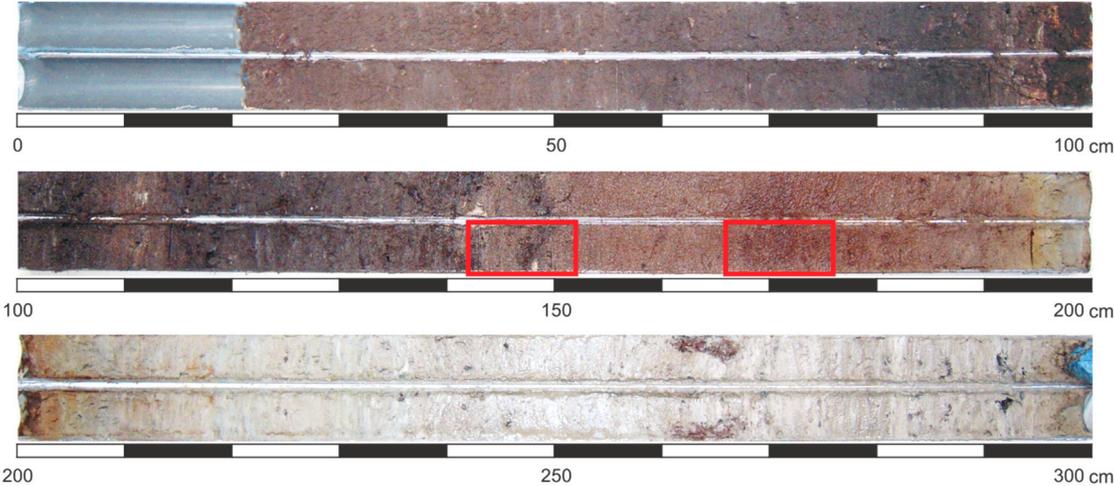
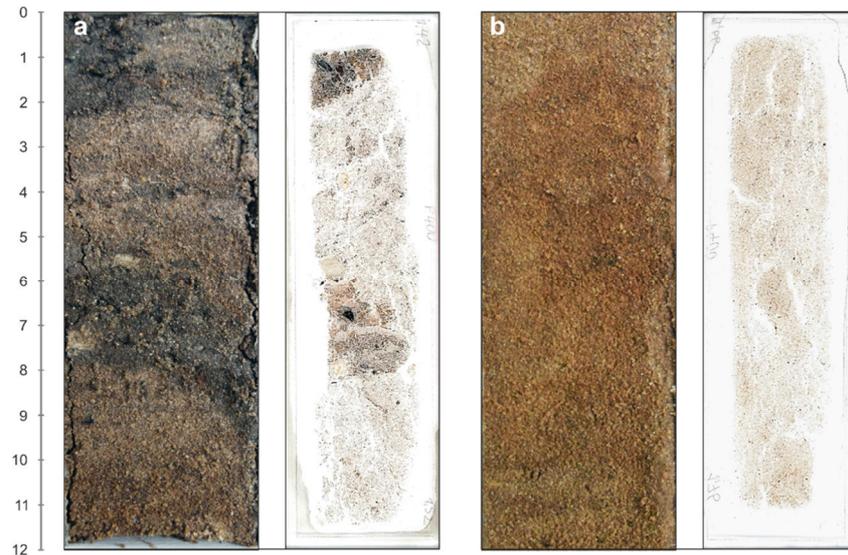


Figure 32. Photographs of the drilling core 400 with thin section locations marked (red frames).

Prior to the analysis, thin sections were scanned in order to obtain an overview of microstratigraphy. Figure 33 shows a close-up photograph of the materials sampled as well as corresponding scans of the thin sections. The detailed micromorphological description of the thin sections can be found in appendix 4.



**Figure 33.** Materials sampled for micromorphological analysis in core 400 and scans of the corresponding thin sections. A: 142 – 152 cm; B: 166 – 176 cm.

In the first thin section (142 – 152 cm below land surface), four parts can be distinguished, which are also well visible in the thin section scan: two heterogeneous OM-rich layers ( $Y_{\text{cult,org}}$ ) in the uppermost and in the central part of the slide as well as two sublayers of brownish sandy deposit (M). All four sublayers have a vughy microstructure, and rounded and subrounded quartz grains dominate their coarse mineral material with presence of feldspars and other rock fragments.

The upper sandy colluvial sediment at a relative depth of 2 – 6 cm is homogeneous, although not as homogeneous as in the lowermost sublayer but also not as heterogeneous as OM-rich sublayers directly above and below. It is well sorted and its coarse mineral fraction is strongly dominated by rounded quartz and feldspar grains of medium sand, which can be well recognized in plain polarized light (PPL) and crossed polarized light (XPL) (Figure 34a, b). It contains a relatively large aggregate of layered silty loam material cemented by organo-mineral material (Figure 34c, d). The lowermost colluvial sublayer is in general similar to the one described previously; however, it is better sorted and is characterized by a c:f ratio of 80:20 (c:f limit 60  $\mu\text{m}$ ) in comparison to 50:50 in the upper sandy deposit. Bioturbation features are present as well as root channels, some of which are filled with material from above. An unknown porous opaque object, probably a metallic artefact, was found in the upper part of the deposit (Figure 34e, f).

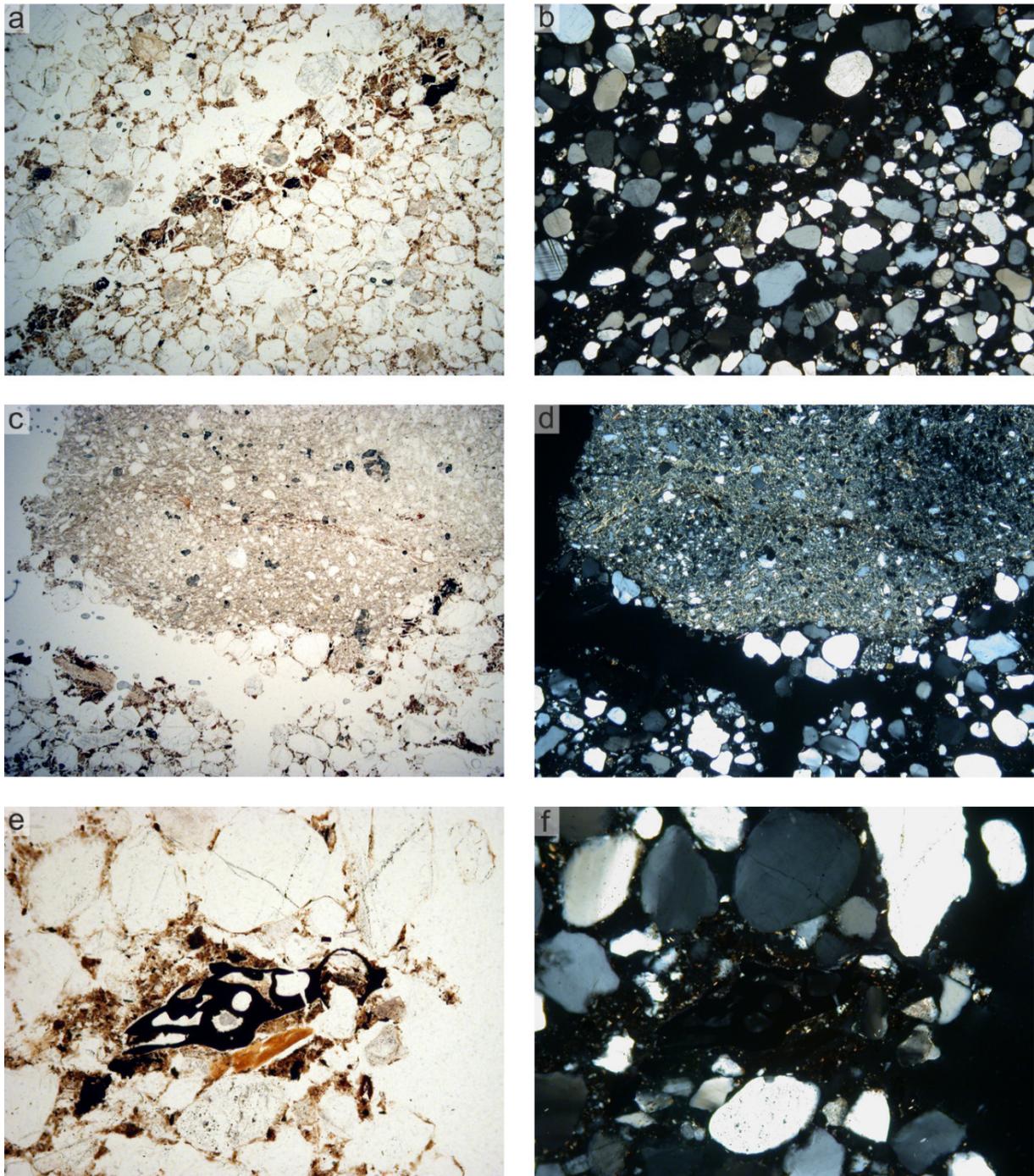


Figure 34. Microphotographs of the colluvial sandy deposit (M) at point 400 at 142 – 152 cm depth. A: Overview of the lower part with a filled root channel or a burrowing structure (PPL, FOV 5.2 mm). B: Same in XPL. C: Partly layered loamy clast in the upper sandy deposit (PPL, FOV 5.2 mm). D: Same in XPL. E: A metallic artefact (PPL, FOV 1.3 mm). F: Same in XPL.

The OM-rich cultural sublayers represent heterogeneous cultural peaty material (Figure 35a, b) with presence of abundant charcoal, woody remains as well as bones, including fish bones (Figure 35e). The fine fabric is represented by silty and slightly clayey material associated with amorphous organic matter. Among fine inclusions, abundant fragmented phytoliths and fungal spores can be pointed out (Figure 35f). The upper cultural sublayer also contains a sediment aggregate with a preserved illuvial clay coating demonstrating a typical crescent birefringence

pattern (Figure 35c, d). Pedofeatures include phosphatisation features in some areas and large quantities of pyrite framboids mostly associated with organic remains. In general, the organic fraction in some parts of the slide resembles excremental material.

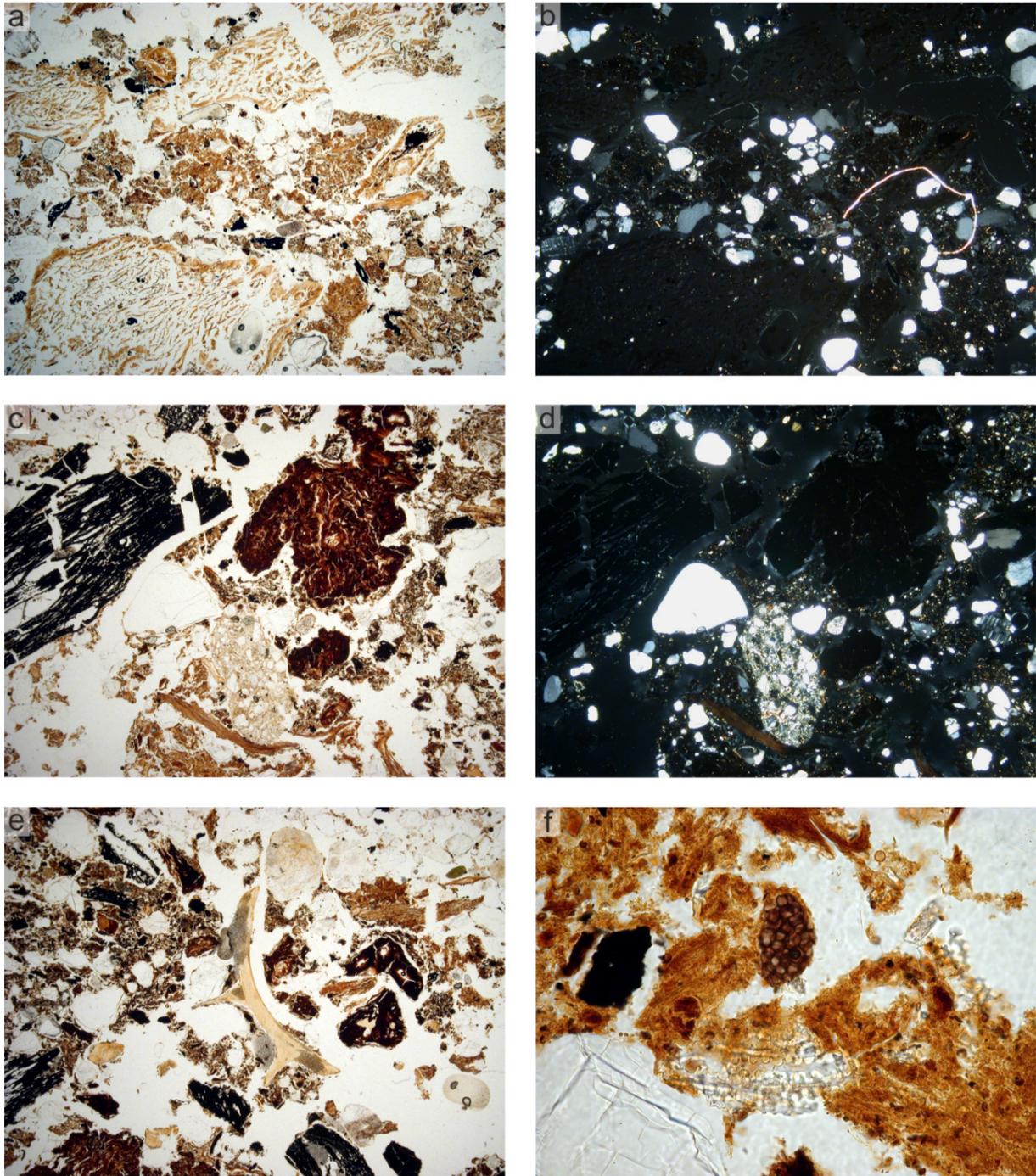


Figure 35. Microphotographs of the cultural peaty material ( $Y_{cult,org}$ ) at point 400 at 142 - 152 cm depth. A: Overview of the middle part (PPL, FOV 5.2 mm). B: Same in XPL. C: Overview of the upper part with the aggregate of redeposited material (PPL, FOV 5.2 mm). D: Same in XPL. E: Fish bone in the upper part (PPL, FOV 5.2 mm). F: Articulated phytoliths and fungal spores in the middle part (PPL, FOV 0.32 mm).

In the second thin section at a depth of 166 - 176 cm, the assumed buried soil horizon was sampled with the aim to examine the genesis of the material. The material of the sample is

moderately sorted and its microstructure is loose and unstructured (Figure 36a, b). Rounded and subrounded quartz grains dominate the mineral fraction with presence of plagioclase, microcline and rock fragments. The c:f related distribution is enaulic to chitonic pointing at the initial stage of illuvial formation of the coatings (Figure 36c, d) and thus suggesting that this is a pre-Viking Bw horizon with pale organo-mineral material representing the fine fraction and initial Fe-OM coatings.

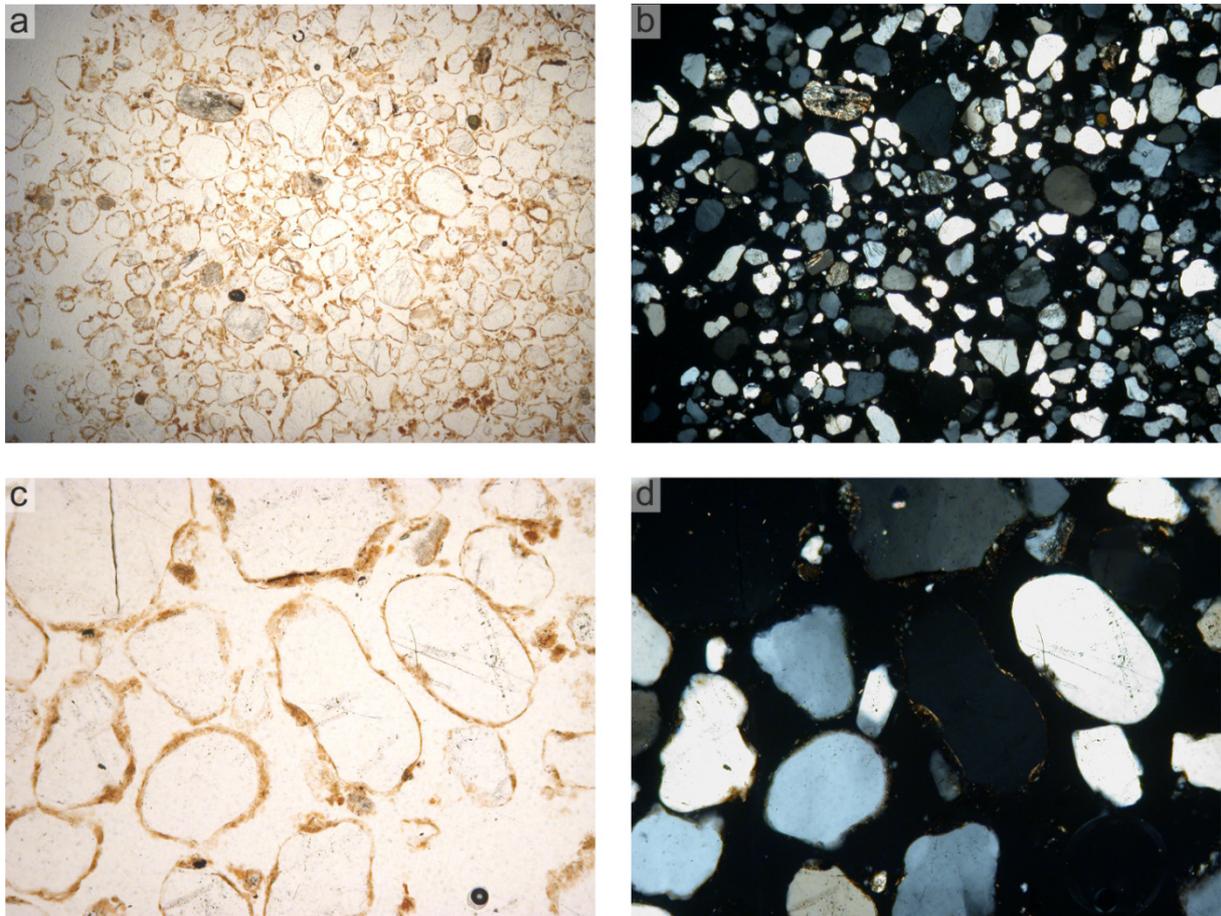


Figure 36. Microphotographs of the Bwb horizon at point 400 at 166 - 176 cm depth. A: Overview of the microstructure (PPL, FOV 5.2 mm). B: Same in XPL. C: Organo-mineral coatings on quartz grains (PPL, FOV 1.3 mm). D: Same in XPL.

The next core analysed is core at drilling point 402, which is located on the opposite side of the brook higher up the slope (Figure 37). Here the stratigraphy is more complex and along with the colluvium of the cultural layer (ploughed in the upper part) it contains an *in situ* cultural layer with an alternation of charcoal-rich layers and sandy layers.

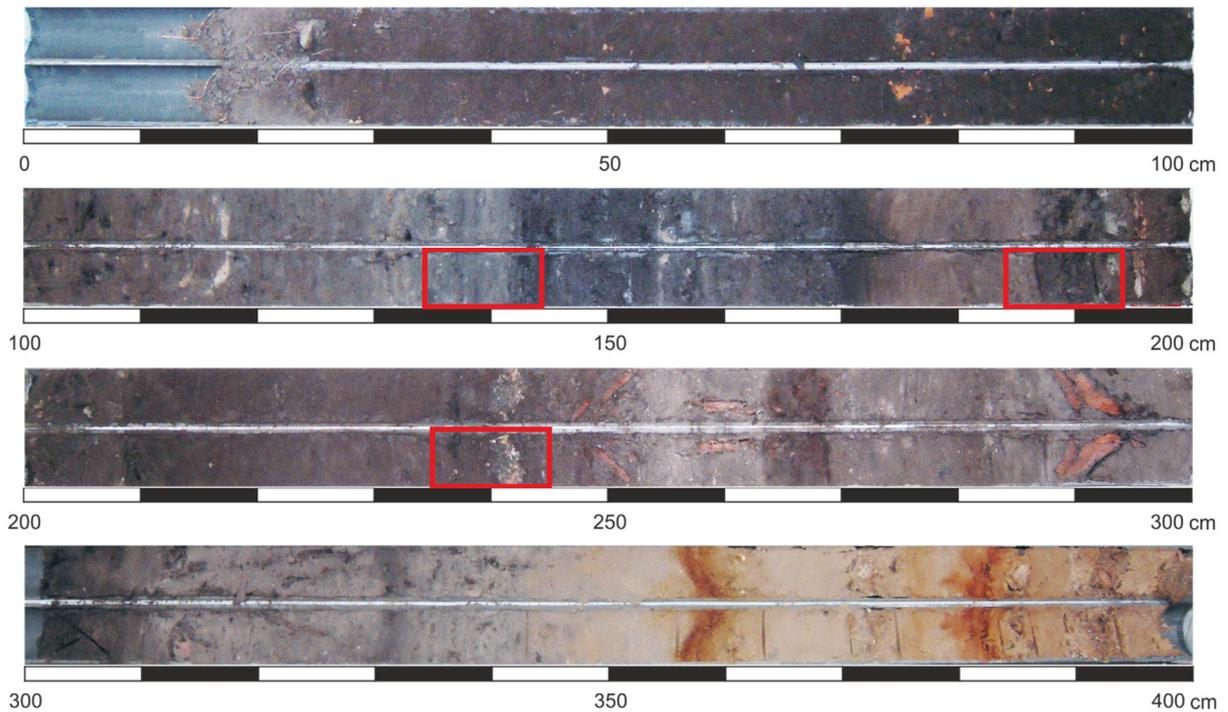


Figure 37. Photographs of the drilling core 402 with thin section locations marked (red frames).

Figure 38 shows close-up photographs of the materials sampled as well as corresponding scans of the thin sections. The detailed description of the thin sections can be found in appendix 5.

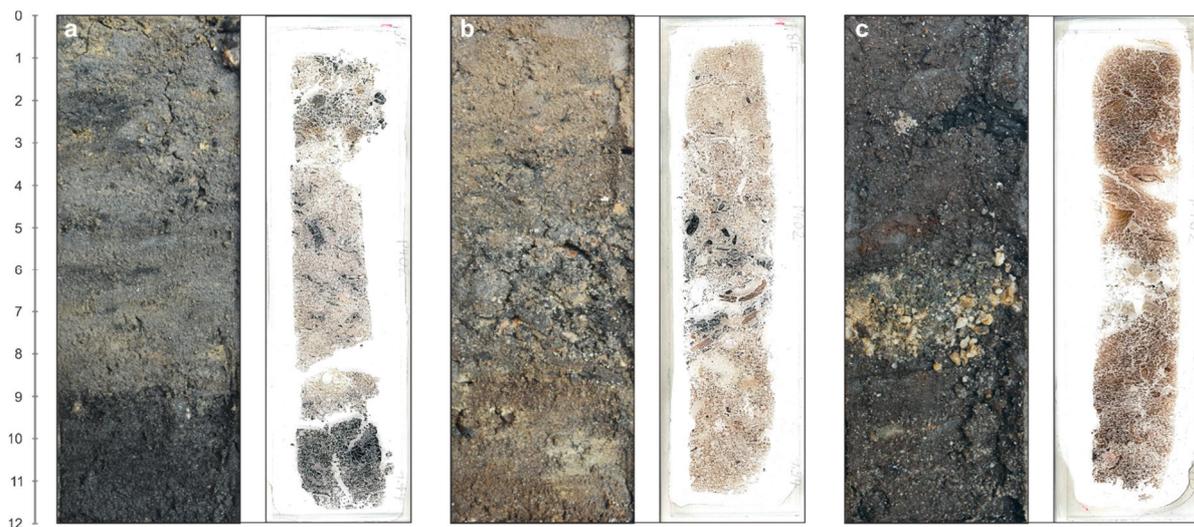
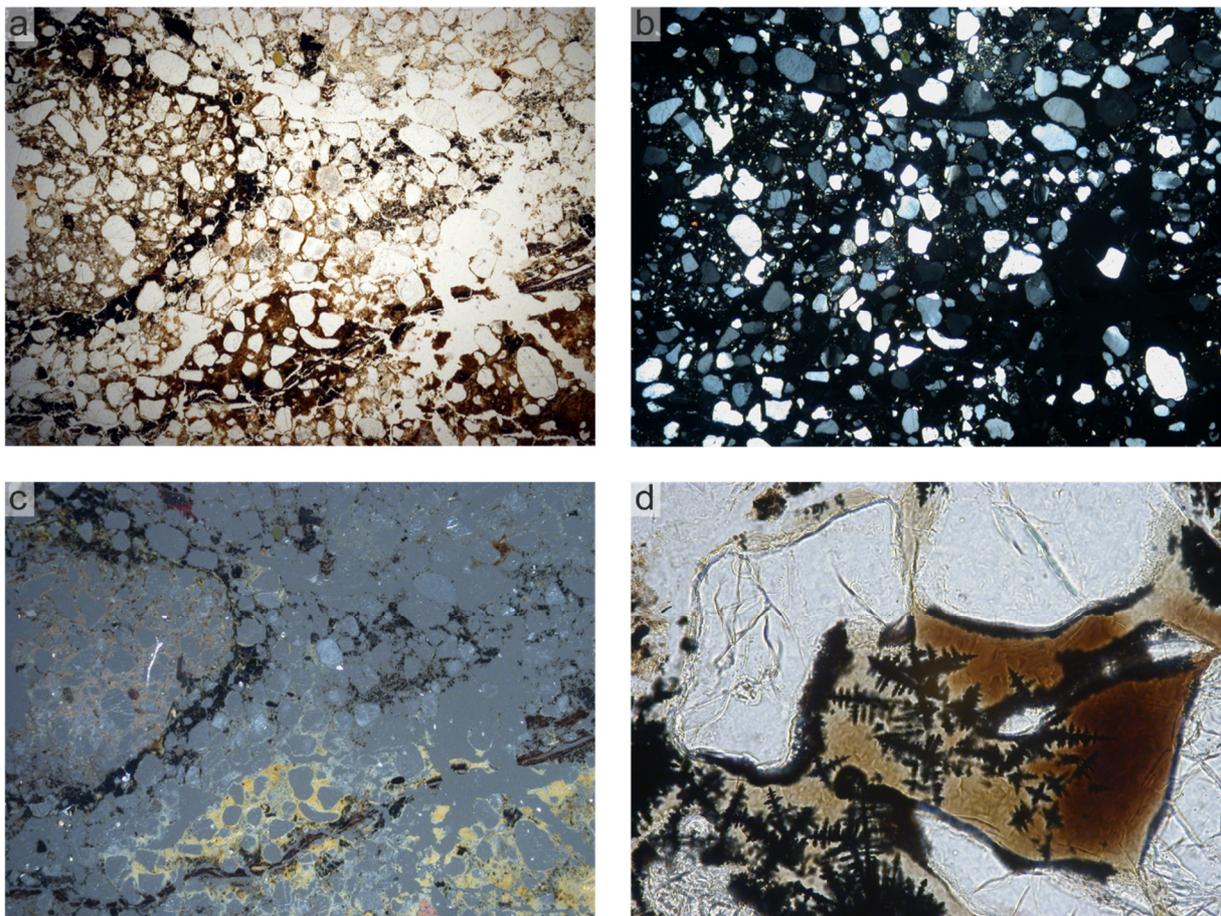


Figure 38. Materials sampled for micromorphological analysis in core 402 and scans of the thin sections. A: 134 – 144 cm depth; B: 184 – 194 cm depth; C: 235 – 245 cm depth.

The uppermost thin section in core 402 was sampled at a depth of 134 – 144 cm at the transition between  $M_{\text{cult}}$  to  $Y_{\text{cult, ch}}$ . The entire thin section is characterized by a strong fragmentation of matrix components, probably due to the desiccation processes during the preparation of the thin section. As it can be seen in the scan of the thin section three main parts can be distinguished: heterogeneous upper  $M_{\text{cult}}$  at 1 – 3 cm relative depth, less heterogeneous lower  $M_{\text{cult}}$  at 3 – 9.5 cm and  $Y_{\text{cult, ch}}$  at 9.5 – 11.5 cm. The three parts have, however, a lot of features in common. All of them

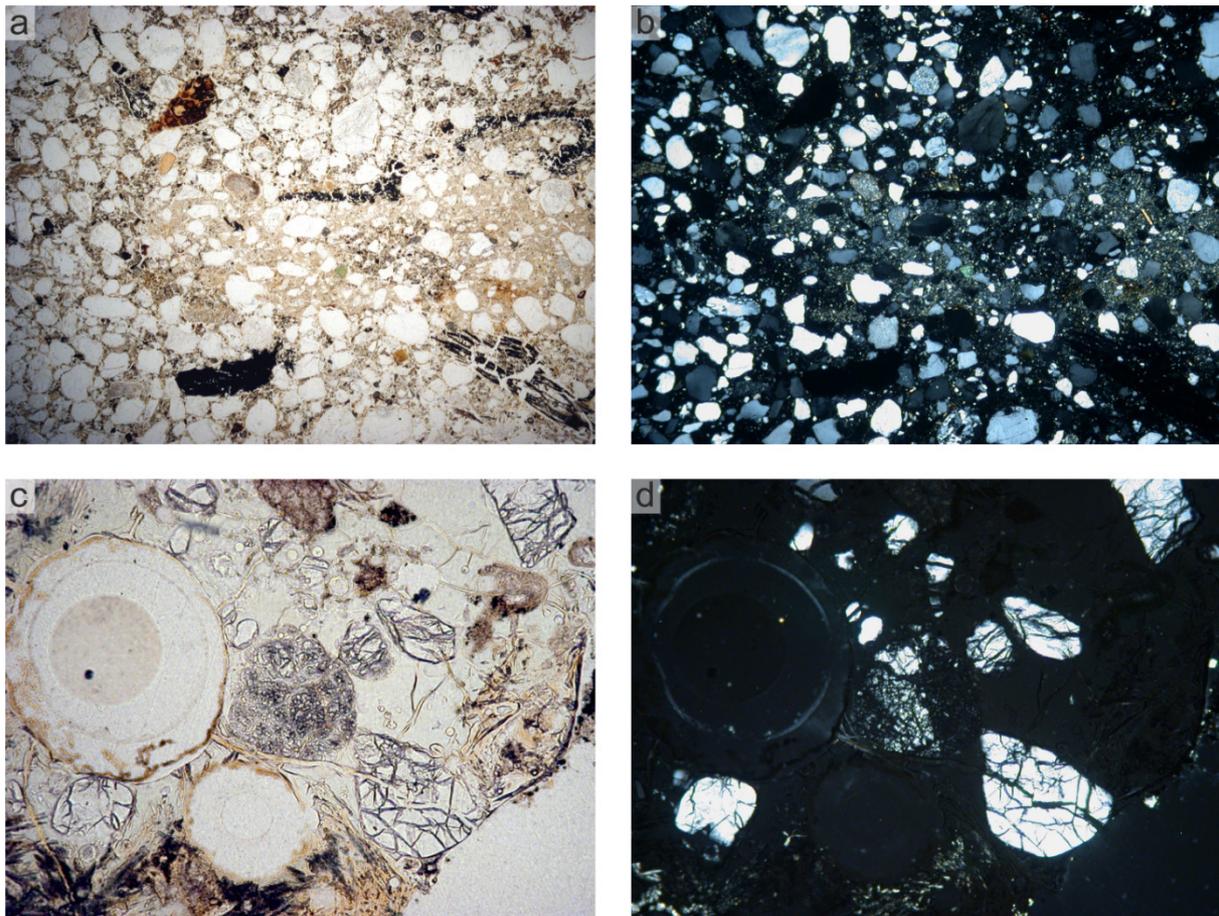
are heterogeneous and poorly sorted with a massive microstructure. Quartz is dominating in the coarse mineral fraction, while some feldspar and rock fragments are present too and the grains are both subrounded and subangular in all three sublayers. In the whole thin section the c:f ratio equals 60:40 and c:f related distribution is enaulic. However, it has to be noted that in the uppermost sublayer some areas with 40:60 ratio and porphyric distribution were found.

The uppermost sublayer represents the lower part of  $M_{\text{cult}}$  layer sampled (1 – 3 cm relative depth). The most specific characteristics of this unit is the presence of strong phosphatisation features (Figure 39a, b), which can be well seen in the oblique incident light (OIL) (Figure 39c). Phosphatisation is observed mostly for aggregates of loose quartz grains cemented by organo-phosphatic material, which seems to be layered in some cases. Abundance of charcoal fragments (all desiccated) and diverse artefacts such as silica slags, small bones and metal slags with a dendritic pattern in plain polarized light has to be pointed out (Figure 39d). Silica slags represent isotropic glassy formations with a vesicular structure and usually with presence of fractured quartz grains.



**Figure 39.** Microphotographs of the upper part of  $M_{\text{cult}}$  layer at point 402 at 134 – 144 cm depth. **A:** Overview of the microstructure with coarse mineral grains cemented with organo-phosphatic material (PPL, FOV 5.2 mm). **B:** Same in XPL. **C:** Same in OIL. **D:** Metal slag fragment with a dendritic pattern in the matrix of coarse quartz grains and charred material (PPL, FOV 0.32 mm).

The underlying lower part of  $M_{\text{cult}}$  is quite similar to the previously described unit; however, no phosphatisation features were identified there. Silt-sized organo-mineral material with amorphous OM and dispersed charred material in the voids represent the fine fabric with mica grains present in the mineral component (Figure 40a, b). Artefacts include also silica slags (largest 0.8 cm size) with fractured quartz grains (Figure 40c, d) and bones as well as fragments of hammerscale (Figure 40a) and metal slags. Abundant burrowing structures filled with fine material were found in the layer. Among pedofeatures, iron staining and pyrite framboids were identified.



**Figure 40.** Microphotographs of the lower part of  $M_{\text{cult}}$  layer at point 402 at 134 - 144 cm depth. A: Overview of the microstructure with charcoal pieces and a hammerscale fragment (PPL, FOV 5.2 mm). B: Same in XPL. C: Silica slag with vesicular microstructure and cracked quartz grains (PPL, FOV 1.3 mm). D: Same in XPL.

The lowest unit is the charred cultural layer with charcoal fragments of different size dominating the matrix (Figure 41a, b). Most of the charcoal fragments are strongly desiccated, which is probably the result of the thin section preparation procedure (Figure 41c, d). The fine fabric is represented by organo-mineral and charred material with a stipple-speckled b-fabric. Artefacts are present here too: abundant silica slags and small bone fragments.

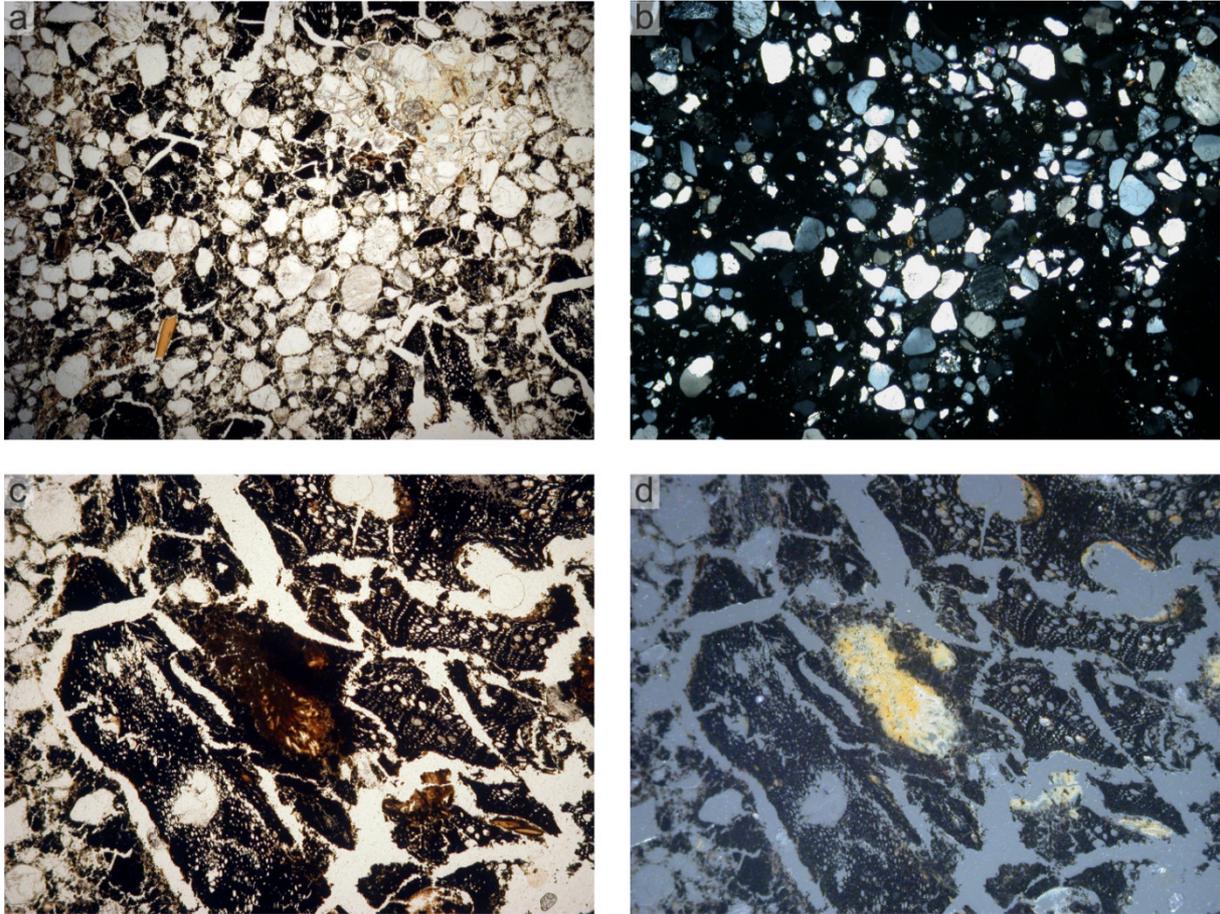
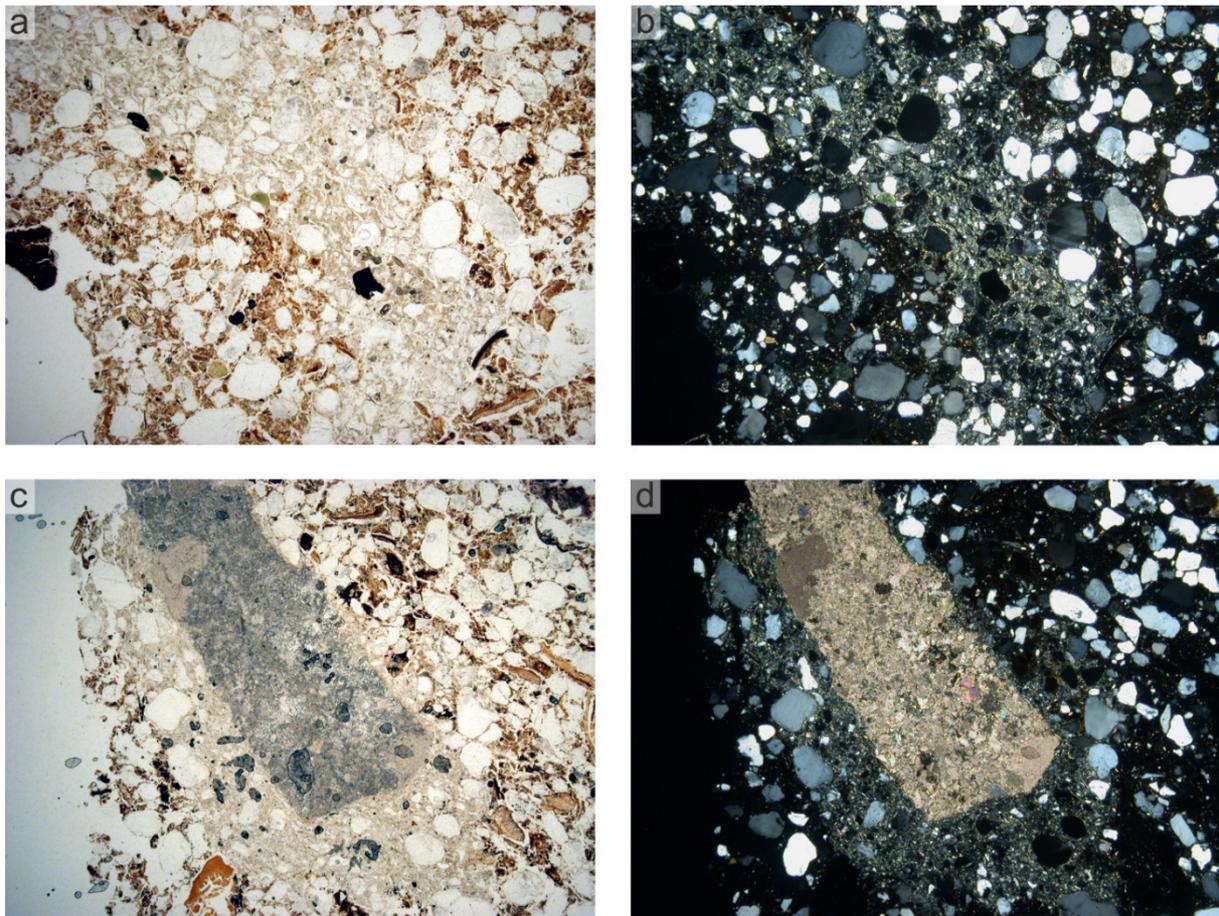


Figure 41. Microphotographs of  $Y_{ch}$  at point 402 at 134 – 144 cm depth. A: Overview of the microstructure with charcoal pieces, silica slags and a bone fragment (PPL, FOV 5.2 mm). B: Same in XPL. C: Strongly desiccated charcoal fragment with presumable phosphatization features (PPL, FOV 2.6 mm). D: Same in OIL.

The second thin section (184 – 194 cm below land surface) was prepared for a heterogeneous part of the cultural material containing clay aggregates and a sublayer of black charred material. Therefore, two units were distinguished in this thin section: a cultural layer at 0 – 4 cm relative depth and at 7/8 – 11.2 cm (inclined border), which is interrupted by a charred cultural layer at 4 – 7/8 cm relative depth.

The cultural layer in the upper and the lower part of the thin section makes a heterogeneous impression due to the presence of inclusions of different organic remains. It is poorly sorted to unsorted with a quite massive microstructure with very few voids. The coarse mineral fraction is composed of mostly quartz and rock fragments, which are rounded and subrounded, with presence of feldspars and very small quantities of other minerals. Additionally, loamy clasts of up to 3 mm size are present in the matrix with mica dominating in the fine fabric of the aggregates and forming a grano-striated b-fabric (Figure 42a, b). The c:f ratio is 60:40 (c:f limit 60  $\mu$ m) and distribution is enaulic. Coarse organic components include diverse plant remains of different degrees of decomposition without birefringence and fungal spores as well as large and small charcoal fragments and woody tissues. The fine fabric is comprised of organo-mineral silty

material with presence of mica in the upper part and mostly organic material in the lower part with a stipple-speckled and undifferentiated b-fabric, respectively. Identified pedofeatures include pyrite framboids (quite abundant), some minor iron staining features and burrowing structures filled with finer and OM-richer material (Figure 42a, b). Anthropogenic inclusions are represented by different loamy clasts, which are possibly fragments of construction materials. One of them embeds a calcareous rock fragment with a high-order birefringence (Figure 42c, d).



**Figure 42.** Microphotographs of the cultural material at point 402 at 184-194 cm depth. **A:** Overview of the lower part with a burrowing structure (PPL, FOV 5.2 mm). **B:** Same in XPL. **C:** Loamy clast embedding calcareous fragment, probably representing construction material, in the lower part of the cultural layer (PPL, FOV 5.2 mm). **D:** Same in XPL.

In the mid-part of the thin section a layer rich in burnt material is present  $Y_{\text{cult, ch}}$ . This material is unsorted and very heterogeneous. It has features of postdepositional mixing processes, probably by bioturbation. The microstructure is vughy, but it can also be described as disturbed. The coarse mineral fraction is the same as in the cultural layers above and below. However, the proportion between the coarse and fine material is somewhat different with a c:f ratio being 40:60. Abundant woody remains and very abundant charcoal pieces (both intact and strongly fragmented) were found in the layer (Figure 43a, b). Artefacts are present here too: a reddish fine material clast (probably a pottery fragment, Figure 43c, d); another construction material fragment (darker brown colour, may be daub); abundant silica slag fragments but without fractured quartz grains

(Figure 43e, f). The fine fabric is represented by organo-mineral silty material with a stippled-speckled b-fabric.

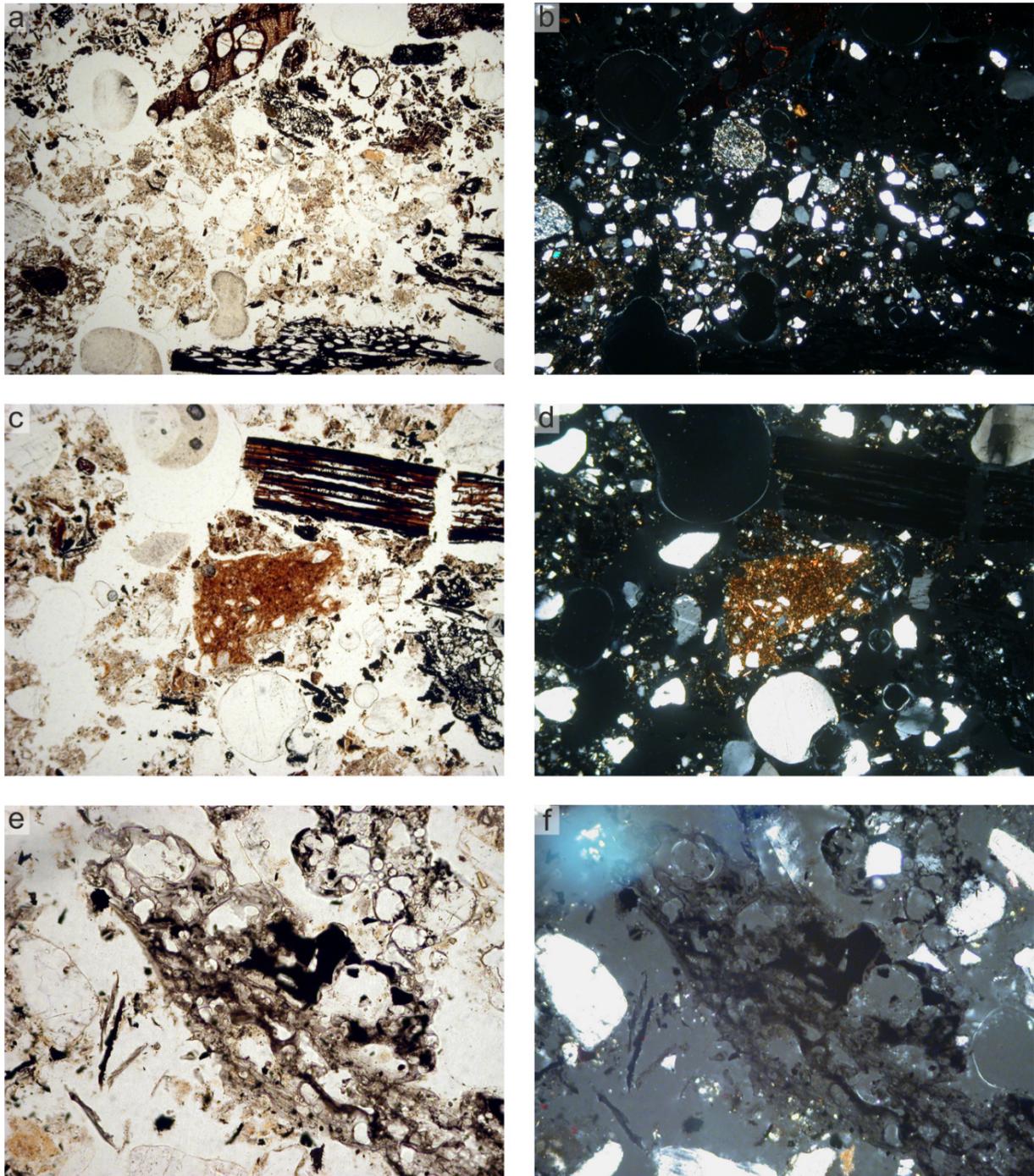


Figure 43. Microphotographs of the sublayer of charred cultural material at point 402 at 184-194 cm depth. A: Overview of the middle part (PPL, FOV 5.2 mm). B: Same in XPL. C: Pottery fragment (PPL, FOV 2.6 mm). D: Same in XPL. E: Silica slag with opaque matter (PPL, FOV 0.65 mm). F: Same in XPL.

The lowermost thin section in this core was sampled at a depth of 235 – 245 cm in a peat-like material containing a weathered stone with a diameter of 4 – 5 cm. The stone includes rock fragments, quartz, microcline, chlorite and other minerals. The peaty material is relatively homogeneous and contains up to 30 % of mineral material (aerial estimation) (Figure 44a, b). The

mineral fraction is moderately sorted (medium and fine sand with a low content of coarse sand) and is strongly dominated by rounded quartz grains (> 90 %) with presence of plagioclase, microcline and rock fragments. The c:f ratio is estimated at 30:70 and c:f related distribution is enaulic. Organic material is very diverse: abundant undecomposed and slightly decomposed plant remains with a visible plant anatomic structure, a few woody remains, single charcoal fragments. Some plant remains possess a birefringence. The fine fabric is dominated by amorphous organic material with undifferentiated b-fabric and with fungal spores, some parts contain silt-sized particles and have a stipple-speckled b-fabric. Some pyrite framboids are present (Figure 44c, d). No anthropogenic components were identified.

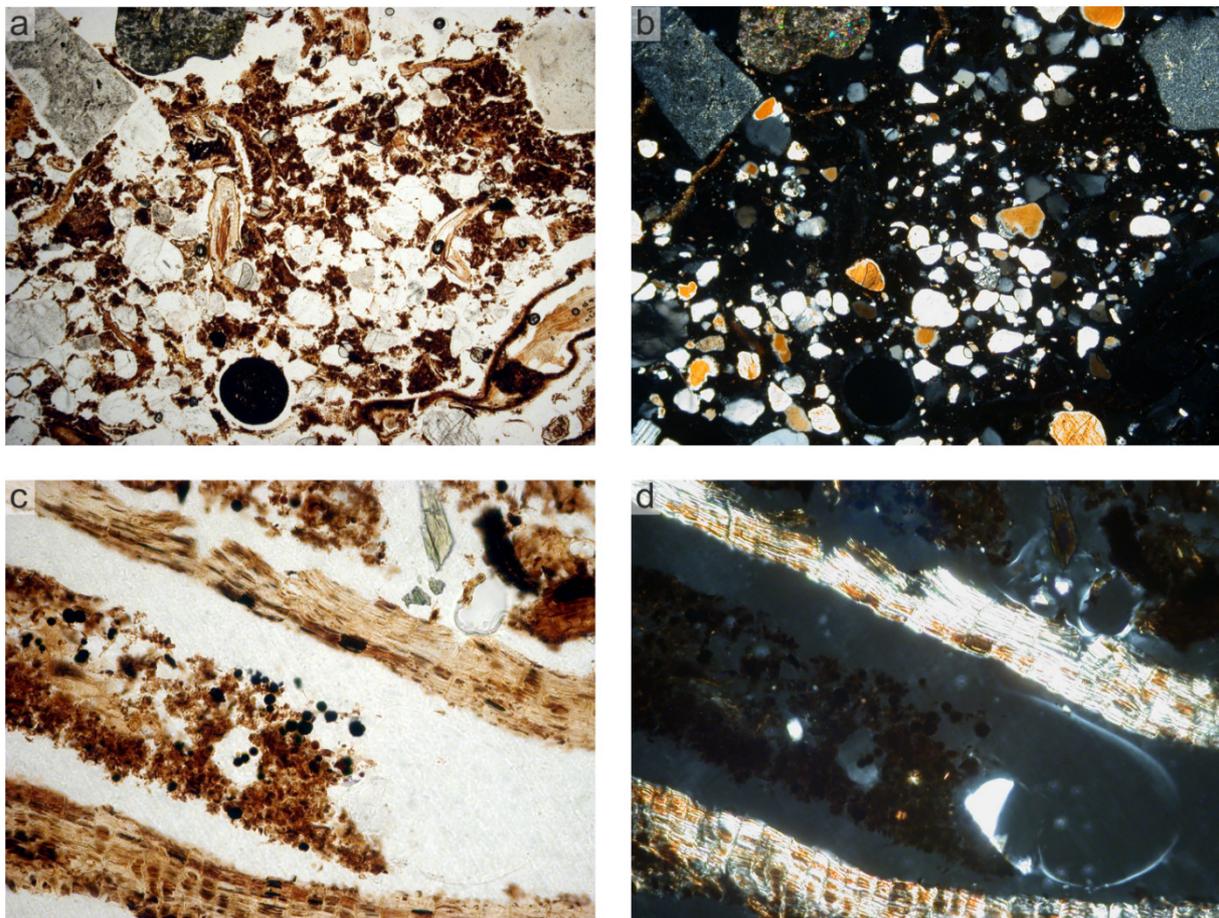


Figure 44. Microphotographs of the peat-like material at point 402 at 235-245 cm depth. A: Overview of the lower part with abundant plant remains and a large fungal spore (PPL, FOV 5.2 mm). B: Same in XPL. C: Pyrite framboids associated with fresh plant remains (PPL, FOV 0.65 mm). D: Same in XPL.

### *Dating of the materials*

Three dates were acquired for the filling of the structure by <sup>14</sup>C dating. Table 8 shows the results of the dating. Two samples were taken for dating at the basis of the structure filling: a hazelnut shell fragment at a depth 355 cm at point 198 and a beech charcoal fragment at 258 cm at point 401. The calibrated age obtained for the nut shell from point 198 (KIA50329) covers a period of 87 years (IntCal 13 producing a 2 $\sigma$  range): 890 – 977 cal AD. The beech charcoal from point 401

(KIA50952) was sampled from the same stratigraphic position. Here, a larger uncertainty range of the calibrated age was obtained from 775 until 970 cal AD, due to the plateau on the calibration curve (Figure 45). Based on the known historic and archaeological records, the first period of 9.2 % probability can be excluded, while the other two periods are probable. Taking into account dating result from point 198, the third period 915 – 970 cal AD is the most probable age of the charcoal fragment at point 401. Therefore, the stratigraphic unit dated in both cores has an age ca. 890 – 977 cal AD.

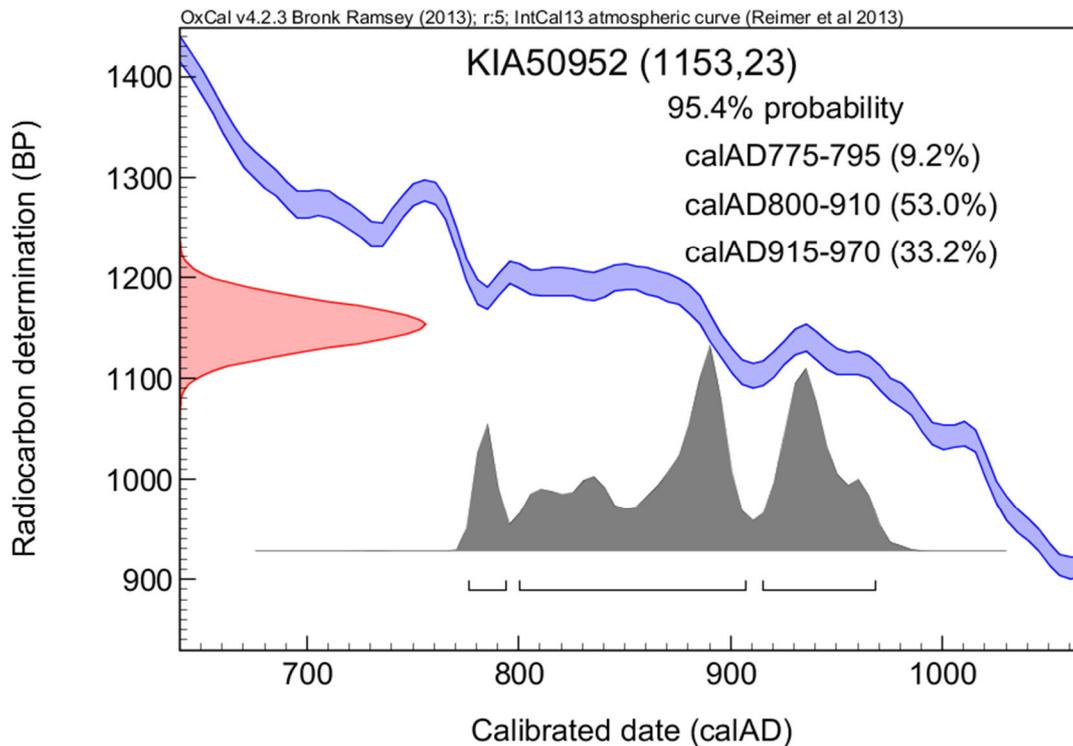


Figure 45. Result of radiocarbon dating of a charcoal fragment from point 401.

The third dating sample represented a charred spelt barley seed (KIA50328) that was found in the cultural organic material underlying the peat layer at point 198. Here, the age obtained falls into the end of the Viking Age. Since Hedeby was destroyed in 1066 AD and the seed was found directly at the border to the peat layer, the age segment 1080 – 1155 cal AD is more probable.

Table 8. Radiocarbon data of materials from points 198 and 401.

Lab number	Sample/material	Point nr./ depth (cm)	Radiocarbon age	Calibrated age (2σ range)	δ <sup>13</sup> C (‰)
KIA50328	Spelt barley seed ( <i>Hordeum vulgare var. vulgare</i> )	198 / 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 ( <i>Corylus</i> )	198 / 355	1105 ± 25 BP 1130 ± 25 BP	890 – 977 cal AD (95,4%)	-26,15 ± 0,09 -27,61 ± 0,22
KIA50952	Charcoal fragment ( <i>Fagus</i> )	401 / 258	1155 ± 25 BP	800 -910 cal AD (53,0%) 915 – 970 cal AD (33,2%) 775 - 795 cal AD (9,2%)	-25,18 ± 0,31

### General stratigraphy of sediments in transect 1

Based on the geo-ecological data obtained for the three cores and taking into account the classification results based on cluster analysis of the properties, the stratigraphy, micromorphological investigations and dating results, a generalized description of the structure can be compiled. The mean values of geo-ecological properties with standard deviations are shown in Table 9 and a generalised stratigraphy of the cores is provided in Figure 47. Additionally, pH measurements were performed for a selection of samples from cores in transect 1.

Table 9. Geo-ecological characteristics of the sediments in the structure (transect 1).

Layer	>2mm (%)		CH/wood (%)		Bones (%)		Artefacts (%)		LOI (%)		MS (10 <sup>-8</sup> m <sup>3</sup> kg <sup>-1</sup> )		pH
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
M <sub>cult-hom</sub>	3.6	1.9	0.0	0.1	0.0	0.0	1.0	1.3	3.7	1.2	95.1	18.7	5.7
M <sub>cult</sub>	3.2	1.6	0.0	0.1	0.1	0.2	1.7	1.5	3.6	1.2	131.0	23.9	5.6
Ha	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	42.1	9.6	11.2	3.8	5.1
Filling <sub>cult</sub>	10.2	9.4	1.5	2.1	5.9	8.2	0.6	1.2	3.3	2.2	111.4	35.2	6.1
Filling <sub>cult,org</sub>	2.3	1.3	3.8	2.7	1.1	1.8	0.7	1.5	11.2	5.5	11.1	6.3	5.1
Sand	2.8	3.1	0.4	0.3	0.0	0.0	0.0	0.0	1.0	0.7	68.5	0.0	6.3
Gully filling	0.4	0.4	2.1	3.1	0.0	0.0	0.0	0.1	2.1	1.9	4.5	1.3	6.0
Gravel <sub>cult</sub>	43.2	13.0	0.0	0.0	0.1	0.2	0.4	0.7	0.6	0.2	330.8	86.5	7.3
Gravel	28.5	12.9	0.0	0.0	0.1	0.2	0.0	0.0	0.6	0.5	27.4	5.0	7.1
Bwsb	0.2	-	0.0	-	0.0	-	0.0	-	1.6	-	1.2	-	n.d.
C <sub>sand</sub>	3.2	3.8	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.3	12.3	5.8	7.7
Clayered	0.7	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.9	25.1	3.7	7.5

The basis of the structure is represented by Pleistocene material of different genesis: fluvio-glacial sand, clastic varves and a gravel layer mostly represented by flints. These deposits have low values of all the parameters as expected for sterile Pleistocene materials. The pH of Pleistocene deposits indicates neutral to slightly alkaline conditions. Pleistocene sediments do not have any features of Holocene soil formation and are directly overlain by Holocene sediments. Only at the margins of the structure, relicts of soil formation were identified. On the northern slope remnants of a probably Bh horizon were found with a peaty material above it. On the southern slope at points 124 and 400 of the structure, a remnant of a Bw soil horizon was discovered. The horizon is comprised of homogeneous medium sand and has a reddish brown colour. During micromorphological investigations pedogenic organo-mineral coatings were identified in this horizon. The soil remnants are characterized by the absence of any anthropogenic features and by a very low organic matter content. The MS value is very low too apparently being affected by reduction conditions. In the northern part of the transect, multiple thin gravel layers were found embedded in Pleistocene sandy material. On the slopes, outside the structure, a cultural layer formed *in situ* was discovered (Y<sub>cult</sub>). This layer is morphologically very heterogeneous and rich in small (mostly micro-) artefacts and charcoal with nearly no bones.

In the central deepest part of the structure, a cultural stone layer ( $\text{Gravel}_{\text{cult}}$ ) was identified at the border between Pleistocene and Holocene sediments. Single stones comprising the layer are up to 5 cm large in the core and they are mostly subangular and subrounded. Rock composition of the cultural gravel layers is much more diverse than in the natural gravel layers. Apart from flint, coarse fragments of gneiss, granite, sandstone and quartzite were identified. The material embedding the stones is varying, in some cores it is dark-coloured fine and medium sand and it often contains artefacts and bones. MS reaches extraordinarily high values of  $330.8 \cdot 10^{-8} \text{m}^3 \text{kg}^{-1}$  on average in the cultural gravel material. It has to be noted that a small structure (found by drilling 401) interrupts the cultural gravel layer. It is apparently a narrow U-shaped structure filled with OM-rich sediments with presence of charcoal and single stones.

Above the gravel layer in the deepest part and above the Pleistocene material on the slopes, a heterogeneous cultural deposit rich in macro-artefacts and other cultural inclusions is located. Artefacts found in this layer (Figure 46) include numerous pottery sherds (0.5 to 3 cm large) of early medieval age as well as bone fragments (0.5 – 5 cm large) and metallurgic slag fragments (up to 5 cm large). This deposit formed in Viking Age and was designated  $\text{Filling}_{\text{cult}}$ . The mineral matrix of this layer is comprised of sand (medium and fine sand) with presence of silt and relatively high organic matter content. This deposit has a high MS as well as a large content of bones; the content of organic matter equals 3.3% on average and pH is 6.1. Due to the presence of charcoal and dispersed charred material, the colour of the layer is from dark grey to black. Sublayers of light-coloured sand material and organically enriched materials are often present.

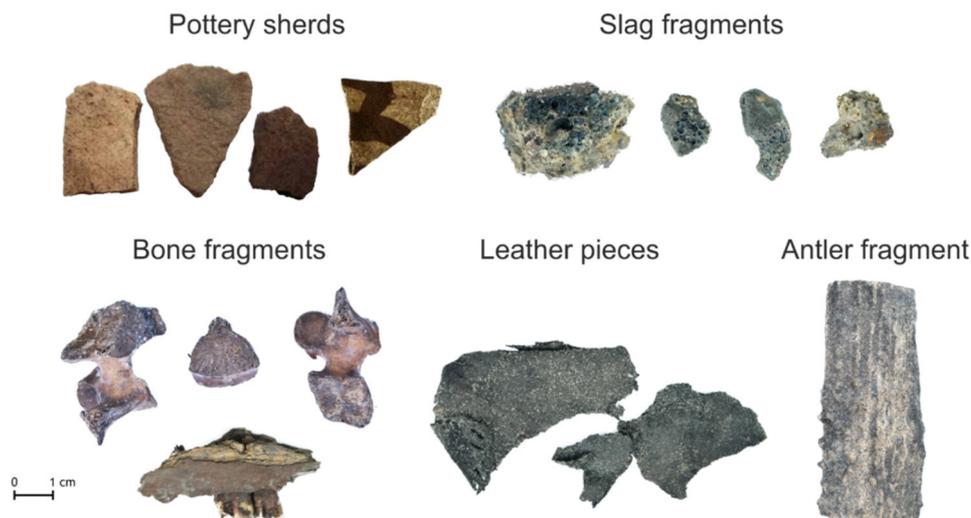


Figure 46. Archaeological finds from the cultural filling in the cores of transect 1.

In some locations, an OM-rich cultural deposit with an average OM content of 11.2 % was discovered. It includes well-preserved as well as partly decomposed wood fragments and often charcoal and was designated  $\text{Filling}_{\text{cult,org}}$ . This material also contains bones and artefacts, but MS of this material is very low –  $11.1 \cdot 10^{-8} \text{m}^3 \text{kg}^{-1}$  as is pH (5.1).

In the central part of the structure investigated, a small gully incised into the filling was identified. The gully is filled with alternating layers of sand and OM-enriched material (Sand+H<sub>layered</sub>). It contains some wood and charcoal with OM content varying in a narrow range with a mean value of 2.1 % and a very low MS.

A peat layer (Ha) with a thickness 10 – 50 cm is lying above the cultural material or the gully filling in the central part of the transect. Formation of the peat material can be attributed to the high medieval period after abandonment of the settlement as suggested by the dating results. The degree of plant remains decomposition varies within the layer, in some parts a considerable amount of sand is present. The peat layer is free of any finds, has a low pH 5.1 and contains 42.1 % of organic matter on average and is characterized by very low values of MS.

Above the peat layer, a thick layer of redeposited cultural material from the neighbouring slopes – the colluvium of the cultural layer (M<sub>cult</sub>) – was identified. This layer is more homogeneous than the *in situ* cultural layer due to the redeposition. It also contains artefacts but in a relatively low quantity and of a small size. MS of this material is quite high having a mean value of  $131 \cdot 10^{-8} \text{m}^3 \text{kg}^{-1}$  and pH equals 5.6.

The upper part of this layer was homogenized by ploughing in late medieval and modern times and is involved into modern soil formation (M<sub>cult-hom</sub>). M<sub>cult-hom</sub> has a stone content mostly below 5 %. However, a few exceptions were observed – due to the presence of single large stones. In M<sub>cult-hom</sub> from all cores investigated for this transect, nearly no bones or charcoal were found, whereas artefacts were common. Small fragments of burnt clay and brick material represent the artefacts. In terms of geochemistry, M<sub>cult-hom</sub> is very similar to M<sub>cult</sub>, which is expectable, as it is the same material, which was ploughed in one case. Vertical distribution of magnetic susceptibility and organic matter content is always quite homogeneous in M<sub>cult-hom</sub> with relatively high values of MS  $98.1 \cdot 10^{-8} \text{m}^3 \text{kg}^{-1}$ , which points at the cultural origin of the material. Organic matter content varies in a narrow range around the mean value of 3.7 %.

Often, independently from depth, sand interlayers were identified. For them elevated values of MS and presence of small amounts of charcoal and wood are typical. The organic matter content equals approximately 1 %.

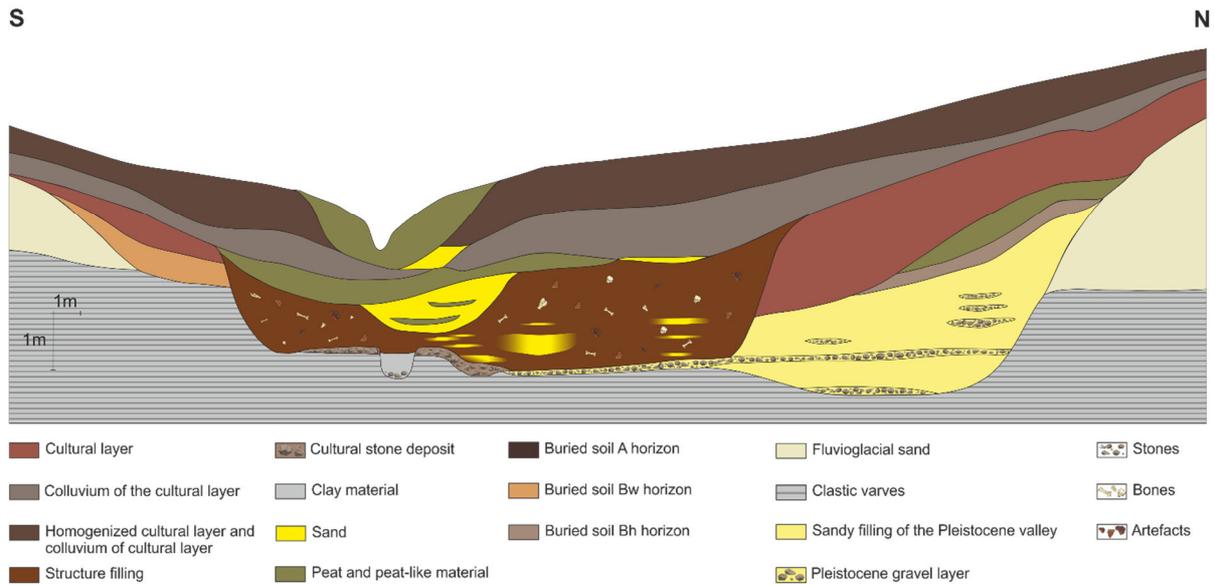


Figure 47. Summarized stratigraphy of sediments in transect 1.

### 5.2.2. DESCRIPTION OF TRANSECT 2

Ten drillings with the Vibracore system were performed to form transect 2 across the Hedeby-brook (Figure 48). Transect 2 is located approximately 60 m east of transect 1 in a flat recent depression in the central part of the settlement where the Hedeby-brook used to turn its flow to the south-east in the Viking Age. This transect also revealed presence of a buried structure with a similar stratigraphy as in transect 1. The width of the structure is smaller than in transect 1 and equals ca. 11 m, while the depth from the modern land surface in the central part is also around 4 m.

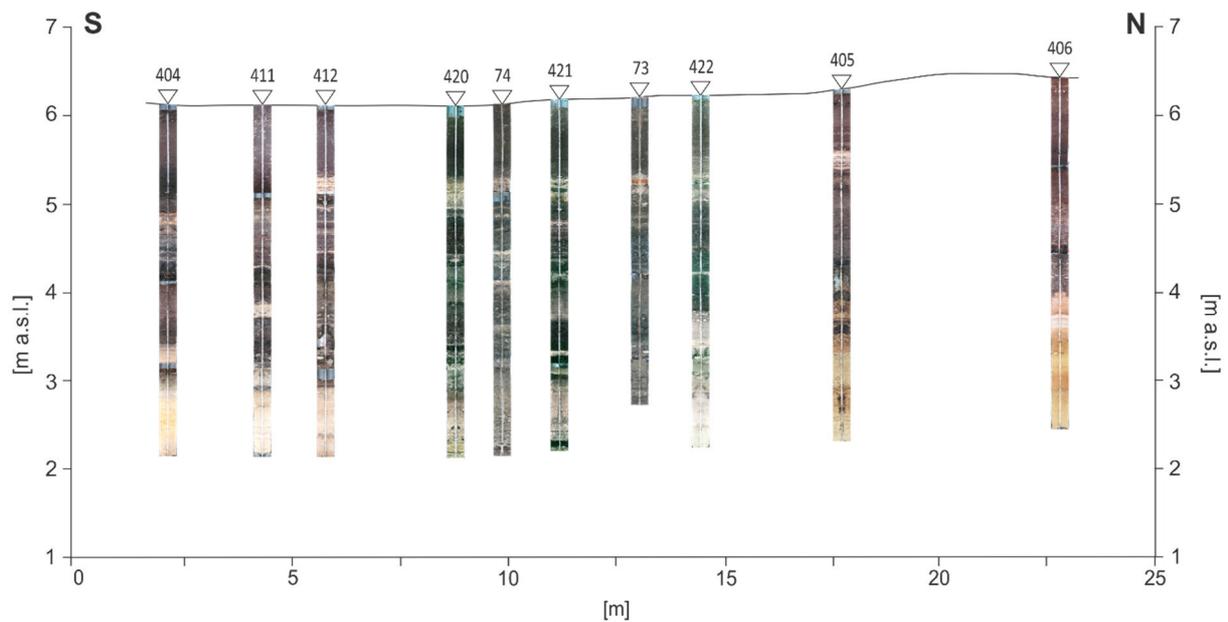


Figure 48. Photographs of drilling cores retrieved in transect 2.

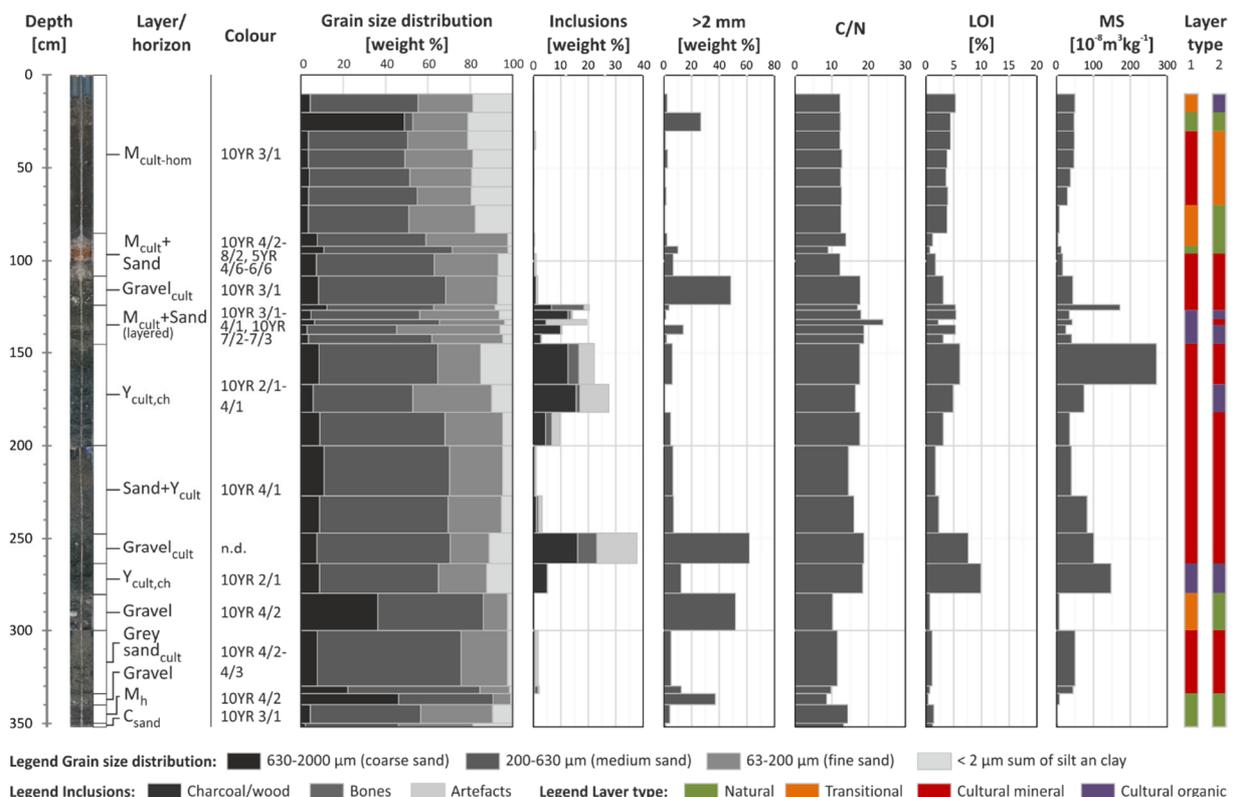
### *Individual cores*

Sediments of two cores (points 73 and 74) located in the central part of transect 2 were analysed in laboratory, involving the determination of the same parameters as in transect 1. XRF measurements were performed for both drilling points.

The distribution of the sediment characteristics in core 73 is shown in Figure 49. Due to technical reasons the drilling was performed to the depth of 3.52 cm. The lowermost 2 cm are represented by well-sorted fluvio-glacial sand that was identical to  $C_{sand}$  deposit identified in other drilling points. This Pleistocene deposit does not contain any anthropogenic inclusions, has a low OM content (1.2 %) and a low MS ( $3.7 \cdot 10^{-8} m^3 kg^{-1}$ ). The first Holocene sediment in the sequence is a dark greyish brown colluvial layer  $M_h$  at 340 – 350 cm, which contains 1.4 % of OM and no anthropogenic features. The gravel layer above it is also free of any anthropogenic inclusions. Using both sets of parameters, the gravel layer, the colluvial layer  $M_h$  and the deposit  $C_{sand}$  were classified as natural deposits. Above, a Grey sand<sub>cult</sub> layer was identified, which contained the first traces of human activities. Bones and artefacts, though in small quantities, were found in the layer, and MS equalled  $44 - 55 \cdot 10^{-8} m^3 kg^{-1}$ . The overlying gravel layer has properties very similar to the gravel layer below. Based on six parameters, it was classified as material with transitional properties, while the classification with ten parameters identified it as a natural deposit. The next sediment package lies between 200 and 280 cm below the recent land surface. It includes  $Y_{cult, ch}$ , Gravel<sub>cult</sub> and Sand+ $Y_{cult}$  and can be referred to as Filling<sub>cult</sub>. The lower part of this deposit contains relatively abundant wood and charcoal fragments, which is accompanied by relatively high values of MS reaching  $147.5 \cdot 10^{-8} m^3 kg^{-1}$ . A sublayer Gravel<sub>cult</sub> can be distinguished in this package at the depth 247 – 264 cm. This gravel layer has a very high content of wood/charcoal as well as bones and artefacts. Also, MS of this material reaches  $101.2 \cdot 10^{-8} m^3 kg^{-1}$ . The upper part of the sediment package considered is dominated by grey sand material with presence of small amounts of wood and charcoal and somewhat lower MS than in the sublayers below, which, however, lies in the range above natural limits.

The next large stratigraphic unit that can be distinguished is the OM-rich Filling<sub>cult, org(layered)</sub> at a depth of 124 – 200 cm, which is finely layered and includes layers  $Y_{cult, ch}$  and  $Y_{cult} + Sand_{(layered)}$ . It is characterized by the presence of large amounts of charcoal/wood and artefacts throughout the whole layer (2.7 – 12.6 %) as well as relatively high OM content from 2.2 to 6.1 %. Within this layer, the highest MS values were measured for this core ( $270.8 \cdot 10^{-8} m^3 kg^{-1}$ ). Above the layered OM-rich filling, another layer of cultural gravel was found at a depth of 108 – 124 cm. However, this gravel layer contains a considerably smaller quantity of anthropogenic inclusions and its MS equals  $44 \cdot 10^{-8} m^3 kg^{-1}$ . Nevertheless, this material was classified as a cultural deposit due to the elevated contents of P and Pb. The following sediment represents a mixture of the colluvium of

the cultural layer  $M_{cult}$  with sand Mix:  $M_{cult}+Sand$ . This layer, which is not present in any of the cores of transect 1, was found in all cores of transect 2 except the most southern and most northern points that lie outside of the structure. It contains small quantities of artefacts and rather low MS and OM content. Due to the presence of a large content of sterile sand, this deposit was classified as natural material when ten parameters were used for classifying. On the contrary, the  $M_{cult-hom}$  layer above is characterized by moderate values of OM content uniformly distributed throughout the layer from 10 to 85 cm below the recent land surface. The same situation can be observed for MS. It varies in a narrow range between 29.6 and 49.8  $10^{-8}m^3kg^{-1}$ . As it is the case in cores of transect 1, among anthropogenic features only low quantities of artefacts are present in  $M_{cult-hom}$ . Samples from the upper 30 cm of  $M_{cult-hom}$  were classified as transitional, cultural organic and natural materials.



**Figure 49. Geo-ecological properties of the sediments of core 73. Layer type column 1: clusters obtained with 6 parameters, layer type column 2: clusters obtained with 10 parameters.**

The same set of elements as for point 198 of transect 1 was analysed for core 73 (Figure 50). In general, the concentration of P lies below 2000 ppm for most parts of the profile. The first increase in relation to the sterile layers at the basis of the sequence is observed at a depth 300 – 330 cm in the Grey sand<sub>cult</sub> layer. Pb and Ca show the first elevated concentration levels in this layer, too. The next prominent increase in P concentration was found at a depth of 247 – 280 cm in the lower part of the cultural filling. Whereas Ca and Zn have an increase at this depth too, concentration of Pb remains at a very low level. However, the next high content of Pb was registered at a depth of

200 – 227 cm, at which other element contents did not change correspondingly. The next distribution peak is shared by all elements considered and lies at a depth of 135 – 157 cm in the OM-rich filling. Here, the concentration of Pb equals 1312 ppm and concentration of P reaches 3558 ppm. It has to be noted that this layer is the one with the highest MS peak in the profile and a large content of anthropogenic inclusions. However, the highest concentrations of all four elements considered were observed in the same unit but at a smaller depth of 124 – 127 cm. This material contains a very high content of bones and also includes wood/charcoal and artefacts. In the upper part of the profile in  $M_{\text{cult-hom}}$  layer, the values of the elements vary slightly between 1300 and 1900 ppm for P and between 0.6 and 0.7 % for Ca, decreasing with depth for both elements. Similar patterns can be pointed out for Pb and Zn.

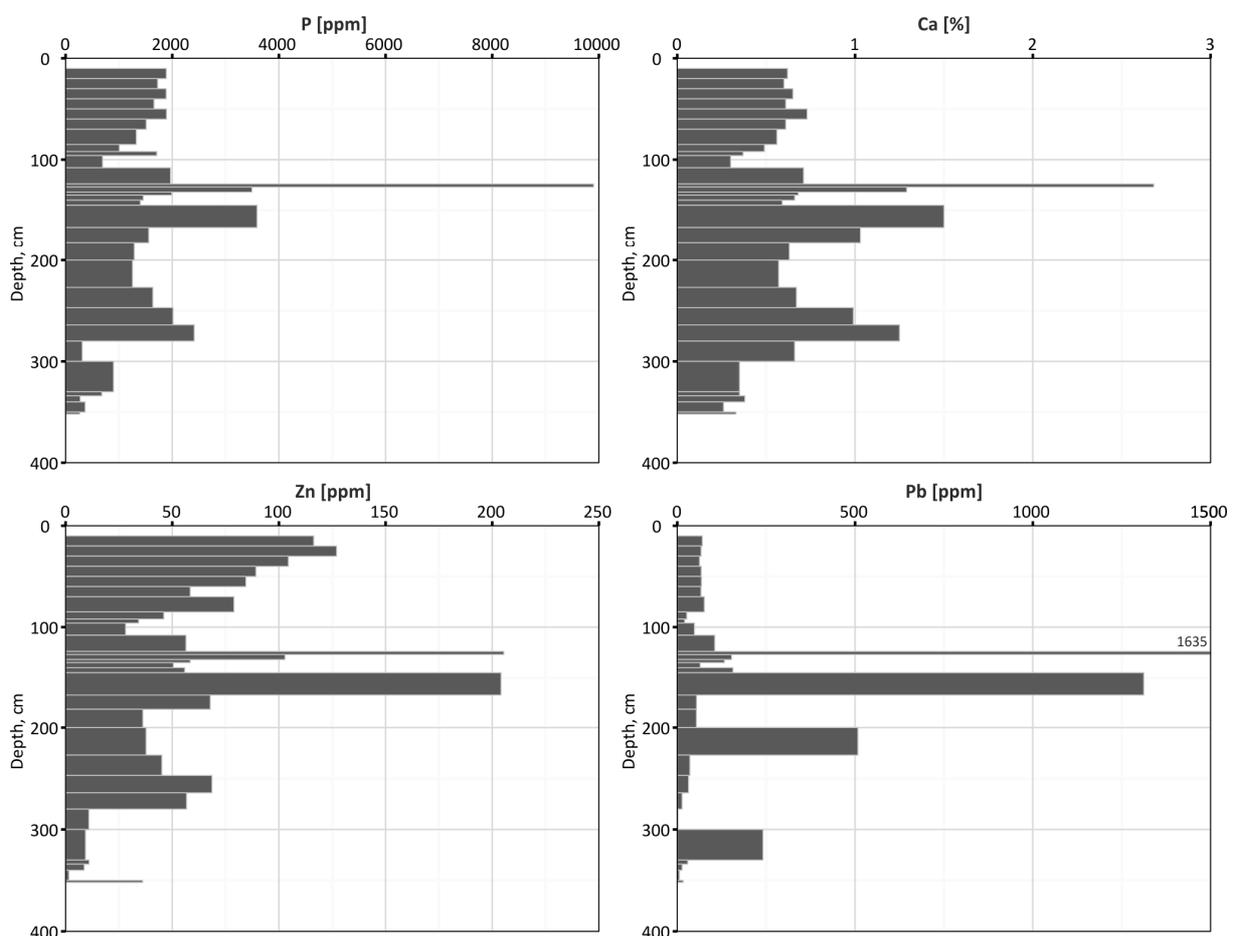


Figure 50. Profile distribution of selected elements in the drilling core 73.

Therefore, the stratigraphy of core 73 can be summarized in the following way (independently from transect 1):

<b>X</b>	0-85 cm	Ploughed colluvium of the cultural layer
<b>IX</b>	85-108 cm	Mixture of colluvium of the reworked cultural layer with sand
<b>VIII</b>	108-124 cm	Cultural gravel layer
<b>VII</b>	124-200 cm	OM-rich cultural filling with a moderate to high charcoal/wood content, high MS and all elements with extreme peaks

<b>VI</b>	200-280 cm	Cultural filling with a high MS, high content of charcoal/wood, bones, artefacts and the elements considered
<b>V</b>	280-300 cm	Natural gravel layer
<b>IV</b>	300-334 cm	Cultural grey sand with anthropogenic features
<b>III</b>	334-340 cm	Natural gravel layer
<b>II</b>	340-350 cm	Colluvial layer
<b>I</b>	350-352 cm	Fine grained Pleistocene deposit

Drilling point 74 was located 3 m southeast of point 73. Although the basis of this sequence is 50 cm deeper than in point 73, the lowermost layer  $M_h$  is identical to the one found at the basis in profile 73 in terms of morphology and properties analysed (Figure 51). The layer overlying  $M_h$  is very different from the one identified in point 73. In point 73 it was a natural gravel layer, whereas here it is a cultural stone deposit  $Gravel_{cult}$  with high MS ( $81.1 \cdot 10^{-8}m^3kg^{-1}$ ) and with presence of considerable amounts of bones and artefacts. The next unit is a relatively coarse Grey sand $_{cult}$ +Gravel layer with abundant stones, high MS and the presence of anthropogenic features, dominated by bones and artefacts. The next layer package is quite unique. It lies between 184 and 288 cm below the recent land surface and includes  $Y_{cult,ch}$ ,  $Gravel_{cult}$ , Sand+ $Y_{cult}$  and  $Y_{cult}$ +Gravel. In general, it represents the cultural filling, however, with very abundant stones in this sequence and the highest concentration of bones determined for all drilling cores studied so far. The bones are present nearly throughout the whole layer; their concentration varies between 2.5 and 7.6 %. Artefacts and wood/charcoal fragments are common in this sediment package too. The peaks of MS reaching values of 219.6 and 289.4  $10^{-8}m^3kg^{-1}$  seem to be associated with the coarse fraction. The next package is the OM-rich filling, which is finely layered in this core and includes layers  $Y_{cult,ch}$  and Sand+ $Y_{cult(layered)}$ . Here, MS is very low (varying from 8.0 to 26.2  $10^{-8}m^3kg^{-1}$ ) as is the content of the > 2 mm fraction (a peak at a depth of 140 – 150 cm was caused by a single large stone). No bones are present and, on the contrary, charcoal and wood are found in amounts up to 9.6 %, which is very high taking into account the very small weight of wood and charcoal in comparison to bones and artefacts. The OM content of this layer is in general also higher than in the sediments below. The next layer represents a mixture of cultural layer colluvium with sand. It corresponds to unit IX in point 73. The properties of these units in both cores are very similar: low MS, heterogeneous OM distribution within the layer as well as absence of anthropogenic inclusions. In the  $M_{cult-hom}$  layer above. As expected, the content of OM as well as MS are very homogeneous and vary in narrow ranges: from 3.8 to 6.4 % for OM content and from 31.2 to 78.1  $10^{-8}m^3kg^{-1}$  for MS. The results of the classification are consistent with each other; however, some differences have to be pointed out. While in the lower part of the sequence the results match exactly, the OM-rich cultural filling was classified as cultural mineral material, when ten parameters were used. Also, as it was the case at point 73, the mixture of the colluvial cultural layer with sand was classified as natural material, when ten parameters were used.

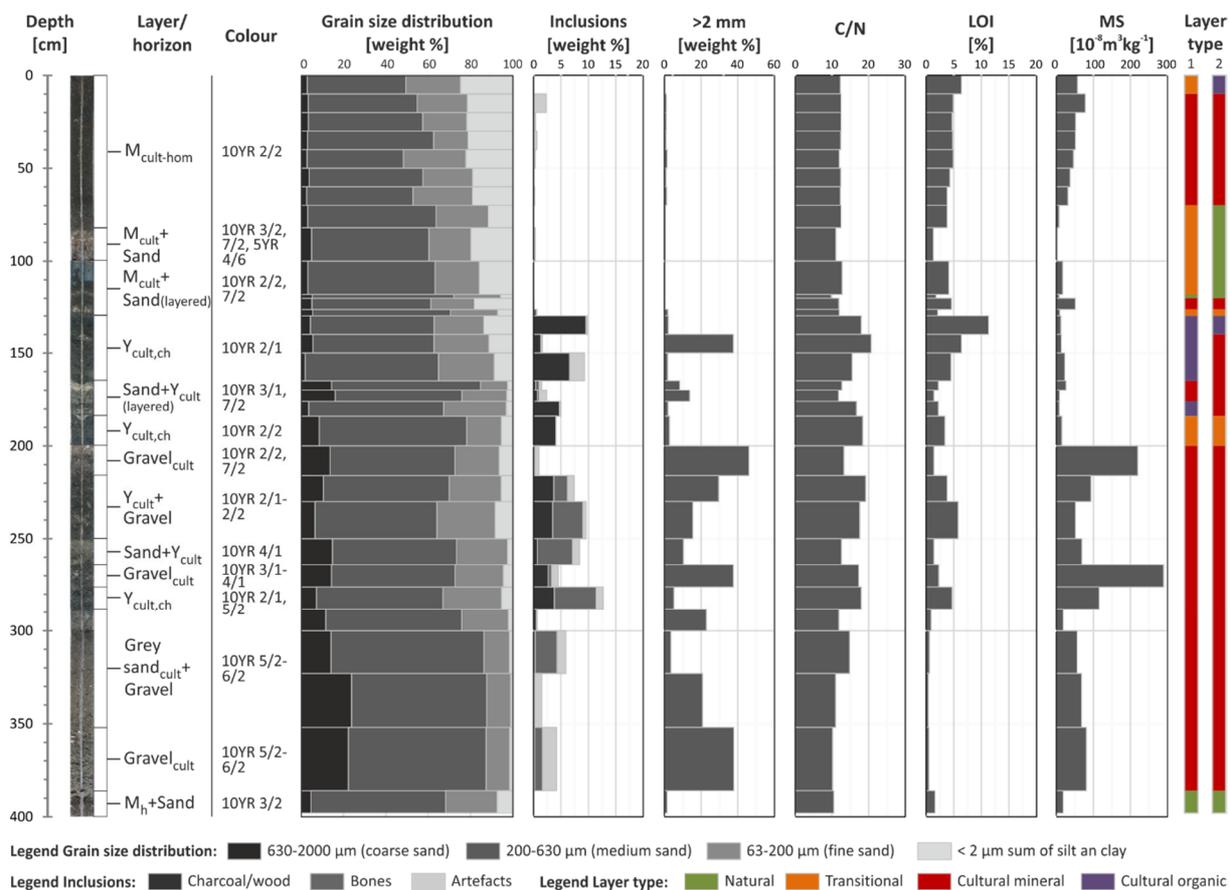


Figure 51. Geo-ecological properties of the sediments of core 74. Layer type column 1: clusters obtained with 6 parameters, layer type column 2: clusters obtained with 10 parameters.

The results of XRF analysis are in agreement with the parameters described previously pointing at the layer at the bottom being not directly affected by human activities. All elements have content values within natural limits. The cultural gravel layer located above the  $M_h$  layer is characterized by sharp increases in the concentrations of the elements considered, particularly of Pb (222.7 ppm). The following Grey sand<sub>cult</sub> layer has somewhat higher than natural concentrations of Pb and Zn, while P and Ca are close to the values in  $M_h$ . The cultural filling on top of it has prominent anthropogenic signatures in element distributions, as it is shown in Figure 52. It has to be noted that the highest MS peak observed in this layer is not accompanied by respectively large contents of Pb or Zn. On the contrary, the OM-rich cultural filling with a very low MS lying above is characterized by extremely high concentrations of the elements considered at a depth of 130 – 150 cm: 3142.6 ppm for P, 1.4 % for Ca, 222.7 ppm for Pb and 143.8 ppm for Zn. In the next layer, the mixture of  $M_{cult}$  with sand, a decrease in all element concentrations is observed, while in  $M_{cult-hom}$  higher values varying in narrow ranges were determined.

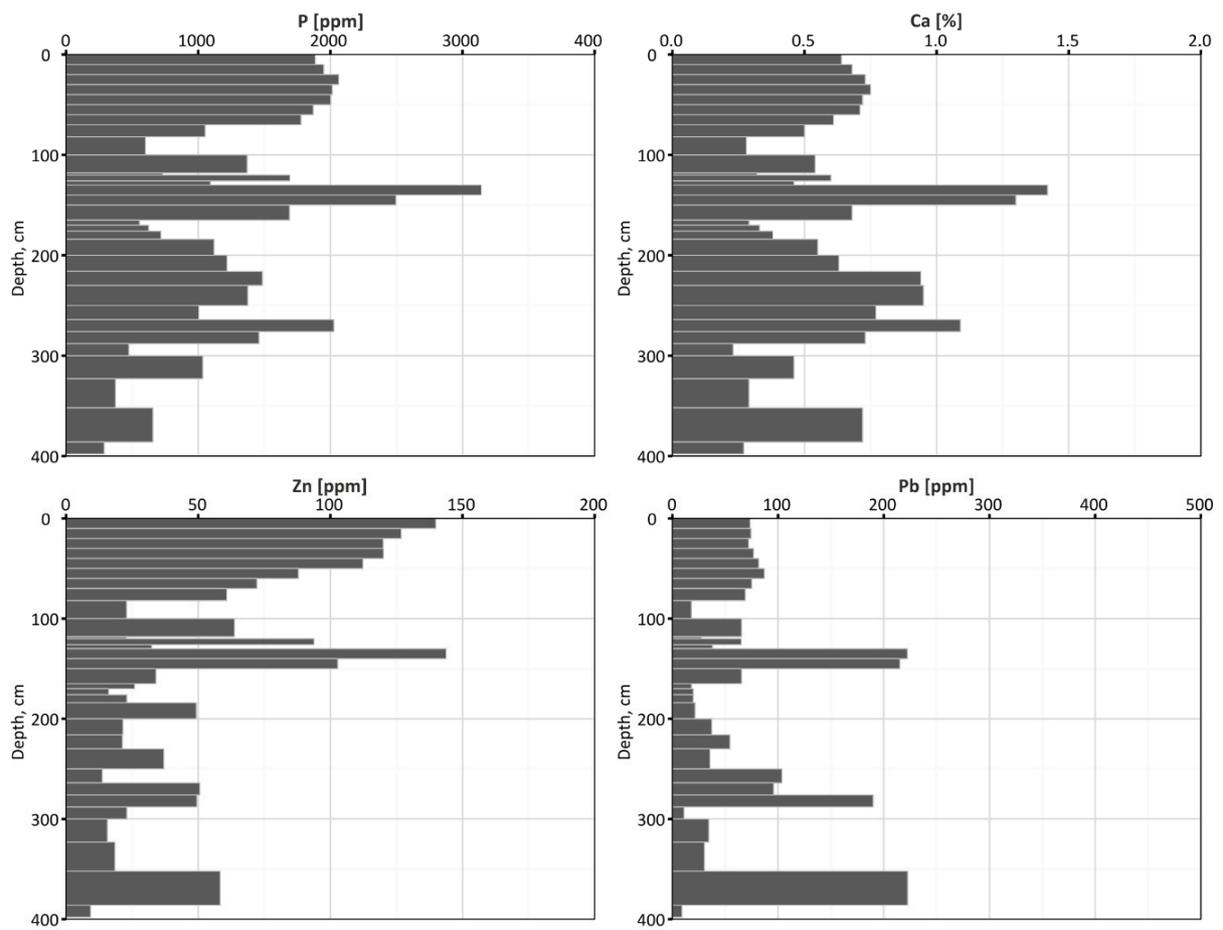


Figure 52. Profile distribution of selected elements in the drilling core 74.

Taking into account the presence of archaeological material and that the stratigraphy of transect 2 is similar to transect 1, no radiocarbon dating was performed for the sediments in transect 2. The summarized stratigraphy of core 74 is given below and in Figure 53 together with other cores in this transect (\* indicates a difference in the unit properties in comparison to the previous core).

<b>X</b>	0-82 cm	Ploughed colluvium of the cultural layer
<b>IX</b>	82-130 cm	Mixture of colluvium of the reworked cultural layer with sand
<b>VII*</b>	130-200 cm	Layered cultural filling with a medium to high content of OM and charcoal/wood and a low MS
<b>VI*</b>	200-300 cm	Very coarse cultural filling with a high MS and very abundant bones
<b>IV</b>	300-352 cm	Cultural grey sand with gravel
<b>III*</b>	352-386 cm	Cultural gravel layer
<b>II</b>	386-400 cm	Colluvial layer

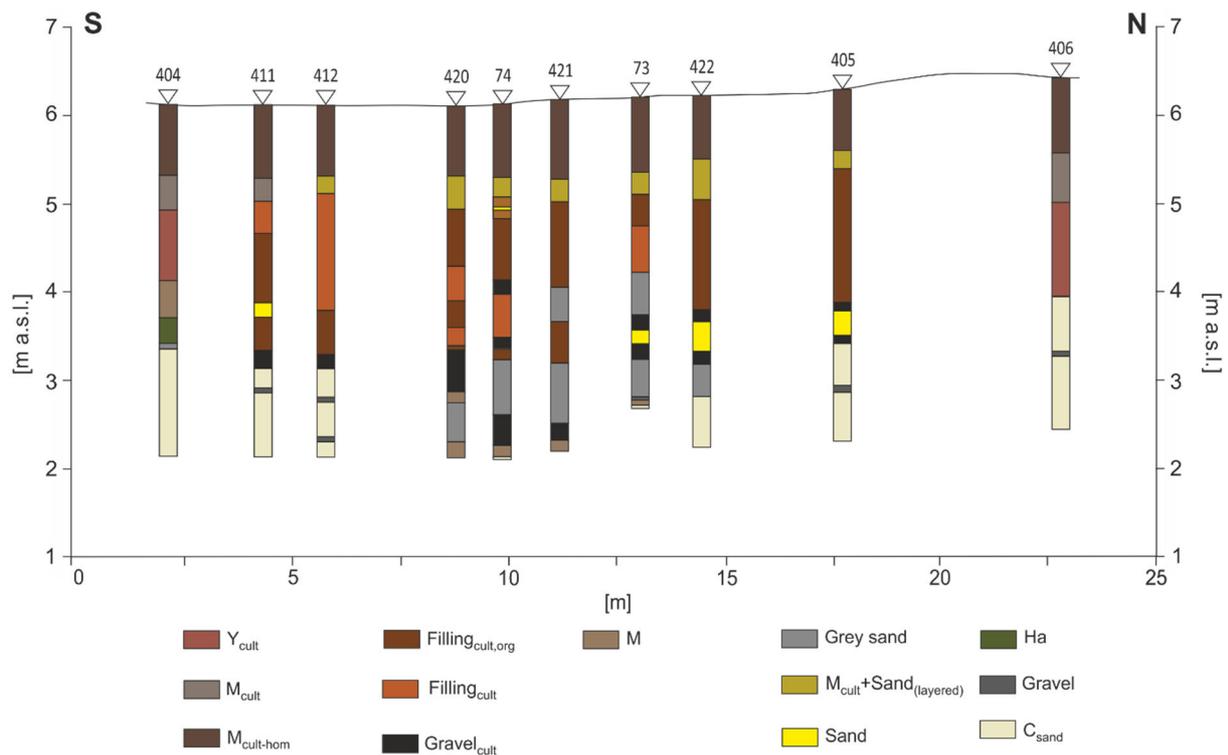


Figure 53. Scheme of stratigraphic sequences in the sediment cores of transect 2.

### General stratigraphy of sediments in transect 2

Following the same procedure that was undertaken for transect 1, based on the geo-ecological data obtained for the two cores and taking into account the classification results, the general stratigraphy and geo-ecological description of the filling of the structure based on mean values was compiled (Table 10).

Table 10. Geo-ecological characteristics of the sediments in the structure (transect 2).

Layer	>2mm (%)		CH/wood (%)		Bones (%)		Artefacts (%)		LOI (%)		MS (10 <sup>-8</sup> m <sup>3</sup> kg <sup>-1</sup> )		pH
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
M <sub>cult-hom</sub>	1.3	0.6	0.0	0.0	0.0	0.0	0.4	0.6	4.6	0.8	47.2	12.4	5.2
Sand+ M <sub>cult(layered)</sub>	1.0	0.7	0.0	0.0	0.0	0.0	0.3	0.4	2.1	1.4	10.1	6.2	5.2
Filling <sub>cult</sub>	4.1	2.6	5.0	5.6	4.3	3.8	3.3	3.1	3.7	1.7	105.5	79.6	5.8
Filling <sub>cult,org</sub>	4.8	5.2	6.7	3.3	0.1	0.1	0.5	0.9	6.1	3.2	27.6	12.1	4.5
Sand	1.2	1.0	0.0	0.0	0.3	0.4	0.0	0.0	1.9	0.2	8.4	1.3	n.d.
Grey sand <sub>cult</sub>	6.2	0.9	0.6	0.4	0.9	0.4	0.8	0.4	1.5	0.7	54.6	19.4	n.d.
M <sub>h</sub>	2.3	1.7	0.0	0.0	0.0	0.0	0.0	0.0	1.4	0.2	8.2	8.9	5.3
Gravel <sub>cult</sub>	38.1	12.9	1.9	1.3	1.5	2.4	1.0	0.8	1.8	1.3	142.2	90.5	6.3
Gravel	44.5	10.2	0.1	0.1	0.1	0.1	0.0	0.0	0.6	0.2	7.5	0.7	n.d.

The basis of the structure identified in this transect is represented by fluvio-glacial Pleistocene sand C<sub>sand</sub> (Figure 54). On the northern and southern ends of the transect (points 404 and 406), a heterogeneous cultural layer (Y<sub>cult</sub>) formed *in situ* was found. Y<sub>cult</sub> contained abundant burnt loam

and brick fragments as well as numerous charcoal pieces. In the southern part of transect 2 (point 404), the stratigraphic sequence is very similar to the one in point 406 with some differences in the lower part of the profile. There, a 29 cm thick layer of peat Ha was identified above the Pleistocene deposits with a colluvial layer M between the peat and the cultural layer. A similar dark brown colluvial layer  $M_h$  was found in the central part of the transect at the basis of the sequence. It has an OM content of 1.4 % in average and is characterized by the absence of any anthropogenic features. The pH of this material equals 5.3.

Above the  $M_h$  layer in the centre of the structure, either grey sand with relatively abundant anthropogenic features (Grey sand<sub>cult</sub>) or a cultural gravel layer (Gravel<sub>cult</sub>) with presence of artefacts, bones, wood and charcoal were found. The grey sand layers in transect 2 are very different from those in transect 1. Here, the material is coarser with 6.2 % of stones and it contains bones and artefacts, which were absent in transect 1. Moreover, MS of grey sand in transect 2 has values above the natural level equalling  $54.6 \cdot 10^{-8} \text{m}^3 \text{kg}^{-1}$ . In comparison to transect 1, Gravel<sub>cult</sub> in transect 2 contains larger amounts of charcoal/wood, bones and artefacts, and the OM content is higher here, too. Nevertheless, MS of this layer in transect 2, being very high  $142.2 \cdot 10^{-8} \text{m}^3 \text{kg}^{-1}$ , is more than twice lower than in transect 1. pH of the cultural stone deposit is slightly acidic. The natural gravel layer (Gravel) was found in the form of thin bands at a few points in the transect. It has a somewhat larger content of stones, the same OM content and a lower MS than in transect 1.

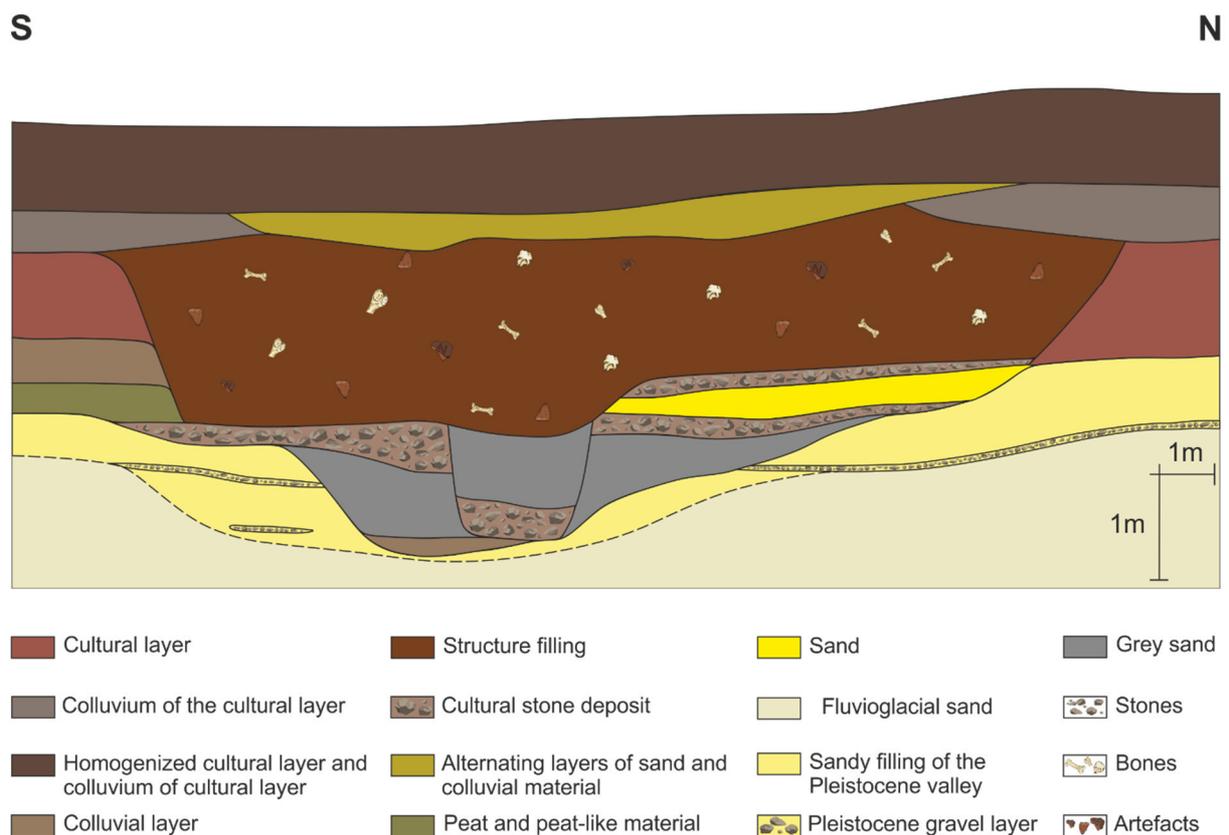
In the central part of the structure, heterogeneous cultural sediments sometimes interrupted with sand layers were found above the gravel. As it is the case in transect 1, two types of the cultural filling could be distinguished. They differ mainly in the content of organic matter.

The first type Filling<sub>cult</sub> has intermediate values of OM content (3.7 %) and high values of MS ( $105.5 \cdot 10^{-8} \text{m}^3 \text{kg}^{-1}$ ); the material is moderately acidic with pH 5.8. This sediment is also very rich in wood/charcoal, bones and various artefacts that include pottery sherds, leather pieces, slag fragments etc. Compared to transect 1, the characteristics are quite similar as long as OM content and MS are concerned, although, MS varies here in a wider range. In transect 2 more wood, charcoal and artefacts are present, but the content of bones and stones is generally higher in transect 1, although a few cultural layers with a high content of stones were found in transect 2. The thickness of Filling<sub>cult</sub> varies between 20 and 100 cm. Also, the cultural filling was finely layered in points 74, 422, 412 and 411.

The second type of cultural deposits is represented by the OM-rich Filling<sub>cult,org</sub>, with 6.1 % of OM on average and a pH 4.5 – indicating strongly acidic conditions. The thickness of the OM-rich sediments varies between 15 and ca. 150 cm. This filling type has less bones and artefacts but more charcoal/wood material embedded. Filling<sub>cult,org</sub> has a somewhat lower content of OM and bones, but a higher MS and charcoal/wood content in comparison to transect 1.

These cultural sediments were overlain by a sediment representing thin layered sand and OM-rich (colluvial) material – Sand+  $M_{\text{cult}(\text{layered})}$  that was not found in transect 1. It contains a small amount of artefacts and its MS is low ( $10.1 \cdot 10^{-8} \text{m}^3 \text{kg}^{-1}$ ), which is probably related to the presence of sterile sand in the sediment. The pH of this layered deposit equals 5.2. Above it, redeposited cultural material  $M_{\text{cult-hom}}$  was located. The uppermost layer, as well as in transect 1, was represented by the homogeneous  $M_{\text{cult-hom}}$  layer, representing ploughed cultural layer or its colluvium on slopes and accumulative positions as it is the case in transect 1. Similarly to transect 1, the homogenized cultural layer  $M_{\text{cult-hom}}$  is characterized by the absence of wood/charcoal and bones and by the presence of moderate amounts of artefacts. In contrast to transect 1, MS is relatively low here and equals  $47.2 \cdot 10^{-8} \text{m}^3 \text{kg}^{-1}$  on average. The stone content is lower too and equals 1.3 %.

Sand interlayers presented in transect 2 are similar to those in transect 1 in terms of texture and anthropogenic features as well as OM content; however, the MS of sandy layers in transect 2 are very low ( $8.4 \cdot 10^{-8} \text{m}^3 \text{kg}^{-1}$ ).



**Figure 54. Summarized stratigraphy of sediments in transect 2.**

### 5.2.3. DESCRIPTION OF TRANSECT 3

Another series of drillings forming transect 3 was performed 40 m east of transect 2 to find out whether the structure continues to the east in the direction of Haddebyer Noor. In this area, seven drillings were executed and only two of them pointed at the presence of a deep structure. However, both drilling points were located in the longitudinal profile of the brook (it turns slightly in the area of points 311 and 424). Therefore, a presence of the wide structure east of the road cannot be confirmed. Descriptions of the drilling points in this transect can be found in the appendix 6.

### 5.2.4. DESCRIPTION OF THE LONGITUDINAL PROFILE

The longitudinal profile is comprised of ten drillings along the former course of Hedeby-brook (Figure 55). The distances between the drillings are between 30 and 40 m. In a few cases, the distances are larger and equal 76 m at maximum. The gradient of the recent land surface is prominent, at the highest drilling point 1406 elevation equals 10.5 m a. s. l. and at the lowest drilling point of the profile 270 it amounts to 3.6 m a. s. l.

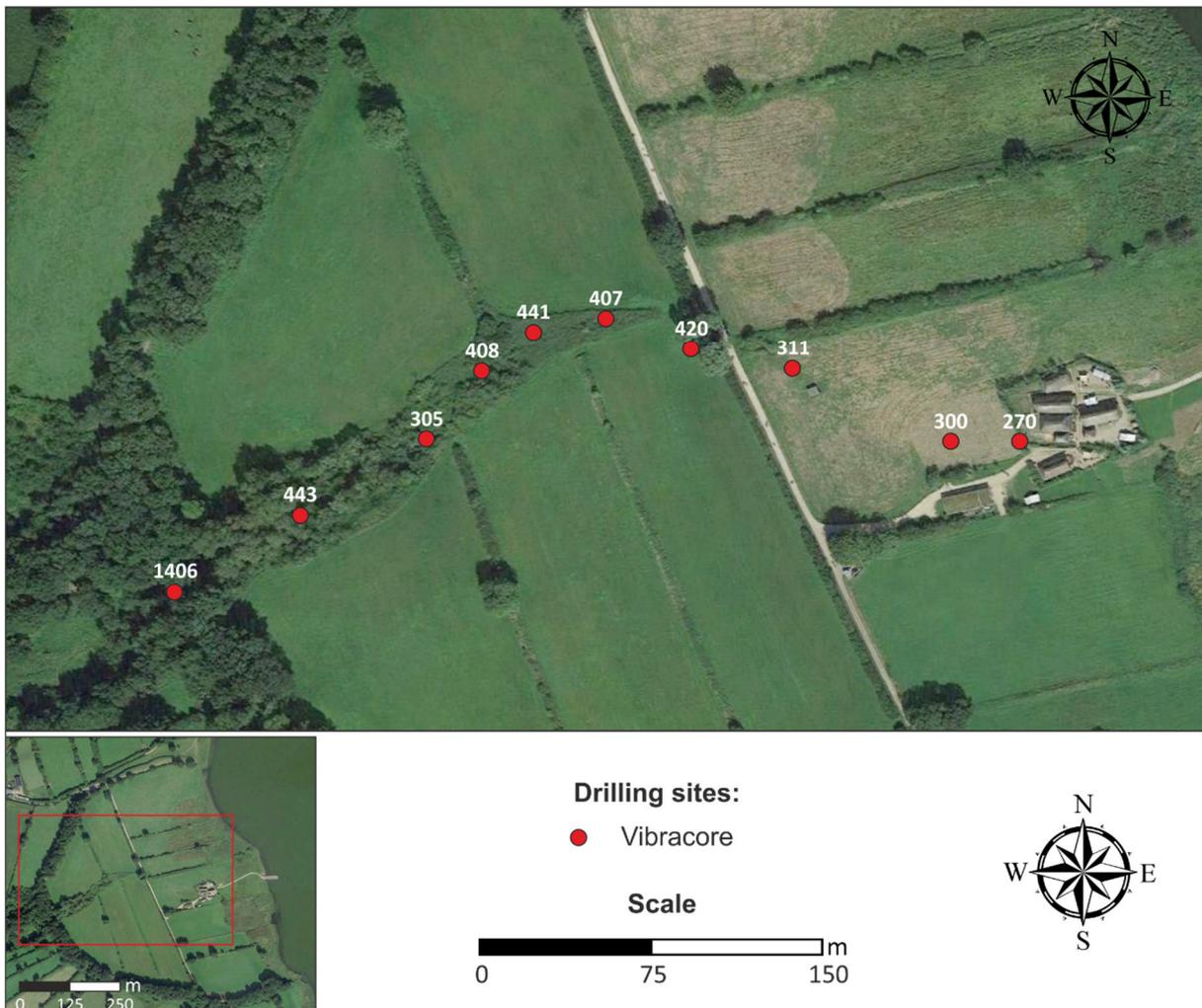


Figure 55. Location of drilling sites in the longitudinal profile.

Two groups of points have to be distinguished: points west of the road Kirchweg (420, 407, 441, 408, 305, 443), where the wide filled structure was discovered, and points east of the road (311, 300, 270), where a narrow brook was present. At point 1406, a core was retrieved in the modern brook bed in the opening of the half-circle wall. In total four drilling cores from the longitudinal profile were analysed by laboratory methods: 441, 311, 300 and 270. The description of the sequence in core 441 is given in the section 5.2.1. devoted to transect 1. For the other points, the same set of parameters was determined: content of stones, charcoal/wood, bones, artefacts and organic matter as well as magnetic susceptibility. Additionally, XRF measurements were performed for sediments at point 270.

### *Individual cores*

The core retrieved at drilling point 311 revealed a 4 m deep sequence with a gravel layer at the basis. The content of stones in the gravel layer reaches 71.5 %, and all other parameters measured have very low values and no anthropogenic features could be found in the layer (Figure 56). The gravel layer was classified as a natural deposit. Above the sterile gravel layer, the first sediment package with cultural layers is located at a depth of 300 – 390 cm. It includes an alternation of pale brown sand and darker brown H sublayers containing charcoal/wood fragments and artefacts including a relatively large pottery sherd (3 cm in diameter). Higher in the profile at a depth of 185 – 300 cm wood-rich layers were discovered with small amounts of stones, moderate values of LOI and wood/charcoal content reaching 13 %. Due to the wood/charcoal being the only inclusion in these deposits, they were classified as materials with transitional properties. Further up the profile, a thick peaty layer was found at a depth of 135 – 185 cm with an OM content up to 30.4 % and with a presence of small amounts of charcoal/wood. Above the organic-rich layer, colluvium of the cultural layer partly mixed with sand is located. It is free of any anthropogenic inclusions but it has an elevated MS ( $35.0 \cdot 10^{-8} \text{m}^3 \text{kg}^{-1}$ ) in comparison to the underlying materials. It should be noted that nearly no bones and only very few artefacts were found in this sequence. In comparison to the cores in transects 1 and 2 west of the road, anthropogenic signals are much less pronounced.

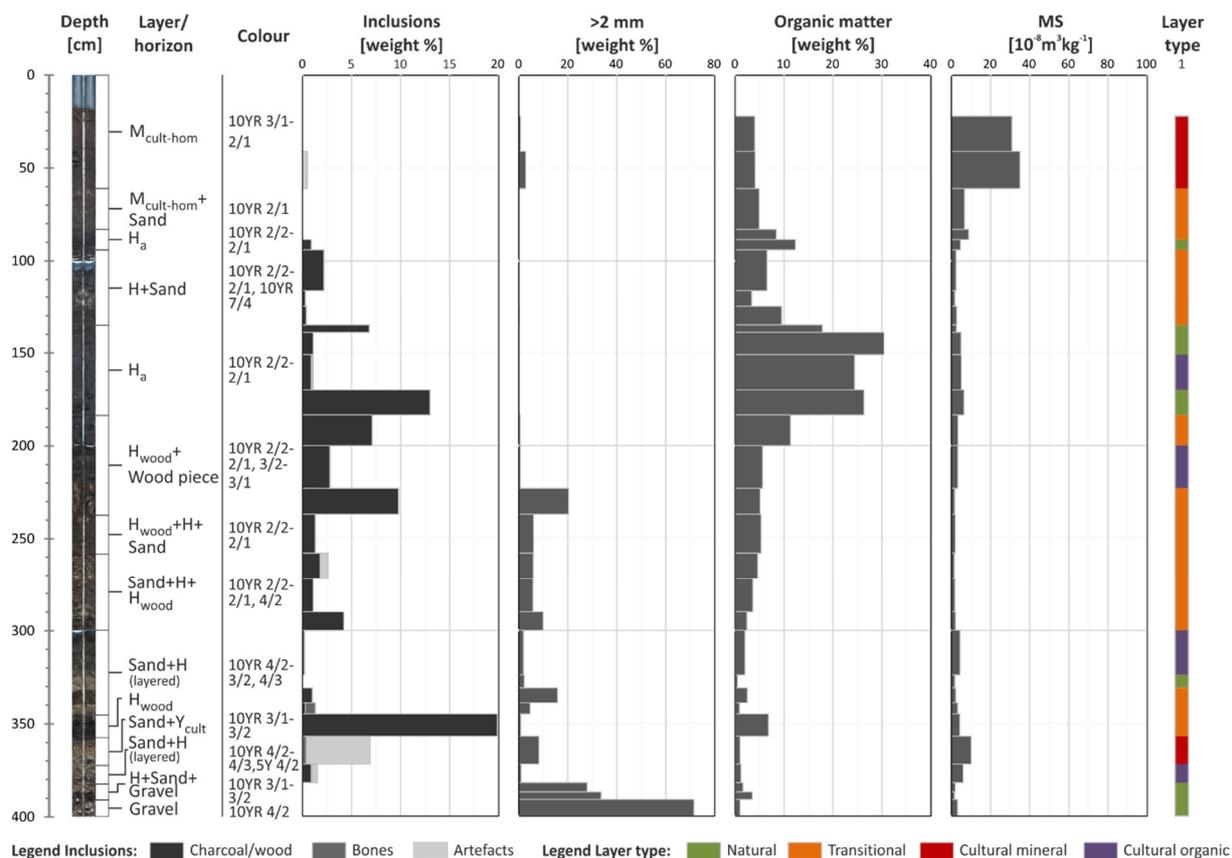


Figure 56. Geo-ecological properties of the sediments of core 311. Layer type column 1: clusters obtained with 6 parameters.

The next core analysed is the drilling point 300. Here, also a gravel layer was found at the basis overlying a varved Pleistocene deposit  $C_{layered}$ . Unlike most of the cores described previously, this is not the only gravel layer in the sequence. Multiple gravel layers, partly cultural gravel layers, are present in the lower part of the sequence below the depth of 250 cm. The first anthropogenic features appear at the depth of ca. 300 cm as indicated by the presence of artefacts as well as elevated values of MS (Figure 57), although the sand layer at 300 – 350 cm below the recent land surface was classified as a cultural deposit. In the sediment package at a depth of 250 – 300 cm, three cultural gravel layers separated by sandy sublayers can be distinguished. At a depth of 200 – 250 cm, heterogeneous cultural sediments are located with high MS reaching  $106.7 \cdot 10^{-8} \text{m}^3 \text{kg}^{-1}$  and with presence of bones and artefacts. Further up the profile at a depth of 125 – 200 cm, a heterogeneous wood-rich deposit was found with charcoal/wood content exceeding 40 % and bone content up to 22 %, while MS is relatively low in this part of the profile. This deposit was classified as cultural organic material. Above, a colluvium consisting of reworked material of the cultural layer mixed with sand is located with a MS ca.  $130 \cdot 10^{-8} \text{m}^3 \text{kg}^{-1}$  between 93 and 126 cm depth. In the uppermost layers, MS is low, whereas the OM content varies between 10 and 20 %. Also, considerable amounts of wood and charcoal were found in this part of the profile. Due to this, this material fell into the group of cultural organic deposits.

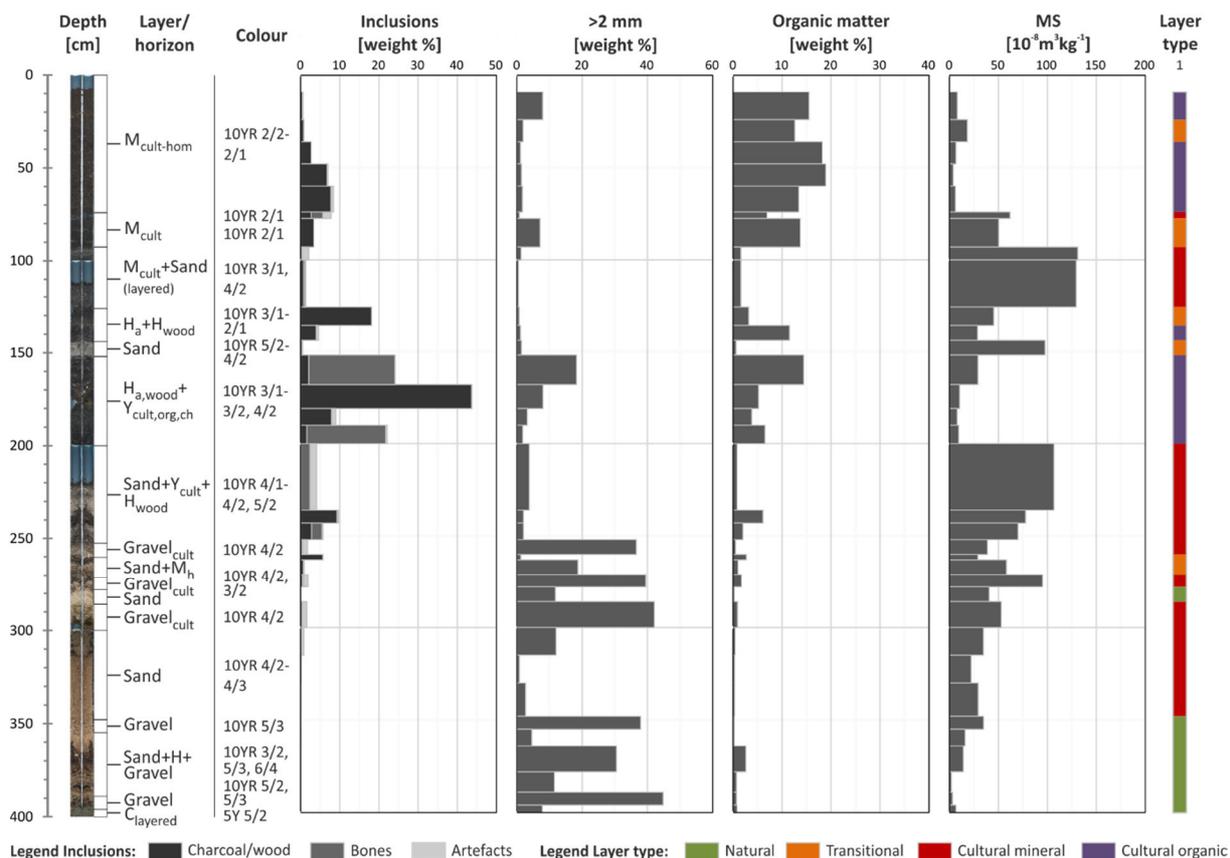


Figure 57. Geo-ecological properties of the sediments of core 300. Layer type column 1: clusters obtained with 6 parameters.

Drilling point 270 was located 30 m to the east of point 300 near the reconstructed Viking houses. The Holocene sequence here is at least 4 m deep (Figure 58). The greyish brown sand deposit located at the bottom has a very low OM content (0.3 – 1.1 %) but it contains inclusions of artefacts (pottery) and bones as well as elevated MS 22.8 – 37.0  $10^{-8} \text{m}^3 \text{kg}^{-1}$ , which is somewhat higher than in Pleistocene deposits. This suggests that Pleistocene deposits were not reached in this core. Above this sand deposit, a gravel layer was identified at a depth of 328 – 341 cm, which does not contain any anthropogenic inclusions but nevertheless has a relatively high MS of 49.4  $10^{-8} \text{m}^3 \text{kg}^{-1}$ . The following sediment is sterile; it has a very low MS and only very small amounts of charcoal present. The following layer (248 – 282 cm below the recent land surface), on the contrary, is characterized by a pronounced cultural signature as reflected by the presence of artefacts, bones and wood/charcoal up to 5.9 % as well as a MS with highest values of 48.4 and 74.9  $10^{-8} \text{m}^3 \text{kg}^{-1}$ . This heterogeneous deposit is overlain by a 10 cm thick homogeneous fine sand layer without anthropogenic inclusions and with an intermediate value of MS (17.7  $10^{-8} \text{m}^3 \text{kg}^{-1}$ ). On top of the fine sand layer, a wood fragment occupying the whole width of the core was found followed by a coarse cultural sediment package at a depth of 164 – 223 cm marked with a high content of bones, presence of gravel and relatively high MS. At a depth of 70 – 130 cm sandy cultural layers are located with a low organic matter content, abundant bones, but, in contrast to the underlying

material, a low MS. The next layer is represented by peaty material with a content of 21.2 % of OM, overlain by the colluvium of reworked cultural material featured by relatively high MS varying between 23.4 and 35.3  $10^{-8}m^3kg^{-1}$ .

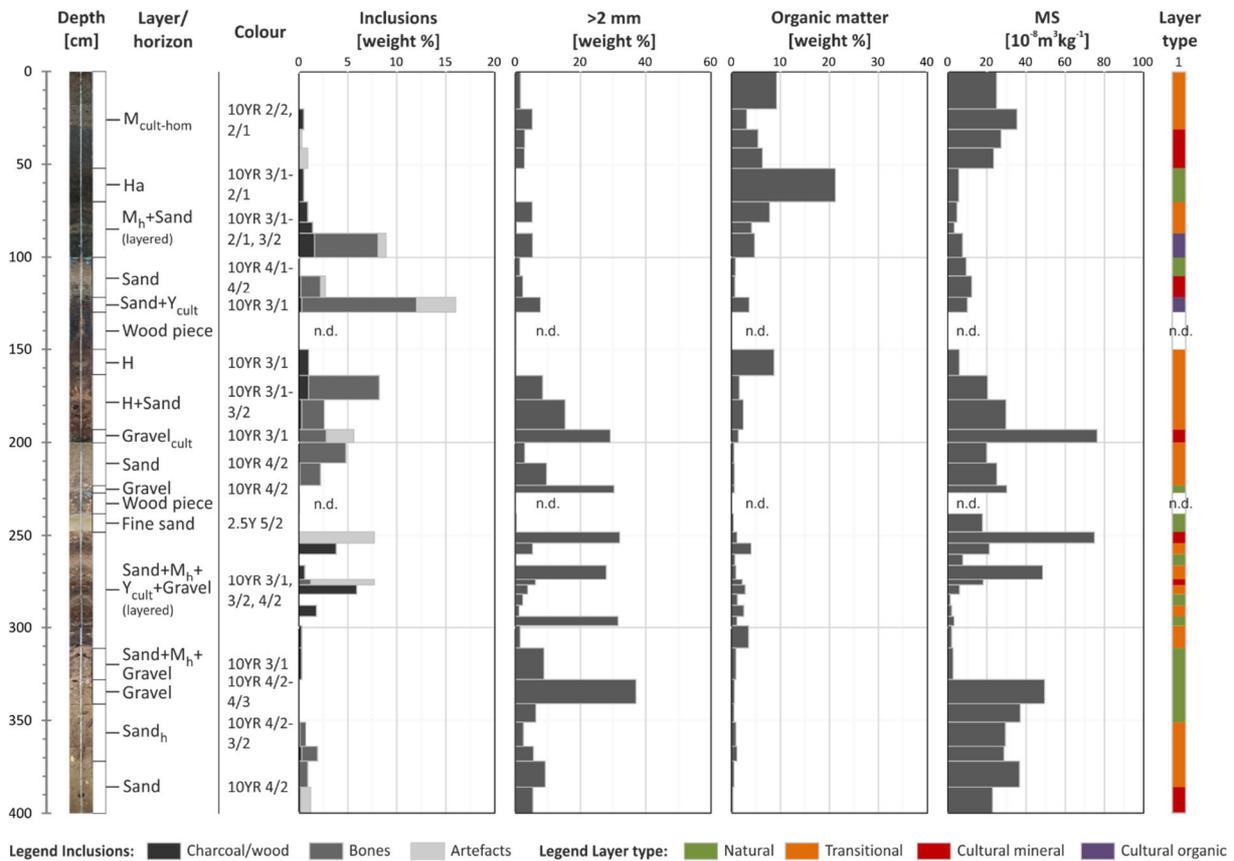


Figure 58. Geo-ecological properties of the sediments of core 270. Layer type column 1: clusters obtained with 6 parameters.

For the sequence in point 270 XRF measurements were performed. The contents of Zn and Pb, which are informative for the cores analysed in transects 1 and 2, were either below detection limit or so low that the measurement error exceeded 10 %. Therefore, only P and Ca were considered for core 270 (Figure 59). Lowest contents of P and Ca were found in the lower part of the profile with a first high peak at 274 – 277 cm depth, at which artefacts and bones were also found. In the distribution of Ca, a weak trend of the concentration increase up the profile can be suggested. For P, high values in the layers above the depth of 120 cm are clearer, particularly in M<sub>cult</sub> layer.

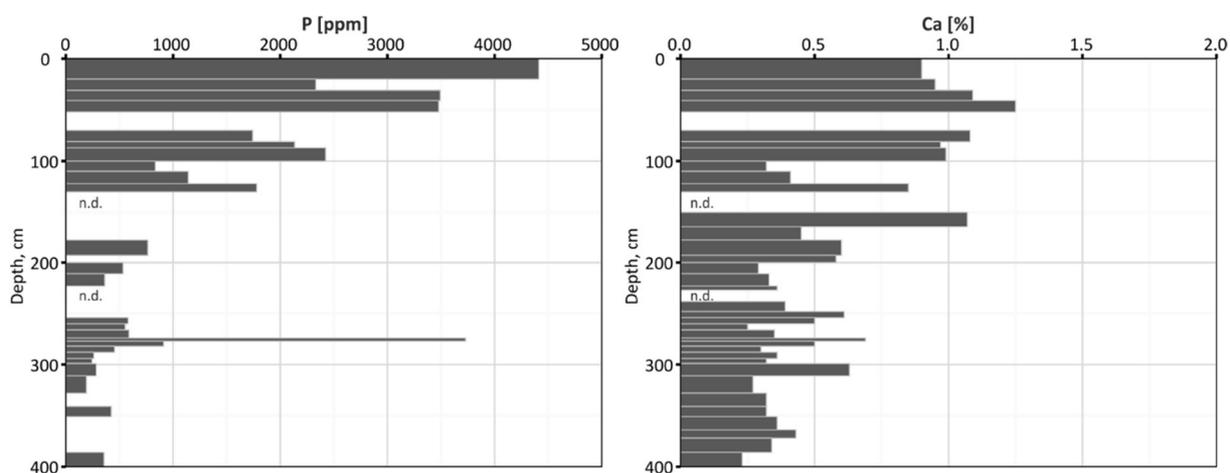


Figure 59. Profile distribution of selected elements in the drilling core 270.

### Dating of the materials

The materials at the points 300 and 311 were dated by the radiocarbon method (Table 11). A charcoal fragment from the material with the first artefacts overlying the gravel layer from point 311 provided a Viking Age date 885 – 995 cal AD (2- $\sigma$ ). This date corresponds to the age of the basis of the sequence in points 198 and 401 of transect 1. In point 300, a significantly older age (probably caused by a redeposited old charcoal fragment) was obtained for the basis of the sequence: 7495 – 6825 cal BC (KIA50330) at 379.5 cm and 1615 – 1450 cal BC at 384 cm (KIA50331). However, a hazelnut shell fragment at 293 cm from the layer with presence of the first anthropogenic features provided nearly the same age as at point 311: 883 – 975 cal AD (Tra11347). As it was the case for the dates of transect 1, a plateau on the calibration curve causes a relatively wide period of 100 years. Interestingly, ca. 50 cm above a depth of 247.5 cm, an age corresponding to the late Vikings Age was obtained: 1016 – 1151 cal AD (Tra11346).

Table 11. Radiocarbon data of materials from points 300 and 311.

Lab number	Sample/ material	Point nr./ depth (cm)	Radiocarbon age	Calibrated age (2 $\sigma$ range)	$\delta^{13}\text{C}$ (‰)
Tra11346	Charred rye seed ( <i>Secale cereale</i> )	300 / 247.5	980 $\pm$ 20	1016 – 1050 cal AD (58.2%) 1084 – 1125 cal AD (30.0%) 1136 – 1151 cal AD (7.2%)	-25.7 $\pm$ 2.9
Tra11347	Hazelnut shell ( <i>Corylus</i> )	300 / 293	1130 $\pm$ 15	883 – 975 cal AD (95.4%)	-26.9 $\pm$ 1.6
KIA50330	Charcoal fragment ( <i>Pinus</i> )	300 / 379.5	8170 $\pm$ 100 BP	7495 – 6980 cal BC (89.8%) 6975 – 6910 cal BC (2.8%) 6885 – 6825 cal BC (2.7%)	-28.08 $\pm$ 0.33
KIA50331	Charcoal fragment ( <i>Alnus</i> )	300 / 384	3250 $\pm$ 30 BP	1615 – 1490 cal BC (80.5%) 1485 – 1450 cal BC (14.9%)	-28.01 $\pm$ 0.20
KIA50333	Charcoal fragment ( <i>Salix</i> )	311 / 376.5	1100 $\pm$ 25 BP	885 – 995 cal AD (95.4%)	-26.01 $\pm$ 0.23

Based on the geo-ecological data obtained for the four cores analysed and the stratigraphy of the rest of the cores, a scheme of the longitudinal profile stratigraphy could be elaborated (Figure 60).

Due to the high spatial heterogeneity and relatively large distances between the drilling points, only gravel at the basis and peat layers were connected in the profile. As it can be seen, drilling points west of the Kirchweg have a similar stratigraphy with a cultural gravel layer at the bottom followed by thick (organic and mineral) cultural deposits and by a peat layer, which started to form at the end of the Viking Age. East of the road, mostly an alternation of sterile sandy layers with materials enriched in charcoal/wood and to a lower extent bones and artefacts were found. Most of the anthropogenic finds at the drilling points west of the road were discovered in the lower parts of the profiles below the peat layer (excluding small artefacts in the colluvium of the cultural layer). Differently, at drilling points east of the road anthropogenic features were found throughout the whole sequences with highest values in the upper parts of the profile.

It has to be pointed out that core 443 contains greyish well sorted silty material (presumably a pond sediment L), which was not found at other drilling points within the settlement. Wendt (in preparation) found similar material in a depression west of the half-circle wall. Core 1406 also has to be mentioned separately as it has a stratigraphy different from other cores in the profile due to its location in the wall opening. Multiple gravel layers were found there starting from the surface as the core was retrieved from the modern brook course.

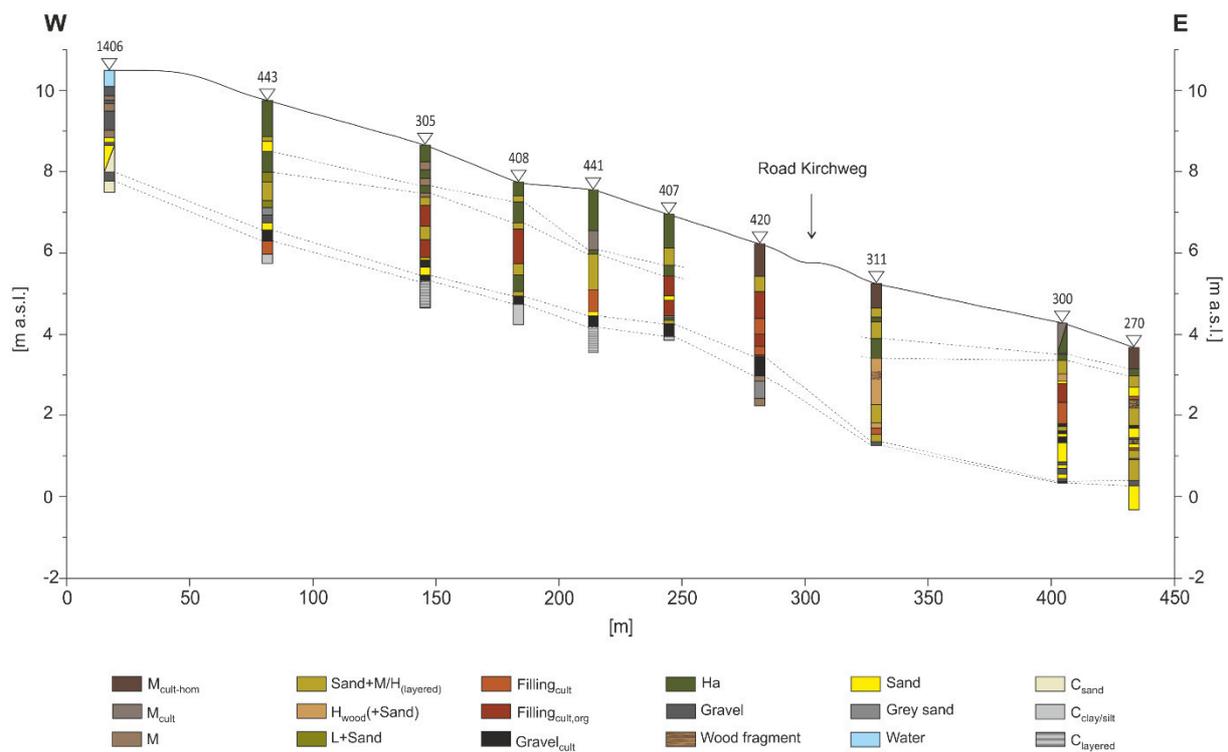


Figure 60. Scheme of stratigraphic sequences in the sediment cores of the longitudinal profile.

### 5.2.5. COMPARISON OF THE TRANSECTS

Figure 61 illustrates geo-ecological data that allow a comparison of the main stratigraphic units that were found in the three areas investigated (transects 1 and 2 and points of the longitudinal profile east of the road).

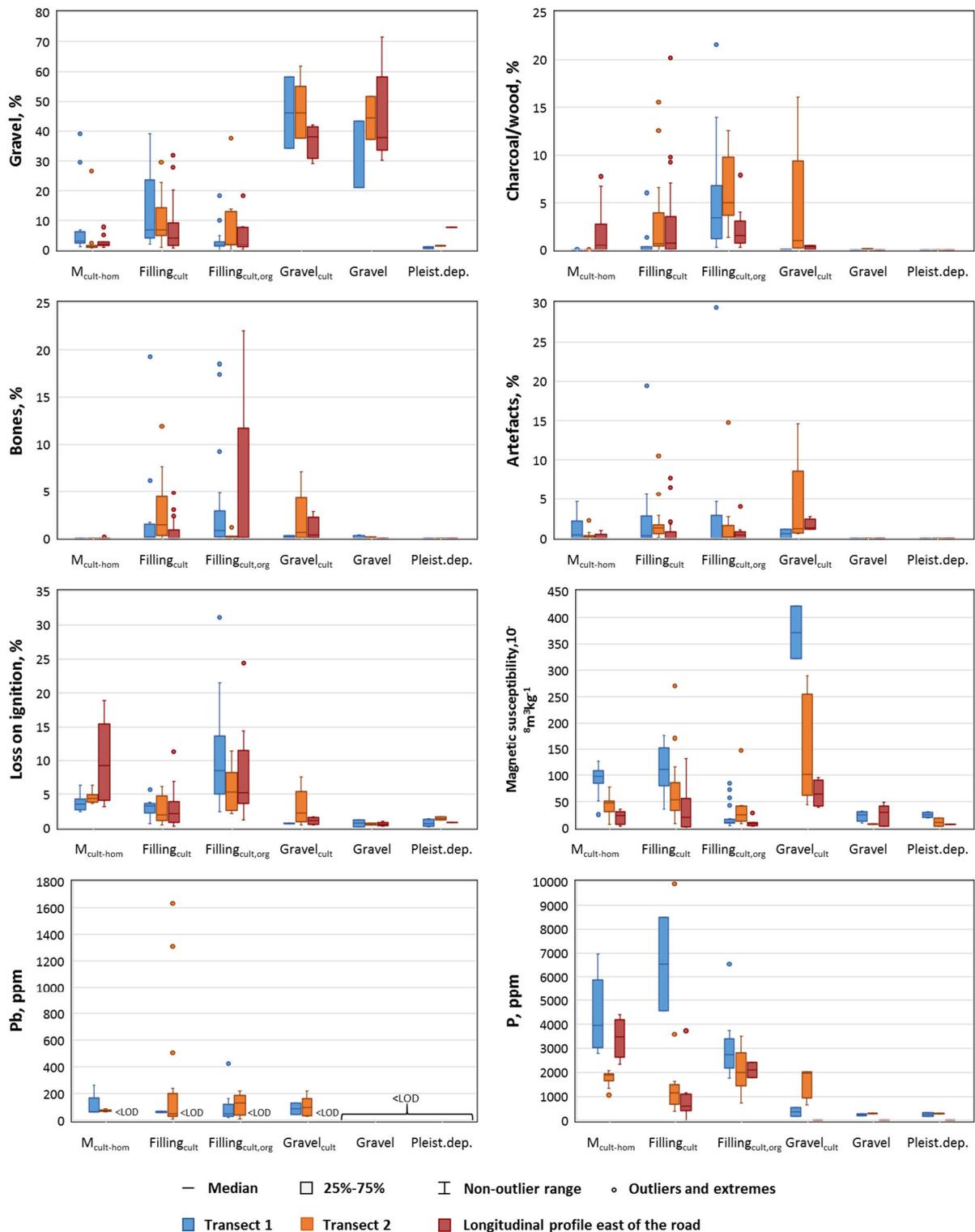


Figure 61. Comparison of the properties of the main stratigraphic units at drilling points west of the road (transect 1 and 2) and east of the road (longitudinal profile).

Natural deposits (gravel and Pleistocene deposits) are similar in all three areas considered. While the content of the coarse >2 mm fraction is somewhat varying in the areas, no anthropogenic features were found in any of them. Content of Pb lies below the detection limit, while content of P is low and lies in ranges typical for deposits not affected by settlement activities. It can be noted that for the whole sequences in the cores east of the road, including cultural deposits, Pb values lie below the limit of detection.

The cultural gravel layers of the three areas have a similar content of the coarse fraction compared with the natural gravel layers, but the rest of the parameters are significantly different. Gravel<sub>cult</sub> in transect 2 is characterized by a significantly higher content of organic matter as well as of different anthropogenic inclusions such as charcoal and wood, bones and artefacts in comparison to transect 1 and points of the longitudinal profile east of the road. Also, the content of P is highest in Gravel<sub>cult</sub> in transect 2. A prominent feature of Gravel<sub>cult</sub> in transect 1 is a very high magnetic susceptibility. This is probably related to the dominating iron slags among artefacts found in the cultural gravel layer in transect 1 and mostly pottery and other artefacts in the cultural gravel layer in transect 2 and points east of the road. A higher organic matter content in Gravel<sub>cult</sub> of transect 2 can be attributed to the presence of multiple gravel layers in the sequence, some of which are located within OM-rich Holocene sediments, while in transect 1 Gravel<sub>cult</sub> layer was always located at the basis of the Holocene sequence, next to the Pleistocene material. The cultural gravel layer east of the road is characterized by moderate values of the parameters considered.

The cultural filling of the structure (both organic and mineral) has different properties in the three areas with wide variations. The organic cultural filling is characterized by elevated values of organic matter content and of the anthropogenic parameters compared to the Pleistocene deposits. Magnetic susceptibility is low in the organic cultural filling of the three areas, which is related to the high content of organic matter and plant/wood remains. A high content of charcoal/wood and P can be pointed out for transects 1 and 2, while at points east of the road, a very high content of bones is observed. Other parameters are similar or lower than in the transects west of the road.

For the mineral cultural filling, a high MS and a very high content of P in transect 1 have to be pointed out as well as single extremely high values of Pb in transect 2. High contents of P coincide with findings of Kiefmann (1983), who identified a strong surface enrichment of P north of the brook, particularly in the area of transect 1. The cultural filling in transect 1 is characterized by very low contents of charcoal/wood and a comparatively low content of bones, while in terms of other parameters, cores east of the road are characterized by lowest values.

The homogenized colluvium of cultural layer  $M_{\text{cult-hom}}$  is in general quite similar in both transects with differences in MS and P content, which probably reflects the variety of the cultural layers on the slopes prior to their erosion. However, at points east of the road,  $M_{\text{cult-hom}}$  has a significantly higher content of organic matter and charcoal/wood remains, and a lower MS.

## 6. DISCUSSION

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### 6.1. SOILS AND SEDIMENTS IN HEDEBY

#### 6.1.1 PROPERTIES

Soils and sediments in Hedeby are diverse due to the complex processes of their formation. Properties of the buried soil horizons point at a formation of Cambisols and Luvisols (woodland soils) on the slopes depending on the parent material at the land surface before settlement activities, which agrees with the existing knowledge about the vegetation cover in the area prior to the Viking Age (Behre, 1983). On sandy deposits, remnants of Bw horizons, often with thin clay illuviation bands, were identified. In some areas, podsolization features of buried A horizons were discovered pointing at land use and vegetation changes. In heathlands, which developed in the early medieval period due to forest clearing and grazing, Podzols developed from Cambisols or Luvisols (Behre, 1983).

In order to address the problem of the classification of heterogeneous settlement deposits of Hedeby, geo-ecological properties of the deposits were determined and analysed statistically. Principal component analysis and cluster analysis of soils and sediments were often applied at habitation sites mostly to simplify data sets and group together those elements with similar spatial enrichment patterns (Entwistle *et al.*, 2000; Dirix *et al.*, 2013). In such studies, however, surface sampling was carried out with the aim to distinguish functional areas within the sites. The approach presented here is fundamentally different as it is attempted to classify materials in deep cores of up to five meters depth with a high variety of soils and cultural as well as natural sediments that developed as a result of considerably different processes and societal and environmental conditions.

A correlation analysis of the variables was performed to identify the processes and features they might reflect. Strongest correlations were obtained for elements related to fine and coarse particle size fractions of the sediments, for instance K, Rb with Al, and Si with coarse and medium sand contents. The main patterns obtained among anthropogenic indicators are in agreement with existing knowledge about the settlement geochemistry. Strong correlations between P, Sr, and Ca were obtained, which is expected since these elements are typical indicator of human activities. They point at the disposal of organic wastes and excrements (Middleton and Price, 1996), which is the case in the large hidden structure discovered at Hedeby-brook. According to Wilson *et al.* (2008) Ca, Ba, Sr, Zn, P and Pb reflect patterns of former human activities on abandoned farm sites. Ca, K and Fe are known to be enriched by processes of *in situ* burning and ash formation (Gauss *et al.*, 2013). Highest contents of Ca were measured in Pleistocene deposits below the soils that

formed during the Holocene. Other elements that are also often found to have elevated levels in former settlements (e.g. Cu, As) (Alexandrovskaya and Alexandrovskiy, 2000) were present only in very low quantities below the limit of detection. Phosphorus, being the most commonly used indicator of settlement activities (Wells *et al.*, 2000), has also shown moderate to strong correlations with anthropogenic parameters, although some of such correlations, as for instance with Pb, are rather indirect correlations suggesting coincidence of different processes in the same material. No significant correlation was found between P content and bones. This is probably caused by the character of sampling, namely by the fact that absence of bones in the cores cannot imply their absence in the sediment itself. For this reason, high contents of P were measured also when no bones were found. When excluding measurements in layers with < 2 % of bones, a significant ( $p < 0.05$ ) correlation coefficient between the content of bones and phosphorus of  $r_s = 0.52$  was obtained.

Other variables indicating human activities (charcoal/wood, bones, artefacts, MS) do not have strong correlations between each other. They are apparently pointing at different types of human activities responsible for their magnitudes. While artefacts deliver mixed signals, bones of domestic animals, particularly with recognizable butcher marks, usually indicate the presence of domestic waste (O'Connor, 2000). Different levels of magnetic enhancement can point at the presence of features of workshop activities, e.g. metal/glass working and pottery production (Schmidt, 2007). It has to be taken into account that due to the point character of information delivered by drillings, the absence of inclusions in the cores does not mean their absence in the corresponding sediments. Also, a strong correlation was found between CH/wood and C/N reflecting the preservation conditions of wooden remains.

Taking into consideration relationships between the variables analysed and the results of the cluster analysis of the variables, six parameters available for all cores (gravel, artefacts, bones, charcoal/wood, loss on ignition and magnetic susceptibility) can be well used as a set of criteria for the classification of the soils and sediments of Hedeby. Among elements, only P and Pb fell into the group of variables that describe anthropogenic features in the materials. MS and artefacts associated with gravel form a group of mineral cultural variables. High MS was obviously associated with the presence of a coarse fraction that might have included pottery fragments, burnt loam construction materials and metal slags. Bones and charcoal/wood were more common in organic matter-rich materials. As it was shown by Milek and Roberts (2013), artefacts and bone distributions used on their own can provide only a limited insight into the use of space. A control of pH is necessary to account for possible diagenetic transformations. In this study, pH varied in a range from 4.5 in cultural organic deposits to 7.7 in partly calcareous Pleistocene sediments. In organic cultural layers somewhat lower values were measured than in cultural mineral layers.

This may have caused less favourable conditions for bone preservation in comparison to other materials. However, bones were present in these slightly more acidic conditions too, although in smaller amounts. In organic cultural layers water stagnation conditions were observed. Although bone and teeth preserve better in alkaline soil conditions (Kibblewhite *et al.*, 2015), bones might persist in slightly acidic conditions at low Eh levels in wet and waterlogged conditions, although some degradation features may occur (Retallack, 1984). Therefore, the effects of pH on bone preservation probably did not reach critical levels due to reducing conditions. Nevertheless, it cannot be excluded that organic cultural layers initially contained more bones during the settlement period. Another question raised by the bone preservation issue is the separation of natural peat layers, which have a similar pH as cultural organic layers and no bones. It could be supposed that bones might have dissolved in the presumably natural peat layers, but the content of charcoal/wood allows distinguishing natural peat and cultural organic materials with low pH (Retallack, 1984).

### 6.1.2. CLASSIFICATION

The set of six parameters including gravel, artefacts, bones, charcoal/wood, loss on ignition and magnetic susceptibility was used in the cluster analysis. The choice of the linkage distance, at which the clusters were separated, was made by an iterative analysis of cluster composition – starting from the largest distance and moving towards smaller distances. At a relative linkage distance of 60 % three large clusters were obtained. They could be primarily identified as natural and cultural sediments, and materials with transitional properties. The transitional sediments show a certain similarity to natural materials (they form one cluster at 80 % Dlink/Dmax). At a relative linkage distance of 8.2 %, 15 meaningful clusters were obtained, which were significantly different from each other in at least one parameter as shown by the post hoc Tukey honestly significant difference test. Since the set of parameters describes only actual properties of the materials without taking into account the genesis and diagenesis of the sediments, a detailed analysis of the composition and properties of the clusters was carried out.

Initial clustering has placed homogenized colluvium of cultural deposits affected by ploughing and soil formation into the cluster of natural materials. Probably, soil formation started to “erase” the cultural signature of the material, which was initially a cultural layer. According to Sycheva (2006) such cultural layers are in the metamorphic stage of their evolution and in case of a pedogenic transformation they overtake the properties of the soil being formed. Colluvium of cultural deposits that was also ploughed but not actively involved into soil formation was classified as material with transitional properties; hence, it is also in the metamorphic stage. Cultural layers that are not exposed at the modern surface and that had not been involved into agricultural land use have better preserved their original features. The geomorphologic situation, the hydrologic

regime and the land use are the main factors affecting the preservation of the cultural layers (Baltakov, 2008). The colluvium of reworked cultural layers was characterized by a high MS of the same magnitude as the cultural layers, but no bones and wood and a lower content of artefacts were found in the colluvium. The measured values of MS correspond to MS values obtained in other studies of habitation deposits of urban and proto-urban settlements in the region (Macphail *et al.*, 2000). Since the inclusion of *in situ* cultural layers into the cluster analysis did not cause the formation of a separate cluster, it can be concluded that local conditions of their formation and post-depositional processes do not allow distinguishing them using the approach proposed here. On the one hand, using additional parameters such as grain size and element distributions, would help to identify them better as it was the case with the analysis of a selection of samples. On the other hand, it is necessary to approach the problem of materials of unclear genesis using their morphological properties and geomorphological situation.

The 15 clusters obtained form four large groups:

- natural material,
- material with transitional properties,
- cultural mineral material, and
- cultural organic material.

Figure 62 illustrates descriptive statistics of these four groups. Contents of gravel and organic matter vary strongly within the groups and thus do not allow a significant differentiation of cultural and natural materials. Indeed, natural and cultural gravel layers as well as natural materials with nearly absent or with a very high organic matter content were identified. Contents of bones, charcoal/wood and artefacts and magnetic susceptibility, on the contrary, have significantly higher values in cultural deposits and in addition they enable a clear separation of mineral cultural from organic cultural deposits.

The observed heterogeneity and complexity of sediments in former settlements is a result of complex combinations of diverse natural and anthropogenic processes responsible for their formation. In the existing scientific literature, no approach for a classification of such deposits could be found. The reason for it is that the classical approach to the investigation of habitation deposits is different from the research conditions in Hedeby. Usually, based on the stratigraphy and the morphological properties of deposits in excavation profiles, it is known what kinds of materials have to be investigated. Therefore, scientists investigate properties of a cultural layer while knowing that it is a cultural layer.

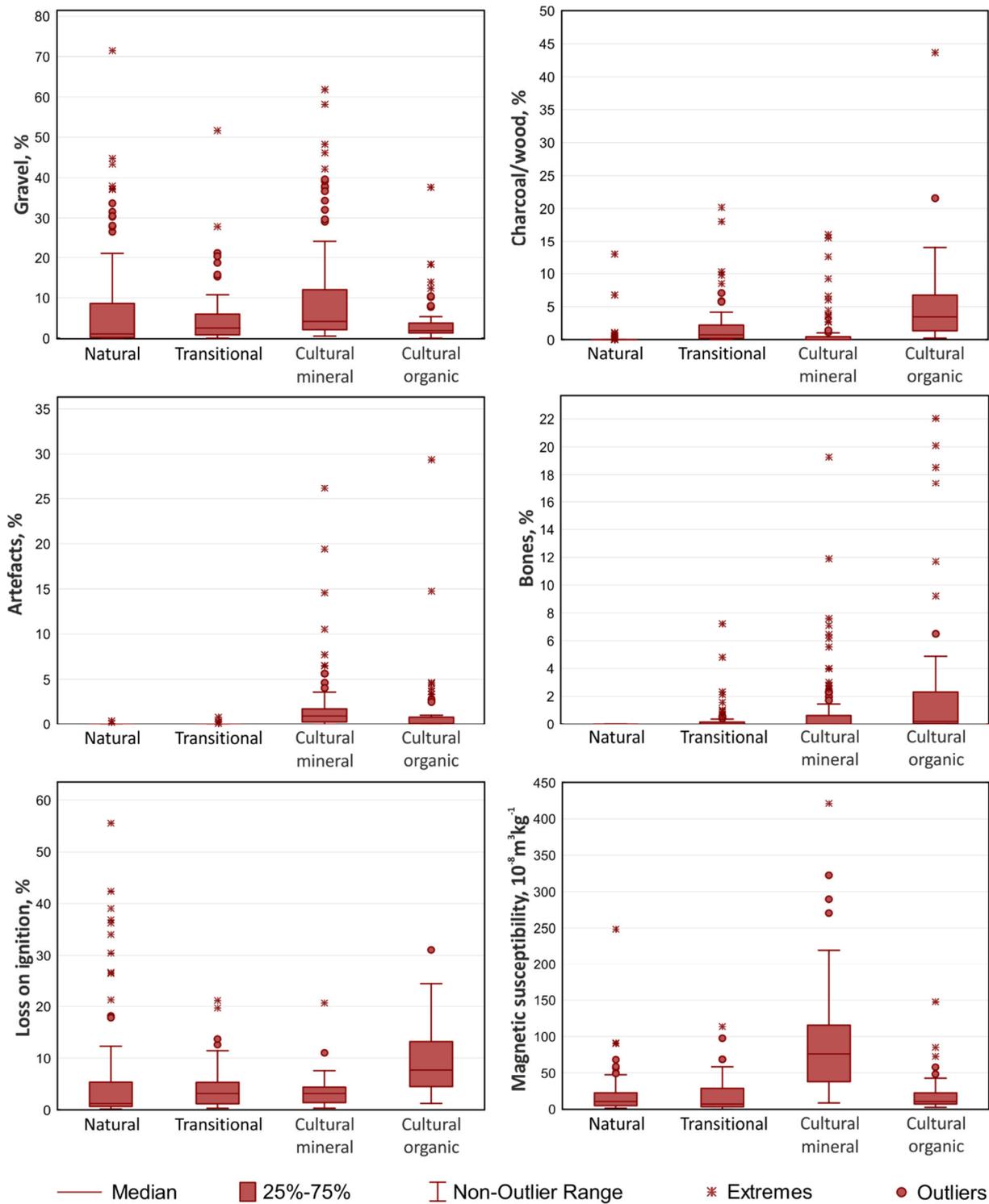


Figure 62. Box plots of the four large groups of sediments.

However, many prominent former settlements represent archaeological monuments, which are protected against strong interferences like excavations. In such cases, field work is limited to non-invasive and minimally invasive methods, like drillings. Since drillings provide only point information, the understanding of the spatial relationships between the sediments of different cores is frequently quite complicated. Moreover, it is often impossible to distinguish unequivocally different cultural deposits from natural ones. In such cases, it is necessary to

employ an objective and reproducible approach for the classification of sediments. However, for such situations no universal methodology exists. Hence, the approach suggested here is particularly valuable in conditions when excavation possibilities are limited.

The developed approach represents the first step in investigation of former settlements. It can be applied for a preliminary sondage of potential human habitation sites by drillings in order to identify them and the function areas within them. Areas that are interesting for larger scale excavations may be found and justified based on objective criteria. Since the set of parameters takes into account different effects of human activities on lithological material, sites unidentifiable by individual methods can be recognized. The approach is based on simple and rapid cost-effective measurements that enable to distinguish natural and anthropogenic deposits and to identify deposits that require further analysis in more detail. By a direct identification and exclusion of clearly natural and clearly anthropogenic deposits (a key task of most archaeological investigations), time and costs can be reduced. Materials with transitional properties can be investigated more goal-oriented. Element composition and grain size distribution can help to make the classification more detailed and help understanding the genesis of material. This statement was confirmed when GSD, Pb and P were used as additional parameters in the principal component analysis and cluster analysis for a selection of samples. The division of clearly natural from clearly anthropogenic groups was the same, but it was possible to better distinguish transitional materials. Some of them could be classified as natural materials, some as cultural layers. Although a group of transitional materials was still present, it was much smaller than in case when only six main parameters were used. Also, for natural and transitional materials, the use of other parameters and other elements that were excluded from the analysis would help to distinguish them and to investigate material genesis and provenance. Based on the vertical distribution of clusters in profiles, important assumptions regarding land use changes over time or re-deposition of material can be made.

Therefore, the approach proposed here enables the classification of habitation deposits in Hedeby based on rapid and cost-effective analyses. The methodology can be enhanced by using additional parameters and by analysing preservation conditions of artefacts, bones and other cultural inclusions.

## **6.2. GEOMORPHOLOGIC CHANGES AT THE HEDEBY-BROOK**

This section aims to discuss the properties of the structure filling discovered in transects 1 and 2 and in cores of the longitudinal profile east of the road. Hypotheses for the formation and development of this structure during and after the settlement period will be suggested.

### 6.2.1. COMPARISON OF THE TRANSECTS

In transects 1 and 2, buried structures at the Hedeby-brook were revealed showing strong similarities and some differences in the stratigraphy and sediment properties, while sediments at drillings points in the longitudinal profile east of the road were quite different. In transect 1, Pleistocene deposits were found at the basis of the sequences that represented two types of materials: clastic varves and fluvio-glacial sand underlain by clastic varves. In transect 2 and at points east of the road, fluvio-glacial sand was found at the basis.

In the transects 1 and 2, a few gravel layers were found within Pleistocene sandy deposits indicating the presence of a flat valley at the end of the last glacial period. Traces of Holocene pre-Viking Age soil formation were found in both transects. On the southern slope of transect 1, a remnant of a Bwb horizon was found pointing at Cambisol formation under woodland before the settlement activities. On the northern slope of transect 1, different local hydrological conditions caused peat formation. This is confirmed by the results of micromorphological analysis of the peat layer of point 402. No artefacts or other anthropogenic features were present in this layer, which can be interpreted as a pre-Hedeby peaty layer. Also, remnants of a peat layer are present in the southern part of transect 2 indicating a stagnating water regime.

Directly above the soil formation remnants or the Pleistocene sediments, cultural layers were identified in the southern and northern parts of the transects 1 and 2. In the central parts of the transects, no features of former soil formation were present and cultural stone layers were found at the contact between Holocene and Pleistocene deposits. In transect 1, one Gravel<sub>cult</sub> layer at the basis of the sequence was found, while at least three Gravel<sub>cult</sub> layers were identified in transect 2. The cultural filling of the hidden structure in both transects is very heterogeneous, rich in artefacts, bones and charcoal/wood. The abundance of archaeological finds and their composition prove the disposal of different types of wastes.

In transect 1, a peat layer follows the cultural filling, while in transect 2 despite the facilitating landscape position no peat layer was found. The next unit in transect 1 is the colluvial layer of cultural layer, while in transect 2 a finely layered sediment was found in the central part of the transect overlying the cultural filling. The alternating layers are composed of sandy material and M<sub>cult</sub> material.

The longitudinal profile of drillings allows establishing a range of considerable differences between the cores west and east of the road Kirchweg, although the Holocene bases of the sequences are in both cases dated to the Viking Age. At drilling points east of the road, no features of pre-Viking Age soil formation were found, as the drillings were located in the former brook course. Cultural gravel layers found in transects 1 and 2 were usually dominated by stones with a diameter of at least 4 – 5 cm, while east of the road, multiple gravel layers dominated by small

stones were found throughout the sequences. This indicates different processes that were responsible for the deposition of the gravel layers. Also, east of the Kirchweg, a larger number of layers with transitional properties were found. They are dominated by sandy material with inclusions of wood and charcoal. The cultural deposits had much weaker anthropogenic features compared to the western cores. A peat layer that was found in the western part of the settlement, as a marker of the end of the settlement period, is absent or younger in the eastern part.

In terms of the properties analysed, cultural deposits east and west of the road are different, particularly in magnetic susceptibility, Pb content and content of artefacts. Also, it has to be noted that differences within the group of points east of the road were observed. They apparently indicate different land use types in the areas near the brook. For instance, a sequence in core 270 is very rich in bones, which probably indicates the proximity of houses, while core 311 is very rich in charcoal/wood. At points west of the road, different types of anthropogenic features were identified. In order to shed light on the possible land use in the direct vicinity of transect 1, micromorphological investigations were carried out.

Micromorphological analysis of a thin section from the southern slope at drilling point 400 revealed the presence of a cultural layer rich in organic matter with features of domestic waste. Based on the morphology of the organic matter and plant tissue remains as well as due to the presence of fragmented phytoliths, fungal spores and phosphatisation features, the presence of different kinds of organic waste material including cess or dung deposits can be suggested for this cultural layer. This is in agreement with Milek and Roberts (2013) who stated that fragmented articulated phytoliths and fungal spores are typical for animal dung, while small bones are common in omnivore excrements. However, these organic remains seem to be not *in situ* as no trampling features could be identified. Possibly, a secondary dumping of plant remains and excremental/dung materials took place here. Such a land use would explain the presence of high quantities of P and a large amount of bones in the filling of the structure. Also, clay coatings with a crescent b-fabric found in this layer are typical textural pedofeatures in illuvial B horizons (Bronnikova *et al.*, 2003), which might indicate the insertion of soil material into the cultural layers.

On the opposite slope at drilling point 402, where a cultural layer was identified too, the properties of the cultural layer are very different. Abundant silica and iron slags were identified in the thin section at 134 – 144 cm. The presence of abundant silica slags with cracked quartz grains imply a heating of the material above 1200 °C corresponding to nearly industrial heating processes (P. Goldberg, P. Karkanis, R. Macphail, personal communications). Therefore, the charred cultural layer and the colluvial layer may contain microartefacts originating from glass and/or metal working, while strong phosphatisation features, the morphology of the organic

fabric as well as the presence of small bones in the upper part of the colluvium of the cultural layer may suggest the presence or the disposal of animal faeces. The importance and a more objective and complete record provided by microartefacts in comparison to macroartefacts has often been emphasized (Weiner, 2010). In the second thin section at 184 – 194 cm, additionally to slags construction material like burnt clay and calcareous loamy clasts is present. Hypothesis about workshops in the vicinity of the Hedeby-brook valley is supported by the results of geomagnetic surveys (Neubauer *et al.*, 2003) and by conclusions of Jankuhn (1938). According to Hilberg (2009), the street with workshops along the brook belongs to the later phases of Hedeby (10<sup>th</sup>-11<sup>th</sup> centuries). The hypothesis of waste disposal in the structure agrees with findings in the sediments of the brook excavated in the eastern part of the settlement by Jankuhn (1943). According to Kalmring (2010), the original brook bed rose two meters above its original basis due to the accumulation of sediments. The brook filling in the eastern settlement part is dominated by alternating fine and medium sand layers of different colour and a few humic layers. Large amounts of butchery waste were found in the brook filling in form of pottery and broken bones. This implies the use of the brook for the disposal of settlement waste, which was partly washed down the stream into Haddebyer Noor.

Therefore, based on the analysis of the stratigraphy and the sediment properties in the hidden structure discovered in both transects, it can be concluded that the structure represents a single wide filled valley-like structure. The difference in properties of the valley filling between the Pleistocene basis and the colluvial material of the cultural layer is apparently caused by the differences in land use in the vicinity of transects 1 and 2.

#### **6.2.2. SPATIAL EXTENSION AND VOLUME OF THE VALLEY-LIKE STRUCTURE**

The spatial extension and the volume of the valley-like structure can be estimated using the data obtained from the transects presented in this thesis as well as based on unpublished results of preliminary drillings performed by Keßler (2008). In transect 3 east of the north-south road, this structure was not found, only a narrow deep course of the brook was identified meaning that the extension of the valley-like structure is restricted to the western part of the settlement.

The drilling transect that was made in 2008 ca. 140 m west of transect 1 revealed the presence of a buried structure with a trapezium-shaped cross-section (Keßler, 2008) (figure 63). This structure had a width of 33.5 m on the modern surface and 13 – 16 m at the basis, while the maximum depth equalled 4.25 m. At the basis of the structure, a gravel layer was identified with stone sizes of a few centimetres. Based on the presence of the archaeological finds (pottery sherds, charcoal, burnt loam fragments), the basis of the structure was dated to the 9<sup>th</sup> – 10<sup>th</sup> centuries AD, while the uppermost part of the filling developed during late medieval and modern times due to

agricultural land use on the territory of the former town, peat formation, soil erosion and colluviation.

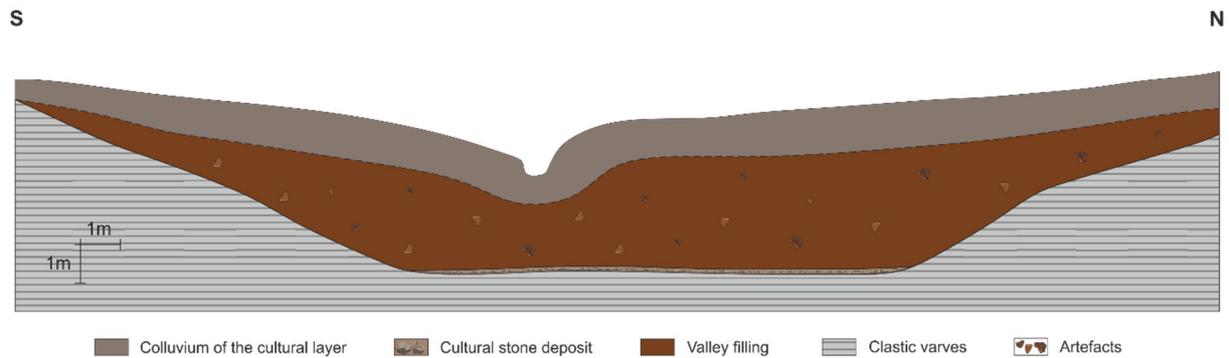


Figure 63. Scheme of the transect 2008 (modified after Keßler, 2008).

The width of the valley in the mid-part of the sequence equals ca. 20.5 m in transect 1, 16.5 m in transect 2 and 21 m in the transect of the year 2008. The average thickness of the cultural filling is approximately 2.5 m. The horizontal extension, on which the existence of the valley has been proven, is around 240 m – between the half-circle wall in the west and the road Kirchweg in the east. The calculated volume of the cultural filling and thus of the extracted material equals ca. 10,000 m<sup>3</sup>.

### 6.2.3. GENESIS OF THE VALLEY-LIKE STRUCTURE

Flat valleys formed due to glacier activity and melt water runoff during the late glacial stages of the last glacial period, the Weichselian. They are not uncommon in young moraine landscapes of northern Germany (Liedtke, 1989). The presence of multiple gravel layers within fluvioglacial sand deposits in transect 1 points at (glacio-)fluvial activity in this area at the end of the last glacial period. At the beginning of the Holocene, shrubs and trees started to grow. A dense woodland developed. Surface runoff was scarce on the slopes and soil formation dominated. Remnants of the soil formation processes were found at the margins of the discovered valley-like structure, whereas at its basis no features of soil formation were found. This is one important indication that the valley-like structure is considerably younger than the Pleistocene flat valley and that the surface of the valley-like structure has not been exposed to weathering over many years. It must have formed shortly before the beginning of its filling. Since it was revealed that the structure started to fill in the Viking Age, the structure itself must have formed in the Viking Age, too.

Which processes caused the development of the valley-like structure? The following considerations have to be discussed. Gravel layers are typical deposits at stream beds with a high-energy transport or they might point at extreme runoff events (Leopold *et al.*, 2012). However, the stone layer found at the basis of the valley-like structure is very different from the Pleistocene gravel layers and it does not possess any typical features of a fluvial transport. The stones have different sizes and shapes from well-rounded to angular. If they were all transported by water,

then only over very short distances of a few meters to a few tens of meters. The stones are embedded in medium to coarse sandy material of greyish brown to dark grey colour. These properties do not correspond to the features of material that would have been transported together with the stones. Also, Viking Age artefacts were identified within the cultural gravel layer such as iron slags and bones. Therefore, it can be concluded that the gravel layer found at the basis of the valley represents a cultural Viking Age deposit and humans most probably deposited it there.

The lake sediment record from Haddebyer Noor provides another argument against the erosion hypothesis. Geo-ecological properties of a lake sediment core from the deepest part of the lake were determined by S. Dreibrodt with colleagues (personal communication) in order to investigate the development of the landscape in the lake catchment. Based on pollen analysis and radiocarbon dating, a chronology of the sediment sequence was established. Zirconium, which is attributed to coarse grains of heavy minerals (Kylander *et al.*, 2013), was chosen as an indicator for erosion in the catchment.

The relative distribution of Zr in the lake sediment sequence shown in Figure 64 indicates that the landscape was stable during the Neolithic period and the Bronze Age, and first large inputs of sediment due to erosion in the catchment probably after clearings took place in Pre-Roman Iron Age followed by comparably high peaks in the Roman Iron Age. A strong decrease of erosion in the catchment of Haddebyer Noor was observed for the first centuries of the early Medieval Age ("Migration period"), whereas in the Viking Age a new increase can be seen. There are single findings that point at local human activities in the area of Hedeby in Roman Empire times. But the very small number of such finds and the presence of wood dated to Viking Age in the lowermost cultural layers speak against an intensive pre-Hedeby occupation (Schultze, 2008b).

Therefore, a strong human impact on the landscapes in the area west of the Haddebyer Noor took place for the first time in the Viking Age. If the valley-like structure had formed due to erosion, a correspondingly high material input would have been reflected on the Zr curve of the lake sediments. The findings mentioned allow the conclusion that the large amount of material that was removed to form the valley-like structure (with a volume of approximately 10,000 m<sup>3</sup>) did not reach the lake. The valley is not an erosional structure. The removed material stayed on land, which could occur only due to human activities. Therefore, the valley-like structure discovered at Hedeby-brook represents a human-made structure.

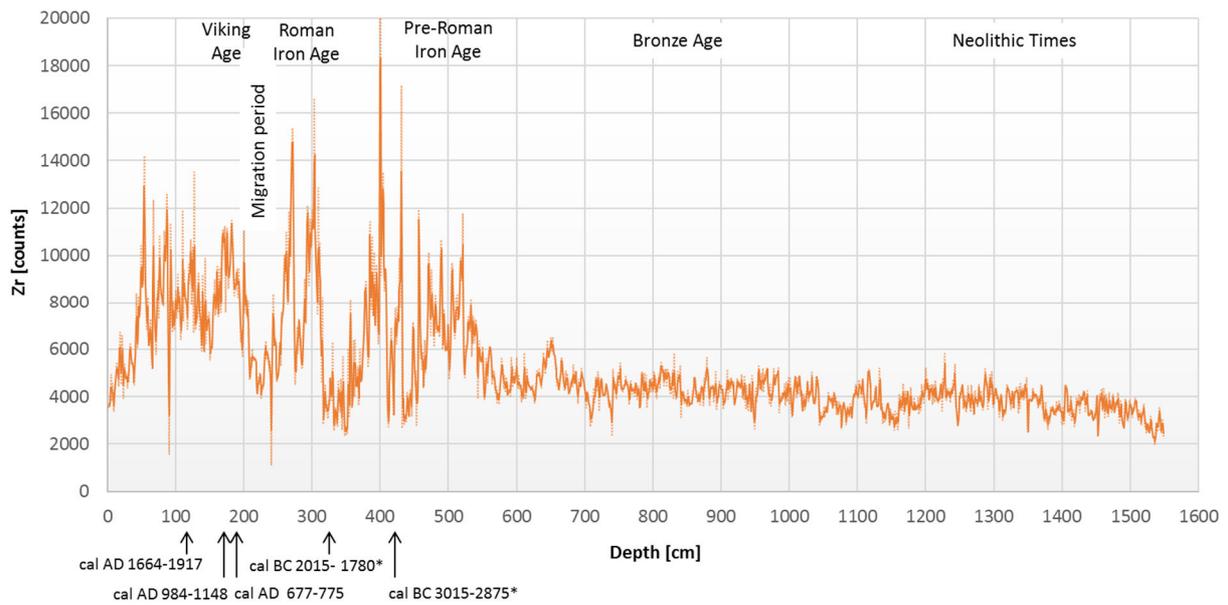


Figure 64. Distribution of Zr in the lake sediment core from Haddebyer Noor (S. Dreibrodt, personal communication).

#### 6.2.4. RECONSTRUCTION OF THE LOCAL LANDSCAPE TRANSFORMATION AND INTERPRETATION OF THE FORMATION OF THE VALLEY-LIKE STRUCTURE

The aspects discussed in the previous subsection allow the conclusion that humans formed the valley-like structure in Hedeby during the settlement period of the Viking Age. Stratigraphy and dating results allow proposing a detailed model for the main stages of the development and filling of the valley (Figure 68).

The presence of clastic varves at the basis of the sequence and at nearly the same depth on the northern and southern slopes proves the existence of a small proglacial lake in this area at the end of the Weichselian glacial period (Figure 68a). Proglacial lakes are common in the study area in which terminal moraines exist (Livingstone *et al.*, 2015). During further glacier melting and flow velocity increase, a gully incised and a thin gravel layer was deposited at its bottom. At the same time, fluviglacial sand was deposited on top of the varved sediments north and south of the gully (Figure 68b). In the following periods of the Late Glacial, fluvial activity in the gully continued and a wider valley formed, while the deposition of fluviglacial sand continued. In result of streambed meandering, multiple gravel layers were deposited and the valley was filled with sandy material (Figure 68c).

In early Holocene, soil formation started to take place in different Pleistocene deposits. On well-drained landscape positions, Cambisols formed under woodland, whereas in the lower landscape positions near the course of the brook, peat formation dominated (Figure 68d). At the beginning of the Viking Age, approximately in the early 9<sup>th</sup> century, the first cultural layers started to form

due to settlement activities. Due to this, the upper soil horizons were disturbed or eroded and only subsoil horizons stayed preserved under the cultural material (Figure 68e).

As for the next stage of landscape transformation, dating results have to be considered in detail. Multiple dating of the basis of the valley-like structure filling (KIA 50329 and KIA 50952) and first cultural deposits in the brook further east (Tra 11347 and KIA 50333) have produced similar ages. However, due to the existence of a plateau on the  $C^{14}$  calibration curve in this period, relatively wide 1- $\sigma$  and 2- $\sigma$  ranges were acquired covering ca. 70 and nearly 100 years respectively. In order to obtain more definite time borders for the events, phase modelling was performed in program OxCal 4.3 (Table 12, Figure 65). The code utilized in the modelling is provided in appendix 7.

Table 12. Results of phase modelling.

Sequence Hedeby	Modelled (BC/AD)						Comments
	from	to	%	from	to	%	
Boundary „Post-Hedeby“	1101	1191	68,2	1084	1361	95.4	Modelled boundary
<b>Phase „Peat formation“</b>							
Last Peat formation	1099	<b>1147</b>	68,2	1090	<b>1151</b>	95.4	Dating
First Peat formation	<b>1086</b>	1114	68,2	<b>1067</b>	1125	95.4	
Span Peat formation	0	24	68,2	0	49	95.4	
R_Combine KIA 50328	1086	1121	68,2	1076	1151	95.4	
R_Date Tra 11346	1090	1120	68,2	1078	1151	95.4	
<b>End of Hedeby</b>	1065	1066	68,2	1065	1066	95.4	Written record
Boundary „Filling end“	938	1066	68,2	927	1066	95.4	Modelled boundary
<b>Phase Early filling</b>							
Last Early filling	939	<b>978</b>	68,2	911	<b>991</b>	95.4	Dating
First Early filling	<b>889</b>	945	68,2	<b>872</b>	965	95.4	
Span Early filling	0	49	68,2	0	89	95.4	
R_Combine KIA 50329	917	968	68,2	894	974	95.4	
R_Date Tra 11347	922	964	68,2	890	971	95.4	
R_Date KIA 50333	905	974	68,2	894	986	95.4	
R_Date KIA 50952	920	966	68,2	872	974	95.4	
Boundary „Filling start“	873	944	68,2	824	961	95.4	
<b>First mention</b>	803	804	68,2	803	804	95.4	Written record
R_Combine KIA 50332	4	56	68,2	-39	70	95.4	Outlier
R_Date KIA 50331	-1606	-1461	68,2	-1612	-1451	95.4	Outlier
R_Date KIA 50330	-7321	-7059	68,2	-7484	-6830	95.3	Outlier

Dates of the first written mention and the record of the destruction of Hedeby were used as additional constraints, which allowed to exclude age intervals lying beyond these markers (Figure 65). The functions “First”, “Last” and “Span” were applied to acquire well-defined intervals of the periods of interest. The phase related to the beginning of the filling process was named “Early filling”, while the period after abandonment of Hedeby reflected in the sequences in peat layers

was named “Peat formation” phase. Outliers (reworked old material) were excluded from modelling.

Although the probability range for the age of the filling basis was not reduced significantly as a result of modelling, it was possible to combine the information from all four dates. As a result, a defined period of the beginning of the filling of the valley-like structure was obtained: from 889 to 978 cal AD (1-  $\sigma$  range). In the same way, a period covering the onset of peat formation with a high certainty was obtained: 1086 – 1147 cal AD.

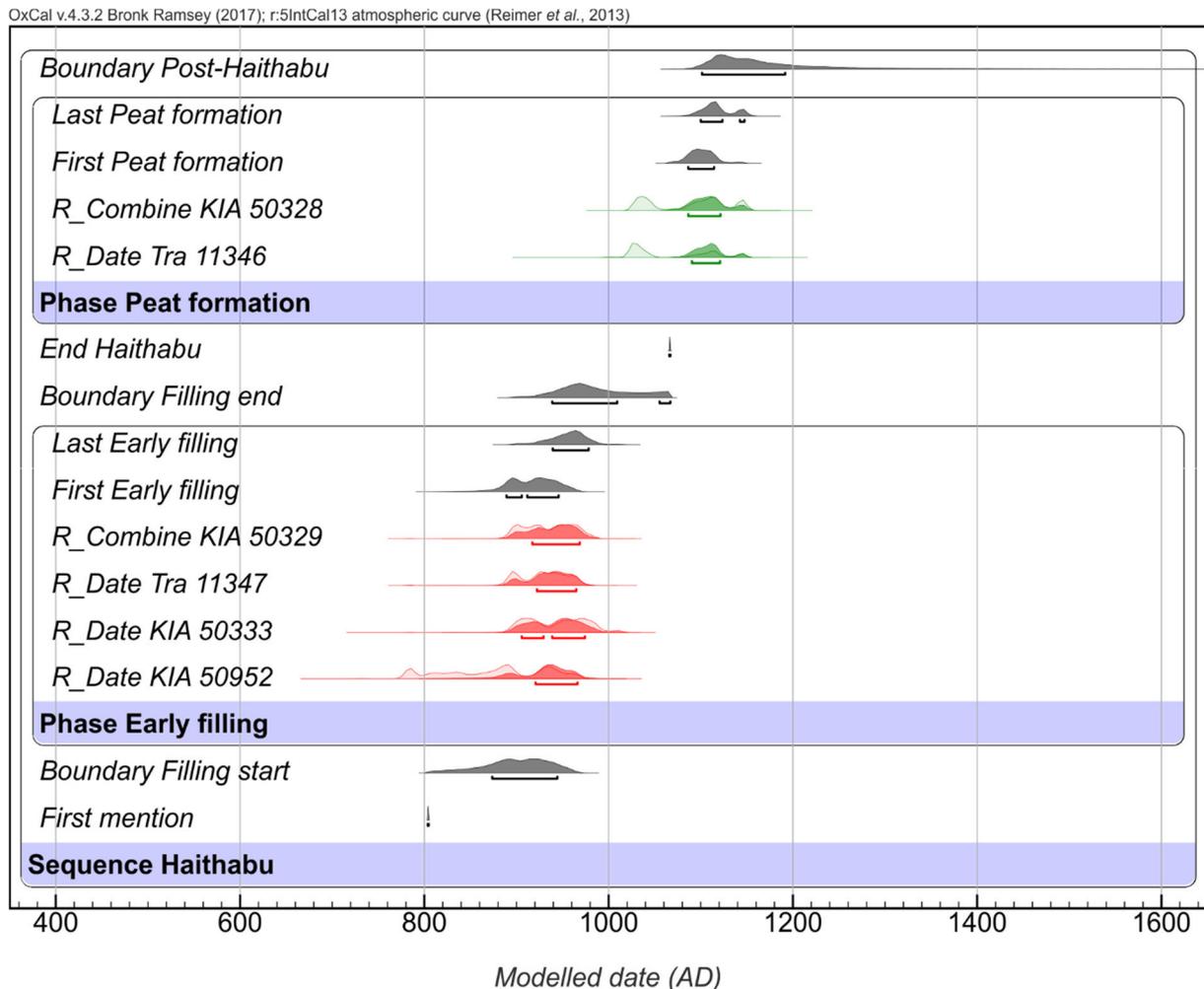


Figure 65. Graph of phase modelling results (marked intervals represent 1- $\sigma$  ranges).

Therefore, the formation of the valley-like structure took place in the 9<sup>th</sup> or 10<sup>th</sup> century (Figure 68f). Since such an important process as the half-circle wall construction took place in the second half of the 10<sup>th</sup> century and since the exact source for the wall material is still unknown, it is reasonable to suggest that the formation of the valley took place at the same time and that the extracted material was at least partly used for the construction of the wall. Nevertheless, it cannot be excluded totally that the valley could have been formed before the construction of the half-

circle wall. However, in this case it would remain unclear, where the enormous amount of material extracted from the valley-like structure was deposited.

Data obtained from the longitudinal profile are in agreement with the scenario considered. At point 300, older inverted sediments were found below the material of the Viking Age. The layer at a depth of 384 cm below the recent land surface has an age of 1615 – 1450 cal BC, while material above at a depth of 379.5 cm has an age 7495 – 6825 cal BC (Table 12). Both dates originate from reworked material. The excavation of the valley-like structure and the construction of the wall caused a local landscape instability and erosion of older material, which was then accumulated at the lower slope positions. In the same core 300, a deposit rich in bone and charcoal was identified above a depth of 250 cm, while material at a depth of 247 cm had a late Viking age. It could be the material that was eroded from the valley-like structure, which would most likely provide a Hedeby age.

The goals of the valley excavation could be the extraction of material for the construction of the half-circle wall and partly for other settlement activities, and, possibly, for an optimisation of the hydrological regime of the area, too. According to the calculations, the total volume of material removed from the valley could account for ca. 10% of the total volume of the half-circle wall, which was estimated to ca. 100,000 m<sup>3</sup> (Wendt, in preparation). The preliminary results of a wall investigation by Broszio (2017) showed that different parts of the wall are composed of different deposits covering a wide range of materials from topsoil horizons rich in organic material to sandy and loamy deposits poor in organic matter and probably originating from Pleistocene deposits. Due to the heterogeneous composition of the half-circle wall, it is not possible to confirm or refute the thesis whether the material extracted from the valley-like structure was used for the construction of the half-circle wall.

The main quarter of Hedeby with metal workshops was located directly north of the brook (Schietzel, 2014). It existed approximately in the same period, when the valley-like structure was formed (Hilberg, 2009). Hence a part of the of material could also have been used for handcraft activities. Since the transects prove the presence of clastic varves underlying fluvio-glacial sand, an extraction of this clay-rich material could represent another goal. Handcraft activities related to metal and glass working require clay for the construction and maintenance of the ovens and furnaces as they were mostly composed of clay and loam material (Westphalen, 1989). Moreover, clay containing calcium carbonate might have been added during the smelting procedure as a flux component to reduce viscosity of the slag and purge iron of chemical impurities (Joosten, 2004). However, archaeological evidence rather speaks for iron smithing and not smelting in Hedeby (Westphalen, 1989). Large amounts of clay and loam material were necessary for the construction of the houses and for the production of pottery (Schietzel, 2014). Until now the source of loam

and clay for the production of pottery and daub for house construction is assumed to be Hedeby itself and its nearest surroundings (Lüdtke, 2013).

It has to be noted that the excavation of such a large structure in the middle of the western-central area of Hedeby only for the sake of material extraction seems rather improbable. Also, the presence of an anthropogenic stone deposit at the basis cannot be explained by material extraction. Excavations in the western opening of the half-circle wall in 1913 (Knorr and Rothmann, 1913) revealed structures composed of tree trunks and large stones under the wall material that were interpreted as wall stabilization measures (Figure 66). Also, a 50 cm thick gravel layer system was discovered under the half-circle wall deposit where the brook passes the wall today (Jankuhn, 1937b, 1938). This gravel layer most probably represents a water filtering system inferring that at this period the brook still played an important role in supplying the settlement with water. Although Jankuhn (1938) questioned this interpretation and pointed out that the amount of water carried by the brook would not have been sufficient for the supply of the town inhabitants, the gravel layer is undoubtedly an anthropogenic deposit as indicated by an anthropogenic wooden structure located within the gravel layer (Figure 66).

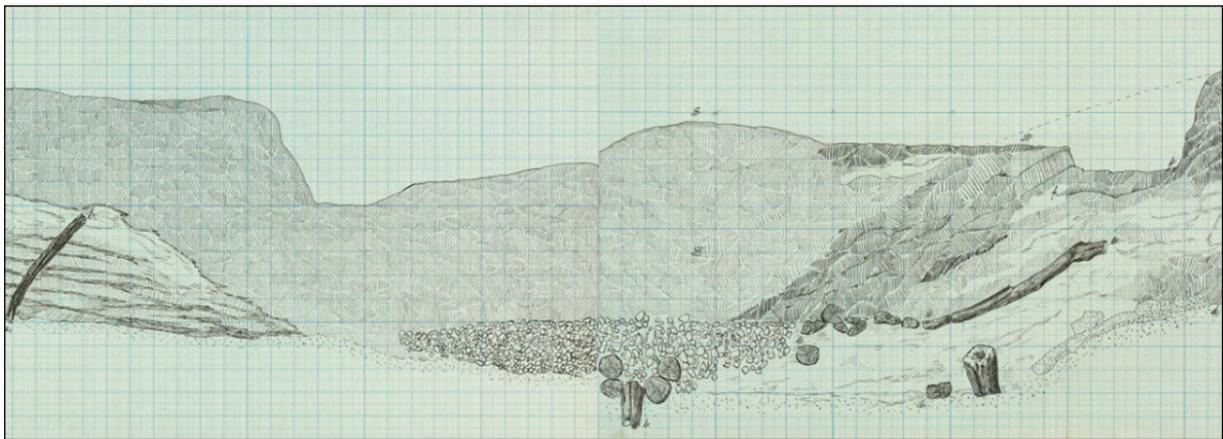


Figure 66. Drawing of the excavation profile in the wall opening in 1913, original scale 1 : 20 (Knorr and Rothmann, 1913).

It can be stated with a high degree of certainty that the gravel layer system was constructed at the beginning of the establishment of the half-circle wall to enable a safe underground passage of the water of the brook. Therefore, the wall apparently was continuous in this area in the Viking Age and served as an (intended) dam. The absence of the opening in the wall in the Viking Age is confirmed by fine sediments in the depression west of the half-circle wall discovered by Wendt (in preparation). These fine sediments point at standing water conditions in this depression. Most probably, these sediments date to the Viking Age as suggested by the preliminary pollen analysis (Wendt, in preparation). The filtering of water under the wall and the deposition of fine material in the depression would have prevented the transport of fine particles into the valley-like

structure in the settlement and hence explain the absence of such sediments in the filling of the structure.

Thus, the gravel layer under the wall indicates the importance of the brook in this period and the excavated valley-like structure could have served a hydrological engineering purpose. Since the water in Haddebyer Noor is brackish and all wells dated were constructed in the 10<sup>th</sup> century (Eckstein and Schietzel, 1977), Hedeby-brook must have been the main freshwater source in the earlier settlement phases in the 9<sup>th</sup> century (Schietzel, 2014). However, it is plausible that in dry seasons Hedeby-brook probably delivered not sufficient amounts of water and during heavy rainfall events, it could have posed a risk on the lower areas of the settlement due to flash floods. Therefore, the brook was artificially widened and deepened by humans perhaps to enhance the freshwater supply by increasing the discharge of percolating surface water into the valley and at the same time to reduce flood risks.

Thus, the valley-like structure would deliver more freshwater for humans and animals in Hedeby as well as to the workshops of the ironsmiths located on the northern slope of the valley. It is well-known that water is vital to the manufacture of iron artefacts and the production of pottery (Wikander, 2000). Although the street with metal workshops appeared in later Hedeby period (late 10<sup>th</sup> or 11<sup>th</sup> century (Hilberg, 2009)), some handcraft workshops were most probably already present there in the 9<sup>th</sup> and early 10<sup>th</sup> centuries. The stone deposit at the valley basis might have served to improve the access to the water and to reduce the muddiness of the ground. A use of coarse material for the stabilisation of the ground is known from the eastern part of Hedeby where iron slag fragments were found between fences and under wooden pathways, presumably to stabilize walking surfaces (Westphalen, 1989). Additionally, with a stone layer at the basis of the valley, the turbidity of the flowing water would be reduced. During this period, the basis of the structure was deepened locally by a narrow channel to a depth ca. 20 cm below the cultural stone layer. The valley-like structure was used until the second half of the 10<sup>th</sup> century.

It can be supposed that the location of the main workshop area in Hedeby at the northern slope of the valley was selected taking into account the access to freshwater provided by the brook. Negative effects of the brackish water from Haddebyer Noor were prevented as salts may cause corrosion of metals during smithing (Graedel, 1990). Importantly, workshop areas in Scandinavia were usually located at settlement margins (Tyler *et al.*, 2003) with a direct access to a water source (Figure 67) but on well-drained ground to avoid absorption of water by furnaces (Rundberget, 2016; Stenvik, 2003).

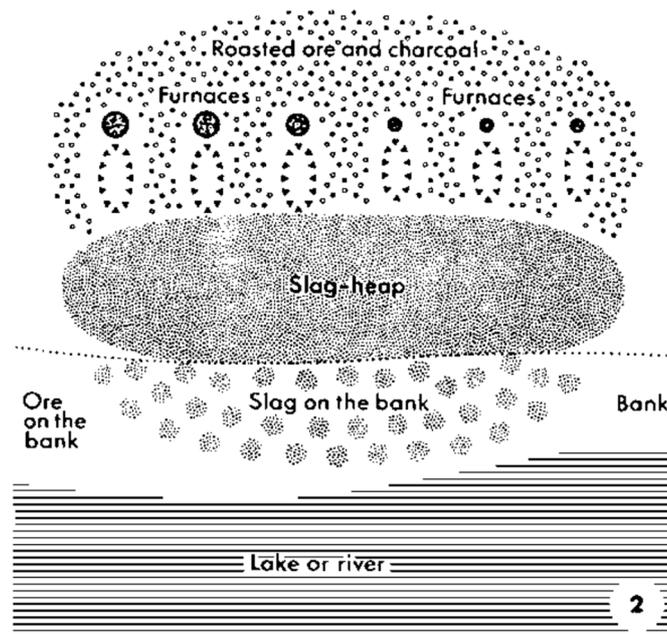


Figure 67. Model of an iron production site at the shore in Jämtland, Sweden. After G. Mangusson (Stenvik, 2003).

The combination of the findings, namely the extracted clay-rich deposits and the modified brook bed, require mentioning a specific technology of energy-based iron working. This method implies the use of water power of streams and rivers to drive bellows and hammers for smelting or preliminary smithing (Rundberget, 2016). Although this technology is known to be mastered in Sweden only in the 14<sup>th</sup> century (Stenvik, 2003) and in the early 15<sup>th</sup> century in England (Tylecote, 1986), the use of water power for other purposes has been known in Northern Europe in the early medieval period and earlier (Rynne, 2015; Wikander, 2000). The earliest water mill so far known in Scandinavia was excavated at Omgård in west Jutland, and it dates to the 10<sup>th</sup> century (Nielsen, 1986).

Thus, one consideration has to be noted in the context of findings in Hedeby. A fragment of a wooden paddle dated into the Viking settlement period presumably belonging to a water mill was found within Hedeby near the brook in the eastern part of the settlement (Westphal, 2013). Although some indirect indications for the existence of a water-power technology in Hedeby were suggested by Jankuhn (1936) and Hübener (1959), no other parts belonging to the presumed mill were found at the site where the paddle was discovered (Westphal, 2013). Therefore, if a water mill did exist in Hedeby, possibly it was initially situated in another part of the settlement or west of it. The human-made valley-like structure discovered seems to potentially suit the conditions necessary for a water mill.

Disregarding the initial purpose of the excavation of the valley-like structure, a large hollow structure was created in the town extending through the whole western part of the settlement. This human-made structure further separated the south-western part of the settlement with

burial grounds from the north-western part with handcraft workshops, which were earlier separated by the narrow brook. This separation must have considerably affected the life of the inhabitants in terms of access to the respective settlement areas or perhaps represented an intentional division of space based on the performed activities.

Some time after the construction of the half-circle wall and after the excavation of the valley structure, either fine material clogged the gravel layer under the wall and water through-flow was hindered or Hedeby-brook lost its importance as a freshwater source for the settlement. In this time period, the human-made valley-like structure started to fill with material eroded by runoff during heavy rainfall events from the neighbouring slopes (that were not well protected by vegetation) and by different waste materials from domestic sources and glass or metal workshops in the surroundings (Figure 68g). These processes started in the second half of the 10<sup>th</sup> century as indicated by multiple radiocarbon dates from the valley structure filling and other cores downstream. This agrees with the existing knowledge that water quality in the brook and in the Haddebyer Noor diminished during the intensive settlement activities due to waste disposal (Jankuhn, 1938; Kalmring, 2010), which probably explains the construction of numerous wells in later settlement phases (Schietzel, 2014). Thus, the excavated valley-like structure was used only for a short period of time (some years).

A small gully incised into the filling of the valley-like structure during the same settlement period, probably at the course of the brook (Figure 68h). Due to the scarce vegetation cover in the settlement, namely on inclined and compacted streets, erosion could take place during heavy rainfall events. Later, this gully was filled with alternating sandy and organic matter rich layers (Figure 68i).

After the abandonment of the settlement after 1066 AD, peat formation started on top of the Viking Age filling of the valley-like structure (Figure 68j). It ended latest during Modern Times, when agricultural land use started in the area of the former settlement. Ploughing had the following consequences:

- the erosion of the cultural layer on the slopes by water and its deposition as colluvium at lower slope positions (Figure 68k, l),
- transport of the material downslope on inclined slopes,
- homogenization of the layer near the land surface.

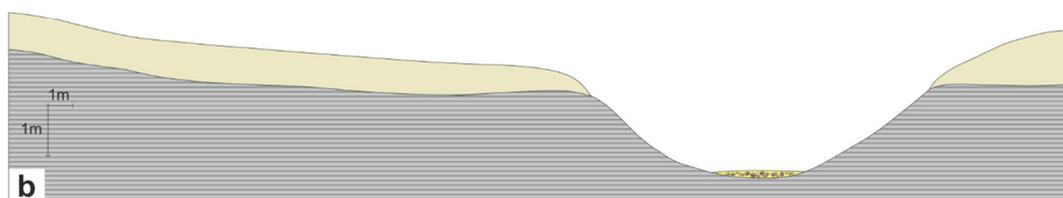
As a result of ploughing and soil erosion, a homogenised colluvial layer has grown during the last centuries at the downslope areas and in the valley-like structure on top of the peat. A few decades ago, intensive land use ended and soil formation in grassland caused the formation of peat at the modern course of the brook and of a humic soil horizon on the slopes (Figure 68l).

To summarize the interpretation, it can be concluded that the discovered valley-like structure represents a human-made form that was created probably by the inhabitants of Hedeby in the Viking Age. It seems likely that a purposeful combination of different practical goals related to some sort of landscape engineering was behind this highly labour-consuming activity. For a more precise interpretation, further research involving full-scale excavations is necessary, as no comparable structures are known from other contemporary sites. Nevertheless, the period of use of the valley-like structure in Hedeby was rather short, as indicated by the features of waste disposal in the structure from different domestic and handcraft sources in the nearest surrounding. The process of waste disposal in the valley structure started already at the end of the 10<sup>th</sup> century latest when the settlement was still in its intensive phase.

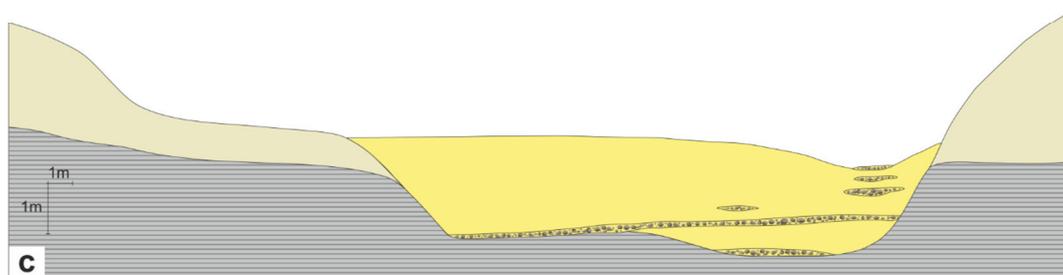
**Late Weichselian glacial stage:** deposition of clastic varves in a proglacial lake



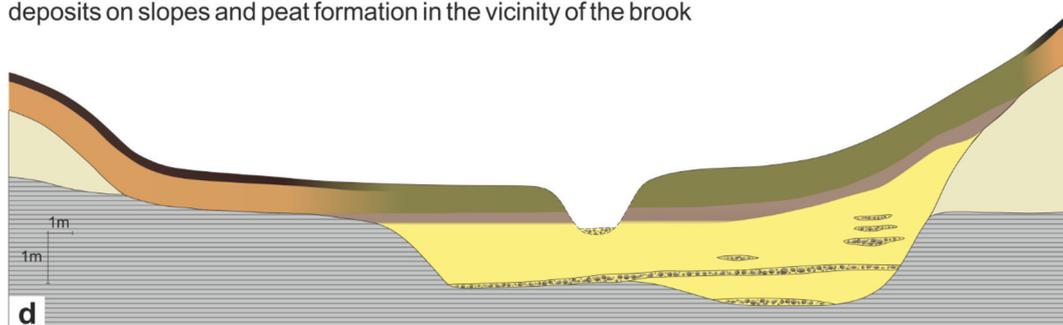
**Late Weichselian glacial stage:** deposition of fluvioglacial sand during further glacier melting and incision of a gully by high velocity runoff



**Late Weichselian glacial stage:** widening of the gully into a valley, meandering of the stream bed and deposition of gravel layers, accompanied by filling of the valley with sandy material



**Early Holocene until early medieval period:** soil formation (Cambisol) in sandy Pleistocene deposits on slopes and peat formation in the vicinity of the brook



**Beginning of the Viking Age, early settlement phase (end of the 8<sup>th</sup> – 9<sup>th</sup> cent. AD):** formation of the cultural layer due to settlement activities

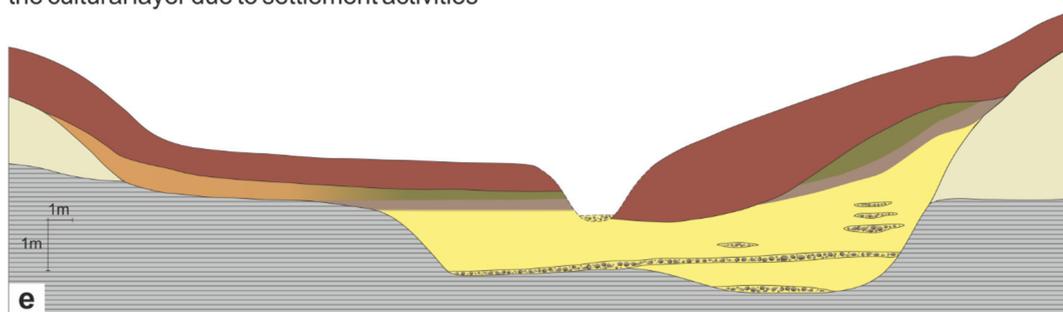
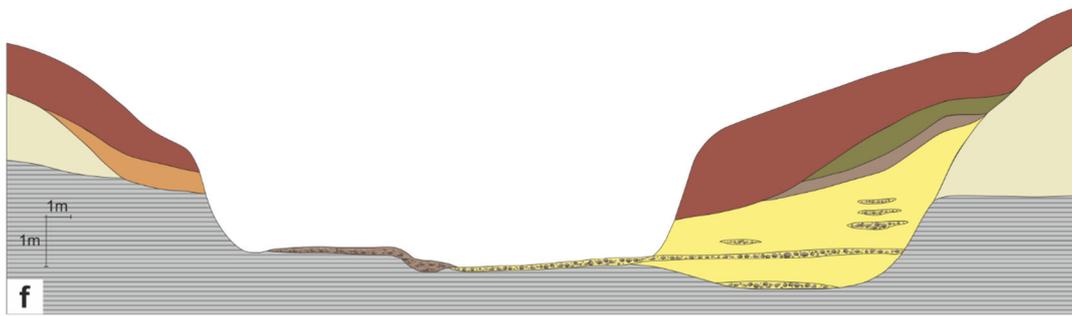
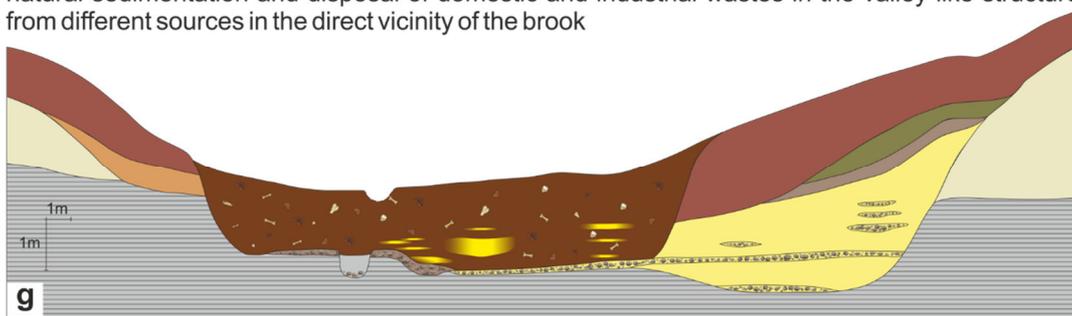


Figure 68. Main phases of local landscape transformation at the Hedeby-brook (a- e) (continued on the next page).

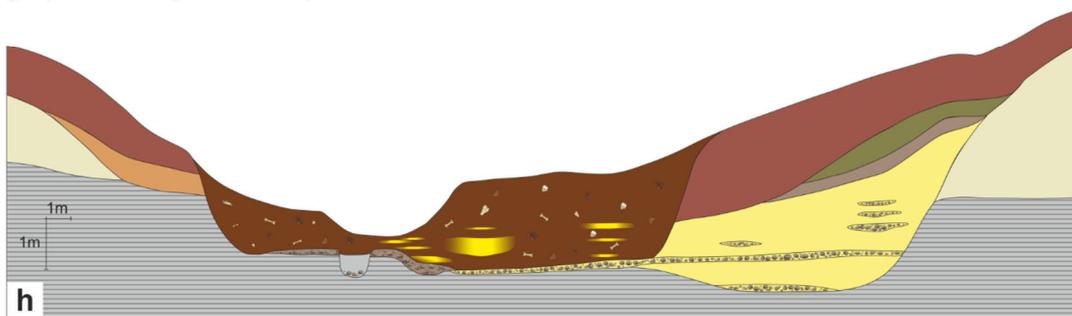
**Viking Age, second half / end of the 10<sup>th</sup> cent. AD:** deepening and widening of the brook by excavation, formation of the valley-like structure and deposition of the cultural stone layer by humans



**Viking Age, intensive settlement activities (after end of the 9<sup>th</sup> / end of the 10<sup>th</sup> cent. AD):** natural sedimentation and disposal of domestic and industrial wastes in the valley-like structure from different sources in the direct vicinity of the brook



**Viking Age, intensive settlement activities (end of the 9<sup>th</sup> - 11<sup>th</sup> cent. AD):** Incision of a small gully in the filling of the valley



**Viking Age, intensive settlement activities (end of the 9<sup>th</sup> - 11<sup>th</sup> cent. AD):** filling of the small gully by alternating layers of sand and material rich in organic matter

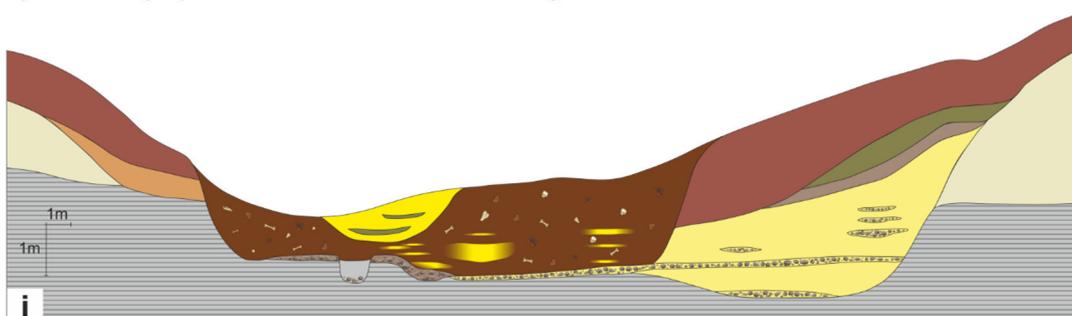
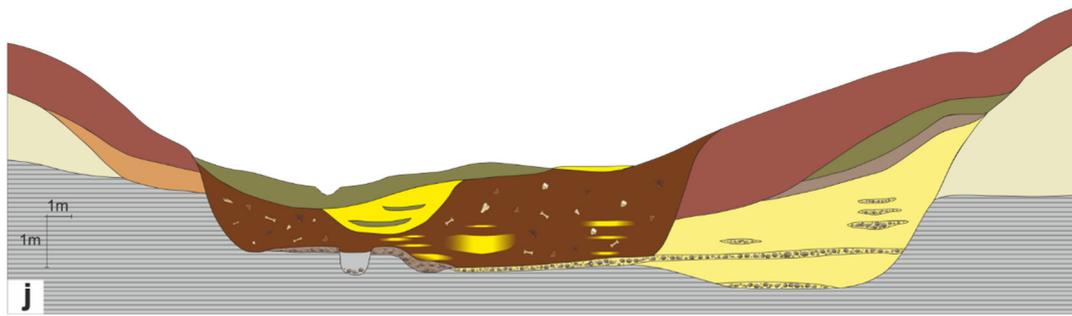
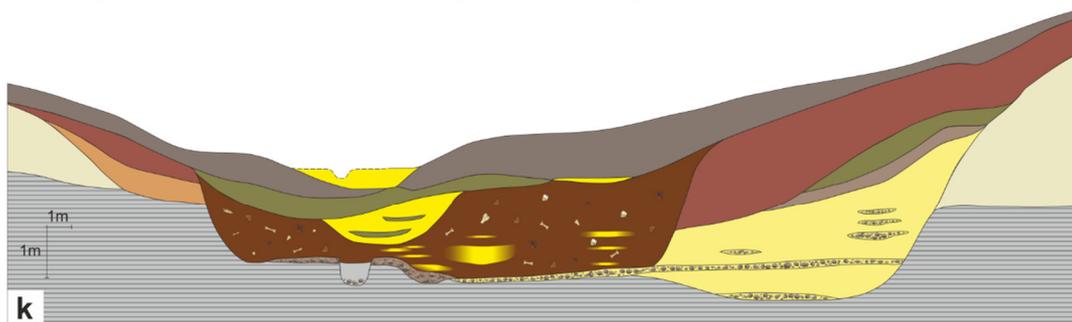


Figure 68. Main phases of local landscape transformation at the Hedeby-brook (f - i) (continued on the next page).

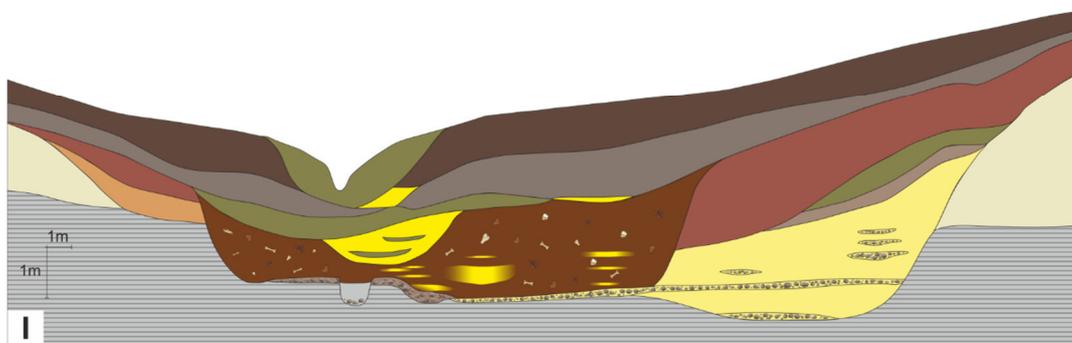
**Mid-11<sup>th</sup> cent. – late medieval period / Modern times:** peat formation after abandonment of the settlement



**Late medieval period – Modern times:** erosion of the cultural layer on the slopes and deposition in the valley in the form of colluvium due to agricultural activity



**Late medieval period – Modern times:** homogenization of the colluvium of the cultural layer by ploughing, peat formation at the modern course of Hedeby-brook



Cultural layer	Sand	Clastic varves
Colluvium of the cultural layer	Peat and peat-like material	Sandy filling of the Pleistocene valley
Homogenized cultural layer and colluvium of cultural layer	Buried soil A horizon	Pleistocene gravel layer
Valley filling	Buried soil Bw horizon	Stones
Cultural stone deposit	Buried soil Bh horizon	Bones
Clay material	Fluvioglacial sand	Artefacts

Figure 68. Main phases of local landscape transformation at the Hedeby-brook (j – l).

## 7. CONCLUSIONS

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For the first time a detailed geoarchaeological research has been carried out in the former Viking town Hedeby. Although Hedeby belongs to the archaeologically most intensively investigated Viking Age sites, only scarce information about local soil and landscape transformation had been available. In the framework of the research presented in this thesis, two main goals were formulated: (1) to describe and classify the heterogeneous soils and settlement deposits of Hedeby and (2) to reconstruct local landscape transformation in the central part of the town at the Hedeby-brook. Based on 178 soil and sediment cores as well as detailed stratigraphic, geo-ecological and micromorphological analyses, the following conclusions corresponding to the research goals were reached:

1. 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. In order to describe and improve the understanding of the complex stratigraphy of the heterogeneous soil and sediment sequences of different genesis sampled by drilling techniques, a new approach for soil and sediment classification was developed. It is based on multivariate statistical analysis of a set of geo-ecological parameters by principal component analysis and cluster analysis. The set of parameters applied in this research includes organic matter content, magnetic susceptibility, contents of the coarse fraction (>2 mm), artefacts, bones and wood/charcoal. These parameters can be determined rapidly and cost-effectively and they proved to be appropriate for the situation in Hedeby. Due to the differing preservation character of the parameters considered, correct conclusions could be drawn, even if some of the parameters were affected by post-depositional changes. Also, since the magnitudes of the parameters were reflecting different kinds of settlement activities, hypotheses regarding land use in the adjacent areas could be made.

An objective and reliable differentiation between natural and cultural deposits could be done. Diverse cultural deposits were further distinguished in terms of organic matter content, coarseness and degree of intensity of anthropogenic signals. For the group of materials with transitional properties it was shown that the application of additional parameters, for instance element contents, can enhance the level of classification detail and quality.

Based on the analysis of buried soils and settlement deposits, soil transformation in the context of settlement activities could be traced. Buried soil horizons that represent remnants of soils that were exposed at the land surface before the Viking Age were analysed. It was revealed that before the onset of settlement activities, the territory of Hedeby represented a woodland with Cambisols as the main soil type. In the beginning of the Viking

Age, due to land use and vegetation changes, soil transformation took place. In some places, probably under heath vegetation, Cambisols acquired podzolization features. In result of settlement activities within the half-circle wall of Hedeby, a wide variety of settlement deposits have formed including cultural layers, waste deposits and other archaeosediments, which could be described using the proposed approach. The resulting classification lead to a much better understanding of the complex stratigraphy and enabled a reliable correlation of sequences in cores, which was necessary to perform the subsequent research steps.

2. The research results allow stating that inhabitants of Hedeby altered the geomorphologic situation within the settlement to a much larger extent than thought before. The evidence suggests that in the western part of the settlement at the brook, which represented the main freshwater source during the early settlement period, humans excavated a large valley-like structure during the Viking Age. Today this structure is filled with sediments and soils of different genesis.

In the Viking Age, approximately ten thousand cubic meters of material were removed by humans and probably used for different settlement activities. This implies high labour costs that had to be invested by the inhabitants of the town and perhaps the neighbouring settlements into the planning and realization of this landscape-engineering project. Based on the analysis of cores, the main phases of local landscape transformation before, during and after Viking age settlement activities were reconstructed. Most probably, the structure was excavated in the same period when the half-circle wall was constructed at the place where a flat Pleistocene valley was located. Some hypotheses were suggested for the intentions behind this activity with material extraction for wall construction and water management being the most probable ones. However, some years later during the intensive settlement period the structure started to be filled with sediments and waste. Results of micromorphological analysis of cultural layers on the slopes of the structure inferred the conclusion that waste material originated from the direct surrounding of the structure. After abandonment of the settlement, peat formation occurred in the structure and later, due to the agricultural land use of the area in late medieval and Modern times, deposition of a colluvium consisting of the reworked cultural layer took place there.

The large valley-like structure undoubtedly played a major role in the organization and functioning of the town at least in the early settlement phase. Moreover, it in fact divided the whole western part of the settlement into a northern and a southern part. Probably, special constructions like wooden bridges were necessary to enable a direct access from the northern to the southern part and vice versa. These research outcomes significantly change our state of knowledge about the characteristics of the landscape of the famous Viking town Hedeby.

The two main results of this research did not only deliver new information about Hedeby, but their outcomes can be used for investigations at other sites regardless their spatial or temporal constraints. The developed approach for the classification of various settlement deposits is well applicable to other settlements, only the set of parameters has to be modified and adapted to the local conditions. Since the classification approach is based on simple and cost-effective measurements, it can be used in the first research step after field surveys to select sites where detailed investigations are necessary and to develop a correct and reproducible stratigraphy. Particularly for sites where only drillings are possible, this approach may significantly help to improve the understanding of the variety of sediments in cores, to provide a better overview of stratigraphy and to prepare a solid and reproducible basis for further research steps. However, it has to be mentioned that the classification approach should not be considered as a completely “automated” procedure of classification but as an assisting tool when large numbers of cores and samples are to be analysed, particularly at such complex study sites as former settlements.

The discovery of the buried anthropogenic valley-like structure in the central part of Hedeby has no analogies at other Viking Age sites. Its interpretation is essential for our understanding of the settlement patterns in the Viking Age. Although hypotheses about possible reasons for its excavation have been suggested in cooperation with archaeologists, further research is necessary to reveal the goal behind this elaborate landscape-engineering project. This finding also emphasizes the importance of interdisciplinary research at archaeological sites with an effective involvement of natural scientists, most importantly, geomorphologists, geoarchaeologists and soil scientists.



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## Appendices

### Appendix 1. Field classification of soils and sediments in Hedeby based on morphological properties.

Horizon/ layer	Description	Colour	Texture*
<b>Pleistocene deposits</b>			
<b>C<sub>sand</sub></b>	homogeneous well-sorted fluvio-glacial sand material	10YR 7/4, 7/3, 6/6, 5/4	Fsa+Msa; Msa+Fsa; Msa; Fsa
<b>C<sub>silt</sub></b>	homogeneous Pleistocene mostly silty material	5Y 6/2, 7/1	Si+Clay
<b>C<sub>clay</sub></b>	homogeneous Pleistocene clay material	10YR 6/6, Gley1 4/10Y-5/10Y, 5Y 3/1-4/1, 2.5Y 6/4-6/3	Clay loam, clay
<b>C<sub>layered</sub></b>	clastic varves representing alteration of thin layers of clay, silt, sand	Depending on redox conditions: 5Y 5/1-5/2, 10 YR 6/3, 5/6, 7.5YR 5/8, 2.5Y 4/1	Fine layering of Clay, Msa, Fsa and silt layers
<b>C<sub>till</sub></b>	dense material of glacial till rich in stones and calcium carbonate	5Y 4/1, 5/1	Si, Cl, Msa+Fsa
<b>Soil horizons</b>			
<b>A<sub>hb</sub></b>	humic horizon of a buried soil	10YR 3/2, 2/2	Fsa+Msa+Si; Msa+Fsa; Fsa+Si
<b>A<sub>Eb</sub></b>	humic horizon of a buried soil with eluviation features	10YR 5/2-4/2	Fsa+Msa+Si; Msa+Fsa
<b>A<sub>p</sub></b>	ploughing layer	10YR 2/2, 3/1, 3/2	Msa+Si; Msa+Fsa+Si; Fsa+Msa+Si
<b>B<sub>wb1</sub></b>	Bw-horizon of a buried soil (reddish due to weathering) (upper part)	10YR 3/3-3/4, 10YR 3/6-4/6	Msa; Msa+Fsa, Fsa and Msa
<b>B<sub>wb2</sub></b>	Bw-horizon of a buried soil (reddish due to weathering) (lower part)	10YR 4/6, 5/6, 6/6	Msa, Msa+Fsa, Msa and Fsa, Fsa+Msa
<b>B<sub>whb</sub></b>	Bw-horizon of a buried soil enriched with organic matter	10YR 3/3, 10YR 4/6	Msa and Fsa
<b>B<sub>tb</sub></b>	B-horizon of a buried soil with clay enrichment bands	10YR 7/3-7/4, 7/6	Msa, (Fsa)
<b>A<sub>hM</sub></b>	Ah-horizon formed in colluvial material	10YR 5/2, 3/1	Msa+Fsa
<b>Mineral layers/deposits</b>			
<b>Gravel</b>	layer (as a rule up to 5 cm) dominated by gravel or pebble with presence of coarse sand	10YR 3/1, 6/3-5/3, 4/2-3/2	Gravel, embedding material: Csa, Msa+Csa
<b>Coarse sand</b>	layer dominated by coarse sand often with presence of gravel	10YR 6/4, 2.5Y 5/2-4/2, Gley1 4/2	Csa, Csa+Gravel
<b>Sand</b>	layer dominated by sand material; Sand <sub>h</sub> if enriched with organic matter	Very different. Tendency: 10YR 5/4, 6/4, 5/3, 6/3, 7/2	Msa, Msa+Fsa, Fsa+Msa, Msa+Csa
<b>Silt</b>	layer dominated by silty material	10YR 5/4, 2.5Y 5/3-5/4	Si, Si+Clay, Si+Fsa
<b>Clay</b>	layer dominated by clay loam material	10YR 5/4, 4/3, 3/3	Clay loam, Clay+Fsa, Clay
<b>Grey sand</b>	layer of relatively well-sorted sand material of light to dark grey colour	10YR 3/1, 4/4-5/4, 4/1	Msa+Fsa, Msa+Csa, Msa, Fsa+Msa
<b>L</b>	pond sediments	10YR3/2, 2.5Y 3/1, 3/2	Clay+Si, Clay+Fsa+Msa

Horizon/ layer	Description	Colour	Texture*
<b>Organic layers</b>			
<b>O</b>	layer dominated by organic matter and undecomposed decomposed plant remains	10YR 3/2, 7.5YR 2.5/2	Mostly organic material
<b>H</b>	dense dark brown layer of very fine decomposed organic material (nearly no mineral material)	10YR 2/2-2/1	Mostly organic material
<b>He</b>	organic H-horizon dominated by weakly/moderately decomposed plant remains	10YR 2/2-2/1, 3/1	Mostly organic material (with occasional presence of Fsa+Msa grains)
<b>Ha</b>	organic H-horizon dominated by highly decomposed plant remains	10YR 2/2-2/1, 3/1	Mostly organic material
<b>H<sub>wood</sub></b>	layer dominated by undecomposed and/or weakly decomposed wood remains with presence of a very low amount of mineral material	10YR 3/2 2/2, 2/1	Strongly dominated by organic material; in case of mineral material presence: Fsa+Si
<b>He<sub>wood</sub></b>	organic H-horizon dominated by weakly decomposed plant remains with presence of undecomposed wood remains	10YR 2/2-2/1	Mostly organic material (with occasional presence of Fsa+Si grains)
<b>Cultural layers and anthropogenically affected sediments</b>			
<b>Y</b>	sediment of anthropogenic origin (wall material, knick material, moat filling, construction material etc.)	Very different depending on material	Very different depending on material
<b>Y<sub>cult</sub></b>	not homogenized cultural layer with artefacts and charcoal (or its colluvium)	10YR 2/1, 3/1, 2/2, 3/2	Fsa+Si, Msa+Fsa+Si, Loamy sand
<b>Y<sub>cult,org</sub></b>	Heterogeneous layer rich in organic matter and with presence of such waste materials as bones, sherds etc. (usually in mixture with Hn)	10YR 2/2, 2/1	Heterogeneous
<b>Y<sub>wood</sub></b>	Mineral cultural material with presence of a large amount of wood remains	10YR 2/2, 2/1	Heterogeneous
<b>Y<sub>cult-hom</sub></b>	homogenized cultural layer (by ploughing) with or without artefacts (or its colluvium)	10 YR 2/2, 3/2, 3/1	Loamy sand, Fsa+Msa+Si, Msa+Fsa+Si
<b>Y<sub>ch</sub></b>	layer of dispersed charred material (often with a high content of charcoal)	10YR 2/1 (black)	Fsa; Fsa+Msa+Si
<b>Y<sub>ash</sub></b>	light to dark grey layer of ash	10YR 2/1, 2.5Y 6/1	ND
<b>Gravel<sub>cult</sub></b>	gravelly material dominated by stones of different shape embedded in fine humic matrix, with presence of artefacts	10YR 3/1, 4/4-5/4, 4/1	Gravel, embedding material: Msa+Fsa+Si
<b>Re-deposited (colluvial) sediments</b>			
<b>M</b>	colluvial layer of unclear origin with presence of organic matter	10YR 2/2, 3/2, 3/1	Fsa+Msa+Si, Msa
<b>M<sub>h</sub></b>	dark-coloured colluvial material with a high content of organic matter (not clear: MAh or AhM)	10YR 3/1, 2/2	Msa+Fsa+Si
<b>M<sub>wall</sub></b>	colluvium of wall material	10YR 3/2, 3/3	Fsa+Msa+Si; Msa+Fsa+Si

<b>Horizon/ layer</b>	<b>Description</b>	<b>Colour</b>	<b>Texture*</b>
<b>M<sub>layered</sub></b>	heterogeneous layer with a prominent alteration of sublayers of different materials	ND	ND
<b>MBw</b>	colluvium of soil B-horizon	10YR 3/4, 5/3	Msa+Fsa+Si, Fsa+Msa
<b>MAh</b>	colluvium of soil Ah-horizon	10YR 2/2	Fsa+Si+(Cl)
<b>M<sub>cult</sub></b>	colluvium of cultural layer: rich in artefacts and charcoal with strong evidence of re-deposition (often layered)	10YR 2/1, 2/2	Fsa+Msa+Si; Msa+Fsa+Si
<b>M<sub>cult-hom</sub></b>	homogenized colluvium of cultural layer	10YR 2/1, 2/2	Fsa+Msa+Si; Msa+Fsa+Si
<b>Disturbance structures and mixed layers</b>			
<b>Y<sub>y</sub></b>	disturbance structure (due to human or animal activity)	Different colours depending on the nature of the disturbance/mixture	Different grain size depending on the nature of the disturbance/mixture
<b>Mix:...</b>	heterogeneous layer representing a mixture of different materials		
<b>Additional indexes</b>			
<b>(ch)</b>	with presence of charred material		
<b>(red)</b>	with reduction features		
<b>(ox)</b>	with oxidation features		
<b>(layered)</b>	with fine layering of more or less the same material (otherwise M <sub>layered</sub> )		
<b>(wall)</b>	wall material		
<b>(knick)</b>	knick material		
<b>(moat)</b>	moat filling		
<b>(an)</b>	affected by animal activity		
<b>(light)</b>	the upper part of the layer becomes considerably lighter in colour during drying		
<b>(trans)</b>	layer transitional to the underlying material		
<b>(hard)</b>	dense and hard material		

\* Csa – coarse sand, Msa – medium sand, Fsa – fine sand, Si – Silt, Cl – clay

**Appendix 2. Composition of the clusters obtained at relative linkage distance 8.2 %.**

Cluster nr.	Layer ID (field classification)	Core nr.	Sampling depth	Sample ID
1	Mcult-hom	73	10-20	A1-1
1	Mcult-hom	73	70-85	A1-7
1	Mix: Mcult-hom+Sand	73	85-92	A1-8
1	Mcult-hom	74	0-10	A2-1
1	Mcult-hom	74	70-82	A2-8
1	Mix: Mcult-hom+Sand(layered)	74	100-118	A2-10
1	Mcult-hom	198	30-40	198-1
1	Mcult-hom	198	50-60	198-3
1	Mix:Ycult+Hwood+Sand(layered)	198	270-277	198-29
1	Hawood	198	342-350	198-39
1	Mcult-hom	270	0-20	270-1
1	Mcult-hom	441	60- 69	441-1
1	Mcult-hom	442	10-20	442-1
1	Mix:Mcult+Sand	311	61-83	311-3
1	Ha	311	83-88,5	311-4
1	Hn(channel?)	413	248-253	413-1
1	B	25	140-155	25-2
1	fBv1	30	72-100	30-1
2	Mh	73	340-350	A1-28
2	Csand	73	350-352	A1-29
2	Mix: Mcult-hom+Sand(layered)	74	118-120	A2-11
2	Mix:Mh+Sand	74	386-398	A2-31
2	Csand	198	373-376	198-44
2	Sand	270	100-110	270-9
2	Mix:Sand+Mh+Ycult+Gravel(layered)	270	260-266	270-24
2	Mix:Sand+Mh+Ycult+Gravel(layered)	270	282-288	270-28
2	Clayered	441	343- 351	441-30
2	fAh/Yy	34	103-118	34-1
2	fBv1	34	118-130	34-2
2	fBv2	34	130-150	34-3
2	Csand	34	150-200	34-4
2	fBv2	36	132-149	36-1
2	fAe1	1401	659-668	1401-1
2	fAe2	1401	668-678	1401-2
2	fAe2-B (trans)	1401	678-688	1401-3
2	fBv	1401	688-700	1401-4
3	Mcult-hom	73	20-30	A1-2
3	Mix: Mcult-hom+Sand	73	92-96	A1-9
3	Gravel	73	334-340	A1-27
3	Sand	198	320-333	198-37
3	Gravel	198	369-372	198-42
3	Csand	198	372-373	198-43
3	Csand	198	376-380	198-45
3	Gravel	270	223-227	270-19
3	Fine Sand	270	238-248	270-21
3	Mix:Sand+Mh+Ycult+Gravel(layered)	270	294-299	270-30
3	Mix:Sand+Mh+Gravel	270	311-328	270-32
3	Gravel	270	328-341	270-33
3	Sand(h)	270	341-351	270-34

Cluster nr.	Layer ID (field classification)	Core nr.	Sampling depth	Sample ID
3	Mix:Sand+Mh(layered)	441	200- 218	441-14
3	Gravel(cult)	441	326- 335	441-28
3	Clayered	441	335- 343	441-29
3	Gravel	442	372-382	442-30
3	Gravel	442	382-391	442-31
3	Clayered	442	391-400	442-32
3	Sand	300	278-286	300-24
3	Gravel	300	348-355	300-29
3	Mix:Sand+H+Gravel	300	355-364	300-30
3	Mix:Sand+H+Gravel	300	364-378	300-31
3	Mix:Sand+H+Gravel	300	378-389	300-32
3	Gravel	300	389-396	300-33
3	Clayered	300	396-400	300-34
3	Mix:Sand+H(layered)	311	324-331	311-21
3	Mix:H+Sand+Gravel	311	382-387	311-28
3	Mix:H+Sand+Gravel	311	387-381	311-29
3	Gravel	311	391-400	311-30
3	fAh	25	120-135	25-1
3	fBbt	30	100-200	30-2
3	fBbt	36	149-178	36-2
3	Csand	36	178-200	36-3
4	Mix: Mcult-hom+Sand	74	82-100	A2-9
4	Mix: Mcult-hom+Sand(layered)	74	126-130	A2-13
4	Ycult(ch)	74	184 - 200	A2-20
4	Mix:Hewood+Ycult	198	184-190	198-16
4	Mix:Hewood+Ycult	198	212-217	198-20
4	Mix:Ycult+Hwood+Sand(layered)	198	248-254	198-26
4	Mix:Ycult+Hwood+Sand(layered)	198	293-297	198-33
4	Sand	198	297-300	198-34
4	Sand	198	304-308	198-35
4	Hawood	198	350-360	198-40
4	Mcult-hom	270	20-31	270-2
4	Mix:Mh+Sand(layered)	270	70-81	270-6
4	Mix:Sand+Mh+Ycult+Gravel(layered)	270	254-260	270-23
4	Mcult-hom	441	87- 100	441-4
4	Mix:Sand+Mh+Hwood(layered)	441	157- 167	441-10
4	Mix:Ycult+Sand(layered)	441	262- 267	441-20
4	Mcult	442	175-190	442-15
4	Mcult-hom	300	24-36	300-2
4	Mcult	300	77,5-93	300-7
4	Mix:Ha+Hwoo	300	126-136	300-10
4	Mix:Sand+Mh	300	260-263	300-21
4	Mix:Hwood+H+Sand	311	237-258	311-16
4	Mix:Sand+H+Hwood	311	258-272	311-17
5	Mix:Ycult+Hwood+Sand(layered)	198	262-270	198-28
5	Mix:Ycult+Hwood+Sand(layered)	198	277-281	198-30
5	Mix:Ycult+Hwood+Sand(layered)	198	281-287	198-31
5	Mix:Mh+Sand(layered)	270	81-87	270-7
5	H	270	150-164	270-13
5	Mix:Sand+Mh+Ycult+Gravel(layered)	270	277-282	270-27

Cluster nr.	Layer ID (field classification)	Core nr.	Sampling depth	Sample ID
5	Mix:Sand+Mh+Ycult+Gravel(layered)	270	288-294	270-29
5	Mix:Sand+Mh+Ycult+Gravel(layered)	270	299-311	270-31
5	Mix:Sand+Mh+Hwood(layered)	441	167-179	441-11
5	Mix:Sand+Mh+Hwood(layered)	441	179- 190	441-12
5	Mix:Sand+Mh(layered)	441	190-200	441-13
5	Mix:Sand+Mh(layered)	441	218- 228	441-15
5	Mix:H+Sand	311	94-116	311-6
5	Mix:H+Sand	311	116-125	311-7
5	Mix:H+Sand	311	125-135	311-8
5	Mix:Hwood+Wood piece	311	184-200	311-13
5	Mix:Hwood+Wood piece	311	223-237	311-15
5	Mix:Sand+H+Hwood	311	272-290	311-18
5	Mix:Sand+H+Hwood	311	290-300	311-19
5	Mix:Sand+H(layered)	311	331-339	311-22
5	Hwood	311	345-357	311-24
5	Mh (channel?)	120	290-296	120-1
6	Ha	198	150-160	198-13
6	Ha	198	160-170	198-14
6	Ha	198	170-178	198-15
6	Ha	270	52-70	270-5
6	Ha	441	147- 158	441-9
6	H	311	88,5-94	311-5
6	Ha	311	135-139	311-9
6	Ha	311	139-151	311-10
6	Ha	311	170-184	311-12
6	Ha	120	168-175	120-2
6	Ha	401	91-97	401-2
6	Ha	413	136-142	413-2
7	Mcult-hom	73	30-40	A1-3
7	Mcult-hom	73	40-50	A1-4
7	Mcult-hom	73	50-60	A1-5
7	Mcult-hom	73	60-70	A1-6
7	Mcult-hom	74	20-30	A2-3
7	Mcult-hom	74	30 - 40	A2-4
7	Mcult-hom	74	40 - 50	A2-5
7	Mcult-hom	74	50 - 60	A2-6
7	Mcult-hom	74	60-70	A2-7
7	Mix: Mcult-hom+Sand(layered)	74	120 -126	A2-12
7	Mcult	198	130-140	198-11
7	Mcult	198	140-150	198-12
7	Mcult-hom	270	31-41	270-3
7	Mcult-hom	270	41-52	270-4
7	Mcult	441	105- 115	441-5
7	Mcult	441	125-136	441-7
7	Mcult	441	136- 147	441-8
7	Mcult-hom	311	22-41	311-1
7	Mcult-hom	311	41-61	311-2
8	Mcult-hom	74	10-20	A2-2
8	Mcult-hom	198	40-50	198-2
8	Mcult-hom	198	60-70	198-4

Cluster nr.	Layer ID (field classification)	Core nr.	Sampling depth	Sample ID
8	Mcult-hom	198	70-80	198-5
8	Mcult	198	80-90	198-6
8	Mcult	198	90-100	198-7
8	Mcult	198	110-120	198-9
8	Mcult	198	120-130	198-10
8	Mcult-hom	441	69- 78	441-2
8	Mcult-hom	442	33-45	442-3
8	Mcult-hom	442	45-58	442-4
8	Mcult-hom	442	58-70	442-5
8	Mcult-hom	442	70-82	442-6
8	Mcult-hom	442	82-91	442-7
8	Mcult-hom	442	91-100	442-8
8	Mix:Mcult+Sand	442	100-120	442-9
8	Mix:Mcult+Sand	442	120-129	442-10
8	Mcult	442	139-150	442-12
8	Mcult	442	162-175	442-14
9	Mix:Sand+Mh+Ycult+Gravel(layered)	270	248-254	270-22
9	Mcult-hom	441	78- 87	441-3
9	Gravel(cult)	441	318- 326	441-27
9	Mcult-hom	442	20-33	442-2
9	Mix:Sand+Mh(layered)	442	200-215	442-17
9	Sand	300	300-315	300-26
9	Sand	300	315-330	300-27
9	Sand	300	330-348	300-28
10	Mix: Mcult-hom+Sand	73	96-108	A1-10
10	Mix:Ycult+Sand(layered)	73	124-127	A1-12
10	Ycult(ch)	73	145-167	A1-17
10	Ycult(ch)	73	167-182	A1-18
10	Ycult(ch)	73	182-200	A1-19
10	Mix:Sand+Ycult	73	200-227	A1-20
10	Mix:Sand+Ycult	73	227-247	A1-21
10	Gravel(cult)	73	247-264	A1-22
10	Mix:Ycult+Gravel	74	216- 230	A2-22
10	Mix:Ycult+Gravel	74	230 -250	A2-23
10	Ycult(ch)	74	276-288	A2-26
10	Mcult	198	100-110	198-8
10	Mix:Hewood+Ycult	198	200-207	198-18
10	Mix:Sand+Mh+Ycult+Gravel(layered)	270	274-277	270-26
10	Mcult	441	115- 125	441-6
10	Mix:Ycult+Sand(layered)	441	257-262	441-19
10	Mix:Mcult+Sand	442	129-139	442-11
10	Mcult	442	150-162	442-13
10	Mcult	300	74-77,5	300-6
10	Mix:Mcult+Sand(layered)	300	93-100	300-8
10	Mix:Mcult+Sand(layered)	300	115-126	300-9
10	Mix:Sand+Ycult+Hwood	300	236-243	300-18
10	Mix:Sand+Ycult+Hwood	300	243-252	300-19
11	Mix:Ycult+Sand(layered)	73	127-132	A1-13
11	Mix:Ycult+Sand(layered)	73	132-135	A1-14
11	Ycult(ch)	74	130-140	A2-14

Cluster nr.	Layer ID (field classification)	Core nr.	Sampling depth	Sample ID
11	Ycult(ch)	74	150-165	A2-16
11	Mix:Hewood+Ycult	198	217-222	198-21
11	Mix:Ycult+Hwood+Sand(layered)	198	242-248	198-25
11	Mix:Ycult+Hwood+Sand(layered)	198	254-262	198-27
11	Mix:Ycult+Hwood+Sand(layered)	198	287-293	198-32
11	Mcult	442	190-200	442-16
11	Ycult,org	442	282-300	442-23
11	Mix:Ycult+Sand(layered)	442	335-346	442-27
11	Mix:Ycult+Sand(layered)	442	346-359	442-28
11	Mcult-hom	300	60-74	300-5
11	Mix:Ha+Hwoo	300	136-144	300-11
11	Ha	311	151-170	311-11
12	Mix:Ycult+Sand(layered)	73	135-140	A1-15
12	Mix:Ycult+Sand(layered)	73	140-145	A1-16
12	Ycult(ch)	73	264-280	A1-23
12	Ycult(ch)	74	140-150	A2-15
12	Mix:Sand+Ycult(layered)	74	176-184	A2-19
12	Mix:Hewood+Ycult	198	207-212	198-19
12	Mix:Mh+Sand(layered)	270	87-100	270-8
12	Mix:Sand+Ycult	270	122-130	270-11
12	Mix:Ycult+Sand(layered)	441	267-273	441-21
12	Mix:Ycult+Sand(layered)	441	282-295	441-23
12	Mix:Sand+Mh(layered)	442	215-224	442-18
12	Ycult,org	442	224-241	442-19
12	Ycult,org	442	241-251	442-20
12	Ycult,org	442	265-282	442-22
12	Mix:Ycult+Sand(layered)	442	313-324	442-25
12	Mix:Ycult+Sand(layered)	442	324-335	442-26
12	Mix:Ha,wood+Ycult,org,ch	300	152-168	300-13
12	Mix:Ha,wood+Ycult,org,ch	300	168-181	300-14
12	Mix:Ha,wood+Ycult,org,ch	300	181-190	300-15
12	Mix:Ha,wood+Ycult,org,ch	300	190-200	300-16
12	Mix:Sand+H(layered)	311	300-324	311-20
12	Mix:Sand+H(layered)	311	372-382	311-27
13	Mix:Hewood+Ycult	198	190-200	198-17
13	Mix:Ycult+Hwood+Sand(layered)	198	222-227	198-22
13	Mix:Ycult+Hwood+Sand(layered)	198	227-237	198-23
13	Mix:Ycult+Hwood+Sand(layered)	198	237-242	198-24
13	Hawood	198	333-342	198-38
13	Mix:Ycult+Sand(layered)	441	249-257	441-18
13	Ycult,org	442	251-265	442-21
13	Mix:Ycult+Sand(layered)	442	359-372	442-29
13	Mcult-hom	300	9-24	300-1
13	Mcult-hom	300	36-48	300-3
13	Mcult-hom	300	48-60	300-4
13	Mix:Hwood+Wood piece	311	200-223	311-14
13	Hn (channel?)	401	190-195	401-1
13	Hn (channel?)	409	260-266	409-1
14	Gravel(cult)	73	108-124	A1-11
14	Grey sand(cult)	73	300-330	A1-25

<b>Cluster nr.</b>	<b>Layer ID (field classification)</b>	<b>Core nr.</b>	<b>Sampling depth</b>	<b>Sample ID</b>
14	Grey sand(cult)	73	330-334	A1-26
14	Mix:Sand+Ycult(layered)	74	165-170	A2-17
14	Mix:Sand+Ycult(layered)	74	170-176	A2-18
14	Gravel(cult)	74	200 - 216	A2-21
14	Mix:Sand+Ycult	74	250-264	A2-24
14	Gravel(cult)	74	264 - 276	A2-25
14	Mix:Grey sand(cult)+Gravel	74	288-300	A2-27
14	Mix:Grey sand(cult)+Gravel	74	300 -323	A2-28
14	Mix:Grey sand(cult)+Gravel	74	323 - 352	A2-29
14	Gravel(cult)	74	352-386	A2-30
14	Sand	270	110-122	270-10
14	Gravel(cult)	270	193-200	270-16
14	Sand	270	386-400	270-38
14	Mix:Ycult+Sand(layered)	441	273- 282	441-22
14	Mix:Ycult+Sand(layered)	441	295- 300	441-24
14	Gravel(cult)	441	311- 318	441-26
14	Mix:Ycult+Sand(layered)	442	300-313	442-24
14	Mix:Sand+Ycult+Hwood	300	222-236	300-17
14	Gravel(cult)	300	252-260	300-20
14	Gravel(cult)	300	271-278	300-23
14	Gravel(cult)	300	286-300	300-25
14	Mix:Sand+Ycult	311	369-372	311-26
15	Gravel	73	280-300	A1-24
15	Sand	198	308-320	198-36
15	Gravel	198	360-369	198-41
15	Mix: H+Sand	270	164-177	270-14
15	Mix: H+Sand	270	177-193	270-15
15	Sand	270	200-211	270-17
15	Sand	270	211-223	270-18
15	Mix:Sand+Mh+Ycult+Gravel(layered)	270	266-274	270-25
15	Sand(h)	270	351-364	270-35
15	Sand(h)	270	364-372	270-36
15	Sand	270	372-386	270-37
15	Mix:Sand+Mh(layered)	441	228- 242	441-16
15	Sand	441	300- 311	441-25
15	Sand	300	144-152	300-12
15	Mix:Sand+Mh	300	263-271	300-22
15	Mix:Sand+H(layered)	311	339-345	311-23

**Appendix 3. Results of the post hoc HSD Tukey test (significant differences are marked with red).**

<b>Unequal N HSD; variable Gravel</b>															
<b>Approximate Probabilities for Post Hoc Tests (Error: Between MS = .45289, df = 272.00)</b>															
Clusters	{1}	{2}	{3}	{4}	{5}	{6}	{7}	{8}	{9}	{10}	{11}	{12}	{13}	{14}	{15}
1		1,000	0,000	0,273	1,000	0,000	0,940	0,101	0,000	0,001	1,000	0,001	1,000	0,000	0,000
2	1,000		0,000	0,047	1,000	0,000	0,564	0,012	0,000	0,000	1,000	0,000	0,965	0,000	0,000
3	0,000	0,000		0,002	0,000	0,000	0,000	0,037	1,000	0,542	0,000	0,653	0,000	0,955	1,000
4	0,273	0,047	0,002		0,246	0,000	0,999	1,000	0,151	0,842	0,635	0,812	0,984	0,000	0,148
5	1,000	1,000	0,000	0,246		0,000	0,977	0,147	0,000	0,000	1,000	0,000	1,000	0,000	0,000
6	0,000	0,000	0,000	0,000	0,000		0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
7	0,940	0,564	0,000	0,999	0,977	0,000		0,974	0,016	0,219	0,996	0,177	1,000	0,000	0,005
8	0,101	0,012	0,037	1,000	0,147	0,000	0,974		0,283	0,992	0,364	0,985	0,902	0,000	0,347
9	0,000	0,000	1,000	0,151	0,000	0,000	0,016	0,283		0,868	0,000	0,894	0,004	1,000	1,000
10	0,001	0,000	0,542	0,842	0,000	0,000	0,219	0,992	0,868		0,012	1,000	0,179	0,007	0,987
11	1,000	1,000	0,000	0,635	1,000	0,000	0,996	0,364	0,000	0,012		0,009	1,000	0,000	0,000
12	0,001	0,000	0,653	0,812	0,000	0,000	0,177	0,985	0,894	1,000	0,009		0,148	0,014	0,993
13	1,000	0,965	0,000	0,984	1,000	0,000	1,000	0,902	0,004	0,179	1,000	0,148		0,000	0,002
14	0,000	0,000	0,955	0,000	0,000	0,000	0,000	0,000	1,000	0,007	0,000	0,014	0,000		0,862
15	0,000	0,000	1,000	0,148	0,000	0,000	0,005	0,347	1,000	0,987	0,000	0,993	0,002	0,862	
<b>Unequal N HSD; variable HK/wood</b>															
<b>Approximate Probabilities for Post Hoc Tests (Error: Between MS = .31116, df = 272.00)</b>															
Clusters	{1}	{2}	{3}	{4}	{5}	{6}	{7}	{8}	{9}	{10}	{11}	{12}	{13}	{14}	{15}
1		1,000	1,000	0,000	0,000	0,000	1,000	0,999	0,997	0,000	0,000	0,000	0,000	0,000	0,000
2	1,000		1,000	0,000	0,000	0,001	1,000	1,000	1,000	0,000	0,000	0,000	0,000	0,000	0,000
3	1,000	1,000		0,000	0,000	0,000	1,000	1,000	1,000	0,000	0,000	0,000	0,000	0,000	0,000
4	0,000	0,000	0,000		0,768	0,813	0,000	0,000	0,001	0,999	0,146	0,114	0,309	0,860	0,526
5	0,000	0,000	0,000	0,768		0,036	0,000	0,000	0,000	1,000	0,993	0,999	0,999	0,008	0,003
6	0,000	0,001	0,000	0,813	0,036		0,000	0,005	0,232	0,256	0,000	0,002	0,001	1,000	1,000
7	1,000	1,000	1,000	0,000	0,000	0,000		1,000	0,999	0,000	0,000	0,000	0,000	0,000	0,000
8	0,999	1,000	1,000	0,000	0,000	0,005	1,000		1,000	0,000	0,000	0,000	0,000	0,000	0,001
9	0,997	1,000	1,000	0,001	0,000	0,232	0,999	1,000		0,000	0,000	0,000	0,000	0,061	0,273
10	0,000	0,000	0,000	0,999	1,000	0,256	0,000	0,000	0,000		0,724	0,787	0,890	0,152	0,063
11	0,000	0,000	0,000	0,146	0,993	0,000	0,000	0,000	0,000	0,724		1,000	1,000	0,001	0,000
12	0,000	0,000	0,000	0,114	0,999	0,002	0,000	0,000	0,000	0,787	1,000		1,000	0,000	0,000
13	0,000	0,000	0,000	0,309	0,999	0,001	0,000	0,000	0,000	0,890	1,000	1,000		0,003	0,000
14	0,000	0,000	0,000	0,860	0,008	1,000	0,000	0,000	0,061	0,152	0,001	0,000	0,003		1,000
15	0,000	0,000	0,000	0,526	0,003	1,000	0,000	0,001	0,273	0,063	0,000	0,000	0,000	1,000	
<b>Unequal N HSD; variable Bones</b>															
<b>Approximate Probabilities for Post Hoc Tests (Error: Between MS = .19594, df = 272.00)</b>															
Clusters	{1}	{2}	{3}	{4}	{5}	{6}	{7}	{8}	{9}	{10}	{11}	{12}	{13}	{14}	{15}
1		1,000	1,000	0,268	1,000	1,000	1,000	1,000	1,000	0,000	0,000	0,000	0,000	0,000	0,000
2	1,000		1,000	0,268	1,000	1,000	1,000	1,000	1,000	0,000	0,000	0,000	0,000	0,000	0,000
3	1,000	1,000		0,111	1,000	1,000	1,000	1,000	1,000	0,000	0,000	0,000	0,000	0,000	0,000
4	0,268	0,268	0,111		0,539	0,624	0,227	0,227	0,881	0,000	0,013	0,000	0,000	0,000	0,000
5	1,000	1,000	1,000	0,539		1,000	1,000	1,000	1,000	0,000	0,000	0,000	0,000	0,000	0,000
6	1,000	1,000	1,000	0,624	1,000		1,000	1,000	1,000	0,000	0,000	0,000	0,000	0,000	0,000
7	1,000	1,000	1,000	0,227	1,000	1,000		1,000	1,000	0,000	0,000	0,000	0,000	0,000	0,000
8	1,000	1,000	1,000	0,227	1,000	1,000	1,000		1,000	0,000	0,000	0,000	0,000	0,000	0,000
9	1,000	1,000	1,000	0,881	1,000	1,000	1,000	1,000		0,000	0,000	0,000	0,000	0,000	0,000
10	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000		0,000	1,000	1,000	1,000	1,000
11	0,000	0,000	0,000	0,013	0,000	0,000	0,000	0,000	0,000	0,000		0,000	0,000	0,000	0,000
12	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	1,000	0,000		1,000	1,000	1,000
13	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	1,000	0,000	1,000		1,000	1,000
14	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	1,000	0,000	1,000	1,000		1,000
15	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	1,000	0,000	1,000	1,000	1,000	

<b>Unequal N HSD; variable Artefacts</b>															
<b>Approximate Probabilities for Post Hoc Tests (Error: Between MS = .20148, df = 272.00)</b>															
Clusters	{1}	{2}	{3}	{4}	{5}	{6}	{7}	{8}	{9}	{10}	{11}	{12}	{13}	{14}	{15}
1		0,992	0,992	1,000	0,992	0,999	0,000	0,000	0,000	0,000	0,000	0,000	0,998	0,000	0,996
2	0,992		1,000	0,767	1,000	1,000	0,000	0,000	0,000	0,000	0,000	0,000	1,000	0,000	1,000
3	0,992	1,000		0,576	1,000	1,000	0,000	0,000	0,000	0,000	0,000	0,000	1,000	0,000	1,000
4	1,000	0,767	0,576		0,615	0,941	0,000	0,000	0,000	0,000	0,000	0,000	0,895	0,000	0,836
5	0,992	1,000	1,000	0,615		1,000	0,000	0,000	0,000	0,000	0,000	0,000	1,000	0,000	1,000
6	0,999	1,000	1,000	0,941	1,000		0,000	0,000	0,000	0,000	0,000	0,000	1,000	0,000	1,000
7	0,000	0,000	0,000	0,000	0,000	0,000		0,340	1,000	0,388	0,533	0,000	0,000	1,000	0,000
8	0,000	0,000	0,000	0,000	0,000	0,000	0,340		1,000	1,000	1,000	0,000	0,000	0,833	0,000
9	0,000	0,000	0,000	0,000	0,000	0,000	1,000	1,000		1,000	1,000	0,005	0,000	1,000	0,000
10	0,000	0,000	0,000	0,000	0,000	0,000	0,388	1,000	1,000		1,000	0,000	0,000	0,765	0,000
11	0,000	0,000	0,000	0,000	0,000	0,000	0,533	1,000	1,000	1,000		0,000	0,000	0,918	0,000
12	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,005	0,000	0,000		0,000	0,000	0,000
13	0,998	1,000	1,000	0,895	1,000	1,000	0,000	0,000	0,000	0,000	0,000	0,000		0,000	1,000
14	0,000	0,000	0,000	0,000	0,000	0,000	1,000	0,833	1,000	0,765	0,918	0,000	0,000		0,000
15	0,996	1,000	1,000	0,836	1,000	1,000	0,000	0,000	0,000	0,000	0,000	0,000	1,000	0,000	
<b>Unequal N HSD; variable LOI</b>															
<b>Approximate Probabilities for Post Hoc Tests (Error: Between MS = .30418, df = 272.00)</b>															
Clusters	{1}	{2}	{3}	{4}	{5}	{6}	{7}	{8}	{9}	{10}	{11}	{12}	{13}	{14}	{15}
1		0,000	0,000	1,000	1,000	0,000	1,000	0,971	0,000	0,977	0,705	1,000	0,032	0,000	0,000
2	0,000		0,784	0,000	0,000	0,000	0,000	0,000	1,000	0,000	0,000	0,000	0,000	1,000	1,000
3	0,000	0,784		0,000	0,000	0,000	0,000	0,000	1,000	0,000	0,000	0,000	0,000	0,267	1,000
4	1,000	0,000	0,000		1,000	0,000	1,000	0,986	0,000	0,975	0,601	1,000	0,020	0,000	0,000
5	1,000	0,000	0,000	1,000		0,000	1,000	0,999	0,000	0,999	0,368	0,993	0,006	0,000	0,000
6	0,000	0,000	0,000	0,000	0,000		0,000	0,000	0,000	0,000	0,000	0,000	0,017	0,000	0,000
7	1,000	0,000	0,000	1,000	1,000	0,000		0,860	0,000	0,882	0,867	1,000	0,074	0,000	0,000
8	0,971	0,000	0,000	0,986	0,999	0,000	0,860		0,003	1,000	0,030	0,600	0,000	0,000	0,000
9	0,000	1,000	1,000	0,000	0,000	0,000	0,000	0,003		0,002	0,000	0,000	0,000	1,000	1,000
10	0,977	0,000	0,000	0,975	0,999	0,000	0,882	1,000	0,002		0,034	0,505	0,000	0,000	0,000
11	0,705	0,000	0,000	0,601	0,368	0,000	0,867	0,030	0,000	0,034		0,974	0,982	0,000	0,000
12	1,000	0,000	0,000	1,000	0,993	0,000	1,000	0,600	0,000	0,505	0,974		0,186	0,000	0,000
13	0,032	0,000	0,000	0,020	0,006	0,017	0,074	0,000	0,000	0,000	0,982	0,186		0,000	0,000
14	0,000	1,000	0,267	0,000	0,000	0,000	0,000	0,000	1,000	0,000	0,000	0,000	0,000		0,996
15	0,000	1,000	1,000	0,000	0,000	0,000	0,000	0,000	1,000	0,000	0,000	0,000	0,000	0,996	
<b>Unequal N HSD; variable MS</b>															
<b>Approximate Probabilities for Post Hoc Tests (Error: Between MS = .44796, df = 272.00)</b>															
Clusters	{1}	{2}	{3}	{4}	{5}	{6}	{7}	{8}	{9}	{10}	{11}	{12}	{13}	{14}	{15}
1		0,678	0,999	1,000	0,000	0,257	0,602	0,000	0,115	0,000	1,000	1,000	0,347	0,003	1,000
2	0,678		0,999	0,922	0,015	1,000	0,001	0,000	0,001	0,000	0,997	0,742	1,000	0,000	0,155
3	0,999	0,999		1,000	0,000	0,852	0,041	0,000	0,011	0,000	1,000	0,999	0,938	0,000	0,826
4	1,000	0,922	1,000		0,000	0,501	0,243	0,000	0,048	0,000	1,000	1,000	0,634	0,000	0,991
5	0,000	0,015	0,000	0,000		0,762	0,000	0,000	0,000	0,000	0,000	0,000	0,374	0,000	0,000
6	0,257	1,000	0,852	0,501	0,762		0,000	0,000	0,000	0,000	0,748	0,300	1,000	0,000	0,025
7	0,602	0,001	0,041	0,243	0,000	0,000		0,001	0,962	0,099	0,211	0,483	0,000	0,862	0,997
8	0,000	0,000	0,000	0,000	0,000	0,000	0,001		0,995	0,996	0,000	0,000	0,000	0,426	0,000
9	0,115	0,001	0,011	0,048	0,000	0,000	0,962	0,995		1,000	0,019	0,097	0,000	1,000	0,481
10	0,000	0,000	0,000	0,000	0,000	0,000	0,099	0,996	1,000		0,000	0,000	0,000	0,987	0,004
11	1,000	0,997	1,000	1,000	0,000	0,748	0,211	0,000	0,019	0,000		1,000	0,864	0,001	0,936
12	1,000	0,742	0,999	1,000	0,000	0,300	0,483	0,000	0,097	0,000	1,000		0,402	0,000	1,000
13	0,347	1,000	0,938	0,634	0,374	1,000	0,000	0,000	0,000	0,000	0,864	0,402		0,000	0,034
14	0,003	0,000	0,000	0,000	0,000	0,000	0,862	0,426	1,000	0,987	0,001	0,000	0,000		0,176
15	1,000	0,155	0,826	0,991	0,000	0,025	0,997	0,000	0,481	0,004	0,936	1,000	0,034	0,176	

#### Appendix 4. Appendix 4: Micromorphological description of samples from the core 400.

Drilling point 400, 142-152 cm sampling depth.

Context: Transition from the upper  $M_{cult}/Y_{cult}$  very rich in charcoal to very fine-layered M.

Properties	Description			
	$Y_{cult,org}$ (1 – 2 cm)	M (2 – 6 cm)	$Y_{cult,org}$ (6 – 8.2 cm)	M (8.2-11.5 cm)
<b>Heterogeneity, sorting</b>	Very heterogeneous, poorly sorted to unsorted	Relatively homogeneous; moderately to very well sorted	Heterogeneous, poorly sorted, similar to the uppermost sublayer	Relatively homogeneous; moderately to well sorted
<b>Microstructure</b>	Vughy	Vughy	Vughy	Vughy
<b>Coarse mineral</b>	The coarse material is strongly dominated by quartz grains with presence of single rock fragments. It contains a fine sediment aggregate with a preserved clay coating/infilling inside demonstrating a typical birefringence pattern (crescent).	Strongly dominated by rounded quartz grains with presence of plagioclase, microcline and rock fragments Size: mostly medium sand. Contains a ca. 4 mm large clast of redeposited silty loam, with original layering preserved; a 3-4 mm large clast of redeposited material - sand cemented by organo-phosphatic material.	Strongly dominated by rounded quartz grains (>90%) with presence of plagioclase, microcline and rock fragments Size: medium and fine sand with a lower content of coarse sand.	Strongly dominated by rounded quartz grains (>90%) with presence of plagioclase, microcline and rock fragments Size: medium and fine sand with a lower content of coarse sand.
<b>C:f limit, ratio, related distribution</b>	60 $\mu$ m; 70:30; single-double spaced enaulic	60 $\mu$ m; 50:50; enaulic	60 $\mu$ m; 60:40; enaulic	60 $\mu$ m; 80:20; enaulic
<b>Coarse organic</b>	Undecomposed plant remains are present as well as humified organic material (not naturally), woody remains (remains with fibers), abundant charcoal.	A few charcoal fragments	Very abundant plants remains, part of which look digested; many relatively large (up to 250 $\mu$ m) charcoal fragments are present.	Some plant tissues and roots
<b>Coarse anthropogenic</b>	A few bones (including a fish bone).	A black porous inclusion similar to the one in the lowermost sublayer	Absent	Black porous inclusion, probably a metallic object
<b>Fine fabric</b>	Light to dark brown in colour, silty and slightly clayey material with OM. In some areas dusty clay material is present. Phytoliths present, single diatoms. Fine organic: fungal spores. B-fabric stipple-speckled.	Fine material is organo-mineral, in some areas dominated by OM and plant remains of strong-moderate degree of decomposition. Amorphous OM forms coatings of mineral grains. B-fabric stipple-speckled Phytoliths are present in the filled burrowing structures.	Contains abundant phytoliths (including cereal husk, articulated but fragmented), abundant round fungal spores.	Organo-mineral material with presence of small quantities of silt- and clay-sized particles. B-fabric undifferentiated, in a few areas stipple-speckled.

Properties	Description			
	Y <sub>cult,org</sub> (1 – 2 cm)	M (2 – 6 cm)	Y <sub>cult,org</sub> (6 – 8.2 cm)	M (8.2-11.5 cm)
<b>Pedofeatures</b>	Some areas are slightly phosphatized. Abundant pyrite framboids	Root channels present; a burrowing structure goes through this sublayer; it is filled with material from above (very humic); pyrite framboids are abundant	Some areas are possibly phosphatized ; pyrite framboids are abundant	Bioturbation by earthworms might be present as well as root channels, some of which are filled with material from above. Pyrite framboids associated with OM concentration / plant remains areas.
<b>Comments</b>	Polymorphous organic material, also resembles a cess/latrine deposit or coprolitic material (probably omnivore)		The morphology of the organic matter resembles cess/latrine sediments	

Drilling point 400, 166-176 cm sampling depth.

Context: Buried soil B horizon

Properties	Description
<b>Heterogeneity, sorting</b>	Homogenous, moderately sorted
<b>Microstructure</b>	Loose unstructured
<b>Coarse mineral</b>	Strongly dominated by rounded quartz grains (>90%) with presence of plagioclase, microcline, biotite and rock fragments Size: medium and fine sand with a lower content of coarse sand
<b>C:f limit, ratio, related distribution</b>	60 µm (silt/sand border); 70:30; enaulic to chitonic
<b>Coarse organic</b>	A few plant remains with recognizable tissue patterns are present (light and dark brown), may be some younger roots
<b>Coarse anthropogenic</b>	Absent
<b>Fine fabric</b>	Fine material is composed by amorphous organo-mineral material, which seems to be depleted of sesquioxides due to the effects of the ground water. B-fabric: undifferentiated
<b>Pedofeatures</b>	Mottles of organo-mineral material, organo-mineral coatings around coarse grains

## Appendix 5. Micromorphological description of samples from the core 402.

Drilling point 402, 134-144 cm sampling depth.

Context: Transition from  $M_{cult}$  to  $Y_{cult}$

Properties	Description		
	$M_{cult}$ upper (1-3 cm)	$M_{cult}$ lower (3-9.5 cm)	$Y_{cult, ch}$ (9.5-11.5)
<b>Heterogeneity, sorting</b>	Heterogeneous, strongly desiccated; poorly sorted	Heterogeneous; poorly sorted	Heterogeneous; poorly sorted
<b>Microstructure</b>	In some areas massive, in some loose, in some disturbed	Massive	Massive
<b>Coarse mineral</b>	Mostly quartz, (subrounded and angular) with presence feldspars and rock fragments; compacted subrounded aggregates dominated by fine sand and with organic material as a cementing agent	Mostly quartz (subrounded, rounded and sharp-edged) with presence of rock fragments and feldspars as well as single grains of other minerals; a few aggregates of fine material are present	Mostly quartz (mostly subrounded with presence of angular grains) with presence of rock fragments and feldspars as well as single grains of other minerals
<b>C:f limit, ratio, related distribution</b>	60 $\mu$ m; 60:40 and 40:60 (in different parts); enaulic and porphyric	60 $\mu$ m; 60:40; enaulic	60 $\mu$ m; 60:40; enaulic
<b>Coarse organic</b>	Abundant fragmented (probabaly desiccated) charcoal fragments	Abundant desiccated charcoal fragments and a few uncharred plant remains and tissues with cell structure preserved	Very large charcoal fragments (also all dessicated as the matrix around and sublayers above)
<b>Coarse anthropogenic</b>	Si slags (at least 3 small fragments), rather small bones, metal slag (a few fragments) with a dendritic pattern in ppl	Long thin fragmented bone, abundant small bone fragments; hammerscale and possibly iron slag fragments, silica slag fragments (largest 0.8 cm)	A few small bones, abundant Si slags; at the border to the upper layer a slag fragment is located, but it has a different morphology and Q grains are not cracked.
<b>Fine fabric</b>	Organo-mineral material, in many places phosphatized	Silt-sized organo-mineral material with amorphous OM and dispersed charred material in the voids and representing part of the fine fabric; mica grains are abundant; phytoliths are present; b-fabric stipple-speckled	Organo-mineral and charred material; b-fabric stipple-speckled
<b>Pedofeatures</b>	Strong phosphatization features in some areas, which seem to be layered. One of the phosphatized clasts contains bones	Abundant burrowing structures filled with fine material; iron staining, pyrite framboids	
<b>Comments</b>	Strong desiccation features observed in the whole thin section probably indicate sample preparation artefacts. Phosphatization features, absence of fresh OM and presence of small bones may suggest presence of excrements	Presence of silica slags with cracked quartz grains imply material heating above 1000 °C corresponding to nearly industrial glass production processes. Therefore, the material probably contains wastes of a glass workshop.	

Drilling point 402, 184-194 cm sampling depth.

Context: Lower part of  $Y_{cult}$  with an  $Y_{cult,ch}$  sublayer and clay aggregates

Properties	Description		
	$Y_{cult}$ (0-4 cm)	$Y_{cult,ch}$ (4-7/8 cm - inclined border)	$Y_{cult}$ (7/8-11.2 cm)
<b>Heterogeneity, sorting</b>	Heterogeneous material with inclusions of different organic remains; poorly sorted to unsorted	Very heterogeneous, seems to have features of postdepositional mixing; unsorted	See description of the sublayer at 0-4.5 cm.
<b>Microstructure</b>	The microstructure is quite massive and compact with very few voids, but some larger channels and vughs are present	Vughy, disturbed	
<b>Coarse mineral</b>	Mostly quartz and rock fragments, rounded and subrounded with presence of feldspars; an aggregate of loamy material is present (~3 mm) with mica dominating in the fine fabric and with a grano-striated b-fabric	Mostly quartz and rock fragments, rounded and subrounded with presence of feldspars and very small quantities of other minerals; loamy aggregates are present too	Mostly quartz and rock fragments, rounded and subrounded with presence of feldspars and very small quantities of other minerals (same as above); aggregates of loamy material are present (1 very large)
<b>C:f limit, ratio, related distribution</b>	60 $\mu$ m; 60:40; enaulic	60 $\mu$ m, 40:60; enaulic	60 $\mu$ m; 60:40; enaulic
<b>Coarse organic</b>	Diverse plant remains are present, no birefringent remains, charcoal (large and small) are present as well as unburnt woody tissues	Abundant woody remains and very abundant HK - intact as well as strongly fragmented (probably bioturbated)	Abundant plant remains of different degree of decomposition, a few very small HK; fungal spores (ca. 250 $\mu$ m)
<b>Coarse anthropogenic</b>	Loamy clast - possibly a construction material.	A reddish fine material clast (probably, a pottery fragment); another darker brown clast, may be daub; probably a Si slag but without cracked Q grains	A clast of calcareous rock embedded in a calcareous loamy aggregate - construction material
<b>Fine fabric</b>	Organo-mineral silty material with presence of mica in the upper part and mostly organic material in the lower part; b-fabric: stipple-speckled	Organo-mineral silty material; b-fabric: stipple-speckled	Organo-mineral material, in some areas strongly dominated by organic material; b-fabric undifferentiated
<b>Pedofeatures</b>	Pyrite framboids (quite abundant), some minor iron staining; burrowing structure filled with finer and OM-richer material	Absent	Burrowing structure or a root channel filled with fine material
<b>Comments</b>	Colluvium is usually dusty. And this material is too clean for a colluvium. Very layered. M.p. not colluvium.	Material is strongly bioturbated, abundant burrowing structures are present filled with material from above. Burnt inclusions did not burn in situ, they were redeposited	On the opposite side of the calcareous fragment - a rock fragment embedding a mineral with a high refraction index?

Drilling point 402, 235-245 cm sampling depth.

Context: Peat-like material

Properties	Description
<b>Heterogeneity, sorting</b>	Relatively homogeneous, well sorted
<b>Microstructure</b>	Vughy
<b>Coarse mineral</b>	Strongly dominated by rounded quartz grains (>90%) with presence of plagioclase, microcline, biotite and rock fragments. One large weathered stone is located in the central part of the TS: rock fragments, quartz, microcline, other minerals and biotite Size: medium and fine sand with a low content of coarse sand
<b>C:f limit, ratio, related distribution</b>	60 µm; 30:70; enaulic
<b>Coarse organic</b>	Abundant undecomposed and slightly decomposed plant remains with visible plant anatomic structure, a few woody remains, single charcoal fragments. Some plant remains possess a birefringence
<b>Coarse anthropogenic</b>	Absent
<b>Fine fabric</b>	Dominated by amorphous organic material with undifferentiated b-fabric, some part contain silt-sized particles and have a stipple-speckled b-fabric
<b>Pedofeatures</b>	Some pyrite framboids
<b>Comments</b>	OM-rich peat-like material. At least temporary water-logging must have taken place leading to the preservation of plant remains. But not permanent water logging (pyrite). Two types of OM: fresh with birefringence and humified. Much more humified than the peat layer from outside the settlement → oxygen access. Could be at least partly due to peat formation.

**Appendix 6. Description of cores from transect 3 (core 311 is described as part of the longitudinal profile).**

Layer designation	Top	Bottom	Description
<b>Core 424</b>			
Mh	0	109	Homogeneous dark brown material (0-55 cm – empty), medium and fine sand with presence of silt. Contains two small fragments of burnt clay/daub material at 80 and 85 cm.
Mix: Mh+Hbottom	109	133	Homogeneous dark brown material, fine sand and silt with presence of clay. The lower part is darker in colour due to the presence of charcoal. Possibly, a muddy sediment deposited in standing water or affected by peat material below.
Mix:Mh+Hn	133	144	Layer rich in organic matter with features of plant remain conservation and with presence of sand grains. Contains a few wood remains and charcoal fragments.
Mix: Hn+Hwood	144	158	A dense (compacted?) layer dominated by organic matter and wood remains. Some mineral material is also present (sand grains are visible). Contains a few small stones 2-3 mm and a larger one (2 cm) at 150 cm.
Hn	158	167	Fine peat material, in the lower part with presence of wood remains and some charcoal.
Mix: Hn+Hwood+(Ywaste)	167	197	Heterogeneous layer dominated by peat material but also with a presence of mineral material in the matrix. Contains abundant partly decomposed and undecomposed wood remains. Ywaste - due to the morphological similarity with the analogous layer in A1-A2 profile and presence of a bone fragment at 192 cm. Also contains charcoal and single stones (e.g. at 196 cm)
Mix: Hn+Hwood+(Ywaste)+Sand	197	208	Heterogeneous layer, a transition to the underlying layer.
Mix: Sand+H	208	232	Mostly light grey medium sand material with patches of OM-rich dark brown material.
Mix: Hn+Hwood+(Ywaste)	232	270	Continuation of the layer at 167-197 cm, formation of which was interrupted by the deposition of sand. Also dark brown in colour, dominated by OM with very abundant wood remains. The content of mineral grains grows with depth. Contains: stones at 260 and 270 cm, a small bone fragment at 247 cm and a relatively large (3 cm) slag piece at 266 cm.
Mix: Gravel+Sa(h)	270	292	Dominated by stones of different size (3mm – 4-5 cm). Three areas can be distinguished based on the properties of the matrix: 270-280 humic medium sandy matrix, 280-287 OM-rich medium sandy material, 297-292 coarse sand. Contains a vivianite aggregate and possibly some burnt clay fragments.
Mix: Csa+H	292	297	Heterogeneous layer with sublayers of coarse sand and OM-enriched finer material.
Gravel	297	300	Probably a natural brook bed. The matrix is coarse sand with a low OM content. Stones are both rounded and sharp-edged.
<b>Core 425</b>			
M	0	69	Homogenous dark brown colluvial layer, silty medium sand.
Mix: M+Sand	69	100	Same as above with a few lighter coloured sand patches.
Mix: M+Sand	100	116	Difficult to distinguish transitions and borders.
Mix: M+Sand	116	142	Presence of material from the lower layer.
Cv	142	200	Homogeneous pale-coloured medium sand.

Layer designation	Top	Bottom	Description
<b>Core 426</b>			
M	0	71	Dark brown Homogeneous dark brown colluvial layer, silty medium sand.
Cv	71	100	Homogeneous yellowish-pale medium sand
<b>Core 427</b>			
Mh	0	107	Homogeneous dark brown material, medium and fine sand with silt, the same as at p. 424. Contains a small brick piece at 99 cm.
Mix: Mh+Hbottom	107	117	Same as the analogous layer at p. 424. Finer and with a higher OM content, more affected by wet conditions than the upper Mh layer.
Mix:Hn+(Ywaste/Ycult)	117	147	Dark greyish brown OM-rich (and/or clay rich) material. It contains mineral material, some medium and fine sand grains are visible. Contains: wood remains at 128 and 140-147 cm, a stone at 132 cm, pottery piece (2 cm) and a relatively large burnt clay piece (2 cm) at 130-132 cm.
Hn	147	163	Layer dominated by OM with presence of partly decomposed plant/wood remains. Contains: charcoal in the lower part.
Mix: Mh+Sa	163	182	Dominated by OM-rich Mh material. At 163-170 cm it contains wood remains, a stone and a weathered stone.
Mix: Sa+Mh	182	191	Similar to the layer above but with a higher sand content (light grey medium sand). Contains: a large (1.5 cm) large charcoal fragment at 185-186 cm.
Sand/Cv	191	200	Homogeneous light brownish medium sand.
<b>Core 430</b>			
M	0	100	Homogenous dark greyish brown colluvial layer. Contains a few stones at 80, 85 and 92 cm
Cv	100	200	Same as at previous points
<b>Core 431</b>			
M	0	60	Same as at previous points , stones at 34, 50 cm
Cv	60	100	Same as at previous points
<b>Core 432</b>			
M/Ycult-hom	0	84	Also homogeneous as at previous points, but darker (in some parts almost black) and more sticky. Contains a small burnt clay piece at 53 cm.
Mix: M+Sand	84	110	Similar to the analogous layer at point 427, but it is somewhat coarser as it contains patches of coarse sand.
Mh	110	144	Silty fine sand with presence of medium sand, comparatively high OM content.
M	144	193	Dark greyish brown material, medium sand. High OM content, with a few charcoal-enriched spots
Mix: M+Sand	193	200	Too wet, not clear, whether already Cv or a transition to it.

## Appendix 7. Code utilized in age modelling in OxCal.

```
Plot("Haithabu Chronology")
{
  Sequence("Haithabu")
  {
    R_Date("KIA 50330", 8170, 100)
    {
      Outlier();
    };
    R_Date("KIA 50331", 3250, 30)
    {
      Outlier();
    };
    R_Combine("KIA 50332")
    {
      Outlier();
      R_Date("KIA 50332-a", 1970, 25);
      R_Date("KIA 50332-b", 1990, 35);
    };
    Boundary("Filling start");
    Date("First mention", 804);
    Phase("Early filling")
    {
      R_Date("KIA 50952", 1155, 25)
      {
        color="Red"; z=258;
      };
      R_Date("KIA 50333", 1100, 25)
      {
        color="Red"; z=376.5;
      };
      R_Date("Tra 11347", 1130, 15)
      {
        color="Red"; z=293;
      };
      R_Combine("KIA 50329")
      {
        R_Date("KIA 50329-a", 1105, 25);
        R_Date("KIA 50329-b", 1130, 25);
        color="Red"; z=355;
      };
      Span("Early filling");
      First("Early filling");
      Last("Early filling");
    };
    Boundary("Filling end");
    Date("End Haithabu", 1066);
    Phase("Peat formation")
    {
      R_Date("Tra 11346", 980, 20)
      {
        color="Green"; z=247.5;
      };
      R_Combine("KIA 50328")
      {
        R_Date("KIA 50328-a", 940, 25);
        R_Date("KIA 50328-b", 980, 25);
        color="Green"; z=187;
      };
      Span("Peat formation");
      First("Peat formation");
      Last("Peat formation");
    };
    Boundary("Post-Haithabu");
  };
};
```



## **Eidesstattliche Erklärung**

Die vorgelegte Arbeit ist nach Inhalt und Form meine eigene, abgesehen von der Beratung durch meinen Betreuer. Der vorliegende Text wurde nicht und auch nicht zum Teil einer anderen Stelle im Rahmen eines Prüfungsverfahrens vorgelegt, veröffentlicht oder zur Veröffentlichung eingereicht. Diese Arbeit wurde unter Einhaltung guter wissenschaftlicher Praxis nach den Regeln der Deutschen Forschungsgemeinschaft erstellt.

Kiel, den

Svetlana Khamnueva