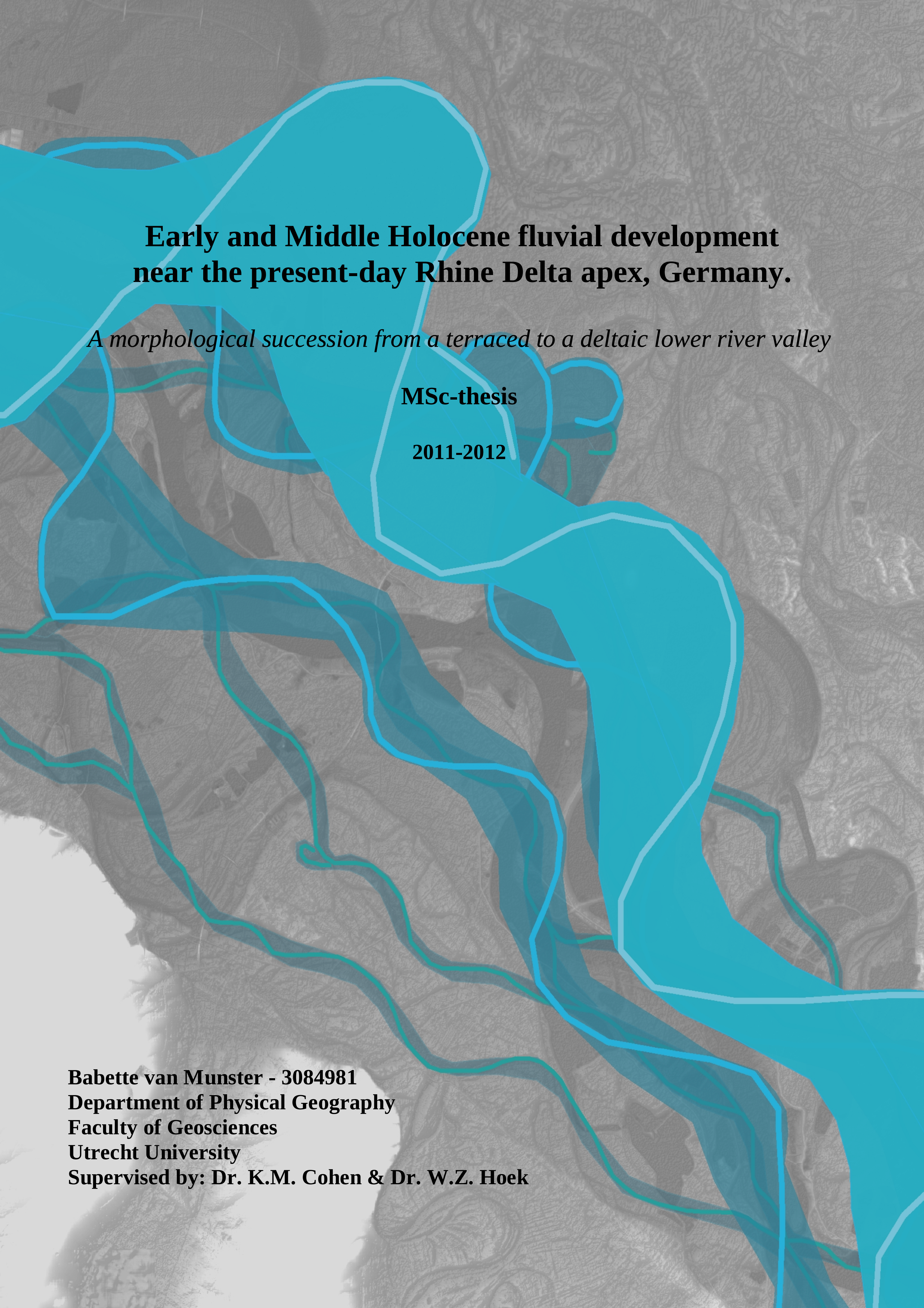

Early and Middle Holocene fluvial development near the present-day Rhine Delta apex, Germany.

A morphological succession from a terraced to a deltaic lower river valley

MSc-thesis

2011-2012

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Abstract

This aim of this study is to produce a detailed Holocene palaeogeographical reconstruction for the transitional area between the Rhine delta and the Lower Rhine Embayment several kilometers upstream of the Dutch-German border, where over time and space a landscape with river terraces turns into a landscape dominated by fluvio-deltaic deposition.

New data is collected in the field along multiple cross-sections. Pollen analysis of channel fills, a longitudinal profile and an age-height correlation of meander and terrace levels are produced. The results are integrated with data collected in previous research. The new insights concern the valley gradient, changes in fluvial style/river morphology and incision-aggradation rates. Especially knowledge on the incision-aggradation transition, i.e. the upward shifting of the Rhine delta, along the western/left side of the river and the Subboreal fluvial development has grown. Insight into river development in response to climate change and human influences will help in mitigating fluvial responses to future climate change.

In total 22 Holocene palaeo-meanders are identified, belonging to the Holocene terrace complex. They can be grouped into 4 meander generations based on fluvial style/river morphology, incision/aggradation rate and palaeo-meander height, besides a transitional terrace zone of the Younger-Dryas/Holocene transition. The latter is a terrace with multiple small and slightly meandering channels that dissect the Younger Dryas braid plain. The oldest Holocene meander generation developed during the Preboreal-middle Boreal (generation I). It was part of a multichannel system with one large and a couple of smaller meandering channels, in modestly incised position. The next meander generation developed during the middle Boreal-Atlantic when flow is concentrated to one main channel and incision increased (generation II). The following meander generation formed during the Subboreal (ca. 5.7-2.6 cal ka BP) while incision turned into aggradation (generation III). Finally, meander generation IV developed during the Subatlantic showing a change in fluvial style/river morphology with coarser floodplain deposits, decreasing size and more central position of the palaeo-meanders.

The transitional zone and the first two meander generation formed in response to the climate warming which results in a clear succession of (a) incision and abandonment of the braid plain, (b) a multichannel system with secondary channels, (c) flow concentration into one single channel and (d) delayed continued incision (lowering of top of in-channel deposits). The third meander generation formed under beginning human impact and minor climate variation but is triggered by a downstream control. This control, the upstream shifting of the delta apex, resulted in aggradation since sometime between 5.7 and 4.0 cal ka BP. The fourth meander generation formed in response to increased human impact (and possible climate change) and is also observed in upstream and downstream areas.

This research shows that fluvial development is a continuous process controlled by multiple succeeding external forcings that drive a complex sequence of river response.

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1 Introduction

1.1 Research context

The River Rhine is Europe's main waterway and its 185 000 km^2 large catchment area is one of the most densely populated areas of Europe. The Rhine flows from the Swiss Alps to the North Sea through Germany and the Netherlands (Fig. 1.1). In the delta, the rivers Rhine and Meuse combine to form the Holocene Rhine-Meuse delta, which covers one sixth of the Netherlands (Erkens, 2009; Preusser, 2007; Stouthamer, 2001). The apex of the Rhine delta is located approximately 10 km upstream of the Dutch-German border near the German city of Rees. The apex region forms a transitional area where the valley landscape with incised river terraces changes into the delta landscape dominated by aggradational river deposition. During earlier parts of the Holocene, this transitional area has progressively shifted upstream to its present location (Erkens, 2009; Favier 2001).

The River Rhine is one of the best studied rivers of the world, which goes for its delta, its valley and it catchment. The area downstream of the research area, the Rhine-Meuse delta, has been an important research subject of many studies. The Rhine-Meuse delta contains a well preserved sedimentary record of especially middle and late Holocene fluvio-deltaic deposits. Examples of recent overview publications on the palaeogeographical development of the Rhine-Meuse delta are Berendsen & Stouthamer (2000, 2001), Stouthamer (2001), Cohen (2005) and Gouw & Erkens (2007). Older publications are summarized by Stouthamer (2001, p. 47).
Directly upstream of the Rhine-Meuse delta lie the Lower Rhine Embayment (LRE). In this area, the Rhine valley has been dominated by incision, has well developed river terraces, and contains a well preserved sedimentary record of Late Pleistocene and Holocene deposits. Important research has been carried out by, amongst others, Brunnacker (1978), Klostermann (1992), Schirmer (1995) and Erkens et al. (2011) concerning the palaeogeographical evolution and development of river terraces.
The transitional area between the Rhine-Meuse delta and the LRE has been the location for research projects for several MSc students of Utrecht University (Favier; 2001; Dingemans, 2001; Greaves 2010; Janssens, 2010; De Molenaar, 2011; Geurts, 2011; this thesis.).

1.2 Problem definition

Although much research has been carried out concerning the palaeogeographical evolution of various parts of the river Rhine catchment area, a complete Holocene palaeogeographical reconstruction of the present-day apex region is lacking. Several studies present considerable amounts of information about

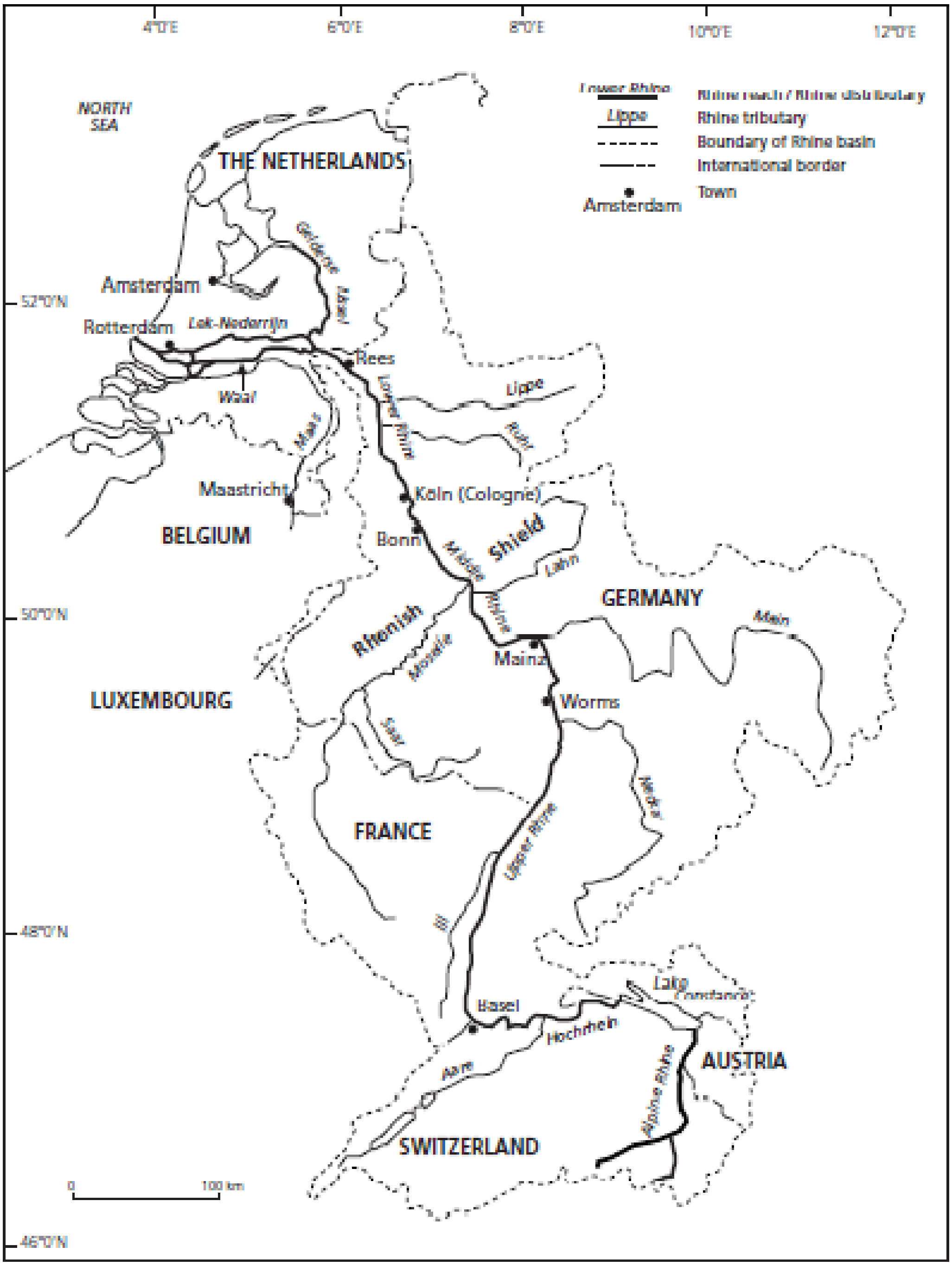

Figure 1.1: Hydrography of the Rhine catchment (Erkens, 2009: adapted from CHR, 1976; after Frings, 2007).

the area**,** but the palaeogeographical evolution in this transitional area is not yet fully understood. Various individual river terrace fragments and palaeo-meanders in the area have not been formally identified and information about height, gradient, age, lithostratigraphy, morphology, incision/aggradation rates, key components for a palaeogeographical evolution, are missing. This concerns in particular the palaeogeographical evolution at the onset of Holocene interglacial, from the river terraces/palaeo- meanders at the southwestern bank (left side) of the Rhine and from the Subboreal period between 5.7 and 2.3 ka yr BP (5700 - 2300 ^{14}C year before 1950) when net incision

turns into aggradation (Berendsen & Stouthamer, 2001; Dingemans, 2001; Erkens, 2009; Favier, 2001; Schirmer, 1995).
A good palaeogeographical understanding of this transitional area will help to extend knowledge on river behaviour through time and the factors controlling it. Besides, it will also be useful for utilizing this area for palaeo-flood reconstruction which will help risk-assessment for future floodings in the Netherlands (Cohen & Lodder, 2007; De Molenaar, 2011; Toonen, in prep.).

The transitional area near Rees is very suitable for making a palaeogeographic reconstruction, following up on mentioned existing knowledge because this area has been dominated by incision for a long time. The developed river terraces contain a well preserved sedimentary record of Pleistocene and Holocene deposits. Owing to of the local width of the valley, many early to late Holocene palaeo-meanders have been preserved.

1.3 Objectives and approach

The aim of this study is to produce a detailed Holocene palaeogeographical reconstruction of the transitional area of the Rhine delta near its present-day delta apex, several kilometers upstream of the Dutch-German border.

The research questions are:

- What is the palaeogeographical development of the river Rhine near its present-day delta apex during the Holocene interglacial, and the transition towards the Holocene?
- What previous research and data are available about the Holocene development of the present-day apex of the Rhine delta and can this be correlated with the new data?
- What river terraces/palaeo-meanders have developed? Can Holocene river terraces/palaeo-meander generations be distinguished by specific characteristics (e.g. height differences of in-channel deposits and fluvial style/river morphology)?
- What was the river response to external forcing (e.g. climate change, human impact) during the Early (11650-8700 cal BP) and Middle Holocene (8700-2600 cal BP); especially considering river gradient, incision-aggradation rate and fluvial style/ river morphology?

The focus is on Early and Middle Holocene deposits (Preboreal, Boreal, Atlantic and Subboreal: 11650 - 2600 cal yr BP). Data, collected during previous studies (Dingemans, 2001; Favier, 2001; Erkens, 2009; Berendsen & Stouthamer, 2001; Tebbens, unpublished), which include Late Holocene data (Subatlantic: 2600 cal yr BP - present), are included in the results.
New data was collected during a four-week fieldwork period by constructing different coring transects in the research area. The availability of an accurate digital elevation model (DEM)

(Landesvermessungsamt Nordrhein-Westfalen, Germany) was very helpful in getting a better understanding of the area and to determine the exact locations of coring transects. Samples of residual channels are taken for pollen analyses to date various palaeo-meanders and to reconstruct vegetation development. Loss On Ignition (LOI) analysis are carried out by De Molenaar (in prep.) for the sampled residual channels, which are used to help understand palaeogeographical development.

1.4 Regional setting

The most southern part of the Rhine, the Alpine Rhine, is located is the Swiss Alps till it grades into Lake Constance (Fig1.1). Downstream, from Lake Constance till Basel, the Rhine is called the Hochrhein. From Basel the so-called Upper Rhine runs axial through the subsiding Upper Rhine Graben (URG), an approximate 300 km long active tectonic rift structure. The URG acted as a sediment sink during the Pleniglacial and became dominated by incision during the Holocene. This resulted in the formation of Holocene river terraces/palaeo-meanders in the URG. Successive palaeo-meanders formed at lower elevations, with exception of the late Holocene palaeo-meanders. The palaeo-meanders group into three terrace levels (Dambeck & Thiemeyer, 2002; Dambeck, 2005; Erkens et al., 2009).

At Mainz, the Upper Rhine turns to the northwest and traverses the mountains of the Rhenish Shield via the Middle Rhine gorge. At Bonn the Lower Rhine enters the Lower Rhine Embayment (LRE), a second tectonic rift that widens for circa 150 km and forms a lowland area in western Germany. The LRE has also been dominated by incision during the Holocene and river terraces/palaeo-meanders have been formed. It is unclear whether the formed palaeo-meanders can be grouped into different river terraces (Klostermann, 1989; Schirmer, 1995), or formed as a continuous process of meandering and meander cutoff (Dingemans, 2001; Favier, 2001).

The LRE passes into the Rhine delta near Rees, where incision turns into fluvio-deltaic deposition. The Rhine-Meuse delta forms a wedge of sediment bounded by Late Pleistocene topography. The Holocene fluvio-deltaic wedge developed from ca. 8500 cal years onwards and ranges in thickness from 1 m at the apex to about 20 m near the North Sea coast (Hijma & Cohen, 2010; 2011). It comprises numerous channel belts with associated natural levees, crevasse-splays and floodplain deposits intercalated with peat layers (e.g. Berendsen & Stouthamer, 2000,2001; Stouthamer, 2001; Gouw & Erkens, 2007).

The research area is located at the most northern part of the LRE, where the LRE passes into the Rhine-Meuse delta (Fig 1.1). The research area reaches form several kilometers downstream of Wesel till circa 20 km downstream near Emmerich, Nordrhein-Westfalen, Germany (Fig. 1.2).

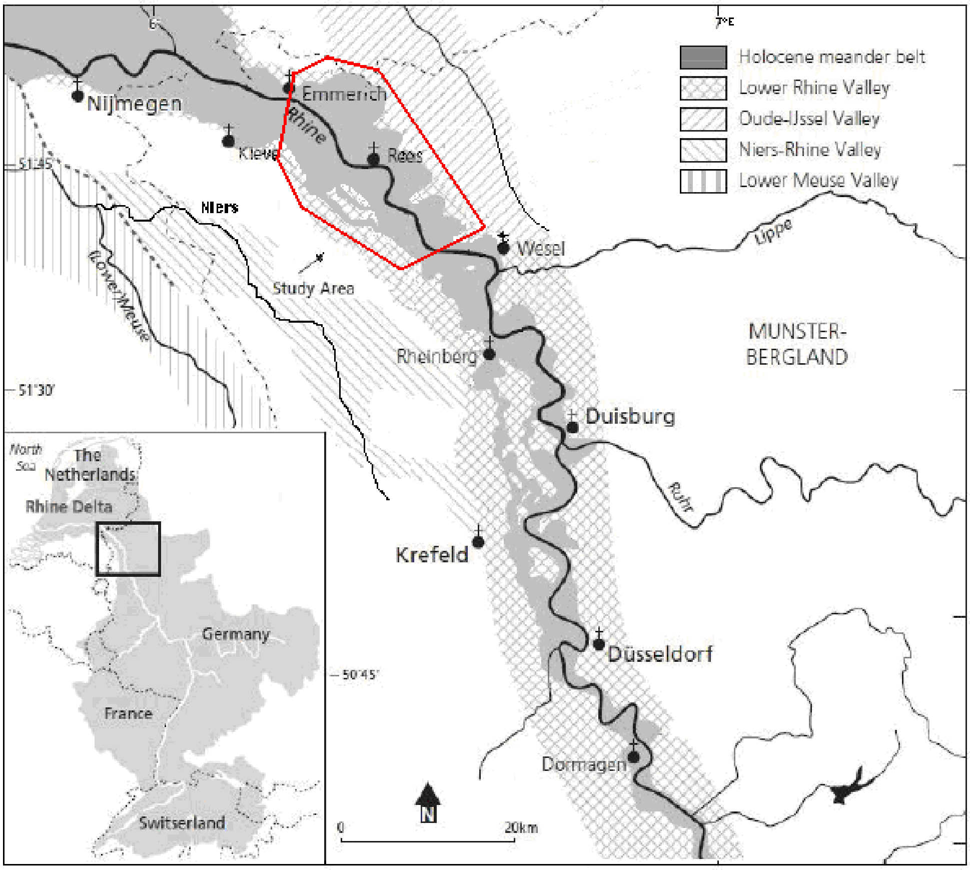

Figure 1.2: Location of the research area (after Erkens et al.,2011 and ref therein).
The approximate distribution of Late Weichselian terraces (NT2/3) in the central Lower Rhine valley (cross-hatch), the lower Meuse valley (stripe), the Niers-Rhine valley and Oude IJssel valley (single hatch), and Holocene palaeo-meanders (grey shade) (after Erkens, 2009: based on Klostermann, 1992; Schirmer, 1990; Zhou, 2000; Shala, 2001)

Besides the main Rhine valley, running towards the Rhine Delta, two other palaeo-Rhine valleys exists (Fig. 1.2). North of the research area, the Oude IJssel Valley runs northwest to the present IJssel Valley. South of the research area the Niers-Rhine Valley runs northwest to the present Meuse valley. Both valleys became fully abandoned shortly after the onset of the Early Holocene, having lost most of the Rhine discharge earlier on in the glacial-interglacial transition, when flow became concentrated in the main branch through the Lower-Rhine Valley (Verbraeck, 1984; Kasse, 2005; Verschuren, 2007; Cohen et al., 2009; Greaves, 2010; Janssens, 2010; Geurts, 2011).

1.5 Thesis outline

In chapter 2, a literature review is presented concerning the Holocene palaeogeographical development of the research area. The areas upstream (Lower Rhine Embayment and Upper Rhine Graben) and downstream (Rhine-Meuse delta) of the research area are included to detect similarities and differences in palaeogeographical development. The literature review ends with an overview of the factors that controlled fluvial development in the latter areas so that a comparison can be made to the research area.

In chapter 3, the approach of this research and the used methods are set out. An overview of the collection of field data and the processing of the gathered data is also included.

The results of the gathered field data are presented in chapter 4. Data presented in previous research are also included. The results include lithogenetic cross-sections through the research area and lab analyses on the core material (Pollen & Loss On Ignition), which are used to identify river terraces and/or palaeo-meanders generations in the research area. The identified river terrace fragments and palaeo meanders are set out in a longitudinal profile and age-height diagram. The results provide information on river gradient, incision/aggradation rate and fluvial style/river morphology.

This allows for reconstruction of the palaeogeographical development of the research area which is discussed in chapter 5 in chronological order. A palaeogeographical map of the research area is presented as well.

Chapter 6, discusses what factors controlled fluvial development in the research area and how the river responded to these factors. A comparison is made with the areas upstream and downstream of the research area to detect trends in fluvial development and separate regional from local controlling factors. Furthermore, it is explored whether river terraces and palaeo-meander generations have developed with age specific characteristics (e.g. height differences of in-channel deposits; aspects of fluvial style/river morphology) that can be used for identification and relative dating.

2 Literature review

In this literature review, an overview is given of important research concerning the Holocene palaeogeographical development of the Rhine. First a description of the Holocene climate and vegetation development (§ 2.1) is given, because both are considered to affect fluvial development. The fluvial development of the Rhine during the Holocene is set out in § 2.2, starting with a review of the upstream movement of the terrace intersection point (§ 2.2.1). Subsequently, the palaeogeographical development of the Rhine Delta (§ 2.2.2) and the terraced landscape (§ 2.2.3) are reviewed.

In § 2.2.3, the terraced landscape, it is chosen to discuss the palaeogeographical development of the Lower Rhine Embayment and the Upper Rhine Graben. Both are relatively wide incised valleys within the Rhine catchment causing a good preservation of Holocene river terraces/palaeo-meanders. Fluvial development and its controlling factors are extensively researched in the Upper Rhine Graben. A comparison between the Upper Rhine Graben and the research area will be used to detect similarities and differences in fluvial development, which hopefully will give more insight in the factors controlling fluvial development.

The incision rates and river gradient will be reviewed in § 2.2.4. Followed by a overview of factors that are considered to have influenced fluvial development (§ 2.2.5) in the Rhine Delta, Lower Rhine Embayment and Upper Rhine Graben during the Holocene.

2.1 Holocene climate and vegetation development

The Holocene interglacial started around 11,650 cal yr BP (= 10,000 ^{14}C yr BP) and is the youngest chronostratigraphical time zone. At the onset of the Holocene, a warming of the climate occurred that was the last phase of the last glacial-interglacial transition. It was accompanied with rising sea-level and vegetation succession to a temperate forest situation. During the rest of the Holocene temperature was relatively stable, variations were in the range of 1-3 ^{0}C. Although temperature fluctuations were relatively small, a subdivision of the Holocene can be made based on changes in vegetation (Fig. 2.1) (Janssen, 1974; Van Geel, 1981). Partly due to growing human impact (deforestation).

In the study area, the open, typically periglacial vegetation cover turned into a gradually closing forest vegetation during the climatic transition. A sharp shift from Non Arboreal (NAP) to Arboreal (AP) marks the onset of the Holocene in almost all pollen diagrams form Northwest Europe. Almost directly after the onset of the Holocene, the climate was suitable for most tree species to develop.

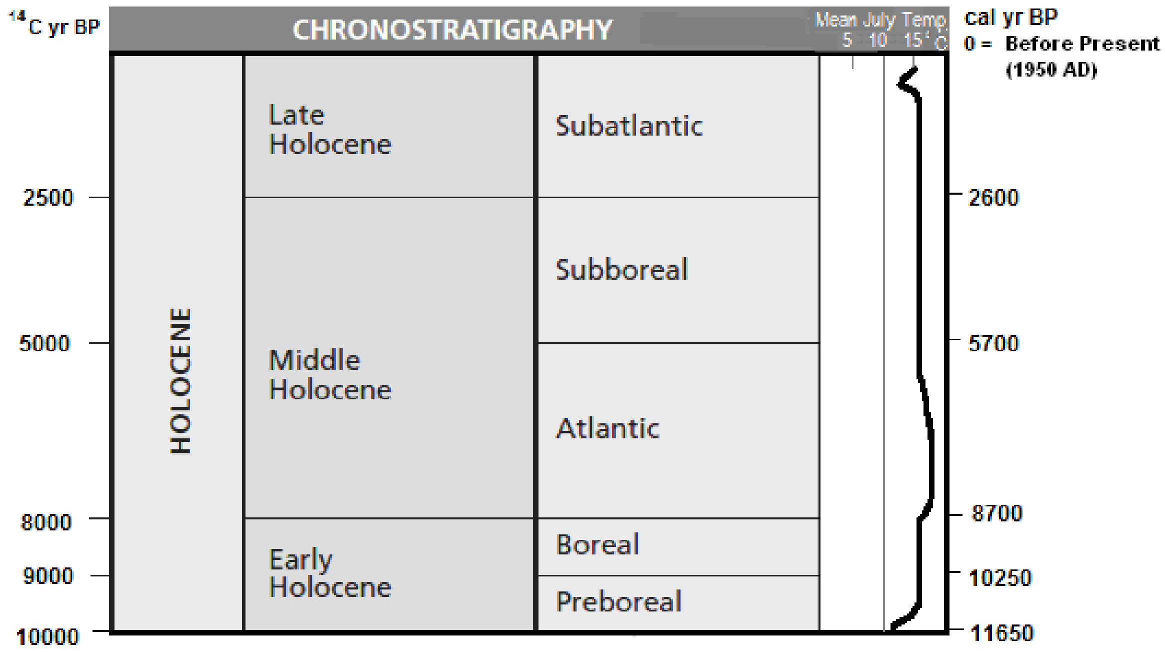

Figure 2.1: Subdivision of the Holocene in the Netherlands (various sources) .

The vegetation succession at the beginning of the Holocene is mainly governed by the dispersion rate of different species and mutual competition, which is initially determined by the shade tolerance, life length and height of the different species. The absence of shade tolerant species at the onset of the Holocene, initially allowed a light tolerant pioneer vegetation. These were successively outcompeted by shade providing species (Janssen, 1974).

A subdivision of the Holocene, based on vegetation changes, is given by Van Geel et al. (1980) who studied the vegetation development from ‘De Borchert’, a site near Denekamp, the Netherlands. Janssen (1974) also compared several Holocene pollen diagrams and gives an overview of the Holocene vegetation succession. Both studies are used to describe the Holocene vegetation development characteristic for the Netherlands and surroundings.

During the first period of the Holocene, the Preboreal, a relatively unstable climate was present. The Preboreal can be subdivided into the Friesland phase (10150 – 9850 ^{14}C BP), the Rammelbeek phase (9850 - 9750 ^{14}C BP) and the Late Preboreal (9700 – 9150 ^{14}C BP) (Van Geel et al., 1981). During the Friesland phase *Betula* spread at a fast rate. *Juniperus, Salix, Empetrum, Cyperaceae, Helianthemum* and other species present during the Late Glacial, occurred in lower percentages or had disappeared, except for *Artemisia* whose percentages remain high until the end of the Rammelbeek phase.

The Rammelbeek phase is characterized by a sharp decline of the *Betula* pollen curve and the concomitant rise of the *Gramineae* curve, the vegetation cover must have remained dense

During the Late Preboreal a characterizing steep fall in the *Graminneae* curve and a rise in the *Betula* pollen occurs. In addition, *Pinus* percentages are increasing: Apparently the immigrated *Pinus* successfully competed with *Betula* and *Populus* which became les important arboreal elements. In the southern Netherlands the rise in *Betula* pollen is often absent, because *Pinus* and *Betula* were closer by at the time of the Late Glacial. From ca. 9250 till 8850 ^{14}C BP *Humulus* appears in relatively high percentages (Van Geel, 1980).

The beginning of the next period, the Boreal (9150 – 7900 ^{14}C BP), is characterized by the appearance of *Corylus*, a scrub species which can expand rapidly because of its shade tolerance and zoochore dispersal. *Corylus* shows high values in the second half of the Boreal when the curves of *Quercus* and *Ulmus* start to rise (from ca. 9000 ^{14}C BP). *Tilia* starts to rise at 8300 ^{14}C BP, a phenomenon which probably caused the decline of *Corylus* later on (Van Geel, 1980). *Alnus* also appears to increase gradually (Janssen, 1974). The pollen of *Viburnum* and *Hedera* are of regular occurrence from ca. 8500 ^{14}C BP onward (Van Geel, 1980).

During the third period, the Atlantic, *Alnus* shows a sharp rise at 7900 ^{14}C BP and from 6700 ^{14}C BP onward, *Fraxinus* becomes a relatively important forest element (Van Geel, 1980). In the Atlantic, the instability of the vegetation came to an end and the climate was probably stable enough to reach climax vegetation (Janssen, 1974).

The transition from the Atlantic to the following Subboreal period (5000 – 2500 ^{14}C BP) is characterized by a decline of *Ulmus* and *Tilia* and the first appearance of *Plantago lanceolata* at ca. 5000 ^{14}C BP (Van Geel, 1980). The latter witnesses, as do some pollen of *Cerealia*, a rise in NAP and the continuous presence or *Rumex* pollen, the presence of human influence (partial deforestation and shifting cultivation). Apart from that, an increase in *Corylus* and *Fraxinus* pollen is visible and *Fagus* and *Carpinus* are present in low percentages (Janssen, 1974). In addition to the impact of humans on the vegetation cover, there might also be a deterioration of the climate at the start of the Subboreal (Janssen, 1974, p. 57 and refs therein).

For the Upper Rhine Graben, upstream of the research area, more stable and drier palaeoecological conditions are described by Dambeck & Thiemeyer (2002) during the Subboreal. Human impact (notably clearing of forests during the Neolithic) is also mentioned as a possible cause of the revival of aeolian activity from 6000 cal BP onwards (Dambeck & Thiemeyer, 2002; Bos et al., 2008; Dambeck, 2005).

The last and still persisting period, the Subatlantic, is characterized by the expansion of *Fagus* and *Carpinus* at the expense of *Corylus, Quercus* and *Betula*. Pollen of *Tilia* and *Ulmus* become rare. The expansion of *Fagus* seems to be related to sandy areas. Likely the onset of the Subatlantic was accompanied by a change in climate, conditions becoming more oceanic (Janssen, 1974; Bos et al., 2008 and refs therein). Human activity further increased. In the Middle Ages widespread deforestation occurs and forest is replaced by meadows, fields and heaths. An increase in *Secale* and *Calluna* pollen is visible and *Fagopyrum* pollen occur regularly (Janssen, 1974).

2.2 Holocene fluvial development of the Rhine

The temperature increase and vegetation development in the early Holocene caused a decrease in peak discharges of the rivers, a general decrease of sediment load and a relatively increased sediment load of fines. This resulted in a change of river pattern from aggrading braided rivers (in existence during glacial periods in the Netherlands, for example the last two stadials: Late Pleniglacial/Lower Terrace and Younger Dryas / Terrace X) to meandering rivers (in existence at glacial-interglacial transitions) (Berendsen & Stouthamer, 2001; Berendsen et al., 1995). Downstream of the study area, since ca 9500 cal yrs ago, rapid sea-level rise began to effect the gradient lines of the rivers. This caused a shift of the terrace intersection eastward, particularly fast between 8500 and 6000 cal yr ago, and continuing thereafter. The initially incising Rhine channel became aggradational and avulsive multi-branched with this transition. (Berendsen & Stouthamer, 2001; Cohen, 2005; Hijma & Cohen, 2011).

2.2.1 Shifting of the terrace intersection

The terrace intersection is defined as the point where incision changes into accumulation (Berendsen & Stouthamer, 2000). The location of the terrace intersection can migrate over time by a change in tectonic movement, climate change (affecting sediment supply and discharge) and a change in base level (due to sea-level change). During the early Holocene, meandering rivers were incising as a consequence of the warming climate and altered sediment delivery. The rising sea-level caused the incised river valleys to fill backwards, especially during the Middle Holocene. Early in the Atlantic, the rise in base level (sea-level change) became noticeable in the central part of the Rhine delta. Rivers could develop new meander loops outside their late glacial and early Holocene incised channel belts and caused renewed deposition on top of the Lower Terrace (Pleniglacial braid plain) (Berendsen & Stouthamer, 2000).

The upstream shifting of the terrace intersection has been reconstructed with the use of groundwater gradient lines (Van Dijk et al., 1991; Stouthamer & Berendsen, 2000; 2001, Cohen, 2003; Gouw & Erkens, 2007) (Fig 2.2). The migration of the terrace intersection is determined by the intersection between the Pleniglacial substrate and the groundwater gradient line. The groundwater gradient line is representative for the river gradient line (Berendsen, 2004). During the Holocene groundwater gradient lines are influenced by the sea-level rise, causing younger gradient lines to attain a higher position. The groundwater gradient lines are reconstructed by dating peat on top of the Pleniglacial Lower Terrace. It is assumed that this peat formation on top of the Pleniglacial substrate is caused by the rising groundwater level (Berendsen, 2004). In reality it is possible that there is a time lag between the incision-aggradation transition and the formation of peat on top of the Pleniglacial braid plain.

In the upper part of the delta, between the Peel Boundary Fault zone (PBF) and the delta apex, the upwards shifting of the terrace intersection is more difficult to reconstruct (Fig. 2.2). Groundwater gradient lines are less usable because peat formation in the eastern part of the delta is limited due to the eastward narrowing of the delta, resulting in smaller floodplains with more clastic deposition (Cohen, 2003). Detailed cross-sections and age control of multiple channel belts are necessary to determine the position of the incision-aggradation transition through time. This method however is less accurate and not directly comparable with the incision-aggradation transition determined by groundwater gradient lines.

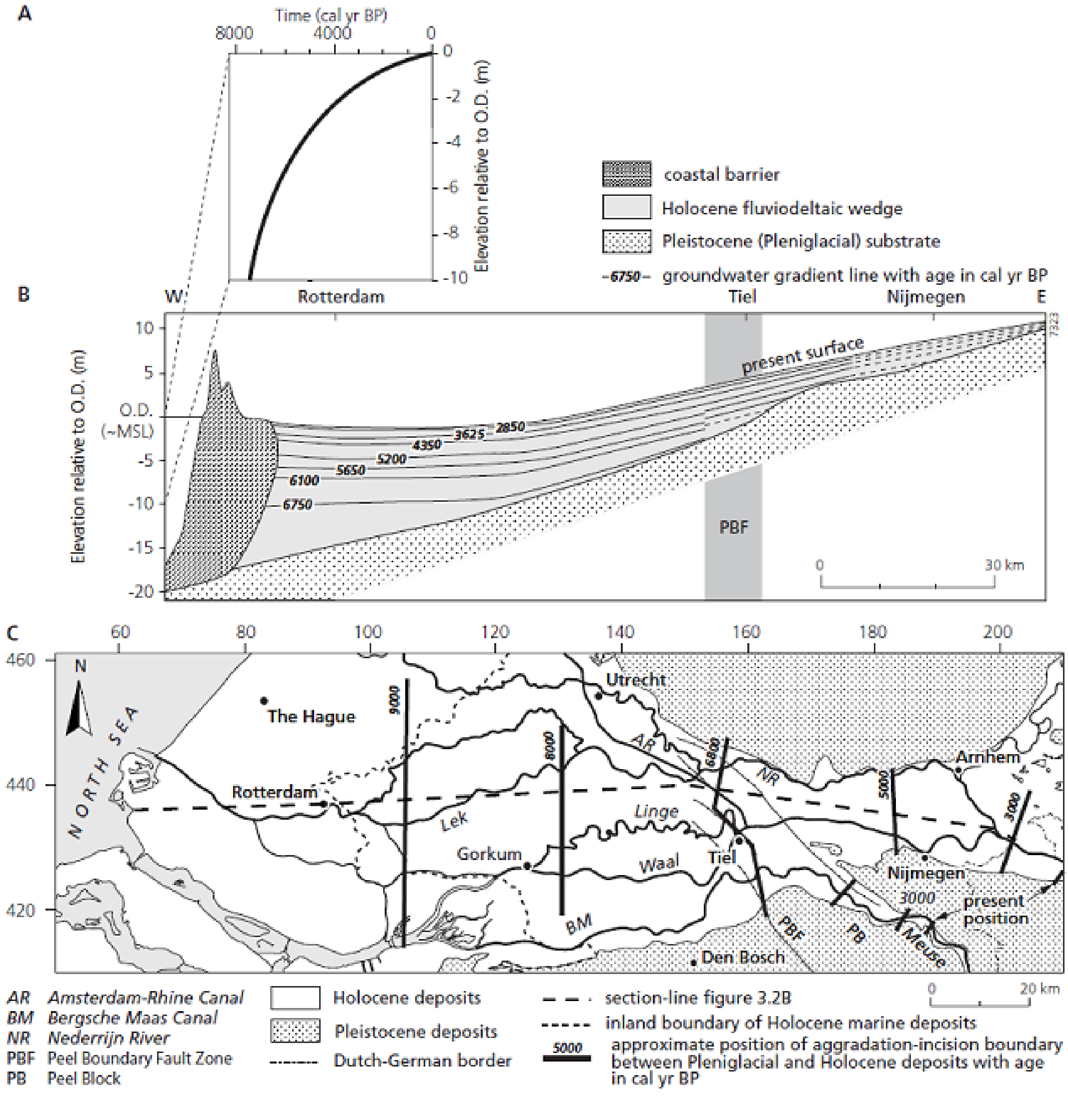

Figure 2.2: a) Relative sea-level rise at the river mouth (Jelgersma, 1979; Van de Plassche, 1982), b) Longitudinal section through the fluvio-deltaic wedge of the Holocene Rhine-Meuse delta with palaeo-groundwaterlines (after Van Dijk et al., 1991; Cohen et al., 2002), and c) upstream migration of the terrace intersection during the Holocene (Stouthamer & Berendsen, 2000; 2001; Cohen et al., 2002). The terrace intersection point marks the eastern boundary of the Holocene fluvio-deltaic wedge and is represented in (b) by the intersection between the groundwater gradient lines and the Pleniglacial braid plain. Ages in cal yr BP. PBF =Peel Boundary Fault zone. Source: Erkens (2009).

In this thesis a subdivision is made between the incision-aggradation transition and the terrace intersection between the Pleniglacial and Holocene deposits determined by Stouthamer & Berendsen (2000; 2001) using groundwater gradient lines. The incision/aggradation boundary is defined as the point were younger Holocene in-channel deposits (the top of bars of aggrading meanders) are located higher than older Holocene in-channel deposits (the top of bars of incisive meanders). In the research area this will mean that after the incision/aggradation boundary the younger Holocene deposits are located higher than older Holocene deposits but still can be deposited lower than the Pleniglacial (Lower Terrace/NT2) and the Younger Dryas (Terrace X/NT3) terrace level.

The upstream shift of the terrace intersection, at least in the Middle Holocene, is mainly determined by the rate of sea-level rise and local tectonics. Fast sea-level rise between ca. 9000 and 5700 cal yr BP caused a fast shift of the terrace intersection eastward. Around 6800 cal yr BP the shift of the terrace intersection temporarily decreased because of the height difference near the Peel Boundary Fault zone (Fig. 2.2) (Stouthamer & Berendsen, 2000; Cohen et al., 2005). After ca. 5700 cal yr BP the terrace intersection point was located near Arnhem/Nijmegen when the eastward shift decreased (Paas & Teunissen, 1978). The shift of the present day terrace intersection point/incision–aggradation boundary in the apex region is not influenced by sea-level rise anymore since eustatic sea-level rise had ceased. Furthermore, the research area is located in a tectonically stable (hinge zone) area which implies that not downstream relative sea level rise, but continued sediment delivery from upstream drove the eastward shifting of the terrace intersection/incision–aggradation boundary and transformed the northern part of the LRE into the Rhine delta apex (Cohen et al., 2005; Gouw & Erkens, 2007; Erkens, 2009). According to Favier (2001), nowadays the terrace intersection point (defined by Stouthamer & Berendsen, 2001: Holocene deposits on top of the Lower Terrace) is located near Megchelen (halfway Emmerich and Rees). The present incision/aggradation boundary is located several kilometers upstream of Rees (Favier, 2001) and moved into the research area between 5.7 en 2.3 ^{14}C ka yr BP (ca. 6.5 – 2.3 cal ka BP) (Dingemans, 2001).

2.2.2 Fluvial development Rhine delta

A description of river pattern evolution from the Rhine-Meuse delta during the Last Glacial – Interglacial transition and the Holocene has been given by Berendsen & Stouthamer (2001, and refs. therein: Pons (1957), Berendsen et al. (1995), Makaske (1998) and Cohen (2003).

Below the present day Rhine-Meuse delta, the braided river pattern that existed during the Younger-Dryas stadial and formed an incised braid plain terrace (Terrace X) turned into a deeply incising, low-sinuosity meandering, or straight river pattern in the late Younger Dryas or early Preboreal (Berendsen et al., 1995; Berendsen & Stouthamer, 2001; Hijma et al., 2009). Early Holocene channels were bounded to the extent of Terrace X until aggradation reached a level that that made deposition outside the incised Terrace X possible. Only a few Early Holocene channels have been mapped in the Rhine-

Meuse delta (Cohen 2005; Cohen et al., 2009). One channel has been described by Berendsen et al. (1995) in the 'Land van Maas en Waal' east of Nijmegen, the Netherlands. The channel had a depth of 6 – 7 m and a width of about 200 m when it became abandoned. Other channels too must have been relatively deep. The infill of the channels indicates a Preboreal - Boreal age. In the central part of the delta residual channels of only a few meters deep were found (Berendsen & Stouthamer, 2001). It seems that the Rhine-Meuse system by then had concentrated in only a few large incised meandering channels and that the smaller channels draining the former Terrace X were in a state of degradation and peat formation (Berendsen & Stouthamer, 2001; Cohen, 2005).

During the Holocene fluvial style changed in the Rhine delta over time and space. In the central delta, channel belts older than 7000 cal yr BP are all of the meandering river type (Törnqvist, 1993; Gouw & Erkens, 2007). Between 7000 and 4000 cal yr BP the fluvial style in the western part of the delta changed into a straight anastomosing river type, while in the eastern part of the delta the meandering river type remained. The northern and southern flanks of the delta kept their meandering river type throughout the Holocene as well. The younger channel belts are all of the meandering type again (Fig. 2.3) (Berendsen & Stouthamer, 2001; Wolfert, 2001).

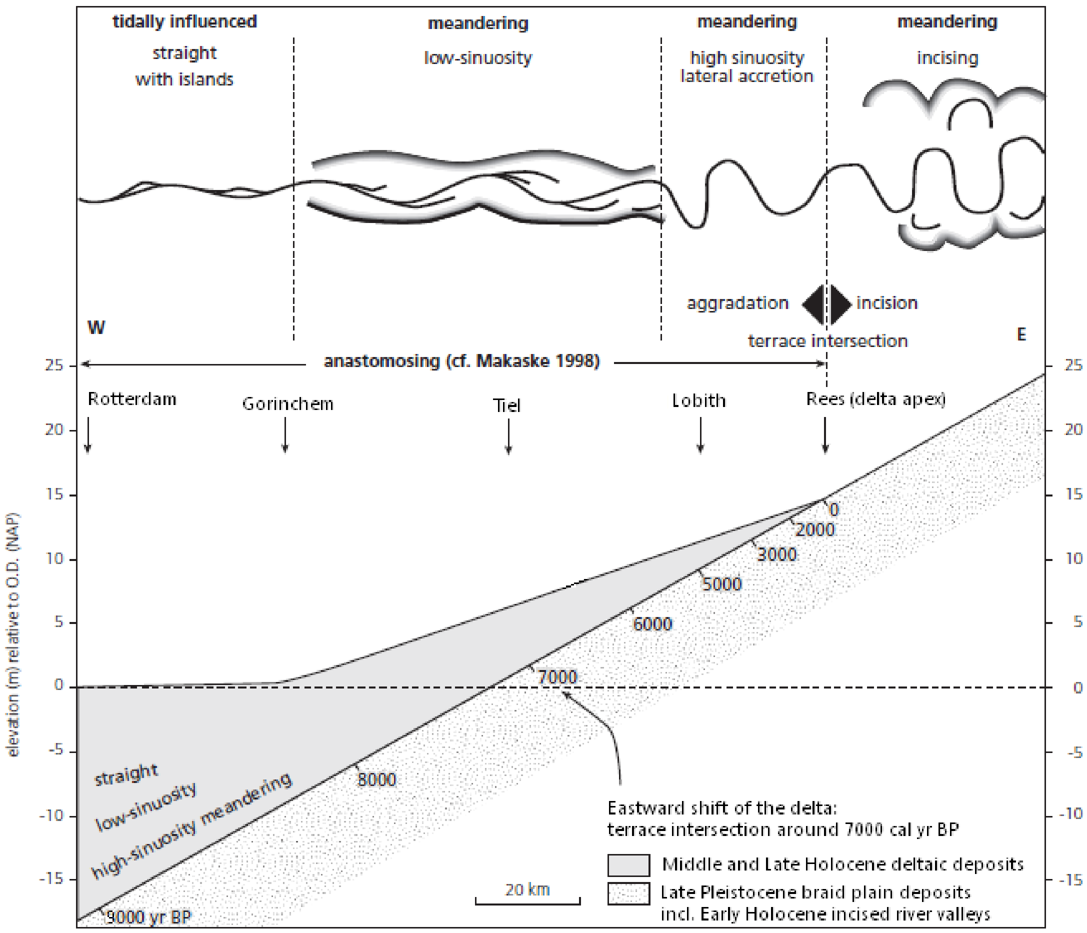

Figure 2.3: Changes in fluvial style. Meandering rivers occur near the terrace intersection, where easily erodible sandy deposits occur at shallow depth, and river gradient is still relatively high. Westward, gradients decrease and depth to the easily erodible sand increases causing fluvial style to become straight. The longitudinal succession of river channel pattern shifted eastward during the Holocene (after Wolfert, 2001; Cohen et al., 2009).

Changes in fluvial style in the Rhine delta are caused by a combination of local factors (position relative to the North Sea, the presence of ice pushed ridges along the northern edge of the delta and the Peel Fault Boundary in the subsurface) and external factors (e.g. Cohen et al., 2009). The most important external factors are sea-level rise (Törnqvist, 1993), differential subsidence between the eastern and western part of the delta (Cohen, 2003) and a increase in fine sediment supply (due to human impact) of the Rhine during the last 3000 year (Erkens et al., 2006; Gouw & Erkens, 2007; Erkens, 2009).

2.2.3 Fluvial development terraced landscape

Central Europe

The river terraces that developed in central Europe during the Holocene have been described by Schirmer (1995). He compared different studies along the Rhine (Lower Rhine, Middel Rhine, Upper Rhine and Main, see figure 1.1), Donau and Weser (Germany), and distinguishes seven Holocene river terraces. For the study of the Lower Rhine river terraces, Schirmer used the study of Klostermann (1989). The seven Holocene river terraces are grouped into the Lower Holocene (HL, 10-7.5 ^{14}C ka BP), Middle Holocene (HM, 7.5-2.5 ^{14}C ka BP) and Upper Holocene (HU, 2.5 ^{14}C ka BP - present). The distinction is mainly based on the floodplain sediment, floodplain thickness, and floodplain soil development. The Lower Holocene is represented by one known terrace, The Lichtenfels Terrace (HL). The HL Terrace has been formed during the Preboreal and is characterized by a thick black soil (pseudochernozem). The Middle Holocene is divided into the Ebensfeld Terrace (HM1) and the Oberbrunn Terrace (HM2). The HM1 Terrace was formed during the Atlantic (ca. 7800 – 6250 ^{14}C yr BP). The terrace is characterized by an increase in flood deposits and a red soil (parabrownearth). The HM2 Terrace was formed during the Subboreal and has a typical brownearth soil and sometimes an enrichment of clay in the flood sediments. The remaining four terraces (HU1-HU4) belong to the Upper Holocene and formed during the Subatlantic. During this period human influence increased strongly. For a detailed description of the HU terrace characteristics, see Schirmer (1995).

Lower Rhine

The subdivision of the seven Holocene river terraces found along the Lower Rhine is made by Schirmer (1995) and also mainly based on the work of Klostermann (1989). A few kilometers upstream of the research area, Klostermann recognized seven river terraces in the area of Xanten and Wesel (Klostermann, 1989; 1992; 2001). He made a correlation with the river terraces as described by Brunnacker (1978) along the entire Lower Rhine. Klostermann's subdivision of the Holocene differs somewhat from the subdivision made by Schirmer (1995), but this author also recognizes seven river terraces.

Klostermann (1989) identified near Wesel two Old Holocene (here: 10 000 - 5500 ^{14}C yr BP), one Middle Holocene (here: 5500 - 2000 ^{14}C yr BP) and four Young Holocene (here: 2000 ^{14}C yr BP - present) river terraces. In this area, Klostermann shows that one river terrace often contains more than one palaeo-meander. One Old Holocene and one Middle Holocene palaeo-meander are located in the research area (palaeo-meander A and B, see Fig. 4.5). The first Old Holocene terrace (palaeo-meander A and two meanders upstream the research area) had been active between 9000 – 6000 ^{14}C yr BP. The second Old Holocene terrace had been active between 6000-5000 ^{14}C BP and the Middle Holocene terrace (palaeo-meander B and also other palaeo-meanders) dates from 5000-2500 ^{14}C BP. Jansen (2001) made a subdivision of the Younger Holocene terraces for the area around Wesel, but these terraces could not be correlated with the river terraces near Xanten because most young terraces are damaged by human intervention.

Klostermann (1989; 1992) and Jansen (2001) also mention that the terraces can be identified by their characteristic soil type (Old Holocene: Braunerde and parabraunerde; Middle Holocene: Braunerde), calcification depth, cross-cutting relationships, elevation and archeological and historical evidence. The Old and Middle Holocene terraces are formed by strongly meandering rivers, while the first Young Holocene terrace at the onset of the Subatlantic probably shows a less meandering, more straight river pattern. The other younger terraces again show a meandering river pattern.

The study by Favier (2001) and Dingemans (2001) in the research area showed that the periods of formation of the Holocene terraces can roughly be correlated with the periods described by Schirmer (1995). However, some terraces can not be correlated to those described by Schirmer. It is possible that the terraces are a result of continuous process of meandering and meander cutoff, resulting in 'terraces' that have randomly been preserved (Dingemans, 2001; Favier, 2001).

The area just upstream of the research area has also been investigated by Erkens (2009; Erkens et al., 2011). He focused on sediment dynamics and gives a quantification of fluvial response to climate change and human impact. One of Erkens' cross-sections is located in the southern part of the research area (cross-section V, through meander A and B). According to Erkens, river incision dominated during (and even before) the onset of the Holocene. At the onset of the Holocene the Younger Dryas braid plain (in Germany NT3 terrace) became abandoned and the flow became concentrated in an incising multi-channel system existing of one large and a couple of smaller (secondary) channels. The multi-channel system started meandering and transformed part of the braid plain morphology into point bars. During the Boreal flow became fully concentrated into a single meandering thread, and the secondary channels were abandoned. The earliest dated palaeo-meander of the system, later to become the main channel, is ca. 9.4 cal ka old. At 9.0 cal ka, the last secondary channel system was abandoned, owing to stronger incision in the main channel. The transition of the Lower Rhine towards a single thread meandering river, resulted in the reworking of large parts of the Late Pleistocene braid plain river terraces. Holocene deposits are arranged in unpaired palaeo-meanders (unconnected cut-off meander bends) of varying age. The mapping of the Holocene meanders given by Erkens is based on that by Klostermann (1992), but the paper does not consider the Holocene meanders-groups to represent separate phases of fluvial activity (Erkens, 2009; Erkens et al., 2011).

The secondary channel systems described by Erkens (2009) can be subdivided by their Late Glacial and early Holocene abandonment ages. The Late Glacial secondary channel systems formed within the Pleniglacial / NT2 braid plain (activity between 14.5-12.8 cal ka BP) and the early Holocene secondary channel systems formed within the Younger Dryas / NT3 braid plain (activity between 12.0-9.0 cal ka BP). The Late Glacial secondary channels sometimes diverse from the central Rhine braid plain (Niers-Rhine and Oude IJssel valley; Kasse, 2005; Verschuren, 2007), while the early Holocene secondary channel systems are aligned parallel to the river Rhine (e.g. cross-section V, Erkens, 2009). Stronger and more competitive incision of the main channel is likely the cause for their abandonment.

Upper Rhine

Further upstream of the Lower Rhine, in the northern Upper Rhine Graben (URG), fluvial development and their controlling factors has recently been intensively researched by Dambeck & Thiemeyer (2002), Dambeck (2005), Dambeck & Bos (2002), Bos et al. (2008) and Erkens et al. (2009). The URG is a relatively stable subsiding tectonic block, and the northern edge of the graben provides a local base level for the river. The width of the Holocene floodplain (ca. 10 km) is comparable with that of the research area, but valley gradient is much less, only 4 cm/km (Fig. 2.4; Ekens et al., 2009 and refs. therein).

The Holocene river terraces that formed in the northern URG form three groups based on fluvial style/ river morphology, overbank sediments characteristics and elevation. Distinguished are a Latest Glacial/Early Holocene (ca. 13-6 cal ka BP), Middle Holocene (ca. 6-3 cal ka BP) and a late Holocene (3 cal ka BP-present) terrace level (Fig 2.4). The Early Holocene terrace hosts well-developed palaeo-meanders. Over the late Preboreal to middle Boreal an increase in channel radius and width is observed in the southern part of the northern URG. During the Boreal channel radius and width decreased, and a single channels be developed (Bos et al., 2008). Erkens et al. (2009) describes two parallel meandering channels of Preboreal to Boreal age in the southern part of the northern URG. The depth of the two channels differs (7 m and 5 m), indicating that discharge was not evenly distributed over the two channels. According to Erkens et al. (2009), the two-channel situation persisted until ca. 8 cal ka BP (Fig 2.5).

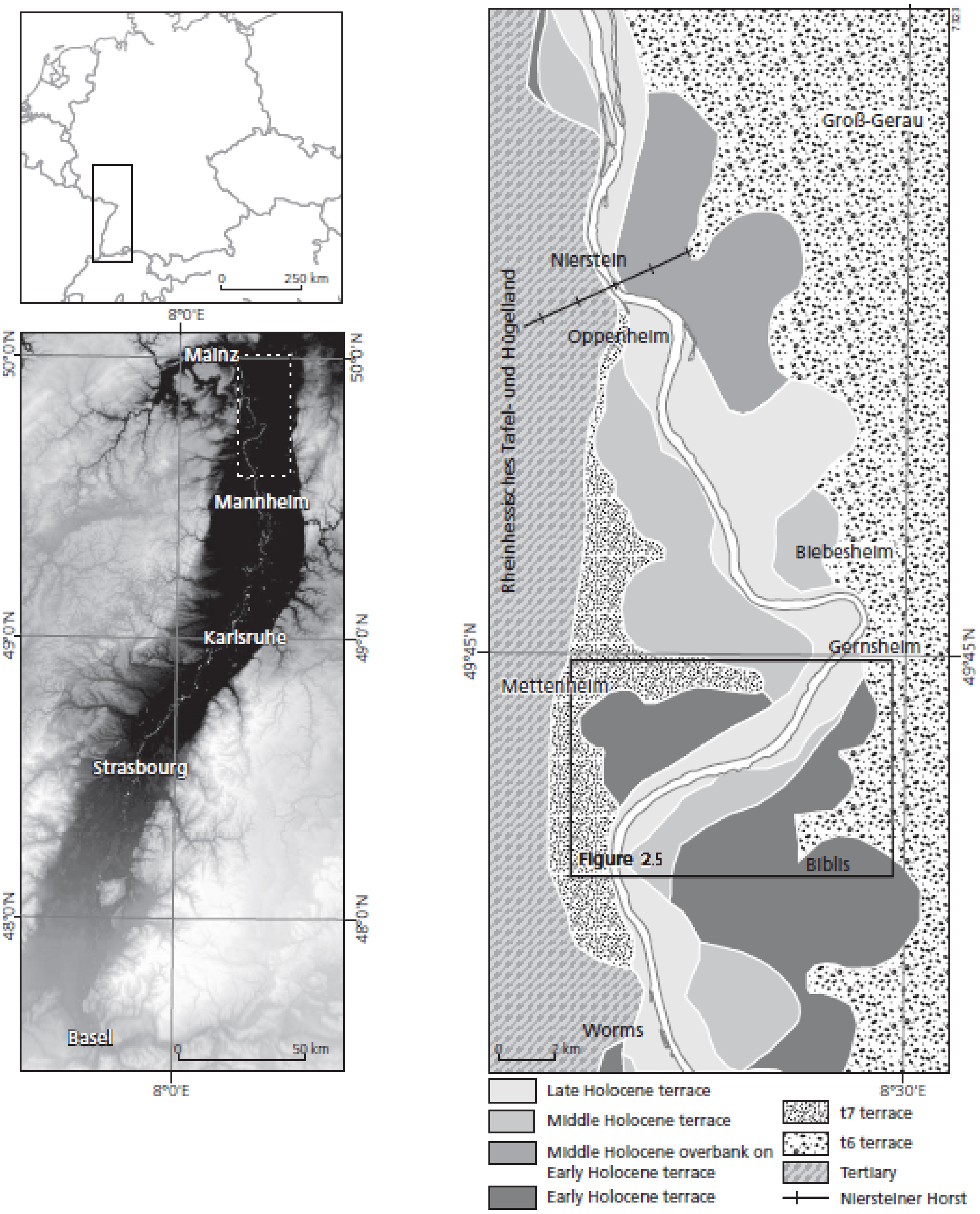

Figure 2.4: Setting of northern Upper Rhine Graben (Germany) with Late Weichselian and Holocene terrace levels (Dambeck & Thiemeyer, 2002; Dambeck, 2005)

During the Atlantic the river Rhine initially maintained its single thread meandering pattern. Later during the Atlantic, however, there is a rapid change in the fluvial system. The Middle Holocene terrace is characterized by strongly decreased meander sinuosity in the southern part of the northern URG and more clayey overbank deposits in the entire URG ("Black Clays"). This resulted in an almost straight river pattern in the south, although more to the north large meanders continued to develop. Erkens et al. (2009) describes the existence of low-sinuosity channels of relatively small

width and shallow depth (> 5 m) in the southern part of the northern URG around ca. 6 cal ka BP. In the northern part of the northern URG, one meandering channel existed during Middle Holocene.
In the Late Holocene, some parts of the river valley are characterized by very large meanders, while in other reaches a straightening of the river channels and narrowing of the floodplain occurred (Bos et al., 2008; Dambeck & Thiemeyer, 2002). In the entire northern URG, flow concentrated into a single low-sinuosity channel again after 2.7 cal ka BP (Erkens et al., 2009). The deposition of mainly clayey overbank sediments ceased and shifted to deposition of predominantly silty sands and sandy silts (Bos et al., 2008; Dambeck & Thiemeyer, 2002).

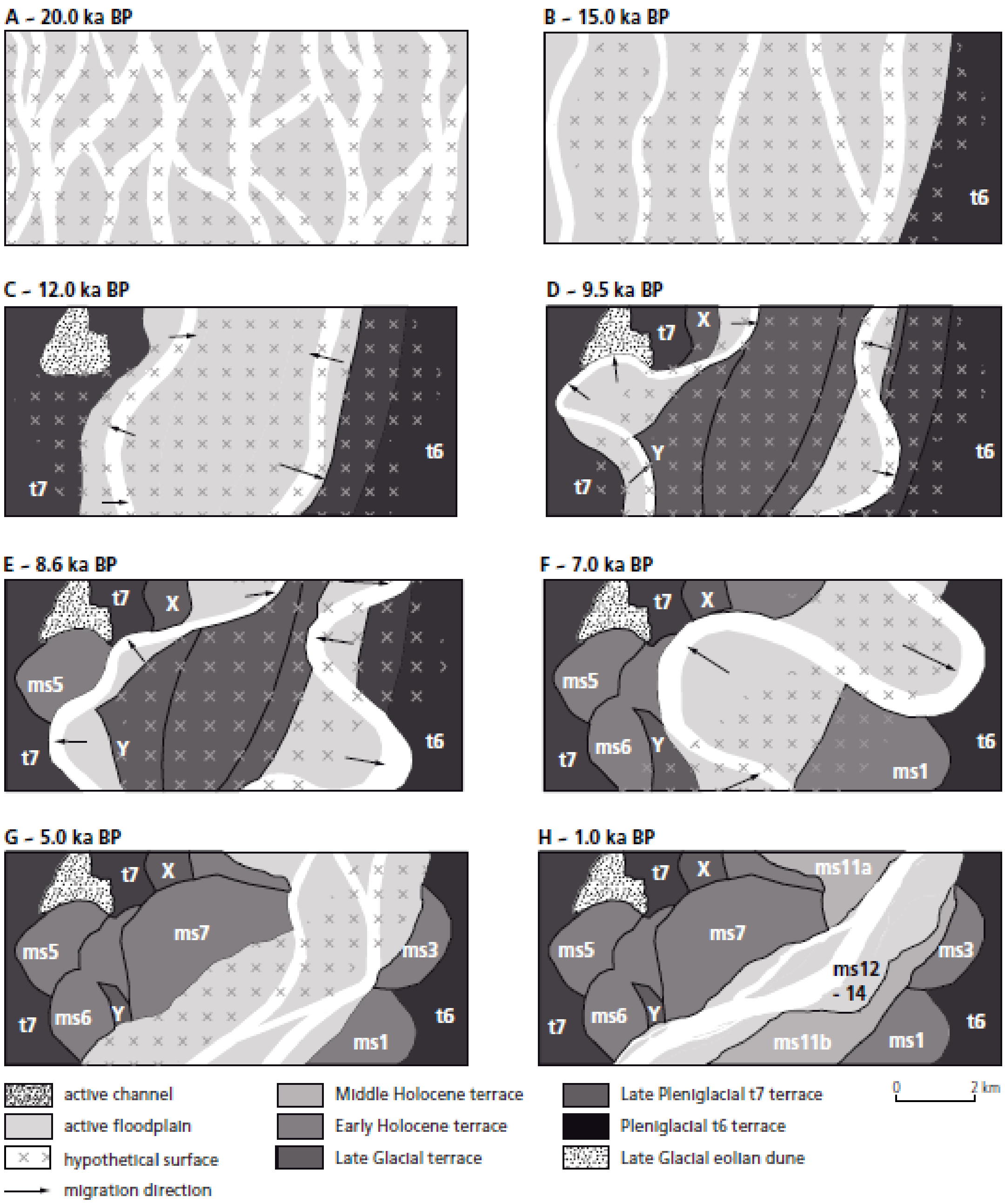

Figure 2.5: Palaeogeographic development of the southern part of the northern Upper Rhine Graben (for location see fig 2.4; Rosenberger et al., 1996; Dambeck, 2005; Erkens et al., 2009)

2.2.4 Incision and valley gradient

Below the Rhine delta, incision (lowering of the channel base and probably also lowering of the water table) only occurred at the onset of the Holocene (Cohen et al., 2009), rapidly followed by aggradation during the rest of the Holocene. In the URG, incision lasted the last 20 ka until the Late Holocene (ca. 2.7 cal ka BP). Holocene palaeo-meanders group into three river terrace levels. Each palaeo-meander formed at a lower elevation, except the Late Holocene river terrace level, which seems not to be incised anymore (note that channel depth did increase). Incision in the URG was caused by a change from a transport-limited to supply-limited river until the Late Holocene. Incision existed because during the Pleniglacial the URG had acted as a partial sediment sink for bed load while the river was transport limited, but this changed with climatic warming and the deglaciation of the Swiss lakes, which made the system supply limited and transformed the URG into a sediment source and initiating incision. Because incision in the URG depends on sediment load/discharge ratio, two explanations are given by Erkens (2009) to explain the Late Holocene decreased incision. The first possibility is that the river had fully adapted its morphology to Holocene discharge and longitudinal equilibrium profile was established or secondly, new external forcing markedly changed the sediment delivery. Total incision was ca. 1.5 m during the Early and Middle Holocene.

The northern part of the LRE (the study area) experiences very modest uplift because it is located in the hinge zone of the North Sea Basin. The southern part (outside the study area) experiences higher uplift rates because the nearby presence of the Eifel volcanic dome. During the Holocene, in the study area tectonic uplift was very modest and part of the net incision in the LRE had a non-tectonic cause, notably upstream external forcing (Klostermann, 1992; Erkens, 2009). In the southern part of the LRE, Erkens (2009) found a total incision of 8.5 m (between the top of the Pleniglacial/NT2 terrace and the Late Holocene terrace, i.e. over 15000 yrs), while in the research area a total incision of respectively 3.5 m and 4.0 m has been described by Dingemans (2001) and Favier (2001). They found a maximum elevation difference of 3.0 m between the highest and lowest Holocene palaeo-meander (each palaeo-meander is treated as a separate river terrace level in their study). The average level of the top of channel deposits of the highest (and oldest, probably Preboreal) Holocene terrace is ca. 1 m below the Pleistocene river terrace level. The lowest Holocene river terrace has been formed ca. 3.5 m to 4.0 m below the Pleistocene river terrace and has an estimated age of 4000 ^{14}C yr BP. The next found river terrace with an estimated age of 2000 ^{14}C yr BP has a higher elevation. All river terraces formed after ca. 2000 ^{14}C yr BP have a higher elevation and are located at the same height as, or even higher than, the Pleistocene river terrace (Dingemans, 2001; Favier, 2001).

The gradient of the Pleniglacial NT2 / Lower Terrace and the Younger Dryas NT3 / Terras X (including Early Holocene) is for the Rhine delta (upstream of Tiel) and the LRE roughly the same, respectively 30 cm/km and 27 cm/km (Pons, 1957; Dingemans, 2001; Cohen, 2003; Erkens, 2009). In the middle of the Rhine delta, Van Dijk et al. (1991) found a river gradient varying from 20 cm/km around 6750 ^{14}C yr BP till 16 cm/km around 2850 ^{14}C yr BP (Fig. 2.1b; Van Dijk et al., 1991). Just upstream of the research area (between cross-section IV-IV' and V-V, Erkens 2009), Erkens found an Early Holocene (11.5 - 6 cal ka BP) gradient of ca. 22.5 cm/km. According to Erkens, Early, Middle and Late Holocene river gradient are roughly the same in the LRE. Just downstream the research area between Kleef and Nijmegen Paas & Teunissen (1978) describe a Holocene gradient of 18 cm/km, not mentioning the exact age.

2.2.5 Factors controlling fluvial development

The main external factors that are commonly used to explain the formation and preservation of the fluvio-deltaic wedge and river terraces are tectonics/base level change (including sea-level change), climate change and human impact (Blum & Törnqvist, 2000), but local (external) factors (e.g. local tectonics, substrate, local gradient differences) and intrinsic river behavior can also cause a part of the catchment to react and produce a terrace , seemingly randomly (Erkens, 2009: p. 27,59,87). A change in tectonic/base level can influence the incision rate (negative or positive) and thus the rate at which river terraces develop or, in contrast, influence the available accommodation space for sedimentation in the delta. The second external factor, climate, drives river discharge and sediment yield through changes in precipitation, temperature (snow or rain), vegetation cover and, consequently, soil erosion intensity. The last important external factor, human influence, also has impact on the vegetation cover resulting in a change in sediment and delivery to the Rhine (Erkens et al., 2006; 2009; 2011)

Rhine delta

Holocene palaeogeographical evolution is a complex interaction between several factors including sea-level change, increased discharge, sediment load and/or within-channel sedimentation (by human influence and climate change) and by several other more local factors (see Berendsen & Stouthamer, 2000). According to Gouw & Erkens (2007) the subsequently dominant external factors that explain the trends in the build up of the Holocene fluvio-deltaic wedge are eustatic sea-level rise, subsidence and sediment supply. A relatively large part of the fluvio-deltaic wedge formed before 5000 cal yr BP by the high aggradation rate during the first part of the Holocene as a result of eustatic sea-level rise. At this moment, the terrace intersection was located ca. 120 km inland from the present-day coast (Fig 2.2). Between 5000 – 3000 cal yr BP, regional basin subsidence (enhanced by compaction of the underlying peat) controlled aggradation. From 3000 cal yr BP onwards, increased sediment supply and discharge from the hinterland caused expansion of the fluvio-deltaic wedge (Cohen, 2005) which might be related to changes in land use due to increased human cultivation (Gouw & Erkens, 2007 and refs. therein). By 3000 yrs ago, the terrace intersection was at 140 km upstream.

Lower Rhine

According to Schirmer (1995) the river terraces in the Central Europe (and thus the Lower Rhine and Upper Rhine) developed because of alternating phases of fluvial activity which proof that climate controlled fluvial rhythmicity both in smaller and in larger rivers. Although local factors influences texture, pattern, structure and floodplain soil types of the terraces and human impact increases from the Neolithic Period (late Atlantic) onwards, the natural imprints remain visible and dominating in this interpretation. Also Favier (2001) concludes that if tectonics and sea-level rise did not influence the formation of river terraces in the LRE, changes in discharge and sediment supply should be de dominating factor. Both climate change and human impact can cause a change in discharge and sediment supply. Dingemans (2001) mentions climate as the dominating factor and notes that in the period in which the transition to net accumulation took place (ca. 6.5 – 2.3 cal ka BP), also the first indications of human influence on the vegetation cover were preserved in the vegetation record.

A recent study by Erkens (2009) focuses on the exact course of events of the Lower Rhine response to changes in allogenic (external) forcing. The Rhine catchment experienced strong changes in upstream external forcing during the last 20 000 years. Climatic changes of the glacial-interglacial transition and steadily growing human impact during the second half of the Holocene forced the Rhine to adapt, resulting in changes in the fluvial morphology. Erkens (2009) describes that during glacial-interglacial transition the river Rhine changed from braided to meandering twice (Pleniglacial-Bølling/Allerød and Younger Dryas-Preboreal transition). During both transitional phases, secondary channels existed with a life span of up to 2500 years. This implies that it took the Lower Rhine considerable time to complete the full morphological transition to a single thread meandering system. Specific aspects of response that require more work, such as morphological transition (point bar/terrace formation, contraction to one channel) take more time than other aspects. Discharge change response (e.g. fluvial style change, abandonment of braidplains, channel bed lowering / incision) seem to have been near instantaneous. The degree of delay of geomorphic response depends for a large part on reach specific conditions that determine intrinsic river behavior. Sizable rivers in low-energy trunk valleys, such as the Rhine, are therefore very likely to show delayed response to external forcing such as that of the glacial-interglacial transition. In contrast, the response to human-induced increased sediment delivery after 2-3 cal ka BP, resulting in thicker and coarser overbank deposits and decreased incision in the northern LRE, seems to be quicker and more straight-forward (Erkens, 2009).

Upper Rhine

The decreased channel radius and width in the Boreal mentioned by Bos et al. (2008) can be related to an increased density of the floodplain vegetation cover and elsewhere in the catchment, leading to higher evapotranspiration. This probably resulted in a lowered channel-forming discharge and river activity in general. During the Atlantic, evapotranspiration gradually reduced and run-off is thought to have increased again, presumably caused by the introduction of agriculture and expanded clearing of forests by Neolithic people (Bos et al., 2008). The shift in river pattern led to a change in the sedimentation pattern which resulted in the deposition of the clayey overbank sediments. The Subboreal/Subatlantic transition (here dated at 2800 cal BP: Bos et al., 2008) was characterized by an abrupt climate change to cooler and wetter conditions and was forced by a decline in solar activity (Bos et al., 2008 and refs. therein). Human influence again further increased. The wetter climate in combination with enhanced deforestation and intensified human activity caused instability of the soils and an increase in surface erosion and run-off probably inducing the change in the meandering pattern. Both the abrupt change to a cooler and wetter climate as well as the intensification of human activity caused the Late Holocene shift in river pattern, although the differential development in various parts of the northern URG suggests an independent development of these fluvial systems (Bos et al., 2008).

According to Erkens et al. (2009), the transition towards a meandering system in the URG can be seen primarily as slow-but-steady complex response to initial climate change during the Late Pleniglacial. The transition took considerable time which is explained by the coexistence of secondary channel systems for some hundreds of years until the middle Boreal. Also Erkens et al. (2011) states that the change in meander sinuosity and/or fluvial style during the Atlantic cannot be explained by changes in climate or human activity only. This is because differences in trend and timing of meander sinuosity occurred in the LRE (e.g. Schirmer, 1995) and the URG during the Holocene. This implies that changes in fluvial style and/or meander sinuosity in the northern URG did not occur on a drainage basin-wide scale, but rather on local scale. If climate is the trigger of the changes in fluvial style, this can only be upheld in combination with complex response and strong local overprint, because different reaches respond differently to the same external factor. But Holocene climate was relatively stable and the Rhine showed no distinct geomorphic response to the larger Late Glacial climate changes, suggesting that it is very unlikely that the small Holocene climate variations caused the river to cross geomorphic thresholds. Also the other external possibility, human impact, can not explain the changes in fluvial style because human impact was very limited until ca. 4 ka. Therefore, Erkens et al. (2009) suggests that Middle Holocene changes in fluvial style and terrace formation are caused by intrinsic response to local factors (low gradient and thus stream power, incised valley). The characteristic Middle Holocene overbank deposits (Black Clays) can also be due to site specific conditions (dense vegetation cover, fixed single channel) that existed only during the formation of the Middle Holocene levels. The external forcing (stable climate conditions) that would have induced the deposition of the Black Clays in alternative explanations, started earlier on and sedimentation of Black Clays did not occur synchronously, or not at al, elsewhere in the Rhine trunk valleys. The Late Holocene change in fluvial morphodynamics is more likely due to human impact than due to the subtle cooling and increase in precipitation, because the considerable change in amounts of overbank sedimentation. In conclusion, in the northern URG, climate change was an important initial trigger during the last glacial-interglacial transition, but did not necessarily influence individual terrace formation afterwards (Erkens et al., 2009).

3 Methodology

3.1 Approach

To establish a Holocene palaeogeographical reconstruction of the transitional area near the present-day apex of the Rhine delta, new data are collected in the field and combined with data from previous research.
New field data were collected by hand borings during a four week fieldwork. This fieldwork aimed to establish lithogenetic cross-sections to determine the build-up of the research area. Samples were taken for pollen and Loss On Ignition (LOI) analyses from channel fills, to have some age control and getting a better understanding of the palaeogeographical development (Fig. 3.1). New data by De Molenaar (2011; LOI) and Geurts (2011; pollen analysis), gathered during this fieldwork, are also used in this thesis. For the LOI analyses is referred to De Molenaar (2011). When possible, LOI results were used in the reconstruction of the fluvial development. High LOI values in a channel fill sediment indicate high organic deposition and suggest a larger distance to the river, while low LOI values indicate low organic deposition and suggest a closer distance to the river (Minderhoud, 2010).

Figure 3.1: Sample taken in the field with the Boncke corer. From left to right: M.M. de Molenaar, A.H. Geurts and dr. W.Z. Hoek.

Data from previous research stored in the archive of Utrecht University (available via Cohen, UU), as well as multiple cross-sections are used to get a better understanding of the lithogentic structure of the area. In addition, geological maps and palaeogeographical reconstructions of the research area were studied. An accurate digital elevation model (DEM) (Landesvermessungsamt Nordrhein-Westfalen, Germany; via Cohen et al., 2009) was used to help distinguish different river terraces and morphological features to get a better understanding of the research area. Dates obtained by radiocarbon-, OSL dating and pollen analysis obtained from literature and the OSL data archive of Utrecht University are collected to help control palaeogeographical reconstruction. New OSL and radiocarbon dating samples were also collected, but results are not yet available during writing of this thesis.

3.2 Mapping

To make a palaeogeographical reconstruction of the research area, first geological maps, palaeogeographical maps of smaller parts of the research area and a digital elevation model are studied.

Geological maps (Geologische Karte von Nordrhein-Westfalen 1:25 000) for the regions Emmerich (4103: Braun & Thiermann, 1981), Xanten (4304: Klostermann, 1989) and Wesel (4305: Jansen, 2001), including explanatory booklets were available. For the areas Kalkar (4203) and Rees (4204) explanatory booklets have not been published, but geological maps are available.

Palaeogeographical studies of smaller parts of the research area (by Klostermann, 1992; Jansen, 2001; Brunnacker, 1978; Berendsen & Stouthamer, 2001; Dingemans, 2001; Favier, 2001; Erkens et al., 2011) have been studied to get a impression of the research area and the different river terraces/palaeo-meanders that have been identified so far. In addition, palaeogeographical studies upstream (Dambeck & Thiemeyer, 2002; Dambeck & Bos, 2002; Bos et al., 2008; Erkens et al., 2009) and downstream (Berendsen & Stouthamer, 2001; Gouw & Erkens, 2007) of the research area have been investigated to get acquainted with the different river terraces, morphology and controlling factors that formed Holocene river terraces along the Rhine.

The DEM (Landesvermessungsamt Nordrhein-Westfalen, Germany, reprojected to Dutch coordinate system, Cohen et al., 2009) is used to help distinguish different river terraces/palaeo-meanders and morphological feature and to determine the best locations for the boring transects (Appendix A). With the use of the DEM, an elevation map relative to the top of the Early Holocene in-channel deposits has been produced (Appendix B). The Relative Elevation map is corrected for an Early Holocene river gradient of 0.19 m/km that is determined with the use of cross-sections by Dingemans (2001) and Erkens (2011) through two Early Holocene meanders that have been dated and show the same age (activity around ca. 10 cal ka BP, Meander A and J, see fig. 4.1 & 4.2, Appendix F & D). The correction for the Early Holocene river gradient was chosen because of the focus of this study on Early and Middle Holocene fluvial development (11.65-8.7 cal ka BP and 8.7-2.6 cal ka BP, respectively). The corrected map gives a better overview of the different river terraces and palaeogeography, and makes a comparison between the river terraces possible.

Finally all collected information gathered in this thesis were combined to produce a Holocene palaeogeographical map of the area between Emmerich and Wesel (Appendix E).

3.3 Cross-sections and borehole data

During the fieldwork, 222 borings are carried out with a total depth of 671.2 m (Appendix A). Borings are placed at an average distance of approximately 200 m, but borehole spacing is irregular and follows the morphology within the area. Four lithogenetic cross-sections with a length varying from 0.5 to 10 km are made across the Holocene part of the research area (Fig. 4.1, Appendix C). The cross-sections are placed in the areas where no or little data was yet available and where presumed Early and Middle Holocene palaeo-meanders are located. The cross-sections run across palaeo-meanders as much as possible perpendicular to the residual channel and, as much as possible, through each meander's central axis. The cross-sections provide information on the terrace height (of in-channel deposits), river gradient, river style/channel morphology and (thickness) of floodplain deposits, all helping to understand palaeogeographical development.

The cross-sections primarily show lithogenetic interpretations (elements comprised of e.g. in-channel deposits, residual channel-fill deposits, floodplain deposits). Original borehole descriptions can be found on the enclosed CD-ROM and in the borehole archive of Utrecht University (available via K.M. Cohen, Dept Physical Geography).

Borings are numbered cf. Berendsen & Stouthamer (2001) and Berendsen et al. (2007), identified by year, group and boring number (2010.10.001 – 2010.10.208). Borings of previous research in the area are also available from this archive. Borings in the research area are incorporated in cross-section made by Dingemans (2001), Favier (2001) and Erkens et al. (2011) (Appendix D, Fig. 4.1).

3.4 Dating

To make a palaeogeographical reconstruction it is essential to determine the age of the different river terraces/palaeo-meanders individually, and consistent in sequence. For the research area, some absolute radiocarbon and Optical Simulated Luminescence (OSL) dates were available from Berendsen & Stouthamer (2001), Tebbens et al. (unpublished, available by Cohen, 2011) and Erkens (2011 and ref. therein) (Appendix F). Uncalibrated ^{14}C ages have been calibrated using CalPal-2007^{online} (Danzeglocke, 2011). New dates are obtained through pollen analysis, by correlation to dated diagrams (see §3.5). Relative ages follow from cross-cutting relationships of the river terraces and

meander residual channels. It is also tried to determine and verify relative and absolute ages using age-height relationships (with valley slope correlation).
Cross-cutting relationships are used to determine the relative age of river terrace fragments (mostly cut-off meander bends). The DEM shows which meander bend has been cut-off by which younger meander bends. This way the relative ages of most river terraces are determined. The relative height of the in-channel deposits of the river terraces is also useful for age correlation because the area has been influenced by incision during the Early and Middle Holocene. Aggradation of younger meanders present a complication, but combined with cross-cutting relationships, relative and absolute ages could be estimated throughout the study area. Terrace height and age are compared over a larger part of the valley; therefore the relative height of the river terraces is estimated compared to the Early Holocene terrace.
The relative elevation of each river terrace is determined using a newly-calculated "Relative DEM" of the Early Holocene valley slope (Appendix B). These elevations do not directly show the terrace height because floodplain deposits overlay the in-channel deposits, but the thickness of the floodplain deposits is known from the cross-sections and the elevation of the terraces can be determined. The river terraces with known ages are plotted in an age-height graph which makes it possible to determine the relative elevation of the river terraces throughout the Holocene (see section 4.3). Undated river terraces are plotted between the dated river terraces in the graph based on terrace height and relative age determined with cross-cutting relationships to indicate their absolute age.
Inferred dates quoted from literature (Brunnacker, 1978; Jansen, 2001; Klostermann, 1989 and after Dingemans 2001 (for the region of Emmerich: Braun & Thierman, 1981) based on historical findings and historical maps are only used if no absolute dates are available. The dates are always checked with cross-cutting- and age-height relationships. Dates based on these findings are used with some care because ages are mostly based on inferences from historical sources which in many cases give a minimal age.

3.5 Pollen analysis

Pollen diagrams are made for four channel fill sites in the Holocene floodplains of the research area: sites Heeren Bril (2010.10.084, Appendix A), Schloss Bellinghoven (2010.10.099), Hohe Ley (2010.10.167) and Vosse Kuhl (2010.10.011, described by Geurts, 2011.). These residual channels are chosen because limited data is available of the river terraces in which the residual channels have been formed, whereas an Early or Middle Holocene age is expected. The pollen diagrams are used to determine age and vegetation development and to reconstruct palaeogeography in combination with LOI results. The combined pollen and LOI data sets (De Molenaar, 2011; Minderhoud, 2010) describe the infilling of the residual channel over time, and allow to determine relative distance to the active river in the valley for subsequent stages in the Holocene, besides allowing the detection of rare-magnitude flooding event-layers. The Heeren Bril channel has been radiocarbon dated at 7020 ± 50 ^{14}C yr BP (Berendsen & Stouthamer, 2001; UtC-09540; 7889 ± 32 cal yr BP), but pollen and LOI analysis were not available before.

Pollen samples are taken from the bottom two meters of the residual channels with an average interval of 5 cm, which is in most cases sufficient to date the residual channels and reconstruct the regional and local vegetation. Before the pollen samples were taken, each collected core was described in detail in the lab (Appendix G). The exact location for pollen samples depends on sequence of the sediment layers within the residual channel. Samples are taken within organic layers and as much as possible above sandy/clastic layers. Because the shallowness of the Hohe Ley, all collected cores are sampled, with exception of the dehydrated and disturbed uppermost part.

In total, 93 pollen slides are prepared according to the standard method (Faegri & Iversen, 1989). *Lycopodium* spores, which are usually added to calculate pollen concentrations, have only been added to the Hohe Ley pollen samples. The soft and sticky sediment (gyttja) of the Heeren Bril and the Schloss Bellinghoven residual channels made it impossible to sample a known sediment quantity with the available equipment, which is necessary to calculate pollen concentrations, and made it impossible to calculate pollen concentrations.

Pollen slides are examined under a microscope with a magnification factor of 400 to 630. Determination has been done with the use of the pollen key developed by Moore et al. (1991). The slides were counted in a random order. Depending on the variation in pollen species between the counted slides, slides are counted at a distance varying between 5 and 20 cm in the core. This means for the Hohe Ley channel, slides are counted with a spacing between 5-10 cm (14 slides). For the Heeren Bril channel, variation in pollen was less and slides are counted with intervals of 10-20 cm (16 slides). For the Schloss Bellinghoven channel an average interval of 20 cm (10 slides) turned out to be sufficient.

Pollen slides of the Hohe Ley have a pollen sum of ca. 150, while the Heeren Bril and Schloss Bellinghoven slides have a somewhat higher pollen sum of ca. 250. Pollen species are divided into different ecological groups. Only regional species (Trees & Shrubs, Dry herbs and, if present, Cultural species) are included in the pollen sum. Local species (Riparian, Aquatics and Ferns and mosses) and grasses (Gramineae) and sedges (Cyperaceae) are excluded to get a better overview of the regional vegetation development. Ericales species (here only *Calluna vulgaris*), usually represented as a separate group, are included in the Dry herbs for the pollen diagrams of the Heeren Brill and Schloss Bellinghoven because of the very limited amount of this type of pollen.

The pollen diagrams are made with the use of TILIA and TG-VIEW computer software (Grimm, 1992) and show the relative amount of pollen in percentages of the pollen sum (Fig. 4.2,4.3, 4.4). The different ecological groups, lithology, LOI and the amount of non arboreal (NAP) and arboreal (NAP) pollen are distinguished in the diagrams. Pollen zones are indicated by comparison with the standard pollen zonation described by Van Geel et al. (1981) and Janssen (1974).

3.6 Collection of field data

3.6.1 Borehole data

New field data are collected with hand-operated drilling equipment: Edelman auger, Dutch gouge and Van der Staay suction corer. The cores are logged in the field at 10-cm intervals by recording texture, median grain size, gravel content (percentage estimated), maximum gravel size, organic (material) content (quantitatively), plant remains, color, Ca and Fe content (qualitatively), oxidation/reduction and groundwater level (according to Berendsen & Stouthamer, 2001). Coordinates of the boring locations are determined with a handheld GPS-devise (accuracy 4-6 m) according to the Dutch Coordinate system. Coordinates are checked with the plotted position in the DEM after which elevations (relative to Dutch Ordnance Datum, MSL) are obtained from the DEM.

The depth of the borings depends on the lithology of the site and varies between 1 and 9 m. Usually the boring is ended when a couple decimeters of sandy deposits are found and the origin of the deposit is determined. Sometimes deeper borings into the sandy deposits are placed when the origin of these deposits remained unclear or the depth of the sandy deposits needed to be determined (e.g. in-channel deposits of meandering river or aeolian deposits).

3.6.2 Field sampling

Based on the borings in cross-section, five Holocene residual channels are selected for further research by pollen and/or LOI analysis. These sites each represent locations (i) from which no or insufficient data were available and (ii) where an Early or Middle Holocene age is expected of the river terraces in which the residual channels have been formed. The chosen sites for pollen and LOI analysis are the Heeren Bril (2010.10.084, see Appendix A), Schloss Bellinghoven (2010.10.099), Hohe Ley (2010.10.167) and Vosse Kuhl (2010.10.011, described by Geurts, in prep.). For Haus Groin (2010.10.073) OSL dates are available and only LOI analysis is carried out.

Samples are taken with the Boncke corer which is used for sampling clayey or peaty materials below groundwater level (Fig 3.2). To sample the entire residual channels, multiple samples with a maximum length of 1 m are taken. Samples of the Hohe Ley, Vosse Kuhl and Haus Groin are collected at the deepest part of the residual channel to cover the largest time span. The Schloss Bellinghoven residual channel still holds water, which made it impossible to sample the deepest part. The Heeren Bril samples are taken upstream of the deepest part of the residual channel because lamination at this part was less disturbed by bioturbation than elsewhere.

All samples are taken to the laboratory of Utrecht University, Faculty of Physical Geography, and stored in the refrigerator. One by one, all samples are cut in half lengthwise and a detailed description supported by photographs (Appendix G) is directly made before LOI and pollen samples are taken. This is done to describe and photograph the samples before discoloration of the cores due to oxidation sets in.

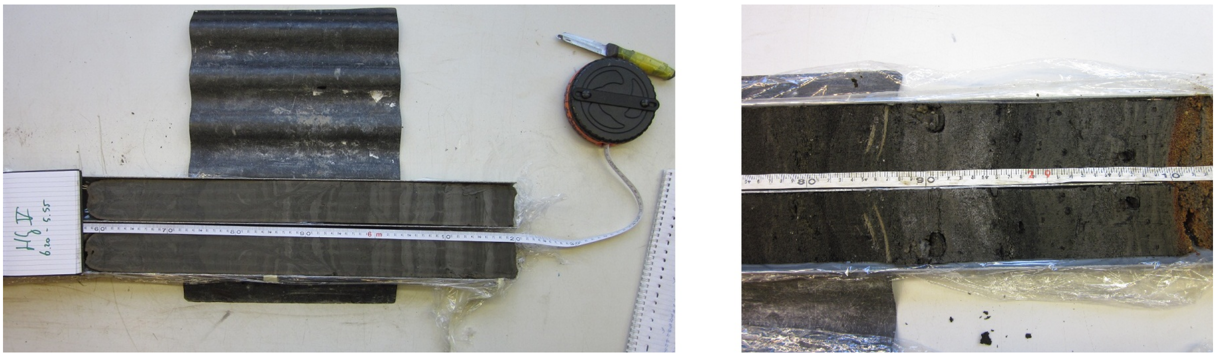

Figure 3.2: Example of two sliced samples taken with the Boncke corer. Left is from the middle of the Haus Groin channel. Right is from the bottom of the Hohe Ley channel. The top of both samples is at the left side.

4 Results

Chapter 4 presents the results of the collected data in the course of this thesis, including data from previous research. This gives information about valley gradient, incision/aggradation rate and fluvial style/river morphology to finally reconstruct the palaeogeographical development of the research area.
First a description and interpretation of the reconstructed lithogenetic cross-sections is given (§4.1, Appendix C). Followed by a short interpretation of the Holocene palaeo-meanders shown in cross-sections by other authors (Appendix D). Then the results for the five channel fills, including pollen and LOI (Loss on Ignition) analysis, are given in § 4.2 (Appendix G, H, I). With the use of the cross-sections and the DEM, almost 25 different river terrace levels/palaeo-meanders have been identified in the research area. All identified river terrace levels/palaeo-meanders (Appendix F) are plotted in one longitudinal profile (§ 4.3) and an age-height diagram (§ 4.4).

Note on terminology

From this chapter onwards there is a distinction made between individual terrace fragments/palaeo-meanders, river terraces and meander generations. The former are of small area, are identified in the cross-sections, have a specific height and specific lithostratigraphic characteristics. A complex palaeo-meander can consist of several levels. These levels are considered individually, because a prior it is not always clear which levels belong to a certain palaeo-meander.
A ‘river terrace’ is defined as a terrace level which can be distinguished over a larger length of the valley segment with specific characteristics (e.g. height, gradient, fluvial style/river morphology). A river terrace can group several meander generations and multiple palaeo-meanders. A collection of palaeo-meander generations over a longer time scale with roughly the same characteristics form a river terrace. The characteristics of meander generations broadly match the overall characteristics of the terrace that they group into, but each generation has its own specific characteristics. individual palaeo-meanders within a meander generation on their turn have their own even more specific characteristics which tend to be rather subtle.

4.1 Cross-sections

Four lithogenitic cross-sections (Fig. 4.1, transects I-IV, Appendix C) are made through the Holocene part of the research area. In the following paragraphs, first a description of each identified terrace level in the cross-section is given. This is followed by an interpretation of the terrace-levels and a description of its development. A short genetic and chronostratigraphic interpretation of palaeo-meanders in the cross-sections is included, to maintain overview. Cross-sections by Dingemans (2001), Favier (2001) (cross-section 1-7) and Erkens et al. (2011) (cross-section 8) in the research area are indicated as well in figure 4.1, these are included in Appendix D and used in the palaeogeographic reconstruction.

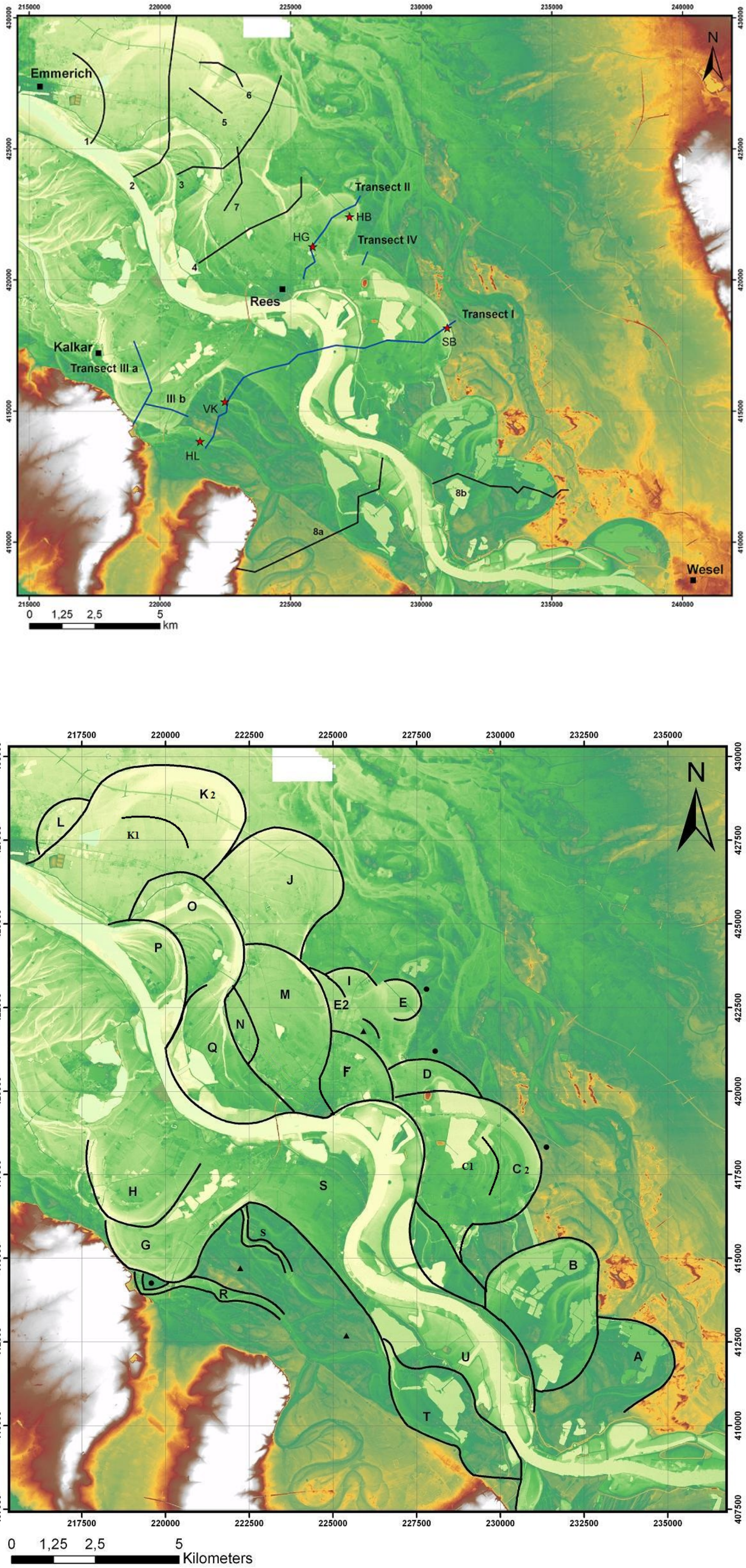

Figure 4.1: a) Locations of reconstructed cross-sections (in blue, Transect I-IV) and sampled cores (red stars) during this fieldwork (HL: Hohe ley; VK: Vosse kuhl; HB: Heeren bril; SB: Schloss Bellinghoven; HG: Haus Groin). Cross-section location of Dingemans (2001) & Favier (2001)(1-7) and Erkens et al. (2011)(8) are also shown. b) Location of the palaeo meanders.

4.1.1 Transect I: Hohe Ley, Vosse Kuhl & Schloss Bellinghoven

Transect I is the longest cross-section and spans the complete width of the Holocene river valley. The transect crosses the present-day Rhine and multiple river terraces, including the large palaeo-meander of Schloss Bellinghoven with a clearly developed pointbar morphology. It also crosses two smaller meandering residual channels of the Hohe Ley and Vosse Kuhl (Fig 4.1). From west to east, there are five terrace levels indicated: level I boring (2010.10.)030-163, level II boring 151-152, level IIa boring 106-103, level III boring 102-091, level IV boring 092-099 and level V boring 107 (Appendix A & C). The height of terrace levels mentioned in these results indicate the average height of the top of sandy (in-channel) deposits, overlaying (sandy) clay loam (floodplain) deposits are not incorporated.

The first, most westward terrace level ranges from boring 030 to 163 with an average terrace height (of the sandy deposits) of around 18 m + msl. The deeper parts of the borings within this terrace level consist mostly of medium coarse and coarse, moderately to very poorly sorted sand. Gravel content varies up to 90% with gravel diameters of up to 4 cm. Some borings consist of multiple fining upward sequences of around 1m, mostly ending in very coarse gravel layers. Usually, the top of the borings consists of finer sand that is covered with (silty) loam. On top of the silty loam, fine to medium sand is deposited in boring 194, 017 and 019. Two types of residual channels, ‘smaller’ and ‘larger’, are located within this river terrace which also can be seen on the DEM. The ‘smaller’ and shallower residual channels (e.g. 018, 021,022,024) that are only a few meters deep and filled with silty loam and clay (loam) and the ‘larger’ (wider and deeper), more winding residual channels (e.g. 011,167), that are filled with clay (loam) and (clastic) peat. Two ‘larger’ residual channels exist with a depth of 2.30 m (Hohe Ley) and 3.90 m (Vosse Kuhl) and a width up to 50 m. These channels are part of secondary channel belts that occur in somewhat incised position with a width between 200-500m.

The second terrace level, somewhat more to the east is between boring 151 till 152, has an average sand height of around 14.5-15.5 m +msl. Borings closer the Rhine consist of well to moderately sorted, medium coarse sand with on top of the sand a layer of (sandy) clay loam. The sand has a gravel content of ~20%, although the most westward borings located within this terrace level show a higher gravel content and consist of coarser sand. Sand coarsens as the depth of the boring increases. The covering (sandy) clay loam deposits are relatively thick (1.5-3.0 m) compared to other palaeo-meanders found in the transects.

Terrace level IIa ranges from boring 106 till 103 and includes the present day Rhine. The lithology is comparable with the eastern/finer part of terrace level II, only the top of the in-channel deposits is somewhat higher. The height of the in-channel deposits is between 15.5-16.0 m + msl. The floodplain deposits are thin due to excavation, as can be seen on the DEM.

The average sand height of the third terrace level is located at a somewhat higher elevation than terrace level II and IV. The terrace is found between boring 102 till 091 with an average sand height of

~16 m +msl. The top of the coarse sand possesses a high percentage of gravel varying between 40-80% and is sometimes impenetrable with the available equipment. On top of the sand a (sandy) clay loam layer is deposited of which a stiff clay (loam) layer (e.g. 101, 102) with iron and manganese oxide stains and some brick parts forms the bottom part.
The next, fourth recognized, terrace level shows clearly developed pointbars which are visible in the field and on the DEM. The Schloss Bellinghoven residual channel has been formed within this terrace level that has a sand height of ~14 m + msl. The top of the sandy deposits contains a very high gravel content of up to 90% which is impenetrable with the available equipment at most locations. The transition from impenetrable sand/gravel layer to the covering (sandy) clay loam layer is almost instant. The thickness of the (sandy) clay loam layer is comparable with that of terrace level II and relatively thick. The Schloss Bellinghoven residual channel has a width of around 600 m and a depth of 6.80 m is found. It is filled with peat, (strong) clastic peat and gyttja.
The most eastern terrace level only contains one coring but is also recognized in Transect II and IV. This terrace level has a height of around 18 m + msl within this transect and a height of ~17 m + msl within Transect II & IV. These borings consist of fine, medium coarse and coarse sand that is mostly deposited in multiple fining upwards sequences of around 1.5-2 m. The sand is well to moderately sorted and contains little gravel. A single sandy layer contains up to maximal 20% gravel.

Interpretation
The Hohe Ley (R, see Fig. 4.1b) and Vosse Kuhl channels are formed within the first terrace level. The height of this terrace level is comparable with that of the fifth terrace level, but their lithology differs considerably. Based on lithology and morphology, the first terrace level is interpreted as a braid plain formed by a braided river. The short fining upward sequences and very high gravel contents are typical for braided river deposits. The morphology visible on the DEM shows multiple smaller residual channels that frequently bifurcate. This, as well as the lithology, indicate a braided river terrace remnant. However, some residual channels show a week meandering pattern and even some small meanders (northwest of Vosse Kuhl, boring 027, 028). The Vosse Kuhl and Hohe Ley (R) residual channels also show a weak meandering pattern and slightly incised their host terrace. The relatively high elevation of the terrace remnant (see also §4.3 & 4.4), lithology and geomorphology suggest that this river terrace probably formed during the Younger Dryas. In the LRE, the Rhine showed a braided river pattern during the Younger Dryas which gradually turned into a meandering river pattern from the very begin of the Holocene onwards (for the pre-Holocene development of the research area: see Geurts, 2011 and Erkens et al., 2011). The residual channels of the Vosse Kuhl and Hohe Ley (R) are part of modestly incised channel belts that are probably formed during the transition from a braided to a meandering river system and were abandoned in the first millennia of the Early Holocene. The sand on top of the braid plain is thought to be an aeolian dune, formed during a sparse vegetation period in theYounger Dryas or the earliest Holocene.

The second terrace levels consists of markedly better sorted and finer sand as compared to the braided river deposits of terrace level one. The top of the sandy in-channel deposits is usually fine and coarsens downward. Terrace level II is formed within the inner-bend of the present-day Rhine. Terrace level IIa has a somewhat higher elevation and because of it position probably formed by the present-day Rhine. Lithology, geomorphology and location confirm that these terrace levels are formed by a meandering river. The diameter of terrace level II is relatively large compared to other palaeo-meanders as can be seen on the DEM (Appendix A). Terrace level II, at the inner bend of the Rhine (S, see Fig. 4.1b) has a somewhat lower elevation than the in-channel deposits of the present-day Rhine (terrace level IIa) and based on DEM residual channel cross-cuts is a relative young meander. It appears to have formed after the incision-aggradation transition, because it has a higher elevation than terrace level III and IV in the sections.

Regarding terrace levels III and IV, the DEM indicates that these probably belong both to the Schloss Bellinghoven palaeo-meander (C1, C2). At depth, a for hand-augers almost impermeable gravel layer characterizes both terrace levels, supporting to equate both to the same meander. The lithological contrast complicates this interpretation, but the characteristic point bar morphology and the presence of the palaeo-meander residual channel clearly support attribution of both to the same meandering channel. Apparently, it is possible for a meandering river to form in-channel deposits with very high gravel contents at this location. The high gravel content can be explained by the presence of old deposits (braid plain terrace remnants) with high gravel contents in the subsurface that are incised and reworked by the meandering river. Dingemans (2001) and Favier (2001) also describe meandering in-channel deposits with a gravel content up to 60% in this area.
Remarkable is that the Schloss Bellinghoven terrace (C1,C2, see Fig. 4.1b) consists of two terrace levels, which possibly indicates that this palaeo-meander has been build up in two phases. The highest terrace level is preserved in the inner-part of the meander and formed first. Then, associated to some incision, the second terrace level formed in the outer part of the meander, probably by a reactivation or a chute-cutoff. Another possibility is that the inner part (C1) is a remnant of an older river terrace/palaeo-meander. Comparison of the terrace heights (§ 4.4) will probably give a solution. The presence of the stiff clay layer in combination with the iron and manganese stains show that soil formation could occur on top of the higher terrace level, indicating that the higher terrace level rarely flooded in younger parts of the Holocene. Both terrace levels formed while incision was still dominant within the area. The minimum age of the Schloss Bellinghoven palaeo-meander abandonment is at least 4000 ^{14}C yr BP since it has been cut off by the Haus Groin palaeo-meander (§4.1.2). This fits with terrace level II and the modern channel. The thick floodplain deposits covering the lowest terrace level suggest a Late Holocene (after ca. 3000 yr BP) age. It is remarkable that the only the lowest terrace level holds these thicker floodplain deposits. Perhaps, the floodplain thickness is part the result

of the low elevation of this terrace in contrast to the rest of the area (it is a fill). The Schloss Bellinghoven palaeo-meander cuts-off the Hagener meer palaeo-meander (Transect IV).
The diameter of the palaeo-meander is quite large, as well as the depth (6.8 m) and width (600m) of the residual channel. Although no borings fully penetrate the total thickness of channel deposits of the Schloss Bellinghoven palaeo-meander, it is assumed that this meander carried the full discharge of the Rhine when active.

The fifth, most east terrace level is located at the same height as the Younger Dryas braid plain, but lithology differs strongly with that of terrace level I and indicates a meandering river pattern. The height and morphology (e.g. dissection by Late Glacial and Holocene secondary meandering channel belts, tributary rivers and cover of aeolian deposits) of this terrace level indicate a pre-Holocene age. Therefore the terrace was most likely formed during the Bølling-Allerød. More information about pre-Holocene deposits in the research area can be found in Geurts (2011) and Erkens et al. (2011).

4.1.2 Transect II: Heeren Bril & Haus Groin

Transect II is located northeast of Rees at the eastern side of the Rhine. The transect crosses one large and one smaller palaeo-meander (Fig. 4.1, Appendix A). From west to east, four terrace levels are indicated: level I boring 090-072, level II boring 071, level III boring 070-060 and level IV. Level IV in this transect corresponds to terrace level V in Transect I and not further described (Appendix C).

Terrace level I (boring 090-072) consists of sandy deposits, covered by a roughly one meter thick layer of (sandy) clay loam. The sandy deposits consists mainly of medium coarse, well to moderately sorted sand, although some coarser layers of several decimeters are found that contain up to 40% gravel. The thickness of the sandy deposits is at least 4 m and coarsens downward. The average height of the terrace level is ca. 15.5 m. +msl. The terrace level has been dated with OSL by Tebbens (unpublished, Appendix E & F) at 4.0 ± 0.3 cal ka BP. The Haus Groin residual channel, located at the eastern rim of this terrace, has a depth of 6.8 m and width of 550 m. The channel is filled with clay loam.
The second terrace level only consists of coring 071. This terrace level distinguishes from the surrounding terrace levels by its high gravel content that is impermeable with the available equipment. The transition from the overlaying clay loam deposits to the underlying sandy/gravel deposits is within a couple of decimeters. The terrace level has a height of 16 m + msl and has been dated with OSL by Tebbens et al. (unpublished) at a depth of 15.4 and 14.5 m + msl. Ages are respectively 11.7 ± 1.2 cal ka BP (Risø-33151) and 24.0 ± 2.0 cal yka BP (Risø-33152) (Tebbens et al., unpublished, OSL database).

The next, third, terrace level ranges from boring 060 to 069. The average height of the sandy deposit is at 15 m +msl, without major variation and the thickness is at least 6 m. The lowest two meters of cored sandy deposit is very coarse, poorly sorted and contains up to 90% gravel. The top of the sandy deposit exists of fine to medium, well to moderately sorted sand and barely contains gravel. One exception is the boring close to terrace level two, which is coarser and gravellier in the top. The (sandy) clay loam deposits on top of the sand show a constant thickness of around 1 m. The Heeren Bril residual channel that is formed at the most eastern part of the terrace level has a depth of 7.5 m and width of 300 m. The top of the residual channel is somewhat wider. The residual channel is filled with clay (loam), (clastic) peat and gyttja and has been dated by Berendsen & Stouthamer (2001) at 0.5 m above the channel lag at 7.89 ± 0.032 ^{14}C ka BP.

Interpretation

Lithology and geomorphology support the interpretation of the first terrace level as the Haus Groin palaeo-meander (F, Fig. 4.1b). The palaeo-meander cuts off the Schloss Bellinghoven (C1, C2), Hagener Meer (D, Transect IV), and probably also the Haspelweide (I) and Heeren Bril (E) palaeo-meander (Transect I)(see Fig. 4.1b, Appendix A). The elevation of the palaeo-meander is slightly higher than that of the Heeren Bril, suggesting that this palaeo-meander formed after the incision-aggradation transition. The OSL date combined with sand elevation and cut-off relation indicate the aggradation-incision transition to have occurred before 4.0 ± 0.3 cal ka BP. The thickness of the clayey floodplain deposits is relatively thin compared to Late Holocene floodplain deposits, which supporting a Middle Holocene age.

The diameter of the Haus Groin palaeo-meander probably has been relatively large, as can be seen on the DEM (Appendix A). The maximum depth of the in-channel deposits has not been determined, but the residual channel is quite large (almost 7 m deep and 550 m wide). Both the residual channel and palaeo-meander size suggest the Haus Groin palaeo-meander carried during formation the full discharge.

Terrace level II is sampled by only one coring, but supported by lithology, the DEM and OSL dates it can be interpreted as an old braid plain terrace remnant. The age of the deepest OSL date suggests this terrace remnant dates from the Pleniglacial, but the upper OSL date implies river activity at the start of the Early Holocene.

Based on morphology and lithology, the third terrace level is interpreted as an in-channel deposit of the Heeren Bril (E) residual channel. The Heeren Bril (E) palaeo-meander probably developed from a very Early Holocene channel that existed at, or close to, the braid plain terrace remnant (terrace level II). Incision (deepening of channel/lowering of channel base) took place at the onset of the Holocene and discharge became concentrated in a couple of channels. This interpretation is supported by the very small height difference between the old terrace remnant and the Heeren Bril (E) palaeo-meander.

As can be seen on the DEM, the Heeren Bril palaeo-meander has a smaller diameter and higher sinuosity compared to the other younger palaeo-meanders, but shows a more meandering pattern (including some point bars) and larger diameter than the Vosse Kuhl and Hohe Ley (R) residual channel. It is suggested that the Heeren Bril (E) existed during the Preboreal and became abandoned during the Boreal.

The residual channel of the Heeren Bril forms an oxbow lake, as can be seen on the DEM and is confirmed by the facies in boring 084 and 085 (Appendix A). At the entrance of the oxbow lake a plugbar is formed (boring 067). The residual channel is quite deep (7.5 m), but relatively small (300 m). In combination with the small diameter of the palaeo-meander it is concluded that the Heeren Bril (E) did not carry the full discharge of the Rhine when it formed. Other channels must have existed running parallel to the Heeren Bril channel to the west, but may not have been preserved due to reworking activity of the younger Rhine.

4.1.3 Transect III: Oy & Hanselaer

Transect III is located at the west (left) side of the Rhine, opposite of Transect II (Fig 4.1a). It crosses two large palaeo-meanders and probably a remnant of a third palaeo-meander based on the DEM (Appendix A). The transect consists of two parts, Transect IIIa and IIIb (Appendix C). Four terrace levels are indentified: level I boring 113, 114 (IIIa), level II boring 130-119 (IIIa) and boring 125-201 (IIIb), level III boring 120-206 (IIIa) and level IV from boring 117 – 205 (IIIb) (Appendix C).

The first terrace level (boring 113, 114) has an average sand height of 16.5 m +msl. The sand at the bottom part of the deposits is coarse with a high gravel content of up to 80%, while the upper 1.5 m consists of well to moderately sorted, medium coarse sand. The overlying (sandy) clay loam deposits are 1.5-2.5 m thick and disturbed by human activities up to at least 1.30 m below the surface. It contains bricks and some bone remains.

The next terrace level, level II, is found in Transect IIIa (boring 130-119) and in Transect IIIb (boring 125-210). The average height of this terrace level is almost 15 m +msl. The sand body found in this transect consists mostly of well to moderately sorted, medium coarse to coarse sand and includes some gravelly layers. The top of the sand body is usually finer and coarsens downward where also the gravel content increases. One boring penetrates the sand body for 8 m and ends on a very coarse gravel layer with a gravel percentage of 30% and gravel diameters of up to 5 cm. The overlying (sandy) clay loam deposit is around 1.5 m thick, but in some borings (sandy) clay loam deposits are found to a depth of 3.0 m protruding into the sand body (boring 136, 201). These (sandy) clay loam deposits contain some organic and more clayey layers. The Oy residual channel is located at the southwestern part of the terrace level and consists of a 2 m thick and 300 m wide packet of clay/clay loam with some plant remains.

The sand body found in the third terrace level is identical to that of the second terrace level, including its height. The overlying (sandy) clay loam is somewhat thicker, 1.5 – 2.0 m, but no protrusions into the sand body are found. Some clayey layers with plant remains are found in the top meters of the sand body. The Hanselaer residual channel is located at the southwestern side of the terrace level and is 500 m wide and 3 m deep. It is less clayey than the Oy residual channel and mainly consists of clay loam.
The top of the sand body found at terrace level IV is finer compared to that of terrace level II and III. The sand is well sorted and some clay loam layers and some small gravels are found. The sand body has a depth of al least two meters. On the DEM, a residual channel is visible but no fine grained or organic fill is found.

Interpretation
The lithology of the first terrace level suggests that the material is deposited by a small meandering channel. With that respect, the meandering Bølling-Allerød deposits found in Transect I (terrace level V) and Transect II (terrace level IV), and the Early Holocene deposits found in the Hohe Ley (R) valley (Transect I, boring 015) are comparable. They are distinct on the associated terrace level height, though. The deposits found in Transect IIIa (level I) are located 1 m above the Early Holocene meandering deposits of the Hohe Ley (R). This explains, because of the ongoing incision, that the meandering deposits in Transect IIIa formed before the Early Holocene. The meandering deposits probably date from the Bølling-Allerød interstadial (see also § 4.3).

The other three terrace levels (level II, III and IV) are all classified as meandering deposits based on lithology and geomorphology. The height difference between the Oy (terrace level II, G) and Hanselaer (terrace level III, H) palaeo-meander seems to be almost zero. But the strongly fluctuating height of the Oy palaeo-meander makes it difficult to determine its exact height. Therefore, it hard to conclude whether these palaeo-meanders formed before or after the incision-aggradation transition.
The strongly fluctuating height of the Oy palaeo-meander can be explained by the appearance of multiple crevasse splays of the adjacent Hanselaer palaeo-meander. As can be seen on the DEM, the top of the Oy palaeo-meander shows an irregular pattern and small channels (Transect III, boring 201, 203 and 136) are visible, which might represent crevasse splays. The presence of crevasse splays suggests that the height of palaeo-meander Oy is slightly lower than the height of the Hanselaer palaeo-meander, which probably encouraged the development of crevasse splays. The Relative DEM (Appendix B) shows also that the Oy meander has a low elevation compared to the younger palaeo-meanders close to the river. The height of the Oy palaeo-meander on the Relative Height maps is comparable with the height of the Early/Middle Holocene palaeo-meanders at the eastern side of the Rhine. The presence of crevasse splays and the elevation (see also § 4.3/4.4) of the palaeo-meanders supports the assumption that at least the Hanselaer palaeo-meander developed after the incision-

aggradation transition. The Oy palaeo-meander likely formed somewhat prior the Hanselaer palaeo-meander, which is around or after the incision-aggradation transition.
According to the assumption that the Hanselaer palaeo-meander formed after the incision/aggradation transition an age younger than 5.7 ^{14}C yr BP (6.5 cal ka BP) can be expected (section 2.2.1, Dingemans, 2001). The minimal estimated age of the Oy palaeo-meander is probably Middle Holocene (>3.0 cal ka BP) because associated floodplain deposits are relatively thin indicative for a Middle Holocene age. The floodplain deposits of the Hanselear palaeo-meander are somewhat ticker, but because the increase is very small, no assumptions are made about its minimum age.
Remarkable is that at this side of the Rhine no well-developed residual channels are found. It is possible that locally available extra sand supply from erosion of the nearby ice-pushed hills and the Younger Dryas river terrace (Transect I) allowed for rapid channel fill, preventing the process of gyttja formation to take place. Another possible explanation is that the deactivation of the palaeo-meanders was very gradual and the new river channel only slowly took over the main discharge. This would indicate that two channel existed next to each other, which would be expected in the apex-region of the delta in the aggradational phase.
It is assumed that both palaeo-meanders did carry the complete discharge of the Rhine during its existence. One boring (199) penetrates the in-channel deposits of the Oy palaeo-meander and a depth of around 8 m is found. Further more, the size and diameter of the palaeo-meanders is comparable with that of other Middle-Holocene palaeo-meanders, as well as the width of the residual channel morphology.

Terrace level IV only contains a couple of borings and terrace level height is comparable to that of terrace level II and III. Only a small part of the terrace level is found and it is unclear whether the terrace level represents a separate palaeo-meander or belongs to the Oy palaeo-meander. Because the terrace is located this close to the Oy palaeo-meander, only a small part is found of which the elevation is comparable. No separate terrace level is distinguished.

4.1.4 Transect IV: Hagener Meer

Transect IV is located at the eastern side of the Rhine between Transect I and II. It crosses one palaeo-meander and two terrace levels are identified (Appendix A, Fig 4.1a). Terrace level I ranges from boring 159-156 and terrace level II only consists of boring 160 (Appendix C). Terrace level II is not further described because it is interpreted to be the same as found in Transect I (terrace level V), Transect II (terrace level IV) and Transect III (terrace level I) and has a pre-Holocene (Bølling-Allerød) age.

The top of terrace level II has formed one meter below terrace level I at around 15 m +msl. The sand body mainly contains medium coarse sands in the top and coarsens downward to coarse sands with a gravel content of up to 20% at 9 m below surface. Close to the residual channel, the bottom of the sandy deposits is much coarser at a smaller depth, gravel content ranches up to 60 %. The overlaying sandy (clay loam) deposits are 1-1.5 m thick. The Hagener Meer (D) residual channel is located at the eastern rim of the terrace level. The residual channel has a depth of 3.5 m and is 100 m wide, it is filled with clay loam that contains some plant remains. The inner point bar of the Hagener Meer is OSL dated at 9.7 ± 0.7 cal ka BP (Risø-33153) and 10.0 ± 0.6 cal ka BP (Risø-33154) (Tebbens et al., unpublished)

Interpretation

Lithology and geomorphology confirm that the Hagener Meer (D, Fig 4.1b) is a palaeo-meander. Although no organic or clastic filled residual channel is found, borings in the point bar show that this palaeo-meander probably had a depth of around 8 m. The depth of the point bar deposits decreases towards the residual channel and braid plain deposits are found at a dept of around 5 m below surface. Suggesting that the depth of the Hagener Meer channel almost halved at the end of it existence. Likely, discharge was slowly taken over by another river branch at the end of its existence. The thickness of the in-channel deposits and the diameter of the palaeo-meander do suggest that the Hagener meer palaeo-meander probably did carry the complete discharge of the Rhine.

4.1.5 Other cross-sections

Other cross-sections in the research area are published by Dingemans (2001), Favier (2001) and Erkens et al. (2011) (Appendix D). The location of the cross-sections is shown in figure 4.1. Cross-section 1-7 are made by Dingemans and Favier, cross-section 8 is made by Erkens (Appendix D). The cross-sections are used to gather information on terrace height (of in-channel deposits), valley gradient, river style/fluvial morphology and (thickness) of floodplain deposits of all palaeo-meanders in the research area. The results for palaeo-meanders are given below in chronological order of age of abandonment. Information about terrace height and age is shown in Appendix F.

The Haspelweide (I) (Fig 4.1b) palaeo-meander probably formed during the Preboreal based on terrace height (cross-section 4, Dingemans, 2001). The palaeo-meanders have a terrace height (in-channel deposits) of around 14.8 m + msl covered with around 1,5 m of floodplain deposits. The residual channel is around 4.5-5.0 m deep and about 250 m wide. The diameter of the Hapselweide (I) palaeo-meander is relatively small and comparable with that of the Heeren Bril (E) (§ 4.1.2: Transect II). Given the size of the residual channel and especially the size of the palaeo-meander, it is assumed that it did not carry the full discharge of the Rhine.

The palaeo-meanders Tote Landwehr (J, Dingemans, 2001; cross-section 3) and Diersfordt (A, Erkens et al., 2011; cross-section 8) both are of Boreal age, based on direct dates (OSL & ^{14}C; Appendix F).
The height of the Tote Landwehr (J) palaeo-meander is around 14 m + msl. The residual channel is 4 m deep and 250-300 m wide. A well developed point bar system can be seen on the DEM (Appendix A). It is also shown that the diameter of the palaeo-meander is quite large, around twice the diameter of the Heeren Bril (E) and Haspelweide (I) palaeo-meander. Therefore, it is suggested that the palaeo-meander did carry the complete discharge of the Rhine, but no borings deep into the in-channel deposits are available to confirm this hypothesis.
The Diersfordt (A) palaeo-meander has a terrace height of around 17.3 m + msl and its residual channel is comparable in size with that of the Tote Landwehr (J) palaeo-meander. The diameter of the palaeo-meander is a little bit smaller than that of the Tote-Landwehr (J) palaeo-meander, but still a lot bigger than that of the Heeren Bril (E) and Haspelweide (I) palaeo-meander. A well developed point-bar system is visible on the DEM (Appendix A). According to Erkens et al. (2011; p110), the Diersfordt (A) palaeo-meander is the first palaeo-meander that was carrying the full discharge of the river Rhine.

The Lowenberg (L, Dingemans; cross-section 1,2) and Lohbrink (E2, Dingemans, 2001; cross-section 4) palaeo-meanders are not dated, but it is expected that they are formed during the Boreal/Atlantic transition based on terrace height (Dingemans, 2001). The Hetter Landwehr (K, Dingemans, 2001; cross-section 1,2,5,6) palaeo-meander has an Atlantic age and also the Esserden (N, Dingemans, 2001; cross-section 4) palaeo-meander remnant probably has an Atlantic age, based on terrace height (Dingemans, 2001). The palaeo-meanders show the lowest elevation of all palaeo-meanders found in the research area, together with the Schloss Bellinghoven (C2) palaeo-meander (§4.1.1: Transect I).
Both the Lowenberg (L) and Lohbrink (E2) palaeo-meander do not have a well developed residual channel and only small parts of the palaeo-meanders are preserved (Appendix A,D). The terrace remnant in cross-section 1 is believed to be part of the Lowenberg (L) palaeo-meander because of its comparable height and its position. The poorly developed residual channels suggest flow was slowly taken over by another river branch. From the palaeo-meanders itself, it is difficult to determine if they carried the full discharge of the Rhine, because only small parts are preserved and no boring reaches the channel lag. But given the size of the next younger palaeo-meander (Hetter Landwehr, K) and the observations in the older Diersfordt (A) palaeo-meander, discharge probably was concentrated in one main channel during the late Boreal and Atlantic. It is assumed that the situation remained unchanged at the Boreal/Atlantic transition.
The Hetter Landwehr (K) palaeo-meander has a height of 11-12 m + msl (Appendix D). The palaeo-meander clearly shows a higher inner bend (K1) and a lower outer bend (K2), indicating that it has been formed during a period of incision. It has a well developed residual channel of more than 7 m

deep and about 300 m wide. A well developed point bar system is also visible on the DEM (Appendix A). The large size of the residual channel in combination with the large diameter of the palaeo-meander suggests that this palaeo-meander did carry the complete discharge of the Rhine.
The Esserden (N) terrace exists only of a small remnant. No residual channel has been found and, except terrace height, no information about the palaeo-meander is available. In cross-section two and three of Dingemans (2001) also two other terrace remnants are found with a low elevation comparable to other Atlantic palaeo-meanders. Except the Esserden (N) terrace, the remnants are not used in the results of this thesis because to less information is available.

In other literature only one channel of Subboreal age is found in the research area. This palaeo-meander, Bislischer Meer (B), is described by Erkens et al. (2011) in cross-section 8 (Appendix D). The Bislicher Meer (B) palaeo-meander has probably been built up in two phases. The oldest part has a slightly lower elevation (16 m +msl) and a well developed residual channel, the youngest part has a slightly higher elevation (16.5 m +msl) and a less developed residual channel. Activity of the oldest (smaller) part stopped at the Atlantic/Subboreal transition and the youngest/largest part of the palaeo-meander formed during the Subboreal. The switch from incision to aggradation took place between the formation of the oldest part (5.75 cal ka B) and the youngest part (3.65 cal ka BP) at this location (Erkens et al., 2011; cross-section 8, Appendix D). Point bars are not visible, probably because large parts of the palaeo-meander have been excavated. The diameter of the palaeo-meander and the size of the residual channel do suggest that the Bislicher Meer (B) palaeo-meander carried the full discharge of the Rhine at its existence.

Six palaeo-meanders of Subatlantic age in the research area are described in other literature. On chronological order these are the palaeo-meanders: Speldrop (M, Dingemans, 2001; cross-section 4), Xanten I (T, Erkens et al., 2011; cross-section 8), Xanten II (U, Erkens et al., 2011; cross-section 8), Reeserward (Q, Dingemans, 2001; cross-section 4), Grietherbusch (O, Dingemans, 2001; cross-section 2,3) and Ortscheward (P, Dingemans, 2001; cross-section 2). All palaeo-meanders are dated (historical and ^{14}C), except the Speldrop (M) palaeo-meander (Appendix F). Because the focus of this thesis is on Early and Middle Holocene palaeogeographical development, the reader is referred to Braun & Thiermann (1981), Berendsen & Stouthamer (2001), Dingemans (2001), Favier (2001) and Erkens et al. (2011) for detailed descriptions of the Late Holocene palaeo-meanders. The terrace heights and location of these palaeo-meanders are used in the next paragraphs to detect trend in incision/aggradation and palaeogeographical development throughout the Holocene.
Late Holocene palaeo-meanders are formed closer to the present-day Rhine, in the middle of the valley, seem to have a smaller diameter (Appendix A) and a higher elevation on the relative DEM (Appendix B) than the Middle Holocene palaeo-meanders. Besides that, a coarsening of the floodplains is seen. Erkens et al. (2011) mentions that floodplain deposits became thicker and relative

coarser (more silty than clayey) in the LRE during the Subboreal (after 2-3 ka). Favier (2001) also describes this coarsening of the floodplain deposits during the late Holocene in the research area, but neither Favier (2001) nor Dingemans (2001) mention an increase in floodplain thickness. The cross-sections by Favier (2001) and Dingemans (2001) do not clearly show an increase in floodplain thickness after 2-3 ka, which might be caused by the location of the research area, it was a very distal floodplain area in the Late Holocene. Because part of the research area is dominated by aggradation during the Late Holocene, floodplain deposits of younger/Subatlantic palaeo-meanders might cover the relative thin floodplain deposits that tops the Middle Holocene palaeo-meanders. For example, the Hetter Landwehr (K) palaeo-meander is covered by younger floodplain deposits (cross-section 1,2, Appendix D). This palaeo-meander originally had thinner floodplain deposits than Late Holocene palaeo-meanders, but is covered later during the Holocene. The channel fill of the Hetter Landwehr as well demonstrates this (pers. comm. W. Toonen, 2011). The older and highest palaeo-meanders, of Early Holocene age, do have thinner floodplain deposits and were not covered by floodplain deposits of Late Holocene palaeo-meanders.

4.2 Core analysis: pollen & LOI

With the use of the cross-section, five sites are selected for additional research with pollen and LOI analysis (Fig 4.1). Pollen diagrams for the residual channels of the Hohe Ley, Heeren Bril and Schloss Bellinghoven are published in this thesis. A pollen diagram of the Vosse Kuhl by Geurts (2011) and LOI analysis by De Molenaar (2012) for all above mentioned channels and the Haus Groin residual channel are shortly described as well.

Pollen and LOI analysis are carried out for locations where little data about age and palaeogeographical settings was available, but an Early or Middle Holocene age is expected (Chapter 3). Pollen analysis has been carried out to determine the age of the residual channel and the river terrace / palaeo-meander. LOI analysis are used to help predict palaeogeographical development. It is expected that organic content in a residual channel partly depends on the presence or absence of active river channels near the residual channel. It is suggested that low organic contents in residual channels occur when an active river channel is close by. Visa versa, high organic contents probably form when active river channel are away. If no residual channel deposit is developed, we assume very gradual abandonment.

A short description of the cores used for pollen analysis published in this thesis is given below, followed by a description of the pollen and LOI analysis for each residual channel. In this paragraph pollen zones are described that are used for dating of the residual channel. Detailed descriptions and photo's of the sampled cores are given in Appendix G. For a lithological description of the remaining cores is referred to Geurts (2011, Vosse Kuhl) and De Molenaar (2011, description of all above mentioned cores sampled for LOI analysis). The Vosse Kuhl pollen analysis (by Geurts, 2011) is shown in Appendix I and the LOI analysis (by De Molenaar, 2011) is given in Appendix H.

4.2.1 Hohe Ley and Vosse Kuhl

A cross-section through the Hohe Ley and Vosse Kuhl residual channels and their host terrace is described in § 4.1.1 (transect I, terrace level I). It was expected that the Hohe Ley and Vosse Kuhl were last active during the Younger Dryas-Early Holocene transition (section 4.1.1). Their channel belts occur in slightly incised position within the Younger Dryas braid plain during the Early Holocene.

LOI and pollen analysis has been carried out for the complete residual channel fill of the Hohe Ley, with exception of the oxidized upper most part. The cored sequence consists of four segments together ranging from 215 to 94 cm depth. The bottom part of the fill has a thin layer of clay loam on top of poorly sorted sand with gravel. The clay loam is covered by more than 150 cm fine homogeneous gyttja. Almost no layering can be seen in the gyttja. The upper part of the residual channel consists of strong clastic peat that turns into clay loam to the top (Appendix G). For a description of the Vosse Kuhl residual channel of similar build up, is referred to Geurts (2011).

Pollen analysis

The pollen diagram of the Hohe Ley is shown in figure 4.2 and the pollen diagram of the Vosse Kuhl (by Geurts, 2011) is given in Appendix I. Two pollen zones are indicated in the Hohe Ley, a description of the oldest and lowest pollen zone is given first, followed by a description of the second and youngest pollen zone.

The oldest pollen zone (210-123 cm) shows low *Pinus* and Gramineae pollen percentages. *Corylus* becomes the dominant species and A*lnus* shows a sharp rise at the beginning of this period. The amount of *Quercus* and *Ulmus* pollen is significant. *Hedera helix* and *Tilia* also become more abundant and some *Fraxinus* pollen grains are found. The found pollen percentages of the different species suggest this is an Atlantic pollen spectrum. The increasing percentages of *Corylus, Quercus, Ulmus* and *Alnus* indicate an early Atlantic age at the start of this zone (compared with Janssen, 1974; Van Geel et al., 1981).

In the bottom pollen sample (210-205 cm) a high percentage of *Pinus* pollen is found. Because the sample is taken from the base of the residual channel at a lithological transition, the sample probably does not reflect the correct vegetation signal. *Pinus* pollen can easily be transported by water and therefore might be overrepresented. The change in the pollen signal of this sample is not considered to be representative for the regional vegetation development.

The youngest zone clearly differs from the previous pollen zone. The Arboreal/Non Arboreal Pollen (AP/NAP) ratio declines from around 90% in zone one to three till 35% in zone four. This is shown by

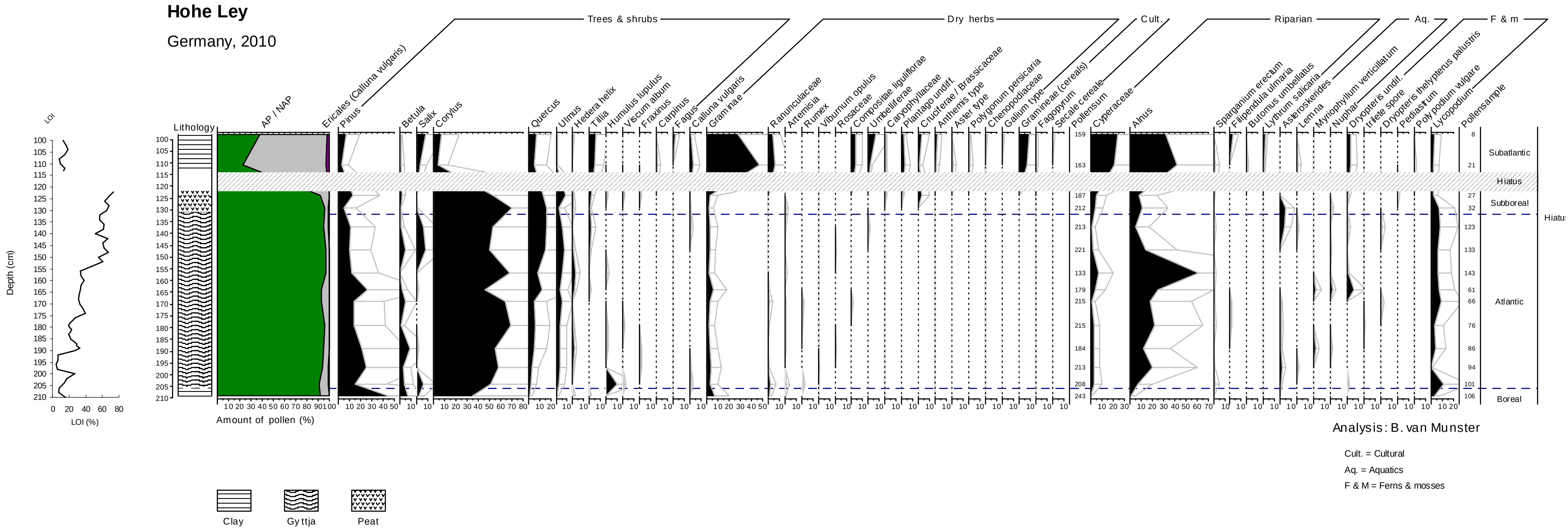

Figure 4.2: Pollen diagram Hohe Ley

the large decrease in *Pinus*, *Betula*, *Corylus* and *Ulmus* and an increase in several Dry herbs species. A strong increase in Cyperaceae and Gramineae pollen is shown and pollen of *Carpinus*, *Fagus* and Cultural species (cereals, *Fagopyrum, Secale cereale)* become present. This pollen spectrum corresponds with the Subatlantic pollen spectrum described by Janssen (1994) and Van Geel et al. (1981). The sudden change in lithology, LOI and pollen percentages supports the presence of a hiatus between the oldest and youngest zone. The immediate presence of *Fagopyrum* (Buckwheat) in the youngest zone indicates a late Subatlantic age. Buckwheat is used as a crop from the 15th century onwards (pers. comm. J.A.A. Bos, 2011).

The pollen diagram from the bottom part (375-295 cm) of the Vosse Kuhl residual channel (Appendix I) is interpreted as being from Boreal age by Geurts (2011) and Bunnik (written comm. 2011, Appendix I). The presence of *Juniperus, Equisetum* and *Urtica* and high values of *Betula* at the bottom part of the pollen diagram indicates a early Boreal age. Therefoer, it can be concluded that the beginning of the infilling of the Vosse Kuhl started before the infilling of Hohe Ley. Fluvial activity of the Vosse Kuhl ended before the Early-Boreal (~10 000 cal yr BP) and fluvial activity of the Hohe Ley probably stopped during the Boreal/early Atlantic (~9000 cal yr BP).

LOI analysis

The Hohe Ley and Vosse Kuhl residual channel are both nested in the same braided river terrace which probably dates from the Younger Dryas. With the start of the infilling of the Hohe Ley channel, fluvial activity on top of the Younger Dryas river terrace stopped. It is expected that the LOI signal in both channel developed roughly the same for both channels since the Early Atlantic onwards, although one channel may have carried more floodwaters than the other and have a more classic fill.

According to the pollen analysis, the fill of the Hohe Ley channel as represented by the LOI curve (Appendix H) has largely been formed during the Atlantic. The bottom part of the LOI curve probably represents the start of the early Atlantic. The most upper part is formed during the Subatlantic and separated from the Atlantic LOI signal by a hiatus. LOI percentages increase during the Atlantic (210-123 cm). The first half (210-155 cm) shows a LOI percentage of around 30%, after which an increase till around 60% is observed between 155-123 cm. The Subaltantic (after the 15th century) is around 15%.

The LOI signal of the Vosse Kuhl covers the Boreal, Atlantic and early Subboreal period. LOI percentages are around 20% during the Boreal period (375-270 cm). At the start of the Atlantic (275 cm) a sharp rise up to 90% is observed. LOI percentages remain high until around 175 cm, which is probably still of Atlantic age (F. Bunnik, written comm., Appendix I). From 175 cm till 135 cm the LOI values decreases till around 50%. Pollen analysis at 150 cm (F. Bunnik, written comm.) shows an early Subboreal age. Probably the decrease in LOI values (175-135 cm) indicates the start of the Subboreal period.

4.2.2 Heeren Bril

A cross-section through the residual channel of the Heeren Bril palaeo-meander is described in § 4.1.2 (Transect II, terrace level III). The infilling of the Heeren Bril is radiocarbon dated at 7.89 ± 0.032 ^{14}C ka BP (Berendsen & Stouthamer, 2001), which is early in the Atlantic, but morphology suggests a very early Holocene age. It is suggested that river activity started during the Preboreal (§ 4.1.2).

LOI analysis has been carried out for the complete Heeren Bril residual channel (Appendix LOI, by De Molenaar, 2011). Pollen analysis has been carried out for the bottom two sampled cores (618-775 cm). The bottom of the residual channel consists of a small layer of sand covered by clay with some sandy layers. Some parts of the clayey infilling are laminated in layers from millimeters up to centimeters. More to the top, gyttja is found and strong bioturbation is present. Detailed description of the sampled cores is given in Appendix G and for LOI analysis is referred to De Molenaar (2011).

Pollen analysis

The pollen diagram of the Heeren Bril is shown in figure 4.3. Two pollen zone are distinguished and described from bottom to top. The bottom pollen zone (760-755 cm) consists of one sample which differs from the upper younger pollen samples. The sample has a relatively low AP/NAP ratio of 65% compared to ~90% for the younger samples. *Corylus* and *Pinus* are present in roughly the same amount (25%) and some pollen of *Quercus, Ulmus, Alnus* and *Tilia* are found. Relatively high values of *Artemisia, Dryopteris undif.* and some pollen of *Juniperus communis, Abies* and *Picea* are present. The occurrence of the above mentioned pollen combination suggests a Boreal age (compared to Janssen, 1974; Van Geel et al., 1981; Bos et al., 2008). It is questionable that the pollen zone only consists of one sample at the bottom of the residual channel, but the pollen signal seems to be correct. High *Pinus* values are missing (which might indicate a flood layer) and typically Boreal species are present.

The upper pollen zone (755-620 cm) consists of relatively high *Pinus* values (~20%) and high *Corylus* values (~40%). *Quercus, Ulmus* and *Alnus* pollen also are present in sufficient amounts. The occurrence of Dry herbs is low, which does not change in the upper part of the pollen diagram. The pollen signal in this zone is interpreted as an Atlantic vegetation signal (compared to Janssen, 1974; Van Geel et al., 1981).

It can be concluded that the infilling of the Heeren Bril residual channel started at the very end of the Boreal/beginning of the Atlantic. The activity of the Heeren Bril meander probably stopped before 8700 cal yr BP.

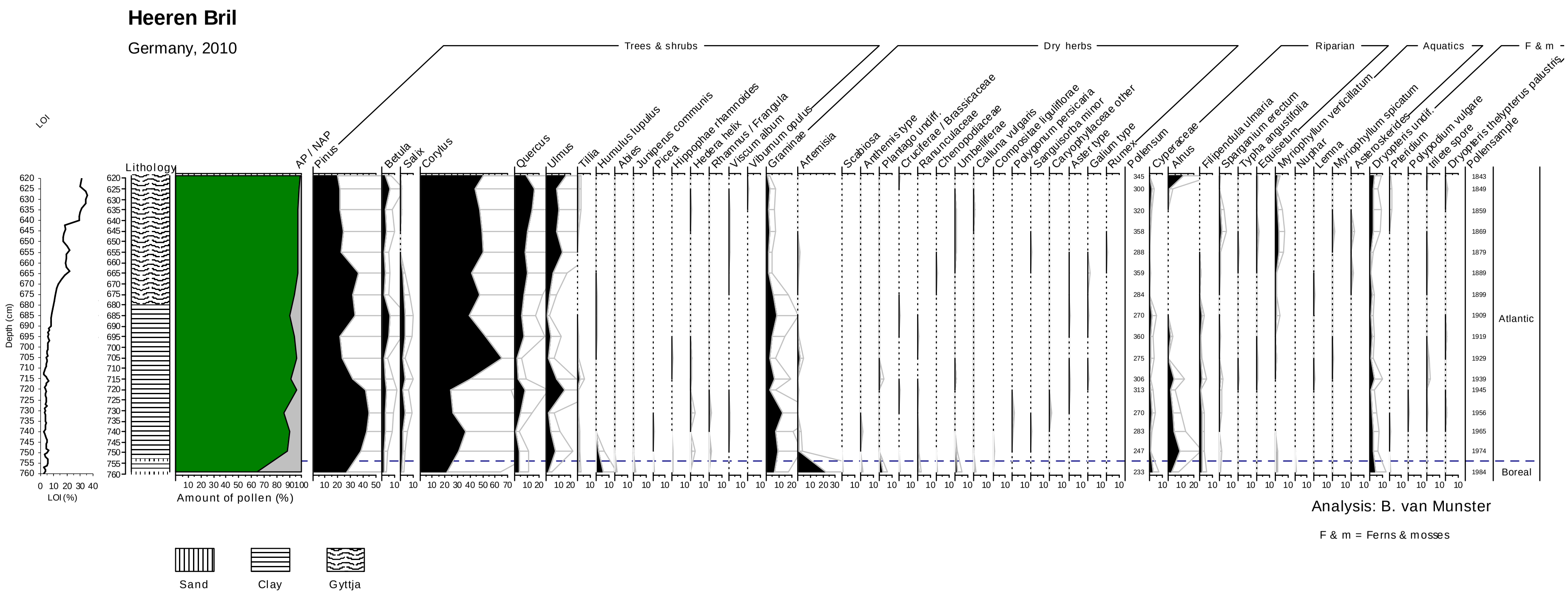

Figure 4.3: Pollen diagram Heeren Bril

LOI analysis

The bottom part of the LOI curve (~770-755 cm) of the Heeren Bril residual channel is estimated to be of Boreal age. LOI percentages are very low (<10%) within this Boreal part (Appendix H). The LOI percentages from the Atlantic part (from ~755 cm onwards) slightly increases from 10% to 35%. The age of the upper part from the LOI curve has not been dated with pollen analysis, but has been formed from the Atlantic onwards. Larger changes the LOI percentage can be seen between 600-340 cm (decrease till 20%) and between 340-180 (increase, divided into two peaks of 70 and 50%). Finally LOI decreases again from 180 cm onward.

4.2.3 Schloss Bellinghoven

A cross-section through the residual channel of the Schloss Bellinghoven palaeo-meanders is described in § 4.1.1 (Transect I, terrace level III & IV). It is expected that the palaeo-meander formed before the incision-aggradation transition. It has been cut off by the Haus Groin palaeo-meander which suggests an abandonment age of at least 4000 ^{14}C yr BP.

LOI analysis has been carried out for the complete residual channel (Appendix H, by De Molenaar, 2011). Pollen analysis has been carried out for the bottom two sampled cores (650-474 cm). The bottom of the residual channel consists of a gravely layer covered with clay and, more to the top, gyttja. Both the clay and gyttja are bioturbated. A detailed description of the for pollen analysis sampled cores is given in Appendix G. For a core description of the complete residual channel used for LOI analysis is referred to De Molenaar (2011).

Pollen analysis

The pollen diagram of the Schloss Bellinghoven residual channel is shown in figure 4.4. The pollen diagram consists of one pollen zone and shows less variation. The AP/NAP ratio within this pollen diagram is around 90%. Pollen of *Corylus, Quercus* and *Alnus* are mainly found but also *Pinus, Betula, Salix, Fraxinus, Tillia and Ulmus* are present in low amounts. With exception of the Graminae pollen, less Dry herbs are present throughout the whole pollen diagram. The described pollen signal corresponds with the Atlantic pollen signal described by Janssen (1974) and Van Geel et al. (1981). It is concluded that the activity of the Schloss Bellinghoven palaeo-meander probably ended during the Atlantic, between 8700-5700 cal yr BP.

LOI analysis

The bottom part of the LOI curve from 650 till at least 480 cm has been dated with pollen analysis to be of Atlantic age. The age of the upper part of the LOI curve has not been dated but formed from the Atlantic onwards. Larger changes in LOI can be seen from 650-530 cm (5%), from 530-380 cm (increase till 10%) and from 380 cm onwards (increase till 20%, with a larger peak between 230-180 cm) (Appendix H)

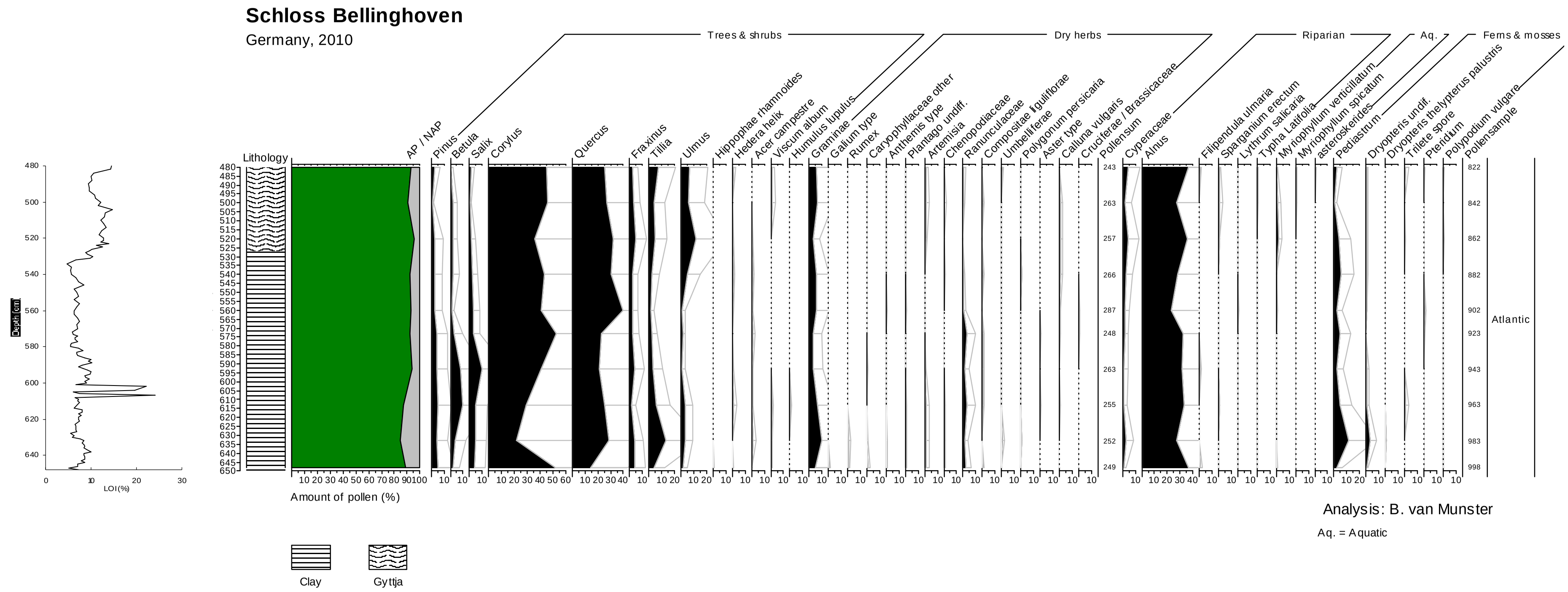

Figure 4.4: Pollen diagram Schloss Bellinghoven

4.2.4 Haus Groin

A cross-section through the residual channel of the Haus Groin palaeo-meander is described in § 4.1.2 (Transect II, terrace level I). The end of activity of the Haus Groin palaeo-meander has been dated with OSL at 4.0 ± 0.3 cal yr BP by Tebbens et al. (unpublished).
A pollen analysis has not been carried out for the Haus Groin residual channel. LOI analysis has been carried out for the whole residual channel (Appendix H, by De Molenaar, 2011) The residual channel is filled with clay. The bottom part of the residual channel is slightly bioturbated, but becomes laminated to the top. For a complete core description is referred to De Molenaar (2011).

LOI analysis
The LOI curve of the Haus Groin residual channel probably covers the Subboreal and Subatlantic period. LOI percentages are relatively low compared to the LOI curves of the other residual channels and do not reach over the 10% (Appendix H). Only small differences can be seen within the LOI curve of the residual channel. LOI percentages of the Haus Groin residual channel are on average around 8%. LOI percentages decrease slightly to the top of the residual channel (from ~330 cm onwards). The sudden decrease between 614-589 cm is considered to be a measurement error, exactly 25 samples show this sudden decrease.

4.2.5 Interpretation LOI analysis

As is suggested, high LOI values occur when fluvial activity in the surrounding is low and visa versa. Both the Vosse Kuhl and Hohe Ley (R) are located close to each other on the same Younger Dryas terrace. It is suggested that both residual channels roughly show the same LOI signal if LOI analysis represents a valley wide signal and can be used for the palaeo-geographical reconstruction. Although the curves of the LOI signals are comparable, the timing of increasing and decreasing values differs. The signal of the Vosse Kuhl increases sharp at the beginning of the Atlantic, while the LOI signal of the Hohe Ley (R) increases half way the Atlantic. The LOI signal of the Heeren Bril (E) and Schloss Bellinghoven (C2) is hard to interpret because only the bottom part of the residual channel has been dated and accumulation rates are unknown. Although the age and location of the residual channels differs, the curves roughly show the same pattern. Remarkably, this is the same pattern as is shown in the LOI analyses of the Hohe Ley (R) and the Vosse Kuhl. All four analyses show relatively low LOI values till around 2/3 of the depth of the residual channel. After 2/3 of the residual channel, LOI values increases, followed by a decrease at the upper ca. 1 m of the residual channel. An exception is the Haus Groin (F) residual channel which shows only low LOI values. Therefore, it is suggested that the Haus Groin residual channel is formed in the vicinity of the follow-up active river branch, supported by its position in the middle of the river valley, and that the remaining residual channels filled at distance of follow-up active branches. Further more detailed usage of the LOI analysis for the palaoegeographical development is omitted, because it is suggested that the LOI signal of a residual channel might reflect other processes or factors. The succession of the infilling of the residual channel and/or external factors (climate change and human impact) seems to overprint the LOI signal. One would have to correct for this to interpret LOI values in terms of proximal-distal to active channels.

4.3 Longitudinal profile & valley gradient

To distinguish different river terraces/meander generations along the Rhine and gather information about valley gradient and the shifting of the incision-aggradation transition into in the research area, all identified terrace levels/palaeo-meander heights (of in-channel deposits) are plotted in a longitudinal profile (Fig 4.5a). The location of the different terrace levels/palaeo-meanders along the Rhine is shown in Figure 4.5b. It includes all terrace level/palaeo-meander heights of Transect I to IV along the Rhine (Appendix C) and the palaeo-meanders identified in the cross-sections by Erkens et al. (2011), Dingemans (2001) and Favier (2001) (Appendix D) are added to the profile. A table with the average terrace level/palaeo-meander height (top of in-channel deposits) and distance along the Rhine is found in Appendix F. Distance along the Rhine is measured across a straight line trough the middle of the Holocene river valley, ranging from the most upstream (coordinate 232083;410483) to the most downstream (coordinate 220309;423083) located palaeo-meander.

It is expected that the terrace levels/palaeo-meanders plot into groups with roughly the same height and valley gradient and that, besides elevation differences, these groups can be distinguished by their own characteristics (e.g fluvial style, river morphology, Chapter 1,2,3). If the identified terrace levels/palaeo-meanders each plot at different heights and local terraces/palaeo-meanders do not group regionally, it is likely that the identified terrace levels/palaeo-meanders formed in continuous development as a reaction to (local) external forcings. In that case, it might still be possibly to group the terrace levels/palaeo-meanders into meander generations. These generations would have formed in continuous development, but can be grouped by specific characteristics (e.g. fluvial style, river morphology).

The series of terrace levels is roughly divided into Preboreal-Boreal, Atlantic and Subboreal-Subatlantic age groups (Appendix F, see also § 4.4). This way it becomes possible to distinguish older and younger Holocene terrace levels and to calculate valley gradient through time. Older and younger Holocene terrace levels/palaeo-meanders (as can be seen in Fig. 4.5a) are roughly located at the same height because of the incision-aggradation transition. The division in groups is only used to easier distinguish different river terrace levels.

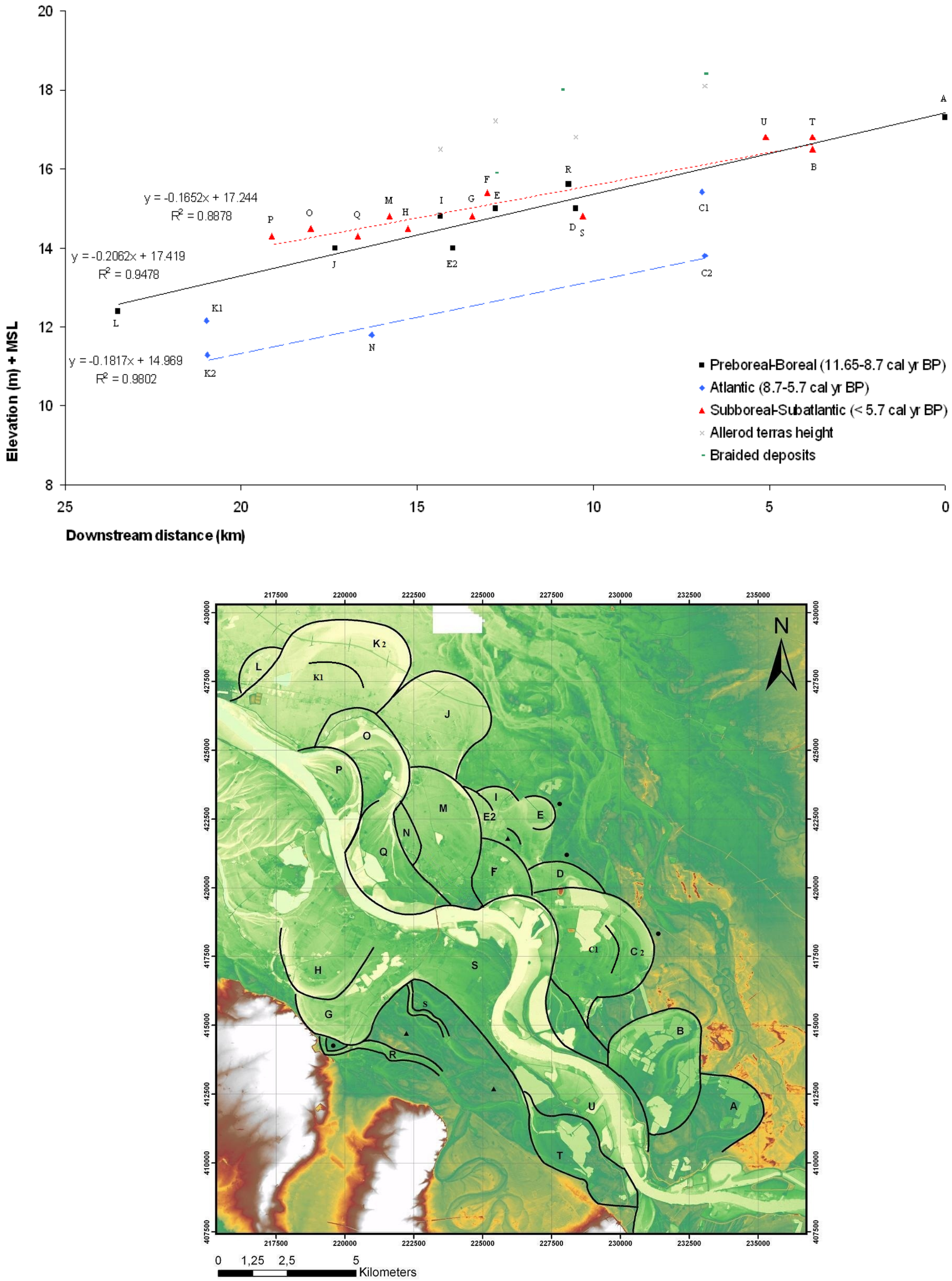

Figure 4.5: a) Longitudinal profile through the average terrace level heights (mostly palaeo-meanders) near the present-day apex of the Rhine , b) location of the identified terrace levels. Terrace levels identified in Transect I to IV are shown (a), as well as terrace levels indicated in cross-sections by Erkens et al. (2011), Dingemans (2001) and Favier (2001). The location of the terrace levels (b) is based on above mentioned references and results gathered during this fieldwork. Dots show locations of Allerød meandering deposit, triangles show locations of braided deposits.

As shown in figure 4.5a, valley gradient in the study area decreases during the Holocene from ~0.21 m/km during the Preboreal-Boreal (11.65-8.70 cal yr BP), ~0.18 m/km during the Atlantic (8.70-5.70 cal yr BP) to ~0.17 m/km during the Subboreal-Subatlantic (5.70 cal yr BP-present). Although valley gradient might vary somewhat along the Rhine trough the research area, this is not evident in the figure.

The Holocene terrace levels plot below the Pleistocene terrace levels (for exact Pleistocene terrace heights, see Geurts, 2011.), and the Atlantic levels plot below Preboreal-Boreal levels. The position of the Atlantic levels indicates in the research area to be incision dominated until at least the Atlantic period. Subboreal-Subatlantic terrace levels plot at a higher elevation than the Atlantic terrace levels in the downstream part of the research area and even higher than the Preboreal-Boreal terrace levels. In the most upstream part Preboreal-Boreal and Subboreal-Subatlantic terrace level heights roughly have the same elevation. Within the Preboreal-Boreal and Subboreal-Subatlantic group, it appears that every terrace level/palaeo-meander has a slightly different elevation too (taking valley gradient into account). Within the Preboreal-Boreal group younger terrace levels mostly are formed at a lower elevation, while in the Subboreal-Subatlantic group it appears that younger terrace levels mostly are formed at a slightly higher elevation. The Atlantic group shows a different pattern.

Within the Atlantic group, the gradient line is determined by the Schloss Bellinghoven (C2) palaeo-meander, Hetter Landwehr (K2) palaeo-meander and the Esserden (N) terrace remnant which form the lowest terrace levels. The Schloss Bellinghoven (C) and Hetter Landwehr (K) palaeo-meanders are both build-up of two terrace levels; a higher older part (K1,C1) and a lower younger part (C2, K2), closer to the residual channel (Appendix C, Transect I & Appendix D, Transect I,II). The lowest and youngest terrace remnant are used to determine the gradient, because these levels probably are formed in the last period of the incision. Besides that, it is most likely that these terrace levels are formed by the latest activity of the channels located next to the terrace levels (Fig 4.5) which are dated. The older terrace levels (C1, K1) show a higher elevation, as well as the terrace levels which are formed at the late Boreal/early Atlantic (Lowenberg, L and Lohbrink, E2).

The found valley gradient lines for the research area are combined with the valley gradient lines for the LRE just upstream of the research area, constructed by Erkens et al. (2011). As can be seen in figure 4.6, the gradient lines in the research area and the rest of the LRE connect well. The upper part of the LRE is dominated by incision throughout the Holocene. The downstream part of the LRE (the research area) is dominated by incision during the Preboreal, Boreal and Atlantic, after which aggradation sets in during the Subboreal and Subatlantic (< 5.7 cal ka BP, § 4.4).

It should be remarked that Erkens et al. (2011) defined the Early Holocene as the period between 11.5-6.0 cal ka BP, the Middle Holocene between 6.0-2.0 cal ka BP and the Late Holocene from 2.0 cal ka BP onwards. For the research area (Fig. 4.6, 115-135 km), the subdivision as in figure 4.5 (Preboreal/Boreal, Atlantic and Subboreal/Subatlantic) is used in figure 4.6. It is believed that this subdivision better reflects the incision-aggradation trends in the research area, because incision-aggradation trends roughly can be subdivided within these periods (see also § 4.4). For the upper part of the LRE (0-115 km), this subdivision is less important, because of the ongoing trend of incision. In the upstream part, the results and subdivision of Erkens et al. (2011) are used.

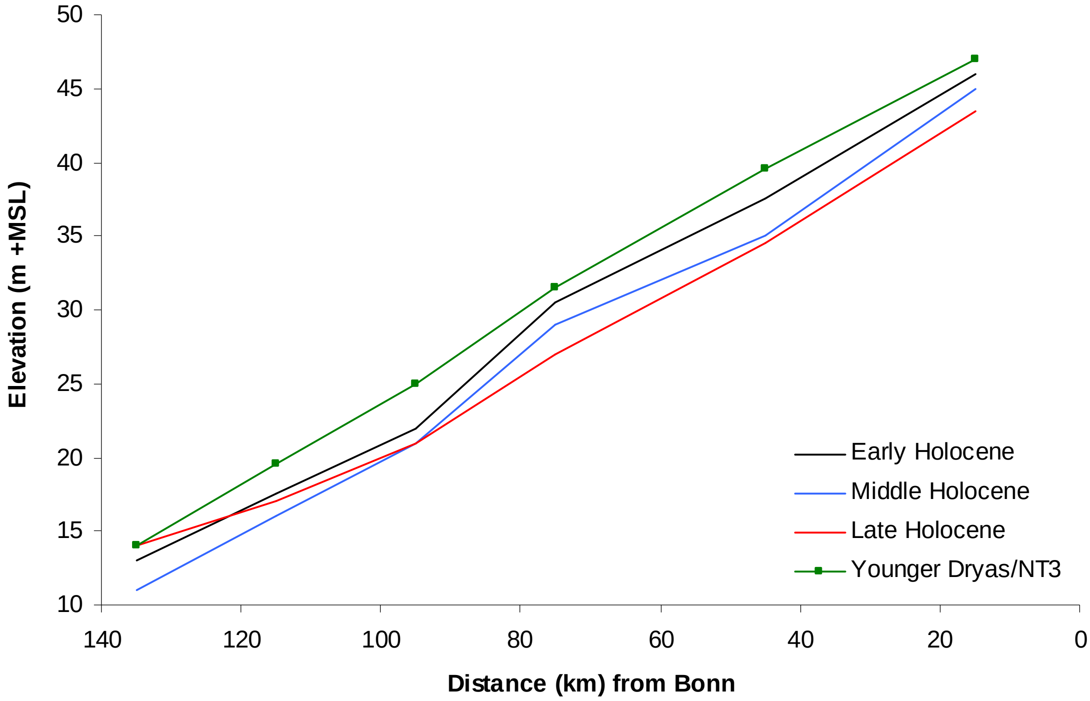

Figure 4.6: Valley gradient lines through the LRE from Bonn to Emmerich. The five green dots from the right, 0-115 km, show the location of cross-sections by Erkens et al., 2011), supplemented with the result found in the research area (between the left two green dots, 115-135 km).

4.4 Incision-aggradation rates and dating

To help reconstruct palaeogeographical development it is important to compare terrace level heights of the found palaeo-meanders through time. Because the palaeo-meanders are formed along the Rhine over a distance of around 20 km in the research area, first a correction for the valley gradient is made. The corrected terrace level heights are plotted against the age of the palaeo-meanders that have been dated (Fig 4.7). The resulting age-height diagram gives an overview of the incision/aggradation rates throughout the Holocene and the levels at which different palaeo-meanders are formed. With the known incision/aggradation rates it is possible to project terrace heights of undated palaeo-meanders in the diagram and determine relative and possible absolute ages.

Absolute terrace heights and floodplain thicknesses of palaeo-meanders are determined with the use of cross-sections published in this thesis (Appendix C) and by Erkens (2009), Dingemans (2001) and Favier (2001)(Appendix D). Relative heights of in-channel deposits from palaeo-meander are determined with the use of a DEM that is corrected for an early Holocene valley gradient of 19cm/km. Relative terrace heights can be calculated when floodplain thickness and relative height of the top of the floodplain deposits are known. The height of the Hohe Ley top of in-channel deposits(R, Transect I) is taken as reference point and set to zero. The diagram shows the minimum and maximum height of the top of in-channel deposits relative to the early Holocene terrace height (of the Hohe Ley, R) for every palaeo-meander. The estimated mean height of the top of the terrace levels (in-channel deposits without floodplain deposits) is indicated as well. The age of a palaeo-meander indicates its period of activity. Because mostly the end of the activity of palaeo-meanders is dated, it is assumed that palaeo-meanders existed for around 1000 yrs, when the start of activity is unknown. Palaeo-meanders that have been dated are shown in orange. Palaeo-meanders that are fitted between the dated palaeo-meanders are shown in yellow. An overview of all used radiocarbon and OSL dates as well as all estimated ages and periods of activity is shown in Appendix F.

Figure 4.7 shows the age-height diagram of all palaeo-meanders in the research area. It is shown that almost all palaeo-meanders have a slightly different height. The oldest palaeo-meanders have a higher elevation than the middle Holocene palaeo-meanders until the end of the Atlantic period. Around the Atlantic/Subboreal transition the height of the palaeo-meanders increases again. The younger paleao-meanders are formed at the same height as the early Holocene palaeo-meanders. The most recently formed palaeo-meanders probably occur at slightly higher elevation than the palaeo-meanders of the early Holocene (but note the spatial trends of Fig 4.5 & 4.6).

The highest formed in-channel deposits belong to the winding channel of the Hohe Ley (R), formed at the onset of the Holocene. Minimal and maximal heights are not shown in the diagram because off the small width of the channel. Only a few borings are located in the channel belt of the Hohe Ley (R). Heights of the Vosse Kuhl are not shown because borings are only placed in the residual channel, but the heights are expected to be the same or even higher than the Hohe Ley (R).
The palaeo-meanders Heeren Bril (E), Haspelweide (I), Tote Landwehr (J), Hagener Meer (D), Diersfordt (A) and Schloss Bellinghoven (C1, inner bend C) roughly plot at the same height within the diagram. The difference in mean estimated height between the palaeo-meanders is less than one meter. The palaeo-meanders formed maximal 1 m below the early Holocene terrace level (Hohe Ley (R)). Except Haspelweide (I), all palaeo-meanders are independently dated. The palaeo-meanders are formed during the Preboreal and Boreal. The dating of the Heeren Brill (E) residual channel probably does not reflect the correct age of the palaeo-meander and is neglected. The Heeren Bril (E) palaeo-meander probably has a somewhat older age than the Haspelweide (I) palaeo-meander. The Haspelweide (I) palaeo-meander has a lower elevation and probably cut off the Heeren Bril (E) palaeo-meander. Although dating of the Heeren Bril (E) residual channel suggests a younger age, this is not supported by the height of the in-channel deposits and the channel morphology. It is therefore

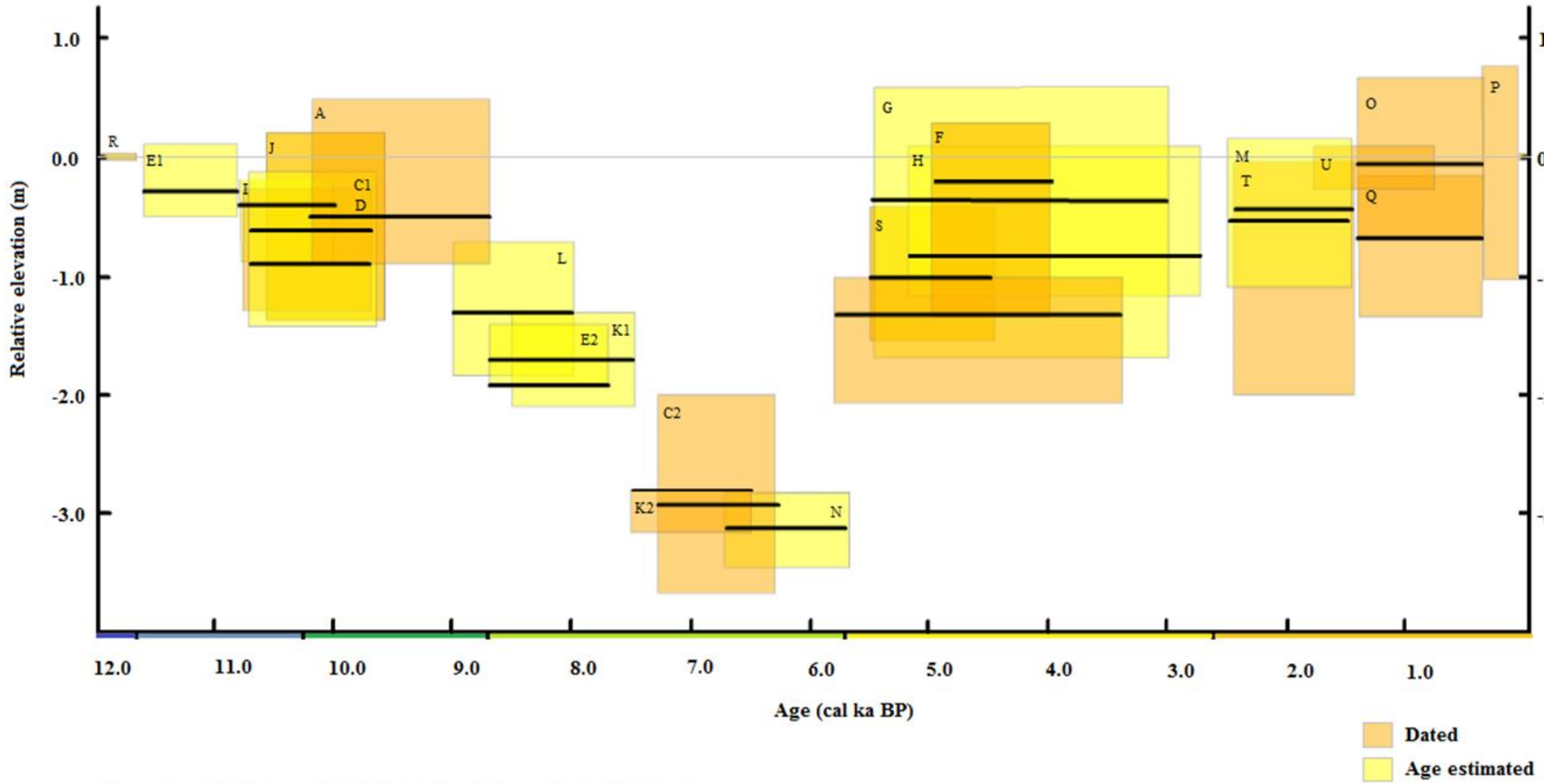

Figure 4.7: Age-height diagram of the Holocene palaeo-meanders in the research area.

suggested that the channel fill does not reflect the correct age of the Heeren Bril (E) palaeo-meanderThe heights of the palaeo-meanders do not clearly decrease with decreasing age (more negative relative height). This might be caused by the small age difference and thus small change in incision between the younger palaeo-meanders Tote Landwehr (J), Hagener Meer (D), Diersfordt (A) and Schloss Bellinghoven (C1, inner bend C). The variation in minimum and maximum sand height of one single palaeo-meanders is in most cases larger than the mean estimated height between the palaeo-meanders. Remarkable is that palaeo-meander Hagener meer (D) and Schloss Bellinghoven (C1, inner bend C) share almost exactly the same terrace height. This suggest association of the inner bend of Schloss Bellinghoven (C1) with the Hagener Meer palaeo-meander.

The younger palaeo-meanders Lowenberg (L), Lohbrink (E2), Hetter Landwehr (K1,K2), Schloss Bellinghoven (C2, outer bend C) and Esserden (N) show clearly lowered elevations with decreasing age. The difference in mean estimated height between the palaeo-meanders of this group is around 1.5 m. The maximal height difference with the early Holocene terrace height (Hohe Ley (R)) is around 3.0 m. The palaeo-meanders Schloss Bellinghoven (C2) and Hetter Landwehr (K1,K2) are dated and Lowenberg (L) has to be older than Hetter Landwehr (K1,K2). The other meanders are relative dated only but plot between the directly dated palaeo-meanders. It is therefore assumed that they formed during the Atlantic, with palaeo-meander Lowenberg (L) having a somewhat older age. The age of the Lohbrink (E2) palaeo-meander is questionable, because only a small remnant has been found. The height of this terrace remnant probably indicates a late Boreal/early Atlantic development, but this is only based on two borings.

The palaeo-meanders Schloss Bellinghoven (C1,C2) and Hetter Landwehr (K1,K2) each are composite of two parts with a different height. The inner bends (C1, K1) of these palaeo-meanders clearly reflect at a higher elevation than the outer bends (C2, K2). The lower terrace levels of the K2 and C2 are explained as a result of ongoing incision (Appendix D, cross-section I,II), in the case of C2 dissecting the D/C1 level.

The next palaeo-meanders Bislicher Meer (B), Nierdermörmter (S), Oy (G), Hanselaer (H) and Haus Groin (F) are formed at a higher elevation than the above mentioned palaeo-meanders. The difference in mean estimated heights between the palaeo-meanders in this group is around 1 m. The height difference with the early Holocene terrace height decreased till around 1,0 m. The palaeo-meanders Bislicher Meer (B) and Haus Groin (F) are dated and show an increasing height with decreasing age. Height of the undated palaeo-meanders suggest they are probably all formed during the Subboreal. Although, the oldest part of the Bislicher Meer (B) palaeo-meander formed somewhat earlier. The oldest part of the palaeo-meander has a somewhat lower elevation dated at an early Subboreal age (Appendix C, F).

The most recent palaeo-meanders, Speldrop (M), Xanten I (T), Xanten II (U), Reeserward (Q), Grietherbusch (O) and Ortscheward (P) have a slightly higher elevation than the Subboreal palaeo-meanders. The youngest palaeo-meanders within this group appear to have formed at the highest elevation. The difference in mean estimated height between the palaeo-meanders is less than one meter. The palaeo-meanders are formed maximal around 0,5 m below the early Holocene terrace, but some are formed at the same height or even above the early Holocene level.

5 Palaeogeographical development

In this chapter an overview of the Holocene palaeogeographic development of the river Rhine near its present-day delta apex is given based on the results of chapter 4. The focus of this palaeogeographical reconstruction (Fig. 5.1) is on the period from the onset of the Holocene (ca. 12 cal ka BP) to the end of the Subboreal period (ca. 2.6 cal ka BP). Furthermore, an attempt is made to identify the factors that controlled fluvial development in the research area. A comparison will be made with the areas upstream and downstream to detect trends in fluvial development and make a distinction between regional and local controlling factors. It will also be discussed if river terraces/palaeo-meander generations have developed with age specific characteristics (e.g. height differences of in-channel deposits and fluvial style/river morphology) that can be used for identification and/or dating.

5.1 The Younger Dryas/Early Holocene transition

The transition from the Younger Dryas to the Holocene (ca. 11.65 cal ka BP), was associated with a change in fluvial style from a braided to a meandering river pattern and discharge becoming more concentrated in fewer channels (Erkens, 2011). The Hohe Ley (R) and Vosse Kuhl (Fig 4.1) are seen as preserved examples from this stage. An anabranching network of channels of 2-4 m deep developed (Fig. 5.1a, light blue), while smaller channels (1-2 m deep) from the braid plain stage (Fig. 5.1, grey-blue plain) became abandoned. The latter filled with silty loam and (clay) loam, whereas the former reshaped bed material into alternating bars, with tops around 1 m below the Younger Dryas braid plain (Fig. 5.1a, dark blue). Possibly larger and deeper channels were active as well, more at the right side of the valley, but have not been preserved. The ongoing incision (lowering of top of in-channel deposits and also channel base) and meandering of the channels caused the formation of small incised river valleys, of around 200-500 m wide near the Hohe Ley (R) and the Vosse Kuhl. The valley gradient probably was somewhat higher than the Preboreal valley gradient of 0.21m/km (Fig. 4.5, 5.2). Already very early in the Preboreal, the multiple meandering channels became abandoned and filled with (clay) loam and (clastic) peat. It is noted that, although fluvial activity of the Hohe Ley (R) stopped at the onset of the Holocene, the channel remained water carrying until the present day, but is no longer connected to the river Rhine.

With the abandonment of the Hohe Ley (R) and the Vosse Kuhl, discharge became further concentrated in a progressively smaller number of channels of which the Heeren Bril (E) and the Haspelweide (I) palaeo-meanders are preserved. These palaeo-meanders probably were part of the main channel belt of the Rhine during the Preboreal. The channels had a depth of around 5-7 m and a width of 250-300 m, which is relatively small compared to the Middle Holocene palaeo-meanders, but bigger than the Hohe Ley (R) and Vosse Kuhl of the previous section. The diameter of the Preboreal meanders is around half the diameter of the single late Boreal/early Atlantic meanders, which indicate

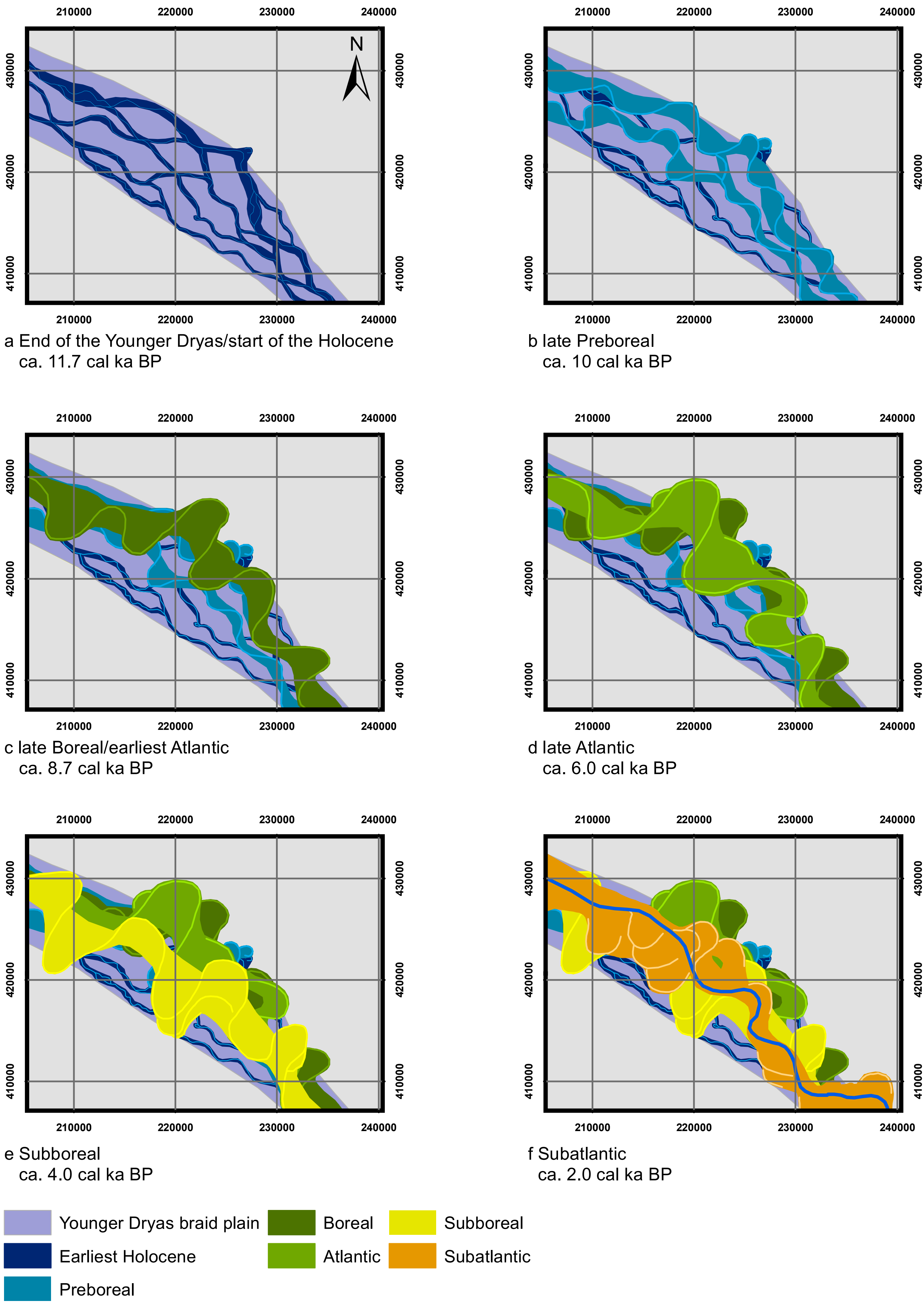

Figure 5.1: Palaeogeographic development of the norther part of the Lower Rhine Embayment

the presence of a secondary channel system. It is suggested that at the beginning of the Preboreal ca. 3 channels were active beside the main channel, at the end of the Preboreal this reduced to ca. 1 channel (Fig. 5.1b, light blue).

The presence of secondary channel systems in the LRE is also described by Erkens et al. (2011). They found a secondary channel that became abandoned at ca. 9.0 cal ka BP and the earliest dated palaeo-meander that became the main channel dates from the Boreal (9.4 cal ka BP old). According to Erkens et al. (2011), stronger and more competitive incision in the largest ‘main’ channel is the cause for the abandonment of the secondary channel systems. Secondary channel systems likely existed parallel to the main channel, and the longest functioning ones were around 4-5 m deep. Remnants of the smaller secondary channel systems described by Erkens et al. (2011) have not been found in the research area. Most likely, they have been eroded later during the Holocene.

Incision (lowering of channel base and lowering of in-channel deposits) continued during the Preboreal. Although incision rates (lowering of in-channel deposits) are quite small compared to the incision rates later during the Holocene (Fig. 5.2c). Incision since the formation of transitional zone until the end of the Preboreal is less than 0.5 m. The valley gradient probably decreased till around 0.21 m/km (Fig. 5.2d). An increase in the sinuosity has also been observed, which likely is related to the decreased valley gradient and the more stable climatic conditions (Fig. 5.2a,b)

5.1.1 Morphological succession as a consequence of Climate change

Climate change at the onset of the Holocene caused the transition from a braided to a meandering system, which according to Erkens et al. (2011), resulted in clear succession in the LRE. Incision and abandonment of the braid plain is usually the initial response. The resultant multi-channel system, with one larger and a couple of smaller channels, than begins meandering and starts to transform braid plain morphology into point bars (change in fluvial style). The last phase of response is flow contraction into a single (meandering) channel and the abandonment of secondary channels. In general, this corresponds with the succession found in the research area, but some additions are made.

The abandonment of the braid plain is explained as a direct, near instantaneous response by Erkens et al. (2011) and meandering starts with the development of the multi-channel system with one larger and a couple of smaller channels. They assume that meandering started immediately with the start of the multichannel system with secondary channels, based on the presence of one strongly meandering early secondary channel older than 11 ^{14}C ka in the research area (Erkens et al., 2011: cross-section V-V’, 2-4 km). Nevertheless, in the research area multiple small and weakly meandering channels slightly incised the Younger Dryas braid plain, suggesting that fluvial style gradually started to change during the abandonment of the Younger Dryas braid plain. It is also suggested by this study that the old, early secondary channel described by Erkens et al. (2011) formed earlier, during the Bølling-Allerød, and is

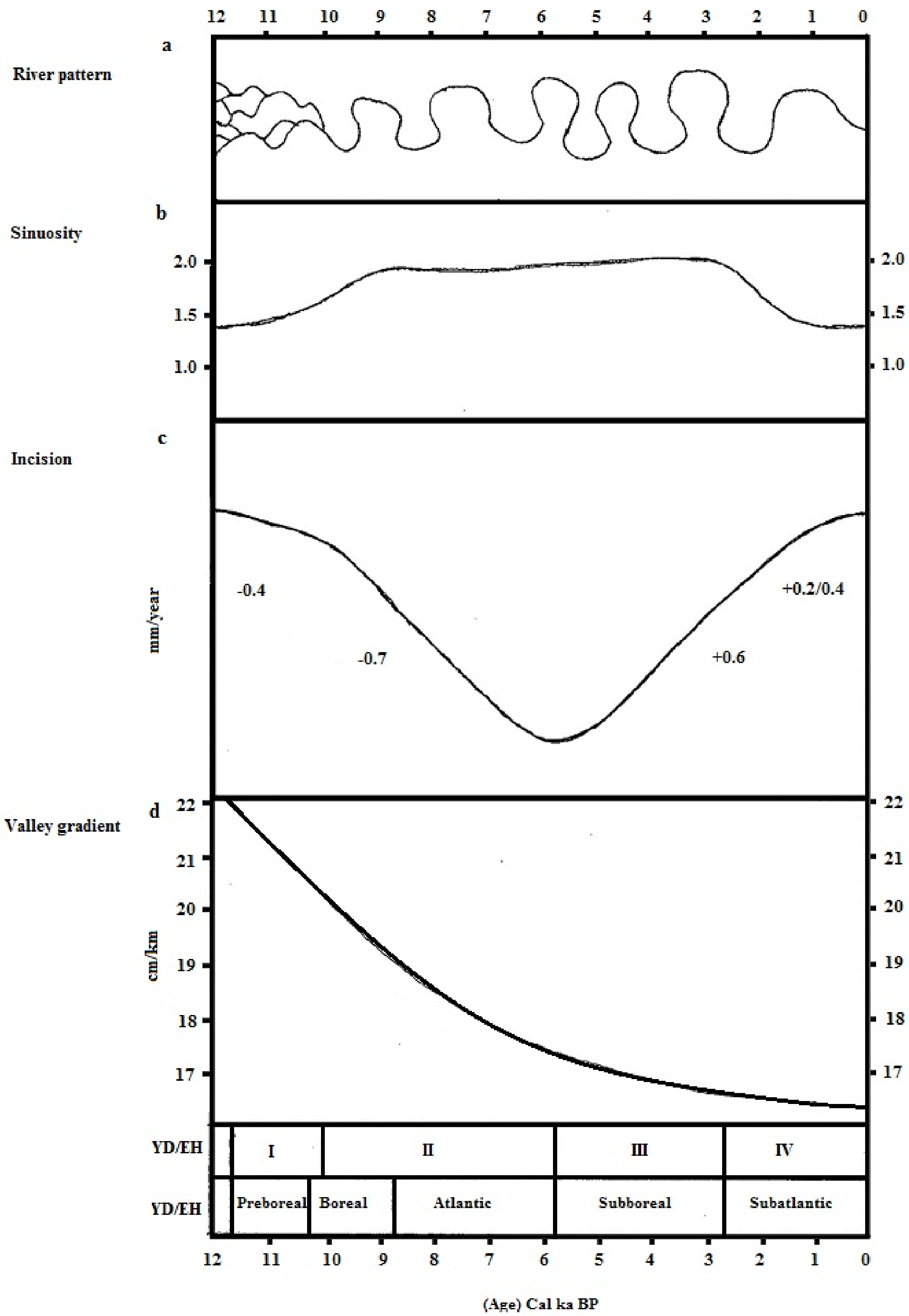

Figure 5.2: Incision, valley gradient and sinuosity during the Holocene in the northern LRE.

not part of the Younger Dryas braid plain/Holocene meander belt (also discussed in Geurts, 2011).The meandering deposits are cut-off by the Younger-Dryas braid plain and also the height of the meander channel deposits supports this. This study assumes that abandonment and incision of the Younger Dryas braid plain and the change in fluvial style probably was a more gradual process that both started with the abandonment of the Younger Dryas braid plain.

Though conflicting in local details, this supports that the notion of a morphological succession by Erkens et al. (2011) also is present in the research area, but the concentration of flow probably is a more gradual transition. First, the channels of the braided system start meandering and flow becomes more concentrated in multiple slightly meandering channels (Fig. 5.1a). After which flow becomes further concentrated resulting in the multiple channel system with one large and a couple of smaller secondary channels during the Preboreal (Fig. 5.1b). Finally, during the last phase, flow again becomes more concentrated and the longest surviving secondary channels systems is abandoned during the Boreal (ca. 10 cal ka BP) in the research area (Fig. 5.1c).

The above mentioned succession can be seen as a ongoing process of changes in discharge and sediment supply throughout the Holocene as a reaction to the climate change at the onset of the Holocene. The succession, which resulted in flow concentrated into one main channel

5.2 Boreal and Atlantic

During the Boreal (10.25-8.7 cal ka BP), secondary channel systems further became abandoned and discharge concentrated in one large channel from ca. 10 ka onwards (Fig. 5.2c, dark green). The Diersfordt (A), Tote Landwehr (J) and Hagener Meer (D and C1) palaeo-meanders are probably the first channels that carried the full discharge of the Rhine. Although the residual channels are quite small, the diameter of the palaeo-meanders is quite large and suggests that Boreal meanders did carry the full discharge of the Rhine. This is supported by the thickness of the in-channel deposits of the Hagener Meer (D) palaeo-meander, which shows a thickness of around 8 m. The thickness of the in-channel deposits of the Diersfordt (A) and Tote Landwehr (J) palaeo-meander has not been determined, but given the equal size and age it is suggested that all three meanders did carry the full discharge of the Rhine. Erkens et al. (2011) too suggests that the Dierfordt (A) meander represents a single main channel. The Tote Landwehr (J) palaeo-meander is presumably the oldest of the meanders that carried the full discharge of the Rhine, and dates from before 9.6 cal ka BP. This implies the last secondary channel systems to have abandoned before ca. 10.0 cal ka BP.

During the Atlantic (8.7-5.7 cal ka BP) large single thread meanders continued to develop (Fig. 5.1d, light green). The Lowenberg (L) palaeo-meander probably formed at the onset of the Atlantic or Boreal-Atlantic transition. The Hetter Landwehr (K), Schloss Bellinghoven (C2) and Esserden (N) palaeo-meander formed during the Atlantic. The above mentioned meanders have the lowest elevation in the research area.. The river channels are about 7 m deep. The width of the channels is relatively large, around 300 m near the bottom and almost 600 m near the top of the channels. The diameter of the palaeo-meanders is also quite large and comparable with that of the late Boreal and Subboreal palaeo-meanders. The valley gradient decreased till around 0.18 m/km during the Atlantic and sinuosity does not change considerably during both the Boreal and Atlantic (Fig 5.2).

The size and infilling of the Boreal and Atlantic residual channels does differ. The full sized Atlantic residual channels that have been found suggest that the Atlantic palaeo-meanders were rapidly abandoned (i.e. cutoff events) in the last part of the Atlantic. In contrast, such residual channels dating from the Boreal are absent. Here, gradual termination resulted in channel fills that are at first more sandy than channel fills that are abruptly abandoned. Indicating that the discharge of the large single thread Boreal meanders was gradually taken over by more incised Atlantic meanders, which do show a rapid abandonment at the end of the Atlantic.

Initially, the Boreal incision rate (lowering in-channel deposits) was comparable with that of the Preboreal and quite low. Since the onset of the Boreal incision increased for 0.5 m and is in total 1.0 m since the earliest Holocene reference level (ca. 11.7 cal ka BP). This is around 0.4 mm/yr during the Preboreal and Boreal (Fig 5.2c). During the Atlantic, incision (lowering in-channel deposits) increased for another 2 m. Maximal incision was in total ca. 3.0 m with the reference level, and ca. 0.7 mm/yr. It seems that the incision rate increased relatively fast at the end of the Boreal/onset of the Atlantic. The increase in incision rate can possibly be explained by a change in incision from lowering of channel base to lowering of in-channel deposits.

The low incision rate of the in-channel deposits during the Preboreal and Boreal is likely caused by an advantage of incision in the form of lowering the channel base. Incision in the form of lowering the channel base is commonly observed simultaneously to a transition from a braided to a meandering river system. The decrease in coarse sediment supply and more stable banks (vegetation, levees) will help discharge to concentrate in a channel with a smaller width/depth ratio. The river can only carry a specific load of bed sediment through its channel to deepen it. This feeds back to the process of concentration of the discharge into one channel. Therefore, incision in the form of lowering channel base hampered the incision in the form of lowering of in-channel deposit which started around the middle Boreal. During the Atlantic, incision in the form of lowering in-channel deposits continued and appears to have increased.

The increase in incision and the formation of relative deeply incised Atlantic palaeo-meanders might also have been affected by the amount of available sediment supply. The climate was probably stable enough over a longer period to reach climax vegetation (Janssen, 1974). The stable conditions with climax vegetation caused a uniform discharge regime (due to increased interception, infiltration and evapotranspiration and a decrease in runoff due to increased surface roughness), less sediment input (stable soil conditions) and more cohesive banks. This may on it self have promoted the lowering of the top of in-channel deposits, even with no change in upstream sediment supply because dense vegetation hampers the lateral movement of meanders, promoting transport of upstream supplied sediment, as mixing and stalling by the lateral deposition process does not occur any more. The consequence is that meanders migrate not as strongly as in the Preboreal and Boreal. Their location appears relative stable in the Atlantic. Lack of sediment supply from upstream and lack of meander migration leaves the channel bed as the only source for sediment, leading to incision of the in-channel deposits (Fig 5.3).

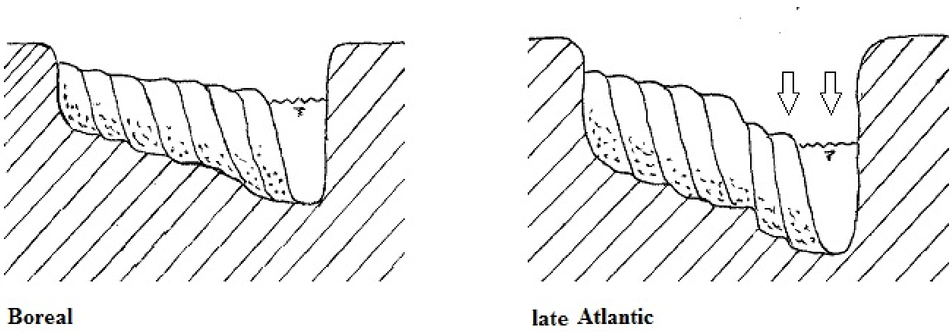

Figure 5.3: Increased incision during the Atlantic.

5.2.1 Final stage of morphological succession by climate change

The fact that no large change in fluvial style/river morphology occurred during the late Boreal and Atlantic in the research area, can be related to the relatively stable climate conditions and the absence of human influence. But, although no changes in fluvial style/river morphology occur, incision (lowering in-channel deposits) increased strongly and the decrease of the valley gradient steadily continues. Both processes probably are related to the stable climate (and vegetation) conditions that are reached during the late Boreal/early Atlantic, influencing discharge and sediment supply. It is suggested that the succession from a braided to a meandering river system caused by a climate change extends to this period ('climax state of the response'). The final delayed reaction to the initial climate change, when stable climate (and vegetation) conditions are reached, is a change from incision in the form of lowering the channel base to incision in the form of lowering the in-channel deposits.

Another explanation is given by Van Balen et al. (2009), who discuss and model incision (lowering in-channel deposits) during climate transitions for braided systems. They mention that it takes several thousand years (ca. 1100-2300 yr) before incision takes place after a transition from a colder to warmer climate (if there is no fluvial style change). This is explained by the fact that despite the reduction of sediment input due to re-vegetation of hill slopes, sufficient sediment remains available for fluvial transport in the channel network itself (which is true with or without fluvial style change). Therefore, they suggested that incision (lowering in-channel deposits) only starts once transportable bed sediment in the channel network diminished which becomes amplified by the stable climate conditions, hampering the input of sediment. This also fits the idea that the incision is a delayed response to the initial climate change that can be seen to complete the succession described by Erkens et al. (2011) at the onset of the Holocene. But the occurrence of fluvial style change overprints this response with additional steps in the succession.

Although no absolute incision rates are known from the upstream part of the LRE throughout the Holocene, it is suggested that similar trends in incision rate occur as measured in the research area. Fluvial development according to the described succession probably was roughly the same. An exception is the southern part of the LRE which experienced a stronger uplifted and no meanders were cut-off until the late Holocene.

5.3 Subboreal

During the Subboreal (5.7-2.6 cal ka BP) large single thread meanders changed from an incisional (lowering channel base) to an aggradational state (Fig. 5.1e, yellow). The palaeo-meanders Bislicher Meer (B), inner bend Rhine (S), Oy (G), Hanselaer (H) and Haus Groin (F) formed during the Subboreal. In dimensions, the Subboreal channels are comparable with the Atlantic channels. The channels have a depth of around 7 m and a width of around 600m. The infilling of the residual channels indicates that some meanders were immediately disconnected from the main flow, while other meanders lost their discharge more gradual to other channels at the end of the Subboreal.

Characteristic for the Subboreal is a shift from incision (lowering of in-channel deposits) to aggradation (rising of in-channel deposits). An aggradation of about 2m is observed, reducing the height difference with the reference level (ca. 11.7 cal ka BP) to about 1 m. The aggradation rate is ca. 0.6 mm/yr (Fig. 5.3d). Subboreal meanders preserved at roughly the same elevation as Boreal meanders. The valley gradient further reduces and sinuosity probably was slightly higher (Fig 5.3a,b)

5.3.1 Local response

According to Erkens et al. (2011), the decreased incision and even aggradation at the northern part of the LRE (Also decribed by Dingemans, 2001; Favier 2001) is a result of deltaic deposition. During the last ca. 3000 years, the delta apex (aggradation zone) shifted upstream to the present position (Berendsen & Stouthamer, 2000; Cohen, 2005: chapter 3; Gouw and Erkens, 2007), as a result of human-induced increased sediment delivery from upstream. According to Erkens et al. (2011), aggradation downstream of Rees in the Rhine delta probably causes congestion of water and sediment just upstream, slowing down incision in the downstream end of the LRE. He also mentions that a response to human-induced sediment delivery seems to be unlikely before 3000 cal BP. The transition

towards aggradation can be seen as a local response, which only effected the downstream part of the LRE. In the upstream part of the LRE incision still dominates.
In the research area (further upstream than considered in above studies) aggradation already occurred earlier, in the Subboreal, before 4.0 cal ka BP (see § 4.4). Therefore, it is suggested that the influence of human impact in fluvial sediments (at least bed sediment) in the research area started earlier on during the late Atlantic/early Subboreal. The influence of human impact on fluvial sediments (although here it includes mostly fines) has also been described by Dambeck & Thiemeyer (2002), Kalis et al. (2003), Bos et al. (2008) and Notebaert & Verstraeten (2010). They all consider human impact to become noticeable in fluvial sediments (fines) and other proxies from the late Atlantic onwards.
The other external factor, climate change, also causes changes in sediment supply and discharge. Although climate changes within the Holocene are small, a deterioration of the climate (mostly lowering of mean summer temperature) at the Atlantic/Subboreal transition is mentioned (Iversen, 1973; Janssen, 1974 and ref. therein, p. 57; Van Geel, 1981). The effect of climate change is probably small in the late Atlantic or Atlantic/Subboreal transition, but it can not be excluded that it affected and/or amplified a change in sediment supply and discharge. Both the degree of human impact and climate change was relative small at that time. The discussion whether it was mostly human impact or human impact amplified by climate change has not yet led to a decisive answer, but the effect of the change in sediment supply and discharge was relatively small during the Subboreal. No changes are noticed in the southern part of the LRE (Erkens et al., 2011) and it was the local factor that triggered the aggradation.

5.4 Subatlantic

During the Subatlantic (2.6 cal ka BP-present) aggradation continued and further morphological change is observed (Fig 5.1f, orange). The Subatlantic palaeo-meanders concentrate in the middle of the valley. The palaeo-meanders Speldrop (M), Xanten I (T), Xanten II (U), Reeserward (Q), Grietherbusch (O) and Ortscheward (P) are all radiocarbon or OSL dated to a Subatlantic age, except for the Speldrop (M) palaeo-meander which is dated based on terrace height (Dingemans, 2001). For a description of the Subatlantic meanders is referred to Dingemans (2001), Favier (2001) and Erkens et al. (2011). In the elevation of top channel deposits, an aggradation of more than 0.5 m is shown, reducing the height difference with the reference level (ca. 11.7 cal ka BP) to a maximum of 0.5 m. The aggradation rate decreases to ca. 0.2-0.4 mm/yr. The youngest palaeo-meanders seem to have no height difference with the Younger Dryas braid plain and some even formed at a higher elevation. The valley gradient decreases further till around 0.17 m/km and the diameter and sinuosity show a decrease as well (Fig 5.2a,b). The decreased sinuosity and incision might be related to an increase in fines as is suggested by Erkens (2009) for the northern URG due to a thickening in overbank deposits, likely caused by increased human impact.

5.4.1 The effect of human impact

In the LRE, Erkens et al. (2011) note a thickening and coarsening of the overbank deposits during the Subatlantic. Favier (2001) also mentioned a coarsening of the overbank deposits, but an increase in thickness has not been observed in the research area of Favier (2001) and Dingemans (2001). However, some older meanders (B, K) do show a small thickening of the overbank deposits which might be influenced by local conditions. It is possible that the older incised meanders became covered with younger floodplain deposits due to aggradation.

Catchment wide deforestation and agricultural land use are mentioned as the predominant cause of the increased fine sediment transport and levee deposition and associated change in channel morphology, in the interpretation of e.g. Kalis (2003) and Erkens et al. (2011 and ref. therein, p. 111). Notebaert & Verstraeten (2010) regard the additional the contribution of climate change as to be hidden: The influence of land use change on the Holocene sediment dynamics throughout Western and Central Europe overwhelms the potential climate signal. They note that any contribution of climate is further hidden due to synchronicity between cultural phases and climatic events. Land use which could mask less important, but not necessarily insignificant, variations in sediment deposition due to other driving forces like climate. Dambeck & Thiemeyer (2001) and Bos et al. (2008) agree that climate can not be excluded to have influenced sediment supply and discharge during the Subboreal. The exact cause of the change in river morphology is not easy to determine, because human impact increases and climate changes (Janssen, 1974; Bos et al., 2008 and refs. therein) at the onset of the Subatlantic, as well as at the onset of the Subboreal. As Bos et al. (2008, p. 86) state: “The effects of human impact were probably intensified by superposition of climatic causes or vice versa”.

5.5 River terraces and meander generations in the LRE

It is shown that almost all palaeo-meanders in the research area have a slightly different height. The palaeo-meanders are formed due to continuous incision after the middle Boreal, followed by aggradation in the Subboreal. The decrease in river gradient is a continuous process throughout the Holocene. Similar, changes in fluvial style/river morphology seems to occur in succession, spread over a longer time after an external forcing occurred. Despite all of these continuous developments, the palaeo-meanders in the research area do subdivide into four distinct palaeo-meander generations. Generation I existed from the Preboreal to the middle Boreal when secondary channel systems were active and incision (lowering in-channel deposits) rates were low. Palaeo-meander generation II formed after generation I, when flow concentrated in one main channel and secondary channels

became abandoned. Generation II is characterized by high incision rates and was formed during the middle Boreal and Atlantic. The next, younger, palaeo-meander generation, generation III, formed mostly during the Subboreal and is characterized by a relatively high aggradation rate, yet fluvial style/river morphology remains the same. The last and youngest palaeo-meander generation, generation IV, is characterized by a change in fluvial style/river morphology. Aggradation continues, although at a somewhat lower rate. Palaeo-meander generation IV formed during the Subatlantic.
The subdivision into generations is only possible where sufficient data of the palaeo-meanders and the surroundings was available, because the diagnostics are subtle. Furthermore, the palaeo-meanders were produced under the influence of succession of external forcing. The interaction between these forcings and their sometimes small magnitudes of change classifies the river valley evolution as complex fluvial response. The resulting differences between the palaeo-meanders are so small, that it is proposed to speak of meander-generations, rather than to speak of river terraces as suggested by Klostermann (1989; 1992), Jansen (2001) and Schirmer (1995). Although the terrace characteristics listed by these authors were also identified in this study, the magic number of seven Holocene river terraces could not be confirmed. The explanation given by Schirmer (1995) for the terrace formation is that they were caused by alternating phases of fluvial activity, which would proof that climate controlled fluvial rhythmicity. But this research shows that fluvial development is a continuous process controlled by multiple external (human impact, climate changes), besides local (deltaic deposition) forcings that make fluvial response complex, and not dominantly the product of instantaneous response to climate fluctuations.

5.6 Incision and aggradation.

Combining new and previous data, gives some new insights about the incision-aggradation transition. Prior to this thesis, less was known about the Subboreal (5.7-2.6 cal ka BP) fluvial development and the incision-aggradation transition. It was mentioned by Dingemans (2001) that the change from incision to aggradation occurred after 6.5 and before 2.3 cal ka BP. Favier (2001) assumed that the transition to aggradation took place later between 2.0 and 1.0 cal ka BP. New results show that the transition towards aggradation occurred in the research area at the end of the Atlantic or in the Subboreal, between 6.5-4.0 cal ka BP. At least incision took place in the research area until the end of activity of the Hetter Landwehr (K2, § 4.1.2: 6.5 cal ka BP) and aggradation was present during the activity of the Haus Groin palaeo-meander (F, § 4.1.5: 4.0 cal ka BP) . Nowadays, the incision-aggradation transition is located upstream of the research area (Fig 4.6). The terrace-intersection point between the Younger Dryas and Holocene is located at the northern part of the research area.

5.7 Comparison to upstream and downstream areas.

The external forcings of human impact and climate change also affected the river Rhine downstream (delta) and upstream (northern URG) the research area during the Holocene. Although the initial forcing is the same, river response is not always comparable, but sometimes differs to a greater or lesser exetent. An extensive comparison of the river response to both climate change and human impact between the Rhine delta, LRE and URG is made by Erkens (2009, p.204), trying to separate local forcings, external forcings and intrinsic behaviour. Two additions are made concerning the reactions to the controlling factors that have been found.

First of all; the described succession to climate warming, (I) incision and partial abandonment of the full-glacial braid plain, (II) the onset of meandering and dissection and (III) step-wise abandonment of secondary meandering channels to a single active channel has been found in both the LRE and URG. Because it is expected that this succession can be extended with (IV) the delayed trend in incision (of the in-channel deposits) in the LRE, it is possible that this trend in incision occurs in the URG as well. Secondly, the reaction to a change in sediment supply and discharge becomes noticeable earlier in the northern part of the LRE than was suggested. Although local factors amplify this reaction, there has to be a change in upstream sediment supply and discharge during the Late Atlantic/Subboreal. A change in sediment supply and discharge has also been indicated in the URG during the Late Atlantic/Subboreal. Apparently, some parts of the river valleys are more vulnerable to these changes than other parts which show no reaction. The cause of the change in sediment supply and discharge probably is related to human impact and climate change, although the exact ratio between both is unknown.

6 Conclusions

Data obtained from previous research combined with new collected data results in a better understanding of the Holocene fluvial development in the northern part of the Lower Rhine Embayment. In total 22 Holocene palaeo-meanders are identified which belong to the Holocene river terrace. The Holocene river terrace can be subdivided into 4 meander generations based on fluvial style/river morphology, incision/aggradation rate and palaeo-meander height and a transitional zone between the Younger-Dryas and Holocene river terraces.

At the Younger Dryas/early Holocene transition discharge starts to concentrate and multiple small and slightly meandering channels incise the Younger Dryas braid plain. The first meander generation, generation I, develops when discharge further concentrates during the Preboreal-middle Boreal (ca. 11.65-10 cal ka BP). This results in a multichannel system with one large and a couple of smaller meandering channels. The incision rate (lowering in-channel deposits) is relatively low. The next meander generation, generation II, develops during the middle Boreal-Atlantic (ca. 10.0-5.7 cal ka BP). Flow is concentrated to one main channel and secondary channels systems are abandoned. Large palaeo-meanders form and incision (lowering in-channel deposits) increases. Maximal incision is reached during the end of the Atlantic. The following meander generation, generation III, is formed during the Subboreal (ca. 5.7-2.6 cal ka BP). Changes in fluvial style/river morphology are absent, but incision turns into aggradation. Finally, meander generation IV develops during the Subatlantic (ca. 2.6 cal ka BP-present). A change in fluvial style/river morphology occurs. Floodplain deposits become coarser and the size of the formed palaeo-meanders decreases. Palaeo-meanders are located in a smaller part in the middle of the river valley, close to the present-day Rhine. Aggradation continues, although in a somewhat lower rate.

The first two meander generation are formed in response to the climate warming which results in a clear succession of (a) incision and abandonment of the braid plain, (b) a multichannel system with secondary channels, (c) flow concentration into one single channel followed by (d) delayed incision (lowering in-channel deposits). Meander generation III formed in response to small changes in human impact and/or climate but is facilitated by a local external factor. This local factor, the upstream shifting of the delta apex, results in aggradation which started between 5.7-4.0 cal ka BP. Present-day, the incision-aggradation transition is shifted upstream of the research area. The fourth meander generation formed in a response to change in human impact and possibly smaller climate fluctuations, since this change is also observed in upstream and downstream located areas. This research shows that fluvial development is a continuous process controlled by multiple (local) external forcings that cause a complex fluvial response.

Recommendations

The response to changes in climate and/or human impact is getting better understood over multiple catchments. However, the ratio between the two controlling factors that cause the river to respond from the late Atlantic onwards remains unclear. The starting time and magnitude of the controlling factors and the response time to changing climate and/or human impact is also relatively unknown. To possibly distinguish the response of a river system to each individual forcing, it is useful to more accurately date the exact response time of a river system. Therefore, it would be helpful to accurately date the period of maximal incision and the (upstream shifting) of the transition towards aggradation. This will result in better insights in the exact timing of the incision-aggradation transition and especially the aggradation rates during the Subboreal and Subatlantic. If aggradation rates are known, more information can be gathered concerning the exact responds time, which might then be linked to a specific forcing. OSL dating of the Schloss Bellinghoven, Oy and Hanselaer palaeo-meander will result in a better understanding (of the upstream shifting) of the incision-aggradation transition and thus the rate of aggradation.

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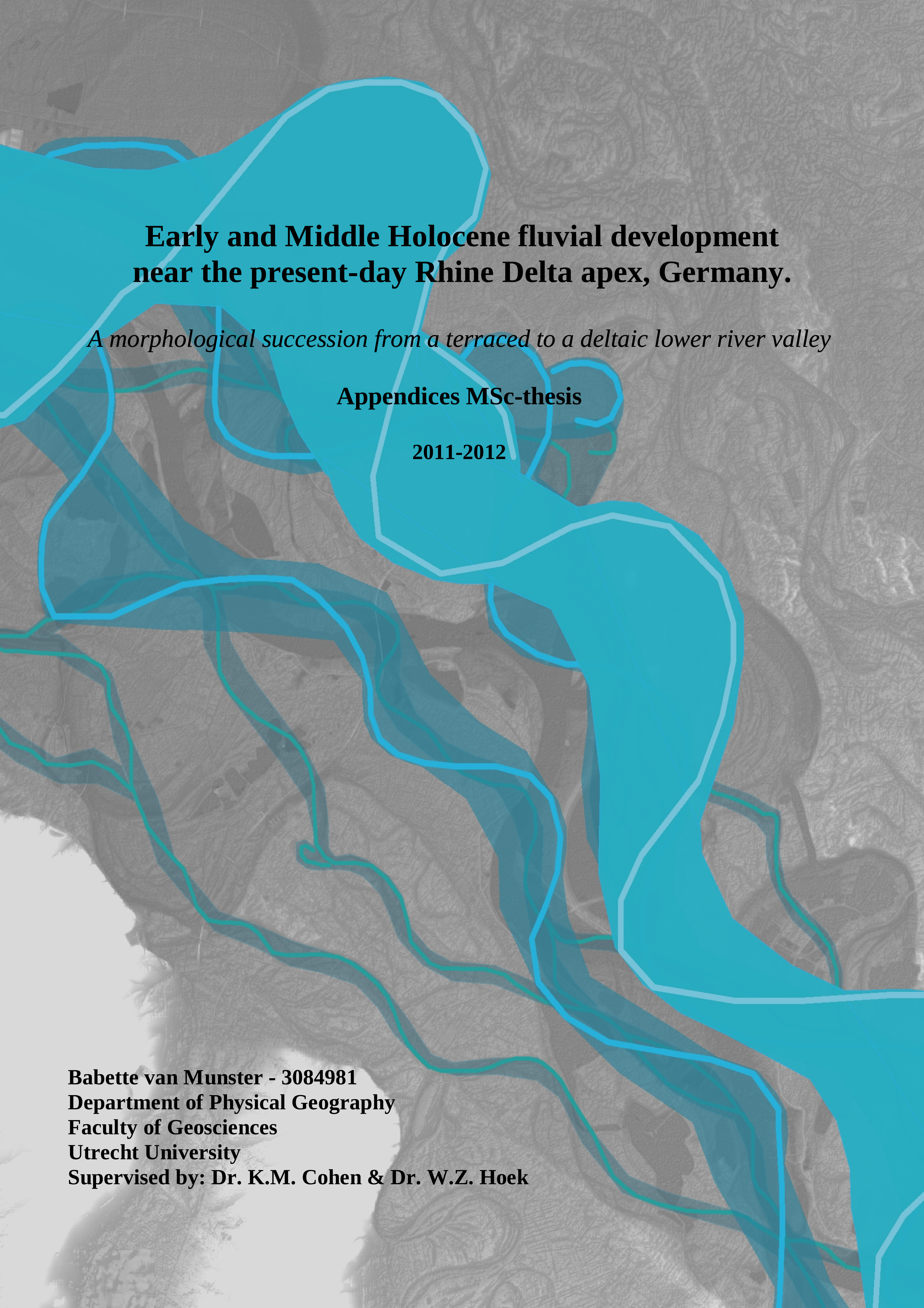

Early and Middle Holocene fluvial development near the present-day Rhine Delta apex, Germany.

A morphological succession from a terraced to a deltaic lower river valley

Appendices MSc-thesis

2011-2012

Babette van Munster - 3084981
Department of Physical Geography
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Early and Middle Holocene fluvial development near the present-day Rhine Delta apex, Germany.

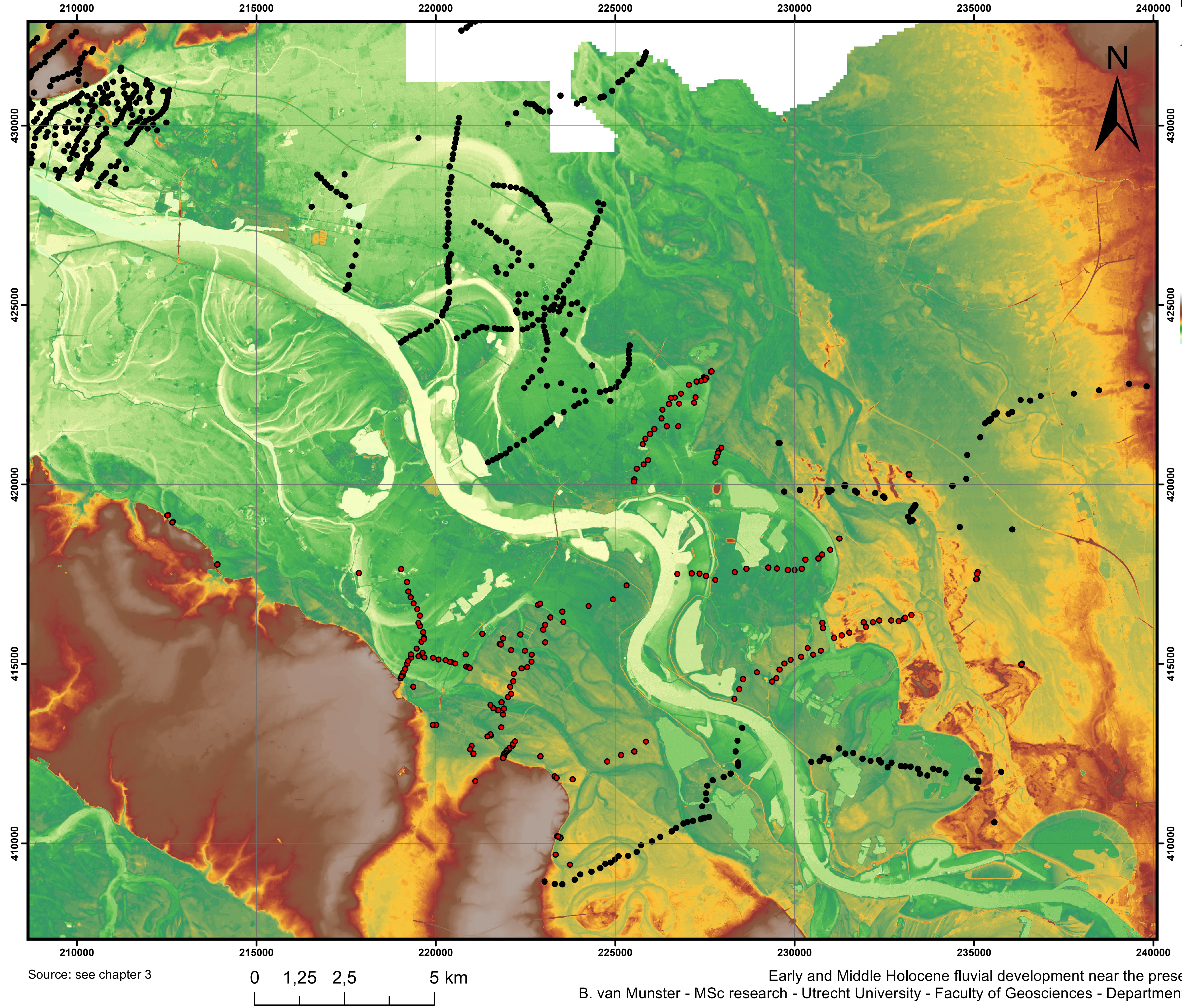
A morphological succession from a terraced to a deltaic lower river valley

Appendices MSc-thesis

2011-2012

DEM with boring locations, Germany 2011-2012

Appendix A

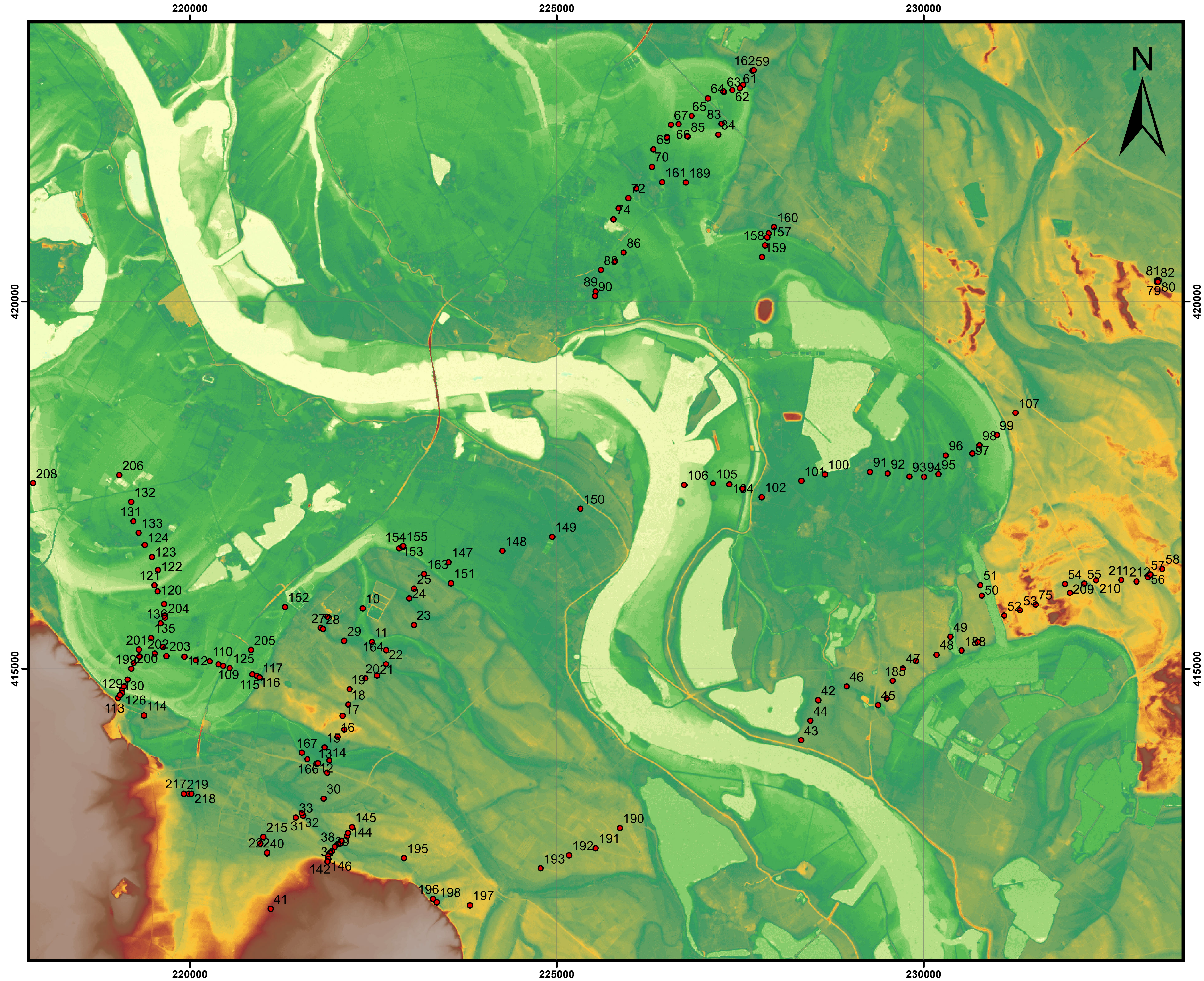


Source: see chapter 3

Early and Middle Holocene fluvial development near the present-day Rhine Delta apex, Germany.
B. van Munster - MSc research - Utrecht University - Faculty of Geosciences - Department of Physical Geography - 2011-2012

DEM with boring locations, Germany 2011-2012

Appendix A

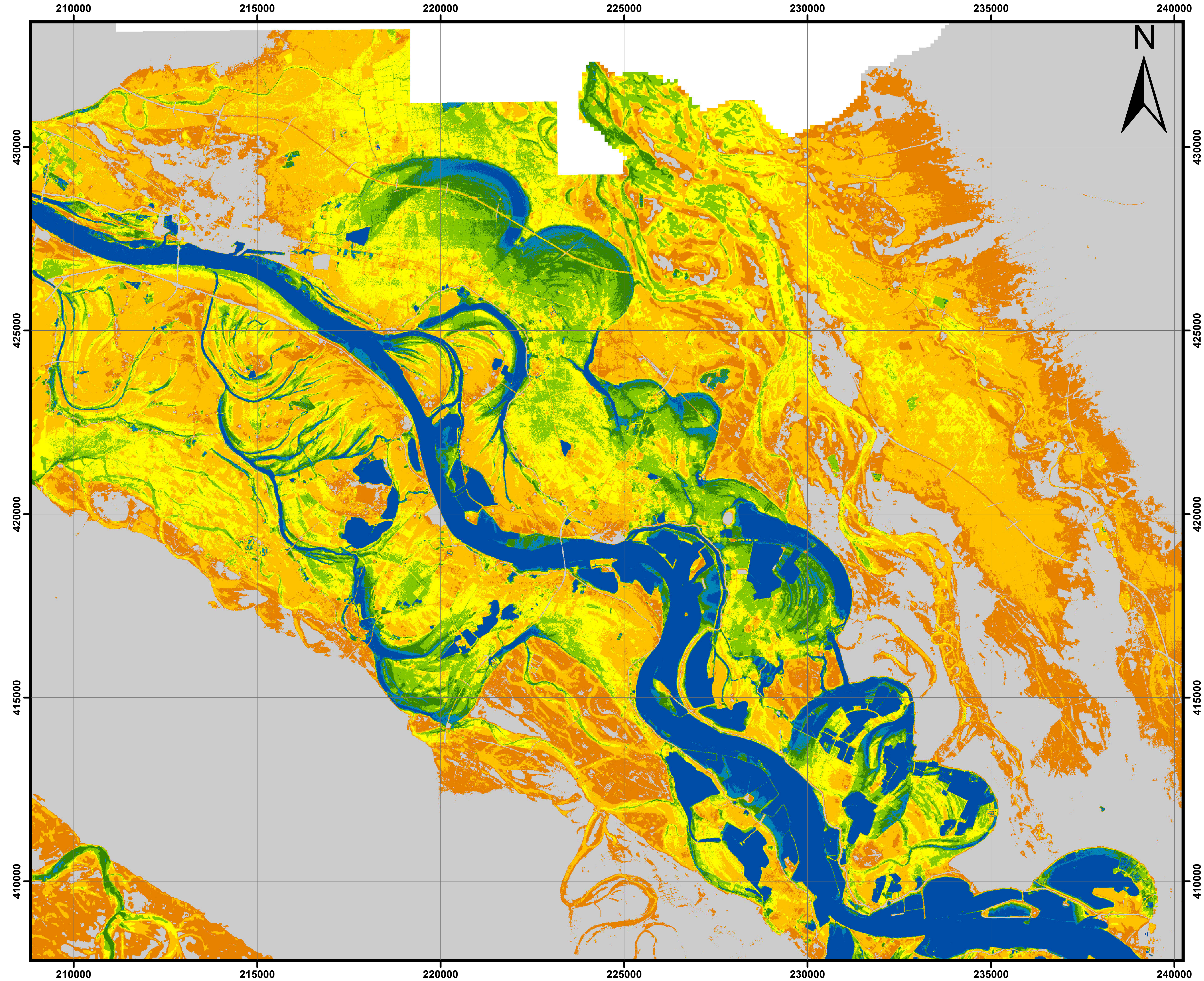


Source: see chapter 3

Early and Middle Holocene fluvial development near the present-day Rhine Delta apex, Germany.
B. van Munster - MSc research - Utrecht University - Faculty of Geosciences - Department of Physical Geography - 2011-2012

Relative DEM early Holocene, Germany 2011-2012

Appendix B



Depth to top of early Holocene deposits (m)

- < 0.0
- 0.0 - 0.5
- 0.5 - 1.0
- 1.0 - 1.5
- 1.5 - 2.0
- 2.0 - 3.0
- 3.0 - 4.0
- > 4.0

Height compared to the in-channel deposits of the Early Holocene river terrace.

0 m = The top of the Early Holocene in-channel deposits with an activity around 10 cal ka yr BP

Note that floodplain deposits overlay the in-channel deposits

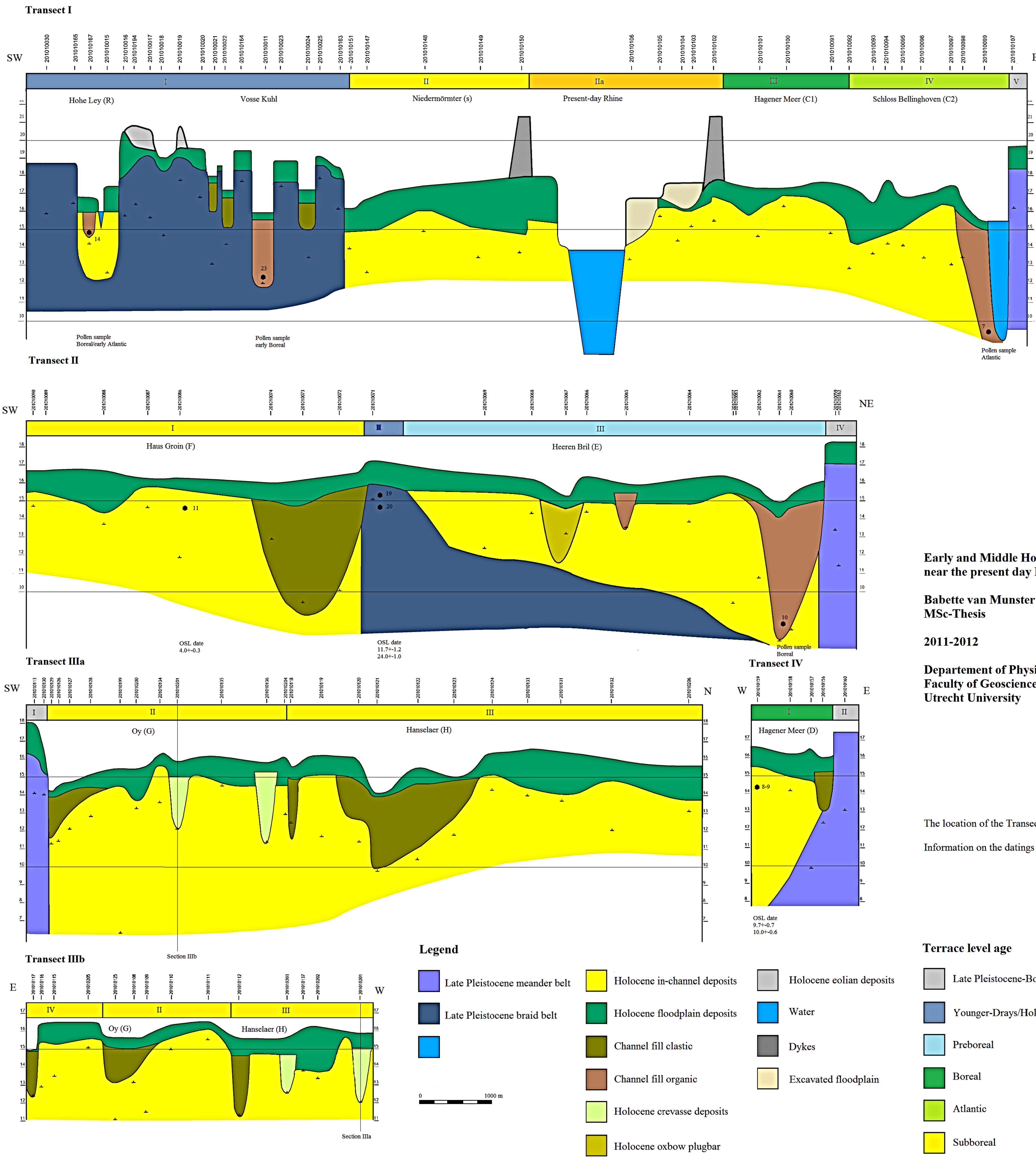
Source: see chapter 3

0 1,25 2,5 5 km

Early and Middle Holocene fluvial development near the present-day Rhine Delta apex, Germany.
B. van Munster - MSc research - Utrecht University - Faculty of Geosciences - Department of Physical Geography - 2011-2012

Transect I-IV Northern part Lower Rhine Embayment, Germany

Appendix C



Early and Middle Holocene fluvial development near the present day Rhine Delta apex, Germany

Babette van Munster
MSc-Thesis

2011-2012

Departement of Physical Geography
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Utrecht University

The location of the Transects is shown in Appendix E

Information on the datings is shown in Appendix F (date nr.)

Terrace level age

- Late Pleistocene-Bolling/Allerod
- Younger-Drays/Holocene transition
- Preboreal
- Boreal
- Atlantic
- Subboreal
- Subatlantic

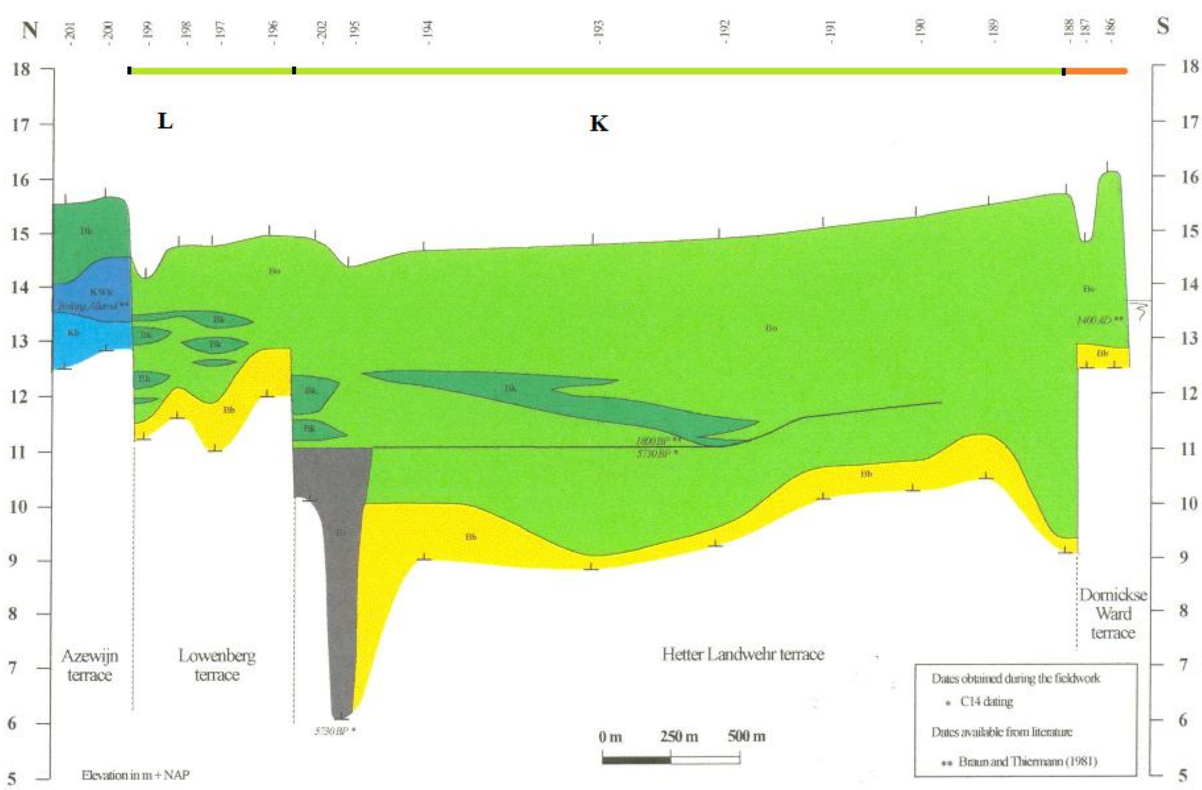
After Dingemans (2001).

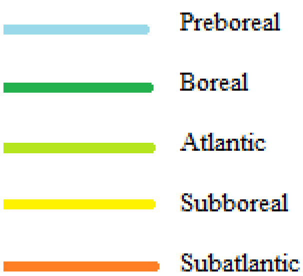
Appendix D

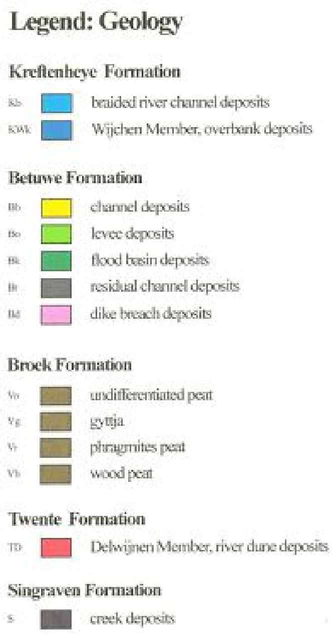
The location of the cross-sections in shown in Fig. 4.1

The coloured lines and letters at the top of the cross-sections show the palaeo-meanders that are identified for this thesis.

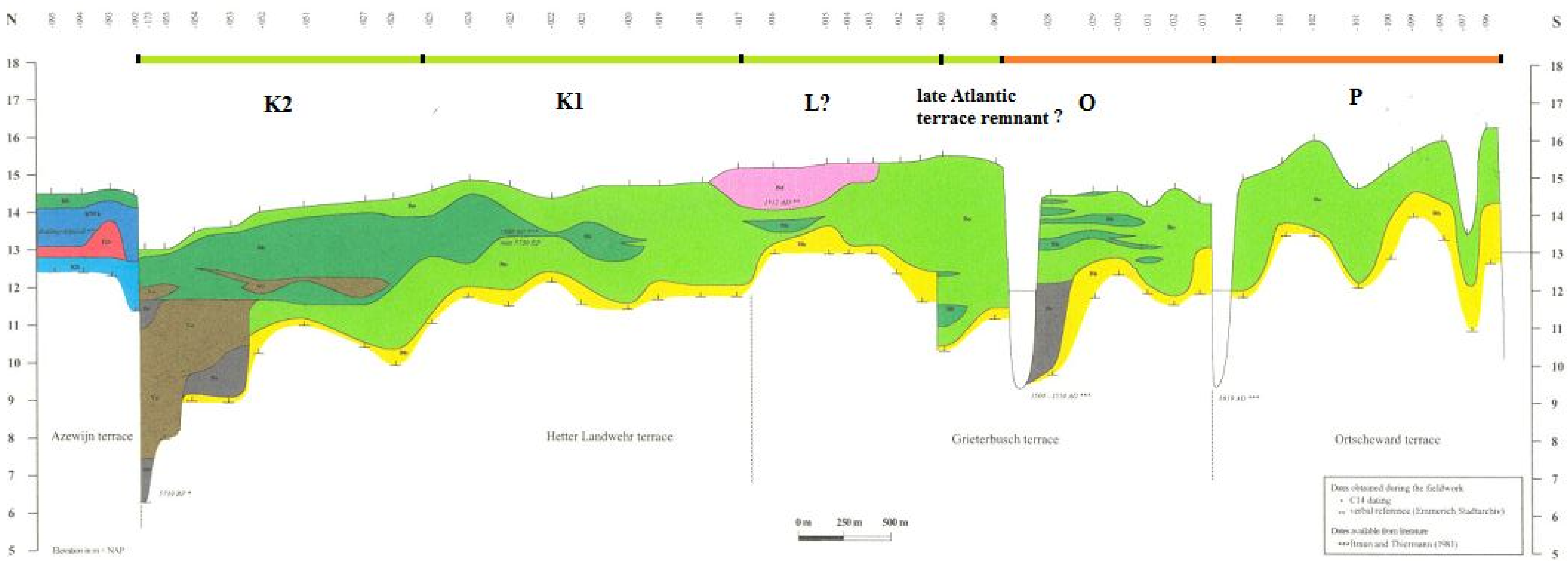
Cross-section 1: Geology from Klein Netterden to the Rhine



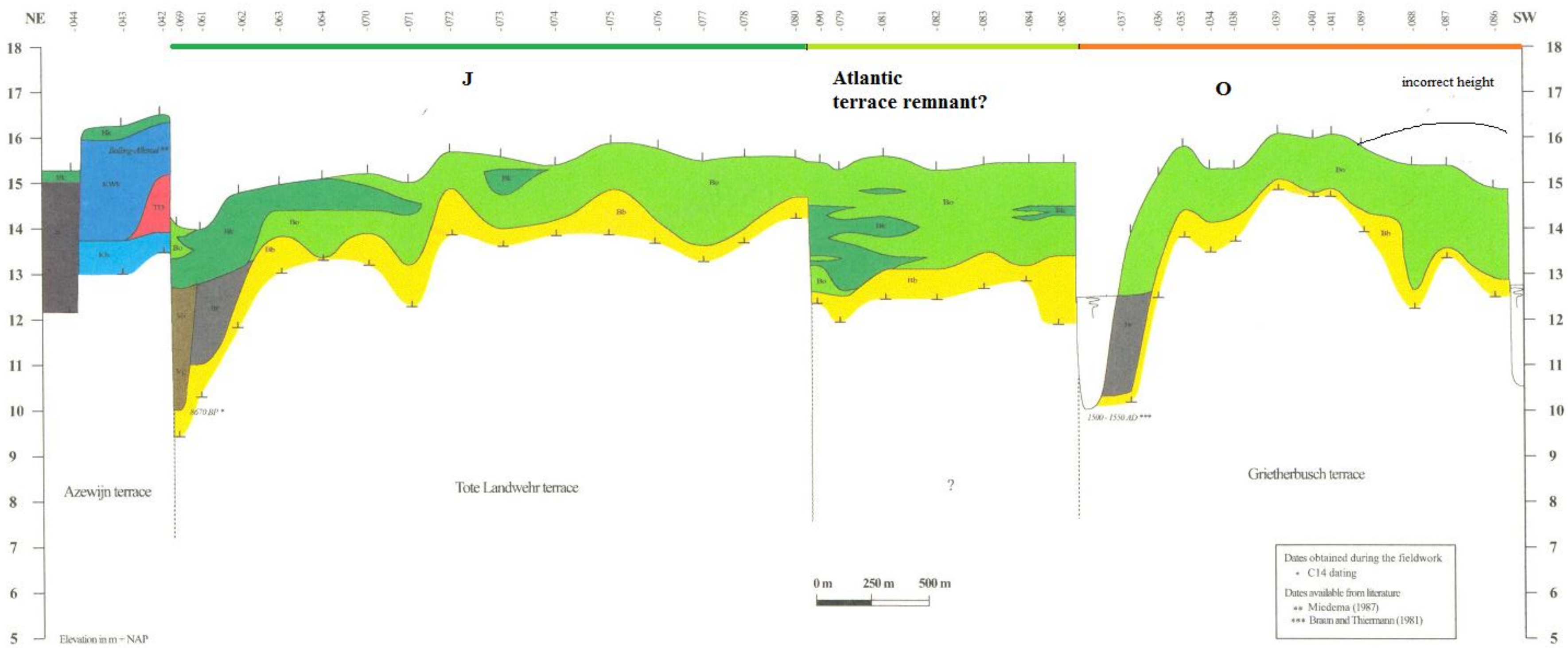




Cross-section 2: Geology from the Bergelandjes to the Rhine

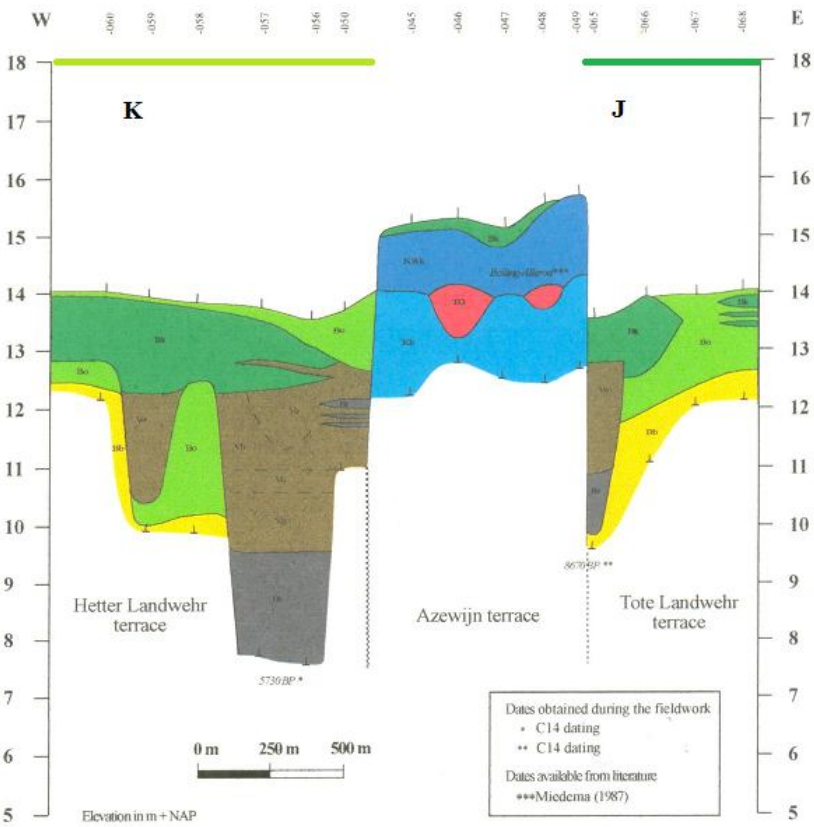


Cross-section 3: Geology from Megchelen to the Grietherorter Altrhein

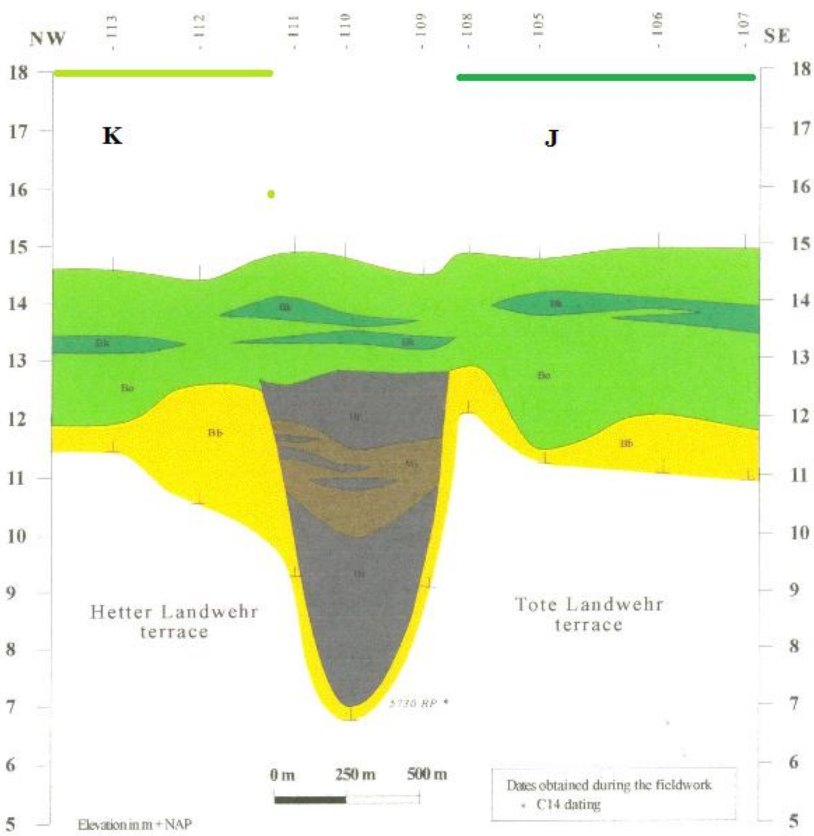


Cross-section 4: Geology from Millingen to the Biener Altrhein

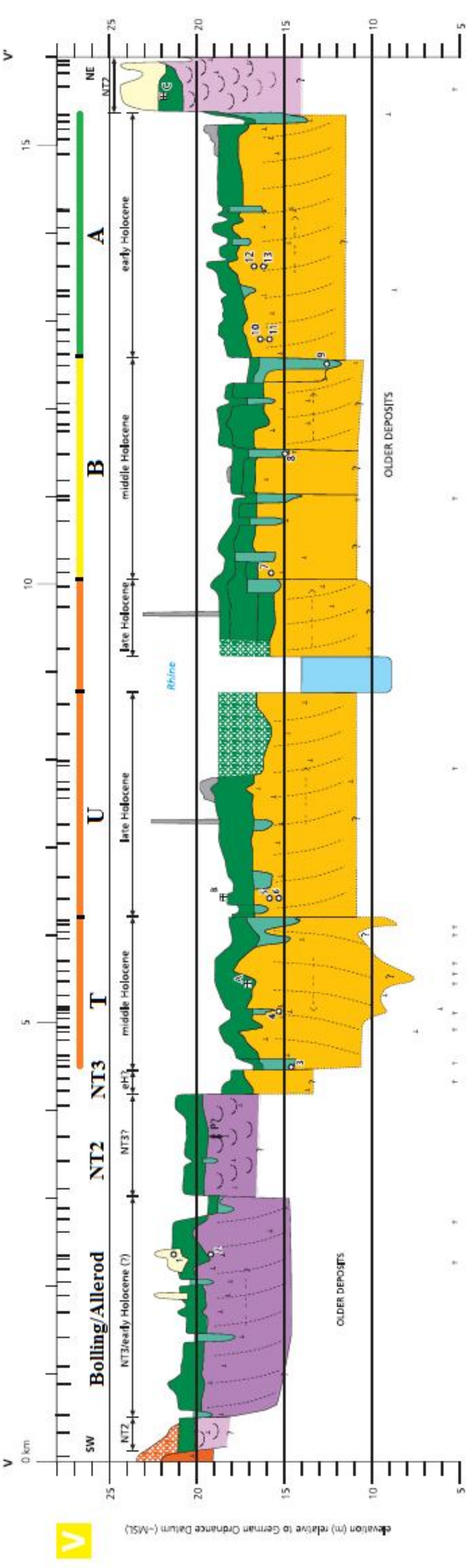
Cross-section 5: Geology from Feldkamp to Hollanderdeich



Cross-section 6: Geology from Meibaum to Hollanderdeich



Cross-section Erkens (2009)

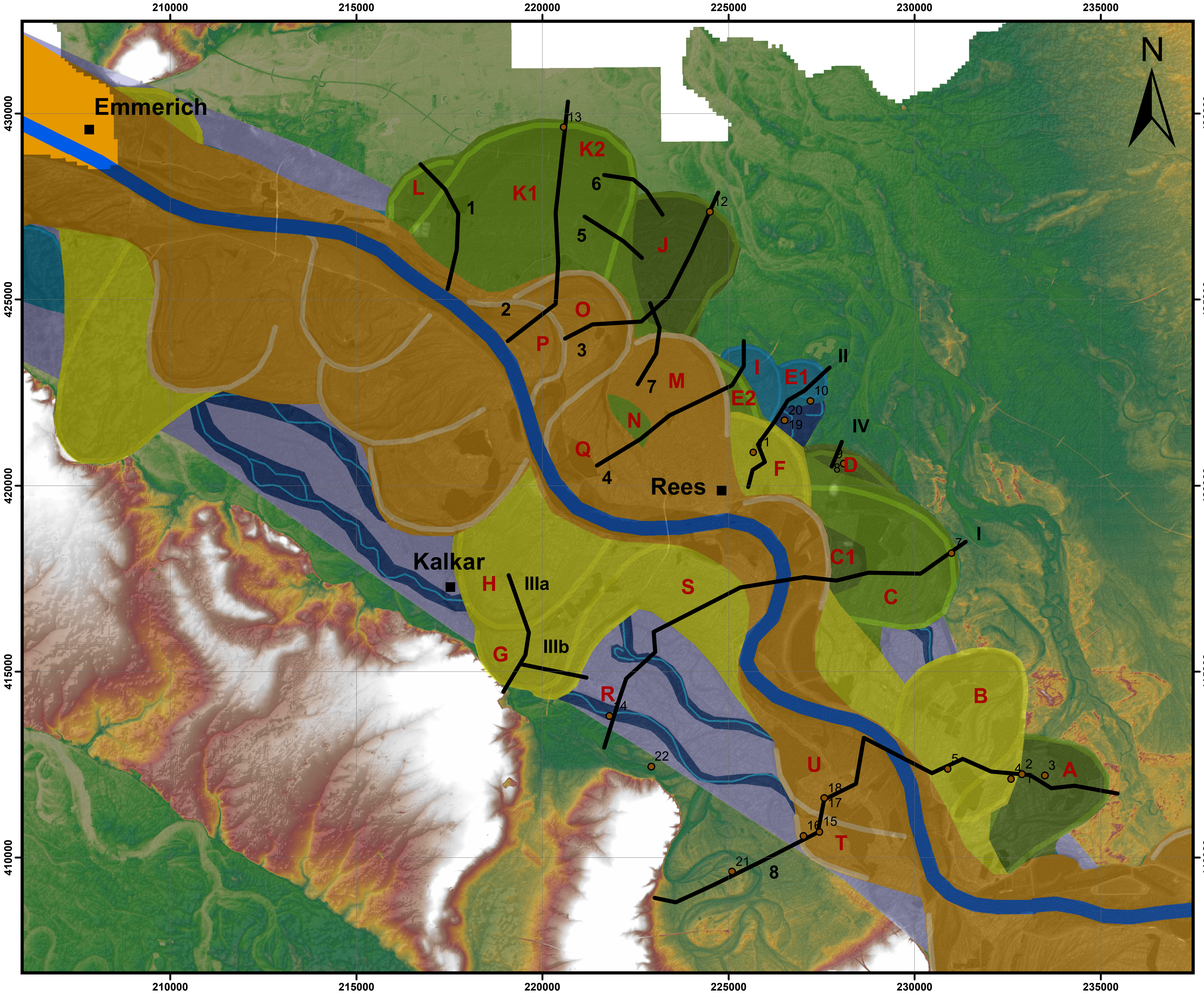


A) 2200 ± 50 (Klostermann, 1989; projected) ***2250***
B) Wardt church (~ 10th cent. A.D., Klostermann, 1989)
C) Allerød pollen spectrum (Jansen, 2001; projected)

1) ***11,720*** ± 520 (NCL-4506077)
2) ***10,910*** ± 570 (NCL-4506078)
3) 1570 ± 50 (UtC-15067) ***1450***
4) ***1920*** ± 90 (NCL-4506086)
5) ***1840*** ± 90 (NCL-4506081)
6) ***1810*** ± 120 (NCL-4506082)
7) ***3650*** ± 220 (NCL-4506085)
8) 3150 ± 45 (UtC-15063) ***3350***
9) 5101 ± 49 (UtC-15066) ***5750***
10) ***9540*** ± 500 (NCL-4506073)
11) ***10,190*** ± 530 (NCL-4506074)
12) ***9220*** ± 490 (NCL-4506075)
13) ***6630*** ± 440 (NCL-4506076)

Geological map Rhine Delta apex, Germany 2011-2012

Appendix E



Age of abandonment (cal ka BP)

- Subatlantic (2.6-present)
- Subboreal (5.7-2.6)
- Atlantic (8.7-5.7)
- Boreal (10.25-8.7)
- Preboreal (11.65-10.25)
- Earliest Holocene (ca. 11.65)
- Younger Dryas (ca. 12.5 ka)
- Present-day Rhine
- 106 m + MSL
- 8.0
- dating (see Appendix F)
- Cross-sections

Cross-sections:
1-7 : Favier, Dingemans (2001)
8: Erkens et al. (2011)
I-IV: this study (2012)

A-T: palaeo-meanders
see also Appendix F

Source: see chapter 3

0 1,25 2,5 5 km

Holocene river terraces and fluvial development near the apex of the Rhine delta, Germany.
B. van Munster - MSc research - Utrecht University - Faculty of Geosciences - Department of Physical Geography 2011-2012

Meander	Name	B&S 2001	Min. Height	Max. height	Mean height	Distance	Estimated Activity	dates (age ka)	14C	Discription
A	Diersfordt		17 m +msl	18.2 m +msl	17.3 m +msl	0 km	10.2-8.7 cal ka	9.54 +-0.50		innerbend OSL (NCL-4506073)
								10.19 +-0.53		innerbend OSL (NCL-4506074)
								9.22 +-0.49		half way meander OSL (NCL-4506075)
B	Bislicher Meer		15.8	16.8	16.5	3.77	5.8-3.4	5.75 cal		outher most channel fill 1st fase 14C (UtC-15066)
								3.65 +-0.22		inner point bar OSL (NCL-4506085)
								3.35 cal		filling larger abandoned channel 14C (UtC-15063)
C1	remnant Hagener Meer (D)		14.8	16.1	15.6	6.82	10.7-9.7			
C2	Schloss Bellinghoven		13.1	14.6	13.8	6.82	7.3-6.3	8.7-5.7 cal		pollen analyses residual channel
D	Hagener Meer		14.6	15.5	15	10.48	10.7-9.7	9.7 +-0.7		end point bar OSL (Risø-33153)
								10.0 +-0.6		end point bar OSL (Risø-33154)
								Neolitic		Historical findings
E	Heeren Brill		14.8	15.5	15	12.77	11.6-10.8	8.5 cal		pollen analyses residual channel
								7.888 +-0.032 cal	7.020 +-0.05 14C	0.5 m above channel sand 14C (UtC-09542)
E2	Lohbrink	509	13.4	14	14	13.98	8.7-7.7			
F	Haus Groin/Smales Meer	515	14.3	15.8	15.4	13	5.0-4.0	4.0 +- 0.3		end point bar OSL (Risø-33155)
								Bronze/Iron age	2800 14C	Historical findings
G	Oy		13.5	15.9	14.8	13.42	5.5-4.5	? >H		
H	Hanselaer		13.7	15.1	14.5	15.27	5.2-4.2	? <G		
I	Haspelweide		14.3	15.1	14.8	14.33	10.8-10.0			
J	Tote Landwehr	517	13.3	14.8	14	17.31	10.6-9.6	9.587 +- 0.019 cal	8.670 +-0.06 14C	residual channel 14C (UtC-09540)
K1	Hetter Landwehr	506	11.6	12.3	12	20.97	8.5-7.5	6.521 +-0.016 cal	5.734 +-0.043 14C	residual channel 1m above channel sand 14C (UtC-09541)
								early Atlantic		pollen analysis
K2			10.4	12.3	11.3	20.97	7.5-6.5			
L	Lowenberg	510	11.8	12.8	12.4	23.49	9.0-8.0			
M	Speldrop	516	13.3	15.2	14.8	15.8	2.5-1.5	< Bronze age		Historical findings
N	Esserden	504	11.5	12	11.8	16.28	6.7-5.7			
O	Grietherbusch	505	13.7	15	14.5	18.03	1.4-0.4	1300-1550 AD / 650-400 BP		Historical maps, Literature
P	Ortscheward	511	12	14.3	14.3	19.13	0.4-0.1	1588-1822 AD / 362-128 BP		Literature
								1600-1850 AD		Historical maps
								16th century		Archeological artifacts
Q	Reeserward		13.7	14.8	14.3	16.7	1.4-0.4	1250-1550 AD / 700-400 BP		Historical maps & documents
R	Hohe ley				15.6	10.7	12.0-11.65	8.8 cal		pollen analysis residual channel
S	inner bend Rhine		14.3	15.5	14.8	10.3	5.5-4.5			
T	Xanten I		16.2	17.9	16.8	5.1	2.5-1.5	1.920 +-0.090 / 80 AD		half way meander OSL (NCL-4506086)
								2250 cal	2.200 +-0.050 14C	tree trunk under floodplain
								1450 cal / 500 AD	1.570 +-0.050 14C	Abandoned channel fill (UtC-15067)
U	Xanten II		16.6	17.3	16.8	3.77	1.8-0.8	1.840+-0.090 / 200 AD		inner bend OSL (NCL-4506081)
								1.810+-0.120 / 200 AD		inner bend OSL (NCL-4506082) (less reliable)
BD1	Braided deposits 1		17.3	18.9	18	10.9				
BD2	Braided deposits 2				18.4	6.82				
BD3	Braided deposits 3				15.9	12.77				
All1	Bølling/Allerød meander				17.2	12.77				
All2	Bølling/Allerød meander				16.8	10.48				
All3	Bølling/Allerød meander				18.1	6.82				
All4	Bølling/Allerød meander				16.5	14.33				
	Earliest Holocene							11.7 +-1.2		(Risø-33151)
	NT2							24 +-1.0		(Risø-33152)
	Bølling/Allerød meander							10.91 +-0.570		(NCL-4506078)
	NT2							15.1 +-0.910		Risø-33129
	Vosse Kuhl							early Boreal		

radiocarbon date
pollen analyses
literature

OSL date

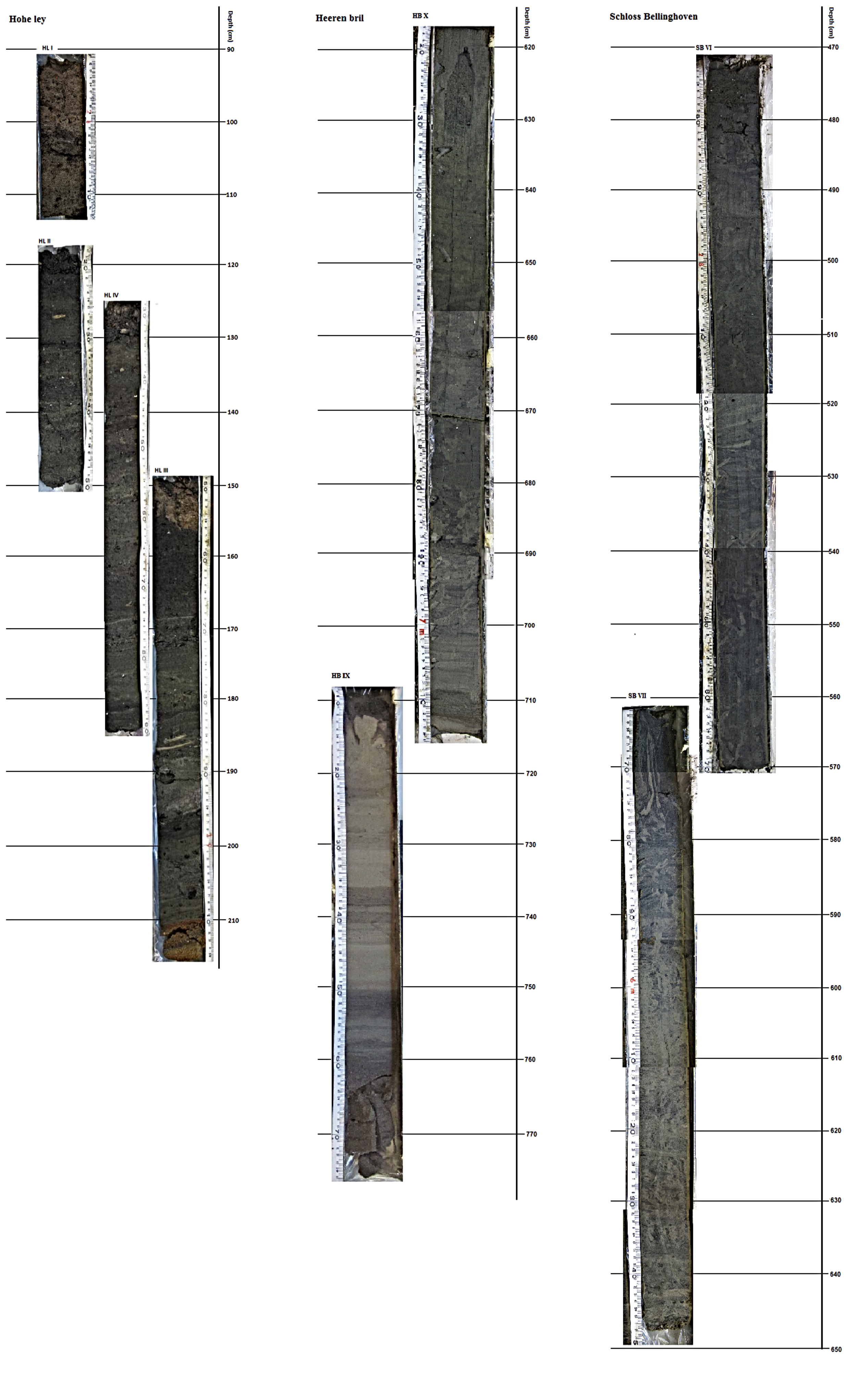
Appendix F

Meander	Name	Source	x coordinate date	y coordinate date	Depth date (m + MSL)	date nr.
A	Diersfordt	Erkens, 2009; Erkens et al., 2011	232886	412239	16.25	1
		Erkens, 2009; Erkens et al., 2011	232886	412239	16.58	2
		Erkens, 2009; Erkens et al., 2011	233503	412207	16.15	3
B	Bislicher Meer	Erkens, 2009; Erkens et al., 2011	232599	412115	12.67	4
		Erkens, 2009; Erkens et al., 2011	230890	412381	15.9	5
		Erkens, 2009; Erkens et al., 2011	232121	412289	14.98	6
C1	remnant Hagener Meer (D)					
C2	Schloss Bellinghoven	Munster, 2011	230999	418178	8.6-10.3	7
D	Hagener Meer	Tebbens, Schirmer, Berendsen (unpublished)	228099	420580	14.25	8
		Tebbens, Schirmer, Berendsen (unpublished)	228099	420580	14.25	9
		Dingemans, 2001 (Brunnacker 1978)				
E	Heeren Brill	Munster, 2011	227205	422269	7.6-9	10
		Berendsen, V. Ree in Berendsen & Stouthamer, 2001	227475	422980		
E2	Lohbrink					
F	Haus Groin/Smales Meer	Tebbens, Schirmer, Berendsen (unpublished)	225670	420887	14.75	11
		Dingemans 2001 (Brunnacker 1978)				
G	Oy	Munster, 2011				
H	Hanselaer	Munster, 2011				
I	Haspelweide					
J	Tote Landwehr	Berendsen, V. Ree in Berendsen & Stouthamer, 2001	224505	427355		12
K1	Hetter Landwehr	Berendsen, V. Ree in Berendsen & Stouthamer, 2001	220575	429625		13
		Dingemans, 2001 (Braun & Lange 1981)				
K2						
L	Lowenberg	Dingemans, 2001				
M	Speldrop	Dingemans, 2001				
N	Esserden	Dingemans, 2001				
O	Grietherbusch	Dingemans, 2001 (Lange, 1978; Braun & Lange 1981)				
P	Ortscheward	Dingemans, 2000 (Braun & Lange, 1981)				
		Dingemans, 2001				
		Dingemans, 2001 (pers. comm. Schirmer)				
Q	Reeserward	Dingemans, 2001 (Lange, 1978)				
R	Hohe ley	Munster, 2011	221716	413706	14.4-15.5	14
S	inner bend Rhine					
T	Xanten I	Erkens et al., 2011.	227444	410692	15.3	15
		Klostermann 1989 (in Erkens et al., 2011)				
		Erkens et al., 2011.	227014	410585	14.53	16
U	Xanten II	Erkens et al., 2011.	227574	411593	15.9	17
		Erkens et al., 2011.	227574	411593	15.5	18
BD1	Braided deposits 1					
BD2	Braided deposits 2					
BD3	Braided deposits 3					
All1	Bølling/Allerød meander					
All2	Bølling/Allerød meander					
All3	Bølling/Allerød meander					
All4	Bølling/Allerød meander					
	Earliest Holocene	Erkens, 2009; Erkens et al., 2011	226250	421558	15.4	19
	NT2	Erkens, 2009; Erkens et al., 2011	226250	421558	14.5	20
	Bølling/Allerød meander	Erkens, 2009; see Geurts 2011	225098	409624	19.3	21
	NT2	Erkens, 2009; see Geurts 2011	222922	412447	19.7	22
	Vosse Kuhl	analysed by Geurts, 2011				23

Meander		**coring**	**Sand h msl**	**fp d**	**Rel h surf**	**Rel h sand**	
A	max	V-V' (Erkens,2009)	18.2	1	2	1	
	min	V-V' (Erkens,2009)	17	1.4	1	-0.4	
	mean		17.3	1	1	0	
B	max	V-V' (Erkens,2009)	16.8	2	1.5	-0.5	
	min	V-V' (Erkens,2009)	15.8	3	1.5	-1.5	
	mean		16.5	2.3	1.5	-0.8	
C1	max	100	16.1	0.9	1.3	0.4	
	min	101	14.8	2.2	1.3	-0.9	
	mean		15.6	1.4	1.3	-0.1	
C2	max	97	14.6	2.6	1.1	-1.5	
	min	96	13.1	3.5	0.4	-3.1	
	mean		13.8	2.8	0.4	-2.4	
D	max	159	15.5	1.1	1.3	0.2	
	min	157	14.6	1.9	1.1	-0.8	
	mean		15	1.5	1.1	-0.4	
E	max	69	15.5	0.9	1.5	0.6	
	min	64	14.8	1.4	1.4	0	
	mean		15	1.2	1.4	0.2	
E2	max	199890124	14	1.4	0.5	-0.9	
	min	199890123	13.4	2	0.6	-1.4	
	mean		14	2	0.6	-1.4	
F	max	87	15.8	0.4	1.2	0.8	
	min	88	14.3	2.4	1.6	-0.8	
	mean		15.4	1.3	1.6	0.3	
J	max	199890072	14.8	0.8	1.5	0.7	
	min	199890071	13.3	1.9	1	-0.9	
	mean		14	1	1	0	
K1	max	199890022	12.3	2	1.2	-0.8	
	min	199890020	11.6	3.2	1.6	-1.6	
	mean		12	2.8	1.6	-1.2	
K2	max	199890051	11.2	3	0.7	-2.3	
	min	199890026	10.4	4	1.4	-2.6	
	mean		10.8	3.5	1.4	-2.1	
G	max	111	15.9	0.6	1.7	1.1	
	min	200	13.5	1.9	0.8	-1.1	
	mean		14.8	0.6	0.8	0.2	
H	max	124	15.1	1.2	1.8	0.6	
	min	206	13.7	1.9	1.3	-0.6	
	mean		14.5	1.6	1.3	-0.3	
I	max	199890119	15.1	1.1	1.4	0.3	
	min	199890118	14.3	1.5	1.1	-0.4	
	mean		14.8	1	1.1	0.1	
L	max	199890196	12.8	2.2	2	-0.2	
	min	199890197	11.8	2.8	1.5	-1.3	
	mean		12.4	2.3	1.5	-0.8	
M	max	199890126	15.2	1	1.5	0.5	Height coring 126 incorrect, estimated.
	min	199890129	13.3	3	1.5	-1.5	
	mean		14.8	1.4	1.5	0.1	
N	max	199890134	12	4.2	1.9	-2.3	
	min	199890133	11.5	4.8	1.9	-2.9	
	mean		11.8	4.5	1.9	-2.6	
O	max	199890039	15	1	2.2	1.2	
	min	199890088	13.7	2.8	2.6	-0.2	Height of coring 199890089,088,087, 086
	mean		14.5	2.1	2.6	0.5	around 1 m to low!
P	max	199890096	14.3	2	3.3	1.3	
	min	199890101	12	2.5	2	-0.5	
	mean		14.3	0.7	2	1.3	
Q	max	199890146	14.8	2.4	2.8	0.4	
	min	199890141	13.7	2.8	2	-0.8	
	mean		14.3	2.2	2	-0.2	
R	mean	15	15.6	1.5	2	0.5	
S	max	148	15.5	1.6	1.7	0.1	
	min	150	14.3	3.4	2.4	-1	
	mean		14.8	2.9	2.4	-0.5	
T	max	V-V' (Erkens,2009)	17.9	1.1	1.8	0.7	
	min	V-V' (Erkens,2009)	16.2	2.3	1.8	-0.5	
	mean		16.8	1.8	1.8	0	
U	max	V-V' (Erkens,2009)	17.3	2.8	3.4	0.6	height not very reliable!
	min	V-V' (Erkens,2009)	16.6	1.3	1.6	0.3	
	mean		16.8	1.3	1.6	0.3	
Allerod1		162	17.2	1.1	3.2	2.1	
Allerod2		160	16.8	0.6	2.2	1.6	
Allerod3		107	18.1	1.3	3.8	2.5	

mean relative height sand has been calculated with the floodplain deposits at the location of the min coring with the mean estimated height.

Appendix G



Hohe ley
HL I
HL II
HL IV
HL III
Heeren bril
HB X
HB IX
Schloss Bellinghoven
SB VI
SB VII
Depth (cm)

Heeren Brill (HB) Core Discription, pollen samples & LOI (M.M. de Molenaar, 2011)

diepte = onderzijde van het monster (oftwel 87 cm betekent monster 86-87 cm)
LOI = (Wd-Wg)/(Wd-Wb)*100%
Wb = gewicht lege gloeischaal empty
Wn = gewicht gloeischaal + natte grond
Wd = gewicht gloeischaal + droge grond dried
Wg = gewicht gloeischaal + gegloeide grond ashed (4 uur op 550 graden)
Gd = gewicht droge grond
Gg = gewicht gegloeide grond

- Clay (Loam)
- Sandy clay loam
- Peat, clastic peat, strong clastic peat
- Gyttja
- sand

Core	Number	depth [cm]	Pollen sample	Wb [g]	Wn [g]	Wd [g]	Wg [g]	Gd [g]	Gg [g]	Vocht [%]	LOI [%]	Description	Color	Remarks
HBX	1	775		7.982	9.469	9.168	9.16	1.186	1.178	20.242	0.674536256	sand	gray	Sand (210-300um) containing some black grains.
	2	773		8.368	10.649	10.192	10.186	1.824	1.818	20.035	0.328947368	sand	gray	Sand (210-300um) containing some black grains. Black layer (3mm)
	3	771		8.193	10.737	10.233	10.222	2.04	2.029	19.811	0.539215686	sand	gray	Sand (210-300um) containing some black grains. Black layer (3mm)
	4	769		8.369	10.23	9.874	9.867	1.505	1.498	19.130	0.465116279	sand	gray	Sand (210-300um) containing some black grains.
	5	767		14.141	15.985	15.647	15.635	1.506	1.494	18.330	0.796812749	sand	gray	Sand (210-300um) containing some black grains.
	6	765	1990	8.528	10.7	10.285	10.269	1.757	1.741	19.107	0.910643142	sand	gray	Sand (210-300um) containing some black grains.
	7	763		8.624	11.882	11.258	11.231	2.634	2.607	19.153	1.025056948	sand	gray	Sand (210-300um) containing some black grains.
	8	761		7.727	8.351	8.237	8.234	0.51	0.507	18.269	0.588235294	sand	gray	Sand (210-300um) containing some black grains.
	9	760		6.823	7.956	7.738	7.716	0.915	0.893	19.241	2.404371585	sand	gray	Sand (210-300um) containing some black grains.
	10	759	1984	17.318	18.593	18.3	18.264	0.982	0.946	22.980	3.66598778	clay	gray	Unstructured mixture of sand and clay
	11	758		7.088	8.305	8.012	7.977	0.924	0.889	24.076	3.787878788	clay	gray	sandy layer
	12	757		7.765	9.45	9.117	9.084	1.352	1.319	19.763	2.440828402	clay	gray	clay layer
	13	756		8.194	10.143	9.608	9.542	1.414	1.348	27.450	4.667609618	clay	gray	Darker colored clay layer 7mm
	14	755	1980	7.89	8.687	8.462	8.432	0.572	0.542	28.231	5.244755245	clay	gray	1cm clay layer
	15	754		14.652	16.068	15.645	15.59	0.993	0.938	29.873	5.5387714	sand	gray	darker colored
	16	753		8.042	9.428	8.966	8.916	0.924	0.874	33.333	5.411255411	sand	gray	darker colored
	17	752		7.666	8.716	8.438	8.408	0.772	0.742	26.476	3.886010363	clay	gray	darker colored
	18	751		7.814	9.511	9.101	9.062	1.287	1.248	24.160	3.03030303	clay	gray	darker colored
	19	750		8.215	9.811	9.317	9.263	1.102	1.048	30.952	4.900181488	clay	gray	Lighter colored clay. Containing poorly visible layers with a thickness of mm's.
	20	749	1974	15.559	16.664	16.297	16.25	0.738	0.691	33.213	6.368563686	clay	gray	Lighter colored clay. Containing poorly visible layers with a thickness of mm's.
	21	748		7.825	8.619	8.358	8.336	0.533	0.511	32.872	4.127579737	clay	gray	Lighter colored clay. Containing poorly visible layers with a thickness of mm's.
	22	747		7.817	8.917	8.557	8.523	0.74	0.706	32.727	4.594594595	clay	gray	Lighter colored clay. Containing poorly visible layers with a thickness of mm's.
	23	746		8.447	9.575	9.203	9.169	0.756	0.722	32.979	4.497354497	clay	gray	Lighter colored clay. Containing poorly visible layers with a thickness of mm's.
	24	745	1970	8.341	9.437	9.07	9.032	0.729	0.691	33.485	5.212620027	clay	gray	Lighter colored clay. Containing poorly visible layers with a thickness of mm's.
	25	744		16.625	17.723	17.354	17.318	0.729	0.693	33.607	4.938271605	clay	gray	Darker colored
	26	743		8.488	9.8	9.368	9.331	0.88	0.843	32.927	4.204545455	clay	gray	Darker colored
	27	742		7.958	9.397	8.958	8.92	1	0.962	30.507	3.8	clay	gray	Darker colored. Sandy layer 2mm
	28	741		7.702	9.363	8.882	8.845	1.18	1.143	28.958	3.13559322	clay with sand	gray	Darker colored
	29	740	1965	7.634	9.738	9.172	9.132	1.538	1.498	26.901	2.600780234	clay with sand	gray	Darker colored
	30	739		8.227	10.008	9.476	9.432	1.249	1.205	29.871	3.522818255	clay	gray	Darker colored. Lighter colored clay layer 5mm
	31	738		8.164	9.275	8.93	8.903	0.766	0.739	31.053	3.524804178	clay with sand	gray	Darker colored
	32	737		7.617	8.997	8.57	8.534	0.953	0.917	30.942	3.777544596	clay with sand	gray	Darker colored
	33	736		8.585	9.874	9.457	9.422	0.872	0.837	32.351	4.013761468	clay	light gray	
	34	735	1960	8.073	8.779	8.549	8.532	0.476	0.459	32.578	3.571428571	clay	light gray	
	35	734		7.679	8.925	8.525	8.492	0.846	0.813	32.103	3.90070922	clay	light gray	
	36	733		8.33	9.644	9.223	9.19	0.893	0.860	32.040	3.695408735	clay	light gray	
	37	732		8.374	9.824	9.349	9.311	0.975	0.937	32.759	3.897435897	clay	light gray	slightly darker colored clay layer 2mm
	38	731	1956	7.317	8.456	8.127	8.102	0.81	0.785	28.885	3.086419753	clay	light gray	
	39	730		7.977	9.497	9.037	8.999	1.06	1.022	30.263	3.58490566	clay	gray	slightly darker colored, layered profile (mm's) of sand and clay layers
	40	729		8.432	9.53	9.218	9.194	0.786	0.762	28.415	3.053435115	clay	gray	slightly darker colored, layered profile (mm's) of sand and clay layers
	41	728		7.975	8.479	8.327	8.31	0.352	0.335	30.159	4.829545455	clay	gray	Fairly homogeneous, slightly organic. Some small (<1mm) plant remains
	42	727		7.92	9.016	8.683	8.657	0.763	0.737	30.383	3.407601573	clay	gray	Fairly homogeneous, slightly organic. Some small (<1mm) plant remains
	43	726		8.081	8.99	8.702	8.676	0.621	0.595	31.683	4.186795491	clay	gray	Fairly homogeneous, slightly organic. Some small (<1mm) plant remains
	44	725	1950	8.206	8.966	8.736	8.714	0.53	0.508	30.263	4.150943396	clay	gray	Fairly homogeneous, slightly organic. Some small (<1mm) plant remains
	45	724		8.529	9.658	9.308	9.275	0.779	0.746	31.001	4.236200257	clay	gray	darker in color, organic clay.
	46	723		8.289	8.962	8.759	8.741	0.47	0.452	30.163	3.829787234	clay	gray	darker in color, organic clay.
	47	722		8.324	9.33	9.024	8.998	0.7	0.674	30.417	3.714285714	clay	gray	reasanobly homogeneous. No layering, some stains. Possibly not in situ (naval)
	48	721		7.997	9.082	8.742	8.711	0.745	0.714	31.336	4.161073826	clay	gray	reasanobly homogeneous. No layering, some stains. Possibly not in situ (naval)
	49	720	1945	8.071	8.874	8.623	8.604	0.552	0.533	31.258	3.442028986	clay	gray	reasanobly homogeneous. No layering, some stains. Possibly not in situ (naval)
	50	719		8.323	9.13	8.877	8.859	0.554	0.536	31.351	3.249097473	clay	gray	reasanobly homogeneous. No layering, some stains. Possibly not in situ (naval)
	51	718		8.091	9.048	8.746	8.716	0.655	0.625	31.557	4.580152672	clay	gray	reasanobly homogeneous. No layering, some stains. Possibly not in situ (naval)
	52	717		7.839	8.822	8.498	8.469	0.659	0.630	32.960	4.40060698	clay	gray	reasanobly homogeneous. No layering, some stains. Possibly not in situ (naval)
	53	716	1940	11.471	12.603	12.176	12.133	0.705	0.662	37.721	6.09929078	clay	gray	reasanobly homogeneous. No layering, some stains. Possibly not in situ (naval)
HB IX	54	715	1939	8.186	8.861	8.655	8.633	0.469	0.447	30.519	4.690831557	clay	gray	laminated in layers from mm's up to 0.5cm
	55	714		8.067	8.868	8.631	8.608	0.564	0.541	29.588	4.078014184	clay with sand	gray	laminated in layers from mm's up to 0.5cm
	56	713		7.957	8.688	8.504	8.491	0.547	0.534	25.171	2.376599634	clay with sand	gray	laminated in layers from mm's up to 0.5cm
	57	712		8.084	9.305	9.011	8.989	0.927	0.905	24.079	2.373247033	clay with sand	gray	laminated in layers from mm's up to 0.5cm
	58	711		8.199	9.134	8.886	8.866	0.687	0.667	26.524	2.911208151	clay with sand	gray	laminated in layers from mm's up to 0.5cm
	59	710		7.684	8.391	8.168	8.15	0.484	0.466	31.542	3.719008264	clay with sand	gray	laminated in layers from mm's up to 0.5cm. Layer with plant remains ~0.6cm.
	60	709	1933	8.163	9.207	8.868	8.837	0.705	0.674	32.471	4.397163121	clay	gray	laminated in layers from mm's up to 0.5cm
	61	708		8.03	9.353	8.896	8.857	0.866	0.827	34.543	4.503464203	clay	gray	laminated in layers from mm's up to 0.5cm
	62	707		8.027	8.905	8.602	8.575	0.575	0.548	34.510	4.695652174	clay	gray	laminated in layers from mm's up to 0.5cm
	63	706		8.052	8.7	8.476	8.455	0.424	0.403	34.568	4.952830189	clay	gray	laminated in layers from mm's up to 0.5cm. Blackish layer ~0.6cm
	64	705	1929	7.863	9.032	8.628	8.594	0.765	0.731	34.559	4.444444444	clay	gray	laminated in layers from mm's up to 0.5cm. Gray-browish layer ~0.4cm
	65	704		8.16	9.122	8.773	8.74	0.613	0.580	36.279	5.383360522	clay	gray	laminated in layers from mm's up to 0.5cm. Blackish layer ~0.2cm.
	66	703		8.206	8.813	8.581	8.563	0.375	0.357	38.221	4.8	clay	gray	laminated in layers from mm's up to 0.5cm. Brownish layer ~0.5cm.
	67	702		8.053	8.692	8.444	8.424	0.391	0.371	38.811	5.115089514	clay	gray	laminated in layers from mm's up to 0.5cm
	68	701		7.656	8.525	8.185	8.156	0.529	0.500	39.125	5.482041588	clay	gray	light bioturbation. Core broken.

69	700	1924	8.327	9.004	8.732	8.709	0.405	0.382	40.177	5.679012346	clay	gray	light bioturbation
70	699		8.479	9.184	8.892	8.869	0.413	0.390	41.418	5.569007264	clay	gray	light bioturbation
71	698		8.029	8.569	8.353	8.335	0.324	0.306	40.000	5.555555556	clay	gray	light bioturbation
72	697		7.959	8.534	8.288	8.266	0.329	0.307	42.783	6.686930091	clay	gray	light bioturbation
73	696		7.85	8.609	8.264	8.239	0.414	0.389	45.455	6.038647343	clay	gray	light bioturbation
74	695	1919	7.77	8.524	8.215	8.189	0.445	0.419	40.981	5.842696629	clay	gray	light bioturbation
75	694		8.123	8.664	8.418	8.4	0.295	0.277	45.471	6.101694915	clay	gray	light bioturbation. Contains some plant fragments
76	693		8.121	8.767	8.46	8.441	0.339	0.320	47.523	5.604719764	clay	gray	light bioturbation. Contains some plant fragments
77	692		8.156	8.807	8.511	8.488	0.355	0.332	45.469	6.478873239	clay	gray	light bioturbation. Contains some plant fragments
78	691		8.136	8.641	8.394	8.378	0.258	0.242	48.911	6.201550388	clay	gray	light bioturbation. Contains some plant fragments
79	690	1914	8.511	9.602	9.058	9.014	0.547	0.503	49.863	8.043875686	clay	gray	light bioturbation. Contains some plant fragments
80	688		15.451	16.869	16.106	16.052	0.655	0.601	53.808	8.244274809	clay	gray	Strong bioturbation. Anoxic stains. Contains some plant fragments
81	686		8.005	9.94	8.907	8.835	0.902	0.830	53.385	7.982261641	clay	gray	Strong bioturbation. Anoxic stains. Contains some plant fragments
82	684	1909 (685cm)	15.534	16.882	16.148	16.095	0.614	0.561	54.451	8.631921824	clay	gray	Strong bioturbation. Anoxic stains. Contains some plant fragments
83	682		8.153	9.144	8.609	8.568	0.456	0.415	53.986	8.99122807	clay	gray	Strong bioturbation. Anoxic stains. Contains some plant fragments
84	680	1904 (680cm)	8.142	9.613	8.794	8.731	0.652	0.589	55.676	9.662576687	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains. Slightly darjker color. Conatins some shell fragments
85	678		15.241	16.341	15.726	15.676	0.485	0.435	55.909	10.30927835	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains. Slightly darjker color. Conatins some shell fragments
86	676		7.776	9.091	8.375	8.309	0.599	0.533	54.449	11.01836394	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains. Slightly darjker color. Conatins some shell fragments
87	674	1899 (675 cm)	15.541	16.44	15.93	15.884	0.389	0.343	56.730	11.8251928	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains. Slightly darjker color. Conatins some shell fragments
88	672		8.117	9.444	8.699	8.629	0.582	0.512	56.142	12.02749141	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains. Slightly darjker color. Conatins some shell fragments
89	670	1894 (670 cm)	7.551	8.611	8.02	7.957	0.469	0.406	55.755	13.43283582	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains. Slightly darjker color. Conatins some shell fragments
90	668		15.495	16.692	16.023	15.939	0.528	0.444	55.890	15.90909091	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains. Slightly darjker color. Conatins some shell fragments
91	666		8.147	9.443	8.728	8.622	0.581	0.475	55.170	18.2444062	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains. Slightly darjker color. Conatins some shell fragments
92	664	1889 (665 cm)	15.239	16.097	15.62	15.535	0.381	0.296	55.594	22.30971129	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains. Slightly darjker color. Conatins some shell fragments
93	662		8.613	10.055	9.23	9.11	0.617	0.497	57.212	19.44894652	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains. Slightly darjker color. Conatins some shell fragments
94	660	1884 (660 cm)	8.051	9.317	8.609	8.501	0.558	0.450	55.924	19.35483871	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains. Slightly darjker color. Conatins some shell fragments
95	658		15.777	17.381	16.428	16.298	0.651	0.521	59.414	19.96927803	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains.
96	656		8.003	9.634	8.684	8.549	0.681	0.546	58.246	19.82378855	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains.
97	654	1879 (655 cm)	15.035	16.362	15.607	15.482	0.572	0.447	56.895	21.85314685	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains.
98	652		8.107	9.762	8.821	8.674	0.714	0.567	56.858	20.58823529	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains. Containing some shell fragments
99	650	1874 (650 cm)	8.157	9.133	8.584	8.51	0.427	0.353	56.250	17.33021077	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains. Containing some shell fragments
100	648		15.34	16.445	15.828	15.744	0.488	0.404	55.837	17.21311475	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains. Containing some shell fragments
101	646		8.227	9.33	8.708	8.621	0.481	0.394	56.392	18.08731809	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains. Containing some shell fragments
102	644	1869 (645 cm)	14.992	16.084	15.462	15.372	0.47	0.380	56.960	19.14893617	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains.
103	642		8.226	9.397	8.722	8.63	0.496	0.404	57.643	18.5483871	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains.
104	640	1864 (640 cm)	8.488	9.63	8.981	8.835	0.493	0.347	56.830	29.61460446	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains.
105	638		7.958	8.706	8.29	8.192	0.332	0.234	55.615	29.51807229	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains.
106	636		7.702	8.9	8.242	8.08	0.54	0.378	54.925	30	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains.
107	634	1859 (635 cm)	7.634	9.327	8.395	8.155	0.761	0.521	55.050	31.53745072	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains.
108	632		8.227	9.858	8.913	8.678	0.686	0.451	57.940	34.25655977	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains. 621-632: large stain in the shape of a bullit containing some coarse sand.
109	630	1854 (630 cm)	8.164	9.417	8.701	8.517	0.537	0.353	57.143	34.26443203	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains. 621-632: large stain in the shape of a bullit containing some coarse sand.
110	628		7.617	9.069	8.262	8.03	0.645	0.413	55.579	35.96899225	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains. 621-632: large stain in the shape of a bullit containing some coarse sand.
111	626		8.585	9.912	9.189	8.981	0.604	0.396	54.484	34.43708609	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains. 621-632: large stain in the shape of a bullit containing some coarse sand.
112	624	1849 (625 cm)	8.073	9.7	8.796	8.577	0.723	0.504	55.562	30.29045643	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains. 621-632: large stain in the shape of a bullit containing some coarse sand.
113	622		7.679	8.664	8.131	7.993	0.452	0.314	54.112	30.53097345	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains. 621-632: large stain in the shape of a bullit containing some coarse sand.
114	620		8.33	9.83	8.987	8.78	0.657	0.450	56.200	31.50684932	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains. Shell 4mm.
115	618	1843 (619 cm)	8.374	9.366	8.815	8.679	0.441	0.305	55.544	30.83900227	gyttja	slightly green - gray	Strong bioturbation. Anoxic stains.

Hohe Ley (HL) Core Discription, pollen samples & LOI (De Molenaar & Van Munster, 2011)

diepte = onderzijde van het monster (oftwel 87 cm betekent monster 86-87 cm)
LOI = (Wd-Wg)/(Wd-Wb)*100%
Wb = gewicht lege gloeischaal empty
Wn = gewicht gloeischaal + natte grond
Wd = gewicht gloeischaal + droge grond dried
Wg = gewicht gloeischaal + gegloeide grond ashed (4 uur op 550 graden)
Gd = gewicht droge grond
Gg = gewicht gegloeide grond

Clay (Loam)
Sandy clay loam
Peat, clastic peat, strong clastic peat
Gyttja
sand

Core	Number	LOI Number	Depth [cm]	Pollen Sample	Wb [g]	Wn [g]	Wd [g]	Wg [g]	Gd [g]	Gg [g]	Vocht [%]	LOI [%]	Core Description	Color	Remarks
HLI	4	1	94		8.038	9.351	8.957	8.865	0.919	0.827	30.008	10.01088	clay Loam with sand.	Gray - light brown	Iron stains and oxidized plant remains. Brick.
	6	2	96		8.084	9.935	9.26	9.128	1.176	1.044	36.467	11.22449	clay Loam with sand.	Gray - light brown	Iron stains and oxidized plant remains
	8	3	98	8 (98 cm)	8.216	9.655	9.122	9.004	0.906	0.788	37.040	13.02428	clay Loam with sand.	Gray - light brownup to 101cm	Iron stains and oxidized plant remains up to 101 cm
	10	4	100		8.069	9.337	8.864	8.765	0.795	0.696	37.303	12.45283	clay Loam with sand.	Brown - gray	oxidized plant remains
	12	5	102		7.891	9.208	8.658	8.53	0.767	0.639	41.762	16.6884	clay Loam with sand.	Brown - gray	oxidized plant remains
	14	6	104	13 (103 cm)	7.794	9.644	8.829	8.638	1.035	0.844	44.054	18.45411	clay Loam with sand.	Brown - gray	oxidized plant remains. Wood remains. 102.5: Gray claye layer. 103: root.
	16	7	106		8.238	9.246	8.822	8.736	0.584	0.498	42.063	14.72603	clay Loam with sand.	Brown - gray	oxidized plant remains till 105cm
	18	8	108		8.018	9.879	9.303	9.201	1.285	1.183	30.951	7.937743	clay Loam with sand.	Gray - light brown	Up to 107: Oxidized plant remains. Iron stains
	20	9	110		7.781	9.735	9.069	8.948	1.288	1.167	34.084	9.39441	clay Loam with sand up till 109 cm.	Gray - light brown	Very sandy, probably MZ 210-300, moderately sorted. Iron stains.
	22	10	112	21 (111 cm)	7.667	9.161	8.537	8.409	0.87	0.742	41.767	14.71264	clay Loam	Brown - gray	Oxidized plant remains, iron stains.
	23	11	113		7.726	8.643	8.26	8.187	0.534	0.461	41.767	13.67041	clay Loam	Brown - gray	Oxidized plant remains, iron stains.
HLII	25	12	122		7.766	8.342	7.879	7.796	0.113	0.030	80.382	73.45133	strong clastic peat	Brown - black gray	No layering, contains crushed shells. Root remains
	27	13	124	27 (124 cm)	8.195	9.067	8.361	8.248	0.166	0.053	80.963	68.07229	strong clastic peat	Brown - black gray	No layering, contains crushed shells. Root remains
	29	14	126		7.84	8.603	7.979	7.892	0.139	0.052	81.782	62.58993	strong clastic peat	Brown - black gray	No layering, contains crushed shells. 126cm: shell valve.
	31	15	128		8.255	9.049	8.383	8.296	0.128	0.041	83.879	67.96875	strong clastic peat	Brown - black gray	No layering, contains crushed shells, 127: small branch 2cm.
	33	16	130	32 (129 cm)	7.891	8.827	8.047	7.945	0.156	0.054	83.333	65.38462	strong clastic peat	Brown - black gray	No layering, contains crushed shells. 130.5: Black seed.
	35	17	132		8.002	9.172	8.223	8.098	0.221	0.096	81.111	56.56109	strong clastic peat up till 131	Brown - black gray up till 131 cm	No layering, contains crushed shells up till 131 cm. 131 - 131.4: Clastic peat (Horizontal layer of plant remains, possible erossion surface)
	37	18	134	37 (134 cm)	7.988	8.75	8.125	8.047	0.137	0.059	82.021	56.93431	gyttja	Dark gray - brown	Fine Gyttja containing some crushed shell remains. Black seed (134)
	39	19	136		8.53	9.355	8.666	8.582	0.136	0.052	83.515	61.76471	gyttja	Dark gray - brown	Fine Gyttja containing some crushed shell remains 135-139 cm: slightly darker color. 135: Fine layer of crushed shells (2mm). 135: Branch.
	41	20	138		7.849	8.825	8.017	7.914	0.168	0.065	82.787	61.30952	gyttja	Dark gray - brown	Fine Gyttja containing some crushed shell remains 135-139 cm: slightly darker color
	43	21	140		7.265	8.285	7.473	7.366	0.208	0.101	79.608	51.44231	gyttja	Dark gray - brown	Fine Gyttja containing some crushed shell remains 135-139 cm: slightly darker color. 139cm: Fine layer of crushed shells (2mm). Black seed (139-140)
	45	22	142		7.894	8.97	8.055	7.948	0.161	0.054	85.037	66.45963	gyttja	Dark gray - brown	Fine Gyttja containing some crushed shell remains. Black seed (141)
	47	23	144		8.545	9.848	8.773	8.635	0.228	0.090	82.502	60.52632	gyttja	Dark gray - brown	Fine Gyttja containing some crushed shell remains. 143: Fine layer of crushed shells (2mm).
	49	24	146		7.938	8.985	8.12	8.007	0.182	0.069	82.617	62.08791	gyttja	Dark gray - brown	Fine Gyttja containing some crushed shell remains. Black seed (145)
	51	25	148		7.972	9.004	8.144	8.028	0.172	0.056	83.333	67.44186	gyttja	Dark gray - brown	Fine Gyttja containing some crushed shell remains
	53	26	150		8.234	9.186	8.419	8.316	0.185	0.082	80.567	55.67568	gyttja	Dark gray - brown	Fine Gyttja containing some crushed shell remains
HLIII		27	152		8.271	9.22	8.462	8.346	0.191	0.075	79.874	60.73298	gyttja	Dark gray - brown	Material not in situ (naval)
		28	154		8.137	9.685	8.441	8.299	0.304	0.162	80.362	46.71053	gyttja	Dark gray - brown	Material not in situ (naval)
		29	156		8.323	9.6	8.632	8.528	0.309	0.205	75.803	33.65696	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering).
	55	30	158		8.048	9.576	8.44	8.304	0.392	0.256	74.346	34.69388	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering).
	57	31	160	56 (159 cm)	8.183	9.762	8.576	8.427	0.393	0.244	75.111	37.91349	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering).
	59	32	162		8.324	9.503	8.621	8.519	0.297	0.195	74.809	34.34343	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering).
	61	33	164	61 (164 cm)	8.206	9.883	8.666	8.511	0.46	0.305	72.570	33.69565	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering).
	63	34	166		8.082	9.211	8.427	8.317	0.345	0.235	69.442	31.88406	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering).
	65	35	168		8.163	9.359	8.522	8.409	0.359	0.246	69.983	31.47632	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering). Fine sand mixed in
	67	36	170	66 (169 cm)	8.069	9.85	8.6	8.424	0.531	0.355	70.185	33.14501	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering). Fine sand mixed in
	69	37	172		8.32	9.798	8.74	8.587	0.42	0.267	71.583	36.42857	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering). Fine sand mixed in till 173
	71	38	174	71 (174 cm)	8.175	9.264	8.489	8.365	0.314	0.190	71.166	39.49045	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering).
	73	39	176		7.914	9.149	8.357	8.236	0.443	0.322	64.130	27.31377	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering).
	74	40	177		8.226	9.044	8.551	8.47	0.325	0.244	60.269	24.92308	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering).
	75	41	178		8.053	8.731	8.347	8.283	0.294	0.230	56.637	21.76871	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering).
	76	42	179	76	8.03	8.854	8.384	8.316	0.354	0.286	57.039	19.20904	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering). Slightly lighter colored containing plant remains and crushed shells
	77	43	180		8.185	9.135	8.593	8.512	0.408	0.327	57.053	19.85294	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering). Slightly lighter colored containing plant remains and crushed shells
	78	44	181		8.153	8.833	8.438	8.373	0.285	0.220	58.088	22.80702	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering). Slightly darker colored.
	79	45	182		7.684	8.677	8.111	8.017	0.427	0.333	56.999	22.01405	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering). Slightly darker colored. Gray branches
	80	46	183		8.027	9.089	8.518	8.424	0.491	0.397	53.766	19.1446	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering). Gray branches
	81	47	184	81	14.415	15.106	14.726	14.662	0.311	0.247	54.993	20.57878	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering). Gray branches
	82	48	185		8.206	9.382	8.701	8.595	0.495	0.389	57.908	21.41414	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering). Gray branches
	83	49	186		7.957	8.869	8.317	8.226	0.36	0.269	60.526	25.27778	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering). Gray branches
	84	50	187		7.655	8.377	7.912	7.837	0.257	0.182	64.404	29.18288	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering). Gray branches
	85	51	188		8.476	9.368	8.784	8.695	0.308	0.219	65.471	28.8961	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering). Gray branches. Sand (210-300UM) mixed in. From 188 and lower: Less organic, more claye and grayer.
	86	52	189	86	15.32	15.965	15.542	15.469	0.222	0.149	65.581	32.88288	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering). Sand (210-300UM) mixed in.
	87	53	190		7.974	8.417	8.142	8.097	0.168	0.123	62.077	26.78571	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering). Sand (210-300UM) mixed in.
	89	54	192		8.199	10.119	9.384	9.302	1.185	1.103	38.281	6.919831	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering). Sand (210-300UM) mixed in.
	91	55	194	91 (194 cm)	8.028	10.332	9.423	9.327	1.395	1.299	39.453	6.88172	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering). Contains a lot of sand (210-300UM) mixed in up to 193cm.
	93	56	196		8.085	9.951	9.388	9.333	1.303	1.248	30.171	4.221028	gyttja	Dark gray - brown	Fine homogeneous gyttja (almost no layering). Contains a lot of sand (210-300UM) mixed in up to 193cm.
	95	57	198	94 (197 cm)	8.163	10.081	9.437	9.365	1.274	1.202	33.577	5.651491	gyttja	Dark gray - brown	Darker colored. Very fine gyttja (shoe polish). Contains wood remains. Till 199cm. After 199: fine gyttja with some plant remains.
	97	58	200	96 (199 cm)	8.043	9.151	8.427	8.324	0.384	0.281	65.343	26.82292	gyttja	Dark gray - brown	Darker colored. Very fine gyttja (shoe polish). Contains wood remains.
	99	59	202		8.12	9.982	8.901	8.765	0.781	0.645	58.056	17.41357	gyttja	Dark gray - brown	Fine gyttja with some plant remains. Containing a lot of Sand. Sand seems to be in layers, but layers disturbed by small branch.
	101	60	204	101 (204 cm)	8.155	9.368	8.741	8.657	0.586	0.502	51.690	14.33447	gyttja	Dark gray - brown	Fine gyttja with some plant remains. Containing a lot of Sand. Sand seems to be in layers, but layers disturbed by small branch.
	103	61	206		8.123	9.569	9.018	8.946	0.895	0.823	38.105	8.044693	gyttja	Dark gray - brown	Fine gyttja with some plant remains. Containing a lot of Sand. Sand seems to be in layers, but layers disturbed by small branch.
	105		207										clay Loam		Containing wood and plant remains in horizontal layers (mm's)
	107		210	106 (209 cm)									clay Loam		Containing wood and plant remains in horizontal layers (mm's)
	109		211										sand		Poorly sorted sand (300-420) with fine gravel (5%) 0.5cm.
			215										sand		Poorly sorted sand (300-420) with fine gravel (5%) 0.5cm. 212: Claye layer with plant remains (0.5cm).

Remark: HLIV moved 7 centimeters up after correcting after comparrison with HLII and HLIII

HLIV	113		127	113 (127 cm)									gytjia		
	115	62	129		8.53	9.355	8.666	8.582	0.136	0.052	83.515	61.76471	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood.
	117	63	131		7.849	8.825	8.017	7.914	0.168	0.065	82.787	61.30952	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood.
	119	64	133	118 (132 cm)	7.265	8.285	7.473	7.366	0.208	0.101	79.608	51.44231	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood. Black seeds 0.3cm-0.4cm. 10 seeds in total over 140-170cm
	121	65	135		7.894	8.97	8.055	7.948	0.161	0.054	85.037	66.45963	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood. Black seeds 0.3cm-0.4cm. 10 seeds in total over 140-170cm
	123	66	137	123 (137 cm)	8.545	9.848	8.773	8.635	0.228	0.090	82.502	60.52632	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood. Black seeds 0.3cm-0.4cm. 10 seeds in total over 140-170cm
	125	67	139		7.938	8.985	8.12	8.007	0.182	0.069	82.617	62.08791	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood. Black seeds 0.3cm-0.4cm. 10 seeds in total over 140-170cm. 146-148 Darker colored, wood, plants
	127	68	141		7.972	9.004	8.144	8.028	0.172	0.056	83.333	67.44186	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood. Black seeds 0.3cm-0.4cm. 10 seeds in total over 140-170cm. 146-148 Darker colored, wood, plants
	129	69	143	128 (142 cm)	8.234	9.186	8.419	8.316	0.185	0.082	80.567	55.67568	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood. Black seeds 0.3cm-0.4cm. 10 seeds in total over 140-170cm
	131	70	145		8.271	9.22	8.462	8.346	0.191	0.075	79.874	60.73298	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood. Black seeds 0.3cm-0.4cm. 10 seeds in total over 140-170cm
	133	71	147	133 (147 cm)	8.137	9.685	8.441	8.299	0.304	0.162	80.362	46.71053	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood. Black seeds 0.3cm-0.4cm. 10 seeds in total over 140-170cm
	135	72	149		8.323	9.6	8.632	8.528	0.309	0.205	75.803	33.65696	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood. Black seeds 0.3cm-0.4cm. 10 seeds in total over 140-170cm. 155-158: Different color: Beige(sideriet)
	137	73	151		8.048	9.576	8.44	8.304	0.392	0.256	74.346	34.69388	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood. Black seeds 0.3cm-0.4cm. 10 seeds in total over 140-170cm. 155-158: Different color: Beige(sideriet)
	139	74	153	138 (152 cm)	8.183	9.762	8.576	8.427	0.393	0.244	75.111	37.91349	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood. Black seeds 0.3cm-0.4cm. 10 seeds in total over 140-170cm
	141	75	155		8.324	9.503	8.621	8.519	0.297	0.195	74.809	34.34343	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood. Black seeds 0.3cm-0.4cm. 10 seeds in total over 140-170cm
	143	76	157	143 (157 cm)	8.206	9.883	8.666	8.511	0.46	0.305	72.570	33.69565	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood. Black seeds 0.3cm-0.4cm. 10 seeds in total over 140-170cm
	145	77	159		8.082	9.211	8.427	8.317	0.345	0.235	69.442	31.88406	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood. Black seeds 0.3cm-0.4cm. 10 seeds in total over 140-170cm
	147	78	161		8.163	9.359	8.522	8.409	0.359	0.246	69.983	31.47632	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood. Black seeds 0.3cm-0.4cm. 10 seeds in total over 140-170cm
	149	79	163		8.069	9.85	8.6	8.424	0.531	0.355	70.185	33.14501	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood. Black seeds 0.3cm-0.4cm. 10 seeds in total over 140-170cm
	151	80	165		8.32	9.798	8.74	8.587	0.42	0.267	71.583	36.42857	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood
	153	81	167		8.175	9.264	8.489	8.365	0.314	0.190	71.166	39.49045	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood
	155	82	169		7.914	9.149	8.357	8.236	0.443	0.322	64.130	27.31377	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood. Containing mixed in clean white sand (210-300 um) and plant remains.
	156	83	170		8.226	9.044	8.551	8.47	0.325	0.244	60.269	24.92308	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood. Containing mixed in clean white sand (210-300 um) and plant remains.
	157	84	171		8.053	8.731	8.347	8.283	0.294	0.230	56.637	21.76871	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood. Containing mixed in clean white sand (210-300 um) and plant remains.
	158	85	172		8.03	8.854	8.384	8.316	0.354	0.286	57.039	19.20904	gytjia	Dark gray - brown	*
	159	86	173		8.185	9.135	8.593	8.512	0.408	0.327	57.053	19.85294	gytjia	Dark gray - brown	*
	160	87	174		8.153	8.833	8.438	8.373	0.285	0.220	58.088	22.80702	gytjia	Dark gray - brown	*
	161	88	175		7.684	8.677	8.111	8.017	0.427	0.333	56.999	22.01405	gytjia	Dark gray - brown	*
	162	89	176		8.027	9.089	8.518	8.424	0.491	0.397	53.766	19.1446	gytjia	Dark gray - brown	*
	163	90	177		14.415	15.106	14.726	14.662	0.311	0.247	54.993	20.57878	gytjia	Dark gray - brown	*
	164	91	178		8.206	9.382	8.701	8.595	0.495	0.389	57.908	21.41414	gytjia	Dark gray - brown	*
	165	92	179		7.957	8.869	8.317	8.226	0.36	0.269	60.526	25.27778	gytjia	Dark gray - brown	*
	166	93	180		7.655	8.377	7.912	7.837	0.257	0.182	64.404	29.18288	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood. Slightly darker colored. 187 - 187.2: Whitish layer.
	167	94	181		8.476	9.368	8.784	8.695	0.308	0.219	65.471	28.8961	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood
	168	95	182		15.32	15.965	15.542	15.469	0.222	0.149	65.581	32.88288	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood
	169	96	183		7.974	8.417	8.142	8.097	0.168	0.123	62.077	26.78571	gytjia	Dark gray - brown	Fine Gyttja. Containing some pieces of wood. Bottom 5mm of core slighly sandy

* Fine homogenous Gyttja. Containing some pieces of wood. Containing mixed in clean white sand (210-300 um) and plant remains. Finer, less clearly layered. 179 - 185: containing 2 black seeds and 4 shell valves.

Schloss Bellinghoven (SB) Core Discription, pollen samples & LOI (De Molenaar, 2011)

diepte = onderzijde van het monster (oftwel 87 cm betekent monster 86-87 cm)
LOI = (Wd-Wg)/(Wd-Wb)*100%
Wb = gewicht lege gloeischaal empty
Wn = gewicht gloeischaal + natte grond
Wd = gewicht gloeischaal + droge grond dried
Wg = gewicht gloeischaal + gegloeide grond ashed (4 uur op 550 graden)
Gd = gewicht droge grond
Gg = gewicht gegloeide grond

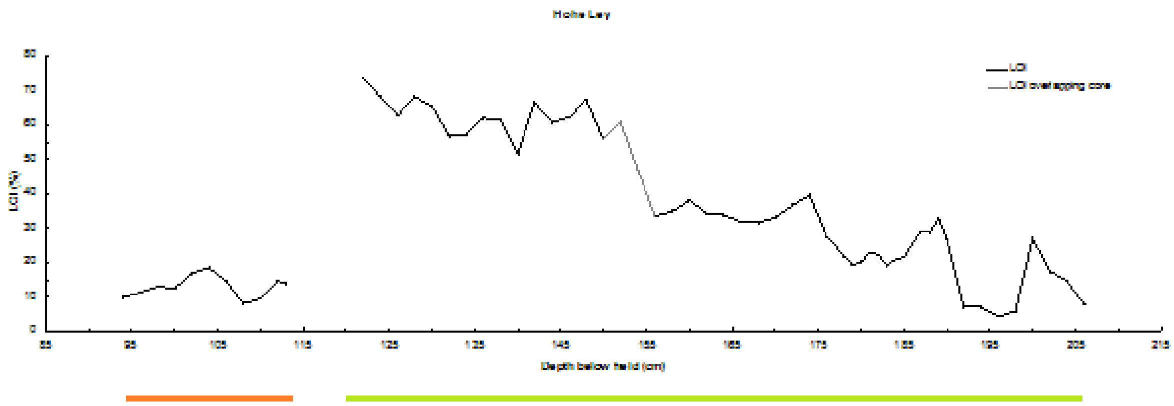
- Clay (Loam)
- Sandy clay loam
- Peat, clastic peat, strong clastic peat
- Gyttja
- sand

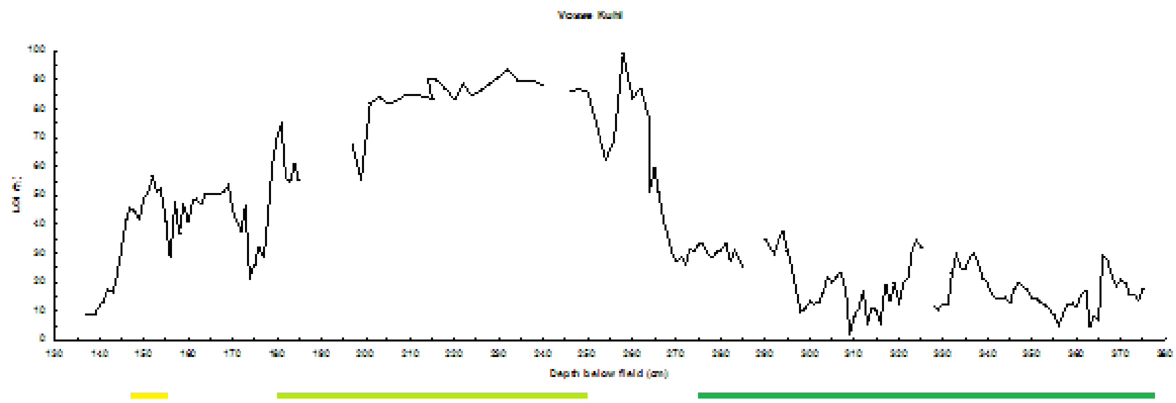
Core	Number	Depth [cm]	Pollen sample	Wb [g]	Wn [g]	Wd [g]	Wg [g]	Gd [g]	Gg [g]	Vocht [%]	LOI [%]	Description	Color	Remarks
SBVII	1000	650		8.171	9.606	9.362	9.329	1.191	1.158	17.003	2.770781	gravel 50%. Fine gravel	gray	50% gravel, mainly fine gravel (FG). Largest gravel diameter 2.0 cm. Sand and clay mixed in.
	999	649		8.091	9.023	8.693	8.66	0.602	0.569	35.408	5.481728	sandy clay	gray	Sand mixed in. Slightly darker color
	998	648	998	8.04	9.247	8.761	8.709	0.721	0.669	40.265	7.212205	sandy clay	gray	Sand mixed in. Slightly darker color
	997	647		8.054	9.563	9.097	9.044	1.043	0.990	30.881	5.081496	sandy clay	gray	Sand mixed in. Slightly darker color
	996	646		8.086	9.753	9.122	9.049	1.036	0.963	37.852	7.046332	sandy clay	gray	Sand mixed in. Slightly darker color
	995	645		8.022	8.832	8.521	8.486	0.499	0.464	38.395	7.014028	clay	gray	
	994	644		8.1	9.252	8.753	8.697	0.653	0.597	43.316	8.575804	clay	gray	Lichter colored
	993	643	993	8.111	9.064	8.679	8.635	0.568	0.524	40.399	7.746479	clay	dark gray	Bioturbation
	992	642		8.018	9.065	8.617	8.565	0.599	0.547	42.789	8.681135	clay	dark gray	Bioturbation
	991	641		8.383	9.197	8.859	8.818	0.476	0.435	41.523	8.613445	clay	dark gray	Bioturbation
	990	640		7.828	8.655	8.304	8.264	0.476	0.436	42.443	8.403361	clay	dark gray	Bioturbation
	989	639		7.782	9.213	8.587	8.519	0.805	0.737	43.746	8.447205	clay	gray	Some bioturbation, slightly lighter colored
	988	638	988	7.794	8.672	8.282	8.233	0.488	0.439	44.419	10.04098	clay	gray	Bioturbation
	987	637		7.945	8.946	8.483	8.435	0.538	0.490	46.254	8.921933	clay	gray	Bioturbation
	986	636		7.836	8.833	8.362	8.318	0.526	0.482	47.242	8.365019	clay	gray	Bioturbation
	985	635		8.003	8.869	8.453	8.414	0.45	0.411	48.037	8.666667	clay	gray	Bioturbation
	984	634		7.471	8.346	7.932	7.893	0.461	0.422	47.314	8.45987	clay	gray	Bioturbation
	983	633	983	7.89	8.775	8.358	8.32	0.468	0.430	47.119	8.119658	clay	gray	Bioturbation
	982	632		8.141	9.176	8.689	8.643	0.548	0.502	47.053	8.394161	clay	gray	Bioturbation
	981	631		8.238	9.382	8.84	8.794	0.602	0.556	47.378	7.641196	clay	gray	Bioturbation
	980	630		7.884	8.819	8.372	8.343	0.488	0.459	47.807	5.942623	clay	gray	Bioturbation
	979	629		7.986	9.163	8.608	8.569	0.622	0.583	47.154	6.270096	clay	gray	Bioturbation
	978	628	978	7.83	8.837	8.357	8.328	0.527	0.498	47.666	5.502846	clay	gray	Bioturbation
	977	627		8.031	9.161	8.628	8.587	0.597	0.556	47.168	6.867672	clay	gray	Bioturbation
	976	626		8.254	9.559	8.938	8.892	0.684	0.638	47.586	6.725146	clay	gray	Bioturbation
	975	625		8.526	9.673	9.119	9.08	0.593	0.554	48.300	6.576728	clay	gray	Bioturbation Layer of a lighter color, 0.2cm
	974	624		7.889	8.992	8.457	8.419	0.568	0.530	48.504	6.690141	clay	gray	Bioturbation
	973	623	973	8.214	9.043	8.645	8.617	0.431	0.403	48.010	6.49652	clay	gray	Bioturbation
	971	621		8.068	8.956	8.51	8.477	0.442	0.409	50.225	7.466063	clay	gray	Bioturbation
	970	620		8.368	9.417	8.905	8.866	0.537	0.498	48.808	7.26257	clay	gray	Bioturbation. Slightly darker colored
	969	619		7.727	9.013	8.394	8.346	0.667	0.619	48.134	7.196402	clay	gray	Bioturbation. Slightly darker colored
	968	618	968	7.764	8.781	8.281	8.24	0.517	0.476	49.164	7.930368	clay	gray	Bioturbation. Slightly darker colored
	967	617		7.665	8.777	8.223	8.182	0.558	0.517	49.820	7.34767	clay	gray	Bioturbation. Slightly darker colored
	966	616		7.982	9.234	8.615	8.564	0.633	0.582	49.441	8.056872	clay	gray	Bioturbation. Slightly darker colored
	965	615		8.194	9.135	8.661	8.623	0.467	0.429	50.372	8.137045	clay	gray	Bioturbation. Slightly darker colored
	964	614	963 (613 cm)	6.824	7.764	7.293	7.264	0.469	0.440	50.106	6.183369	clay	gray	Bioturbation
	961	611		8.366	9.314	8.833	8.798	0.467	0.432	50.738	7.494647	clay	gray	Bioturbation
	960	610		8.191	9.334	8.76	8.72	0.569	0.529	50.219	7.029877	clay	gray	Bioturbation
	959	609		8.445	9.254	8.849	8.82	0.404	0.375	50.062	7.178218	clay	gray	Bioturbation
	958	608	958	8.34	9.637	8.99	8.948	0.65	0.608	49.884	6.461538	clay	gray	Bioturbation
	957	607		7.814	9.145	8.475	8.315	0.661	0.501	50.338	24.20575	clay	gray	Bioturbation
	956	606		8.622	9.542	9.079	9.045	0.457	0.423	50.326	7.439825	clay	gray	Bioturbation
	955	605		15.319	16.594	15.944	15.906	0.625	0.587	50.980	6.08	clay	gray	Bioturbation
	954	604	953 (603 cm)	7.974	8.929	8.438	8.347	0.464	0.373	51.414	19.61207	clay	gray	Bioturbation
	952	602		7.838	8.938	8.366	8.249	0.528	0.411	52.000	22.15909	clay	gray	Bioturbation
	951	601		7.085	8.294	7.677	7.638	0.592	0.553	51.034	6.587838	clay	gray	Bioturbation
	950	600		8.504	9.736	9.093	9.04	0.589	0.536	52.192	8.998302	clay	gray	Bioturbation
	949	599		15.449	16.667	16.025	15.975	0.576	0.526	52.709	8.680556	clay	gray	Bioturbation
	948	598	948	8.001	8.823	8.386	8.349	0.385	0.348	53.163	9.61039	clay	gray	Bioturbation
	947	597		15.536	16.714	16.084	16.036	0.548	0.500	53.480	8.759124	clay	gray	Bioturbation
	946	596		8.151	9.308	8.69	8.643	0.539	0.492	53.414	8.719852	clay	gray	Bioturbation
	945	595		8.142	9.28	8.665	8.614	0.523	0.472	54.042	9.751434	clay	gray	Bioturbation Wood remains, diameter 0.5cm
	944	594		15.237	16.375	15.784	15.729	0.547	0.492	51.933	10.05484	clay	gray	Bioturbation
	943	593	943	7.771	9.212	8.446	8.384	0.675	0.613	53.158	9.185185	clay	gray	Bioturbation
	942	592		15.54	17.246	16.331	16.266	0.791	0.726	53.634	8.217446	clay	gray	Bioturbation
	941	591		8.112	9.254	8.639	8.601	0.527	0.489	53.853	7.210626	clay	dark gray	Bioturbation Disturbed dark gray layer 1cm
	940	590		7.549	8.499	7.993	7.957	0.444	0.408	53.263	8.108108	clay	gray	Bioturbation
	939	589		15.495	16.449	15.925	15.881	0.43	0.386	54.927	10.23256	clay	gray	Bioturbation black layer, 0.3cm
	938	588	938	8.148	9.393	8.713	8.66	0.565	0.512	54.618	9.380531	clay	gray	Bioturbation
	937	587		15.239	16.248	15.7	15.654	0.461	0.415	54.311	9.978308	clay	gray	Bioturbation
	936	586		8.613	9.477	9.01	8.976	0.397	0.363	54.051	8.564232	clay	gray	Bioturbation
	935	585		8.051	9.294	8.615	8.575	0.564	0.524	54.626	7.092199	clay	gray	Bioturbation
	934	584		15.772	16.79	16.222	16.191	0.45	0.419	55.796	6.888889	clay	gray	Bioturbation
	933	583	933	8.004	8.925	8.414	8.386	0.41	0.382	55.483	6.829268	clay	gray	Bioturbation
	932	582		15.032	16.115	15.531	15.49	0.499	0.458	53.924	8.216433	clay	gray	Bioturbation
	931	581		8.223	9.544	8.828	8.784	0.605	0.561	54.201	7.272727	clay	gray	Bioturbation
	930	580		8.224	9.78	8.925	8.887	0.701	0.663	54.949	5.420827	clay	gray	Bioturbation
	929	579		14.992	15.89	15.388	15.366	0.396	0.374	55.902	5.555556	clay	gray	Bioturbation

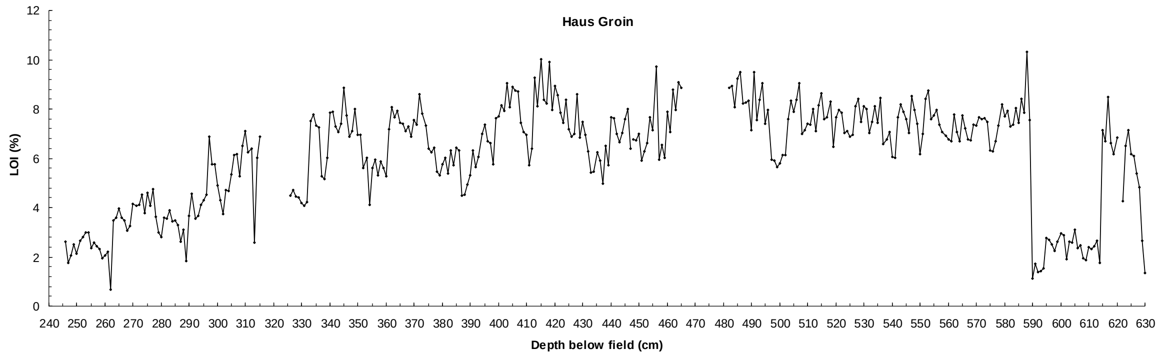
	928	578	928	15.342	16.522	15.853	15.824	0.511	0.482	56.695	5.675147	clay	gray	Bioturbation
	927	577		15.241	16.898	15.957	15.907	0.716	0.666	56.789	6.98324	clay	gray	Bioturbation
	926	576		8.104	9.704	8.788	8.744	0.684	0.640	57.250	6.432749	clay	gray	Bioturbation Vertically disturbed by coring methode. Might be not in situ (naval)
	925	575		8.183	9.2	8.613	8.585	0.43	0.402	57.719	6.511628	clay	gray	Bioturbation Vertically disturbed by coring methode. Might be not in situ (naval)
	924	574		8.324	9.597	8.861	8.823	0.537	0.499	57.816	7.07635	clay	gray	Bioturbation Vertically disturbed by coring methode. Might be not in situ (naval)
	923	573	923	7.972	8.836	8.336	8.314	0.364	0.342	57.870	6.043956	clay	gray	Bioturbation Vertically disturbed by coring methode. Might be not in situ (naval)
	922	572		8.271	10.1	9.047	9.001	0.776	0.730	57.572	5.927835	clay	gray	Bioturbation Vertically disturbed by coring methode. Might be not in situ (naval)
	921	571		17.319	18.543	17.837	17.803	0.518	0.484	57.680	6.563707	clay	gray	Bioturbation Vertically disturbed by coring methode. Might be not in situ (naval)
SBVI	912	570	912 (570 cm)	7.938	9.593	8.633	8.584	0.695	0.646	58.006	7.05036	Gyttja	dark gray	Bioturbation and anoxic stains.
	910	568		7.683	9.342	8.377	8.329	0.694	0.646	58.168	6.916427	Gyttja	dark gray	Bioturbation and anoxic stains.
	908	566	907 (565 cm)	8.546	10.218	9.233	9.182	0.687	0.636	58.911	7.423581	Gyttja	dark gray	Bioturbation and anoxic stains.
	906	564		8.049	9.746	8.735	8.686	0.686	0.637	59.576	7.142857	Gyttja	dark gray	Bioturbation and anoxic stains.
	904	562		16.73	17.671	17.117	17.093	0.387	0.363	58.874	6.20155	Gyttja	dark gray	Bioturbation and anoxic stains.
	902	560	902 (560 cm)	8.155	9.759	8.815	8.774	0.66	0.619	58.853	6.212121	Gyttja	dark gray	Bioturbation and anoxic stains.
	900	558		8.137	9.791	8.827	8.78	0.69	0.643	58.283	6.811594	Gyttja	dark gray	Bioturbation and anoxic stains.
	898	556	897 (555 cm)	7.264	8.721	7.873	7.828	0.609	0.564	58.202	7.389163	Gyttja	dark gray	Bioturbation and anoxic stains.
	896	554		7.894	9.544	8.59	8.547	0.696	0.653	57.818	6.178161	Gyttja	dark gray	Bioturbation and anoxic stains.
	894	552		16.15	17.657	16.801	16.754	0.651	0.604	56.802	7.219662	Gyttja	dark gray	Bioturbation and anoxic stains.
	892	550	892 (550 cm)	8.122	10.059	8.986	8.926	0.864	0.804	55.395	6.944444	Gyttja	dark gray	Bioturbation and anoxic stains.
	890	548		7.849	9.558	8.579	8.533	0.73	0.684	57.285	6.30137	Gyttja	dark gray	Bioturbation and anoxic stains.
	888	546	887 (545 cm)	7.959	8.756	8.29	8.262	0.331	0.303	58.469	8.459215	Gyttja	dark gray	Bioturbation and anoxic stains.
	886	544		8.12	9.627	8.744	8.699	0.624	0.579	58.593	7.211538	Gyttja	dark gray	Bioturbation and anoxic stains.
	884	542		16.942	18.854	17.732	17.679	0.79	0.737	58.682	6.708861	Gyttja	dark gray	Bioturbation and anoxic stains.
	882	540	882 (540 cm)	8.232	9.86	8.906	8.868	0.674	0.636	58.600	5.637982	Gyttja	dark gray	Bioturbation and anoxic stains.
	880	538		8.53	10.111	9.171	9.136	0.641	0.606	59.456	5.460218	Gyttja	dark gray	Bioturbation and anoxic stains.
	878	536	877 (535 cm)	8.325	9.717	8.9	8.867	0.575	0.542	58.693	5.73913	Gyttja	dark gray	Bioturbation and anoxic stains.
	876	534		8.289	9.216	8.67	8.652	0.381	0.363	58.900	4.724409	Gyttja	dark gray	Bioturbation and anoxic stains.
	874	532		14.143	15.014	14.499	14.475	0.356	0.332	59.127	6.741573	Gyttja	dark gray	Bioturbation and anoxic stains.
	873	531		8.159	8.94	8.477	8.446	0.318	0.287	59.283	9.748428	Gyttja	dark gray	Bioturbation and anoxic stains.
	872	530	872	8.159	9.39	8.66	8.608	0.501	0.449	59.301	10.37924	Gyttja	dark gray	Bioturbation and anoxic stains. Somewhat lighter colored
	871	529		8.202	9.527	8.73	8.681	0.528	0.479	60.151	9.280303	Gyttja	dark gray	Bioturbation and anoxic stains. Somewhat lighter colored
	870	528		8.025	9.136	8.471	8.432	0.446	0.407	59.856	8.744395	Gyttja	dark gray	Bioturbation and anoxic stains.
	869	527		16.777	17.72	17.159	17.122	0.382	0.345	59.491	9.685864	Gyttja	dark gray	Bioturbation and anoxic stains.
	868	526	868	8.198	9.482	8.7	8.649	0.502	0.451	60.903	10.15936	Gyttja	dark gray	Bioturbation and anoxic stains. Lighter colored layer 0.4cm
	867	525		8.046	9.14	8.479	8.425	0.433	0.379	60.420	12.47113	Gyttja	dark gray	Bioturbation and anoxic stains.
	866	524		8.079	9.1	8.482	8.437	0.403	0.358	60.529	11.16625	Gyttja	dark gray	Bioturbation and anoxic stains.
	865	523		7.86	8.724	8.175	8.131	0.315	0.271	63.542	13.96825	Gyttja	dark gray	Bioturbation and anoxic stains.
	864	522		15.46	16.64	15.906	15.852	0.446	0.392	62.203	12.10762	Gyttja	dark gray	Bioturbation and anoxic stains.Lighter colored layer 0.3cm
	863	521		8.024	9.143	8.44	8.387	0.416	0.363	62.824	12.74038	Gyttja	dark gray	Bioturbation and anoxic stains.
	862	520	862	8.023	9.726	8.647	8.567	0.624	0.544	63.359	12.82051	Gyttja	dark gray	Bioturbation and anoxic stains.
	860	518		8.32	10.686	9.219	9.113	0.899	0.793	62.003	11.79088	Gyttja	dark gray	Bioturbation and anoxic stains.
	858	516	857 (515 cm)	8.472	10.356	9.173	9.087	0.701	0.615	62.792	12.26819	Gyttja	dark gray	Bioturbation and anoxic stains.
	856	514		16.938	18.818	17.634	17.541	0.696	0.603	62.979	13.36207	Gyttja	dark gray	Bioturbation and anoxic stains.
	854	512		8.077	9.711	8.668	8.593	0.591	0.516	63.831	12.69036	Gyttja	dark gray	Bioturbation and anoxic stains.
	852	510	852 (510 cm)	8.204	10.17	8.901	8.816	0.697	0.612	64.547	12.19512	Gyttja	dark gray	Bioturbation and anoxic stains.Some small, blakck plant remains.
	850	508		8.055	9.923	8.71	8.625	0.655	0.570	64.936	12.9771	Gyttja	dark gray	Bioturbation and anoxic stains.Some small, blakck plant remains.
	848	506	847 (505 cm)	7.653	9.426	8.281	8.198	0.628	0.545	64.580	13.21656	Gyttja	dark gray	Bioturbation and anoxic stains.
	846	504		15.718	16.915	16.14	16.078	0.422	0.360	64.745	14.69194	Gyttja	dark gray	Bioturbation and anoxic stains.
	844	502		7.975	9.695	8.571	8.502	0.596	0.527	65.349	11.57718	Gyttja	dark gray	Bioturbation and anoxic stains.
	842	500	842 (500 cm)	7.923	9.568	8.494	8.425	0.571	0.502	65.289	12.08406	Gyttja	dark gray	Bioturbation and anoxic stains.
	840	498		7.686	9.215	8.243	8.182	0.557	0.496	63.571	10.95153	Gyttja	dark gray	Bioturbation and anoxic stains.
	838	496	837 (495 cm)	8.188	10.416	8.978	8.893	0.79	0.705	64.542	10.75949	Gyttja	dark gray	Bioturbation and anoxic stains.495: Shell
	836	494		16.265	18.152	16.945	16.879	0.68	0.614	63.964	9.705882	Gyttja	dark gray	Bioturbation and anoxic stains.
	834	492		7.884	9.872	8.598	8.53	0.714	0.646	64.085	9.52381	Gyttja	dark gray	Bioturbation and anoxic stains.493: Lichter colored layer 1.2 cm
	832	490	832 (490 cm)	7.983	10.017	8.727	8.657	0.744	0.674	63.422	9.408602	Gyttja	dark gray	Bioturbation and anoxic stains.
	830	488		7.828	9.312	8.382	8.326	0.554	0.498	62.668	10.1083	Gyttja	dark gray	Bioturbation and anoxic stains.
	828	486	827 (485 cm)	8.031	9.502	8.57	8.516	0.539	0.485	63.358	10.01855	Gyttja	dark gray	Bioturbation and anoxic stains.
	826	484		8.252	9.901	8.843	8.78	0.591	0.528	64.160	10.6599	Gyttja	dark gray	Bioturbation and anoxic stains.
	824	482		7.997	9.185	8.382	8.327	0.385	0.330	67.593	14.28571	Gyttja	dark gray	Bioturbation and anoxic stains.
	822	480	822 (480 cm)	7.469	8.736	7.895	7.833	0.426	0.364	66.377	14.55399	Gyttja	dark gray	Bioturbation and anoxic stains.
	820	478		7.887	8.949	8.199	8.142	0.312	0.255	70.621	18.26923	Gyttja	dark gray	Bioturbation and anoxic stains.
	818	476	817 (475 cm)	8.137	9.975	8.732	8.638	0.595	0.501	67.628	15.79832	Gyttja	dark gray	Bioturbation and anoxic stains.
	816	474		8.236	9.302	8.611	8.566	0.375	0.330	64.822	12	Gyttja	dark gray	Bioturbation and anoxic stains.

LOI analyses (M.M. De Molenaar, in prep.) **Appendix H**

Dates obtained from pollen analysis:
Hohe Ley, Heeren Bril, Schloss Bellingehoven (this thesis)
Vosse Kuhl (Geurts, in prep.; Bunnik, pers. comm.)





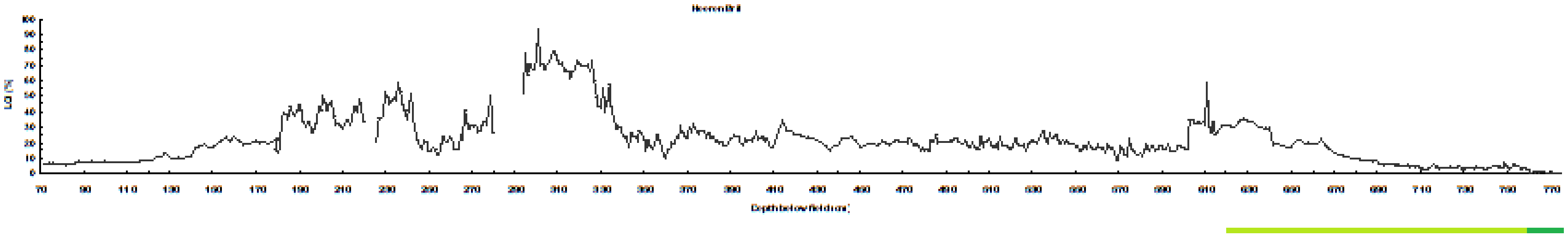


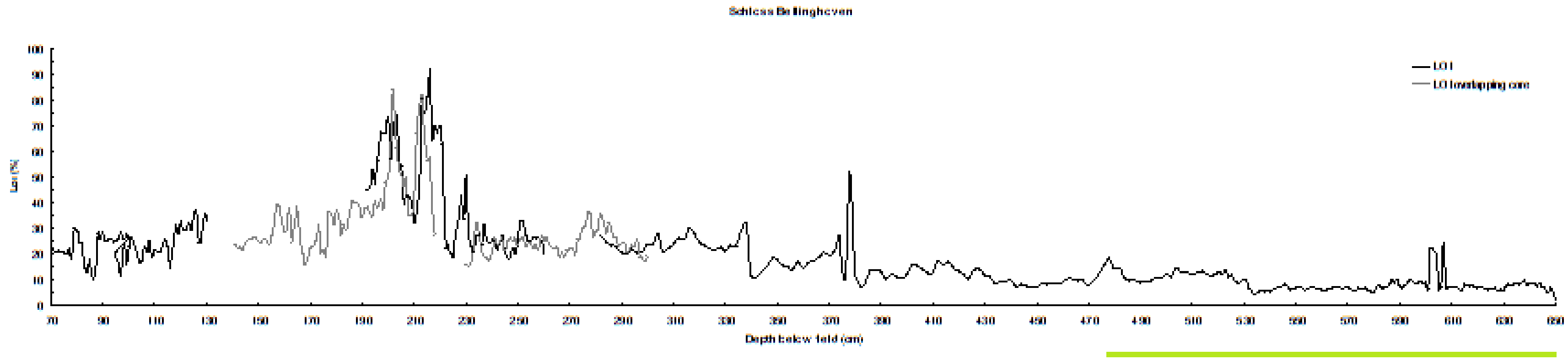
Boreal

Atlantic

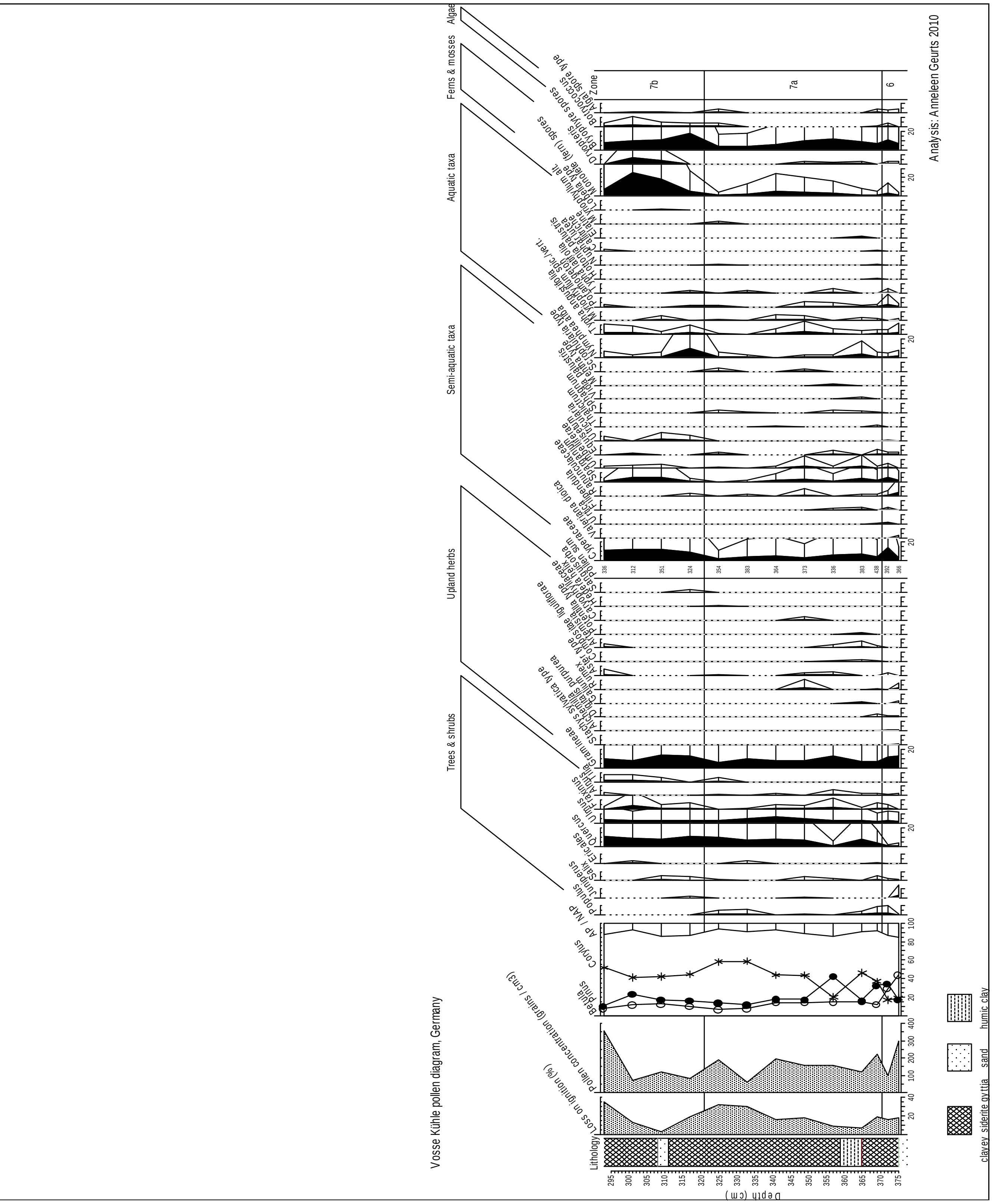
Subboreal

Subatlantic


LOI (%)
Depth below field (cm)


Schloss Bellinghoven
LOI (%)
Depth below field (cm)
LOI
LOI overlapping core

Appendix I



Vosse Kühle pollen diagram, Germany
Analysis: Anneleen Geurts 2010
Trees & shrubs
Upland herbs
Semi-aquatic taxa
Aquatic taxa
Ferns & mosses
Algae
Lithology
Loss on ignition (%)
Pollen concentration (grains / cm3)
Betula
Pinus
Corylus
AP / NAP
Populus
Juniperus
Salix
Ericales
Quercus
Ulmus
Fraxinus
Alnus
Tilia
Gramineae
Cyperaceae
Zone
7b
7a
6
Depth (cm)
clayey siderite gyttja
sand
humic clay

Pollenscans boringen ‘Vosse Kühle’

1. Vosse Kühle

Van deze boring zijn 8 pollenmonsters gescand om de datering van de venige afzettingen vast te stellen. De monsters bevatten alle voldoende redelijk tot zeer goed geconserveerde palynomorfen om zinvolle uitspraken te doen over het type veen en de datering. De pollenscans zijn genomen uit het venige traject van 1,40 tot (in aansluiting op de reeds uitgevoerde analyses)

Korte karakterisering van de pollenassemblages van diep naar ondiep. AP=boompollen, de belangrijkste groep voor datering, de rest van de assemblage geeft de lokale vegetatie en de invloed van de mens.

- 2,75 m
  AP: Corylus dominant, Quercus en Pinus duidelijk aanwezig, enkele korrels van Ulmus, Tilia, Betula, Acer en Hedera. Lokaal veel Poaceae, Dryopteris (Thelypteris) en Sparganium, enkele korrels van Typha latifolia en Cyperaceae.

Interpretatie: hazelaarstruweel met dennen en eiken. Lokaal: moerasvarenrijke rietkraag
Datering: (Laat)-Boreaal

- 2,50 m
  AP: Corylus nog wel dominant maar nu duidelijk ook Quercus, Ulmus en Alnus in relatief hoge aantallen aanwezig. Lokaal minder Poacaeae en dryopteris, veel mosblaadjes. Een enkele Calluna

Interpretatie: Gemengd eikenbos met lokaal beginnend elzenbroekbos
Datring: Atlanticum

- 2,25 m
  AP: als vorige spectrum, nu minder Corylus en een enkele Salix. Lokaal: Nuphar, slijmcellen, Dryopteris, Cyperaceae en enkele Poaceae.

Interpretatie/datering: Als vorige spectrum

- 2.00 m
  AP: Pinus sterk dominant (> 60%), rest als in het vorige spectrum, nu ook Hedera en Viscum

Interpretatie: Gezien de absolute dominantie van Pinus is hier een overstromingslaag bemonsterd.
Datering: Atlanticum

- 1,80 m
  AP vergelijkbaar met die van 2,50 m met grote hoeveelheden Alnus (in klonten, dus zeer lokaal. Ook enkele korrels van Typha latifolia, Nuphar en Dryopteris

Interpretatie: Gemengd eikenbos, lokaal elzenbroekbos en open water.
Datering: Atlanticum

- 1,50 m

AP: Alnus dominant, veel Quercus, Corylus en Pinus, nu ook Picea. Eerste aanwezigheid van Fagus, Ulmus, Acer in zeer lage percentages. NAP: Calluna, Liguliflorae, Poaceae, Polygonum aviculare, Pteridium en nu ook meerdere korrels van Cerealia en Hordeum

Interpretatie: immigratie van Fagus en eerste duidelijke aanwezigheid van akkerbouw
Datering: O.g.v. aanwezigheid van beuk, granen en de lage percentages voor iep: Vroeg Subboreaal.

- 1,40 m

Zeer diverse pollenassemblage met uitstekende conservering
AP: Pinus en Alnus (vaak in clusters) in grote percentages aanwezig, daarnaast redelijk veel Quercus en Corylus, Fagus, Tilia, Ulmus, Acer, Betula, Hedera, Prunus naast Picea en Abies duidelijk aanwezig.
Het niet boompollenspectrum en de lokale assemblage is uitermate divers met cultuurgewassen/cultuurvolgers als Cerealia, Hordeum type, Chenopodiaceae, Anthemis type, Plantago lanceolata, P. maior, Calluna, Artemisia, Rumex acetosa, Scleranthus annuus type, Ranunculus acris type en talrijke kruiden van open landschappen als Liguliflorae, Caryophyllacea, Centaurea jacea type, Botrychium, Succisa, Geranium molle type en Polygonum persicaria type. Ook de water en moerasflora is divers met Thelyperis palustris, Spirogyra, Sparganium, Alisma plantago-aquatica, Sagittaria, Typha latifolia, Cirsium type en een grote rijkdom aan diatomeeën.

Interpretatie: Mogelijk gezien de duidelijke aanwezigheid van Picea en Abies (uit het achterland afkomstig) naast redelijk veel den, ook hier een overstromingslaag. Het landschap vertoont met akkers en grasland de duidelijke invloed van landbouw en veeteelt.
Datering: Beuk duidelijk aanwezig, veel en divers NAP, geen haagbeuk (!): Laat-Subboreaal/Voeg Subatlanticum (IJzertijd).