Living, not surviving, in a dynamic landscape? An early Holocene environmental reconstruction for the Vrouw Vennepolder, Western Netherlands, and implications for human occupation

Lange, Pieter de

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By Pieter de Lange

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An early Holocene environmental reconstruction for the Vrouw Vennepolder, Western Netherlands, and implications for human occupation

Pieter de Lange

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Supervisor: Dr. M. H. Field

Leiden University, Faculty of Archaeology

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Table of content

List of figures and appendices

Figures

Appendices

1. Introduction

1.1. The dynamic Dutch coastal environment

As part of the North Sea coastal system, the Dutch coast has proven to be a naturally dynamic environment. Since the transition to and onset of the Holocene warming following the Weichselian Late Pleistocene glacial period, a considerable sea level rise has taken place over time – the Holocene transgression – that resulted in a changing coastal morphology and geography of the land surface (e.g., Fairbanks, 1989, pp. 639-641; Hanebuth et al., 2009, pp. 76-77, 82-83 and references therein). Various rivers (e.g., the Rhine, Meuse, Scheldt, Vecht, IJssel) flow and scour through the landscape, with changing course positions and different styles through time, transporting freshwater and sediment to the North Sea. Aeolian proceses created and erosive processes (partially) removed river and coastal dunes. Over time, the coastline shifted its location due to erosion and sedimentation. Nowadays, different landscape types occur in the Netherlands, like tidal areas and islands along the northern coast, areas with traces of glacial periods, in the form of glacial outwash, in the Central, Eastern and Northern Netherlands, river valleys and loess landscapes (e.g., see Amkreutz, 2013, pp. 59-64 and references therein; Hoek, 1997b, pp. 77-78; Hoek, 2000, pp. 499-501). Vegetation patterns also changed through time, generally becoming more open during glacials and forested during temperate phases and becoming more diverse if the prevailing circumstances permitted it (e.g., Bos et al, 2007; Hoek, 1997a, pp. 21, 29; Hoek et al., 2017, pp. 103, 107, 110-111). Regional differences occurred.

During the first part of the Holocene, the Preboreal (ca. 11,650 – 10,250 cal. BP), *Betula* trees colonised parts of the Netherlands (e.g., Bos et al., 2005a; Bos et al., 2007, p. 1931; van Geel et al., 1981, pp. 398, 410). As the Preboreal developed, with fluctuating climate (Bohncke & Hoek, 2007, pp. 1968-1971; Bos et al., 2007, pp. 1930-1931, 1937, 1943-1944, 1946-1947; Hoek & Bos, 2007, pp. 1901-1904 and references therein), *Pinus* also entered the landscape and settled in the landscape (Hoek, 1997a, pp. 26-27; Woelders et al., 2016, pp. 184-185), sometimes also with *Populus* (e.g., Bos et al., 2005a, pp. 266, 278; Bos et al., 2005b, pp. 30, 37-38; Bos & van Geel, 2017, pp. 123-124; Hoek et al., 2017, p. 16; van Geel et al., 1981, pp. 397-399). *Corylus* became part of the vegetation towards the transition to the Boreal period (ca. 10,250 – 8,700 cal. BP) too and the first *Quercus* and *Ulmus* also appeared in North-western Europe (Bakels, 2017, p. 179; Bohncke & Hoek, 2007, p. 1968).

During the Boreal, there was a continental climate, with higher temperatures and relatively limited precipitation compared to the Preboreal (e.g., Brouwer Burg, 2013, p. 2311 and references therein; van Geel et al., 1981, p. 412). A feature of the Boreal was the abundance of *Corylus* (Bos & van Geel, 2017, p. 124; Cappers & Neef, 2012, p. 359; Hoek, 1997, p. 27). The first part of the Boreal is dominated by *Betula*, *Pinus* and *Corylus* (Cappers & Neef, 2012, p. 360; Hoek, 1997a, p. 27; Hoek, 1997b, p. 78; van Geel et al., 1981, p. 399). The later Boreal formation of mixed, deciduous forests was caused by the establishment of *Quercus*, *Ulmus*, *Tilia* and *Alnus*, following individualistic patterns of dispersal, competition, tolerances and responses to environmental conditions (Bos et al., 2007, p. 1937; Bos & van Geel, 2017, p. 124; Cappers & Neef, 2012, p. 361; Woelders et al., 2016, p. 185; Zuidhoff & Bos, 2017, pp. 145-146). The landscape was characterised by forests, heath landscapes and marshes, which developed because of the rise of the groundwater table following relative sea level rise (e.g., Hijma et al., 2009, pp. 24, 26, 37-38; van Staalduinen, 1979, pp. 11, 40-42). In the transition towards the Atlantic period (ca. 8,700 – 5,700 cal. BP), *Alnus* became more common if the conditions allowed (e.g., Cappers & Neef, 2012, p. 360; Janssen & Törnqvist, 1991, their Figure 1).

The Atlantic marks the early Middle Holocene and is characterised as a warm and moist period, with a climatic optimum (Cappers & de Neef, 2012, p. 363; Janssen, 1974, p. 56; Zagwijn, 1994, p. 82). There was a considerable expansion of *Alnus*, *Ulmus*, *Quercus*, *Tilia*, *Fagus* and *Fraxinus*, as well as *Hedera helix* and *Viscum*, in the Netherlands, whereas *Corylus* became relatively less common than in the Boreal (e.g., Cappers & Neef, 2012, pp. 261, 263; Kasse & Aalbersberg, 2019, p. e4-6; van Geel et al., 1981, p. 399; Zagwijn, 1994, p. 74; Zuidhoff & Bos, 2017, p. 146).

1.2. Environmental opportunities and challenges for human exploitation

During the late Quaternary, humans made their way to suitable, newly available environments, adapting themselves to the surrounding, altering the environment or moving away from unfavourable ecological situations (e.g., Cohen et al., 2012; Hijma et al., 2012). The late Pleistocene and Early Holocene environmental change impacted Palaeolithic and Mesolithic people's choices on where to exploit resources and what locality to occupy in order to support a broad-spectrum subsistence economy.

Humans sometimes also left traces of their presence behind, like modified flint, stone and bone tools (see, e.g., Amkreutz, 2013 and references therein; Hijma et al., 2012 and references therein). The seasonal occupation of the hunter-gatherer groups of the late Pleistocene to early Middle Holocene Netherlands was mostly centred on the coversands, levees and dunes near lakes, rivers, oxbow lakes, fens and wetlands (swamps, marshes), where abundant and diverse food sources would have been available in the vicinity (e.g., Amkreutz, 2013, pp. 107-110, 300-301 and references therein; Brouwer Burg, 2013, p. 2311; Kasse et al., 2018, p. 4 and references therein; Louwe Kooijmans, 1980, pp. 110, 112; J. H. M. Peeters et al., 2015, pp. 287-300, 303-313, 315-317 and references therein). Non-active coastal barrier and higher-lying and dry parts of mudflats and saltmarshes could as well have been suitable places for habitation (e.g., Amkreutz, 2013, pp. 63, 300-301, 332 and references therein; Vos et al., 2015, p. 83). The Atlantic period witnessed the first features of the Neolithic farming practices and animal husbandry in the Netherlands (e.g., Amkreutz, 2013, pp. 27-30, 39-41, 44, 46-47, 124-128, 349 and references therein; Louwe Kooijmans et al., 2005; Out, 2009 and references therein).

The archaeological record provides some evidence for ecological exploitation by Early Holocene humans in the Netherlands. Hazelnut (*Corylus*) seems to have been an important component of the diets during the Mesolithic, for they provide fat and proteins (e.g., Bos & Urz, 2003, p. 32 and references therein; Kubiak-Martens et al., 2015, p. 280; Verbruggen, 2023, p. 182 and references therein). Some even attributed the spread of *Corylus* (partially) to human preferences (cf., Smith, 1970; Bos & Urz, 2003, p. 33; Huntley, 1993; Sevink et al., 2018; Theuerkauf et al., 2014, pp. 183-184 and references therein). More becomes known of the human exploitation of other plants (Kubiak-Martens et al., 2015, pp. 272-273, 276-285 and references therein).

Generally, the late Pleistocene to Early Holocene Netherlands likely provided suitable habitats for humans to survive, live in and exploit resources. Nevertheless, people likely also faced ecological challenges in several localities in the landscape.

1.3. Human exploitation of the late Pleistocene to Middle Holocene Western Netherlands

Not much is known about the lives of the Palaeolithic and Mesolithic hunter-gatherers of the Western Netherlands (see the ARCHIS database of the *Rijksdienst voor het Cultureel Erfgoed* of the Dutch Ministry of Education, Culture and Science (https://archis.cultureelerfgoed.nl/)). This mostly has to do with the depth of sedimentary layers in which Palaeolithic and Mesolithic finds would be preserved, *if* they lived in the environment. Prospective and investigative research normally does not reach the Basal Peat and Pleistocene sand layers, which are preserved many metres below ground level, even up to 22 metres below NAP (Dutch ordnance level) along the coast, like in the Yangtze Harbour (e.g., Peeters et al., 2017, pp. 36-37; Vos & Cohen, 2015, p. 63).

Nevertheless, the coastal Western Netherlands is likely to have offered favourable, diverse exploitation areas too (see, e.g., Amkreutz, 2013, pp. 107-110, 300-301 and references therein). Reconstructing the environment of the late Pleistocene to Middle Holocene Western Netherlands could lead to valuable insights into the suitability of the environment in the past, with possible implications for prospection of Palaeolithic and Mesolithic archaeology.

1.4. Background of the Vrouw Vennepolder and research questions

The Vrouw Vennepolder is located in the Western Netherlands near Oud Ade, in the surrounding of Leiden, and it offers an interesting setting in the dynamic Dutch coastal environment. It is located in the municipality of Kaag en Braassem, province of Zuid-Holland (Figure 1.1).

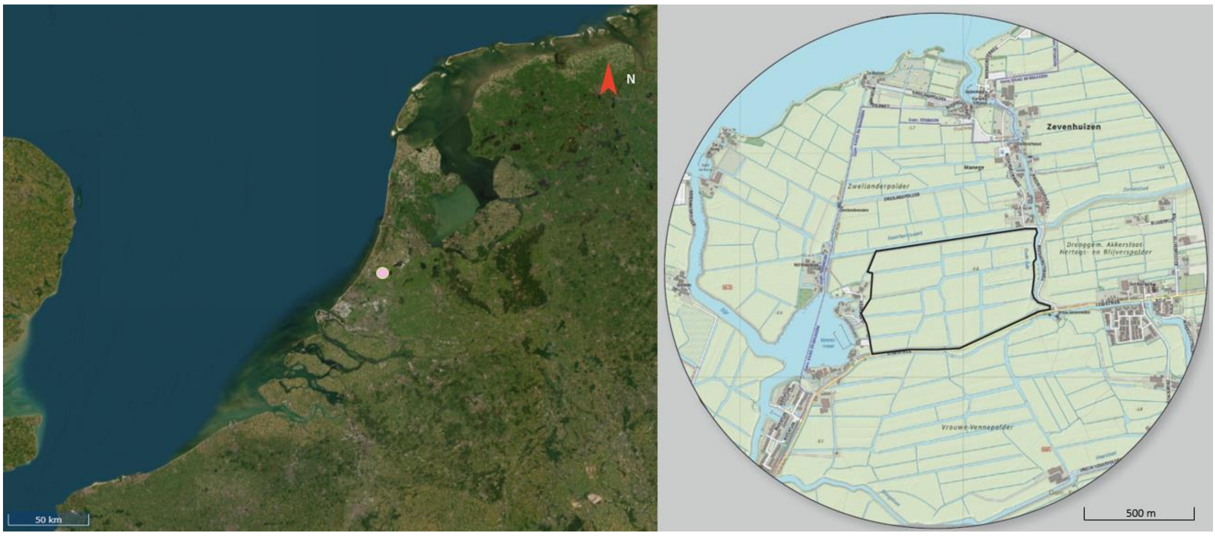


Figure 1.1: Map of North-western Europe, with the location of the Vrouw Vennepolder, Oud Ade, the Netherlands, annotated with a pinkish dot. The black line in the smaller map in the circle outlines the Vrouw Vennepolder's location in the polder landscape near Oud Ade. Source: modified map from a partial screenshot of https://apps.neotomadb.org/explorer/ and map from 'de plannen voor Oud Ade/Polderlab Vrouwe Venne' (https://landvanons.nl/perceel/oud_ade/).

In the past, the site was part of the dynamic coastal environment and, in the wider surrounding, the Rhine and Old Rhine had been heading on their way to the North Sea and they marked their presence (e.g, Berendsen & Stouthamer, 2000, p. 324; Hijma et al., 2009, p. 15). In addition, the polder is currently positioned some kilometres behind coastal dunes. A polder was created at the site at some time during the 17th century CE, where a fen was located previously (Koekkelkoren, 2014, p. 10). Besides, unlike parcels in the surrounding, the Vrouw Vennepolder has not been subjected by peat reclamation, turf winning and building activities. It provides a fairly undisturbed, well-preserved record of the dynamic geological history in the area from at least the late Pleistocene onwards, presenting an opportunity to study the environmental genesis of the coastal landscape in this part of the Netherlands. This thesis focusses on the lithological and palynological deepest parts of a lithological core that were retrieved from the polder, which, as will be discussed, dates to the late Pleistocene to the Early Holocene, especially the (later) Boreal in the transition towards the Atlantic.

Understanding changes in the depositional environment and vegetation from the polder increases our knowledge on the palaeoenvironmental development of this part of the Western Dutch coast, particularly during the late Pleistocene and Holocene. It also provides insights into the local coastal dynamics and formation of the Basal Peat, from which several palynological samples were extracted.

No Palaeolithic nor Mesolithic artefacts have been unearthed in the surrounding of the polder (https://archis.cultureelerfgoed.nl/). By studying the available environmental data, it is possible to gain insights into what ecological conditions humans could have faced *if* they were present, on a regional and local scale. Thereby, this thesis contributes to studying possible abiotic ecological challenges for human exploitation and habitation, in relation to the changing natural environment. One could then reflect on the suitability of a region for human exploitation and habitation, and possible natural barriers for human expansion on a more local scale. In turn, this has implications for archaeological prospection. Thinking about, assessing and understanding what ecological conditions, and challenges, people could have faced in the transition to and during the time of progressive marine transgression during the late Pleistocene and Holocene might prove to be fruitful, perhaps also with the prospects for potential future conditions for humans (see e.g., van Koningsveld et al., 2008), such as transgression and future drowning of parts of the landscape of the Low Countries.

Nonetheless, one should first consider the environmental conditions in the past in order to assess implications for human exploitation and occupation. The research questions in this thesis are:

1. What did the regional and local vegetation and environment of the Vrouw Vennepolder look like through time, during the times of deposition of the analysed microfossil assemblages?

2. How could humans have coped with the local, abiotic challenges for ecological exploitation and habitation in and near the Vrouw Vennepolder environment during the late Pleistocene to the Middle Holocene, according to the available environmental and archaeological data?

1.5. Thesis outline

Chapter 2 provides a further background of the Vrouw Vennepolder study area. It then specifies the age determination of the lithological units and analysed palynological samples. It additionally provides a background about the Dutch coastal landscape development since the Saalian, the Rhine and Old Rhine river along the Dutch coast and reconstructing early Holocene vegetation in the Western Netherlands, using past palynological investigations. Chapter 3 discusses the vegetational and environmental development of the Vrouw Vennepolder, human ecological opportunities and challenges in and near the Vrouw Vennepolder, hazard perception – likely important in how people coped with ecological challenges – and prospection of the Palaeolithic and Mesolithic Western Netherlands. Thereafter, in Chapter 4, conclusions from this paper are presented, by answering the research questions and providing suggestions for future research.

2. Contextual background

This chapter starts with a more elaborate description of the study area. Subsequently, an age determination of the analysed samples is given. It is described that the pollen assemblage from the sands might originate from the Pleistocene and that the pollen assemblages from Basal Peat and Wormer Member clay point to a (late) Boreal age. Further in this chapter, information about the development of the coast of the Netherlands from the Saalian onwards is provided. This is because the Kreftenheye Formation sand formed during the Pleistocene since the (middle) Saalian and the glaciation profoundly impacted the landscape. The evolution of the Rhine and Old Rhine in the Dutch landscape is discussed as well, because of the influence they had on the environment, including in study area. The succeeding section offers information on inferring early Holocene vegetation in the Western Netherlands through palynology. This is all to obtain contextual background information, which helps place the yielded palynological dataset from the Vrouw Vennepolder into a temporal and spatial context.

2.1. Study area

Currently, the Vrouw Vennepolder is a peat meadow area (Dutch: *veenweidegebied*), west of the village Oud Ade, grazed by livestock. Contrary to the wider surrounding polder areas, peat extraction was not undertaken in the Vrouw Vennepolder.

The polder is owned by the 'Land van Ons' foundation and is part of a research project called 'Polderlab Vrouwe Venne'. The cooperation is composed of individuals who purchase parcels of land. The land is used to investigate soil quality, carbon uptake, subsidence, recreation and how agriculture can be performed and managed sustainably and with the aim of a liveable future for farmers, while increasing biodiversity and keeping the groundwater level high (https://landvanons.nl/onderzoek-vrouw-vennepolder/; https://landvanons.nl/onsplan/; https://landvanons.nl/perceel/oud_ade/). The project works together with Leiden University, Leiden Centre for Applied Bioscience (LCAB), Naturalis Biodiversity Center, Institute of Environmental Sciences (CML), *Nederlands Instituut voor Ecologie* (NIOO-KNAW), Holland Rijnland (a cooperation with different municipalities) and the local community.

A coring project by the Faculty of Archaeology of Leiden during the summer of 2022 in the Vrouw Vennepolder, in which I participated, aimed to reveal the development of the landscape of the polder through time. The fieldwork, during which 62 lithological corings were described, offered a well-preserved lithological, palynological and malacological record. The locations of the corings in the polder are shown in Figure 2.1. The palynological samples that are researched in this thesis come from coring 51, of which a lithological description is included in Appendix 1. For a description of the analysed samples and methodology, one is referred to Appendices 2 and 3.

Figure 2.1: Coring locations and their numbers in the Vrouw Vennepolder, Oud Ade, the Netherlands. 62 corings were researched, in three transects. For this thesis, coring 51 (its location is indicated with an orange dot, with coordinates X: 97724.065; Y: 467502.659; -2.195 m NAP (‘*Normaal Amsterdams Peil*’, the Dutch ordnance level) was studied for its archaeobotanical content. To the east of the polder in the present-day situation, the watercourse the Oude Ade flows behind a levee. North of the polder flows the Boekhorstvaart and the Vennemeer is positioned to the west of the polder. South of the polder, a road – the Leidseweg – is located. The polder itself is cut by several small channels and comprises an area of approximately 33 hectares (https://landvanons.nl/perceel/oud_ade/). Source: modified map from the BA3-intership report of de Lange, 2022, his Figure 2 on p. 5, after the map made by Hanmeng Li.

2.2. Age determination

Radiometric dating from the Vrouw Vennepolder could have yielded a high-resolution age of a part of the sequence. However, no terrestrial macrofossils were obtained to provide an absolute age determination. Aquatic remains and bulk materials are not favourable for dating, because of severe limitations (e.g., Philippsen et al., 2013; Quik et al., 2022, pp. 3-5, 10, 13-20, their Fig. 1, their Table 1 and references therein; Shore et al., 1995; Törnqvist et al., 1992; van de Plassche, 1982), so no radiometric dates were obtained from the Vrouw Vennepolder itself.

In the absence of suitable materials for AMS ^{14}C-dating, narrowing down the age determination of the sampled sequence at Vrouw Vennepolder will have to rely on relative age determination, i.e., through lithostratigraphic and biostratigraphic comparisons.

2.2.1. Lithostratigraphy

A lithological profile from the coring project in the Vrouw Vennepolder shows the evolution of the Late Quaternary landscape through time (Figure 2.2 and references therein).

The deepest layer that was reached during the coring campaign was a sand layer. It generally is slightly silty and shows a fairly variable sand grain size range – between 75 and 420 μm; a grain size description for coring 51 lacks. Because of the depths, variable sand grain size and sand grain size of up to 420 (which is coarser than would be expected from coversands of the Wierden Member of the Boxtel Formation (see TNO-GDN, 2023a), of which the presence was indicated in the municipality (Huizer et al., 2011, p. 14; Nales, 2018, p. 6)), poor sorting and (mainly) yellowish colour association, these sand deposits can be correlated to the Kreftenheye Formation, which has a fluvial origin and possible late Middle Pleistocene (late Saalian) to Early Holocene age of deposition (TNO-GDN, 2023b and references therein; van Staalduinen, 1979, p. 29).

On top of the Kreftenheye Formation sand, peat developed. It forms a brown and compact layer, usually not thicker than 1.5 meters, and is referred to as Basal Peat (see also section 2.3. and references therein; TNO-GDN, 2023c). There was an unconformity between the deposition of the Kreftenheye Formation sand and Basal Peat (see section 2.2.2.1.), which makes the lithostratigraphic age determination for the layers on top of the Kreftenheye Formation sand less certain. An unconformity is 'a break in sedimentation' (Nichols, 2009, p. 302), 'a boundary surface between two units, which represents a period of nondeposition and possibly erosion'

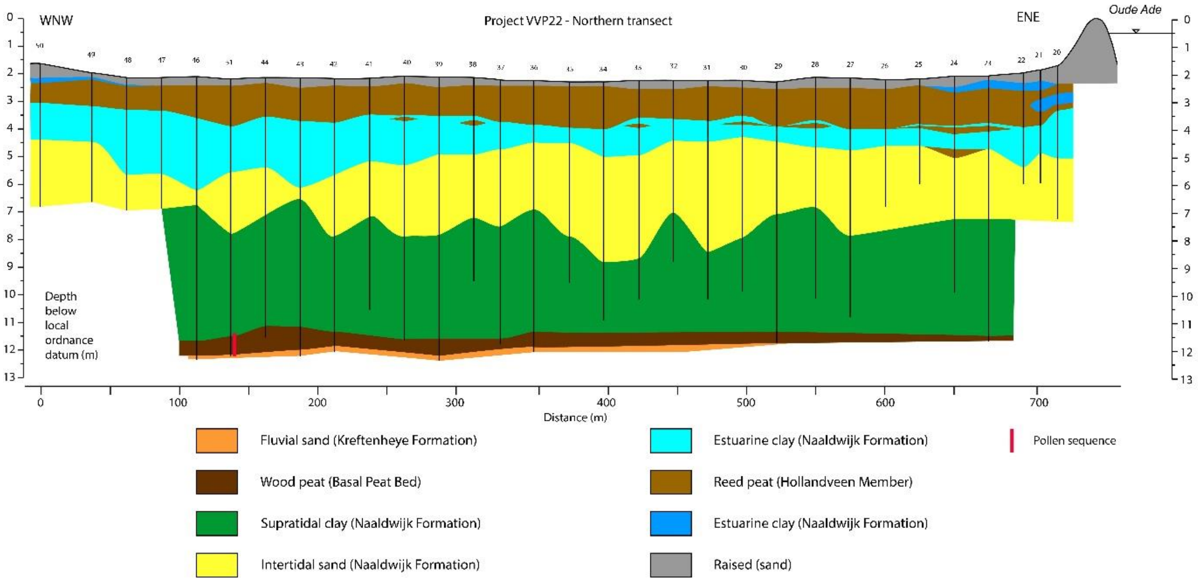


Figure 2.2: Lithological profile of the northern transect from the Vrouw Vennepolder, from corings 20 to 51. Coring 45 is left out and replaced by coring 51, which was placed one metre south of coring 45 and studied in the thesis. The colours represent different lithologies and depositional environments. Multiple layers are present, and these are also represented in the southern transects from the polder. Correlation of the lithology is mainly based on geological profiles and developments from the surroundings of Rotterdam, The Hague and Haarlem (for references on the landscape development of the Western Netherlands, see sections 2.3.), but also on smaller-scale investigations in the surrounding of Oud Ade (see de Rijk et al., 2020; de Rijk & Kruidhof, 2020; Huizer et al., 2011; Koekkelkoren, 2014; Koekkelkoren & Moerman, 2012; Leuvering, 2021; Mol, 2021; Nales, 2018; Nieuwlaat, 2022; Pape-Luijten, 2020; Wilbers & de León Subías, 2019). The depth of the profile is indicated in metres below NAP (‘*Normaal Amsterdams Peil*’, the Dutch ordnance level). Source: modified after Dr. J. A. Mol, 2023, https://landvanons.nl/diep-bodemonderzoek/?src=mailing, by Dr. J. A. Mol and me.

(Marshak, 2018, p. 458). These layers presumably are of Holocene age. Figure 2.2 gives probable correlations of the Holocene lithostratigraphic layers. Due to the dynamic environment with coastal and fluvial processes, some lithological units are difficult to interpret and categorise. The layer on top of the Basal Peat consists of clay, likely saltmarsh/supratidal deposits given the plant matter content and (moderate) firmness, that are correlated to the Wormer Member, which were Early and Middle Holocene estuarine and tidal deposits (TNO-GDN, 2023d and references therein).

Botanical sample 1 was extracted from the deepest sand layer. Based on lithostratigraphy, sample 1, retrieved from Kreftenheye Formation sand, was deposited during a period in the late Pleistocene and/or early Holocene. Samples 2 to 8 were extracted from the Basal Peat and sample 9 was from the Wormer Member clay. Samples 2 to 9 were, then, probably deposited during some periods in the early (Early and/or parts of the Middle) Holocene.

2.2.2. Biostratigraphy

The biostratigraphic age determination is based on the pollen assemblages from the Kreftenheye Formation sand, Basal Peat and Wormer Member clay from the Vrouw Vennepolder (Figure 2.3a and b; see Appendix 3 for the methodology; Appendix 4 for the palynological counts). Because age determination is essential for placing the data into context and the discussion of this paper concerns the reconstruction of the regional and local vegetation and environment, the pollen diagram is already presented in the contextual background chapter, rather than placed it in a separate results chapter.

To aid biostratigraphic correlation with sequences obtained from other locations in the Western Netherlands, cluster analysis was applied to the Vrouw Vennepolder dataset. This resulted in the identification of two distinct Local Pollen Assemblage Zones (LPAZs): VVP-1 and VVP-2, with a zone boundary at 970 centimetres below depth (Figure 2.3a and b). A distinction can namely be made between regional and local pollen assemblage zones. Local pollen assemblage zones (LPAZs) are established based on the principal terrestrial taxa (e.g., Lowe & Walker, 2015, p. 189 and references therein) and can differ from one location to the other. Regional pollen assemblage zones (RPAZs) are established due to shared similarities of the pollen record to sites in the region (e.g., Lowe & Walker, 2015, p. 189 and references therein).

2.2.2.1. LPAZ VVP-1

Kreftenheye Formation sand

Sample 1 was extracted from Kreftenheye Formation sand from the Vrouw Vennepolder. It is characterised by the dominance of *Betula* shrub (*Betula nana*) and *Pinus* pollen (including many halves, i.e., broken grains consisting of a single saccus, with or without part of the corpus attached). In addition, *Corylus* is represented too, approximately 12 %. The percentage of herbaceous and shrub taxa is small – approximately 15 %. Additionally, many pollen grains were damaged to the point that they were unidentifiable. Preservation of organic remains in sand is generally known to be poor (see, e.g., Cushing, 1967). It is important to note that the pollen deposition from the fluvial sands covers a period of unknown duration, as riverine transport and surface runoff, reworking, mixing and/or dispersal by wind may have influenced the palynological record from the sample (cf., Birks et al., 2016, p. 16 and references therein; Bos et al., 2001, p. 280 and references therein; Hoek, 1997a, pp. 23-24). *Corylus*, *Alnus* and *Pinus* existed in the Netherlands during the Eemian interglacial (e.g., Janssen, 1974, pp. 49-50), whereas the (*Betula* and *Juniperus*) shrub representation might point to colder phases according to its ecological tolerance (cf., Bos et al., 2005a, p. 276; Buchwal, 2023, pp. 493, 497, 501-504; de Groot et al., 1997, p. 243; Kasse et al., 1995, pp. 401-402; van Geel et al., 1981, pp. 408-409) and common identification in Late Glacial deposits in the Netherlands (Hoek, 1997a, p. 28). The percentual contribution of *Betula nana* pollen to palynological records in the Netherlands is believed to decline towards the Holocene (Hoek, 1997a, p. 28). As the sand has a fluvial origin, some pollen grains could have been subjected to long-distance transport, with sources further away in the river catchment area. Reworking, redeposition and bioturbation could also have occurred and disturbed the pollen record from the sand. Preservation was also poor compared to the preservation of the record of the other samples. Additionally, uncertainty of an age prevails as just one sample from the sand was studied and it would have been better to be able to compare sample 1 to deeper samples. Furthermore, the pollen accumulation rate is not known, so it is not known how long it took for the sample to be deposited and how much time is represented in the sample. It might, because of the problems with biostratigraphic correlation, only be possible to assign a Pleistocene age to the sand from the Vrouw Vennepolder.

Unconformity

Between the Kreftenheye Formation sands and Basal Peat layer in the Vrouw Vennepolder, an unconformity is present. The hiatus in the sedimentary record could be caused by the cessation of sedimentation and/or erosional processes. One explanation could be that the river channel influence moved a greater distance away from the area, sedimentation stopped and erosion (and reworking and/or blowing in of sediment) took place during times of low sea level. When the groundwater table level rose during the Holocene (see section 2.3.), peat formed on top of the quite consolidated sand substrate, which would prevent further erosion. It is thus likely that some time (of the Early Holocene and perhaps Pleistocene) is not represented between samples 1 and 2. The presence of a hiatus is also shown in the 'sudden' increase of *Corylus* percentages above the sand–peat contact zone.

Basal Peat

Despite being on the other side of the unconformity and being extracted from another lithological unit, cluster analysis suggests that the pollen assemblage from the bottommost sample (2) of the Basal Peat is also part of LPAZ VVP-1 and that it is distinctly separate from that of the overlying Basal Peat sequence (samples 3 to 8).

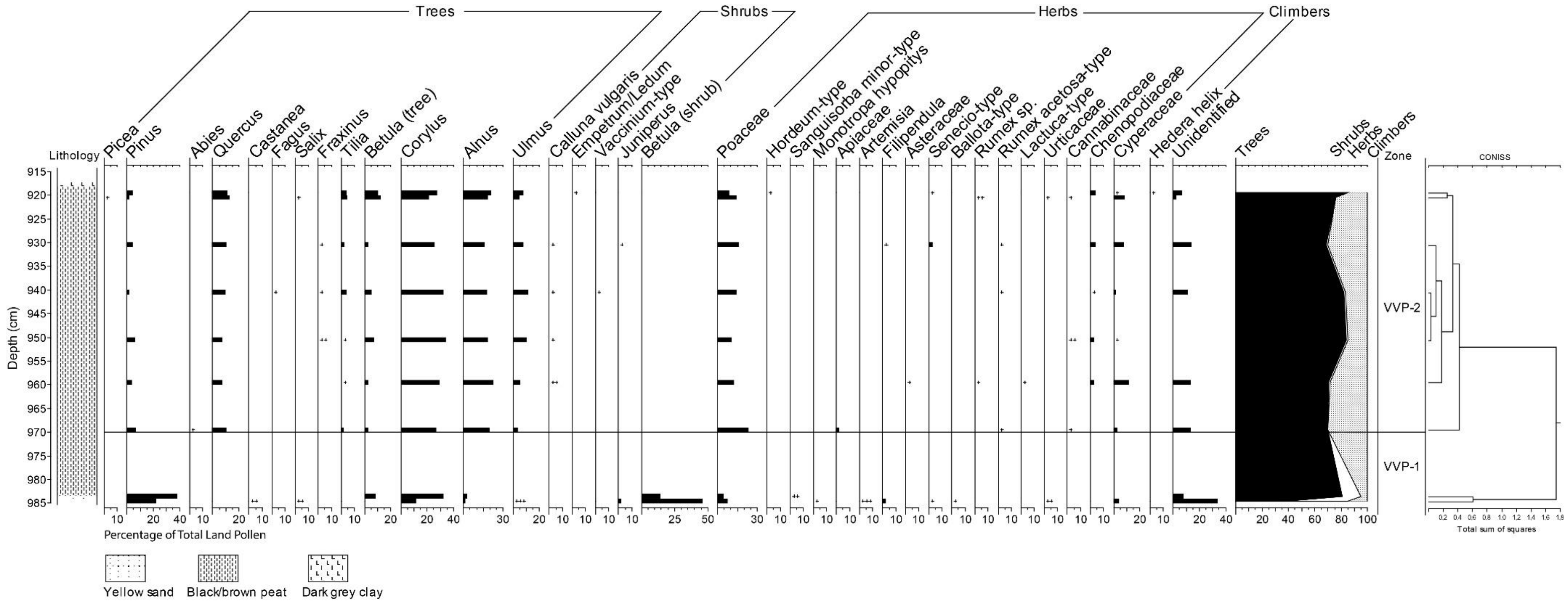


Figure 2.3a: Pollen diagram of the analysed palynological sequence from the Pleistocene sand, Basal Peat and Wormer Member clay from the Vrouw Vennepolder, the Netherlands. Percentages of tree, shrub, herb and climber plant taxa relative to the Total Land Pollen Sum (TLP) are shown. A CONISS cluster analysis is added, making it possible to discern two local pollen assemblage zones (LPAZs VVP-1 and VVP-2). The zone boundary is drawn directly below the beginning of the second pollen zone. The pollen diagram was made using TILIA, by me with the aid of Dr. Ilse M. Kamerling.

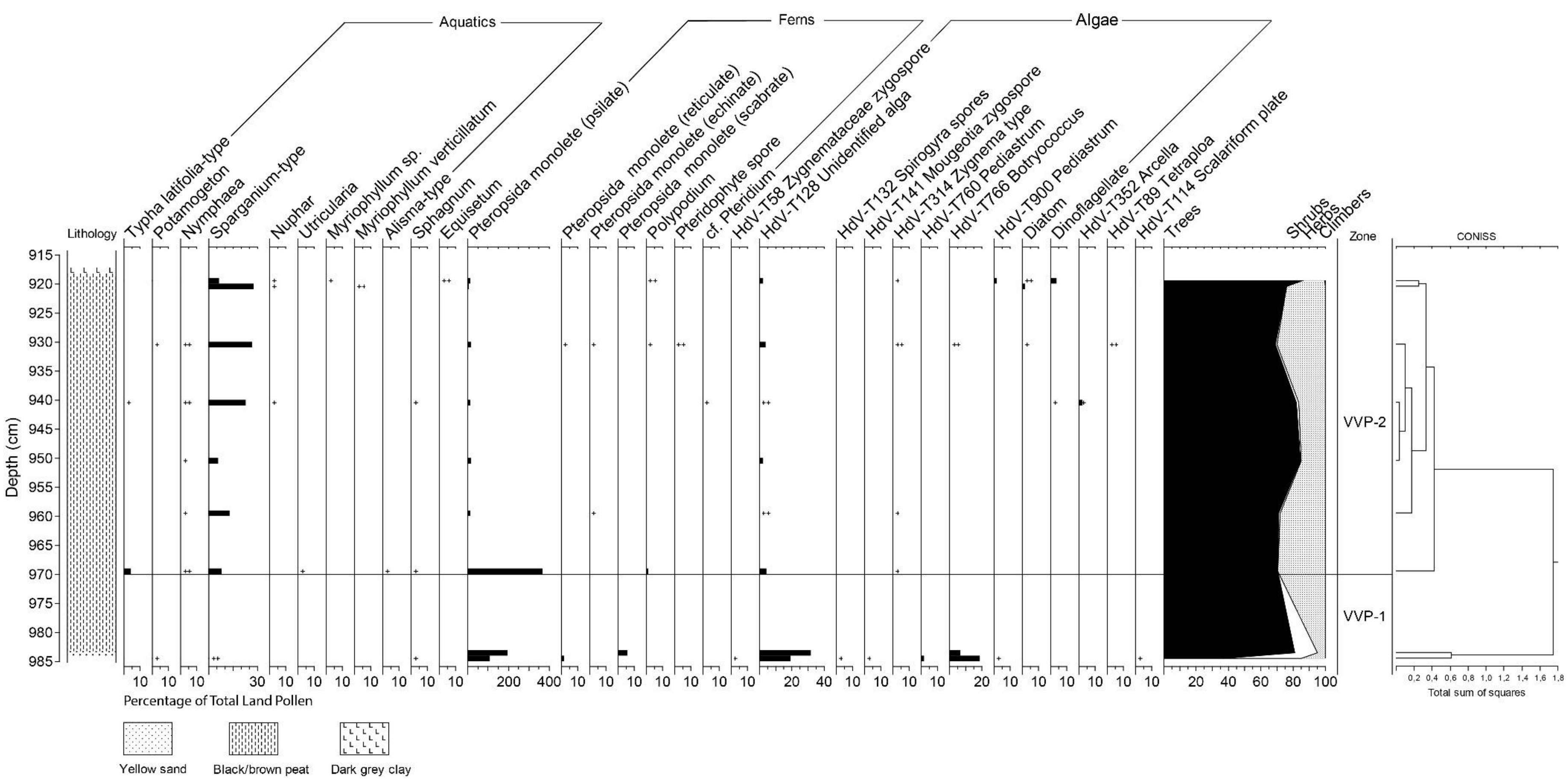


Figure 2.3b: Pollen diagram of the analysed palynological sequence from the Pleistocene sand, Basal Peat and Wormer Member clay from the Vrouw Vennepolder, the Netherlands. Percentages of aquatic plant and fern taxa, *Sphagnum*, *Equisetum*, algae and other non-pollen palynomorphs remains relative to the Total Land Pollen Sum are shown. A CONISS cluster analysis is added, making it possible to discern two local pollen assemblage zones (LPAZs VVP-1 and VVP-2). The zone boundary is drawn directly below the beginning of the second pollen zone. The pollen diagram was made using TILIA, by me with the aid of Dr. Ilse M. Kamerling.

The most marked difference of sample 2 with other samples from the Basal Peat is that sample 2 still comprises a high amount of *Pinus* pollen and some *Betula nana*, in addition to some tree *Betula*, and that *Alnus* was recorded at less than 5 % of the total land pollen sum (TLP). The percentage of the *Pinus* prominently decreases and *Betula nana* becomes 0 % in the younger Basal Peat samples. Moreover, contrary to younger samples from the peat, no *Quercus*, *Tilia* and *Ulmus* were counted in sample 2. Sample 2 might be of Early Holocene/Boreal age, given the high percentual values of *Pinus* and *Corylus* and (medium-high) percentages of *Betula* (Cappers & Neef, 2012, p. 360; Hoek, 1997a, p. 27; Hoek, 1997b, p. 78; van Geel et al., 1981, p. 399).

The pollen record from sample 2 also differs from sample 1. The samples come from two different lithologies too, with an unconformity in between. The Basal Peat of sample 2 did contain some sand, of which the presence might be explained by mixing, deflation of sand in the past and/or bioturbation. It would have been better to have more than one palynological sample from the Kreftenheye Formation sand for comparison in order to determine whether a subdivision in LPAZ VVP-1 could have been created, forming a zone or subzone boundary, to distinguish the pollen from the Basal Peat and Kreftenheye Formation sand. However, they both share the dominance of *Pinus*, *Corylus* and *Betula* pollen, so no additional subdivision was placed between the two samples.

2.2.2.2. LPAZ VVP-2

Basal Peat and Wormer Member clay

Corylus dominates the pollen percentages in all the samples of LPAZ VVP-2 (samples 3 to 9), which were extracted from Basal Peat and Wormer Member clay. Pollen diagrams from North-western Europe from the early Holocene generally show an increase in *Corylus* pollen percentages and they indicate an increase in the pollen percentages of *Quercus*, *Tilia*, *Ulmus* and *Alnus*, mostly at the cost of *Pinus* pollen, in the later Boreal, towards the Boreal–Atlantic transition (e.g., Bos & van Geel, 2017, p. 124; Cappers & Neef, 2012, p. 361; Hoek, 1997a, p. 27; van Geel et al., 1981, pp. 399, 414; Zuidhoff & Bos, 2017, pp. 145-146). It is therefore plausible that the pollen assemblages from the Basal Peat and Wormer Member clay with LPAZ VVP-2 signal suggest that these were deposited during the later Boreal period. Further to this, the percentages of *Pinus* prominently decrease, *Betula nana* disappears and medium-high percentages of *Quercus*, *Tilia* and *Ulmus* and quite high values of *Alnus* (around 20 %) are recorded, which were not represented like that in VVP-1.

According to several pollen records, *Alnus* pollen percentages become higher during the Atlantic age than in the Early Holocene, as *Alnus* expanded, though regional differences occurred (e.g., Cappers & Neef, 2012, p. 357; Woelders et al., 2016, p. 185; van Geel et al., 1981, p. 399; Zuidhoff & Bos, 2017, p. 146). Higher percentages in a pollen diagram might also be explained by more local presence of *Alnus* trees. Nevertheless, during the Atlantic, *Corylus* and *Pinus* decrease at the expense of (among other tree taxa but mostly) *Quercus* (e.g., Janssen, 1974, p. 56; Zuidhoff & Bos, 2017, p. 146). That is not the case in the pollen diagram from the Vrouw Vennepolder. The pollen samples from the Basal Peat and Wormer Member clay layers from the Vrouw Vennepolder have high *Corylus* pollen percentages (ca. 25 – 33 %), but the pollen of other thermophilous trees (e.g., *Quercus*, *Ulmus*, *Alnus*, *Tilia*) do not yet dominate the pollen spectrum. Very few (less than 1 %) pollen of *Fraxinus* and *Fagus*, of which the expansion occurred during the Atlantic period, are present in the samples. These pollen likely were from early established trees and the percentages are not as high as would be expected during the Atlantic, suggesting the pollen spectrum still points to the later Boreal period.

Hedera helix is sometimes described as an 'Atlantic' taxon (e.g., Cappers & Neef, 2012, p. 363; Janssen, 1974, p. 56; van Geel et al., 1981, p. 411; Zuidhoff & Bos, 2017, p. 146), because it prefers fairly high winter temperatures (e.g., Cappers & Neef, 2012, p. 363), but it was also present in the Netherlands earlier during the Holocene (van Geel et al., 1981, p. 399; Zagwijn, 1994, p. 74) and is often underrepresented in the microfossil record (Bottema, 2001, pp. 162, 165-166). The single *Hedera helix* pollen grain in sample 9 assumably was produced by a pioneer. The pollen assemblage of sample 9 further corresponds to samples 3 to 8. Likewise, it does not signal the Atlantic, but it represents the late Boreal in the transition to the Atlantic too.

Even though it is difficult to correlate, LPAZ VVP-2 from the Vrouw Vennepolder might be correlated to the record of Baambrugge, the Netherlands (Cleveringa, 1985; de Jong, 1981; de Jong, 1984). The pollen zone from Baambrugge with the highest percentages of *Corylus* and *Alnus*, but also *Pinus*, in addition to medium-high percentages of *Betula*, *Quercus* and perhaps the first *Tilia*, provides an absolute age determination of approximately 9,500 and 8,700 cal. BP. The beginning of LPAZ VVP-2 might then also have a date in this time period, roughly corresponding to the late Boreal. An age determination for LPAZ VVP-1 stays disputable due to the possibility of reworking and/or mixing of the pollen signal.

2.3. Development of the Western Netherlands coast

2.3.1. The late Pleistocene (Saalian to Weichselian)

The sea was an important contributor to the landscape and ecological changes in the coastal environment of the Western Netherlands. The Saalian, during which ice sheets reached the Netherlands (Hijma et al., 2012, p. 29; Zagwijn, 1974, p. 375), altered the landscape by, e.g., shifting drainage patterns and changing the coastline, scouring into the underground and creating ice-pushed ridges and other ice-related landscape features (Busschers et al., 2008, pp. 377-379, 394 and references therein; J. Peeters et al., 2015, pp. 179, 181-183 and references therein; Peeters et al., 2016, pp. 225, 227 and references therein; Verbraeck, 1984; Zagwijn, 1989, pp. 118-119), until the warm Eemian interglacial (Zagwijn 1974, p. 375), which caused marine transgression that inundated parts of the landscape and created estuaries and lagoons along the coast (J. Peeters et al., 2015, pp. 178, 182-183; Peeters et al., 2016, pp. 221-222, 225, 227 and references therein).

During the Weichselian glacial period, the ice never expanded as far south as the Netherlands (Zagwijn, 1974, p. 376), but the dropping of the sea level during stadials (i.e., colder climatic periods) still affected the Dutch coastal morphology and large parts of the Netherlands were characterised by coversands (Berendsen & Stouthamer, 2000, pp. 320-322; Busschers et al., 2007, pp. 3239-3242 and references therein; Cohen et al., 2014, pp. 21-22; Hoek, 2000, pp. 499-500; Peeters et al., 2016, pp. 227-229 and references therein).

2.3.2. The Holocene

The Holocene (approximately 11,650 cal. BP to present) witnessed the relative sea level rise, which gradually inundated former terrestrial lands (de Haas et al., 2018a, p. 149; Hijma & Cohen, 2011, p. 1464; Koster et al., 2016, pp. 785, 789; Pierik et al., 2017, p. 183), and various developments that modified the coastal morphology and landscape of the Netherlands (Figure 2.4). During the Preboreal, the coastline was still positioned several kilometres more to the west (e.g., J. H. M. Peeters et al., 2015, p. 313), but its position and morphology shifted eastwards as the sea level rose. During the Early Holocene, there was a fairly rapid relative sea level rise, but the relative sea level rise slowed down since the Boreal to Middle Atlantic (Hijma & Cohen, 2019, pp. 69-73, 76-77 and references therein).

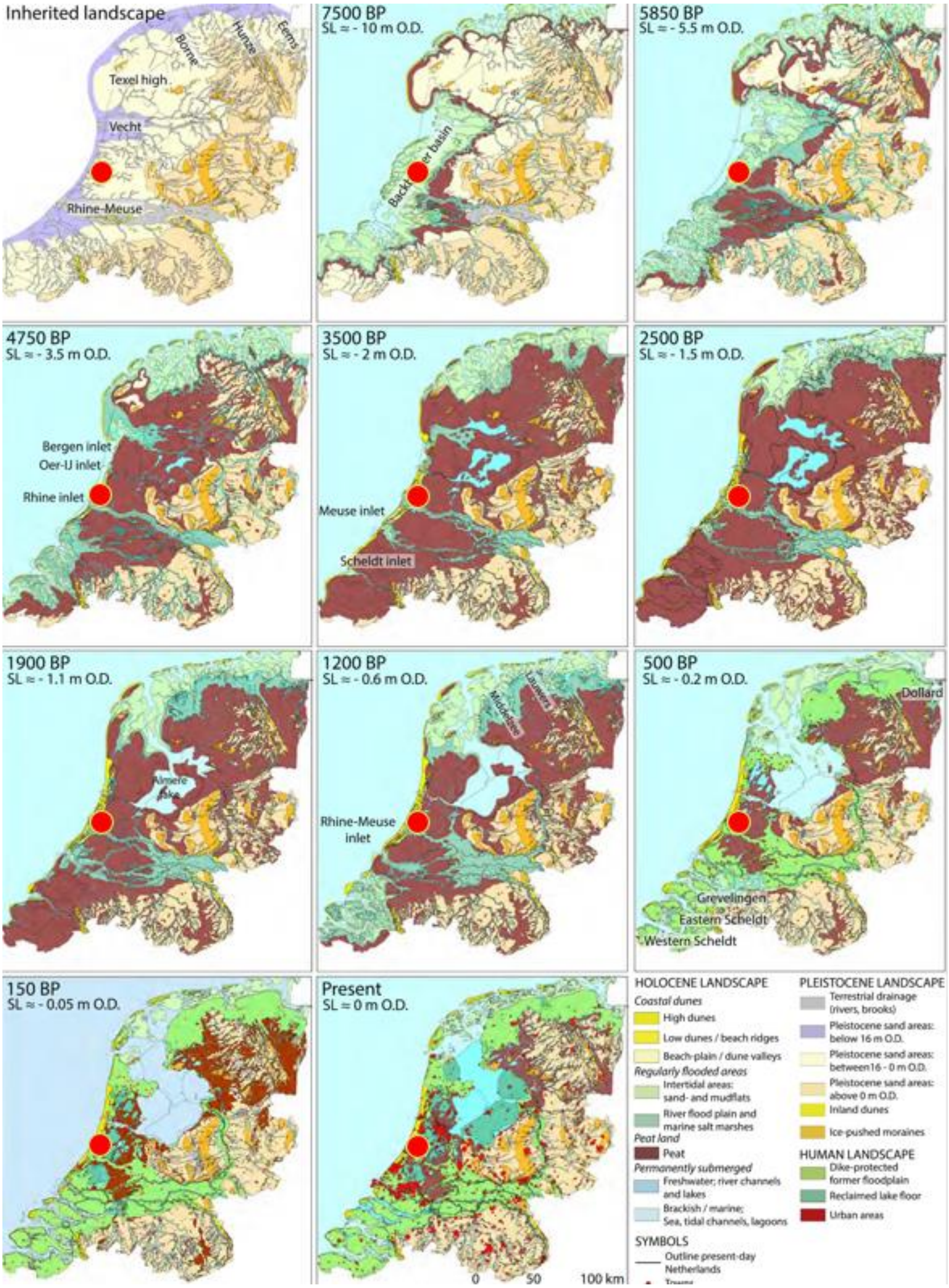


Figure 2.4: Palaeogeographical maps of the Netherlands, showing the simplified, general Holocene geomorphological development through time, based on numerous corings and inter- and extrapolation of data. Around the early Atlantic, the contemporary coastline position was approached (de Haas et al., 2018a, p. 149). The location of the Vrouw Vennepolder is indicated with red dots. Source: de Haas et al. (2018a, their Fig. 4 on p. 146), who modified maps initially made by Vos et al. (2015).

The Holocene drowning of the land by the sea created a shallow sea, which reworked the Pleistocene sand underground by tidal and storm wave action, after which the reworked sediments were subjected to transport (Stouthamer et al., 2015, p. 253). There likely was an Early Holocene coastal barrier system situated off the shore of the Western Netherlands, which was composed of the reworked Pleistocene sand and (to a lesser extent – Beets et al., 1992, pp. 428, 434, 436-437; Beets & van der Spek, 2000, pp. 10, 12-13) sediments brought by the rivers flowing into the North Sea, and protected a tidal basin (Beets et al., 1992, pp. 428-434; Beets et al., 1995, pp. 243-245; Cleveringa, 2000, p. 20; Rieu et al., 2005, p. 414; Stouthamer et al., 2015, pp. 253-254). Dunes could form on top of the coastal barriers (Stouthamer et al., 2015, p. 253).

Because of the coastal barrier system, the back-barrier basin was partly protected from the sea. The Basal Peat formed diachronously during the Early to Middle Holocene (Boreal to Middle Atlantic) in wetlands and marshes in the back-barrier areas upstream of the river mouths (e.g., Beets et al., 2003, pp. 119-120, 123-124; de Haas et al., 2018b, p. 89 and references therein; Hijma & Cohen, 2019, pp. 70-73 and references therein; van der Woude, 1983, pp. 1, 75-82, 84-88, 92-92), as the groundwater table rose in response to, among other things (Quik et al., 2023, p. 965 and references therein; van Asselen et al., 2017, pp. 1694-1696 and references therein), the relative sea level rise (e.g., Beets et al., 1995, p. 243; Beets et al., 2003, p. 124; Berendsen et al., 2007, pp. 333-334; Koster et al., 2016, pp. 775-776, 784 and references therein; van Staalduinen, 1979, pp. 11, 40-42).

The Early Holocene Dutch coastal barrier system was not a closed system. The early Atlantic coastal barrier drowned and a new beach barrier system with several tidal inlets had formed more landward, during retrogradation (Beets et al., 1992, pp. 430-431; Beets et al., 1996, pp. 118-128 and references therein; Beets & van der Spek, 2000, pp. 8, 13; Cleveringa, 2000, p. 16). Consequently, the formation of coastal barriers, with still numerous large tidal inlets, affected Early and Middle Holocene coastal landscape of the Netherlands, as marine, estuarine and tidal deposits assigned to the Wormer Member were sedimented (Cleveringa, 2000, p. 16; de Haas et al., 2018a, p. 149). The Wormer Member, which generally formed diachronously on top of the Basal Peat – developing earlier in the west than in the east (Cleveringa, 2000, p. 16) – reflects the former coastal landscape of tidal flats, mudflats, tidal creeks and saltmarshes (e.g., Beets et al., 1992, pp. 430-431; de Haas et al., 2018a, pp. 149-150; TNO-GDN, 2023d and references therein). In the Vrouw Vennepolder, the Naaldwijk Formation (TNO-GDN, 2023e and references therein), of which the Wormer Member is part, is represented too (Figure 2.2). The plant content, (moderate) firmness and maturity of the oldest, (dark) blue and/or clay layer suggest saltmarsh (supratidal) deposits (TNO-GDN, 2023d and references therein). Superimposed is a (dark) greyish layer with predominantly sand content. It often also contained thin clay layers, reed fragments and/or (fragments of) shells. The layer reflects sediments of a sandy tidal flat (intertidal zone) that can be correlated to the later Early to Middle Holocene Wormer Member deposits too (TNO-GDN, 2023d and references therein). The Naaldwijk Formation estuarine clay layer on top is occasionally humic and crumbly and contains reed and sometimes thin detritus layers and can also be correlated to the Naaldwijk Formation.

Due to the late Atlantic and Subboreal (5,700 – 2,600 cal. BP) progradation of the coast and slowed-down sea level rise, beach barriers increasingly became connected to each other as tidal inlets closed, except for where rivers discharged into the North Sea (Beets et al., 2003, p. 121 and references therein; Cleveringa, 2000, p. 17; de Haas et al., 2018a, p. 150; Vos, 2015, p. 83; Zagwijn, 1986), and, as a consequence, tidal back-barrier basins, protecting lagoons and (fluvio)lacustrine environments (see, e.g., Cohen, 2005, pp. 352-353, 359; van der Woude, 1984, p. 399; van der Woude, 1985, pp. 269-271) developed along the Dutch prograding beach barrier coast (Beets et al., 1992, pp. 429-434, 436-439; Beets & van der Spek, 2000, pp. 4, 8-10, 13; Cleveringa, 2000, pp. 16-18, 20; de Haas et al., 2018b, p. 101; van der Spek et al., 2007, pp. 1129-1932, 1139). Since the later Atlantic, approximately 5,000 years ago, coastal dune formation occurred (see Figure 2.5 and references therein). Because of the halt of the retrogradation (van der Valk, 1996b, pp. 210, 224-225) and progressive infilling of the back-barrier basins during the late Atlantic and Subboreal (Cleveringa, 2000, pp. 18, 20; Hijma & Cohen, 2011, pp. 1467, 1477; Hijma et al., 2010, pp. 208-209; Pierik et al., 2017, p. 184 and references therein; van der Valk, 1996a, pp. 151, 182, 184-189 and references therein), the tidal inlets and tidal channels along the coast gradually closed and marine influence in the back-barrier zone was reduced (Beets et al., 1992, pp. 431-434, 436-439; Beets et al., 2003, p. 121; Beets & Van der Spek, 2000, pp. 7-13; de Haas et al., 2018a, p. 149; van der Spek et al., 2007, pp. 1131-1132). The progradation of the coast commenced at different times at different parts along the coast (Hijma et al., 2009, p. 16; van der Valk, 1996a, p. 195).

As marine influences on the land reduced due to the protection of the beach barrier (Hijma & Cohen, 2011, p. 1477; Pierik et al., 2017, p. 184 and references therein), Hollandveen Peat formation (TNO-GDN, 2023f and references therein) happened further inland in the coastal plain, as marshes, fens, swamps and bogs formed between the branches of the rivers and in (former) back-barrier basins during and after the Subboreal (Beets et al., 2003, p. 120; Cleveringa, 2000, pp. 16-17; de Haas et al., 2018b, pp. 89, 97-101; Pierik et al., 2022, pp. 22-23; Zagwijn, 1986). Until Early Medieval times, the extensive Hollandveen Peat deposits developed in the municipality of Kaag en Braassem (de Rijk & Kruidhof, 2020, p. 10), where the Vrouw Vennepolder is situated.

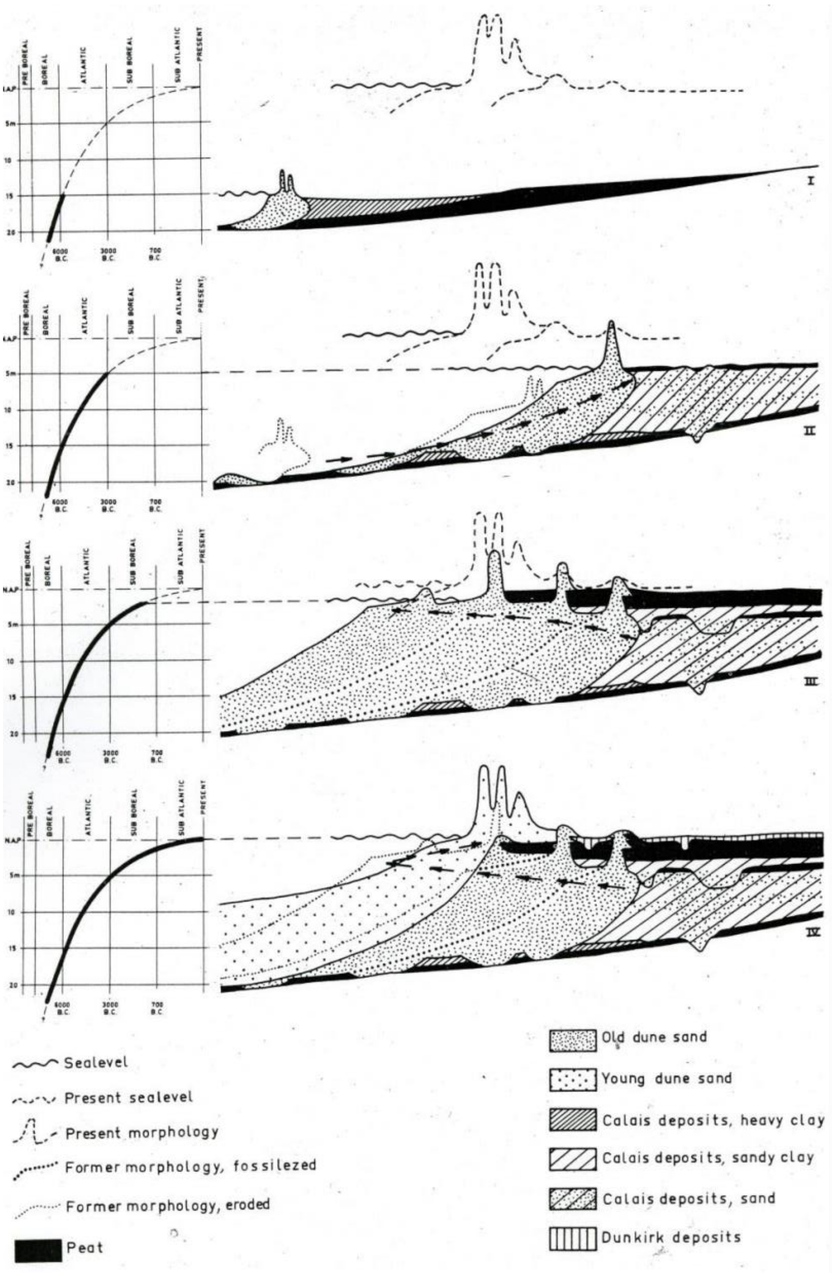


Figure 2.5: The development of the Dutch coastal zone, with the Older Dunes, Younger Dunes, Wormer (previously called Calais) Member and Walcheren (previously called Dunkirk – Pierik & Cohen, 2020, p. 9; TNO-GDN, 2023g and references therein) Member deposits, in relation to the Holocene relative sea level rise in the Western Netherlands. The Old Dune formation commenced on top of the coastal barrier, which formed as sediment supply outpaced the slowed-down relative sea level rise, during the late Atlantic or early Subboreal to the early Subatlantic (Jelgersma et al., 1970; Jelgersma et al., 1995, p. 95; van der Valk, 1992, pp. 138, 167, 210-212; van der Valk, 1996a, pp. 151, 155, 177, 181-190; Zagwijn, 1984, pp. 259-260, 265). Since in the Subatlantic (2,600 cal. BP – present), aeolian activity produced relatively high, parabolic dunes, compared to the older dunes, along the coast of the Western Netherlands – the Younger Dunes (Hageman, 1969, p. 387; Jelgersma et al., 1995, p. 95; van der Valk, 1992, pp. 79-81; Vos et al., 2015, pp. 133-136 and references therein; Zagwijn, 1984, pp. 259-267). Coastal dune deposits, including organic layers within them, are part of the Schoorl Member (TNO-GDN, 2023h). Source: Hageman (1969, his Fig. 9 on p. 386).

The marine influences on the coastal landscape of the Western Netherlands generally increased again during the Subatlantic, when the beach barriers partially opened and marine ingressions occurred (de Haas et al., 2018a, pp. 150, 152 and references therein; Pierik et al., 2017, pp. 184, 187, 189-192). Because of the wide beach barrier complex, the Western Dutch coast was protected from marine incursions (Pierik et al., 2017, p. 189). The marine ingressions produced the Walcheren Member estuarine sediments (de Haas et al., 2018a, pp. 150-152; Hijma et al., 2009, pp. 16-17; Pierik et al., 2017, pp. 184, 187, 189-192; TNO-GDN, 2023g and references therein; van Staalduinen, 1979, pp. 40, 55-67). Local floodings, likely of estuarine/fluvial origin, also occurred in the Vrouw Vennepolder, as indicated by clay layers on top of the Hollandveen Peat (Figure 2.2). Nowadays, the coast is stabilised and maintained (Frings et al., 2019, p. 20 and references therein; Stouthamer et al., 2011, p. 220; van Heteren et al., 2002, p. 7).

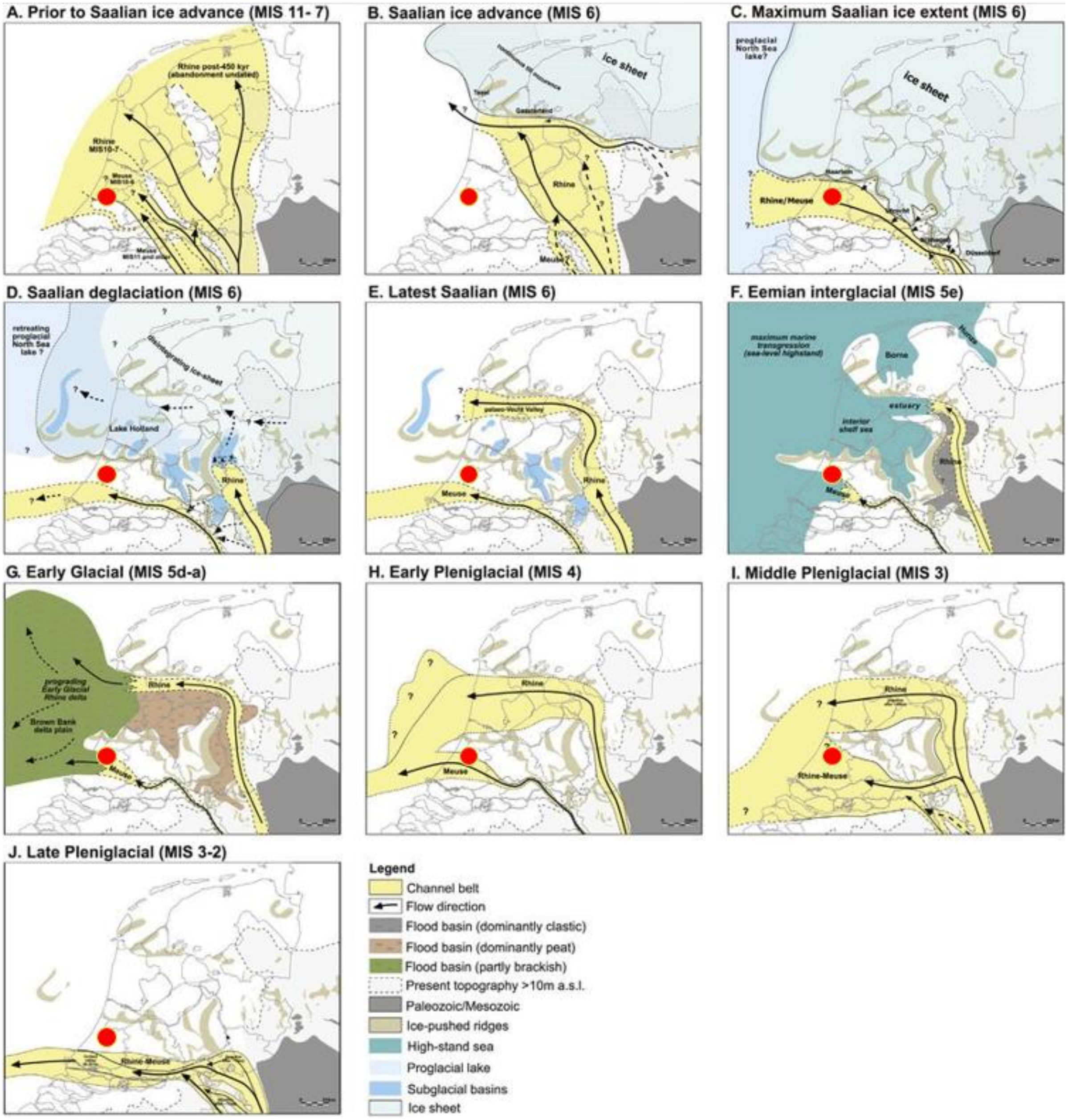
2.4. The Rhine and Old Rhine

2.4.1. The late Pleistocene (Saalian to Pleniglacial) Rhine

In the wider surrounding of the Vrouw Vennepolder, the Rhine and Old Rhine marked their presence. During the Pleistocene Saalian to Weichselian, the Rhine changed its course and pattern several times (Figure 2.6; e.g., Berendsen & Stouthamer, 2000, pp. 320-322; Cohen et al., 2002, pp. 393-394, Fig. 2 and references therein; J. Peeters et al., 2015, pp. 178-179, 181-184 and references therein; Peeters et al., 2016, pp. 213, 225, 227-229 and references therein), and incision and reworking were important in the preservation of the fluvial sediments (e.g., Berendsen & Stouthamer, 2000, pp. 322-323; Busschers et al., 2007, pp. 3241-3244).

2.4.2. The Late Glacial and Holocene Rhine and Old Rhine

The Rhine–Meuse system generally maintained its position in the south of the Netherlands during the Late Glacial to early Middle Holocene, with changing pattern (e.g., braided, meandering; see, e.g., Autin, 2008, pp. 303-304 and references therein; Busschers et al., 2007, p. 3242; Cohen et al., 2003, pp. 129, 132; de Groot & de Gans, 1996, pp. 234-237, 240; van Heteren et al., 2002, pp. 10-11) and channel locations through time (Berendsen & Stouthamer, 2000, pp. 322-326; Berendsen & Stouthamer, 2001; Busschers et al., 2007, p. 3242; Cohen, 2003, pp. 108-111, 113-116, 122-125, 127-129, 132; Hijma et al., 2009, pp. 15-16 and references therein). The Late Glacial to


A. Prior to Saalian ice advance (MIS 11- 7)

B. Saalian ice advance (MIS 6)

C. Maximum Saalian ice extent (MIS 6)

D. Saalian deglaciation (MIS 6)

E. Latest Saalian (MIS 6)

F. Eemian interglacial (MIS 5e)

G. Early Glacial (MIS 5d-a)

H. Early Pleniglacial (MIS 4)

I. Middle Pleniglacial (MIS 3)

J. Late Pleniglacial (MIS 3-2)

Figure 2.6: The palaeogeographic evolution of the Rhine during the Saalian to the Weichselian Late Pleniglacial. The riverine and (fluvio)lacustrine deposits of the Late Saalian until Early Holocene are part of the Kreftenheye Formation (TNO-GDN, 2023a and references therein). Over time, the course of the Rhine changed its spatial position and pattern (e.g., Busschers et al., 2007, pp. 3237, 3239-3242; Busschers et al., 2008, pp. 393-394; de Groot & de Gans, 1996, pp. 232-233; Gouw & Erkens, 2007, p. 24; Peeters et al., 2016, pp. 225-229 and references therein). The location of the Vrouw Vennepolder is indicated with red dots. Source: J. Peeters et al. (2015, their Fig. 4 on p. 180).

Holocene river channels scour(ed) through and reworked the existing Pleistocene deposits (Berendsen & Stouthamer, 2001; Busschers et al., 2007, pp. 3242-3244; Gouw & Erkens, 2007, p. 25; Hijma & Cohen, 2011, p. 1464; Hijma et al., 2009, pp. 16, 33, 46-47 and references therein), following the pre-existing relief in the underground (de Groot & van Gijssel, 1996, pp. 21-24). Aeolian river dunes (Boxtel Formation, Delwijnen Member) formed along the rivers in the Rhine–Meuse area during the Younger Dryas and Early Holocene (e.g., de Groot & de Gans, 1996, p. 238; Hijma et al., 2009, pp. 16, 26, 34, 47-48 and references therein; Kasse et al., 2020, pp. 1-4 and references therein; TNO-GDN, 2023i and references therein; Vos & Cohen, 2015, pp. 109-129).

The main river channel(s) of the Rhine flowed towards the North Sea through the Rotterdam area during the earlier Holocene (Figure 2.7). During approximately the late Atlantic to early Subatlantic, the Rhine river branches likely discharged into the North Sea the surrounding of Leiden, through an old tidal inlet and palaeovalley (Berendsen & Stouthamer, 2002, p. 104; de Haas et al., 2018b, p. 91; Hijma & Cohen, 2011, p. 1470; Hijma et al., pp. 16, 33, 48), whereas it, like the Meuse (Berendsen & Stouthamer, 2000, pp. 104, 107-108; de Groot & de Gans, 1996, p. 241), discharged into the North Sea in the Rotterdam area earlier in the Holocene (Berendsen & Stouthamer, 2000, pp. 322-324; Cohen et al., 2012; de Haas et al., 2018b, p. 91; Hijma & Cohen, 2011, p. 1470; Hijma et al., 2009, pp. 16, 33, 48).

During most of the later Atlantic/Subboreal to the beginning of Subatlantic, the main distributary of the Rhine river system was the Old Rhine (Berendsen & Stouthamer, 2000, pp. 324-326, 328-330; Berendsen & Stouthamer, 2002, pp. 105, 107-108; Cohen et al., 2012; de Haas et al., 2018b, pp. 91, 93, 95-103 and references therein; Hijma et al., 2009, p. 16). The main discharge channel of Old Rhine estuary was eventually abandoned, became less active in terms of sediment input and gradually silted up, especially following avulsions (e.g., Berendsen & Stouthamer, 2002, pp. 105, 107-108), embankments of the main channels and damming further upstream near Wijk bij Duurstede in 1122 CE (Berendsen & Stouthamer, 2000, pp. 324, 329-330; de Haas et al., 2018b, pp. 86-87, 95-96, 102-103; Pierik et al., 2018, pp. 935-937 and references therein; Pierik et al., 2022, pp. 205-206; van Dinter et al., 2017, pp. 255, 257 and references therein). Afterwards, the Rhine discharged into the North Sea in the Rotterdam area again (Berendsen & Stouthamer, 2002, p. 107).

2.5. Early Holocene vegetation in the Western Netherlands based on palynological investigations

Palynological investigations have also been undertaken for vegetation reconstructions of the Netherlands (see, among others, the references in section 1.1. and 2.2.2.). *Corylus* appeared in the birch and pine woodlands of the Netherlands during the early Boreal, or even the late

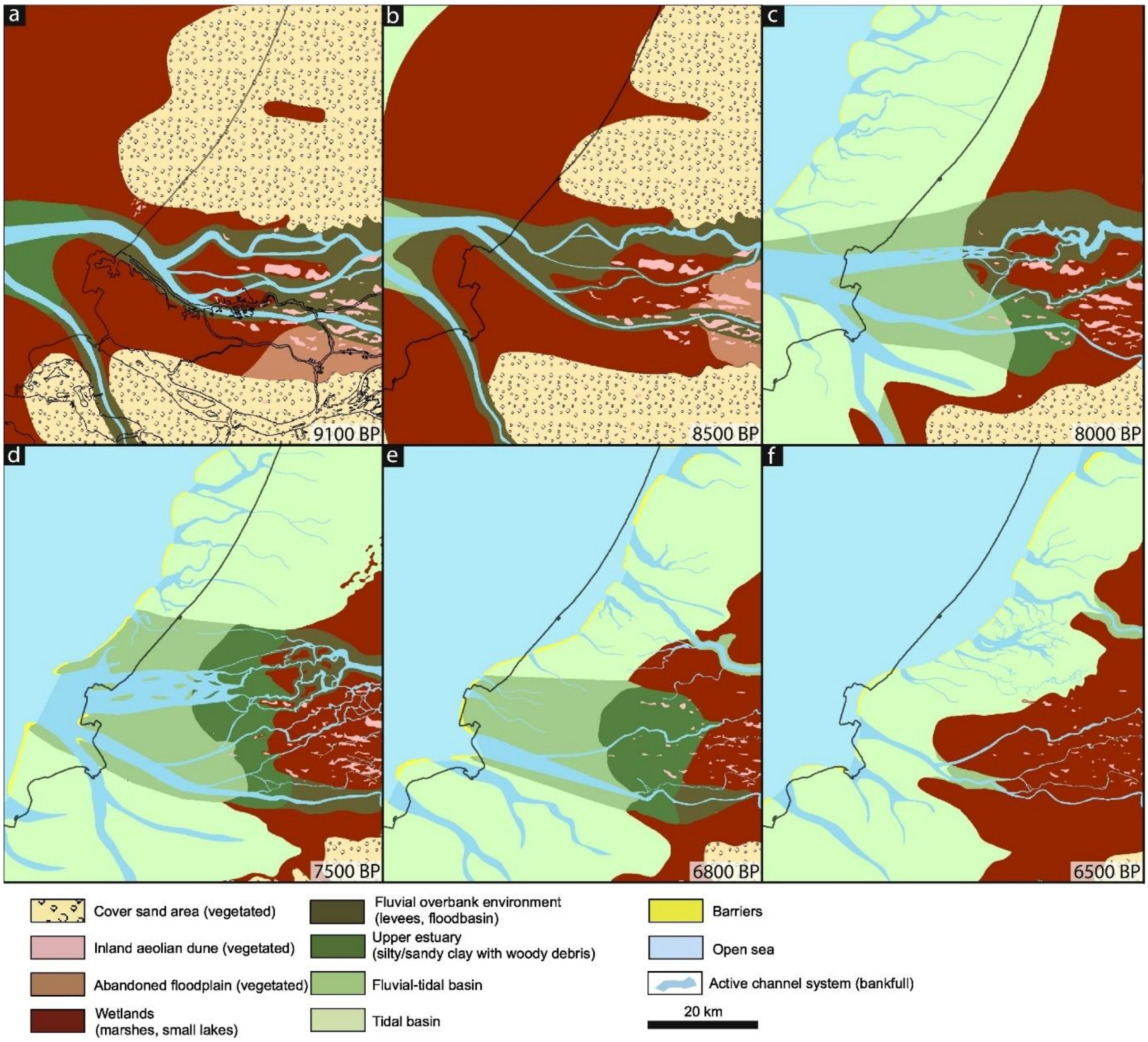


Figure 2.7: The palaeogeographic evolution of the Rhine and Meuse river mouth area during the Early and early Middle Holocene. The gradual northward migration of channels of the Rhine and the changing of the main Rhine river mouth is visible in map views d, e and f. The upper part represents the north. Its levees and extensive peatlands that (had) formed on both sides of the river channel would restrict the lateral movement of the channel (de Haas et al., 2018b, pp. 97-101; Hijma & Cohen, 2011, pp. 1464, 1467, 1470, 1473). During the middle Atlantic period, smaller, secondary Rhine branches also existed, but the southerly outlets of the Rhine became abandoned as the Old Rhine gradually shifted north and an outlet formed (Hijma et al., 2009, pp. 29, 33). The river became part of an estuary which was, at the time, situated in a wide coastal plain. Holocene clastic deposits associated with fluvial activity of the Rhine and Meuse river and river mouth area are fall under the Echteld Formation (TNO-GDN, 2023j and references therein). Source: from de Haas et al. (2018a, their Fig. 6 on p. 148), who modified maps initially made by Hijma & Cohen, 2011.

Preboreal, followed by *Quercus* and *Ulmus* (e.g., Cappers & Neef, 2012, pp. 359-361; Zuidhoff & Bos, 2017, pp. 146-146). *Tilia* came in later in the Boreal and *Alnus* establishes itself in the wetter parts of the Netherlands in the transition towards the Atlantic period (e.g., Cappers & Neef, 2012,

p. 360; Janssen & Törnquist, 1991, their Figure 1). *Betula* trees had already expanded in the Preboreal and, together with *Pinus*, they were also still present and part of the late Boreal, deciduous forest.

The described vegetational development in the Western Netherlands is predominantly captured as a regional signal in pollen diagrams, in regional assemblage zones (RPAZs). Local differences in vegetation composition occurred, and these can be reflected in local pollen assemblage zones (see section 2.2.2.). The palynological record from the Vrouw Vennepolder provides new insights into the regional and local vegetation and environment development in the late Pleistocene to Middle Holocene Western Netherlands.

3. Discussion

This chapter begins with vegetation and environmental reconstructions of the Vrouw Vennepolder, based on the analysed palynological samples signalling the late Pleistocene, Early Holocene/Boreal and late Boreal. The chapter further deals with the question of how humans could have coped with the abiotic ecological challenges for human exploitation and habitation in the late Pleistocene to Middle Holocene environment in and near the Vrouw Vennepolder. Reconstructions of the local environmental development of the polder in the mentioned timeframe are made in this chapter, followed by an evaluation of the abiotic ecological challenges that might have prevailed in the Vrouw Vennepolder environment. Human hazard perception of the long- and short-term abiotic challenges is discussed, since this likely impacts how people – given the timeframe, it were Palaeolithic or Mesolithic hunter-gatherers, with a broad-spectrum subsistence economy – could have coped with the local environment and challenges, with succeeding repercussions on the archaeology in the region. The chapter ends with reflecting on the prospection of Palaeolithic and Mesolithic archaeology, because this is important in studying what we actually know of the Palaeolithic and Mesolithic human responses to the abiotic ecological challenges in and near the Vrouw Vennepolder during the late Pleistocene to Middle Holocene.

3.1. Vegetation and environmental reconstruction of the Vrouw Vennepolder

Section 2.5. provided information on what is known about the past regional vegetation in the late Boreal Netherlands. The pollen record from the Vrouw Vennepolder (Figure 2.3a and b, with pollen counts in Appendix 4) offers an additional dataset of a particular point in space through a particular section of time: it is a new contribution to the regional and local vegetational and palaeoenvironmental reconstruction of the late Pleistocene to Early Holocene Western Netherlands. The pollen assemblages from the polder are subdivided into two local pollen assemblage zones, LPAZs VVP-1 and VVP-2. Environmental reconstructions of these LPAZs are based on the ecological tolerances described and referenced in Appendix 5.

Non-pollen palynomorphs were occasionally also documented. These findings were added in the pollen diagram (Figure 2.3b). Their ecological implications are found in Appendix 6.

Not only the palynological record from the Vrouw Vennepolder was investigated to reconstruct the palaeoenvironment. The lithological development of the Vrouw Vennepolder was studied, illustrated in Figure 2.2 and elaborated on in sections 2.2.1 and 2.3.; Appendix 1 is the lithological description of coring 51.

Furthermore, the site generated some malacological data. The results can be found in Appendix 7 and one is referred to Appendix 3 for the methodology of the shell sampling.

3.1.1. Vegetation reconstruction based on the pollen from the Vrouw Vennepolder

3.1.1.1. *LPAZ VVP-1*

Both sample 1 and 2 reflect LPAZ VVP-1. In sample 1, various plant taxa are represented. Higher-lying areas could have been inhabited by *Betula nana*, sandy grounds by *Juniperus* and there were some *Pinus* trees (cf., Bos & Urz, 2003, p. 28). Other represented tree taxa are *Castanea*, *Salix*, *Alnus* and *Ulmus*. *Salix* likely grew in wetter parts (cf., e.g., Hoek, 1997a, p. 24; Tutin et al., 1964, pp. 43-54). Herbs like Poaceae, *Monotropa hypopitys*, *Filipendula*, *Artemisia*, producers of *Senecio*-type and *Ballota*-type, Urticaceae and Cyperaceae were represented. Many herbs stay environmentally indeterminate, because it is not possible to identify their pollen to species level and the various species within these families, genera or types cover a wide range of different habitats. Some *Filipendula* could have lived in the river floodplain or drier grassland (cf., Bos & Urz, 2003, p. 30). Aquatic, damp and waterside plant taxa also grew in the palaeovegetation of the Vrouw Vennepolder. (Semi-)aquatic taxa like *Sparganium*-type pollen producers (*Sparganium* sp. or *Typha angustifolia*) and *Potamogeton* are sparsely represented. There seems to have been an undergrowth of ferns in a wet environment, given the abundance of Pteridopsida psilate monolete spores (Bakels, 2017, p. 177) and the presence of *Sphagnum* spores. Sections of the latter can grow on wet substrates and some *Sphagnum* can even be classed as (semi-)aquatic (e.g., Bos & van Geel, 2017, pp. 124-125; Hájek, 2009; Paffen & Roelofs, 1991). Nevertheless, much remains open for interpretation, especially due to relatively poor preservation compared to the other samples, reworking, mixing and, consequently, concerning the age and timespan of deposition of the sample's record.

Sample 2 is somewhat different from sample 1, despite the similarities. Again, cluster analysis (Figure 2.3) suggests that VVP-1 might possibly be subdivided into two subzones, VVP-1a and VVP-1b, which would be supported by the fact that the two samples come from two different lithologies. However, it is undesirable to place a zone boundary based on one sample and it would have been better to have more than one palynological sample from the Kreftenheye

Formation sand for comparison in order to determine whether it is statistically correct to create a subdivision in LPAZ VVP-1. Yet, they share a dominance of *Pinus*, *Corylus* and *Betula* pollen, and ferns are still represented by relatively many monolete Pteridopsida spores. *Corylus* would prevail in the area and stands or woodlands of *Betula* are also represented in the pollen spectrum of sample 2, just as some *Pinus* trees (cf., Bos et al., 2005b, p. 37). In sample 2, most shrub and herbaceous taxa were not encountered anymore, only Poaceae and *Sanguisorba minor*-type. Aquatic taxa were not reported in this sample. Some of the pollen could have been mixed, however, as the underside of the sample did still contain some sand. The interpretation for the palaeoenvironmental reconstruction for sample 2 is, just as sample 1, debateable due to possible mixing.

The palynological record of LPAZ VVP-2 also contained non-pollen palynomorphs and these also add to the vegetational and environmental reconstruction. For example, the assemblage of HdV-T58 Zygnemataceae zygospore, HdV-T128 Unidentified alga, HdV-T132 *Spirogyra* spore, HdV-T314 *Zygnema* type, HdV-T760 *Pediastrum*, HdV-T766 *Botryococcus* and HdV-T900 *Pediastrum* point to shallow, stagnant, meso- to eutrophic freshwater conditions. They were most notably present in sample 1. HdV-T128 Unidentified alga and HdV-T766 *Botryococcus* were also noticed in sample 2.

3.1.1.2. *LPAZ VVP-2*

The composition of the pollen spectrum in LPAZ VVP-2 is not constant throughout; most herb and aquatic taxa were not encountered in every sample. The tree pollen spectrum from samples 3 to 9, from the Basal Peat and Wormer Member clay, shows a mixed forest, with *Corylus*, *Quercus*, *Betula* tree, *Ulmus*, *Tilia* and *Alnus*. *Betula* tree woods were still present in the region, perhaps in slightly wetter parts or on lighter, dryer soils further away from the marsh where the peat developed (cf. Bos et al., 2005b, p. 37; Bos & van Geel, 2017, p. 124). Wetter parts of the forest and/or marsh were likely locally inhabited by *Alnus*, while higher parts in the region of the environment could have been vegetated by *Quercus* and *Tilia* (cf., van der Woude, 1983, pp. 29-34, 36). *Ulmus* could have established itself in on the higher parts of the marsh and in the transition towards the marsh area, but perhaps also on higher grounds (cf., van der Woude, 1983, pp. 32-34, 36). As described earlier, the pollen of *Fraxinus* and *Fagus* from some samples could have originated from pioneer trees in the region, or could have arrived from an extra-regional source through long-distance transport. *Salix* also prevailed in the region. The forest edge and/or undergrowth of the forested areas were maybe vegetated by

Corylus, among other plants. Additionally, Ericales, represented by *Calluna vulgaris*, *Empetrum*/*Ledum*, *Vaccinium*-type pollen, grew in the region, perhaps in acidic heathlands, marsh and peatlands, poor grassland or fairly open, lighter parts of the forest. Scattered shrubs of *Juniperus* occurred in the region too.

As a whole, LPAZ VVP-2 presents a wide range of herbaceous plant taxa, such as Poaceae, *Rumex* (or *Oxyria*), *Filipendula*, *Artemisia* and other Asteraceae (including *Senecio*-type producers), *Lactuca*-type producers, Apiaceae, Cannabinaceae, Chenopodiaceae and Cyperaceae. Herbs could have lived in the undergrowth of forests or in more open places, but can also represent damp and waterside plants (cf., Bos et al., 2001, p. 274, p. 280; Bos & van Geel, 2017, pp. 121, 124; Kubiak-Martens et al., 2015, p. 239). One grain of *Hordeum*-type pollen was found, but it does not necessarily imply a barley (*Hordeum*) pollen grain, as there are (other) cereals and wild grasses that produce such pollen-types (Andersen, 1979; Beug, 2004, p. 81). Its presence is not necessarily evidence for agriculture in the region, it may just indicate the presence of a wild grass. It is probable that quite open or light habitat was preferred by the herbs growing in the Vrouw Vennepolder environment. Some herbaceous taxa, e.g., *Artemisia*, *Rumex* sp. and Urticaceae, also potentially point to disturbed grounds (see Appendix 5). *Hedera helix* eventually also grew in the forest. Ferns that lived in the forest undergrowth or along a waterbody were represented as well (by, e.g., Pteridopsida monolete spores, *Polypodium*, Pteridophyte spore). *Equisetum* could have flourished as riparian plant or undergrowth. Moreover, slightly higher, peaty stands with *Sphagnum* might have existed.

LPAZ VVP-2 additionally shows a diverse assemblage of aquatic plant taxa through time, suggesting a wet environment. In and along the water, *Typha* (and potentially *Sparganium*) grew. *Nymphaea*, *Nuphar*, *Utricularia*, *Alisma*-type pollen producers, *Potamogeton* and *Myriophyllum* inhabited the wet parts of the marsh. Not all were encountered in each sample.

Non-pollen palynomorphs from LPAZ VVP-2 samples roughly correspond with the ones from LPAZ VVP-1. HdV-T114 Scalariform plate confirms the presence of *Betula*, *Alnus* or *Corylus*, but it could have originated from *Myrica* (Pals et al., 1980, p. 403).

3.1.2. Taphonomy, preservation and representation issues

Several factors were considered while interpreting the palaeovegetation with the pollen record (Figure 2.3a and b; Appendix 5). These include procedural limitations, but also the site context, life and sexual strategies of plants and taphonomic considerations, e.g., pollen and spore productivity and dispersal, predation, reworking of microscopic materials and diagenesis (e.g., Birks & Birks, 1980; Campbell, 1999; Holloway, 1989; Lebreton et al., 2010; Xu et al., 2016). Also, even though microscopic analysis yields information about past vegetation and environmental conditions, palynological studies mostly face that pollen are often not identifiable to species level, which hampers inferring environmental conditions with high resolution.

During the counting of pollen during the microscopic research, samples were processed by three different analysts, and there possibly was an operator bias in the identification and counting of non-pollen palynomorphs. Preparation of the slides in silicon oil may lead to differential dispersal of the pollen on the slide (Brooks & Thomas, 1967); as the oil spreads, larger pollen will remain in the centre of the slide, while smaller pollen are more easily transported to the edges. Consequently, different counting strategies could have affected the representativeness of the data.

Another consideration is the pollen sum for the counted samples. When more pollen are counted, it is assumed that the pollen data are statistically representative of the whole sample. The aim was to reach at least 200 terrestrial pollen per slide, in order to obtain statistically representative data considering factors as described in Moore et al. (1991, pp. 170-172), as is done more often (Bradley, 2015, p. 411). Due to issues of low pollen concentrations, this did not always apply, however, as was the case of sample 4 and 5 (for which, respectively, a sum of 131 and 152 total land pollen was achieved). If the samples were counted to a higher total land pollen sum (more than 200), there is a chance more of the 'rare' taxa were encountered more often, or that other 'rare' taxa may have been encountered. It might, additionally, be appropriate to apply higher pollen counts when one or more taxa are super-abundant (e.g., *Pinus* and *Betula* in boreal forests or Poaceae in grasslands), but this was not the case in the palynological record from the Vrouw Vennepolder, so a total land pollen sum of 200 was appropriate. As pollen analysis is a time-consuming method, it was not feasible within the time available to count more than 200 land pollen. Despite some the operator bias, the data were quite uniform, especially in LPAZ VVP-2, and there is no need to assume that it will have affected the data to the point where the results would be unreliable. Bias due to operator bias likely was limited.

The site context determines which and how many plants are able to vegetate the locality and region, the level of preservation and, as a consequence, which pollen are represented in the pollen record (cf., Moore et al., 1991, pp. 12-14, 183-184). Open vegetation likely makes it easier for pollen to be dispersed by wind. On the other hand, the canopy of woodlands and tall herbaceous plant might hinder the dispersal of some pollen. In the case of the Basal Peat palaeoenvironment, some trees might have hindered the dispersal of some pollen grains.

Further considerations for the dispersal and representation of pollen include the basin size, transport medium (wind and/or water, air currents in the canopy, animals), precipitation, the microclimate, a local or gravity component of nearby pollen sources and the influx of secondary or washed-in pollen.

Different depositional contexts generate different preservation potentials. Pollen from sample 1 were deposited in sand, which generally does not preserve organic materials very well (Cushing, 1967), whereas the microfossils may have preserved better in peat and clay/tidal deposits (e.g, Bradley, 2015, p. 406; Chmura & Eisma, 1995, pp. 185-186, 189-199; Cushing, 1967, p. 97; and references therein; Moore et al., 1991, pp. 11, 17). It may thereafter be assumed that the preservation potential of samples 2 to 9 is higher than that of sample 1. In fact, during the microscopic analysis, more pollen grains were labelled 'unidentified' in the sand. Not all pollen are created equal and differential preservation is also determined by characteristics of the pollen themselves (e.g., Fægri & Iversen, 1989, pp. 146-147 and references therein; Moore et al., 1991, p. 183). Palynomorphs can, as a result of poor preservation, degrade, corrode, crumple and/or fragment, which may cause difficulties in identifying a pollen grain (cf., Cushing, 1967; Moore et al., 1991, pp. 169-170). Cyperaceae pollen grains are quite easily subjected to crumpling, because they have thin walls (Tipping, 2000, p. 23). Obviously, absence of evidence does not equal evidence of absence.

Besides, palynological records can be affected by erosion, redeposition, bioturbation, reworking and the lack of sedimentation (e.g., Fægri & Iverson, 1989, pp. 137-141). Yet, such things were considered before the sampling of the samples from the sequence and the record did not seem disturbed. Reworking activities could have taken place in the Kreftenheye Formation sand, leading to mixing of materials and difficulties in studying how long it took for the sample to be deposited. Reworking and mixing is perhaps seen by the presence of thermophilous tree taxa such as *Castanea*, *Corylus*, *Alnus* and *Ulmus*, which might have originated from reworked Eemian deposits (cf., Hoek, 1997a, pp. 23-24). It also could be that some Early Holocene pollen (of, e.g., *Corylus*, *Ulmus*, *Alnus* and possibly *Pinus*) mixed with Pleistocene pollen in the Kreftenheye Formation sand substratum that was likely still exposed during the earlier Holocene. The presumably fairly open Pleistocene vegetation with *Betula* and *Juniperus* shrubs could have made the environment exposed to wind, leading to erosion, reworking, deflation and/or re-deposition of sand. River, and later perhaps wave and tidal, activities in the depositional environment might as well cause the influx of allochthonous pollen into the record.

Moreover, the representation of a taxon is influenced by its sexual strategy, most importantly pollen productivity and dispersal methods. Except for *Tilia*, which predominantly aims at pollen dispersal by animals, the represented deciduous trees are wind-pollinated. *Tilia* is a low producer of pollen and their pollen are mostly dispersed by insects. This could cause underrepresentation in the fossil record (Bakels, 2017, p. 180; Chiverrell et al., 2023, p. 22). Trees that disperse pollen by wind, like *Quercus*, *Betula*, *Pinus*, *Corylus* and *Alnus*, tend to produce many pollen to increase their chances of success (Bradley, 2015, p. 410; Fægri & Iverson, 1989, pp. 13-14). These taxa can, consequently, become overrepresented in the pollen record, especially if the source plant is nearby. Hermaphroditic plants may rely on spreading pollen through animals, like *Nymphaea* and *Nuphar* do, and consequently are not producers of many pollen (Bradley, 2015, p. 410; Fægri & Iverson, 1989, p. 12). These can, as a result, be underrepresented in the record, especially when wind-pollinating taxa dominate in the region. Yet, some of the zoophilous pollinator taxa do still produce many pollen, like *Calluna vulgaris* (Fægri & Iverson, 1989, pp. 12-13). Also, some animals, including pollinators, eat pollen (e.g., Labandeira et al., 2000, p. 234), but predation of pollen will likely have a very minimal effect on the representation of palynological record. Taxa that self-pollinate could be underrepresented or lacking in the pollen record, as they produce relatively few pollen compared to plants that disperse pollen through wind or animals (Bradley, 2015, p. 410; Fægri & Iversen, 1989, p. 12).

Finally, another important taphonomic consideration for the representation of pollen taxa is proximity, which also strongly relies on dispersal, productivity and plant habit. As implied earlier, pollen signals might, for instance, be of local or regional origin (e.g., Fægri & Iversen, 1989, pp. 141-147; Moore et al., 1991, p. 13). It can generally be assumed that relatively more pollen of a taxon are expected closer to the source plant than further away from the source plant. A local source plant could be overrepresented, for example. Overrepresentation of pollen can also occur if, for instance, pollen-bearing catkins are very near to, or even dropped directly into, the sampled sediment as it was deposited. The distinction between regional and local pollen signals from the Vrouw Vennepolder can probably mainly be based on tree – and possibly shrub – pollen, which indicate a more regional signal (though it cannot be ruled out that some specimens may have occurred locally or extra-locally), versus pollen and spores of (some) herbs, *Hedera helix* (as it is an insect-pollinator and its dispersal and representation in surface samples is poor, even close to the source; Bottema, 2001, pp. 162, 165-166; Jacobs et al., 2009, p. 1397), aquatic taxa, ferns, *Sphagnum* and *Equisetum*, which represent the local vegetation. *Alnus* could as well have grown in or near the marsh. Additionally, it might be possible that the presence of some of the few *Fraxinus* and *Fagus* pollen grains in the record indicates the presence of this tree in the broader Vrouw Vennepolder region. It is also possible that some have arrived through long-distance transport. Herbs could have grown as undergrowth in the (regional) forest, suggesting a regional signal, as well as in local damp and waterside locations. In order to spread their pollen further, some of the anemophilous (wind-pollinated) trees, produce pollen with sacci (bladders), which increases their buoyancy and makes them common long-distance travellers. These can therefore be represented in a pollen diagram, despite their distant, (extra-)regional source. This might be an explanation for the presence of some Pinaceae pollen, like *Pinus*, *Abies* and *Picea*, in a LPAZ VVP-2 sample. In the late Pleistocene (sample 1) and Early Holocene (sample 2) surrounding of the Vrouw Vennepolder, *Pinus* could have grown locally, as percentages exceed the 'rational limit' of 20 %; percentages higher than 20 % attributed to *Pinus* pollen relative to the TLP suggest local presence (cf., Bos et al., 2001, p. 274; Lotter et al., 1992, p. 195). Lower percentages of *Pinus* might be explained by a (slow) reduction of (extra-)local and/or the contribution of regional *Pinus* trees.

3.1.3. The local environment of the Vrouw Vennepolder

During some time in the Pleistocene, the regional landscape of the Vrouw Vennepolder consisted of sand, which was previously deposited by a river, with perhaps some vegetation. Again, it is uncertain what the duration of the depositional period was and what time is represented by the pollen signal. Consequently, the vegetation interpretation at the time of deposition persists to be ambiguous.

What becomes clear from the local pollen record from the Vrouw Vennepolder Basal Peat is that the Early Holocene/Boreal to late Boreal local landscape became characterised by a marsh environment, a wet locality with aquatic, damp and waterside plants and algae living in and along shallow to somewhat deeper water (cf., Kubiak-Martens et al., 2015, p. 256). A meso- to eutrophic, stagnant, open freshwater body may have prevailed in the environment, according to the aquatic taxa, some herbs and algal microfossils. *Alnus* may also have been part of the local vegetation in or near the marsh. The (preservation of the) peat itself also implies wet conditions.

Later, the Vrouw Vennepolder developed into a tidal environment, as indicated by a clay layer on top of the Basal Peat, likely representing saltmarsh deposits. The malacological taxa from the saltmarsh and younger sandy tidal plate deposits mainly suggest brackish or saline tidal circumstances, but there was freshwater influx too (see Appendix 7). The molluscs were likely not deposited, but lived in the environment and were covered by deposits. During the transition towards the saltmarsh depositional context, the pollen signal does not seem to change significantly compared to the signal from the older analysed samples.

The regional pollen signal from the Vrouw Vennepolder corresponds with records from other parts of the Netherlands. Given that these other parts of the Netherlands with a similar vegetational composition were subjected to (seasonal) human exploitation for plant food and other natural products (cf., Bigga, 2018, pp. 81-105; Bohncke & Hoek, 2007, pp. 1970-1971; Kubiak-Martens et al., 2015, pp. 223-224, 270-273, 276-285 and references therein) and habitation or had the potential for it, this suggest this would also have been possible in the Vrouw Vennepolder region during the late Pleistocene to Middle Holocene, in various (terrestrial, freshwater and marine) landscape zones (cf., Amkreutz, 2013, pp. 81-84, 133-135, 144-145, 229-230, 242-247, 298-301, 349-350, 426 and references therein; Brouwer Burg, 2013, p. 2313 and references therein; Dusseldorp & Amkreutz, 2020, pp. 122-123, 131-133 and references therein; Peeters et al., 2017, p. 42), also considering the potentially available prey, e.g., otter, beaver, wild boar and red deer (cf., Amkreutz, 2013, pp. 321-323; Lauwerier et al., 2005, pp. 43-46; Zeiler et al., 2015, pp. 204-220), and suitable prevailing climate (van Geel et al., 1981, pp. 411-412). The suitable temperature conditions during the late Boreal, which were on average likely even hotter than nowadays, is further evidenced by the presence of temperature indicators, such as *Hedera helix*, *Corylus* and *Typha* pollen (cf., Hoffmann et al., 1998, p. 274; Isarin & Bohncke, 1998; Iversen, 1944; Kolstrup, 1979, pp. 378-380; Kolstrup, 1980). The local pollen signal additionally could point to plant resources that potentially were exploitable for humans, like *Filipendula*, *Typha* and *Equisetum* (cf., Bigga, 2018, p. 81; Bos et al., 2005b, p. 39 and references therein; Bos & Urz, 2003, p. 32; Kubiak-Martens et al., 2015, pp. 271, 281), though the taxa from the polder are not identified to species level.

3.2. **Human ecological challenges in and near the Vrouw Vennepolder**

Although the biotic factors present at the Vrouw Vennepolder during the late Pleistocene to late Boreal offered potential opportunities for human ecological exploitation of the region, the local palynological, lithological and malacological record from the polder suggests that this part of the Western Dutch coastal landscape likely posed a variety of abiotic challenges for humans. The time period would imply the involvement of Palaeolithic and Mesolithic people (Amkreutz, 2013 and references therein). Four major abiotic contributors – the influences of the sea, storms, the rivers (Rhine and Old Rhine) and wind – and their potential consequences for human exploitation will be discussed before 3.3. elaborates on hazard perception and the possible human responses.

3.2.1. The sea

The coastline of the Netherlands during the Boreal still was situated somewhat westward than today (de Haas et al., 2018a, p. 149; Rieu et al., 2005, p. 409). In the Early Holocene, the sea gradually inundated and changed previously dry lands of the North Sea (see section 2.3.), and (later) also parts of the Netherlands. The input of saline water to the freshwater marsh environment has some impact on vegetation (composition) and the (formerly freshwater) ecosystem, like physiological, morphological and anatomical stress and disorders of plants, a reduction of species richness and replacement of freshwater plants by salt-tolerant (halophytic) and/or halophilic plants and other organisms (see, e.g., Hoffmann Moreira et al., 2023, pp. 2-10 and references therein; Hopfensperger et al., 2014, pp. 793-794, 800, 802-804 and references therein; Tully et al., 2019, pp. 372-376; Venâncio et al., 2018, pp. 1-2, 8-11 and references therein). Long-term and short-term events could cause the influx of saline water into the marsh: main factors are the relative sea level rise (transgression) and storms. Other impacts of the relative sea level rise are the subterranean seeping in of saline water and the consequent rising groundwater table.

3.2.1.1. Transgression

The relative sea level rise would lead to long-term influence of saline water in the environment, as the sea drowned previous terrestrial landscapes, and changed the morphology and geography of the land surface. The marsh area in the Vrouw Vennepolder, which formed on the Pleistocene sand substratum, transformed into a tidal environment – first a saltmarsh and later a sandy tidal flat. The malacological remains from the Wormer Member clay layers confirm a tidal influence in the Vrouw Vennepolder area. Taxa like *Cerastoderma edule*, Hydrobiidae and *Spisula* sp. live in intertidal, fresh- or brackish water conditions. Nevertheless, the occurrence of *Lithoglyphus* sp. at circa 7.5 metres below ground level implies freshwater input in the area too.

The local pollen signal from the Vrouw Vennepolder does directly not reflect influence of the marine transgression on the prevailing vegetation. Many plants of the Chenopodiaceae are salt-tolerant plant species. Chenopodiaceae percentages do not show a marked difference in representation in the studied sequence of the polder, however. Some halophytic taxa might also be found in Cyperaceae and Poaceae. Cyperaceae are, however, very sparsely represented in sample 9 from the saltmarsh environment. Besides, some species of *Potamogeton* tolerate brackish conditions, just like *Myriophyllum spicatum*. Again, a greater pollen sum might have led to the identification of more or other pollen of aquatic and herbaceous taxa. Yet, it is not known whether the pollen were produced by halophytic species and most aquatic taxa point to freshwater conditions, just as most pollen of herbs and shrubs and non-pollen palynomorphs (e.g., Zygnemataceae). It is, then, safer to assume that a major change in vegetation type due to the saline water incursions caused by the Holocene transgression is not reflected in the palynological samples from the Basal Peat. For the one sample from the clay, it is also not known how long it took for the sample to be deposited and perhaps the change of the environment into a saltmarsh happened quickly and it may have took some time for the vegetation to (fully) respond to the change. Also, only one sample from the clay was analysed, so vegetation change following the transition into a saltmarsh and tidal environment might not be reflected in the analysed sample, but it could be reflected in more recent Wormer Member clay from the polder. Additionally, most of the pollen signal from the palynological samples is regional (of the trees) rather than local, so it is possible that the input of local and extra-local taxa is simply not found and that the regional sample just prevails. Furthermore, the potential absence of halophytic plants from the Wormer Member clay sample may as well have persisted because of some input of freshwater, confirmed by the finding of a *Lithoglyphus* shell in the clay from the polder, as a tidal flat does not have to be a fully saline environment (e.g., Friedrichs & Perry, 2001, pp. 23, 25 and references therein).

Because of the strength of the sea and changing morphology and geography of the land surface, marine transgression could, nonetheless, have impacted the opportunities for exploitation and habitation by people. When the polder became part of a tidal zone, the area was flooded every once in a while (cf., Friedrichs & Perry, 2001, pp. 8-12, 14, 16-19 and references therein), with alternations of freshwater and brackish conditions, and some landscape parts to the west became permanently inundated. Regular occurrences of high tides are not favoured if one aims to create a longer-term habitation site.

3.2.1.2. High groundwater table

The rising groundwater table, among other factors, caused peat to develop in the back-barrier zones and preserve, due to waterlogging, on top of the Kreftenheye Formation sand (e.g., Cleveringa, 2000, p. 16; de Haas et al., 2018b, p. 89 and references therein; Hijma & Cohen, 2019, pp.

70-73 and references therein; van Asselen et al., 2017, pp. 1695-1696, 1704 and references therein). The favourable environmental conditions persisted in and near the Vrouw Vennepolder during the late Boreal. That the local area became wetter is reflected by the representation of aquatic, damp and waterside plant and algal microfossils preserved in the waterlogged peat.

However, wandering through and exploiting a marsh for a prolonged time period could be difficult, not even to mention permanently living in a wet marsh. Especially in colder weather, moving through a marsh can be unpleasant (cf., Brouwer Burg, 2013, p. 2312). The regional signal also shows the presence of plants that could have been used for various purposes, and such environments, rather than the marsh, could have also attracted prey animals. Exploring and exploiting the wider surrounding of the Vrouw Vennepolder – instead of the marsh itself – could, then, also have been preferred by humans.

3.2.1.3. Subterranean seeping in of saline water

Because of the sea level and related groundwater level rise, it is possible that saline water is drawn up into the terrestrial environment, which can lead to salinisation (de Louw, 2013, pp. 11, 15-16 and references therein; de Louw et al., 2010, pp. 494-496, 499, 502 and references therein). Salinisation can negatively influence the potential for sustainable exploitation of freshwater grounds and limits the potential of an area for agriculture (de Louw, 2013, pp. 11, 19; de Louw et al., 2010, p. 494; Halvorson, 1988, pp. 179, 181). Again, the investigated local pollen record in the Vrouw Vennepolder does not seem to point to regular inflow of saline water and, perhaps, the sea had not risen enough relative to the land.

3.2.2. Storms

Short-term events, like storm surges, can impact landscape development (Goslin & Clemmens, 2017, pp. 80-114 and references therein). For example, they can cause the transport of sediments and saline water from the sea. The Dutch coast was also subjected to storms (e.g., Beets et al., 1995, p. 241; Cleveringa, 2000, pp. 19, 44-47; van der Molen & de Swart, 2001, pp. 1725, 1727-1728, 1734, 1736, 1740, 1743-1744; van der Valk, 1996a, pp. 152-153, 191-192), so saline water could have reached further inland (e.g., de Haas et al., 2018b, p. 103; van Dinter, 2013, pp. 18-19 and references therein). However, the storm intensity influences the extent of its impact. Freshwater vegetation is impacted by marine incursions because of the saltwater influx (e.g., earlier mentioned sources and Friedrich & Perry, 2001, p. 20 and references therein; van Dinter, 2013, p. 19), but such short-term saltwater surges due to storm activity in the marsh area are likely not recorded in the palynological record (see above). Nevertheless, the impact of storms could have been felt by people. Storms can be high-energy and intense and cause unsafe circumstances, for example.

3.2.3. The river

River floodings can occur occasionally and may be large-scale and/or long-term (Cohen et al., 2016, p. 14). Several big palaeofloodings of the Rhine in the Lower Rhine area have been reported (Figure 3.1; Cohen et al., 2016, pp. 40, 43-45 and references therein, their Tabel 1; Toonen et al., 2013, pp. 143-150, their Figure 3). As there was a relatively high flooding frequency during the Atlantic compared to some later periods (Cohen et al., 2016, pp. 40, 43-44 and references therein, Tabel 1; Toonen et al., 2013, their Figure 3), it is probable to assume floodings of the Rhine also occurred during the late Boreal. Floodings likely also have repercussions on human behaviour and, in turn, the potential archaeological archive. Flooding has the potential to be devastating, because much energy can be involved, and it can remove or deposit sediments. Objects could be carried away or deposited and habitation and, later in the Holocene, agricultural grounds may become covered in clay or destroyed.

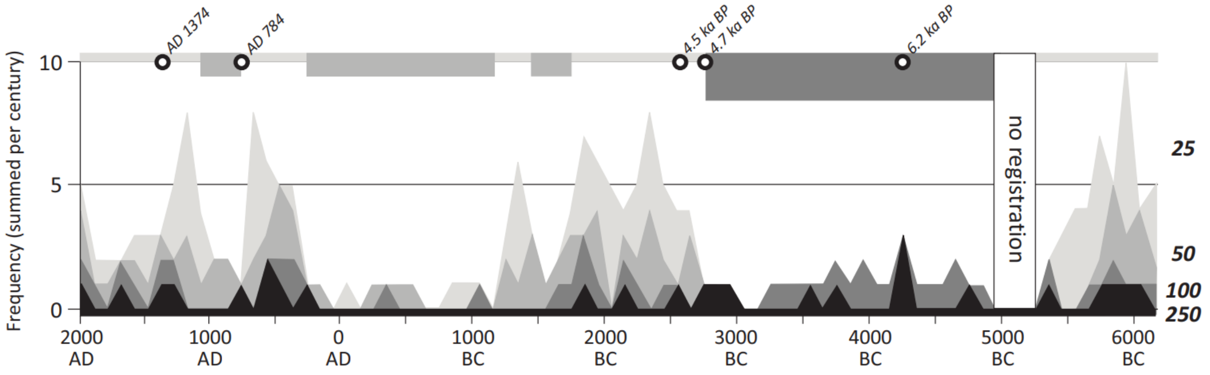


Figure 3.1: The flooding frequency, of various flooding magnitudes, in the (Lower) Rhine per millennium. The exceeding of recurrence times of 250, 100, 50 and 25 years are marked by a, respectively, black, dark grey, grey and light grey colour. Large floodings have higher recurrence times; they are relatively rare compared to smaller floodings. The extent and impact of flooding differ per event and locality and with distance from the river (e.g., Cohen et al., 2016, p. 40). The dots with timings in the upper part of the figure signify the timing of millennial floodings. Apparently, there is variability in the occurrence of flooding events. Source: Toonen et al. (2013, their Figure 3 on p. 143).

Considering the development of the Rhine during the late Boreal, it is possible that floodings in and near late Boreal Vrouw Vennepolder did not occur, as the Rhine's main channel still discharged in the Rotterdam area at that time (e.g., Berendsen & Stouthamer, 2000, p. 324; Berendsen & Stouthamer, 2002, pp. 104-105; Cohen et al., 2012; de Groot & de Gans, 1996, p. 241; de Haas et al., 2018b, pp. 85-86, 97, 101; Gouw & Erkens, 2007, p. 51; Hijma & Cohen, 2011, p. 1470; Hijma et al., 2009, pp. 16, 18, 29, 33, 38; Roep et al., 1991, pp. 119-120; Stouthamer & Berendsen, 2007, p. 323). Perhaps, a local channel or tributary of the Rhine still discharge water away towards the North Sea in the area, but it is not sure whether it influenced the Vrouw Vennepolder area. Nonetheless, the impact of the river was uncovered in the Holocene Vrouw Vennepolder. Earlier than the Boreal, the riverine Kreftenheye Formation sand was deposited by the Rhine. Some of the shells in the Wormer Member layers likely point to freshwater (fluvial) input from the (Old) Rhine. Moreover, fluvial influence on the landscape might be suggested by clay layers in the Hollandveen Peat. So, if people did exploit the Vrouw Vennepolder environment times before and after the late Boreal, they could have faced the influence of river flooding.

3.2.4. The wind

The Kreftenheye Formation sand zone could have been inhabited by fairly open vegetation of mostly herbs and shrubs. The transition to a marsh, and later a saltmarsh and tidal flat, also likely changed the openness of the vegetation. During the Younger Dryas, a south-westerly wind may have prevailed during most of the time, especially in the summer (Kasse et al., 2018, pp. 5, 23-24 and references therein; Kasse et al., 2020, p. 16). (South-)westerly winds currently dominate (Beets & van der Spek, 2000, p. 5; de Haas et al., 2018a, p. 145; Pierik et al., 2017, p. 183; van der Molen & de Swart, 2001, pp. 1744-1745), though there was a net longshore sediment transport with a northerly or north-easterly direction (Beets & van der Spek, 2000, pp. 4-6). Generally, saltmarsh and tidal flats are not vegetated by trees, so shelter was likely not close by in the direct vicinity, though it may have been there in the wider surrounding. Also, it is windier in the coastal areas than further inland. Winds might have been unpleasant for people due to the force, cold feeling and (unexpected) transport of materials.

3.3. Hazard perception and human responses to human ecological challenges

The palynological samples from the Kreftenheye Formation sand may date to the late Pleistocene and the other samples date signal the Early Holocene/(late) Boreal and this means the archaeological time periods involved are the Palaeolithic and Mesolithic (Amkreutz, 2013 and references therein). People would have had a broad-spectrum subsistence economy (e.g., Lauwerier et al., 2005, p. 43; Louwe Kooijmans, 1993, pp. 136-137) and it appears that there were ecological opportunities in the Vrouw Vennepolder environment during that time for humans. During the Early Holocene to late Boreal, the transition from a fluvial sand area to a marsh to saltmarsh environment changed the environment and challenges. Hazard perception may be an important control in how people could cope with the environment. In turn, this affects (the distribution of) Palaeolithic and Mesolithic activity and archaeology.

The abiotic ecological challenges of the Vrouw Vennepolder can be subdivided into long-term and short-term landscape developments, which may have had effects on human hazard perception.

3.3.1. Long-term ecological challenges

It is probable that the long-term changes were not directly observed by people. However, over the generations (or even within a lifetime), the landscape change may have been noticed. The gradual inundation of landscapes due to the Holocene transgression might have affected how humans looked at the potential of the environment for exploitation and habitation, potentially influencing people's behaviour and perception of the landscape and its hazards (cf., Amkreutz, 2013, p. 426). One would have been protected from the influences of the rising sea level on higher-elevated terrains or more inland. Though erosion should be considered for the palaeotopography, the direct vicinity of the polder does not seem to have pronounced higher-elevated landforms, though erosion should be considered (see Appendix 8). The new conditions as a result of the marine transgression may have also provided new opportunities, like easier access to marine resources. The human perception may just have been pragmatic and flexible, seeing the environment as a naturally dynamic setting with ecological opportunities, instead of perceiving the transgression and landscape's alteration as a hazard, and becoming accustomed to change.

The development of a marsh may also be considered a longer-term change of the environment, potentially producing circumstances that were cold, wet and difficult to move through and inhabit. Hence, and potentially to save energy, the wet environment might have been avoided or people could have applied a strategy of targeting particular places and task division. Despite the potentially unfavourable abiotic conditions of the marsh, wetland environments like marshes kept being exploited, for they produce a diverse set of resources for food procurement, among others (e.g., Amkreutz, 2013; Dusseldorp & Amkreutz, 2020, pp. 122-124, 132-133 and references therein; J. H. M. Peeters et al., 2015, pp. 291-292; Kubiak-Martens et al., 2015, pp. 270-273, 276-285; Zeiler et al., 2015, pp. 204-220). Humans apparently knew how to deal with the high groundwater table. Different food procurement strategies may have complemented each other. One possible response to the challenges of the environment would be seasonal exploitation and habitation by humans. Canoes, like the Mesolithic ones from the Dutch sites of Pesse and Hardinxveld-Giessendam De Bruin (Akreutz, 2013, pp. 237-238; J. H. M. Peeters et al., 2015, p. 316; Louwe Kooijmans et al., 2001; van Zeist, 1957), may additionally have been used for transport. Even later during the Mesolithic, and the Neolithic when cultivars and domesticates arrived in the region, wetlands remained to be exploited by humans (e.g., Amkreutz, 2013, pp. 320, 424, 427-430 and references therein; Dusseldorp & Amkreutz, 2020, pp. 122-124 and references therein). Higher-elevated terrains in and near the marsh environment of the Vrouw Vennepolder could have been favoured by humans. Later in the Holocene, instead of creating arable lands, having livestock on higher areas may have been preferred, initially next to the continued exploitation of 'wild' animals (e.g., Dusseldorp & Amkreutz, 2020, pp. 131-133 and references therein). Difficulties due to the rising groundwater table could therefore have been perceived by humans not as a limiting factor or hazard, but as offering opportunities.

3.3.2. Short-term ecological challenges

Short-term ecological challenges, like storms, harsh wind and river floodings, may have been perceived by humans as events that just happened, perhaps handled with pragmatic solutions. Storms may have been perceived as hazards because of their potential force and capability of carrying materials. Nonetheless, a pragmatic approach of sheltering or moving to areas further from the sea may have been applied. Later in the Holocene, agriculture may have been practiced in areas without saline water influx caused by storms, like elevated terrain, where subterranean seeping in of saline water would also not be present. The hazard and unpleasant feeling of harsh winds may have been overcome by avoiding open places, such as the – perhaps sparsely or fairly open vegetated – sandy area of the late Pleistocene and saltmarsh, and sheltering in more forested areas or behind higher landscape features. Additionally, windshields or tents could have been produced for protection (see, e.g., Bos et al., 2013, p. 34; Deeben & Schreurs, 2012, pp. 311, 313). Moreover, river floodings can be sudden and destructive and may have posed a threat to habitation sites. Again, the force of the river may be (largely) bypassed by occupying higher grounds further away from the river, which could as well be an important provider of resources and means for mobility and communication. During later stages, however, the floodplain potentially provided fertile grounds for the growth of plants and farming. The floodplains could also have been allocated for animal husbandry.

3.3.3. Experiencing ecological challenges

Hazard perception is likely also affected by the recognition, (previous) experience, duration, frequency and expectedness of the events and of their results, be they long- or short-term. The long-term developments (transgression, rising groundwater level) presumably did not pose unexpected hazards, whereas unexpected, yet potentially frequently occurring, short-term events (storms, harsh winds, floodings) could have been perceived differently, also per locality and person.

It is possible that people, if present, perceived the landscape as being dynamic, interactive and 'living' (cf., Amkreutz, 2013, p. 441), where change was seen as a familiar part of the environment from which numerous resources could be yielded. The abiotic ecological challenges, shaped and governed by the influence and force of freshwater, saline water and wind, were potentially perceived as inherent parts of the landscape conditions, rather than as hazards that disturbed the ways of life of humans.

Yet, much remains to be discovered in terms of the technical, economic, social and ideological hazard perceptions, as well as the solutions and answers of humans to the abiotic ecological challenges. Archaeological research may shed light on some human responses.

3.4. Prospection of the Palaeolithic and Mesolithic Western Netherlands

The region of the Vrouw Vennepolder is quite unknown in Palaeolithic and Mesolithic archaeology, according to the archaeological database of the Netherlands (see the ARCHIS database, https://archis.cultureelerfgoed.nl/), and difficult to study. Some of the concerns of prospection and other research on and discovery of Palaeolithic and Mesolithic archaeology in the Western Netherlands, thus including the Vrouw Vennepolder region, are discussed below.

The late Pleistocene to Middle Holocene depositional horizons potentially enclosing Palaeolithic and Mesolithic archaeology are generally present many metres below ground level in the Dutch coastal zone (cf., Peeters et al., 2017, pp. 36-37). Archaeological investigations in the Netherlands are generally undertaken to determine whether building activities will disturb archaeological finds and features in the underground (cf., Peeters et al., 2017, p. 19). Yet, when layers with archaeological remains are buried below metres of sediments, they are very likely not disturbed, not required to investigate and consequently generally not subjected to in-depth prospective research (cf., Peeters et al., 2017, pp. 37, 210-211). Also, if artefacts were to be present in such deep (and waterlogged) depositional contexts, the scale and complexity of the archaeological excavation in terms of size and depth would make such investigations impractical and costly (cf., Amkreutz, 2013, p. 92). Most archaeological projects in the Netherlands are carried out by commercial firms, and this generally does not involve extensive prospection and archaeological research at these depths (cf., Peeters et al., 2017, p. 208). In general, if a site is expected to be disturbed and no archaeological remains are expected, the decision-making process usually leads to the decision not to conduct archaeological research (cf., Peeters et al., 2017, p. 36). This depth-related problem also applies to late Pleistocene to Middle Holocene environmental records in the Western Netherlands, including the region of the Vrouw Vennepolder (see de Rijk et al., 2020; de Rijk & Kruidhof, 2020; Huizer et al., 2011; Koekkelkoren, 2014; Koekkelkoren & Moerman, 2012; Leuvering, 2021; Mol, 2021; Nales, 2018; Nieuwlaat, 2022; Pape-Luijten, 2020; Wilbers & de León Subías, 2019).

Moreover, the location of archaeological prospection and excavations follows patterns in (planning of) building, construction and economic activities (Bos et al., 2005a, p. 261; Peeters et al., 2017, pp. 36-37; Vos, 2015, p. 82). In more rural areas, such as the Vrouw Vennepolder region, large-scale building activities are not regularly undertaken.

The methodology of prospection is also an important consideration. For example, augering or grid sampling, at certain scales, does not capture the full archaeological potential for prospection (cf., Peeters et al., 2017, pp. 211-216). This is, on top of the problem of the depth of Palaeolithic and Mesolithic archaeological layers and especially when 'single event' scattered materials would be involved, not beneficial for predictive modelling and prospection.

An additional factor that could cause bias in the archaeological record and, consequently, prospection is the familiar knowledge of Palaeolithic and Mesolithic archaeology. Where no archaeological finds are expected, research – in the form of excavations – is generally avoided. The more 'uncertain' sites are not researched to their full potential. This can influence predictive modelling, which can lead to 'self-fulfilling prophecies' and this can affect the decision whether or not to further research and area and to excavate (cf., Peeters et al., 2017, pp. 201, 204, 209-210). For example, there seems to be a bias towards some landscape zones and settlements, instead of exploitation sites and, for example, wetland, peatland, brook valley sites (cf., Amkreutz, 2013, p. 49; Peeters et al., 2017, p. 83). There may still be a tendency to perceive wetlands and marshes as not the most optimal locations for human exploitation and occupation (cf., Amkreutz, 2013, pp. 49-50), even though the predictive and prospective value of wetland and marsh archaeology might fail to reflect reality. There is a general bias of archaeological prospection for areas with late Pleistocene to Middle Holocene sand dunes, as these are relatively close to the surface and are thought to have a high(er) archaeological potential than other landscape parts and features, despite potential taphonomic processes like erosion and possible removal of (some) artefacts and palaeoecological remains (cf., Amkreutz, 2013, pp. 49, 63, 76-81, 107-112, 135 and references therein; de Mulder et al., 2003, pp. 223-224; Peeters et al., 2017, pp. 35-36).

Besides, most (but not all – e.g., Amkreutz, 2013, pp. 49, 96) development-led research takes place in areas with relatively poor preservation of organic materials, whereas sites and layers with higher archaeological potential are deeply buried with sediments (cf., Amkreutz, 2013, pp. 66, 68-70; Peeters et al., 2017, pp. 74, 77, 166). Because of the relatively poor preservation of (non-carbonised) organic remains in the former areas, the exploitation of organic materials is often not documented in the archaeological record, also for the Mesolithic (e.g., Amkreutz, 2013, pp. 49, 66; Peeters et al., 2017, p. 76). This all might also have negative implications for inferring the representativeness of the archaeological record, prospection and further research.

A further concern in prospection and archaeological research is the spatial scale of research. The archaeological record is fragmentary and generally does not cover the wider region of potential human ecological exploitation and habitation (cf., Peeters et al., 2017, p. 205), though some (e.g., isotope) research gives some clues about mobility and whether or not people had a (partially) marine diet (see Peeters et al., 2017, p. 171 and references therein). As, additionally, parts of the Western Netherlands are underrepresented in the archaeological record, much stays unknown about the exploitation of various localities and ecological zones in the dynamic Western Dutch coastal environment. The prospective approach then also hinders intra-site comparisons (cf., Peeters et al., 2017, p. 205). Further to this, archaeological artefacts from the Palaeolithic and Mesolithic are also retrieved through activities near the coast, from trawling activities, dredged sands from harbour maintenance and sand extraction for beach nourishment (e.g., Hijma et al., 2012, p. 21; J. H. M. Peeters et al., 2015, pp. 298-299), but specific archaeological context of such finds is not known in such instances, however. Accordingly, a huge knowledge gap in how human exploitation choices and perceptions were affected by (changes in) the palaeoenvironment persists.

Prospection and discovery of archaeological finds would be needed for inferring whether and how people exploited the landscape and coped with abiotic ecological challenges. As the sea level rose relative to the land, the old barrier systems (partially) eroded and new barrier systems were established landward of the old ones (Beets et al., 1992, pp. 430-431). One would have expected Palaeolithic and Mesolithic finds west of the Vrouw Vennepolder, as the youngest coastal barrier is situated west of the Vrouw Vennepolder (see, e.g., Beets et al., 1992; Cleveringa, 2000, pp. 16-18 and references therein; Hijma et al., 2009, Figure 1) and people would prefer to live landward of old/inactive coastal barriers and perhaps the levee of the (Old) Rhine or coastal and river dunes, as these provided high and dry circumstances (Amkreutz, 2013 and references therein; Brouwer-Burg, 2013 and references therein). Yet, with the coastal system shifting eastward in the past, erosion likely removed older coastal barriers and artefacts seaward of the barrier systems (Beets et al., 1992, p. 438; Beets & van der Spek, 2000, pp. 8, 12; de Haas et al., 2018a, pp. 150, 155-156; Rieu et al., 2005, pp. 409-410, 417-418; Roep et al., 1991, pp. 119-120). Then, to search for Palaeolithic and Mesolithic artefacts to infer information on human ecological exploitation and habitation, tracing archaeological layers in the area west of the polder and east of the youngest coastal barrier could be suggested.

4. **Conclusion**

The Vrouw Vennepolder lithological, palynological and malacological record contributes to reconstructing regional and local vegetation and environment in and near the polder. It provides a new contribution to the palaeoenvironmental record of the Western Netherlands at approximately 11.5 to 12.15 metres depth, representing a certain time period. So, what did the regional and local vegetation and environment of the Vrouw Vennepolder look like through time, during the times of deposition of the analysed microfossil assemblages?

The analysed pollen sequence was subdivided into two local pollen assemblage zones (LPAZ VVP-1 and VVP-2). The vegetation of LPAZ VVP-1 is characterised by *Pinus*, which could have grown locally and/or (extra-)regionally, *Betula* shrubs – especially in the bottommost sample – and the representation of *Corylus*. The pollen record from the Kreftenheye Formation sands potentially was influenced by reworking of older sediments and mixing with more recent pollen, which might explain the representation of (some) thermophilous tree pollen (*Castanea*, *Corylus*, *Alnus*, *Ulmus*) in sample 1. *Betula* tree and *Corylus* did become established in the area, just as some *Alnus* trees in wetter parts in the topmost sample of LPAZ VVP-1. Herbaceous taxa and ferns were also represented in LPAZ VVP-1, just as *Sphagnum* and *Salix*. These plants would have grown in an environment with sandy substratum, on which a marsh developed that first also captured the LPAZ VVP-1 pollen signal. Aquatic plants and non-pollen palynomorphs indicate fairly stagnant, meso- to eutrophic, open freshwater conditions in the marsh environment.

The other samples – 3 to 9, extracted from Basal Peat and Wormer Member saltmarsh clay – were categorised into LPAZ VVP-2. The marsh environment and wider region was vegetated by abundant *Corylus* and other trees (*Alnus*, *Salix*, *Ulmus*, *Quercus*, *Tilia*, *Betula*, *Fraxinus*, *Fagus*), shrubs, waterside and damp ground-tolerating herbs, ferns, *Equisetum*, *Sphagnum* and aquatic plants. *Pinus*, *Abies* and *Picea* perhaps lived (extra-)regionally. As the environment became a saltmarsh, the pollen spectrum kept reflecting LPAZ VVP-2.

The age of the analysed palynological samples from the Kreftenheye Formation sand is uncertain, because of relatively poor preservation, possible reworking and/or mixing and because it is not known how long it took for the sample to be deposited. The deepest Basal Peat sample (2) suggests an Early Holocene/Boreal age, due to high percentages of *Corylus* and the representation of *Pinus* and *Betula*. LPAZ VVP-2 can be correlated to the late Boreal, following values of *Corylus*, *Quercus*, *Ulmus*, *Tilia* and *Alnus* in the pollen assemblages.

The late Pleistocene to late Boreal Vrouw Vennepolder environment probably was suitable for human exploitation and occupation, as various ecological resources may have been available. Additionally, the climate offered suitable temperature conditions for humans, as can be argued from the representation of *Hedera helix* in sample 9, among others. The local environment would, nevertheless, also have posed abiotic ecological challenges for people. Yet, how could humans have coped with the local, abiotic challenges for ecological exploitation and habitation in and near the Vrouw Vennepolder environment during the late Pleistocene to the Middle Holocene?

Potential ecological challenges for humans resulted from influences of the sea, storms, river floodings and harsh winds. Ecological challenges include the changing morphology and geography of the land surface, salt in the underground, high groundwater level, flooding, the consequent removal and deposition of sediments and objects and harsh wind. Human hazard perception – determined by the recognition, (previous) experience, duration, frequency and expectedness of events and their results – may have impacted how people dealt with such challenges. The Palaeolithic and Mesolithic hunter-gatherers, who lived in North-western Europe in the given time period, potentially were pragmatic, seeing environmental opportunities, applying diverse strategies to overcome ecological challenges, like occupying higher-elevated terrain, and/or avoiding non-exploitable and uninhabitable localities.

Whether and how people actually exploited and inhabited the Vrouw Vennepolder area during the late Pleistocene to Middle Holocene is difficult to study. Like in other parts of the Western Netherlands, the prospection and discovery of Palaeolithic and Mesolithic archaeology is poor, especially because of the depth of relevant layers. However, the lack of archaeological finds is not evidence for the absence of sites and past human presence. To gain insights into the Palaeolithic and Mesolithic human ecological exploitation of and responses to local ecological challenges in the Western Netherlands, including the polder, improvements in prospection and more excavations are needed.

As the future will most certainly pose various ecological challenges for people, it will be useful to obtain knowledge about how people in the past coped with ecological challenges. The future will tell whether and how people will be able to survive and live in the dynamic landscape of the Western Netherlands.

Abstract

For this thesis, the Vrouw Vennepolder lithological, palynological and malacological record, obtained through a coring campaign, was analysed. The new dataset contributes to the palaeoenvironmental record of the late Pleistocene to Middle Holocene Western Netherlands. The thesis aims to answer two research questions, concerning how the vegetation and environment of the polder looked like during the time of deposition of the analysed microfossil assemblages and how ecological challenges influenced human exploitation and habitation in and near the late Pleistocene to Middle Holocene Vrouw Vennepolder.

Two local pollen assemblage zones (LPAZs VVP-1 and VVP-2) were distinguished from a palynological sequence from the polder. The oldest sample of LPAZ VVP-1 came from Pleistocene fluvial sand and may have undergone reworking and/or mixing. Plants living on the sand substratum included *Betula* shrub, *Pinus*, some *Corylus*, *Alnus*, *Juniperus*, herbs, ferns and aquatic plants. Sample 2, extracted from Basal Peat and reflecting LPAZ VVP-1, implies a marsh environment with *Pinus*, *Corylus*, *Betula* shrubs and trees, *Alnus*, herbs and ferns. Vegetation of LPAZ VVP-2 – captured in younger Basal Peat and Wormer Member saltmarsh clay – comprised trees, shrubs, herbs, ferns and aquatic plants. Because of poor preservation, possible reworking and mixing, the deposition time of the sand is difficult to determine biostratigraphically. Given the values of *Corylus*, *Pinus* and *Betula* trees, sample 2 likely dates to the Early Holocene/Boreal. The dominance of *Corylus* and medium-high representation of *Quercus*, *Ulmus*, *Tilia* and *Alnus* pollen suggest a late Boreal age for LPAZ VVP-2.

The dynamic environment in and near the late Pleistocene to Middle Holocene Vrouw Vennepolder likely presented ecological opportunities and challenges – influenced by the sea, storms river and wind – for humans. Potential human ecological challenges were the changing morphology and geography of the land surface, saline water, high groundwater level, flooding, removal or deposition of sediment and objects and harsh wind. The possible role of hazard perception and potential human responses to ecological challenges are discussed too. Yet, such responses are difficult to study for the given time period, because of the research, prospection and discovery pattern of Palaeolithic and Mesolithic archaeology in the Western Netherlands, which normally does not go deep enough into the ground and offers additional problems. This thesis concludes that improving prospection and executing more excavations uncovering Palaeolithic and Mesolithic archaeological layers could help understand whether and how humans could have coped with ecological challenges in the late Pleistocene to Middle Holocene Vrouw Vennepolder environment and Western Netherlands in general.

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Appendices

Appendix 1: Lithological description of coring 51, with coordinates X: 97724.065; Y: 467502.659; -2.195 m NAP (‘*Normaal Amsterdams Peil*’, the Dutch ordnance level). The depth of the layer refers to centimetres below the ground level.

Depth of layer (in cm)	**Lithological description**	**Additional information**
0 – 30	Moderately clayey humic sand	Iron stains, few brick fragments
30 – 70	Black peat	No plant remains, partly oxidised
70 – 115	Reed peat, dark brown	Contains wood
115 – 135	Slightly clayey peat, greyish brown	
135 – 245	Moderately silty clay, slightly humic, light grey	Normal consistency, shell fragment, not differentiated
245 – 345	Slightly silty clay, light grey	Sand layers and detritus layers, shell grit
345 – 470	Slightly silty clay, light grey	Reed fragments, rooted (vertical)
470 – 560	Slightly sandy clay, grey	Lower boundary abrupt, shell grit
560 – 585	Slightly silty, humic clay, light greyish brown	
585 – 605	Slightly clayey peat, grey brown	Reed peat
605 – 623	Moderately silty clay, slightly humic, light grey	Firm consistency
623 – 635	Very clayey peat, grey brown	
635 – 770	Moderately silty clay, slightly humic, brown grey	Firm consistency, *Hydrobia* snails, shell grit, thin detritus layers
770 – 862	Moderately silty clay, slightly humic, brown grey	Thin sand layers and detritus layers
862 – 920	Moderately silty clay, humic, dark-brown grey	Abrupt top boundary Core part VPC1(1) was sampled for botanical remains at 900 to 930 cm. Core part VPC1(2) was sampled for botanical remains at 885 to 985 cm.
920 – 984	Compact peat, brown	Core part VPC1(3) was sampled for botanical remains at 970 to 987 cm.
984 – 987	Slightly silty sand, yellow	Kreftenheye Formation sands
987 – 1005	Sand, but not sampled (lost)	

Appendix 2: Description of the nine sampled sections from coring 51. The depth of the layer refers to centimetres below the ground level. The *Lycopodium* tablets, each containing 9,666 spores, originate from batch 3862. Per section sample, two *Lycopodium* tablets were added.

Section number	**Description**	**Volume (in cm^3)**	**Number of *Lycopodium* spores added as a spike**	**Comments**
1	984 – 985 cm depth, sand, VPC1(3)	1.6	19,332	
2	983 – 984 cm depth, peat, VPC1(3)	1.4	19,332	Underside was sandy, not fully organic.
3	969 – 970 cm depth, peat, VPC1(3)	2.0	19,332	May contain small quantity of the centimetre above due to crumbliness.
4	959 – 960 cm depth, peat, VPC(3)	2.0	19,332	
5	950 – 951 cm depth, peat, VPC1(2)	2.1	19,332	
6	940 – 941 cm depth, peat, VPC1(2)	2.0	19,332	
7	930 – 931 cm depth, peat, VPC1(2)	2.0	19,332	
8	920 – 921 cm depth, peat, VPC1(2)	2.0	19,332	
9	919 – 920 cm depth, grey clay, VPC1(2)	2.0	19,332	

Appendix 3: Description of the methodology applied for the lithological, palynological and malacological analysis of record from the Vrouw Vennepolder.

Coring

During the coring campaign at the Vrouw Vennepolder in the summer of 2022, 62 lithological corings were unearthed from three roughly eastwardly to westwardly oriented transects (see Figure 3.1). There was 25 or 20 metres distance in between the coring locations. For the coring, the more topmost layers until the peat were extracted from the ground with a 7-cm-diametre-Edelman core, while the deeper layers were reached with a 3-cm-diametre-gouge auger core. The sediments were laid out on the ground along a measuring tape and the content of the core was analysed and described. The coarse sand layer at about 10 or 11 metre depth was the end point of the core, as it became impossible to reach deeper with the available coring equipment. The lithological description included texture, colour, degree of humic and organic content, the presence of small-scale layers and consistency, as well as the type of boundary. In addition to archaeobotanical samples, shell remains were sampled as well during the coring procedure. GPS was used for the determination of X-, Y- and Z-coordinates. The data were processed in the computer programme Deborah.

Material from coring number 51, which was circa one metre away from coring 45, was used for the current study of the local vegetation and landscape changes. For coring 51, a depth of 9.87 metres was reached (see Appendix 1). Depths are indicated in metres or centimetres below the surface level. The surface height of the core was measured at 2.184 m above sea level, with coordinates 97722.123 E and 467502.552 N. The deepest layers were extracted in three separate core parts, named VPC1(1), VPC1(2) and VPC1(3). This research focusses core 51.

The sequence of studied and sub-sampled the laboratory comprises three separate sections – named VPC1(1), VPC1(2) and VPC(3), from which 9 sub-samples were taken (see below and see Appendix 1 and 2). The core sections were transferred into plastic guttering or left in the gouge auger, which were wrapped in plastic foil and stored in a cooled space in the Van Steenis building, in Leiden, for preservation.

Pollen sampling

The deepest layers of coring 51 were extracted in three separate sections, VPC1(1), VPC1(2) and VPC(3). Core part VPC1(1) comprises the lithology between approximately 9 and 9.30

metres depth and contains 20 centimetres of grey clay and 10 centimetres of peat deposit. Core part VPC1(2) contained sediments from approximately 8.85 metres to 9.70 metres deep. In the lithology, an abrupt change is present at 9.20 metres depth, with a transition from grey clay to peat. The deeper core part VPC1(3) contained the lithology of between 9.70 and 9.87 metres depth. Also in this part, an abrupt change was present, with peat above 9.84 metres and sand was present below the contact with the peat. Because of time constraints, not every part of the core was sampled and studied for their palynological content. Therefore, a total of nine sub-samples (three for each analyst) was taken from core part VPC1(2) and VPC1(3) from core 51. Even though the lithological data come from two separate parts, it is proposed that they represent one sequence of deposit formation. The original depths were described and noted on the core description, compared, juxtaposed and interpreted as successive layers.

VPC1(2) and VPC1(3) contain three types of deposits, dark brown-greyish clay, peat and sand. The nine sub-samples come from different parts of the cores (for further description, see Appendix 2), and most have a thickness of 1 centimetre (with the exception of samples 1 and 2, which were 2 centimetres thick), which is necessary to allow for approximately 2 cm^3 of sediment. Sample 1 is the top part of the sand, where there is direct contact with the peat above. The 1 centimetre of peat directly above the contact was also sampled (sample 2). Materials above this peat were sub-sampled at intervals of ten centimetre (samples 3 and 4 were taken from VPC1(3) and 5, 6 and 7 from VPC1(2), until the contact between peat and clay was reached. Again, a 1-centimetre-thick sample was taken either side of this contact (samples 8 and 9, in the peat and the brown-greyish clay respectively). The slices followed the original horizontal position and sedimentation, in order to gain information on the landscape through several, short timeframes; thicker slices would reduce the temporal resolution and could then contain more types of vegetation.

During sampling and preparation procedure, which was undertaken by Dr. Ilse M. Kamerling in the Laboratory of Archaeo- and Palaeobotany in the Van Steenis Building in Leiden, it is important to avoid contamination. The outer parts of these sections, which touched the inner wall of the gauge auger or were exposed when the core was cut once aboveground, were not sampled, as these outer parts may be contaminated with more pollen during the coring itself, during the transfer to the surface and from the atmosphere. Thereby, scraping off the superficial material yields a sample extracted from the *in-situ* conditions. The scalpel utilised for scraping off the superficial material of the surfaces of the core parts was also cleaned with distilled water in-between the sub-samples.

In addition, a known amount of exotic spores – the 'spike' – was included in the sample. This has a two-fold benefit: (1) it gives the palynomorphs contained within the sample something to 'cling to' during the preparation procedure, which is important especially when pollen concentrations are expected to be low, and (2) it enables the calculation of pollen concentration and/or influx rate data. For this, two *Lycopodium* tablet were added to each sample. One tablet from batch 3862 contains a known number 9,666 already chemically treated spores of *Lycopodium*. Concentration data would make it possible to compare the relative abundance of individual palynomorphs through time independent of the relative proportion of all the other taxa present in the sample. If the sediment accumulation rate is known, the ratio of fossil pollen to the spike can be used to determine the pollen accumulation rate through time (i.e., the influx rate). Furthermore, when material is lost during the preparation procedures, it is assumed that the ratio between fossils and spikes remains unaltered.

Sub-sample volume was determined through the volumetric displacement in a measuring cylinder. Approximately 4 ml of distilled water was added, following which sediment was added to raise the level by ca. 2 ml, meaning that a sub-sample volume of ca. 2 cm^3 had been achieved. Not every sub-sample comprised a volume of 2 cm^3 of material, so the exact volume, needed for pollen concentration calculations, was determined by reading the level of the meniscus and subtracting the known volume of water added (see Appendix 2). The samples were each poured into a centrifuge tube with corresponding number and filled with DI water, to which the spike was added. Samples 1 and 2 did not provide enough material to be able to extract the 2 cm^3, even though a 2-centimetre-thick cube was extracted from the core.

Laboratory preparation

In order to study the pollen and spores from the sample, it is needed to separate the palynomorphs from other organic matters and the (minerogenic) sediment matrix. A laboratory treatment was undertaken, following a standard procedure (cf. Moore *et al.*, 1991, pp. 42-46, 49-50). The samples were individually treated to avoid contamination. Following is an overview of the treatment of the samples.

To begin with, tetrasodium pyrophosphate (0.1 M) was added to the samples. This is to break the electrical bonds between clay minerals and aid disaggregation. The samples were placed on the whirlimix stirrer (also called vortexmixer) and placed on a heating block, warmed at 90 °C, for 10 minutes. Afterwards, the tubes were placed in the centrifuge at 3,600 rotations per minute (rpm) for 3 minutes. The supernatant was poured out. Two water washes were then carried out. A water wash entailed topping the tubes containing the samples up with demi (DI) water, placing the tubes in the whirlimix, centrifuging them at 3,600 rpm for 3 minutes and decanting the supernatant.

Subsequently, the samples were treated with 10 % potassium hydroxide (KOH), for disintegration of humic acids and organic fractions. KOH pellets are dissolved in DI water combined in a measuring cup in a ratio of 10 % weight per volume (10 % w/v). Approximately 10 ml of the hot 10 % KOH is added to the centrifuge tubes and the tubes are then placed in the pre-heated heating block, so they are heated at circa 100 °C for 20 minutes. During the heating, glass rods are used for stirring in the samples to optimise the interaction between the sediment matrix and the KOH.

The samples were sieved utilising separate sieves for each sample, with mesh size of 200 microns (µm), and the small remains are intercepted in flasks. The remainder that is left in the sieve is disposed of.

By adding 10 % (w/v) hydrochloric acid (HCl), it was found that samples 1 and 2 contained calcium carbonate, which was removed by adding further 10 % HCl, until the reaction ceased.

The pollen samples were then treated with glacial acetic acid (CH_3COOH; 99-100 % acetic acid), as all the water should be removed from the samples in order to prevent violent reactions during the following acetolysis step. All the samples were transferred to smaller 12/13-ml-tubes with rounded bottoms to improve the interaction of each particle within the sample with the glacial acetic acid and acetolysis mixtures. The tubes with pollen residue were topped up with the glacial acetic acid and then centrifuged (x3,600 for 3 minutes) and the supernatant was decanted. This step was performed two times to ensure that all the water is removed.

The following step was acetolysis, which is carried out to break down cellulose and lignin, so only pollen are present. The acetolysis mixture is an oxidising mixture made up with a ratio of 9 parts acetic anhydride and 1 part sulphuric acid (96 %). The pellet was whirlimixed to loosen it up and ca. 6 ml of the acetolysis mixture was added per tube. The tubes were then heated in a pre-heated heating block of 90 °C for 3 minutes. The samples were stirred in the meantime.

Glacial acetic treatment follows after the tubes, and stirring rods in them, were removed from the heating block. The washing with this mixture was undertaken, so that the acetolysis reaction ceases and is removed from the tubes before water washing three times.

The process was followed up by the utilisation of sodium polytungstate (SPT) for heavy liquid flotation. The specific solution produced has a relatively high density of 1.85 g/mL and this makes the organic material (including palynological remains) float on the SPT. Before SPT was added, any remaining water should be removed to avoid diluting and altering the density. The mixture with SPT was then whirlimixed for some time, especially when clumps are present, such as in sample 5, to loosen the organic remains. The samples were placed in the centrifuge for 20 minutes at 2,000 rpm, so that the remainder of the (minerogenic) sediments can sink. Subsequently, the floating pollen were carefully transferred into another tube with DI water in it with transfer pipettes. There should not be too much SPT coming with the pollen, because then it will not sink. The pipetting process, which was repeated a couple of times, yields most of the pollen, whilst it was not possible to transfer every grain. However, with the assumption of homogeneity, the ratio of palynological remains does not change. The smaller tubes with pollen were vortexmixed and centrifuged at 3,600 rpm for 3 minutes.

When enough botanical material was extracted, are subjected to the water washing process three times. The remains further prepared another day, so the tubes were topped off with water, whirlimixed and stored at room temperature.

The samples were subsequently dehydrated in ethanol (EtOH; 96 % alcohol). Firstly, the tubes were centrifuged and the supernatant was decanted off. Circa 1 ml of the EtOH was added to each centrifuge tube with pollen residue in them with transfer pipettes. The mixture with pollen residue was transferred to 1.5-ml-tubes, whirlimixed and centrifuged at 2,000 rpm for 2 minutes. The supernatant EtOH was poured out and the dehydration in ethanol was repeated for one more time.

The samples were then dehydrated in 2-propanol (IPA; isopropanol, isopropyl alcohol). Some IPA was transferred into the 1.5-ml-tubes and these were whirlimixed, centrifuged at 2,000 rpm for 2 minutes. The supernatant was decanted off.

Finally, silicon oil (15,000 cSt) was added to the samples in roughly the same volume as the volume of the remaining pellet, and the samples were placed in a pre-heated heating block at 40 °C for several hours. In the meantime, stirring was done occasionally to allow the last of the IPA to evaporate.

Microscopic analysis

After the palynological samples were chemically treated in the laboratory, they were mounted on slides. A small aliquot of the remains were transferred on a slide, a few drops of silicon oil were added and the mixture were carefully spread on the slide. Following this, a coverslip was placed. The coverslips were not sealed off, so that coverslip, and consequently the pollen, could gently be moved for identification purposes. The pollen were analysed under 400x magnification using a Leica DM 750.

For each of the nine samples, the aim was to count at least 200 terrestrial pollen grains and to note them on a form. This 200 thus excludes the *Lycopodium* spikes, spores and pollen of aquatic plant taxa, yet these were counted as well. In addition, the occurrence of other microfossils (non-pollen palynomorphs), like diatoms, dinoflagellates, (other) algal microfossils and amoebas was also documented. Mieke Bulder worked on samples 2, 5 and 8, Andrew Lynch documented the content of samples 1, 4 and 7 and the author of this thesis analysed samples 3, 6 and 9. Because of the relatively less-abundant pollen record on the slides, coupled with preservation issues, 131 land pollen grains were counted in sample 5. Moreover, it was decided to stop counting pollen in sample 4, also because of time constraints, resulting in a total of 152 land pollen being counted.

The identification of the pollen and plant spores was determined with the help of the identification keys by Beug (2004) and Moore et al. (1991), see Appendix 4. The nomenclature of the pollen morphology is based on Beug (2004). The identification of the plant spores followed the nomenclature of Moore et al. (1991). Some other microfossils (non-pollen palynomorphs) were documented too, see Appendix 6, and the nomenclature was based on Kuhry (1997), Pals et al. (1980), van der Wiel (1982), van Geel (1776), van Geel (1778) and van Geel et al. (1981). Diatoms and dinoflagellates were not identified beyond that and were just mentioned as being present. However, not all microfossils, like non-plant spores and ascospores, were identified or noted down.

The identification of plant microfossils went down to the highest resolution as possible, to the level of family, genus or type. More precise identification to species level generally was not feasible. A type comprises a morphological shape that could occur in several taxa. For example, a *Hordeum*-type pollen was identified. This can be produced by some cereal plants and some wild grasses (see also Appendix 5). Based on morphological characteristics (see also Andersen (1979)), it was possible to distinguish the *Hordeum*-type pollen grain from Poaceae pollen. When possible, a distinction between *Betula* shrub and *Betula* tree was made – *Betula* shrub

(*Betula nana*) pollen are smaller and other *Betula* larger than 20 µm, though there is an overlap in their ranges – see Birks (1968) and Karlsdóttir et al. (2007). *Pinus* was sometimes partially encountered, for example only by one saccus, with or without (part of) the corpus. In that case, halves were individually counted and two separate halves would be considered to make one individual. Sometimes, 'sp.' is applied in the identification, as in the case of *Myriophyllum* sp. and *Rumex* sp.. This is not in correspondence with Beug (2004), but the notation is applied when it was not possible identify further than that it is assumed the genus is represented by the pollen grain. Some pollen were noted as 'unidentified'. This could be as a result of uncertainties due to poor preservation resulting from corrosion, degradation, folding, fragmentation and/or other remains hindering a full scope of diagnostic features of pollen.

Pollen dataset

The data from the counting sheet were digitised in Excel and subdivided into several categories: trees, shrubs, herbs, climbers, aquatics, Pteridophytes, Equisetopsida spores, Bryophyte spores, the spike (*Lycopodium*), unidentified, algae and others. Together with the data on the depth of the samples, the data were processed in TILIA. The pollen sum was based on the total land pollen (TLP), and these include the trees, shrubs, herbs and climbers. All percentages calculated are determined relative to this TLP sum. Pollen that were identified with 'cf.' (compares favourably) were stacked under the taxonomic name that it resembled. Taxa represented only by a 'cf.' – cf. *Acer*, cf. *Pedicularis*, cf. *Ephedra* and cf. *Valeriana* – were left out, except for cf. *Pteridium*. Each sample is represented in bars, so the pollen diagram works without interpolation between samples. The presence of rare taxa – i.e., ones that are represented at a percentage of ≤ 1 % – is indicated with one or more '+'. More '+'s indicate a higher percentage below 1 %. The lithological log of the core is included as well.

Moreover, a CONISS (constrained incremental sum of squares) cluster analysis was executed to inform the placement of local pollen assemblage zones (LPAZs). A summary diagram based on the trees, shrubs and herbs is also added to the pollen diagram, and this works with inter- and extrapolated visualisation. Pollen zones were distinguished in the pollen diagram, and these are noted as local pollen assemblage zones (LPAZs) VVP-1 and VVP-2. A line is added to the pollen diagram to separate the zones. The line is placed below where the new zone starts, but it remains uncertain if the zone boundary could be placed lower, as there are gaps between the sampled intervals.

Shell sampling

Some shells and shell fragments were sampled during the coring campaign in the Vrouw Vennepolder (Appendix 7). The shell content of some corings was not sampled at all. The samples were washed over a very fine sieve. For this, their coring number and depth in the coring were noted. The identification of the shells was aided by the books of de Bruyne *et al.* (2013) and Poppe & Goto (1993a; 1993b), with the help of Dr. Laura Llorente-Rodriguez of Leiden University. The habitat and ecology are inferred from these book too. The malacological data can further improve the understanding of the depositional context through time of the Vrouw Vennepolder landscape.

Appendix 4: Counts of the different palynomorphs per palynological sample from the Vrouw Vennepolder. The nomenclature follows the ways described in Appendix 3.

Sample	9	8	7	6	5	4	3	2	1
Picea	0	1	0	0	0	0	0	0	0
Pinus	9	4	8	3	8	5	14	84	79
Abies	0	0	0	0	0	0	1	0	0
Quercus	22	26	21	19	9	11	21	0	0
Castanea	0	0	0	0	0	0	0	0	2
Fagus	0	0	0	1	0	0	0	0	0
cf. *Acer*	0	0	0	0	0	1	0	0	0
Salix	0	1	0	0	0	0	0	0	2
Fraxinus	0	0	1	1	2	0	0	0	0
Tilia	7	9	4	8	1	1	3	0	0
Betula (tree)	21	25	6	10	9	4	6	18	0
Corylus	56	53	51	65	45	44	57	71	41
Alnus	42	37	32	36	24	34	41	5	5
Ulmus	16	10	16	23	13	8	7	0	3
Calluna vulgaris	0	0	1	1	1	2	0	0	0
Empetrum/Ledum	1	0	0	0	0	0	0	0	0
Vaccinium-type	0	0	0	1	0	0	0	0	0
Juniperus	0	0	0	0	0	0	0	0	6
Betula nana	0	0	0	0	0	0	0	31	165
Hedera helix	1	0	0	0	0	0	0	0	0
cf. *Ephedra*	0	0	0	1	0	0	0	0	0
Poaceae	17	29	32	29	14	19	50	10	26
Hordeum-type	1	0	0	0	0	0	0	0	0
cf. *Pedicularis*	1	0	0	0	0	0	0	0	0
Sanguisorba minor-type	0	0	0	0	0	0	0	2	0
Monotropa hypopitys	0	0	0	0	0	0	0	0	1
Apiaceae	0	0	0	0	0	0	4	0	0
Artemisia	0	0	0	0	0	0	0	0	3
cf. *Filipendula*	0	0	0	0	0	0	1	0	0
Filipendula	0	0	1	0	0	0	0	0	7
Asteraceae	0	0	0	0	0	1	0	0	0

Sample	9	8	7	6	5	4	3	2	1
Senecio-type	1	0	5	0	0	0	0	0	1
cf. *Valeriana*	0	0	0	0	0	0	1	0	0
Ballota-type	0	0	0	0	0	0	0	0	1
Rumex sp.	0	2	0	0	0	1	0	0	0
Rumex acetosa-type	0	0	0	0	0	0	1	0	0
Lactuca-type	0	0	0	0	0	1	0	0	0
cf. Cannabinaceae	0	1	0	0	1	0	0	0	0
Cannabinaceae	0	0	0	0	0	0	1	0	0
Urticaceae	0	1	0	0	0	0	0	0	2
Chenopodiaceae	8	0	7	1	3	4	0	0	0
Cyperaceae	1	17	15	3	1	17	6	0	13
Typha latifolia-type	0	0	0	1	0	0	9	0	0
Potamogeton	0	0	1	0	0	0	0	0	1
cf. *Nymphaea*	0	0	0	1	1	0	0	0	0
Nymphaea	0	0	1	0	0	1	2	0	0
Sparganium-type	12	56	53	45	7	19	16	0	2
Nuphar	1	1	0	1	0	0	0	0	0
Utricularia	0	0	0	0	0	0	1	0	0
Alisma-type	0	0	0	0	0	0	1	0	0
Myriophyllum sp.	1	0	0	0	0	0	0	0	0
Myriophyllum verticillatum	0	2	0	0	0	0	0	0	0
Pteridopsida monolete (psilate)	18	0	0	18	17	16	651	429	285
Pteridopsida monolete (reticulate)	0	0	1	0	0	0	0	0	6
Pteridopsida monolete (echinate)	0	0	1	0	0	1	0	0	0
Pteridopsida monolete (scabrate)	0	0	1	0	0	0	0	22	0
Polypodium	2	0	1	0	0	0	3	0	0
Pteridophyte spore indet.	0	0	2	0	0	0	0	0	0
cf. *Pteridium*	0	0	0	2	0	0	0	0	0
Sphagnum	0	0	0	1	0	0	1	0	1

Sample	9	8	7	6	5	4	3	2	1
Equisetum	2	0	0	0	0	0	0	0	0
Spike (*Lycopodium*)	32	27	13	18	33	25	36	28	47
Unidentified	13	5	28	22	0	20	28	17	120
HdV-T58 Zygnemataceae zygospore	0	0	0	0	0	0	0	0	1
HdV-T128 Unidentified alga	6	0	7	2	3	2	9	70	69
HdV-T132 *Spirogyra* spores	0	0	0	0	0	0	0	0	1
HdV-T141 *Mougeotia* zygospore	0	0	0	0	0	0	0	0	1
HdV-T314 *Zygnema* type	1	0	1	0	0	1	1	0	0
HdV-T760 *Pediastrum*	0	0	0	0	0	0	0	0	40
HdV-T766 *Botryococcus*	0	0	2	0	0	0	0	19	66
HdV-T900 *Pediastrum*	3	0	0	0	0	0	0	0	1
Diatom	2	3	1	0	0	0	0	0	0
Dinoflagellate	7	0	0	1	0	0	0	0	0
cf. *Arcella*-type 352	0	0	0	4	0	0	0	0	0
HdV-T89 *Tetraploa aristate* spore	0	0	2	0	0	0	0	0	0
HdV-T114 Scalariform perforation plate	0	0	0	0	0	0	0	0	1

Appendix 5: Palynological microfossils from plant taxa from the corings from the Vrouw Vennepolder and notes on their preferred ecology and habitat tolerance. The used sources for their habitat and ecology are also mentioned. Following an uniformitarianistic approach, these ecological tolerances probably were also the tolerances in the past. Palynology generally does not provide high-resolution taxonomic identification, so the ecology and habitat tolerances are not very specific.

Taxon	**Ecology and habitat tolerance**	**Source**
Picea	Lives in forests.	Duistermaat, 2020, pp. 86-87
Pinus	Has a wide living range, is able to live on heath, sand drift and peat areas.	Bos & Urz, 2003, p. 30; Duistermaat, 2020, pp. 85-86; Tutin et al., 1964, pp. 32-35
Abies	Can form extensive forests, also in mountainous areas.	Duistermaat, 2020, pp. 88-89; Tutin et al., 1964, pp. 29-30
Quercus	Favours dry to moist, acidic and nutrient-rich grounds. They can also form quite open stands.	Duistermaat, 2020, pp. 404-405; Bakels, 2017, p. 180
Castanea	Prefers well-drained, dry to moderately moist, acidic grounds in and/or near forests, and mountain slopes.	Duistermaat, 2020, p. 403; Tutin et al., 1964, p. 61
Fagus	Favours moist or dry, well-drained places that are moderately nutrient-poor to moderately nutrient-rich, possibly and calcareous grounds.	Duistermaat, 2020, pp. 403-404; Tutin et al., 1964, p. 61
Salix	May live in wet or dry environments, like in the dunes or in marsh and peat areas, along rivers and in forest edges.	Duistermaat, 2020, pp. 423-428; Hoek, 1997a, p. 24
Fraxinus	Lives in wet to moist areas that are nutrient-rich and have a clayey component, like floodplains, natural levees and river banks.	Duistermaat, 2020, p. 630; Kubiak-Martens et al., 2015, p. 265; Tutin et al., 1981, pp. 53-54; van der Wiel, 1982, p. 95

Tilia	Favours moist, moderately nutrient-rich, calcareous grounds. *Tilia* trees cause a lot of shade.	Bakels, 2017, p. 179; Duistermaat, 2020, pp. 457-458; Zuidhoff & Bos, 2017, p. 146
Betula (tree)	Depending on the species, such trees live in dry to moist, acidic to moderately nutrient-rich environments, marshes, fens or dry dune slopes.	Bos et al., 2005b, p. 37; Bos & van Geel, 2017, p. 124; Duistermaat, 2020, pp. 400-401
Corylus	Tends to live in moderately nutrient-rich, somewhat moist and calcareous areas, in or near forests as undergrowth and forest edges. It requires sufficient light in order to germinate.	Bos, 2001, p. 201; Duistermaat, 2020, pp. 402-403; Kasse et al., 2022, p. 10
Alnus	Favours wet habitats and tends to live along watersides and in marshes. Does not tolerate a heavily fluctuating groundwater table.	Duitsermaat, 2020, pp. 401-402; Kubiak-Martens et al., 2015, p. 267
Ulmus	Prefers moist, nutrient-rich grounds.	Duistermaat, 2020, pp. 397-398
Calluna vulgaris	Lives in moist to dry, acidic ground, moors and heaths and it can be part of poor (Dutch: *schrale*) grasslands or light forests.	Duistermaat, 2020, p. 558; Kubiak-Martens et al., 2015, p. 239; Tutin et al., 1981, p. 8
Empetrum/Ledum	Can vegetate wet to dry, acidic sandy grounds, heath, moor, marsh and peat areas.	Duistermaat, 2020, pp. 557- 559; Tutin et al., 1981, pp. 13-14
Vaccinium-type	Could have been produced by various Ericales. Plants of Ericales can live in wet to moist, acidic heathlands, peatland, poor grassland and light forests. They usually live in poorer, acidic ground.	Bakels, 2017, p. 180; Duistermaat, 2020, pp. 556-562; Hoek, 2000, p. 504
Juniperus	Can live in areas with sandy substratum, in oligotrophic conditions, like with sand drift, cover sand ridges, heath areas and in (river) dunes, in addition to mountain areas and dry hills.	Duistermaat, 2020, p. 90; Hoek, 2000, p. 504; Kubiak-Martens et al., 2015, p. 265;

		Tutin et al., 1964, pp. 38-39
Betula nana	Tolerates in quite cold and open environments, but also in moorlands and bogs, and the growth is affected by snow cover.	Buchwal, 2023, pp. 493, 497, 501-504; de Groot et al., 1997, p. 243; Tutin et al., 1964, p. 58; Kasse et al., 1995, pp. 401-402
Hedera helix	Can climb over trees, rock and other landscape features and prefers damp conditions. It reacts quickly to winter frost and only flowers when the minimum winter temperatures are at least -1.7 to -2 °C and average summer temperatures are above 13 °C – its presence in the fossil record can be used as a temperature marker.	Duistermaat, 2020, pp. 775-776; Iversen, 1944; Tutin et al., 1968, p. 314; Zagwijn, 1994, pp. 69, 78
Poaceae	The ecological tolerances of the Poaceae as a family ranges quite far: from moist to dry, nutrient-rich to nutrient-poor, calcareous or not and some genera tolerate brackish conditions. Most favour open or light places.	Duistermaat, 2020, pp. 205-294; Tutin et al., 1980, pp. 118-267
Hordeum-type	Pollen are produced by some genera of Poaceae. They could have been produced by cereals or wild grasses: *Hordeum distichon*, *Hordeum vulgare*, *Hordeum murinum*, *Hordeum nodosum*, *Hordeum maritimum*, *Oryza sativa*, *Elymus arenarius*, *Agropyron junceum*, *Agropyron intermedium*, *Agropyron caninum*, *Agropyron littorale*, *Spartina maritima*, *Glyceria fluitans*, *Glyceria plicata*, *Bromus mollis*, *Bromus erectus*, *Bromus inermis*, *Secale cereale*, *Triticum monococcum*. Just like most other Poaceae, an open or light habitat is favoured.	Andersen, 1979, pp. 82, 91; Beug, 2004, p. 81; Duistermaat, 2020, pp. 205-294; Tutin et al., 1980, pp. 118-267
Sanguisorba minor-type	Could have been produced by different genera, belonging to the Rosaceae. Can possibly live in dry grasslands and/or rocky terrains, or wet to moist, nutrient-rich grounds along waters.	Duistermaat, 2020, pp. 367-368; Tutin et al., 1968, pp. 33-34
Monotropa hypopitys	Favours growing in damp woods.	Tutin et al., 1981, p. 5

Apiaceae	The family consist of many species, which can grow in wet and moist to dry, calcareous grounds in dunes, grasslands, deciduous forests, marsh forests, saltmarshes, along waterbodies, seepage and disturbed areas. Some species tolerate moderately nutrient-poor grounds, but mostly (moderately) nutrient-rich environments are preferred.	Bos & van Geel, 2017, p. 125; Duistermaat, 2020, pp. 746-775; Tutin et al., 1968, pp. 315-375
Artemisia	Prefers open, salt-tolerant, moist or dry, sandy areas. It can also indicate disturbed grounds.	Duistermaat, 2020, pp. 714-716; Tutin et al., 1984, pp. 178-186
Filipendula	Can live in dry grasslands, steppes, scrubs, light forests or nutrient-rich and damp or wet places.	Bos & Urz, 2003, p. 28; Bos & van Geel, 2017, p. 124; Duistermaat, 2020, p. 366; Hoek & Bohncke, 2002, p. 128; Tutin et al., 1968, pp. 6-7
Asteraceae	Species of this family grow in a wide variety of habitats, quite open places.	Tutin et al., 1984, pp. 103-410
Senecio-type	*Senecio*-type pollen are produced by particular Asteraceae. These two pollen groups, like the other herbs, likely also point to quite open places.	Tutin et al., 1984, pp. 103-410
Ballota-type	Could have been produced by various species of Lamiaceae – *Betonica*, *Ballota nigra* and *Stachys*. Such plants may have lived in moist or dry, nutrient-rich reworked grounds, potentially open or along the forest edge.	Duistermaat, 2020, pp. 611-612, 614-616; Tutin et al., 1981, pp. 149-157
Rumex sp.	Can be encountered in a range of habitats with different conditions, including disturbed grounds and as riparian plants. *Rumex aquatica* lives in freshwater tidal areas.	Bos & van Geel, 2017, p. 121; Duistermaat, pp. 547-552
Rumex acetosa-type	Can be encountered in a range of habitats with different conditions, including disturbed grounds and as riparian plants.	Bos & van Geel, 2017, p. 121; Duistermaat, pp. 547-552

Lactuca-type	Might point to which open, damp, (moderately) nitrogen-rich and disturbed grounds.	Duistermaat, 2020, pp. 682, 687-689
Cannabinaceae	Can be produced by *Cannabis* or *Humulus*. The latter grows in moist and wet, nutrient-rich environments in deciduous woodlands, shrublands and marsh forests where it can climb trees and shrubs.	Bos et al., 2005b, p. 38; Duistermaat, 2020, p. 360
Urticaceae	May live in dry to moist, nitrogen-rich environments. It can also live along the water and in disturbed grounds.	Bos & van Geel, 2017, pp. 124-125; Duistermaat, 2020, pp. 398-400; Tutin et al., 1964, pp. 67-69; van Geel et al., 1981, p. 403
Chenopodiaceae	Can live in wet and moist conditions, like along rivers, and they usually inhabit open, nutrient-rich places. Many of the many species are ruderals or halophytic; they tolerate brackish and saline conditions and live in saltmarshes and other sites along the coast, or in steppe and semi-desert.	Duistermaat, 2020, pp. 500-515; Tutin et al., 1964, pp. 90-111
Cyperaceae	Usually live in fairly wet or moist, quite open areas. Dryer and more shady places are sometimes also regarded as living area of some Cyperaceae. Some live in nutrient-rich environments and as riparian species, while others tolerate nutrient-poor grounds. Some live in brackish environments.	Duistermaat, 2020, pp. 156-192; Tutin et al., 1980, pp. 276-323
Typha latifolia-type	*Typha* species prefer moist or wet and nutrient-rich environments, such as swamps.	Duistermaat, 2020, pp. 296-297
Potamogeton	May grow in somewhat deeper parts in a waterbody, but some *Potamogeton* species prefer shallower settings, often nutrient-rich, but some also nutrient-poor. It can live in stagnant or flowing water. Some *Potamogeton* tolerate brackish conditions.	Bos et al., 2013, pp. 30-31; Duistermaat, 2020, pp. 109-116; Tutin et al., 1980, pp. 7-11
Nymphaea	Tends to live in somewhat deep water, which may be stagnant or slowly flowing and nutrient-rich but also poor and acidic.	Bos & van Geel, 2017, p. 125; Duistermaat, 2020, pp. 92- 93

Sparganium-type	Can be produced by *Sparganium* species or *Typha angustifolia*. *Sparganium* species tend to grow – stand erect or float – in or near shallow, nutrient-rich waterbodies. *Typha angustifolia* is also a (semi-)aquatic plant.	Duistermaat, 2020, pp. 294-295; Tutin et al., 1980, pp. 274-275
Nuphar	Favours somewhat deep and nutrient-rich water.	Bos & van Geel, 2017, p. 125; Duistermaat, 2020, p. 93
Utricularia	Are carnivorous plants that can grow in peat areas. They commonly prevail submerged in fairly nutrient-rich watery bodies, like ponds, river channels and fens.	Duistermaat, 2020, pp. 627-629
Alisma-type	Could have been produced by species of *Alisma* or *Baldellia ranunculoides*, and these are aquatic, shore and marsh vegetation.	Beug, 2004, p. 466; Duistermaat, 2020, pp. 96-98; Tutin et al., 1980, p. 2 Kubiak-Martens et al., 2015, p. 239; Tutin et al., 1980, p. 2
Myriophyllum sp.	Generally are submerged, freshwater plants. The genus includes species that tolerate nutrient-rich and - poor waters, and these waters could be creeks, ponds or small channels. *Myriophyllum spicatum* tolerates brackish environments.	Duistermaat, 2020, pp. 329-331; Tutin et al, 1968, pp. 311-312
Myriophyllum verticillatum	Lives in stagnant or flowing water, fens and in river clays, and may indicate seepage or fairly deep parts of a waterbody.	Bos et al., 2013, pp. 30-31; Bos & van Geel, 2017, p. 125; Duistermaat, 2020, p. 329
Pteridopsida	Are perhaps undergrowth plants.	Bakels, 2017, p. 177
Polypodium	Can be undergrowth plants. They can tolerate dryness and can live in dry, nutrient-poor, usually calcareous grounds and in a light forest or shrub environment.	Duistermaat, 2020, p. 84; Tutin et al., 1964, p. 23; Weeda et al., 1985, p. 50
Pteridium	Are terrestrial, undergrowth plants.	Tutin et al., 1964, p. 12
Sphagnum	Can live in (higher, more acidic and nutrient-poor parts of) swampy environments. They can also be (semi-)aquatic.	Bos et al., 2005a, pp. 277-278; Bos et al., 2013, p. 31;

		Bos & van Geel, 2017, pp. 124-125; Hájek, 2009; Paffen & Roelofs, 1991
Equisetum	Could have lived in fairly shallow waterside of a waterbody or marsh, as herbaceous land, undergrowth or swamp plants.	Bos & van Geel, 2017, pp. 124-125; Duistermaat, 2020, pp. 64-67

Appendix 6: Identified non-pollen palynomorphs (NPPs) from the corings from the Vrouw Vennepolder and notes on their preferred ecology / habitat. The nomenclature of the shells follows Kuhry (1997), Pals et al. (1980), van der Wiel (1982), van Geel (1776), van Geel (1778) and van Geel et al. (1981). The habitat and ecology are also inferred from these sources.

Non-pollen palynomorph	**Ecology**	**Source**
HdV-T58 Zygnemataceae zygospore	Are produced in stagnant, shallow and mesotrophic fresh water. The favoured conditions for production are present during the spring.	van Geel, 1976, pp. 340, 342
HdV-T128 Unidentified alga	Present in shallow, eutrophic freshwater conditions, optimally in predominantly stagnant water.	Pals et al., 1980, p. 407
HdV-T132 *Spirogyra* spores	Can be produced by several species. *Spirogyra* is fairly common in shallow, stagnant water.	Pals et al., 1980, p. 409; van der Wiel, 1982, p. 81
HdV-T141 *Mougeotia* zygospore	No further environmental tolerances and habitats of this genus of Zygnemataceae are indicated.	van der Wiel, 1982, p. 81
HdV-T314 *Zygnema* type	Zygospores or aplanospores of Zygnemataceae or Oedogoniaceae. Commonly occur in shallow, meso- to eutrophic, open waterbodies.	van Geel et al., 1981, p. 427
HdV-T760 *Pediastrum*	Could point to stagnant water.	e.g., Kasse et al., 1995, p. 404
HdV-T766 *Botryococcus*	Could point to a shallow or deep waterbody. Lives in meso- to eutrophic and open water conditions.	Bos et al., 2013, p. 31; van Geel et al., 1981, pp. 403, 407
HdV-T900 *Pediastrum*	Could point to stagnant water. It occurs in meso- to eutrophic conditions.	Kuhry, 1997, p. 222; Kasse et al., 1995, p. 404
Diatom	Aquatic environment.	Jones, 2007, pp. 479-482 and references therein
Dinoflagellate	Aquatic environment.	Matthiessen et al., 2005, pp. 14-16; Taylor & Pollingher, 1987
Arcella-type 352	Present in *Sphagnum fuscum* peat.	Kuhry, 1997, p. 217; van Geel et al., 1981, p. 434
HdV-T89 *Tetraploa aristate* spore	On leaves and stems, above the soil. They are quite widespread and are known to live on *Ammophila*, *Carex*, *Cladium*, *Cyperus*, *Dactylis*, *Deschampsia*, *Juncus*, *Phaseolus*, *Phragmites* and *Triticum*.	van Geel, 1978, p. 96

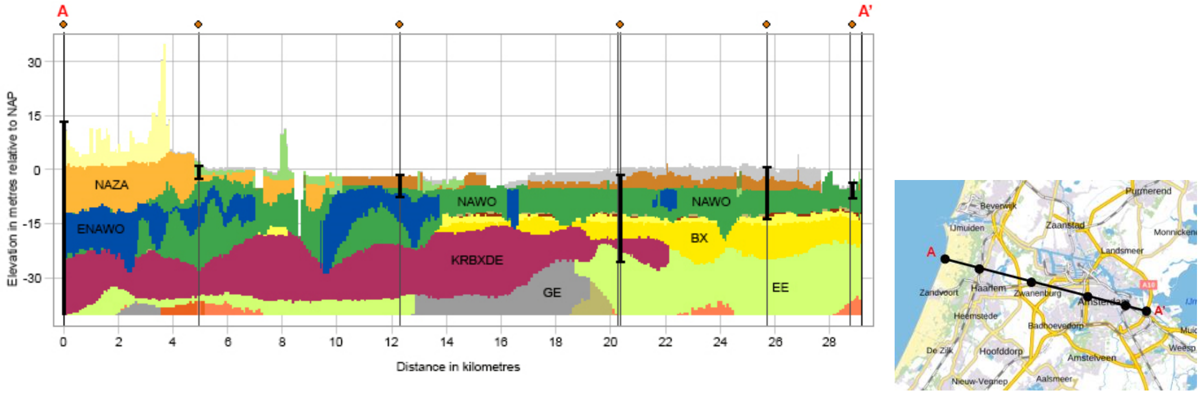
HdV-T114 Scalariform perforation plate	Part of a wood vessel of *Betula*, *Alnus*, *Corylus* or *Myrica*. They generally appear to be present in clay sedimented in marine conditions and did not grow locally.	Pals et al., 1980, p. 403

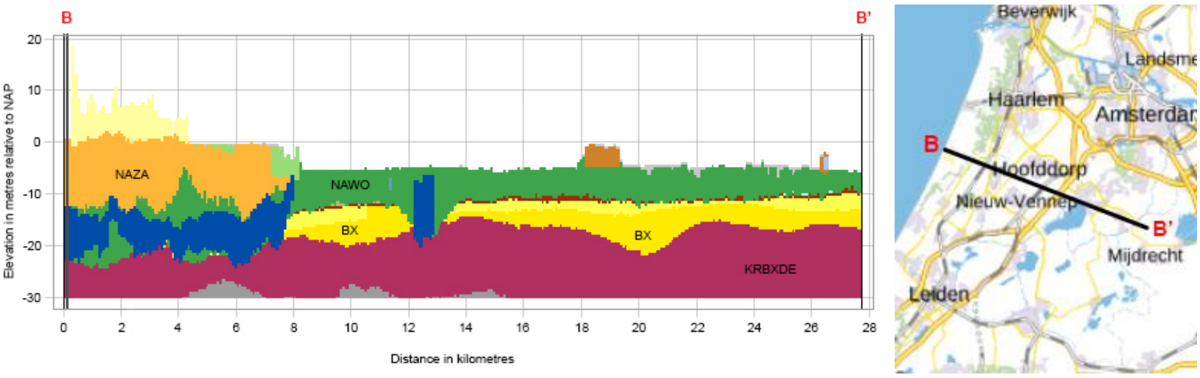
Appendix 7: Sampled malacological taxa from the corings from the Vrouw Vennepolder, their depth (centimetres below the ground level, though without correction to NAP) in the corings and notes on their preferred ecology / habitat. The nomenclature of the shells follows de Bruyne et al. (2013) and Poppe & Goto (1993a; 1993b). The habitat and ecology are also inferred from these sources.

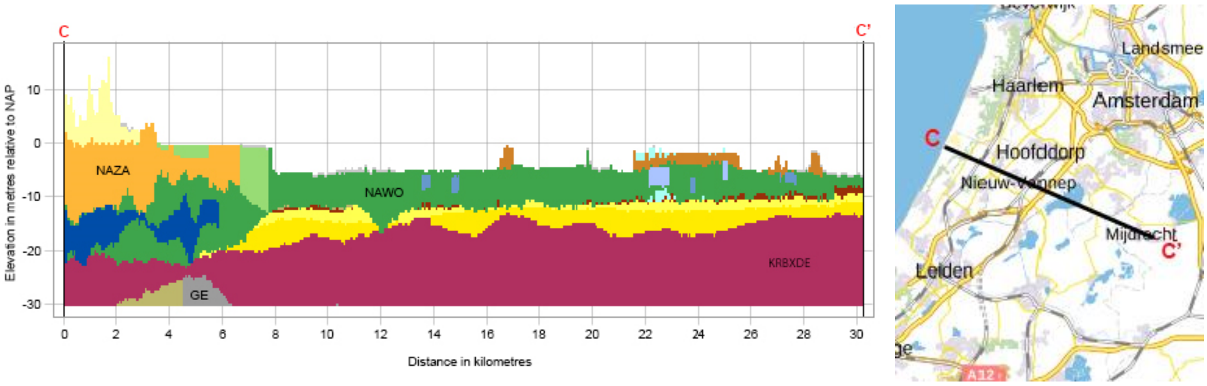
Taxon	**Coring number**	**Upper boundary (in cm)**	**Lower boundary (in cm)**	**Ecology / habitat**
Spisula sp.	19	225	226	Sublittoral or intertidal, coarse sand, loose on seabed or shallowly burrowed
Spisula sp.	22	255	256	Sublittoral or intertidal, coarse sand, loose on seabed or shallowly burrowed
Lutraria sp.	22	255	256	Marine, burrows in sand
Spisula sp.	57	355	356	Sublittoral or intertidal, coarse sand, loose on seabed or shallowly burrowed
Spisula sp.	21	375	376	Sublittoral or intertidal, coarse sand, loose on seabed or shallowly burrowed
Spisula sp.	39	385	450	Sublittoral or intertidal, coarse sand, loose on seabed or shallowly burrowed
Spisula sp.	60	375	376	Sublittoral or intertidal, coarse sand, loose on seabed or shallowly burrowed
Cerastoderma edule	39	385	450	Intertidal, shallow water, salinity to 36‰
Spisula sp.	32	420	430	Sublittoral or intertidal, coarse sand, loose on seabed or shallowly burrowed
Hydrobiidae sp.	60	420	455	Fresh or brackish water
Spisula sp.	58	450	451	Sublittoral or intertidal, coarse sand, loose on seabed or shallowly burrowed
Hydrobiidae sp.	58	450	451	Fresh or brackish water
Spisula sp.	31	463	464	Sublittoral or intertidal, coarse sand, loose on seabed or shallowly burrowed
Spisula sp.	42	490	492	Sublittoral or intertidal, coarse sand, loose on seabed or shallowly burrowed
Cerastoderma edule	29	560	570	Intertidal, shallow water, salinity to 36‰
Spisula sp.	4	575	576	Sublittoral or intertidal, coarse sand, loose on seabed or shallowly burrowed
Cerastoderma edule	29	600	601	Intertidal, shallow water, salinity to 36‰
Littorina sp.	35	600	601	Intertidal

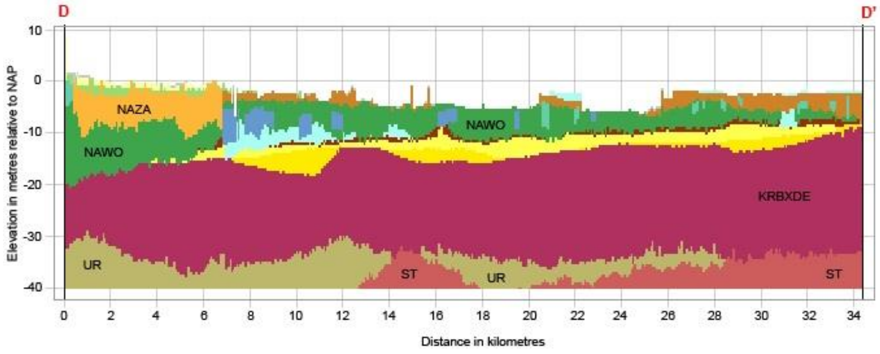
Cerastoderma edule	30	625	626	Intertidal, shallow water, salinity to 36‰
Hydrobiidae sp.	30	625	626	Fresh or brackish water
Littorina sp.	30	625	626	Intertidal
Cerastoderma edule	34	675	676	Intertidal, shallow water, salinity to 36‰
Hydrobiidae sp.	28	750	751	Fresh or brackish water
Lithoglyphus sp.	28	750	751	Freshwater
Theodoxus fluviatilis	46	905	906	Fresh or brackish water

Appendix 8: Lithological cross-sections of the Vrouw Vennepolder area and Western Netherlands. The surface on which (Palaeolithic and Mesolithic) people could have moved and on which the Basal Peat could later form – the relevant surface for this thesis – comprises late Pleistocene and Early Holocene sandy substratum of fluvial and aeolian sediments of the, respectively, Kreftenheye and Boxtel Formation (e.g., Bos et al., 2012, pp. 689-690, 693-694). One should also consider later erosion of the Pleistocene substratum. The direct vicinity of the polder apparently did not house pronounced higher-elevated terrains, though some areas to the north and south did. The legend for the lithological profiles is found below the profiles. NAP is '*Normaal Amsterdams Peil*', the Dutch ordnance level. Source: lithological profiles made using https://www.dinoloket.nl/ondergrondmodellen/kaart.

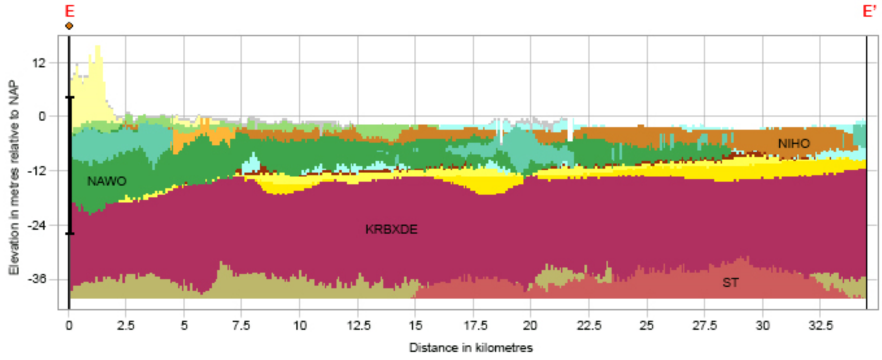




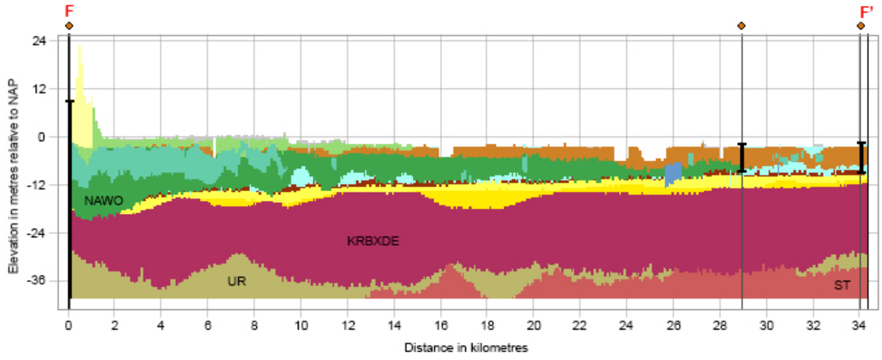



D
D'
Elevation in metres relative to NAP
10
0
-10
-20
-30
-40
NAZA
NAWO
NAWO
KRBXDE
UR
ST
UR
ST
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
Distance in kilometres

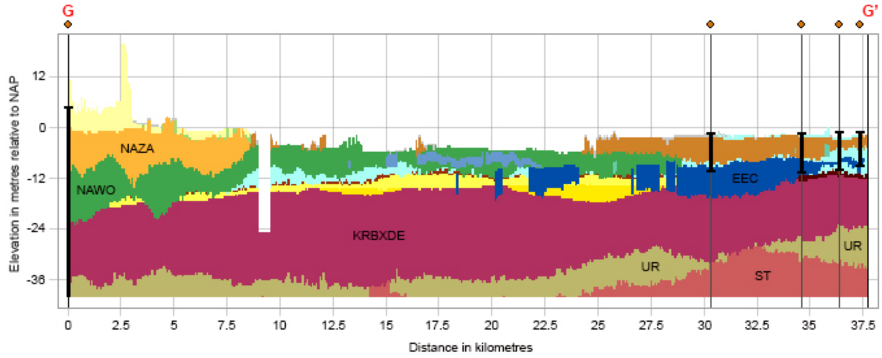

Haarlem
Amsterdam
Hoofddorp
Nieuw-Vennep
D
Mijdrecht
Leiden
D'
A12
Gouda
Rotterdam


E
E'
Elevation in metres relative to NAP
12
0
-12
-24
-36
NIHO
NAWO
KRBXDE
ST
0
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25
27.5
30
32.5
Distance in kilometres

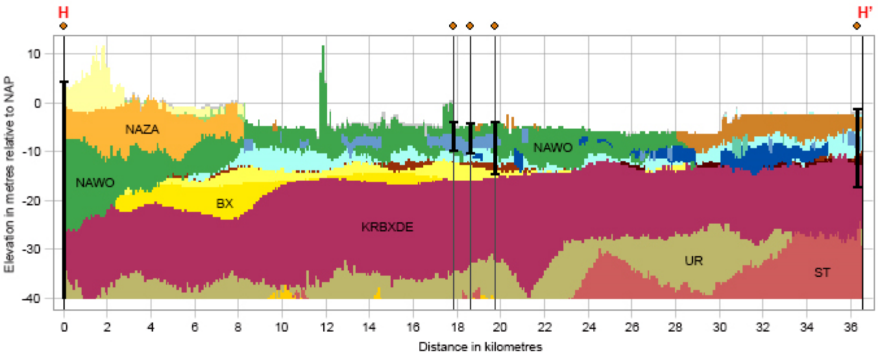

Haarlem
Amsterdam
Hoofddorp
Nieuw-Vennep
E
Mijdrecht
Leiden
E'
A12
Gouda
Rotterdam


F
F'
Elevation in metres relative to NAP
24
12
0
-12
-24
-36
NAWO
KRBXDE
UR
ST
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
Distance in kilometres


Hoofddorp
Nieuw-Vennep
F
Mijdrecht
Leiden
A12
Gouda
F'
Rotterdam


G
G'
Elevation in metres relative to NAP
12
0
-12
-24
-36
NAZA
NAWO
EEC
KRBXDE
UR
UR
ST
0
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25
27.5
30
32.5
35
37.5
Distance in kilometres


Hoofddorp
Nieuw-Vennep
Mijdrecht
G
Leiden
's-Gravenhage
A12
G'
Rotterdam
Spijkenisse
Dordrecht



Legend

Geological unit

■ AAOP = Anthropogenic deposits, *opgebrachte grond*

■ NASC = Naaldwijk Formation, Schoorl Member

■ NAZA = Naaldwijk Formation, Zandvoort Member

■ ANAWA = Naaldwijk Formation, Walcheren Member (channel deposits generation A)

■ BNAWA = Naaldwijk Formation, Walcheren Member (channel deposits generation B)

■ BEC = Echteld Formation (channel deposits generation B)

■ EC = Echteld Formation

■ NAWA = Naaldwijk Formation, Walcheren Member

■ NIHO = Nieuwkoop Formation, Hollandveen

■ CEC = Echteld Formation (channel deposits generation C)

■ DNAWO = Naaldwijk Formation, Wormer Member (channel deposits generation D)

■ DEC = Echteld Formation (channel deposits generation D)

■ ENAWO = Naaldwijk Formation, Wormer Member (channel deposits generation E)

■ EEC = Echteld Formation (channel deposits generation E)

■ NAWO = Naaldwijk Formation, Wormer Member

■ NAWOVE = Naaldwijk Formation, Wormer and Velsen Members

■ NIBA = Nieuwkoop Formation, Basisveen

■ BXWISIKO = Boxtel Formation, Wierden, Singraven and Kootwijk Members

■ BX = Boxtel Formation

■ KRWY = Kreftenheye Formation, Wijchen Member

■ KRBXDE = Kreftenheye Formation and Boxtel Formation, Delwijnen Member

■ EE = Eem Formation

■ DR = Drenthe Formation

■ DRGI = Drenthe Formation, Gieten Member

■ GE = *Gestuwde afzettingen:* pushed deposits

■ UR = Urk Formation

■ ST = Sterksel Formation

■ PZWA = Peize Formation and Waalre Formation