Substrate control on the Lateglacial and Early Holocene lithological and palynological fill of multiple pingo remnants in the Netherlands.

Maaike Zwier

Photo on front page: Coring of Elpermeer, by Anja Verbers.

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By Maaike Zwier
4074513

First supervisor: Dr. W.Z. Hoek
Second supervisor: Dr. T.H. Donders

Department of physical geography
Utrecht University

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Abstract

Multiple proposed pingo remnants in Drenthe have been investigated both lithologically and palynologically to get a better understanding of the regional vegetation cover during the Lateglacial and Early Holocene. Furthermore, the influence of the substratum on the local variations in vegetation development is investigated. The subsurface of Witteveen (ø 200 m, 4 m deep) is located at the edge of an old stream valley in sand from the Peelo formation. Two other locations, Esmeer (ø 600 m, 13 m deep) and Elpermeer (ø 500m, 1 m deep), formed in the till of the Drenthe formation. The pollen diagrams of Esmeer and Witteveen show a Bølling age for the basal fill and a consecutive vegetation development following the general evolution of the Lateglacial to Early Holocene vegetation for the Netherlands. This indicates that the regional vegetation cover must have been very uniform. The Elpermeer section shows only a small section of the Lateglacial to Early Holocene transition starting in the Allerød. When looking at the local taxa Esmeer, Witteveen and Elpermeer show some slight variations, comprising mainly the riparians and aquatics. Additionally, a difference in lithology of the fills is evident: Esmeer and Elpermeer have a larger aeolian sand input compared to Witteveen. On top of that, the Allerød is thinner than the Younger Dryas in all cores except Witteveen, where the Younger Dryas is thinner than the Allerød. These differences in sand content and accumulation rate could account for some of the local vegetational differences.

Preface and Acknowledgments

This study was conducted for a MSc thesis project. The report is part of the master Earth, Life and Climate, track Climate Reconstructions and Biogeosciences and Evolution at Utrecht University.

This thesis would not have been possible without some help, therefore I would like to thank several people. First, I would like to thank my supervisor Wim Hoek for setting up the project and guiding me through all the laboratory work. Thanks to Timme Donders for being my second supervisor, the quick Tilia instruction and letting the Elpermeer core be analysed in his course. I would like to thank them both and Kees Kasse for some very useful discussions. The recovery of the Witteveen was possible due to the Pingo summer school organised by Anja Verbers of the Pingo Programma and I would like to thank her for setting up the interesting program during this fieldtrip. Thanks to Hessel Woolderink for his help during the retrieval of the Witteveen core. Moreover, Arjan van Eijk, Kees Nooren and Archana Sadhoeram are acknowledged for their help during the fieldtrip to Elpermeer. Thanks to Marjolein Gouw-Bouman for helping me with the identification of some Holocene pollen and her help with detailed Tilia questions. Finally, thanks to Marjolein Veneman for her company during the many hours behind the microscope and joining me in making a poster for the NAC.

1. Introduction

Pingo remnants are important archives for vegetation and landscape changes throughout the Lateglacial and Holocene*.* They often contain a well-preserved infill of gyttja and peat that can reveal information on past vegetation and climate development. These records can help us understand how natural systems react to climate changes on different time scales. This also gives us the opportunity to improve climate models and predict how present day periglacial ecosystems might develop under the continuous anthropogenically induced climate change. However, not only regional climate changes influence the lithological and palynological fill of the pingo remnants, local variations in lithology, geomorphology and geohydrological conditions also contribute to the patterns of vegetation development.

Overall, there is relatively little research done on substrate control on the fill. Therefore, the aim of this thesis is to find out whether and how the different substrates in Drenthe had an impact on the Lateglacial and early Holocene filling of a pingo remnant. Furthermore, analysis of the fills can support the hypothesis that the presumed pingo remnants in Drenthe were indeed true pingo remnants or whether they are aeolian depressions or other types of landforms.

Both lithological and palynological data will be used to differentiate fill types of multiple presumed pingo remnants in Drenthe. Pollen analysis on the deepest part of the pingo remnants will be used to estimate the timing of the pingo collapse. A vegetation reconstruction based on pollen data and sediment characteristics will be presented. Both the vegetation reconstruction and the substrate of the different sites will be compared to test the following hypothesis: 'The substrate underlying a pingo remnant will affect the fill of the circular depression.

To answer the main research question, multiple sub-questions have been formulated:

1. On what kind of subsurface can pingo remnants be found in Drenthe?
2. Can a clear difference in pingo remnant fill be distinguished in the pingo remnants under investigation?
3. How do the pingo remnant fill types relate to the subsurface and landscape position/evolution?
4. How is the regional variation in vegetation cover?

2. Pingo evolution

Over time, active pingos develop into pingo remnants that are filled up with sediment and organic matter. Currently, a pingo fill of gyttja and peat supplies information regarding past vegetational and climatic developments. However, before a pingo remnant is filled with sediment, an active pingo goes through several stages of growth and collapse. Furthermore, it is also important to note that most morphological landforms were covered by cover sands during the last part of the Weichselian and therefore, landforms with a different origin developed a very similar appearance (Flemal, 1976). This will be highlighted in section 2.4 Similar morphological landforms.

2.1 Pingo formation

Pingos are ice frost hills that only occur in areas influenced by permafrost (Mackay, 1998) and are perennial landforms (Flemal, 1976). The core of the hill is formed by a growing ice lens located underneath a top layer of soil and vegetation (Harris et al., 1988). The ice lens is fed by pore- or groundwater and grows due to continuous water supply. Over time the ice lens pushes the overlying layer or soil upward (de Gans, 2008). Pingos can grow up to 100 m in height (Jahn, 1968) and over 300 m – 1,200 m in diameter (French, 2007). The rate of growth of the ice lens varies greatly and can last from a few minutes to over 1000 yr (Mackay, 1973). Pingos are mostly circular or oval, but especially pingos on slopes can depart from the circular shape to an ellipse (Flemal, 1976).

At present, Pingos occur in periglacial climates in higher latitudes ranging between 65-75° N (Flemal, 1976), in areas like the Mackenzie Delta in North-West Canada and Siberia in Russia (Kluiving et al., 2010). Formation can occur in both continuous and discontinuous permafrost, but depth of the pingo is dependent on the depth of the active layer (de Gans, 1983). There are two types of pingos, that differ in the way the ice lens is established. Hydraulic system pingos, also called open-system pingos, are formed in discontinuous permafrost and fed by groundwater. They are often found near the base of slopes and valleys or along geological faults. In these sites the groundwater penetrates through the weakest parts of the permafrost layer due to hydraulic pressure (Ballantyne & Harris, 1994). However, besides the elevation difference, the pressure can also be provided by a nearby warm-based glacier (e.g. in Spitsbergen (Liestøl, 1977)) and thus these type of pingos might also be found on flat terrain (Flemal, 1976). This type of pingo still exists in Alaska, where it can occur in clusters where young pingos form over scars of older pingos, suggesting a cycle of growth and decay (Ballantyne & Harris, 1994).

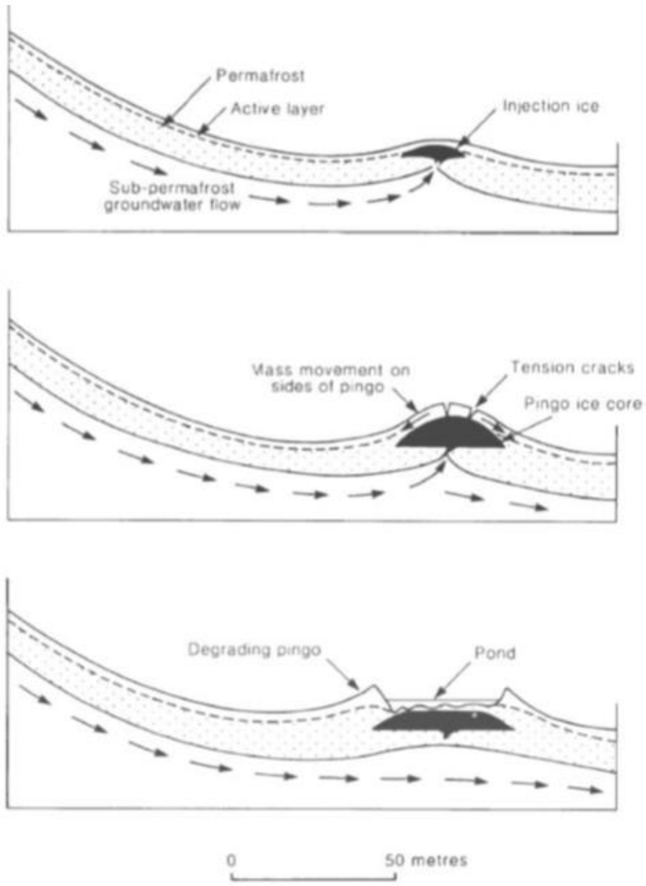

Figure 2.1 Formation of a hydraulic system pingo (Ballantyne & Harris, 1994).

Hydrostatic system pingos, or closed-system pingos, usually occur in relatively flat areas and are formed in the active layer of continuous permafrost (Flemal, 1976). The ice lens is fed by pore water that is excluded during permafrost aggradation which often occurs underneath the bottoms of drained lakes in saturated sand (Mackay, 1998). The sudden drainage of the lake causes permafrost aggradation, starting from the surrounding areas where permafrost was already present. The hereby created pressure causes the water to collect in the unfrozen area underneath the drained lake, where it eventually freezes to form an ice lens. Hydrostatic system pingos are very common in the Mackenzie Delta in Canada (Ballantyne & Harris, 1994).

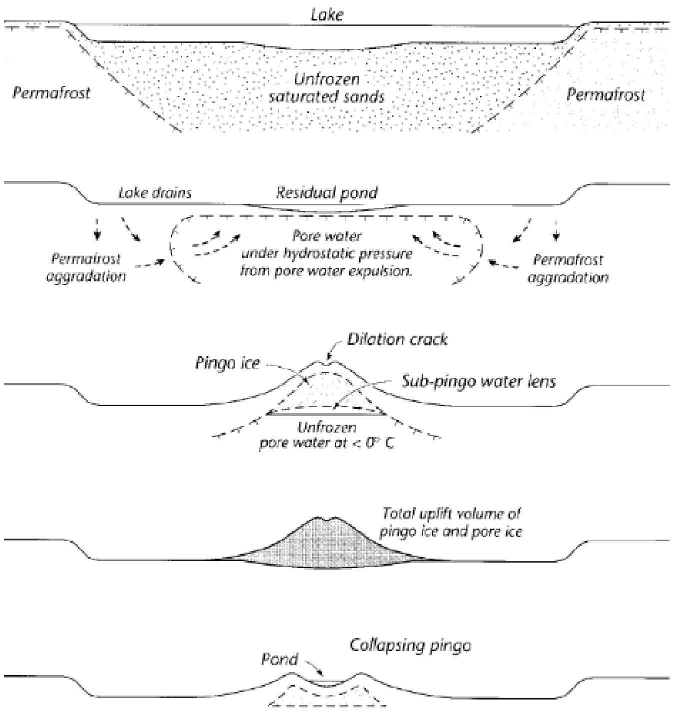

Figure 2.2 Formation of a hydrostatic system pingos (Mackay, 1998).

2.2 Pingo collapse

Due to the internal ice lens, an active pingo is bound to collapse eventually. Either before or after an active pingo reaches its maximum size it can become unstable and collapse of the pingo will occur. When the overlying slab of soil cannot cover the continuing growing ice lens anymore because the ice lens has grown too large, the overburden sediment will break open at the top in tension fractures. The sun can then reach the ice inside and the ice lens will slowly disappear by sublimation and melting of the ice during the warm season. This is a natural process that is not necessarily dependent on increasing temperatures due to climate change or permafrost degradation it but could be prematurely triggered by these changes. Exposure of the ice lens can also occur if the top layer of soil is eroded (Flemal, 1976). When the ice lens has completely melted, a craterlike circular depression with a circumference the size of the original pingo remains. This makes pingo remnants a very nice example of relief inversion. The top layer is also known to slide off the side of the ice (solifluction) and can thus form an enclosing rampart (de Gans, 2008). Additionally, pingo remnants can form when the pingo is not yet at its maximum size, but the temperature increases sufficiently to melt the ice lens and degrade the permafrost. If the pingo decays very rapidly, the top layer of soil can collapse vertically and no topographic evidence in the form of a rampart will remain (Mackay, 1988).

The ‘perfect’ pingo remnant has a rampart surrounding the depression, created by both the initial up thrusting of the dome (Flemal, 1976) and mass wasting of the top cover during the pingo decay (K. Kasse & Bohncke, 1992). However, in the field this rampart is not always observed (K. Kasse & Bohncke, 1992). This could be due to erosion of the rampart, either natural or human induced (e.g. agricultural activity (Flemal, 1976)), or due to slumping of the rampart into the depression after initial pingo decay. The slumping occurs mainly in open system pingo remnants that are still fed by springs, when the sediment is saturated by water (Flemal, 1976). The presence of pingo remnants can be an important indicator for former existence of permafrost if the remnant is identified with confidence (Mackay, 1998). Furthermore, the maximum depth of pingo remnant also gives an indication for the minimal depth of the permafrost layer in which the pingo was formed (de Gans, 1983; Hoek, 2012).

2.3 Pingo remnant fill

After collapse of a pingo, a circular depression the size of the former ice lens remains. The resulting circular depression is often filled with water to form a small lake because water stagnates in the depression. In these lakes a lot of autochthonous organic lake sediment, originating from algal organic matter production within the lake, accumulates. Due to the lack of oxygen at the bottom in deep stratified lakes, the organic material is usually preserved. The lake will also trap windblown sediments and material that is washed into the pingo remnant. Over time the lake develops from a lake into a (peat) bog, that is often dependent on rain water (Hoentjen et al., 1993). Currently, only the larger pingo remnants are still lakes e.g. Mekelermeer or Uddelermeer (de Gans, 2008) and Esmeer, used in this study. The accumulated organic matter partly consists of pollen and spores from vegetation within and around the lake. Pingo remnants can also contain aeolian sands and windblown tephra, and some of these depressions are filled with calcareous gyttja, indicating that the hydrostatic pressure and groundwater exfiltration persisted after melting of the ice lens (Hoek, 2012). The classical fill of pingo remnants occurring in the Netherlands consist of a basal layer of gyttja that is deposited during the Bøllinger/Allerød (figure 2.3). Subsequently, a sandy layer originating from the Younger Dryas is found. During this cold interval sand was blown into the pingo remnants. The aeolian activity is related to the absence of a closed vegetation cover (Cleveringa & de Gans, 1978). The upper part of the pingo remnant fill consists of peat, deposited during the Holocene (Hoek, 1997a). Due to favourable preservation of organic matter in an anoxic environment the vegetational history can be reconstructed from the layered infill (Woltinge, 2011). This makes pingo remnants a very important archive for climate reconstructions of the Lateglacial and Holocene.

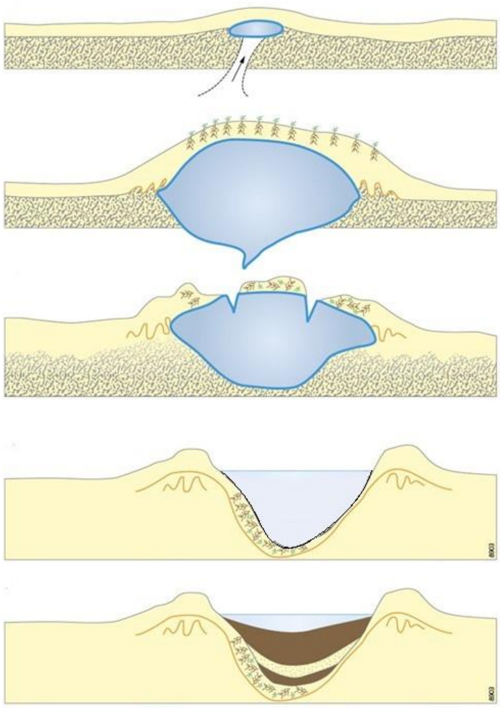

Figure 2.3 Evolution of pingo formation, collapse and characteristic tripartite fill (adapted from Stouthamer et al., 2015).

2.4 Similar morphological landforms

It is important to note that not all circular depressions are pingo remnants. Other types of processes can form very similar circular depressions, and it is necessary to study the infill and inner rampart structure in combination with the location of the depression to derive the origin of the landform. For instance, on elevation maps of the Netherlands, aeolian depressions have a very similar appearance as pingo remnants. As the base of aeolian depressions is often shallower and has a plane bottom (de Gans, 2010) in contrast to the conical bottom of a pingo remnant. This plane bottom forms due to the aeolian erosion of the sediment until groundwater level. However, this can only be seen in a lithological profile and thus fieldwork is necessary to distinguish pingo remnants from other morphological features. Aeolian depressions also have a sand blown rim, and if the rim surrounds the entire depression the wind must have blown from multiple directions (de Gans, 2010). Especially in Drenthe it is important to account for these aeolian depressions, for during the Lateglacial and possibly also the early Holocene, aeolian sands were deposited through the Netherlands, covering the initial relief (Cleveringa et al., 1977). A more recent formation of circular waters are the Holocene 'dobben'; these pools were excavated to serve as a watering place for cattle (Kluiving et al., 2010). However, the name 'dobben' is also commonly used for pingo remnants which were excavated for their peat layers (van der Voo, 1962). Other mechanisms that can result in forms that resemble pingo remnants are set out in Flemal (1976) but are of lesser importance for the area under study in this thesis.

3. Study area Drenthe

3.1 Subsurface of Drenthe

The development of the landscape in Drenthe has been greatly influenced by at least three ice ages (Elsterian, Saalian and Weichselian). During the Elsterian (430,000 – 300,000 years ago) large erosion channels formed in Drenthe. The river Rhine deposited sand and gravel in these erosion channels and in lakes thick layers of 'potklei' were deposited. These clays were later used for pottery, hence its name. Together these deposits form the 'Peelo formation' (Weerts et al., 2000).

During the following interglacial (Holsteinien, until 250,000 years ago) sea levels were higher and in northern Drenthe peat deposits formed in the peatlands that bordered the coast. In the south-west of Drenthe, more Rhine deposits accumulated. In the subsequent Saalian ice age (until 130,000 years ago), the northern part of the Netherlands was covered by land ice. The Drents plateau was created from till deposits belonging to the formation of Drenthe, consisting of a clayey or sandy matrix with sand, gravel and boulders (Hoek, 2000; van Dodewaard, 1997; Weerts et al., 2000). Characteristic landscape elements created by the Scandinavian ice in the eastern part of the plateau are the hills and small stream valleys in an NNW-ZZO direction (Huisman, 2003). This NNW-ZZO direction originates from the flowing direction of the ice (Bregman et al., n.d.). The most profound hill is the Hondsrug, located in the most eastern part of the plateau. East and south of the Hondsrug, the meltwater valleys of the Hunze and the Vecht are located. Parallel to the Hondsrug are the smaller hills of Tynaarloo, Rolder and Zeijen. After the ice retreated, sea levels rose, and peat developed in the large stream valleys during the Eemien (until 100,000 years ago). A part of the Hunze valley was filled with clay and sand.

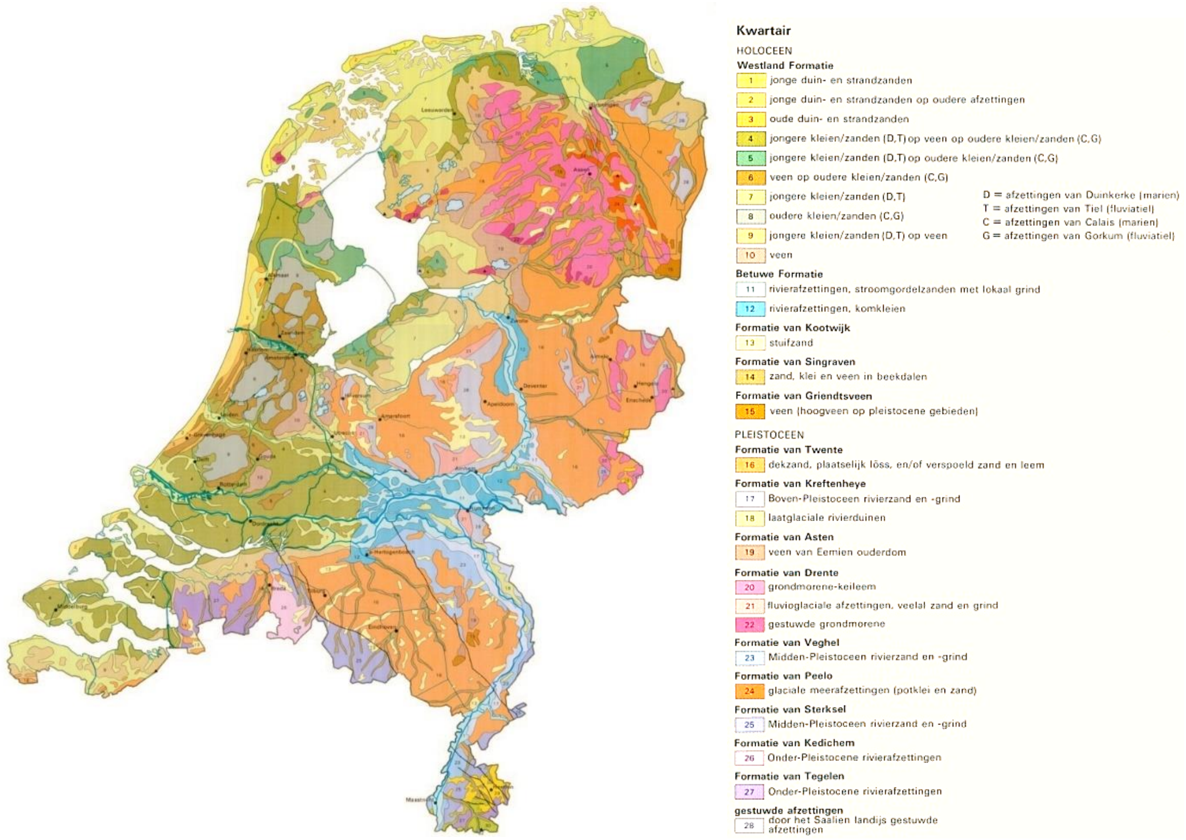

Figure 3.1 Geological map of the Netherlands. To show older formations, the cover sands deposited in the Weichselian are only displayed if the layer is more than 2 m thick ("Atlas van Nederland, deel 13: Geologie, 1985," 2001).

Thereafter, in the Weichselian (until 11,700 years ago), the land ice did not reach the Netherlands. Instead a vast tundra was present, with a periglacial climate and permafrost (Zagwijn, 1975). The Drenthe plateau was cut through by numerous stream valleys, that were subsequently filled with meltwater deposits and cover sands. Various landforms developed during the periglacial conditions, among which pingos. The open character of the landscape, together with the generally low relief, permafrost degradation and increased aridity in the later part of the Weichselian allowed the wind to catch hold of unconsolidated sand deposits (Kasse, 1997). Large parts of the Netherlands were covered by multiple layers of cover sands belonging to the Twente formation, with the sand originating from the immediate vicinity. Within the cover sands aeolian depressions were formed, sometimes surrounded by a rim of drift sand, making its appearance very similar to the pingo remnants concealed by the cover sands. Finally, during the Holocene (11,700 years ago and onward) a warmer climate caused sea levels to rise and a denser vegetation to grow on the formerly bare tundra plains. In the wetter parts of Drenthe large peatbogs developed, while on the dryer parts a primeval forest arose.

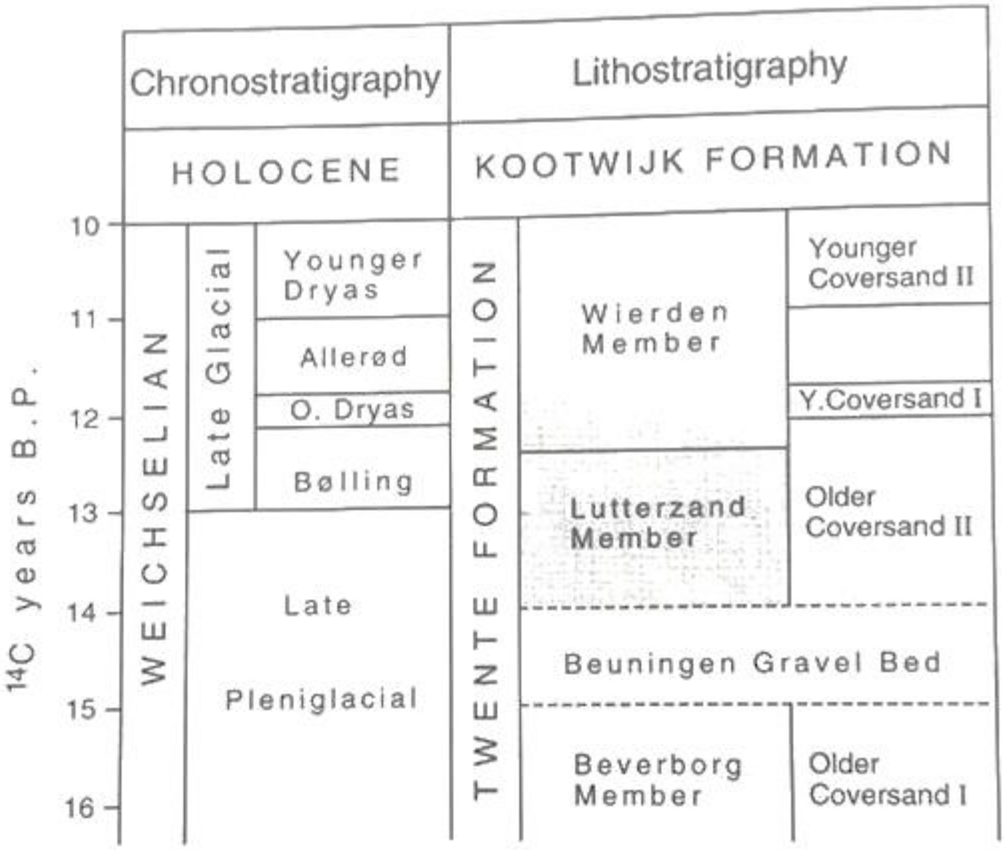

Figure 3.2 Stratigraphy of the Weichselian Late Pleniglacial and Lateglacial after Kasse (1997).

Currently, in the northern part of Drenthe and west of the Hondsrug some river deposits from before the Saale reach the surface: mostly sand and 'potklei' from the Elsterian and river sands formed in the Tertiary (e.g. at Schoonloo). The presence of these deposits at the surface is probably due to up-doming of salt formations in the subsurface. This caused overlying layers to be eroded by land ice during the ice ages, revealing the older river deposits underneath.

3.2 Pingo remnants in Drenthe

Pingo remnants have been found throughout the entire Netherlands, though a very high density of pingo remnants occurs in the Northern provinces. It is suggested that there are over 2,500 possible pingo remnants in Drenthe (Landschapsbeheer Drenthe, 2017). Most presumed pingo remnants occur in the upstream parts of former stream valleys on the Drents-Fries till-plateau (de Gans, 2008). Compared to the currently known largest pingo field, the Mackenzie Delta that contains about 1450 pingos (Mackay, 1973), Drenthe has a very high pingo density. Therefore, it is important to know whether all these circular depressions are real pingo remnants and not other morphological features.

Pingo remnants on the Drents plateau were first described by Maarleveld & van den Toorn (1955) and later multiple pingo remnants in the Drentsche Aa were analysed by de Gans (1982). De Gans (1982) discovered that a lot of pingo remnants are located in tributary valleys of the major old stream valley systems that were active during the Pleniglacial but were covered by aeolian sands in the Lateglacial. This explains why a group of pingo remnants in the upstream area of former Pleniglacial valleys are often seen in a row (de Gans, 1983; Huisman, 2003; Kluiving et al., 2010). De Gans (1982) also suggests that because of the absence of a strong relief, the pingos were of a hydrostatic (closed-system) type. He motivated this type also with the presence of impermeable layers in the substrate on which the pingos formed, that prohibited a continuous water supply (Ballantyne & Harris, 1994). However, it is currently thought that the pingos in the Netherlands are of a hydraulic type (de Gans, 1988), given that there was a discontinuous permafrost in the Netherlands.

De Gans (1983) distinguishes different types of pingo remnants based on their location in the landscape and their relation to the subsurface. Besides the pingo remnants in the upper part of the stream valleys, he identifies the Mekelermeer-type pingo as a different one from the type found in the Drentsche Aa, because it is found in places where foothills of valleys cut through 'sand intrusions' in thicker till deposits instead of fluvial sands. The Mekelermeer pingo remnant itself is one of the deepest pingo remnants of the Netherlands and is 12 m deep (de Gans & Sohl, 1981).

Dating of the sediment in the deepest part of pingo remnants indicates the age when filling of the pingo remnant started. Up until now dating of organic matter at the base of pingo remnants in Drenthe resulted in an age of 14,000 ^{14}C yr BP (de Gans, 2008). Dating of the material underneath a pingo remnant gives an age to the formation of the pingo. Active pingos formed in Drenthe roughly between 25.000 and 18.000 ^{14}C yr BP during the coldest part of the Weichselian (de Gans 1983; Paris et al. 1979). Pingo collapse must then have occurred in between 18,000 ^{14}C yr BP and 14,000 ^{14}C yr BP. The circular depressions were subsequently filled with gyttja during the Lateglacial and with peat during the Holocene (Maarleveld & van den Toorn, 1955). Since the cover sand area of Drenthe is naturally nutrient poor and has a low calcareous content (Hoentjen et al., 1993), the lake water in the bogs that developed in the pingo remnants was nutrient poor and slightly acidic as well. This could also have a significant effect on the local vegetation.

4. Material and methods

4.1 Selecting fieldwork sites

In total, three new pingo fills were investigated for this thesis. Esmeer was already cored by Timme Donders and colleagues in 2013. Witteveen was cored for this research during a summer school in June 2017. The summer school was part of the Pingo Programma Drenthe, carrier out by Landschapsbeheer Drenthe, and was led by Anja Verbers. Lastly, the Elpermeer location was cored during a field campaign in September 2017. The locations were selected based on the general elevation map of the Netherlands (Actueel Hoogtebestand Nederland, AHN). The elevation map was used to find circular depressions, with a size matching common pingo remnants (Harris et al., 1988). Based on historical maps the possible pingo remnants were checked for peat excavations during the last few centuries that could hinder a good continuous sediment record. The three locations in Drenthe were chosen for their relative proximity to each other but difference in substratum. Witteveen is located 8 km northeast of Esmeer, Elpermeer is located 19 km southeast of Esmeer and Witteveen and Elpermeer are 21 km apart (figure 4.1). Because the sites are relatively close together it is expected that the cores will show similar regional trends in vegetation development. Furthermore, the climate during the Lateglacial is expected to only show some minor spatial differences due to the small research area and the relatively large distance to the former coastline. Any climate gradient induced by the sea can therefore be neglected for this period (Hoek, 1997b). This gives the opportunity to distinguish local variations and provides a possibility to investigate what kind of effect the substratum has on the lithological and palynological fill of the pingo remnants.

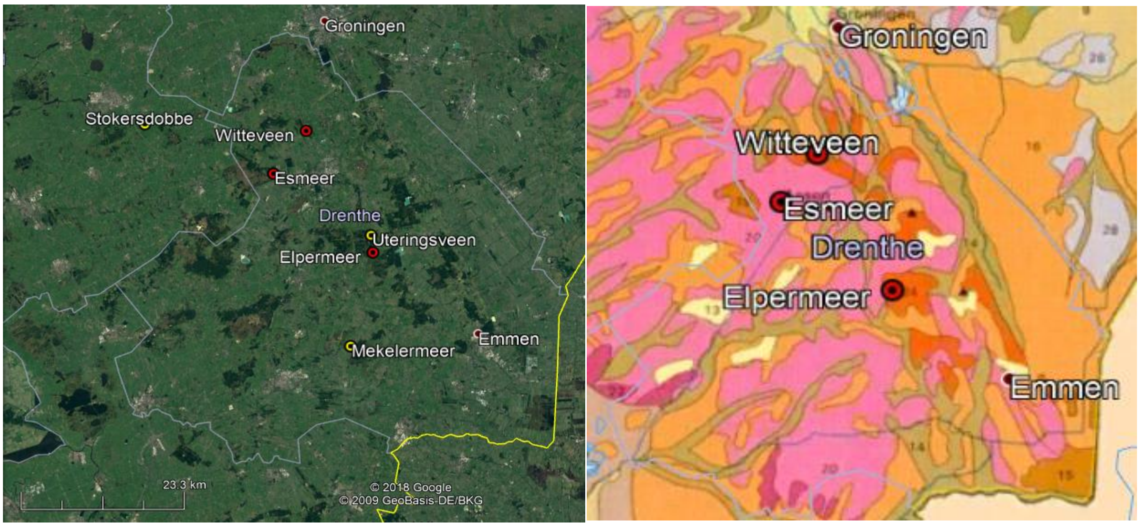

Figure 4.1 Left: locations of Esmeer, Witteveen and Elpermeer as indicated by the red dots. Other pingo remnants used in this study are indicated by the yellow dots. Right: geology of the study area.

4.2 Field analysis

4.2.1 Esmeer

Esmeer (N53.00612° E006.45863°) is located west of Assen on the Drents Plateau. The depression has a diameter of ~500 m and a water depth of ~5 m. The base of the infill reaches 13 m (de Gans, 2008). This makes Esmeer one of the larger pingo remnants in the Netherlands and, as indicated by the name, Esmeer is currently still a lake. In figure 4.2 it is clearly visible that there is a rampart present, most profound on the north-eastern side of the pingo remnant. The substratum of Esmeer consists of basal till belonging to the Formation of Drenthe, deposited during the Saalian glaciation (Paris, 1977).

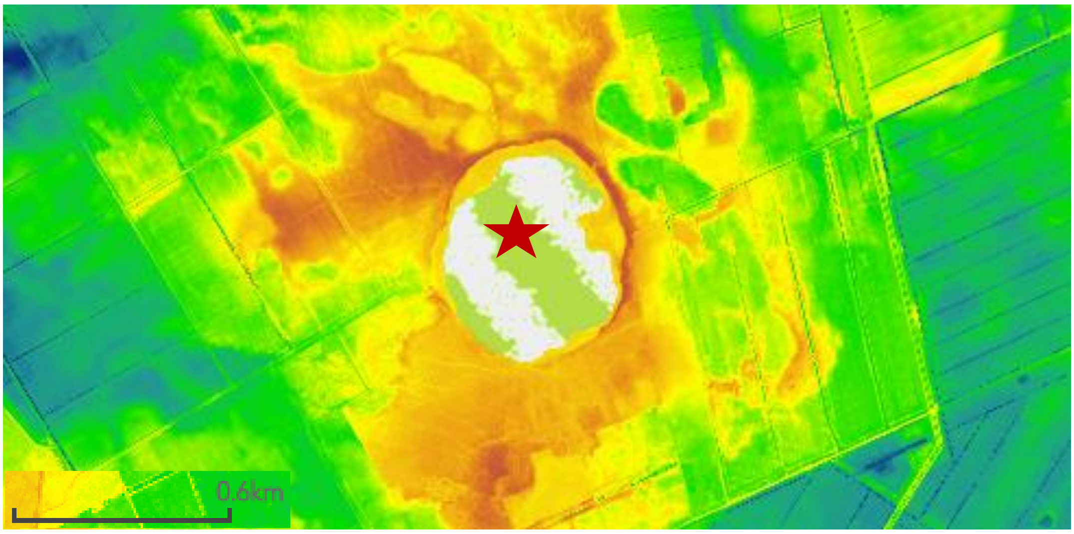

Figure 4.2 Elevation map of Esmeer, coring location indicated by the red star, a rim is clearly visible around the north-eastern edge of the pingo remnant. Source: AHN viewer AHN2- maaiveld Blauw / Groen / Oranje (dynamische opmaak).

4.2.2 Witteveen

Witteveen (N53° 03.918' E006° 31.757') is located in a small thicket of birch forest between agricultural fields surrounding Zeijen: a small village northwest of Assen on top of the basal till ridge of Zeijen ("Atlas van Nederland, deel 13: Geologie, 1985," 2001). The pingo remnant is located near the flank of an old stream valley (figure 4.3). Most of the till on the ridge of Zeijen is eroded to a thin layer. Especially near stream valleys the till layer becomes very thin and the clay and sand of the Peelo formation reach the surface (Huisman, 2003). The sand has characteristic micas that are easily recognizable in the field (Weerts et al., 2000). The cross-section of the pingo remnant measures about 200 m and Witteveen has developed into a full peat bog. However, according to historical maps, peat excavations took place in Witteveen and therefore the top part of the record might be missing (TMK, 1850).

First, a transect of boreholes was taken at Witteveen to get an indication of the possible pingo remnant depth and to construct a lithological profile. Eleven cores ware taken at 15 m distance from each other in a south-southeast to north-northwest direction, starting from the edge of the rampart of the presumed pingo remnant. Locations were determined using a hand-held GPS. A hand auger (Edelman corer) was used for the dry sandy sediment and a gouge was used for the peat and gyttja. The lithological characteristics were all described in the field; coordinates, depth, material, colour and special features were noted down. This field survey was performed by a group of participants joining the Pingo Programma summer school, consisting of students and volunteers with various backgrounds. It was aimed to take notes as uniformly as possible, however, details of the annotations differ slightly.

Subsequently, based on the descriptions of the transect the location for the final coring location used for sampling was determined. These cores were taken with a Piston corer at two sites in the centre of the pingo remnant. At both locations two cores were taken at alternating depths to have an overlay if any disturbances or hiatuses at the top or bottom of one of the cores are observed after opening. After retrieving the cores, they were placed in two halves of PVC tubes and wrapped in plastic foil for protection.

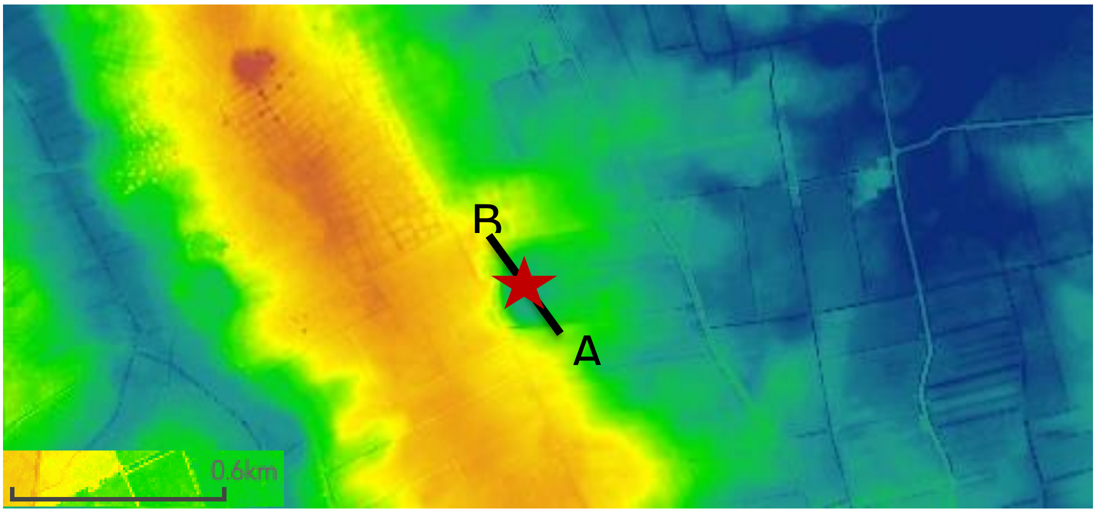

Figure 4.3 Elevation map of Witteveen. The lithological profile was taken along transect A-B, the red star indicates the location of the analysed core. Source: AHN viewer AHN2-maaiveld Blauw / Groen / Oranje (dynamische opmaak).

4.2.3 Elpermeer

Elpermeer (N52° 53.830' E006° 40.549') forms a large, shallow lake in the middle of a heathland that is partially forested (figure 4.4). The lake has a diameter of ~500 m and has a water level of only 30 cm. According to the geological map of the Netherlands it is located in glacial lake deposits consisting of sand and clay belonging to the formation of Peelo.

In Elpermeer a core was taken using the UWITEC universal sampling platform. The coring platform was anchored in the middle of the lake using a guiding cable stretching from one side of the lake to the other, fastened to a tree and a large sedge bush. A tripod was mounted on top of the platform, equipped with a piston corer. The cores were retrieved in a PVC tube within the casing of the piston corer. This allowed for extraction of the cores without disturbing the sediment before opening the cores in the laboratory. Lids were placed at both ends of the tube to prevent oxidation of organic matter.

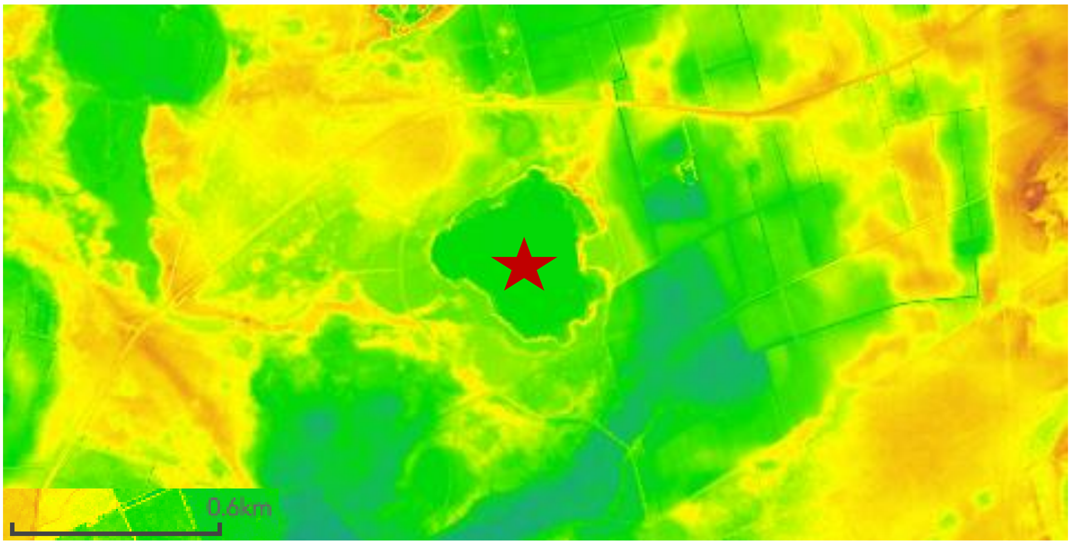

Figure 4.4 Elevation map of Elpermeer. A very irregular rim is visible around the lake. The red star indicates the location of the core taken for analysis. Source: AHN viewer AHN2- maaiveld Blauw / Groen / Oranje (dynamische opmaak).

4.3 Laboratory analysis

All cores that were taken were stored at 4 – 5 °C to minimize degradation of the material. The cores of Elpermeer were packed in intact PVC tubes, these were cut in half using the 'Eijkenschneider' developed by Arjan van Eijk. Subsequently, the sediment was cut in half using an iron wire, starting from the bottom of the core to prevent contamination of older material by younger material. Tough peat material was cut using a sharp knife. The Witteveen core was cut similarly, though it did not require the Eijkenschneider. Directly after opening of the cores pictures were taken and visual lithological analysis was performed (Appendix 2 – 4).

4.3.1 Loss on ignition measurements

Loss on ignition (LOI) is an objective method to determine the organic content of sediment. LOI analysis was performed as a quantitative method to describe the lithostratigraphy. Furthermore, it might be used as a rough indication for the time period included in the cores since LOI-profiles of other sites in the Netherlands show similar trends during cold and warm intervals of the Lateglacial (Hoek et al., 2012). Moreover, it can be used as an indication of the openness of the vegetation cover.

Samples for LOI were taken every centimetre and weighted. The samples were kept in a drying oven at 105 °C at least one night, the dry weight was subsequently measured, and the samples were placed in the oven. The temperature was raised to 550 °C in one hour and kept at this temperature for four hours. Overnight the oven cooled down again to 70 – 40 °C and samples were weighted again to obtain the loss on ignition. This difference between the dry weight and the weight after heating indicates the total amount of organic matter in the sample (Heiri et al., 2001). The loss on ignition profile of Witteveen and Elpermeer are constructed from multiple cores. The LOI data from each core was aligned with the values from the subsequent core starting with core IVb in Witteveen and core ELP I in Elpermeer. These fitted depths are used throughout the rest of this thesis.

4.3.2 Pollen sampling

Palynological analysis provides information for the reconstruction of the local, in and around the lake, and regional vegetation history of the area surrounding the possible pingo remnants. Moreover, changes in climatic developments, relative water depth and trophic levels can be deduced from the pollen analysis (Cleveringa & de Gans, 1978).el Based on the loss on ignition profile the sampling depths for the pollen samples were determined. Samples were prepared following the standard method described by Faegri and Iversen (1989) (appendix 1). Pollen grains were removed from the mixture using heavy liquid separation. The residue was mixed with glycerine and sealed on a slide with paraffin wax.

4.4 Pollen analysis

Identification of the pollen grains was based on the pollen keys from Moore et al. (1991) and Beug (2004). The pollen analysis was performed at the lowest taxonomic level possible using a light microscope at a 400X magnification. For percentage computing the pollen sum varied between ca. 200 and 300. Included in the pollen sum were all arboreal pollen (AP), non-arboreal pollen of dry herbs (NAP), grasses and heathers. *Salix* and *Betula* have been included in the AP sum even though they also include several dwarf shrub species, mainly occurring in the colder phases of the Lateglacial. Local taxa, riparian herbs including Cyperaceae, aquatics and spores were excluded from the pollen sum. These taxa are however still useful for interpretation of the local vegetational and climatic changes.

4.4.1 Construction of the pollen diagram

TiliaIT and Tilia-graph (v. 2.0.41), developed by Grimm (1992) were used for the construction of the pollen diagrams, the general lay out was composed according to the method introduced by Iversen (1942). Using this method, the most important taxa are displayed in a main diagram that also shows the AP/NAP ratio to get an indication of the forest density. It is important to note that a change in AP/NAP does not necessarily mean a direct change in climate causing this change, it can also represent a lag in the migration of plant taxa and changes in lake level or hydrosere of the lake (plant succession that leads to natural drying out of the lake) (Bennett, 1986).

The pollen diagrams were subsequently divided into zones based on a regional zonation by (Hoek, 1997c) in which the major shifts in in the main arboreal pollen taxa (*Pinus*, *Betula* and *Salix*) are used for the construction of a regional zonation. These shifts are radiocarbon dated in multiple pollen diagrams throughout the Netherlands and therefore also provide a rough age-depth model. In this general regional Lateglacial and Holocene pollen diagram 5 zones are recognized, with some zones being subdivided (table 4.1). Note that the term 'Late-' and 'Early Dryas' is used for the description of the biozones that correspond to the associated chronozones of the 'Younger-' and 'Older Dryas' (Hoek, 1997c).

Table 4.1 Regional pollen zonation scheme for the Lateglacial and Holocene in The Netherlands.

Zone	**Subzone**	**Age of the base (^{14}C years BP)**	**Name (van Geel, 1989)**	**Van Geel 1981**	**Characteristics of the base**
V	V	9,500 BP	Boreal	*Late Preboreal*	Increase in *Pinus*
IV	IVc	9,750 BP	Preboreal		Increase in *Betula*
	IVb	9,950 BP		*Rammelbeek phase*	Decrease in *Betula*, decrease in AP
	IVa	10,150 BP		*Friesland oscillation*	Increase in *Betula*, decrease NAP
III	IIIb	10,550 BP	Late Dryas – *Empetrum* phase		Increase in *Empetrum*
	IIIIa	10,950 BP	Late Dryas		Decrease in *Betula* and *Pinus*
II	IIb	11,250 BP	Allerød – *Pinus* phase		Increase in *Pinus* (to values exceeding 20%)
	IIa2	11,500 BP	Allerød – *Betula*		Decrease in *Betula*,

			phase2		increase in *Pinus*
	IIa1	11,900 BP	Allerød – *Betula* phase1		Increase in *Betula* and AP, decrease in NAP
I	Ic	12,100 BP	Earlier Dryas		Decrease in *Betula*, increase in *Salix* and NAP
	Ib	12,450 BP	Bølling		Increase in *Betula* and AP
	Ia	12,900 BP	Earliest Dryas		Start organic matter accumulation. Rise in *Artemisia*

4.5 Non-pollen palynomorphs

Non-pollen palynomorphs (NPPs) are microfossils of various origin other than pollen that are often preserved during the pollen preparations and encountered in pollen slides (van Geel, 2002). NPPs can act as paleoenvironmental indicators and comprise spores of fungi, remains of algae, cyanobacteria, and invertebrates but also cell wand structures of plants. In the material under study in this thesis various NPPs were encountered and counted in the pollen slides or, if very abundant, noted on whether they were present or not (yes/no).

4.5.1 Gelasinospora (T.1 and T.2) and charcoal

The ascospores and retispores of Gelasinospora are often found in layers with charred material under relative dry, oligotrophic conditions (van Geel & Aptroot, 2006). These spores require high temperatures to initiate the germination and therefore this genus of fungi is a typical fire indicator (van Geel 1978, type 1 and 2). Together with the presence of charcoal in the pollen diagram, At the onset of the Younger Dryas a vast mortality among the trees, mostly *Pinus*, resulted in an opportunity for forest fires to ignite. These forest fires have been found in records throughout all of Europe and America (Paris, 1977).

4.5.2 Sclereids (T. 129) of Nymphaeaceae

The presence of squamous cells as well as sclereids are an indication for the presence of *Nymphaea* and *Nuphar* in the environment (Marrotte et al., 2012). Because these entomophilous plants have a very low pollen production and can thus be underrepresented in pollen diagrams, these two NPPs can improve the vegetational reconstruction. Sclereids are present in the intercellular spaces of stems and leaves to provide support and are hard, needle like branched cells, described as trichosclereids (Type 129 by van Geel, 1998) or astrosclereids. A study by Marrotte et al. (2012) showed that sclereids of *Nuphar lutea* are likely to survive pollen treatment and therefore can be a useful proxy for plant presence. In this study the sclereid structures were counted when clearly recognizable, though degraded forms could have been missed. Their presence is taken as an indicator for local Nymphaeaceae growth.

The presence of sclereids is very useful for a temperature reconstruction since aquatics can be very good temperature indicators. Compared to terrestrial taxa, they are less dependent on light, soil development, and competition for their growth. This causes them to react to temperature changes more rapidly, furthermore they may also give an indication for water level changes and the trophic state of the water (Hoek, 1997a; Paris, 1977). Therefore, remains of the green algae *Botryococcus* and *Pediastrum* were counted as well.

4.5.3 *Isoetes* microspore

Isoetes is a semi-aquatic plant that favours mineral substrates and an oligotroph environment. It is also linked to the increased soil formation during the second phase of the Allerød, that caused an acidification of the groundwater due to an increase in humic-acids. Because a lot of pingos are not only fed by rainwater, but also by groundwater, the lake water of the pingo remnant can become increasingly oligotroph. This link to soil leaching can be confirmed by an concurrent increase in *Pinus* and *Ericales* pollen (Paris, 1977). *Isoetes* microspores are bilateral and have a bean-like shape with an outer coat with few folds that is separated from the inner coat with a gap, except at the concave side of the 'bean' where the inner wall projects as a ridge or keel. A monolete scar is visible when carefully analysed.

5. Results

5.1.1 Lithology Esmeer

The Esmeer core was described by W. Koster (appendix 2). He investigated the palynology of the Holocene sequence of Esmeer. He described the lithology of the Lateglacial sequence as being mostly clay. However, it is more likely that he mistook fine gyttja for clay. The 'clay' is overlain by a sandy gyttja, partly containing rootlets. At irregular intervals the gyttja is intermitted by layers of sand. The upper part of the Esmeer core contains gyttja and a thick (~ 2 m) layer of sand covered by another layer of sandy gyttja on top (figure 5.1). For this thesis, only the Lateglacial sequence was investigated.

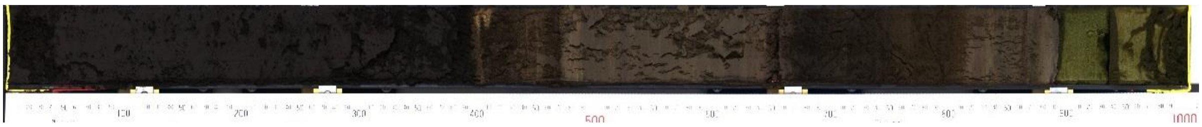

Figure 5.1 Esmeer core.

5.1.2 Lithology Witteveen

The lithological profile of Witteveen (figure 5.2) shows a very nice conical shape for the bottom; an ideal pingo remnant shape (Flemal, 1976). It is little over 4 meters deep and contains gyttja at the base. This is overlain by a sandy layer and the upper section consists of a thick layer of peat (appendix 3). The rampart was cored as well and showed till overlying the Peelo sand. The deposition of the sandy layer, which is most probably aeolian, gives an indication of the relative age, for it was most likely been deposited during the Younger Dryas (Hoek, 1997c).

Figure 5.2 Witteveen core.

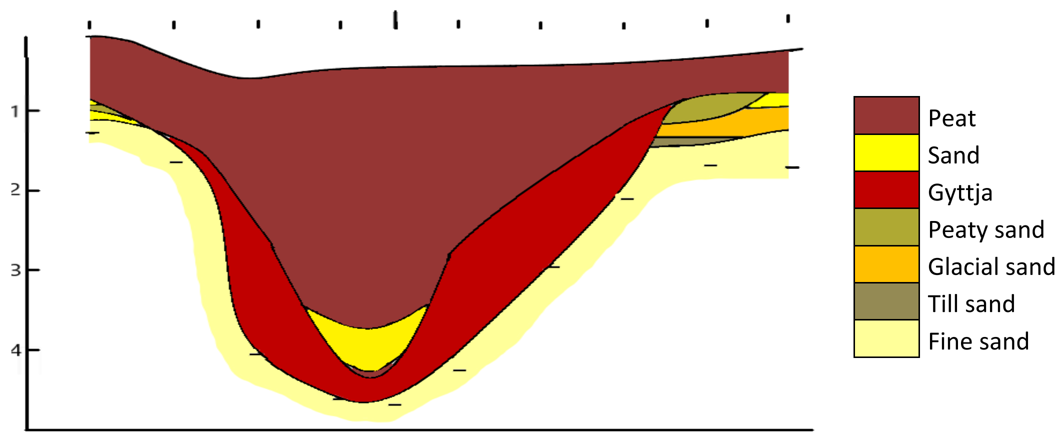

Figure 5.3 Lithological profile of Witteveen, cores are spaced at 15m from each other. The core used for analysis was taken in the middle (large bar), vertical axis in meter.

5.1.3 Lithology Elpermeer

According to the Geological map of the Netherlands, the subsurface of Esmeer consists of the formation of Peelo. However, till was found in the bottom of the core at only 124 cm depth. The fill consisted of ~1 meter of peat, becoming sandy at the top (appendix 4).

Figure 5.4 Elpermeer core.

5.2 Loss on Ignition

The Loss on ignition results show a partly comparable picture as displayed in figure 5.5. Note that the scale of the y axis differs.

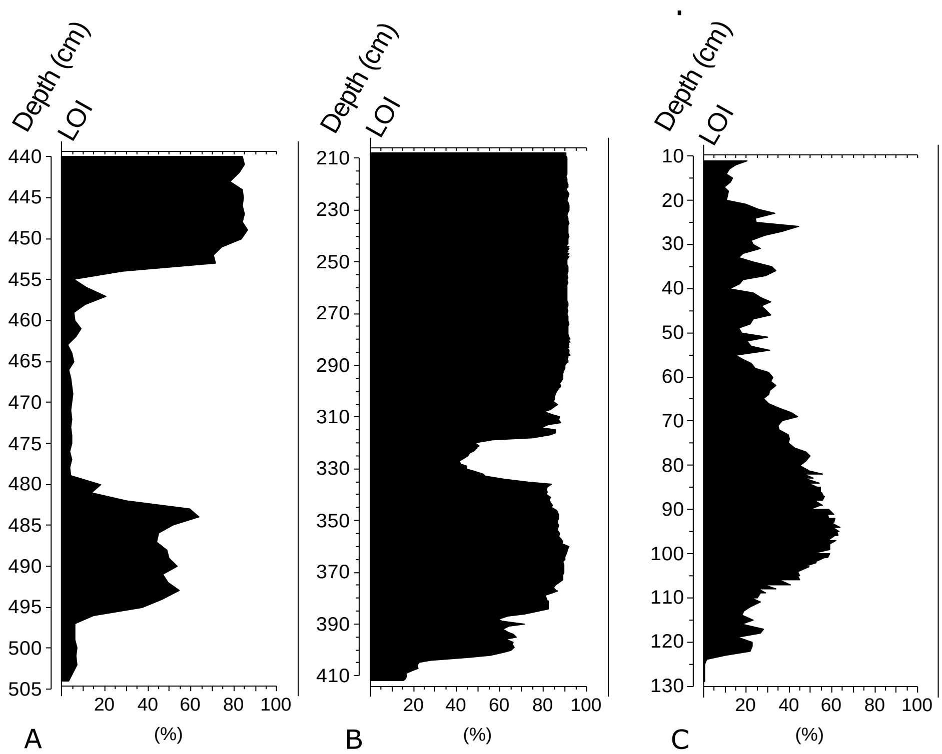

Figure 5.5 Loss on ignition profile of the Lateglacial sequence of a) Esmeer, b) Witteveen and c) Elpermeer.

5.2.1 LOI of Esmeer

The loss on ignition profile of Esmeer (figure 5.5a) is very characteristic for Lateglacial - Early Holocene loss on ignition profiles (Hoek et al., 2012). The profile starts with a very low organic content averaging 7 % at the bottom and increases between 497 cm and 479 cm to around 50 %. The LOI values then decline again and starting at 455 cm depth, the organic content of the core reaches values over 80 %. The first increase in LOI is usually seen as the Bølling – Allerød interstadial and the second one as the onset of the Holocene.

5.2.2 LOI of Witteveen

The fitted LOI profile of Witteveen (figure 5.5b) shows a general very high LOI percentage with values rising from 15 % to over 60 % at 405 cm depth. At 388 cm the organic matter content rises even further to > 80 %. Between 334 cm and 318 cm the LOI percentage declines, however, percentages remain above 40 %. For the remainder of the core values average around 90 %. This LOI profile also shows the classic tripartite Lateglacial pattern.

5.2.3 LOI of Elpermeer

The loss on ignition profile of Elpermeer (figure 5.5c) does not immediately show a characteristic profile for the Lateglacial and Holocene, this suggest that Elpermeer only recorded a section of the Lateglacial or Holocene. The LOI profile shows an increase starting at 125 cm depth reaching values around 20 %, from 110 cm upward the LOI percentage gradually increases towards 60 % at 95 cm depth. The organic matter content then declines to ~20 % again but shows a lot of variation. Based on this LOI pattern only, it is difficult to estimate the age of the fill.

5.3 Interpreting the LOI profiles

The LOI profiles show a quantification of the lithological changes in the core sequences. Using the zonation of the pollen diagrams in combination with the distinction of the zone boundaries in the LOI profiles, the different study sites show some clear differences (table 5.1). Mainly the difference of the organic matter content of the different zones (as established by Hoek, 1997). Exceptional is the overall relatively high LOI percentage of Witteveen, especially during the Younger Dryas (> 40 %). Note the very large difference in the thickness of the Younger Dryas sediment layer as well (figure 5.5). This zone is very thick in Esmeer and the LOI values indicate that this is due to a larger amount of aeolian sand blown into the pingo remnant which increases the sedimentation rate. When we look at the entire Lateglacial, it is evident that Esmeer has received a larger amount of minerogenic material. With a paleo-wind direction mostly from the south-west and west the Witteveen site could have been shielded from the sand by the ridge lying next to it (figure 4.3) (Isarin et al., 1997; Kasse, 1995). This could possibly also be seen in Korstverloren Veen that has relatively high LOI values throughout the Younger Dryas (Hoek et al., 2012).

Table 5.1 Average LOI percentage per zone of all locations used in this thesis.

LOI (%) per Zone	Site				
	Esmeer	Witteveen	Elpermeer	Mekelermeer	Uteringsveen
IV	90 %	90 %		80 %	40 → 90 %
III	5 %	50 %	25 %	2 %	5 %
II	50 %	90 %	40 → 60 %	40 %	40 %
I	10 %	20 %	20 %	5 %	15 %

5.4 Pollen diagrams

5.4.1 Pollen diagram Esmeer

Pollen samples is Esmeer were taken every 2 - 4 cm, this would account for roughly one sample every 140 yr. Additionally, after counting an initial set of samples, the resolution was increased at the zone boundaries to be able to improve the zone boundary positions. This resulted in one sample every 110 years for the BØlling-AllerØd and one sample every 160 yr for the Younger Dryas (figure 5.6).

Zone Ib (504 cm – 499 cm) → Bølling

The lowermost zone is characterized by a low *Pinus* percentage and relative high *Betula* percentage. *Juniperus* makes its first appearance in the pollen diagram in this zone. The AP/NAP ratio is roughly 50/50. Herbs like *Artemisia*, *Filipendula*, *Galium* and *Helianthemum* are well represented. Among the aquatics *Potamogeton*, *Stratiotes* occur in very high percentages. The algae *Pediastrum* and *Botryococcus braunii* are present as well.

Zone Ic (499 cm – 496 cm) → Earliest Dryas

In this subzone the *Betula* percentage decrease and the percentage of herbs increases. *Juniperus*, *Artemisia* and *Potentilla* show a maximum. *Galium* declines to very low percentages, while *Helianthemum* and *Rumex* continue in moderate values. *Thalictrum* rises in percentage throughout the zone and some heather is present. Cyperaceae rises to over 40 %, a peak in *Potamogeton* and *Pediastrum* is seen, while *Botryococcus* and *Stratiotes* decline in percentage. Both *Myriophyllum alterniflorum* and *Myriophyllum spictatum/verticillatum* appear in the diagram. A peak of *Selaginella selaginoides* is also present.

Zone IIa (496 cm – 485.5 cm) Allerød Betula-phase

This subzone starts with a vast increase in *Betula* pollen. The AP percentage almost reaches 90 %. *Juniperus* disappears and *Myrica* comes into the pollen diagram. The end of the zone is characterized by a slight increase in *Pinus* pollen and a little decrease in *Betula*. *Galium* declines and is absent in most of the zone, *Artemisia* also declines slightly in percentage. Cyperaceae declines hugely in the transition of zone Ic to zone IIa, as well as *Sparganium* and *Stratiotes* which decline and disappear from the pollen diagram. Halfway through the zone *Dryopteris* is represented with a single spore occurrence. *Myriophyllum alt*. stays present in very low percentages. *Pediastrum* and *Botryococcus* initially stay stable but decline halfway zone IIa. *Selaginella selaginoides* disappears in the beginning of zone 2a.

Zone IIb (485.5 cm – 481 cm) Allerød Pinus-phase

The second part of zone II starts with an increase of pine at the cost of birch, the AP/NAP ratio is equal to zone IIa. The presence of most herbs stays roughly similar to the previous zone, though *Rumex* percentage increases and *Helianthemum* is represented by a single occurrence. The heathers show a more diverse composition. A small peak in percentages of *Botryococcus* and *Pediastrum* is seen. *Sparganium* appears again but does not show a continuous occurrence. At the start of zone IIb *Equisetum* peaks.

Zone IIIa (481 cm – 474 cm) Younger Dryas

The onset of this zone is distinguished by a large decrease in *Pinus* percentage and a small increase in *Betula* and *Salix* percentages. *Myrica* is still present and increases in percentage at the start of zone IIIa. The NAP percentage increases and the diversity in herbs rises considerably. Chenopodiaceae come into the pollen diagram and Caryophyllaceae increase in abundance, *Potentilla* is present again. *Artemisia*, *Rumex*, *Galium* and *Filipendula* are all present at moderate percentages. *Saxifraga oppositifolia* is seen in a single occurrence in zone IIIa. Cyperaceae and Poaceae increase at the onset of zone IIIa and stay relatively abundant. *Botryococcus* disappears while *Pediastrum* increases in percentage, *Myriophyllum* and *Potamogeton* are present in low percentages. *Sparganium* stays present, as well as Equisetum. The pollen diagram of Esmeer also shows the presence of *Gelasinospora* and charcoal during this zone as well as some corroded pollen.

Zone IIIb (474 cm – 462.5 cm) Younger Dryas – *Empetrum* phase

Throughout this zone the *Pinus* percentage slowly rises and *Betula* percentages slowly declines. *Juniperus* reappears into the pollen diagram and *Myrica* disappears. At the onset of zone IIIb the total AP percentage declines and NAP increases. This is mostly due to an increase in *Empetrum*, though *Artemisia*, *Helianthemum* and *Thalictrum* increase in percentage as well. In contrast, *Filipendula*, *Gallium* and *Rumex* decline and the first two disappear halfway through zone IIIa. A slight increase in Cyperaceae is seen and although *Pediastrum* is still present, *Botryococcus* disappears completely. Increases in *Myriophyllum*, *Potamogeton* and *Sparganium*-type percentages are seen as well. Very characteristic is a huge increase in monolete spore and *Polypodium vulgare* percentage.

Zone IV (462.5 cm – 456 cm) Preboreal

The transition from zone III to zone IV starts with a small increase in *Betula* and a large decrease in *Empetrum* percentage though the total NAP percentage remains practically the same due to an increase in Poaceae. *Juniperus* is still present and *Myrica* comes back again. *Artemisia* and Chenopodiaceae decline in percentage while *Filipendula*, *Rumex* and *Thalictrum* increase. In this zone the diversity in overall non-arboreal pollen changes (Apiaceae, Asteraceae, Brassicaceae, Ranunculaceae). *Botryococcus* returns in the diagram again and a lot of *Myriophyllum alterniflorum* is present. While *Equisetum* increases in percentage and *Typha latifolia* makes an appearance, all the ferns decline immensely in percentage at the start of zone IV. Also, some *Gelasinospora* and charcoal are found in this zone.

Zone V (456 cm - 445 cm) Boreal

This zone starts with a huge decrease in *Betula* percentage concurring with a large increase in *Pinus* percentage, with *Pinus* percentage exceeding those of *Betula* for the first time. Thermophilous trees like *Corylus, Quercus, Ulmus, Alnus, Tilia* and *Fraxinus* come in, respectively in this order. This leads to an AP increase to over 90 %. Especially *Corylus* becomes important and reaches over 20 % of the pollen sum. The onset of zone V is marked by a huge decrease in Poaceae and most herbs decline and disappear halfway through zone V. While *Empetrum* disappears, *Calluna* increases in percentage and some other Ericales are also found. *Ephedra fragilis* is represented by a single occurrence. The algae *Botryococcus* is still present but *Pediastrum* declines in percentage. *Myriophyllum alt*. declines and disappears as well. At the top of the pollen diagram, halfway through zone V *Typha angustifolia* is found. Corroded pollen increases in percentage.

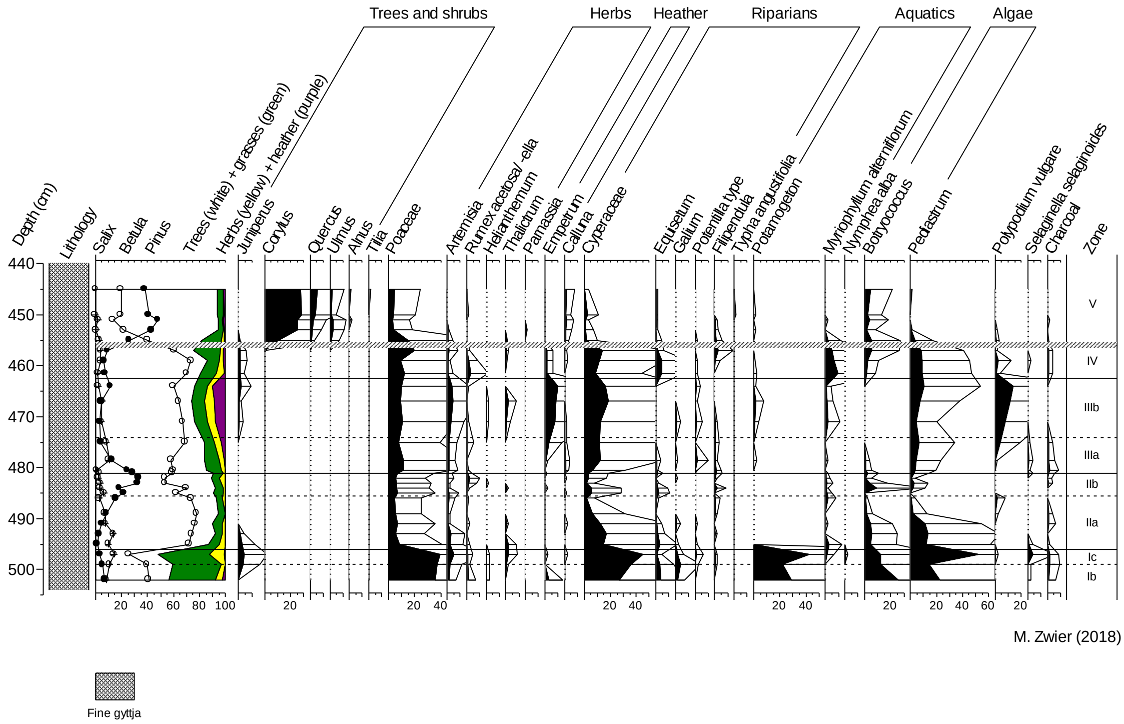

Figure 5.6 Pollen diagram with selected species from Esmeer, black lines show the zonation according to Hoek (1997), the dashed line indicates a hiatus.

5.4.2 Pollen diagram Witteveen

The pollen samples of Witteveen were taken every 10 cm, a higher resolution. With the assigned zonation based on the LOI profiles and pollen diagram, the resolution of the pollen diagram shows one sample every 140 years for the BØlling-AllerØd and 250 yr for the Younger Dryas (figure 5.7).

Zone Ib (406 cm – 392 cm) Bølling

Zone Ib starts off with *Betula* percentage around 35 %, *Salix* percentage around 15 % and *Pinus* percentage below 10 %. The largest part of the NAP is taken up by grasses. Some *Juniperus* is present, there is a large diversity in herbs and a lot of Cyperaceae. The percentage of *Botryococcus* increases throughout zone Ib while the percentage of *Pediastrum* declines. From the *Myriophyllum* taxa, only *Myriophyllum spic*. is present. *Selaginella* starts off with a very high percentage at the bottom of the core but declines in abundance through the zone while aquatics like *Potamogeton* and *Stratiotes* increase in percentages. Some *Equisetum* is present as well.

Zone Ic (392 cm – 384 cm) Older Dryas

The start of zone Ic in Witteveen is recognized by a decline in *Betula* and *Salix* pollen and an increase in NAP percentage, mainly due to an increase in Poaceae. *Juniperus* peaks in this zone, while *Myrica* comes in as well. In the herbs a peak in *Artemisia, Rumex* and *Thalictrum* is seen, while *Filipendula, Galium* and *Potentilla-type* decline. The percentage of Cyperaceae stays stable around 40 %. The algae *Botryococcus* and *Pediastrum* show a maximum and *Myriophyllum alt*. increases hugely in percentage, other aquatics show peaks as well and both *Nuphar* and *Nymphaea* is present. Only *Selaginella* declines in percentage. The end of zone Ic is characterised by a huge decline in all aquatics and algae.

Zone IIa (384 cm – 379 cm) Allerød – Betula phase

The base of the zone is characterized by a large increase in *Betula* percentage, with a decline in *Salix*, the *Pinus* percentage remains low. The arboreal pollen percentage rises to over 85 %. The shrubs *Juniperus* and *Myrica* decline and become absent. *Artemisia, Rumex, Thalictrum* and the Poaceae decline, while *Filipendula* and *Galium* show an increase. The percentage of most aquatics and algae declines greatly at the onset of zone IIa, but within the zone a peak of *Myriophyllum alt*. is seen. *Menyanthes* pollen are seen in the diagram for the first time.

Zone IIb (379 cm – 335 cm) Allerød – Pinus phase

The onset of zone IIb is characterised by a huge increase in *Pinus* pollen, with a concurrent decline in *Betula* percentage. The NAP percentage remains around 80 – 90 %. The composition of the NAP does not change a lot compared to zone IIa, except for the disappearance of *Potentilla-type*, a further decline in Poaceae percentage and an increase in the *Calluna* and *Empetrum* percentages. There are less algae and *Myriophyllum alt.* declines in percentage. At the onset of zone IIb some *Nuphar* pollen are found as well as *Stratiotes*, while *Myriophyllum spic*. Is found later in zone IIb. There are almost no mosses and fern spores found. The percentage of corroded pollen increases towards the top of the zone.

Zone IIIa (335 cm – 325.5 cm) Younger Dryas

The base of zone IIIa is in the Witteveen core characterised by a sharp decline in *Betula* pollen and a low *Pinus* percentage. Herbs increase towards 40 % at the end of the zone, with mainly heliophilous herbs increasing in percentage. *Myrica* pollen disappear and *Juniperus* comes back in the pollen diagram. Poaceae and *Empetrum* percentages as well as Cyperaceae increase. While *Botryococcus* decreases, *Pediastrum* percentage increases. *Menyanthes* is not found in zone IIIa and *Selaginella* spores decline. Furthermore, the percentage of corroded pollen declines.

Zone IIIb (325.5 cm – 319 cm) Younger Dryas – Empetrum phase

Throughout this zone the *Betula* percentage increases while the *Pinus* and *Salix* percentages remain low. The high percentage of herbs remains but declines towards the top of zone IIIa. A large part of the NAP consists of *Empetrum*. Though *Artemisia,* Caryophyllaceae, Chenopodiaceae, *Filipendula, Galium, Gentiana, Helianthemum, Potentilla,* Ranunculaceae and *Rumex* all peak at the base of the zone. There is almost no *Botryococcus* present, while the percentage of *Pediastrum* remains relatively high in zone IIIb and declines at the top boundary. The diversity in aquatics and riparians is low in this zone, only some *Myriophyllum alt*. and *Myriophyllum spic*. are present, as well as *Equisetum*. *Selaginella* is absent, but a single occurrence of another clubmoss, *Lycopodium annotium*, and the fern *Huperzia selago* were found.

Zone IV (319 cm – 313.5 cm) Preboreal

Zone IV is characterised by a further increase in *Betula* and a rapid decline in NAP percentage. *Pinus* and *Salix* percentages remain low, *Juniperus* is present. The diversity in herbs declines, again, *Artemisia, Filipendula, Rumex* and *Thalictrum* are still found. At the base of zone IV, the *Empetrum* percentage declines rapidly and other heathers decline and disappear as well. The algae *Botryococcus* and *Pediastrum* increase in percentage throughout the zone. *Potamogeton* increases in abundance and peaks at the top, *Nymphaea* comes into the pollen diagram. For the riparians; *Equisetum* increases in abundance towards the top of the zone, some occurrences of *Sparganium* and *Typha latifolia* are found as well.

Zone V (313.5 cm – 214 cm) Boreal

The onset of zone V starts with an increase in *Pinus* percentage and a decline in *Betula* percentage that continues through the entire zone. When *Pinus* shows a peak between 305 cm and 290 cm, the NAP shows a minimum. The point where NAP, *Botryococcus, Pediastrum, Potamogeton* and *Equisetum* percentages have declined to low values coincides with an increased percentage of monolete spores. After this peak in monolete spores NAP percentage increases again and a larger diversity of dry herbs is seen.

Thermophilous trees are first seen in the diagram, starting with *Corylus*, *Quercus*, *Ulmus* and *Alnus*. They all increase in percentage at ~290 cm depth when *Pinus* declines in percentage. At this point also *Tilia*, *Fraxinus*, *Carpinus* and *Fagus* come into the pollen diagram. The presence of *Hedera* is first seen in the diagram. Heliophilous plants like *Artemisia*, and *Rumex* decrease in percentage or disappear altogether. The percentage Cyperaceae remains at a minimum, *Pediastrum* disappears in the bottom of zone IV, where *Botryococcus* declines in percentage but remains present. *Myriophyllum alt.*

disappears as well, while *Nymphaea* and, later, *Nuphar* are present. After the peak in *Potamogeton* in the transition from zone IV to zone V, *Potamogeton* declines and disappears in the top of the zone.

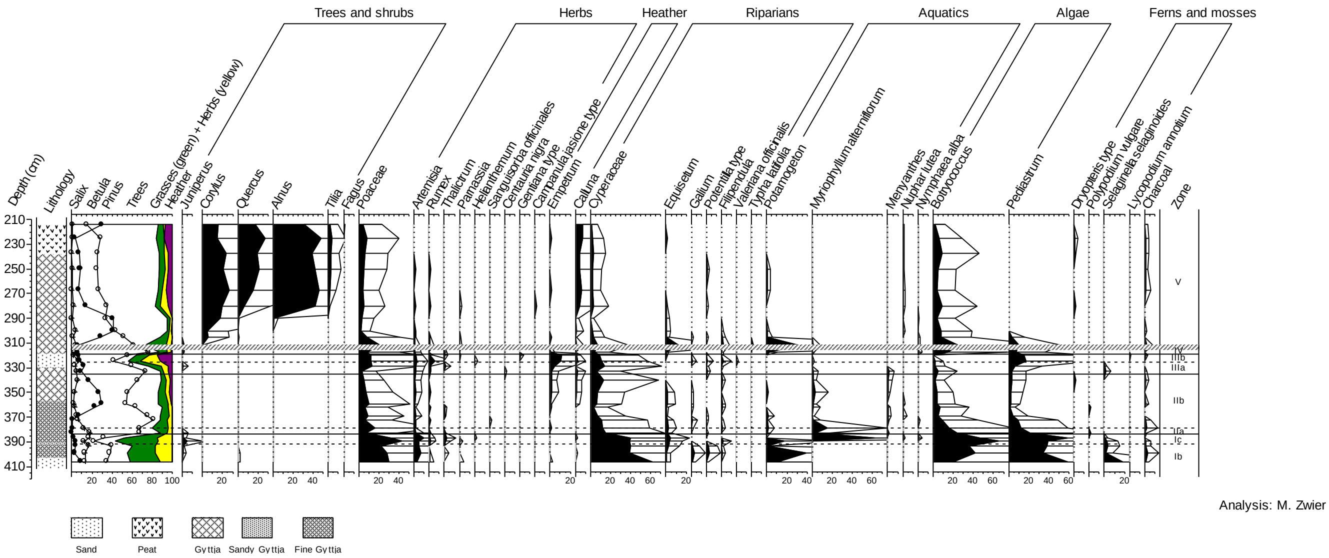

Figure 5.7 Pollen diagram with selected species from Witteveen, black lines show the zonation according to Hoek (1997). Grey striped line indicates a hiatus in the pollen diagram.

5.4.3 Pollen diagram Elpermeer

The pollen samples of Elpermeer were counted by students, who determined pollen for the first time, therefore the results might not be entirely confident. The total pollen sum is also generally low, ranging from 37 – 188, but averages around 80. The resolution shows one sample every 70 yr in the AllerØd and one sample every 100 yr in the Younger Dryas (figure 5.8).

Zone II (129 cm – 75 cm) Allerød

The onset of zone II of the Elpermeer pollen diagram (130 – 110 cm) is characterised by a low *Salix* and *Pinus* percentage and an increase in *Betula* percentage, with a concurring decrease in NAP percentage from ~60 % to ~20 %. The low NAP percentage is mostly due to a large decrease in Poaceae percentage in the bottom 10 cm. Steppe plants like *Artemisia, Galium* and *Helianthemum* are more abundant in the lower part of the pollen diagram (until ~90 cm depth), but don’t decrease in percentage as fast as the Poaceae. In the lower part of the pollen diagram, *Menyanthes* and *Potamogeton* are present and a maximum in *Selaginella* is reached. Further up, *Betula* has reached its maximum and remains at values around 60 %. Heather comes into the pollen diagram while *Artemisia* declines in percentage. *Myriophyllum alterniflorum* and *Equisetum* are found. *Sphagnum* appears in to the pollen diagram and increases in percentage to form a continuous curve.

Zone III (75 cm – 25 cm) Younger Dryas

In the upper part of the pollen diagram (90/75 – 25 cm) *Betula* is still abundant and *Pinus* percentages increase. Heather increases in percentage, mainly consisting of *Calluna*, after the LOI value has reached its maximum. *Artemisia*, *Galium* and *Rumex* are still present in low percentages, as well as the warm loving *Filipendula*, but overall the diversity in herbs declines. *Myriophyllum alt*. disappears while *Sparganium* and *Sphagnum* increase in percentage.

Zone V (25 cm – 11 cm) Boreal

In the top of the pollen diagram (<25 cm) thermophilous trees (*Corylus, Alnus* and *Quercus*) are found*. Equisetum* and *Myriophyllum alt*. reach a maximum and *Sparganium* is still present.

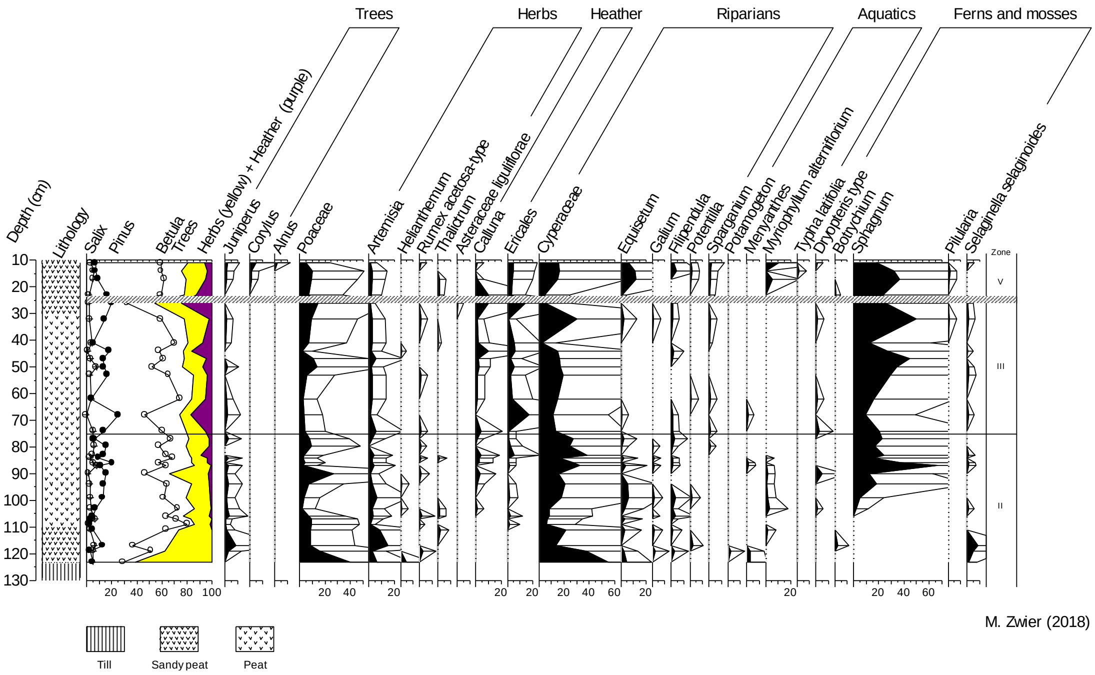

Figure 5.8 Pollen diagram of Elpermeer with selected species, black lines show the zonation according to Hoek (1997). Grey striped line indicates a hiatus in the pollen diagram.

5.5 Interpretation of the pollen diagrams

5.5.1 Palynostratigraphy of Esmeer

Zone Ib Bølling (12,450 BP – 12,100 BP)

The *Betula* and *Salix* pollen are mostly belonging to the shrub-species. The high percentages of *Salix* indicate that it is growing locally (Paris, 1977). High NAP values, ranging to almost 50% and the presence of steppe plants as *Artemisia*, *Galium* and *Helianthemum* are indicative for a very open landscape with hardly any trees and a cold climate. *Potamogeton*, *Thalictrum* and *Filipendula* imply a eutrophic lake. *Stratiotes* prefers cold water and sometimes appears to be associated with calcareous rich water.

Zone Ic Earlier Dryas (12,100 BP – 11,900 BP)

The increase of herbs and the decrease of *Betula* is commonly interpreted as a decrease in summer temperature (Cleveringa et al., 1977). The high percentages of Cyperaceae and *Selaginella* can point to a lowering of the water level that leads to a broader area suitable for sedge growth, or the rim of the lake that comes closer to the central point. During the earlier Dryas, the permafrost layer in the Netherlands disappeared, this is supposed to results in a general lowering of the water table and drier conditions (Hoek, 1997c). A lowering of the water table could also have caused the algae to develop optimally closer to the centre of the lake. The presence of the algae, *Myriophyllum spic./vert.* and *Nymphaea* indicate that the lake is still eu- mesotrophic and the water level is not very high (Hannon & Gaillard, 1997; Paris, 1977).

Zone IIa Allerød *Betula*-phase (11,900 BP – 11,250 BP)

The high percentage of AP pollen indicates an expansion of the forest due to a warmer climate. This is affirmed by the presence of *Myrica*. The decline in heliophilous herbs is most likely caused by this expansion of the trees, since they are intolerant to shade (Hoek, 1997c). The disappearance of *Selaginella* might subsequently not necessarily be due to a dryer climate, but due to a decreasing openness of the vegetation. Nonetheless, *Artemisia* does not disappear completely, so the vegetation must still remain relatively open and the climate remains partly continental (Paris, 1977). The decline of the algae halfway through the zone might be caused by an increase in water level and subsequent increase in turbulence. A wetter climate supplies more nutrient poor rainwater to the lake, with the consequence that the previous very abundant *Potamogeton* disappeared under a mesotrophic environment. Additionally, an increase in the lake level leads to an increased distance from the lake edge to the middle of the pingo remnant and a reduced signal of aquatics in the lake centre. Moreover, the aquatic species composition and decline in *Thalictrum* indicate a meso-oligotrophic environment.

Zone IIb Allerød *Pinus*-phase (11,250 BP – 10,950 BP)

In the second phase of the Allerød *Pinus* becomes increasingly important and reaches values over 25 %, indicating that pine is actually growing locally (Hoek, 1997c). Together with the presence of *Empetrum* this indicates increased soil formation and acidification of the ground in the surrounding areas (Cleveringa et al., 1977). The continuous presence of *Myriophyllum alt.* also points towards a slightly acidic environment that becomes more oligotrophic. (But *Galium* and *Helianthemum* point to calcareous soils). This could also explain the decline in algae.

Zone IIIa Younger Dryas (10,950 BP – 10,550 BP)

The combination of a decrease in arboreal pollen and the diversification of herbs and presence of a lot of steppe plants, and the return of *Selaginella*, indicates a colder, more continental climate with an open vegetation. During the Younger Dryas a lot of aeolian sand ends up in the lake as seen by the decrease in LOI values. A high percentage of corroded pollen from thermophilous trees indicates reworking of older material, which could also be due to the aeolian activity. Furthermore, *Gelasinospora*, which is a fire indicator, and charcoal point to frequent fires. Previous literature mentions that due to the colder and wetter climate during the younger Dryas a high tree mortality occurred, especially among pine trees, giving the opportunity for forest fires to arise (Bohncke, 1993; Paris, 1977). With the lower percentage of *Pinus* pollen, *Empetrum* would have the opportunity to expand its range.

Zone IIIb Younger Dryas – *Empetrum* phase (10,550 BP – 10,150 BP)

The increased percentage of heliophilous herbs suggest that the landscape becomes even more open than in the first phase of the Younger Dryas. Species like *Empetrum*, *Juniperus* and *Polypodium vulgare* grow well on sandy substrates and indicate that the aeolian activity increases. The disappearance of some steppe plants is probably because they cannot handle burial by sand to well.

Zone IV Preboreal (10,150 BP – 9,500 BP)

Declining percentages in steppe herbs and the appearance of *Myrica* indicate a warmer climate. The presence of *Typha latifolia* is found in the remaining of zone IV and indicates fluctuating water levels and dry mud surfaces (Hoek, 1997c). The increased percentages of *Gelasinospora* and charcoal point towards an increased fire recurrence. Equisetum percentages are very high, indicating a eutrophic environment, also implied by the presence of *Typha latifolia* (Paris, 1977). The *Betula* phase of the Preboreal that is recognised in some other diagrams (Hoek, 1997c) is missing in Esmeer. This could be due to a drier climate with lower lake levels or a completely drying out of the lake, in which no sedimentation took place. Likewise, the large amount of amorphous organic matter in the pollen slides suggest desiccation of the pingo remnant (Hoek, 2017).

Zone V Boreal (9,500 BP –)

The deciduous trees that come into the pollen diagram indicate a further warming of the climate. *Fagus* and *Carpinus* indicate a late Holocene (Atlanticum) age. However it is more likely that some mixing from top sediment occurred. Deciduous tree species, together with a single occurrence of *Ephedra fragilis* indicate a warm, maritime climate with higher temperatures during the winter (Cleveringa et al., 1977). The absence of most herbs suggests an increased forestation. The disappearance of *Myriophyllum alt*. points towards a lowering of the water level and/or increased eutrophication of the lake, also seen by the presence of *Potamogeton* and *Typha ang*. (Inoue & Tsuchiya, 2009).

5.5.2 Comparison Esmeer and Mekelermeer

Esmeer is compared to Mekelermeer MII (Bohncke et al., 1988), a pingo remnant in the Northern Netherlands till region with a diameter of 250 m and of 12 m depth. These dimensions and the similar subsurface allows a good comparison between these pingo remnants. Loss on ignition analysis of Mekelermeer was performed by Bohncke & Wijnstra (1988). Overall the two pollen diagrams are very similar to each other (figure 5.9). One clear distinction is that the *Pinus* record from Esmeer does not reach values as high as Mekelermeer during the second phase of the Allerød (zone IIb). In Esmeer *Pinus* percentages only reach up to 40 %, while they reach over 60 % in Mekelermeer, possibly indicating that pine was not growing locally in as large quantities as near Mekelermeer. Though values over 20 % are seen as the local occurrence of pine (Huntley & Birks, 1983). Although the increase in NAP during the Younger Dryas reaches higher values in Mekelermeer. During the Younger Dryas the rise in NAP and especially Ericales in Esmeer, is not as large as seen in the pollen diagram of Mekelermeer. Following in the Preboreal compared to Mekelermeer, *Equisetum* percentages are very high, indicating a eutrophic environment, also implied by the presence of *Typha latifolia* (Paris, 1977).

Since Esmeer is very deep, it is likely that the base of the pingo remnant cuts through the till layer into the Peelo formation below. However, for the comparison of local vegetation, the substrate of the remnant closest to the surface is most important for this is directly affects the vegetation.

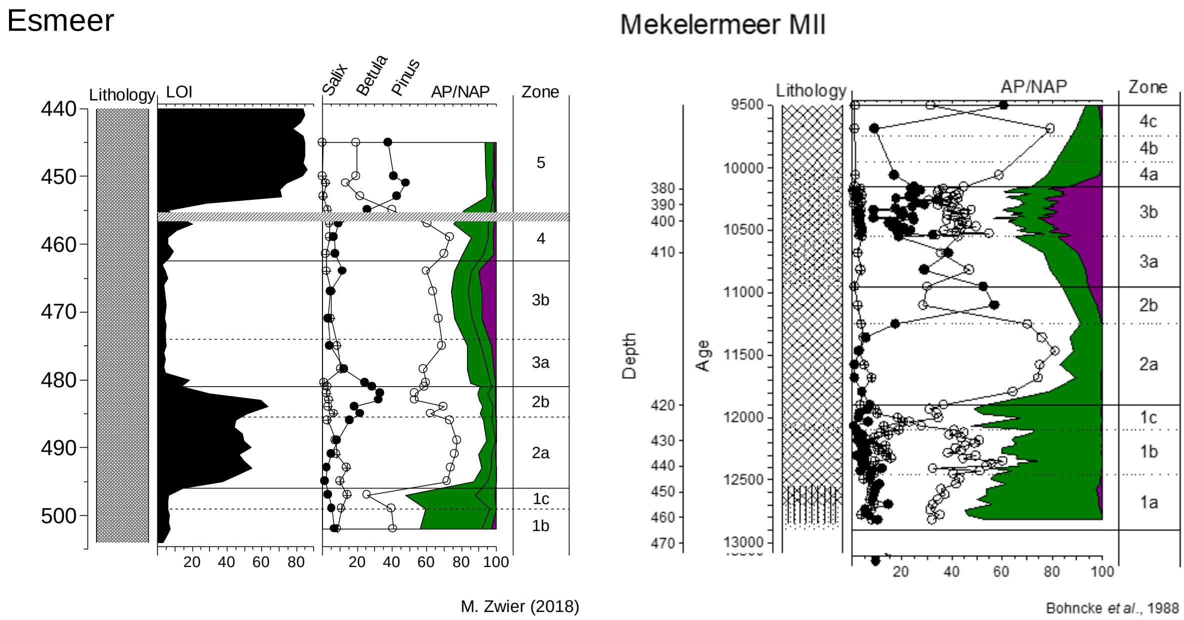

Figure 5.9 Comparison of Esmeer and Mekelermeer.

5.5.3 Palynostratigraphy of Witteveen

Zone Ib Bølling (12,450 BP – 12,100 BP)

The high percentage of heliophilous herbs indicates an open vegetation with sandy soils that starts out relatively dry. The increase in Cyperaceae and aquatics can be seen as a closeness of the lake edge to the centre of the pingo remnant. The water is eutrophic. The arboreal pollen from *Betula* and *Salix* are most likely originating from the shrub species.

Zone Ic Older Dryas (12,100 BP – 11,900 BP)

In subzone Ic the environment becomes more steppe-like as seen by an increase in heliophilous herbs and a decline in Betula and Salix. The abundance of the various aquatics and presence of *Nuphar lutea* and *Nymphaea alba* indicate summer temperatures above 13 °C. The huge peak in *Myriophyllum alterniflorum* indicates that the winter temperature must have been above -13 °C as well and the water must have been meso- oligotrophic and the lake level was relatively shallow. The peak in *Rumex* also indicated dry conditions.

Zone IIa Allerød Betula-phase (11,900 BP – 11,250 BP)

The area becomes increasingly more forested, although most heliophilous taxa do not disappear completely, so the vegetation must still have an open character. The climate becomes warmer, which can explain the disappearance of *Selaginella selaginoides*. In contrast, the appearance of *Menyanthes trifoliata* is a typical pioneer and indicates the onset of the hydroseral succession (Hoek, 1997c). The lake changes from a more eutrophic to mesotrophic environment.

Zone IIb Allerød Pinus-phase (11,250 BP – 10,950 BP)

In the second phase of the Allerød the climate probably did not change a lot, but the soil development continued and influenced the vegetation. As evident by increasing percentages of pine and heathers, mainly *Empetrum*. There is some discussion on whether the immigration of pine is responsible for the soil development and thereby the acidification of the soil, or whether pine only migrated to areas where soil development had already started (Paris, 1977). The gyttja becomes more course and there is some sand input in the upper part of zone IIb, but the sediment still contains quite some organic material. The sand input probably also contributed to the corroded pollen that were reworked from older layers. The presence of *Myriophyllum spic*. indicates the continuation of the hydroseral succession, but suggest that there is still eutrophic, open water.

Zone IIIa Younger Dryas (10,950 BP – 10,550 BP)

The presence of herbs increases significantly, together with the decline in *Betula* pollen this is evident for a colder climate with a more open vegetation cover. The environment becomes more continental and locally there are very little aquatics. The presence of *Empetrum* and *Juniperus* point to aeolian activity and the percentage corroded pollen does imply a lot of reworking of older material. There is some charcoal, but there is no big increase as was seen in Esmeer and that is characteristic for the beginning of the Younger Dryas (Paris, 1977). However, the presence of *Gelasinospora* indicates that there is some fire activity going on. The typical presence of *Selaginella selaginoides* indicates a colder period. In the Witteveen core the lithology mainly consist of sand, though the LOI profile shows a relative high organic matter content.

Zone IIIb Younger Dryas – *Empetrum* phase (10,550 BP – 10,150 BP)

A high diversity and abundance of heliophilous plants indicate a very open vegetation cover. *Empetrum* becomes very important in this zone, indicating a fairly high precipitation (Cleveringa et al., 1977) and a further increase in aeolian activity. However, there are almost no aquatics and riperians present in this zone, except for some *Pediastrum* and *Myriophyllum* species. Indicating a meso-eutrophic lake environment. The club-moss and fern *Lycopodium annotium* and *Huperzia selago* (previously named *Lycopodium selago*) indicate very cold temperatures these taxa grow among moist heathlands.

Zone IV Preboreal (10,150 BP – 9,500 BP)

The decline in NAP indicates that the landscape becomes more vegetated by *Betula* trees, but since species like *Artemisia* still occur, the landscape keeps its open character. The increase in aquatics and algae indicate a sequence in which the lake becomes more filled in. It is evident that there must be a hiatus in the Witteveen core. The increase in *Betula* and *Juniperus*, characteristic for the Friesland oscillation, as well as a small peak in grasses, characteristic for the Rammelbeek phase, are observed. However, the further increase in *Betula*, characteristic for the Preboreal, is lacking.

Zone V Boreal (9,500 BP –)

The increase in arboreal pollen indicates a warming of the climate, with a succession form *Betula* to *Pine* followed by a mixed forest of thermophilous trees dominated by *Alnus, Corylus* and *Quercus*. The shade provided by the trees caused a decline in (heliophilous) herbs. Occurrences of *Hedera*, *Fagus* and *Viscum* point towards increasingly higher temperatures. The trophic condition of Witteveen became increasingly eutrophic, as evident by the disappearance of *Myriophyllum. alt.* and appearance of *Nymphaea* and *Nuphar*. These species also indicate that there was still open water present and a full peat bog developed only later.

5.5.4 Comparison Witteveen and Stokersdobbe

Witteveen is compared with Stokersdobbe because it also developed close to a Pleniglacial river valley and both pingo remnants have similar dimensions, though Stokersdobbe is almost twice as deep (8 m depth, 100 m in diameter). It was first described by Paris et al. (1979). Zone IIIa In the Witteveen core the lithology mainly consist of sand, though the LOI profile shows a relatively high organic matter content (> 40 %, figure 5.10). When we compare this to Stokersdobbe, only some sandy gyttja is seen, suggesting a higher aeolian input in Witteveen, though unfortunately no LOI profile of Stokersdobbe is available. Also interesting is the large peak in *Myriophyllum alt.* in Stokersdobbe at the end of zone IIIa that is missing in Witteveen. This could be caused by a higher trophical state in Witteveen, for *Myriophyllum alt.* is intolerant to high nutrient levels.

When comparing the diagram of Witteveen with Stokersdobbe I, it is evident that there must be a large hiatus in the Witteveen core during the Preboreal. The decline in herbs and heathers is very rapid in comparison to the gradual decline in Stokersdobbe I. The peak in *Myriophyllum alt.* that is seen in zone IV of Stokersdobbe is also lacking in Witteveen, this can however not contribute as an argument for the hiatus in Witteveen, since the *Myriophyllum* peak was missing in Witteveen in zone IIIa as well.

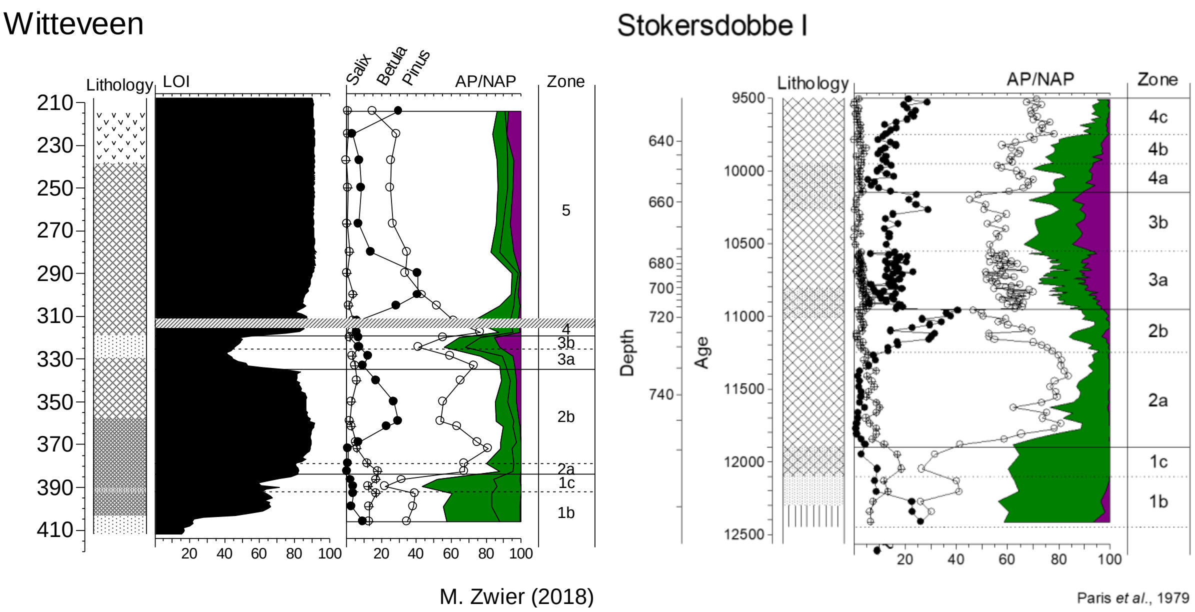

Figure 5.10 Comparison of Witteveen with Stokersdobbe.

5.5.5 Palynostratigraphy of Elpermeer

Zone II Allerød (11,900 BP – 10,950 BP)

The decrease in NAP (mainly less grasses) suggest that the climate becomes somewhat warmer and becomes increasingly forested, but the landscape has still an open character because heliophilous taxa like *Artemisia*, *Galium* and *Helianthemum* are still present. Furthermore, the occurrence of *Selaginella selaginoides* and *Myriophyllum alt.* suggest that the sediment could have a Pleniglacial, early Lateglacial age. However, also in the Uteringsveen and many other pingo remnants, these taxa are found up to the Preboreal (Hoek, 1997a). Further up in this zone the *Betula* curve roughly stabilizes. The presence of sphagnum (and peat lithology) indicates that there was most likely a sphagnum peat bog. Overall, the pollen diagram is very stable, but in this zone the diversity in herbs is at its maximum.

Zone III Younger Dryas (10,950 BP – 10,150 BP)

The diversity in herbs declines and the presence of *Pilularia* indicates that the lake level is variable; it grows on places that partially dry up during the summer and is a poor competitor, indicating a species-poor vegetation.

Zone V Boreal (9,500 BP –)

In the upper part of the pollen diagram of Elpermeer, thermophilous trees are found. This would suggest that the material is of an Early Holocene age. Nonetheless, it is important to realize that there is also a certain amount of reworking and mixing of the upper layers. A study on redeposition of pollen grains in lake sediment mentions that in a large and shallow lake (<1 m deep over most of its area) the reworking is spatially very variable and only involves the uppermost 6-12 mm of sediment (Davis, 1973).

5.5.6 Age estimate for Elpermeer

In the Elpermeer pollen diagram, only a small section of the vegetation development between the Lateglacial and Early Holocene is recorded. Therefore, the question arises where this incomplete section is positioned in respect to the general biostratigraphical zonation of the Netherlands. The LOI did not provide a clear picture regarding the age of the fill, fortunately the pollen diagram can provide additional information.

The Elpermeer core sequence most likely shows the transition from the Lateglacial to Early Holocene, mainly evident by the occurrence of thermophilous trees in the upper part of the diagram and the lack of them in the major bottom part of the pollen diagram. The rise in *Betula* pollen in the lower part of the diagram matches with the onset of the Allerød. Subsequently, the fluctuation of the *Pinus* curve at the point where the heather comes into the diagram can be recognized as the Younger Dryas. The LOI profile of Elpermeer also fits with this hypothesis and shows similarities with the LOI profile of Kostverloren Veen (Davies et al., 2005).

The fact that Elpermeer lacks the tripartite Lateglacial pattern might be unfavourable and Cleveringa & de Gans (1978) stated that gyttja accumulated during the Lateglacial and peat formation started during the Holocene. This would suggest that Elpermeer is not a pingo remnant but some other morphological feature. However, while drilling the till underlying Elpermeer was found to be very impermeable. This insinuates that an ice lens of the former active pingo did not have the ability to penetrate the till. Therefore, it is more likely that the ice lens had a relatively flat bottom. Moreover, the development of gyttja or peat is dependent on the water level and numerous other depressions that record the Lateglacial, such as Usselo, Den Treek, Ossendrecht and Bosscherheide consist entirely of peat as well (Bohncke et al., 1993; Schwan, 1991; van Geel et al., 1989). The impermeability of the till, caused by its heterogeneity and compaction, leads to a relatively high ground water level (Hoek, 2000). Subsequently, in Elpermeer a peat bog already developed during the Allerød.

5.5.7 Comparison Elpermeer and Uteringsveen

The comparison between Elpermeer and Uteringsveen is made because they both have till in the subsurface, are very shallow (Uteringsveen is 2,5 m deep) and are located very close together (Paris, 1977). Overall the two pollen diagrams show a good comparison (figure 5.11). This gives an increased confidence that the Elpermeer core indeed shows the Allerød and Younger Dryas. In Uteringsveen and Elpermeer there are almost no aquatic taxa present, especially during the Younger Dryas. Cleveringa et al. (1977) suggest that this is either due to the fast accumulation of sand into Uteringsveen, or that the depression was drained by a brooklet. In Elpermeer, however, the percentage of Sphagnum increases tolerably, representing the formation of a Sphagnum peat bog. Therefore, the lack of aquatics is Elpermeer is due to the natural hydroseral succession of the depression.

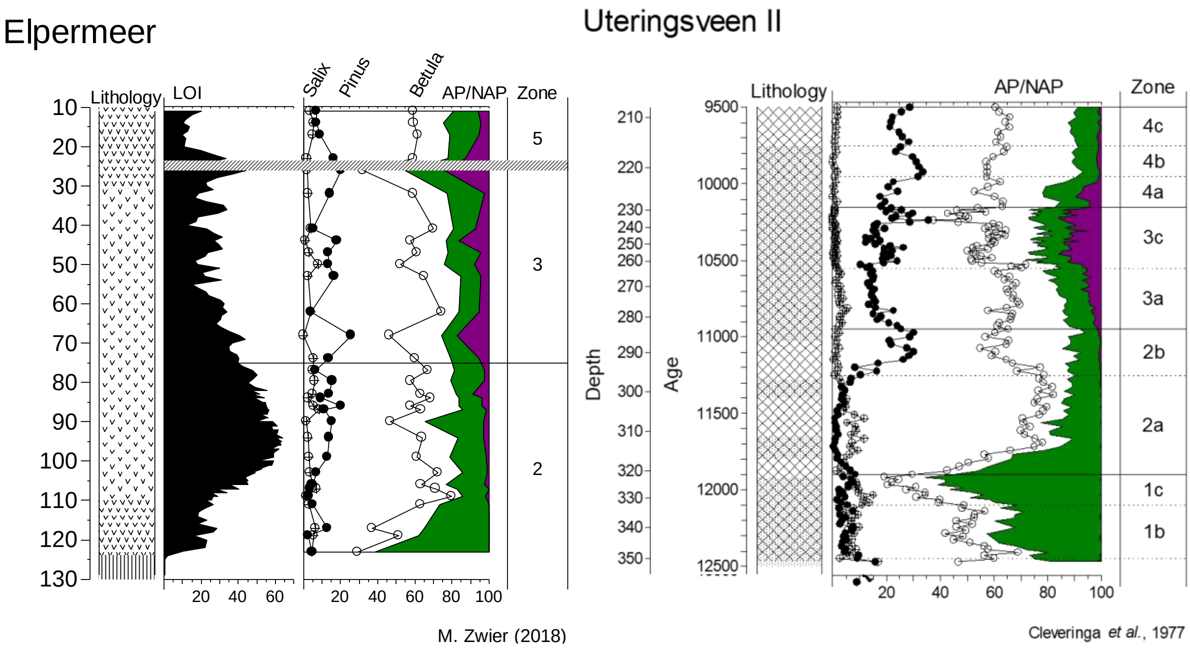

Figure 5.11 Comparison of Elpermeer and Uteringsveen.

6. Discussion

6.1 Relation of the substratum and fill.

The lithological fill of the pingo remnants differs for the three depressions. All cores were taken in the middle of the circular depressions for consistency. However, since Witteveen is much smaller than Esmeer and Elpermeer, it is expected that the representation of local taxa is more evident in Witteveen since the rim of the lake is closer to the coring location. Additionally, this would suggest that the aeolian sand input in Witteveen should be higher. For example in Mekelermeer it is seen that the sandy layer representing the Younger Dryas is thicker in the west side of the depression as a result of the prevailing westerly winds (e.g. in Mekelermeer; de Boer, 2017). Interestingly, there is only a thin Younger Dryas sequence in Witteveen and there is almost no sand visible in the Elpermeer core. For Witteveen this thin sandy layer might be explained by the ridge west of the depression that blocks part of the aeolian sand from the westerly winds (figure 4.3). In Elpermeer an irregular rim is seen around the lake, taken that there used to be a sphagnum peatbog in Elpermeer that was excavated before any historical maps were made, this rim could represent the edge of the peat bog that blocked the sand from entering the depression. The peat might also cause the irregular loss on ignition profile.

The relation between the substrate and the vegetation is prone to a complicated interaction. The substrate does not only affect the hydrology and nutrient availability for vegetation growth, but the vegetation development also affects the abiotic landscape (Hoek, 1997c). For example, the vegetation development effected sedimentation and erodibility but also soil formation (Hoek, 1997c; Paris, 1977). The different types of substrate in which the pingo remnants under investigation in this study are located might affect the vegetation development. As stated before, the Drents plateau is largely constructed by till. There are however different types of till to be found (Huisman, 2003). Both the lithological composition and origin of the glacial erratics differ. The composition of the till can have consequences for the abiotic environment and vegetation growth. One of the most obvious distinction is the calcareous content. Esmeer and Elpermeer are both located in decalcified till (Huisman, 2003; Rappol, 1984). Moreover, the till is relatively impermeable and hence could influence the hydrological conditions of the region. Not all taxa grow well in areas with high groundwater levels (e.g. *Helianthemum*), while others (e.g. *Ericales*) prefer poorly drained soils in the nutrient poor till region (Hoek, 1997a). In contrast, the sand of the Peelo formation is very permeable (Beard & Weyl, 1973). There are numerous species occurring that prefer sandy substrates and lower groundwater levels e.g. *Juniperus* (Hoek, 1997c). The effect of the aeolian activity on the vegetation developments is also an important factor. It is seen that numerous heliophilous herbs decrease in abundance during the Younger Dryas, while *Empetrum* increases in abundance. However, although not all pingo remnants collected a thick sand layer during the Younger Dryas, the local area surrounding the pingo remnants were affected by the deposition of cover sands (e.g. the rim around Elpermeer).

Furthermore, when comparing the trophic level of Esmeer and Witteveen (section 6.1 and 6.2, table 6.1) they show a very similar trend. Though, initially Witteveen seems to have a lower nutrient level during zone I. In the AllerØd the trophic level of Witteveen is relatively high, this might be linked to the soil formation and leaching that is favoured by the presence of pine and heather (Hoek, 2000; Paris, 1977). The hiatus at the Betula-phase of the Preboreal suggest that the region must have been very dry, resulting in a change in lake level, generating no sedimentation under low water levels. Thereafter in the Early Holocene both pingo remnants are becoming increasingly eutrophic, due to increased nutrient availability (Hoek, 1997a).

Table 6.1 Change in trophic level and water level fluctuations in Esmeer and Witteveen.

Zone	**subzone**	**Esmeer**	**Witteveen**
V	V	Eutrophic	Eutrophic
IV	IVc	Hiatus/low water level	Hiatus/low water level
	IVb	Eutrophic	Meso-eutrophic
	IVa	Eutrophic/low water level	Meso-eutrophic/start hydrosere
III	IIIIb		Meso-eutrophic/high water level
	IIIa	Mesotrophic/ high water level	Eutrophic
II	IIb	Meso-oligotrophic/acidification soil	Eutrophic/acidification soil
	IIa	Meso-oligotrophic/increase water level	Mesotrophic
I	Ic	Eu-mesotrophic/lower water level	Meso-oligotrophic/low water level
	Ib	Eutrophic/cold/calcareous rich	Eutrophic/low water level

6.2 Complications

General complications of interpreting pollen diagrams comprise problems related to the representatively of the pollen that are preserved. Differences in pollen production of anemophilous and entomophilous taxa, dispersal and preservation, all contribute to an over- or underrepresentation of certain taxa in the pollen diagram. In pingo remnants another complication arises with the differential 'pollen rain' in the lake. The edges of lakes receive more pollen from local taxa and aquatics, while the middle of the lake mainly captures the regional taxa (Moore et al., 1991). All cores used in this study where taken from the middle of the pingo remnants to get a record as continuous as possible. But also, to get both the local and regional pollen signal, considering that the influence of the riparian vegetation is higher at the edge of the lake and overshadows the regional pollen rain. Previous research has showed that it matters whether a core is taken in the middle of a lake or bog or at the edges (Paris, 1977). However, since the size of the depressions in this study vary, local and regional input will differ at the 3 locations. Furthermore, both in the Witteveen and Esmeer pollen diagrams corroded pollen are found, among which *Corylus*, *Alnus* and *Carpinus*. The corrosion is due to oxidation of the pollen grains and this suggests that the pollen grains are most likely reworked from older layers (Wilmshurst & McGlone, 2005). When looking at the onset of the Holocene, it is important to distinguish reworked pollen from in situ pollen to prevent an underestimation of the relative age of the core sections.

6.3 Future research

To get an even better understanding of the substrate control on pingo fills, it is advisable to study more pingo remnants. For example Kluiving et al. (2010) looked at 45 presumed pingo remnants in Friesland. Since the Peelo formation also contains clay, it might be interesting to include a third type of substrate to the comparison. Additionally, it would be very interesting to look at the fill of pingo remnants in other parts of the Netherlands, for this might provide larger differences in the substrate and therefore might also provide more distinct differences in the vegetation development around the pingo remnants (Hoek, 2000). However, it should be noted that the influence of climatic differences might also be greater and hence the immediate effect of the substratum might be depressed. Moreover, it would be nice to include ^{14}C -dating or tephrochronology in order to adopt a better age–depth model for the cores under study. The Esmeer core is currently investigated on the presence of the Vedde Ash and Laacher See Tephra (Veneman, in progress). Additionally, studies on macrofossils and *Chironomideae* could also be used for a detailed temperature reconstruction and habitat type.

7. Conclusion

Based on the research questions the following conclusions can be drawn.

1. On what kind of subsurface can pingo remnants be found in Drenthe?

In Drenthe pingo remnants can be found in sandy deposits in old stream valleys, these are classified as the Drentsche Aa-type (de Gans, 1983). Witteveen, with a subsurface of sand from the Peelo formation, belongs to this category. Furthermore, pingo remnants can be found on till of the Drents plateau, classified as the Mekelermeer-type. Both Esmeer and Elpermeer belong to this category with a substrate consisting of till from the Drenthe formation.

2. Can a clear difference in pingo remnant fill be distinguished in the pingo remnants under investigation?

Looking at the lithological components from the loss on ignition profile, Esmeer has relatively high levels of mineralogical material in the Younger Dryas sequence. In contrast, the organic matter content of the Witteveen core is very high. Furthermore, the Elpermeer core lacks the characteristic tripartite fill of gyttja, sand and peat, instead it only consists of peat.

3. How do the pingo remnant fill types relate to the subsurface and landscape position/evolution?

The very low aeolian sand input in Witteveen can be explained by the ridge west of the pingo remnant that partly blocks the depression from sand transported by the prevailing westerly winds. Due to the impermeable till underlying the Elpermeer, the depression created by the ice lens is very shallow. The shallow depression is filled up by a *sphagnum* peat bog from the Allerød onward. The peat will likely have blocked the aeolian sand from entering the depression during the Younger Dryas.

4. How is the regional variation in vegetation cover?

Overall, the pollen diagrams of Esmeer and Witteveen follow the general zonation as described by Hoek (1997a), with deposition starting in the Bølling. This indicates that the regional vegetation cover must have been very uniform as is expected from the Weichselian Lateglacial that only has minor spatial differences in climate due to the relative large distance to the former coastline. The Elpermeer section shows deposits from the Lateglacial to Early Holocene transition, with deposition starting during the Allerød. When looking at the local taxa Esmeer, Witteveen and Elpermeer show some slight variations that could be due to local lithological differences, both from the differential aeolian sand input and the characteristics of the subsurface.

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Appendices

Appendix 1 Pollen preparation technique

Work instructions Pollen preparation UU-FG In particular step 2 strong acids are used, consult the fact sheets about the chemicals to be used. In case of uncertainty, always consult Wim Hoek

1 Decalcify and leaching

- Approx. 0.3 cm^3 of material in a 15 ml centrifuge tube, fill with aqua destillata to prevent oxidation.
- For calcareous material: acidify with 5% acetic acid, then wash twice with aqua dest. to remove the acid (fill with aqua dest, vortex, centrifuge 1 min at 2000 r.p.m. and decant).
- (If necessary add 2ml Lycopodium (1.068 Lyc. per sample), for absolute pollen diagrams). Add 5 ml of KOH 5% to remove humic compounds.
- Heat for 60 minutes in stove at 70 ° C.
- Vortex until well mixed, then sieve over 200 mu, directly into a 15 ml centrifuge tube (clean the sieve thoroughly after every sample).
- Wash twice with aqua dest. to remove KOH (fill with aqua dest., vortex, centrifuge 1 min at 2000 r.p.m. and decant) and fill with aqua dest.

2 Acetolysis (to be carried out by qualified staff)

(Always drain acids into a special acid container)

- Wash twice with glacial acetic acid to remove water (fill to 5 ml).
- Acetolysis mixture: 9 parts acetic anhydride + 1 part H_2SO_4 (for 48 samples this is 180 ml + 20 ml).
- Add 4 ml acetolysis mixture and mix. Heat for 5 min at 100 °C in a heat bath. In between (after reaching 100 °C) vortex once.
- Centrifuge, drain the acetone mixture into special acid container.
- Wash twice with aqua dest. to remove acid in another waste container (fill with aqua dest., vortex, centrifuge 1 min at 2000 r.p.m. and decant).

3 Heavy liquid separation

(Always remove heavy liquid in plastic washing bottle for heavy liquid).

- Vortex or shake mixture, centrifuge, drain.
- Add 4 ml of heavy liquid (sodium-polytungstate (SPT) with d=2.0). Vortex and mix well.
- Centrifuge for 15 minutes at 2000 r.p.m. to separate on specific gravity.
- Decant the collar in a conical centrifuge tube. Fill with aqua dest. to 10 ml, shake and centrifuge for 5 minutes at 2000 r.p.m. decant the remaining heavy liquid. Repeat once.
- Wash twice with aqua dest.

4 Finishing

- Rinse 2 or 3 times with water after centrifuging for 1 min. at 2000 r.p.m.
- After decanting, add 1.5 ml of Alcohol.
- Vortex and transfer to Eppendorf cup.
- Centrifuge for 1 min at 2000 r.p.m.
- Decant the Alcohol and add glycerine (similar amount of glycerin as sample).
- Leave open Eppendorf cups in a stove overnight at max. 70 °C

5 Preparation of pollen slides

- Stir the glycerine and pollen with a stirring rod (e.g. a blunt cocktail stick).
- Apply a drop of approximately 0,5 cm diameter on a labelled microscope slide that is based on a 91 – 100 °C thermal plate, add more glycerine if necessary.
- Apply wax next to the droplet and cover with a cover slip.
- Cool and wipe away any remaining wax. Store horizontally.

Appendix 2 Core description Esmeer (by W. Koster)

Core	Depth start (cm)	Depth end (cm)	Description
A1	50	134	Gyttja, sandy, no rootlets
A2	134	234	Gyttja, sandy (coarse)
	168		Sand (210-300 µm)
	184		Sand (150-210 µm)
	190		Sand (150-210 µm)
	193		Sand (150-210 µm)
	198		Sand (150-210 µm)
	204		Sand (150-210 µm)
	207		Sand (150-210 µm)
	214		Sand (150-210 µm)
	222		Sand (150-210 µm)
A3	234	329	Gyttja, sandy, no rootlets
	235		Sand (150-210 µm)
	236		Sand (150-210 µm)
	240		Sand (150-210 µm)
	246		Sand (150-210 µm)
	250		Sand (150-210 µm)
	251		Sand (150-210 µm)
	255		Sand (150-210 µm)
	258		Sand (150-210 µm)
	260		Sand (150-210 µm)
	263		Sand (150-210 µm)
	267		Sand (150-210 µm)
	295		Sand (150-210 µm)
B1	308,5	323,5	Gyttja, sandy, no rootlets
B2	323,5	415	Gyttja, sandy, with rootlets
	330		Sand (75-110 µm)
	352	355	Wood fragment
	390	392	Hiatus
	406	407	Hiatus
	411,5		Sand (420-600 µm)
B3	415	504	
	415	444	Gyttja, sandy, black
	444		Sand (150-210 µm)
	444	471	sandy clay, silt, no organic material, grey
	471	504	sandy clay, silt, no organic material, grey/black

Appendix 3 Core description Witteveen

Core	Depth (cm)	Corrected depth using LOI profile (cm)	Description
IIIa	191.5-208	179.5-196	Sedge peat, dark brown/black
	208-260	196- 248	Course detritic gyttja with a lot of plant remains, dark brown/black
IVa	228-236	231-239	Sedge peat, dark brown/black
	236-285.5	239-288.5	Course detritic gyttja with a lot of big plant remains, dark brown/black
	285.5-296	288.5-299	Gyttja with some plant remains, brown
	296-300	299-303	Fine gyttja, dark grey/black
IIIb	271-288.4	267- 283.4	Course detritic gyttja with a lot of course plant remains, dark brown/black
	288.4-294	283.4-290	Course gyttja with plant remains, dark brown
	294-316.5	290-312.5	Gyttja with some plant remains, brown
	316.5-323	312.5-319	Sandy gyttja with some plant remains, grey brown
	323-335	319-331	Sand with micas, grey
	335-353	331-349	Course detritic gyttja with a lot of plant remains, dark brown/black
	353-360	349-356	Humic fine detritic gyttja, dark brown
IVb	307-315	307-315	Course gyttja with a lot of plant remains, dark brown/black
	315-319	315-319	Gyttja, dark brown/black
	319-330	319-330	Humic sand, grey
	330-335	330-335	Fine sandy gyttja, brown
	335-342	335-342	Course detritic gyttja with a lot of plant remains, dark brown
	342-346	342-346	Course gyttja, some plant remains, dark brown
	346-358	346-358	Humic course gyttja with a lot of plant remains and micas, dark brown
	358-364	358-364	Fine gyttja with plant remains, dark brown
	364-369	364-369	Humic fine gyttja, dark brown/black
	369-371	369-371	Humic fine gyttja with micas, brown
	371-373	371-373	Humic fine gyttja with micas, dark brown
IVb	373-387.5	373-387.5	Humic fine gyttja with micas, dark brown with bands of light brown
	378.5-390.4	378.5-390.4	Humic fine gyttja with micas, light brown
	390.4-400	390.4-400	Humic fine detritic gyttja with micas and plant remains, brown/dark brown

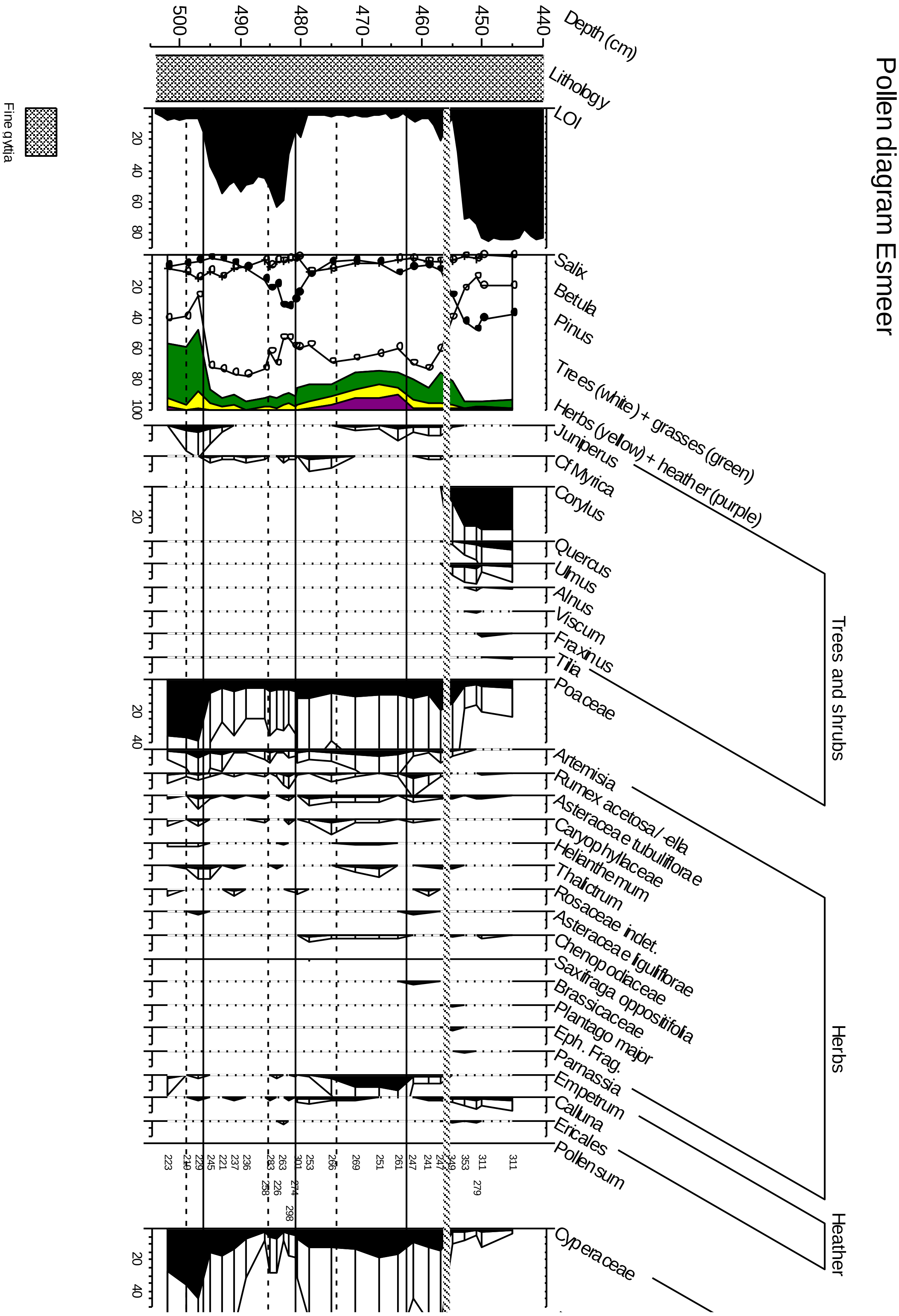
IIIc	360-367	367-374	Course detritic gyttja, dark brown/black
	367-377.5	374-384.5[1]	Humic fine gyttja, brown
	377.5-383.2	384.5-390.5	Humic fine gyttja with plant remains, dark brown
	383.2-385.2	390.5-392.5	Humic fine silty qyttja, light brown
	385.2-396	392.5-403	Humic fine gyttja with a band of plant remains at 393-394 cm, dark brown
	396-405	403-412	Humic sand with micas, brown grey

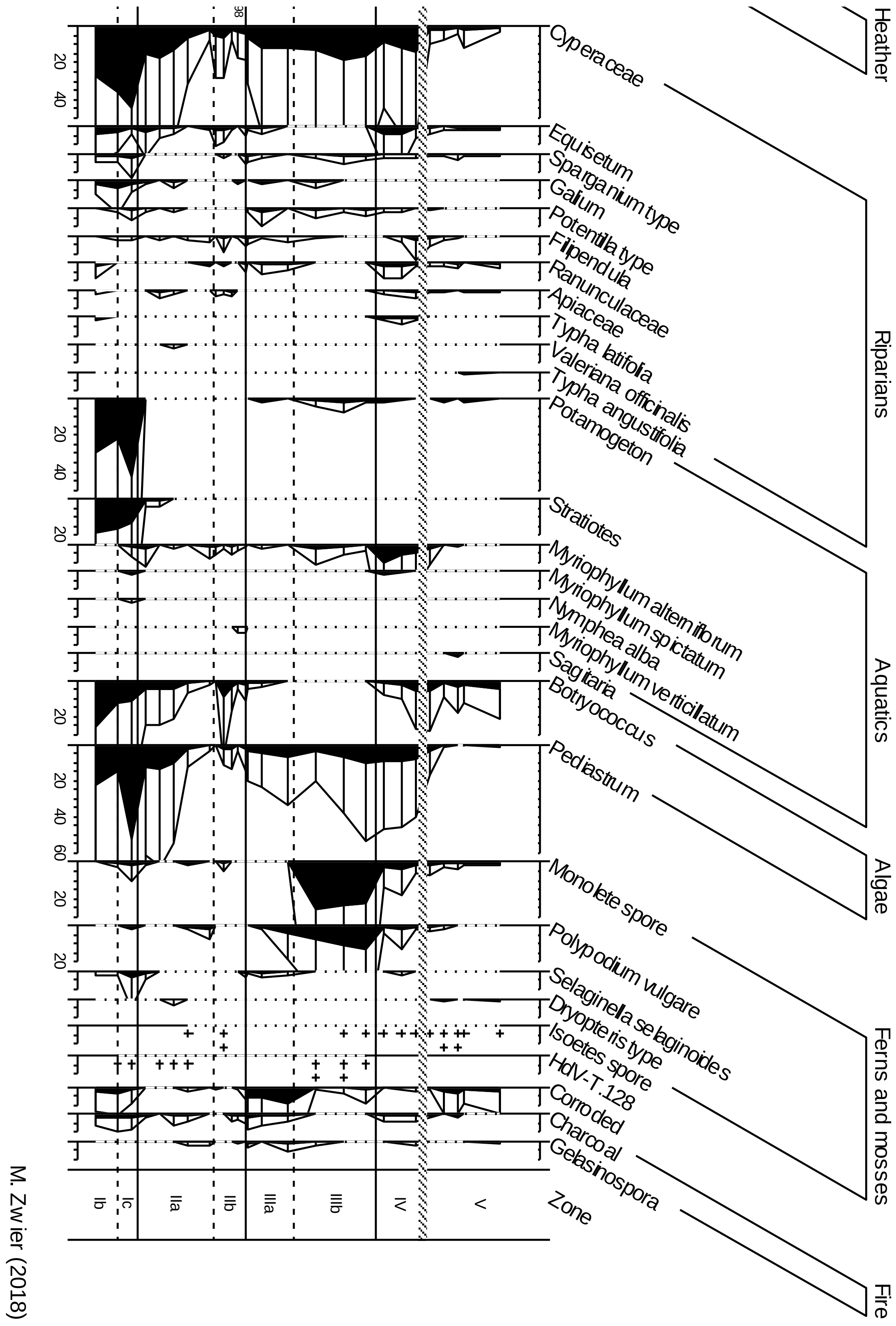
[1] In red: depths used for the pollen diagram and fitted LOI profile.

Appendix 4 Core description Elpermeer

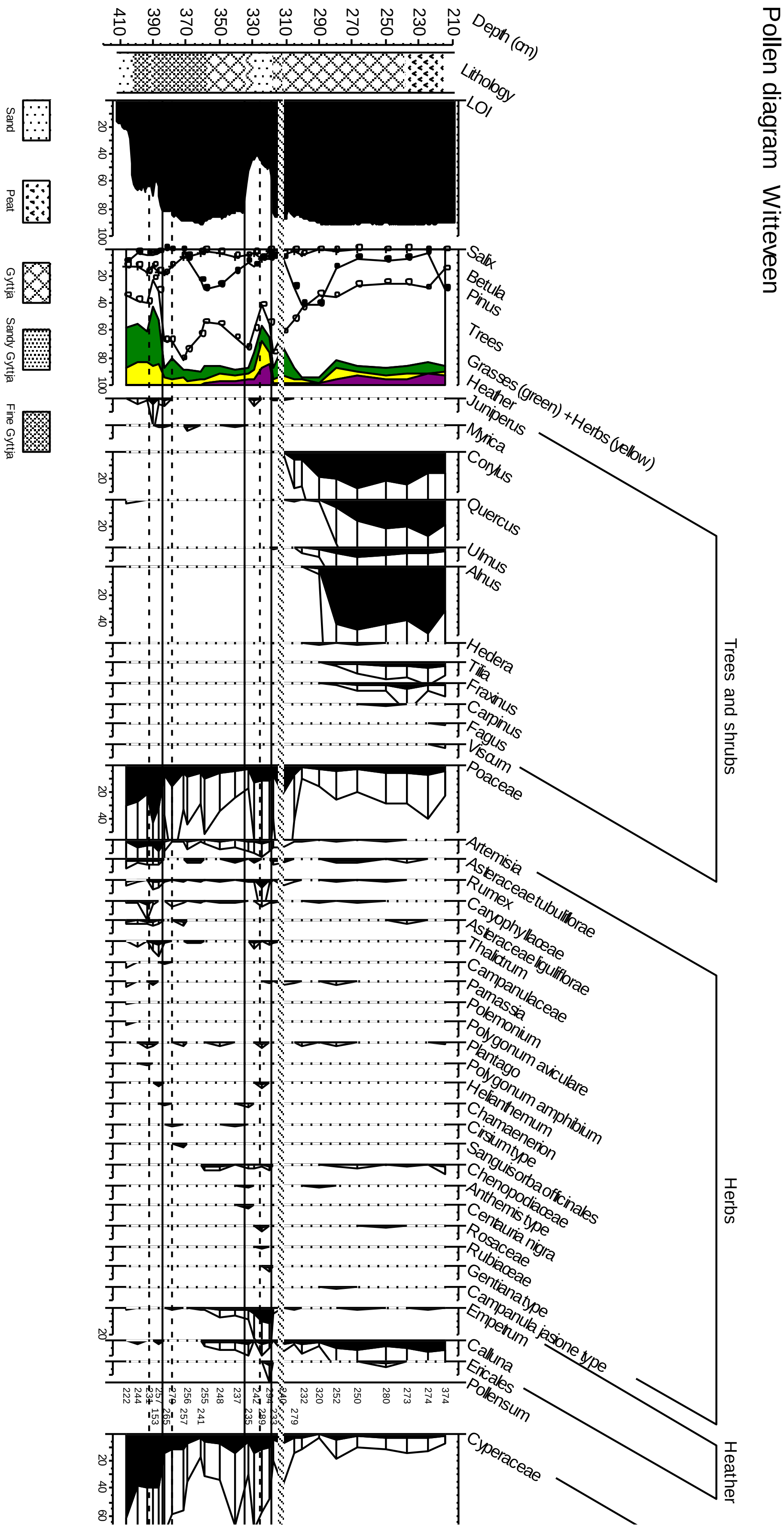
Core	Depth (cm)	Corrected depth (using LOI profile)	Description
Core I	10 – 31		Sandy peat with rootlets, dark brown with black smudges
	31 – 54.5		Peat, some rootlets, dark brown
	54,5 – 55,5		Peat, some rootlets, light brown
	55,5 – 110		Peat, some rootlets, dark brown
Core II	104 – 108	76 – 80	Mud, contamination
	108 – 126	80 – 98	Peat, some rootlets, dark brown
	126 – 138	98 – 110	Course Peat, dark brown to black
	138 – 152	110 – 124	Sandy peat, brown. Sand layer at 147 cm
	152 – 207	124 – 179	Till, small pebbles on top and larger pebbles at the bottom
	207 – 210	179 – 182	Plastic plug possibly compacted other material

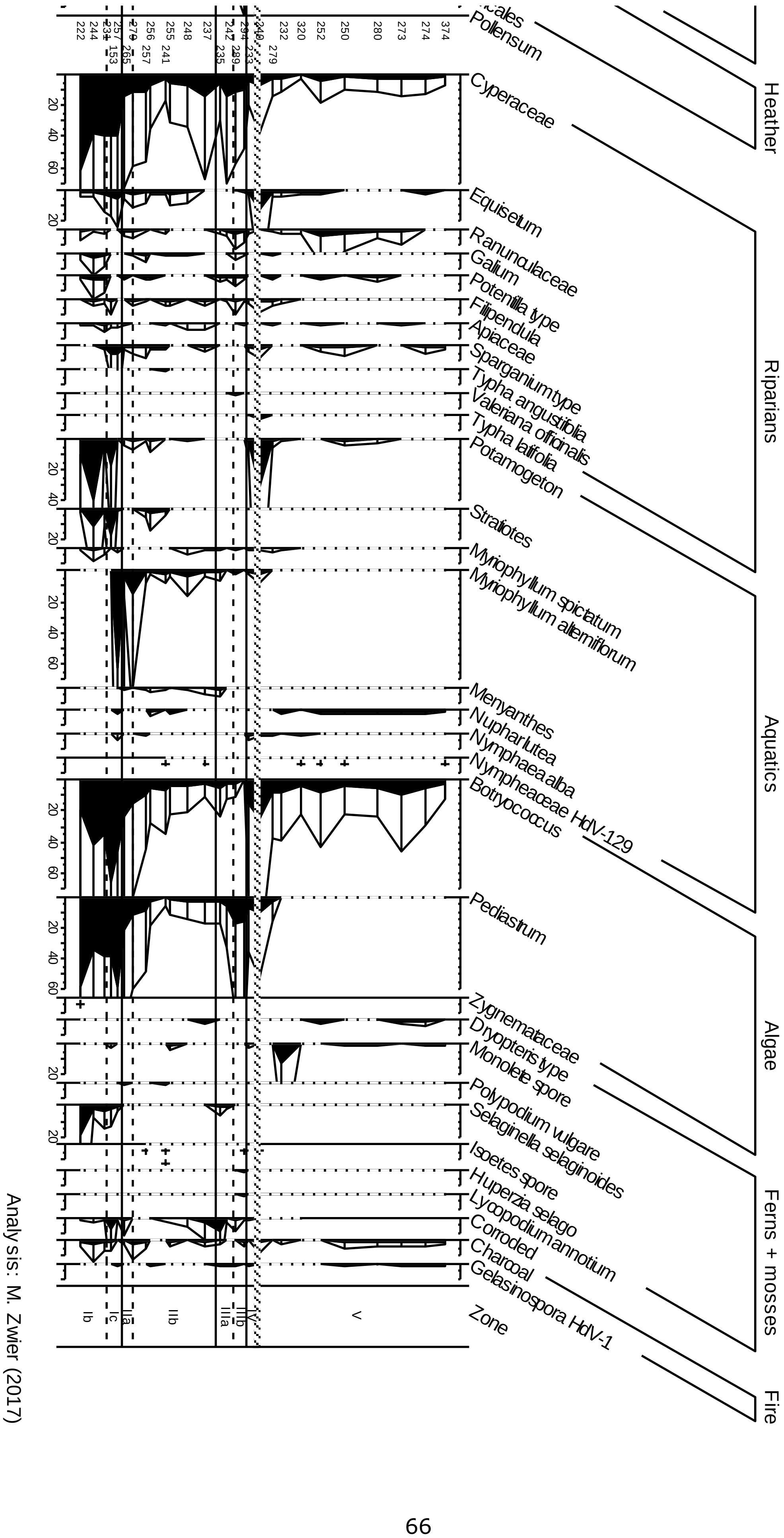
Appendix 5 Full pollen diagram Esmeer




Heather
Riparians
Aquatics
Algae
Ferns and mosses
Fire
Cyperaceae
Equisetum
Sparganium type
Galium
Potentilla type
Filipendula
Ranunculaceae
Apiaceae
Typha latifolia
Valeriana officinalis
Typha angustifolia
Potamogeton
Stratiotes
Myriophyllum alterniflorum
Myriophyllum spicatum
Nymphea alba
Myriophyllum verticillatum
Sagitaria
Botryococcus
Pediastrum
Monolete spore
Polypodium vulgare
Selaginella selaginoides
Dryopteris type
Isoetes spore
HdV-T.128
Corroded
Charcoal
Gelasinospora
Zone
Ib
Ic
IIa
IIb
IIIa
IIIb
IV
V
M. Zwier (2018)

Appendix 6 Full pollen diagram Witteveen




Pollensum
Cyperaceae
Equisetum
Ranunculaceae
Galium
Potentilla type
Filipendula
Apiaceae
Sparganium type
Typha angustifolia
Valeriana officinalis
Typha latifolia
Potamogeton
Stratiotes
Myriophyllum spicatum
Myriophyllum alterniflorum
Menyanthes
Nuphar lutea
Nymphaea alba
Nympheaceae HdV-129
Botryococcus
Pediastrum
Zygnemataceae
Dryopteris type
Monolete spore
Polypodium vulgare
Selaginella selaginoides
Isoetes spore
Huperzia selago
Lycopodium annotinum
Corroded
Charcoal
Gelasinospora HdV-1
Zone
Ib
Ic
IIa
IIb
IIIa
IIIb
IV
V
Heather
Riparians
Aquatics
Algae
Ferns + mosses
Fire
Analysis: M. Zwier (2017)

Appendix 7 Full pollen diagram Elpermeer