MSc thesis Astrid Ruiter

Relict pingos and permafrost
A comparison between active landforms in the Canadian Arctic and relict permafrost features in the Netherlands and adjacent Germany

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Photo on front page: Pingo in the Mackenzie Delta, Canada (A.S.Ruiter, 2011)

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Abstract

Pingos are periglacial landforms which currently are present in permafrost areas in Alaska, the Canadian Arctic, Greenland, Svalbard and Siberia. In permafrost areas with a continuous water supply, ice lenses can form and pingos can grow. Isolated circular and most often ramparted depressions are left behind when pingos degrade. In the Netherlands, especially the provinces Friesland, Groningen and Drenthe, hundreds of isolated circular, most often ramparted depressions are regarded as being remnants of these periglacial landforms. According to previous research, these pingos formed during the cold Weichselian Pleniglacial, when discontinuous permafrost conditions caused increasing hydraulic groundwater pressures in the partially frozen upper aquifers. During the warmer Lateglacial Interstadial, these landforms collapsed when the permafrost gradually started to thaw. For this study 17 possible pingo remnants in the Netherlands and Germany and 2 in Canada are investigated. In combination with literature, all information is combined for a pingo catalogue for the Netherlands. The spatial distribution and dimensions of these remnants show similarities with pingos in active permafrost regions. Whether or not these features are pingo remnants and to what extent these pingos have degraded as a result of climate change is important for understanding the impact of climate change on the permafrost and periglacial environment in the past, present and future.

Preface and Acknowledgements

This MSc thesis is a report of the MSc project as part of the MSc physical geography, track Quaternary Geology and Climate Change.

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1. Introduction

The development and occurrence of closed circular depressions in the Netherlands and Germany is still a point of uncertainty. Whether these depressions are pingo remnants or formed by other processes is important to know before using these depression as pingos in reconstructions of past climate conditions. More insight in the occurrence of these depressions and the sensitivity to climate change is important for understanding the response of the permafrost environment to climate change. This importance is not only restricted to past climate conditions: as the permafrost is now degrading in the high Arctic as well, understanding pingo response may help detect the impact of global warming which is an ongoing debate (pers. comm. Hans-Wolfgang Hubberten and Chris Burn). More insight in palaeoclimate reconstruction can help in understanding the process of degrading permafrost and the response of corresponding landforms (e.g. pingos) and can help to get insight in the seriousness of the contemporary permafrost degradation.

The research questions of this thesis are:

- *What is the spatial distribution of the pingo remnants in both actual and past permafrost environments?*
- *What are the constraints for the spatial distribution?*
- *When did pingo formation start?*
- *What were the palaeogeographical and climatological conditions during formation and decay?*
- *Can pingos be used as indicators for climate change?*
- *On which time-scales has climate change influenced the occurrence of permafrost and periglacial landforms in the past?*
- *Is this climate change impact comparable with the contemporary degradation of the permafrost as a result of recent global warming?*

The first chapter of this thesis, describes previous research and basic definitions and conceptions of pingos and permafrost. The second chapter describes the study area with geological background and in chapter three the methods for the field, laboratory and GIS analysis used for this study are described. In the following chapter, the results of these methods are described. This chapter is subdivided into different sections per study area and describes the results, interpretation and a short conclusion per cross-section. A complete interpretation of all cross-sections is given as well as the results of the GIS analysis. In the discussion chapter the results from this research are evaluated and comparisons with other literature is described and discussed. This thesis ends with a conclusion.

1.1 Definitions and general concepts

Actual pingos and the process and conditions forming them are extensively described by several authors, for example by Mackay (e.g. 1961, 1977, 1986, 1988 and 1998) and Pissart (1988, 2002 and 2003). It is important to understand the process of pingos growth and collapse before looking in detail to the remnants of the pingos.

1.1.1 Permafrost and the periglacial environment

Pingos occur only in areas with active permafrost. Permafrost by definition is shallow soil with a temperature at or below 0° Celcius for longer than two annual cycles (French, 2007; Mackay, 1998 and Burn, 2010). The permafrost does not necessarily have to contain moisture; the definition is based on temperature alone and not whether the soil contains ice or not. However, for the formation of pingos, soil moisture, groundwater and freezing up thereof, is essential. The definition of permafrost is classified into continuous permafrost (90 to 100 % of the surface area has permafrost excluding unfrozen areas beneath lakes and river channels), discontinuous permafrost (50 to 90 % is permafrost and most of the permafrost terrain is separated by areas of unfrozen ground), sporadic (10 to 50 % is permafrost, usually called permafrost islands, often occurring beneath organic sediments) and isolated (0 to 10 % is permafrost, similar to sporadic) (French, 2007). Depending on the area, the mean annual air temperature corresponding to areas of continuous and of discontinuous permafrost varies with respectively -9° to -12° Celcius and -1° to -10° Celcius (French, 2007).

1.1.2 Definition of a pingo

A pingo (figure 1.1) is named by the Inuit and means (growing) hill. This hill is formed by a growing ice-lens just beneath the active layer of the permafrost and can only exist in permafrost environments (Mackay, 1998). The ice-cored hill pushes the ground upward through the intrusion of pressurized water (Mackay, 1961 and 1972). Pingos can grow over 60 meters in height and 300 meters in diameter (French, 2007). The pressure of the growing ice-lens can push 1 up to 10 meter of overburden sediment, which needs to be thicker than the active layer for the pingo to persist.

Figure 1.1: Active pingo in Adventdalen, Svalbard (A.S.Ruiter, 2011)

Pingos are described in several (cold climate) places in the world. There are a lot of similarities that proof that these all are pingo (remnants). However, there are some differences as well, which can be related to the physical conditions of the area and, therefore, the process of growth. The main two different types of pingos are hydraulic (open) and hydrostatic (closed) system pingos.

1.1.3 Hydraulic (open) system pingos

Hydraulic system pingos (also known as open system pingos) are pingos which are fed by groundwater from within or beneath the permafrost layer. The permafrost layer has to be relatively thin or discontinuous to allow them to form (Müller, 1959; Watson, 1971). The process is similar to a frozen form of an artesian well. Growth occurs as long as there is a hydraulic gradient delivering water. It occurs on locations of weakly developed permafrost, where upwelling of groundwater penetrates the uppermost permafrost layer. This can be along valley sides, on valley floors or along (geological) faults (figure 1.2). This type of pingo is, therefore, most common in areas with a significant elevation difference (French, 2007; Mackay, 1998). Areas where hydraulic system pingos exist are for example Svalbard and Greenland. This type of pingo is as well named East Greenland type to where it was described first (Müller, 1959). Most hydraulic system pingos occur in areas with discontinuous permafrost (Harris & Ross, 2007). While pingos grow separately, they occur often in clusters or in a sequence of active and relict pingos (Liestøl, 1976; Ballantyne & Harris, 1994). While most hydraulic system pingos occur in areas with topographical relief, the pingo system can also occur in plain areas with a water source of seepage or abundant water supply, for example from nearby glaciers (Flemal, 1976; De Gans, 1988; Etzelmüller & Hagen, 2005).

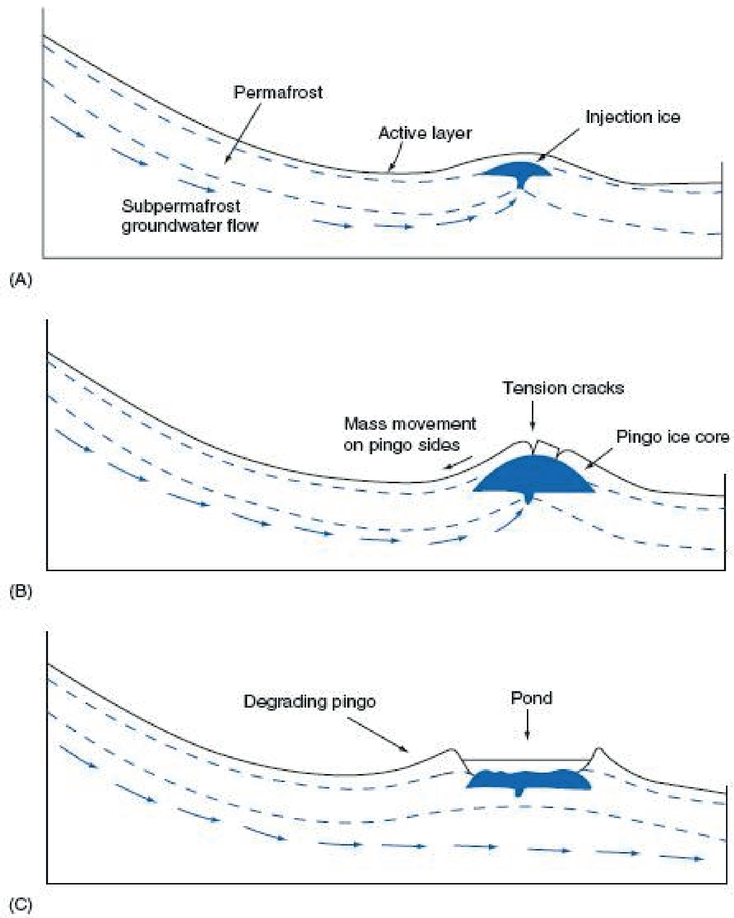

Figure 1.2: Formation of hydraulic system pingos (Ballantyne & Harris, 1994)

1.1.4 Hydrostatic (closed) system pingos

Hydrostatic system pingos (closed system pingos) are pingos which occur in areas with continuous permafrost. These pingos develop under the bottoms of small and shallow (thermokarst) lakes (Mackay, 1988; French, 2007) or at locations of old frozen-up lake floors (Pissart, 1988; Burn, 2010; Mackay, 1988). Among the conditions in which hydrostatic system pingos can easily form (French, 2007) are thick permafrost, coarse-grained sediment and a substantial number of drained (thermokarst) lakes. The growth of a hydrostatic pingo starts after sudden lake drainage, which causes permafrost aggradation. A talik, unfrozen saturated sediment, sandwiched between frozen topsoil and impermeable (frozen) substrate, is left behind if the lake drains.

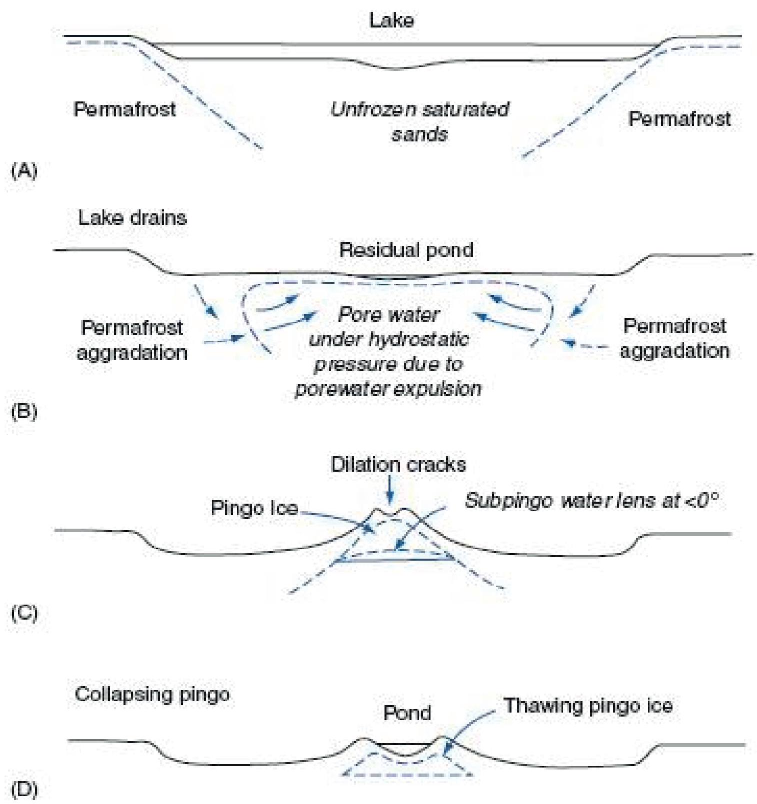

Figure 1.3: Formation of hydrostatic system pingos (Mackay, 1988)

This talik starts to freeze from above when there is no water to shield it from the cold winter air. A thin permafrost layer at the top of the unfrozen lake bottom causes pore water pressure. This abundance of water freezes slowly from all sides and can form an ice lens. The ice lens then grows further by segregation of pore water under hydrostatic pressure (Mackay, 1988; Mackay, 1998; French, 2007). When ice lens growth is large enough, it can push the frozen ground up and a pingo results (figure 1.3). In contrast to artesian pressure of hydraulic system pingos, hydrostatic system pingos form through cryostatic pressure (Washburn, 1973). Hydrostatic pingos occur mostly in plain areas with an abundance of water. This type of pingo system occurs widespread along the arctic coast of Canada on the Tuktoyaktuk Peninsula and in the Mackenzie River Delta, and are therefore also known as Mackenzie-type pingos (Mackay, 1988).

1.1.5 Pingo collapse

While there is a large difference between hydraulic and hydrostatic pingos as regarding to genesis and location, the basic process of growth and especially collapse is similar for both types (Mackay, 1987). The decay-sequence starts with the formation of faults and ruptures. The overburden sediment opens due to the continuous growing of the pingo and therefore thinning of the upper sediment layer (De Gans, 1988) (also called 'Pingo skin '(Watson, 1971; De Gans, 1982)). This mechanical collapse can occur in any environment, and may have nothing to do with climate change or degradation of permafrost. It is an internal mechanism that causes the pingo to collapse if it becomes too large for its sediment cover to protect the entire ice lens from solar radiation (Mackay, 1987). The ruptures and faults in the pingo skin expose the inner ice-lens to solar radiation, which causes it to melt. The process launches a positive feedback, because the melting exposes more of the ice-lens to the sun. Eventually, this causes the pingo to collapse. The mechanical collapse of pingos can occur relatively fast if the pingo has steep slopes: in decades to centuries. However, commonly the complete collapse of a pingo can take many centuries and occurs in various stadia (Mackay, 1988). The decay of pingos in areas of degrading permafrost is a little different. Even though the phenomenon of rupturing is similar to mechanical collapse, the exposure to solar radiation is now not the only source of melting. Degradation of the permafrost causes an abundance of melt water, which flows through the ruptures and other outlets. The ice-lens will then melt from the inside as well as from the outside. If the degradation of the permafrost occurs fast, persists and finally the permafrost degrades completely, the pingo will just collapse vertically and little to no topographic evidence in the form of a rampart of the pingo will remain (Mackay, 1988). Most commonly, however, the collapse of a pingo reverses the relief and forms a depression of some meters deep, often filled with water, and a peripheral ridge (Flemal, 1976) as can be found in the Netherlands and Germany. The depression gradually fills with organic autochthonous lake sediments, when enough time is available and hydrological conditions permit so. In the lowermost part of the pingo remnant, the first organic sediments may be dated to get an age estimation for the collapse of the pingo. However, on top of a (degrading) pingo, vegetation can already develop (figure 1.4). Due to preferential (katabatic) winds, the vegetation growth on the pingo can become patchy. These winds can also erode parts of the rampart and may enhance the collapse of the pingo (Mackay & Burn, 2011 in prep) and filling of the depressions. Remnants of willow leaves are found in pingo remnant lakes in the Mackenzie Delta (Burn & Koklej, 2009) and remnants of Betula Nana at the bottom of a pingo remnant the Netherlands (pers. comm. Wim Hoek).

Figure 1.4: Collapsed pingo with ice wedges in the depression, Canada (A.S.Ruiter, 2011)

1.2 Types of pingos in the Netherlands

The discussion to which of the types the Dutch pingos belong (i.e. hydraulic system vs. hydrostatic systems) has changed through time. At first, the pingos remnants were interpreted as former open-system pingos (Flemal, 1976; Müller, 1959). After that, it was thought that the pingo remnants were rather former closed system pingos than open system pingos (De Gans, 1982). This was concluded from the fact that most pingo remnants where found on top of an impermeable clay layer (fluvio-periglacial deposits) (Bijlsma & de Lange, 1983) and therefore there was no continuous supply of water available (Ballantyne & Harris, 1994). Nowadays, the general opinion is back to the first hypothesis, meaning that the pingo remnants in the Netherlands derived from hydraulic system pingos (De Gans, 1988). This is because the open-system pingos can be found in discontinuous permafrost. This seems to be the most logical situation in the Netherlands as otherwise, when this area would have been a continuous permafrost region, evidence of discontinuous permafrost should have been found south of the Netherlands (Mackay, 1972). Furthermore, the presence of calcareous gyttja deposits in several pingo remnants can only be explained by continiuous carbonate rich ground water seepage after decay of the pingos. But up to now, nothing has been found that could be evidence for permafrost more south than the lithalsas (small pingo-like features in peaty areas) found in the Hautes Fagnes Plateau in Belgium (Pissart, 2002; Pissart, 2003).

1.3 Depressions in Northwest Germany

As the discussion in the Netherlands is about the type of pingo origin, in Germany, the discussion is whether these similar depressions are pingo remnants or not. On the geomorphological map of Husum in north Germany, some depressions are classified as being pingo relicts (Barsch et al, 1979). Garleff (1968) described and mapped many depressions in the Lower Saxon lowlands (North-Western part of Germany) of which only a few are indicated as being pingo remnants. Most of the depressions in Germany are interpreted as being either aeolic depressions (Garleff, 1968; Czudek & Demek, 1971), caused by subrosion (karst) (Garleff, 1968), thermokarst or depressions caused by the melt of remnants of glacier ice in glacial till sediments (pers. comm. Hans-Wolfgang Hubberten).

1.4 Palaeoenvironmental conditions

As stated before, pingo remnants are evidence of former permafrost environments (Gurney, 1998; Mackay, 1998; De Gans, 1988). Pingo remnants in the northern part of the Netherlands are up to 20 meters deep (De Gans & Sohl, 1981; Heiri et al., 2007), while the pingo remnants in the southern part are only a few meters, 3 to 5, meters deep (Kasse & Bohncke, 1992; Hoek & Joosten, 1995). The depth of the pingo remnants may be an indication of the minimum thickness of the former permafrost (Hoek & Bohncke, 2002). From this it is inferred that the thickness of the former permafrost gradually thins from north to south in the Netherlands. For example according to De Gans & Sohl (1981) at the Hijkermeer pingo remnant, the minimum depth of the permafrost layer is 17 meters, which is the depth of the pingo remnant. An infilling of about 2 meters points to a minimum thickness of the active layer of 2 meters. In the Southern Netherlands, there are some pingo remnants near Weert in the province of Limburg. These pingo remnants are only 3 - 5 meters deep, which indicates a minimum depth of the permafrost of about a few meters as well (Hoek & Joosten, 1995; Van Asch et al., 2012). It must be noted, however, that these values are only reasonable during the growth period of these pingos.

From the presence of pingo remnants, and therefore permafrost, temperature reconstructions have been made. The mean annual air temperature (MAAT) is most commonly used as the most important climate variable (Huijzer & Isarin, 1997). The thickness and existence of discontinuous permafrost points to a MAAT just below 0°C, commonly between -1°C and -5°C (Washburn, 1973; Williams & Smith, 1989; Hubberten et al, 2004). Both De Gans (1988) and Mackay (1998) have defined some criteria for present-day circular depressions to be a pingo remnant. De Gans (1988) defined five main criteria: (1) The minimum depth of the depression must be 1,5 meter and minimum diameter 25 meter. (2) The bottom of the depression must be at a lower level than the surrounding ground. (3) At least a part of the rampart is present and consists of sediment derived from the depression, often as outward-dipping strata. (4) Pingo remnants mostly occur on a small slope (max 5°) and (5) are accompanied by other permafrost phenomena. Mackay (1998) has defined some additional criteria specified for the rampart: (1) The volume of the rampart must correspond approximately with the volume of the depression. (2) Remains of dilation cracks and (3) normal faults can be found across the ramparts. The peripheral deposits are associated with mass movements and erosion processes.

1.5 Climate reconstruction

The Quaternary is defined as the last 2,6 million years (Gibbard et al, 2007) and characterized by a rapidly changing climate. During the entire Quaternary history, more than 30 glaciations and interglaciations occurred (De Mulder et al, 2003).

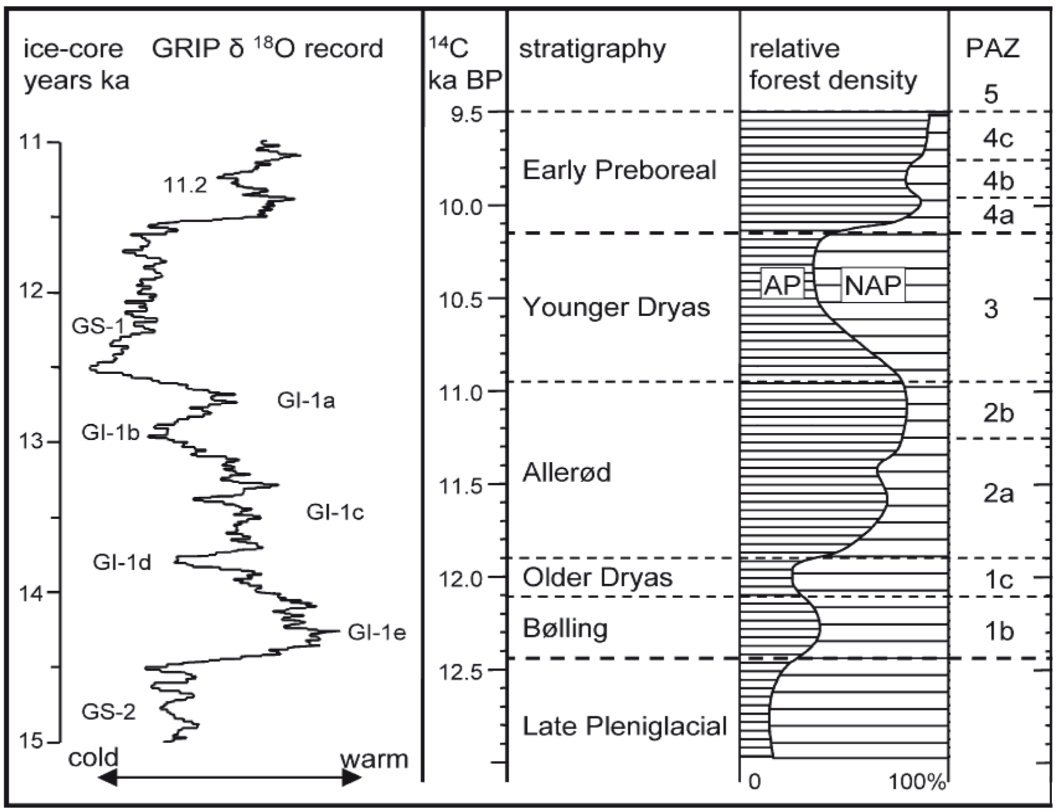

Figure 1.5: Climate and vegetation evolution since the Late Glacial (Kasse et al, 2005). GRIP oxygen isotope record and event stratigraphy after Björk et al, (1998) and stratigraphy, relative forest density and pollen assemblage zones (PAZ) after Hoek (1997)

This thesis only focuses on the last part of the Quaternary history, the last 130,000 years. The second last glaciation, the Saalian, has reshaped the subsurface of the Netherlands and Germany. The hills in the middle of the Netherlands are formed by forces of Scandinavian Ice sheet. North of this maximum extent of this ice sheet, glacial deposits are widespread deposited in the subsurface (see section 2.2). The last Interglaciation, the Eemian lasted from around 126,000 to 115,000 years before present (Lowe & Walker, 1997). After that warm period, the Weichselian Ice Age dominated this area. The last glacial period, the Weichselian, is characterized by a variety of warmer and colder periods, stadials and interstadials (Lowe & Walker, 1997) (figure 1.5).

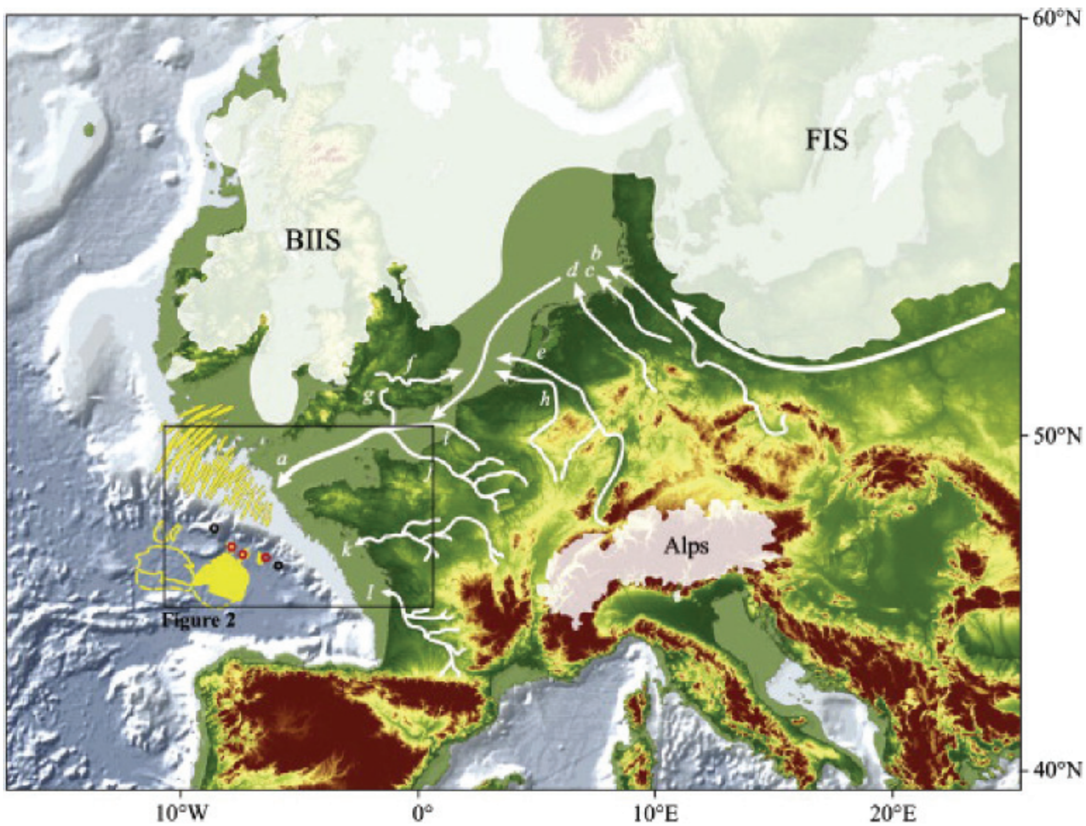

Figure 1.6: Maximum ice extent for Lateglacial maximum (Ehlers and Gibbard, 2004)

The coldest stage of the Weichselian period, the Last Glacial Maximum (LGM), ended around *15,000* calender years before present. The maximum ice extent of the Scandinavain Ice Sheet, which was reached during the LGM, has been as far south as Denmark (figure 1.6). The Netherlands and Northwestern Germany where both unglaciated but a cold periglacial climate characterized this landscape. Which means that this area was sparsely vegetated, and therefor a cold, dry and windy area with the presence of permafrost and the formation of associated landforms such as pingos. After the LGM in the Pleniglacial, the climate gradually warmed in different steps. During the Bølling interstadial, a very short warmer period between 12.5 and 12.1 ^{14}C ka Before Present, a small increase in forest density has been reconstructed (Hoek, 1997). A very small cold period, the Older Dryas, marks the transition to the Allerød interstadial. Because the Older Dryas was very short and not widely recognizable, this interstadial is mostly seen as one interstadial, the Bølling/Allerød interstadial. One last cold period occured before the Holocene started, the Younger Dryas. During this period, northwest Europe was dominated by tundra vegetation and the forest density decreased again. The Younger Dryas ended very rapidly with the warm climate of the Holocene. The Early Preboreal is the first period of the Holocene in which the forest density increased and warmer climate vegetation started to grow.

Permafrost and climate reconstruction is possible in the Netherlands because of the special conditions in the Netherlands according to climate and hydrology. Because the Netherlands is located at a transition point. If the sea level is high, the Netherlands has a marine climate. In contrast to the situation during a glacial, where the sea level is low, the coastline is located far away and the Netherlands is dominated by continental climate conditions. This is a reason why the climate changes and therefore vegetation transitions are very well expressed in organic depositions in the Netherlands. The lack of this transition situation in Germany and Poland can be the reason why there are less climate and time reconstructions available for these regions. Even though these regions where characterized by a periglacial climate as well as the Netherlands during the last glacial.

1.6 Past hydrology

The past hydraulic situation is dependent on several conditions: climatological, cryological, topographical and geological differences. The climatological differences define the entire setting as well as the sea level elevation. Event though the sea level was around 100 meter lower during the Last Glacial, this does not mean that the ground water was 100 meter lower. The ground water elevation has been reconstructed using a calculation for hydraulic head, based on basic physical components and an estimation for discharge by the mean annual precipitation surplus (De Vries, 1974). The results of these calculations are shown in figure 1.7.

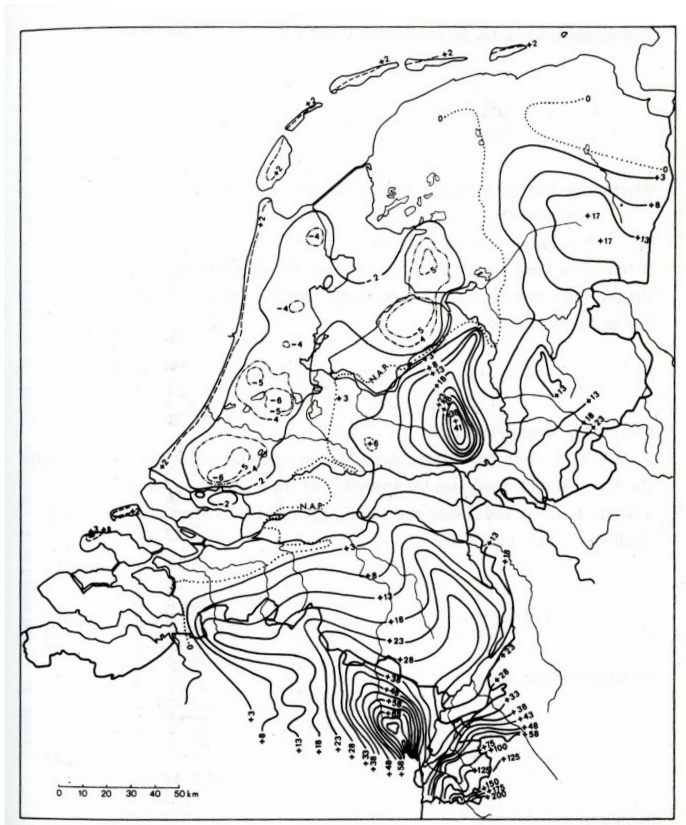

Figure 1.7: Contour map of the average hydraulic head of the Pleistocene aquifer relative to NAP (De Vries, 1974)

The groundwater table was near the topographical surface (less then 1 meter below ground surface) for the Pleistocene area, with an exception of the ice-pushed ridges, which was a several tenths of meters lower (De Vries, 1974). Related to the climatological factors, the cryological situation has been different during the Last Glacial. The temperature determines if the precipitation falls in liquid of solid state, and therefore the drainage. However, the cryology have had most effect on the hydrology because of the presence of permafrost or not. Permafrost causes the occurence of an impermeable layer in the subsurface and a bifurcation of the groundwater flow. A kind of through flow is possible in the active layer above the permafrost and in the deep subsurface, below the permafrost. This differential ground water flow has caused the development of small river valleys during the last glacial (De Vries, 1974).

The topography of the Netherlands has changed as well since the Last Glacial. In figure 1.6, the situation during the Last Glacial Maximum is shown. In this figure, the location of the ice sheets and shoreline is shown. The Netherlands is located in the North Sea Basin and dominated by the deposits of the Rhine-Meuse river systems (Busschers et al., 2007). The pressure of the Scandinavian Ice Sheet has caused a isostatic adjustment, which means that Fennoscandia was pushed downwards and the surrounding of the ice sheet became uplifted, the forebulge effect (Vink et al., 2007). The maximum uplift area was situated in the Netherlands. The presence of the forebulge has changed the hydrology on a large scale, and may have caused a increase groundwater pressure.

2. Study area

This study is a combination of actuo processes and palaeo reconstructions. Therefore, the fieldwork consisted of two different parts. For the actuo processes, the study area is located in the Mackenzie Delta, Canada. The paleo reconstruction study will be in the Northern part of the Netherlands and adjacent Germany.

2.1 The Mackenzie Delta, Northwest Territories, Canada.

The Mackenzie Delta is the largest Arctic delta of North America, located in the Northwest Territories, northernmost Canada and ending in the Beaufort Sea (figure 2.1). It is characterized by widespread continuous permafrost and corresponding landforms, with large areas covered by polygons and the world's largest population of pingos (Burn, 2010). This area is characterized by a high arctic climate, which has very low winter temperatures (-20 to -30°C) and a low amount of precipitation (French, 2007). In the Tuktoyaktuk Peninsula, where most pingos are located, the mean annual air temperature is around -7,3°C and the total annual precipitation is only 151 mm (Burn, 2010).

During the last glacial maximum, the Mackenzie river drained eastwards into the Atlantic Ocean. During that period, the entire contemporary Mackenzie Delta area was covered by the Laurentide Ice Sheet (Lemmen et al, 1994; Duk-Rodkin & Lemmen, 2000; Murton, 2009). During deglaciation, the outermost part of the Mackenzie Delta was covered by a proglacial lake, holding clamps between the Mackenzie Mountains at the western side and the ice sheet (Lemmen et al, 1994). The Mackenzie Delta has been a large sedimentary basin (at the northernmost extent of the Western Canada Sedimentary Basin) since then, and still receives mega-tons of mainly silty sediments each year (Burn & Kokelj, 2009). After deglaciation sea-level rise caused submerging of large parts of the outer delta and development of permafrost. Some parts of this outermost part of the delta have been unglaciated for more than 100.000 years and at these places (while nowadays submerged) the permafrost exceed more than 500 m in depth (Smith, 1976; Burn, 2010). However, most of the

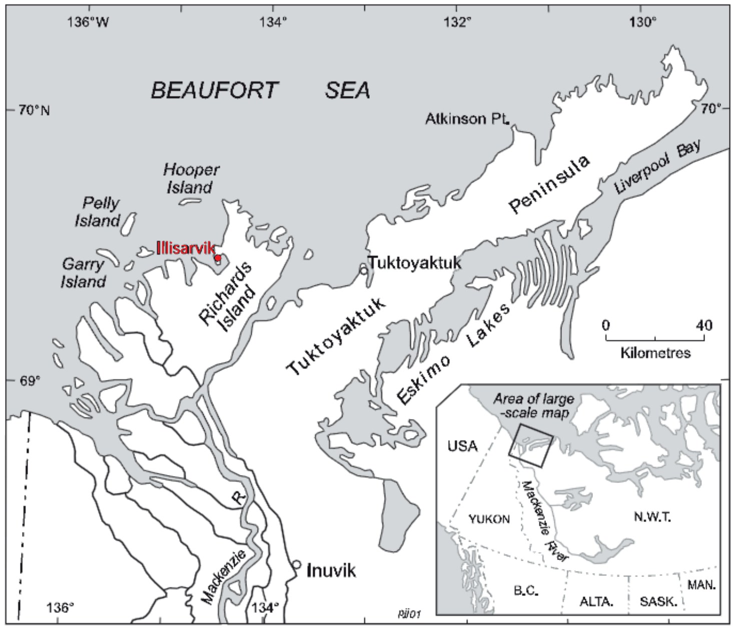

Figure 2.1: Topographical setting of the Mackenzie Delta (Mackay and Burn, 2002)

delta area has a permafrost depth of less than 100 m, with an exception of the lakes and river channels, where the water never freezes up to the bottom (Smith, 1976). Permafrost can start to form if river avulsions or lake drainages occur. The area is covered by thousands of lakes and around one to two lakes in the Mackenzie Delta drain each year by coastal or river erosion (Burn, 2010). This leads to the development of permafrost and pingos (section 2.2.2). In August 1978, the Illisarvik lake has been drained artificially to know the exact starting point of the development of the permafrost. Since then, the development of the depth of the permafrost, growth of ice-wedges, patterned ground and pingos has been monitored every year (Mackay & Burn, 2002).

2.2 The northern Netherlands and adjacent Germany

The northern part of the Netherlands and Germany experienced different glaciations with different extends towards the south (Berendsen & Stouthamer, 2001; Pierik, 2010). During the Saalien Glacial Period, the Scandinavian Ice Sheet has left a layer of glacial till in large parts of the area (figure 2.2). At the Drenthe Plateau (area 2 in figure 2.2) many authors have described the occurrence of pingo remnants (e.g. Maarleveld & Van der Toorn, 1955; De Gans & Sohl, 1981; De Gans, 1982; Bijlsma & De Lange, 1983). Besides glacial till sediments, large parts of the area are covered by (aeolian) sand and marine deposits, and in the northernmost part peat covers large parts of the surface (Zagwijn, 1985; Berendsen & Stouthamer, 2001; De Mulder et al, 2003). Also in these areas, several of pingo remnants have been described (Paris et al., 1979; Kluiving & Verbers, 2007). The exact distribution of the surface sediments can be found on geological maps (Zagwijn & Van Staalduinen, 1975; Bosch, 1990) and in publications of the geological survey of the Netherlands (TNO; Weerts et al., 2000).

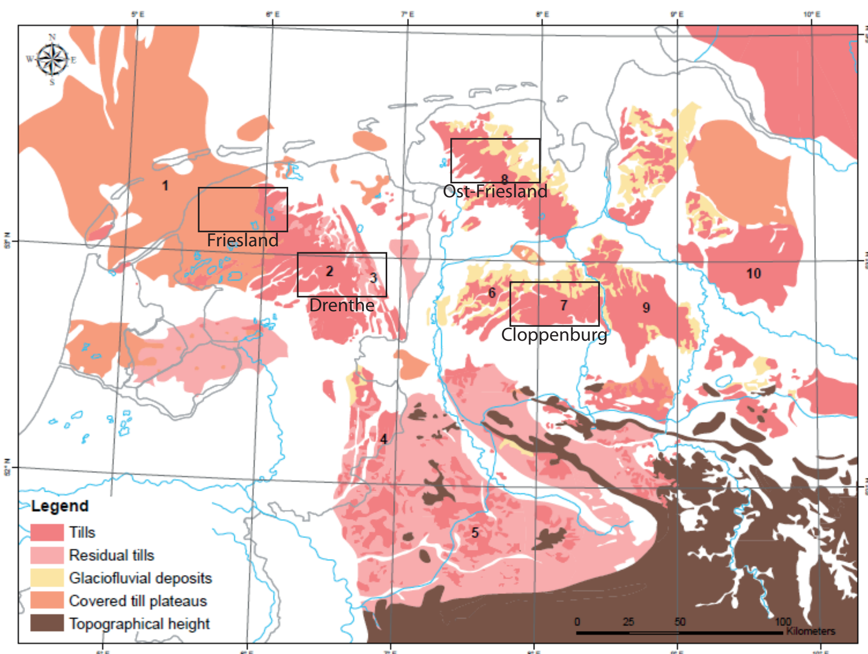

Figure 2.2: The distribution of glacial deposits; 1. North Sea till plateau, 2. Drenthe till plateau, 3. Hondsrug, 4. Twente-Achterhoek till plateau, 5. Mnsterland till plateau, 6. Hmmling, 7. Cloppenburg Geest, 8. Ost-friesland, 9. Syke Geest, 10. Lneburger heide (Pierik, 2010).

2.2.1 Friesland area, The Netherlands

Fieldwork has been carried out in four different regions, shown in figure 2.2. The first field data are from the Friesland area. During this fieldwork period three different depressions have been investigated; Egypte, Laarzenpad and Opende.

The geology of the Friesland area is shown in figure 2.3 (after TNO). In this figure all studied pingos are plotted to get an indication in which geological settings these pingos are situated. Most researched pingos are clusered around the town of Buitenpost, on which is zoomed into to get a better view. As can be seen on this map, all pingo ruins are located in two different geological units. The first of these units is (1) ground moraine with sand coverage, of Pleistocene age (Dutch: *Dr2: Grondmorene met een zanddek; Laagpakket van Gieten met een dek van formatie van Boxtel, laagpakket van Wierden*). The other unit is (2) coversand, of Pleistocene (Dutch: *Bx5: Dekzand; Formatie van Boxtel, laagpakket van Wierden*). The geology of Friesland is further characterized by Holocene marine influences, which are the green colours. In these areas no pingo renmants can occur and all glacial deposits are eroded or covered with Marine sediments.

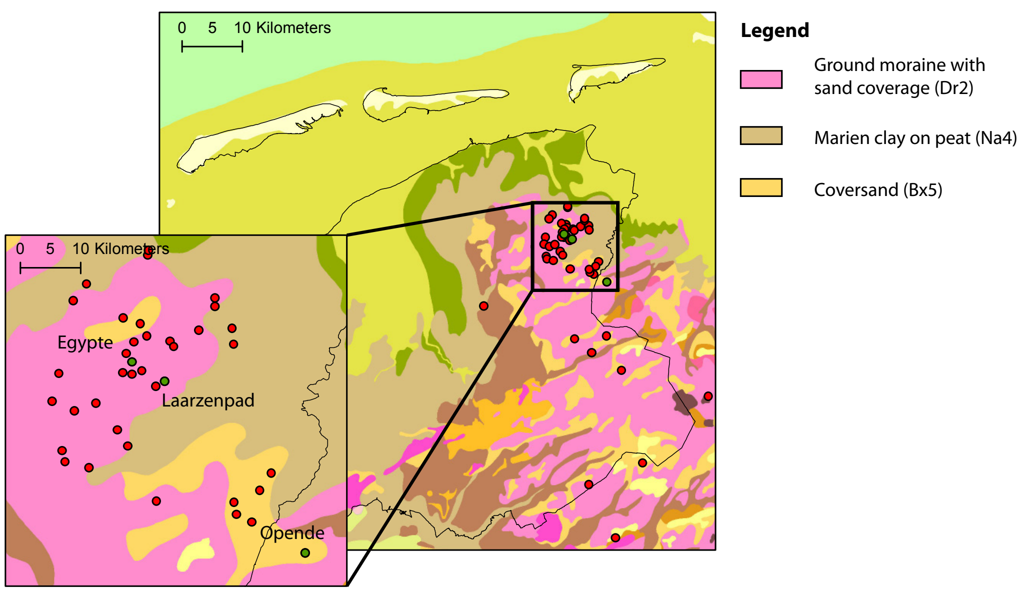

Figure 2.3: Geology of Friesland

The depressions are also plotted on the geomorphological map (Alterra) in figure 2.4. On this map, most of the depressions coincide with the depressions indicated on the map as depressions with or without rampart, which are shown in this figure as blue circles. The location of these depressions and the circular depressions of the literature are located in the ground moraine area, also shown on the geological map. The depressions occur often in clusters and at the head of cuurently dry valleys.

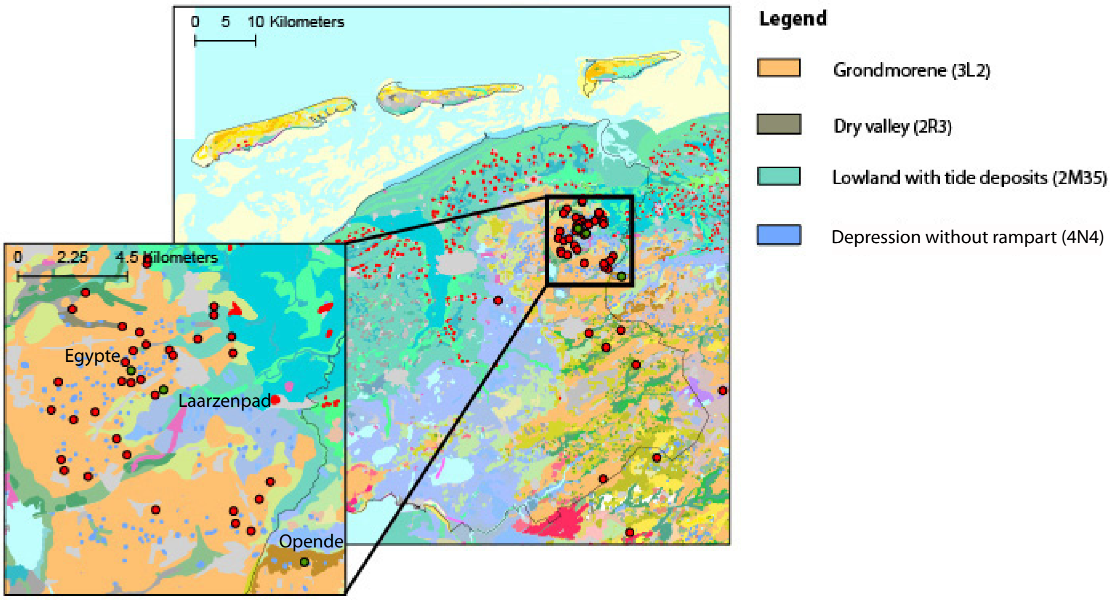

Figure 2.4: Geomorphology of Friesland

2.2.2 Drenthe area, The Netherlands

The second field region is the south western part of Drenthe. In this area similar research about these depressions has been carried out before. In this area four depressions have been investigated, Vlierendijk, Sleenerstroom I and II and Lammeer, of which only the first two in detail.

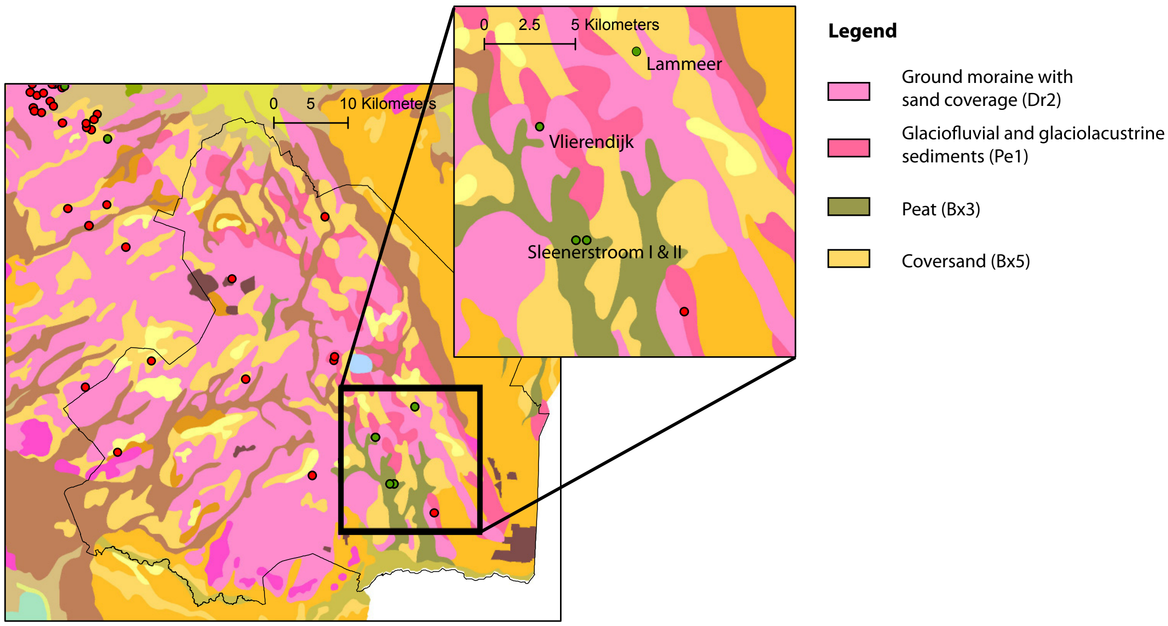

Figure 2.5: Geology of Drenthe

In the Drenthe area, the pingo remnants are much more spread over the entire area, which can be seen on the geological map (figure 2.5 (TNO)). However, most of the pingo depressions are located in the same geological units as in the Friesland area, ground moraine or coversand. More different geological units are present in the Drenthe area compare to Friesland. (1) Ground moraine with sand coverage, of Pleistocene age (Dr2: Grondmorene met een zanddek; Laagpakket van Gieten met een dek van formatie van Boxtel, laagpakket van Wierden), (2) Coversand, of Pleistocene (Bx5: Dekzand; Formatie van Boxtel, laagpakket van Wierden) (3) Peat, of Pleistocene age (Bx3: Veen; Formatie van Boxtel, laagpakket van Singraven) (4) Glaciofluvial and glaciolacustrine sediments of Pleistocene age (Pe1: Glaciofluviale afzettingen (grof tot fijn zand) en glaciolacustrine afzettingen (zwak siltige klei, potklei); Formation van Peelo). (5) Peat, of Holocene age (Ni1: Veen; Formatie van

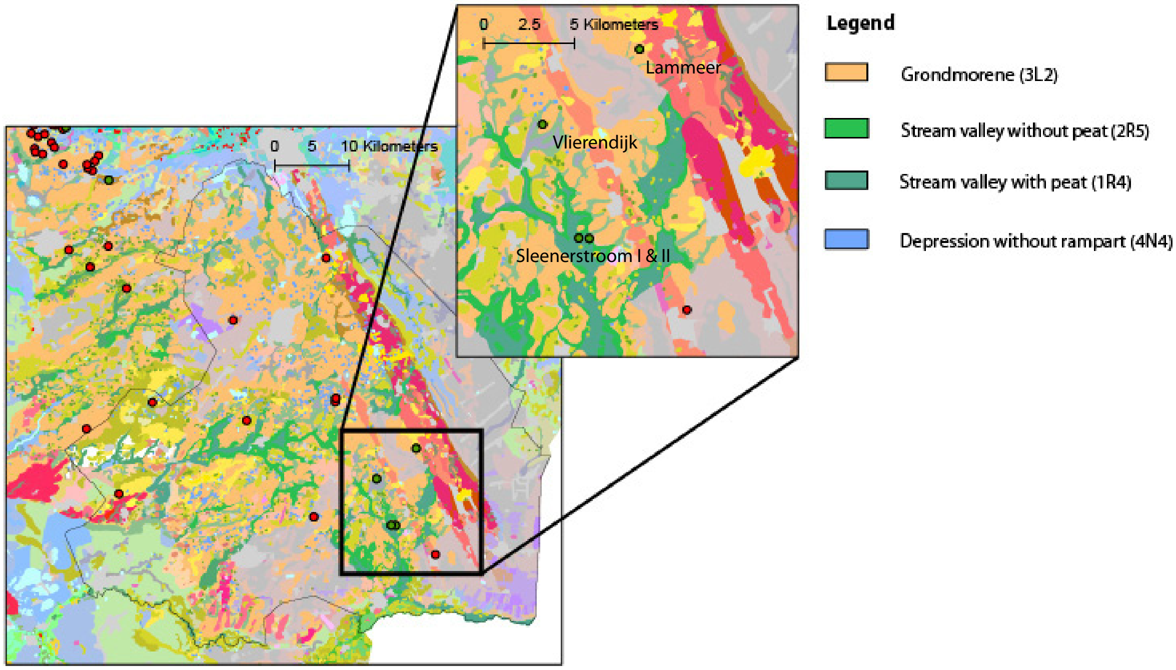

Figure 2.6: Geomorphology of Drenthe

Nieuwkoop).

The geomorphology of the Drenthe area is more complex than in the Friesland area (figure 2.6 (Alterra)). The red structure traverse the entire Drenthe area is the *Hondsrug*, presumably originating from previous ice advances, in which the maximum extent of the ice was up till half of the Netherlands. The Drenthe area is also dominated by ground moraine deposits with some stream valleys (Dutch: *Broekdalen*) intersect this plateau. Many of the pingo remnants, studied or indicated by a blue circle, are located in clusters at the head of these stream valleys.

2.2.3 Ost-Friesland area, Germany

The third fieldwork region is Ost-Friesland, Germany. The geological map is shown in figure 2.7 (Hinze et al., 1981).

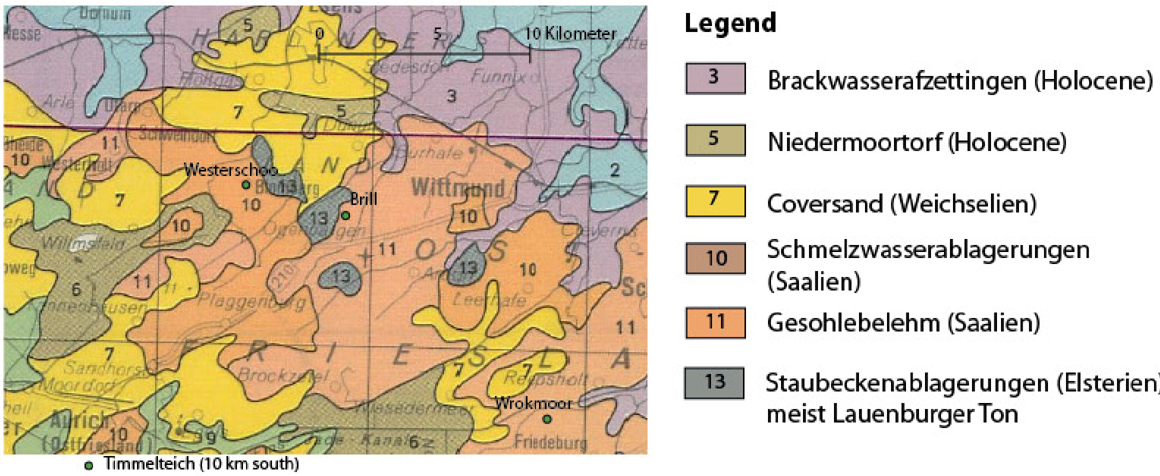

Figure 2.7: Geology of the Ost-Friesland area

In this area five depressions have been investigated; Timmelteich, Westerschoo, Brill, Wrokmoor and Mamburg. With an exception of Westerschoo all depressions are described in detail. All depressions are located in the Saalien and Weichselien deposits (described in section 2.2.2). This area is different from Cloppenburg area because of the marine influence. This marks the northern border of the occurrence of pingo depressions.

2.2.4 Cloppenburg area, Germany

The last field region is the area around the towns Emstek and Cloppenburg, around 50 km southwest of Bremen. The geological map (figure 2.8) shows the surface geology of this area (Hinze et al., 1981).

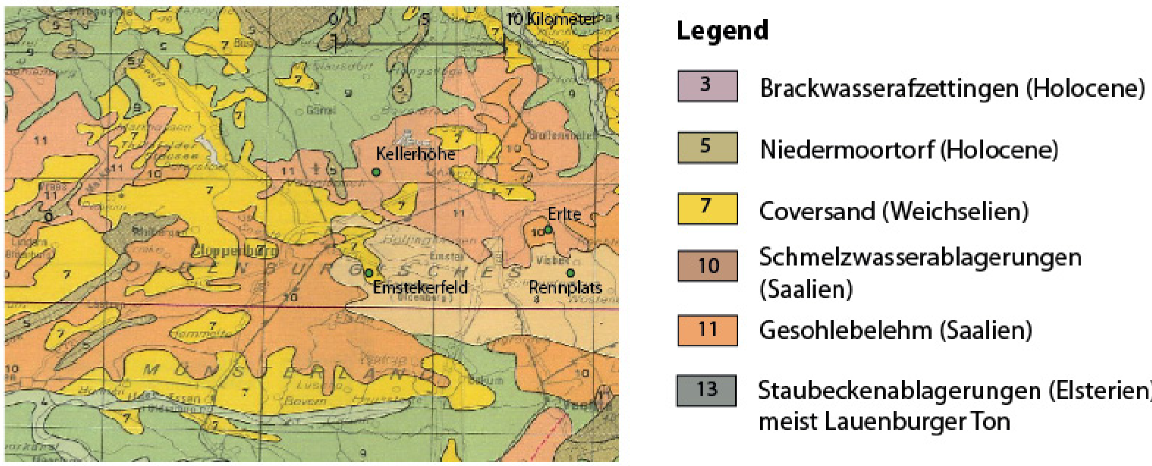

Figure 2.8: Geology of the Cloppenburg area

During the fieldwork in the Cloppenburg area several depressions were described shortly and only the Emstekerfeld depression has been investigated in detail. The area around Cloppenburg is dominated by Saalien glacial depositions; meltwater deposits (German: *Schmelzwasserablagerungen*) and glacial till (German: *Gesohlebelehm*). Coversand (German: *Flügsand und Dünen*) from Weichselien age is also widely present in this area. These geological units are similar to the units in the Dutch study areas. Some younger (Holocene peat) and older (depostits from Elsterien, German; *Lauenburger Ton*) are present in this area, but do not have any relation with pingo occurance. The Lauenburger Ton can also be found in the deeper subsurface, below the coversand and glacial deposits. In the Netherlands, this geological unit is comparable with the Peelo formation, an impermeable but highly varying glacial deposit from Elsterien age.

3. Methods

3.1 Field analyses

Two different field analyses are carried out for this study, one in the Mackenzie Delta, Canada, and one in the Netherlands and adjacent Germany.

3.1.1 Field analysis in the Mackenzie Delta, Canada

The fieldwork in the Mackenzie Delta (section 3.1) consisted mainly of gaining information about the formation and degradation of pingos. The focus was on the different stages of degradation and their infill and rampart formation. Different pingos were visited to have a close look at the denudation cracks and their relation to frost cracks, their scale and morphology, vegetation cover and location according to water bodies in the surrounding. The topography of two developing pingos have been measured. Those two pingos have been formed after drainage of the lake Illisarvik (see section 2.1).

Figure 3.1: Altimeter used for elevation profile of both pingos at Illisarvik, Canada

An altimeter has been used to measure the exact elevation at every meter, along a cross-transect over both pingos. The width of the denudation cracks at the oldest pingo, the Alak pingo, has been measured between two benchmarks. Those benchmarks are cored at both sides of the crack into the permafrost in the pingos, a few years ago. Since then, the distance between the benchmarks is measured a few times annually. The height and angle of the benchmarks is measured as well, to check if the benchmarks are still penetrating deep enough into the permafrost. Besides measurements of the hight of the two pingos in the Illisarvik area, a several more pingos are investigated in their appearance. There has been looked at the vegetation, location with respect to the landscape and the occurance of water. The study of pingos in different stages of degradation shows the development of the pingos after degradation, and the influence of climate change or not. The effect of the presence of vegetation on the stability of the pingo and the occurence of frost cracks and other periglacial landforms.

3.1.2 Field analysis in the Netherlands and adjacent Germany

In the Netherlands, the field analyses consisted of a comparison between different areas in a transect from east to west. Starting in the area of Friesland (NL) where there are many known pingo remnants (Kluiving, 2010) towards the east into northern Germany. In 4 areas (described in chapter 2) different depressions are investigated. The exact location of the pingos has been decided in the field based on the DEM, topographical map and availability in the field. Each pingo remnant was surveyed by several boreholes to make a morphological cross section, depth indication and lithological description. The boreholes are positioned on a transect, with an average borehole spacing of 10 meter, and the location has been determined using a hand GPS. The boreholes were carried out with an Edelman corer plus dutch anger (*guts*) and described according to a standard method in which every transition between layers is described (Berendsen and Stouthamer, 2001). The characteristics described are: colour, grain size and texture, organic matter content and the presence of unusual aspects and details like coatings, soil development or the occurrence of plant remains (Berendsen, 2005). Samples have been taken at the deepest location of the depressions to use for pollen analysis to get an age estimation for the first infill of the depression (section 5.2). At a few locations cores were taken for further analysis. These cores have been taken using a 'Bohncke-modified Livingstone Piston corer' with a diameter of 6 cm. This coring method has been used widely to sample lake deposits (Lowe and Walker, 1997). The cores are stored air-tight in a cold storage to avoid degradation and oxidation.

3.2 Loss on Ignition

The Loss on Ignition (LOI) analysis is a method to analyse the percentage organic content of a sample. The samples are taken from a core, which is first split, photographed and described lithogically. The LOI samples are taken with an interval of one or two centimetres (depending on the type of sediment) and the samples do not cross lithological boundaries. The samples have been dried in a stove at 105°C for at least 12 hours and weighted afterwards to get the dried weight DW_{105} in grams. The dried samples have been put into an oven at 550°C for 4 hours, excluding 1 hour to reach this temperature. In the oven all organic components burn into CO_2. The weight after being in the oven gives the DW_{550} and is used in equation (3.1) to calculate the LOI values, which gives a good indication for the original organic content of the sample (Heiri et al, 2001).

$$LOI = \frac{DW_{105} - DW_{550}}{DW_{105}} * 100\% \tag{3.1}$$

3.3 Pollen analysis

The pollen samples preparation starts with taking samples from a core at the depths of interest. For this research, the date of first infill is essential, so the samples have been taken round important lithological boundaries, the boundary at the base of the depression. At this transition pollen samples have been taken above and below the transition to get an age estimation of the first infill and, if possible, of the last activity before infill. The pollen samples have been extracted with a sampler with a constant volume (0.3 cc) and acidic acid (5%) is added to protect the samples and avoid dehydration and oxidation. The preparation of the pollen samples consists of degrading all material of the sample until it only consists of pollen. More information about the pollen analysis can be found in R. de Bruijn, 2012.

3.4 Spatial distribution of pingo depressions

The research area is shown on figure 3.2. In this figure, all known pingos are plotted. The red dots are pingos studied by other authors and projects and therefore only described in literature. The green dots are the pingo locations for this project and described in more detail in the next chapter, when the results of the spatial density will be explained.

All information gathered with the field analysis has been be put into a geographical information system (GIS), to get an overview of the studied depressions. This is combined with previous research in the literature which gives information about cross section or depth of the infilling of the depressions in the Netherlands and Germany interpreted as being pingo remnants. All different pingo remnants give a spatial distribution in the occurrence of the pingo remnants. In combination with the subsurface, elevation or occurrence of other permafrost landforms (Isarin, 1997; Meyer, 2010) this could give an indication about the origin of the pingo remnants. The spatial distribution of the (maximum) depth of the relict pingos, gives an indication of the minimum permafrost depth (section 3.2.3). Rather than in the field, most pingo depressions are visible in satalite or high resolution elevation data. With the use of computer programming, most of these depressions can be classified. In this GIS analysis, only the area of the Netherland is usable for recognizing pingo depressions, because the lack of detailed elevation information for Germany. During many field surveys in the past, pingo remnants have been classified in the field, and are drawn on the geomorphological map (Alterra, 2008), geological map (pers. comm. TNO, 2011) and special surveys for Drenthe (Provincie Drenthe, 2009) and Friesland (Kluiving & Verbers, 2007). With exception of the new geomorphological map of Drenthe, all classifications are made sithout high resolution elevation data.

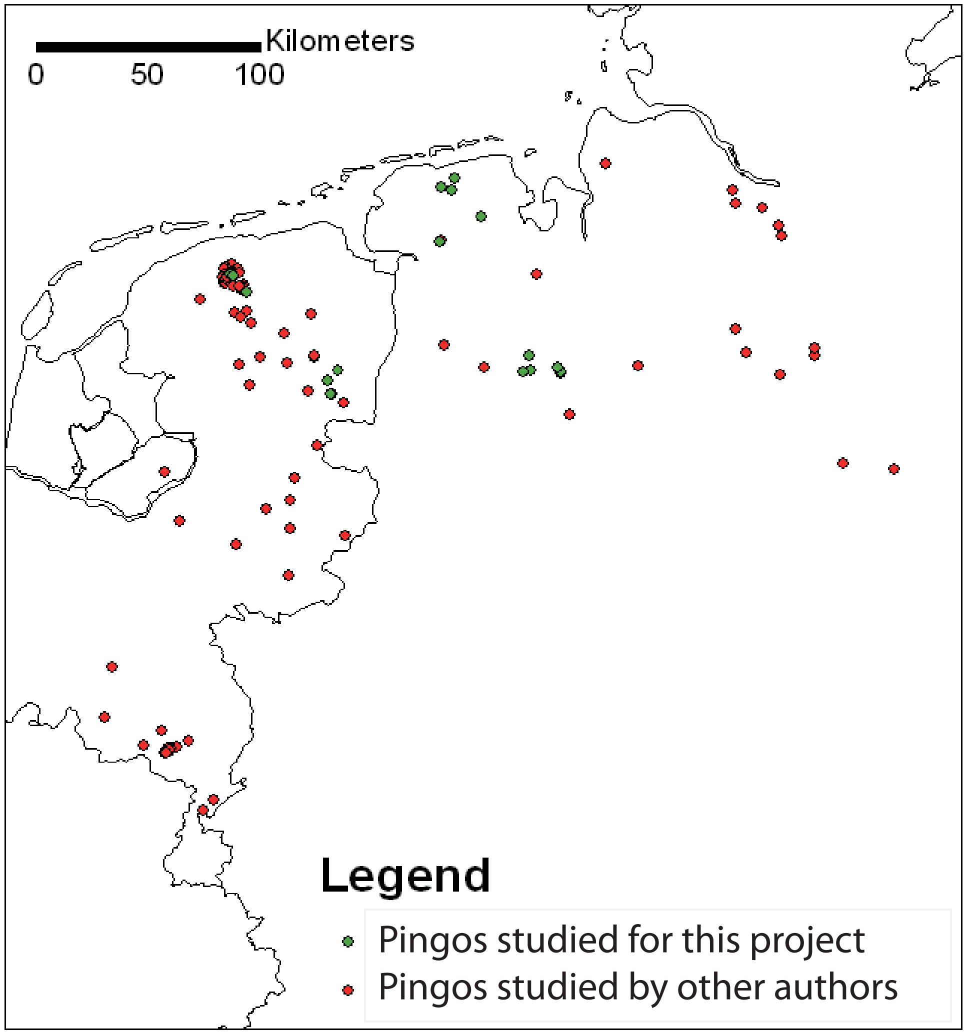

Figure 3.2: Pingos in the Netherlands and adjacent Germany

3.4.1 Depression recognition with ArcGIS

The recognition of depressions with ArcGIS is easily visible with the naked eye in the dataset of the digital elevation model of the Netherlands (AHN) (Rijkswaterstaat AGI, 2005). However, because this consists of a raster dataset, the computer cannot classify any objects in this data. Therefore, the raster dataset have been converted into a feature or polygon dataset, following flowchart 3.3A. This has been done by making contour lines of the elevation information. With an elevation interval of 20 cm this gives reasonable results in making circular depressions to circular contour

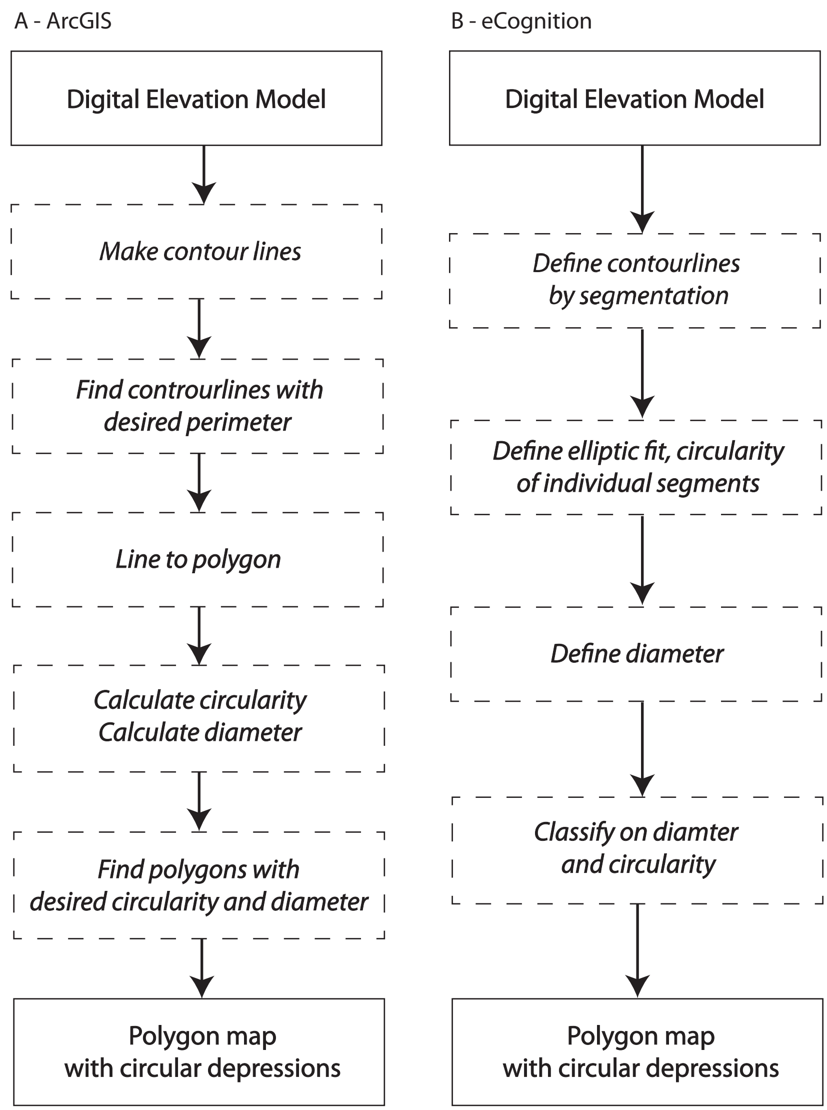

Figure 3.3: Flowchart depression recognition using (A) ArcGIS or (B) eCognition

lines. However, this yielded many problems with ditches, roads, fieldborders and other artificial objects. The contour lines give the perimeter of the depression and has been converted to polygons. First, the desired perimeter has been selected, to avoid circles in circles (donut-effect). If this results in singular contour lines, the function *line to polygon* has been applied to create individual polygons. The circularity and diameter has been calculated from these polygons, after which the polygons with the desired circularity (¿ 0,6) and diameter (between 20 and 400 meter) has been selected with a SQL function. This circularity is calculated using equation (3.2);

$$circularity = \frac{4\pi area}{perimeter^2} \tag{3.2}$$

When this selection of polygons with fit the criteria is exported into a new layer file, this resulted in a polygon map with circular depressions. This method might be an automatic way to recognize depressions from a singular (high quality) digital elevation map as an input.

3.4.2 Depression recognition with eCognition Developer

The recognition with eCognition Developer is based on raster dataset and using defined parameters to classify features. This program is developed for classifying remote sensing and medical data. Pattern recognition such as circular depressions can be classified using eCognition according to the flowchart of figure 3.3B.

3.4.3 Pingo catalogue

All information about pingo depressions, research in the past and including this project has been merged into a catalogue which describes all information available of pingos in Netherlands and adjacent Germany. This catalogue is partly based on the Atlas to Palaeogeography of Lateglacial Vegetations (Hoek, 1997). In this thesis, all pollen information is merged together into a vegetation atlas for reconstructing past climate. Because many of these lateglacial pollen diagrams originate out of pingo depressions (long and mostly undisturbed peat sequences) this Atlas is used as a start for the pingo catalogue. All research about pingo remparts in the Netherlands and adjacent Germany is adding to this catalogue. The entire list of used researches and their information availability can be found in appendix 1.

4. Results and interpretations

The results of this study are summarized below, starting with the description of two active pingos in Illisarvik, Canada, followed by the reconstruction part of the Dutch and German pingos. More results about the infill, sedimentation and correlation between the different Dutch and German pingo remnants can be found in R. de Bruijn, 2012.

4.1 Active pingos in Illisarvik, Canada

When the lake directly south of Illisarvik drained (around 5,000 years ago) the lake level dropped with almost 5 meters. A pingo started to develop in the drained lake basin at the residual pond of the sourthern former lake. At this moment, this pingo does not show any sign of growth or degradation as the pingo ice is still covered with sediment and has no growing denudation cracks at the top.

Figure 4.1: A foto of the drained lake Illisarvik, Mackenzie Delta, Canada (Chris Burn, 2010)

Figure 4.1 shows the outline of the drained lake Illisarvik (located at WGS 84: 69°28'77"N - 134°35'00"W; around 0 meter above sea level), with the drainage channel in the western side of the former lake and the two pingos located just west of the residual pond. The Alak pingo, which started to grow after the drainage of the northern lake Illisarvik (in 1978) is now about 15 years old. The overburden sediment has a thickness of about 4 meters, which is visible in the cracks. Since 2008, the width of the denudation cracks is measured twice a year, at the start and the end of the summer period (figure 4.1).

	June	August
2008	-	201 cm
2009	204.1 cm	203.3 cm
2012	205.7 cm	204.4 cm
2011	206.4 cm	206.1 cm

Table 4.1: Table of denudation crack change

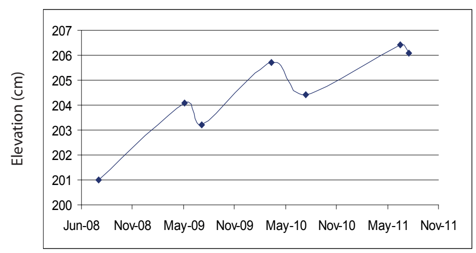

Figure 4.2: Graph of denudation crack change

As the numbers (table 4.1) and graph (figure 4.2) above show, the width of the denudation crack changes throughout the year. It expands during the winter period when ice accretion takes place, and it shrinks during the summer period when the uppermost part of the permafrost layer thaws and the denudation crack converges. This process has been described as Pulsating pingos by Mackay (1977). The total height of this pingo (at benchmark 701) has been measured in 2008 and 2011, and it has grown 7.19 cm in these 3 years. The profile measured in August 2011 is shown in figure 4.3. The denudation cracks can be seen in both north-south and east-west profiles at the distance of respectively -3 and +2 meters.

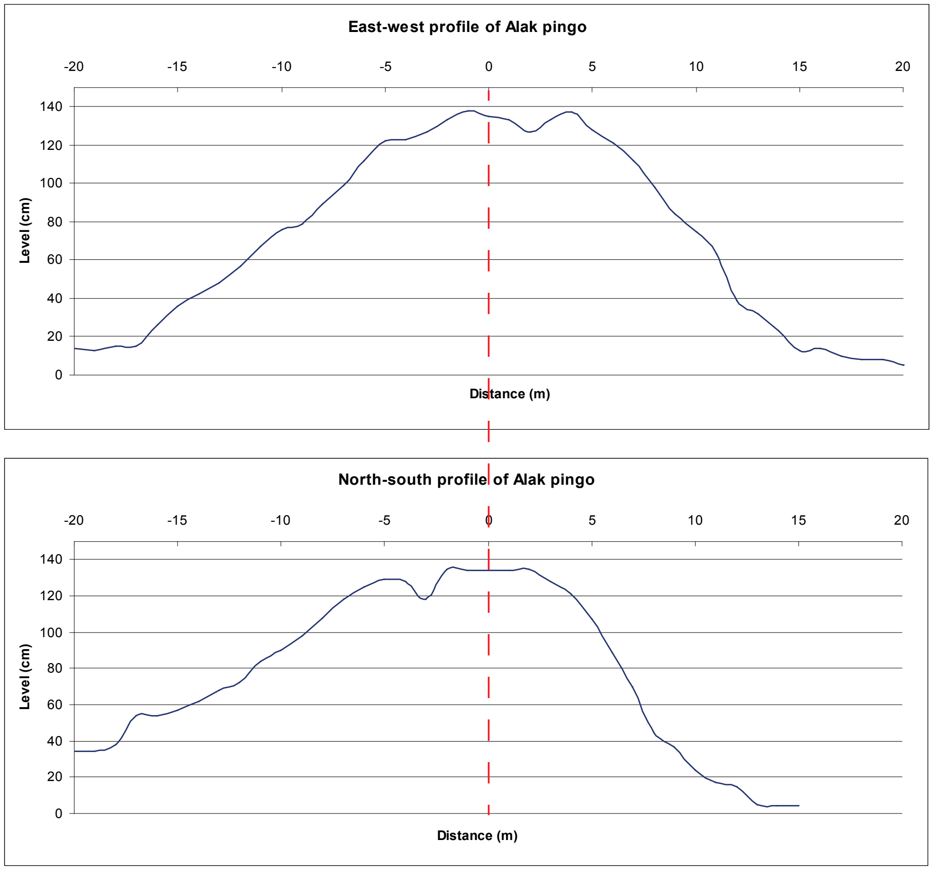

Figure 4.3: Elevation profile of the Alak pingo, Illisarvik, Canada

The residual pond has been shrinking significantly during the last few years, which could be the end of the water provision for both active pingos in Illisarvik. The residual pond now acts as a chimney, in which the unfrozen lake bottom can release heat during the winter period as the pingos accrete ice from below. As the size of the lake continues to decrease and becomes shallower than 4 (!) meters, the lake will freeze entirely during the winter which means the end of the chimney-system and water source. Even though the water source of the residual pond of Illisarvik reduces, a new pingo has formed at the other side of this pond. A second pingo in Illisarvik started to grow in the year 2000. In July 2011 only series of segregated ice lenses have been found during drilling activities (Burn, 2011). No large or consecutive ice lenses were found. However the morphology and occurrence of fast growing segregated ice generate the expectance of being a new growing pingo remnant. The profile of this presumed pingo is shown in figure 4.4.

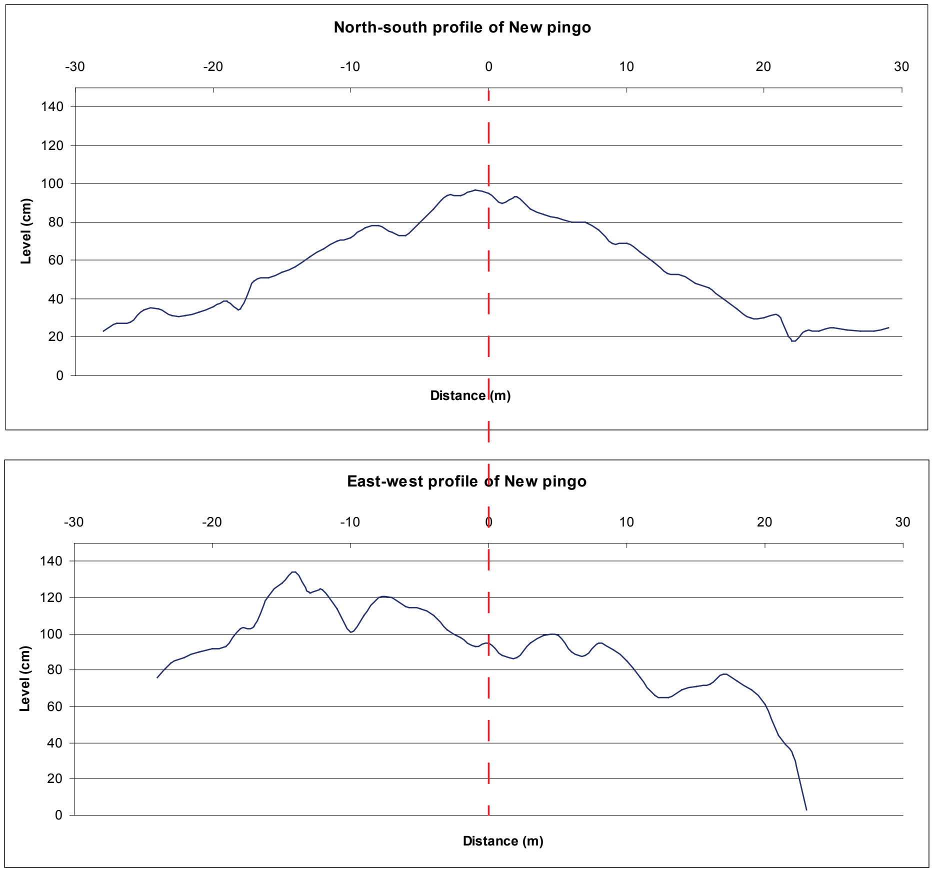

Figure 4.4: Elevation profile of the New pingo, Illisarvik, Canada

The profile of the New Pingo shows a relatively clear hill shape in the north-south direction. The east-west direction of the profile shows an irregular shape, with at the east side the highest elevations and at the west side an elevation step of about 80 cm towards the residual pond. Apart from denudation cracks, also old thermal expansion cracks from the lake bottom can be found at this location, as well as a part of the old drainage channel. The location of this new forming pingo is therefore unexpected and not yet understood. The surface of this location is exposed since some decades and therefore is presumed to have formed permafrost deep enough to separate the surface from the old talik.

Many more pingos are present in the Mackenzie Delta. During the route towards the Illisarvik lake a several more pingos have been investigated by their state of occurence, vegetation cover, size and morphology. Figure 4.5 shows the location of the pingos which are described below, and the location of Illisarvik and Inuvik as a reference.

Figure 4.5: The route from Inuvik towards Illisarvik with a several pingos indicated by the letters A, B and C, Mackenzie Delta, Canada

The first pingo on the route is located at location A (located at WGS 84: 69°26'55"N - 134°37'03"W; around 5 meter above sea level; figure 4.6). This pingo is located at the ocean side and shows degradation by coastal erosion. This is a very rare situation, which gives the opportunity to see the inner part of the pingo. Pure ice is visible underneath the parts of the pingo which are most exposed by coastal erosion and mass movements. The ice has some mixture of sand and a dark-blue colour, which indicates that the ice consists of very little air.

On location B, two pingos are visible. The first described is located at the north side (located at WGS 84: 69°18'40"N - 134°20'03"W; around 30 meter above sea level) and is shown in figure 4.7. On this figure, a close-up of the top of the pingo shows

Figure 4.6: A pingo in the Mackenzie delta, the location is indicated on figure 4.5 and an eagle indicates the scale, the pingo is about 20m high (A.S.Ruiter, 2011)

the presence of a small pond on top of the active pingo. Vegetation is present at the sides of of the pingo and in the middle in which the pond is present. At the sides of the pond, steep sides with active mass movements shows that the degradation of the pingo is occuring at the moment. On the larger scale, the pingo is surrounded by an abundance of water.

The maximum size of the pingo had been reach because the shorelines of the lake reach up to the pingo itself at some parts of the periphery. Four very small pingos are located at both sides of the pingo. These features are called 'satellite pingos' or 'secondary pingos'. They can occur when the maximum width of the pingo is reached, but the water pressure is large enough to start the growth of a new pingo close to the pingo. These can also originates from the start of the pingo formation, when the growth dit not started at one clear point. The exact formation of these secondary pingos is not completely clear, but all pingos have the same talik as a source for their growth.

At the south side of location B, another pingo has been visited (located at WGS 84: 69°17'97"N - 134°21'30"W; around 20 meter above sea level). This pingo is

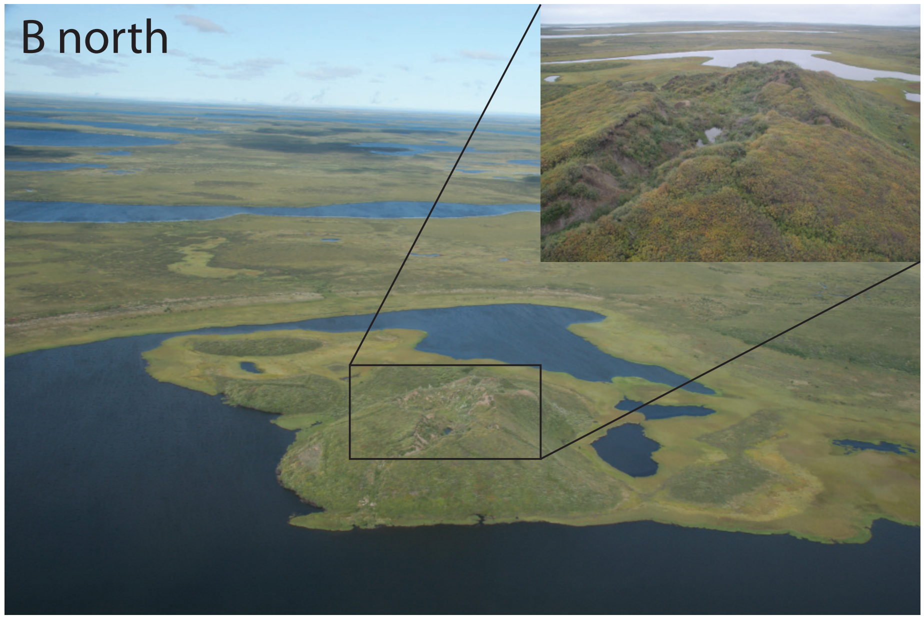

Figure 4.7: A pingo in the Mackenzie delta, the location is indicated on figure 4.5, the pingo is presumably more than 40m high (A.S.Ruiter, 2011)

already completely degraded and only a rampart is still present (figure 4.8 and 1.4). A helicopter and person indicate the scale of this pingo remnent, the rampart has a hight of about two meters and a several hundreds of meters in diameter. In the middel of the pingo remnant polygons show the presence of permafrost and the inactivity of the pingo for a long time, presumably a several hundreds to thousend years (pers. comm. Chris Burn).

At location C (located at WGS 84: 69°14'78"N - 134°21'48"W; around 50 meter above sea level) another pingo has been visited (figure 4.9). This pingo is very circular and has steep sides. The pingo has been started to degrade which is shown by the depression in the middle of the pingo. However, the depression has been covered with veretation, which shows that the degradation is in a relatively stable stage of degradation. The steep sides and location direct surrounded by water show that the pingo has reached a very maximum of growth before starting to degrade. A small pingo is visible at the other side of the lake. This pingo is still growing because it does not show any sign of degradation.

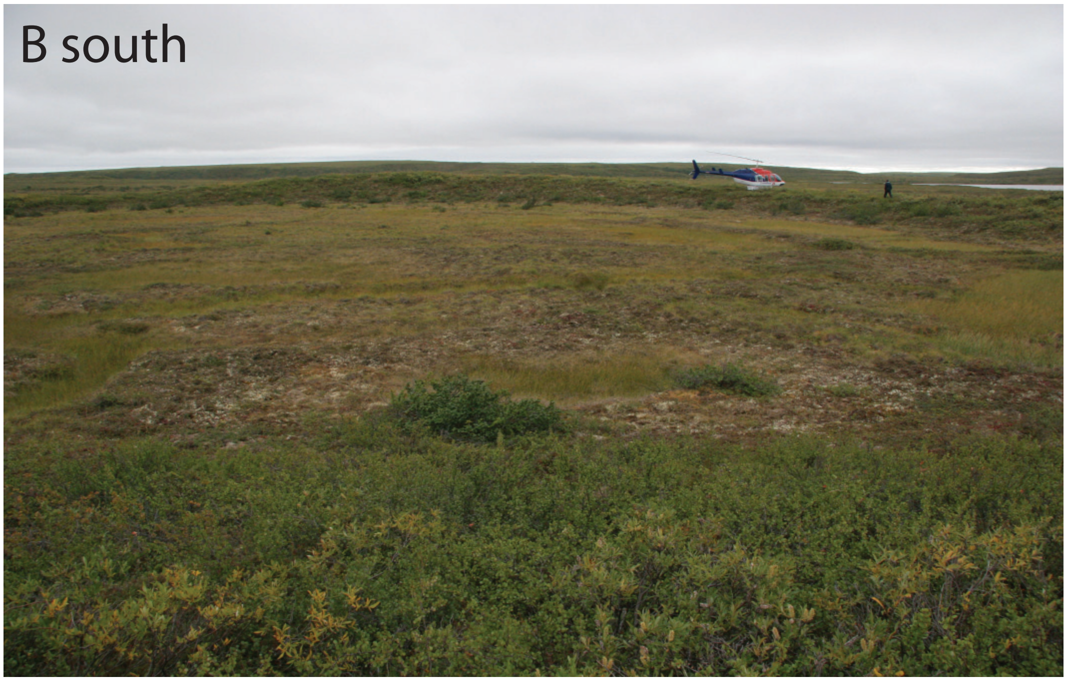

Figure 4.8: A completely collapsed pingo in the Mackenzie delta, the location is indicated on figure 4.5 the Helicopter and and person show the scale of the rampart (A.S.Ruiter, 2011)

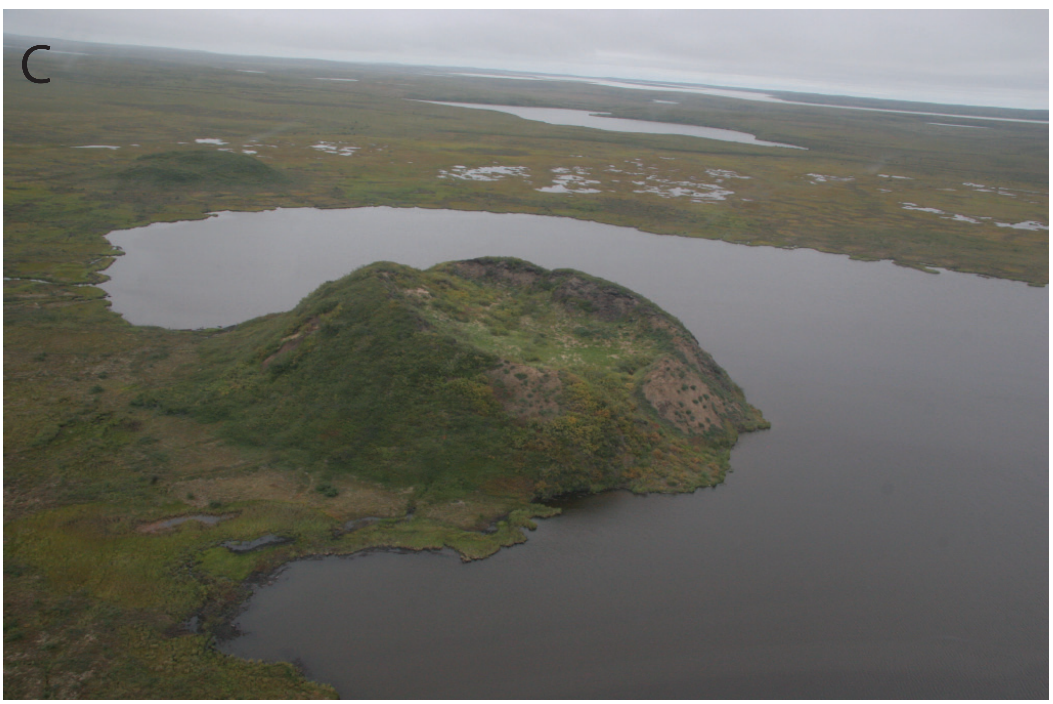

Figure 4.9: A pingo in the Mackenzie delta, the location is indicated on figure 4.5(A.S.Ruiter, 2011)

4.2 Friesland cross sections, Netherlands

In the Friesland area three depressions have been investigated. The geological background can be found in section 2.2.1. All three depressions are located in glacial till or coversand areas and are classified on the geomorphological map (Alterra, 2008) as dobbe (dutch word for round lake) or depression.

4.2.1 Egypte

The Egypte depression (WGS 84: 53°15’08”N - 6°06’35”O or Rijksdriehoekstelsel: 203225-585303; around 1 m NAP) is located around 1.5 km west of the village Buitenpost in Friesland. The depression is located in an agricultural area. Half of the depression is being used for grassland and the other half is covered by a small wet forest with mainly willow and alder trees. The depression has a diameter of about 120 meters and is clearly visible in the topography of the grassland, which is about 1 meter higher at both sides along the transect. The cross section has been made on the basis of 13 boreholes from south-east to north-west along a ditch in the middle of the depression (figure 4.10 and 4.11).

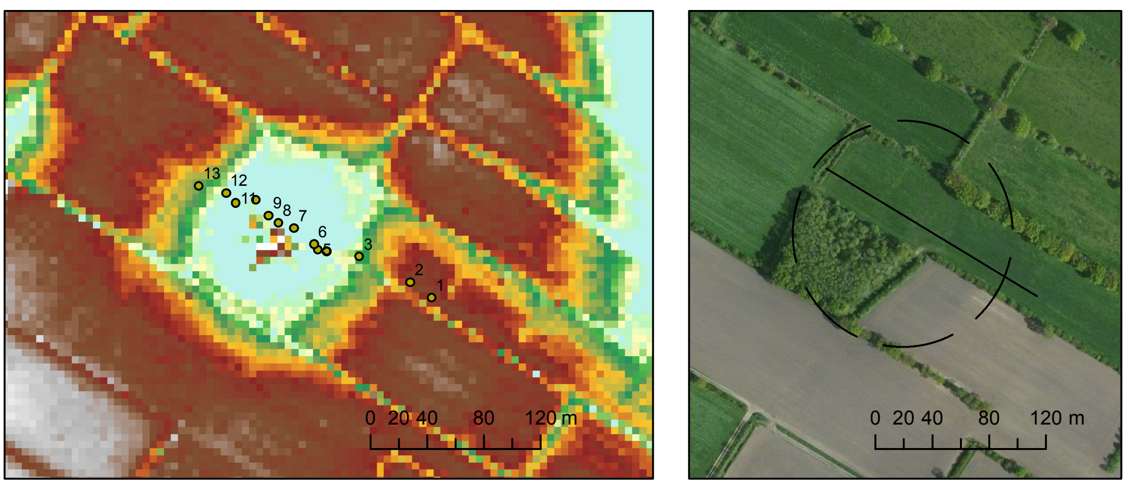

Figure 4.10: Location of Egypte, Netherlands.

The profile shows a clear depression with thick organic material of almost 3 meters. Each borehole of the cross section ends in fine sand. The grain size of this sand varies between 150-210 and 210-300 μm and has a grayish colour. At the south-eastern part of the profile the sand is loamy or has loamy blocks and contains gravel up to 5 percent. In the north-western part, the sand in the lowest part of each borehole is a little humic and becomes lighter of colour downwards in the profile, has been interpreted as being glacial till (see section 2.2.1). The glacial till of probably Saalian age has been deposited and mixed by the ice sheet. In this substrate, a depression formed during the Weichselian. The lowest infill of the depression is laminated, very fine humic sand, grain size varying between 75 and 150 μm, with a light brown colour. This laminated fine sand has been interpreted as a lake deposit. This was deposited when the depression was filled with water. This gyttja layer is probably aeolean deposition with some organic mixture. In borehole number 009 several samples, at a depth of 235, 250 and 270 cm, have been taken to have a quick pollen scan for an age indication (R. de Bruijn, 2012, in prep.).

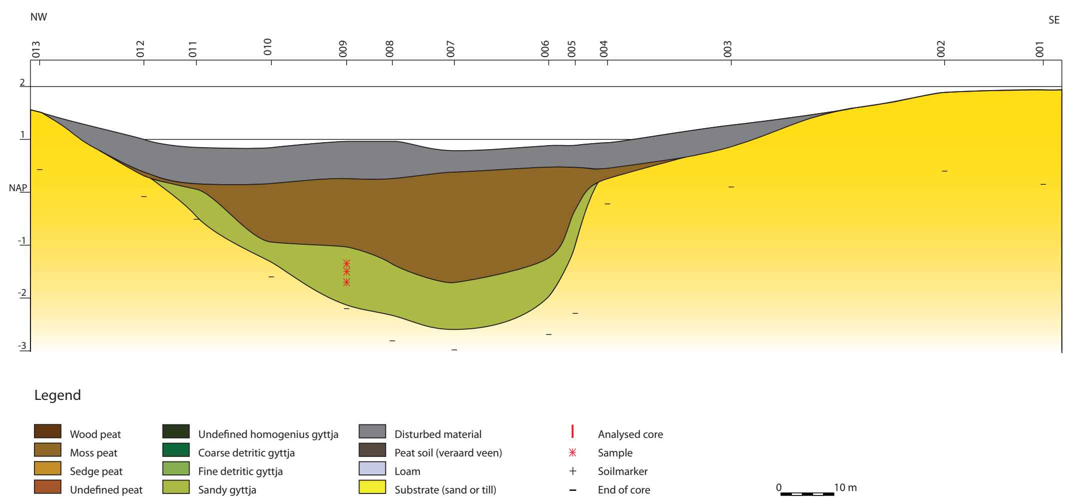

Figure 4.11: Lithological profile of Egypte.

The uppermost few centimetres of this fill are darker and have remnants of birch-wood. This indicates a dry period of soil development. When the birch would have been found in situ, this dry period was stable and long enough to let a small forest grow, however most likely this birch fall into the depression (probably filled with water) and was therefore preserved. A thick peat layer is found on top of this lowest fill. The thickness of the peat layer varies between almost 2 meters in the middle of the depression to only a few decimetres at the sides of the depression. No peat is

found at the sides of the profile. The peat is brown to orange brown and contains many recognisable plant remains. The plant remains consist mainly of mosses, but as well sedges in the lowest part of the layer and cotton grass are mixed through the layer. In the water more (aquatic) plants started to grow and slowly the entire depression shallowed and changed into a peat bog, until the entire depression was filled with peat. Disturbed material was found over almost the entire surface of the cross section, with an exception of the tree outermost boreholes at the sides of the profile, which have a higher surface elevation. This disturbed material consists of brown or grey-brown sandy peat with no clear plant remains and some gravel, bricks or flint mixed through the material. This surface layer is presumably disturbed by recent farming activities, and thus regarded as an antropogenic fill.
The Egypte depression can be interpreted as being a pingo remnant of Weichselian age, with a substrate in glacial till.

4.2.2 Laarzenpad

The Laarzenpad depression (WGS 84: 53°14'42"N - 6°07'52"O or Rijksdriehoeks-telsel: 204571-584515; around 0 m NAP) is located just south west of the village Buitenpost in Friesland. The depression is completely covered with grassland. The depression has a diameter of about 150 meters but is hardly visible in the field

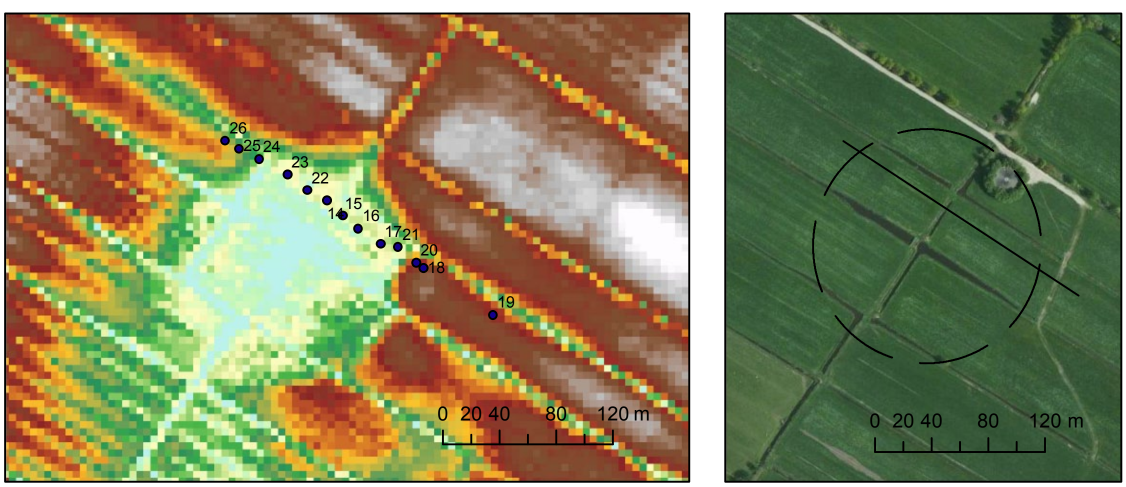

Figure 4.12: Location of Laarzenpad, Netherlands.

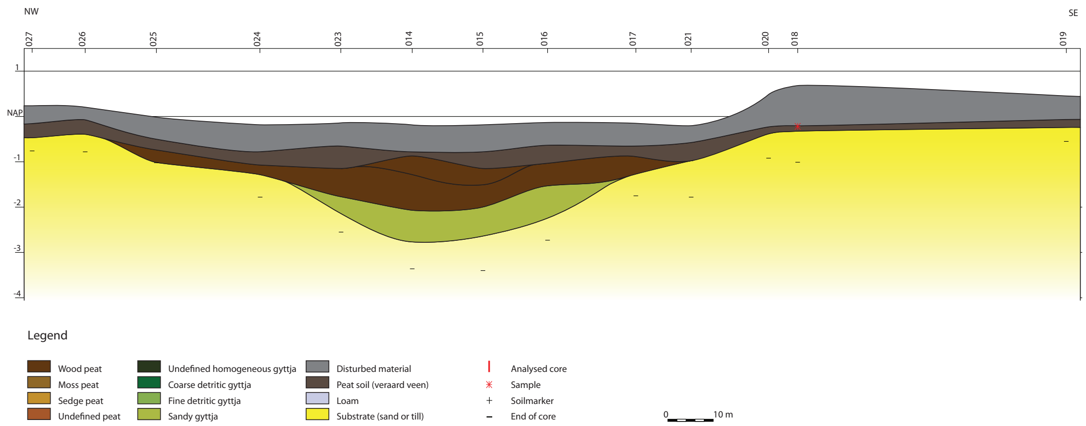

Figure 4.13: Lithological profile of Laarzenpad.

without an elevation map of the area. A silo is located at a little higher elevation just at the site of the depression (figure 4.12). A cross section has been made based on 15 boreholes along a north-west south-east transect (figure 4.13). The substrate of the cross section consist of greyish loamy sand to sandy loam, with a mean grain size diameter around 105 to 210 μm. This layer contains gravel up to 10 percent and a diameter of 3 cm or more and is interpreted as a glacial deposit of Pleistocene age (see section 2.2.1). The four deepest boreholes, 014, 015, 016 and 023, have a layer of sandy peat on top of the sand. This sandy peat layer is very laminated, has a light brown colour and contains some visible plant remains, is interpreted as sandy gyttja. This means that this layer is deposited in deep water with a mixture of aeolic sand. On top of this layer, another sandy peat layer is found. This layer is a little wider and is less sandy then the underlying layer. The peat has a dark brown colour and contains a lot of plant remains of twigs, woods and roots. During the sedimentation the depth of the depression has decreased and more terrestrial plants formed the peat deposit. This forest peat has still some aeolian sand influx. A narrow layer of loose peat with only plant remains and no sand mixture is found on top of this layer, but only in the middle of the depression, borehole 014 and 015, which could point to a dry period. Over the entire profile a peaty soil with disturbed material is found. This layer becomes sandier in the lowest part and more mixed at the top, which indicates a dry period with soil development. The top part is very mixed and contains blocks of clay, gravel and some bricks, due to antropogenic mixing. The

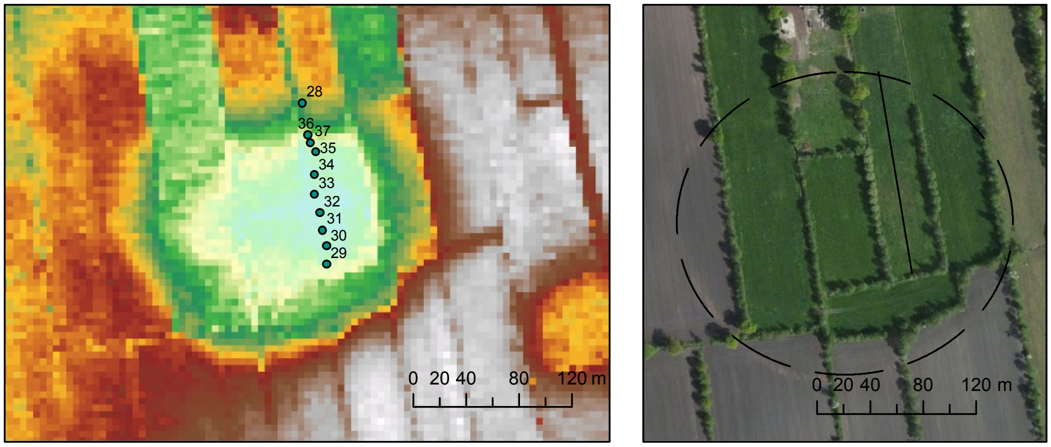

Figure 4.14: Location of Opende, Netherlands.

Laarzenpad depression is presumably a possible pingo remnant of Weichselian age. The substrate consists of impermeable glacial till.

4.2.3 Opende

The Opende depression (WGS 84: 53°10'52"N - 6°12'58"O or Rijksdriehoekstelsel: 210386-577409; around 0 m NAP) is located just north of the village Opende (figure 4.14). The depression is partly used for maize and partly for sheep but the largest part is too wet for agricultural purposes and covered with grass.

The depression has a diameter of a little more than 200 meters. One part of the depression is not visible in the field because it was covered with maize during the fieldwork period. Therefore, it is hard to estimate the entire diameter of the depression directly in the field. The part which is covered with grass is very wet and clearly lower than the surrounding area. At the northern site of the depression a house is located on a higher elevation of about 1.5 meters. This elevation step is very steep and clearly visible in the field. The owner of the house told that there has been a ditch at this location, which was now filled with sand.

The Opende cross section is based on 10 boreholes from north west to south east (figure 4.15) as far as the depression was covered with grass. At the south east side, the cross section of the depression is not entirely complete. The substrate of the depression consists of grey to grey-brown medium sand, with an average grain size diameter varying between 210 and 420 μm. The sand is at some locations a little loamy of humic and contains some gravel. This substrate has been interpreted in the field as glacial till. However, according to the geological and geomorphological maps (section 2.2.1), the Opende depression is located in coversand area, at the edge of this area and the groundmoraine area. Presumably this substrate is a mixture of both landforms as they present a gradual transition. The transition between the substrate and the first infill is very sharp between sand and peat. The peat consists of a many plant remains of mainly sedges. This layer is found at a depth between one and almost four meters in almost all boreholes; with an exception of the highest two boreholes in the north west side of the profile, 028 and 036. The peat is strongly laminated and brown to gray-brown of colour, it is therefore interpreted as being a "sedge gyttja". This means that the peat has grown in relatively deep water, but shallow enough to grow sedges. The sharp transition between substrate and infill without any sign of soil development means that the depression was filled with water directly after degradation. A very thin layer of weakly laminated, humic, very fine sand, diameter of 105-150 μm, is found on top of the laminated peat in the deepest two boreholes, 032 and 033. Over almost the entire with of the profile, homogeneous peat can be found on top of the laminated layers. The peat has a homogeneous matrix but contains a lot of plant remains. The plant remains are not all recognisable, but mosses and sedges has been found in this layer. Most of the plant remains are horizontally present and the entire layer is laminated. A very thin layer of laminated, humic very fine sand is found on top of this layer in only two boreholes, 035 and 037. This thin layer has the same characteristics of the thin sand layer below the peat in boreholes 032 and 033. Within the peat infill, some sandy layers can be found horizontally in the sediment. Those sand layers consist of very fine or silty material and are probably aeolian sand infill of periods with more wind and/or less vegetation. A peat layer is found over almost the entire width of the profile, with again the exception of borehole 036 and 028. This peat layer consists of many plant remains of sedges, but also cottongrass and some mosses are recognized. Even though much cotton grass has been found in this depression, this could also be caused by the good preservation ability of this plant. The water level

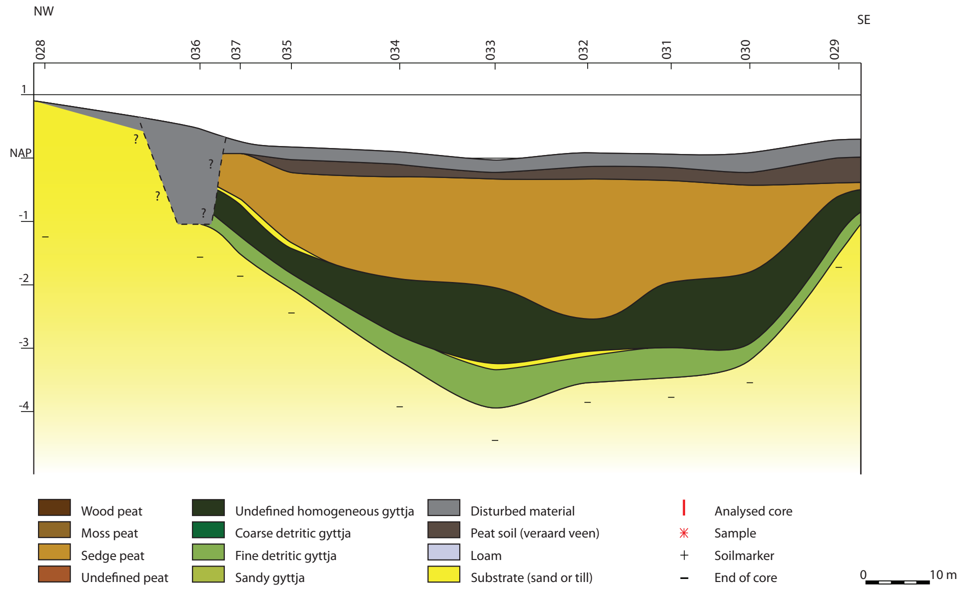

Figure 4.15: Lithological profile of Opende.

in the depression dropped gradually until the depression was filled with peat. The uppermost layer is found over the entire profile and consists of a mixed and disturbed sand layer, with in the lowest part peat soil (Dutch: *veraard veen*). As described above, borehole 028 and 036 are no part of the depression. Borehole 028 has the same properties as the substrate, with the only exception of the colour, which is brown in the top and lighter downwards. Borehole 036 has substrate properties in the lowest part of the core, from 140 cm downwards. The upper 140 cm consists of a mixed sand, 150-210 μm, with a brown colour lighter downwards. Mixed in the sand are some plant remains, and a flint part (Dutch: *vuursteen*). The material looks disturbed and similar to the uppermost few decimetres of the rest of the profile. No peat is found, even though this borehole is only a few meters distance of borehole 037 which consists of almost one and a half meter peaty material.

At the south-east side, the depression has not been investigated. The northwestern side consists of the same material as the substrate, with the only exception that soil development is present. At the location of borehole number 036 excavations have presumably disturbed this area, to make a ditch for drainage of the depression (pers. comm. farmer). The Opende depression is a pingo remnant on a substrate of glacial till and/or slope material in coversand.

4.3 Drenthe cross sections, Netherlands.

From the Drenthe area, 4 depressions are investigated and described below. The geological background can be found in section 2.2.3.

4.3.1 Sleenerstroom I

Sleenerstroom I is located (WGS 84: 52°45'24"N - 6°46'50"O or Rijksdriehoekstelsel: 249056-530848; around 12 m NAP) around 2 km south west of the village Sleen in Drenthe (figure 4.16). The Sleenerstroom I depression is a relatively large depression with a diameter of about 250 meters. The depression is completely covered with grassland and therefore clearly visible in the field. The field has an extensive subsurface drainage system which makes the field now useable for grassland. Before the construction of this drainage system the lowest part of the depression was very wet and gave a lot of problems with farming (pers. comm. parcel owner). The site has been investigated with georadar by E. Bregman and M. Bakker.

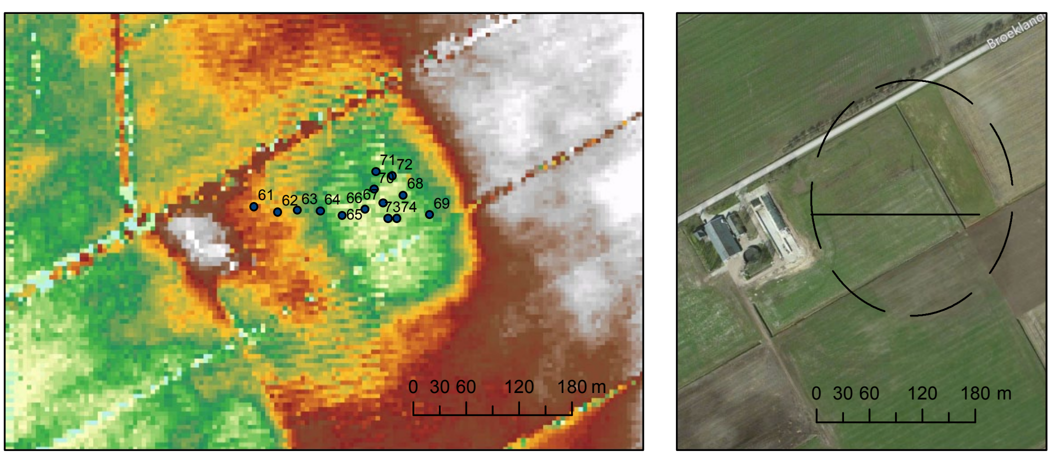

Figure 4.16: Location of Sleenerstroom I, Netherlands.

The Sleenerstroom I lithological profile (figure 4.17) is based on twelve boreholes in the depression, from west to east. More boreholes are located in the depression;

those are used to get a better idea of the dimensions, but were not used to make the lithological profile. The twelve boreholes all end in grey loamy sand with some gravel. The grain size of the sand varies between 105 to 210 μm in diameter. The loamyness is not constant but varies substantially over short distances, which indicates a glacial deposit. This in contrast to the geological map (section 2.2.3) which shows a Pleistocene peat deposition on the border with coversand of Pleistocene of Holocene age. The sand is interpreted as glacial sediment. The depression is formed in this sand layer. The first infill of the depression can be found over almost the entire width of the depression and consists of very sandy and fine horizontally laminated peat. The thickness of this layer is less than 1 meter and becomes thinner towards the sides of the depression. The laminated peat has a gummy-like appearance and is greenish-brown of colour. These characteristics indicate a fine detrital gyttja. Some small white dots are recognizable in this layer (siderite). The presence of siderite points to a relative deep water. Seepage was observed in the surrounding ditches, which could have been a source of water during the formation of this depression. On top of this layer a brown peat layer is found. This layer also has horizontal lamination and similar characteristics as in the lowest layer but coarser plant remains; some sedge remains and red seeds have been found at the bottom of this layer. These characteristics indicate a coarse detrital gyttja. The gyttja layer becomes sandier upwards, which indicate a colder climate with less vegetation and/or stronger aeolian activity. The layer on top of this peat is similar, but even sandier and has a distinct horizontal lamination. The uppermost layer consists of more terrestrial peat which indicates a dryer depression. The colour of this sandy peat layer is grey-brown, while the underlying layers are only brown or a little greenish. This layer is a sandy gyttja, without a difference between fine or coarse detrital gyttja. At the western site of this depression a dark brown or at some places blackish brown layer has been found, which is very homogeneous peat but with some roots. At the eastern side of the depression and in the middle on top of this homogeneous peat layer, another brown peat layer is found with more plant remains, mainly woods and some mosses. The transition between both peat layers is gradually but recognizable. The uppermost layer, which covers the entire depression, is a mixed and disturbed sand layer, presumably cultivated by farmer activities. The description according the lithological profile coincides with the results of the GPR measurements (Marcel Bakker and Enno Bregman). A similar trichotomy has been found in both profiles. An infill with high organic content, followed by a sandy peat and ends with a terrestrial peat. The dimensions of both profiles as well give similar results.

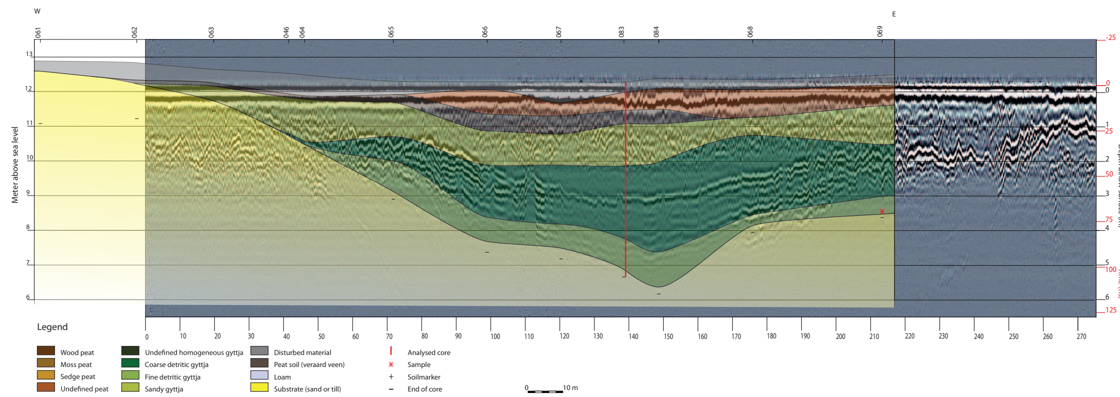

Figure 4.17: Lithological profile of Sleenerstroom I.

The Sleenerstroom I depression is interpreted as a pingo remnant. The depression has a relative large diameter and shallow infill, but matches the criteria. The substrate of the depression is presumably a glacial deposit and seepage has been a source of water for a long period.

4.3.2 Lammeer

The Lammeer depression (WGS 84: 52°50'59"N - 6°49'26"O or Rijksdriehoekstelsel: 251819-541257; around 19 m NAP) is located around 2 km west of Odoorn, Drenthe. The depression is located in the middle of a forest and clearly visible in the field and on aerial imagery (figure 4.18). The surface of the depression is about 1 meter lower than the surrounding rim. There is a clearly distingable ridge in a perfect circle around the depression. The diameter of the depression is a little more than 200 meters.

In the Lammeer depression only one coring has been carried out. This borehole

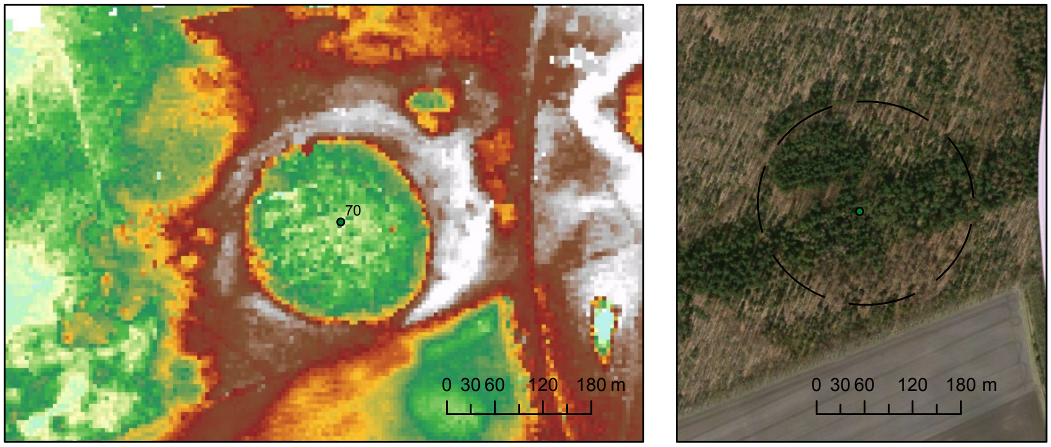

Figure 4.18: Location of Lammeer, Netherlands.

consists of only sand with less then 2 percent gravel. The grain size diameter of the sand varies from 210-300 μm in the lowest 150 cm to 105-150 μm in the uppermost 250 cm. This upper 250 cm is a little humic and has a brownish colour which slowly changes from light brown to light greyish brown at the end of the core and most likely more grey further downwards. The uppermost 20 cm is disturbed by plant roots and organic material and has a dark grey colour. This profile consists of a very long sequence of soil development. According to the geomorphological map the Lammeer is a depression with rampart (including ping remnant), surrounded with a small part low land dunes with plains and depressions within a larger area of ground moraine / glacial deposits. In the surrounding area, many depressions, with and without rampart, are present. This could be due to active coversand deposition, including blowing-out depressions. The elevation model (AHN) shows a perfect circular depression with rampart which coincides with the characteristics of a pingo remnant. The Lammeer depression does not have any organic infill. Therefore it is not a pingo remnant according to the criteria of De Gans (1982). However, the shape and dimentions of the depression match the characteristics of a pingo remnant. Therefore it is not excluded that the Lammeer is no pingo remnant. If the pingo has been active in coversand material, no visible remnants or infill will remain which could give an indication of past permafrost and heave activities.

No dating is available during this study to give a proof about the origin of this depression because of the lack of organic material.

4.3.3 Vlierendijk

Vlierendijk is located (WGS 84: 52°45’24”N - 6°46’50”O or Rijksdriehoekstelsel: 251819-541257; around 17 m NAP) around 8 km south-east of the village Odoorn in Drenthe. The depression is mostly covered with a small forest with a ditch at both sides and grassland and maize around (figure 4.19). The forest is relatively open, with birch and willow trees and high grasses and mosses at the surface. The middle of the forest is a little higher and drier, while at the sides up to around 1 meter water is present. The deepest parts are probably due to peat excavations, because of the steep sides and squared shapes of the water areas. The forest has a diameter less then 150 meters.

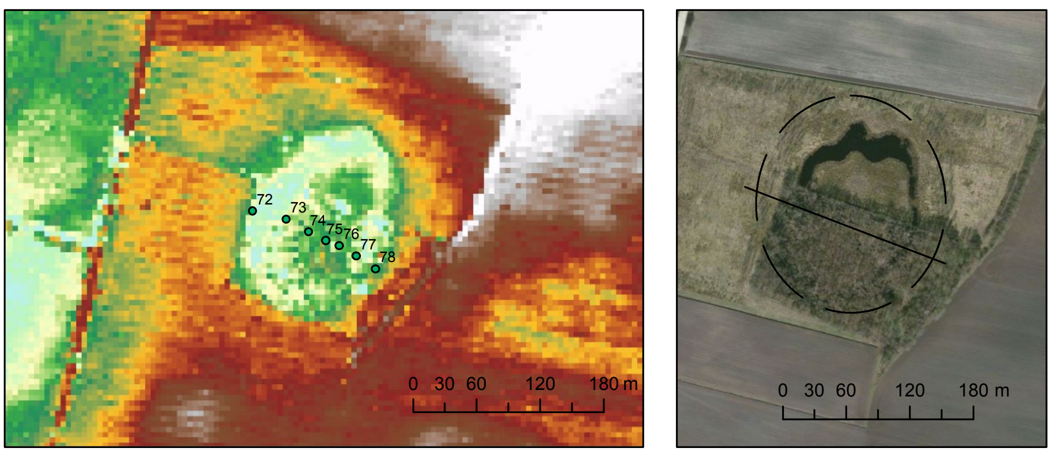

Figure 4.19: Location of Vlierendijk, Netherlands.

The cross section of Vlierendijk is based on seven boreholes, from north-west to south-east (figure 4.20). All seven corings end in grey fine sand, with a grain size diameter of 150-210 μm. The sand contains some gravel and is a little loamy. This can be interpreted as ground moraine material or glacial till deposits. The first infill of the depression, which is found over the entire width of the depression, is a very fine light brown grey sandy gyttja. This layer is very thin, 10 cm or less and homogeneous. This means that the depression has been filled with water directly after the collapse and the infill could form by degradation of fine plant remains and aeolian fine sand. On top of this thin layer, a thicker layer of very sandy peat has been found. This layer is laminated, has a greenish brown/grey colour, and contains some horizontal positioned plant remains, a result of deep water with some aquatic plants. This layer is most pronounced in the southeastern side of the depression. At the northwestern side, up to borehole 075, another peat layer is found on top. This layer has a homogeneous matrix and contains some plant remains or sand. This layer is interpretated as an undefined homogeneous gyttja, because the same characteristics are found over the entire width of the layer and no clear structures are recognized.

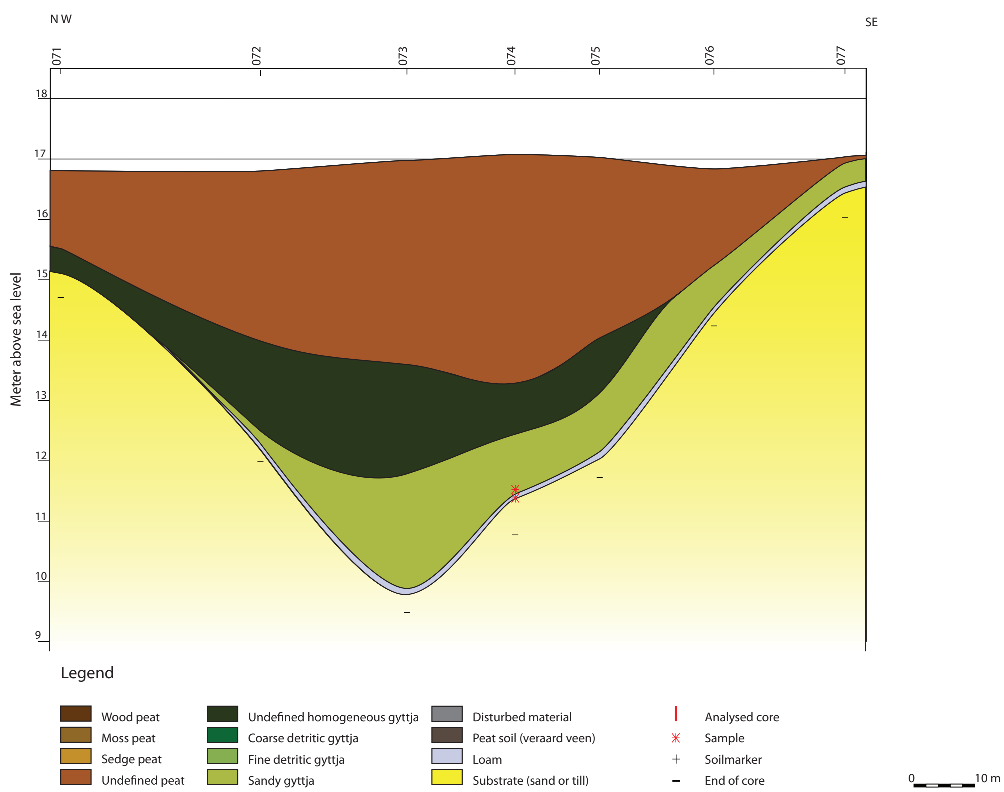

Figure 4.20: Lithological profile of Vlierendijk.

On top of this layer, a brown peat layer is found. This peat layer contains many plant remains, mainly sedges and cottongrass. More wood and mosses are found in the uppermost part of this layer. The peat gradually changes from a sedge peat to a wood peat, but no clear transition depth could be found. This is a result of a reducing water level during the infill of the depression, as the aquatic peat/gyttja gradually changes into sedge peat, with mainly sedges and cotton grass remains, towards wood peat, with remnants of wood and mosses. According to the geomorphological map (see section 2.2.3), the Vlierendijk depression is located in ground moraine area, which coincides with the substrate found in the lowermost part of the boreholes. The location of the pingo is interesting because it is located just upstream of old small wet valleys (*Dutch: broekdalen*). This means that there was enough water available for the formation of ice-lenses.

According to the profile, dimensions, shape and location the Vlierendijk depression has been interpreted as being a pingo remnant. A pollen analysis will give an age indication of this depression.

4.3.4 Sleenerstroom II

Sleenerstroom II is located (WGS 84: 52°45'24"N - 6°46'50"O or Rijksdriehoeksteltsel: 248473-530867; around 12 m NAP) around 2 km south west of the village Sleen in Drenthe (figure 4.21), only a few hundred meters north-east of Sleenerstroom I. The entire depression is located in a grassland area but the depression is almost invisible in the field. The grassland has a extensive subsurface drainage system.

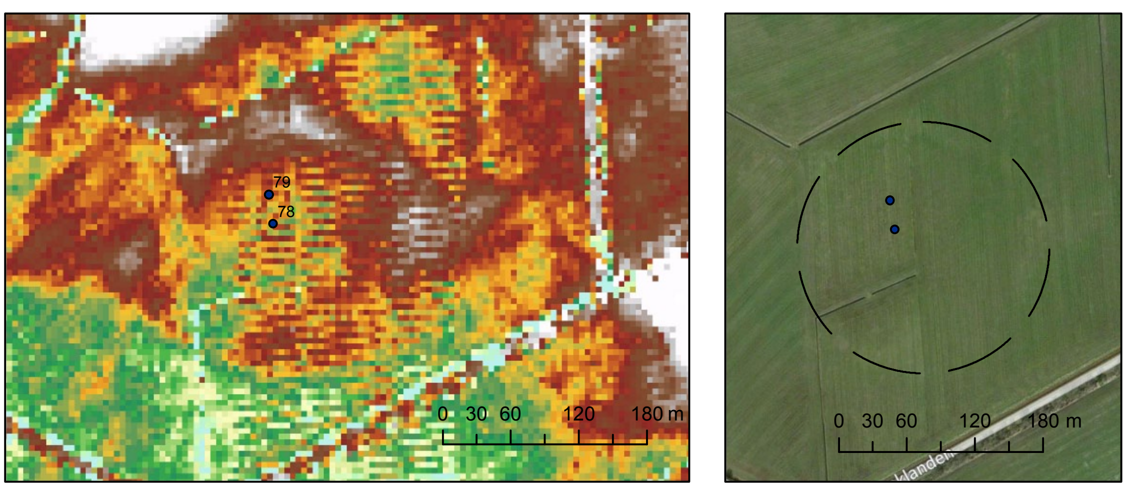

Figure 4.21: Location of Sleenerstroom II, Netherlands.

The Sleenerstroom II depression has been investigated with two boreholes, at the lowest location in the field, according to the AHN and field observations. Boreholes, 078 and 079 are 150 cm and 240 cm deep, respectively. The lowermost parts of the cores consist of grey and loamy sand, with a grain size of 150-300 μm in diameter. On top of this layer, a peat layer has been found in both boreholes. This peat is has a dark brown colour and contains many plan remains, mostly wood residues and twigs. One homogenised peat layer has been found at a depth of around one-third of the peat layer. The uppermost 30 cm of the cores consist of sandy peat with a disturbed structure. The lowest loamy part of the boreholes are interpreted as being glacial deposits, the substrate of the depression. The infill of the depression is relatively shallow, a little more than 1 meter, does not convene with the expectations of a pingo remnant. The depression is probably caused by a shallow valley system, which is present at the southern site of the this depression. The Sleenerstroom II depression is not a pingo remnant, but presumably part of a larger shallow valley system, with some aeolian activity causing the formation of a rim in the northeastern part.

4.4 Ost-Friesland cross sections, Germany.

In the Ost-Friesland area in north-west Germany, 5 depressions were investigated.

4.4.1 Timmelteich

The Timmelteich depression (WGS 84: 53°22'01"N - 7°31'34"O; around 12 m above sea level (Normal Null)) is a depression at the north side of the village Timmel in Germany (figure 4.22). The depression is in use as a park with a pond (in German; Teich) in the middle. At the western site a provincial road is present trough the depression and at the other site of the road a church is build on top of a higher hillock (terp). Underneath the church 50 cm peat is found (pers. comm. Axel Heinze). The diameter of the entire depression is probably a little more than 200 meters.

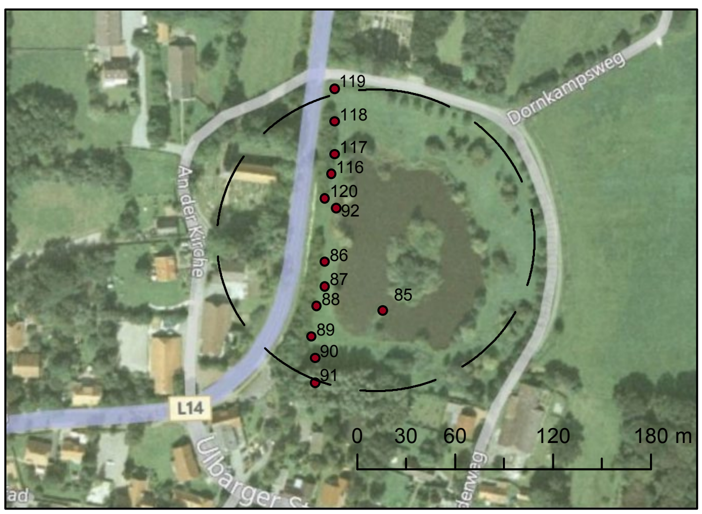

Figure 4.22: Location of Timmelteich, Germany.

The Timmelteich profile is based on 12 boreholes from north to south (figure 4.23). At the location of borehole number 120 a core has been taken which is analysed in the laboratory. In all 12 boreholes of the cross section, sand is found at the base of the depression. The grain size of the sand has a diameter of 150-210 μm. The sand is light brown grey to grey of colour and has a little humic and or loamy blending. This has been interpreted as the substrate of the depression, indicating a presumably glacial origin of the sedimentation. The deepest infill consists of a sandy, rigid and gummy-like material which is horizontally laminated and greyish of colour. Some very small plant remains are horizontally situated in the material. These macro fossil remnants have been found at a depth of 526-527 cm. These organic remnants in the lowest part of the core are sampled for ^{14}C dating. First microscopic analysis have shown that this organic material are leaves and small twigs of *Salix polaris* (pers. comm. Hanneke Bos). This species occur in tundra environments and polar deserts (Bos et al, 2009)and are dry terrestrial species. These species where present in this area during the Pleniglacial, when a periglacial climate was dominant and therefore tundra species where present. This layer in the depression is presumably from early Late Glacial period. Because this area is now a depression, filled with peat, it could be that this *Salix polaris* was growing on top of the active pingo, as this species needs a dry and cold environment. In northern Canada, these species are present on top of pingo remnants and other higher elevations in the permafrost area. A higher elevation is needed to have a dry soil mainly in the summer period, when the active layer is thawing and the permafrost areas become large swamp areas. The entire layer has the characteristics of a fine detrital gyttja (Bos et al, 2011). This has presumably been deposited during a cold period with high aeolian activity and only little organic sedimentation. Pollen analysis and 14C have to show the real age of this layer but interpretation from the LOI curve (see section 4.7) presumes a late glacial age. Over the entire width of the depression, a overlying layer is found which has similar characteristics as the lower layer, but many more and larger plant remains and less gummy and rigid. This layer is a coarse detrital gyttja (Bos et al, 2011). In the lowest part of the depression, between borehole 116 and 086, another sequence of layers is found on top of the previous described layers. The lowest layer is a brown peat layer, with some plant small remains and some sand mixed. The layer above has more and larger plant remains and is not sandy. Both layers are laminated and interpreted as being gyttja, with the lowest layer as fine and the upper layer as coarse detrital gyttja. On top of that entire width of the profile, a peat layer is found. This peat layer contains many plant remains of wood, roots, leaves and twigs and some sedges locally, which means that this peat is presumably a wood peat. The transition between this peat layer and the coarse detrital gyttja below is gradually and not always recognizable. This period could be the Allerd age and is followed by a windier and colder period, the Younger Dryas, recognizable between 480 and 450 cm in the LOI curve. The transition to the almost 90 percent organic content of the core is probably the transition to the Holocene period. This transition is gradually because the vegetation has to develop and recover from a cold period, which always gives a time-lag between climate development and vegetation development. The gradual transition between fine and coarse detrital gyttja in the profile may correspond to this same transition to the Holocene period. The surface layer over the entire width of the profile is a disturbed and mixed layer and not reliable for any analysis. Borehole 091 is different than expected because the gyttja layer is deeper than the depression shape/dimension would suggest. Nevertheless, the same sequence as in the depression has been found without recognizable disturbance.

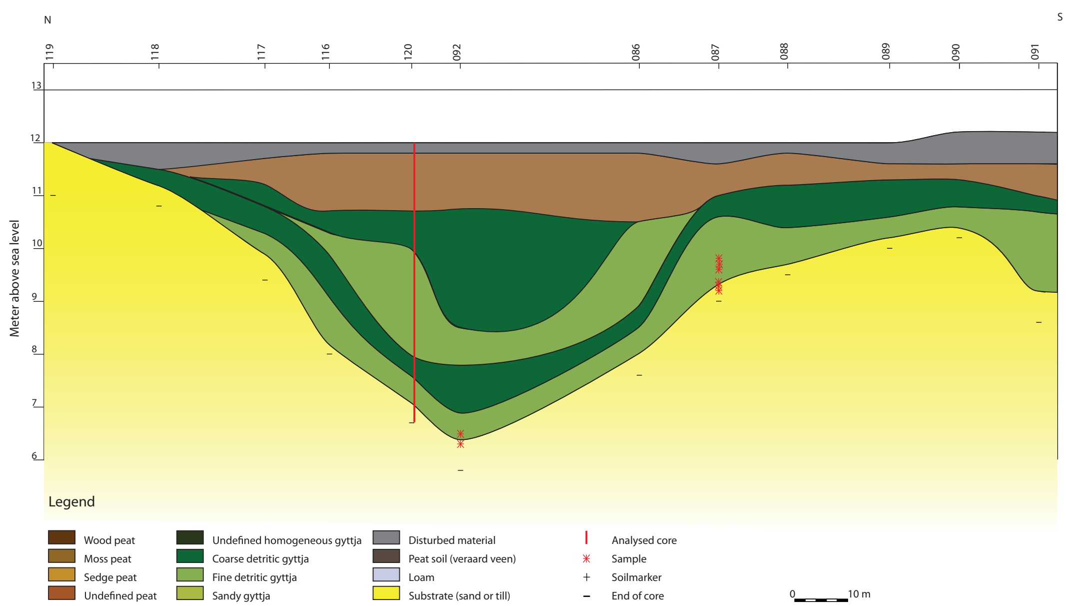

Figure 4.23: Lithological profile of Timmelteich, Germany.

The Timmelteich depression is interpreted as a pingo remnant. The dimensions and characteristics of the depression agree the expectations of a pingo remnant. The macro fossils of *Salix polaris* confirm this expectation because this species can only grow on dry and cold areas, not in a wet depression.

4.4.2 Westerschoo

The Westerschoo depression (WGS 84: 53°35’18”N - 7°32’34”O) is located in the middle of a forest less then 1 kilometer northeast of Westerschoo (figure 4.24). The depression is very clearly visible on aerial imagery and in the field as a perfect circle of smaller trees. This area has completely been reforested at the end of the 16th century. Therefore, small parallel ditches cross the entire forest. In the depression these ditches are completely filled with water and it is not possible to cross the ditches. The depression itself is very wet and covered with small trees, mainly Birch, and grasses and mosses. The depression has a diameter of around 200 meters.

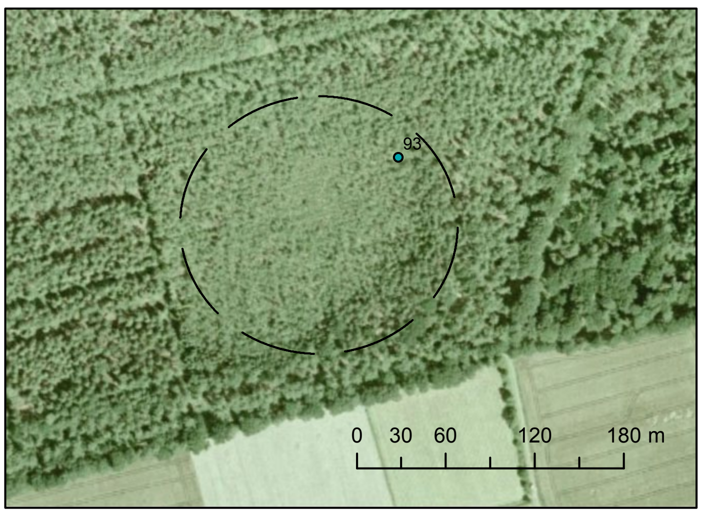

Figure 4.24: Location of Westerschoo, Germany.

The Westerschoo depression was too big to make a cross section and too wet to carry out coring analysis. One test-core has been made to get an indication of the subsurface, however, this borehole was located at the side of the depression. The lowermost part of the core consist of sand, which is presumably the substrate. The uppermost part consists of peat with mosses and wood remains, the vegetation which was still present at the borehole location. Peat development is therefore still going on, even though the artificial drainage systems have made reforestation possible. The Westerschoo depression is relatively large to be a pingo remnant. But even though a pingo remnant might be a good explanation for the origin of this depression, a final conclusion can be made only when more boreholes and a good profile can ensure this depression to be a pingo remnant.

4.4.3 Brill

The Brill depression (WGS 84: 53°34'32"N - 7°37'09"O) is located a few kilometers south of the city Esens in Germany, at the western site of the provincial road (figure 4.25). The depression is partly covered with a small forest with mainly birch trees and brambles and nettles. The provincial road crosses the eastern site of the depression and the southern site is disturbed and now used as a horse paddock. The western and southern site the area is almost 1 meter higher (but flattened) and now covered with maize.

Figure 4.25: Location of Brill, Germany

The Brill cross section is split into two different parts due to human influences in the depression area. One part is taken from north to south, and based on five boreholes, and one part is based on five usable boreholes in a west-east direction (figure 4.26). Both parts of the cross section intersect at borehole 095. Borehole 097 can be excluded, because it was only disturbed material. Most of the other boreholes end in fine sand, with a grain size diameter of 105-210 μm and a little loamy texture. This is presumably the substrate in which the depression has formed.

However there was no clear transition between the sand substrate and the first infill, sandy gyttja. The first infill consists of sandy gyttja. The material is very rigid and dry, has a gummy like-appearance and clear lamina, which can be explained by the forming of peat in relatively deep water conditions with a large aeolian influx of sand. Therefore, the transition between the substrate and infill is not very clear, as similar material has been deposited within a gradually changing environment. The gyttja changes towards a more detritic gyttja with less sand influx. This can be interpreted as a stabilising environment with less wind influence.

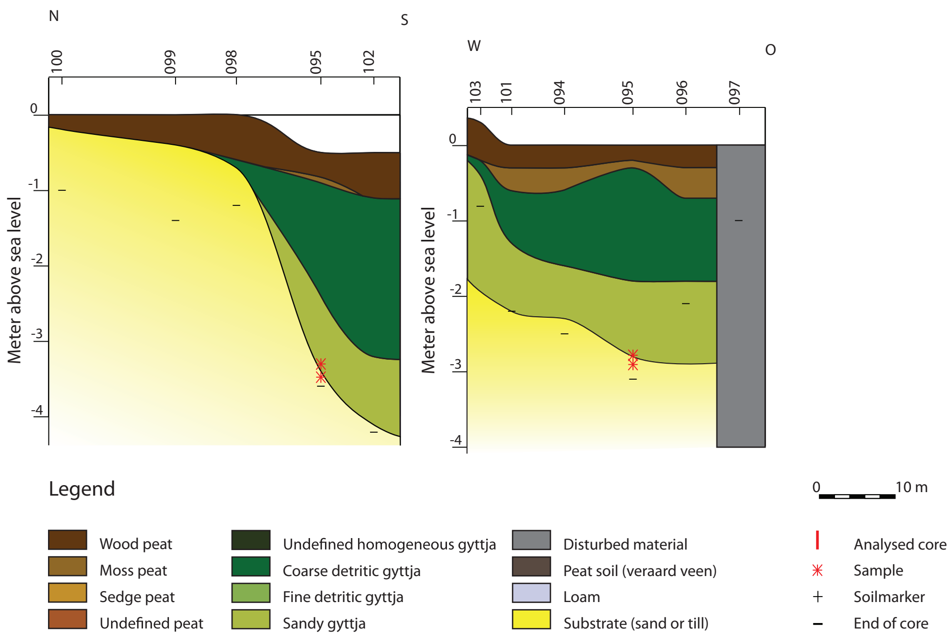

Figure 4.26: Lithological profile of Brill, Germany.

Due to problems with coring in this rigid layer, the basis of the depression is not always reached. On top of this sandy gyttja, a dark brown peat layer is found. This layer consists of many horizontally located plant remains and has a gummy-like appearance and horizontal breaking planes, which indicates to a coarse detrital gyttja. At the transition between both gyttja layers, soil development has been observed in several boreholes, which points to a period of stable and dry situation. This can be recognized by a dark and smoother layer with no clear plant remains and a lighter colour downwards from this dark layer. On top of these layers, an orange brown peat layer is found. This layer contains many plant remains mainly mosses. This moss peat is found over almost the entire width of the west-east profile, although in the north south profile this layer is only found at borehole 095 (intersect borehole). The sequence of these layers pronounce a fluctuating water level. Over the entire surface of the core, in both profiles, a peat layer with many different distinct plant remains, twigs, leaves, wood parts, is found. This wood peat has some disturbances and sandy parts, which are probably due to recent antropogene activities. At the east side of the depression, an entire core has been found disturbed, which could be due to the remnants of a ditch or other excavation. Other disturbance is caused by the provincial road which has been build partly on top of the depression.

The Brill depression matches the characteristics of a pingo remnant, even though the diameter is relatively small. The infill is not distinctive but probably caused by fluctuations in water level and wind influence.

4.4.4 Wrokmoor

The Wrokmoor depression (WGS 84: 53°27'50"N - 7°48'41"O) is located around 2 km north east of the city Friedenburg, Germany (figure 4.27). The depression is well visible in the field because it is almost perfectly circular and around 1,5 meter lower than the surrounding. In the middle of the depression a small circular and very wet forest is located with mainly birch trees. The ground surface is mainly covered with grasses and at the wetter locations moss is grows extensively. The diameter of the Wrokmoor depression is a little over 100 meters.

The Wrokmoor cross section is based on twelve boreholes on a north-west south-east transect (figure 4.28). All twelve boreholes end in sand. This sand is a little loamy, has a grain size diameter of 105-210 μm and has a grey and sometimes blue colour. This is interpreted as glacial till (Lauenburger Ton). The two outermost boreholes at both sides consist of only sand and soil development can be recognized from the surface downwards. Soil development could form at these locations as the sand has been on the surface for a long and stable period. From borehole 106 to 113 the depression is filled with organic material. The first infill of the depression consists

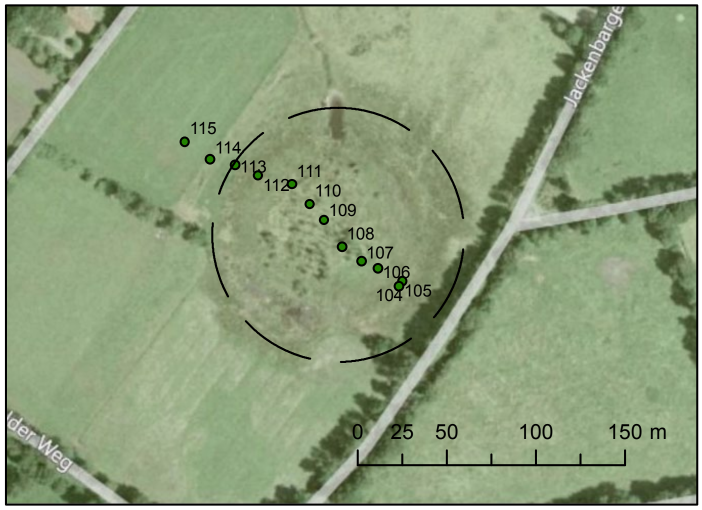

Figure 4.27: Location of Wrokmoor, Germany.

of very sandy, laminated, grey-brown material. This points to a sandy gyttja. The sandiness is not constant over the entire layer, sandier at the north-west side and sandier at the lowest part of the layer, but has same characteristics. The sandiness is not constant over the entire profile, which can be explained by difference in aeolian influx. On top of this layer a peat layer is found with many horizontal layered plant remains of mainly sedges. This layer can be recognized as a coarse detrital gyttja, which points to a deep water level which slowly decreases. At the north-west side of the depression, borehole 109 to 113, a grey brown fine detrital gyttja is found on top of the other gyttja layers. This layer is a little sandy and has some small laminations and plant remains, but the matrix has a smooth and homogeneous structure. This layer may originate from a period of cold water temperatures, with an ice covered depression, in which the gyttja deposited very slow. On top of this undefined homogeneous gyttja different peat layers can be found. The transition between the different peat layers is not or poorly recognizable, but this shows a slow shallowing sequence in the different flora. The lowermost part of this peat contains more sedges and mosses and towards above some cotton grass and trees have been found. The present-day vegetation consists of mosses and sedges, with active peat development and some trees at the dryer areas. At the lowest part of the organic infill in the deepest boreholes, 110 and 111, samples were taken to have a quick pollen scan and

LOI analysis to get an age-indication of the first organic infill.

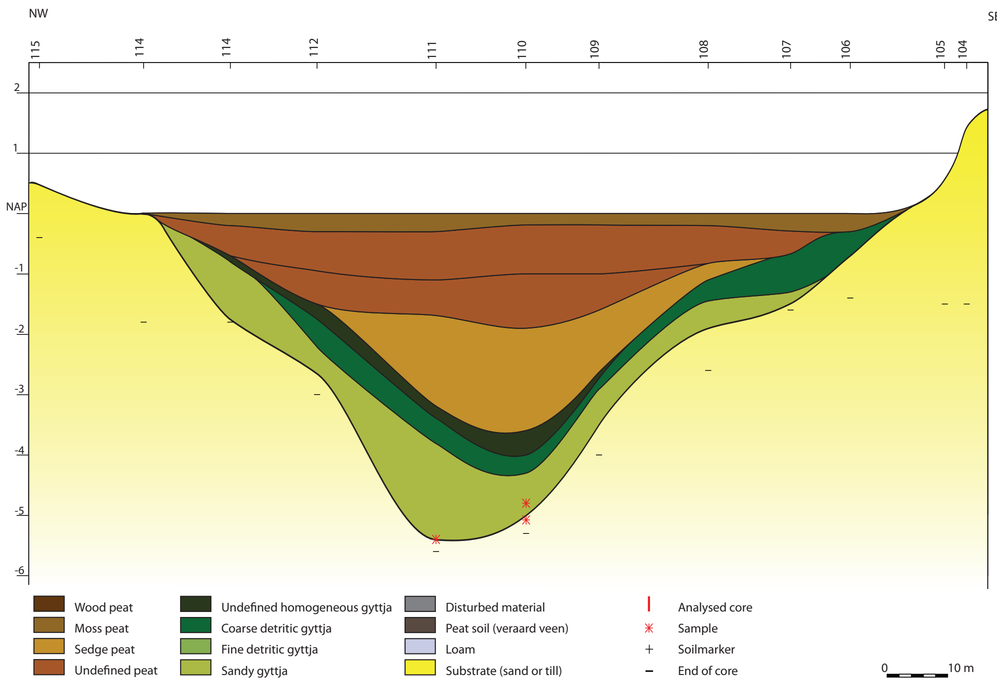

Figure 4.28: Lithological profile of Wrokmoor, Germany.

The Wrokmoor depression is interpreted as a pingo remnant. The dimensions and infill perfectly match the characteristics of a pingo remnant. The results of the pollen samples have yet to confirm this interpretation.

4.4.5 Mamburg

The Mamburg depression (WGS 84: 53°37'32"N - 7°38'20"O) is located around 2 km south east of the city Esens, Germany (figure 4.29). The depression is not very clearly visible on aerial imagery, in contrast to the field observations, where the elevation of the surrounding field clearly shows the presence and size of the depression. The height difference is a little more than 50 cm between the middle of the depression and the surrounding fields. In the middle of the depression, the lowest elevation, the grassland is very wet and the ditches are wider than further away. The surrounded area is all covered with maize, and therefore the overall relief is hardly visible, but there appears to be an overall smooth hill relief. The diameter is of the depression is around 150 meters.

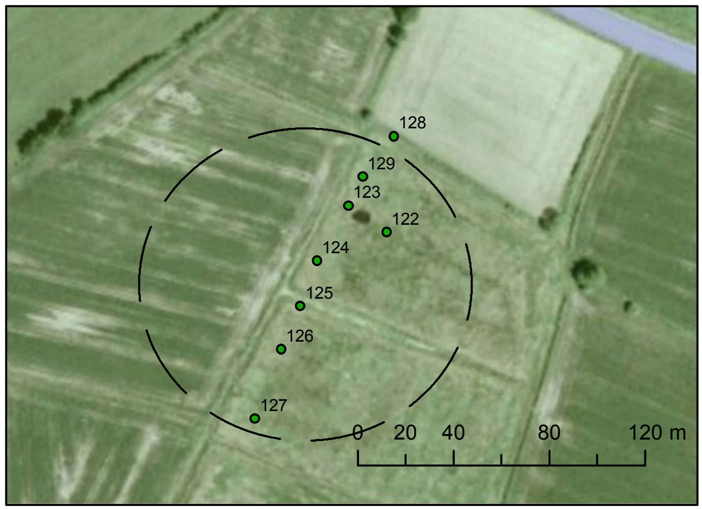

Figure 4.29: Location of Mamburg, Germany.

The Mamburg cross section is based on seven boreholes in a north-east south-west transect. All boreholes end in sand. This sand has similar characteristics in all boreholes. It has a brown grey to grey colour, is a little loamy or humic and has a grain size diameter of 75-105 μm. This substrate has the characteristics of a glacial deposit. The deepest organic infill of the depression consists of a laminated sandy peat, with some sedge and other small plant remains. This fine detrital gyttja has a grey brown colour which becomes greyer downwards in this layer. In borehole 124 some samples were taken to get an age estimation by pollen and LOI analysis. A layer of almost 1 meter thickness and many different plant remains and small different layers can be found on top of the fine detrital gyttja. These different plant remains are all horizontally situated and are mainly sedges, cotton grass, mosses, and some twigs and leaves. This layer is interpreted by a coarse detrital gyttja. The transition from fine to coarse detrital gyttja, together with the plant remains, show a gradual transition from deep to more shallow water depth. The uppermost layer of the cross section consists of disturbed and very sandy peat, with in the lowest 10 to 20 cm a peat soil, shows the influence of human activity and recent soil development.

The Mamburg deperssion shows a characteristic infill of a pingo remnant. Even though the depression is a little small and shallow, the Mamburg depression has been interpreted as a pingo remnant.

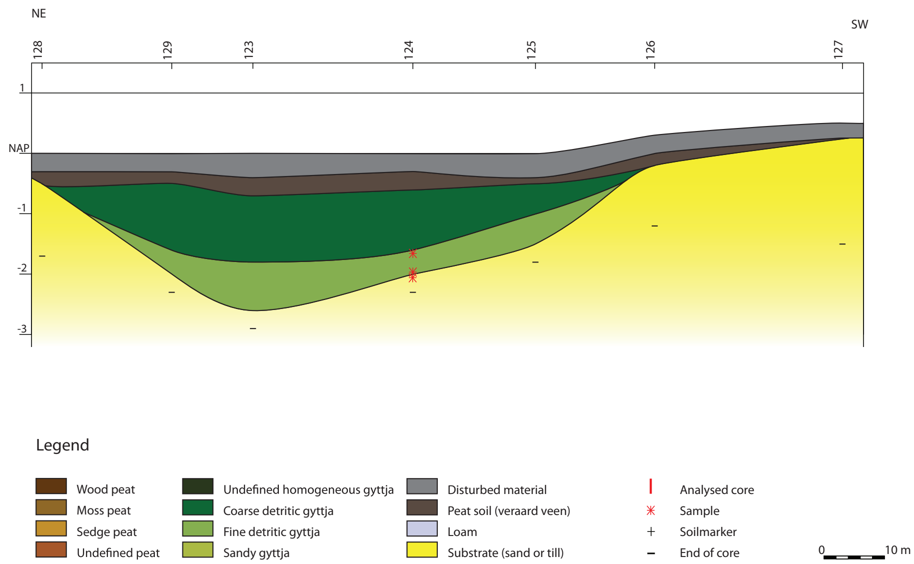

Figure 4.30: Lithological profile of Mamburg, Germany.

4.5 Cloppenburg cross sections, Germany.

In the Cloppenburg area five depressions are investigated. The exact position of these depressions is determined, based on an old topographical map (1970), aerial imagery and field observations.

4.5.1 Kellerhöhe

The depression (WGS 84: 52°53'33"N - 8°05'45"O; around 40 m above sea level (Normal Null)) just south of the village Kellerhöhe in Germany, is partly covered with maize and there is a provincial road though one side of the depression (figure 4.31). The surrounding area has a rolling landscape. This depression shows a clear circular ridge of almost 2 meters higher than the center of the depression. However, only the south side is clearly visible because the rest is covered with maize. The depression has a diameter of about 250 meters. Three boreholes have been taken from south west to north-east.

Figure 4.31: Location of Kellerhöhe, Germany.

All boreholes consist entirely of very fine sand with a diameter of 105-150 μm. Some darker colours can be found in the uppermost part of the boreholes and the colour gradually become lighter downwards. Some sporadic gravel and iron stains are found. The Kellerhöhe depression fill consists presumably of aeolian coversand. The gradual colour transition is the result of soil development in the recent period of non-activity. The Kellerhöhe depression is probably no pingo remnant, but more likely a coversand depression. However, a pingo remnant can not be excluded because the sand cannot act as an aquitard and trap water, so no peat can form in these depressions. Also the collapse of pingos consisting of only sand will not leave any remnants of distortion or change in infill.

4.5.2 Rennplats

The depression Rennplats (WGS 84: 52°49'10"N - 8°18'01"O) is located around 2 km south of the centre of the city Visbek and has a small pond in the middle of the depression (figure 4.32). The pond is entirely surrounded by trees and brambles, around the trees all fields are in use for agricultural purposes. The depression is poorly visible in the field, mainly because of the presence of the pond and trees. The depression has a diameter of about 100 meters and in the surrounding area more similar depressions are visible on aeral imagery. However, most of these depressions are now completely filled with water. As the location was mostly inaccessable, only one borehole was possible, close to the pond.

Figure 4.32: Location of Rennplats, Germany.

The one borehole consists of coarse sandy (diameter: 300-420 μm) loam and contains 2-5 percent gravel up to 3 cm in diameter, at the lowermost part of the core, 240-280 cm depth. Above this grey sandy loam, 60 cm of light brown grey very loamy sand (diameter: 105-150 μm) is found. The lowest part of the core can be interpreted as being glacial till (which coincides with see section 2.2.2). This could explain the wet depression, as the water cannot drain into the impermeable glacial till. The sandy fill could be aeolian sand from the surrounding, as this loction is characterized by the presence of widespread coversand areas (see section 2.2.2). The colour transition between both layers is gradual and is grey at a depth of 210 cm and lower. The core becomes more sandy and less loamy towards the surface. Between 100 and 160 cm depth, humic sandy gyttja or clay is found. This layer is light brown and the grainsize of the sand is very fine (75-105). At a depth of 80-100 cm, the colour becomes brown and the sand grades towards sandy peat. The uppermost part of the core consists of sandy clay, which is mixed and disturbed by plant roots. The Rennplats depression is a possible pingo remnant. However, the organic infill of the depression is less than 1 meter, which is not enough for a pingo, according to the criteria of De Gans (1982). However, a sandy infill does not seem unreasonable, because the location within a coversand area, and can still explain formation of the depression by pingo collapse. Unfortunatly, no profile could be made from this depression, which might explain more of the dimensions of the depression. The characteristics in the landscape point to the Rennplats depression being a pingo remnant.

4.5.3 Erlte

The Erlte depression (WGS 84: 52°50'14"N - 8°17'09"O) is located just north of the village Erlte (figure 4.33). The depression is clearly visible in the field and at the north side is a relatively large pond. Around the pond and at the south side of the pond a small grove covers the depression, mainly birch and alder trees. The depression has a diameter of about 150 meters and the surface elevation in the grove is around 1 meter lower than the surrounding agricultural fields.

In the depression of Erlte, three boreholes were carried out. No profile has been made because the boreholes were to shallow to use for a profile. The lowermost part of all boreholes, between 100 and 160 cm depth, consists of sandy loam, with a sand

Figure 4.33: Location of Erlte, Germany.

grain size diameter of 210-300 μm and up to 10 percent gravel. This part has the characteristics of glacial till, which is the substrate of the depression. The uppermost part of the depression consists of humic fine sand with a grain size diameter around 150-210 μm. The colour of the sequence is gradually changing from brown at the top towards greyish brown to grey at 100 cm depth. Coversand is present in the surroundings of this depression, which presumably acts as the source for the infill of this depression. The humicness and colour transition can be explained by a long period soil development and therefore a stable situation. The Erlte depression is a possible pingo remnant. Even though the infill of the depression is too shallow according to the criteria of De Gans (1982), the pingo could be filled and/or blown out with coversand.

4.5.4 Emstekerfeld

The Emstekerfeld depression (WGS 84: 52°49'51"N - 8°06'06"O) is located halfway between the cities Emstek and Cloppenburg in Germany, (figure 4.34). The depression is not visible in the field and completely covered with a small forest. The small forest is hidden between the maize and is wetter in the middle. The forest has a diameter of a little less than 200 meters and has a circular outline.

The Emstekerfeld lithological profile is based on thirteen boreholes, from north-west to south-east (figure 4.35). At the north-west and south-east side two boreholes,

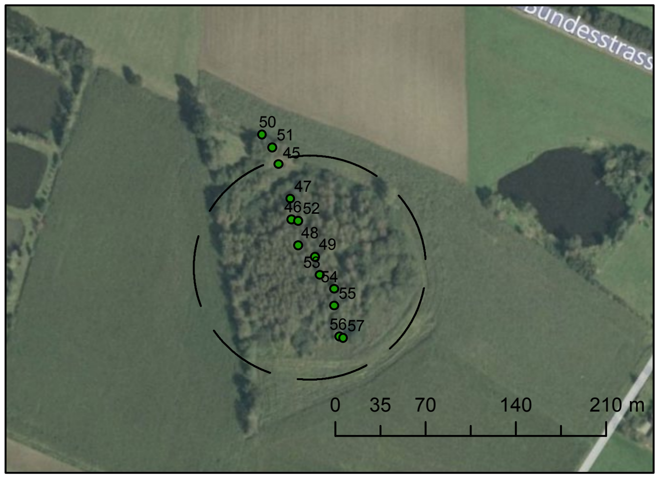

Figure 4.34: Location of Emstekerfeld, Germany.

respectively 050 & 051 and 056 & 057, are taken outside the depression. No peat is found in these 4 boreholes and all 4 end in loamy sand, with a broad grain size distribution from 105 to 420 μm in diameter. This sand contains gravel and is greyish of colour. This sand is also found in the lowest part of most boreholes. A grey and sandy loam layer with clear lamina is found at both sides of the depression. The grey and sandy loam layer with lamina could probably also be found in the middle of the depression, where the boreholes are not deep enough to reach the end of the fine gyttja layer. This laminated layer probably formed by aeolian activity directly after the forming of the depression. The mixed sand is very fine and some organic remnants are found in the loam layer. On top of this loam layer, a sandy and fine horizontally laminated peat is found. It might be that these laminations are similar to varves, annual layering by fine grained sediment related to ice cover in the depression. This layer originates probably from Older Dryas age. The peat is brown and sometimes a little greenish of colour. It contains some plant remains, mainly unrecognisable species, but the peat matrix is homogeneous and a gummy-like appearance. The fine horizontally laminated structure and the sometimes greenish colour and has a gummy-like appearance indicate fine detrital gyttja (Bos et al, 2009). The lowest part of this layer does not contain sand, and indicates a relatively warm and quiet period, probably Allerd. Higher in the same layer more sand is mixed, which indicates a colder period with less vegetation, which coincides with the early part of the Younger Dryas. This layer varies in thickness from 1 meter or even more, to just 10 cm or less, at the north-west side of the depression. The 3 boreholes in the middle of the depression all end in this layer because of the limited length of the bore equipment at boreholes 048 and 049. Borehole 053 was stuck in this layer and could therefore not show the end of this layer. On top of this laminated peat a similar peat layer has been found, however this layer contains more and larger plant remains, mainly consisting of sedges and some *Potamogeton* (pondweed, *dutch: fonteinkruid*). The presence of identifiable plant remains indicates a coarse detrital gyttja. Three boreholes at the north-west side of the depression, coring 052, 046 and 047, have a layer with homogeneous peat layer with some unrecognisable plant remains. This layer is (dark)grey-brown of colour and lacks any sedimentary structures. The (dark)grey-brown layer at the north-west side of the depression lacks any sedimentary structures or identifiable plant remains and can therefore be interpreted as being amorphous organics (Bos et al, 2011). This may or may not be a gyttja and does not tell more about the deposition conditions.

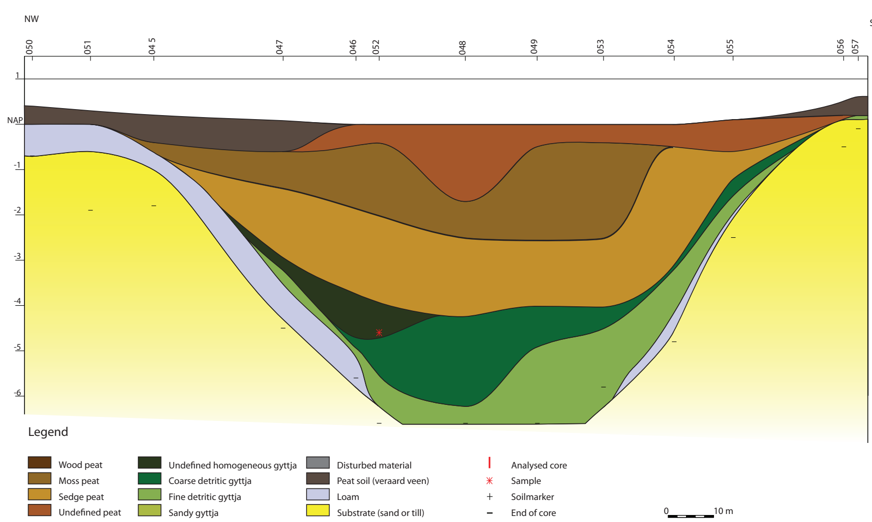

Figure 4.35: Lithological profile of Emstekerfeld.

The transition between the laminated and homogeneous peat layers and the layer on top is very sharp, and clear in colour difference. The layer on top consists of pure peat with many plant remains of sedges and some cottongrass. The thickness of this layer in most boreholes is more than 1 meter and gradually becomes a similar peat on top, with contains still sedge remains, but also mosses and some twigs and wood remains. Which points to a slow shallowing sequence of the water depth, with gradually more terrestrial organics. The uppermost layer at the middle of the depression consist of dark brown peat with a lot of different plant remains, amongst others sedges, cottongrass, red small twigs, mosses and wood remains. At the sides of the depression the upper part is sandy dark peat.

The Emstekerfeld depression is a possible pingo remnant. The dimensions and infill agree with the expectations and the interpretation of similar depressions of pingo remnants in the Netherlands.

4.5.5 Sevelte

The Sevelte depression (WGS 84: 52°49'18"N - 8°03'18"O) is located just south of Cloppenburg, north of the small village Sevelte (figure 4.36). A small round forest is located in the middle of the depression, surrounded with grassland. In the grassland a rim is visible around the forest, with a elevation of more than 1 meter. In the middle of the forest a small lake is present, presumably as a result of peat excavation. The small forest is very similar to the Emstekerfeld site but has a diameter of only 100 meters. The total depression has a diameter of approximately 150 meters.

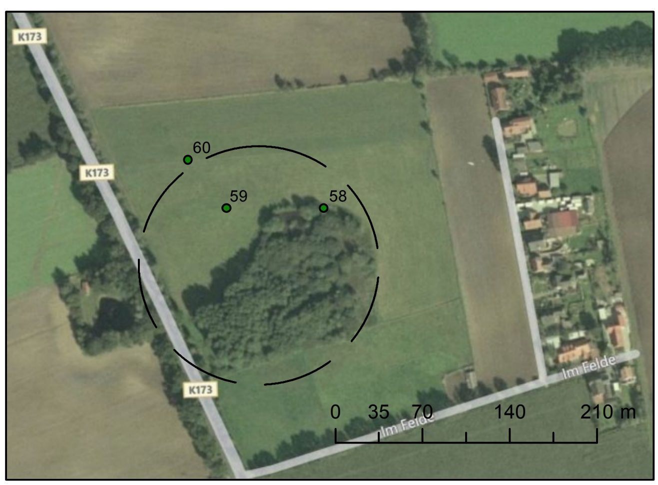

Figure 4.36: Location of Sevelte, Germany.

A cross section is not available, but 3 boreholes have been performed, one in the depression, one on the ridge around and one outside that area. The borehole in the depression, number 058, is almost 5 meters deep. The Sevelte depression has a similar infill as the Emstekerfeld depression. The substrate of this depression is presumably below the deepest part of the boring and therefore has not been reached. In the lowest part of the core at a depth between 250 and 490 cm, the material consists of peat with mainly horizontal laminated plant remains. From down to the top, the colour changes from dark greenish grey to to brown grey and grey brown in the upper part of this layer. The peat has a gummy-like appearance and contains more visible plant remains towards the top, this all points to gyttja, which becomes more coarse detritic towards above. This means that during the accumulation of this material, the waterlevel in the depression gradually decreased. Some *Potamogeton* seeds have been found at a depth around 440 cm and between 400 and 420 cm, the gyttja contains some sand. On top of this layer, between 240 and 160 cm depth, the peat has a orange brown colour. In this peat, plant remains from mosses, sedges and cotton grass are found. The plant remains are not perfect horizontally laminated, but breaks with a preferred orientation with a small angle with respect to the horizontal plain. The layer between 150 and 80 cm depth consists of sandy peat with a dark brown colour contains plant remains of cottongrass and roots. The uppermost part of the depression, indicates a oligotrophic condition, in which sedge peat and moss peat could form. The cotton grass remains are mixed in large parts of the core, but these may originate from other parts of the core. The sand has a fine grain size, with a diameter of 150-210 μm. The uppermost 80 cm of the core consists of humic fine sand, with a mixture of loam, sand and plant remains. Towards the top, this part becomes more humic and rooted. No clear structure could be found in this layer. The borehole at the side of the depression (number 059) with an elevation of about 1.5 meters above the previous borehole has a total depth of 370 cm. The lowest part of the core, between a depth of 370 and 330 cm, consists of peat, with many small horizontal sandy layers. These laminations have a thickness varying between 2 to 5 mm and the sand has a grainsize of 105-150 μm. The colour varies between brown and brownish grey. Laminated peat, gyttja, and sedges are indicating to a relatively deep water depth. On top of this layer, the remnants of a tree have been found. Up to a depth of 200 cm, similar peat has been found. These are probably not in-situ, but the tree has fallen into the depression when water was present in the depression. Towards the top, the samples consists of more and larger plant remains. Some *Potamogeton* seeds are found at a depth of 250 cm. The layer between 200 and 80 cm depth consists of a matrix of fine sand with a greyish brown colour. The grain size of the sand varies between 150-210 μm to 420-600 μm. At the lowest 50 cm of this layer, some clusters of loam are mixed in the sand. Also gravel up to 5 percent is present in the uppermost 50 cm of this layer. The uppermost layer of the core, from 80 cm upwards, consists of sand with a grain size of 210-300 μm in diameter. This sand has some clusters of loam and a little gravel, less then 3 percent, but with a diameter up to 5 mm. Different particoloured parts are mixed within the greyish brown matrix. This sand is therefore not only from aeolian origin, but could be caused by antropogene supply from the sides. This coincides with the findings in borehole 060 at the other side of the rampart. The borehole at the other side of the rampart, number 60, has a depth of 130 cm. The lowest part of the core, between 130 and 60 cm depth, consists of loam with a pronounced orange colour. Some sand with a diameter of 210-300 μm and some gravel parts up to a diameter of 1,5 cm are mixed in the matrix. The uppermost part, from 60 cm and above, consists of grey fine sand, 105-150 μm with some loamy and iron clusters. This boring consists of mainly sand and loam with the characteristics of glacial till. This may be the substrate of the depression as well and redeposited at the side of the depression which formed the rampart.

The Sevelte depression has the characteristics of a pingo remnant. A clear rampart around a circular depression with a depth and diameter indicates the presence of a pingo remnant. But the peat underneath the rampart does not agree with the characteristics. The peat underneath the rampart has a similar composition as in the middle of the depression and therefore the rampart must be formed after the infill of the depression. The depression could still be the remnant of a pingo, but the rampart not. This could be formed by aeolian processes in the Holocene, or by human activity. A complete profile and boreholes down to the substrate are required to provide a final conclusion about this depression.

4.6 Overall interpretation of cross sections

Most of the circular depressions studied for this project have similar characteristics. From the 17 described depressions, 10 have complete cross section of the subsurface. These 10 cross sections all show similar morphology and fill. The first infill of all depressions on top of the substrate starts with gyttja. Whether or not this gyttja is sandy or not is dependent on the climate and geographical settings during the sedimentation. Stronger wind results in a sandier fill, while deep and quiet water conditions result in a clear organic fill. The wind is not only a local factor, but is dependent on the regional climate. The LOI results of the depressions show a regional climate variable in the amount of sand influx in the organic infill. Pollen analysis will provide an age estimate for the first infill of the depressions. According to the fill sequence, the depressions originate from around the Late Pleniglacial and all depressions start with organic sedimentation in the Early Late Glacial. The entire profile of most depressions shows a similar sequence of shallower water depths towards the top. The plant remains in the organic deposit become more terrestrial towards the surface of the depression. This indicates a continuous fill of the depression with organic material without external disturbances. Some of the depressions show different layers or a double sequence of terrestrialisation, which can be explained by a changing groundwater level.

4.7 Loss on Ignition

The results of the Loss on Ignition analysis are shown figures 4.37 and 4.38. The first figure (figure 4.37) shows the LOI curves of two German depressions, Emstekerfeld (A) and Timmelteich (B) and their correlation. The second figure (figure 4.38) shows the LOI curves of two depressions in the Netherlands, Sleenerstroom I (A) and Krakenven (B) and their correlation. The correlation interpretations are based on the LOI curves and lithological descriptions and has to be confirmed by pollen analysis (R. de Bruijn, in prep.).

The Timmelteich LOI curve shows the organic content of the samples at a 1-2 centimeter interval over the entire depth of the core. The deepest part of the core

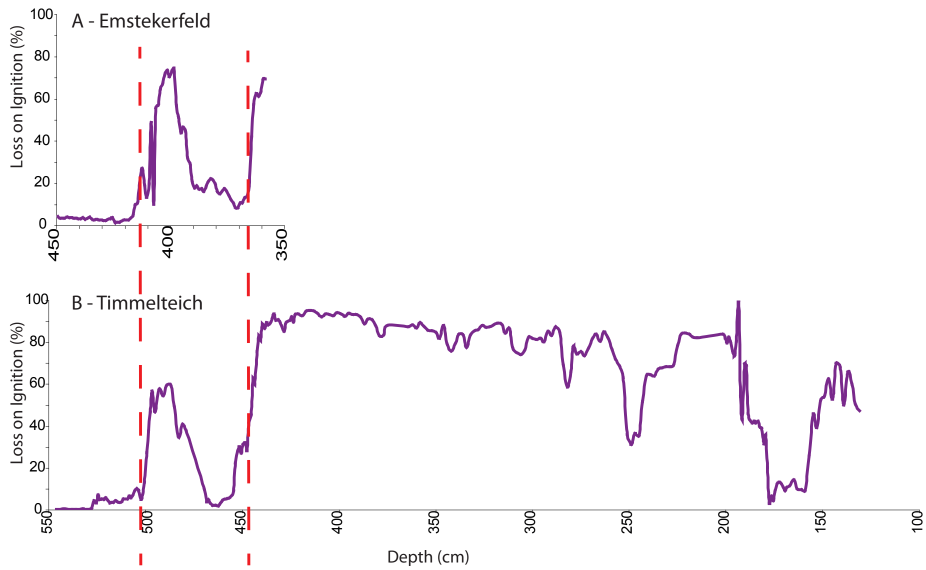

Figure 4.37: LOI of Emstekerfeld and Timmelteich.

(550-530 cm) consists of almost 100 % inorganic material, which coincides with the lithological description of the core, purely sand. From a dept of 530 cm more organic material is present in the samples. This coincides with the sandy gyttja layer in the core. From a depth of 500 to 480 cm a distinct peak of organic material up to 60 percent can be recognized. This peak in organic content is the result of less sand influx or slower sedimentation rate during sedimentation in the depression. The influx of sand becomes higher between 480 and 450 cm depth. Above this depth the percentage of organic content becomes almost 90 percent. The transition between the sandy gyttja and very organic layer is gradually and occurs with some steps. After this, the organic content stays relatively high but decreases very slowly. Some small and sandier variations in the graph can be distinguished and become larger towards the surface of the depression. The Emstekerfeld LOI curve shows a very similar pattern, even though this core is less than 1 meter long. The red lines in figure 4.37 show possible correlations between both curves. The left line gives the transition between substrate and infill, which coincides with the starting age of the first infill, presumably the end of the cold Late Pleniglacial. The peak in organic material directly after the left red line can be interpreted as the warmer Bølling/Allerød interstadial. In the Emstekerfeld graph the Bølling might be distinguished separately at a depth of 415 cm, just before the high peak of the organic material starts. After the Bølling/Allerød interstadial, the graph shows lower organic content, this coincides with the Younger Dryas cold period. During this period, a larger sand influx was present regionally. The start of the Holocene is interpreted as the right red line. Only the Timmelteich curve is long enough to see the relative stable warm period, recognizable as a high organic content with some variations in sand influxes. These variations, from 250 cm upwards, might be caused by the human forest clearance. The peak at a depth of 195 cm was a piece of wood, which gives a distortion in the continuity of the curve.

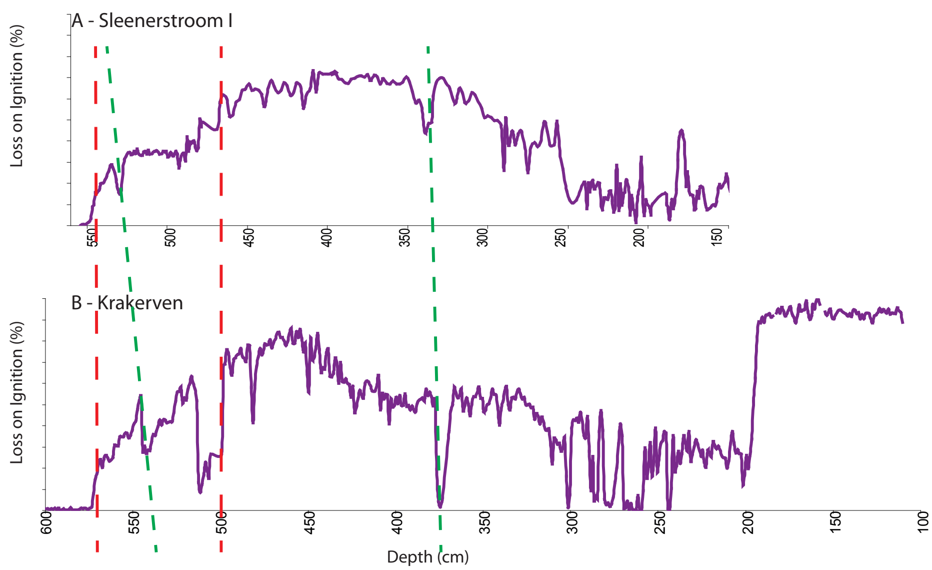

Figure 4.38: LOI of Sleenerstroom I and Krakenven (Woolderink, in prep).

The LOI curves of both Krakenven and Sleenerstroom I are shown in figure 4.38. These curves are not very distinct in the transitions between warm and cold periods. The first infill of the depressions is indicated by the left red line. This depth shows the transition between the substrate and the first infill, and the start of the Bølling/Allerød interglacial. The curves show a different pattern after this first transition. The second red line might indicate the start of the Holocene, after a lower organic content during the Younger Dryas. However, in the Sleenerstroom I curve, the Younger Dryas is not distinct. A constant LOI value for the depth between 530 and 480 cm cannot be explained by the Younger Dryas cold period, but might be a distortion in sampling or caused by mixing processes(bio- or cryo- turbation). The Younger Dryas cold period seems to be more distinct in the Krakenven LOI curve, just before the second red line. This curve shows very low organic content between a depth of 500 and 520 cm with sharp transitions towards higher values. The left green line connects a small depression in both curves within the cold period before the Holocene starts. This might indicate the Older Dryas cold period, which separates the Bølling and Allerød interstadial. Even though this period was relatively short (less then 200 years) and might not have influenced the organic content in the sedimentation sequence of these depressions, this could be an explanation for the lower values in the curves. The second green line shows a similar depression in the LOI values, which cannot be explained yet.

4.8 Spatial distribution of pingo depressions

The idea of making pingo maps from a digital elevation model is easier than the actual action. The eCognition Developer is a useful program to recognize patterns. Even though the entire analysis has not yet been carried out, it showed that it is possible to recognize circular depressions in an elevation model, which could be used in future studies. For the recognition of depressions with use of only the digital elevation model as input, a small area is used as a test location. In this area (figure 4.39) clear circular depression are present, as well as some roads, villages and agricultural patterns.

4.8.1 Depression recognition

With ArcGIS, the contour lines provide the best results for the recognition of circular depressions with a contour interval of 30 cm in elevation (figure 4.40A). However, this

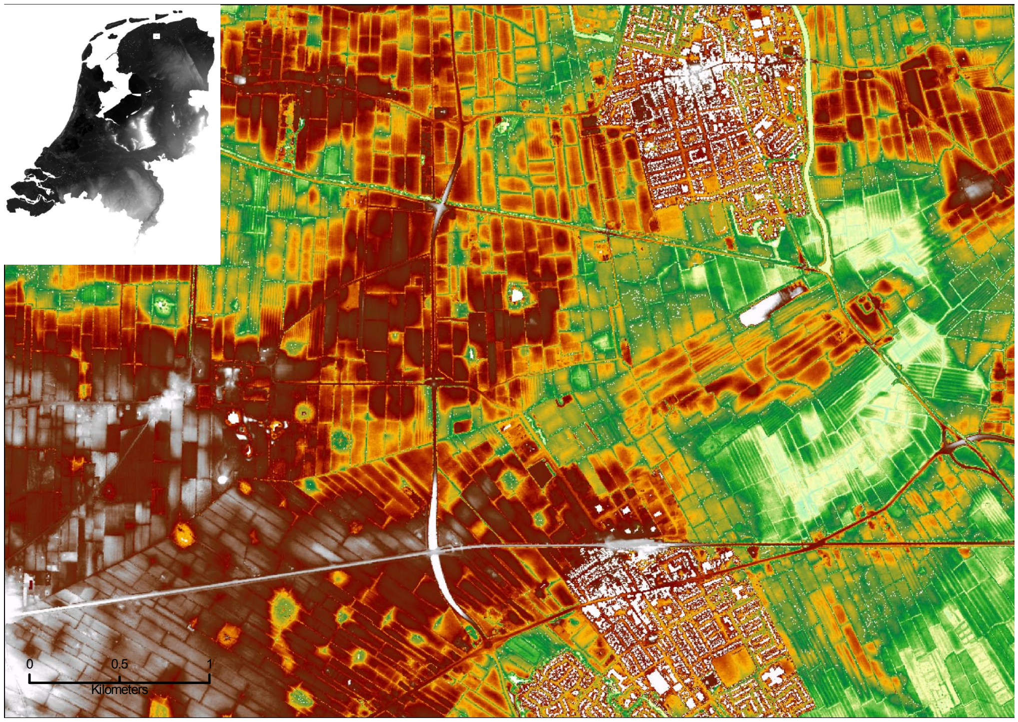

Figure 4.39: The digital elevation model test area

is dependent on the area. The elevation difference of the surrounding and depressions determine the contour interval which is needed to recognize the depression in the surface elevations. In this figure, the problems caused by ditches and roads are clearly visible. The colours in the figure are elevations, with yellow indicating the higher contour lines and red the lower.

The resuls of the eCognition process are shown in figure 4.40B. This program is made for recognizing patterns and classifying these by criteria of the user. For depression recognition the diameter and circularity of the depressions are used as classification criteria. In this figure, the colours indicate the different classifications. Red are all circular depressions which do not meet any criteria, the light blue blocks are depressions with a diameter smaller than 30 m and the circular depressions the depressions with a circularity larger than 0.9. Only the dark blue blocks in the figure meet both criteria; have a diameter larger than 30 m and a circularity larger than 0.9.

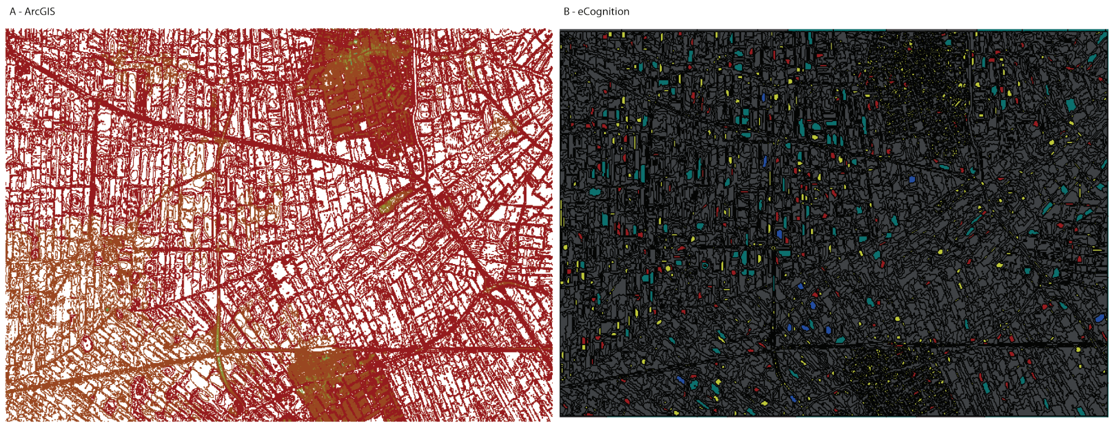

Figure 4.40: The result of depression recognition with (A) ArcGIS and (B) eCognition on the test area

4.8.2 Pingo catalogue

For this research, all pingo literature has been put into one database. In addition to the literature, previous data from geological and geomorphological maps are shown in figure 4.41. This figure shows a large difference between the different maps. This could be because of the different sources of information, field, corings or satellite data, and the difference in date, before and after the AHN was available. The geomorphological map of the Netherlands seems to cover most depressions. However, in this pingo classification, it covers as well circular depressions with and without a rampart, which could be pingo remnants, aeolian depressions or other circular depressions. Excavated depressions are filtered out of this class, as most of these depressions occur in large scale peat areas and have squared shapes. Even though these excavations are filtered out, some depressions occur in the south and middle Netherlands, where literature on the existence of pingo remnants is scarce.

Most of the depressions can be found on the till-plateau in the northern Netherlands. This could be due to a several reasons; (1) most research has been done in this region; (2) preservation of the pingo remnants has been best in this region; (3) pingo remnants occurred mostly in this region.

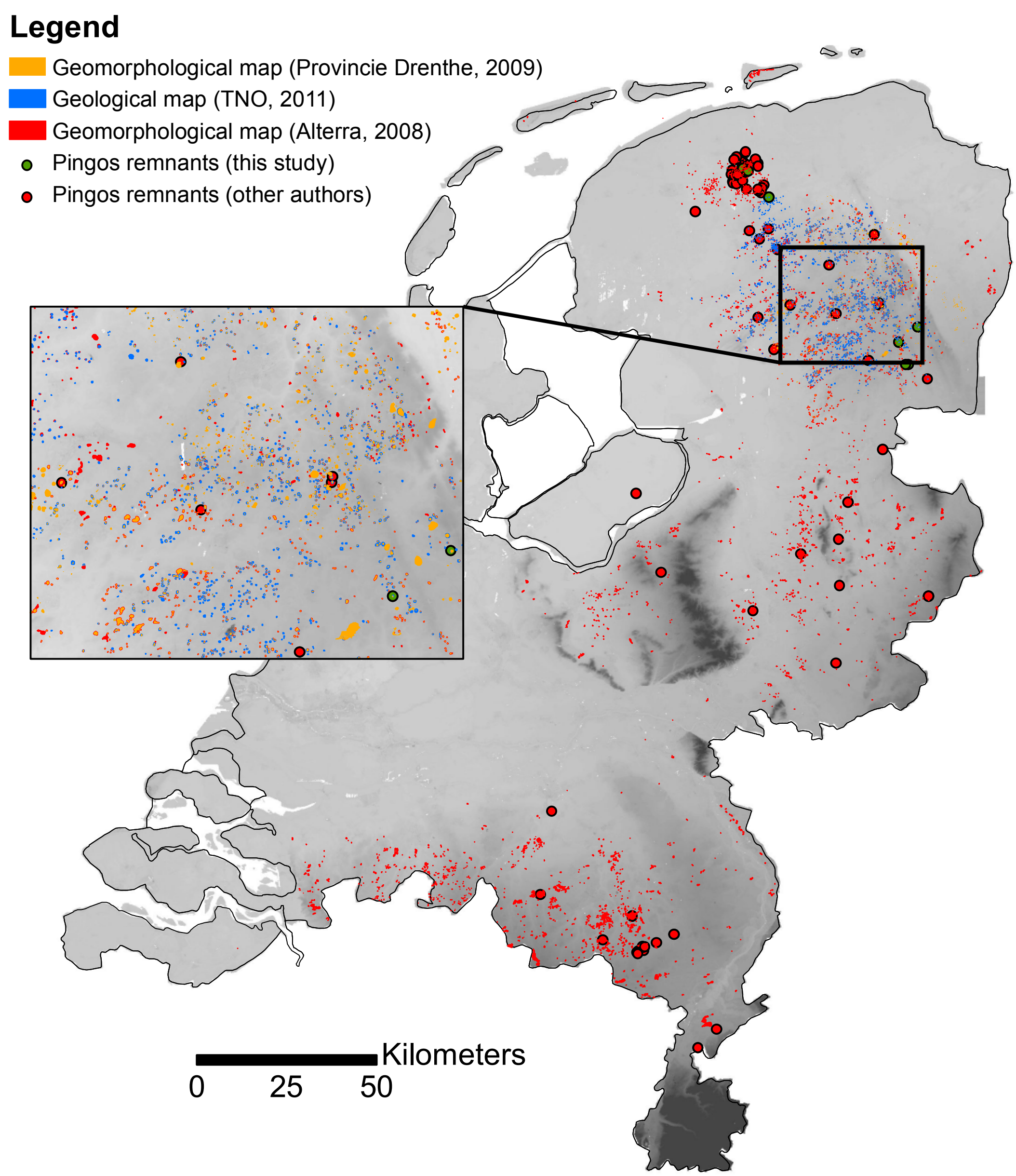

Figure 4.41: Spatial distribution of pingos according to TNO (Blue), Provincie Drenthe (Yellow) and Alterra (Red).

4.8.3 Density analysis

The spatial analyses of the pingo remnants in the Netherlands show a similar distribution (table 4.2) to pingo distribution in the Mackenzie Delta in Canada (figure 4.42). This indicates that the distribution of the pingo remnants in the Netherlands is not impossible and the pingos could have been active simultaneously. Similar spatial distribution patterns are found in Northern Alaska (Jones et al, 2012) and Northern Asia (Grosse and Jones, 2011). A quantitative analysis has been done by Grosse and Jones (2011), who have calculated a spatial density distribution for most parts of the world in the number of pingos per 100 km^2. This number has been averaged over large regions, but gives an indication about possible densities of pingos. In table 4.2 the results fron Grosse and Jones (2011) are shown, including the inferred density for the Netherlands.

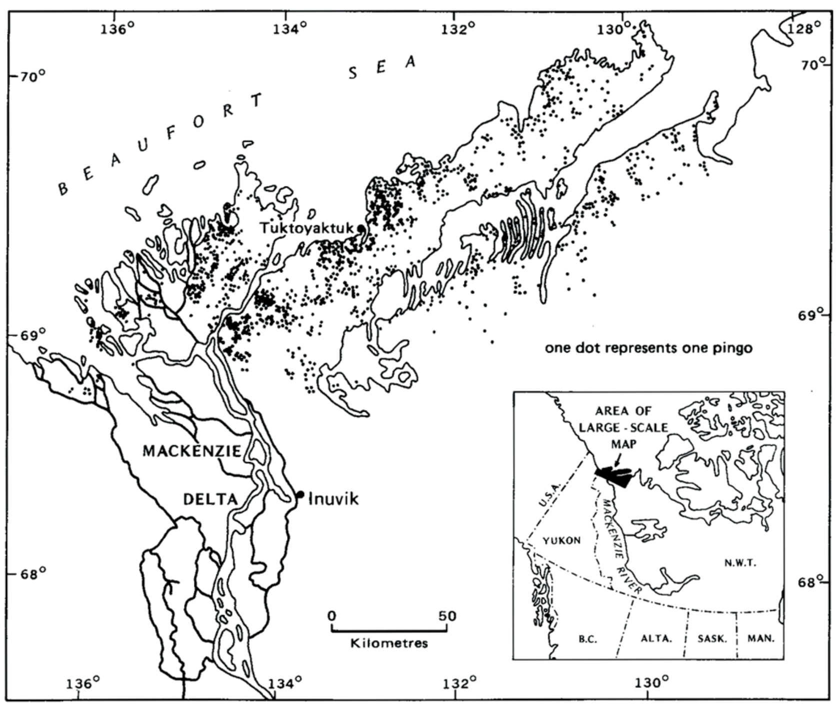

Figure 4.42: Pingo distribution in the Tuktoyaktuk Peninsula and Mackenzie Delta Areas, Western Arctic Coast, Canada (Mackay, 1962).

Region	Density (per km^2)	Source
Alaska		
Interior Alaska	less than 1	Holmes et al, 1968
Alaska Coastal plain		Walker et al, 1985
Flat thaw lake plains	0.096	
Gently rolling thaw lake plains	0.286	
Floodplains	0.012	
Hills	0.027	
Siberia		Grosse & Jones, 2011
Yamal Peninsula	0.13	
Gydan Peninsula	0.21	
Taymyr Lowland	0.12	
Khatanga-Anabar Lowland	0.13	
Lena River Delta	0.06	
Central Yakutian Lowland	0.28	
Yana River Delta	0.08	
Indigirka Lowland	0.14	
Kolyma Lowland	0.12	
Anadyr River Valley	0.28	
NW Canada		
Yukon region	less than 1	Hughes, 1969
Mackenzie region	less than 8	Stager, 1956
Greenland		
Traill Island	less than 11	Worsley & Gurney, 1996
Netherlands		This study
Drenthe	0.74	
Friesland	0.26	
Groningen	0.05	

Table 4.2: Pingo density in different regions (after Grosse and Jones, 2011)

5. Discussion

5.1 Pingo criteria and geometry

De Gans (1982) has introduced some criteria for circular depressions to be a pingo remnant or not. These criteria are widely used by other researchers in the Netherlands, to give an indication of the origin of a circular depression. One of these criteria is the presence of a rampart. However, the present research shows that this is not a rigid criterium. Of the 17 pingos studied for this report, the two with the most pronounced ramparts are interpreted as deflation depressions and not as pingo remnants. In addition to this, the catalogue of all studies of pingos in the Netherlands and North-west Germany contains only a few depressions with a visible rampart. In this study the presence of a rampart is therefore not used as a primary criterion. But if the depression is interpreted as a pingo remnant, the presence of a rampart is an extra proof of the depression being a remnant of a pingo. In Germany, many depressions are present in the subsurface as well as in the Netherlands. However, only a few of them are studied in detail and almost none of them are interpreted as being pingo remnants. One of the reasons is that Garleff (1968), one of the few people who have looked into detail to these depressions, uses a criterion of Wiegard, (1938) that pingo remnants need a rampart for being a pingo remnant. But the most important reason is that it is generally accepted that all these depressions are dead ice holes, thermokart lakes, aeolian depressions or caused by subrosion (karst). Dead ice holes and thermokarst lakes usually does not show any sign of slumping. In the relict features of this study almost no signs of slumping have been found either. However, the investigations where not on this level of detail to be able to recognize slumping. But because slumping evidence is very rarely found this is an accepted explanation of the circular depressions in the northern part of Germany. Böse (1995), draws this explanation of dead ice and ground ice into question, mainly because undisturbed Laachersee tephra is found in organic sediments in many of depressions around the area of Berlin. The dead ice and ground ice must have been melted away before early Bølling at latest as dead ice is not able to sustain a winter in which the lake floor of a depression is not frozen. Apart from this, the formation of dead ice need the preservation of glacier ice. For depressions with an late-Holocene infill, this glacier ice must have been from the Weichselian ice-age. However, no proof of glaciation as far south as the study area of this study has been reported. Dead ice holes are often difficult to reconstruct as they occur mainly in irregular end-moraine topography and/or glacial till deposits. This does not explain the occurrence of circular depressions in the northern Netherlands and adjacent Germany and in addition, dead ice depressions are rarely filled with organic sediments as they are situated well above the water table (Böse, 1995).

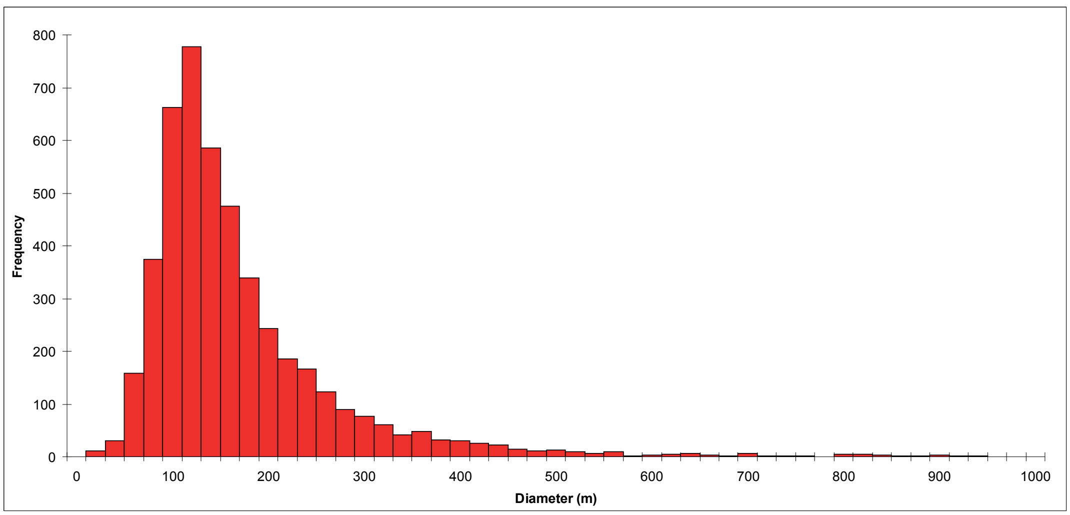

Figure 5.1: Histogram of the different diameters of the circular depressions in the Netherlands

Other criteria of De Gans (1982) regard diameter and depth, a minimum depth of 1.5 meter and minimum diameter of 25 meter. For this study, similar criteria are used, as well as that circularity has been taken into account. The criterion for diameter is based on the histogram of figure 5.1, according to the data of three digital maps (Alterra, TNO, province of Drenthe). All circular depressions from these three datasets are analysed and the histogram of figure 5.1 shows a clear maximum occurrence with a diameter of 140 meter. Below 20 meter and above 600 m almost no circular depressions are interpreted as pingo remnants. Therefore, these criteria are used as a diameter criteria in this study for any further analysis. The circularity, perimeter and diameter of all these depressions is determined with the use of ArcGIS. In figure 5.3 the relation between the perimeter and the circularity is shown in a scatter plot. Note that this scatter plot excludes the depressions with a diameter smaller than 20 m or larger than 600 m and depressions with a circularity of 0.6 and larger. The application of these criteria causes the cut-off at the applied circularity in the scatter plot.

For the analysis in eCognition, a minimum of 30 meters and circularity of 0.9 is used. This was done to get the best indication of this method for the test area. When applying this method for the entire Netherlands, the criteria of pingo depressions must be consequent and correct. More research about the exact criteria is needed and extensive analysis with eCignition can give better density patterns of the occurrence of pingo remnants in the Netherlands. Satellite photographs can be used in future research in addition or instead of the high resolution digital elevation model. Then, this method can be used for a larger area, when no high resolution digital elevation data is available.

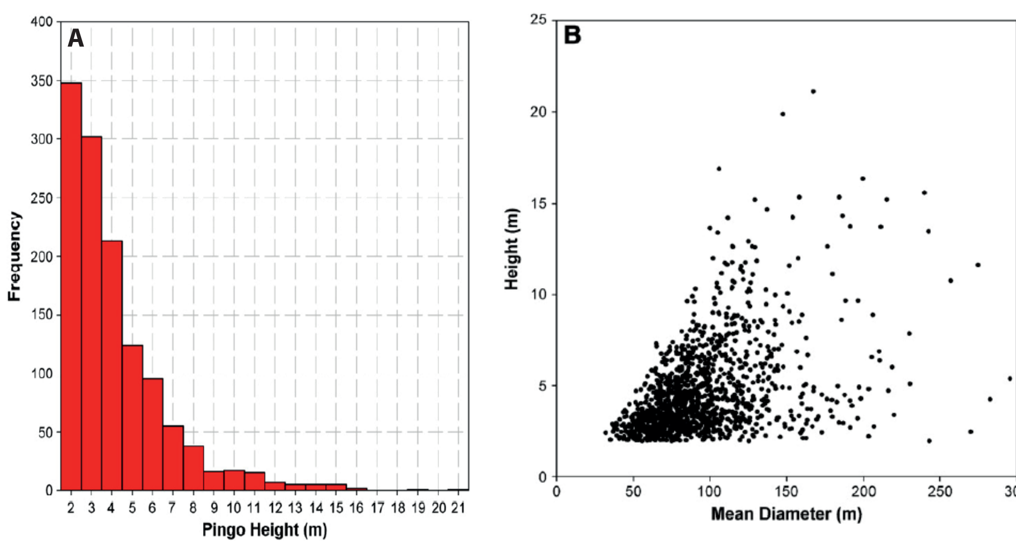

Figure 5.2: (A) Histogram of pingo height for 1247 researched pingos, taller than 2 meter and (B)a scatterplot showing the relation between diameter and height (Jones et al., 2012)

The different pingo characteristics of active pingos are extensively described by Jones et al., 2012. In this paper, the geometry of 1247 Alaskan pingos has been investigated. From this pingo database, different were carried out. The basal diameter has been categorized in three classes; small (¡100 m), medium (100 to 200 m) and large (¿200 m). According to these categories, most of the pingos in the Netherlands can be classified as being medium (figure 5.1). The height of all pingos has been categorized into similar classes; short (2 to 5 m), medium (5 to 10 m) and tall (¿10 m). According to Grosse and Jones, 2011 and Jones et al., 2012, it appears that most (95,5 %) pingos are lower than 10 meters (figure 5.2A). Even it is known that pingos can grow up to 60 meters in height (French, 2007), this seems to be the exception on the main occurrence. It is most likely to find pingos with a elevation around 5 meters. The relation between height and diameter (figure 5.2B) does not show a perfect relation, but can be used to give an indication of the height of relict pingos, when the diameter is known.

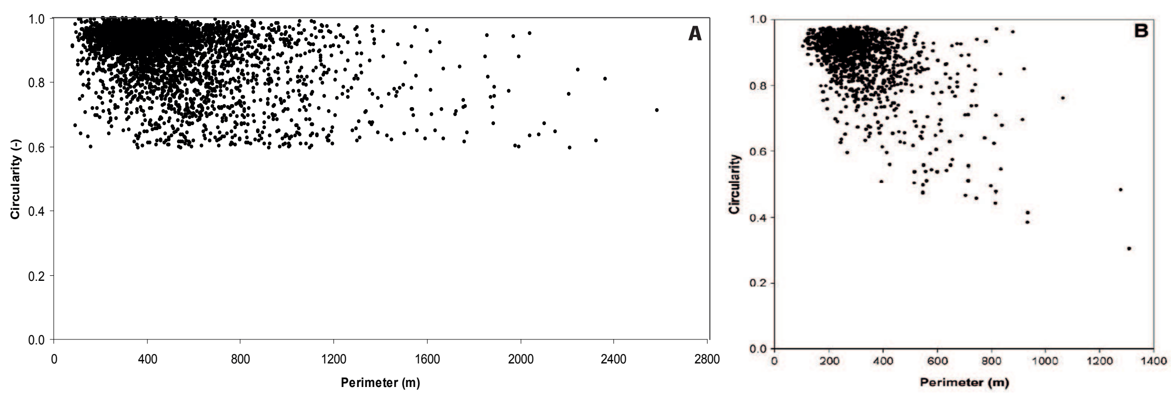

Figure 5.3: Scatter plot showing the relation between perimeter and circularity for (A) this study and (B) Jones et al. (2012)

Both scatter plots (figure 5.3) show a similar relation, when the perimeter increases, the circularity decreases. However, the scale of the perimeter is twice as large for this study, which could give a distorted view on the graphs. The difference could be explained by the measurements methods, or could be the result of a different pingo formation system (open vs closed). Closed system pingos have a limited perimeter caused by the limited availability of water while open system pingos have a continuous water supply.

The pingos in the Mackenzie Delta are closed system pingos and their size is limited by the talik in which their water supply is stored. According to Mackay (1979) the basin in which a pingo forms has to be at least 4 times as large as the diameter of the pingo, to supply sufficient pore water. The formation of Newpingo in the Illisarvik lake basin is therefore very strange. The Alak pingo already uses the water in the residual Illisarvik pond, which is shrinking sufficient since the last years. The Newpingo uses the same water source, which could explain the recent shrinking of the pond, but generation of a new pingo is unexpected. Presumably the pond cannot supply both pingos and both Alak and Newpingo will stop growing in the near future. The morphology of active pingos is not only dependent on the source of water and therefore the pingo system, but also on the amount and type of sediment and subsurface and the slope on which the pingos occur. Jones et al, 2012 (figure 8) show different topographical cross sections of active pingos, which are very similar to the two cross sections in Illisarvik (section 4.1).

5.2 Pingo formation

The formation of pingos in the Netherlands is a main point of discussion. The relation with the subsurface might explain the occurrence of many pingo remnant depressions in the Northern Netherlands and Germany. Similar studies in Wales show that the permeability of the superficial sediments is essential to increase the hydraulic pressure, and the formation of pingos. The impermeable glacial till has caused an increasing groundwater pressure (Mackay, 1983; Ross, 2007). Pingo genesis in the Netherlands has therefore most likely been open system. Not only because of the subsurface, but also because there is no evidence of permafrost further south of the Netherlands, which decreases the possibility of the presence of continuous permafrost on a large scale. Because closed system pingos require continuous permafrost conditions and an unfrozen talik, this type of pingo genesis is less likely, but might be possible on a small scale. If both pingo systems can occur simultaneously has never been shown, but according to their genesis the remnants of both pingo systems should be different. Open system pingos leave behind deeper remnants with an inverted cone shape. The intrusion ice has its source below the impermeable layers and will generate a deeper root of the pingo and which leave a relative deep depression with steep sides. These kind of depressions are found in the Netherlands, for example Freaymaborg with a depth of 20 meters (Nijhuis, 2006). Closed system pingos have their water source close to the surface. The segregation ice, which forms the pingo ice lens, forms in the upper part of the permafrost (close to TTOP), in which the permafrost is most ice-rich (French, 2006). The remnants of these closed system pingos are presumably shallow and do not penetrate deep into the subsurface. The diameter of the depression is dependent on the available water supply to form the ice lens, and is only limited for closed system pingo depressions.

The pingo occurrence in relation to the subsurface has been researched before by Williams et al, 1977. This study was about the relation between pingo distribution and density and superficial geological units. However, this study compares aeolian, marine and floodplain sand and silt deposits of different thickness and no glacial till deposits are taken into account. Aeolian sand is shown to have the largest occurrence of pingos (up to 0.18 pingos per km^2).

5.3 Pingos and vegetation

Vegetation cover on top of pingo hills could be a mechanism to protect the pingo against aeolian erosion. Almost all pingos in the Canadian Arctic are covered with tundra vegetation. This protects them from erosion, especially when strong (katabatic) winds are blowing from one dominant wind direction. In the Mackenzie Delta, Canada, only one known pingo has shown aeolian erosion over the last ~100 years (at historical pictures of 1910 and 2011, pers. comm. Chris Burn). However, in the high Arctic, no vegetation covers the pingos, which exposes them to strong winds and aeolian erosion. The vegetation cover can have influence on the degradation speed, when the degrading pingo needs solar exposure to continue collapsing. Many pingos degrade in different stadia. When the upper part degrades, the overburden sediment resettles and can keep the pingo stable for many decades, as long as the ice lens stays below the active layer. Figure 5.4 shows a picture of a pingo which is in a stable degradation state. Even though the pingo has started to degrade, the internal ice lens is now stable and might stay stable for many decades if no external changes occur.

Figure 5.4: A partly collapsed but now stable pingo in the Mackenzie Delta, Canada (Mackay & Burn, 2011)

In the Netherlands, katabatic, dry and cold winds where presumably present during the last glacial (Hubberten et al, 2004). Tundra vegetation was present (Hoek, 1997) and might have covered pingo hills as well. In the Timmelteich depression (section 4.5.1) *Salix polaris* leaves have been found at the transition between the substrate and the first infill of the pingo depression. This could be evidence for a vegetation cover on top of the active pingo. Because *Salix polaris* is a species that requires dry and cold climate, it is not likely that this species grew in a depression. Comparable with this, plant remains of *Betula nana* has been found in the lowest part of a presumed pingo depression elsewhere in the Netherlands as well (pers. comm. Wim Hoek).

5.4 Growth and degradation of permafrost

During the last glacial period, the Netherlands has been covered with permafrost. A long period of consecutive cold winters can grow permafrost. The exact time needed to grow permafrost is strongly dependent on the type of sediment, thermal properties and water content (French, 2007; Ballantyne and Harris, 1994). Presumably the last glacial period has been cold enough to grow permafrost for a least a several meters thickness (pers. comm. Chris Burn). The degradation of permafrost is a slow process. The recent global warming, which has shown to be higher in the Arctic areas, might be the reason for thinning of the permafrost. The end of the last glacial maximum has been shown to end with an even more abrupt climate warming at the onset of the Lateglacial, round 14.7 ka (Lowe et al., 2008). This could have caused a fast degradation of permafrost. However the thawing of permafrost is not only dependent on the temperature, but as well on the thermal properties of the substrate. The Mackenzie Delta has shown the first proof of degrading permafrost in the form of an increasing number of thaw slumps. The pingos in this area do not show any sign of degradation caused by climate change. However, presumably the pingo degradation caused by climate warming will have a time delay because the melt of the internal ice lens consumes energy. As long as the depth of the active layer does not exceed the thickness of the overburden sediment covering the pingo, the pingo will be protected from degradation. Other signs of degrading permafrost can mainly be found in fine grained or organic sediment. This is because sand does not show large changes after thawing of the permafrost. The pore space between the sand grains is large enough for ice crystals to expand without changing the internal structure of the sediment (French, 2007). The entire sediment layer does not subside and therefore no large changes may be recognized. The only evidence of past permafrost in sandy areas is caused by frost wedges or structures caused by cryoturbation.

5.5 Spatial distribution

An indication in the spatial distribution of pingo remnants in the Netherlands and Germany has been given in this study, based on the geology, geomorphology and digital elevation maps (Alterra, TNO and Provincie Drenthe). The density analysis is based on the mapping studies, not special focussing on pingo remnants. The density is therefore dependent on the quality of the maps and the amount of available data. The table of pingo density (table 4.2) is based on the amount of mapped circular depressions. The Drenthe area might have had appropriate conditions for pingos to grow, but also has the most detailed maps by the Province of Drenthe. This will distort the results of the density analysis.

Between the different geology, geomorphology and digital elevation maps, large differences occur between the maps and some circular depressions are not taken into account. In figure 5.5 a snapshot has been taken from an intermediate state of the pingo analysis in ArcGIS. This figure shows how some circular depressions visible in the digital elevation map that are not mapped as pingo remnants or mapped with a different size, other depressions have strange shapes, two depressions might be merged or divided because they occur on a different subsurface or because they intersect with topographical or administrative boundaries.

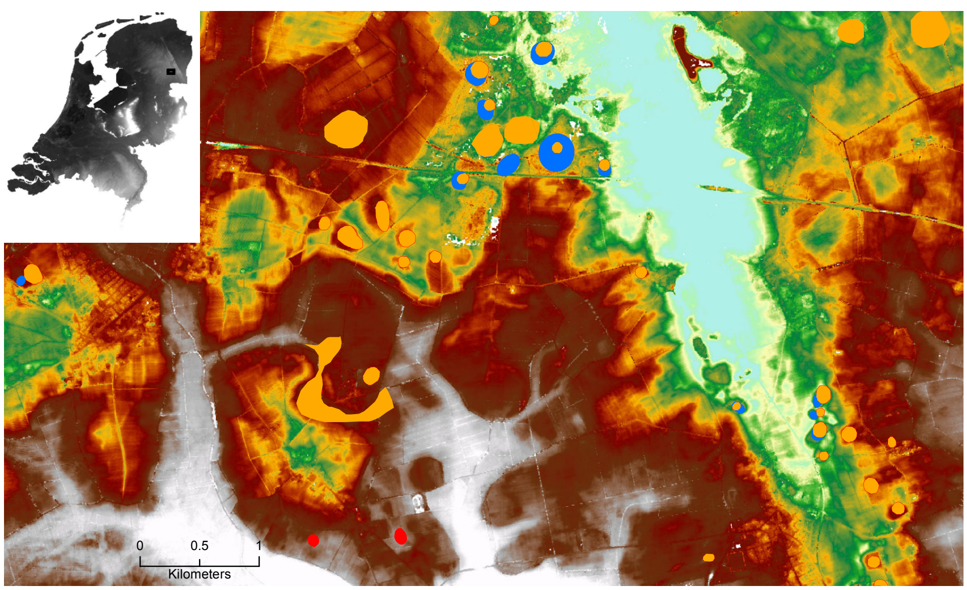

Figure 5.5: A snapshot during the density analysis using ArcGIS. The different blues show presumed pingo remnants with different circularities, plotted on the digital elevation model with brown showing the higher areas.

In active permafrost areas, most pingos occur in continuous permafrost regions. In Asia, more than 97 % of the pingos occur in continuous permafrost regions (Grosse and Jones, 2011). In the Canadian Arctic, a similar situation dominates the pingo occurrence (Mackay and Burn, 2002; Stager, 1956). In Alaska (Holmes et al, 1968; Walker et al, 1985) less then 5 % of the pingo depressions do not occur in continuous permafrost regions. In Greenland (Worsley and Gurney, 1996) and Svalbard, most pingos occur in the valleys of down slope of permafrost (and glacier) rich mountain sides. Those pingos are almost all located in discontinuous permafrost. However, the situation in the Netherlands has been different from all active permafrost regions mentioned above. The topographical and subsurface situation is dominated by the increasing hydraulic pressure in the upper frozen aquifer. Not much signs of continuous permafrost have been found in the Netherlands or surrounding areas, which presumes discontinuous permafrost conditions during the formation of these pingos. The absence of slopes covered with glaciers in the surrounding excludes the formation of pingos by this theory, however the abundance of water will presumably have caused the formation of pingos by open sources of water.

The Glacial isostatic adjustment of the Last Glacial Maximum has had influence on the surface elevation in northwestern Europe and Scandinavia (Benn & Evans, 2007).

This non-linear elevation difference may have had an effect on the Rhine-Meuse river system during the Late Pleistocene (Busschers et al, 2007) as the elevation difference of the foreland has been largest in the northern part of the Netherlands. This effect of the forebulge updoming could have an extra external control on the river systems in this area as there has been an induced lateral tilting effect (Busschers et al, 2007). Most recent models have shown an area of maximal uplift in the northern Netherlands (Peltier, 1994; Steffen, 2006; Steffen & Kaufmann, 2005) with a relative updoming of 5 to 10 meters compared with central Germany and central France (Busschers et al, 2007). According to Wim Hoek (pers. comm., 2011) this forebulge uplift could have a positive effect on the formation of pingos in the Netherlands. During the Weichselian, the maximum ice area of the Scandinavian ice sheet extended to Denmark and northern Germany (see section 1.5). During

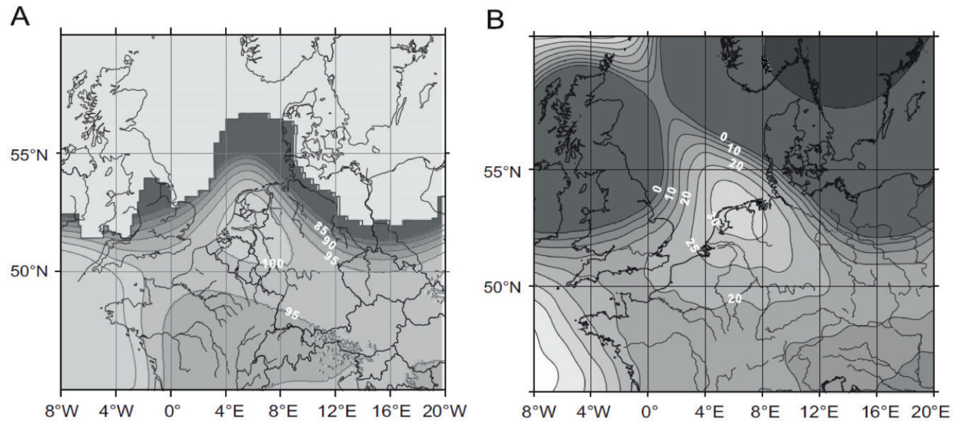

Figure 5.6: Predictions of maximum forbulge uplift at 21 ka by the current glacio-hydro isostacy models. (A) Peltier (2004) with elevation above contemporary MSL and (B) Steffen (2006) as elevation compared to present topography (Busschers et al, 2007)

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this period, permafrost was present south of the ice sheet (41-38 BP: Huijzer and Isarin, 1997; Isarin, 1997; French, 2008; Kasse and Bohncke 1992; Hoek, 1997). This layer of permafrost closed the ground for penetrating water, similar to present permafrost areas (French, 2007). With a warming climate and retreating ice front, the permafrost slowly started to thaw and the release of heat will take time before water can freely move trough the ground. During this period the forebulge slowly collapsed (Vink et al, 2007; Steffen and Wu, 2011; Meyer and Harff, 2005). The collapse of the forebulge might have caused an increased water pressure beneath the forebulge area, as the permafrost still covered the surface. As the water pressure continued to increase, new wells will have occurred when the water penetrated trough weak points in the permafrost. At these locations brook-valleys could form. These small valleys can be found in the northern part of the Netherlands and are a result of an abundance of (ground)water. The presence of brook-valleys seems to be coincide with the occurance of pingos (Ruiter, 2010). Because these sources of water could develop into pingos as pingos need abundance of water and permafrost. This relation between forebulge and pingo occurance seems to be confirmed as the pingo remnants are found in the same region as where the maximum forebulge has been active (figure 5.6).

6. Conclusion

This study focusses on the relict and active permafrost features, pingos. Based on the research questions the following conclusions can be drawn.

- *What is the spatial distribution of the pingo remnants?*

The spatial distribution of pingo remnants is strongly dependent on the area and pingo system. The occurrence of close system pingos is dependent on the availability of taliks in the permafrost. The occurrence of open system pingos is dependent on the hydraulic pressure and weaknesses in the permafrost layer. Presumably open system type pingos were present in the northern Netherlands and adjacent Germany during theWeichselian glacial period. The substrate of glacial till and impermeable permafrost top layer in combination with a slow collapse of the forebulge will likely have caused the occurrence of pingos in the this area.

- *What were the constraints in the spatial distribution?*

A pingo density as high as in the northern Netherlands is not found elsewhere on earth. However, density analysis of Grosse and Jones (2011) show comparable numbers for some areas in Northwest Canada and Alaska. The sources of water and increased ground water pressure can only partly explain the presence of this high amount of pingo remnants. Some problems might have occurred by the mapping or interpretation of these depressions, which possibly overestimates the number of pingo remnants in the northern Netherlands.

- *When did pingo formation start?*

The start of the pingo formation is difficult to reconstruct as this can only be estimated by the conditions needed for the formation process. Temperature, lithology, groundwater and process reconstruction all together can give an indication of the age of pingo formation. The temperature must be cold enough, which was possible throughout the Weichselian glacial period, with the coldest period around 24 ka BP. The occurrence and dating of frostwedge activity might add knowledge about the coldest period and the activity of cryologenetic processes. If the collapse of the forebulge has influenced the formation of pingos, this formation could be related to the deglaciation period, just after the Late Glacial Maximum.

- *What were the palaeogeographical and climatological conditions during formation and decay?*

The palaeogeographical and climatological conditions during the formation and decay of the pingo remnants were comparable with the present day situation in, amongst other places, the Canadian Arctic. The presence of permafrost and tundra vegetation dominated this area during the Weichselian glacial period. After collapse of the pingos the groundwater level gradually changed from deep water to a shallow water level in the pingo remnant depressions. The infill of these depressions consists mostly of organic sediments with different organic content depending on the temperature and wind differences. The decay of pingos seems to be coincide with a strong temperature rise at the onset of the Lateglacial (around 14.7 ka). An extensive climatological and botanical reconstruction can be found in R. de Bruijn, 2012.

- *Can pingos be used as indicators for climate change?*

The occurrence of pingos is dependent on both climate and hydrological conditions. Pingos can therefore not be used as a direct indicator for climate change. However, as an indirect climate indicator, a multiple pingo collapse will be caused by a large scale external force. This force could be the change of either hydrological or climatological conditions. Together with other climate indicators, pingos might in this case be used as indicators for climate change.

- *In which time-scales has climate change influenced the occurrence of permafrost and periglacial landforms in the past?*

The time-scales matching permafrost and periglacial processes are dependent on a several factors. Lithological, climatological, hydrological and cryological processes depend on the rate of climate change and its influence on the occurrence of permafrost and periglacial landforms. Climate and hydrology strongly dominate the occurrence of permafrost. The amount of water available in the subsurface and the groundwater flow determines the amount of frost activity and formation of periglacial landforms. The lithology covers the variation in for example thermal condition and permeability of the substrate. This is important for the rate in which permafrost can penetrate into the subsurface.

- *Is this climate change impact comparable with the contemporary degradation of the permafrost as a result of recent global warming?*

The present day climate change does not show much collapse of permafrost features yet, with exception of an increased number or thaw slumps visible in the Mackenzie Delta and a slow thickening of the active layer shown by long term measurements. A very abrupt climate warming characterized the end of the last glacial, which was much more distinct than the recent global warming. Especially, in northwest Europe, due to chenge in ocean circulation. The climate warming at the end of the last glacial has probably caused a large scale collapse of pingo systems, while nowadays no increase of pingo degradation has been observed.

Further research is needed for a better density analysis for the Netherlands. The methods of recognition circular depressions (with eCognition and/or GIS) can be used in future research to produce a pingo distribution map based on equal quality data for the entire Netherlands. Qualitative calculations on Late Glacial water pressure as a result of the forebulge collapse and the presence of permafrost might confirm this theory.

BIBLIOGRAPHY

[1] AGI. Actueel Hoogtebestand van Nederland. Rijkswaterstaat-Adviesdienst Geoinformatie & ICT, Delft., 2005.

[2] C.K. Ballantyne and C. Harris. *The Periglaciation of Great Britan*. Cambridge University Press, 1994. 330 p.

[3] D. Barsch, O. Frnzle, H. Leser, H. Liedtke, and G Stblein. Geomorphologische Karte der Bundesrepubliek Deutschland 1:100 000, Blatt C1518 Husum. Geomorphologische Detailkartierung in der Bundesrepublik Deutschland., 1997.

[4] D.I. Benn and D.J.A. Evans. *Glaciers and Glaciation*. Arnold Publisher, London, England, 734 p., 2007.

[5] H.J.A. Berendsen. *Fysisch-geografisch ondezoek; Themas en methoden*. Koninklijke van Gorcum (Assen), 2005. 319 pp.

[6] H.J.A. Berendsen and E. Stouthamer. *Palaeogeographic development of the Rhine-Meuse delta, The Netherlands*. Koninklijke Van Gorcum (Assen), 2001. 268 p.

[7] S. Bijlsma and G.W. De Lange. Geology, palynology and age of a pingo remnant near Daarle, province of Overijssel, The Netherlands. *Geologie en Mijnbouw*, 1983.

[8] I.J. Bos, F.S. Busschers, and W.Z. Hoek. Organic-facies determination: a key for understanding facies distribution in the basal peat layer of the Holocene Rhine-Meuse delta, The Netherlands. *Sedimentology*, 2011.

[9] I.J. Bos, H. Feiken, F.P.M. Bunnik, and J. Schokker. Influence of organics and clastic lake fills on distributary channel processes in the distal Rhine-Meuse delta (The Netherlands). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 284:355–374, 2009.

[10] J.A.A. Bos, J.H. Dickson, G.R. Coope, and W.G. Jardine. Flora, fauna and climate of Scotland during the Weichselian Middle Pleniglacial - palynological, macrofossil and coleopteran investigations. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 204:65–100, 2004.

[11] J.H.A. Bosch. *Toelichting bij de geologische kaart van Nederland 1:50.000. Blad Assen west (12W) en Blad Assen oost (12O)*. Rijks Geologische Dienst, Haarlem, 1990.

[12] M. Böse. Problems of dead ice and ground ice in the central part of the North European Plain. *Quaternary International*, 28:123–125, 1995.

[13] C.R. Burn. *Geomophological Landscapes of the World*, chapter The Mackenzie Delta: An Archetypal Permafrost Landscape., page 375 pp. Springer, 2010.

[14] C.R. Burn and S.V. Kokelj. The Environment and Permafrost of the Mackenzie Delta Area. *Permafrost and Periglacial Processes*, 20:83–105, 2009.

[15] F.S. Busschers, C. Kasse, R.T. Van Balen, J. Vandenberghe, K.M. Cohen, H.J.T. Weerts, J. Wallinga, C. Johns, P. Cleveringa, and F.P.M. Bunnik. Late Pleistocene evolution of the Rhine-Meuse system in the Southern North Sea Basin: imprints of climate change, sea-level oscillation and glacio-isostasy. *Science Reviews*, 26(25-28):3216–3248, 2007.

[16] T. Czudek and J. Demek. Pleistocene cryoplanation in the Cesk vysocina highlands, Czechoslovakia. *Transactions of the institute of Britisch Geographers*, pages 95–112, 1971.

[17] R. De Bruijn. Infill of Late Weichselian pingo remnants reveals rapid climate change. Master's thesis, Universiteit Utrecht, 2012.

[18] W. De Gans. Location, age and origin of pingo remnants in the Drentsche aa valley area (The Netherlands). *Geologie en Mijnbouw*, 61:147–158, 1982.

[19] W. De Gans. *Pingo scars and their identification*. PhD thesis, Vrije Universiteit te Amsterdam, 1988. 132 pp.

[20] W. De Gans and H. Sohl. Weichselian pingo remnants and permafrost on the Drente plateau (The Netherlands). *Geologie en Mijnbouw*, 60:447–452, 1981.

[21] E.F.J. De Mulder, M.C. Geluk, I.L. Ritsema, W.E. Westerhoff, and T.E. Wong. *De ondergrond van Nederland*, chapter Geologie van Nederland, deel 7. Utrecht: Nederlands Instituut voor Toegepaste Geowetenschappen., 2003.

[22] J.J. De Vries. *Groundwater flow systems and stream nets in the Netherlands*. PhD thesis, Vrije Universiteit te Amsterdam, 1974. 226 pp.

[23] A. Duk-Rodkin and D.S. Lemmen. Glacial history of the Mackenzie region. *Bulletin of the Geological Survey of Canada*, 547:11–20, 2000.

[24] J. Ehlers and P. Gibbard. Extent and chronology of Quaternary glaciation. *Episodes*, 31(2):211–218, 2004.

[25] B. Etzelmüller and J.O. Hagen. Glacier-permafrost interaction in Arctic and alpine mountain environments with examples from southern Norway and Svalbard. *Geological Society, London, Special Publications*, 242:11–27, 2005.

[26] R.C. Flemal. Pingos and pingo scars: Their characteristics, distribution, and utility in reconstructing former permafrost environments. *Quaternary Research*, 6:37–53, 1976.

[27] H.M. French. *The Periglacial Environment*. John Wiley AND Sons Ltd, England, 2007. 458 pp.

[28] H.M. French. Recent contributions to the study of past permafrost. *Permafrost and Periglacial Processes*, 19:179–194, 2008.

[29] K. Garleff. *Geomorphologische Untersuchungen an geschlossen Hohlformen (Kaven) des Niedersachsischen Tieflandes*. Im Selbstverlag des Geographischen Instituts der Universitat Gottingen., 1968. 142 pp.

[30] P.L. Gibbard, S. Boreham, K.M. Cohen, and A. Moscariello. Global chronostratigraphical correlation table for the last 2.7 million years v. 2007b. *Subcommission on Quaternary Stratigraphy, Department of Geography, University of Cambridge, Cambridge, England*, 2007.

[31] G. Grosse and B.M. Jones. Spatial distribution of pingos in northern Asia. *The Cryosphere*, 5:13–33, 2011.

[32] S.D. Gurney. Aspects of the genesis and geomorphology of pingos: perennial permafrost mounds. *Progress in Physical Geography*, 22(3):307–324, 1998.

[33] C. Harris and N. Ross. Pingos and pingo scars. *Periglacial Landforms*, pages 2200–2207, 2007.

[34] O. Heir, A.F. Lotter, and G. Lemcke. Loss on Igintion as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology*, 25:101–110, 2001.

[35] O. Heiri, H. Cremer, S. Engels, W.Z. Hoek, W. Peeters, and A.F. Lotter. Lateglacial summer temperatures in the Northwest European lowlands: a chironomid record from Hijkermeer, the Netherlands. *Quaternary Science Reviews*, 26:2420–2437, 2007.

[36] C. Hinze, H-C. Höfle, H. Jordan, H. Mengeling, D. Meyer, K, P. Rohde, and H. Streif. Geologische Übersichtskarte von Niedersachsen und Bremen, 1:500.000., journal = Niedersächsisches Landsamt für Bodenforschung., year = 1981,.

[37] W.Z. Hoek. *Atlas to Palaeogeography of Lateglacial Vegetations; Maps of Lateglacial and Early Holocene landscape and vegetation in the Netherlands, with an extensive review of available palynological data.*, volume 231. Nederlandse Geografische Studies, 1997. 165 pp.

[38] W.Z. Hoek and S.J.P. Bohncke. Climatic and environmental events over the Last Termination, as recorded in The Netherlands: a review. *The Netherlands Journal of Geosciences*, 81(1):123–137, 2002.

[39] W.Z. Hoek and J.H.J. Joosten. Pingo-runes en kalkgyttja in het Weerterbos. *Natuurhistorisch maandblad*, 84(10):234–241, 1995.

[40] G. W. Holmes, D. M. Hopkins, and H. Foster. Pingos in central Alaska. *US Geological Survey Bulletin, 1241-H, Washington*, 1-40:44, 1968.

[41] H.W. Hubberten, A. Andreev, V.I. Astakhov, I. Demidov, J.A. Dowdeswell, M. Hendriksen, C. Hjort, M. Houmark-Nielsen, M. Jakobsson, S. Kuzmina, E. Larsen, J.P. Lunkka, A. Lyså, J. Mangerud, P. Möller, M. Saarnisto, L. Schirrmeister, A.V. Sher, C. Siegert, M.J. Siegert, and J.I. Svendsen. The periglacial climate and environment in northern Eurasia during the Last Glaciation. *Quaternary Science Reviews*, 23:1333–1357, 2004.

[42] O.L. Hughes. Distribution of open system pingos in central Yukon Territory with respect to glacial limits. *Geological Survey of Canada, Paper*, pages 69–34, 1969.

[43] A.S. Huijzer and R.F.B. Isarin. The reconstruction of past climates using multi-proxy evidence: an example of the Weichselian Pleniglacial in northwest and central Europe. *Quaternary Science Reviews*, 16:513–533, 1997.

[44] R.F.B. Isarin. Permafrost distribution and temperatures in Europe during the Younder Dryas. *Permafrost and Periglacial Processes*, 8:313–333, 1997.

[45] B.M. Jones, G. Grosse, K.M. Hinkel, C.D. Arp, S. Walker, R.A. Beck, and J.P. Galloway. Assessment of pingo distribution and morphometry using an IfSAR derived digital surface model, western Arctic Coastal Plain, Northern Alaska. *Geomorphology*, 138:1–14, 2012.

[46] C. Kasse, W.Z. Hoek, S. J. P. Bohncke, M. Konert, J. W. H. Weijers, M. L. Cassee, and R.M. Van Der Zee. Late Glacial fluvial response of the Niers-Rhine (western Germany) to climate and vegetation change. *Journal of Quaternary Science*, 20(4):377–394, 2005.

[47] K. Kasse and S. Bohncke. Weichselian upper Pleniglacial aeolian and ice-cored morphology in the southern Netherlands (Noord-Brabant, Groote Peel). *Permafrost and Periglacial Processes*, 3:327–342, 1992.

[48] S.J. Kluiving and A. Verbers. Evaluatie van het onderzoek naar vijfenveertig locaties van vermeende pingorunes in het oosten van de Provincie Friesland: Pingo Project Frysln (PPF) en Catalogus Pingo Project Frisln 2006-2007. GEO-LOGICAL-reeks 02., 2007.

[49] S.J. Kluiving, A.L.L.M. Verbers, and W.J.F. Thijs. Lithological analysis of 45 presumed pingo remnants in the northern Netherlands (Friesland): substrate control and fill sequences. *Netherlands Journal of Geoscience*, 89(1):61–75, 2010.

[50] D.S. Lemmen, A. Duk-Rodkin, and J.M. Bednarski. Late glacial drainage systems along the northwestern margin of the Laurentide ice sheet. *Quaternary Science Reviews*, 13:805–828, 1994.

[51] O. Liestø l. Pingos, springs, and permafrost in Spitsbergen. *Norsk Polarinstitut Årbok*, 7(29), 1975.

[52] Lowe and Walker. *Reconstructing Quaternary Environments*. Pearson, London, second edition, 1997.

[53] G.C. Maarleveld and J.C. Van der Toorn. Pseudo-solle in Noord-Nederland. *Tijdschrift Koninklijk Nederlands Aardrijkskundig Genootschap*, 72:344–360, 1955.

[54] J.R. Mackay. Aklisuktuk (Growing Fast) Pingo, Tuktoyaktuk Peninsula, Northwest Territories, Canada. *Arctic*, 34:207–273, 1961.

[55] J.R. Mackay. Origin of the pingos of the Pleistocene Mackenzie Delta Area, N.W.T. *Geological Survey of Canada*, 74(1):389–390, 1962.

[56] J.R. Mackay. The world of underground ice. *Annals of the Association of American Geographers*, 26(1):1–22, 1972.

[57] J.R. Mackay. Pulsating pingos, Tuktoyaktuk Peninsula, N.W.T. *Canadian Journal of Earth Sciences*, 14:207–222, 1977.

[58] J.R. Mackay. Pingos of the Tuktoyaktuk Peninsula Area, N.W.T. *Gographie physique et Quaternaire*, 33(1):3–61, 1979.

[59] J.R. Mackay. Downward water movement into frozen ground, western Arctic coast, Canada. *Canadian Journal of Earth Sciences*, 20:120–134, 1983.

[60] J.R. Mackay. Growth of the Ibyuk pingo, western Arctic coast, Canada, and some implications for environmental reconstructions. *Quaternary Research*, 26:68–80, 1986.

[61] J.R. Mackay. Some mechanical aspects of pingo growth and failure, western Arctic coast, Canada. *Canadian Journal of Earth Sciences*, 24:1108–1119, 1987.

[62] J.R. Mackay. Pingo collapse and paleoclimatic reconstruction. *Canadian Journal of Earth Sciences*, 25:495–511, 1988.

[63] J.R. Mackay. Pingo growth and collapse, Tuktoyaktuk Peninsula Area, western Arctic coast, Canada: a long-term field study. *Gographie physique et Quaternaire*, 52(3):271–323, 1998.

[64] J.R. Mackay and C. R. Burn. The first 20 years (1978-1979 to 1998-1999) of ice-wedge growth at the Illisarvik experimental drained lake site, western Arctic coast, Canada. *Canadian Journal of Earth Sciences*, 39:95–111, 2002.

[65] J.R Mackay and C.R. Burn. A century (1910-2008) of change in a collapsing pingo, Parry Peninsula, western Arctic coast, Canada. *Permafrost and Periglacial processes*, 2011. FOR PEER REVIEW.

[66] H. Meyer, L. Schirmeister, K. Yoshikawa, T. Opel, S. Wetterich, H.W. Hubberten, and J. Brown. Permafrost evidence for severe winter cooling during the Younger Dryas in northern Alaska. *Geophyscal Research Letters*, 37, 2010.

[67] M. Meyer and J. Harff. Modelling palaeo coastline changes of the Baltic Sea. *Journal of Coastal Research*, 213:598–609, 2005.

[68] F. Müller. Beobachtungen über Pingos. *Meddelelser om Grønland*, 153:127, 1959.

[69] J.B. Murton. Stratigraphy and palaeoenviroments of Richards Island and the eastern Beaufort Continental Shelf during the last glacial-interglacial cycle. *Permafrost and periglacial processes*, 20:107–125, 2009.

[70] M.M. Nijhuis. Loss on ignition as a method to determine the age of a possible pingo remnant near Slochteren, the Netherlands. Bachelor thesis, department of physical geography faculty of Geosciences, Utrecht University, 2006.

[71] F.P. Paris, P. Cleveringa, and W. De Gans. The Stokersdobbe: Geology and palynology of a deep pingo remnant in Friesland (The Netherlands). *Geologie en Mijnbouw*, 58:33–38, 1979.

[72] W.R. Peltier. Ice Age Paleotopography. *Science*, 268:195–201, 1994.

[73] H.J. Pierik. An integrated approach to reconstruct the Saalian glaciation. GIS-based construction of a new phase model for the Netherlands and NW-Germany. Master's thesis, Utrecht University, 2010. 142 pp.

[74] A. Pissart. Pingos: An overview of the present state of knowledge. *Advances in Periglacial Geomorphology*, page 480, 1988. Edited by M.J. Clark.

[75] A. Pissart. Palsas, lithalsas and remnants of these periglacial mounds. a progress report. *Progress in Physical Geogr*, 26(4):605–621, 2002.

[76] A. Pissart. The remnants of Younger Dryas lithalsas on the Hautes Fagnes Plateau in Belgium and elsewhere in the world. *Geomorphology*, 52:5–38, 2003.

[77] N. Ross. *A re-evaluation of the origins of Late Quaternary ramparted depressions in Wales*. PhD thesis, School of Earth, Ocean and Planetary Sciences Cardiff University, 2006.

[78] N. Ross, C. Harris, P.J. Brabham, and T.H. Sheppard. Internal structure and geological context of ramparted depressions, Llanpumsaint, Wales. *Permafrost and Periglacial Processes*, 2011.

[79] A.S. Ruiter. Remnants of pingo remnant ramparts. *Bachelor's Thesis, Utrecht University*, 2010. 26 pp.

[80] M.W. Smith. Permafrost in the Mackenzie Delta, N.W.T. *Geological Survey of Canada: Ottowa*, 75(28), 1976.

[81] J.K. Stager. Progress report on the analysis of the characteristics and distribution of pingos east of the Mackenzie Delta. *Canadian Geography*, 7:13–20, 1956.

[82] H. Steffen. *Determination of a Consistent Viscosity Distribution in the Earths Mantle Beneath Northern and Central Europe*. PhD thesis, Institute of Geological Sciences, FU Berlin, 2006.

[83] H. Steffen and G. Kaufmann. Glacial isostatic adjustment of Scandinavia and northwestern Europe and the radial viscosity structure of the earth's mantle. *Geophysical Journal Int.*, 163:801–812, 2005.

[84] H. Steffen and P. Wu. Glacial isostatic adjustment in Fennoscandia A review of data and modeling. *Journal of Geodynamics*, 52:169–204, 2011.

[85] N. van Asch, A.F. Lutz, Heiri O. Duijkers, M.C.F., S.J. Brooks, and W.Z. Hoek. Rapid climate change during the Weichselian Lateglacial in Ireland: Chironomid-inferred summer temperatures from Fiddaun, Co. Galway. *Palaeography, Palaeoclimatology, Palaeoecology*, 315:1–11, 2012.

[86] J. Vandenberghe and A. Pissart. Permafrost changes in Europe during the last glacial. *Permafrost and Periglacial Processes*, 4:121–135, 1993.

[87] A. Vink, H. Steffen, L. Reinhardta, and G. Kaufmannb. Holocene relative sea-level change, isostatic subsidence and the radial viscosity structure of the mantle of northwest Europe (Belgium, The Netherlands, Germany, southern North Sea). *Quaternary Science Reviews*, 26:3249–3275, 2007.

[88] D. A. Walker, M. D. Walker, K. R. Everett, and P. J. Webber. Pingos of the Prudhoe Bay Region, Alaska. *Arctic Alpine Res.*, 17:321–336, 1985.

[89] A.L. Washburn. *Periglacial processes and environments*. Edward Arnold, London, 1973. 320 pp.

[90] A.L. Washburn. Permafrost features as evidence of climate change. *Earth-Science Reviews*, 15:327–402, 1980.

[91] E. Watson. Remains of pingos in Wales and the Isle of Man. *Geological Journal*, 7(2):381–392, 1971.

[92] H.J.T. Weerts, P. Cleveringa, J.H.J. Ebbing, F.D. de Lang, and W.E. Westerhoff. De lithostratigrafische indeling van Nederland. Formaties uit het Tertiair en Kwartair. TNO-Rapport 00-95-A. Utrecht: Nederlands Instituut voor Toegepaste Geowetenschappen TNO., 2000.

[93] J.R. Williams, W.E. Yeens, L.D. Carter, and T.D. Hamilton. Preliminary surficial deposits map of National Petroleum Reserve-Alaska. Technical report, U.S. Geological Survey, 1977. Open-File Report, 255-274 pp.

[94] P.J. Williams and M.W. Smith. *The Frozen Earth: Fundamentals of geocryology.* Cambridge, Cambridge University press, 1989. 306 p.

[95] P. Worsley and S.D. Gurney. Geomorphology and hydrogeological significance of the Holocene pingos in the Karup Valley area, Traill Island, northern east Greenland. *Journal of Quaternary Science*, 11:249–262, 1996.

[96] W.H. Zagwijn and C.J. Van Staalduinen. *Toelichting bij de Geologische Overzichtskaart van Nederland.* Rijks Geologische Dienst, Haarlem, 1975.

[97] W.J. Zagwijn. An outline of the Quaternary stratigraphy of the Netherlands. *Geologie en Mijnbouw*, 64:17–24, 1985.

[98] P.A. Ziegler. Cenozoic rift system of western and central Europe: an overview. *Geologie en Mijnbouw*, 73:99–127, 1994.

Object_ID	Name	Year	Hoek	Morpholog	Literature	vervolg	Diam	Depth (n	Oudste Invull	Litholo	Pollen	LOI	C14	Other	X-RD	Y-RD
1	5	2006		Pingo	Kluiving, 2010			1.55							205989	586616
2	23	2006		Pingo	Kluiving, 2010			2							203578	586894
3	26	2006		Pingo met	Kluiving, 2010			3.12							202861	587124
4	40	2006		Pingo, mog	Kluiving, 2010			0.35	5						203878	589708
5	41	2006		Pingo, mog	Kluiving, 2010			0.7							203906	589923
6	46	2006		Pingo	Kluiving, 2010			0.5	2.1						201348	588525
7	47	2006		Pingo	Kluiving, 2010			0.75	2.5						200800	587833
8	68	2006		Pingo	Kluiving, 2010			1.3	4						200218	584827
9	96	2006		Pingo	Kluiving, 2010			0.65	3.3						203845	586380
10	99	2006		Pingo	Kluiving, 2010			2.05	2.7						207375	586702
11	100	2006		Pingo	Kluiving, 2010			2.55	3.7						206648	587601
12	102	2006		Pingo	Kluiving, 2010			1.8	4.2						206658	587953
13	180	2006		Pingo	Kluiving, 2010			2.3	4						200343	581636
14	181	2006		Pingo	Kluiving, 2010			4	8						200466	581181
15	342	2006		Pingo	Kluiving, 2010			2.2	340						202629	582489
16	360	2006		Pingo	Kluiving, 2010			0.7	270						204805	586156
17	361	2006		Pingo	Kluiving, 2010			1.5	440						204956	585942
18	373	2006		Pingo	Kluiving, 2010			2	5						203632	584938
19	376	2006		Pingo	Kluiving, 2010			1.3	4.2						203230	584800
20	379	2006		Pingo	Kluiving, 2010			2.65	4						202842	584860
21	400	2006		Pingo	Kluiving, 2010			2.15	4.1						199924	583682
22	401	2006		Pingo	Kluiving, 2010			1.2	2.8						208983	580723
23	408	2006		Pingo (laat	Kluiving, 2010			2.5	6.05						208178	578686
24	418	2006		Pingo	Kluiving, 2010			1.8	3.1						201447	580934
25	424	2006		Pingo	Kluiving, 2010			0.9	3.25						203059	581819
26	439	2006		Pingo	Kluiving, 2010			3.3	5.4						204245	579553
27	486	2006		Pingo	Kluiving, 2010			1.8	3						200846	583282
28	543	2006		Pingo	Kluiving, 2010			1.5	2.55						201740	583600
29	575	2006		Pingo	Kluiving, 2010			0.85	3						203311	586119
30	576	2006		Pingo	Kluiving, 2010			0.75	2.2						202992	585653
31	603	2006		Pingo	Kluiving, 2010			2.9	6.5						207435	586030
32	780	2006		Pingo	Kluiving, 2010			1.5	2.5						204216	584295
33	403-d	2006		Pingo	Kluiving, 2010			2.7	3.8						208517	579995
34	409-e	2006		Pingo	Kluiving, 2010			0.75	2.6						207547	579000
35	412-f	2006		Pingo	Kluiving, 2010			2.45	4						207452	579506

36	Achterste Hou	1995			Hoek en Joosten, 1995				Atlanticu	8.000-7.000						174125	367800
40	Berkenven	1995			Hoek en Joosten	Nelleke van Ash, unpu			Bolling	13.0(	Yes	Asch			isotopen, cl	174100	367925
41	Bleekermeer	1988	188	Pingo	Bohncke et al, 1988							Polak, 1963b				173550	495150
42	Brill (D)	2011		Pingo	2011						Yes					302817	623409
43	Daarle	1983	86	Pingo	Bijlsma and de Lange, 19		200	5			Yes	Yes				232325	492700
44	Dobbe Bakker	1957	92	Pingo	Paleobotanie 17H-4, 1957											254435	526930
45	Doezen	2010			Ruiter		300	2								211748	535103
47	Egypte	2011		Pingo	2011						Yes					203225	585303
49	Elper Noorder	1978	193	Pingo	Cleveringa & De Gans, 1978											239700	566900
50	Elper Noorderveld C		256	Pingo	unpubl											240900	547500
51	Elte (D)	2011		Aeolean de	2011											350332	542836
52	Empe	2007			Hoek & Van Ash, unpubl.						Yes	Yes	Yes		CaCO3	206000	462500
53	Emstekerfeld (	2011		Pingo	2011						Yes					337912	541636
54	Esmeer	2010			Ruiter		200	13								227150	558500
56	Grashut	1995			Hoek en Joosten, 1995				Bolling	13.000-12.000						174200	368100
57	Groot Ven	1995			Hoek en Joosten	Nelleke van Ash, unpu			Bolling	13.0(	Yes	Asch			CaCO3, isc	173875	367675
58	Groote Veen	1966	19	Pingo	Ter Wee, 1966		200	3								216270	547450
59	Gulickshof I	1997	249	Pingo	Hoek, 1997		200	3				Florschütz,		Yes	Molluscs	190729	341214
60	Gulickshof II		250		Hoek							Hoek, unpul		Yes	Macro,	190729	341214
61	Halder	1971	20	Pingo	P 607, 1971											150075	406825
62	Het Peelke	1995			Hoek en Joosten, 1995				Allerod (\	11.800-11.300						175650	368250
63	Hijkermeer	1949	215	Pingo	Van der Hammeı	Heiri et al, 2007					Yes	Heiri ε	Hoek, 2011,		Chronomid	229000	545000
64	Hoenderboom	1973			Bisschops, 1973							Yes				172520	377860
66	In den Vloed	1995			Hoek en Joosten, 1995				Atlanticu	8.000-7.000						175600	369050
67	Kellerhohe (D)	2011		Aeolean de	2011											337283	548531
68	Kievitsloop	1969			Koelbloed, 1969							Yes				179225	370380
69	Klein Hasselsv	1987			Van Leeuwarden & Janssen, 1987							Yes				164200	371200
70	Klein Ven	1995			Hoek en Joosten	Nelleke van Ash, unpu			Bolling	13.0(	Yes	Asch	Asch		isotopen, cl	173775	367725
71	Koordes	1964	120	Pingo	Paleobotanie 27H-2, 1964											219310	478260
73	Laarzenpad	2011		Pingo	2011						Yes					204571	584515
74	Lammeer	2011		Aeolean de	2011											251819	541257
76	Lichtenbergerv	1981	134	Pingo	Paleobotanie 28C-5, 1981											229825	482465
77	Maartensdobb	1992	198	Pingo	Kasse & Boncke, 1992							Yes				184075	372710
78	Maartensdobbe 906		202		Bohncke, unpubl											184075	372710
79	Mallemoer	1995			Hoek en Joosten, 1995				Preboreε	11.800-9.000						175975	369275
80	Mamburg (D)	2011		Pingo	2011						Yes					303974	628950

81	Mariënvelde De Riete		139	Closed dep	DLO-Staring, unpubl		200	4								229045	448045
82	Mekelermeer	1951		Pingo	Hammen, 1951	De Gans & S		12				Yes		Yes		238000	532000
83	Mekelermeer I	1988	200	Pingo	Bohncke et al, 1988		250	12					Bohncke an		Macro and	238000	532000
84	Middelbeers Meerven		142	Pingo (La v	DLO-Staring, unpubl			2.5								146945	383750
85	Mierlo Van Ho	1973	34	Pingo	Bisschops, 1973		50	3.5						no		172520	377860
86	Molenmoer	1995			Hoek en Joosten, 1995				Preborea	11.800-9.000						175275	369325
87	Nieuwe Veen	1983	148	Pingo	Bijlsma, 1983											241984	507286
88	Oostvierdepar	1959	40	Pingo	P 204, 1959			6								207375	543900
89	Opende	2011		Pingo	2011						Yes					210386	577409
91	Putbroek	2007	210	Pingo	Janssen and Ijze	Hoek en RQE						Yes	Yes		CaCO3, isc	195900	346400
92	Rennplats (D)	2011		Aeolean de	2011											351346	540914
93	Scheemda A	1987	47	Pingo	De Groot et al, 1987											172520	377860
95	Selmien-Urete	1971	216	Pingo	Cnossen, 1971											205000	568000
96	Sevelte (D)	2011		Pingo	2011											334752	540550
97	Siegerwoudstermeer		211	Pingo	Jäger, -											210300	568500
98	Sleenerstroom	2011		Pingo	2011						Yes					249056	530848
99	Sleenerstroom	2011		Aeolean de	2011											248473	530867
100	Stokersdobbe	1979	244	Pingo	Paris et al, 1979	De Gan	100	8			Yes	Yes		no		207850	565695
101	Stokersdobbe	1979		Pingo	Paris et al, 1979	De Gans & Sohl, 1981					Yes	yes		18.000 +- 200 BP		207850	565695
102	Stokkumerbroek		172	(La volgen	DLO-Staring, unpubl									no		229990	469620
103	Timmelteich (D	2011		Pingo	2011						Yes		Yes			297318	599991
104	Uddelermeer	1988	205	Pingo	Bohncke et al, 1988		300	17				Polak,	Bohn	Yes	Macro and	180450	473200
105	Usselo	1951			Hammen, 1951											254725	466600
106	Usselo I	1989	243	Coversand	Van Geel, 1989		50	1						Yes	Coleoptera	254725	466600
107	Uteringsveen I	1977	206	Pingo, zelf	Cleveringa et al, 1977							Yes		No		241000	548000
108	Uteringsveen I	1977	207	Pingo	Cleveringa et al, 1977		150	4				Yes		no		241000	548000
110	Vliegersgat	1995			Hoek en Joosten	Nelleke van Ash, unpu			Allerod (l	11.3(	Yes	Asch			Isotopen	175925	369225
111	Vlierendijk	2011		Pingo	2011						Yes					246482	537116
112	Wartena	1962	62	Pingo	P 316, 1962											190000	573425
113	Waskemeer	1960	257	Pingo	Casparie and van Zeist, 1960											212800	562800
114	Weerterbos	1996	248	Pingo	Van Joolen, 1996											173875	367675
115	Westerstroo (D	2011		Pingo	2011											297617	624684
117	Wrokmoor (D)	2011		Pingo	2011						Yes					315980	611354
118	Zuidven	1995			Hoek en Joosten, 1995				Atlanticu	8.000-7.000						174075	367300
119	1f	1968		Kryogene l	Garleff, 1968											371929	635578
120	10a	1968		Pingo-relik	Garleff, 1968											430352	617180

121	10b		1961	Kryogene I	Hagedorn, 1961		429098	623208
122	14a		1968	Pingo-relik	Garleff, 1968		430208	560125
123		16	1968	Kryogene I	Garleff, 1968		450435	539251
124	Graffelkuhle		1952	Pingo-relik	Illies, 1952		435057	549300
125	17b		1968	Kryogene I	Garleff, 1968		442569	615289
126	Trelder Moor		1968	Interglacial	Garleff, 1968		450825	602480
127		22	1968	Interglacial	Garleff, 1968		449360	607115
128	25b		1968	Kryogene I	Garleff, 1968		465931	547879
129	25c		1968	Kryogene I	Garleff, 1968		465698	551534
130	33e		1968	Interglacial	Garleff, 1968		1313020	602142
131	39c		1968	Kryogene I	Garleff, 1968		1316980	574001
132		40	1968	Kryogene I	Garleff, 1968		1310130	560224
133		44	1968	Kryogene I	Garleff, 1968		501408	496418
134	48a		1968	Kryogene I	Garleff, 1968		478641	498988
135	64b		1968	Kryogene I	Garleff, 1968		386476	543362
136		67	1968	Kryogene I	Garleff, 1968		355282	521321
137		69	1968	Kryogene I	Garleff, 1968		351398	539903
138	75a		1968	Kryogene I	Garleff, 1968		317272	543099
139	81a		1968	Kryogene I	Garleff, 1968		299393	552615
140		91	1968	Kryogene I	Garleff, 1968		340719	585082
141	Frauenmeer		1938	Kryogene I	Wildvang, 1938 und Lundbeck, 1938		340719	585082