# Chapter 6

# Paleo-thaw lakes and their role as CH$_4$ sources

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## 6.1   Abstract

Thaw (thermokarst) lakes develop in sedimentary lowlands as ice-rich permafrost thaws. Their formation can be initiated by any process interfering with the soil heat balance and causing an increased soil heat flux. These lakes are known to emit large amounts of methane (CH$_4$), which comes from the decomposition of organic matter in thawing sediments. Under present climate warming conditions, the area of thaw lakes is thought to be expanding due to increased lake formation, but contracting as a result of drainage. At the Last Glacial termination, rapid expansion of thaw lakes may have contributed to a sharp rise in atmospheric CH$_4$. However, older interstadials may also have shown a similar process of thaw lake expansion. Paleo-thaw lake deposits dating from the Last Glacial (Oxygen Isotope Stage 3) have been found in basin and valley fill successions in western and eastern Europe. Like present-day arctic thaw lakes, these paleo-thaw lakes may have been important sources of CH$_4$ and therefore contributed significantly to atmospheric CH$_4$ increase during interstadials and the last glacial termination. This study presents new evidence of paleo-thaw lake successions of the Last Glacial in Europe, discussing their sedimentary facies and the criteria by which they can be recognized as thaw lake deposits. The new data, from the same area where these deposits have been described first, show that thaw lake formation may have occurred repeatedly during the Last Glacial.

## 6.2   Introduction

Thaw lakes are prominent features of present-day arctic lowlands, in particular on the northern coastal plains of Siberia and Alaska and in central Yakutia. They have recently attracted attention as large sources of methane (CH$_4$), which results from the decomposition of organic matter liberated from thawing permafrost [1]. Although this type of

lake is known in the terminology adopted by the International Permafrost Association as "thermokarst lake", "thaw lake" is preferred, because it is the process of phase change of water that creates these lakes, rather than rock dissolution as implied by the term "karst". Thaw or thermokarst lakes occur abundantly in sedimentary lowlands underlain by permafrost and result from the thawing of ice-rich permafrost [98]. This permafrost may contain ice volumes over 90% [129], well above the normal pore volume of unconsolidated mineral soils ($\sim$40%), which causes settlement and depressions upon thawing of the permafrost.

Thaw lake formation is initiated by change in climatic factors (increased precipitation, snow cover, temperature balance [119, 113, 135, 98]) or anthropogenic and natural processes altering the soil heat balance (e.g., disruption of vegetation cover which changes the soil heat balance by human activities [197], wildfires, natural erosion [50, 51] and peat degradation on palsas or peat mounds [149, 16]. Thawing starts preferentially at ice-rich spots such as the ice wedges in arctic polygonal soils or palsas [119, 33, 50, 136, 85, 149, 16], triggered by important environmental factors, such as precipitation, rising air temperatures, increased snow cover thickness [113] and flooding [127, 85]. Such processes initially results in an increase of thaw depth and a formation of a terrain depression by loss of excess ice volume [136]. Once a water-filled depression is formed, thawing of ground ice is enhanced [50, 135]. Alternatively, lakes may be initiated by water accumulation in pre-existing depressions, after an increase of precipitation [135]. Lakes may expand laterally by thermal and mechanical erosion, driven by waves and wind-blown surface currents [119, 112, 146, 98, 34] and, when persistent wind patterns occur, their shape elongates with orientation of the length axis roughly perpendicular to the prevailing summer wind direction, caused by the development of wind-driven circulation cells [112].

The thaw lakes have a relatively short lifetime. They may be depleted by drainage through unfrozen sediment, by erosion which establishes contact with rivers and other lakes [119, 168, 112, 114, 248], or by infilling with sediment [275, 142, 135, 10, 170, 16]. Audry [16] recorded carbon stocks in thaw lake sediments in west siberian peatlands of $14 \pm 2$ kg m$^{-2}$. Anthony-Walter [10] recorded carbon accumulation in lake sediments as much as 47 g C m$^{-2}$ yr$^{-1}$. Lake drainage by erosion is often triggered by high precipitation and runoff events, and by warm summers [169, 168, 170]. After lake drainage or infilling, ice-rich permafrost may regrow if the climate is sufficiently cold, with formation of ice wedges and lenses in the sediment, frost heave and eventually in the development of pingos by release of pressurized water from the talik [192]. Initial growth of ice wedge width in drained thaw lake basins (DTLBs) may be as rapid as 3 cm per year [169]. The generally poorly drained basins may accumulate considerable carbon stocks by peat growth [111] and may be net carbon sinks [270, 180]. Re-establishment of large amounts of ground ice subsequently can be followed by renewed lake formation [33, 136, 111], often starting from remnant lakes [135, 146]. Repeated lake formation and drainage can cause large areas to be covered by overlapping DTLBs [111].

The concept of an autocyclic, rather than a climate-driven thaw lake cycle has been proposed and discussed by several authors [119, 33, 111, 135]. However, the processes involved in this cycle may have been too slow for completion of a full cycle during the Holocene [135]. The main period of rapid lake formation and expansion for many areas may be the LG termination [305], while repeated lake formation thereafter in DLTB's originating from these lakes appears to be comparatively slow and starting from remnant lakes [146, 192].

During past climate warming intervals thaw lake expansion contributed to $CH_4$ emissions from permafrost to the atmosphere [305]. Sharp rises of atmospheric $CH_4$ concentration in climate warming phases during and at the termination of the last Glacial have been recorded in ice cores [47, 46] and, as mentioned in Chapter 1 of this thesis, have been attributed to numerous variations in wetland sources and atmospheric sinks (northern wetlands [46, 276], marine gas hydrates [145], wetlands and atmospheric sink changes [265, 101], and changes in tropical wetlands [95]. Amongst these, northern wetlands may have been a prominent source and are considered to be an analogue for future development of present-day northern wetlands under a scenario of rapid climate warming [31**?**]. Thaw lakes also need to be considered as a $CH_4$ source during interstadials. Although forming today, many of these lakes date from the last glacial termination or the Holocene thermal maximum [222, 213, 112, 142, 305, 113, 34].

However difficult to date [34], lacustrine deposits originating in the middle part of the Last Glacial (Oxygen Isotope Stage 3, OIS 3 hereafter) in sedimentary basins and valley fills in western and eastern Europe have been interpreted as thaw lake deposits [72, 275, 140, 45, 274, 215]. Older deposits with similar facies and ages up to 400 ka in a tectonic basin in the south of the Netherlands [238, 237] may also be interpreted as thaw lake deposits.

Sedimentary successions of (sub)recent thaw lakes have been studied by various authors [118, 194, 314, 235, 234, 84]. Hopkins and Kidd [118] describe a succession of thawed-out material with ice wedge pseudomorphs, overlain by a basal transgressive sequence with lake sediment with peat lumps eroded from the banks, followed by central basin lake sediments, see Figure 6.2 on page 97.

Murton [193, 194] describes a succession from northern Canada, where coarse-grained deposits occur in both the substrate and lake infill. Such succession consists of beds with large foresets overlain by well-stratified fine sands and peat debris, representing lateral infilling by material eroded from the lake banks; the foresets represent the riser from the deeper part of the lake basin towards a shallower shelf area, which is present in many thaw lakes [194].

The lake sediments in the western siberian peatlands described by Audry [16] have total organic carbon (TOC) percentages of up to 30%, while Holocene thaw lake sediments in the yedoma areas in northern Siberia have TOC percentages in th order of 7 $\pm$9% [313] and their cyclic variations are common [194, 34]. Walter-Anthony [10] describes north siberian lake sediments containing large amounts of organic matter reworked from thawing lake banks and in situ primary production, including peat formation by benthic brown mosses (Amblystegiaceae). The high in situ production is supported by nutrients released by erosion from the lake banks and the resulting sedimentary succession consist of alternating lacustrine silts, muddy peats and moss peats. The deposits underlying lakes are known as "taberal" deposits or "taberites", representing sediment that has been thawed and subsequently refrozen [99, 314, 235, 234, 10]. Hopkins and Kidd [118] mention the presence of ice wedge pseudomorphs in these taberites, however it may not be a prerequisite for thaw lake succession, since degradation of palsas and peat plateaus also produce the same result [16].

Pleistocene thaw lake deposits have been described from Weichselian age deposits in glacial basins and in river valleys in a broad West-East belt, stretching from the North Sea basin into eastern Europe [275, 215, 140, 45, 40, 273]. De Gans [72] was the first to suggest that the many silt and gyttja beds in these successions might represent thaw lakes.
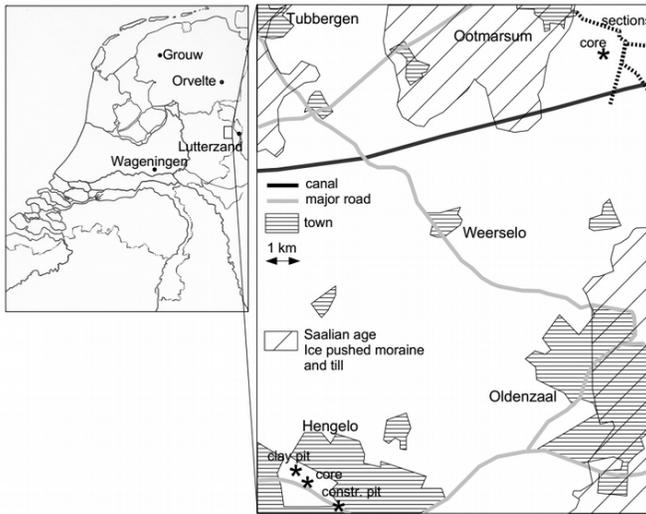
**Figure 6.1:** Location of the sites mentioned in the text (left) and detail of the Twente area.

Silt and gyttja beds in a similar succession in near Grouw in the north of the Netherlands, were interpreted by Kasse [140] as thaw lake sediments. Bohncke [40] ascribed a gyttja deposit overlying cryoturbated sand in the Reichwalde lignite mine in eastern Germany as thaw lake sediment. A 0.6 m thick peat deposit overlain by clayey lake sediment, in the Weichselian infill of a Saalian age glacial basin near Wageningen (Netherlands) was ascribed to a possible thaw lake infill by Van Geel [273].

This work presents new data from the first detailed sedimentological description of a paleo-thaw lake succession outside the present permafrost extent (Twente region in the Netherlands [275, 215]). The samples studied in this chapter were cored from this succession, in order to find new insight about the processes governing their life cycle, to be used to improve the accuracy of estimates of the storage of organic carbon in these paleo-thawlakes and the value of their contribution to CH$_4$ emissions from northern wetlands. The succession was exposed in a highway construction pit shown in Figure 6.3 on page 97 and included in sediments of Middle Weichselian age, dating approximately between 42,000 and 33,000 ^{14}C years BP. A complete description of the cores is reported in the appendix, while a detailed history of previous studies and an extensive overview of this area are given by van Huissteden (Paleo thaw lakes during MI Stage 3 J. van Huissteden, C. Berrittella, J. M. Warnsloh, in prep. / pers.comm.)

## 6.3   Study area

The Twente region, in the east of the Netherlands, is a region of Weichselian age non-glacial continental deposits [269]. The town of Hengelo (see Figure 6.1 on page 96) is situated in a glacial basin dating from the Saalian. The succession, from which the cores were extracted, consisted of loessic silt with peat beds and ice-wedge pseudomorphs ($\pm$ 1.2 m), overlain by an erosional level with lumps of peat ($\pm$0.25 m) and silt followed by laminated lacustrine silt without cryogenic disturbance ($\pm$0.75 m). Above these, two

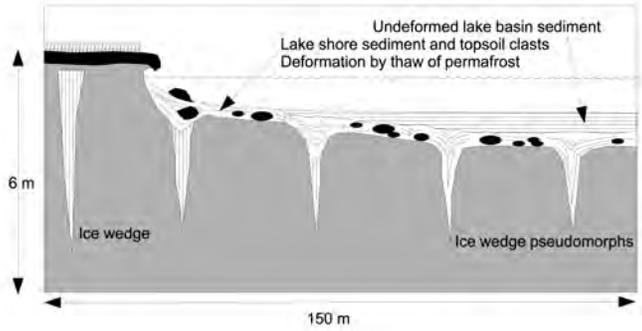**Figure 6.2:** Thaw lake sedimentary succession as described by Hopkins and Kidd [118].
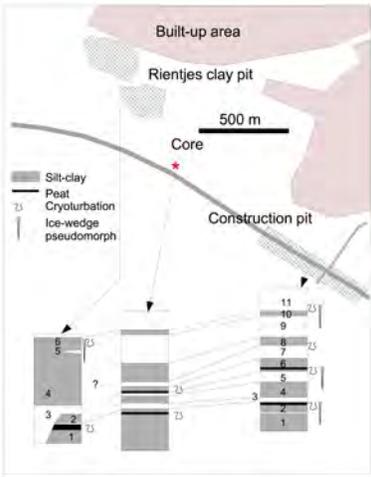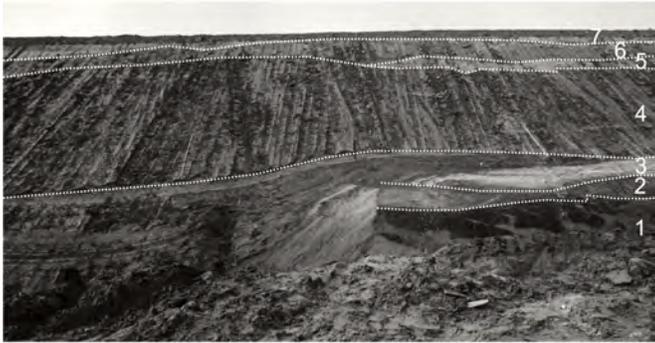


**Figure 6.3:** Location of Hengelo core and exposures (above) and inferred stratigraphical relations (below)

**Figure 6.4:** Rientjes clay pit, photo taken while the pit was still in use before 1980. Numbers refer to units in the text.

other sandcryoturbation/ice wedge psuedomorph -silt successions have been found. These successions have also been interpreted as being of thaw lake origin.

The younger Eemian/Weichselian basin fill (Boxtel Formation / former Twente Formation) is up to 9 m thick and consists of interbedded sands, silts, peat and gyttja [316, 268]. Several exposures resulting from construction works [316, 275, 268] revealed a Middle Weichselian succession with several fine-grained silt/clay beds of a presumed lacustrine origin. Two exposures with thick lacustrine successions of probable thaw lake origin have been found in this area, the Hengelo highway construction pit (HHCP) and Rientjes clay pit (RCP) shown in Figure 6.4 [275]. Here a 10 m core section was studied, located in between these pits (see Figure 6.1 on page 96).

A deeper glacial basin (Nordhorn basin) occurs to the northeast of the Hengelo basin, in which the Dinkel river and its tributaries have deposited a thick sequence of fluvial deposits during the Weichselian. The Nordhorn basin is separated from the Hengelo basin by the Ootmarsum ice-pushed ridge of Saalian age. A gap in this ridge, known as the Tilligte basin, may have interconnected the Hengelo and Nordhorn basins in the past, although at present the same area is a drainage divide. Van Huissteden [275] describes lake infilling consisting of calcareous gyttja in Middle Weichselian deposits in this area based on detailed borehole sections. In this area a second core has been drilled of which the upper 10 m was studied in detail for sedimentary evidence of thaw lakes. De Gans [72] first suggested the presence of paleo-thaw lakes in Weichselian deposits, based on his study of river valley infillings on the Drenthe till plateau. In an archaeological excavation in the Orvelte area lacustrine gyttja beds of Weichselian age have been exposed, which we have analysed for organic carbon content.

## 6.4   Methods

### 6.4.1   Cores and section logs

The cores were taken by a Begemann corer operated by Fugro BV [92], providing near continuous, 29 mm wide cores. Core loss / compression was relatively small, in the order 5-20% depending on the cored material (largest core losses non-cohesive sands). The cores were cut in two halves and sampled at the TNO in Utrecht. A precise log,

photos and description of the sedimentary structures were made before sampling. OSL age determination was based on unpublished reports by Wallinga and Versendaal (pers. comm., 2011), while radiocarbon ages from the Ootmarsum core were obtained from Bos (pers. comm.) and compared to our data.

## 6.4.2 Grain size distribution analysis

Grain size analysis was done with a Fritsch Analysette (model 22) laser particle sizer. Pre-treatment of the samples consisted of boiling with hydrogen peroxide ($H_2O_2$) to dissolve organic material and heating with hydrochloric acid (HCl) to remove ferric oxide and carbonate cement, according to the procedure given by Konert and Vandenberghe [154]. Results are shown in Table 5.3 on page 81.

## 6.4.3 Organic Carbon analysis

A thermo-gravimetric analyser (TGA, TGA-601, from Leco Corporation) with a multiple sample furnace has been used to determine the weight loss as a function of temperature in a controlled environment, to determine both organic matter and carbonate content. A set of standard 3 g samples was dried in an oven overnight at 60°C and pulverized in an agate ball mill. In the thermo-gravimetric analyzer the samples were then heated in steps to 1000°C with heating plateaus at 105°C (water loss) and 500°C (loss on ignition). Results for Hengelo and Ootmarsum sites are shown in Figures 6.9 and 6.10 on page 105, while numeric values are reported in the tables 6.1 and 6.2 for Hengelo and Ootmarsum samples.

## 6.4.4 DNA analysis

The samples collected were also analysed by the first author to investigate the possible presence of bacterial DNA. PCR and DGGE profiling were performed, using the same procedure previously described in Chapter 5. The final analysis of DGGE tracks was performed by Dr. W. Röling, from the VU University Biology Department.

## 6.4.5 Radiocarbon dating

Carbon and nitrogen stable isotopes were analysed using a Flash-IRMS system, which consists of a Flash NC 1112 series Elemental Analyser coupled to a Thermo Finnigan DeltaPlus XP Isotope Ratio Mass Spectrometer (IRMS). The Elemental Analyser is connected to the IRMS via the open split technique (Conflo II). The analytical method of the elemental analyser is based on ash combustion, a reaction that converts all organic and some inorganic substances into combustion products by instantaneous and complete oxidation of the sample. The resulting products ($CO_2$, $N_2$, $NO_x$, $SO_2$ and $H_2O$) pass through a reduction furnace (where $NO_x$ is converted to $N_2$) and a water trap prior to the chromatographic column with helium acting as the carrier gas. Before the gasses reach the IRMS, they are diluted in the Conflo II open split system, which also regulates the reference gasses entering the IRMS. For $\delta^{13}C$ analysis, the sample gas is measured against a $CO_2$ reference gas. Official standards are measured simultaneously. For Graphite $\delta^{13}C$ was used ($\delta^{13}C$ = -16) and PEF ($\delta^{13}C$ = -31.8) as official standards and a peat sample

"Gagel" with a known value ($\delta^{13}$C = -28.4) as an in-house standard. For $\delta^{15}$N a N$_2$ reference gas is used. The official standards are IAEA-N1 (0.43), IAEA-N2 (20.41) and IAEA-N3 (4.72). After the measurements, the official standards are used to make a linear calibration line, in order to calculate stable isotope values of samples and lab standards. For both isotopes the precision is close up 0.2‰ (SD). Results are shown in tables 6.1 and 6.2.

## 6.5    Results

This research progressed from an empirical model of a peatland to a real wetland in Siberia to find new insight and data to validate both the model and the chosen approach. We found valuable information about the role of the sphagnum mosses.

Such new evidence could only be considered, however, when applied to ecosystems under present conditions. In the past these species were not present in wetlands, none or scarce pollen evidence has been found in all the areas studied so far. As mentioned in Chapter 3, in MIS 3 and 2 in Europe sphagnum mosses are lacking from sediments containing peat [26, 214, 124]. The same can be said about the last glacial environments in Siberia [100, 298, 317, 319].

In fact this missing piece - the mitigating effect such mosses have on major CH$_4$ emissions - could very well be one of the reasons these gaseous releases went straight to the atmosphere and impacting the climate and causing the increase in temperature registered in all EPICA ice cores.

One more issue adding to the complexity of all CH$_4$ studies, is the fact that, for this gas, no proxy is available. All known data about past episodes of global warming came from air bubbles trapped in the ice cores or similar frozen-in-time sources. As there is no proxy to be used as comparison, cores from a past, similar environment can be used instead, hoping to draw enough information to paint a picture. Comparing the two images found, past and present, leaves room for the possibility they might, even if partially, overlap. The same factors we knew from out previous work, so grain size, mineralogy, soil layout and OM content all proved themselves capable of adding useful details and confirming the similarities between these sites.

### 6.5.1    Cores and section logs

Figures 6.5 and 6.7 show the upper 10 m of the core log of Hengelo and Ootmarsum, respectively, with OSL and $^{14}$C dating ($^{14}$C derived by correlation with Van Huissteden [275]), together with all analysis results from this study. Full core log descriptions are presented in the appendix.
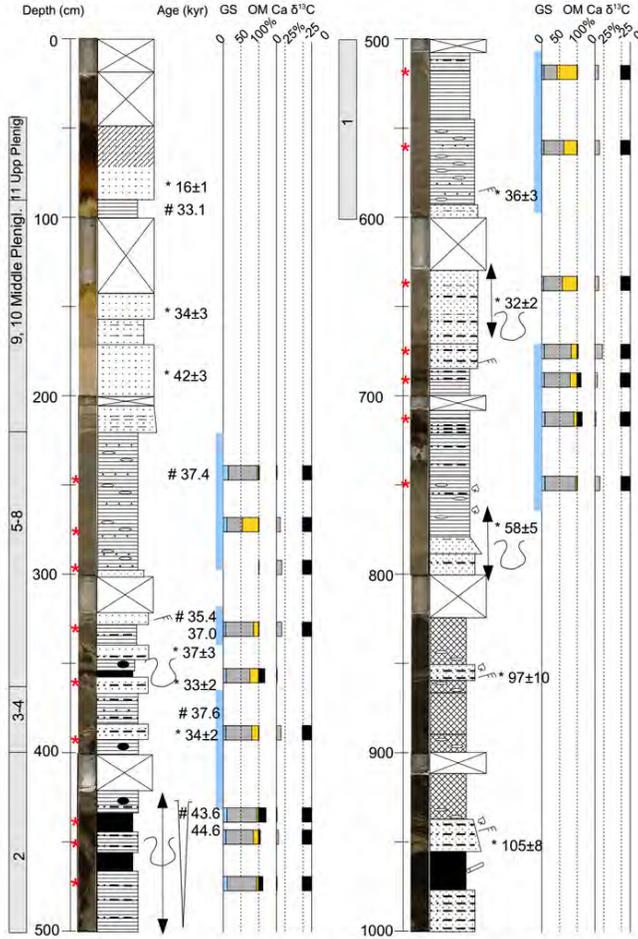
**Figure 6.5:** . Core log of the upper 10 m of the Hengelo core with OSL and $^{14}$C dating ($^{14}$C derived by correlation with Van Huissteden [275]) and analysis results. Analysis results columns: GS is grainsize summary (blue: clay fraction; grey: silt fraction; yellow: sand fraction); OM is organic matter percentage; Ca is carbonate percentage; $\delta^{13}$C of organic matter fraction. Blue: lacustrine sediments. The unit numbers are the same as in Figure 6.4.
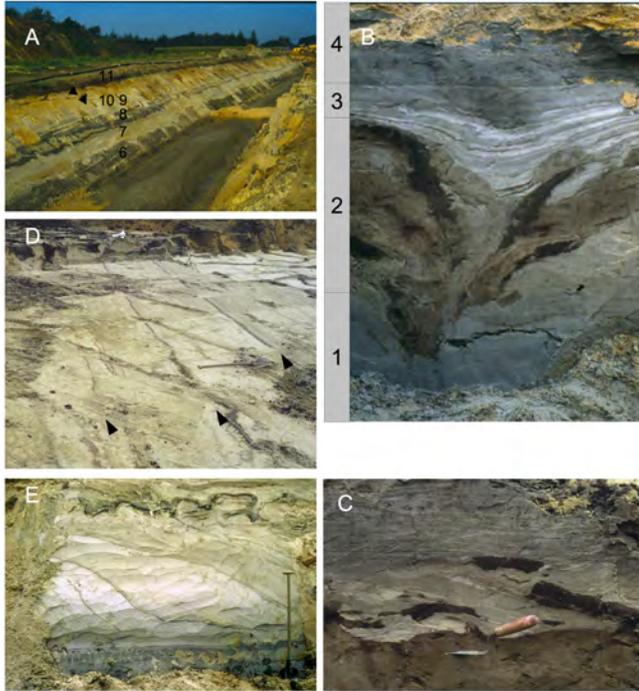
**Figure 6.6:** A: Top units of Hengelo highway construction pit section, numbers indicate units distinguished by Van Huissteden (1990). B: Detail of thaw lake succession, unit numbers cf. Van Huissteden [275]. Units 1 and 2 are substrate for ice wedge cast, unit 3 partial infilling of cast and eroded material at base of lake sediments of unit 4. C: detail of unit 3, with eroded lumps of peat or soil organic horizon. D: Remarkably straight foresets in unit 5, horizontal section. E: foresets in unit 5, vertical section, and cryouturbated base of unit 6.
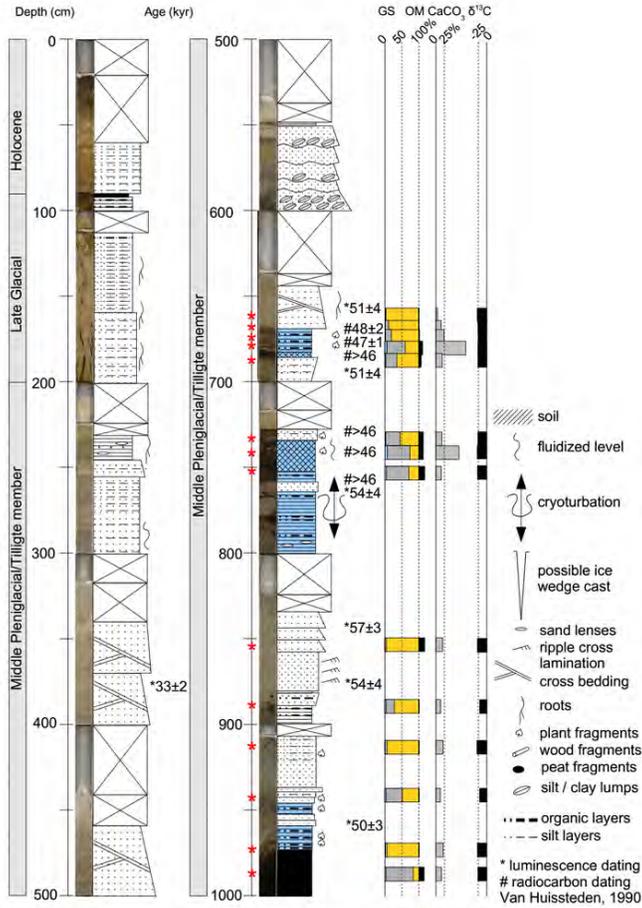
**Figure 6.7:** Core log of the upper 10 m of Ootmarsum core with OSL and $^{14}$C dating and analysis results. Analysis results columns: GS is grainsize summary (blue: clay fraction; grey: silt fraction; yellow: sand fraction); OM is organic matter percentage; Ca is carbonate percentage; $\delta^{13}$C of organic matter fraction. Blue: lacustrine sediments.
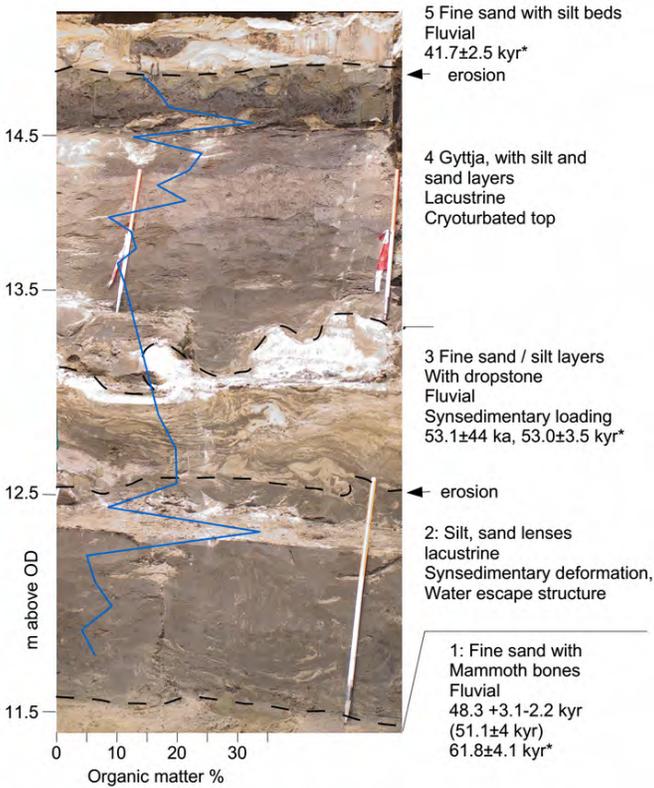
**Figure 6.8:** Orvelte section. Blue line indicates the organic matter percentage. Ages marked with * are OSL ages. $^{14}$C date: calibrated age between brackets.

## 6.5.2    Grain size distribution analysis

Tables 6.1 and 6.2 and Figures 6.9 and 6.10 show the results of the sediment analysis of the Hengelo and Ootmarsum cores, respectively. The mineral fraction has a bimodal distribution, with grain size modes centred around 30-40 m and 200-300 m. However, the silt fraction dominates in the samples from the Hengelo core, while the sand fraction dominates in the Ootmarsum core. The grain size distribution of beds with high organic matter content in the Hengelo core samples do not differ markedly from those without organic matter. However, in the Ootmarsum core some of the more organic beds show a lower sand content compared to under- and overlying deposits.

## 6.5.3    Organic Carbon analysis

The organic matter content ranges from less than 1% to about 20% in the Hengelo core organic beds. Similar values occur in the Ootmarsum core, except in the lowermost sample, which has an OM content of nearly 60%. Several core samples that visibly appear to be organic sediment, classify either as strongly silty peat or very humic silt according to Dutch geological mapping limits (the limit between the two being 15% for low clay content samples).
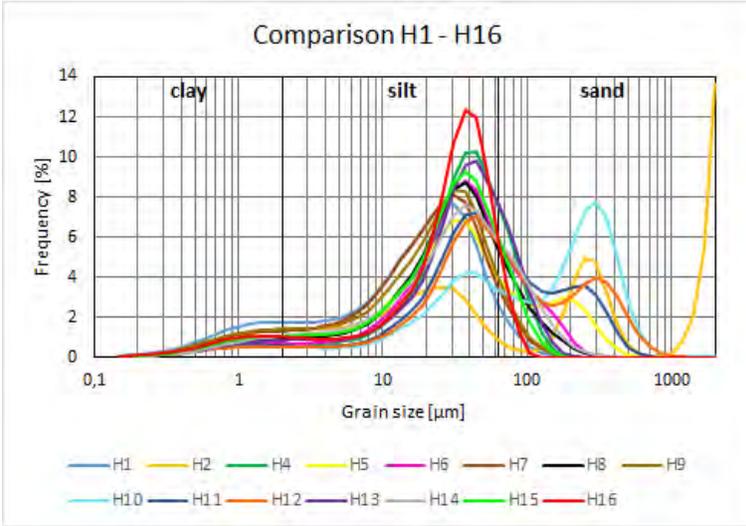
**Figure 6.9:** Hengelo cumulative results. The output for each single core can be found in detail in Appendix I
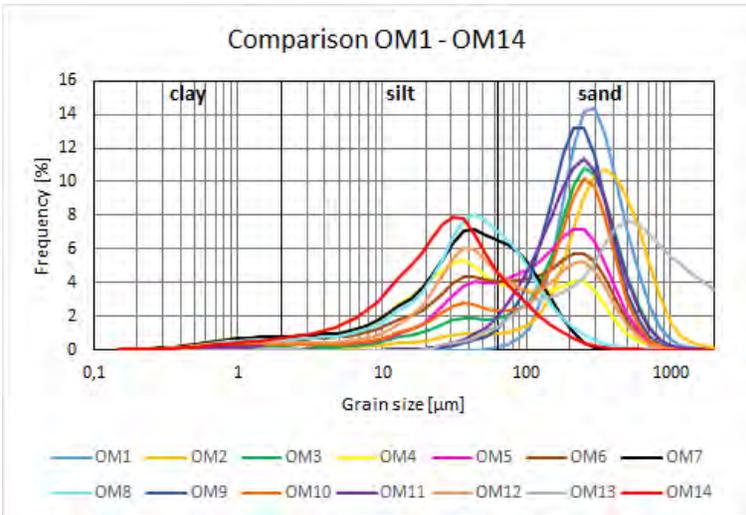


**Figure 6.10:** Ootmarsum cumulative results. The output for each single core can be found in detail in Appendix II

**Table 6.1:** Results of various analyses performed on soil samples from Hengelo.

| SAMPLE NUMBER HENGELO | ORGANIC MATTER CONTENT | MEAN | STANDARD DEVIATION | SILT | CLAY | SAND | CaCO$_3$ Tot (%) | $\delta^{13}$C (‰ vs VPDB) |
|---|---|---|---|---|---|---|---|---|
| 1 | 1.58 | 6.36 | 1.95 | 81.10 | 14.41 | 3.78 | 2.35 | -26.22 |
| 2 | 1.28 | 3.94 | 3.54 | 43.62 | 9.36 | 46.68 | 11.32 | -26.31 |
| 3 | 1.31 | 5.26 | 1.72 | n.a | n.a. | n.a. | 14.59 | -26.31 |
| 4 | 1.08 | 5.19 | 2.13 | 78.01 | 6.63 | 15.32 | 15.39 | -27.01 |
| 5 | 17.36 | 5.21 | 1.82 | 66.97 | 7.61 | 25.45 | 1.78 | -27.04 |
| 6 | 0.74 | 6.05 | 1.84 | 73.4 | 6.55 | 20.04 | 12.45 | -26.97 |
| 7 | 20.81 | 5.48 | 1.86 | 83.88 | 10.48 | 5.65 | 1.86 | -26.97 |
| 8 | 5.45 | 6.02 | 1.92 | 77.42 | 7.75 | 14.84 | 6.27 | -27.35 |
| 9 | 12.39 | 3.76 | 2.40 | 81.96 | 11.48 | 6.52 | 1.58 | -26.72 |
| 10 | 0.93 | 4.56 | 2.12 | 36.6 | 5.73 | 57.7 | 10.20 | -26.62 |
| 11 | 0.79 | 4.23 | 2.15 | 56.16 | 6.16 | 37.7 | 12.48 | -26.97 |
| 12 | 1.22 | 5.24 | 1.75 | 52.77 | 4.81 | 42.41 | 11.37 | -27.04 |
| 13 | 3.42 | 5.41 | 1.90 | 76.1 | 6.47 | 17.41 | 20.73 | -26.95 |
| 14 | 10.48 | 5.62 | 1.84 | 73.32 | 7.34 | 19.35 | 6.80 | -27.48 |
| 15 | 14.42 | 5.61 | 1.78 | 80.77 | 8.63 | 10.61 | 2.49 | -28.05 |
| 16 | 0.79 | 6.36 | 1.95 | 86.23 | 9.04 | 4.74 | 13.88 | -25.88 |

**Table 6.2:** Results of various analyses performed on soil samples from Ootmarsum.

| SAMPLE NUMBER OOTMARSUM | ORGANIC MATTER CONTENT | MEAN | STANDARD DEVIATION | SILT | CLAY | SAND | $CaCO_3$ Tot (%) | $\delta^{13}C$ (‰ovs VPDB) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.08 | 1.82 | 0.91 | 0.22 | 0.43 | 99.37 | 2.51 | -27.08 |
| 2 | 1.13 | 1.98 | 1.61 | 9.12 | 0.96 | 89.93 | 7.86 | -25.72 |
| 3 | 2.44 | 2.72 | 1.77 | 17.53 | 1.58 | 80.88 | 12.14 | -24.46 |
| 4 | 11.71 | 4.59 | 2.27 | 53.71 | 6.26 | 40.07 | 44.92 | -26.41 |
| 5 | 0.73 | 3.46 | 1.95 | 31.79 | 2.78 | 65.46 | 9.28 | -25.85 |
| 6 | 12.93 | 3.95 | 2.13 | 42.34 | 3.41 | 54.26 | 33.86 | -28.04 |
| 7 | 17.34 | 5.09 | 1.93 | 65.59 | 6.60 | 27.81 | 8.04 | -26.75 |
| 8 | 11.17 | 4.89 | 1.84 | 65.78 | 5.14 | 29.05 | 10.17 | -27.49 |
| 9 | 0.11 | 2.33 | 1.15 | 4.09 | 0.88 | 95.04 | 6.83 | -20.52 |
| 10 | 1.22 | 3.25 | 2.16 | 25.40 | 3.79 | 70.79 | 10.37 | -28.80 |
| 11 | 0.16 | 2.4 | 1.35 | 6.09 | 1.31 | 92.58 | 6.57 | -21.36 |
| 12 | 0.96 | 4.08 | 2.12 | 47.68 | 4.33 | 47.97 | 10.37 | -26.78 |
| 13 | 14.57 | 1.28 | 1.47 | 4.80 | 0.21 | 94.99 | 7.90 | -26.15 |
| 14 | 59.07 | 5.38 | 1.69 | 79.52 | 4.48 | 15.98 | 1.86 | -25.82 |

### 6.5.4   DNA analysis

The objective of this analysis was to find microbes named *Archaea*, which are responsible for the formation of CH$_4$. To this purpose, all the samples extracted from the cores have been analysed as described in Section 3.3. Results are shown in Figure 6.11, which compares the samples from the ice cores from Hengelo and Ootmarsum to the Siberian ones (as previously shown in Chapter 5). The results did confirm the presence of Archaea in most of the samples. The cluster shown in samples O5-H7a shares a common band (also present beside other bands in H8b, O11). Most interestingly, those samples originate from all three locations.
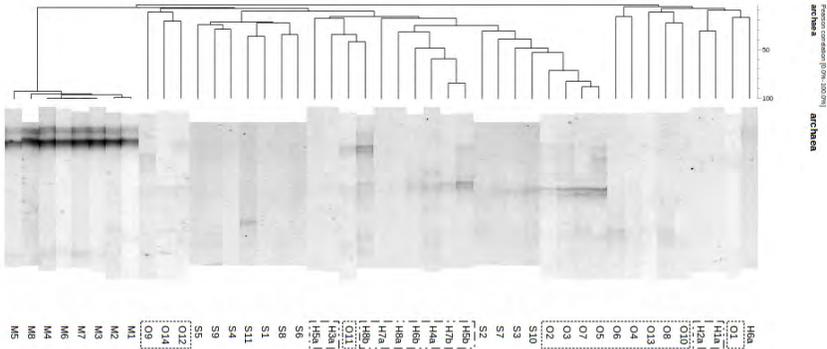


**Figure 6.11:** Cluster analysis. Results from two ice cores from The Netherlands, dated around the Weichselian, and present-day Siberian samples. M = Marker, S = Siberia (11 lanes identified, 1-11), H = Hengelo (a = gel a [8 lanes identified, 1-8], b = gel b [only 4 lanes identified, first 4 appear empty, therefore labelled 5-8], Numbers = lane on gel for particular gel, O = Ootmarsum (14 lanes, numbered 1-14).

### 6.5.5 Radiocarbon dating

The carbon isotope values do not differ markedly for most samples, varying between $\delta^{13}$C values of -25.75 and -27.5. In the Ootmarsum core a few samples with markedly higher $\delta^{13}$C values are found, up to -20.5. These are samples with a very low OM content. The data from our samples were reviewed as follows: data of OSL age determination were used to correct our data by courtesy of Wallinga and Versendaal (pers. comm., 2011, unpublished reports), while radiocarbon ages from the Ootmarsum core were compared to those obtained from Bos (pers. comm.).

### 6.5.6 Stratigraphy

A correlation between the Hengelo core and nearby exposures (HHCP, RCP, [275, 215] is indicated in Figure 6.3 on page 97.

   The strongly cryoturbated silt-peat horizon between 4 and 5 m depth corresponds most likely with unit 2 in the highway construction pit, and unit 1 in the clay pit; in the clay pit it is slightly older. The pronounced erosion level (unit 3) in HHCP correlates with a similar erosion level in RCP, and the overlying laminated silt is found in both exposures (unit 2 in RCP and 4 in HHCP). This erosion level is not clearly present in the core but may be located between 4 and 3.8 m; at this level peat lumps and a sand layer occur. The overlying lacustrine silt of unit 3 in the HHCP appears to be thin in the core, restricted to a laminated silt between 3.8 and 3.6 m. In the RCP, this succession is truncated by the fluvial channel fill of unit 3. Based on its radiocarbon date, such fill should be younger than unit 4 in the HHCP, but older than unit 6 and the cryoturbated silt and peat bands at about 3.5 m in the core. The channel fill is overlain by up to 3 m of silty lacustrine clay in the RCP (unit 4−6), with only one sandy intercalation (unit 5). At this level, the HHCP and the core contain more stratigraphical differentiation. Unit 5-8 in the HHCP may correlate with the succession of silt and sands between 3.6 m and 2.2 m in the core; we infer that the sand layer 5 is much thinner in the core, the cryoturbated peat around 3.5 m correlates with the cryoturbated peaty base of unit 6, the sand of unit 7 is thinner in the core and the silt of unit 8 is thicker in the core. The sands of unit 9 and the cryoturbated silt bed of unit 10 are present in the core at comparable depths and thickness. We assume the 3 m thick lacustrine clay succession of unit 4-6 in the RCP as laterally equivalent to unit 5−10 in the HHCP and the sediments between 3.6 and 0.8 m in the core. This thick silt succession in the RCP therefore appears to split up into separate lacustrine beds with intercalated sands in an easterly direction.

   The radiocarbon and OSL chronologies agree well for both the Hengelo and Ootmarsum cores with a few exceptions. One dating at 1.86 m depth gives anomalous age of 42 kyr and is considered questionable by Wallinga and Versendaal (pers. comm., 2011). The other OSL dates above ±4.5 m match with the $^{14}$C dates in the exposures, which range between 37.6 and 33.1 kyr. Between 5.8 and 6.5 m depth in the Hengelo core, two OSL ages of 36 ±3 and 32 ±2 are reported, the topmost one also considered questionable by Wallinga and Versendaal (2011). However, the remaining age of 32 kyr also may be anomalous. The overlying cryoturbated peat bed at ±4.5 m depth very likely correlates with the peat at ±4.5 m depth in the core, and the top of unit 1 in the RCP. This peat has been dated between 44.6 and 46.8 kyr [275]. An alternative interpretation is possible, but would require 1) rejection of the radiocarbon dates or 2) the correlation between the peat beds in the core and the exposures, assuming a considerable hiatus between the core and

the exposures, and 3) the assumption of very high sedimentation rates of at least 5.5 m of sediment in a very short time. There is no age difference between the top and bottom dates of the core succession between 1 and 6.5 m, a part of the succession that also includes peat beds, generally indicating a low sedimentation rate.

For the Ootmarsum core the OSL and 14C chronology derived from nearby borehole sections generally agrees. The clustering of ages in the range of ±60 to ±50 kyr in the sand and silt/gyttja units between 6.5 and 9.8 m also suggest a quite high sedimentation rate.

### 6.5.7    Sedimentation rates

Based on the chronology, there are clear and opposing trends in sedimentation rate between the Hengelo and Ootmarsum cores. In the Ootmarsum core sedimentation rate is highest in the lowest 4 m, with ages 50 kyr and older (deposition rate 44 cm per kyr). The overlying fluvial sands show a deposition rate of 12.5 cm per kyr, which however includes a large erosional hiatus. The trend in the Hengelo core and sections is opposite, sedimentation rate being lower in the lowest 3.6 m (up to the top of unit 2 in the HHCP), 24 cm per kyr. It increases in the succession overlying unit 2 in the HHCP, up to 34 cm per kyr. This reflects the absence of large erosional hiatuses. In general, $^{14}$C datings in Middle Weichselian basin fills indicate a decreasing sedimentation rate throughout this time interval [275].

### 6.5.8    Weichselian environmental change recorded in the Hengelo area

The Late Eemian / Early Weichselian succession below 8.00 m depth in the Hengelo core consists of terrestrial peat, overlain by crossbedded sands and thick gyttja deposit, which confirms lacustrine conditions. Based on the OSL age of $\sim$ 58 ±5 kyr at the base of this succession, it follows after the OIS4 cold phase from which abundant permafrost evidence is found in the Netherlands [289] as ice wedge pseudomorphs in a former highway construction pit a few kilometres northwest of the study area [268]. The base of the silty sand bed appears to be cryoturbated, indicating this succession could be originated by a thaw lake; the silts in particular indicate a lacustrine environment. Current ripple lamination suggests a fluvial origin for the overlying fine sands, which may attest to fluvial infilling of the lake. However, an alternative interpretation of the succession between 8.00 and 6.00 m is a fine-grained fluvial channel fill analogous to those ones of unit 3 in the RCP. For the succession between 4.00 and 6.00 m and upwards, correlative units are found in the RCP and HHCP exposures (see above).

In the core and the HHCP a fining-upward and terrestrializing succession is visible, with possible cryoturbations in the sandy base of the silt bed and at the transition from unit 1-2 in the HHCP, although poorly exposed. This could be explained by the presence of a cryoturbation level at the transition between unit 1 and 2 in the HHCP. In unit 2, paleobotanical evidence [215] suggests that, at the base, lacustrine conditions represent a second lake phase, with cryoturbations indicating that again permafrost thaw may have been the cause of lake formation; while, at the top, it shows dry and cold conditions and increase of bare soil, attributed to intense periglacial activity and growth of permafrost, pointing towards a terrestrialization of the lake through peat formation and regrowth of ice-rich permafrost [215].

Towards the top of unit 2 the sand content decreases, and the silt grades into strongly cryoturbated silt and peat beds above 5 m depth, that correlates with units 1 and 2 in the HHCP. These cryoturbations are possibly due to an ice-wedge pseudomorph, similar to those occurring at the same level in the HHCP, showing in the horizontal plane a clear polygonal pattern (Figure 6.6 on page 102). The silt at the top of the succession was deemed of loess origin, based on its grain size analysis, and together with peat beds and ice-wedge pseudomorphs indicate a stable terrestrial surface with slow eolian [275] and organic sedimentation, underlain by continuous permafrost. This surface can be correlated between the RCP (erosion remnant, unit 1), the core and the HHCP (unit 2). In the HHCP, infilling in the ice-wedge pseudomorphs indicate lacustrine deposition while wedge ice was still present, showing a rapid subsidence or rise of water table on the previous surface. This succession strongly resembles the type of succession described Hopkins and Kidd ([118], Figure 6.2 on page 97) and therefore has been interpreted as a thaw lake succession [275].

The succession shows clear indication of the thaw of ice-rich permafrost, followed by lacustrine conditions. Soil subsidence and rising water level should have been under way during thawing of the ice wedges in unit 2, followed by lake expansion causing the deposition of unit 3 and the peat and silt clasts eroded from unit 2. Next, unit 4 indicates full lacustrine conditions. In the core this succession is thinner and the layers between 4.00 and 3.60 m may represent units 3 and 4, while their combined thickness also gives an indication of the depth of the lake: it should have been at least 2.5 m deep.

The entire sequence of units 3-5 seems to represent a complete thaw lake cycle: subsidence by permafrost thaw and lake creation, followed by infilling of the lake with sediment, after which permafrost has been established again. As shown above, this may be the third thaw lake cycle in the entire Hengelo succession, the portion between 5 and 8 m in the core containing two earlier cycles. However, by contrast to the previous episodes this cycle is exceptionally well documented by three-dimensional sedimentological evidence in a larger exposure [275, 215]. A difference with the previous cycle is that the lake deposits at the base of unit 2 showed gradual terrestrializing, while in units 4-5 the infilling with sediment from bank erosion and possibly fluvial transport is more important. The base of 6 consists of strongly cryoturbated silt/sand/peat layers, followed by hardly deformed lacustrine silt with thin moss bands.

A fourth lake cycle is shown by the succession in the HHCP with units 6-7, again less well visible and thinner because it corresponds to cryoturbated silt/peat layers, silt and sands between 3.6 and 3.0 m. Correlation with the RCP is even more difficult, due to the large channel structures of unit 3. These are probably contemporaneous with part or all of the succession of units 5-7 in the HHCP. This is followed by a fifth lake cycle. At its base, unit 8 is strongly cryoturbated, but again much less deformed at its top. It consists of silt with sand intercalations; wave ripple lamination is found at several levels of the unit, indicating shallow lacustrine conditions. In the core, the correlative sandy silt bed between 2.0 and 3.0 m is thicker but shows similar characteristics. In the overlying sand unit (9) sedimentary structures are poorly visible, but indications for a similar foresetted structure as in the previous sand units are found. This is capped by a strongly cryoturbated silt bed (unit 10) which forms the top of the Middle Weichselian succession.

In the Hengelo sections several fine-grained units have been interpreted here as lake sediments. However, in particular the more sandy silts may also be fluvial channel fill sediments. This is for instance illustrated by channel fills in the RCP, consisting of al-

ternations of fine sand and silt, often with current ripple lamination. This makes it very difficult to have a clear distinction between finegrained channel fills and lake deposits in cores. The information on the geometry of the silt sediment bodies in the exposure therefore proved indispensable. Although the majority of the fine-grained deposits in the Hengelo area are lacustrine, they show also the close proximity of river channels.

### 6.5.9    Weichselian environmental change recorded in the Ootmarsum area

The Middle-Upper Weichselian in the Ootmarsum core is considerably thicker than that in the Hengelo core. The studied section of the core starts 10 m depth with a ∼25 cm thick peat layer which is of Early Weichselian age. According to the OSL dates these sands date from the earliest part of the Middle Weichselian. It cannot be excluded that the lacustrine silt is a thaw lake deposit because of its chronostratigraphic position shortly after the OIS 4 cold phase, but any other indications of permafrost thaw are lacking. In the lower gyttja bed, clear evidence for shallow lacustrine conditions is found by the presence of seeds of Potamogeton sp. (Bos, pers. comm); in the second gyttja bed Potamogeton is found only at the base. In both gyttja beds the paleobotanical data indicate a transition to a sedge-dominated fen.

At about 6.70 m a course fluvial sand layer covers the upper part of the succession. From 6.00 to 3.00 m, the course, cross-bedded sand with gravel and intraclasts suggest the presence of a channel with substantial discharge. Considering the position of the core, very close to the present-day drainage divide between the Dinkel and Regge basins, this indicates that drainage from the Hengelo Basin was routed to the north through the Ootmarsum area into the Dinkel basin during the Middle Weichselian, instead of the present northwest drainage to the Regge river. At this location also the present drainage divide is very low, as it occupies a gap in the Oldenzaal-Ootmarsum ice-pushed ridge. Also the silt beds in the Ootmarsum core are markedly coarser grained than their equivalents in the Hengelo core (Figures 6.5 and 6.7), and comparative grain size curves in Figures 6.9 and 6.10 on page 105. Likely this relates to a more dynamic fluvial environment in the Ootmarsum area compared to the Hengelo area.

In nearby detailed borehole sections ([275], Figure 6.1 on page 96) a silt and gyttja/peat bed is found at depth of about 3 m, with ^{14}C ages between 36.53 ±0.41 and 37.06 ±0.30 kyr (uncalibrated, cal. age BP range: 41.63 ±0.34 and 41.88 ±0.32). This lacustrine unit is missing in the Ootmarsum core, probably due to younger erosion, as indicated by the OSL age of 33 ±2 kyr at that depth on fluvial sands. The course-grained sand sequence starting at about 6 m in the core is also present in the sections, as a distinct course-grained fluvial unit with an erosive base. In these sections, this unit cuts through silt and gyttja beds of comparable age range ($39.2 - 44.3$ kyr, cal. BP $43.0 - 48.7$) as unit 2 in the Hengelo highway construction pit described above (the unit with Middle Weichselian ice wedge pseudomorphs). The silt, gyttja and peat beds below 6.7 m are also found in the borehole sections, and have ^{14}C dates ranging between 46.2 and 55.7 kyr , cal. BP >47.4, comparable to the OSL ages in the core between $50.3 - 57.3$ kyr. In general, both the core and the nearby sections indicate rapid sedimentation from the start of OIS Stage 3 up to ∼40 kyr, followed thereafter by fluvial erosion and slower sedimentation rate.
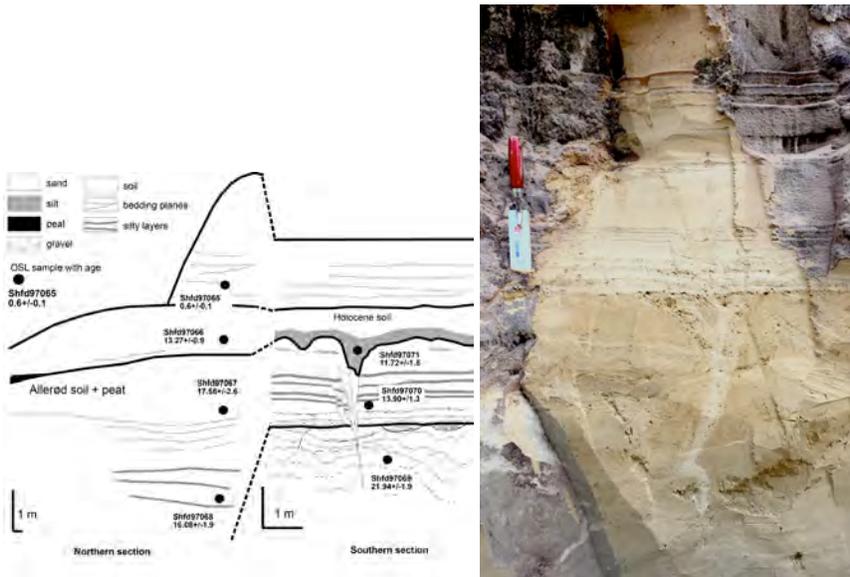
**Figure 6.12:** The Dinkel river / Lutterzand section after Bateman and van Huissteden [21]. Left: schematic overview of section stratigraphy; Right: example of frost crack below Beuningen Gravel bed in southern section

### 6.5.10 Weichselian environmental change recorded in the Orvelte exposure

The base of the succession in which the Mammoth remains are found consists of fluvial sand, which is overlain by a 0.8 m thick fine-grained lake deposit consisting of gyttja with sand and silt. Water escape structures indicate overpressurized conditions in the sand layer, possibly resulting from permafrost thaw and related cryoturbation. Interpretation of this unit as a thaw lake remains uncertain because evidence of ice-wedge pseudomorphs is lacking and cryoturbation cannot be gauged in this rather small exposure. Similar beds in this area have been previously interpreted as thaw lake sediments [72]. The sandy fluvial deposit overlying the lake has eroded these lake deposits and contains a dropstone, testifying to floating ice transport of debris and cold climate conditions. The top of this unit is again cryoturbated, probably from Late Pleniglacial age.

## 6.6 Discussion

The new data presented in this chapter are consistent with the idea that, during the Middle Weichselian, temperature shifts of smaller magnitude could have caused widespread thaw lake development [290], while the same effect has been proven for the Late-Weichselian Holocene climate transition [310]. The paleobotanical evidence found in this area is in general fragmentary, lacking continuous records from a full cycle, because of the erosional nature of the forming processes. Wetlands in the past are lacking the presence of mosses and similar species, none or scarce pollen evidence has been found in all the areas studied so far. As mentioned in Chapter 3, in MIS 3 and 2 in Europe Sphagnum mosses

are missing from sediments containing peat [27, 218, 124]. The same can be said about the last glacial environments in Siberia [100, 303, 323, 325]. The overall scarcity of vegetation and OM content, highlighted from the previous studies, could be likely attributed to the processes taking place in these areas during the Middle Weichselian. There is a clear connection of thaw lake formation with fluvial activity, as seen in the Hengelo exposures. In the clay pit, a large fluvial channel infill occurs at the base of the uppermost thick lacustrine silt unit. The sediment of the sandy lake shore shelves in the Hengelo construction pit is at least partly of fluvial origin. The distinction between thaw lakes and river floodplain lakes is not sharp, as the latter may also show features of expansion by permafrost thaw and thaw lakes may transfer into floodplain lakes by contact with the river system [285]. Examples are lakes in the Mackenzie Delta [110] and the floodplain of the Berelegh river near Kytalyk research station in northeastern Siberia [285].

In the Hengelo area there are five lake cycles stacked above each other (Figure 6.6 on page 102). Most of these lake cycles have a clastic infilling of silt and sand eroded from the lake banks or from the fluvial system, after which permafrost could re-establish; while the second cycle, in unit 2 of the HHCP, shows instead terrestrialization by peat formation and regrowth of ice-rich permafrost. The silt and gyttja beds in the Ootmarsum area lack unequivocal evidence of permafrost thaw because only borehole information is available, but it is likely by analogy of the Hengelo area and by the larger amount of organic matter in the sediment, indicating an environment dominated by peat deposition. Several calcareous gyttjas occur in the Ootmarsum area, possibly due to the upwelling of Ca-rich groundwater. This indicates that if there were any thaw, this may have penetrated the permafrost creating contact with the deeper calcareous groundwater. The lake sediments at Hengelo constitute a considerable part of the basin fill, culminating in the thick lacustrine succession of the RCP. At the HHCP site, at least three, and likely four, stacked thaw lake units can be discerned. However, these may not have been all independently formed new thaw lakes, but rather repeated expansion and contraction phases of the same lake, at least after ∼40 kyr BP, similar to model results of a previous study [146].

During the Middle Weichselian, the area must have been a poorly drained basin. Towards the edges of the basin, sand beds dominate [275, 316]. In particular the area of the RCP has been a more persistent lake during the younger part of the Middle Weichselian, but the site of the core and the HHCP may have been located at a more marginal position. The foresetted sand beds between the silts above unit 4 in the HHCP represent lake shore shelves (see above). During the development of these lake shore shelves, permafrost has been re-established on their surface, since the base of the overlying silts show both large cryoturbations and ice wedge pseudomorphs.

After 40 kyr BP, also fluvial activity appears to increase in the succession, which may be linked to better drainage of the Hengelo basin associated with establishment of drainage towards the north at the site of the Ootmarsum core. The question arises, whether this is an independent cyclicity of the system [33], or whether it is climate-driven by the Dansgaard-Oescher oscillations of the Middle Weichselian as suggested by various authors [140, 40, 45]. Bohncke [40] also report five lake cycles in the Reichwalde lignite mine in Eastern Germany. In one of the lake successions, they found paleobotanical and chironomid evidence for a high minimum mean July temperature of ∼12−14°C shortly after the formation of the lake, and during the initial period of deposition followed by colder conditions thereafter. Climate oscillations linked to lake deposits have also been invoked by other authors [215, 273].

Apart from the Early Glacial gyttja beds in the Hengelo core, predominantly organic lake sediments are absent in the Middle Weichselian part of the Hengelo succession. The organic carbon content of the silt beds ranges between 1.7 and 8.4% ([275]). By contrast, organic lake sediments are much more common in the Middle Weichselian succession in the Ootmarsum core and borehole sections, and in the Orvelte section, which largely consists of gyttja that, upon analysis, contains relatively modest amounts of organic matter, rarely more than 35%, in good agreement with organic carbon content from thaw lake basins developed in a peat substrate in western Siberia [16]. The gyttja and humic silt beds in the Ootmarsum area and Orvelte section have been deposited in a river valley environment rather than a basin setting. The $\delta^{13}$C values of the organic matter varies little for most samples, between -25.7‰ and -28.8‰ indicative of rather freshly deposited organic matter derived from C3 plants, that was not subject to strong decomposition. Similar values were found in soils at the northern Siberian forest-tundra transition [224]. However, in the Ootmarsum core a few outliers up to -20.5‰ occur, from older soil carbon ([224] and references therein), probably redeposited in the more dynamic fluvial environment of the Ootmarsum area.

## 6.7 Conclusions

The sections at Hengelo demonstrate that during the Middle Weichselian thaw lakes developed in ice-rich permafrost, similar to present-day permafrost areas. Up to five phases of lake expansion may be present near Hengelo. In at least one case unequivocal evidence of a thaw lake origin of lacustrine sediments is presented, in the shape of ice wedge pseudomorphs directly below the lake sediments. Sedimentary structures of the lake infilling indicate the presence of actively eroding banks, providing sediment to shelf-like benches along the lake shore. The lake may have been at least 2.5 m deep. In other cases the evidence of permafrost below lacustrine deposits consists of large involutions and sporadic ice wedge pseudomorphs. The lake deposits near Hengelo may have resulted from repeated new formation of lakes but more likely has been part of a larger, frequently expanding and contracting lake system. Indications of interference with the fluvial system have been found, which is common also in present-day thaw lake systems. Lake infillings range from largely clastic (silts) with a few percent of organic matter to organic (gyttja) or silts with interbedded (benthic) mosses. Also in the gyttjas the clastic contribution is relatively large. The isotopic signature indicates mostly organic matter that has not been strongly decomposed.

Thaw lake formation may have occurred throughout the periglacial zone in the Middle Weichselian, triggered by climate oscillations at that time; however, hard evidence is lacking because of the fragmentary nature of the associated paleoclimatic records. Cyclic behaviour of the thaw lake system itself cannot be excluded, but is less likely, because the permafrost may have been relatively thin and could have been penetrated by lake talik formation. In contrast to the Middle Weichselian, permafrost degradation at the termination of the LG occurred under drier conditions in Europe. Processes of formation and rapid expansion of thaw lakes are generally linked to sharp rises of atmospheric $CH_4$; this study presents an array of data that agree with such a statement. The isotopic values found in the samples, together with their OM content, the drier climate of the Middle Weichselian and the highly changing environment of the investigated area; all give significant clues,

to help understanding the processes governing CH$_4$ emissions. They could be used as valid indications for future modelling experiments, in order to reconstruct climate and environment of Middle Weichselian and sharpen the accuracy of modelled CH$_4$ flux values, which are generally overestimated.