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## Palaeoecological study of a Weichselian wetland site in the Netherlands suggests a link with Dansgaard-Oeschger climate oscillation

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### Abstract

Botanical microfossils, macroremains and oribatid mites of a Weichselian interstadial deposit in the central Netherlands point to a temporary, sub-arctic wetland in a treeless landscape. Radiocarbon dates and OSL dates show an age between ca. 54.6 and 46.6 ka cal BP. The vegetation succession, starting as a peat-forming wetland that developed into a lake, might well be linked with a Dansgaard-Oeschger climatic cycle. We suggest that during the rapid warming at the start of a D-O cycle, relatively low areas in the landscape became wetlands where peat was formed. During the more gradual temperature decline that followed, evaporation diminished; the wetlands became inundated and lake sediments were formed. During subsequent sub-arctic conditions the interstadial deposits were covered with wind-blown sand. Apart from changes in effective precipitation also the climate-related presence and absence of permafrost conditions may have played a role in the formation of the observed sedimentological sequence from sand to peat, through lacustrine sediment, with coversand on top. The Wageningen sequence may correspond with D-O event 12, 13 or 14. Some hitherto not recorded microfossils were described and illustrated.

**Keywords:** Dansgaard-Oeschger cycles, microfossils, non-pollen palynomorphs, Oribatida, pollen, Weichselian.

### Introduction

In 2004 a large, more than 4 m deep building excavation was made in Wageningen (Fig. 1) in order to prepare the foundation of a new university building (so-called Forum Building). Dr Monique Heijmans of the Nature Conservation and Plant Ecology Group of Wageningen University informed the first author about a peat deposit, covered by a lake deposit, as it was exposed in the profiles of the building excavation. The Wageningen-Forum site is situated in a former Saalian tongue

basin. During the Weichselian this basin was filled in with alternating fluvial meltwater deposits from the ice-pushed ridges and aeolian cover sands. During relatively humid phases drain water from the ice-pushed ridges caused seepage in the basin and therefore lakes and fens could develop in the depressions in the landscape. Lake sediments and peat deposits were overblown with sand during periods of aeolian activity. The Forum site shows an example of well-preserved peat and lake sediments covered by aeolian sand. In the same tongue basin northwest of Veenendaal a peat deposit of Allerød

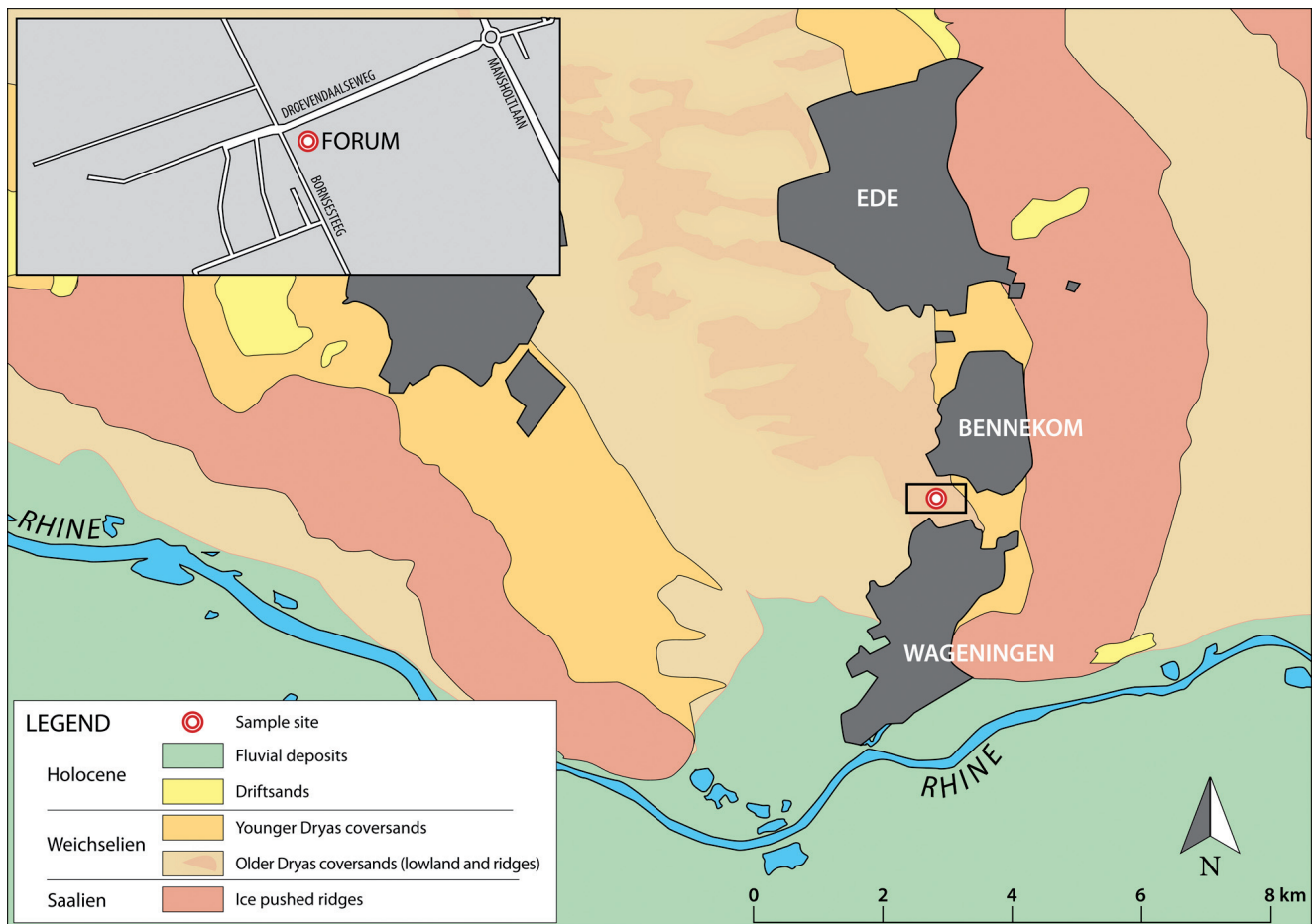


Fig. 1. The Wageningen-Forum site in geological context.

age was covered by aeolian sand (Van Mourik & Slotboom, 1995). The southern part of the ice-pushed ridges was eroded by the Rhine-Meuse river system during the second half of the Weichselian (Busschers et al., 2007).

On October 18<sup>th</sup> 2004 Henry Hooghiemstra and the first author visited the site for sampling. From the geological setting it was evident that the lake deposit was covered by Upper Pleniglacial coversand, including a Beuningen Gravel Bed (Van der Hammen et al., 1967; Van Huissteden et al., 2000). BGBs are polar desert pavements formed between ca. 22 and 16 ka when permafrost degradation took place (Van Huissteden et al., 2000). At many places along the profiles the peat/lake deposit was heavily disturbed and uplifted by ice-wedge casts and cryoturbations, originating from BGB levels. A sampling site, relatively undisturbed by frost phenomena, was selected along the northern east-west profile (coordinates 51° 59' 08.34" N; 5° 39' 49.05" E) and there three vertical sections were made, step-wise on top of each other (Fig. 2). The deposit, including the transitions from the sand underneath and the sand on top, was sampled in three metal boxes, each one 50 × 15 × 10 cm, open at one side. Sample boxes 2 and 3 had an overlap (estimation based on lithology) of 26 cm. The sampled Wageningen-Forum sequence is indicated below as WGNF.

## Material and methods

### Lithology of the sampled deposit

The Holocene soil surface around the excavation had already been disturbed before our fieldwork and therefore the distance between the ground surface level and the top of the sampled sequence could only be estimated. The minimal thickness of the coversand deposit on top of the collected material was 1.9 m. In that sandy deposit strings of small pebbles could be recognized as the Beuningen Gravel Bed (Fig. 2). The choice for the location of the sampling site WGNF was based on limited disturbance of the peat and lake deposits, but an infilled frost crack could not be avoided (represented in box 3 by the sample at 37 cm; see Fig. 2 and below).

The sample from the upper one cm thick layer in box 3 is indicated as '1 cm'; a sample from 4-5 cm was indicated as '5 cm', et cetera. The lithology of the combined contents of the three metal boxes, taking into account an overlap of 26 cm between boxes 2 and 3, can be described as follows:

1-40 cm Grey clayey lake deposit, showing a frost crack filled up with sand and lake deposit (infilled represented by sub-sample 37). Other sub-samples at 1, 5, 9, 13, 17, 21, 25, 29 and 33 cm.

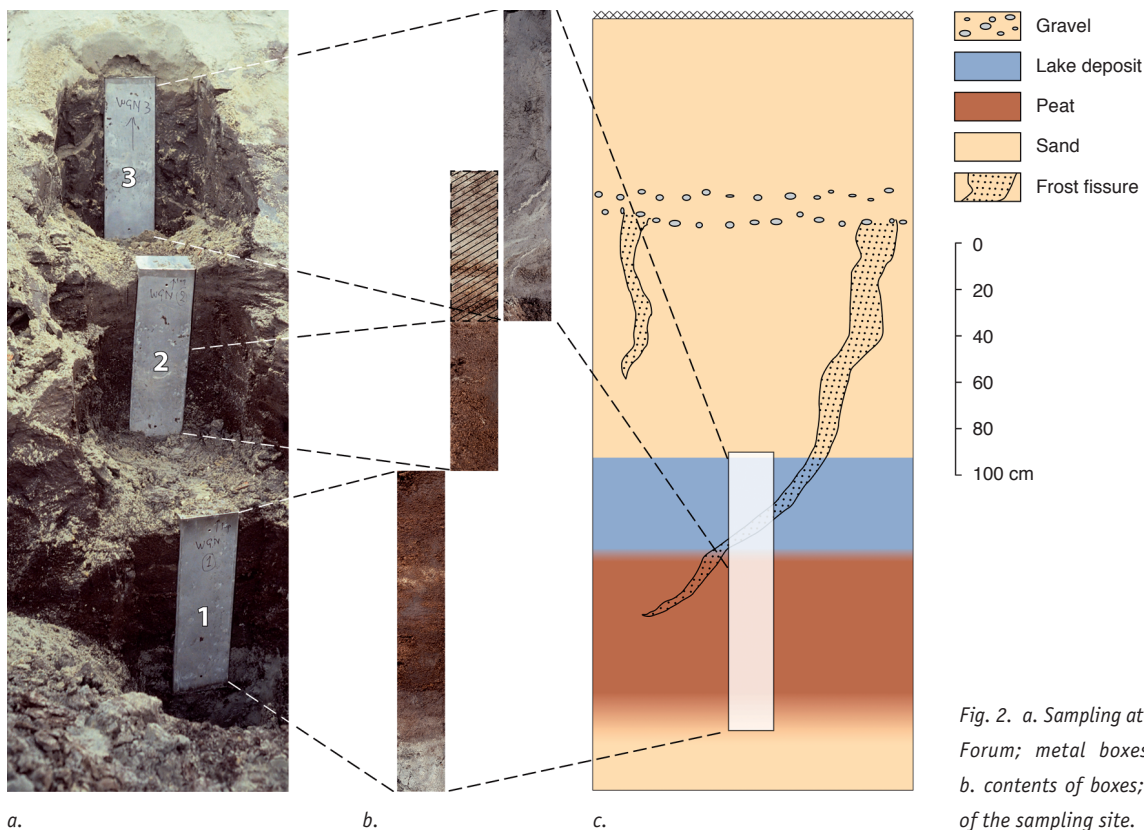


Fig. 2. a. Sampling at the site Wageningen-Forum; metal boxes are 50 cm high; b. contents of boxes; c. schematic profile of the sampling site.

41-45 cm	Transition between peat and lake deposit; with some horizontal peaty layers. This transitional layer is represented by sub-samples at 41 and 45 cm.
46-107 cm	Peat, mainly consisting of well preserved mosses. Sandy peat at 91 and 93 cm levels. Sub-samples at 49, 53, 57, 61, 65, 69, 73, 77, 81, 85, 89, 91, 93, 97, 101 and 105 cm levels.
108 cm	Transition between well-preserved peat and dark, highly decomposed sandy peat.
109-116 cm	Transition from dark, sandy peat to peaty sand (increasingly sandy towards the base). Subsamples at 109, 111, 113 and 115 cm.
117-124 cm	Sand. The subsample at 117 cm was extremely poor in pollen (no spectrum in diagram), but this sample is represented in the macrofossil diagram.

### Microfossils and macroremains

In the laboratory at the University of Amsterdam subsamples were taken for the analysis of microfossils and macroremains. Microfossil samples of 0.95 cc were treated with KOH and subsequently acetolysed according to Faegri and Iversen (1989). For the separation of organic material from sand and clay a bromoform-ethanol mixture (specific gravity 2) was used. The material was embedded in glycerine jelly and sealed in with paraffin wax. Non-pollen palynomorphs (NPP) were recorded in addition to pollen grains. Type numbers for NPP, as mentioned in the microfossil diagram, are based on illustrations

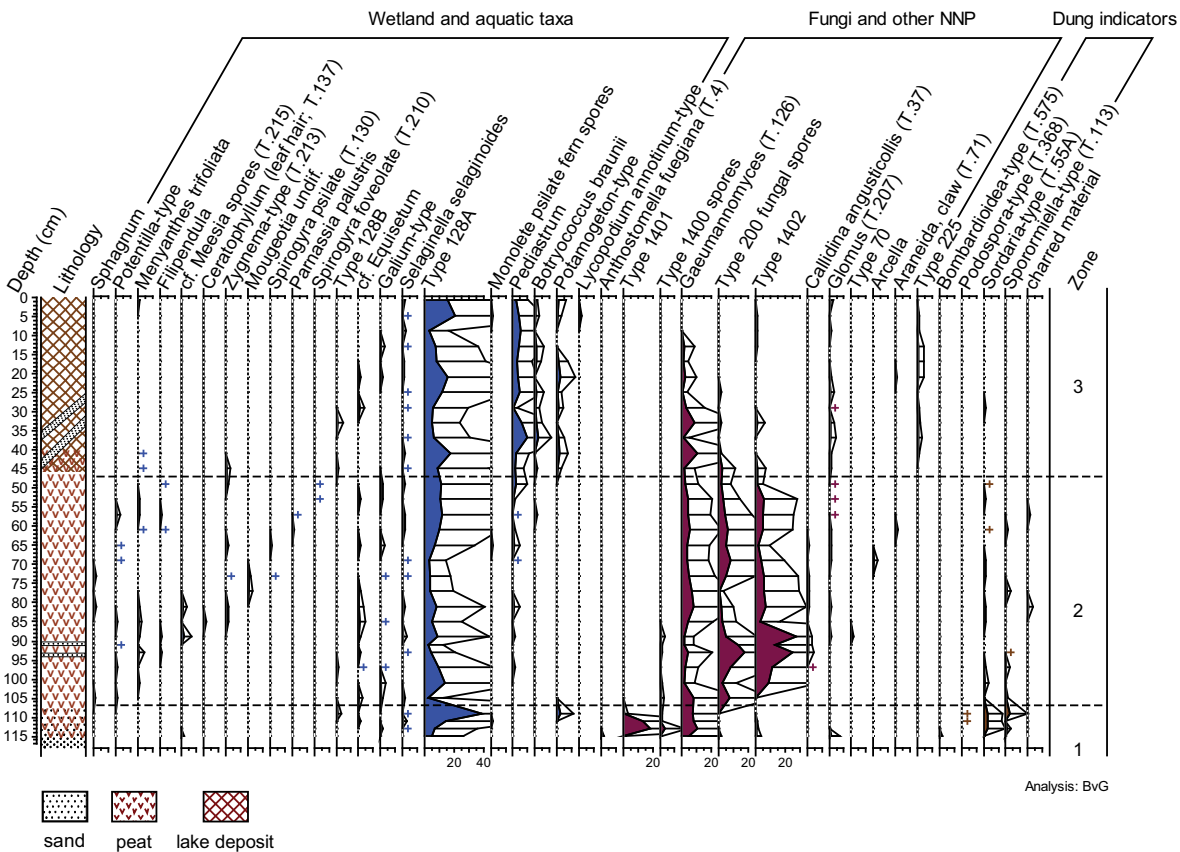
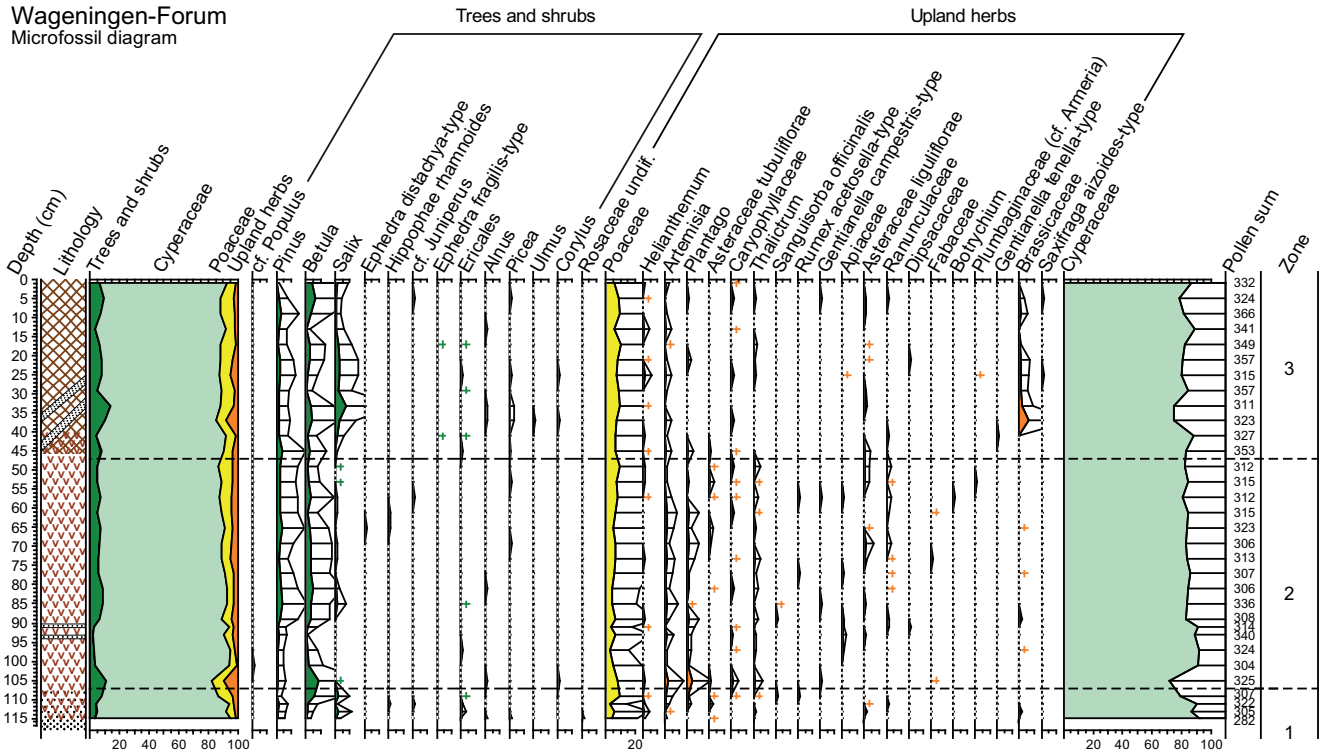
and descriptions given by Van Geel (1978), Van Geel et al. (1981, 1989), Pals et al. (1980) and Van Geel & Aptroot (2006).

Macrofossil samples of ca 4.9 cc each were prepared according to Mauquoy & Van Geel (2007). Mosses were identified using Siebel & Düring (2005) and Touw & Rubers (1989). Oribatid mites were collected during the macrofossil analysis and identified using Weigmann (2006). Diagrams showing the representation of microfossils and macroremains (Figs 3 and 4) were constructed using the Tilia, Tilia.graph and TG.view computer programs (Grimm, 1992). Results of the study of mites and relevant ecological and biogeographical information are shown in Tables 1 and 2.

### Radiocarbon dating

Three subsamples were selected for radiocarbon dating at the AMS-facility of the Centre for Isotope Research at the Groningen University (Table 3). Samples were chemically treated following the AAA procedure (Mook & Streurman, 1983). Amounts of ca 1 mg of treated sample material in Sn-capsules were combusted in an Elemental Analyser/Mass Spectrometer (EA/MS) combination (Aerts et al., 2001). The resulting purified CO<sub>2</sub> was transferred into graphite and placed in the ion source of the AMS, which measures the <sup>14</sup>C/<sup>12</sup>C isotope ratio (Van der Plicht et al., 2000). The EA/MS also measured the <sup>13</sup>d value of the sample.

Wageningen-Forum  
Microfossil diagram



Analysis: BVG

Fig. 3. Microfossil diagram Wageningen-Forum. Exaggeration of curves 5x.

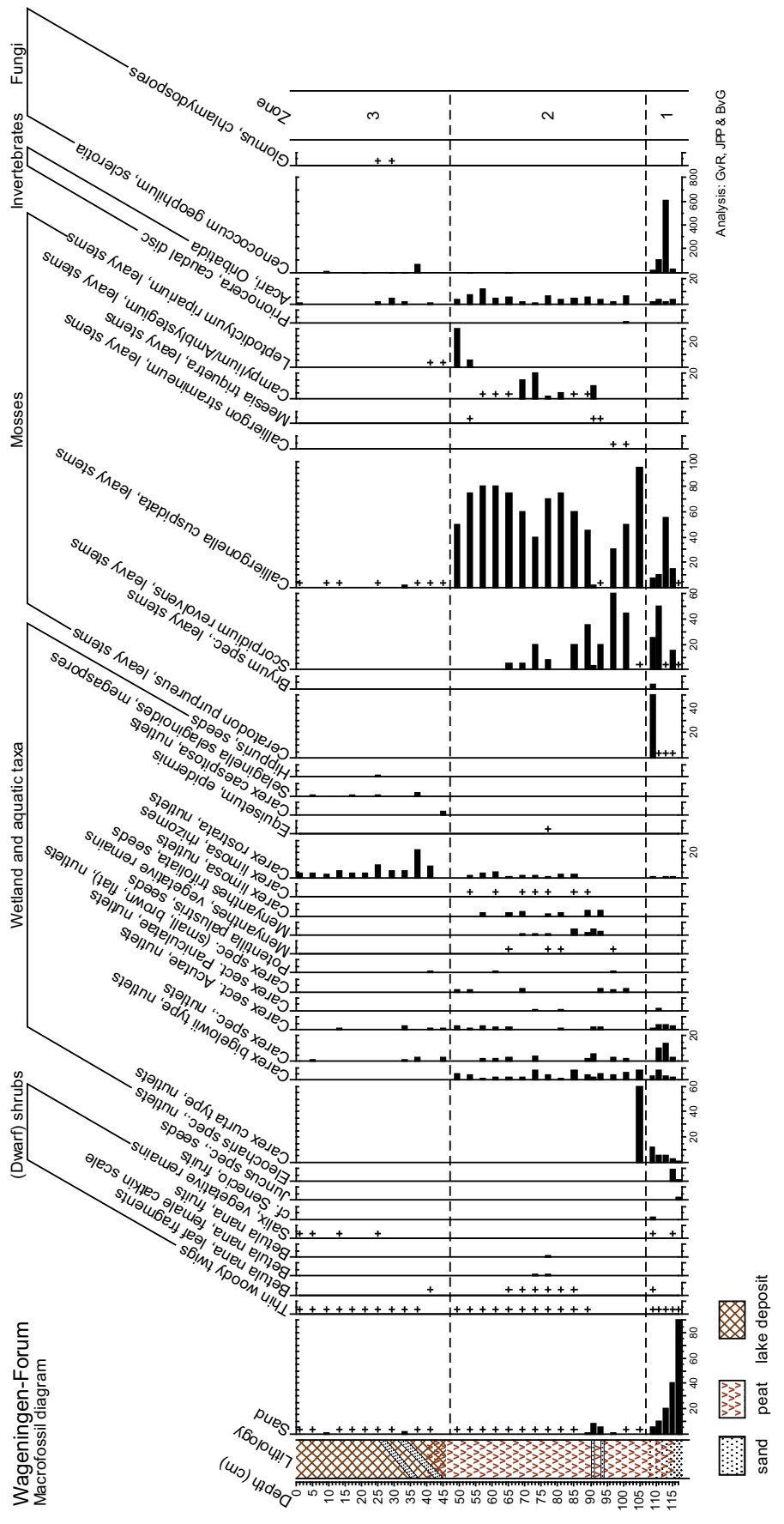


Fig. 4. Macrofossil diagram Wageningen-Forum.

Table 1. Acari Oribatida of the WGNF-sequence in different samples and depths (! means: identification certain; ? means: identification uncertain). [1] Hydrozetes lacustris; [2] Hydrozetes thienemanni; [3] Hydrozetes sp. juv.; [4] Limnozetes ciliatus; [5] Eupelops strenzkei; [6] Eupelops strenzkei or hygrophilus; [7] Eupelops sp.; [8] Peloptulus phaenotus; [9] Trichoribates sp.; [10] Liebstadia similis. The transition from peat deposit to lake sediment is at 46 cm depth.

Depth in cm	Specimens	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	Indet
1	1											1
25	2						1 (?)					1
29	4		1 (!)						1 (?)	1 (?)	1 (!)	
33	2					1 (!)						1
41	1											1
49	3							1 (?)				2
53	7		1 (!)									
			1 (?)									5
57	12		3 (!)		2 (?)			4 (?)				3
61	4				1 (?)	1 (?)						2
65	5		1 (?)					1 (?)				3
69	2											2
73	2		2 (!)									
77	6	1 (?)	1 (?)	1	1 (?)	2 (?)						
81	3					1 (?)						2
85	4		1 (!)			2 (?)						1
89	5		3 (!)				1 (?)					1
93	3		1 (!)			1 (?)						1
97	2		1 (!)									1
101	6		4 (!)		1 (!)	1 (?)						
109	12	3 (!)				1 (!)	1 (?)			1 (?)	1 (!)	
		1(?)				4 (?)						
111	3						3 (?)					
113	2					2 (?)						
115	3					3 (?)						
<b>Sum</b>	<b>94</b>	<b>5</b>	<b>20</b>	<b>1</b>	<b>5</b>	<b>19</b>	<b>6</b>	<b>6</b>	<b>1</b>	<b>2</b>	<b>2</b>	

### OSL dating

Samples for OSL dating (NCL-5107001 and 5107002) were obtained from the contents of the metal boxes in the safelight conditions of the Netherlands Centre for Luminescence Dating (NCL) in Delft. Unfortunately the top of box 3 did not contain enough material of the sand layer on top of the lake deposit to process for OSL dating. Therefore, a sample from these deposits (NCL-5107003; coordinates 51° 59' 08.15" N; 5° 39' 46.69" E) was separately obtained at a later date, at short distance from the former pit, using a hand auger at night. The cored sediment was emptied into a light-tight container. Only the top and bottom samples (NCL-5107001 and NCL-5107003) were dated at the NCL (Table 4).

The Optically Stimulated Luminescence (OSL) signal of quartz grains is erased upon light exposure and builds up after burial due to ionizing radiation from the surrounding sediments and a small contribution from cosmic rays. Thereby the method determines the time of deposition and burial of the sediments,

provided that light exposure prior to burial is sufficient to reset the OSL signal of at least part of the grains (e.g. Wallinga et al., 2007). To obtain an OSL age, two quantities need to be determined: 1) the amount of ionizing radiation received by the sample since the last exposure to light; the equivalent dose (De, Gy) and 2) The millennial radiation dose the sample is exposed to in its natural environment; the dose rate (DR, Gy/ka). The age is then obtained through:

$$\text{Age (ka)} = \text{Equivalent dose (Gy)} / \text{Dose rate (Gy/ka)}.$$

In laboratory safelight conditions samples were split in two. One part was used for equivalent-dose estimation. This sediment was sieved to obtain grains in size range 180-212 µm and chemically treated with HCl, H<sub>2</sub>O<sub>2</sub>, and concentrated HF to obtain a pure and etched quartz extract. All luminescence measurements were made on a Risø TL/OSL-DA-20 TL/OSL reader (Bøtter-Jensen et al., 2003). This machine is equipped with an internal Sr/Y source delivering a dose rate of ~0.11 Gy/s to

Table 2: Acari Oribatida of the WGNF-sequence (data on present distribution and ecology from Weigmann, 2006 and Schatz, unpublished).

#### Fam. Hydrozetidae

*Hydrozetes lacustris* (Michael, 1882) [1] – Ecology: limnic, frequently in peat bogs, on *Sphagnum* and on algae. Present distribution: Europe, Siberia, Japan, North America, Arctic; holarctic. Known from the Netherlands (Buitendijk 1945, Schelvis 1990).

*Hydrozetes thienemanni* (Strenzke, 1943) [2] – Ecology: limnic, submerged to semiterrestrial, also in wet meadows. Present distribution: Europe, Arctic, North America; holarctic.

#### Fam. Limnozetestidae

*Limnozetestes ciliatus* (Schrank, 1803) [4] – Ecology: hygrophilous to limnic. Present distribution: Europe, European Arctic. known from the Netherlands (Buitendijk 1945; Schelvis 1990).

#### Fam. Phenopelopidae

*Eupelops hygrophilus?* (Knülle, 1954) [6 part. ?] – Ecology: hygrophilous. Present distribution; Central Europe.

*Eupelops strenzkei* (Knülle, 1954) [5, 6 part.?] – Ecology: hygrophilous. Present distribution; Central Europe.

*Eupelops* sp. [7]

[contains possibly *E. plicatus* (C.L. Koch, 1835) – Ecology: mesohygrophilous. Present distribution: Europe, Siberia, North America, Arctic; holarctic. Known from the Netherlands (Buitendijk 1945).]

*Pleoptulus phaenotus?* (C.L. Koch, 1844) [8] – Ecology: open areas, wet meadows. Present distribution: Europe, Central and Eastern Asia, Siberia, Arctic; palaeartic. Known from the Netherlands (Schelvis 1990).

#### Fam. Ceratozetidae

*Trichoribates* sp. [9]

[*Trichoribates novus?* (Sellnick, 1929) in sample 29 – Ecology: open areas, wet meadows. Present distribution: Europe, Central and Eastern Asia, Siberia, Arctic; North America; holarctic. Known from the Netherlands (Buitendijk 1945)]

#### Fam. Scheloribatidae

*Liebstadia similis* (Michael, 1888) [10] – Ecology: open areas, wet habitats, springs Present distribution: Central and Eastern Asia, Siberia, Arctic; North America, New Zealand; holarctic to semicosmopolitan. Known from the Netherlands (Buitendijk 1945, Schelvis 1990).

quartz grains at the sample position. The machine is equipped with an array of blue diodes (470 nm, ~35mW/cm<sup>2</sup>) for stimulation. Tests with infrared stimulation indicated that no feldspars remained in the refined extracts. Equivalent doses were measured on small aliquots (centre 2 mm covered with

grains) using the Single-Aliquot Regenerative dose (SAR) procedure (Murray & Wintle, 2003). A preheat of 220° C for 10s in combination with a 200° C cutheat was chosen based on a preheat plateau test. Data were accepted for analysis if the recycling ratio was within 10% from unity, and recuperation

Table 3. Radiocarbon dates of the WGNF-sequence. Depths are in relation to the depth in cm as given in the microfossil and macrofossil diagrams (Figs 3 and 4). All uncertainties quoted here are 1-sigma.

Sample and depth in cm	GrA	C%	<sup>13</sup> d	<sup>14</sup> a <sub>N</sub>	sigma	Calculated age BP	Sigma	Reported age BP	Sigma	Expected age BP
W1 (1+2)	35382	51.9	-27.27	0.39	0.04	44,900	+900 -700	44,900	+900 -700	40,000
W2 (46-48)	35383	39.1	-31.36	0.28	0.03	47,300	+1400 -900	>47,300		42,000
W3 (112-115)	35386	42.1	-28.23	0.19	0.03	52,000	+inf, -1700	>47,300		45,000
<b>Background</b>				<sup>14</sup> a <sub>N</sub>		<b>calculated age BP</b>				
AN				0.28		47,300				
RH				0.12		54,000				
GR				0.09		57,000				



Table 4. Results of OSL dating. Depth is given in meters below estimated soil surface. Sample NCL-5107003 represents the base of the sand on top of the lake deposit and sample NCL-5107001 the sand directly below the peat deposit.

Sample	Location			Equivalent dose (Gy)	Dose rate (Gy/ka)	Age (ka)	Validity
	X	Y	Depth (m)				
NCL-5107003/WGN III	171654	444161	1.685	30.6±1.7	1.43±0.05	21.4±1.4	Likely OK
NCL-5107002/WGN II	171699	444167	2.23	Lacustrine infill of frost crack; not measured			—
NCL-5107001/WGN I	171699	444167	3.105	62.7±2.5	1.21±0.04	51.9±2.7	Likely OK

was below 10%. With the adopted procedure, a laboratory dose could be accurately recovered (dose recovery ratio  $1.01 \pm 0.03$ ;  $n = 6$ ) and recycling was near perfect ( $1.002 \pm 0.007$ ;  $n = 53$ ). Equivalent dose distributions showed more scatter than expected based on the measurement uncertainties of the individual sub-samples. For the top sample this may be related to contamination during sampling with a hand auger; we cannot exclude the possibility that some grains from overlying deposits were mixed with the sample. For the lower sample the excess spread may be related to heterogeneity in the dose rate due to the nearby peat layer. To avoid bias by outliers of the distribution, we adopted an iterative procedure where individual estimates further than two standard deviations from the sample mean were excluded. The average equivalent dose on the remaining population is expected to be an accurate estimate of the dose received by the sample since deposition and burial.

The second part of the sample was used for dose-rate estimation. It was dried, ashed and then cast in wax pucks for measurement of radionuclide activity concentrations using a broad energy gamma-ray spectrometer; results were converted into infinite matrix dose rates. From these, the effective dose rates to the quartz grains used for equivalent dose measurement were calculated taking into account grain size attenuation, water attenuation (assuming water saturation throughout burial; 20% water by weight), and small contributions from cosmic rays and internal alpha radiation.

## Results

### Regional vegetation development

The regional vegetation as reflected in the microfossil diagram (Fig. 3) does not show much change and therefore the zonation of the diagrams (zones 1, 2 and 3) is largely based on the local taxa (mostly represented by macrofossils; see Fig. 4). All pollen spectra are dominated by cyperaceous pollen, like in other deposits formed during the Pleniglacial interstadials in the Netherlands (Kolstrup, 1980; Ran, 1990; Brinkkemper et al., 1987). The presence of achenes of various *Carex* species throughout the record and hyphopodia of the fungus *Gaeumannomyces* (parasite occurring on vegetative parts of *Carex* species; Pals et al., 1980; Van Geel et al., 1989) indicates that part of the cyperaceous pollen was produced locally or nearby.

*Pinus* pollen can be considered as long distance transport, while *Betula* pollen can be linked to the occurrence of *Betula nana* in the surroundings of the wetland (some macrofossils were recorded; see Plate 1). Among the tree and shrub taxa *Salix* shows some major changes: willows (probably dwarf willows) show relatively high percentages in zones 1 and 3. Herbs that are characteristic for upland soils were, among others, Poaceae, *Helianthemum*, *Artemisia* and other Asteraceae, *Plantago*, Caryophyllaceae, *Thalictrum*, Ranunculaceae, and in zone 3, Brassicaceae. The regional vegetation during this period can be characterized as a steppe-tundra with various herbs and low shrubs such as dwarf birch, willow and possibly some sea-buckthorn. Taxa such as *Juniperus*, *Empetrum nigrum* and *Dryas octopetala* that are usually recorded in Pleniglacial deposits in the Netherlands, are absent in this record. Those taxa are frost susceptible and their absence from the botanical assemblage may suggest a climate with harsh winters and low precipitation (i.e. without a thick protecting winter snow cover; cf. Van der Hammen, 1951; Iversen, 1954). *Betula nana* macroremains point to presence in the vegetation, at least during the formation of the lower part of the sequence. *Betula nana* prefers a snow cover (Kasse et al., 1995) but can persist winters with less snow cover.

In the upper part of the sequence (zone 3) higher values of *Salix*, *Helianthemum*, *Saxifraga aizoides* type, Brassicaceae and Poaceae are recorded, pointing to a vegetation with more grasses and heliophilous herbs. The slight increase of long-distance transported taxa (*Picea*, *Alnus*, *Corylus*, *Ulmus*) may suggest a decline in total regional pollen production.

Furthermore, there is a difference in the representation of *Selaginella selaginoides* when comparing zone 2 with zone 3. Megaspores of *Selaginella* are absent in zone 2, but were recorded in zone 3. As *Selaginella* microspores (Fig. 3) are represented in both zones, the presence/absence of the megaspores may well be related to differences in transport possibilities towards the sampling site (hampered in the situation of floating mosses of zone 2, but more easy when the wetland had developed into a lake). Also erosion may have increased in a landscape with open soils. Therefore *Selaginella* megaspores may have been transported more easily towards the lake during zone 3.



Plate 1. Selected macroremains and microfossils and some newly distinguished microfossils from site Wageningen-Forum. 1a-1c. Leaf fragments of *Betula nana*; 2a-b. Female catkin scales of *Betula nana*; 3. Twig of *Salix* sp. showing axillary buds and leaf scars; 4a-b. Seeds of *Menyanthes trifoliata*; 5. *Carex* sp.; 6. *Ceratodon purpureus*; 7a-b. *Scorpidium revolvens*; 8. *Calliergonella cuspidata*; 9. *Meesia triquetra*; 10. *Leptodictyum riparium*; 11. Macrospore of *Selaginoides*; 12a-b. Microspores of *S. selaginoides*; 13. Type HdV-1400 spores; 14. Type HdV-1401 microfossils; 15. Type HdV-1402 microfossils.

## Local vegetation development

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The reconstruction of the local vegetation succession at the WGNF sampling site is mainly based on the macrofossil analysis (Fig. 4), with additional information from a variety of microfossils (Fig. 3).

### Zone 1

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This zone represents the transition from an originally dry soil surface to the start of a peat forming wetland. Zone 1 is characterized by a sandy deposit with - from base to top - an increasing amount of organic material. Originally, the sand-peat transition may have been less gradual, as roots of younger age (coming from levels in zone 2) will have penetrated into the underlying sand; thereby diluting the sand component. Sclerotia of *Cenococcum* were formed in the sandy soil by the fungus that forms mycorrhizas on the roots of a variety of flowering plant species (Pigott, 1982).

The original dryness of the site is witnessed by the moss *Ceratodon purpureus*, which is nowadays known to grow as a pioneer on disturbed sites, especially after fires. It is most abundant on exposed, compact, mineral, dry, gravelly or sandy soils. Some mixing of the sandy deposit (bioturbation) may have taken place after a rise of the ground water table, because some indicators for moist conditions, like *Scorpidium revolvens*, *Calliergonella cuspidata*, *Eleocharis*, *Carex* species, Type 128B (algal spore) and hygrophilous oribatid mites were also recorded.

*Sordaria*-type ascospores and cells of the *Sporormiella*-type, produced by coprophilous fungi (Van Geel & Aptroot, 2006), indicate that faeces were deposited nearby, which suggests that the carrying capacity of the vegetation must have been adequate to support herbivores. However, the *Artemisia* and Poaceae pollen percentages at the WGNF site are too low to infer a typical regional mammoth steppe vegetation. This discrepancy between vegetation and forage requirements of large herbivores has been explained by a much greater diversity of herbaceous plant communities (grasses, sedges, shrubs) during the Pleistocene in comparison to areas today with tundra, steppe-tundra or steppe vegetation. (e.g. Guthrie, 1990; Ukraintseva, 1993; Walker et al., 2001; Yurtsev, 2001). The subsequent decline in percentages of spores of coprophilous fungi at the start of zone 2 does not necessarily mean a reduction of the population density of herbivores. The decline is probably related to the lateral extension of the WGNF-wetland, making the sampling site less accessible for herbivores. Type 1401 microfossils and Type 1400 ascospores (described and illustrated below) are also characteristic for zone 1, but at the present state of knowledge we do not yet have ecological information about these microfossils.

### Zone 2

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After a rise of the ground water table, peat growth started. Initially a representative of the *Carex curta* type was dominant. Peat growth continued with various *Carex* species and the hygrophilous mosses of neutral to alkaline environments *Calliergonella cuspidata*, and *Scorpidium revolvens*. When peat formation progressed, a decline of the trophic degree occurred (around sample 95). This is evident from the appearance of *Menyanthes trifoliata*, *Carex limosa*, *Meesia triquetra* (vegetative remains and spores; Wieggers and Van Geel, 1984), and *Callidina angusticollis* (Rotifera). Such transitions are part of the internal dynamics of peat-forming vegetation: peat deposits form a barrier between growing fen plants and nutrients transported by ground water in the mineral subsoil, and therefore the plants become more dependent on rain water. Hygrophilous oribatid mites are of regular occurrence in zone 2.

Microfossils of the 'Type 1402' are characteristic for the peat deposit. At the transition from zone 2 to zone 3 the bryophyte *Leptodictyum riparium* appears. Nowadays this species is common in wet nutrient-rich habitat; it often occurs alongside stagnant or flowing open water, often at the base of flowering plants. The percentages of representatives of the algal genus *Pediastrum* start to increase at the end of zone 2, and this might be indicative for mixing of lake sediment (zone 3) with the underlying peat, but temporary inundations preceding the lacustrine phase may also have occurred.

### Zone 3

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At the start of the lake deposit of zone 3, taxa of open water (*Botryococcus*, *Potamogeton*) appear, while the *Pediastrum* values show an increase. Aquatic mosses are virtually absent; only some remains of *Calliergonella cuspidata* were observed. Achenes of *Carex rostrata* are more common in zone 3 than in the zones 1 and 2, but this may have to do with an easier transport of the achenes in open water (zone 3) than crossing a floating mat of aquatic mosses (zone 2).

## Identification and distribution of mites

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Empty exoskeletons of oribatid mites are often preserved in peat deposits and lake sediments, forming subfossil or fossil taphocenoses (Erickson, 1988; Krivolutsky et al., 1990; Solhøy & Solhøy 2000). Numerous reconstructions of Holocene environmental and climatic conditions in bogs and lakes, based on these exoskeletons, are reported (e.g. Karppinen & Koponen, 1973, 1974; Sidorchuk, 2004; Larsen et al., 2006; Wild et al., 2007; Schelvis & Van Geel, 1989). Studies on more recent material were carried out from archeological excavations (e.g. Schelvis 1987, 1990; Schelvis & Eryvnyck, 1992; Schatz et al., 2002). The remains of oribatid mites have been shown to

provide reliable information about past ecological conditions (Erickson, 1996; Solhøy 2001; Erickson et al., 2003).

The WGNF samples contained numerous bodies and fragments of mites in different states of preservation. Several specimens showed well-preserved body remnants with recognizable species-specific characteristics allowing identification at species level. On the other end of the scale were rudiments from carapaces without useful morphological features. A total of 94 body fragments were found, 67 of which could be assigned to a certain taxon (Table 1; for data on present distribution and ecology see Table 2).

One specimen (sample 93) belongs to the suborder Actinedida, but it did not show useful taxonomic characteristics for further identification. All other utilisable remnants were members of the suborder Oribatida which could be identified to generic or species level. A total of five species could be identified with certainty. Three further species are listed tentatively, as no specific characteristics were preserved for a secure identification. The identified taxa belong to 6 genera and 5 families. The most frequent species are *Hydrozetes thienemanni* and *Eupelops strenzkei*, followed by *Hydrozetes lacustris* and *Limnozetes ciliatus*. The identification of several specimens was questionable, but after comparison with species from other samples these specimens could be identified with some confidence.

Table 1 illustrates the distribution of the species in particular samples of the deposit. Most species were found at different depths, especially *H. thienemanni* and *E. strenzkei* were present in most peat samples. *Hydrozetes lacustris* and *L. ciliatus* were found only in the peat deposit, while the single specimen of cf. *Peloptulus phaenotus* was recorded in the lake deposit. The two specimens of *L. similis* do not show a clear pattern; one specimen was found in the peat deposit, the other in the lake deposit.

All recorded species are known as hygrophilous to limnic, inhabiting open wetlands. At present, most species have a wide general distribution (Europe, Palaearctic or Holarctic region), *Eupelops strenzkei* (and cf. *E. hygrophilus*) is known from Central Europe. Six of the species mentioned have been recorded from the Netherlands (Buitendijk, 1945; Schelvis, 1990).

### OSL and radiocarbon dating

Three samples for radiocarbon dating were collected from the contents of the metal sample boxes. Sample WGN-1 represents the base of the peat deposit and WGNF-3 the top of the lake deposit. Sample WGN-2 was taken at the transition from the peat to the lake deposit. The samples consisted of selected moss remains and achenes of *Carex* and *Eleocharis*. Results are given in Table 3.

Table 3 shows the Organic Carbon content (C%) and  $^{13}\text{d}$  values, which can be used as sample quality control parameters (Mook & Streurman, 1983). These values are within normal

range. The measured  $^{14}\text{C}$  activity ratios ( $^{14}\text{a}_\text{N}$  as defined in Mook & Van der Plicht, 1999) are normalized for isotopic fractionation using the  $^{13}\text{d}$  values. From these, the  $^{14}\text{C}$  ages are calculated in BP, using the conventional half-life. Because the results are close to the detection limit, the errors in the  $^{14}\text{C}$  age are asymmetric (see Van der Plicht & Hogg, 2006 for conventions). Crucial for such old  $^{14}\text{C}$  samples is a proper background determination. The three Wageningen samples were part of an AMS batch containing 58 samples, which included seven backgrounds. The latter are samples with an infinite age on the  $^{14}\text{C}$  timescale: Anthracite (AN, 6 samples) and Rommenhöller (RH, 1 sample). AN represents the background of all laboratory treatments; RH is a natural gas, and is indicative for the background of the graphite system. Also included in the table is a typical value for GR, an industrial Graphite Rod, not subject to any laboratory treatment and thus indicative for the background of the AMS system proper. The activity ratios measured for AN (6 samples averaged), RH and GR are shown in the table. The anthracite background  $^{14}\text{C}$  counts are subtracted from those of the samples. This yields the numbers shown as 'calculated age' in the table.

As can be seen from Table 3, only one sample (Wageningen-1) shows a value above the background value (the 6 AN averaged). Wageningen-2 has the same value as the background value; Wageningen-3 shows even an older date than the background.

The background for this batch is determined to be 47,300 BP, the average value for the 6 AN measurements. Therefore this number is taken as the limit for this particular AMS batch. Thus, W-2 and W-3 are reported as not significantly different from the background, i.e. >47,300 BP. This is in accordance with the common practice in most AMS laboratories, which have typical background values between 45-50 kBP. This number is largely determined by sample nature and quality, and by laboratory practice. Only in exceptional cases the '50 kBP barrier' may be broken. We should note that the Radiocarbon method becomes extremely sensitive to contamination at these ages, either in the laboratory or in the sample. The  $^{14}\text{C}/^{12}\text{C}$  ratio is  $10^{-15}$  for ages this old, which is truly minute.

Thus, the Wageningen sequence only yields one measurable date; the other samples cannot be distinguished from the background; they are simply too old for the  $^{14}\text{C}$  method. In order to compare this one  $^{14}\text{C}$  date with other chronological records – in particular, ice cores in order to compare with D/O events, and OSL dates as discussed in this paper – it needs to be calibrated into absolute age. Also here we encounter the limit of the Radiocarbon method. Recently, the  $^{14}\text{C}$  calibration curve has been updated to 50,000 calBP, i.e. absolute years relative to 1950 AD (Reimer et al., 2009). The endpoint of the intcal09 curve, 50,000 calBP, corresponds to a  $^{14}\text{C}$  date range of 46,000-46,800 BP. The Wageningen-1 date is close to this limit, but calibration based on the data available yields a range of 46,600-49,800 calBP.

We should also recognize that the number of data points from which the intcal09 curve is constructed at this time range is small, and that their errors are large. In addition, these data are derived from marine records, so that the curve includes a reservoir correction. This has uncertainties that are hard to quantify at present. Indeed, the intcal09 curve needs to be revised already because of more recent insights in marine and other archives (Intcal Workshop, 28/29 June 2010, Belfast). The calibrated age range quoted above should be treated as our best estimate.

For both OSL samples similar dose rates were determined, and values are similar to those obtained from similar deposits in this area. Equivalent doses on both samples differ by a factor of two. Resulting ages indicate an age of  $51.9 \pm 2.7$  ka for the sands just below the organic layer, and an age of  $21.4 \pm 1.4$  ka for the sands above the organic layer (all uncertainties given as 1-sigma).

## Discussion

The OSL dates provide a wide window during which the peat deposit and the overlying lake deposit on top of it may have developed (54.6-20.0 ka, including 1-sigma uncertainty ranges). The radiocarbon ages indicate that the entire sequence formed at, or beyond the limits of the radiocarbon age range; but for the top of the lake deposit a radiocarbon age of 46.6-49.8 ka calBP was obtained. Combining radiocarbon and OSL age information, we infer that the entire sampled sequence must have formed between ca 54.6 and ca 46.6 ka. The upper OSL age and the radiocarbon date of the top of the lacustrine deposit point to a hiatus, reflecting a long period of non-deposition and/or erosion. The younger part of the Middle-Pleniglacial and part of Upper Pleniglacial (e.g. Van Huissteden, 1990) are not represented at the Wageningen sampling site. Originally the lake deposit of WGNF may have been covered by wind-blown coversands, but those were deposited in a very dynamic landscape (vegetation virtually absent; erosion and sedimentation of sandy deposits), and coversands that originally may have been present on top of the lake deposit, may have been eroded until the resistant, compact lake sediment appeared at the surface. Finally, sand (OSL-dated  $21.4 \pm 1.4$  ka) was deposited on top of the lake deposit. The radiocarbon and OSL dates and the absence of trees may indicate that the organic WGNF deposit represents an early Middle Pleniglacial interstadial (Oerel or Glinde interstadial; Behre & Van der Plicht, 1992). However, radiocarbon dating of Early Glacial interstadials is problematic and therefore we will try to link the WGNF sequence with the climate shifts of one of the Dansgaard-Oeschger events as recorded in Greenland ice. Alternative explanations for the recorded sequence will be given as well (see beyond).

Based on OSL and radiocarbon dating we conclude that the WGNF deposit is older than organic sequences formed during

the later part of the Middle Pleniglacial period as studied and dated by Brinkkemper et al. (1987) and Ran (1990) in Twente (eastern Netherlands) but more or less comparable in age to the one that was studied at Ootmarsum (eastern Netherlands) by Bos et al. (in prep.). The development of the local environment at the WGNF site is similar to many studied Middle Pleniglacial deposits (Brinkkemper et al., 1987; Ran, 1990): initially a peat-forming wetland developed on top of a sandy deposit, later the wetland developed into a lake, where lacustrine deposits were formed with a considerable clastic component (compare Ran & Van Huissteden, 1990). Finally, the lake deposits were covered by wind-blown coversand.

In this paper we hypothesize that many Middle Pleniglacial organic deposits in the Netherlands were formed during Dansgaard-Oeschger (D-0) oscillations. From climate reconstructions based on Greenland ice cores (Wolff et al., 2010) and climate reconstructions from elsewhere in the northern hemisphere (Voelker, 2002; Haesaerts et al., 2009; Ampel et al., 2010) we know that the D-0 cycles are globally synchronous and are characterized by rapid changes from cold to relatively warm conditions, followed by a gradual cooling. For the landscape development in the Netherlands and adjacent areas the following development is hypothesized:

1. During cold climatic phases vegetation was sparse, ice-rich permafrost was aggrading (Van Huissteden, 1990) and sand was deposited by fluvial and aeolian processes.
2. When temperatures and winter precipitation quickly rose during the start of D-0 interstadials, vegetation still remained sparse in the high and dry sandy areas, but in depressions in the landscape peat-forming wetlands like WGNF could develop.
3. In successions similar to this one (Van Huissteden, 1990; Ran et al., 1990; Kasse et al., 1995; Bos et al., 2001; Bohncke et al., 2008) these depressions evolved into thaw lakes by the thaw of underlying ice-rich permafrost (e.g. Jorgenson & Shur, 2007). Although permafrost presence (e.g. ice wedges) below the WGNF deposit was not clearly visible due to the poor exposure, the further rise of the water table may be related to permafrost thaw and a grey clayey lacustrine deposit was formed on top of the peat deposit. During the period of a gradual mean temperature decline, characteristic for the later part of D-0 interstadials, thaw lake development may have continued, driven by the altered surface heat balance, or diminished evaporation contributed to a further rise of the water table. Ultimately, the lake may have come into contact with a river by continued lake expansion and/or fluvial channel migration.
4. When the climate had become extremely cold and dry again, permafrost was re-established and coversand deposition took place on top of the lake deposits.

The frequent occurrence of permafrost thaw during D-0 interstadials in Europe has been observed in several Middle

Weichselian sedimentary successions (Van Huissteden, 1990; Kasse et al., 1995; Bos et al., 2001; Kind, 2000) and has been attributed to rapid climate warming. Besides temperature rise, alteration of the surface heat balance by increased snow cover strongly enhances thermokarst. Substantial winter precipitation is indicated by the presence of *Betula nana* which requires a protecting winter snow cover (Kasse et al., 1995). In general, the thaw lake successions consist of ice wedges and large cryoturbations overlain by relatively undisturbed peat and lacustrine deposits (usually gyttja, but laminated silts also occur). Like the lake deposit described here, these deposits generally grade from organic into clastic, presumably by increasing fluvial sediment input. Alternatively, this type of succession may have formed by fluvial backswamp sedimentary cycles (Van Huissteden, 1990). However, in this case a lake of substantial depth with distinct lacustrine sedimentation appears to have developed which persisted for a considerable time, which makes interference of thermokarst processes more likely.

Based on the OSL and radiocarbon age control obtained for our study and after comparison with the independent ages of D-0 events (Table 3; Wolff et al., 2010) we hypothesize which D-0 event is most likely reflected by the Wageningen sequence. Adopting 1-sigma uncertainty ranges in all dates, we conclude that D-0 events 12-14 fit within our age window of 54.6 to 46.6 ka (Table 5). The resolution of our age estimates does not allow inferences on which one of these three D-0 events is recorded. However, the D-0 events 12 and 14 (at 46,960 ka b2k, respectively 54,220 ka b2k; Wolff et al. 2010) in the Greenland ice-core record are more prominent and the magnitude of the rapid warming is larger (rapid T jump 12-12.5° C, Table 2, Wolff et al., 2010) than in D-0 event 13. Furthermore, D-0 event 13 probably did not last long enough and was not warm enough for diverse biota to develop. From the early Middle Pleniglacial interstadials, D-0 interstadial 14 is apparently the most likely one to find in the terrestrial records of NW Europe (compare Helmens et al., 2008; Bos et al., 2009; Bos et al., in prep.).

Table 5. Age (start) of Dansgaard-Oeschger warming events 11-17 in Greenland ice cores (after Wolff et al., 2010). BP <sup>14</sup>C age is defined as conventional calBP calendar age relative to 1950 AD (OSL, calibrated <sup>14</sup>C), b2k means calendar age relative to 2000 AD (NGRIP ice core).

D-0 event	Age/ka (b2k)	1 sigma uncertainty	age/ka (calBP)
11	43,340	868	43,290
12	46,860	956	46,810
13	49,280	1015	49,230
14	54,220	1150	54,170
15	55,800	1196	55,750
16	58,280	1256	58,230
17	59,440	1287	59,390

## Conclusions

The sedimentological sequence (from sand, to peat, to lake deposit, to sand) at the Wageningen-Forum site shows a characteristic pattern that was also observed during studies of Weichselian organic deposits in Twente (eastern Netherlands). We suggest that such sequences were caused by the climate fluctuations characteristic for Dansgaard-Oeschger oscillations and that permafrost thaw has influenced these successions. Based on OSL and radiocarbon data and biostratigraphical information we concluded that the Wageningen sequence may correspond with D-0-event 12, 13 or 14.

## Some newly distinguished microfossil Types

### Type HdV-1400 (Plate 1, 13)

Microfossils (ascospores ?) spindle-shaped, unequally one-septate, 45-46 × 10-12 µm, ornamented by a dense pattern of longitudinal ridges. Type HdV-1400 spores are of regular occurrence in zone 1 and the lower part of zone 2.

### Type HdV-1401 (Plate 1, 14)

Globose microfossils with a double wall. Outer wall light-brown, thin, with many irregularly formed, from 4 µm up to 12 µm wide holes. Most specimens with broken outer wall, but intact microfossils 50-63 µm in diameter. Inner wall thick, darkbrown, closely covered with up to 2 µm high appendages. Diameter of inner spore 40-57 µm.

The biological origin of the Type HdV-1401 microfossils is unknown. They only occur in the sandy base of the peat layer (zone 1), together with, a.o. taxa, *Cenococcum sclerotia*, *Sordaria*-type ascospores, *Scorpidium revolvens* and *Calliergonella cuspidata*.

### Type HdV-1402 (Plate 1, 15)

Microfossils globose, 48-75 µm in diameter, with lamellate walls, consisting of up to ca. 8 very thin, loosely arranged layers. Type HdV-1402 microfossils are common in the peat layer of zone 2 and become of rare occurrence in the lake deposit of zone 3. From a morphological point of view Type HdV-1402 has much in common with Type HdV-91 (in Holocene raised bog deposits; Van Geel, 1978) and/or Type HdV-819 (Sub-arctic Marion Island; Yeloff et al., 2007).

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