Catena 188 (2020) 104453

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Repeated aeolian deflation during the Allerød/GI-1a-c in the coversand lowland of NW Belgium

Philippe Crombé[a,*], Johanna A.A. Bos[b], Frédéric Cruz[c], Jeroen Verhegge[a]

[a] Department of Archaeology, Ghent University, Sint-Pietersnieuwstraat 35, B-9000 Gent, Belgium
[b] ADC ArcheoProjecten, Nijverheidsweg-Noord 114, 3812 PN Amersfoort, the Netherlands
[c] Gate BVBA, Dorpsstraat 73, B-8450 Bredene, Belgium

ARTICLE INFO

Keywords:
Paleogeography
Aeolian deflation
Western Europe
Sand-belt
Pleistocene
Allerød
Cooling events
Vegetation dynamics
Forest fires
Hunter-gatherers

ABSTRACT

The results of multi-disciplinary research carried out on the deposits of the Moerbeke "Driehoek" site, located along the northern bank of the extensive Moervaart palaeolake (NW Belgium), are presented. The multi-proxy study, including sedimentological (organic matter, calcium carbonate and grain-size) and botanical (pollen, macrofossils, NPP) analyses, provided evidence of repeated aeolian deflation during the Allerød. Our results demonstrate, in combination with evidence from other soil archives within the Moervaart area, that the Allerød period in NW Europe was sedimentologically much less stable than hitherto assumed, especially during the GI-1c2 event and middle Allerød. Some of the Allerød deflation events were caused by centennial abrupt climatic oscillations, such as the short but pronounced cold GI-1c2 event, while others were likely the result of intense forest fires or a combination of both. These observations call for a revision of the existing Lateglacial litho- and chronostratigraphic schemes for the sand-belt of northern Europe.

1. Introduction

During the Final Pleniglacial and Lateglacial the extensive sand-belt of northern Europe (northern Belgium, The Netherlands, northern Germany, Poland and Russia), has known many phases of widespread aeolian activity, leading to (re)deposition of coversands and the formation of coversand dunes. The latter are archaeologically important as they constitute preferred settlement locations for prehistoric hunter-gatherers. Many studies have dealt with the timing and history of these aeolian events, resulting into different litho- and chronostratigraphical schemes (Van der Hammen, 1971; Koster, 1982; Vandenberghe, 1991; Kasse, 1999, 2002; Schirmer, 1999; Hilgers, 2007; Derese et al., 2012; Rychel et al., 2018; Kasse et al., 2018; Kasse and Aalbersberg, 2019; Konstantinov et al., 2019). Nearly all of these studies conclude that the Allerød period (GI-1a-c), dated between 13,954 and 12,896 b2k (Rasmussen et al., 2014), sedimentologically was a stable phase during which aeolian deposition decreased markedly or even ceased. This conclusion is mainly based on the presence of either a (slightly) organic (A) and/or leached (E) horizon or a brownish weathered (Bw) horizon separating the Younger Coversand I deposits (Kasse, 2002), dated to the Older Dryas (GI-1d), from the Younger Coversands II, dated to the Younger Dryas (GS-1). This paleosol is referred to as the Usselo or Finow soil (Kaiser et al., 2009) and is considered as an indication of landscape stability, resulting from the installation of birch and pine forests during the (late) Allerød and transition to the Younger Dryas.

However, in some regions of the N(W) European sand-belt recent projects focusing on optically stimulated luminescence dating of aeolian sediments (Derese et al., 2009; Vandenberghe et al., 2013; Kruczkowska et al., 2020) seem to indicate that aeolian deflation may have been fairly continuous throughout the entire Lateglacial, although the limited time resolution of the OSL-dates does not allow to demonstrate with certainty the occurrence of intra-Allerød deflation events prior to the formation of the Usselo/Finow soils. Yet, the latter might have occurred given the climatic variability during the Allerød as demonstrated by the ice core records, indicating the occurrence of at least two distinct "cooling" events, the GI-1c2 and GI-1b (Rasmussen et al., 2014).

In this paper a multi-proxy palaeoenvironmental approach, applied to the coversand area of NW Belgium (Fig. 1), will be used to demonstrate intra-Allerød aeolian sedimentation. Geoarchaeological research into the environment of the last hunter-gatherers within this lowland region has revealed several soil archives with two to three superimposed organic layers, separated by aeolian sand deposits (Bos et al., 2018a, 2018b; Crombé et al., 2012). This paper deals with one of these sequences, named Moerbeke "Driehoek", situated on the northern bank of an extensive palaeolake.

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* Corresponding author.
E-mail addresses: philippe.crombe@ugent.be (P. Crombé), h.bos@archeologie.nl (J.A.A. Bos), jeroen.verhegge@ugent.be (J. Verhegge).

https://doi.org/10.1016/j.catena.2020.104453
Received 7 September 2019; Received in revised form 4 December 2019; Accepted 4 January 2020

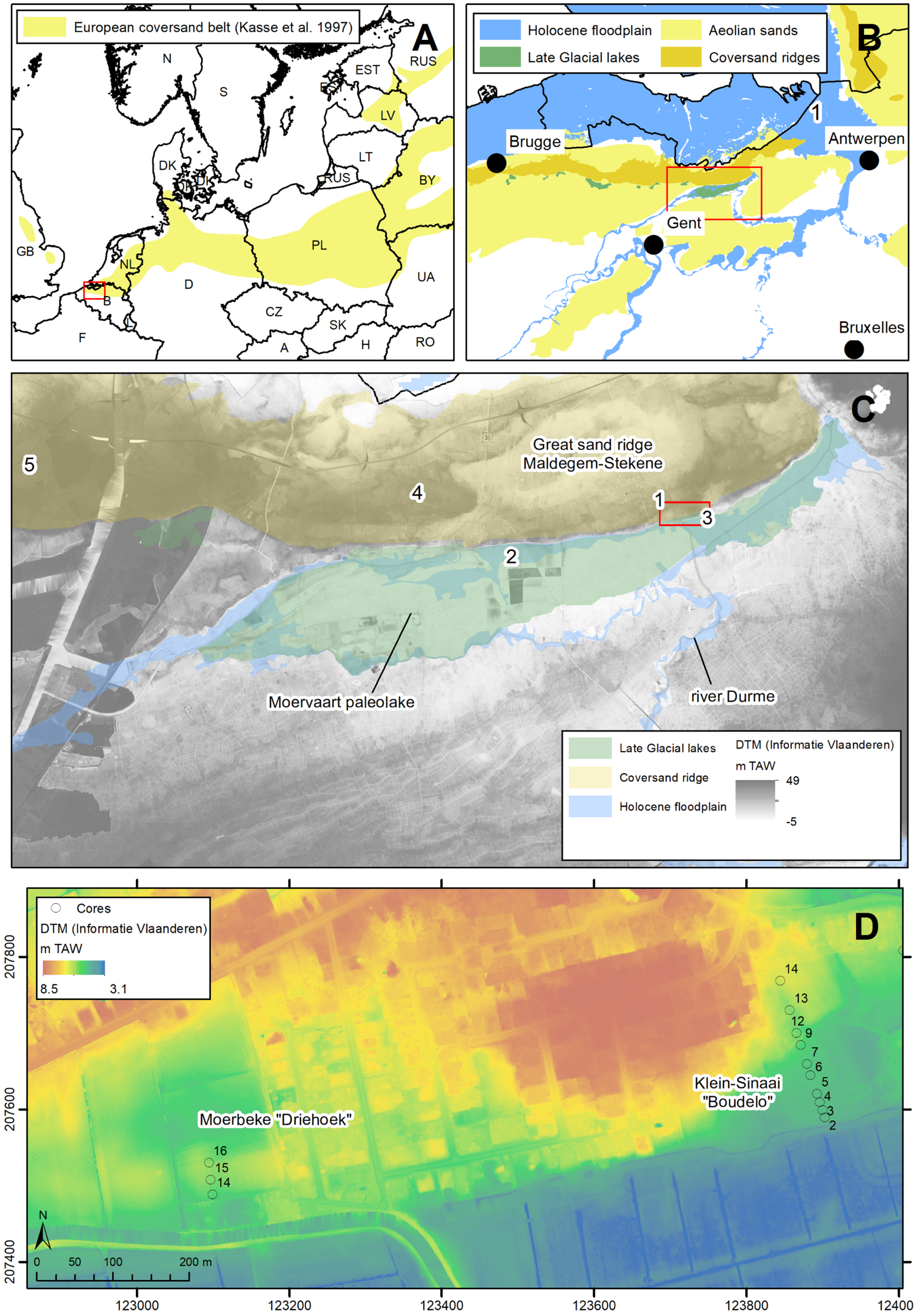

Fig. 1. A. Extent of the European coversand belt. NW Belgium is indicated with an open square. B. Schematic map of Belgium, showing some of the major rivers and the Pleistocene sedimentation areas in NW Belgium. Nr. 1 is the location of the Beveren "Prosperpolder-Zuid" site. C. Topography of the Moervaart study area with the maximum extent of the Moervaart depression along the southern edge of the Great Sand Ridge of Maldegem-Stekene. Nrs. 1–5 refer to sites mentioned in the text: 1. Moerbeke "Driehoek"; 2. Moerbeke "Suikerfabriek"; 3. Klein-Sinaai "Boudelo"; 4. Wachtebeke "Heidebos"; 5. Rieme "Noord" (TAW = Belgian ordnance level, −2.33 m MSL). D. Detail of the sites of Moerbeke "Driehoek" and Klein-Sinaai "Boudelo" indicating the manual coring transects. The analysed mechanical cores 3B and 4B at Moerbeke "Driehoek" correspond with the position of the manual core 14.

2. Site and general geological context

The site of Moerbeke “Driehoek” is situated along the steep southern, leeward side of an extensive dune-complex, known as the Great Sand Ridge of Maldegem-Stekene (De Moor and Heyse, 1978; Heyse, 1979; Crombé et al., 2012) (Fig. 1-C). This east-west running dune complex (c. 80 km length, 1.5–3 km width and mean height of c. 5 m) consists of a microrelief of small intersecting and overlapping ridges and irregular elongated deflation depressions (dune-slacks), indicating a complex depositional history. It is generally assumed that its formation started during the Final Pleniglacial when drier conditions led to increased aeolian reworking of sands deposited into the “Flemish Valley”, a large and deep palaeovalley dating back to the Saalian glacial stage. These redeposited sands belong to the lithostratigraphical formation recently defined as the Opgrimbie Member within the Ghent Formation (Beerten et al., 2017), characterized by well-sorted relatively pure fine sands with a median grain size of 125–250 µm and equivalent to the Younger and Older Coversand deposits distinguished by Kasse (2002).

However, the presence of relatively thin intercalated organic-rich horizons (humic to peaty sediments), representing the infilling of former dune-slacks or ponds, were observed at several locations on the large dune complex of Maldegem-Stekene. The oldest ones were attributed to the Bølling or GI-1e, the younger ones are related to the Allerød or GI-1a/c on the basis of pollen biostratigraphy and radiocarbon dates (Kolstrup and Heyse, 1980; Heyse, 1979; Verbruggen, 1979; Crombé et al., 2012; Bos et al., 2013). These sediments and palaeosols prove that aeolian sedimentation continued during almost the entire Lateglacial and progressively increased the height of the coversand ridge Maldegem-Stekene. As a result, the pre-existing northwards surface water run-off through the ‘Flemish valley’ was blocked, locally leading to the formation of medium to large-sized, shallow freshwater lakes along the steep southern edge of the dune complex. By far the largest lake, the “Moervaart” palaeolake (Heyse, 1983) covered c. 25 km^2 (Fig. 1) and was situated immediately south of the studied site of Moerbeke “Driehoek”. It was formed during the Bølling, reaching its largest extension and greatest depth (c. 3–4 m) at the end of the early Allerød (Bos et al., 2017). By the end of the late Allerød the lake turned into a marshy depression in order to disappear entirely at the start of the Younger Dryas.

3. Material and methods

3.1. Field work

Field work started in 2011 along the southern slope of the coversand ridge Maldegem-Stekene using manual core survey in several transects in the direction of the Moervaart depression (Bats et al., 2011) (Fig. 1-D). This led to the discovery of aeolian sand deposits on top of lacustrine sediments at several locations (Fig. 2). One of these transects, Moerbeke “Driehoek” (MDH-1), was selected for further palaeoenvironmental investigation and mechanical core samples were collected up to a depth of c. 6 m (i.e. Begemann cores 3B and 4B) into the Pleniglacial substrate.

3.2. Laboratory analyses

3.2.1. Sedimentological analyses (grain-size and LOI)

The cores were described macroscopically, recording Munsell color and samples were collected for loss-on-ignition (LOI) and granulometry measurements. The lowermost samples were taken from the 4B core (240–314 cm), the upper samples (168–240 cm) from the 3B core. Organic matter and $CaCO_3$ contents were estimated on samples with 2 cm resolution by automated loss-on-ignition (LOI) using a PrepASH 229 Precisa following Heiri et al. (2001). Grain-size analysis was carried out following Mulitza et al. (2008). Organic material was removed by H_2O_2 (35%), $CaCO_3$ by HCl (10%) and biogenic opal by NaOH (6%). Then, an dispersing agent (Na4P2O7*10H2O) was used before the analysis was performed by a Malvern Mastersizer 3000 (laser granulometer). The distributions, ranging from 0.1 to 3500 µm, were classified according to Folk (1954) and Folk and Ward (1957).

3.2.2. Microfossil analyses

Microfossil sampling focused on the sediments situated between 170 and 310 cm because the pollen preservation in the upper sandy layers turned out to be extremely poor. Sampling intervals vary between 10 and 20/25 cm (Fig. 3). Samples (2–3 cm^3) were prepared following Fægri and Iversen (1989) and Moore et al. (1991) with additional treatment with warm (80 °C) 40% HF and sieving over 150 µm. Residues were mounted in glycerine jelly and sealed. A light microscope (magnification 400× and 1000×) was used for analysis. Pollen and spore types were identified by comparison to modern reference material and identification keys of Moore et al. (1991), Beug (2004) and Punt (1976–2003). When a specific pollen type or group name is based on either of these identification keys, this is indicated with an ‘M’, ‘B’ or ‘P’ behind the –type or –group name, respectively. Identification of non-pollen palynomorphs (NPP-types) was based on the type classification of van Geel and colleagues (Miola, 2012). Microfossil taxa were divided into regional and (extra-)local components following Janssen (1973). Combined AP and NAP totals were employed for percentage calculations. The pollen sum (445 average) includes trees, shrubs, Ericales, upland herbs and Poaceae. This pollen sum is directly comparable with the pollen sum of the Dutch and northern Belgium Lateglacial regional pollen zonation scheme (Hoek, 1997) and similar to the scheme used in the other nearby sites (Bos et al., 2013, 2017, 2018a, 2018b). Pollen and spores of the local aquatic or marsh vegetation (including Cyperaceae) and thermophilous trees (like *Quercus robur*-group and *Alnus glutinosa*-type) were excluded. The latter could be derived from long-distance transport or (i.e., fluvial, run-off) erosion of older deposits in the area. Furthermore, it should be noted that, in some parts of the record, wetland grasses may have contributed to the Poaceae group. When enough pollen and spores were counted for statistical reliable pollen sum, the whole slide was scanned to infer whether some species were not detected during analysis. These species are indicated with a ‘+’ in the pollen diagram. The pollen diagram was constructed using TILIA and TG.VIEW (Grimm, 1992–2004).

3.2.3. Macrofossil analysis and radiocarbon dating

Macrofossil samples were collected from the cores at six different levels to obtain an accurate chronostratigraphic framework for the sediments at Moerbeke “Driehoek”. Plant macroremains were recovered by washing the subsamples over a 125 µm mesh sieve and handpicked from the residue. A dissecting microscope (magnification of 8–40×) was used for isolation and identification. Plant macrofossils were identified by comparison with modern reference material and identification keys of Berggren (1969, 1981), Anderberg (1994) and Cappers et al. (2006). All samples, however, only revealed aquatic plant taxa. Due to the absence of sufficient datable ‘terrestrial’ material reflecting atmospheric ^{14}C concentrations, no samples could be radiocarbon dated.

4. Results

4.1. Sedimentological results

The Moerbeke “Driehoek” sequence consists of an alternation of almost pure fine sand and very coarse silty fine sand layers (i.e., lake marls). Five main sedimentological units could be identified within the sequence. Based on the sedimentological analyses, some of these units were further subdivided (Table 1 and Figs. 3 and 4a–c):

Unit I (0–170 cm): unstratified yellowish brown (10YR 5/4) fine sand, with remains of a podzol, analyzed and determined as moderately

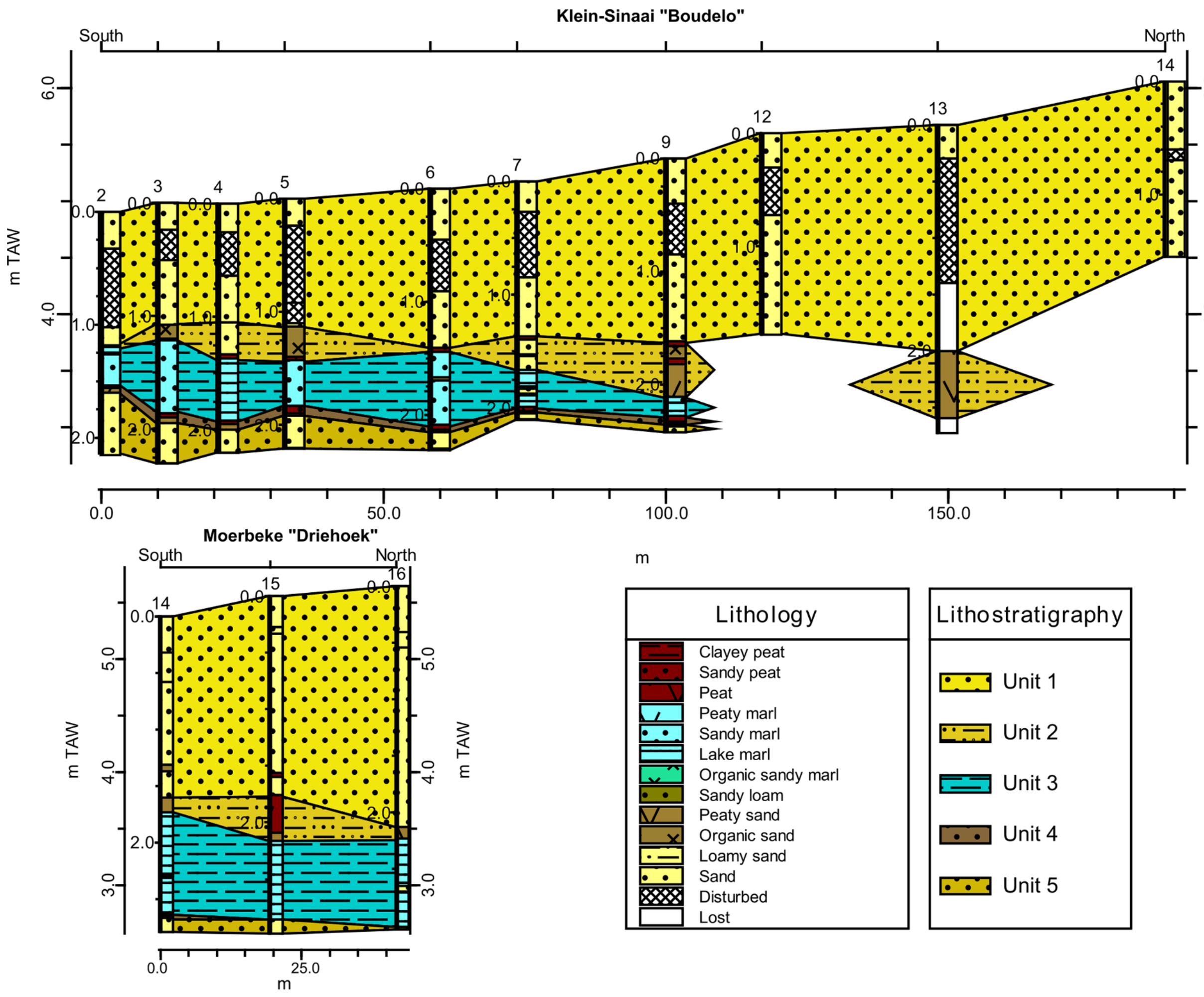

Fig. 2. Transects of the manual corings at Moerbeke "Driehoek" and Klein-Sinaai "Boudelo". The analysed mechanical cores 3B and 4B at Moerbeke "Driehoek" correspond with the position of the manual core 14.

well sorted fine sand with a very low organic matter (OM) and calcium carbonate ($CaCO_3$) content (< 1%).

Unit II (170–222 cm): Unit II was subdivided into 5 subunits:

(1) subunits IIa-IIc (170–200 cm): these subunits are characterized by stratified, moderately well-sorted fine sand with a very low amount of silt (mean < 1%) and $CaCO_3$ (mean 0.2%) and closely resemble subunit IId. The main difference is the mean OM content, which is higher in IIb (2.7%) compared to IIa and IIc (resp. 0.7% and 1%). The latter subunit also locally contains very fine gravels (< 1%; 192–194 cm) as well as very coarse sands. Clay is absent.

(2) subunit IId (200–210 cm): stratified very dark brown (7.5YR 2.5/3) layer consisting of moderately well sorted fine sand. Compared to the underlying layer (IIe), this subunit presents a lower mean content of silt (3.8%), $CaCO_3$ (0.3%) and OM (2.5%).

(3) subunit IIe (210–222 cm): organic-rich layer with a color changing from black (10YR 2/2) at the base to very dark brown (10YR 2/1) towards the top. This corresponds with a marked decrease in OM from 9.3% to 3.4%. Within unit II, this subunit presents the highest mean amount of silt (13.5%) and $CaCO_3$ (0.5%). Furthermore, the grain-size differs from the other subunits and was determined as poorly very coarse, silty fine sand, with a small amount of fine gravel (< 1%) at its base.

Unit III (222–305 cm): reddish calcareous silty sand with mollusks (cf. Table 1). Unit III differs from the above- and underlying units by a much higher proportion of $CaCO_3$ (24.7–34%), a higher frequency of coarse sand, very coarse sand and clay (0.4–0.8%) and a slightly higher OM content (3–5%). However, unit III presents a fine internal sedimentological stratification. As such it was subdivided into 3 subunits. The upper (IIIa) and lower (IIIc) subunits present a higher amount of OM (resp. 5% and 4.4%) and $CaCO_3$ content (resp. 29.1% and 34%). Subunits IIIa and IIIb are classified as poorly sorted, very coarse, silty/very fine sand. The intermediate subunit IIIb has a slightly lower proportion of both OM (3.1%) and $CaCO_3$ (24.7%). IIIc is composed of very coarse, silty/very fine sand to very fine sandy/very coarse silt at the base. Gravel is only present in subunit IIIb (< 1%; 264–266 cm).

Unit IV (305–311 cm): weakly stratified, very dark grayish brown (2.5Y 3/2), moderately well sorted fine sands, with much lower amounts of $CaCO_3$ and OM compared to the above-lying unit III, resp. 2.4% and 0.7%. Silts represent 6.5% mean, while clays amount to mean 0.2%.

Unit V (311–658 cm): moderately well sorted fine sand with 99.3% of sand and 0.7% of silt and no clay. The OM and $CaCO_3$ content are very low, 0.5% and 2.3% respectively.

A further analysis of the ratios between the different sand fractions – very fine, fine and medium sized – allows for a more detailed interunit comparison (Fig. 4b). Within upper units I and IIa-d, as well as the lowest units IV and V, the ratios between fine and very fine sands are similar. These layers are characterized by an absolute predominance of fine sands, which amount to 50–60%, followed by very fine sands (30–40%). The coarser sand fractions are limited to ca. 10%. Moreover, within subunits IIa-d a gradual increase of fine sands towards the top is noted. On the other hand, the intermediate unit III displays a different

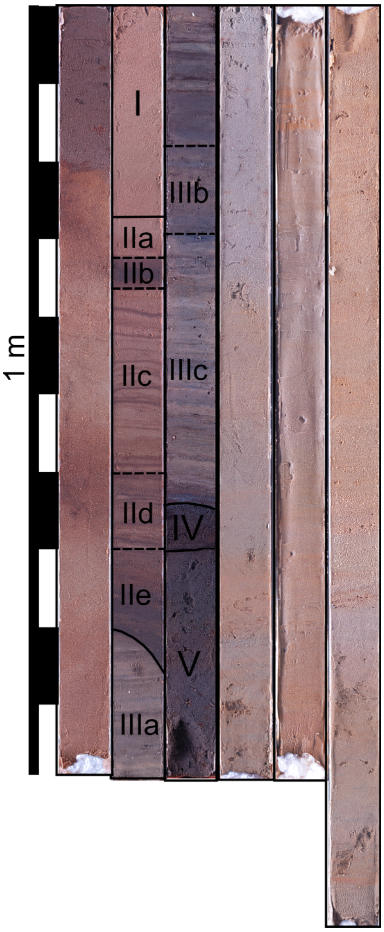

Fig. 3. The Moerbeke "Driehoek" sedimentological sequence. High-resolution photo of the Begemann-core with indication of the five litho-stratigraphical units.

grain-size composition. Overall it is characterized by a predominance of very fine sands (50–80%) with a gradual decrease from bottom (IIIc) to top (lower part IIIa). In the upper half of IIIa and IIe, fine and very fine sands show similar proportions; this is also observed within subunit IIIb. Compared to the under- and above-lying layers, unit III is also characterized by a higher proportion of coarser sand fractions.

Finally a comparison of the grain-size frequency curves between the different units (Fig. 5) allows to define three different main classes:

Type 1: unimodal curve centered around the fine sands (units I-IIc and V).

Type 2: bimodal curve composed of one large peak of fine sands and a second weak peak of medium and coarse silts (units IId, IIIa, IIIb and IV). Unit IIe is very similar though the large peak tends more towards the very fine sands.

Type 3: trimodal curves, presenting a principal peak of very fine sands, and two smaller peaks, one of medium and coarse silts and another of medium and coarse sands (units IIIa, IIIb et IIIc).

4.2. Microfossil and macroremain record

In the pollen diagram (Fig. 6) and section below we will refer to the Lateglacial regional pollen zones (Zone 1a, etc.) as established by Hoek (1997) for the coversand of northern Belgium and The Netherlands.

In the lowermost pollen sample (303.25 cm depth, unit IV) the AP values are relatively high (65%), including mainly pollen of willow (*Salix*), juniper (*Juniperus*) and birch (*Betula*), while sea-buckthorn (*Hippophae rhamnoides*) and herbs such as composites (*Artemsia, Aster*

Table 1
The main sedimentological units in the Moerbeke "Driehoek" sequence and their characteristics.

Unit	Limit (cm)		Lost on ignition (mean)			Grain-Size (mean)						Colour	
	Top	Base	OM%	CaCO3%	Residue%	Sediment name	Sorting	Gravel%	Sand%	Silt%	Clay%	Munsell	Name
I	168	170	0.49	0.16	99.3	fine sand	moderately well sorted	0	99.7	0.3	0	10YR 5/4	yellowish brown
IIa	170	173	0.7	0.2	99.1	fine sand	moderately well sorted	0	99.5	0.5	0	10YR 5/3	brown
IIb	173	177	2.7	0.2	97.1	fine sand	moderately well sorted	0	99.5	0.5	0	7.5YR 2.5/3	very dark brown
IIc	177	200	1	0.2	98.8	fine sand	moderately well sorted	< 0.1	99.2	0.8	0	10YR 5/3	brown
IId	200	210	2.5	0.3	97.2	fine sand	moderately well sorted	0	96.2	3.8	0	7.5YR 2.5/3	very dark brown
IIe	210	222	5.7	0.5	93.8	very coarse silty very fine sand	poorly sorted	< 0.1	86.3	13.5	0.2	10YR 2/2 10YR 2/1	gradation from black to very dark brown
IIIa	222	258	5	29.1	65.9	very coarse silty very fine sand	poorly sorted	0	65.8	33.6	0.6	5Y 4/2 5YR 3/2	stratified olive gray and dark reddish brown
IIIb	258	272	3.1	24.7	72.2	very coarse silty very fine sand	poorly sorted	< 0.1	67.4	32.2	0.4	5YR 5/2	reddish gray
IIIc	272	305	4.4	34	61.6	very coarse silty very fine sand very fine sandy very coarse silt	poorly sorted	0	53.9	45.3	0.8	2.5YR 4/1 2.5YR 4/2	stratified dark reddish gray and dusky red
IV	305	311	0.7	2.4	96.9	fine sand	moderately well sorted	0	93.3	6.5	0.2	2.5Y 3/2	very dark grayish brown
V	311	314	0.5	2.3	97.2	fine sand	moderately well sorted	0	99.3	0.7	0	2.5Y 6/1	gray

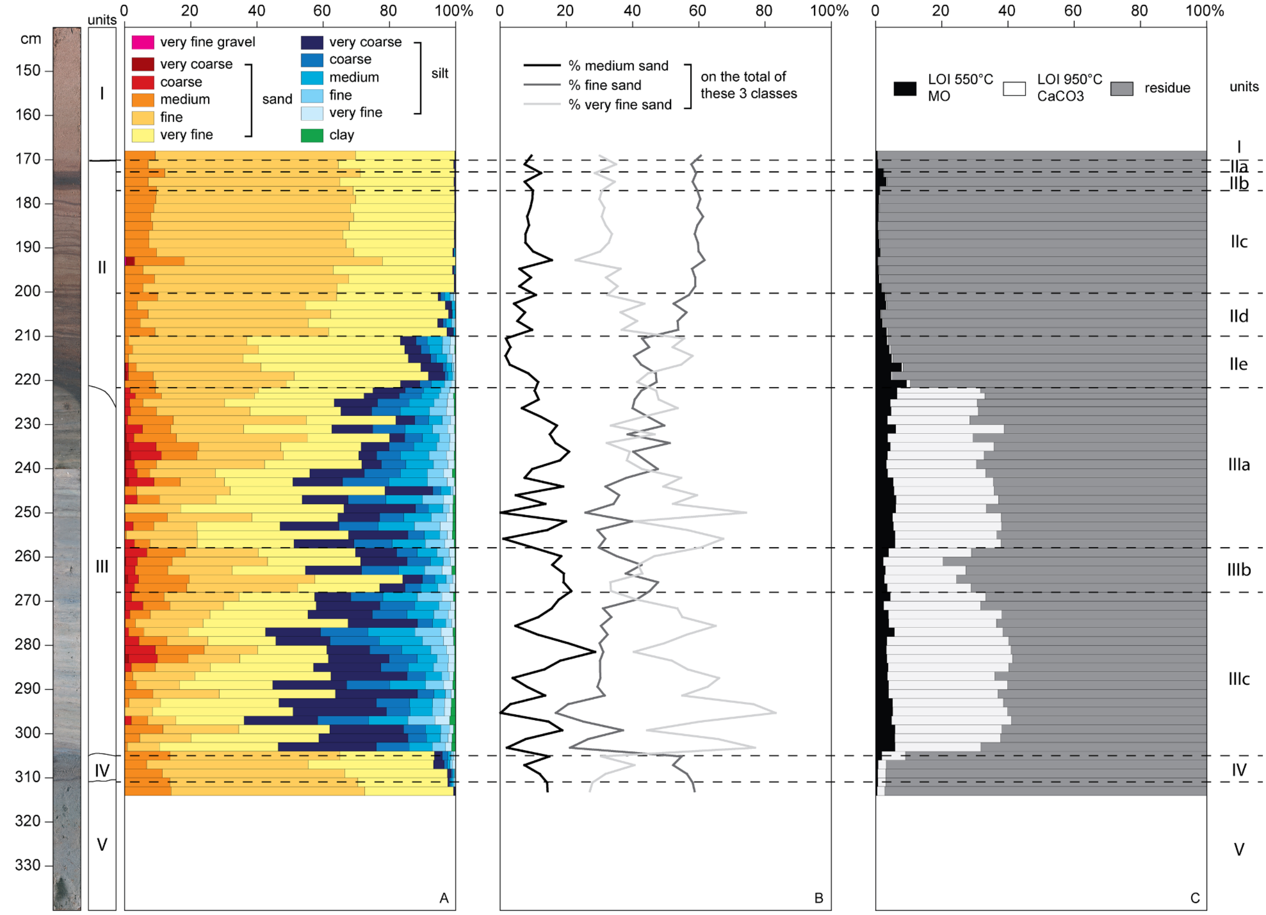

Fig. 4. a. Grain-size data, b. represents the ratio between medium, fine and very fine sands, calculated on the total amount of the three classes per layer and c. LOI data.

type, *Anthemis*-type), saxifrages (*Saxifraga*), plantain (*Plantago* cf. *alpina*) and grasses (Poaceae) were present (Fig. 6). This suggests that a dwarf shrub tundra with pioneer communities of heliophilous herbs and scattered (dwarf) shrubs developed in the area. Taxa such as sedges (Cyperaceae), semi-aquatics (*Sparganium* and/or *Typha, Equisetum, Glyceria*-type) and Characeae and algae (Fig. 6, Table 2) indicate the formation of a local marsh with pools of open water, probably as result of an increase in effective precipitation, an increase in lateral groundwater input from the surrounding coversand ridges and melting of permafrost (e.g. Bohncke, 1993; Hoek et al., 1999; Hoek and Bohncke, 2002; Bos et al., 2006). This level corresponds to Hoek's biozone 1b.

The strong decrease in the AP values accompanied by a strong increase in the Poaceae values at 293.5 cm depth (lower part unit IIIc) suggests a drier and colder climate with more barren ground and a larger abundance of grasses in the vegetation, resulting in the development of a grass-steppe-tundra. This fits with biozone 1c of Hoek (1997). Locally the water table in the marsh lowered and a wet meadow developed at the site.

Above this level (222–289 cm depth, units IIIa, IIIb and upper part of unit IIIc) the AP (especially tree birch, *Betula pubescens*-type) values increase again and the Poaceae values decrease, reflecting the immigration of tree birch and the development of boreal birch forests in the Moervaart area, while the diversity of herbs increases as well. This pollen zone reflects the regional biozone 2a1 of Hoek (1997). In the local flora, taxa of open water communities appear (e.g., Characeae, *Potamogeton, Myriophyllum* spp., *Ceratophyllum, Ranunculus aquatilis* group, *Nymphaea alba, Nuphar lutea, Lemna, Menyanthes trifoliata*, Fig. 6, Table 2) indicating the presence of a lake with submerged vegetation in the deeper parts and floating vegetation in the more shallow parts. The shores were fringed by a rich semi-aquatic vegetation (e.g. *Carex, Typha, Equisetum, Filipendula, Lysimachia* and Apiaceae, Fig. 6, Table 2). In this pollen zone also a number of dung indicators (*Sporormiella, Podospora, Sordaria* and *Bombardoidea*-type) are found indicating the nearby presence of large herbivores including elk (*Bombardoidea*-type is often associated with elk dung, Bos et al., 2005). High values of *Sordaria*-type are especially recorded at 267.5 cm depth. Furthermore, a number of fire indicators (microscopic charcoal, charred stomata and charred epidermis from grasses and sedges) are recorded, with peaks especially at the transition from unit IIIc to unit IIIb. In unit IIIb (at 267.5 and 260 cm depth), the values of *Betula* are strongly decreased. This is accompanied by high values of herbs (e.g. *Artemisia, Thalictrum, Plantago, Rumex and Helianthemum*), Poaceae, Cyperaceae, algae and *Myriophyllum spicatum* pollen. A similar but smaller shift in the AP/NAP ratio occurs at 232 cm depth within unit IIIa.

In the samples between 173 and 222 cm depth (unit IIb-IIe) the birch values remain stable, but their values are slightly decreased in relation to the previous zone. The pine (*Pinus*) pollen values start to increase to a maximum of 12.5% and the herb diversity increases further. In the uppermost pollen sample (173 cm depth) the pine values are still below the rational limit of pine of 20% (Lotter et al.,1992), which suggests that this tree species was not yet present locally. The gradual increase of the pine values within unit II, however, suggests that it was present regionally and was within the reach of the Moervaart depression. Based on this, units IIb-IIe can be correlated with the regional biozone 2a2 of Hoek (1997). The influx of sand around 222 cm depth and abrupt lithological change from lake marl to sand with organic layers is clearly reflected in the local pollen assemblage. Cyanobacteria of the *Gloeotrichia* type, *Myriophyllum verticillatum* and

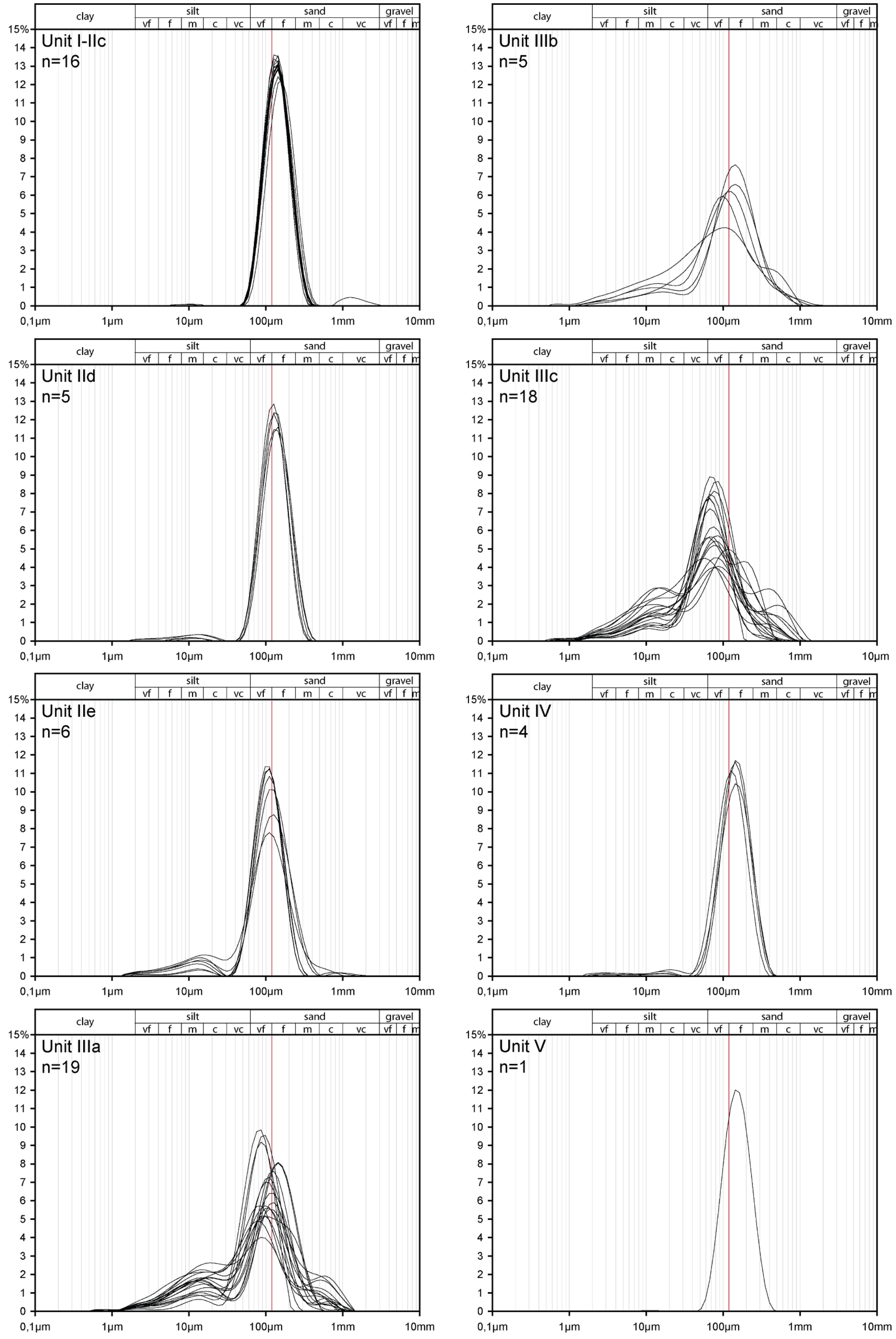

Fig. 5. Frequency curves of the granulometric classes according to the stratigraphic units.

Nymphaeaceae remains (Types HdV-129 and HdV-127a, indicating the local presence of Nymphaeaceae, Pals et al., 1980) strongly decrease or disappear. Furthermore, spores of the *Dryopteris*-type become more abundant. Thus both the lithology and palynology point towards a drastic lowering of the water table. Due to the lake level lowering and increased sand influx the water clarity and local vegetation near the shores of the lake changed. Initially open water plants (e.g., *Nymphaea alba, Nuphar lutea, Menyanthes trifoliata*) remained present, which is

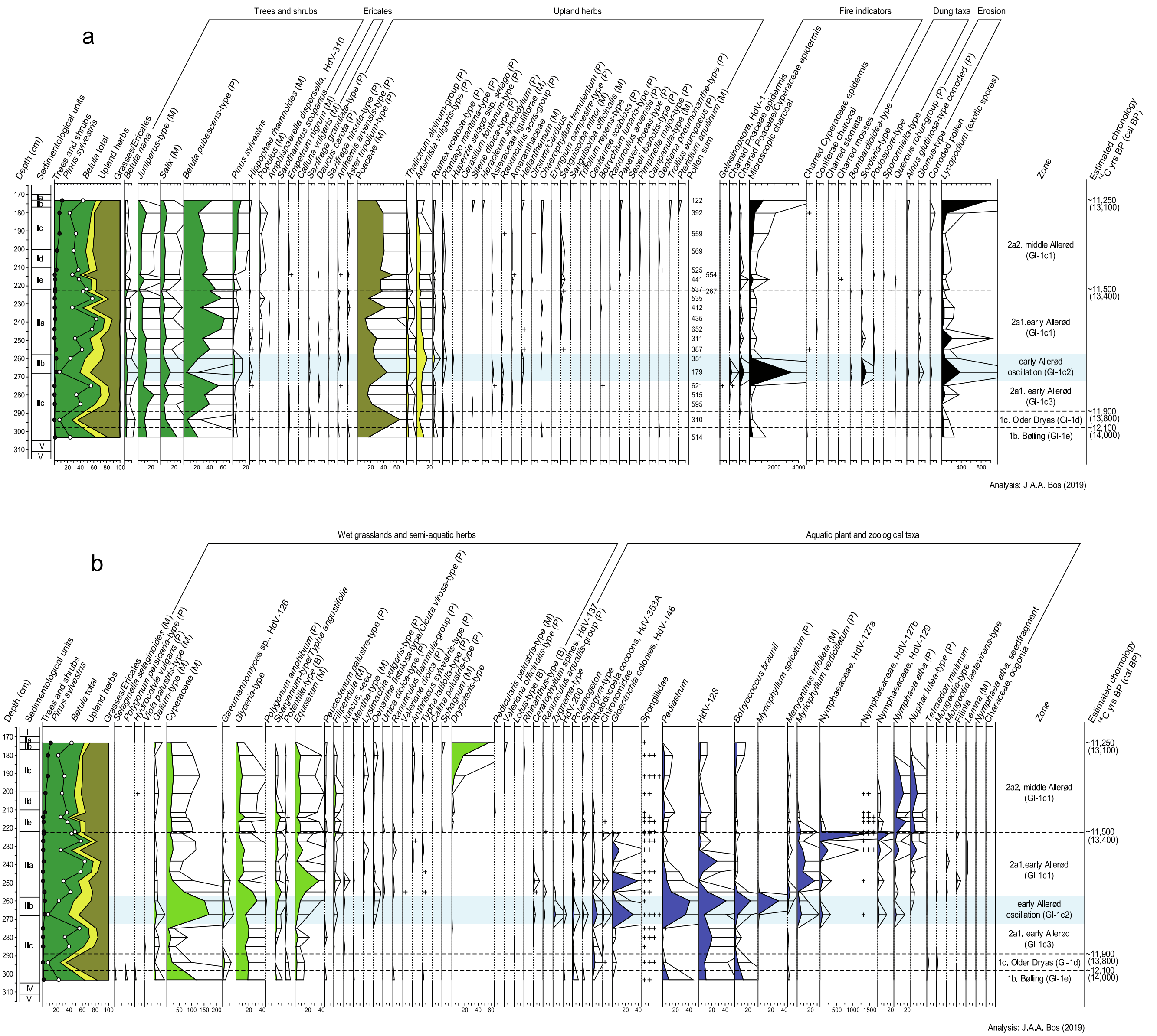

Fig. 6. Pollen diagram of the Moerbeke “Driehoek” site. In the pollen diagram (MHD-1 sequence), the botanical taxa are arranged stratigraphically and grouped by habitat. Microfossils are shown as curves (%). Abundances of some taxa are indicated as: + = present, + + = often present and + + + = abundant. When enough pollen and spores were counted to get a statistical reliable pollen sum, the whole slide was scanned to infer whether some species were not detected during the analysis. Radiocarbon ages are in ^{14}C years BP (as well as in cal BP) and are adapted after Hoek (1997). a. Summary, regional pollen, dung, fire and erosion indicators, b. Summary and local pollen. The *Betula* total curve in the summary diagram consists of the values of *Betula pubescens*-type and *Betula nana* together.

Table 2

List of macrofossil samples analysed of the Moerbeke “Driehoek” sequence (Presence was indicated as: − = absent, + = present, + + = often present and + + + = abundant.

Sample nr.	Sample content	Core depth (cm)
1	–	173–175
2	Rootlets + +; Worm eggs + +	216–218
1	Characeae + +	213–216
2a	Characeae + +; Chironomidae +; Worm eggs + +; Cladocera + + +; Acari +; Trichoptera +; *Carex* cf. *hirta/riparia* 1x fragment nutlet; *Typha* sp. 1x seed; *Nymphaea alba* 2x seed fragments, *Menyanthes trifoliata* 1x seed; *Nuphar lutea* 2x seeds	267–270
2b	Characeae + +; *Cristatella mucedo* + +; Trichoptera cocoons + +; Worm eggs + +	272–274
3	*Typha* sp. 2x seeds, cf. Asteraceae 1x fruit; Characeae +; Acari + +; Worm eggs; Shells + +, Gastropoda + +, Cladocera + + +, Stem fragments +, *Bithynia* +; Trichoptera +	304–307
4	Characeae + +; Worm eggs + +; Acari (mijten) + +; *Cristatella mucedo* + +; Potamogetonaceae stems + +; *Groenlandia densa* 1x fruit; *Menyanthes trifoliata* 0,2x seed; *Carex* sp. 0,3x nutlet	397–398,5

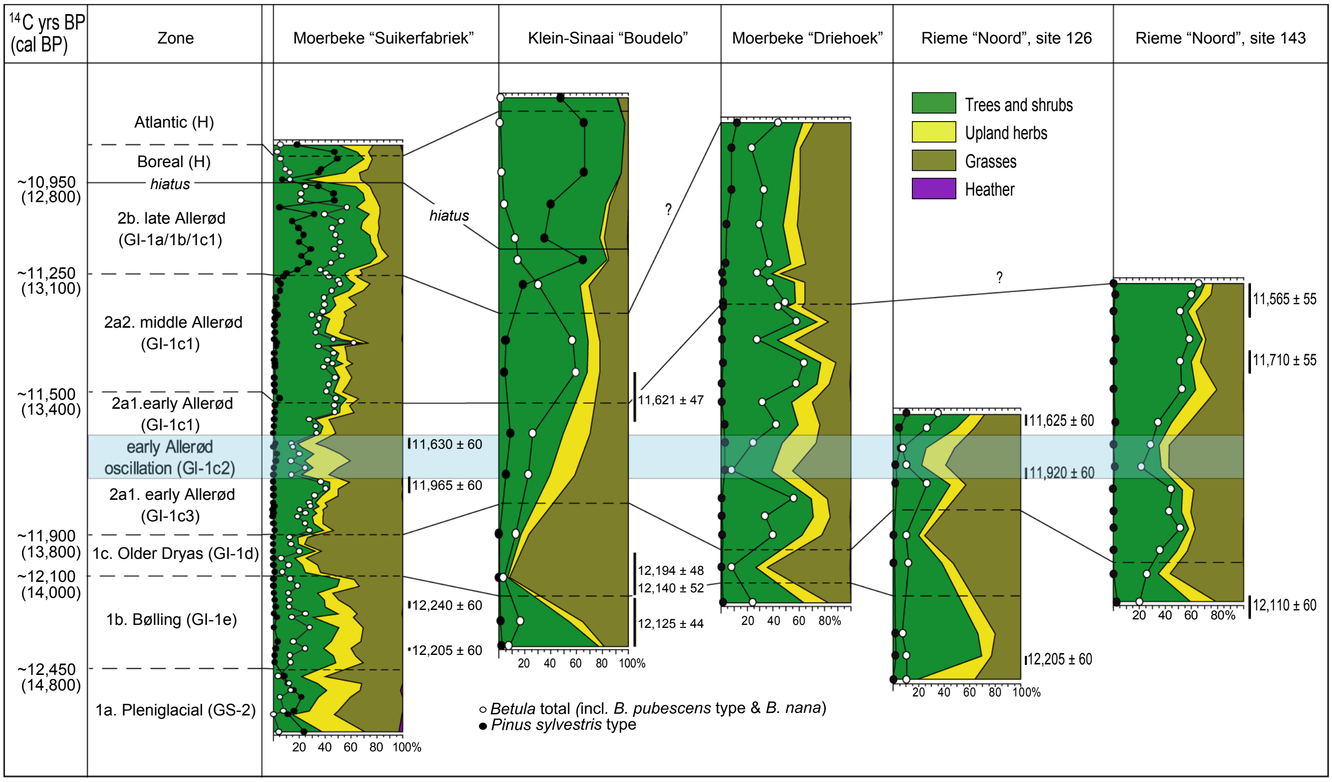

Fig. 7. Correlation of the radiocarbon-dated pollen diagrams available from the Moervaart area, i.e. Rieme "Noord" (Bos et al., 2013), Moebeke "Suikerfabriek" (Bos et al., 2017, 2018a) and Klein-Sinaai "Boudelo" (Bos et al., 2018b), showing the uncalibrated (as well as calibrated) ^{14}C dates for every site. The figure shows that the biozones of Moerbeke "Driehoek" can be correlated with the zones of the regional biostratigraphy of Hoek (1a,b,c, 2a1, 2a2, etc.; 1997) and the event stratigraphy used by the INTIMATE group (Rasmussen et al., 2014). In light blue, the position of the intra-Allerød cold GI-1c2 event is indicated. In the Klein-Sinaai "Boudelo" site this oscillation was not recorded due to the low sample resolution. The *Betula* total curve displayed in the summary diagrams consists of the values of *Betula pubescens*-type and *Betula nana* together. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

also reflected in the organic layers that were formed in between the sandy deposits. However, when the water depth at the sampling site became too shallow, due to the continued influx of sand, these taxa also disappeared. Only algae, semi-aquatic taxa and ferns remained present until the deposition of organic layers and accumulation of pollen ceased and the lake deposits were completely covered by ca. 50 cm of pure sand. The pollen diagram of Moerbeke "Driehoek" ends most likely at the end of the middle Allerød. In the upper three spectra of this zone the microfossil charcoal values increase to a maximum.

In the upper 1.73 m of sand (units IIa and I) pollen is hardly preserved, hindering a biostratigraphical correlation.

5. Discussion

5.1. Sedimentological interpretation

The lowest level (unit V) of the studied sequence, characterized by well-sorted, weakly carbonate fine sands, can be interpreted as an aeolian deposit (Reineck and Singh, 1980). The weak increase of organic matter and clay in the top of this sediment (unit IV) probably refers to a gradual increase of the groundwater table, under continued aeolian activity.

The abrupt and strong increase of carbonates that coincides with a slight increase of organic matter within unit III points to the establishment of a lacustrine environment, i.e. the Moervaart lake. Previous research (Bos et al., 2017, 2018a; Crombé et al., 2014) showed that the formation of the Moervaart lake started in the Bølling period. In unit IIIc, the clastic component probably corresponds with a fluvial input rather than an input from the dune slope. This fluvial influence was probably connected to the existence of an anastomosing river system in the western section of the Moervaart depression (Crombé et al., 2013). In the above-lying units IIIb and IIIa, the main peak of very fine to fine sands (Fig. 5) points to a mixture of fluvial (very fine sands) and aeolian sediments. The latter is based on the similarities with the peak of fine sands within units I–IIc and V.

The sudden drop in the $CaCO_3$ values at the transition from unit III to unit II can be linked to a disappearance of the lacustrine environment either as a result of an abrupt drainage or a marked decrease of the ground water level. Since the studied sequence is situated along the northern margin of the large Moervaart lake, it might indicate that the lake became smaller with the shores falling dry. Earlier research at the nearby Moerbeke "Suikerfabriek" sequence has clearly demonstrated a marked drop of the lake level at the start of the middle Allerød (Bos et al., 2017, 2018a; Crombé et al., 2013), probably caused by the formation of an outlet, i.e. the Kale/Durme meandering river. The oblique morphology of the contact between unit III and II could point to an erosion phase, which resulted in a truncation of the subhorizontal stratification in the top of unit IIIa. In absence of gravels in unit IIe, water erosion seems most likely, e.g. surface water run-off along the dune slope as a result of a lack of vegetation and/or the lowering of the lake level. The similarities in sand fraction composition between unit II and the lower units V and IV clearly indicate that aeolian activity was the main sedimentary process at that time. Based on the large variability in grain size in unit IIe and to a lesser extent IId, ranging from very coarse sands, over silts to clay, it may be suggested that initially aeolian sedimentation still took place under limited lacustrine influence, e.g. on a lake shore that was temporally (seasonally?) inundated. This may point to a lowering of the water level in a lake that due to natural infilling in combination with the continued influx of sands on the shores was gradually getting smaller.

The gradual increase of the fine sand fraction in units IIe and IId can be interpreted as a reflection of an increased aeolian activity in the area, blowing sands from the Great Sand Ridge of Maldegem-Stekene on top of the former lake shore. Aeolian activity probably stabilized from level 192–194 cm onwards, after a maximum in the strength of aeolian activity as indicated by the punctuated deposition of fine gravel and coarser sands. The presence of interstratified organic and inorganic bands over the entire depth of unit II indicates that aeolian sedimentation alternately occurred in wet and dry conditions, the latter culminating at the level of unit IIb. From ca. 170 cm onwards, aeolian deposition continued under dry conditions, as indicated by the total absence of organic layers in unit I of the studied sequence.

5.2. Bio- and chronostratigraphical interpretation

The pollen diagram (Fig. 6) of the Moerbeke “Driehoek” sequence reflects a vegetation development from tundra to boreal forest with birch and later also pine. This is typical for the Lateglacial in the Moervaart coversand area (Bos et al., 2013, 2017, 2018a, 2018b; Verbruggen, 1979; Verbruggen et al., 1996) and fits well with the regional biozone scheme of the Netherlands and northern Belgium (Hoek, 1997). Despite the total absence of radiocarbon dates in the studied sequence, these biozones can be securely linked to the major Lateglacial climatic events, as identified in Hoek’s biostratigraphy and in the Greenland oxygen isotope records (Rasmussen et al., 2014) (Figs. 6 and 7). This is further supported by a series of radiocarbon dates from other Lateglacial sequences in the Moervaart area, e.g. at Moerbeke “Moervaart” (Verbruggen, 1979), Moerbeke “Suikerfabriek” (Bos et al., 2017, 2018a), Klein-Sinaai “Boudelo” (Bos et al., 2018b), Rieme “Noord” (Bos et al., 2013) and Wachtebeke “Heidebos” (Derese et al., 2010; Crombé et al., 2012) (Fig. 7). These correlations demonstrate that the Moerbeke “Driehoek” sediment sequence covers a large part of the Lateglacial Interstadial (GI-1), with accumulation starting during the late Pleniglacial (unit V). The lowermost pollen sample (303.25 cm depth, unit IV) reflects the climate amelioration that occurred at the start of the Bølling, corresponding to GI-1e (Rasmussen et al., 2014). Sample 293.5 cm depth (lower part unit IIIc) is typical for the Older Dryas, corresponding to GI-1d, while the upper part of unit IIIc matches with the early Allerød period, corresponding to GI-1c3. The high pollen values of herbs, grasses and sedges and decreased values of *Betula* in unit IIIb were radiocarbon dated in the Moerbeke “Suikerfabriek” palaeolake record between 13,940–13,730 and 13,550–13,400 cal yrs BP (calibration according to Reimer et al., 2013), allowing correlation with the early Allerød oscillation GI-1c2 (Bos et al., 2017) (Fig. 7). The latter is dated in the oxygen isotope record of the Greenland ice-cores between 13,610 and 13,550 cal yrs BP (Rasmussen et al., 2014). Unit IIIa reflects the period after this oscillation, corresponding to the early part of GI-1c1. The sandy deposits between 222 and 173 cm (unit II) largely reflect the middle Allerød period, corresponding to the later part of GI-1c1.

5.3. Intra-Allerød aeolian deflation

The studied Moerbeke “Driehoek” sequence provided evidence of repeated aeolian deflation during the Lateglacial in the Moervaart area. Most importantly it yielded proof of repeated periods of deflation occurring during the Allerød period, a phase which until now was generally considered as an overall stable period in between the colder and drier Older and Younger Dryas (see Introduction).

Based on the lithostratigraphy (Fig. 4), the record can be roughly divided into three parts: (1) below 305 cm depth (unit V and IV), (2) between 305 and 222 cm depth (unit III) and (3) above 222 cm depth (unit I and II). The fine sand layers immediately below (units V and IV) and above (unit II and I) the lacustrine sediments of unit III are characterized by a good grain-size sorting and an almost complete absence of silt or clay, indicating an aeolian origin. The former most likely belong to the final Pleniglacial and consist of locally reworked coversands from the infilling of the Flemish Valley. The ca. 45 cm thick layer of stratified sands on top of the lacustrine deposits (unit II) on other hand are palynologically clearly linked to the middle Allerød, which can be roughly dated between ca. 13,400 and 13,100 cal BP (Fig. 7) based on the low frequency of pine pollen. A similar deposition of wind-blown sands has recently been found ca. 25 km further to the east of Moerbeke “Driehoek” on the same Great Sand Ridge of Maldegem-Stekene at Beveren “Prosperpolder-Zuid” (Fig. 1). Here a ca. 60 cm thick packet of coversands situated between two thin organic layers was dated between 11,872 ± 49 ^{14}C yrs BP (13,776–13,565 cal BP) and 11,285 ± 52 ^{14}C yrs BP (13,260–13,060 cal BP), also before the massive expansion of pine. Both sites definitely prove that the middle Allerød was a phase of intense aeolian deflation within the coversand region of NW Belgium. So far it remains unclear whether deflation continued uninterrupted during the final Allerød (*Pinus* stage) into the Younger Dryas. The complete lack of pollen unfortunately does not allow to date the upper 1.73 m of sand deposits (units IIa and I) at Moerbeke “Driehoek”. However, at the nearby site of Beveren “Prosperpolder-Zuid” the presence of an organic horizon in between the middle Allerød sands and the upper sands clearly refers to an intermediate stability phase, corresponding to the final “*Pinus*” stage of the late Allerød. It is not unlikely that the thin organic unit IIb at Moerbeke “Driehoek” corresponds to this stability phase. This could suggest that the deposition of the sandy unit I dates to the Younger Dryas, which is not unlikely given the many indications of intense aeolian deposition in the coversand area of NW Belgium at that time (Derese et al., 2010; Crombé et al., 2012; Bos et al., 2013).

Further, though less pronounced evidence of sand influx, has been found within the early Allerød lacustrine sediments of unit III at Moerbeke “Driehoek”. The gradual decrease of very fine sands in favor of fine sands within units IIIb and IIIa point to a gradual increase of the sand influx in the Moervaart lake during this period. The grain-size data clearly demonstrates that this was an almost continuous process, however, with two short-term peak events: one between 258 and 272 cm depth (unit IIIb) and a second between 230 and 246 cm depth (upper part of unit IIIa). The first peak corresponds with a marked drop in the $CaCO_3$ values, minimal birch percentages and maximal values in herbs, grasses and sedges in the pollen assemblages, which was linked to the GI-1c2 oscillation (see 5.2). A similar correlation was attested at the nearby Moerbeke “Suikerfabriek” site, where this oscillation was recorded in multiple proxies (i.e. lithology, OM, $CaCO_3$, Chironomids, *Bithynia*, pollen) and resulted in the deposition of multiples thin layers of aeolian sands deposited as lake infill beds on the lake surface during episodes of freezing. Aeolian activity during the GI-1c2 oscillation was also reported at Beveren “Prosperpolder-Zuid”. Here a 35 cm thick sand layer was found in between two ^{14}C dated organic horizons, the lower one dated at 11,947 ± 48 ^{14}C yrs BP (13,980–13,594 cal BP) and the upper horizon at 11,872 ± 49 ^{14}C yrs BP (13,776–13,565 cal BP). The pollen spectra of these horizons also fit with an early Allerød age. Finally, at two sites at Rieme “Noord”, situated ca. 10 km to the west on the same coversand ridge, intercalated sandy layers were recorded suggesting aeolian activity during the early Allerød (Bos et al., 2013). These events, however, could not be precisely timed, but radiocarbon dates from an overlying organic layer suggest that they occurred sometime before 11,625/11,710 ^{14}C yrs BP or ca. 13,600/13,400 cal BP (Fig. 7).

A possible second peak of sand influx in the lake-phase of the Moerbeke “Driehoek” sequence, situated between 230 and 246 cm depth (upper part of unit IIIa) and partially corresponding to a decrease of birch pollen in favor of herbs and grasses, cannot be dated precisely but clearly dates to a later stage of the early Allerød (Fig. 7). The timing can be similar as at Rieme “Noord”, where sand influx also increased dramatically after 11,625/11,565 ^{14}C yrs BP or ca. 13,400/13,300 cal BP, covering many ponds and dune slacks on the Great Sand Ridge of Maldegem-Stekene (Bos et al., 2013).

The repeated phases of aeolian deflation during the early and middle Allerød ultimately led to the formation of an increasing higher sand ridge along the northern bank of the Moervaart lake. These events also resulted in a gradual migration of this sand ridge in southern direction, covering parts of the former lake bank with wind-blown sands. According to the manual core survey data, the dune edge moved over a distance of at least 100 m (Figs. 1 and 2), but the overall aeolian deposition reached much further into the Moervaart lake as illustrated by the sandy admixture within the lacustrine sediments at Moerbeke "Suikerfabriek" and Klein-Sinaai "Boudelo" (Fig. 1).

5.4. *Triggers of aeolian activity*

As aeolian erosion can only occur when the soil surface is sparse of vegetation, discussion on the possible triggers of intra-Allerød deflation should focus on the processes which may be responsible for a marked decrease of vegetation. Above we already argued that the oldest early Allerød deflation event most likely was connected to the short but abrupt climatic oscillation GI-1c2. At Moerbeke "Driehoek" as well as the other regional records (Moerbeke "Suikerfabriek" and Rieme "Noord"), this event corresponds with a distinct dip in the pollen values of trees and a strong increase in herbaceous pollen, especially grasses, sedges and various herbs (Fig. 7). This suggests that the landscape became more open, with more barren ground and herb, sedge and grass vegetation (Bos et al., 2017). However, it is questionable whether the gradually increasing deposition of the aeolian sands in unit II during the middle Allerød can also be linked to a climatic deterioration event. The second intra-Allerød abrupt cooling event within the Greenland ice-core record, named GI-1b was dated between ca. 13,260–13,050 cal yrs BP (Rasmussen et al., 2014) and corresponds to the late (pine) phase of the Allerød. However, some fluctuations in the chironomid and *Bithynia* records during at least two intervals within the middle Allerød in the nearby palaeolake record at Moerbeke "Suikerfabriek" may suggest temporal drier and colder phases with lower winter and/or summer temperatures and periods of frost persisted during most of the spring (Bos et al., 2017). These might correspond to minor and less intense climatic oscillations, visible as small wiggles in the Greenland ice-core isotope records. Alternatively, the observed fluctuations are not climatically induced but indicate a temporal lowering of the lake level (Bos et al., 2017).

Other processes possibly played a role in the activation of wind erosion besides climatic fluctuations as well. The occurrence of peaks of microcharcoal and charred stomata and epidermis from grasses and sedges at different levels within the Moerbeke "Driehoek" sequence are particularly interesting in this respect. A first peak, situated at 267.5 cm (unit IIIb), is correlated with the location of the GI-1c2 oscillation, which indicates that there may be a causal relationship between the colder and drier conditions and increased wildfires, e.g. of grass and sedge vegetation along the lake shores. This was also attested at the nearby Rieme "Noord" sites (Bos et al., 2013) demonstrating that these wildfires were probably not a local but rather a regional phenomenon. Smaller charcoal peaks in the Moerbeke "Driehoek" record situated between 219.5 and 173 cm (unit IIe-IIb), date to the middle Allerød. A few hundred meters southeast of this location, at Klein-Sinaai "Boudelo", a similar association between aeolian sands deposited on top of lacustrine sediments and a charcoal peak has been reported (Bos et al., 2018b). Higher levels of microscopic charcoal are also recorded in the top levels of the lacustrine sediments in the Moerbeke "Suikerfabriek" palaeolake record (Bos et al., 2017, 2018a). However, at both sites, these microcharcoal concentrations are dated to the late Allerød. These later fires might be linked to the increasing importance of Scotch pine, a species which is known to be very fire sensitive (Rowe and Scotter, 1973; Dreibrodt et al., 2010; Bishop et al., 2015; Marlon et al., 2013; Cui et al., 2015). The Usselo soils present in this area, consisting of (white) sand and pine charcoal and generally dated to the late Allerød and early Younger Dryas (Hoek, 1997; Kaiser et al., 2009), are the testimony of these forest fires during this period. These fires may have been responsible for the removal of all vegetation, at least locally, creating the ideal conditions for wind erosion. However, the discussion still remains whether these later forest fires were naturally induced or anthropogenic in origin, or both. Based on ethnographical parallels several researchers (Mellars, 1976; Mellars and Dark, 1998; Bos et al., 2005; Scherjon et al., 2015) claim that the vegetation was locally burned down by prehistoric hunter-gatherers in view of creating openings, which stimulated the growth of herbs and shrubs in order to attract herbivores. Fire also could be used as a direct hunting technique in order to drive game together or simply to create easy access to the lake by burning down the shore vegetation. There is plenty of evidence that the northern bank of the Moervaart lake was intensively occupied by hunter-gatherers during the Lateglacial; at least six camp-sites belonging to the Final Palaeolithic are known, one of them situated at Moerbeke "Driehoek" (Crombé et al., 2013). Yet, it is very unlikely that these hunter-gatherers were responsible for the forest fires during the early and/or middle Allerød. Situated in the top 0.5 m of the soil, these surface-sites definitely date to a later stage of the Allerød or the Younger Dryas. Of course, it is possible that camp-sites contemporaneous with the fire events are still present within the aeolian deposits, but these have not yet been discovered due to their deeper stratigraphic position. One such site, attributed to the *Federmesser* Culture of the Allerød, was discovered in 1971–1972 during the excavation of a Medieval abbey at the nearby site of Klein-Sinaai "Boudelo". Unfortunately, exact stratigraphic information is missing, but the excavation report (Vanmoerkerke and De Belie, 1984) mentions a position of the prehistoric finds "in a sand layer with iron concretions, situated 10 cm above a thick bleached horizon with numerous scattered charcoal fragments at the top." The latter might correspond to the Usselo soil, indicating that the *Federmesser* site of Klein-Sinaai "Boudelo" dates to the late Allerød at the earliest (see Fig. 8).

6. Conclusions

The analysis of the sediment sequence of Moerbeke "Driehoek", in combination with evidence from other archives within the Moervaart depression, has demonstrated that the Allerød period in NW Europe on a local/regional level was sedimentologically much less stable than hitherto assumed. This study shows that phases of intense aeolian deflation have occurred, some of which most probably were caused by centennial abrupt climatic oscillations, while others were likely the result of intense forest fires or a combination of both. These observations now call for a revision of the existing Lateglacial part of the litho- and chronostratigraphic schemes for the sand-belt of northern Europe. In these schemes, coversands situated below the late Allerød Usselo or Finow soils have been commonly interpreted as Younger Coversands I, dating to the Older Dryas. The present study strongly suggests that these Younger Coversands can include different phases of aeolian sedimentation, some of which date back to the early or middle stages of the Allerød. Furthermore, this study has pointed out that aeolian activity during the Allerød, at least in NW Belgium, was as intense as during the preceding Older Dryas. These observations are not only important for future geomorphological and palaeoecological research, but are also relevant for archaeological research as they underline the potential existence of Lateglacial hunter-gatherers camp-sites sealed below thick packets of aeolian sands, the latter indicating a possibly better preservation of the archaeological remains.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

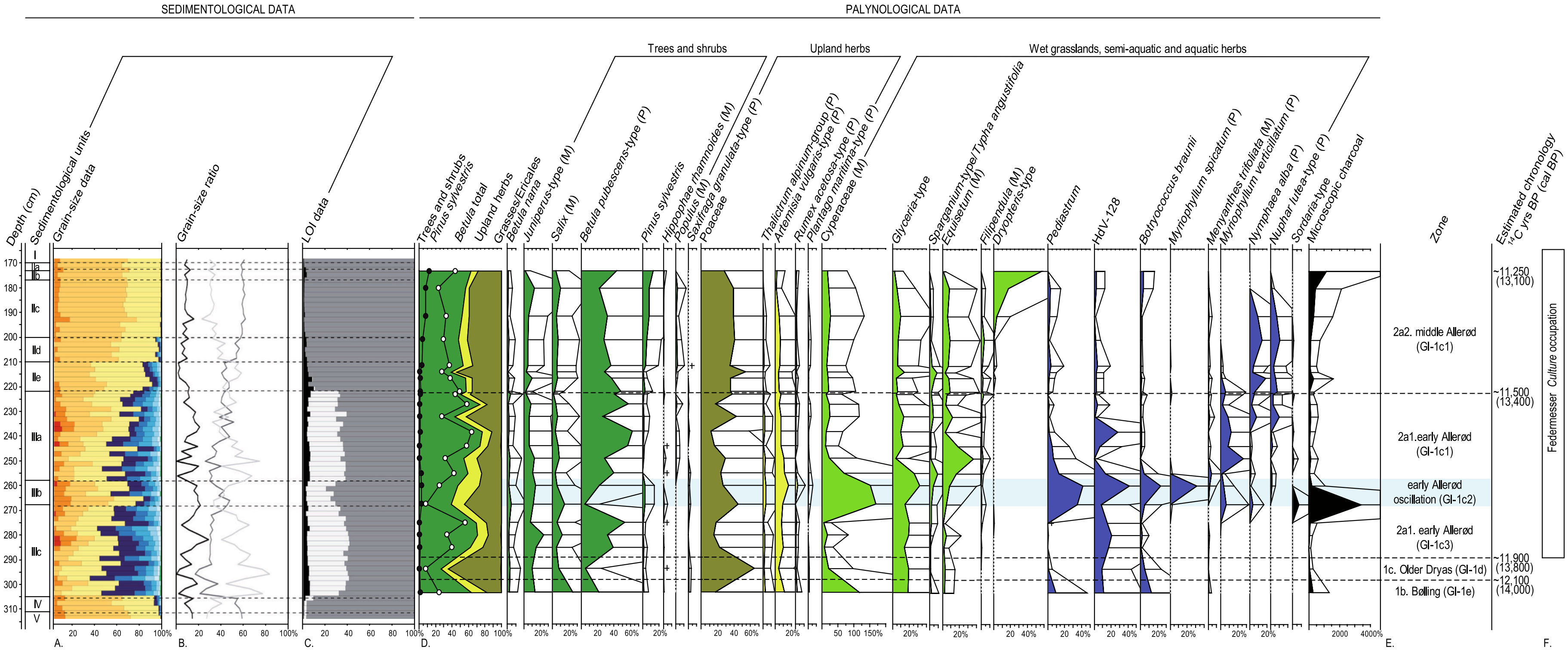

Fig. 8. Summary overview combining the multi-proxy data of the Moerbeke “Driehoek” sequence, e.g., sedimentological units, grain-size data, LOI, $CaCO_3$, pollen and other microfossils. a. grain-size data, b. represents the ratio between medium, fine and very fine sands, calculated on the total amount of the three classes per layer, c. LOI and $CaCO_3$ data, d. palynological data and e. biostratigrapical zonation and chronology. Radiocarbon ages are in ^{14}C years BP (adapted after Hoek, 1997) and in cal years BP. In f. also the *Federmesser* Culture period is indicated. For the legend of the sedimentological analyses we refer to Fig. 4.

Acknowledgements

We would like to thank the landowners and leaseholders for giving the permission to access and work on their lands, as well as colleagues and students that helped us out in the field. We are also grateful towards reviewer Knut Kaiser (GFZ German Research Centre for Geosciences, Potsdam) for his valuable and much appreciated comments on an earlier version of this paper.

Funding

The project was funded by Special Research Fund (BOF) of Ghent University: "Prehistoric settlement and land-use systems in Sandy Flanders (NW Belgium): a diachronic and geo-archaeological approach" (BOF08/GOA/009; PI: Philippe Crombé).

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2020.104453.

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