



Ecology and fluvial dynamics of an Early Holocene medium-sized European lowland river valley (Upper Scheldt, northern Belgium)

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The fluvial environment of Early Holocene small- to middle-sized lowland rivers in northwest Europe is mostly unstudied due to a lack of preserved and accessible deposits. A rescue excavation in the Scheldt valley in northern Belgium offered the opportunity to study a Boreal alluvial succession in detail. The results of palaeoecological and sedimentological analyses (diatoms, pollen, botanical macro-remains, molluscs, grain size) characterize the biotic and physical environment in the middle reach of this medium-sized river system. Although the Early Holocene in the Scheldt Basin has often been portrayed as a period of fluvial stability with marshy conditions and diffuse discharge, this study showed evidence of point bar formation by a small, low-energy meandering river between ~9.5 and ~8.8 ka BP. The point bar was at least temporarily vegetated and shows a shift from herbaceous riparian vegetation to an open willow-dominated alluvial forest. This evidence points to a more open vegetation and a more energetic environment than traditionally described for rivers of this size and age. A link to the 9.3 ka BP cooling event is suggested and possible reasons for the scarcity of records of this type of deposits are discussed.

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Following a period of major geomorphic transformations in response to the abrupt climatic change at the onset of the Holocene, the remainder of the Early Holocene (*sensu* Walker *et al.* 2012) in northwest European small- and medium-sized lowland river systems is generally described as a period of relative stability (Antoine 1997; Bos *et al.* 2005; Notebaert & Verstraeten 2010; Meylemans *et al.* 2013; Turner *et al.* 2013). In these valleys the Lateglacial palaeochannels were generally being filled by organic aggradation, under first sub-aquatic, and then marshy conditions. Discharge and sediment load were very limited. This lack of fluvial dynamics led to the near-absence of fluvial architectural features in the subsoil. Therefore, the opportunities to study fluvial characteristics of Early Holocene small- to medium-sized lowland rivers of northwest Europe are scarce.

However, an exceptional opportunity occurred to examine this type of fluvial environment in the Early Holocene, when a complex of fluvial deposits was revealed in an archaeological rescue excavation in 2003 during the construction of a weir on the Upper Scheldt at Oudenaarde. The deposits did not only contain archaeological material, but also a substantial amount of botanical and zoological remains (Ameels *et al.* 2003). One section showed an alternation of more and less silty sand layers, dating from the Early Holocene (Boreal biozone, *sensu* Verbruggen *et al.* 1996). Here we present the results of a multiproxy analysis of these sediments, including

palaeoecological analyses (diatoms, pollen, botanical macro-remains and molluscs), grain-size distribution measurements and radiocarbon dating. The aim is to reconstruct the palaeoenvironment of an Early Holocene medium-sized river. Reconstruction of the depositional environment includes definition of sedimentological processes, flow energy and fluvial style. The reconstruction of the biotic environment focusses on both aquatic life and riparian vegetation development. Additionally, the results are linked to the Early Holocene climatic context and possible reasons for the scarcity of this type of deposits are explored.

Study area

The Scheldt is a rainfed lowland river flowing over ~350 km from its source in northern France, through Belgium to its mouth in the North Sea in the southwest of the Netherlands (Fig. 1A). The Scheldt and its tributaries drain an area of ~22 000 km². The Upper Scheldt is the non-tidal part of the river and consists of the upper reach (*sensu* Kiden 1991), between its source (~100 m TAW) and Tournai (~15 m TAW), and the middle reach, down to the confluence with the Lys at Ghent (~4 m TAW), (TAW: Belgian ordnance level). The lower reach, downstream of Ghent, is called the Lower Scheldt and is currently a tidal river.

The studied site is located along a canalized segment of the middle reach of the Scheldt, between the city centre of

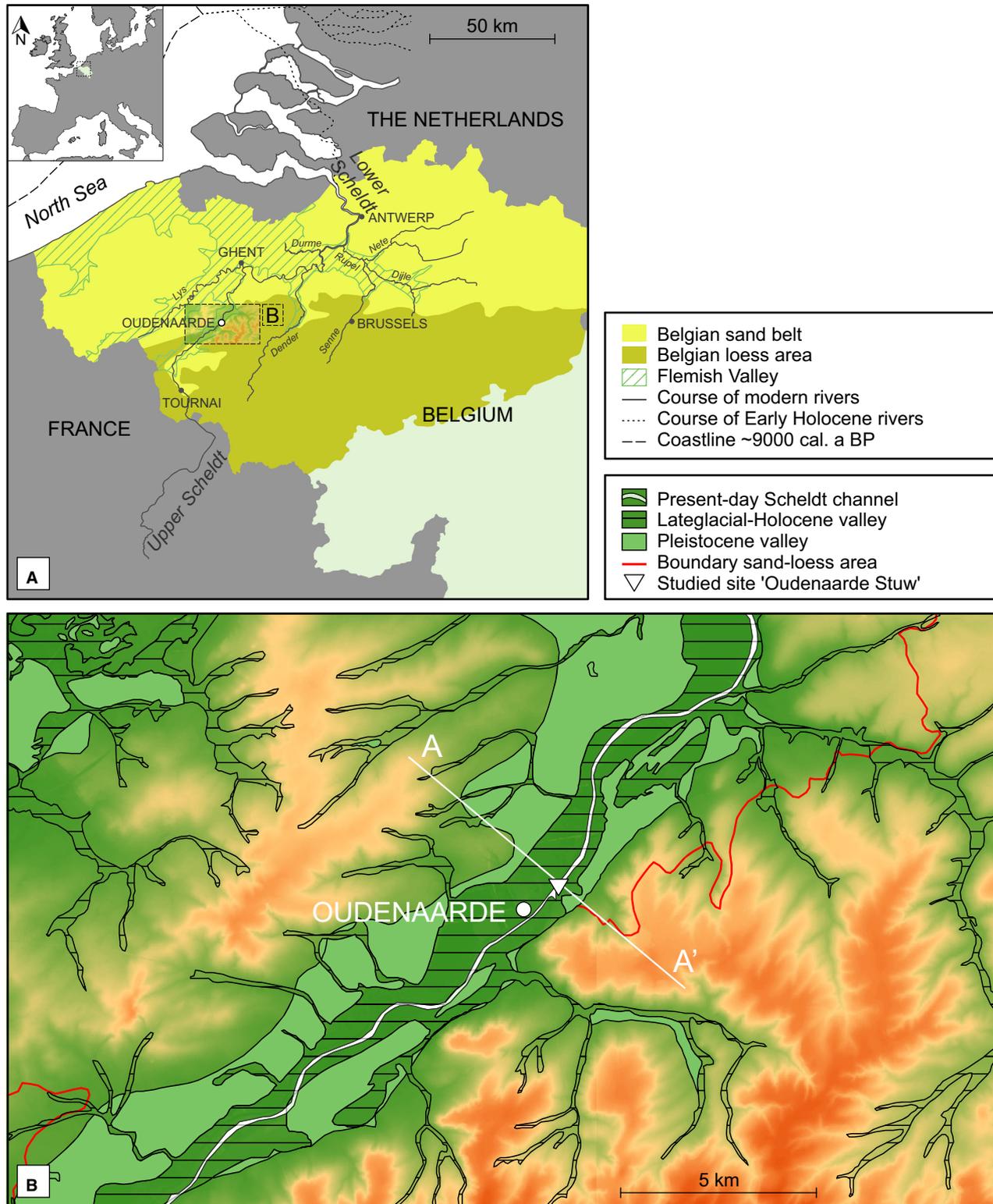


Fig. 1. A. Location of the study area within the Scheldt Basin, with indication of the Flemish valley (Tavernier & De Moor 1974), Belgian sand belt and loess area (Beerten *et al.* 2017), Early Holocene course of the Lower Scheldt (Kiden 1995), connection with the Meuse-Rhine system ~9.1 cal. ka BP (Hijma & Cohen 2011), and coastline ~9.0 cal. ka BP (Sturt *et al.* 2013). B. DEM (AGIV 2014) with the Pleistocene and Holocene valleys (DOV 2005) and the location of the studied site (triangle) and cross-section A–A' in Fig. 2. [Colour figure can be viewed at www.boreas.dk]

Oudenaarde and the village of Ename (Fig. 1B). At this point, ~150 km from the source, the upstream catchment area is ~5600 km², the slope is ~0.15‰ and the mean flow rate is ~35 m³ s⁻¹.

The middle reach of the Scheldt follows the course of a larger Pleistocene valley that was connected with the Flemish Valley to the north (Tavernier & De Moor 1974; Fig. 1A). This valley was incised in early Eocene marine layers and filled with fluvial deposits during the Late Pleistocene (DOV 2005; Fig. 2). Subsequently, the valley sides and floor were covered by aeolian sediments: sand in the Belgian sand belt, north of Oudenaarde (Gent Formation, Beerten *et al.* 2017) and silt in the loess area, south of Oudenaarde (Romont Group, Haesaerts *et al.* 2011) (Fig. 1B). At the end of the Pleniglacial or the beginning of the Lateglacial, the braided river system of the Scheldt transformed to a meandering river system (De Moor & Heyse 1978; Kiden 1991; Verbruggen *et al.* 1991; Meylemans *et al.* 2013), which reworked the aeolian sediments and evacuated part of it, lowering and flattening a part of the valley floor. The flattened part became the flood-plain for the Lateglacial and Early Holocene Scheldt (Kiden 1991; Bogemans *et al.* 2012; Meylemans *et al.* 2013; Fig. 2).

The river system of the Early Holocene middle and lower reach of the Scheldt and its tributaries is described as ‘underfit’, diffuse streams in a marsh environment within the confines of the Lateglacial meandering palaeochannel. Due to increasing afforestation and low discharge, depositional processes were largely limited to peat accumulation, without significant channel formation or lateral erosion (De Smedt 1973; Kiden 1991; Verbruggen *et al.* 1991; Huybrechts & Verbruggen 1994; Huybrechts 1999; Bogemans *et al.* 2012; Meylemans *et al.* 2013; D’Haese 2015). This peat was formed in an environment of first fens, succeeded by carr vegetation (Storme *et al.* 2017). From the Middle Holocene (*sensu* Walker *et al.* 2012) onwards, peat also accumu-

lated outside the Lateglacial palaeochannels, and eventually covered the entire flood-plain. During the Late Holocene (*sensu* Walker *et al.* 2012), increased human impact on the surrounding landscape caused the formation of the modern meandering river system with small dimensions, and associated mud accumulation on the flood-plains (Meylemans *et al.* 2013; Broothaerts *et al.* 2014b). Finally, the system was canalized from the Middle Age onwards.

At Oudenaarde the Lateglacial/Holocene Scheldt valley is located in the eastern side of the Pleistocene valley and is filled up to +10 to +12 m TAW (Fig. 2). This paper presents the results of the study of part of this infill, between ~5 and ~7 m depth.

Most previous palaeoecological studies on Early Holocene deposits in the Scheldt valley were carried out on the infill of Lateglacial palaeomeanders of the Lower Scheldt (Verbruggen 1971; Bos *et al.* 2005; Deforce 2008; Storme *et al.* 2017). In these locations, the Boreal biozone corresponds to peat accumulation in a fen vegetation with ferns, horsetails, sedges and reeds, which was gradually succeeded by carr vegetation with willow and, from the Atlantic onward, alder as a dominant vegetation component (Storme *et al.* 2017). These marshes were surrounded by forest with hazel, pine, oak and elm (Boreal biozone, Verbruggen *et al.* 1996; Scheldt basin biozone SB4, Storme *et al.* 2017).

Peat deposits in palaeochannels along the middle reach of the Scheldt (Kerkhove, Roose 1985; Oudenaarde Donk, Depredomme 1986 and Ename Castrum, Storme *et al.* 2017), close to the study site of this paper, document a very similar vegetation evolution to the one described for the Boreal in the Lower Scheldt. The wetlands of the upper Scheldt valley consisted of fen vegetation including ponds with bur-reed and other aquatics and did not show a clear succession to carr vegetation before the appearance of alder (Pont-à-Chin, de Heinzelin *et al.* 1984; Valenciennes, Ruchard *et al.* 1991).

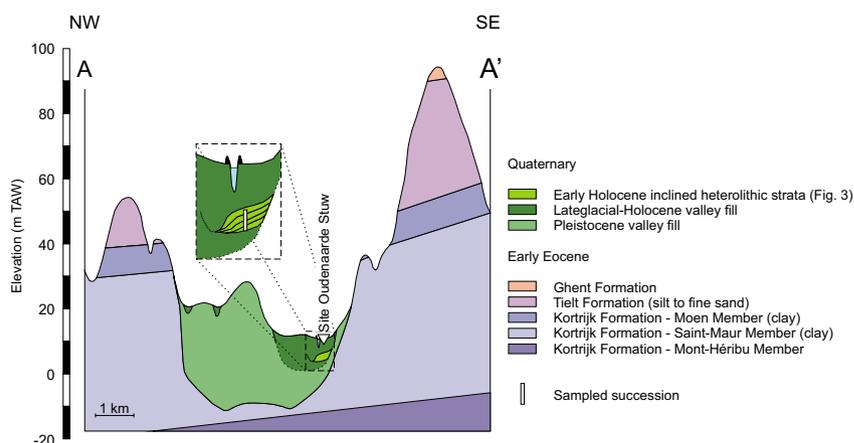


Fig. 2. Cross-section through the middle reach of the Scheldt valley with location of the studied succession at Oudenaarde Stuw and tentative distribution of the inclined early Eocene strata (based on geological and elevation maps: DOV 1999a, b, 2005, 2008; AGIV 2014). [Colour figure can be viewed at www.boreas.dk].

Geomorphological studies of the Scheldt valley (Kiden 1991; Deschodt 2002, 2014; Bogemans *et al.* 2012; Deschodt *et al.* 2012; Meylemans *et al.* 2013; Boulen *et al.* 2014) and its tributaries (Vandenberghe & de Smedt 1979; Notebaert *et al.* 2011; Broothaerts *et al.* 2014a) show marshy conditions with peat formation within the Lateglacial palaeochannels during the Boreal.

Material and methods

A sediment succession of ~2 m was sampled in overlapping boxes that were pushed into the cleared vertical profile (Fig. 3). The boxes were subsampled in the laboratory for palaeoecological and sedimentological analyses and for radiocarbon dating. The subsamples were labelled according to their position within the box and recalculated to depth below the surface, ranging from 5.02 to 7.13 m (Fig. 4).

Sedimentology

The stratification of the deposits is visually described from the cross-section (Fig. 3, terminology following Thomas *et al.* 1987), while the sediment composition is recorded from the sample boxes and complemented with grain-size analyses of 43 subsamples from the sampled succession. Organic matter and carbonates were removed prior to grain-size measurements (procedure adapted from Mulitza *et al.* 2008) and samples were subsequently boiled in sodium hexametaphosphate (2%) to ensure complete disaggregation of the particles. Grain-size measurements were obtained using a Malvern Mastersizer 3000 and sample quantity was adjusted to obtain a laser beam obscuration of between 3 and 20% (see Table S1 for the resulting volume percentage data).

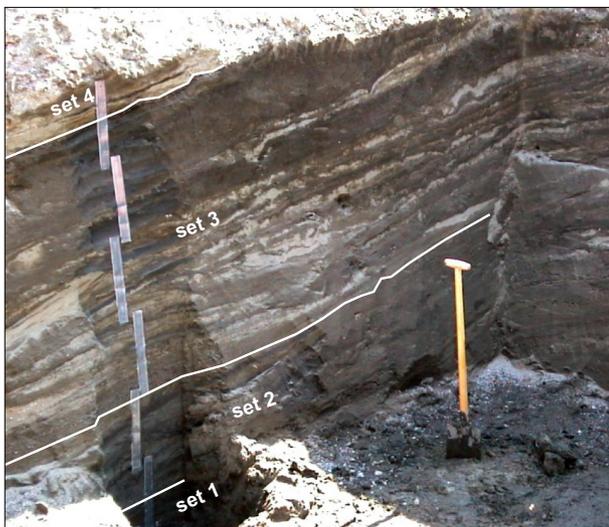


Fig. 3. Photograph of the studied section with sample boxes. Four coarse to fine sets are indicated. [Colour figure can be viewed at www.boreas.dk]

Grain-size classes are according to Wentworth (1922) and sediment texture classification follows Folk (1954).

In order to structure and scrutinize the data, the resulting grain-size distributions were grouped in five types, based on the Bray–Curtis similarity of the volume percentage data and plotted using multidimensional scaling (MDS) in Primer (Clarke & Gorley 2006).

End members of the grain-size distributions were determined using AnalySize software, with a lognormal distribution used as the parametric curve fit type of the end members (Paterson & Heslop 2015). These end members are related to certain sediment sources and/or depositional processes and are used to interpret the defined grain-size groups. End member analysis of all distributions together yielded multiple fine sand and coarse silt peaks, without producing a fine silt peak, which is nevertheless clearly visible in the distributions of some silt samples, but overshadowed by the variations in the coarse peaks of the sandy samples. Trials revealed that the optimal match is obtained by performing end member analysis upon type 1–2 distributions and type 3–5 distributions separately, resulting in two sets of end members. The relative abundance of each of the contributing end members to a sample, as calculated by AnalySize, is plotted vs. sample depth (Fig. 4).

Finally, the results were presented in a CM diagram (Passega 1957) by plotting the first (coarsest) percentile (C) as a function of the median grain size (M), in order to infer depositional processes by comparing the results to plots from known depositional environments. As it has been shown that CM patterns differ amongst rivers (Bravard & Peiry 1999), our samples are not compared to the original pattern based on Mississippi sediments (Passega 1957). Instead, the Dijle valley in the eastern part of the Scheldt Basin is chosen as a reference, as data from modern deposits are available (Notebaert *et al.* 2011).

Diatoms

Diatom subsamples were taken at 12 levels (Fig. 4) and treated using standard techniques (Battarbee 1986). Diatom preservation was assessed under a transmitted light microscope. Only the sample at 5.49 m depth contained sufficient diatoms and was further studied. A total of 325 valves was counted, of which 312 were identified to 10 different species using transmitted light and scanning electron microscopy (Table 1). Identifications are mostly based on Krammer & Lange-Bertalot (2008). The nomenclature follows algaebase (Guiry & Guiry 2016). Taxa are classified according to compilations by Denys (1991) and Van Dam *et al.* (1994).

Pollen, spores and non-pollen palynomorphs

Subsamples (~1 mL) for palynological analysis were taken approximately every 8 cm (Fig. 4) and treated

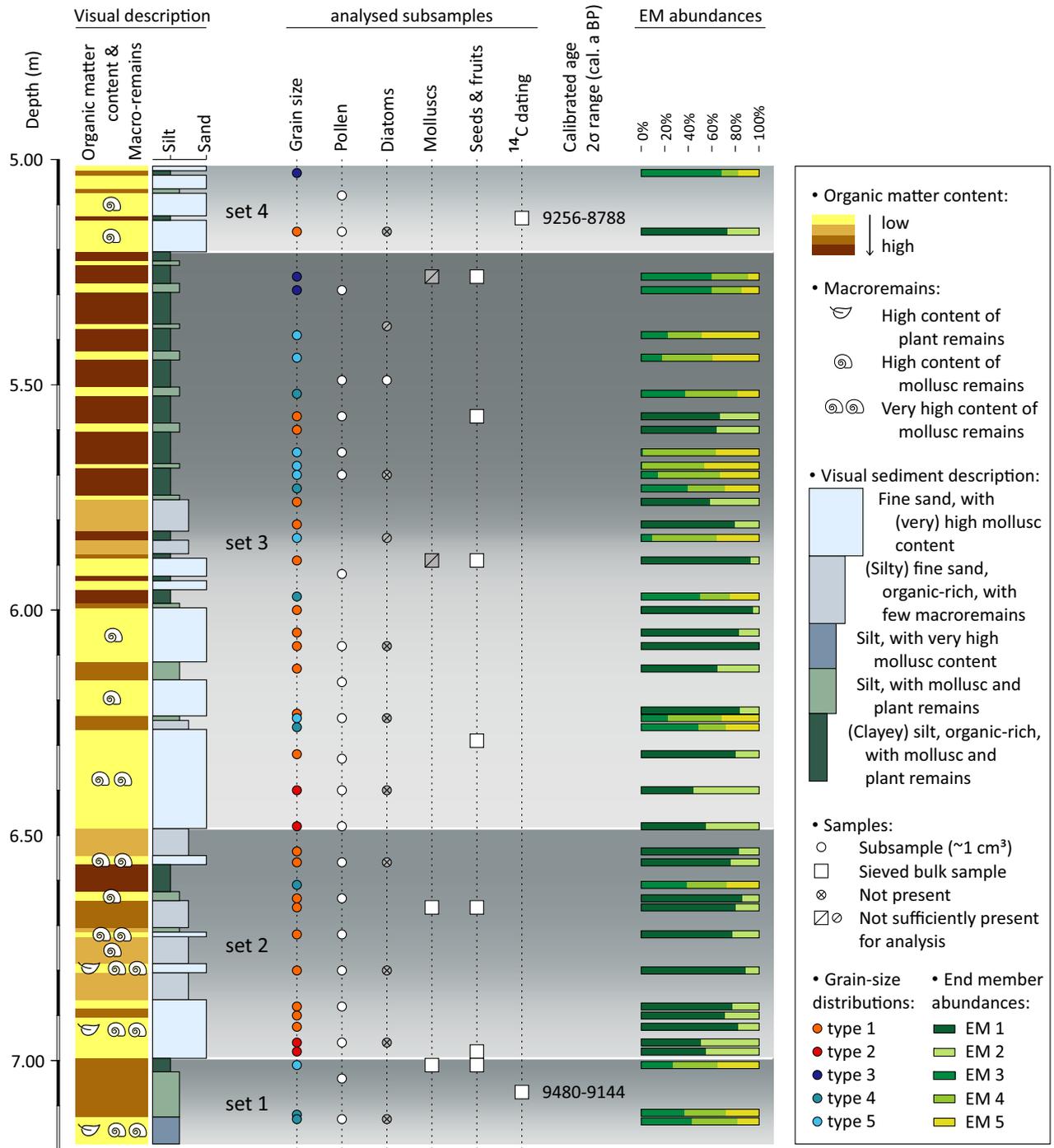


Fig. 4. Lithology, location of the analysed subsamples, radiocarbon dating results, grain-size distribution types and relative abundances of the end members in the sedimentological samples. [Colour figure can be viewed at www.boreas.dk]

following standard procedures for pollen analysis (Moore *et al.* 1991). Identifications of pollen and spores are based on Moore *et al.* (1991), Beug (2004) and a reference collection, while the nomenclature of pollen types follows Beug (2004). All palynomorphs (pollen, spores, algae) are expressed as percentages of the pollen sum, which includes all pollen types except aquatic taxa. A pollen sum of at least 500 specimens was counted in every sample. The

counts were plotted in a percentage diagram using Tilia software (Grimm 2015).

Seeds and fruits

Seven samples were analysed for seeds and fruits (Fig. 4). The 3-cm-thick samples were sieved with tap water on a sieve with a 0.25 mm mesh size. Sample volumes,

Table 1. Abundances (raw data) of the identified diatom valves.

Diatoms	5.49 m depth
Aquatic and limnophilous	
<i>Martyana martyi</i> (Héribaud-Joseph) Round	91
<i>Ulnaria capitata</i> (Ehrenberg) Compère	5.5
Amphibious and indifferent to current	
<i>Fragilaria ulna</i> (Nitzsch) Lange-Bertalot complex	22
<i>Cocconeis placentula</i> var. <i>euglypta</i> (Ehrenberg) Grunow	2
<i>Cocconeis neodiminuta</i> Krammer	14
<i>Amphora pediculus</i> (Kützing) Grunow ex A. Schmidt	5
<i>Epithemia adnata</i> (Kützing) Brébisson	3
<i>Gyrosigma attenuatum</i> (Kützing) Rabenhorst	80
<i>Aulacoseira crenulata</i> (Ehrenberg) Thwaites	8
<i>Ellerbeckia arenaria</i> (Moore ex Ralfs) Crawford	81
Indeterminata	13
Total diatom valves	324.5

determined by water displacement, varied slightly and were standardized to 30 mL. Identifications are based on the reference collection of the Flanders Heritage Agency and the seed atlas by Cappere *et al.* (2006). Taxonomy follows (Lambinon *et al.* 1998). The ecological interpretation is based on Weeda *et al.* (1985–1994) and Oberdorfer (2001).

Molluscs

Subsequent to extraction of the botanical macro-remains, the 0.5-mm sieve residue was air-dried for the study of molluscs. These were retrieved from a subsample of 30 mL. Counts (Table 2) represent the minimum number of individuals (MNI), which for gastropods corresponds to specimens with an apex and for bivalves to remains with an umbo. The number of bivalve valves was divided by two.

Identification was carried out with a stereoscopic binocular microscope and based on Kerney & Cameron (1980), Glöer & Meier-Brook (2003), Gittenberger & Janssen (2004), Killeen *et al.* (2004) and Cameron (2008). The taxonomy follows de Jong (2013).

Only in the lower part of the succession was the number of individuals sufficient for a reliable analysis (Fig. 4, Table 2). Only two of the four samples are therefore included in the diagrams of the ecological groups. The sample at 6.66 m depth contained a relatively large portion (around 50%) of grey-coloured, possibly reworked material.

Radiocarbon dating

Subsamples for AMS radiocarbon dating were taken from the base and the top of the succession. These 3-cm-thick samples were sieved and the residues were scanned for macro-remains of terrestrial plants. Twigs from respectively *Salix* sp. and *Quercus* sp. were selected and dated (Table 3). The resulting ages were calibrated using

OxCal v4.3.2 (Bronk Ramsey 2009) based on IntCal13 atmospheric data (Reimer *et al.* 2013).

Results

Description of the outcrop

The deposits show inclined heterolithic stratification (Thomas *et al.* 1987). The couplets each consist of a coarser and a finer bed, and show an average apparent inclination of $\sim 10^\circ$ in the cross-section. The individual beds are very thin to medium (Boggs 2006), ranging from ~ 1 to 22 cm, and are bounded by sharp, often bioturbated or undulating bedding planes. The coarse-to-fine couplets are in turn part of coarse-to-fine sets. In the studied cross-section, four of these sets are present (Fig. 4), of which sets 2 and 3 are probably complete. The boundaries between sets are largely parallel.

All beds contain at least a moderate amount of mollusc fragments (both bivalves and snails) and small amounts of macroscopic plant remains such as roots and wood fragments. Beds with higher concentrations of mollusc or plant remains are marked in Fig. 4. Additionally, small amounts of calcium carbonate concretions (lumps or 1-mm-diameter hollow cylinders) and rare fish bones are found. The coarser beds typically consist of fine sand with very high (>50%) to moderate mollusc content and the presence of wood fragments. Finer beds are generally characterized by a texture ranging from silty fine sand to silt, higher organic matter content and usually few mollusc fragments. The precise sediment composition of the beds varies between and within the beds (cf. grain-size analysis).

The inclined strata are cut off by a younger channel filled with carbonate-rich sediment. Otherwise the relationship to the underlying, overlying and laterally adjacent units is unclear due to the limited extent of the excavation.

Grain-size analysis

The sediments range from sandy silt to sand and are all bi- or multi-modal. Based on their similarity, five types of grain-size distributions can be distinguished in the MDS plot (stress = 0.01, Fig. 5). End member analyses result in two sets of end members: two end members for the type 1–2 distributions (96.2% of the data set variance) and three end members for the type 3–5 distributions (98.5% of the data set variance) (Fig. 6, Table 4). The modes of EM1 and 3 are slightly dissimilar, but can be regarded as the result of the same depositional processes. The same applies to EM2 and 4.

Each grain-size distribution type can now be characterized by the presence and relative abundance of the end members. Type 1 represents a very uniform group of 16 bi-modal distributions consisting of a high fine sand peak (EM1) and a low but distinct medium to coarse silt

Table 2. MNI and ecological characteristics of the identified mollusc taxa.

Molluscs	Ecological characteristics			Depth (m)			
	Wetness	Flow velocity	Vegetation	7.01	6.66	5.89	5.26
Terrestrial							
<i>Carychium minimum</i>	Swamp	n.a.		2	1	–	–
<i>Carychium tridentatum</i>	Hygrophilous	n.a.	Shade	–	1	–	–
<i>Oxyloma elegans</i>	Swamp	n.a.		4	–	–	–
<i>Punctum pygmaeum</i>	Hygrophilous	n.a.	Shade	–	1	–	–
<i>Vitrea</i> sp.		n.a.		–	1	–	–
<i>Oxychilidae</i>		n.a.		2	–	–	–
Amphibious							
<i>Galba truncatula</i>	Drought-tolerant			1	1	–	–
Aquatic							
<i>Bithynia leachii</i>		Stagnant/slow-flowing	Well-vegetated	5	4	–	–
<i>Bithynia tentaculata</i>				3	14	–	–
<i>Valvata macrostoma</i>	Drought-tolerant	Stagnant/slow-flowing		8	21	3	–
<i>Valvata piscinalis</i>		Stagnant/slow-flowing	Well-vegetated	5	15	–	–
<i>Valvata cristata</i>	Drought-tolerant	Stagnant/slow-flowing		9	6	–	2
<i>Acroloxus lacustris</i>		Stagnant/slow-flowing		–	3	3	–
<i>Lymnaea stagnalis</i>		Stagnant/slow-flowing	Well-vegetated	–	1	–	–
<i>Radix labiata/balthica</i> complex				2	9	1	–
<i>Stagnicola palustris</i> complex	Drought-tolerant	Stagnant/slow-flowing	Well-vegetated	1	–	–	–
<i>Anisus vortex</i>		Stagnant/slow-flowing	Well-vegetated	–	1	–	–
<i>Gyraulus crista</i>	Permanent water	Stagnant/slow-flowing	Well-vegetated	24	26	8	–
<i>Gyraulus albus</i>				28	25	–	–
<i>Gyraulus laevis</i>		Stagnant/slow-flowing		1	2	–	–
<i>Hippeutis complanatus</i>	Permanent water	Stagnant/slow-flowing	Well-vegetated	4	1	1	–
<i>Planorbarius corneus</i>	Permanent water	Stagnant/slow-flowing	Well-vegetated	–	–	2	–
<i>Pisidium amnicum</i>		Faster-flowing		1	1	–	–
<i>Pisidium casertanum</i>	Drought-tolerant			–	3	2	–
<i>Pisidium henslowianum</i>		Faster-flowing		16	19	5	1
<i>Pisidium moitessierianum</i>		Faster-flowing		1	5	3	–
<i>Pisidium nitidum</i>				14	11	6	–
<i>Pisidium subtruncatum</i>	Permanent water			2	7	4	–
<i>Pisidium supinum</i>		Faster-flowing		3	1	–	–
<i>Sphaerium corneum</i>	Permanent water			–	–	3	–
<i>Sphaerium rivicola</i>				6	13	–	–
<i>Sphaerium solidum</i>				–	1	–	–
<i>Sphaerium</i> sp.				–	4	–	–
<i>Sphaeriidae</i>				–	–	2	2
Indeterminata				25	24	5	–
Total MNI				167	222	48	5

peak (EM2). The same two end members are present in the type 2 distributions; however with a higher contribution of EM2 and a less clear separation between them. Type 3 includes three distributions with a sand peak (EM3) finer than in types 1 and 2, and a gradual tail to the finer side (EM4 and 5), which indicates poorer sorting. Type 4 comprises seven tri-modal distributions where the (very) fine sand peak (EM3) is always most important, followed by the coarse silt peak (EM4) and the fine silt peak (EM5). This composition results in apparently unimodal, left-skewed distributions with a wavy tail. Finally, type 5 is a rather heterogeneous type of eight

poorly sorted grain-size distributions with a dominant coarse silt peak (EM4) as a common characteristic. The height of the sand peak (EM3) is variable, ranging from near-absent to almost equal to EM4.

The relative abundance of the respective end members and the derived grain-size distribution types plotted vs. their depth, next to the corresponding beds (Fig. 4), allows the characterization of the sets. Set 1 consists of only one coarse-to-fine couplet (20 cm thick) and is characterized by the predominance of silt (types 4–5). As the downward continuation of this bed is unknown, it is unclear whether set 1 is the fine top of a separate set or

Table 3. AMS radiocarbon dating results.

Laboratory ID	Depth (m)	Dated material	¹⁴ C age (uncal. a BP)	2σ calibrated age (cal. a BP)	Mean value (cal. a BP)
KIA-24818	5.115–5.145	<i>Quercus</i> sp. wood	8105±50	9256–8788	9049
KIA-24810	7.055–7.085	<i>Salix</i> sp. wood	8340±50	9480–9144	9355

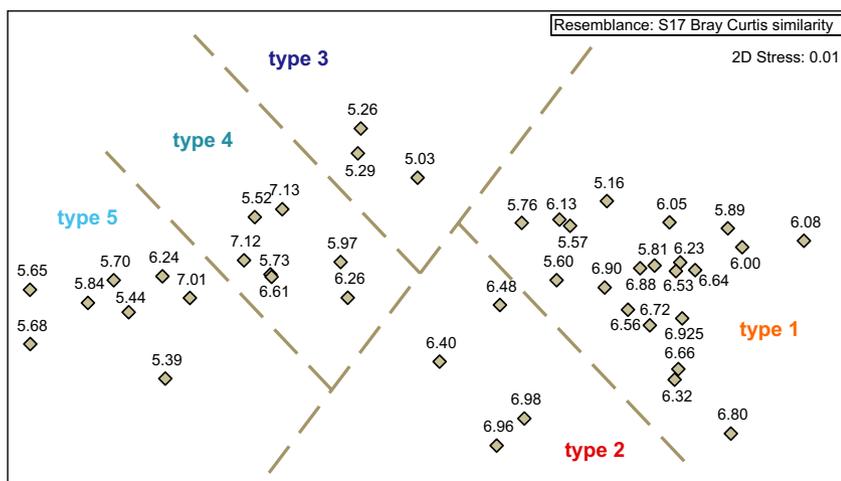


Fig. 5. MDS plot of the grain-size distributions. Labels correspond to sample depth (m). Delimitation of five types of grain-size distribution, based on this plot, is added in dashed lines. [Colour figure can be viewed at www.boreas.dk]

rather part of set 2. Set 2 is ~50 cm thick and consists mainly of fine sand (types 1–2), where beds with high mollusc content alternate with more organic-rich beds. In the upper part an organic-rich silt bed (type 4) is observed. Set 3 is 130 cm thick and can be divided into two major parts. The lower half shows dm-scale fine sand beds (types 1–2) which are very rich in molluscs and are separated by thin, silty beds (types 4–5). In the upper half the finer beds, which typically consist of (clayey) silt (type 5) with low sand addition and high organic matter content, are thicker than the coarser beds (silty fine sand, types 1–3). The coarser beds in the lower part of set 3 are often discontinuous and internally cross-stratified (Fig. 3) and lateral fining can be observed when following the set up-dip in the cross-section. Set 4 is dominated by fine sand beds (type 1) consisting of mollusc-rich fine sand and probably represents the base of a new coarse-to-fine cycle. The described succession is a repetition of inclined fining upward sand-silt couplets, as typically seen in point bars (Jackson 1981; Thomas *et al.* 1987).

The coarsest vs. mean grain sizes of each sample are plotted in a CM diagram (Fig. 7). To explore correspondence, the zones enclosing the measurements from contemporary depositional environments in the Dijle catchment (Notebaert *et al.* 2011) are added to the plot. A partial typical CM pattern appears, allowing the ranges of pelagic, uniform and graded suspension to be added (Passega 1957; Bravard & Peiry 1999). Combining these two data sets shows that all measurements from Oude-naarde Stuw roughly correspond to the scatter of point bar samples from the contemporary Dijle. The samples belonging to the same grain-size distribution type clearly form clusters in the CM plot, thus adding structure within the zone of Dijle point bar sediments. The type 1 and type 2 samples plot at the boundary between the uniform and graded suspension ranges, close to channel base deposits as sampled from the Dijle. Samples with type 3, 4 and 5

distributions correspond to material transported by uniform suspension and fit with point bar deposits from the Dijle, with type 5 samples plotting in the overlap zone with the Dijle natural levee samples.

Diatoms

All identified diatom species (Table 1) are typical of eutrophic, alkaline freshwater environments (Denys 1991). *Martyana martyi* and *Ulnaria capitata*, which make up ~30% of all counted valves, are both limnophilous aquatic species, which prefer living in a stagnant or slow-flowing water body (Fig. 8). All other diatoms are resistant to periodic water or wet subaerial conditions and to current. Different life forms are found together: bottom-dwelling species, both attached (epontic) and free-living (benthic) and tycho planktonic species, which spend part of their life cycle as benthos.

Pollen, spores and non-pollen palynomorphs

The results of the palynological analysis of 22 levels are plotted in a percentage diagram (Fig. 9). The pollen concentration is high in all samples and the preservation was moderate. Both the AP/NAP ratio and the percentages of the individual taxa show little variation between the different sample depths. The single high percentage of *Betula* at 5.16 m is probably the result of the presence in that sample of an anther, the pollen-producing part of a flower. In all other levels *Corylus avellana* is dominant (35–60%, generally higher values in the upper part), followed by *Quercus*, *Pinus* and *Ulmus*. *Betula*, *Salix* and climbers such as *Humulus* and *Hedera helix* are also nearly continuously present, but in much lower amounts. A variety of shrubs is sporadically present, such as *Cornus sanguinea*, *Viburnum opulus* type, *Sorbus* group and *Sambucus nigra* type. This combination of taxa, and

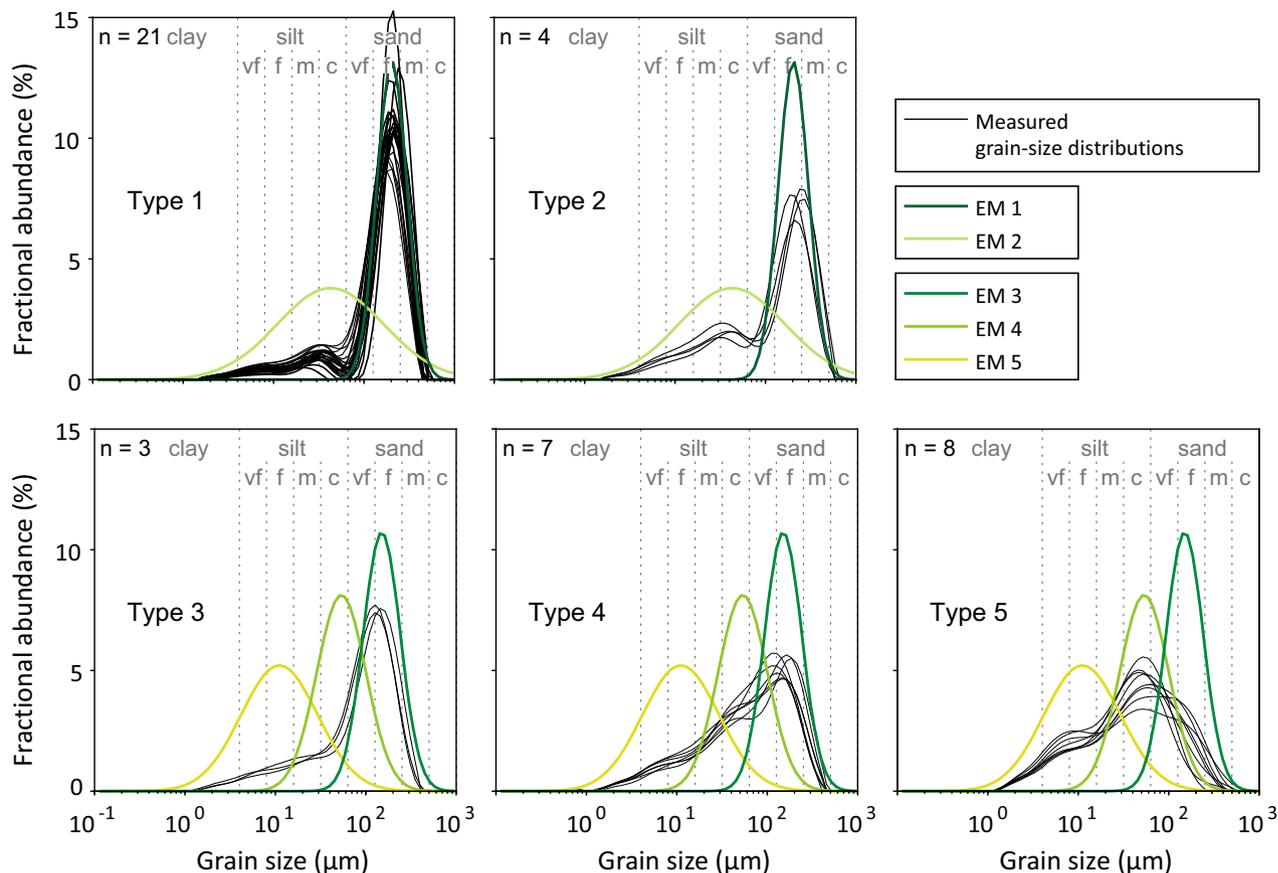


Fig. 6. Grain-size distributions (black) per type (Fig. 5), plotted with the respective sets of end members (coloured); vf = very fine; f = fine; m = medium; c = coarse. [Colour figure can be viewed at www.boreas.dk]

the absence of *Tilia* and *Alnus*, meets the description of Scheldt Basin biozone 4, which is dated between ~10.6 and ~8.6 cal. ka BP (Storme et al. 2017) and which correlates to the Boreal biozone (Verbruggen et al. 1996). A few individual pollen grains of *Cornus mas* type (including *Cornus suecica*), *Hippophae rhamnoides* and *Empetrum* (not included in Fig. 9) point to reworking of Lateglacial material rather than being relic taxa.

The herb percentages are always low (10–30%), with Poaceae undiff. as the dominant taxon, followed by Cyperaceae. Other frequently occurring taxa are Apiaceae, *Senecio* type, *Solanum dulcamara*, *Urtica dioica* type, *Artemisia* and *Filipendula*, which point to open, possibly disturbed areas. *Filipendula*, *Mentha*, *Lythrum* and *Solanum dulcamara* indicate a humid environment. The riparian vegetation is represented by *Sparganium* and *Typha*, while *Myriophyllum*, *Nuphar*, *Potamogeton* and *Pediastrum* are indicators of open water. Their frequencies are slightly lower in the upper part of the diagram. The recovered dinoflagellate cysts most likely originate from the early Eocene marine deposits incised by the Scheldt in the region upstream of the study area.

Although the pollen percentages show little overall temporal variation, some trends are visible within set 3, the clearest coarse-to-fine cycle. The *Salix* percentages

increase towards the fine top, along with – more modestly – *Humulus lupulus* and *Sambucus nigra*. The opposite trend is observed for some herb taxa (Apiaceae, *Artemisia*, *Filipendula*, *Senecio* type), aquatic plants, *Pediastrum* and *Pinus*.

Seeds and fruits

In terms of number of taxa, dryland herbs dominate over aquatics (Table 5). In terms of numbers of remains, herbs and aquatics are almost equal, while *Urtica dioica* accounts for more than half of the herb remains. Trees are almost absent (*Betula albalpendula* and *Corylus avellana*). Aquatics present (almost) throughout are *Ceratophyllum demersum* and *Potamogeton* spp. The ecological range of potential *Potamogeton* species is too broad to pinpoint to a specific environment, but *Ceratophyllum demersum* is a strong indicator for stagnant or slowly running water with plenty of nutrients. Other aquatics present are *Alisma plantago-aquaticallanceolatum*, *Nuphar luteum* and probably *Sparganium* sp. The identified herbs are mostly species occurring in nutrient-rich wet woodland and/or nutrient-rich riparian vegetation (*Lycopus europaeus*, *Lythrum salicaria*, *Myosoton aquaticum*/*Stellaria nemorum*, *Oenanthe aquatica*, *Ranunculus sceleratus*, *Solanum*

Table 4. End member characteristics.

End member	Clay (%) <8 μm	Silt (%) 8–63 μm	Sand (%) >63 μm	Main fraction	Mode (μm)	Deposition during
EM1	0.0	0.1	99.9	Fine sand	211	Peak discharge
EM2	3.7	58.0	38.3	Coarse silt	43	Lower-energy flow
EM3	0.0	3.2	96.8	Fine sand	153	Peak discharge
EM4	0.0	59.4	40.6	Coarse silt	55	Lower-energy flow
EM5	13.5	82.7	3.8	Fine silt	11	Calm period

dulcamara, *Urtica dioica*). Most species thrive well in both vegetation types. A riparian position is also assumed for *Chenopodium album*, *Chenopodium polyspermum*, *Polygonum lapathifolium* and *Matricaria maritima*, nowadays mostly known as weeds on arable land, but also growing in nutrient-rich riparian environments. Notwithstanding their somewhat broader ecology in flood-plains *Chenopodium album*, *Chenopodium polyspermum*, *Lythrum salicaria*, *Oenanthe aquatica*, *Polygonum lapathifolium*, *Ranunculus sceleratus* and *Alisma plantago-aquatica* could fit into one habitat type: they are indicative of pioneering vegetation growing on nitrogen-rich and open soil along dynamic rivers, where the deposition of sediment, erosion and/or long inundations hamper the long further development of the vegetation (Natura 2000 habitat type 3270; Decler 2007). This indicates that vegetation development on the point bar itself was possible during calmer periods.

Molluscs

The two mollusc-rich samples reflect a similar environment (Fig. 10): the vast majority of the identified species

and individuals are of aquatic origin. Drought-tolerant and permanent water taxa are equally represented. There was stagnant or slow-flowing water, as well as faster-flowing water, but individuals assigned to the first group prevail. The (relatively few) terrestrial species indicate damp, marshy habitats in the vicinity. These terrestrial molluscs may have been responsible for many of the bioturbation structures in the cross-section (Pryor 1967).

Radiocarbon dating

AMS radiocarbon dating of the top and the base of the succession reveals mean values of 9355 and 9049 cal. a BP, which point to an Early Holocene age (Table 3). This age is in accordance with the obtained biostratigraphical position. With only ~300 years difference between the means, the ages are close to each other and in stratigraphical order. The deposition of these sediments must have been rather fast, with a sedimentation rate of at least 28 cm 100 a⁻¹, based on the most distant ages of the 2 sigma calibrated age ranges or ~63 cm 100 a⁻¹, based on the mean values of these ranges.

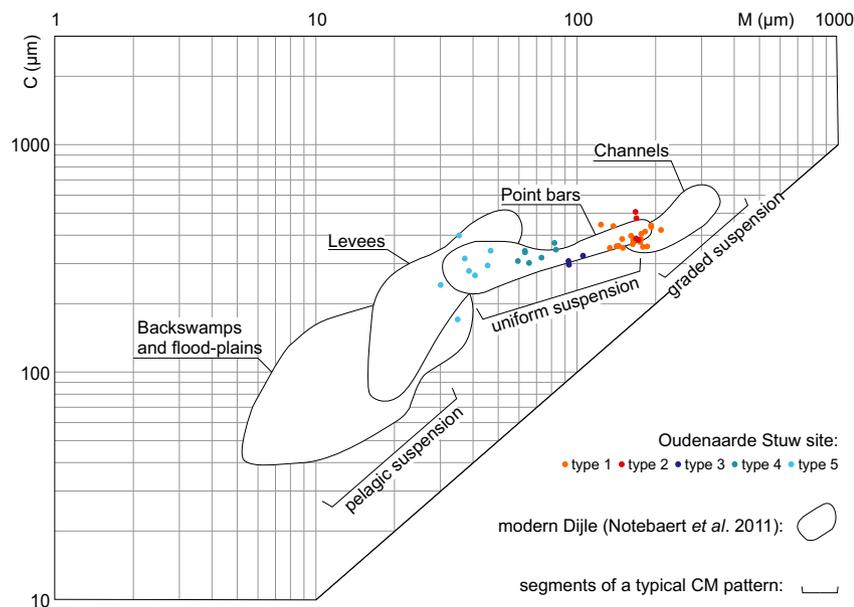


Fig. 7. CM diagram with the grain-size measurements from Oudenaarde plotted as dots (types 1–5, Fig. 5). Additionally, zones with measurements from different bedforms of the modern Dijle are outlined (Notebaert et al. 2011) and segments of a typical CM pattern (Passega 1957) are indicated with their corresponding transport processes. [Colour figure can be viewed at www.boreas.dk]

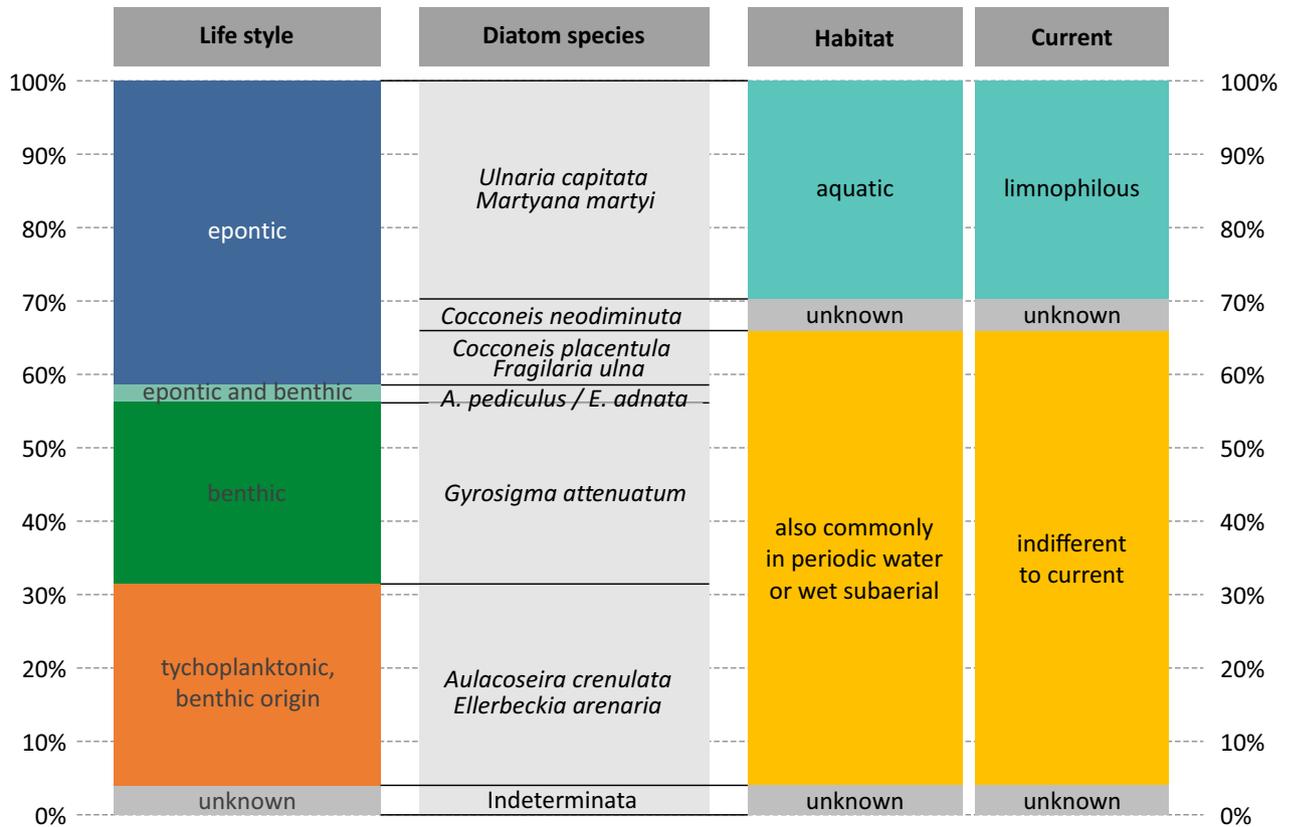


Fig. 8. Ecological characteristics of the diatom species at 5.49 m (based on codes by Denys (1991) and Van Dam *et al.* (1994)). [Colour figure can be viewed at www.boreas.dk]

Discussion

The fluvial environment

The interpretation of the inclined sets of fining-upward sand-silt couplets at the Oudenaarde Stuw site as point bar deposits implies the presence of a migrating river that transported silt to fine sand. One meander at the studied location created multiple, successive point bars, which may have slightly eroded each other, each of them consisting of a fining-up succession. This interpretation fits with the observed correspondence in the CM plot between the samples from Oudenaarde Stuw and the modern point bar samples from the Dijle catchment (780 km²) (Notebaert *et al.* 2011). The maximum set thickness of 130 cm points to a small parent channel (bankfull depth <3 m, Allen 1965), which is similar to the channel dimensions of the present-day Dijle (~3 m) and much smaller than the Lateglacial Scheldt in whose infill the Early Holocene channel is incised. This narrowed-down activity of the Early Holocene channel, compared to the Lateglacial, is presumably owing to the forests that had established in the valley floors and caused reduced discharge and sediment input. The relatively fine grain sizes point to a low-energy depositional environment with fine sand only being transported during peak discharges and silt during calmer

periods. There may even have been episodes without significant flow in the channel. The variations in grain size are thus interpreted as the result of hydrodynamic sorting during transport by the stream, as also reflected in the segments of the CM diagram (Fig. 7).

The aquatic ecological indicators (*Ceratophyllum demersum*, diatoms, aquatic molluscs) point to standing to slowly running, eutrophic water. Some of the mollusc and diatom species tolerate stronger flow, but do not require it. Nevertheless, the presence of temporary more energetic flow can be deduced from the presence of fine sand deposits transported in graded suspension. The co-existence of diatoms and molluscs with different flow velocity preferences can be explained by within-channel variation of stream intensity in the meandering stream. Probably periods of quiet flow were interrupted by possibly seasonal bankfull events, responsible for the deposition of the fine sand beds and the supply of a mix of aquatic organisms, living and reworked, from various subenvironments within the stream. Between these peak discharges, occasional high water would only supply silt-sized material as the stream was not strong enough to transport sand onto the point bar. During these calmer periods, vegetation development was possible, both subaquatic and on the emerged part of the point bar, and caused the higher organic matter content in the silt beds.

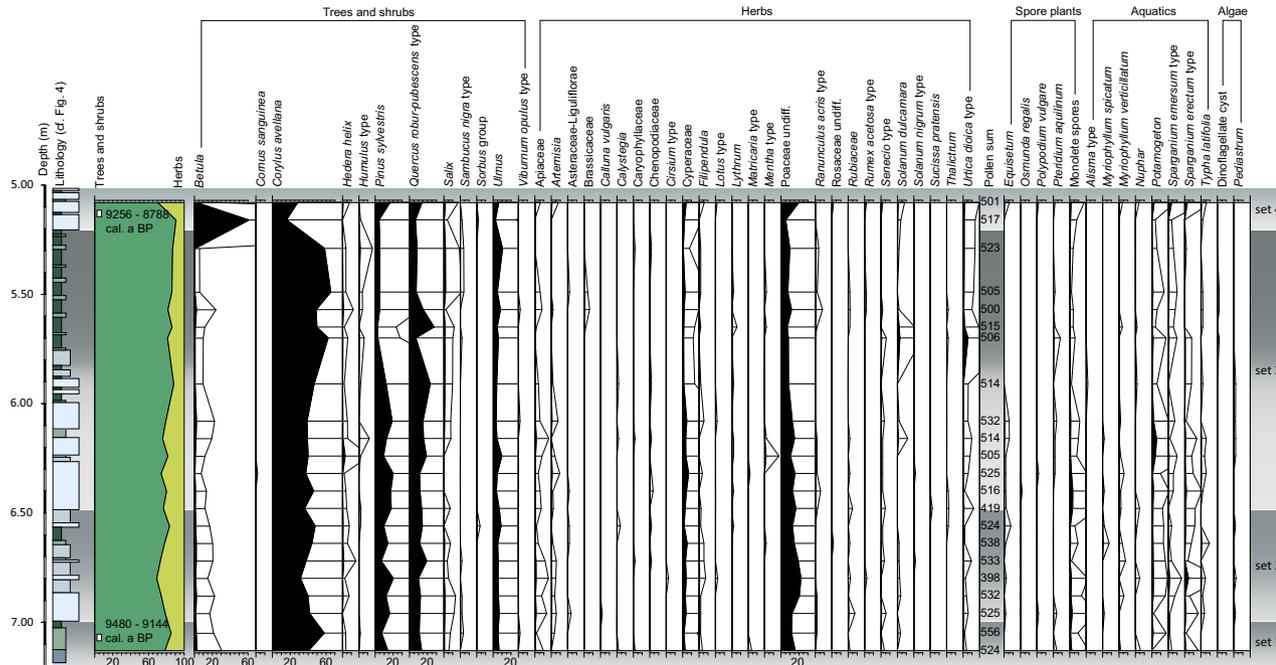


Fig. 9. Percentage pollen diagram. Exaggeration 10 \times . Dates are 2 σ calibrated age ranges. [Colour figure can be viewed at www.boreas.dk]

Only a small part of the structures built by this river system is represented in the cross-section: the overbank fine deposits and channel-fill were not observed and the base and top of the point bar deposit are not reached due to the cross-section being part of an archaeological rescue excavation with limited time and spatial extent. It is therefore impossible to reconstruct the characteristics of the parent palaeochannel in more detail.

The valley floor terrestrial environment

The local vegetation on the point bar appears to be dominated by herbs, especially nitrophilous species, which are typical of the wash zone and as understorey in wet woodlands or their margins. These vegetation types must have contrasted with the surrounding landscape outside the river valley, which consisted of a dense forest, dominated by *Corylus* and *Quercus* as indicated by the results of the pollen analysis.

The near-absence of seeds from trees in the samples suggests that the point bar itself was not forested. However, pollen (up to 2.0%, Fig. 9) and a wood fragment (Table 3) of *Salix* indicate the possibility of local willow thickets, which are flood tolerant and typical of alluvial forests. Herbs such as *Solanum dulcamara* and *Urtica dioica* are common in such an environment (Weeda *et al.* 1985–1994). Indeed, *Salix* has been recognized as an important element in the valley vegetation of the Early Holocene Scheldt Basin, although it is generally under-represented in pollen counts due to its poor pollen production and dispersal, especially in the larger valleys with a more regional signal (Storme *et al.* 2017). Seeds are usually not recovered in sieve residues and wood was not

systematically studied here. The absence of botanical macro-remains of *Salix* therefore does not exclude its presence in the local vegetation.

The shift in the pollen percentages observed within set 3 may partly be the result of hydrodynamic sorting of palynomorphs during transport (Catto 1985), corresponding to the observed shift in grain size. By contrast, the ecological preferences of the concerned taxa indicate that most of the variation can be explained as a local vegetation shift, responding to the changing physical environment linked to the changing environmental conditions as seen in the sedimentological analysis. The higher percentages of herbs in the lower half of set 3, which include possible pioneer taxa colonizing soil disturbed by river dynamics, point to a rather open vegetation cover on the point bar. The parallel higher percentages of aquatic plants and *Pediastrum* algae indicate an important river supply. The same may be true for *Pinus*, which is a well floating pollen type that can be transported by water over large distances. By contrast, the observed increase of *Salix*, *Humulus lupulus* and *Sambucus nigra* pollen in the top of set 3 is indicative of alluvial forest development. Together, these trends indicate a succession from an open herb-dominated, possibly temporarily barren point bar when the river dynamics were too intense to allow tree growth, to a more closed alluvial forest as the flood frequencies and intensities decreased locally.

Similar vegetation successions in modern meandering river valleys are described for the Volga in west Russia (Middelkoop *et al.* 2005), the Allier in France (Geerling *et al.* 2006) and the Waal in the Netherlands (Geerling *et al.* 2008). These studies show that natural succession

Table 5. Abundances of seeds and fruits (mesh size 0.25 mm; volume 30 mL; .. = whole specimens/fragments).

Seeds and fruits	Depth (m)						
	7.01	6.98	6.66	6.29	5.89	5.57	5.26
Trees							
<i>Betula albalpendula</i>	–	–	–	–	–	–	1
<i>Corylus avellana</i>	–	0/1	0/1	–	–	–	–
Herbs							
Apiaceae	0/1	–	–	–	–	–	–
<i>Carex</i> spp.	–	1	1	–	0/1	–	–
<i>Chenopodium album</i>	–	–	1	–	–	–	–
<i>Chenopodium polyspermum</i>	–	–	–	–	–	1	–
<i>Lycopus europaeus</i>	–	–	–	–	–	–	1
<i>Lythrum salicaria</i>	–	–	1	–	–	1	1
<i>Matricaria maritima</i>	–	–	–	–	1	–	–
<i>Mentha</i> sp.	1	–	1	–	–	–	1
<i>Myosoton aquaticum</i>	2	–	1	1	1	2	–
<i>Stellaria nemorum</i>	–	–	–	–	–	–	–
<i>Oenanthe aquatica</i>	–	–	–	–	–	–	2
<i>Polygonum lapathifolium</i>	–	–	1	–	–	1	–
<i>Ranunculus sceleratus</i>	2	–	–	–	1	–	–
<i>Solanum dulcamara</i>	–	–	–	–	1	–	1
<i>Solanum dulcamara/nigrum</i>	–	–	–	–	–	0/1	–
<i>Stachys</i> sp.	–	–	–	–	–	1	–
<i>Urtica dioica</i>	2	–	6	–	3	5	28
Aquatics							
<i>Alisma plantago-aquaticum/lanceolatum</i> fruit	–	–	–	–	–	1	–
<i>Alisma</i> sp.	–	–	1	–	–	–	–
<i>Ceratophyllum demersum</i>	0/1	–	3/7	2/4	0/7	1	1/1
<i>Nuphar luteum</i>	–	–	0/1	–	–	–	1
<i>Nuphar</i> sp.	–	–	–	–	0/1	0/6	–
<i>Potamogeton</i> spp.	5/1	4	2	4	2/1	1/2	2/5
cf. <i>Sparganium</i> sp.	–	–	–	–	–	–	0/1
Indeterminata	1	2	–	–	–	–	3

will eventually end in a climax forest if a location was to rise above flood level by accretion. However, in the studied case a return to more dynamic conditions, as seen in set 4, probably led to rejuvenation of the vegetation.

The comparison of the pollen assemblages of the study site to those of contemporaneous peaty deposits (biozone SB4) in the nearby residual channel at Ename Castrum (Storme et al. 2017) reveals some differences between the respective environments: a flood-plain with clastic point bar accretion and a channel-fill with carr vegetation. *Hedera helix*, *Humulus lupulus* and *Sambucus nigra* are more important on the point bar, and reflect rather open and light-penetrating conditions, typical of alluvial forests (Schnitzler 1994). *Salix* by contrast is more abundant on the peaty substrate of Ename Castrum, probably forming the tree layer of a carr forest before being largely outcompeted by *Alnus* in this type of environment from ~8.6 cal. ka BP onwards. Herbs such as Poaceae, *Filipendula*, *Solanum dulcamara* and *Urtica*

show considerably higher percentages in the point bar and are in agreement with a riparian or open wet woodland ecology. Some taxa that are absent in the peat deposits are present in low percentages in the point bar deposits and generally indicate wet or disturbed conditions (*Lythrum*, *Mentha* type, *Solanum nigrum* type, *Succisa pratensis*, *Thalictrum*). By contrast, Cyperaceae, *Sparganium* and *Equisetum* are found much more frequently in the peat and characterize the undergrowth of the carr vegetation. Open water aquatic plants are better represented in the point bar deposits, representing a pollen influx from the stream during floods.

Evidence of fluvial activity during the Early Holocene

The Early Holocene Scheldt valley, after the Lateglacial-to-Holocene transition, has long been regarded as a marshy area without significant fluvial activity such as erosion and the deposition of minerogenic sediments (Kiden 1991; Huybrechts & Verbruggen 1994; Huybrechts 1999). However, several indirect indications for localized Early Holocene fluvial activity (flow and sediment transport) within the confines of the Lateglacial palaeochannel of the Lower Scheldt have been reported recently by Bogemans et al. (2012) and Meylemans et al. (2013), and described as ‘zones of fine clastic sediments, interrupting the peat growth’. In the Dijle valley (eastern Scheldt Basin, Belgium) deposits of fine to medium sand in coarse fluvial cross-bedding are described, intercalated with peaty silt layers that increase upward in number and thickness (De Smedt 1973). These deposits show Early to Middle Holocene pollen spectra characteristic of the Boreal to Atlantic biozones *sensu* Verbruggen et al. (1996) and are interpreted as the infill of a meandering channel (De Smedt 1973; Vandenberghe & de Smedt 1979). This channel with low transport capacity would have been incised during the Early Holocene and gradually filled due to a decreasing flow rate. This description seems to be the only unequivocal account of Early Holocene active meandering in the Scheldt Basin, well after the Pleistocene–Holocene transition, and comparable to the deposits from Oudenaarde Stuw. Increased river activity in the Middle and Late Holocene related to human impact is beyond the scope of this discussion.

Outside the Scheldt Basin, in the majority of west and central European river systems this same broad picture is seen, with the Early Holocene as a stable phase dominated by organic sedimentation, at least as long as one sticks to river reaches with feeding catchments of the same scale (Gibbard & Lewin 2002; Notebaert & Verstraeten 2010).

When comparing to river systems of the same age and dimensions in northwest Europe, only a few studies mention some kind of fluvial activity. In the Mark valley (Rhine-Meuse Basin, Belgium and The Netherlands) renewed fluvial activity is recognized during the middle of the Boreal, based on a gradual increase of the clastic content in the peat. This was interpreted as the

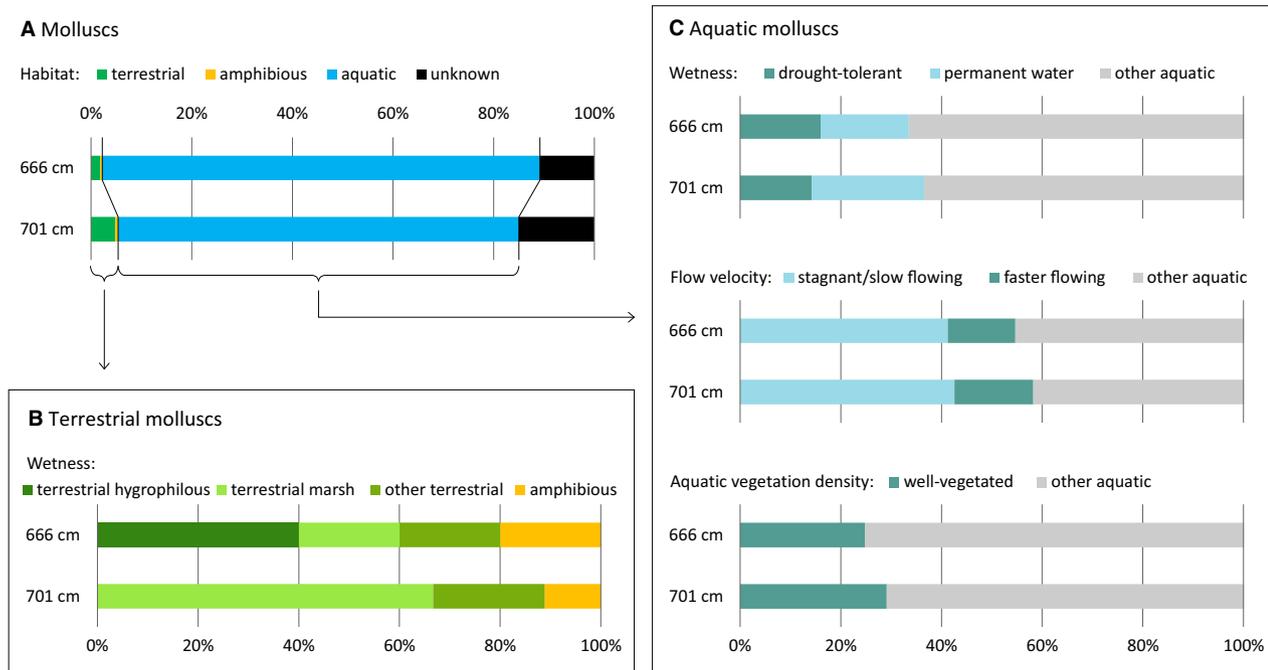


Fig. 10. Ecological characteristics of the mollusc taxa. A. Abundance of habitat types. B. Subdivisions of molluscs from terrestrial habitat. C. Subdivisions of molluscs from aquatic habitat. [Colour figure can be viewed at www.boreas.dk]

re-establishment of a regular longitudinal river profile without renewed vertical erosion (Vandenberghé *et al.* 1984). In the Somme basin (France), a disappearance of channelling is described for the Early Holocene, except for channels bordering the marsh, which migrated progressively towards the foot of the valley slope and resulted in diachronic deposits of organic-rich loam along the valley edges (Antoine 1997). However, in the Selle valley (Somme Basin, France), evidence of a single channel is found, which was filled with bedded organic silt with plant debris and aquatic molluscs during the Early Holocene (Boreal biozone) (Antoine 1995). This contrasting observation was linked by the latter author to a steeper slope of the longitudinal profile. Also in the Mue valley (Seulles Basin, France), grey silts are interpreted to correspond to overbank deposits related to a meandering system (Lespez *et al.* 2008).

Although these accounts do not represent the clear evidence of meander erosion and migration described for the Dijle (De Smedt 1973) and presented in this study for the Upper Scheldt, they do indicate transport of clastic material through well-defined channels during the Early Holocene, as opposed to the general idea of a marsh with diffuse flow. Such deviations from the general pattern can be a response of the fluvial system to the exceedance of geomorphic thresholds during short periods of climate change (Schumm 1979; Gibbard & Lewin 2002). The period of point bar formation in the Scheldt valley at Oudenaarde corresponds to the 9.3 ka BP cooling event, dated between 9310 and 9180 cal. a BP (Rasmussen *et al.* 2014). This is one of a few abrupt and short-lived climatic

anomalies in the Early Holocene that were triggered by changes in oceanic circulation pattern in the North Atlantic region (Yu *et al.* 2010; Hou *et al.* 2011). In northern Europe, these are reflected in lake sediment records (Korhola *et al.* 2002; Marshall *et al.* 2007; Lang *et al.* 2010) and evidence of Mesolithic sociocultural change has been linked to the 9.3 ka BP event (Robinson *et al.* 2013; Crombé 2018). However, evidence of fluvial or vegetational response to this cooling event is scarce and difficult to obtain due to the required high resolution for the detection of such short-lived events (Crombé 2018). Moreover, contemporaneity does not necessarily imply a causal relationship.

Nevertheless, a possible cause for the point bar sediments from Oudenaarde related to the 9.3 ka BP event is proposed. The possibility has been raised that the prevailing pines were affected by the cooling, leading to increased desiccation. This made the forests more vulnerable to burning, a process which locally triggered slope instability (Dreibrodt *et al.* 2010; Crombé 2018; P. Crombé, L. Allemeersch, K. Aluwé, F. Cruz, K. Deforce, J. Mikkelsen, J. Sergeant, A. Storme & H. Vandendriessche, unpublished data). If this was the case higher up in the Scheldt catchment, this may have resulted in increased sediment transport and fluvial activity in the middle reach. The lack of significant slopes downstream of Oudenaarde would explain the absence of similar bedforms in the Lower Scheldt valley.

It is however unlikely that this reach of the Scheldt Basin would be an exception in terms of river behaviour and valley morphology during the given period. It is

expected that fluvial activity took place in the majority of this type of river during the Early Holocene, at least during cooler periods, such as the Preboreal oscillation and the 9.3 and 8.2 ka BP events, in regions with similar vegetation and sufficiently steep slopes. Nevertheless, the resulting sedimentary archives, such as point bar deposits or natural levees, are seldom observed. The scarcity of such evidence is probably the result of the self-destructing nature of migrating river systems, especially in quite narrow valleys (Ghinassi *et al.* 2016), which is the case in many of the northwest European Early Holocene lowland rivers, accumulating within the confines of their Lateglacial channels. However, the detection of point bar deposits, with their limited lateral and longitudinal extension, is usually hampered by the standard survey practices used in alluvial geomorphological investigations, including hand coring in transects with a spacing of several tens of metres to often over 100 m (e.g. Lespez *et al.* 2008; Makaske *et al.* 2008; Bogemans *et al.* 2012). It may not be a coincidence that this type of deposit is here described in a cross-section of an excavation pit, which allows greater lateral continuity. Future studies in a denser grid or in excavations may provide more opportunities to study this kind of limited-size bedform and shed more light on the fluvial systems of northwest European rivers during the Early Holocene and their possible response to climate oscillations.

Conclusions

The discovery at the Oudenaarde Stuw site of an Early Holocene channel offers a rare opportunity to study little-known aspects of river evolution, including sedimentological processes and ecology of the aquatic and terrestrial environments.

The inclined heterolithic strata are interpreted as point bar deposits created by a small, generally low-energy, Early Holocene meandering river, which was subject to variations in stream intensity during the short period of deposition. These results contrast with the prevailing view of a stable phase with diffuse flow within a broad marsh in the medium-sized lowland rivers of northwest Europe. It is suggested that the occurrence of these fluvial deposits is related to the 9.3 ka BP cooling event. A possible mechanism involves more frequent pine forest fires, causing slope instability in the catchment, leading to increased sediment transport and hence the formation of bedforms related to migrating meandering rivers.

The scarcity of this type of evidence is probably caused by the self-destructing nature of migrating river systems and by the low chance of discovery due to the small size of these Early Holocene river systems compared to the very wide Lateglacial valleys.

This study documents at least two fining-upwards sets, expressed by the increasing thickness of finer beds towards the top and the decreasing grain size of both finer and coarser beds. Diatoms, aquatic molluscs and botanic

remains of aquatics reflect the various subenvironments within the meandering stream, ranging from sheltered zones to higher flow velocities. Vegetation development on the point bar was at least temporarily possible and shows a succession from herbaceous riparian vegetation to a rather open willow-dominated alluvial forest during the deposition of a fining upwards set.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at <http://www.boreas.dk>.

Table S1. Grain-size distribution (%).