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A medieval embankment near the lost harbour of Mude (Zeeland, the Netherlands): A palaeoenvironmental reconstruction based on palynology and diatom analysis

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ABSTRACT

Mude, known today as Sint Anna ter Muiden (Zeeland, the Netherlands), was one of the outports of Bruges (northern Belgium) that developed along the Zwin tidal inlet during medieval times. The coastal plain of the medieval County of Flanders became embanked via the massive construction of dikes. Yet, little is known about the environmental conditions in which the medieval Zwin harbour region developed. Recent archaeological research allowed us to carry out the first environmental study of a complete sequence ranging from natural deposits to a raised soil associated with an embankment in the coastal plain using palynological and diatom analyses. The presence of tidal flat deposits influenced by a direct marine influx was confirmed. Sods from different origins, tidal flat deposits and a mixture of sediments and anthropogenic waste, were used to build an embankment. A layer holding a large number of shells was deposited on top of the sods likely for levelling and water management. The palynological assemblages from the sods and the shell-rich layer confirm human activity in an embanked area, such as the use of hemp for rope making and the digging of peat for fuel. Cultivated plants were grown in the area, while figs were imported from the Mediterranean region. The diatoms point to local brackish-freshwater conditions, indicating that the embankment was outside of the daily tidal reach by a tidal channel. A cultural soil developed on top of the embankment that was possibly used as a pathway for sheep herding, in a region famous for its wool production, while the signal of crops suggests the active use of the land in the vicinity.

1. Introduction

The North Sea coastal regions stretching from northern France to Denmark, including the southern and eastern shores of the United Kingdom, were similarly transformed during the medieval period, albeit distinct social agencies shaped these different societies (Thoen et al., 2013; Soens et al., 2014). Large-scale reclamation and embankments altered natural saltmarshes and mudflats, which eventually led to artificial polders that still characterise Europe's most 'open' landscape today (Soens et al., 2014). The coastal plain of what is now called West

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Flanders in Belgium and Zeelandic-Flanders in the southern Netherlands were both part of the medieval County of Flanders. After 800 CE, tidal areas in this area gradually silted up and saltmarshes expanded (Vos, 2015). From the tenth century onward, the region of Flanders underwent important societal and environmental changes (Tys, 2013; Trachet, 2016). The Counts of Flanders held official power and started to reclaim the coastal wetlands for financial and political purposes. By the thirteenth century, the comital estates developed the necessary technical skills to shape the layout of the coastal region, of which large parts were embanked through the construction of dikes and drained via ditches (Tys, 2013; Trachet et al., 2015). In the coastal plains bordering the North Sea, embankment generally started with low dikes and shallow ditches, which protected arable land from floods only during the summer, while higher surges in the winter brought an ideal fertile layer of marine sediments (Behre, 2002; Tebrake, 2002; Thoen et al., 2013; Soens et al., 2014; Nieuwhof et al., 2019). But by the thirteenth century, the dikes were raised and interconnected to assure continuous protection of the land behind them.

However, the massive construction of hydraulic structures had unpredicted ecological repercussions. The reduced water storage capacity eventually led to higher storm-surge level and flood disasters (Vos, 2015; Trachet, 2016), such as for instance the storm surge of CE 1134, when dikes were breached in large parts of the southern North Sea area and floods scoured out a large tidal inlet (later named the Zwin) in the direction of Bruges. This initial catastrophe quickly turned into an economic opportunity as the Zwin inlet became dotted with a series of outports, one of them being the harbour of Mude (Fig. 1, Trachet et al., 2015). Through this network of ports, the city of Bruges developed into an international trade hub and "cradle of capitalism" during the late Middle Ages (Murray, 2005; Brown and Dumolyn, 2018). Political and economic factors, in combination with the silting up of the tidal Zwin inlet, resulted in the eventual downfall of Bruges as an economic centre in the sixteenth century. Deprived of their function and an easy access to the sea, the harbours shrunk from cities into hamlets or even disappeared entirely from the landscape.

This paper aims to contribute to the environmental evolution of the medieval Zwin harbour region by reconstructing the ecological palaeoenvironment through palynology and diatom analysis. Undisturbed natural sediment deposits are traditionally studied for palynology, but these natural deposits are often absent in the uppermost part of the geological record in settlement areas. In that case, palaeoenvironmental research with microfossils relies on low-lying buried archaeological features, such as wells and cesspits (Deforce, 2020). Dikes and other structures such as burial and dwelling mounds, on the other hand, are positive relief elements and are therefore susceptible to oxidation and erosion (Lascaris and de Kraker, 2013). They can also occur buried through renewed sedimentation or partial destruction. Palynological analysis was previously demonstrated to be successful on elevated features such as burial mounds (Andersen, 1993; Collis et al., 1996).

We sought to determine whether elevated features in the coastal landscape are useful for providing palaeoenvironmental information. Palynological and diatom analyses were already carried out on sediments from a Roman dike and a dwelling mound at Stene situated along the Belgian coast, ca. 30 km southwest Mude (Demey et al., 2013). At Mude, a comparative analysis of the terrestrial and aquatic records of palynomorphs and diatoms was carried out on the natural sediments and

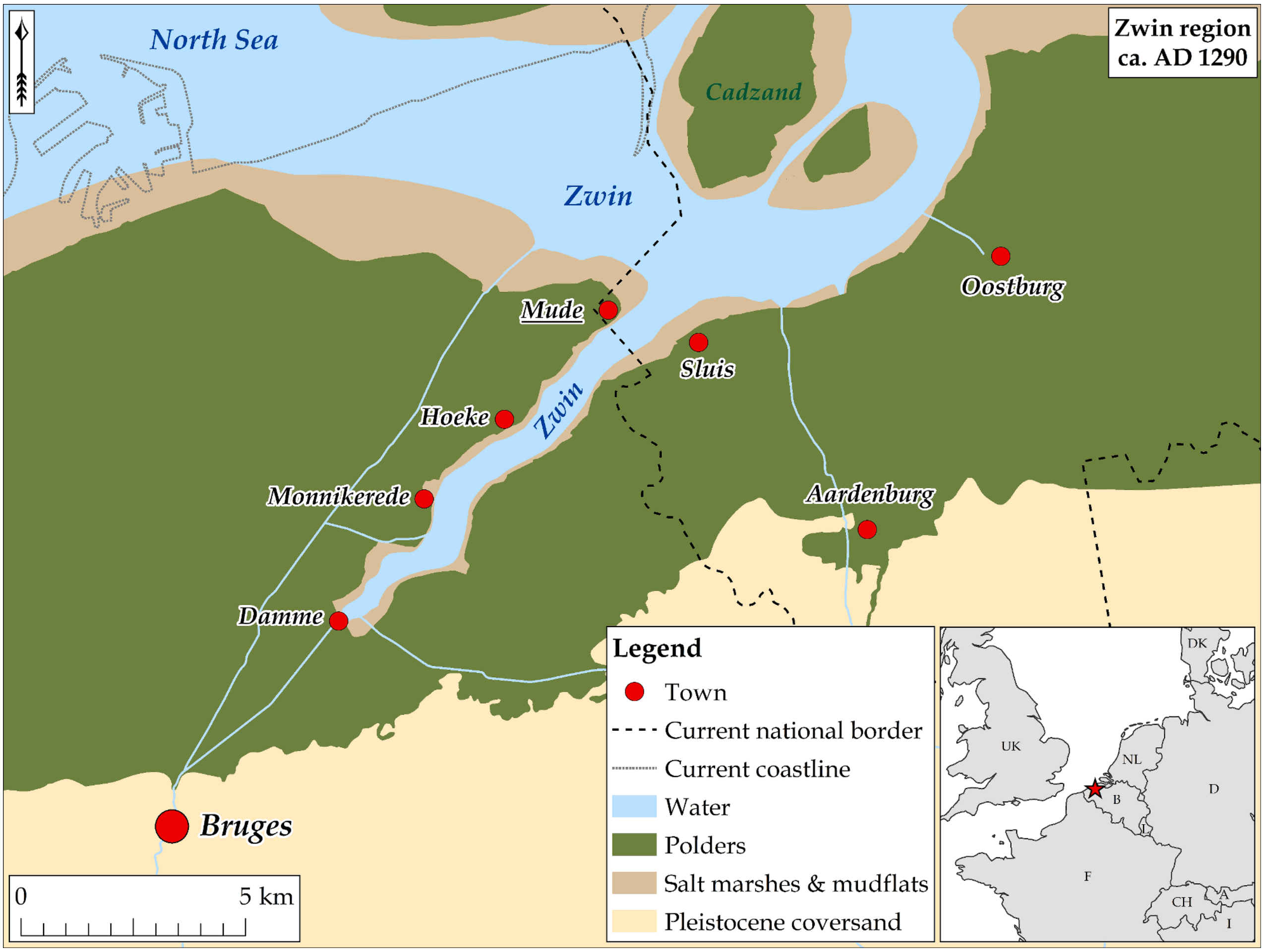

Fig. 1. Reconstruction of the Zwin region *c.* 1290 CE, with a projection of the current coastline and state borders.

the deposits used for the construction of an embankment. The results contribute to our understanding of human activity in an area where embankment took place and furnish insights into the local and regional palaeoecological landscapes.

2. Study area

Sint Anna ter Muiden is a village in the Dutch province of Zeeland in the southwestern part of the Netherlands of which the largest part of the landscape was formed under the influence of the sea (Vos, 2015). However, the current landscape is not a natural tidal landscape but is the result of an interaction of natural and anthropogenic processes. Human influence on natural processes in the region started in the Roman period and increased from the Middle Ages onward (Vos, 2015; Bogemans et al., 2024).

Sint Anna ter Muiden was known in medieval times as Mude. Its impressive church, its topography determined by centuries of embankment and land reclamation, and the many ballast stones that are reused in the pavement (De Clercq et al., 2017), are reminiscent of its bustling past as a harbour town. Whereas the other Zwin harbours of Damme, Hoeke, Monnikerede, and Sluis (Fig. 1) have been thoroughly studied archaeologically during the past years (Leloup and Vannieuwenhuyze, 2013; Trachet et al., 2017a, 2017b; Leloup, 2018; De Clercq et al., 2020), this is less so for the town of Mude, which hardly received any attention. The most relevant publications all date from the nineteenth century (see discussion Dillen, 2022).

The name *Mude* could refer to 'mudflat' or 'muddy area' pointing to a place near the mudflats of the Zwin estuary, or 'mouth' meaning a place at or near the mouth of the Zwin (de Langhe, 1992). Like many of Bruges' harbours such as Monnikerede and Damme (Fig. 1), Mude likely started as a fishing settlement (Degryse, 1944; De Clercq et al., 2020). The area became embanked and known as the Greveningenpolder sometime between the presumed origin of the Zwin in CE 1134 (Verhulst, 1959; Ryckaert, 1989) and the first historical reference of Mude in CE 1213 as *la Mue* in the context of a naval battle between the French and English fleet in the mouth of the Zwin inlet (Dillen, 2022). In 1242, the settlement had already obtained urban privileges which reflected Mude's demographic and economic importance. Home of the water bailiff, the town played a key role in regulating the everyday life on the Zwin and in mediating in various conflicts (Dillen, 2022). However, its relevance clearly decreased by the fourteenth century, most likely the result of profound local environmental changes and the growing importance of the neighbouring harbour of Sluis on the opposite side of the Zwin (Fig. 1). While historians have started to carve out the institutional role of Mude by investigating the application of criminal justice by the water bailiff (Dillen, 2022), much remains to be known about its origins, the environmental conditions in which it grew, and factors contributing to its decline.

3. Material

An archaeological excavation on a construction site, carried out in 2019 and 2021 by Artefact! in the Anworpstraat (Fig. 2), exposed for the first time a section through a raised soil, probably an embankment on the left bank of the Zwin channel. Three sample boxes for palynological and diatom analysis were taken from two profiles. In profile A (Fig. 3),

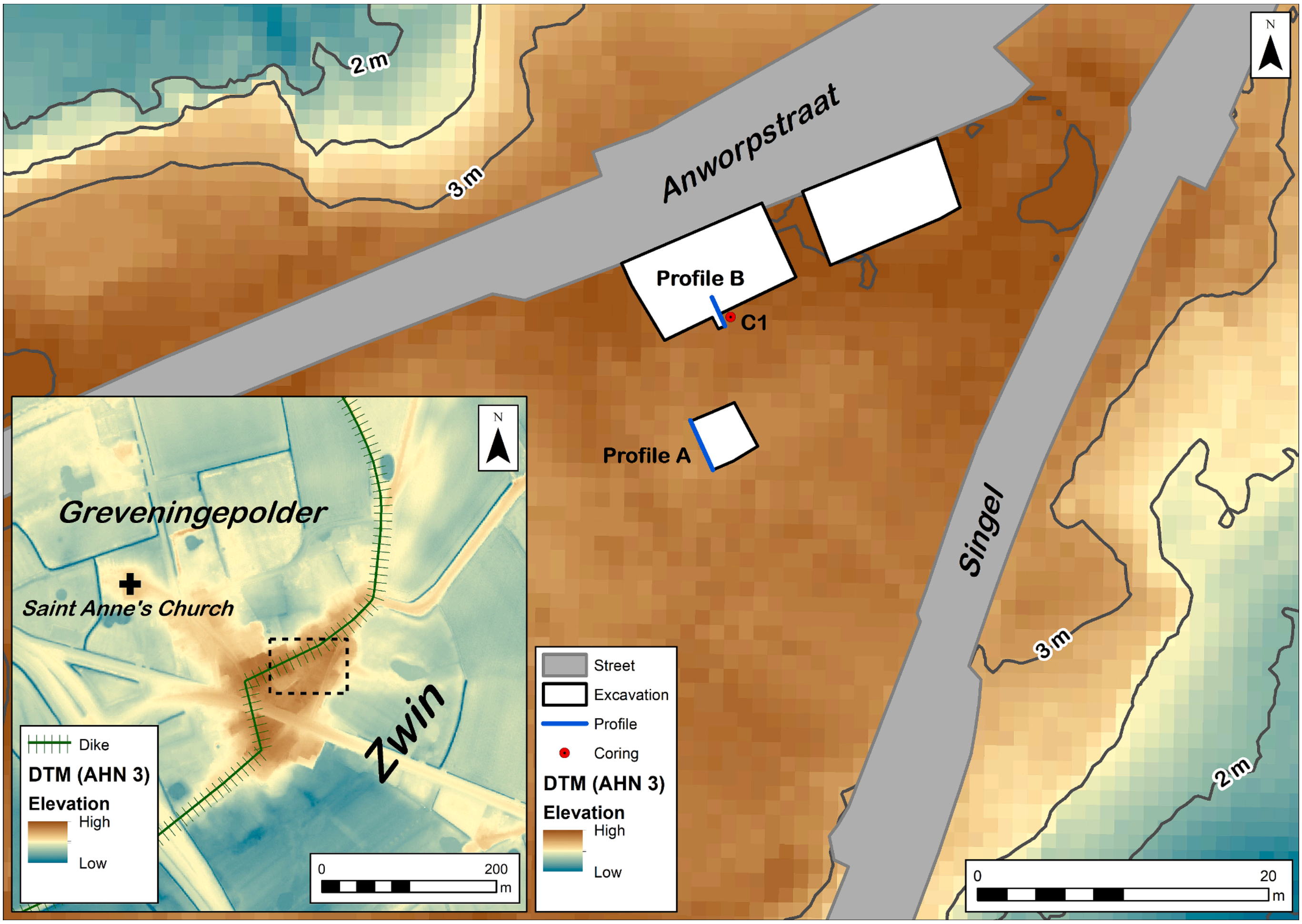

Fig. 2. Location of profiles A and B, and core C1 in the village of Sint Anna ter Muiden.

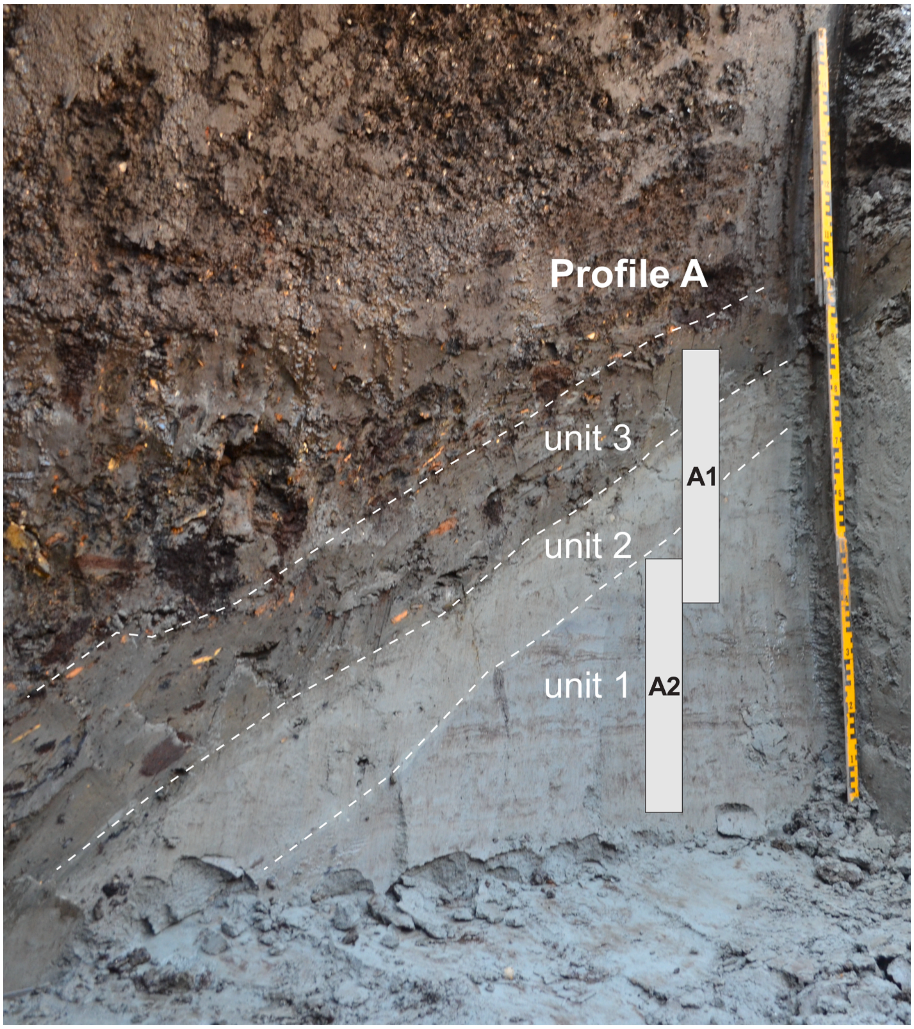

Fig. 3. Profile A displaying units 1–3 in sample boxes A1-A2.

the sample boxes A1-A2 (−0.16 to + 0.71 m NAP, NAP refers to the Dutch Ordnance Datum; equivalent to the mean sea level) should hold the evolution of a natural environment (units 1 and 2) into the anthropogenic unit 3. In profile B (Fig. 4), sample box B1 (+2.52 to + 3.02 m NAP) was taken in the top part of the raised soil (units 4, 5, and 6). Core C1 was taken during the archaeological fieldwork and holds organic matter that was intercalated in natural sand deposits. The earliest archaeological finds are dated to the thirteenth-fourteenth century on top of unit 3 (profile A), while unit 5 (profile B) is dated to the 1300 s based on associated ceramics.

A total of 33 subsamples (21 subsamples in profile A and 12 subsamples in profile B) were taken every four centimetres in the sample boxes and processed for palynological and diatom analyses (Fig. 5). The organic matter in core C1 was also studied for palynology. Only unit 3 holds suitable material for botanical macroremains analysis.

4. Methods

4.1. Palynological analysis

About 1 cm^3 of each subsample was macerated following standard pollen preparation procedures (Moore et al., 1991), including HCl, KOH and HF treatment and acetolysis. The pollen concentration was calculated through the addition of *Lycopodium* tablets (Appendix 1). The identification and nomenclature of the pollen and spores follows Moore et al., (1991) and Beug (2004), while non-pollen palynomorphs (NPPs) follow Miola (2012) and references therein. The pollen sum groups all regional terrestrial plants (trees and shrubs, heathland shrubs, and herbs) and is used to calculate the percentages of all pollen, spores, and NPPs. Pollen from aquatic plants, which reflect the local environment, as well as spores and NPPs, are not included in the pollen sum. A minimum of 400 regional pollen grains were counted per subsample. Palynological results are plotted in two pollen diagrams (Figs. 6 and 7) using Tilia (version 3.0.1. Grimm, 2020). Palynological assemblage zones (PAZ) were defined according to the CONISS function (stratigraphically constrained cluster analysis, Grimm, 1987), which included all pollen types, spores, and NPPs.

4.2. Macrobotanical analysis

About 120 ml was sieved over 500 and 250 μm meshes. The classification of ecological groups (Table 1) is based on Runhaar et al. (2004).

4.3. Diatom analysis

About 0.5 g of each subsample was treated with H_2O_2 to remove organic material (Battarbee, 1986). Diatom analysis was carried out using a transmitted light microscope (Zeiss AxioImager A1) and the valve identification was mainly based on Witkowski et al. (2000), Krammer and Lange-Bertalot (2008), and Bey and Ector (2013). A total of at least 400 valves were counted for each subsample (Appendix 2) and the present-day nomenclature was verified based on Algaebase (Guiry

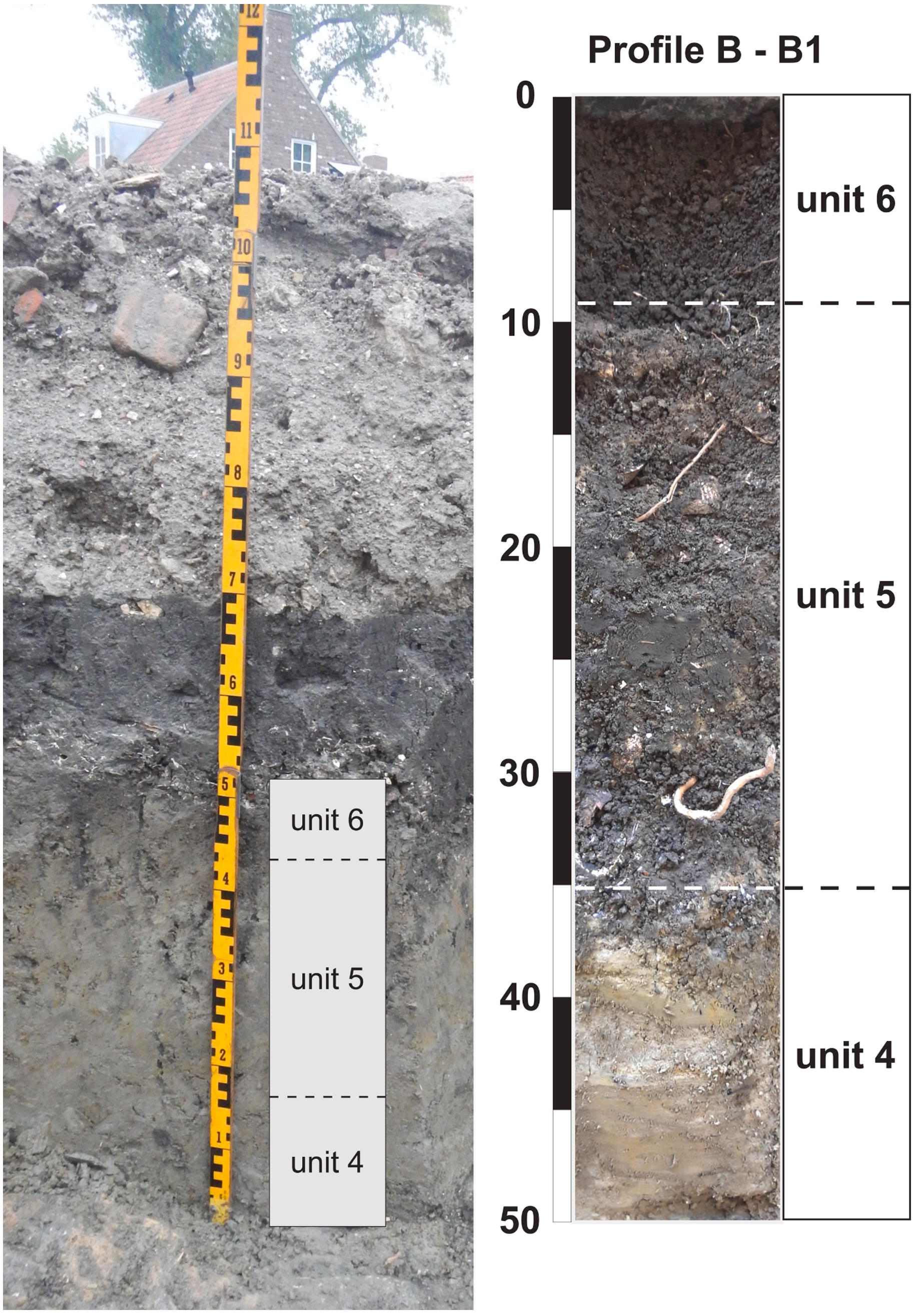

Fig. 4. Position of sample box B1 in profile B. Detail of sample box B1 taken during laboratory work to display the limits of the units.

and Guiry, 2023). The ecological parameters, life form, salinity classification, and habitat were attributed to each species following the ecological classifications of Denys (1991) and Van Dam et al. (1994). Taxa (including species, subspecies and varieties) occurring with at least two valves in the counts, are plotted in two percentage diagrams (Figs. 8 and 9), and grouped according to their salinity classification, life form, and habitat preference. The CONISS function was applied to define diatom assemblage zones (DAZ) (Grimm, 1987).

In general, diatoms from natural sedimentary deposits are classified according to their life form, with (tycho)planktonic species considered allochthonous and epontic and benthic species designated as autochthonous (Vos and de Wolf, 1993). The true niche occupied by tychoplanktonic diatoms is, however, not fully known, and hence they may be autochthonous. In profile A, which holds natural deposits, the diatoms followed the classification of Vos and de Wolf (1993) and were classified according to their life form (Fig. 10). Profile B, on the other hand, only consists of reworked sediments as it is part of the embankment that was most probably above the daily tidal limit. In such anthropogenic deposits, the distinction between autochthonous and allochthonous diatoms was made according to their habitat (Fig. 11): diatoms living in sub- and intertidal conditions were deemed allochthonous, while diatoms preferring supratidal conditions were considered living locally in the embankment.

5. Results

5.1. *Pollen, spore, and non-pollen palynomorph assemblages – Profile A*

5.1.1. *Zone PA1*

The first zone in sample boxes A1-A2 (zone PA1, Fig. 6) includes 18 subsamples collected from predominantly fine-grained sand deposits (units 1 and 2, Fig. 5). Trees and shrubs dominate the pollen sum (~66

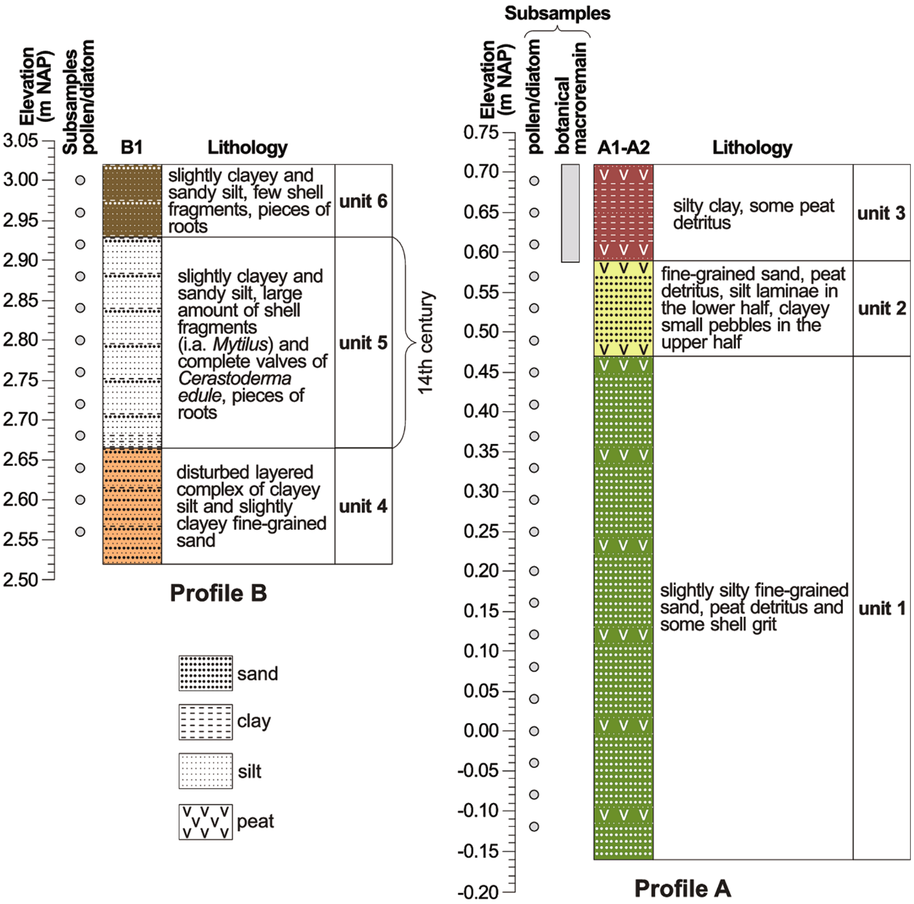

Fig. 5. Lithology of the units and location of the subsamples in the sample boxes in profiles A and B.

%) and are mostly represented by *Corylus* (~23 %) and *Alnus* (~17 %), followed by *Quercus* (~11 %). Other trees that are frequent include *Betula, Pinus sylvestris,* and *Fagus sylvatica* (<5%). *Carpinus betulus, Fraxinus excelsior, Salix, Ulmus,* and bisaccate pollen types are continuously present in low percentages (<1%). Heathland shrubs are frequent (~4%) and are mostly associated with *Calluna vulgaris*. Herbs are abundant (~30 %) and are mostly represented by Poaceae (~17 %) and Chenopodiaceae (~7%). Cyperaceae are also frequent (~2%), while other herbs such as *Plantago lanceolata, Artemisia, Senecio* type, and Plumbaginaceae are more sporadic (<1%).

Aquatic taxa include species such as *Potamogeton* type and *Sparganium* type, which are rare (~1%). The spores are dominated by Filicales (~19 %) followed by *Sphagnum* (~7%) and some *Pteridium aquilinum* (~1%). A part of the Filicales is identified as *Thelypteris palustris.* NPPs are mostly represented by taxa such as type HdV-700 (foraminifera linings, ~2%), acritarchs (~1%), and algae (~8%) including *Pediastrum* spp., dinoflagellate cysts, and type HdV-128 (*Sigmopollis*).

5.1.2. Zone PA2

The second zone (zone PA2, Fig. 6) includes three subsamples that belong to a silty clay layer (unit 3, Fig. 5). Trees and shrubs remain dominated by *Corylus*, *Alnus,* and *Quercus* but significantly decrease from ~ 66 % to ~ 25 %, while heathland shrubs remain frequent (~3%). The pollen sum becomes dominated by herbs (~72 %). Poaceae account for the bulk of the herbs (~25 %), followed by Cerealia type (~11 %) and Brassicaceae (~10 %). Chenopodiaceae and Cannabaceae display peaks at + 0.61 m NAP, respectively ~ 19 % and ~ 11 %. Other taxa present in lower percentages include *Senecio* type, *Trifolium*, and Apiaceae (~2%), as well as Asteraceae-Liguliflorae, *Centaurea cyanus,* and *Matricaria* type (~1%).

Aquatic taxa almost disappear. Filicales decrease (~3%) but *Sphagnum* remains frequent (~7%). Protozoa, acritarchs, and algae quasi disappear, while the fungus type HdV-55A (*Sordaria*, ~3%) and the egg cuticles of the parasitic whipworm *Trichuris* sp. (type HdV-531, ~2%, Fig. 12) are recorded.

5.2. Pollen, spore, and non-pollen palynomorph assemblages – Profile B

5.2.1. Zone PC1

The organic matter in core C1 holds a distinct pollen assemblage (zone PC1, Fig. 7). Trees and shrubs are abundant (~17 %) and mostly represented by *Corylus, Alnus,* and Quercus, while heathland shrubs are frequent (~4%). Herbs dominate the pollen sum (~79 %) and are largely represented by Cerealia type (~50 %), followed by Poaceae (~23 %). Chenopodiaceae (~3%) are also frequent.

Sphagnum (~11 %) is also frequent, while Filicales and *Pteridium aquilinum* are rarer (<2%). The egg cuticles of the parasitic whipworm *Trichuris* sp. (type HdV-531, ~9%) are relatively abundant, together with two unknown NPPs (type unknown Mude-1 and type unknown Mude-2, Fig. 12), which are only present at this level and this in high percentages, i.e. ~ 133 % and ~ 26 %.

5.2.2. Zone PB1

The first zone in sample box B1 (zone PB1, Fig. 7) includes three subsamples that are part of a disturbed composite complex (unit 4, Fig. 5). The pollen spectrum in zone PB1 (Fig. 7) is similar to the one in zone PA1 (Fig. 6). Trees and shrubs are dominant (~65 %) and mostly represented by *Corylus* (~23 %) and *Alnus* (~20 %), followed by *Quercus* (~12 %). *Pinus sylvestris* and *Betula* are present in lower percentages (<5%), while *Ulmus, Tilia, Fagus sylvatica,* and other saccate pollen types

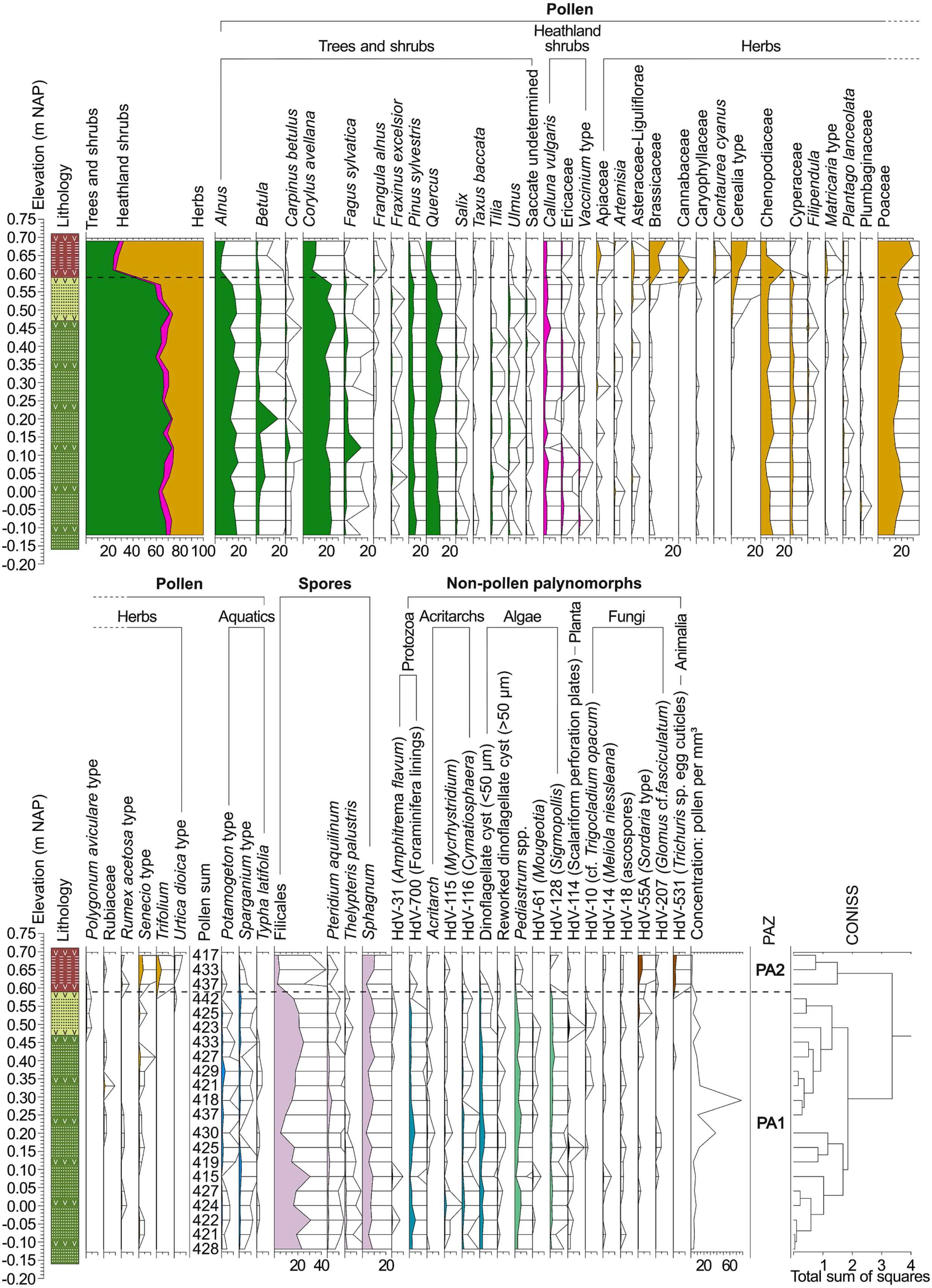

Fig. 6. Pollen diagram (%) of the regional and local vegetation in profile A (exaggeration x10, lithology key Fig. 5, selected taxa). PAZ: Pollen assemblage zones.

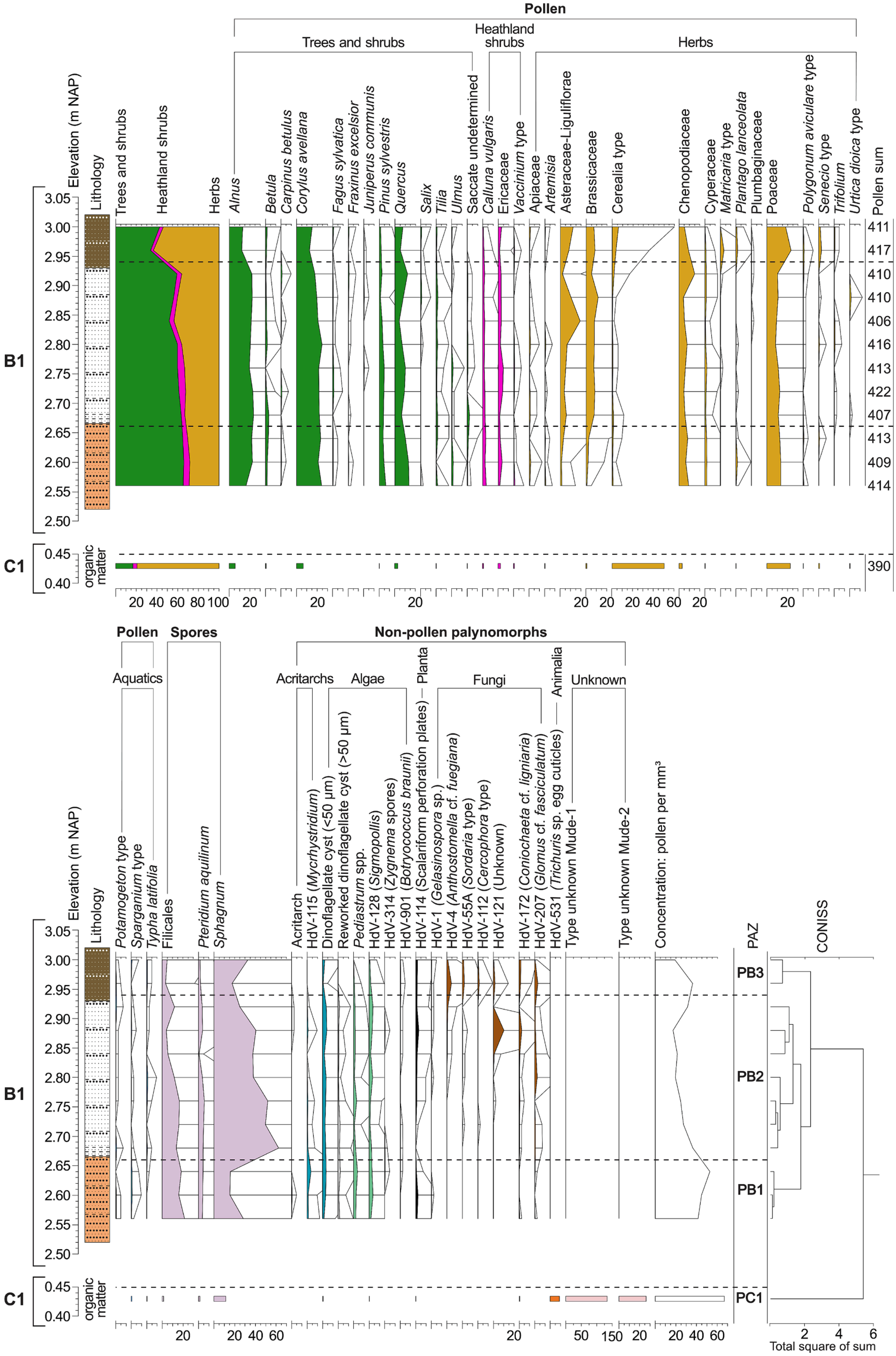

Fig. 7. Pollen diagram (%) of the regional and local vegetation in profile B (exaggeration x10, lithology key Fig. 5, selected taxa). PAZ: Pollen assemblage zones.

Table 1

Results of the macrobotanical analysis in section 3 of profile A. (500 and 250 µm mesh size; volume 120 mL), oc: occasionally; sp: sporadic;../.. = whole specimens/fragments.

	+0.59 to + 0.71 m NAP
Cultivated plants	
Ficus carica	2
Prunus domestica	1
Brassica rapa	1
Consumed plants	
Corylus avellana	−/1
Wild plants	
open water and pioneer, nutrient-rich	
Ranunculus subg. *Batrachium*	1
wet to moist pioneers, nutrient-rich	
Anthemis cotula	1
Atriplex sp.	2
Sinapis arvensis	1
Sonchus asper	2
Papaver argemone	2
moist, very nutrient-rich	
Chenopodium album	1
Solanum nigrum	3
brackish, open to short vegetation	
Glaux maritima	2
unknown ecology	
Rumex sp. (fruit)	1
Mosses	
Sphagnum sect. Cuspidata	sp
Sphagnum austinii	oc
Charred	
Cyperaceae	1
Agrostemma githago	−/4

are rare (<1%). Heathland shrubs are frequent (~6%). Herbs are abundant (~29 %), mostly with Poaceae (~13 %) and Chenopodiaceae (~8%). Herbs such as Asteraceae-Liguliflorae, Cyperaceae, and Brassicaceae are present in low percentages (<2%), as well as Cerealia type and *Plantago lanceolata* (<1%).

Aquatic plants (e.g. *Sparganium* type) are rare. *Sphagnum* (~20 %) and Filicales (~19 %) are both abundant, while *Pteridium aquilinum* (~4%) is frequent. NPPs are dominated by acritarchs (~2%) such as type HdV-115 (*Micrhystridium* sp.) and algae (~8%) such as *Pediastrum* spp., dinoflagellate cysts, and type HdV-128 (*Sigmopollis*, Fig. 12).

5.2.3. Zone PB2

The second zone (zone PB2, Fig. 7) holds seven subsamples that belong to a shell-rich slightly clayey and sandy silt layer (unit 5, Fig. 5). Trees and shrubs remain dominant (~59 %), with *Corylus* and *Alnus* (both ~ 21 %) and *Quercus* (~8%). *Pinus sylvestris* (~3%) is frequent, while *Betula* and *Tilia* are rarer (~1%). Heathland shrubs remain frequent (~5%). Herbs increase from 29 % to 36 % and remain dominated by Poaceae (~10 %), as well as Brassicaceae, Asteraceae-Liguliflorae, and Chenopodiaceae (all ~ 8 %). Cyperaceae and Cerealia type are rare (~1%).

Aquatic plants are present in very low percentages (<1%). *Sphagnum* doubles from ~ 20 % to ~ 44 % and becomes dominant, followed by Filicales (~11 %), and *Pteridium aquilinum* (~4%). Acritarchs (~1%) and algae (~7%) slightly decrease. Fungi become more frequent, such as types HdV-207 (*Glomus* cf. *fasciculatum*) and HdV-172 (*Coniochaeta* ascospores), as well as HdV-121 (ascospores), which shows a peak of ~ 10 % at + 2.88 m NAP.

5.2.4. Zone PB3

The third zone (zone PB3, Fig. 7) includes the two subsamples that were collected in the upper layer, which consists of slightly clayey and sandy silt (unit 6, Fig. 5). Trees and shrubs remain dominated by *Corylus* (~14 %), *Alnus* (~13 %), and *Quercus* (~7%), although in lower percentages in comparison with zone PB2, from ~ 59 % to ~ 38 %. *Pinus sylvestris* and *Tilia* are present in low percentages (<2%). *Heathland* shrubs remain frequent (~3%). Herbs become dominant (~59 %), mostly with Poaceae (~21 %). Asteraceae-Liguliflorae, Brassicaceae, and Chenopodiaceae are also frequent (>7%). Cerealia type (~5%) becomes more frequent, with *Senecio* type, *Matricaria* type, and *Plantago lanceolata* present in smaller percentages (<2%).

Aquatic plants remain rare (<1%). All the spores decrease, but *Sphagnum* remains very abundant (~25 %). Filicales and *Pteridium aquilinum* are frequent (<4%). Acritarchs disappear, and algae decrease to ~ 3 %. Fungi have become more frequent, including types HdV-55A (*Sordaria*), HdV-172 (*Coniochaeta* cf. *ligniaria*), HdV-112 (*Cercophora* type), as well as HdV-207 (*Glomus* cf. *fasciculatum*) and HdV-121 (unknown). Fungus type HdV-4 (*Anthostomella* cf. *fuegiana*) shows a peak of ~ 4 % at 2.96 m NAP.

5.3. Macrobotanical assemblages – Profile A (unit 3)

A lot of straw and charred straw remained after sieving. Unit 3 (Fig. 5) holds a few badly preserved seeds and plant fragments (21 complete seeds and 5 small parts of seeds, Table 1). The seeds refer principally to taxa from cultivated lands and from a moist, very nutrient-rich environment. Cultivated plants include species such as *Ficus carica*, *Prunus domestica* and *Brassica rapa*. Fragments of peat mosses (*Sphagnum*) are occasionally present.

5.4. Diatom assemblages – Profile A

5.4.1. Zone DA1

A total of 92 species belonging to 55 genera were identified in profile A. The first zone (zone DA1, Figs. 8 and 10) indicates that the fine-grained sand deposits (units 1 and 2, Fig. 5) contain mostly tychoplanktonic marine-brackish diatoms (~88 %). *Delphineis minutissima* (~27 %) and *Cymatosira belgica* (~22 %) are the dominant species, followed by *Delphineis surirella* (~15 %), *Paralia sulcata* (~10 %), and *Rhaphoneis amphiceros* (~7%). Epontic and benthic diatoms are also present, but in low percentages (~9%), and are mostly represented by brackish-marine diatoms such as *Diploneis aestuarii*, *Navicula perminuta* group, and *Tryblionella navicularis*. Both tychoplanktonic and epontic/benthic diatoms indicate sub- to intertidal conditions.

5.4.2. Zone DA2

In the second zone (zone DA2, Figs. 8 and 10), the amount of marine-brackish tychoplanktonic diatoms gradually decreases from ~ 58 % in the uppermost subsample of the fine-grained sand deposits (+0.57 m NAP, unit 2, Fig. 5) to ~ 15 % in the uppermost subsample of the silty clay deposits (+0.69 m NAP, unit 3, Fig. 5). The epontic and benthic diatoms follow an opposite evolution and become more abundant in the silty clay (unit 3, Fig. 5). In general, the brackish species *Halamphora coffeiformis* (~11–35 %) dominates the epontic/benthic assemblages in zone DA2, while the brackish-freshwater species *Navicula cincta* (~3%) is also noticeable. The brackish-marine species *Nitzschia ovalis* (~8%), *Navicula microdigitoradiata* (~5%), and *Navicula perminuta* group (~3%) show peaks in the two lowest subsamples (+0.57 to + 0.61 m NAP). The two upper subsamples (+0.65 to + 0.69 m NAP) are more represented by the brackish-freshwater species *Nitzschia capitellata* (~30 %), *Nitzschia umbonata* (~9%), and *Nitzschia frustulum* (5 %). Diatoms of intertidal conditions are dominant in zone DA2, which is also characterised by diatoms of supratidal environments reflected by species such as *Navicula cincta* and *Nitzschia frustulum*.

5.5. Diatom assemblages – Profile B

5.5.1. Zone DB1

A total of 67 species belonging to 44 genera were identified in profile B. The first zone (zone DB1, Figs. 9 and 11) indicates that the disturbed composite complex (unit 4, Fig. 5) and the lowest subsample from the shell-rich slightly clayey and sandy silt layer (unit 5, Fig. 5) are

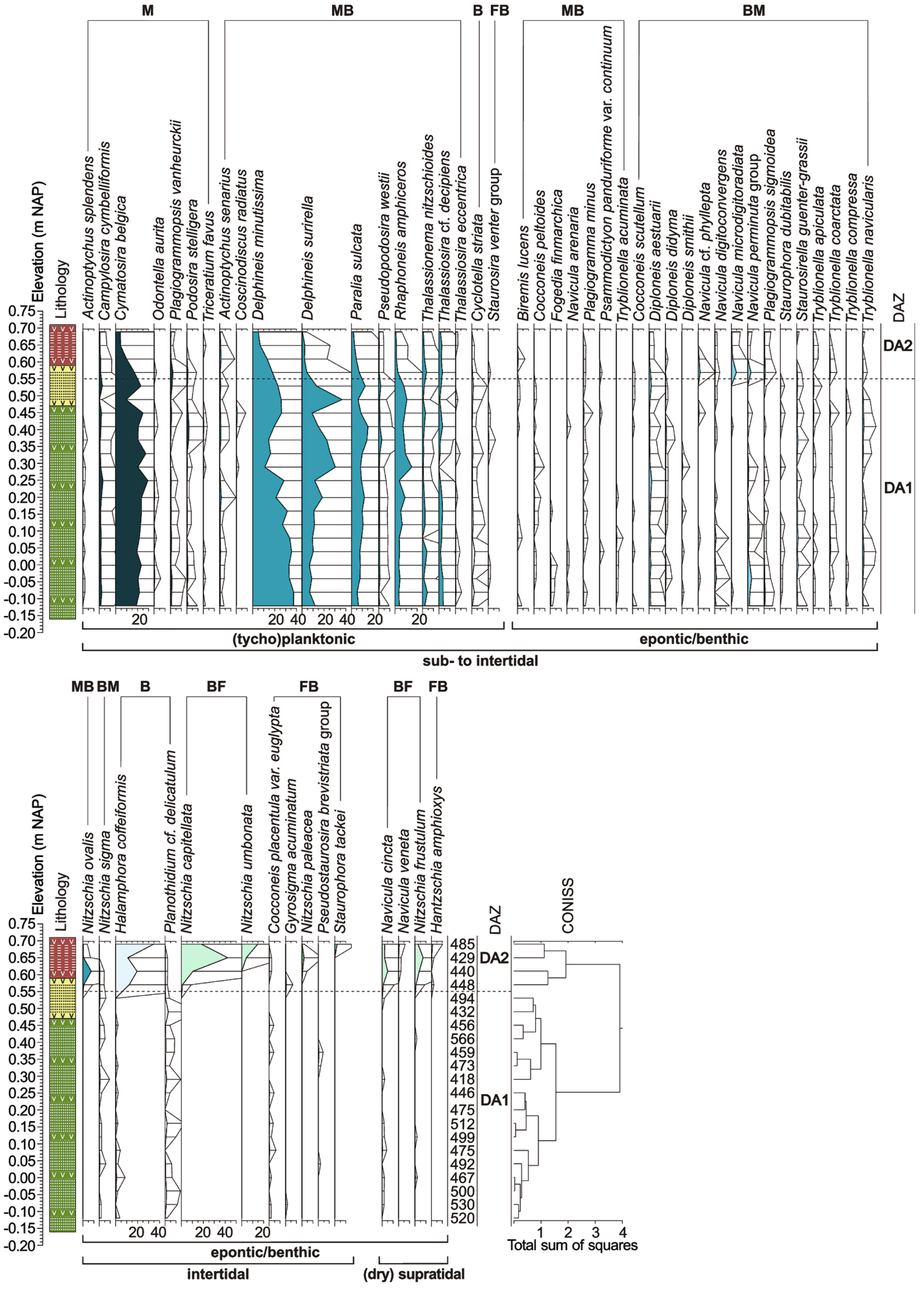

Fig. 8. Diatom diagram (%) of the aquatic palaeoenvironment in profile A (exaggeration x10, lithology key Fig. 5, selected taxa). M = marine; B = brackish; F = freshwater. DAZ: Diatom assemblage zones.

dominated by sub- and intertidal diatoms (~97 %), of which ~ 88 % are marine-brackish tychoplanktonic species. *Paralia sulcata* (~22 %) and *Cymatosira belgica* (~20 %) are dominant, while *Delphineis surirella* (~14 %) and *Rhaphoneis amphiceros* (~8%) are abundant. Sub- and intertidal epontic and benthic diatoms are present in low percentages (~8%) and are mostly represented by brackish-marine species such as *Tryblionella navicularis* and *Diploneis aestuarii*.

5.5.2. Zone BD2

From + 2.72 m NAP upwards, the second zone (zone DB2, Figs. 9 and 11) includes the shell-rich slightly clayey and sandy silt layer (unit 5, Fig. 5) and the overlying slightly clayey and sandy silt layer (unit 6, Fig. 5), which remains mostly characterised by the same sub- and intertidal marine-brackish species, although they are reduced in comparison with zone BD1 (from ~ 97 % to ~ 66 %). Beside the subtidal signal, diatoms living in drier conditions are also recorded (~34 %). The drier signal only includes epontic and benthic diatoms living in brackish-

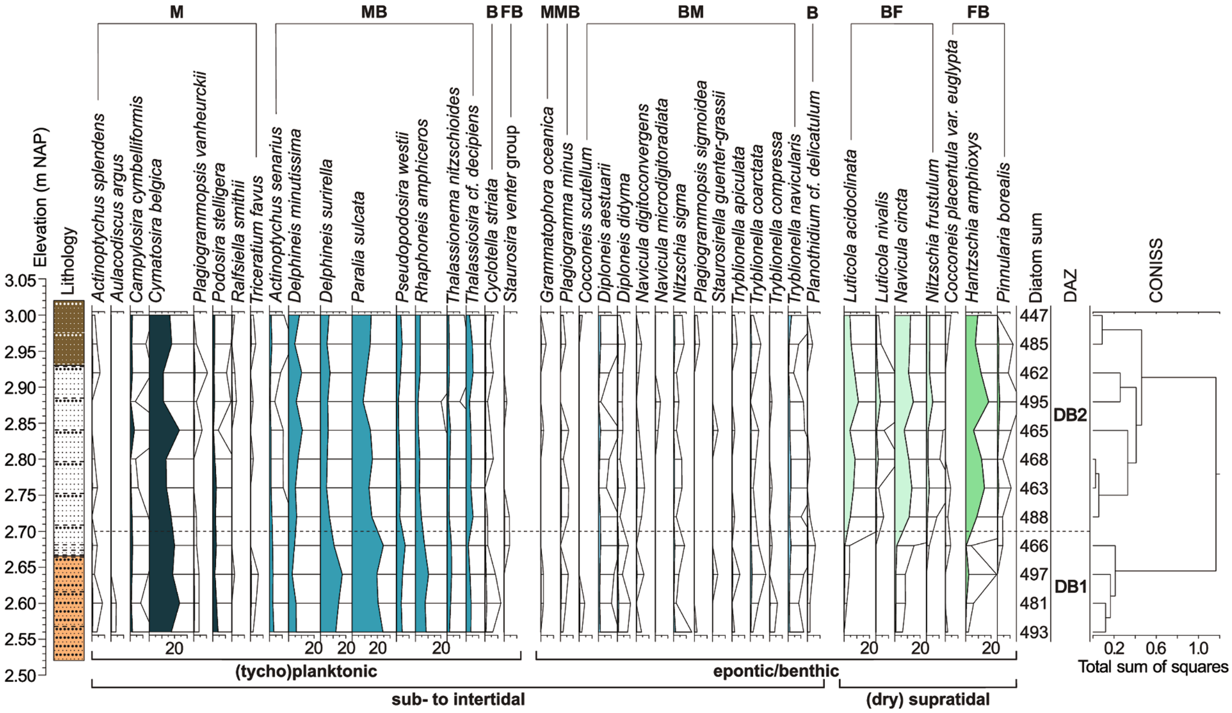

Fig. 9. Diatom diagram (%) of the aquatic palaeoenvironment in profile B (exaggeration x10, lithology key Fig. 5, selected taxa). M = marine; B = brackish; F = freshwater. DAZ: Diatom assemblage zones.

freshwater conditions, mostly represented by *Navicula cincta* (~12 %), *Hantzschia amphioxys* (~11 %), and *Luticola acidoclinata* (~7%). Other species with a similar ecology but more rare (~<2%) involve *Nitzschia frustulum, Luticola nivalis,* and *Pinnularia borealis*.

6. Interpretation and discussion

6.1. The deposits prior to the embankment of the area

The pollen spectrum of the natural sediments (unit 1, Fig. 3) deposited prior to the embankment reflects a woodland-dominated regional landscape (zone PA1, Fig. 6), mostly represented by *Corylus*, *Alnus*, and *Quercus,* which grow in different habitats. While *Corylus* and *Quercus* grow more preferably on dry soils, *Alnus* is a wetland species. The woodland signal is most likely coming from the sandy hinterland as forests were normally absent in the coastal plain.

These deposits are also characterised by NPPs of marine origin (e.g. dinoflagellate cysts, acritarchs, and foraminifera linings), as well as tychoplanktonic marine-brackish diatoms (zone DA1, Figs. 8 and 10). Altogether, these taxa reflect the presence of a tidal flat (Fig. 13) influenced directly by marine influx, presumably through a nearby tidal channel (Vos and de Wolf, 1993). Large (>50 μm) poorly preserved dark brown coloured dinoflagellate cysts (mostly *Spiniferites* spp.) are presumably reworked from pre-Quaternary deposits. A part of the dinoflagellate cysts (<50 μm) may also be reworked (Fig. 12).

Pollen from herbs are also common in these deposits and are mostly represented by Poaceae and Chenopodiaceae. Since the sediments were deposited in a saline intertidal environment, one can assume that Chenopodiaceae is here mostly represented by halophytic taxa (e.g. *Salicornia* and *Atriplex* species), originating from the nearby coastal plain. Some Poaceae might be associated with reeds, such as *Phragmites australis,* which grow in marshes and are possibly present in the vicinity. Furthermore, a part of the Filicales was identified as *Thelypteris palustris*, which also points to the presence of marshes in the coastal plain. Another possibility is that these marsh taxa might have been reworked from lower parts of older eutrophic peat below the tidal deposits. Peat started to form before 7000 cal. BP in the eastern coastal plain of Belgium (Allemeersch et al., 2023) and developed on a large scale when the tidal landscape evolved into a vast freshwater marsh because of a sea-level rise deceleration from about 7 m/ka in the period before ca. 7500 cal. BP to about 0.70 m/ka around ca. 5500–5000 cal. BP (Vos and van Heeringen, 1997; Baeteman et al., 1999; Baeteman, 2018). The peat accumulated over 2000–3000 years and eventually evolved into raised bogs (Allemeersch, 1991). *Sphagnum,* which grows in oligotrophic peat and ombrotrophic bogs, was most probably eroded and transported via tidal channel activity. Although in lower percentages, pollen grains of Cyperaceae and *Sparganium* type together with freshwater algae such as *Pediastrum* spp. and type HdV-128 (*Sigmopollis*), might also be part of the reworked peat component or might reflect a freshwater environment in the vicinity.

Given the nature of the boundary between the units 1 and 2 on profile A (Fig. 3), it is clear that a part of the tidal flat (unit 1) has been dug out and removed, possibly for the construction of an embankment. The sedimentary structures (oblique stratification) of the overlying 20–30 cm thick layer (unit 2) suggest that these sediments were probably washed into the depression excavated by humans (Fig. 13). These sediments are by origin tidal flat deposits as they have similar pollen and diatom assemblages as the underlying deposits (unit 1) and form the zones PA1 and DA1.

6.2. The presence of manure

The organic matter in core C1 (zone PC1, Fig. 7) is characterised by a large amount of Cerealia type and the eggs of the intestinal parasitic whipworm *Trichuris* sp. (type HdV-531, Fig. 12). Cerealia type is most probably associated with grains or straw used as animal fodder. Type unknown Mude-1 resembles type HdV-367 and could be associated with stagnant shallow open water (Van Geel et al., 1983), possibly drunk by the animals which produced the faeces. Such an assemblage points to the presence of manure. The position and quantity of manure in the natural infill of the tidal channel suggests intentional dumping. This assumes human activity nearby the tidal channel at that time. Another

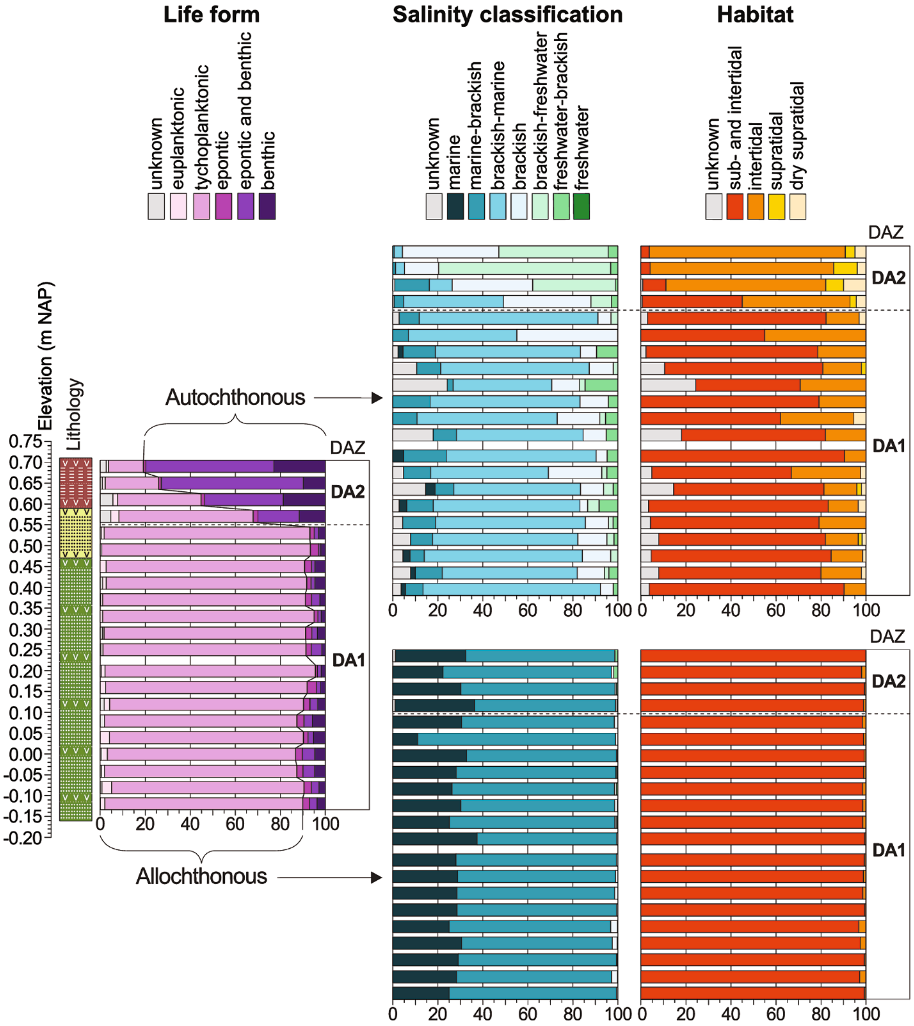

Fig. 10. Diagram (%) of the ecological parameters (life form, salinity classification, and habitat) for allochthonous and autochthonous diatoms in profile A (lithology key Fig. 5). DAZ: Diatom assemblage zones.

explanation for the presence of the manure in this stratigraphic position, is the possibility of it being intrusive in the channel sediments. This cannot be ruled out due to the applied augering technique, which does not guarantee closed samples.

6.3. The embankment

6.3.1. Sods

The internal structure observed in the silty clay of profile A (unit 3, Fig. 3) clearly shows the concentration of clayey lumps or sods (Fig. 13). Pollen and macrobotanical analysis are useful tools to combine because they complement each other. While most pollen types include several species with different ecological requirements, macrobotanical remains can often be identified at species level, which supports the interpretation of the pollen results. On the other hand, some plants are not visible in the macroremains because they are of local origin or they do not preserved as well as the more resistant pollen (Deforce et al., 2019).

The pollen spectrum of the sods is dominated by numerous herbs associated with anthropogenic activity and domesticated plants (zone PA2, Fig. 6). Besides wild species, Apiaceae include vegetables such as celery and carrots, while Brassicaceae include cabbages and many other crops. The macrobotanical analysis confirmed the presence of cultivated plants such as *Brassica rapa* and *Prunus domestica* and cultivated plants such as *Ficus carica*, which is imported from the Mediterranean area (Table 1). It cannot be excluded in an intertidal environment that some Brassicaceae are linked to shoreline species, such as sea-kale (*Crambe maritima*) and scurvy-grass (*Cochlearia*).

The pollen types Asteraceae-Liguliflorae, Asteraceae-Tubuliflorae (*Senecio* and *Matricaria* types), and Brassicaceae include ruderal species, which indicate a disturbed environment linked to human and/or animal activity (Behre, 1981). This is confirmed by the macrobotanical remains of *Sonchus asper* (Asteraceae-Liguliflorae) and *Sinapsis arvensis* (Brassicaceae), as well as *Papaver argemone* and *Solanum nigrum*. A part of Chenopodiaceae also reflects disturbed soils, as indicated by the macrobotanical remain of *Chenopodium album*, while another part of the Chenopodiaceae pollen probably comes from halophytes in the surrounding marine tidal environment (e.g. *Salicornia* and *Atriplex*). Although the macrobotanical remains of *Atriplex* sp. were not identified at the species level, they might be associated with *Atriplex patula*, which is a pioneer of very nutrient-rich, rather wet soils, while the other *Atriplex* species are typical of brackish or even salt water (Runhaar et al., 2004). The macrobotanical remains of *Glaux maritima* can also be related to saltmarsh vegetation.

Pollen of *Centaurea cyanus* and Cerealia type can originate directly from cereal cultivation on the site or might also be the product of threshing (Hunt et al., 2001; O'Brien et al., 2005). Cornflower (*Centaurea cyanus*) was already growing in the Netherlands from the Early Middle Ages but only became abundant in cultivated fields during the High to the Late Middle Ages (Bakels, 2012). The cereals can also be part of dumped material, such as food, straw, or dung. The latter is

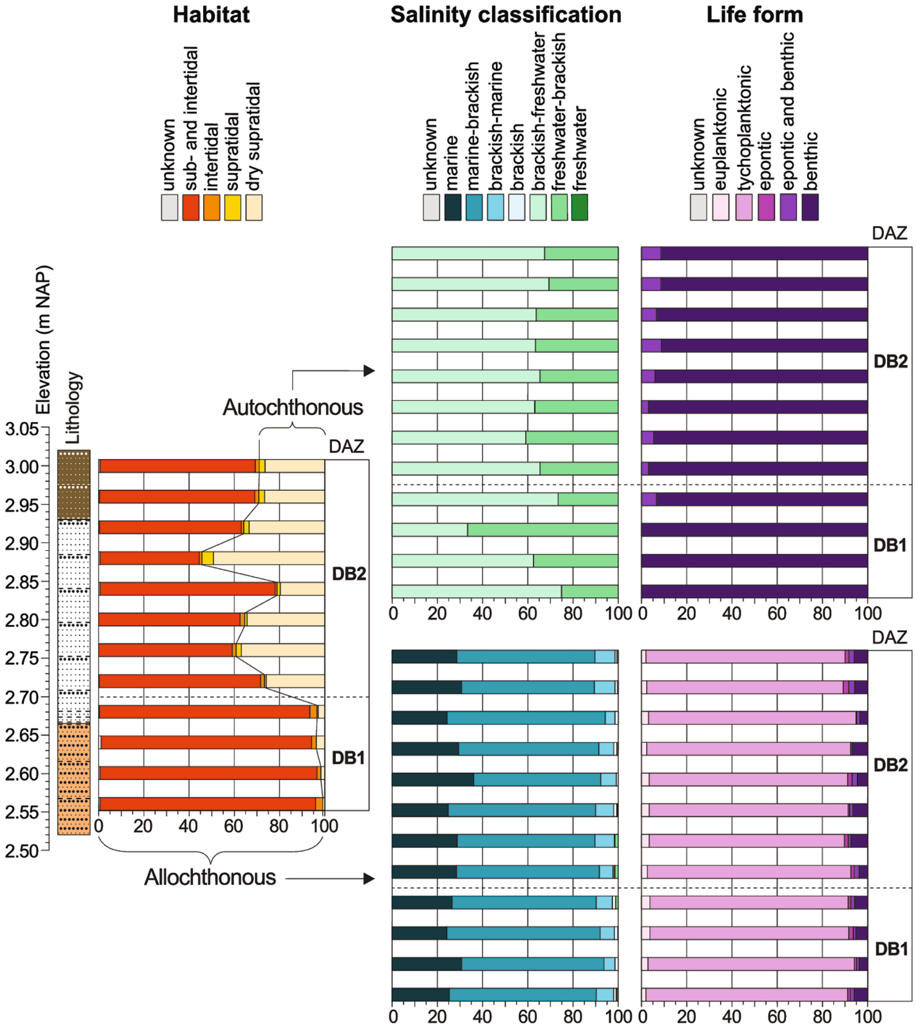

Fig. 11. Diagram (%) of the ecological parameters (life form, salinity classification, and habitat) for allochthonous and autochthonous diatoms in profile B (lithology key Fig. 5). DAZ: Diatom assemblage zones.

highly possible as coprophilous fungi and parasitic eggs from human and/or domesticated animal origin reflect the presence of faeces. Furthermore, straw was also observed during macrobotanical analysis.

The peak of Cannabaceae can be linked to *Cannabis sativa* or hemp, which was typically used for rope making and hempseed oil production in harbour cities (Fleming and Clarke, 1998). Finally, both palynological and macrobotanical records indicate that this layer also contains peat mosses (*Sphagnum*) reworked from oligotrophic peat possibly used for fuel (Fig. 6, Table 1).

The disturbed composite complex in profile B (zones PB1 and DB1, Figs. 7, 9, and 11) holds very similar terrestrial and aquatic palaeoenvironmental conditions to those observed in profile A (zones PA1 and DA1, Figs. 6, 8, and 10), characteristic of the tidal deposits in profile A. Thus, these disturbed deposits or sods (unit 4, Fig. 4) were most likely dug from the local tidal flat and were used to build the embankment (Fig. 13).

Dikes and terps dating from the Roman period were constructed in the area using material directly accessible in the coastal plain, such as blocks of clay and peat, to which waste was sometimes added (Demey et al., 2013; Verwerft et al., 2019). Lascaris and de Kraker (2013) mentioned the striking resemblance in technical aspects and land use of the protected area between dikes from the Roman period and late-medieval times in Kampereiland (the Netherlands). The medieval embankment in our study area was constructed with local surface deposits, namely tidal flat deposits, as well as deposits with human-related material.

6.3.2. *The shell-rich layer and the cultural layer*

The silt layer (unit 5, Fig. 4) contains a large number of shell fragments that correspond to waste, most probably from sea-food consumption, that was dumped on top of the sods likely for levelling and paving against wet and muddy conditions (Fig. 13). The palynomorphs of the shell-rich layer record high percentages of trees and shrubs, which could at first sight be interpreted as the reflection of a woodland-dominated landscape (zone PB2, Fig. 7). This woodland-signature is, however, misleading. Woodland was not only mostly absent in the coastal plain but also in the southward hinterland, it became scarce from the high-medieval period onwards. High-medieval Ghent, for example, witnessed the transition of taxa used for timber and fuel from dryland trees of high quality (e.g. *Quercus* and *Betula*) during the tenth century, to wetland species of lower quality (e.g. *Alnus*) during the twelfth century and thus reflects overexploitation of the woody resources farther inland (Deforce, 2017). The shortage of wood is concurrently documented in historical sources, which indicate an increased import of timber for construction from abroad (Sosson, 1977). Most Flemish forests were highly impacted by forest clearance and overgrazing, leading to reduced hunting reserves by the thirteenth century (Verhulst, 1995; Verheyen et al., 1999).

Moreover, as wood became scarce, peat became the primary source of energy over the entire region (Deforce et al., 2007; Jongepier et al.,

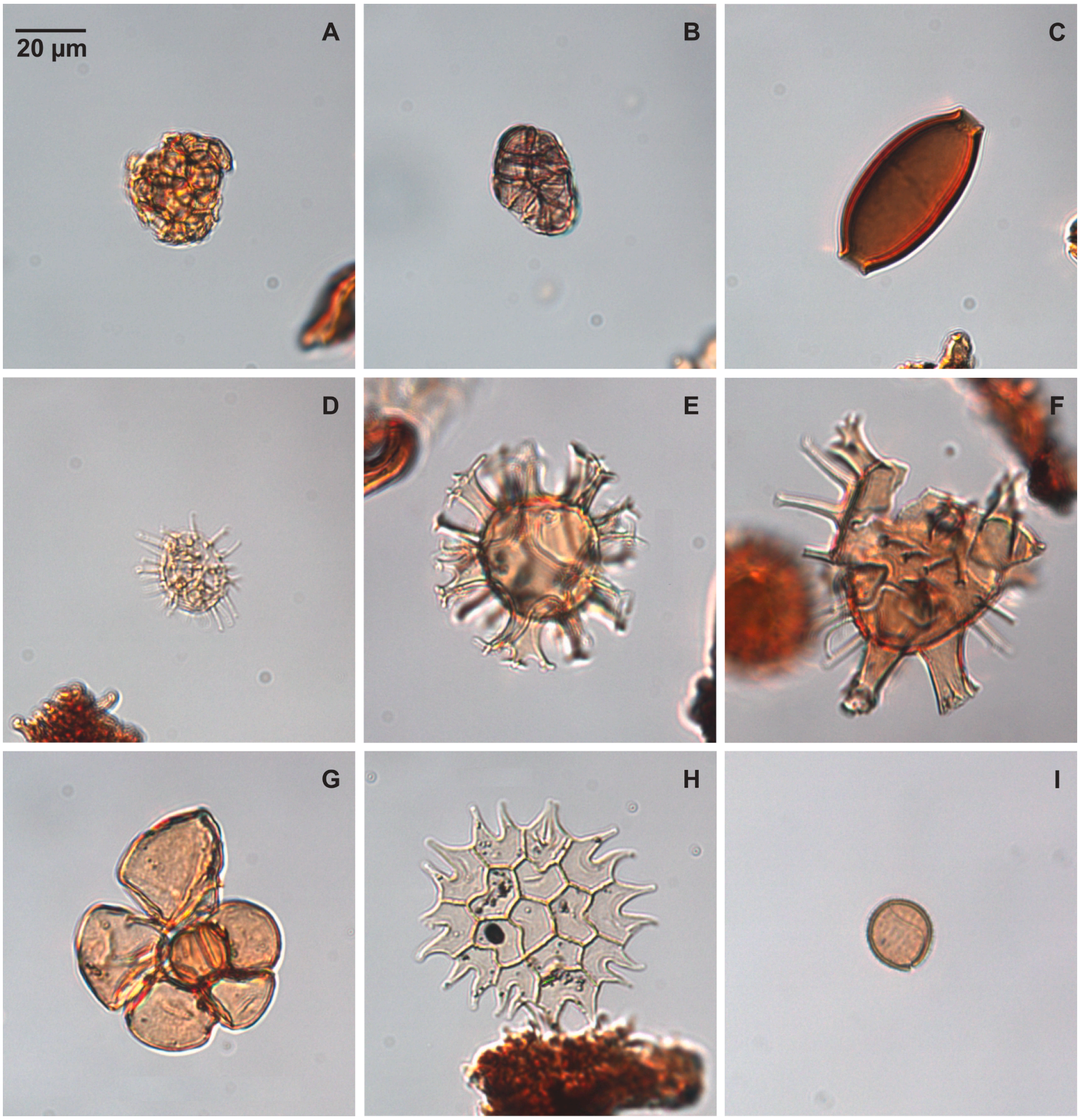

Fig. 12. Photomicrographs of Non-Pollen Palynomorphs. A: type unknown Mude-1; B: type unknown Mude-2; C: egg cuticles of the nematode *Trichuris* sp. (type HdV-531); D: cyst of *Protoperidinium faeroense*; E: dinoflagellate cysts *Spiniferites* sp.; F: *Hystrichokolpoma* sp.; G: lining of a foraminifera; H: *Pediastrum boryanum*; I: Type HdV-128 (*Sigmopollis*). A-C: abundant in the organic matter (core C1). D-I: marine and freshwater NPPs.

2011; Deforce, 2017). The large amount of *Sphagnum* in the shell-rich layer is therefore most probably linked to the digging of peat for fuel. Indeed, peat was exploited for fuel on a large-scale in the coastal areas of Belgium and the Netherlands and was transported during medieval times over long distances towards cities located more inland (Verhulst, 1995; van Dam, 2001; Deforce et al., 2007; Jongepier et al., 2011). More specifically, medieval city accounts of the neighbouring harbour sites of Hoeke and Monnikerede mention the purchase of peat for fuel (ARA, Rekenkamers, 35682; ARA, Rekenkamers, 36393), further evidencing the local custom of using peat as combustible. Consequently, the dominance of tree and shrub pollen in the shell-rich layer is most probably older and can be attributed to reworked peat. Although forests seem to have been reduced in the region, a part of the pollen from trees and shrubs can also reflect the regional environment since these travel further.

Finally, the palynological analysis of the shell-rich layer also records herbs associated with ruderals (e.g. Asteraceae-Liguliflorae, Brassicaceae, and Chenopodiaceae) reflecting the presence of disturbed soil (Fig. 7). The dominance of these herbs together with Poaceae and the signals of crops and coprophilous fungi on top of the shell-rich layer (unit 6, Fig. 4) suggest that a cultural soil developed at the top of the dike (zone PB3, Figs. 7 and 13). The embankments in the coastal plain of the county of Flanders were commonly used as pathways for sheep herding or travel by horse (Zwaenepoel and Vandamme, 2016). The derived products, particularly wool used in textiles, also contributed to the economy of the region (Verhulst, 1998; Vos, 2015). The signal of Cerealia type pollen might result from the threshing of the grain at this location but can also be related to agricultural activities in the vicinity of Mude, as arable farming was predominant in the embanked coastal wetlands in the Zwin region (Soens et al., 2014).

6.3.3. *Aquatic conditions in the embankment*

Different aquatic palaeoenvironments were distinguished between the shell-rich layer and the cultural layer (units 5 and 6 in profile B) and the layer composed of sods (unit 3, profile A) (Figs. 10 and 11). The shell-rich layer and the cultural layer on top of the embankment (zone DB2, Figs. 9 and 11) are dominated by tychoplanktonic marine-brackish diatoms, which may originate from different sources. The marine

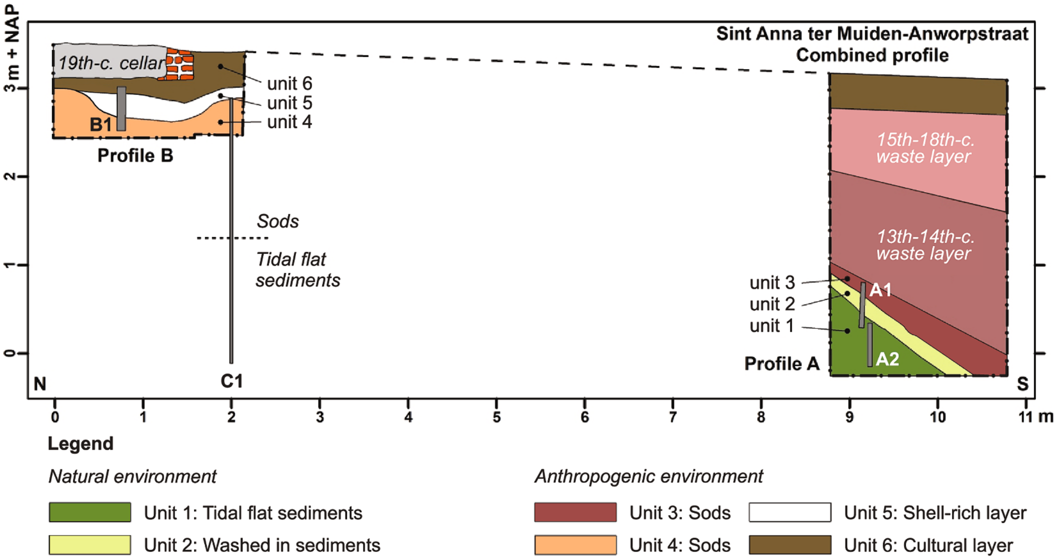

Fig. 13. Cross section through Mude's embankment on the left bank of the Zwin. Location of the combined profiles A and B, with the position of the sample boxes, core and the interpretation of the units.

diatoms could have been present on the marine shells, but are most probably reworked from the underlying sods or were directly deposited during occasional storm surges. Brackish-freshwater diatoms, indicative of more terrestrial conditions, were living locally on the embankment. These diatoms are considered aerophilous as they are adapted to intermittently wet conditions that most likely occurred in the surface layer that was regularly fed by rainwater (Vos and de Wolf, 1993). Similar intermittently wet conditions, mostly represented by *Navicula cincta,* also dominate the Roman dike and terp at Stene (Demey et al., 2013).

The local environmental conditions are more humid in the sods of profile A (zone DA2, Fig. 10) than in the shell-rich layer and the overlying layer of profile B (zone DB2, Fig. 11), the latter being located at a higher level (Fig. 13). Marine-brackish conditions at the base of the sods in profile A (unit 3) evolve gradually towards brackish-freshwater conditions. This evolution, together with a decline in marine tychoplanktonic species points to a decrease in marine conditions, which indicate that the embankment became located beyond the reach of frequent influence by a tidal channel. The complete disconnection of Mude with the sea and the re-location of its primary functions to a new settlement called 'Nieuw-Mude' during the 15th century is documented by Dillen (2022).

Finally, the diatoms that are found locally in the anthropogenic deposits are indicative of eutrophic conditions. The macroremains also show wild plants living in a moist, nutrient-rich environment, which could have grown on or directly next to the base of the embankment (Table 1).

7. Conclusions

Palynological, macrobotanical, and diatom analyses from an excavation at Mude allowed the reconstruction of the transition from a tidal flat into a man-made raised soil associated with an embankment in the coastal plain. Sods used in the construction of the embankment were either directly dug from the nearby tidal flat or consisted of a mixture of natural deposits and human waste, which reflect human activity in the area. Indications for hemp, used for rope making amongst other things, perfectly fit with the portuary activities of medieval Mude. The numerous indications of cultivated plants suggest agricultural practices in the vicinity, and the fig seeds point to import of food products from the Mediterranean region. The observed woodland-signature is unlikely to be contemporaneous with the embankment; it is rather older and associated with the large amount of uncovered and reworked Middle (to Late) Holocene peat. In the tidal flat sediments, the reworked peat was most probably eroded and transported via tidal activity, while in the human-raised layers, it can also be linked to the locally extracted or imported peat for fuel which was common practice in the North Sea coastal wetlands during the Middle Ages. The diatoms indicate local brackish-freshwater conditions in the anthropogenic layers and reflect that the embankment was no longer within daily tidal reach. The presence of manure within the natural sediments also points to human activity, at least in the nearby area, which was most probably used for animal grazing. The contents of the cultural layer that developed on top of the embankment suggest that the dikes were not only used as a protective measure against the tides but were also used, for instance, as pathways for sheep from the medieval times onwards.

CRediT authorship contribution statement

Coralie André: Writing – review & editing, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Dante de Ruijsscher:** Writing – review & editing, Visualization, Investigation. **Maxime Poulain:** Investigation, Visualization, Writing – review & editing. **Jan Trachet:** Investigation, Writing – review & editing. **Wim De Clercq:** Conceptualization, Funding acquisition, Investigation, Supervision, Writing – review & editing. **Frieda Bogemans:** Writing – review & editing, Investigation, Methodology. **Annelies Storme:** Writing – review & editing, Methodology, Investigation. **Koen Sabbe:** Writing – review & editing, Methodology, Investigation. **Bart Van de Vijver:** Writing – review & editing, Methodology, Investigation. **Luc Allemeersch:** Methodology, Investigation. **Frederik D'hondt:** Writing – review & editing, Investigation. **Stephen Louwye:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

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.

Data availability

Data will be made available on request.

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Archival sources

General State Archive Brussels (ARA), Rekenkamers, n° 36393, f. 4v.
General State Archive Brussels (ARA), Rekenkamers, n° 35682, f. 6v.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2024.104520.

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