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The palaeoecological conditions of the tidal channel network of the Zwin region (Flanders, Belgium)

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ABSTRACT

The northeastern coastal plain of Belgium was a well-developed region during the late medieval period when Bruges and a series of smaller harbours became connected to the North Sea via the Zwin tidal channel. Yet, ecological data related to the evolution of the regional environment of the former Zwin region are still lacking. Diatoms, pollen, and macrobotanical remains have been studied for the first time from two cores drilled in the surroundings of the lost harbour of Hoeke. The sediments in both cores were deposited in four successive tidal channel systems spanning the pre-Roman to late medieval periods. Marine tychoplanktonic and planktonic diatoms were dominant and confirmed the presence of open marine tidal channels, while marine epipsammic diatoms were specific to channel deposits (systems 1 and 4) and marine epipelic diatoms characterised channel and accretion deposits (systems 2 and 3). The sediments of the late medieval Zwin main channel and tributary (system 4) are both characterised by marine tychoplanktonic and epipsammic species. The palynomorphs were typical of marine tidal deposits and (reworked) peat, while macroremains pointed to freshwater plants growing in the vicinity. The palynomorphs (system 4) suggest a more open landscape associated with the extensive reclamation and embankment of the Zwin region. Diatoms in the superjacent tidal deposits indicate that the late medieval Zwin silted up rapidly.

KEYWORDS

Late Holocene,
palynology,
diatom analysis,
tidal channel system,
medieval harbour

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1. Introduction

The landscape of the eastern Belgian coastal plain was transformed when, according to historical sources, a large tidal channel developed following a storm surge in 1134 (Verhulst, 1959; Trachet et al., 2015; De Clercq et al., 2021). The tidal channel, called the Zwin, ensured for the entire region access to the sea. Despite its location further inland, the Zwin allowed the city of Bruges (Fig. 1) to grow into an important medieval metropolis as it became strategically located at the convergence of the newly established maritime gateway and the traditional continental trade routes. However, maritime commerce from Bruges via the North Sea was only viable through a network of harbour towns that emerged on the banks of the Zwin tidal channel, one of which was Hoeke (Dumolyn & Leloup, 2016; Trachet, 2016; Fig. 1).

Traditionally, the overall development of the medieval Zwin landscape was reconstructed from historical sources (e.g. Verhulst, 1959; Pannier, 1970). In recent years however, the region has received new academic interest, notably from archaeological studies carried out at lost harbour sites, such as Monnikerede and Hoeke (Trachet, 2016). Despite this growing scholarly attention, geological and ecological data remained limited for the area. A recent research project provided a synthesis of both legacy and newly collected data specific to Holocene peatlands and archaeological findings in the eastern coastal plain of Belgium (Allemeersch et al., 2023). Furthermore, comprehensive geophysical, geological, and archaeological research in 2021 at Hoeke presented a unique opportunity to better understand the dynamics that shaped the late medieval Zwin tidal channel and its possible predecessors (De Clercq et al., 2022). In the shallow subsoil of Hoeke and its surroundings, the remains of a complex network of chronologically successive tidal channel systems appeared to be well preserved, covering a period from the pre-Roman period until the Late Middle Ages, the period in which the Zwin became the gateway of Bruges. The Quaternary evolution of these sedimentary environments has recently been described by sedimentological analyses of cores taken at Hoeke (Bogemans & Heyvaert, 2023; Bogemans et al., 2024).

This paper aims to advance our understanding of the regional landscape evolution by investigating the ecological conditions in the different tidal channel systems of the Zwin region. Diatom and palynological assemblages were analysed throughout the sedimentary deposits from two undisturbed mechanically drilled cores (cores B3 and B5), while preserved macrobotanical remains were also investigated at specific levels in core B5. The primary objective was to assess whether diatom assemblages could effectively distinguish between the sedimentary subenvironments described by Bogemans & Heyvaert (2023) and thus follow the dynamics of the tidal channel systems and tidal flat over time. Additionally, we sought to investigate potential differences in environmental conditions during activity of the different types of channels with a focus on a main tidal channel and a tributary channel, to gain insights into the later phases of the Zwin's evolution. Finally, palynological and macrobotanical analyses were carried out to determine whether distinct sources of material could be detected within the various sedimentary deposits, thereby contributing to our understanding of the overall development of this historical landscape.

2. Material

Following electrical cone penetration test (CPT-e), seven cores were mechanically retrieved near Hoeke in 2021 using a hollow stem auger, yielding undisturbed 1 m liners (Bogemans & Heyvaert, 2023). The cores were sedimentologically described in detail for colour, texture, bedding types (primary sedimentary structures), deformation structures, biogenic structures, bedding plane characteristics and the presence of palaeontological and archaeological remains and pedological features. The grain size classes of the sand fraction were determined using a sand ruler. The sedimentary analysis of the cores allowed the identification of a series of architectural elements within a tidal environment, including channel elements sensu stricto, low energy channel

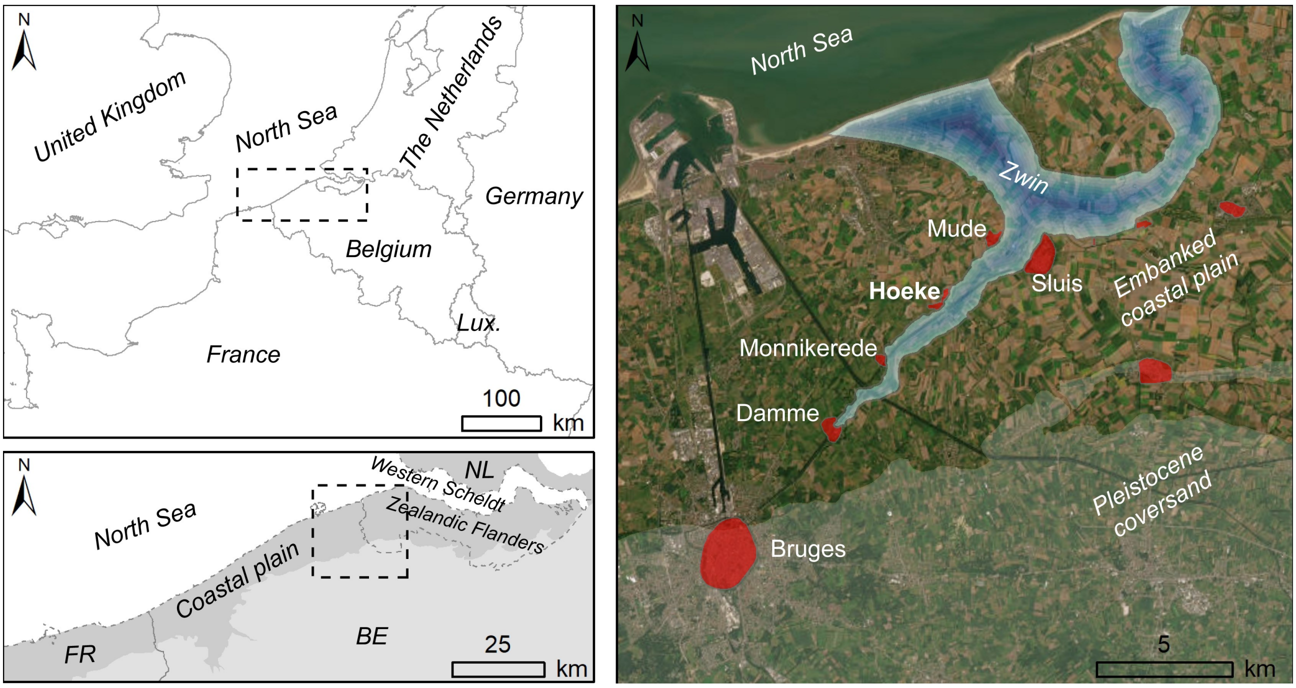

Figure 1. Location of the current Belgian coastal plain and the lost harbours (red areas) of the medieval Zwin region. The embankment of the coastal plain already started in the Middle Ages (modified from Bogemans et al., 2024).

elements, accretion forms, intertidal flats, salt marshes (supratidal), and abandoned channels (Bogemans & Heyvaert, 2023; Bogemans et al., 2024). The intertidal flat and salt marsh deposits are in this paper lumped under the term tidal flat deposits.

Two cores (B3 and B5) were selected for palaeo-ecological analyses since they penetrated all four tidal channel systems detected in the cited sedimentary studies, dating from pre-Roman to late medieval times (Figs 2 and 3). Furthermore, the latest tidal channel system 4 also known as the Zwin is recorded in both cores. It was this channel that was active during the late medieval heyday of Bruges period (ca 1134–1500 AD).

Core B3 includes a more than 12 m thick Holocene sequence (Fig. 4), most of which consists of channel s.s. deposits (Bogemans & Heyvaert, 2023; Bogemans et al., 2024). However, these channel s.s. deposits are part of two different tidal channel systems; the oldest being active in the pre-/early Roman period (tidal channel system 1). The youngest system (tidal channel system 4) most probably developed after the storm surge of AD 1134 (according to historical sources), subsequently grew into an important commercial artery, but also silted up during the Late Middle Ages (Bogemans et al., 2024).

The seven metre core B5 consists mostly of channel s.s. and accretion form deposits that belong to three different tidal channel systems (Fig. 5). The oldest tidal channel system 2 is dated to the mid-Roman period based on the articulated shell (*Macoma*) observed in living position at 5.37 m depth, which was radiocarbon dated to 195–489 AD (Laboratory code RICH-30446) (Bogemans et al., 2024). A second articulated shell (*Cerastoderma*) at 4.10 m depth radiocarbon dated to 548–795 AD (RICH-30447) allows to date tidal channel system 3 to a period in early medieval times. Archaeological excavations revealed the upper layers of channel system 3, which completely silted up and evolved into a salt marsh (De Clercq et al., 2022). A fragment of charcoal (*Alnus*) was dated to 682–880 AD (RICH-30881, youngest phase of the early medieval period), providing a terminus ante quem for the period of activity of system 3. Over more, a shallow cultural layer containing fragments of pottery and charcoal was found on top of it. The charcoal (*Quercus*) was radiocarbon dated to 895–1025 AD (RICH-30878, high medieval period). Finally, an abandoned/low energy channel is part of tidal channel system 4 (Bogemans et al., 2024). Along this channel the late medieval harbour of Hoeke emerged. It was demonstrated during archaeological excavations that this tributary channel was lined by a dike from which a wooden quay bordered the channel, indicating that the area was used as a harbour and location for ship repair during the late 13th and early 14th century (De Clercq et al., 2022). This channel 4 cut the aforementioned cultural layer for which the latter provides a terminus post quem dating, which is also well in line with the historical arguments for the emergence of the system in AD 1134 or shortly after.

The final natural tidal channel system (4), active in the high and late medieval period and often referred to as the medieval Zwin, is thus documented in both cores B3 and B5 (tidal channel system 4, Fig. 3). Core B3 records the tidal channel s.s. deposits of the main navigable waterway during the heyday of Bruges, while the channel deposits in core B5 are thinner and correspond to a shallower tributary of the main tidal channel.

Finally, intertidal and supratidal deposits (tidal flat deposits) cover the medieval Zwin channels deposits at both locations. The upper 30 to 40 centimetres are associated with plough layers from more recent periods.

A total of 51 levels including sandy, clayey, and organic material were sampled for diatom analysis in core B3 (22 levels, Fig. 4) and core B5 (29 levels, Fig. 5). Organic deposits were only observed in core B5, especially in the accretion form deposits of system 2. A total of 17 levels, including these

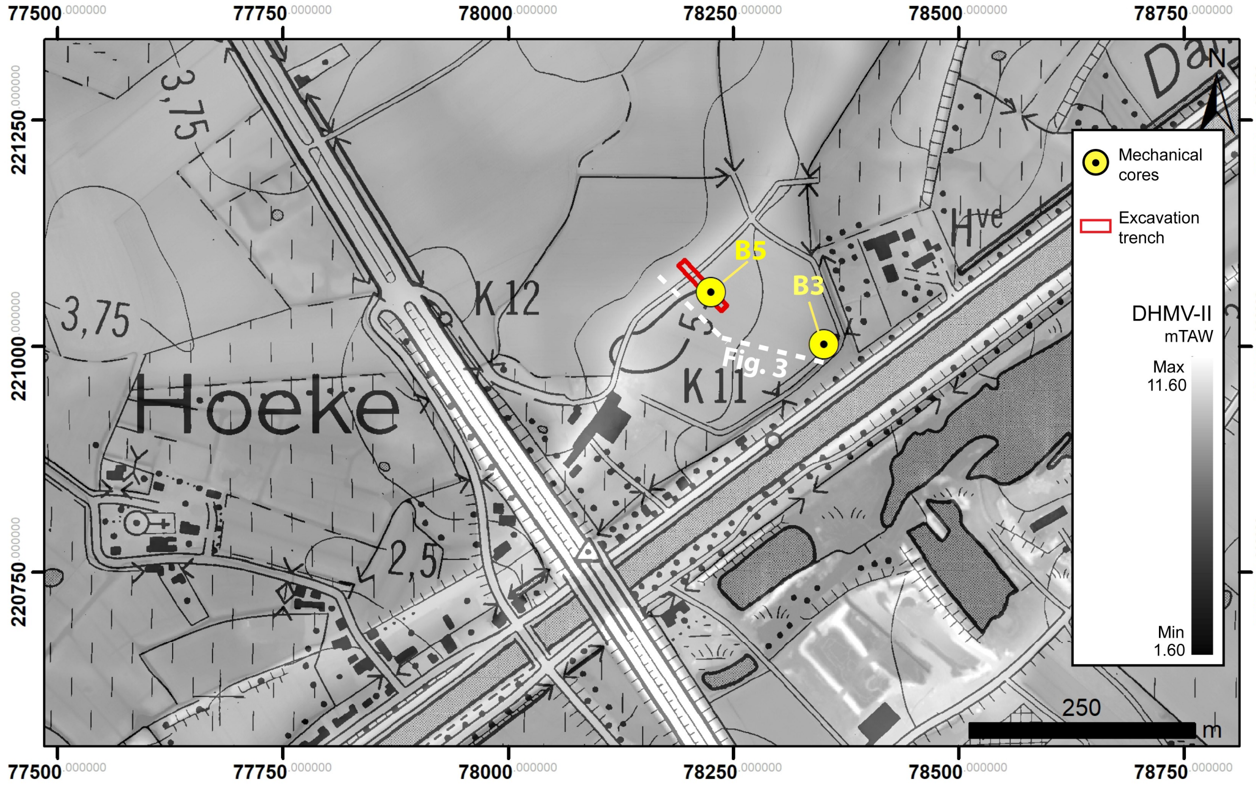

Figure 2. Study area of Hoeke with the location of the cores B3 and B5 (yellow circle) that were studied for ecological data in this paper. The white dashed line corresponds to the transect displayed in Figure 3. TAW = *Tweede Algemene Waterpassing* (Belgian Ordnance Datum).

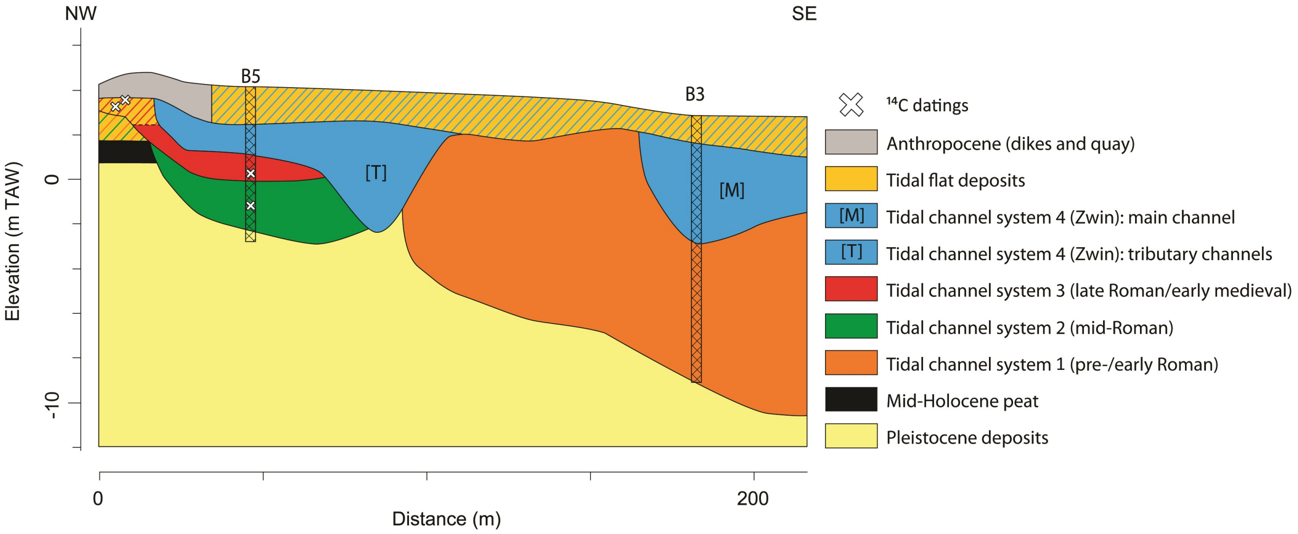

Figure 3. Schematic profile of the shallow subsurface near Hoeke with the location of cores B3 and B5. The sedimentary paleoenvironmental interpretation is based on the sedimentary analysis of data from undisturbed cores, observations made in the archaeological trenches, complimented with CPT-e data (the latter are calibrated on the basis of the core data). A more detailed description of the northwest section of the profile is given in figure 5 of Bogemans et al. (2024). The coloured stripes indicate what tidal channel system the tidal flat deposits belong to.

organic levels, together with silty clay levels intercalated in the different sediments of systems 3 and 4 in core B5, were also sampled for palynological analysis. The uppermost tidal flat deposits were not studied for palynological analysis, as spots of oxidation indicate poor pollen preservation. Macrobotanical analysis was only conducted on the very organic material accumulated in the accretion form deposits of system 2 between 4.56–4.92 m in core B5 (Fig. 5).

3. Methods

3.1. Diatom analysis

Each sampled level (~0.5 g) was macerated for standard diatom analysis using H_2O_2 to remove organic material (Battarbee, 1986). At least 400 valves were counted using a ZEISS Axio Imager A1 transmitted light microscope at magnification 1000x (numerical aperture 1.3). The identification mainly follows Witkowski et al. (2000) and Lange-Bertalot et al. (2017) and the detailed taxonomy is given in Appendix 1 (see Supplementary material). The nomenclature was verified with AlgaeBase (Guiry & Guiry, 2024). The diatoms were classified according to life form and salinity preferences following the methodology developed by Vos & de Wolf (1993).

3.2. Palynological analysis

About 1 mL of sediment was macerated following standard procedure for pollen analysis using HCl, KOH and HF treatments and acetolysis (Moore et al., 1991). The pollen concentration was calculated through the addition of *Lycopodium* tablets (batch number 100320201, X = 14 285, Appendix 2 in Supplementary material). The palynomorphs were analysed using a ZEISS Axio Imager A1 transmitted light microscope at magnification 400x (numerical aperture 0.75).

The identification and nomenclature of the pollen and spores follow Moore et al. (1991) and Beug (2004), while non-pollen palynomorphs (NPPs) follow Miola (2012) and references therein, and Shumilovskikh et al. (2022). The pollen sum, used as a base for percentage calculations, includes only terrestrial pollen grains, for which at least 400 grains were counted. Other observed palynomorphs such as pollen grains from aquatic environments, spores and NPPs were also counted but not included in the pollen sum.

3.3. Macrobotanical analysis

About 1800 mL of sediment was sieved over metal screens with a 500 µm and 250 µm mesh size. Material was picked under a binocular microscope Euromex ZE.1624 with magnification 10–45x. Macroremains of vascular plants have been identified using Cappers et al. (2006), Grosse-Brauckmann & Streitz (1992), Knörzer (2009) and a personal reference collection. Nomenclature of the vascular plants follows Lambinon et al. (2004). The classification of the ecological groups follows Runhaar et al. (2004).

3.4. Data analysis

The diatom and palynological assemblages are plotted on percentage diagrams using Tilia (Grimm, 2020). Principal Component Analysis (PCA) was applied to both diatom and palynological records using Canoco (Ter Braak & Šmilauer, 2012) to interpret variation patterns in diatom succession through time. All levels were included in the PCA, except the diatom sample at 0.26 m in core B3, which represents an outlier with a very different species composition (see section 4.1.), related to distinctly different environmental conditions. All the species counted in both diatom and palynological analyses were included in the PCA, but for the readability of the figures, the number of species plotted was limited to the 50 best fitted species to the first two axes. The levels were classified according to lithology and the architectural elements defined by Bogemans & Heyvaert (2023).

4. Results

4.1. Diatom assemblages in core B3

The channel s.s. deposits (systems 1 and 4, Fig. 4) and the overlying tidal flat deposits are dominated by marine (tycho) planktonic diatoms (~61–94%, Fig. 6). *Delphineis minutissima* (~26%) and *Cymatosira belgica* (~21%) are the dominant species. *Delphineis surirella*, *Paralia sulcata* and *Rhaphoneis amphiceros* are present in lower percentages (<8%). In addition, a large variety of marine/brackish epipsammic species (e.g.

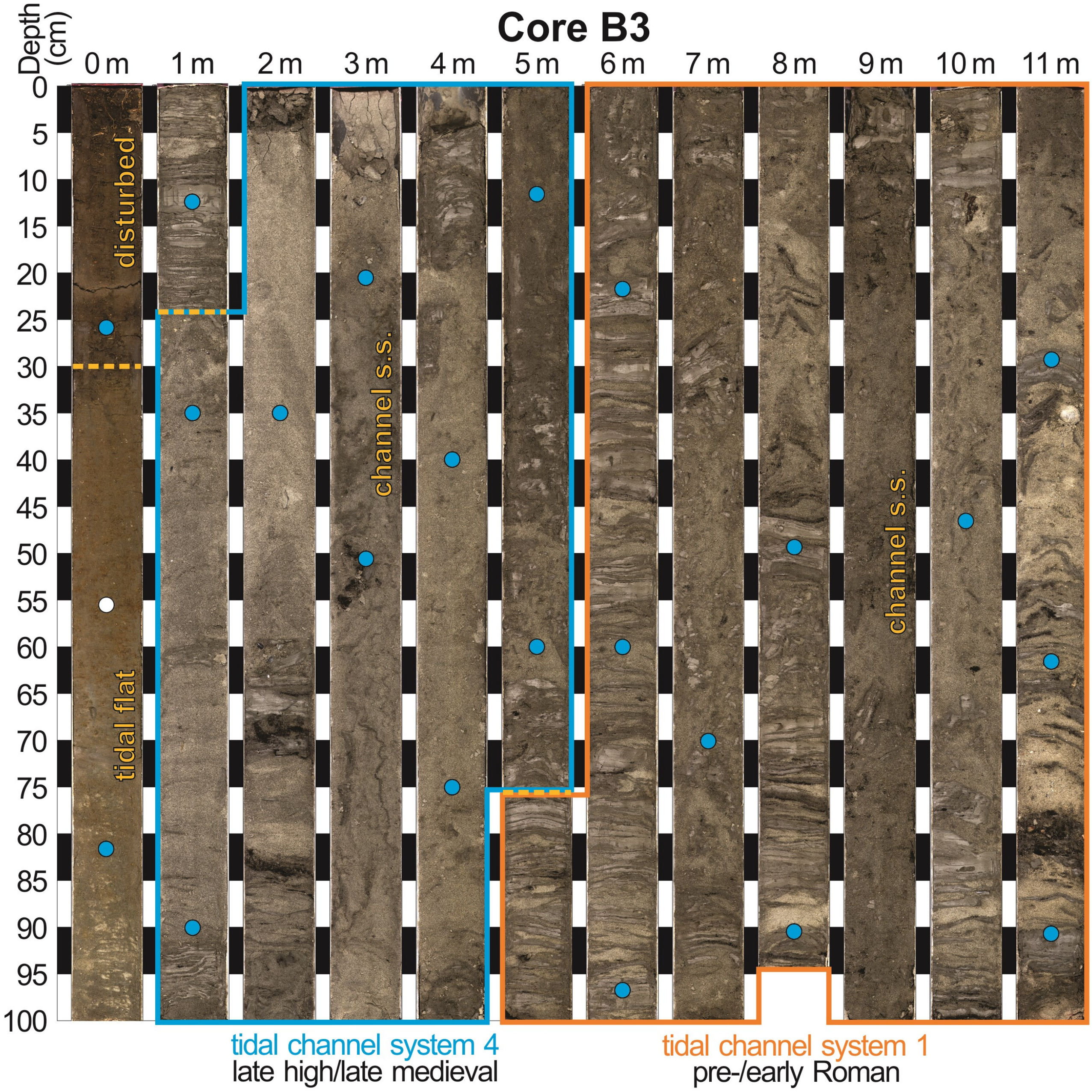

Figure 4. Location of the samples taken at 22 levels for diatom analysis (blue circles) in the depositional environments in core B3 (12 m deep) and their associated tidal channel systems. White circle: non-productive sample.

Navicula perminuta group and *Plagiogrammopsis sigmoidea*) are observed in lower percentages (~2–24%).

The diatoms from the tidal flat sediments at 0.56 m were not counted because of the poor preservation of the valves, most likely due to dissolution. Although the uppermost disturbed deposits at 0.26 m hold fewer valves, they display an entirely different diatom assemblage than all lower levels, namely a reduction of the marine (tycho)planktonic species (~7%) and a dominance of brackish/freshwater species (~74%), mostly represented by *Gedaniella* cf. *flavovirens* (~30%) and species belonging to the genus *Planothidium* (~23%) and *Gomphonema* (~10%). The brackish epipelic *Navicula cincta* is also frequent (~6%). The diatom assemblage in this disturbed layer clearly points to eutrophic conditions.

4.2. Diatom assemblages in core B5

Marine (tycho)planktonic diatoms (~74–93%) dominate the sedimentary deposits in the three different tidal channel systems (2, 3, and 4, Fig. 5) and in the tidal flat deposits in core B5 (Fig. 7), while a multitude of marine/brackish epipelic and epipsammic diatoms are present in lower percentages (~4–20%). Five marine tychoplanktonic species (*Cymatosira belgica*, *Delphineis surrirella*, *D. minutissima*, *Paralia sulcata* and *Rhaphoneis amphiceros*) dominate the diatom assemblages in core B5, although their ratio varies within the different depositional entities.

The accretion form deposits (system 2, Fig. 5) and the overlying channel s.s. deposits (system 3) display similar diatom assemblages dominated by *Cymatosira belgica* (~23%), *Delphineis surirella* (~16%) and *D. minutissima* (~13%). The accretion form deposits (system 3), the abandoned/low energy channel deposits (system 4) and the level at 1.54 m in the tidal flat deposits are dominated by *Delphineis minutissima* (~34%) and *Cymatosira belgica* (~20%). Finally, *Paralia sulcata* (~28%) and *Cymatosira belgica* (~23%) are dominant in the two uppermost sampled levels at 0.65 m and 1.06 m in the tidal flat deposits. The contribution of epipsammic and especially

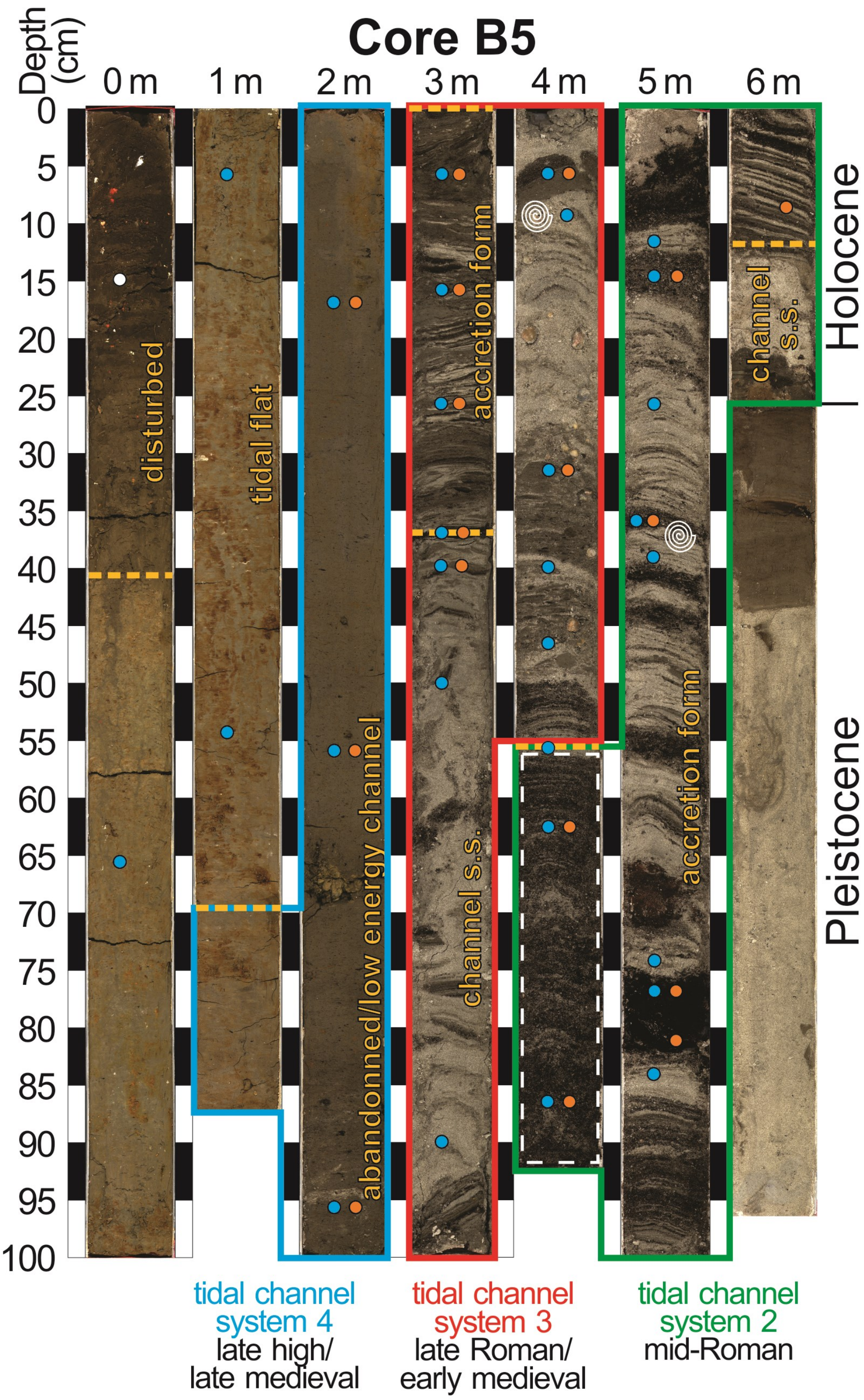

Figure 5. Location of the samples taken at 29 levels for diatom analysis (blue circles) and at 17 levels for palynological analysis (orange circle) in the depositional environments in core B5 (7 m deep) and their associated tidal channel systems. White circle: non-productive sample. The white dashed line between 4.56 and 4.92 m corresponds to the location of the macrobotanical remains that were analysed. The two shells analysed for radiocarbon dating are indicated at levels 4.10 and 5.37 m.

epipelic species is slightly higher in the accretion form deposits than in the channel deposits.

4.3. PCA of diatom assemblages in cores B3 and B5

Axis 1 explains about 20% of the variation in the data and Axis 2 explains about 12%. The levels taken from the different architectural elements in cores B3 and B5 plot rather separately but do not show clusters with a specific lithology (Fig. 8). The channel s.s. deposits (systems 1 and 4) in core B3 plot close to each other and are characterised by a higher contribution of marine/brackish epipsammic species such as *Plagiogrammopsis minima*, *Biremis lucens* and *Catenula adhaerens*. The marine (tycho)planktonic *Brockmanniella brockmannii*, *Plagiogrammopsis vanheurckii* and *Thalassiosira angulata/decipiens* also characterise both channel s.s. deposits in core B3. The marine/brackish epipsammic *Navicula perminuta* group seems more typical of the oldest channel s.s. deposits. Also, the marine tychoplanktonic *Odontella aurita* and *Delphineis minutissima* seem more specific to the channels s.s. deposits of system 1, while *Ralfsiella smithii* and *Campylosira cymbelliformis* are more prevalent in the channel s.s. deposits of system 4.

The sedimentary environments are well delimited in core B5. The levels from the channel s.s deposits (system 3) belong to one group mostly represented by heavily silicified diatoms such as the marine planktonic *Paralia sulcata* and *Podosira stelligera* and the tychoplanktonic *Rhaphoneis amphiceros*,

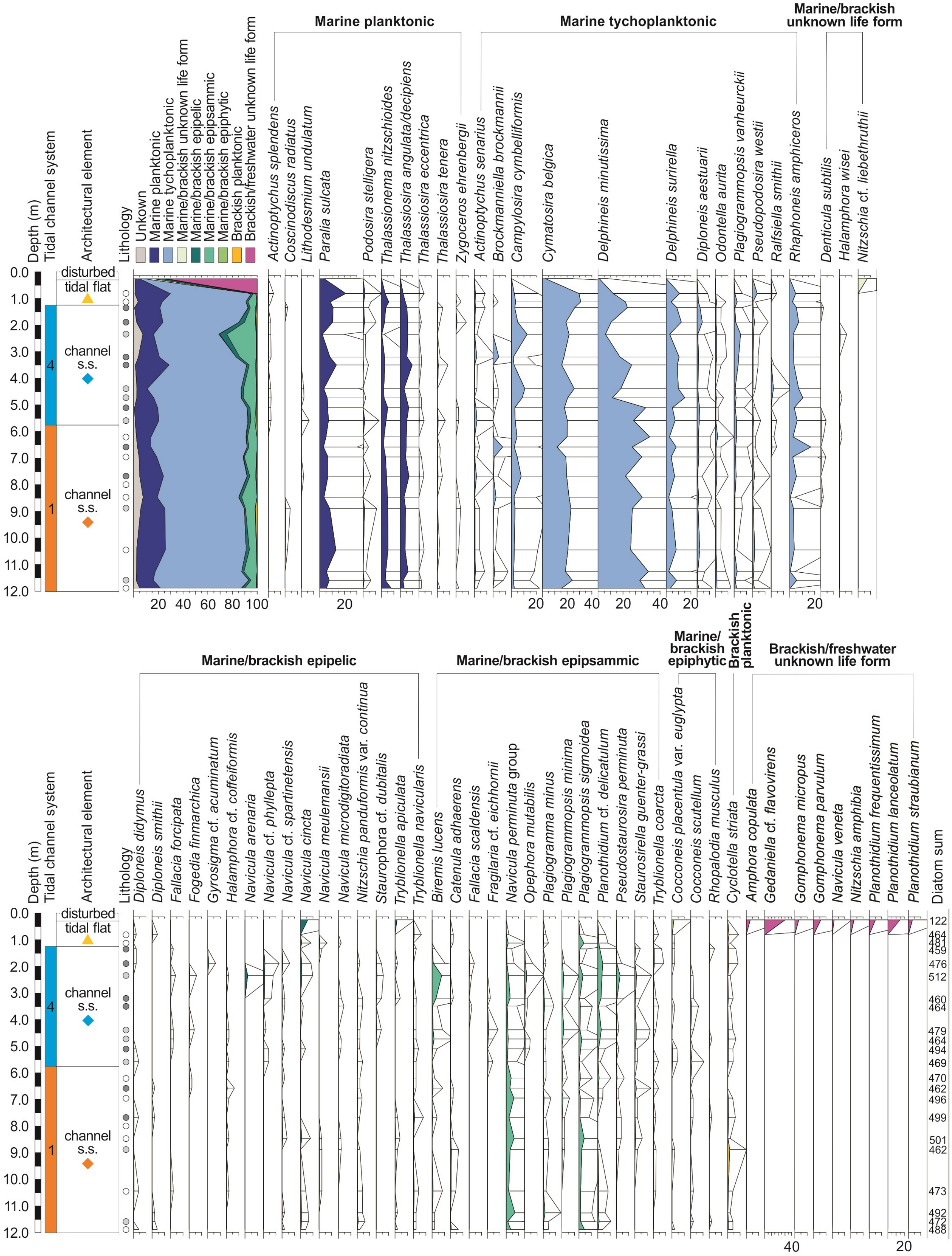

Figure 6. Percentage diatom diagram of core B3 (exaggeration x10, selected taxa) following the classification of Vos & de Wolf (1993). The legend of the lithology is given in Figure 8. The coloured geometrical symbols are specific to each architectural element within a tidal channel system and are used in the PCA analysis in Figure 8.

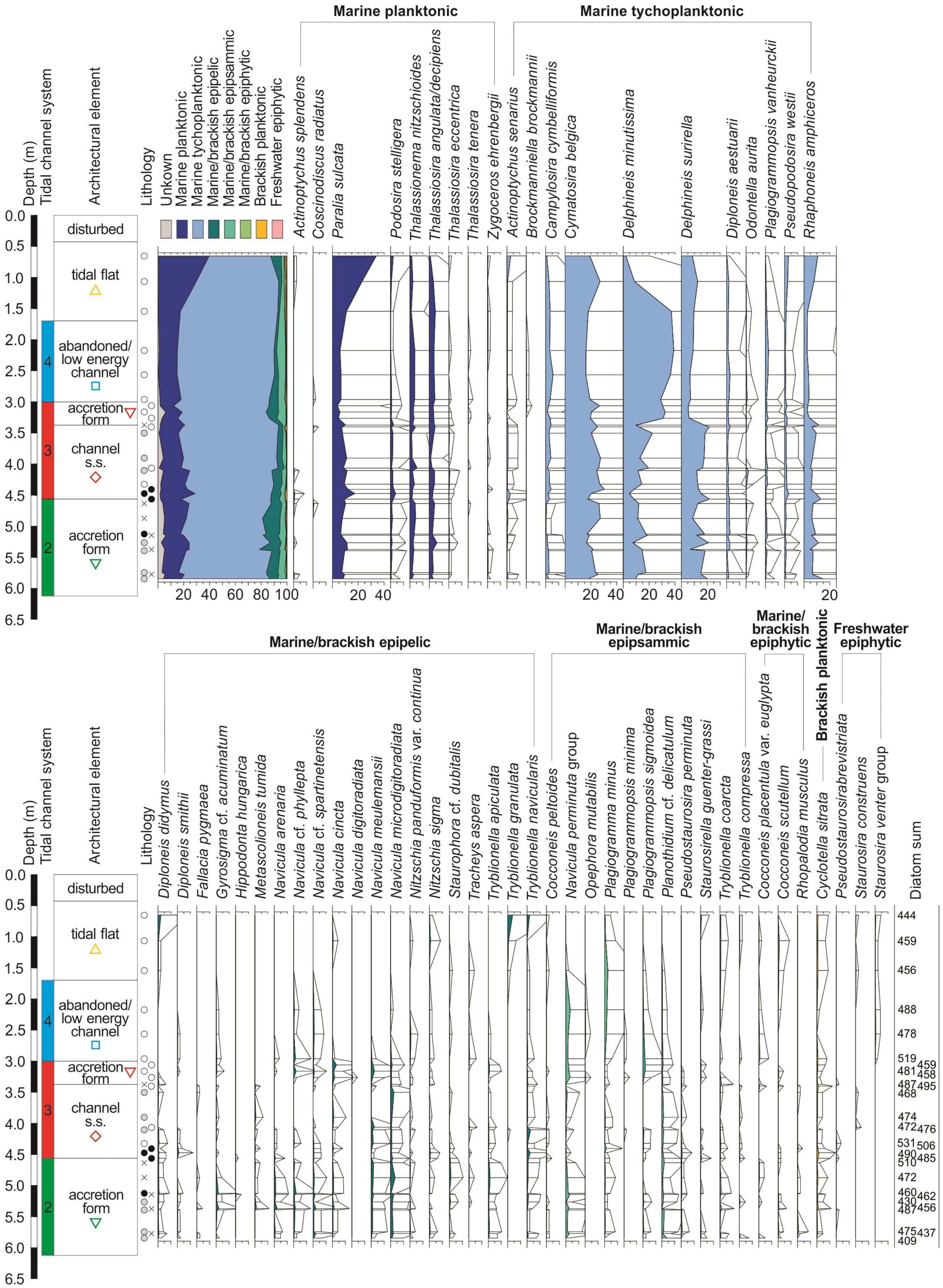

Figure 7. Percentage diatom diagram of core B5 (exaggeration x10, selected taxa) following the classification of Vos & de Wolf (1993). The legend of the lithology is given in Figure 8. The coloured geometrical symbols are specific to each architectural element within a tidal channel system and are used in the PCA analysis in Figure 8.

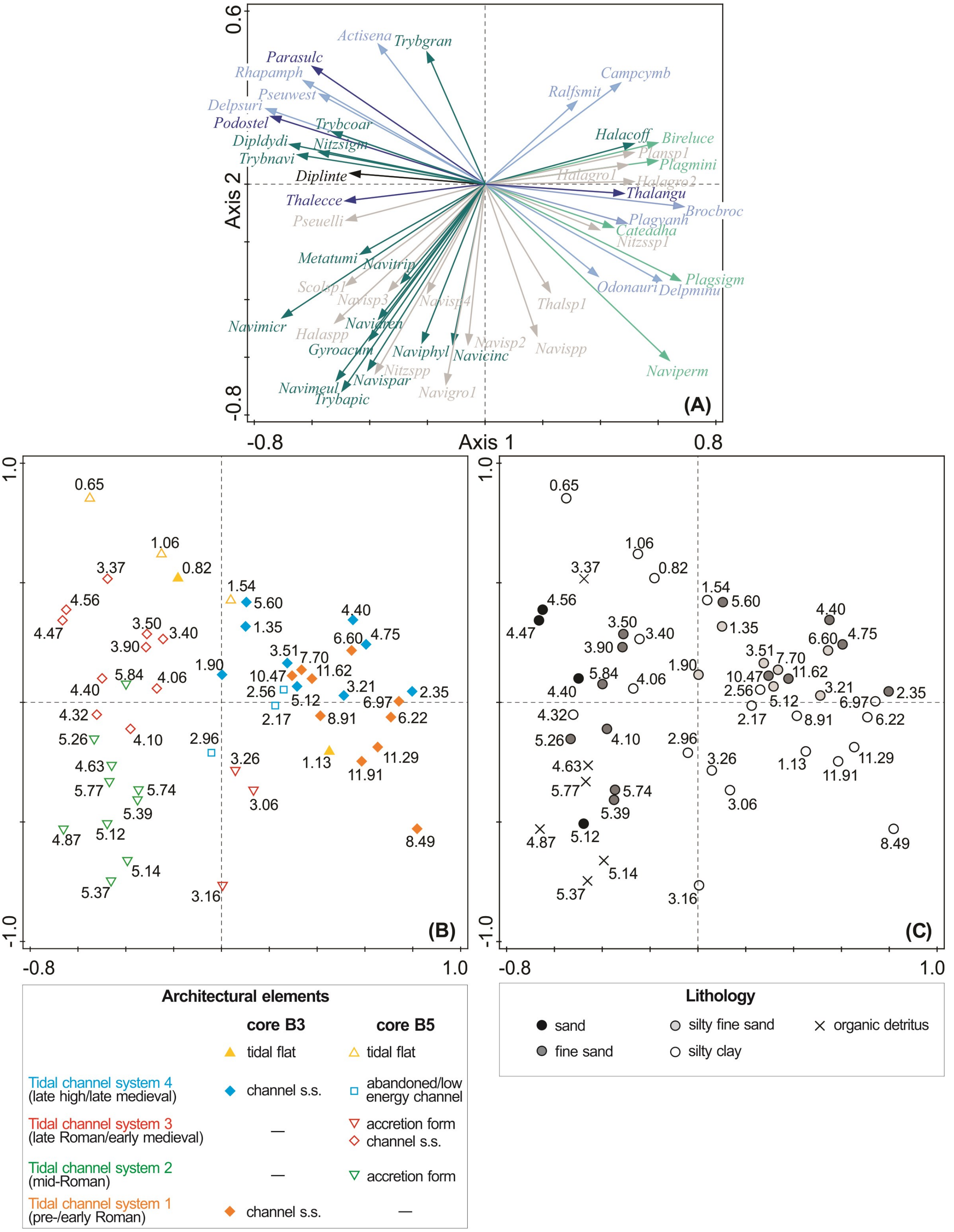

Figure 8. PCA plot of the 50 best-fit diatoms (**A**) in relation to the architectural elements (**B**) and lithology (**C**) in cores B3 and B5. The numbers plotted correspond to depth (m) and the colours of the arrows follow the ones used for the ecological groups in the percentage diatom diagram in Figure 7.

Delphineis surirella and *Pseudopodosira westii*. Interestingly, *Delphineis surirella* and *D. minutissima*, which are dominant, display a negative correlation. The marine epipelic diatoms *Diploneis didymus*, *Tryblionella navicularis*, *T. coarctata* and *Nitzschia sigma* also characterise these channel s.s. deposits.

The levels from both accretion form deposits (systems 2 and 3) plot close to each other in another group and are mostly represented by marine/brackish epipelic species that belong mostly to the genus *Navicula* (e.g. *N. meulemansii*, *N.* cf. *phyllepta*, and *N. cincta*), together with other epipelic species, such as *Gyrosigma* cf. *acuminatum* and *Tryblionella apiculata*. The lowest level at 2.96 m in the abandoned/low energy channel deposits (system 4) plots together with the underlying accretion form deposits (system 3), while the two upper levels at 2.56 m and 2.17 m in the abandoned/low energy channel deposits plot close to the channel s.s. deposits (systems 1 and 4) present in core B3.

Finally, the levels taken from the tidal flat deposits in both cores seem more characterised by the marine tychoplanktonic *Actinoptychus senarius* and *Paralia sulcata*, as well as by the marine epipelic *Tryblionella granulata*, except for level 1.13 m in core B3 which plots more closely to the channel s.s. deposits (systems 1 and 4) of core B3.

4.4. Palynological assemblages in core B5

The pollen assemblages from the organic levels and the silty clay levels taken throughout the sedimentary record in core B5 (Fig. 9) are dominated by trees and shrubs (~55–81%). *Corylus* (~14–36%), *Alnus* (~9–22%), and *Quercus* (~8–14%) are the most abundant taxa. Other frequent trees include *Betula* (~7%) and *Pinus sylvestris* (~4%). Although present in low percentages on average (<2%), some trees display peaks in the organic level at 5.82 m in the accretion form deposits (system 2), such as *Tilia* (~5%), *Ulmus* (~3%), and *Fraxinus excelsior* (~3%). Heathland shrubs are frequent (~2–14%) and are mostly represented by *Calluna vulgaris*, which shows two peaks: the first (~10%) together with *Vaccinium* type (~4%) in the organic level at 5.82 m, and the second (~9%) in the silty clay level at 3.26 m in the accretion form deposits (system 3). Herbs reach on average ~19% in the organic layers in the accretion form deposits (system 2), with a minimum of ~5% at 5.82 m, and gradually increase to ~33% from 4.32 m onward in the silty clay intercalations present within the entities of systems 3 and 4. This is especially visible for Chenopodiaceae (~3% in system 2 vs ~8% in systems 3 and 4). Furthermore, herbs are dominated by Poaceae (~3–22%), while Cyperaceae are also frequent (~1–5%). From 3.26 m in the accretion form deposits (system 3) and in the overlying abandoned/low energy channel deposits (system 4), other herbs have become more common but still only in small percentages (<2%), such as *Artemisia*, Asteraceae-Liguliflorae, Cerealia type, Brassicaceae, and *Senecio* type.

Aquatic taxa are mostly characterised by *Sparganium* type (~2%). Spores are mostly represented by Filicales and *Sphagnum*, and to a lesser extent by *Pteridium aquilinum*. Some Filicales were identified as *Thelypteris palustris* (~1%). Filicales and *Sphagnum* display opposite peaks in both accretion form deposits (systems 2 and 3). *Sphagnum* displays a peak of ~53% at 5.82 m (system 2), whereas Filicales reach only ~9%. Filicales is more abundant (~30%) in the upper accretion form deposits (system 3), together with *Pteridium aquilinum* (~3%), while *Sphagnum* is present in lower percentages (~3%). The fungus type HdV-13 (cf. *Entophlyctis lobata*, ~5%) and the protozoa types HdV-31 (*Amphitrema flavum*, ~5%) and HdV-32 (*Assulina*, ~2%) display peaks at 5.82 m. The protozoa type HdV-700 (linings of foraminifera, ~2%), acritarchs (~1%), and algae (e.g. *Pediastrum* spp., ~5%, and dinoflagellate cysts, ~3%) become more frequent from 4.32 m onward in the silty clay intercalations present in the entities of systems 3 and 4, except in the organic level at 3.37 m.

4.5. PCA of the palynological assemblages in core B5

Axis 1 explains about 35% of the variation in the palynological data from core B5, and Axis 2 about 13%. Both architectural elements and lithology display well-delimited clusters (Fig. 10). The levels of silty clay plot separately from organic detritus, with distinct palynological assemblages, except for level 4.06 m where the silty clay intercalation is also rich in fine organic detritus; it plots together with the organic detritus.

The organic samples display a cluster for the accretion form deposits (system 2), except level 5.82 m, which plots separately. Levels 3.37 m and 4.06 m from the channel s.s. deposits (system 3) plot close to the organic levels within the lower accretion form deposits (system 2). The organic deposits are globally characterised by *Sphagnum*, *Botryococcus braunii*, and *Corylus*. The organic level at 5.82 m in the accretion form deposits (system 2) is more characterised by Ericaceae (including *Calluna vulgaris* and *Vaccinium* type) and *Ulmus* and *Tilia*, as well as by the fungi types HdV-13 (cf. *Entophlyctis lobata*), HdV-31 (*Amphitrema flavum*), and HdV-32 (*Assulina*). *Alnus*, *Taxus baccata*, and *Salix* seem to be more typical of the other organic levels.

The silty clay intercalations plot opposite to the organic detritus and are divided into two clusters: the first is specific for the accretion form deposits (system 3), and the second includes two levels from the channel s.s. deposits (system 3) and the abandoned/low energy channel deposits (system 4). Both clusters are mostly characterised by dinoflagellate cysts, type HdV–700 (linings of foraminifera), and Chenopodiaceae, together with *Pediastrum* spp., Asteraceae–Liguliflorae, and *Senecio* type. *Pinus sylvestris*, *Fagus sylvatica*, *Carpinus betulus*, and Cerealia type are also specific for these deposits, although to a lesser degree.

Additionally, the first cluster differs by taxa from or nearby aquatic environments, such as *Menyanthes trifoliata*, algae (e.g. types HdV-61 *Mougeotia* cf. *gracillima* and HdV-315 *Spirogyra* sp.), as well as Cyperaceae. The second cluster is more represented by herbs such as Poaceae, Brassicaceae, and *Polygonum aviculare*. Finally, *Quercus* seems to be equally significant in both silty clay and organic detritus intercalations from the two accretion form deposits (systems 2 and 3).

4.6. Macrobotanical assemblages

Two groups of macrobotanical remains were identified based on differences in preservation: one group had very good preservation, while the other had poor preservation (Table 1). Within the first group, two categories of taxa are observed. The first category holds seven types of mostly freshwater plants. Only *Hippuris vulgaris* and some species of the group *Ranunculus subg. Batrachium*, such as *Ranunculus baudotii* and *Ranunculus trichophyllus*, grow in brackish water (Runhaar et al., 2004). The second category includes three types, namely *Atriplex* sp., *Glaux maritima* or *Anagallis arvensis*, and *Ranunculus sceleratus*. More than 90% of the specimens belong to undifferentiated *Atriplex* sp. Seeds/fruits of species such as *Urtica dioica*, *Chenopodium album*, *Stellaria media*, *Persicaria* div sp., mostly very abundantly present in deposits of ruderal vegetations, are here totally absent. All the poorly preserved specimens in the second group belong to species that are present in peat, e.g. *Alnus glutinosa* and *Menyanthes trifoliata* (Allemeersch, 1991). The moss leaves of *Sphagnum palustre* and *Drepanocladus* sp. are also related to peat.

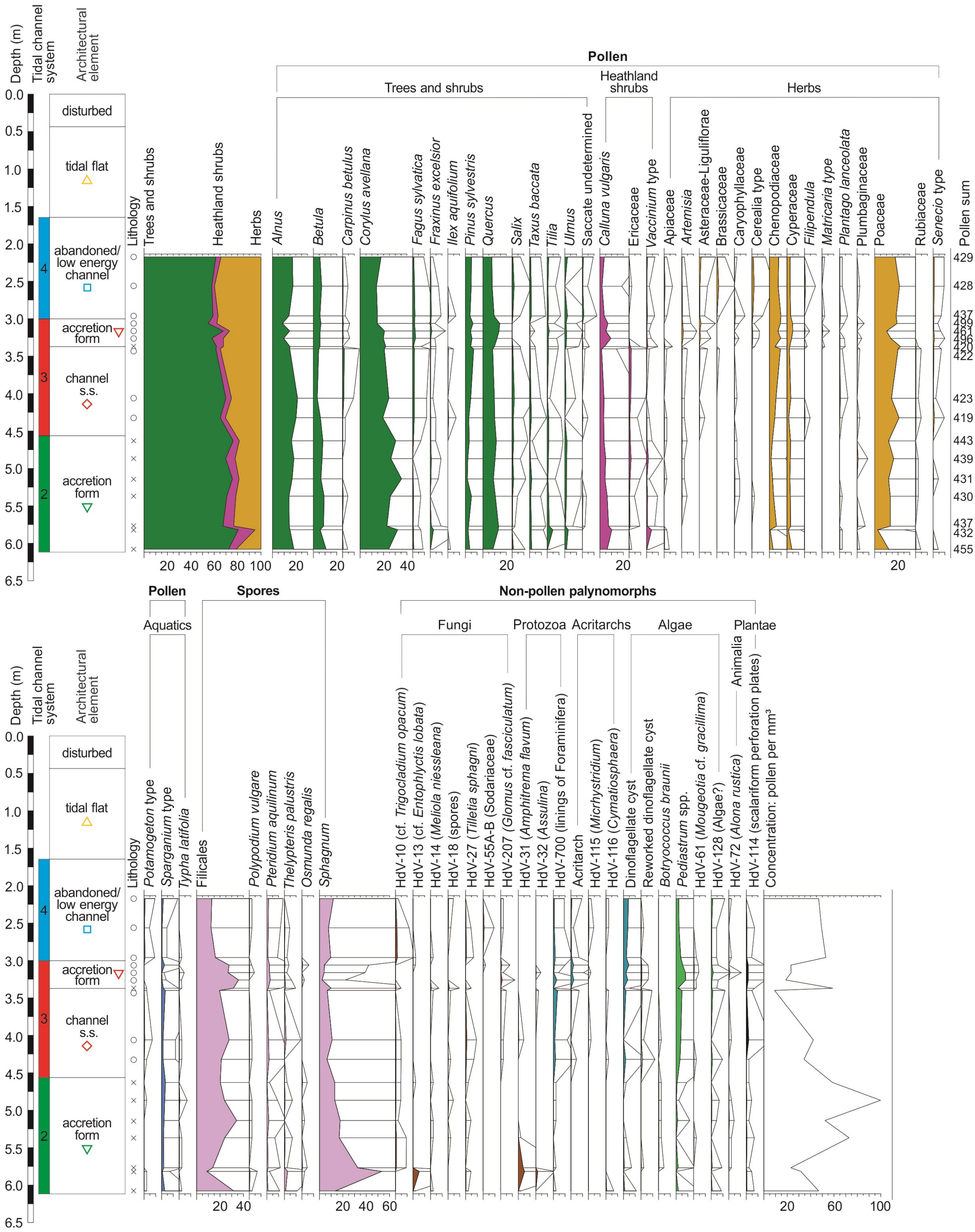

Figure 9. Percentage pollen diagram of core B5 (exaggeration x10, selected taxa). The legend of the lithology is given in Figure 10. The coloured geometrical symbols are specific to each architectural element within a tidal channel system and are used in the PCA analysis in Figure 10.

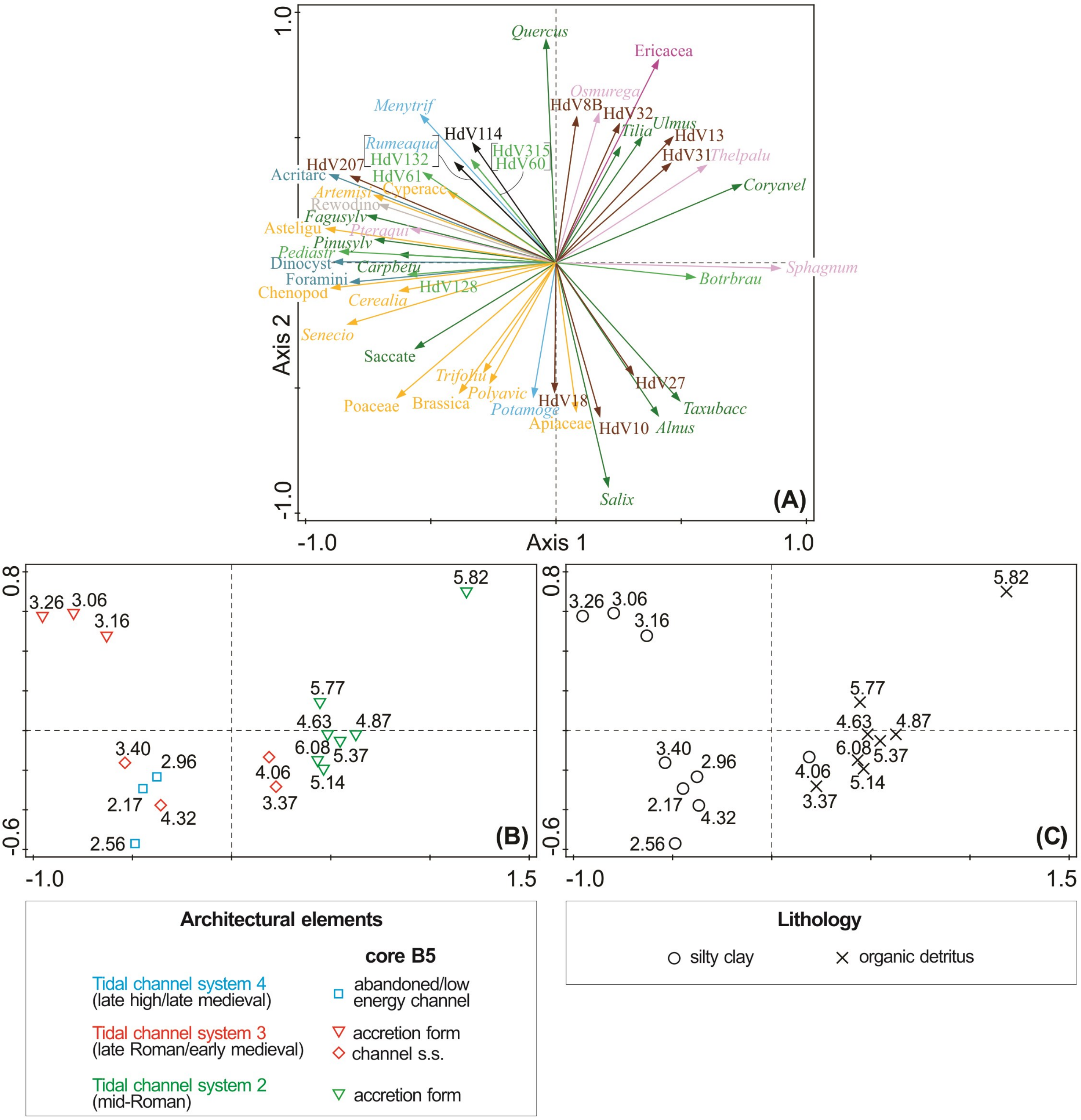

Figure 10. PCA plot of the 50 best-fit palynomorphs (**A**) in relation to the architectural elements (**B**) and lithology (**C**) in core B5. The numbers plotted correspond to depth (m) and the colours of the arrows follow the ones used for the ecological groups in the percentage pollen diagram in Figure 9.

5. Discussion

5.1. The evolution of the diatom assemblages during the Late Holocene

Diatom analysis has been widely used in palaeoenvironmental reconstruction of the Holocene coastal sequence in Belgium in the western coastal plain (Denys, 1985, 1989, 1994, 1999) and in east Flanders (Denys & Verbruggen, 1989), as well as in the Netherlands (Vos & de Wolf, 1993, 1994, 1997). No information however is available for the former Zwin region, where ecological data related to diatoms (and palynomorphs) are investigated for the first time in this study in the different tidal channel systems. Diatoms are usually studied in cores located adjacent to (and not directly in) tidal channels and inlets. It is important to stress that the infill of the tidal channel systems does not represent the environments where the diatoms actually lived but where the empty valves, behaving like mineral sediment particles, were transported into and deposited.

The diatom assemblages from both cores are dominated by marine/brackish planktonic and tychoplanktonic species. In the Scheldt estuary, the dominance of these diatoms was always indicative of a usually less dynamic depositional environment with high silt content (Sabbe & Vyverman, 1991). Vos & de Wolf (1993) assume that marine planktonic and tychoplanktonic diatoms live in the offshore zone and that they are transported by tidal currents further inland, thus considering them to be allochthonous in the Dutch Holocene coastal deposits. Marine (tycho)planktonic diatoms outnumber local communities (benthic and epiphytic groups) in the very dynamic environments of coastal waters, tidal channels and inlets, but also sometimes in other sedimentary environments influenced

Table 1. Results of the macrobotanical analysis of a sample between 4.56 and 4.92 m in core B5. Sieved on 500 and 250 µm mesh size; sample volume 1800 mL; sp = sporadic; ../.. = whole specimens/fragments. All remains are seeds unless mentioned differently.

	+4.56 to +4.92 m
Very good preservation	
Open water and riparians	
Ranunculus subg. Batrachium	6
Alismataceae	1
Nymphaea alba	3
Potamogeton sp.	10
Sparganium sp.	1
Myriophyllum spicatum	1
Hippuris vulgaris	2
Wet to moist pioneers, nutrient-rich brackish, open to short vegetation	
Atriplex sp.	31
Glaux maritima or Anagallis arvensis	2
Ranunculus sceleratus	1
Bad preservation	
Eutrophic to mesotrophic peat	
Alnus glutinosa	10
Frangula alnus	1
Betula pendula/pubescens	4
Rubus fruticosus	3
Menyanthes trifoliata	8/5
Eleocharis palustris/uniglumis	3
Hydrocotyle vulgaris	2
Silene flos-cuculi	2
Mentha aquatica/arvensis	3
Cladium mariscus	2
Lycopus europaeus	1
Polygonaceae	2
Cyperaceae	28
Unclear origin	
Cirsium cf. *vulgare*	1
Urtica dioica	1
Ranunculus acris/repens	6/1
Unknown ecology	
Indet.	3
Viola sp.	1
Mosses from mesotrophic peat	
Sphagnum palustre	sp
Drepanocladus sp.	sp
Animals	
Trichoptera	1

by tides (e.g. intertidal and supratidal areas), which can hinder local palaeoecological reconstruction (Vos & de Wolf, 1993).

Following the classification of ecological groups and sedimentary environments developed by Vos & de Wolf (1993), the dominance of marine tychoplanktonic and planktonic species in this study confirms the presence of open marine tidal channels that were strongly influenced by the sea. In such context, non-diatom criteria are often required to help the interpretation of the palaeoenvironmental conditions (Vos & de Wolf, 1993, 1997). Here, the results of the diatom analysis were combined with sedimentological characteristics. Furthermore, although marine tychoplanktonic and planktonic diatoms are dominant (Figs 6 & 7), it was still possible to differentiate the depositional entities in cores B3 and B5 based on diatom analysis, as they plot in distinct clusters (Fig. 8).

The pre-/early Roman channel s.s. deposits (system 1) in core B3 are characterised by clay deposits with marine tychoplanktonic, as well as epipsammic species, which originally live on sandflats and in more exposed places (Sabbe & Vyverman, 1991; Vos & de Wolf, 1993).

The mid-Roman to early medieval accretion form deposits in core B5 consist of an alternation of fine sand and organic detritus (system 2) and silty clay (system 3). Although the accretion form deposits hold different sediments, they are both more represented by epipelic species that are typical for mudflats and dominant in sheltered habitats. These epipelic diatoms must have been part of the local environment in the accretion form deposits during periods of lower energy, while a part might have been eroded and transported from nearby mudflats. In between the two accretion form deposits, the late Roman/early medieval channel s.s. deposits (system 3), composed of more sandy material, are characterised by strongly silicified marine (tycho)planktonic species, together with some epipelic species, reflective of more dynamic conditions, as well as mudflats in the vicinity.

The medieval Zwin main channel deposits in core B3 (system 4) and the tributary channel deposits in core B5 (system 4) share similar diatom assemblages, and thus ecological conditions. Described as an abandoned/low energy channel by Bogemans & Heyvaert (2023), the tributary channel deposits are, however, characterised by marine (tycho)planktonic and epipsammic diatoms, which typically live in more exposed areas. The infill of the tributary channel consists of clay deposits and most probably received sediments and diatoms from a more dynamic environment such as sandflats located further away or from the main tidal channel recorded in core B3. The presence of a harbour along the tributary, where ship repairs occurred, suggests that the area must have been less dynamic compared to the main tidal channel.

Aerophilous diatom assemblages that are adapted to intermittently wet conditions are usually abundant, together with marine planktonic and tychoplanktonic diatoms in supratidal environments (Vos & de Wolf, 1993). However, aerophilous diatoms were rare in the tidal deposits, i.e. *Navicula cincta* <1%. The tidal flat deposits in cores B3 and B5 consist of clay that is characterised by very similar diatom assemblages, with marine/brackish epipelic species of the high mudflat (*Diploneis didymus* and *Tryblionella navicularis*) together with marine (tycho)planktonic species (*Paralia sulcata* and *Pseudopodosira westii*). Such assemblages were also described in the western coastal plain of Belgium where intertidal sedimentation occurred (Denys, 1994, 1999). This suggests that marine conditions persisted in a more sheltered area. The reduction of the tidal influence in this area is most likely linked to the large-scale embankment that took place during the High and Late Middle Ages (Tys, 2013; Soens et al., 2014; Trachet et al., 2015). In addition, the much lower proportions of marine autochthonous diatoms (epipelic) compared to allochthonous diatoms (planktonic and tychoplanktonic) suggest that the sedimentation occurred at a fast rate (Denys, 1999).

Level 0.26 m in core B3 is part of the plough layer, the top section of tidal flat deposits that has been disturbed by recent agricultural activity and hence reflects the local environmental conditions, namely eutrophic conditions and a decrease of the marine influence after embankment in more recent periods.

5.2. Terrestrial environments in tidal channel systems

The pollen spectrum shows rather homogeneous terrestrial assemblages for the period from mid-Roman to late medieval times (systems 2, 3, and 4, Fig. 9). The sedimentary deposits are part of a dynamic environment, in which clastic sediment and organic material were transported in the tidal channel systems. Palynological data give us a general picture of the organisms and remains accumulated in the sedimentary deposits but do not provide a precise palaeoecological reconstruction of the surrounding environment. For example, the dominance of trees and shrubs does not necessarily reflect a woodland-dominated landscape during the entire period under study; instead, the sedimentary deposits include reworked material that can be much older than the landscape present at the time of deposition.

The tidal channel systems received material from different sources. The organic layers in accretion form deposits of system 2 (mid-Roman period) are mainly associated with reworked peat, especially at 5.82 m, which has most probably been eroded and transported via tidal activity through channels. Indeed, the deceleration of the relative sea-level rise (to about 0.70 m/ka around 5500–5000 a cal BP) and the development of coastal barriers and dunes had resulted in an almost closed-off tidal landscape in the region, which gradually became covered by peatlands (Vos & Van Heeringen, 1997; Vos, 2015; Baeteman, 2018; Allemeersch et al., 2023). The peat accumulated over 2000–3000 years and eventually became an oligotrophic bog with taxa such as *Sphagnum* and Ericaeae. Such taxa are typical of the organic material, which most probably comes from mid-Holocene peat.

The dryland trees and shrubs *Ulmus*, *Tilia*, and *Corylus avellana* also characterise the organic layers and were either part of the regional vegetation in the sandy inland at the time of peat growth or later at the time of tidal sediment deposition. This also applies to the wetland trees *Salix* and *Alnus*, which thrive in more humid environments. *Taxus baccata* was part of the carr vegetation in the coastal plain of Belgium during the deposition of the Subboreal biozone (the last half of the 5th and the 4th millenniums) and disappeared at the top of the Subboreal biozone (3rd millennium), when carr vegetation evolved into oligotrophic bogs (Deforce & Bastiaens, 2007). The peat deposits are rather thin at Hoeke (~1.20 m thick), and shallow tidal activity was sufficient to erode the stages of carr vegetation with *Taxus*.

The badly preserved macrobotanical remains between 4.56 and 4.92 m in the accretion form deposits (system 2, Table 1) are also associated with older eutrophic to mesotrophic peat, which has most probably been reworked via tidal activity. Moreover, the well-preserved freshwater plants were not growing in situ at this location in the accretion form deposits, as a mix of organic and clastic material in these deposits indicates regular marine tidal influence, confirmed by the two levels at 4.63 and 4.87 m that were also studied for diatom analysis. Given their very good preservation, they most likely originate from the nearby vegetation, such as on salt marshes where freshwater pools could have developed. The seeds and fruits of the freshwater taxa may have been subsequently dispersed by floating upon the surface of the water, in the water column, or by aquatic birds such as ducks and geese (Oberdorfer, 1979).

Despite some freshwater pools, a brackish environment remains characteristic of system 2. *Atriplex* sp. is dominant but could not be identified at the species level. The genus includes species such as *Atriplex patula*, which is a pioneer of very nutrient rich and rather wet soils, while the other *Atriplex* species are typical of brackish or even saltwater environments (Runhaar et al., 2004). In the absence of ruderal species, and with the type of material studied, the great number and nearly exclusive presence of *Atriplex* sp. within the group of pioneers indicates the presence of a brackish environment in the vicinity. The same problem occurs with *Anagallis arvensis* and *Glaux maritima*, which have very similar seeds that cannot be differentiated. *Anagallis arvensis* is more of a pioneer of nutrient-enriched wet soils, whereas *Glaux maritima* is present in brackish environments.

The silty clay layers within the tidal channel systems 3 and 4 are mostly characterised by marine NPPs such as acritarchs, dinoflagellate cysts, and lining of foraminifera, which are typical of marine tidal deposits. Pollen types group several species thriving in different ecological conditions. In such marine tidal environment, the pollen types of many herbs are most probably associated with halophytes that grow in salt marshes, such as Chenopodiaceae (incl. *Salicornia*, *Atriplex* and *Suaeda* species), *Senecio* type (*Aster tripolium*), and *Artemisia* (*Artemisia maritima*) (Storme et al., 2020). Plumbaginaceae group only two species (*Armeria maritima* and *Limonium vulgare*), which are also typical of salt marshes. On the other hand, the freshwater environment identified in the macroremains suggest that some pollen types might also be associated with freshwater wetland taxa, such as Poaceae (*Phragmites australis*) Cyperaceae (e.g. *Bolboschoenus*), as well as freshwater aquatics (*Sparganium* type), that were also part of the surrounding vegetation.

The dryland trees, *Fagus sylvatica* and *Carpinus betulus*, are more specific to the silty clay layers than the organic-rich layers. This might reflect the presence of beech-hornbeam woodland at the time systems 3 and 4 were active. Deforce et al. (2020) recently demonstrated the expansion of *Fagus* north of Belgium from about AD 600, associated with climatic conditions that became cooler and moister. Although in low percentages, *Fagus* does increase from 4.32 m onward, which corresponds to the phase in which the late Roman/early medieval tidal channel system 3 was active, a period that perfectly fits with the time of expansion of *Fagus* in the region, between AD 300 and 800 (Deforce et al., 2020).

Finally, it seems that already in the accretion form of system 3 (late Roman/early medieval times), as well as in the medieval tributary channel deposits of system 4 (late high/late medieval times), the entities were characterised by more herbs from grassland and from agricultural activity, suggestive of an open landscape. This can be linked to the reclamation of the coastal plain, which became embanked on a large scale and was used for agriculture and pasturing (Tys, 2013; Soens et al., 2014).

6. Conclusion

Ecological data were retrieved for the first time from sediment records of the former tidal channel systems in the Zwin region, spanning a period from pre-Roman to late medieval times. Although the tidal channel systems were dominated by allochthonous marine (tycho)planktonic diatoms that were transported from offshore, this research demonstrated that the sedimentary entities can be differentiated as they hold distinct diatom assemblages. These include marine/brackish epipsammic and epipelic diatoms, which indicate that the different tidal channel systems received material from mudflats and sandflats located further away. The pre-/early Roman channel s.s. deposits (system 1) consist of clay deposits that are mainly defined by epipsammic species originating from a dynamic environment located further away. The subsequent active tidal channel systems from the mid-Roman to the early medieval period (systems 2 and 3) include accretion form deposits that hold epipelic species, typical of more sheltered habitats. The channel s.s. deposits in between these accretion forms consist of more sandy material that is also characterised by epipelic diatoms, although different species, together with strongly silicified (tycho)planktonic diatoms, which are indicative of a more dynamic environment. The palynological assemblages are different in silty clay layers holding taxa typical of marine tidal deposits and organic layers mainly associated with reworked mid-Holocene peat, which has been eroded and transported via tidal activity. The macrobotanical remains included a poorly preserved group that is also associated with reworked peat, while the group with good preservation indicates the presence of brackish as well as freshwater plants, which were most probably growing in the vicinity. A beech-hornbeam woodland was probably part of the regional landscape from late Roman/early medieval times. During the later phases, the main and tributary tidal channels from the high and late medieval Zwin (system 4) share a similar aquatic ecology, with tychoplanktonic and epipsammic diatoms. Palynomorphs from grassland and possibly from agricultural activity in the tributary channel suggest an open landscape that can be linked to the reclamation and embankment of the coastal plain. The diatom assemblages in the tidal flat deposits overlying the deposits of the last tidal channel system of both cores suggest that the area rapidly silted up.

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Author contributions

Coralie André, Stephen Louwye and Wim De Clercq carried out the conceptualization and the realisation of this study. Wim De Clercq, Jan Trachet and Maxime Poulain provided the studied material. Coralie André acquired the ecological data (pollen and diatom analysis) and performed the statistical analysis. Guidance in diatom analysis was performed by Bart Van de Vijver and Koen Sabbe. Guidance in palynological investigation was carried out by Annelies Storme. Frieda Bogemans conducted the sedimentological analysis and Luc Allemeersch realised the macrobotanical analysis. The draft of the manuscript was written by Coralie André and Stephen Louwye and all authors read and approved the final manuscript.

Data availability

The diatom and pollen counts are available in Appendices 1 and 2 (see Supplementary material). The samples of this study are stored in the collection of the Geology Department at Ghent University.

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