

The Roman to medieval landscape transformation at Aardenburg (southern The Netherlands) based on palynology and diatom analysis

CORALIE ANDRÉ , DANTE DE RUIJSSCHER, WIM DE CLERCQ, FRIEDA BOGEMANS, BART VAN DE VIJVER, ANNELIES STORME AND STEPHEN LOUWYE

BOREAS



André, C., de Ruijsscher, D., De Clercq, W., Bogemans, F., Van de Vijver, B., Storme, A. & Louwye, S. 2024 (January): The Roman to medieval landscape transformation at Aardenburg (southern The Netherlands) based on palynology and diatom analysis. *Boreas*, Vol. 53, pp. 88–105. <https://doi.org/10.1111/bor.12640>. ISSN 0300-9483.

The region of Bruges (Flanders, Belgium) was an economic and cultural centre during the Late Middle Ages because it was connected to the North Sea via a large tidal inlet called the Zwin, along which smaller towns developed. One of these towns was Aardenburg (Zeeland, The Netherlands), which developed from a Roman *castellum* to become one of the important medieval towns in the hinterland of Bruges. Unfortunately, archaeological, historical and (palaeo) environmental data about the Roman to medieval evolution of the Zwin area are scarce. However, the continuous occupation of Aardenburg during the first millennium AD and its location on a Pleistocene sand ridge bordering the coastal plain provide a unique opportunity to investigate the natural dynamics of the coastal evolution and the interplay with the human impact that shaped the Zwin region before its heyday. The variable character of the depositional environments on the dynamic coastal plain makes local environmental studies essential for understanding larger patterns, which were previously reduced to a simplistic outdated model over the entire region. Palynological and diatom assemblages of two sequences in Aardenburg allow the reconstruction of the terrestrial and aquatic palaeoenvironments from the Middle Holocene to the high Middle Ages. The results reveal landscape evolution in relation to woodlands, peat bogs, coastal environments and human presence, consistent with previous regional landscape evolution. A distinct increase in marine influence during the Roman and early medieval periods, when human activities played a significant role, was followed by an increase in inland indicators from the high medieval period onwards. This evolution is in accordance with the expansion of the town and the reclamation of the coastal landscape as it evolved to become a cultural centre in the Late Middle Ages.

Coralie André (coralie.andre@ugent.be) and Stephen Louwye, Department of Geology, Ghent University, Krijgslaan 281-S8, B-9000 Ghent, Belgium; Dante de Ruijsscher and Wim De Clercq, Department of Archaeology, Ghent University, Sint-Pietersnieuwstraat 35, B-9000 Ghent, Belgium; Frieda Bogemans, Geological Survey of Belgium, Royal Belgium Institute of Natural Sciences, Jennerstreet, 131000 Brussels, Belgium; Bart Van de Vijver, Research Department, Meise Botanic Garden, Nieuwelaan 38, 1860 Meise, Belgium and Department of Biology, University of Antwerp, ECOSPHERE, Universiteitsplein 1, 2610 Wilrijk, Belgium; Annelies Storme, Ruben Willaert nv, Ten Briele 14.15, 8200 Sint-Michiels, Belgium; received 3rd May 2023, accepted 18th October 2023.

Bruges (Flanders, Belgium) and its hinterland flourished economically and culturally in the Late Middle Ages because of its connection with the marine trade network via a harbour system along the Zwin tidal inlet, which originated following a storm surge in AD 1134 (Brown & Dumolyn 2018). The environmental and human dynamics that shaped the Zwin region throughout the millennium preceding its heyday are not well understood because historical and archaeological sources for this region are very scarce. One of the few sites with archaeological and historical datasets for this period is Aardenburg (Zeeland, The Netherlands, Fig. 1), which developed from a 2nd and 3rd century AD Roman auxiliary fort (*castellum*) into one of the most important medieval towns in the hinterland of Bruges (De Vries 1968; de Melker 1987; van Dierendonck *et al.* 2013).

Situated at the edge of the coastal plain, it can be assumed that the environmental change in Aardenburg followed the general trend of coastal landscape development observed widely in the southern North Sea area. The ‘Dunkerque Transgression Model’ considered the alternation of transgressions and regressions as the driving force of geomorphological processes in the

entire region and was conveniently accepted until the 1980s. However, the model has been refuted, among other things, with the input of new archaeological and environmental data from different coastal areas along the North Sea (Rippon 2000; Baeteman 2013; Trachet *et al.* 2015). The study of the genesis of the coastal plain in The Netherlands by Vos & Van Heeringen (1997) and in Belgium by Baeteman (2005, 2007) followed a new model where environmental conditions are not assumed to have changed synchronously throughout the entire coastal plain over the last 2000 years. The development of the coastal landscape was based on multiple environmental factors, and, for the first time, human activities were considered.

The geomorphological research in the adjacent regions emphasises that the main factors influencing the landscape evolution around Aardenburg during most of the Holocene were environmental, including the rate of relative sea level rise, sediment budget, accommodation space and morphology of the flooded surface (de Boer 2006; Baeteman 2018). Around 5500 BC, a large part of Zeeland became a tidal area shaped by tidal channels, mudflats and salt marshes seaward, while peat

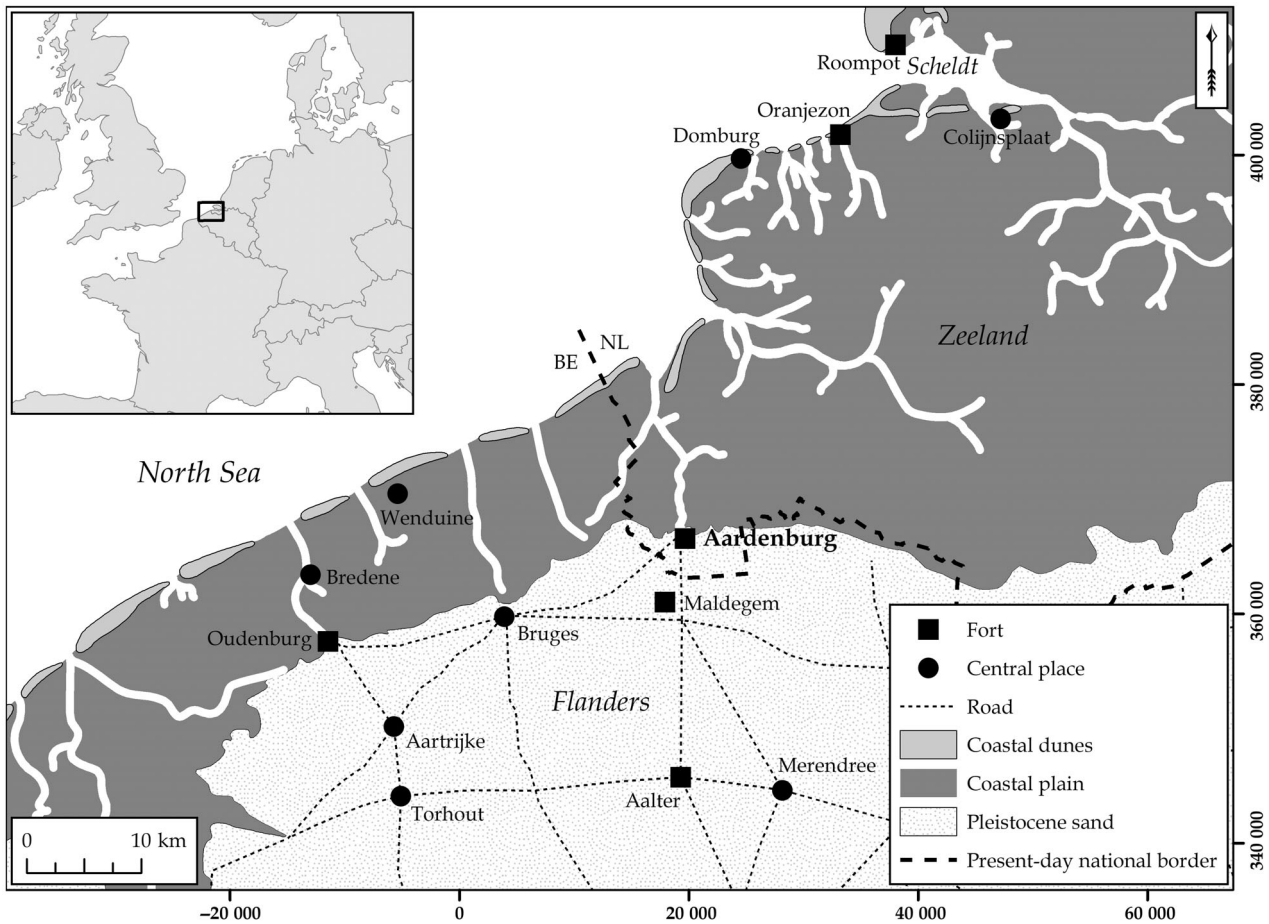


Fig. 1. Reconstruction of the region surrounding Aardenburg during the high Roman period.

developed landward, bordered by the higher Pleistocene sands (Vos 2015). The peat started to expand and this resulted in vast peat areas in the third millennium BC, after the coastline was almost closed off. During the Iron Age, the coastal barrier was breached and marine influence increased in the coastal plain, thereby stopping peat growth and starting a process of erosion by tidal systems and sedimentation of marine deposits (Vos 2015). Only from the Iron Age and particularly from the Roman period onward, did human activities gradually influence the evolution of the coastal landscape in this region (de Boer 2006; Vos 2015). In particular, the Roman army contributed to the landscape evolution by constructing many forts on the coastal plain of the southern North Sea, one of which was at Aardenburg (Dhaeze 2021). Coring surveys have shown that the Roman fort at Aardenburg was built on an outcrop of Pleistocene sand, which was surrounded by a peat landscape at the edge of the coastal plain (Fig. 2; Ova 1957; van Rummen 1965). Peat was excavated to use as fuel since it was more accessible than wood, which was scarce in the coastal area (Vos & Van Heeringen 1997; Braadbaart *et al.* 2017). Natural and artificial drainage of the peat, as

well as peat extraction, lowered the level of the peat surface. In conjunction with other environmental factors (e.g. sediment budget), the sea flooded the (low-lying) peat area from AD 270 (Vos 2015). The fort had a natural marine connection via the river Ee, although the river silted up before the start of the embankment of the region during the high Middle Ages (de Ruijsscher *in press*). From about AD 800, the area progressively silted up and became entirely embanked, leading to the present-day characteristic landscape (Tys 2013).

Aardenburg, as one of the few sites with continuous occupation during the first millennium AD, and its location on a Pleistocene sandy ridge on the edge of the coastal plain, provides a unique opportunity to investigate the coastal evolution of this particular area and assess the interplay between human activities and the dynamics of the natural environment during the Roman, early and high medieval periods. Palaeoenvironmental data are crucial to this understanding, but until now have been limited at Aardenburg to a study of macrobotanical bulk samples from a Roman well and a high medieval pit at the Hof Buize II excavation 400 m SE of the fort (Fig. 3) (Kooistra & de Man 1995). In this study, we

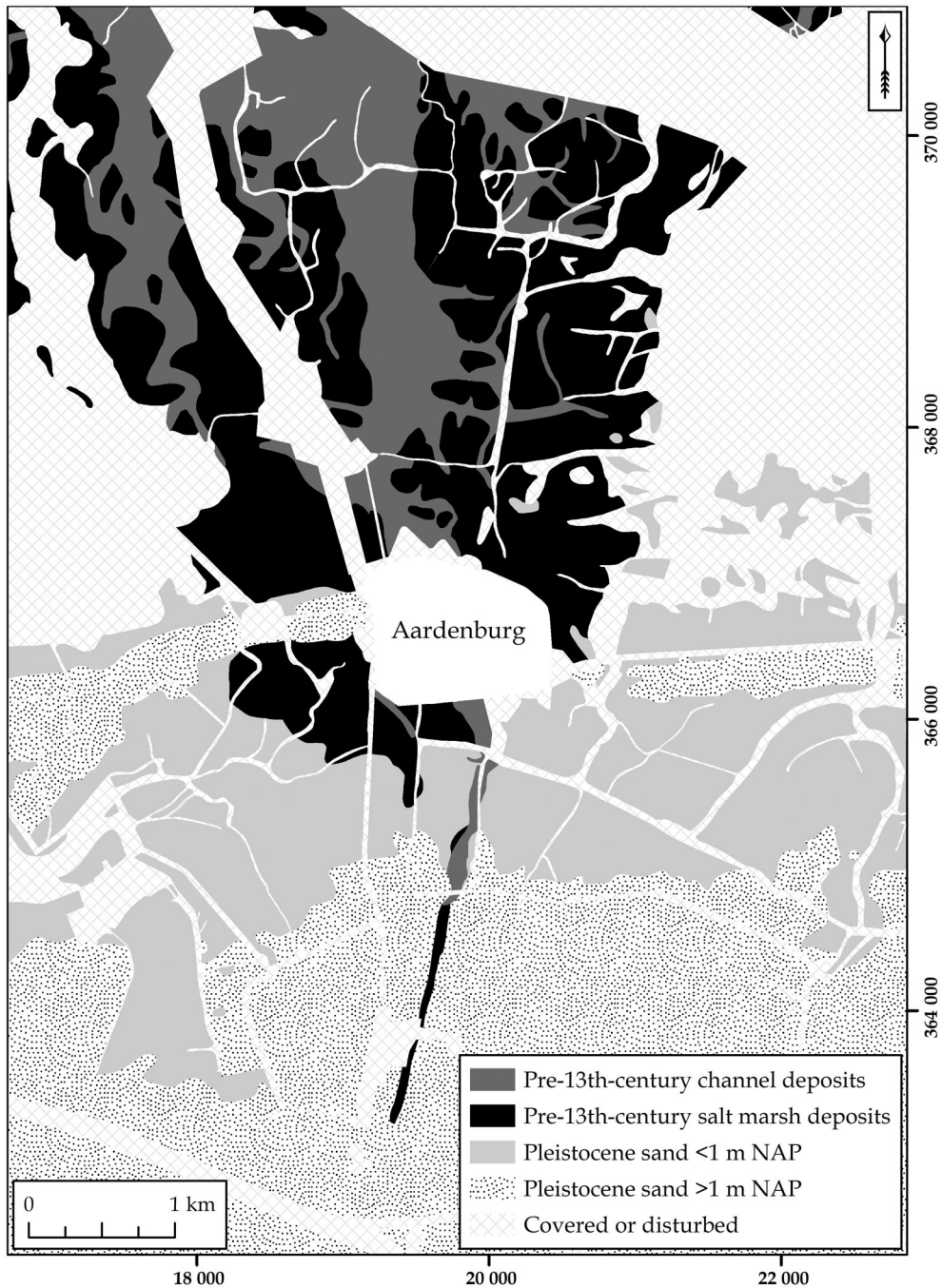


Fig. 2. Simplified geological map of the Aardenburg region, after Ovaal (1957).

examined the palynomorph and diatom records of two sedimentary sequences covering the Middle Holocene peat, and Roman and medieval settlements to reconstruct the regional and local vegetation and palaeoenvironment. Such local environmental studies are essential for understanding coastal development because of the dynamic character of the depositional environments (barriers, tidal channels, mudflats and salt marshes) that evolve according to local conditions and thus cannot be

extrapolated for the entire region (Ervinck *et al.* 1999; Baeteman 2013).

Materials and methods

Location of the sample boxes and the subsamples

The first sample box was taken in June 2020 during an archaeological excavation along the Peurssensstraat,

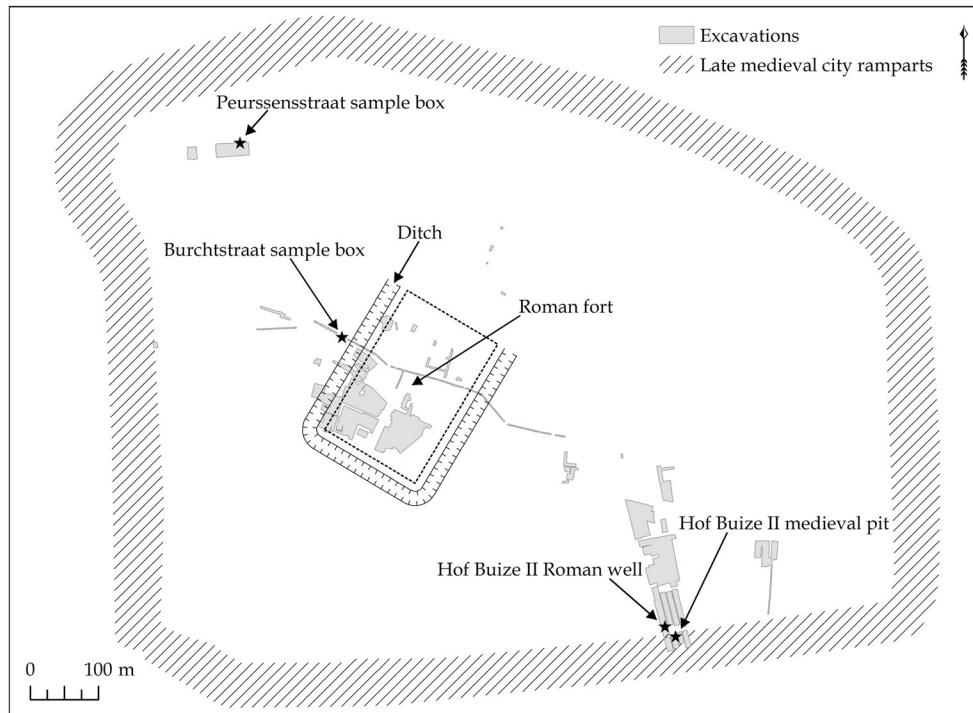


Fig. 3. Location of the samples within the centre of Aardenburg. The two sample boxes were investigated for palynological, diatom and sedimentology analyses and the Roman and medieval structures for macrobotanical analysis.

300 m NW of the fort (Figs 3, 4), on a west–east profile between a height of 0.4 m NAP (Amsterdam Ordnance Datum) and 0.9 m NAP. The second sample box was taken in March 2019 during the renewal of the sewer system in the Burchtstraat, 20 m west of the late 3rd century defensive ditch of the fort (Figs 3, 4), on a south–north lined profile between a height of 0.7 m NAP and 1.2 m NAP.

The sample boxes Peurssensstraat and Burchtstraat were described sedimentologically and analysed for palynology (pollen, spores and non-pollen palynomorphs or NPPs) and diatoms in order to reconstruct the past landscape. Subsamples were taken every 4 cm, except in the Roman waste layer and the marine clay layer at Peurssensstraat, where the resolution was doubled. This resulted in 28 subsamples for palynological analysis and 28 subsamples for diatom analysis (Fig. 5).

Palynological analysis

Subsamples of ~1 mL for palynological analyses were macerated following standard procedures for pollen analysis (Moore *et al.* 1991). *Lycopodium* tablets (Peurssensstraat: batch number 161018201m, X = 17461 to Burchtstraat: batch number 100320201, X = 14285) were added for calculation of the pollen concentration. The identification and nomenclature of the pollen and spores mainly follow Moore *et al.* (1991) and Beug (2004). Non-pollen palynomorphs (NPPs) are

identified and counted following van Geel (1972, 1978), van Geel *et al.* (1980), Pals *et al.* (1980) and Miola (2012). All pollen, spores and NPPs are expressed as percentages of the pollen sum, which includes all regional pollen types (trees and shrubs, heathland shrubs and dryland herbs). Herbaceous pollen of halophytic, riparian and aquatic taxa are considered as local. Chenopodiaceae (e.g. *Atriplex* sp., *Salicornia* sp.) and *Senecio* type (e.g. *Aster tripolium*) include species from several environments, but in this coastal context, they are considered as possible halophytes (Storme *et al.* 2020). Plumbaginaceae are obligatory halophytes since in this region they only include the salt marsh species *Armeria maritima* and *Limonium vulgare*. Local pollen types as well as spores and NPPs were excluded from the pollen sum. A pollen sum of at least 400 pollen grains was counted for each subsample. Palynological results were plotted in percentage diagrams (Figs 6, 7) using Tilia (Grimm 2019). The CONISS function (stratigraphically constrained cluster analysis, Grimm 1987) was used for delimiting the palynological assemblage zones, where changes in regional and local environments must have occurred. All pollen and plant spore types were included in the CONISS analysis.

Diatom analysis

From each subsample ~0.5 g was treated following standard diatom preparation methods (Battarbee 1986).

Wet sediment was sampled to assure a better preservation of the valves (Flower 1993). The analysis was carried out using a transmitted light microscope (Zeiss AxioImager A1) and a scanning electron microscope (Tescan mira). The identification of the valves is based on Witkowski *et al.* (2000), Krammer & Lange-Bertalot (2008) and Bey & Ector (2013). The current nomenclature was verified using Algaebase (Guiry & Guiry 2022). For the reconstruction of the aquatic palaeoenvironment, the ecological parameters are plotted by classifying the taxa according to life form, salinity classification and habitat following the codes of Denys (1991) and Van Dam *et al.* (1994) (Figs 8, 9). For the salinity classification and habitat, the results are presented separately (Fig. 10) for allochthonous species (eu- and tycho planktonic), which provide information about the surrounding environment and autochthonous species (epontic and benthic), which reflect the local diatom population and hence the local sedimentary environment (Vos & de Wolf 1993). Species without a defined ecology are referred to as ‘unknown’ (Fig. 10).

Results and interpretation

Sedimentological description

The sample box Peurssensstraat includes a succession from Pleistocene humic fine-grained sand, overlain by a peat layer containing siliciclastic sediments (Fig. 4). This layer is covered by a Roman waste layer, on which clay was deposited. The ‘siliciclastic’ peat layer is assumed to have been at the surface at the start of high Roman occupation, which is supported by the waste layer containing pottery from the second half of the 2nd

century in combination with waste from the Roman salt industry (Dekoninck *et al.* 2022a). As no datable material was available, the clay deposit could only be roughly dated after the deposit of the underlying waste layer and before the embankment during the 11th and 12th centuries. The top of the uppermost clayey deposit was not sampled since it is part of the reworked topsoil.

The sample box Burchtstraat stratigraphically includes a succession starting from the top of an *in situ* peat layer into clayey and sandy sediments deposited from the Roman defensive ditch, covered by high medieval waste layers (Fig. 4). It is supposed that the peat layer was at the surface at the start of the Roman occupation since the displaced sediments directly on top of it could only be deposited after the creation of the defensive ditch. A previous excavation of the Roman defensive ditch itself revealed that the silted up ditch was levelled with a layer containing late 9th century/early 10th century pottery (Trimpe Burger 1985). This dates the deposition of the sediment between the peat and waste layer roughly between the late 3rd century and the early 9th century. Charred organic material attached to locally produced greyware pottery found in the lowest parts of the high medieval waste layers on top of the Roman sediments provided a radiocarbon dating between AD 1030 and 1160 (Table S1).

Palynological analysis – Peurssensstraat

Zone Pe1. – The three lower subsamples (P050, P049 and P048) are from the Pleistocene humic fine-grained sand between 0.40 and 0.54 m NAP, while the superjacent subsample (P047) is taken in the ‘siliciclastic’ peat between 0.54 and 0.57 m NAP (Fig. 5).

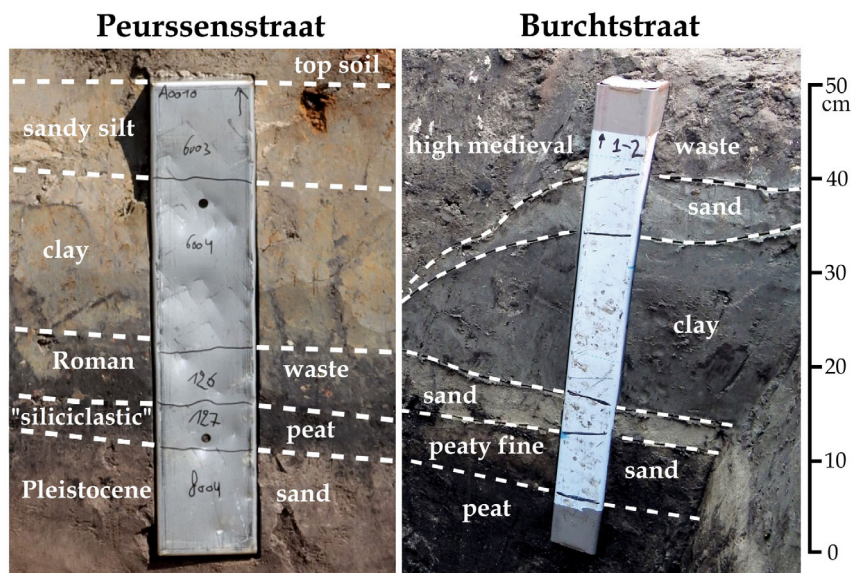


Fig. 4. Photograph of the profile from which the sample boxes were collected with the different units observed during fieldwork.

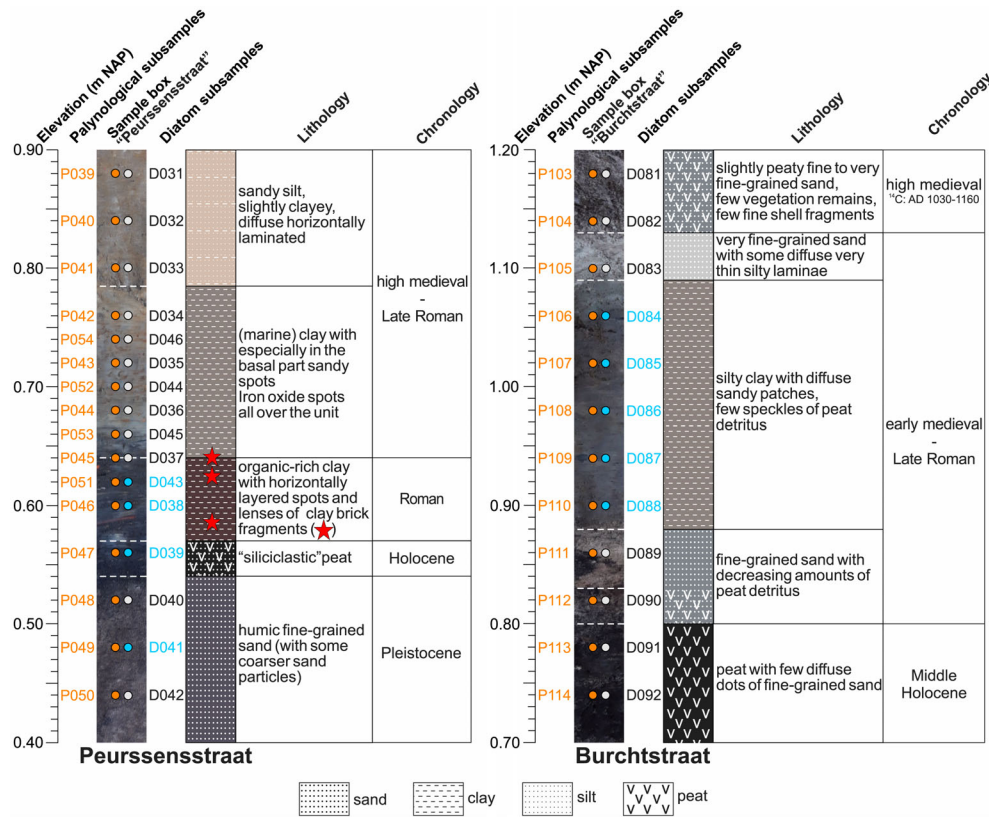


Fig. 5. Location of the subsamples for palynological and diatom analyses (white circles are non-productive subsamples) associated with the lithology and the chronology.

The spectrum is dominated by trees and shrubs, which account for ~98% of the pollen sum, whereas herbs are rare and consist mostly of Poaceae (Fig. 6). This indicates an entirely forested landscape. The three dominant taxa, *Corylus avellana*, *Quercus* and *Alnus*, produce and disperse a large quantity of pollen (Deforce *et al.* 2007). However, *Corylus* and *Quercus* grow in dryland forests while *Alnus* thrives in wetland. Other dryland trees such as *Tilia* and *Pinus sylvestris* are present in lower percentages. Most of the dryland trees grew in the sandier hinterland or on higher locations within the coastal plain and alder must have been part of the wider surroundings as well.

Zone Pe2. – Three subsamples (P046, P051, P045) belong to the Roman organic-rich clay layer between 0.57 and 0.64 m NAP and five subsamples (P053, P044, P052, P043 and P054) are part of the superjacent marine clay between 0.64 and 0.79 m NAP (Fig. 5). Trees and shrubs remain dominant (~82%) mainly with *Corylus*, *Alnus* and *Quercus* (Fig. 6). *Tilia* also remains frequent, while *Pinus* becomes more abundant and increases from ~1 to 9%. The latter taxon produces many saccate pollens that are easily transported over large distances with their high floating capacity and are often recorded in high percentages in tidal

environments (Heusser & William 1977). *Carpinus betulus* and *Fagus sylvatica* appear at the top of the zone in low frequency.

Poaceae, which groups grasses from various habitats, gradually increase from 0.66 m NAP upwards (P053) while other herbs such as Apiaceae, *Artemisia*, Brassicaceae, Caryophyllaceae, Cerealia type, *Plantago lanceolata* and Asteraceae–Tubuliflorae (*Senecio* type) are rare. Asteraceae–Liguliflorae is on average frequent and shows a clear peak of ~35% at 0.64 m NAP (P045) in the uppermost part of the organic-rich clay layer. The mirroring decrease observed in the AP (Arboreal Pollen) does not imply the openness of the woodland but rather results from the differential preservation of pollen in the oxidised subsample P045. Most pollen grains were corroded, even the ones highly resistant to corrosion Asteraceae–Liguliflorae. However, Asteraceae–Liguliflorae remains easily recognisable even when strongly corroded (Bottema 1975). Therefore, the peak 0.64 m NAP probably over-represents this robust taxon. Asteraceae–Liguliflorae includes ruderals species pointing to disturbed soils caused by human and/or animal activity (Behre 1981).

Chenopodiaceae increase between 0.62 and 0.68 m NAP up to ~7% and show a clear peak up to ~30% from 0.70 m NAP onwards. Chenopodiaceae include herbs

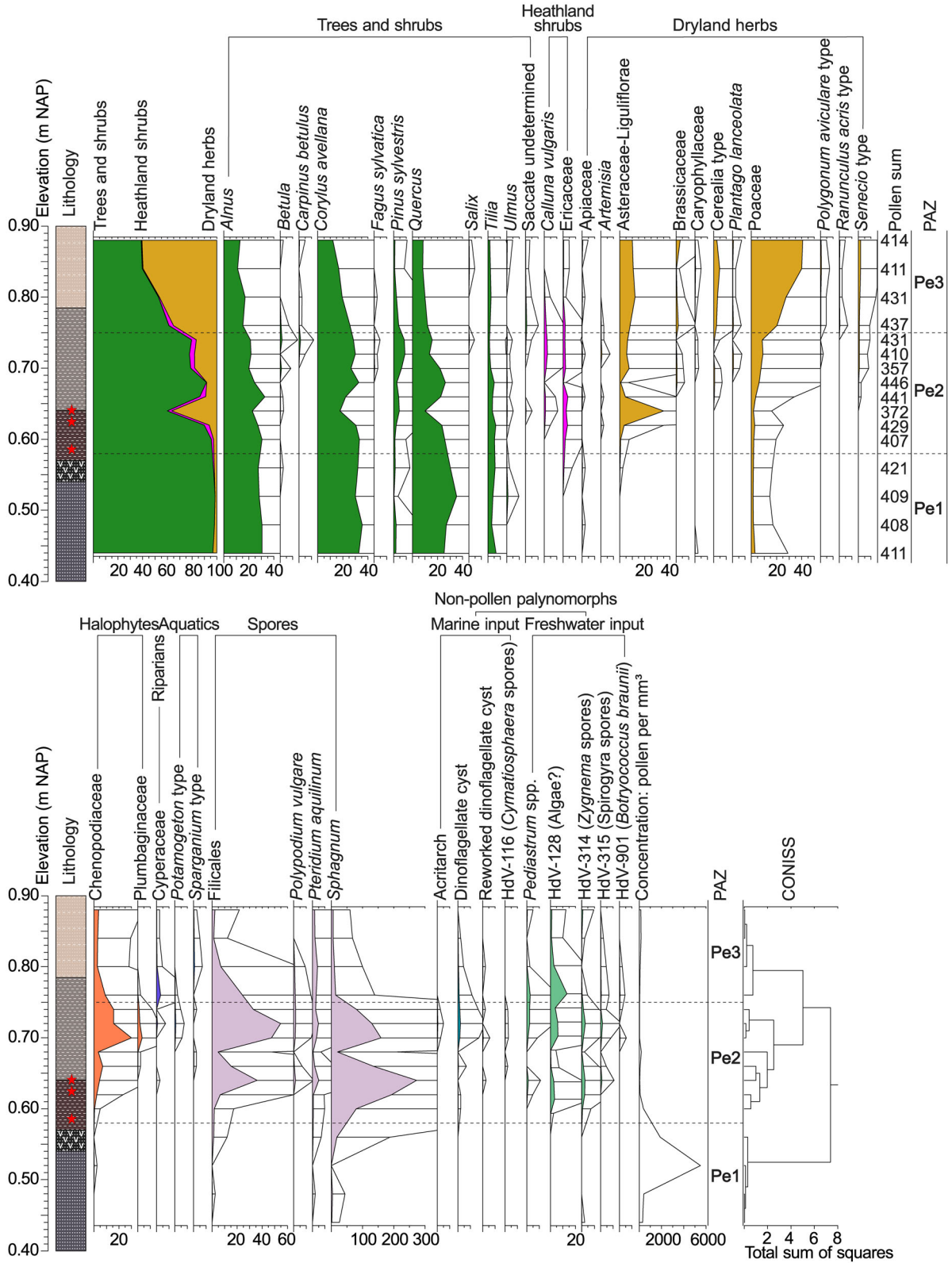


Fig. 6. Percentage pollen diagram reconstructing the regional and local vegetation at Peurssensstraat (exaggeration $\times 10$, lithology key Fig. 5, selected taxa).

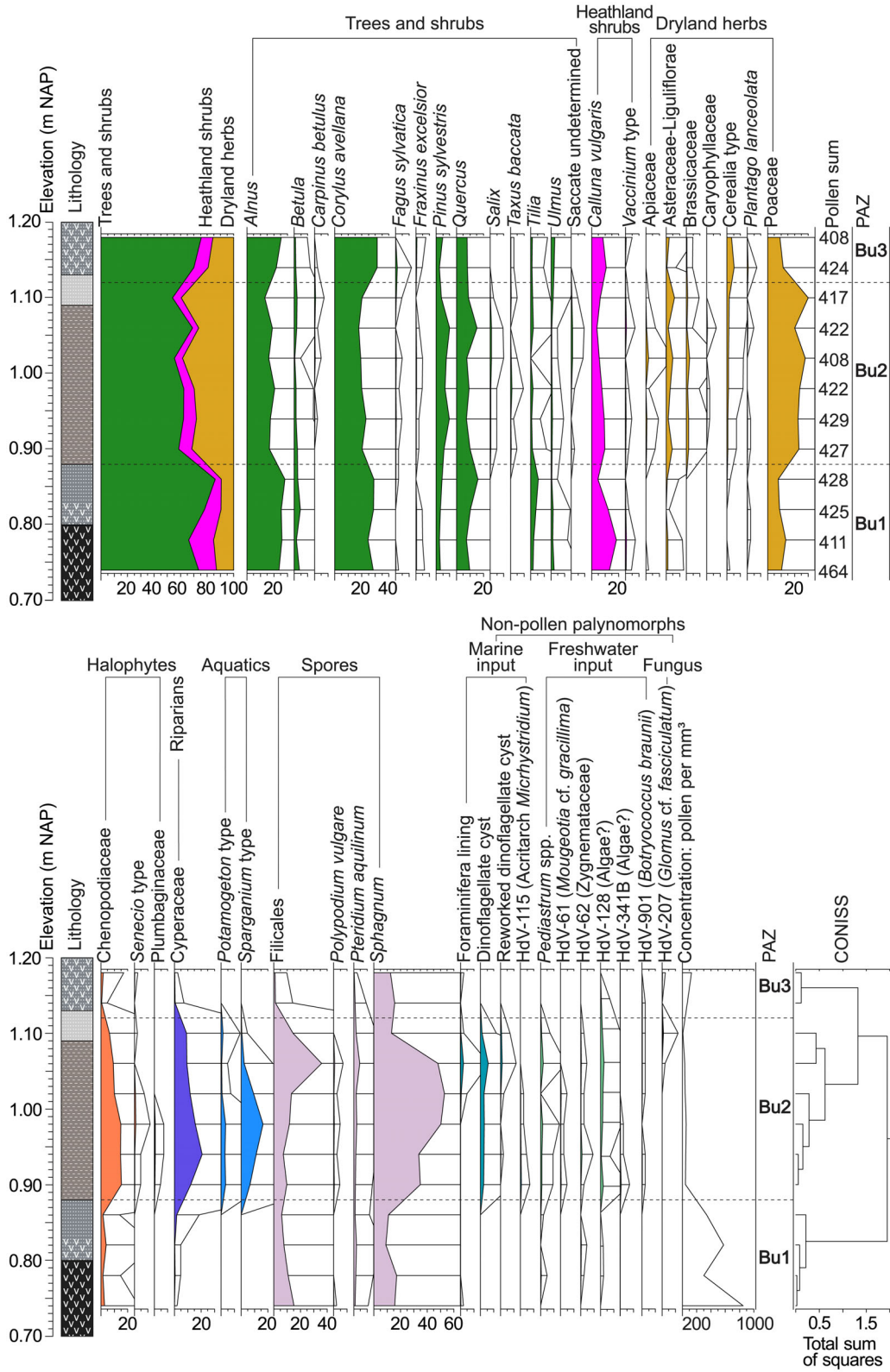


Fig. 7. Percentage pollen diagram reconstructing the regional and local vegetation at Burchtstraat (exaggeration $\times 10$, lithology key Fig. 5, selected taxa).

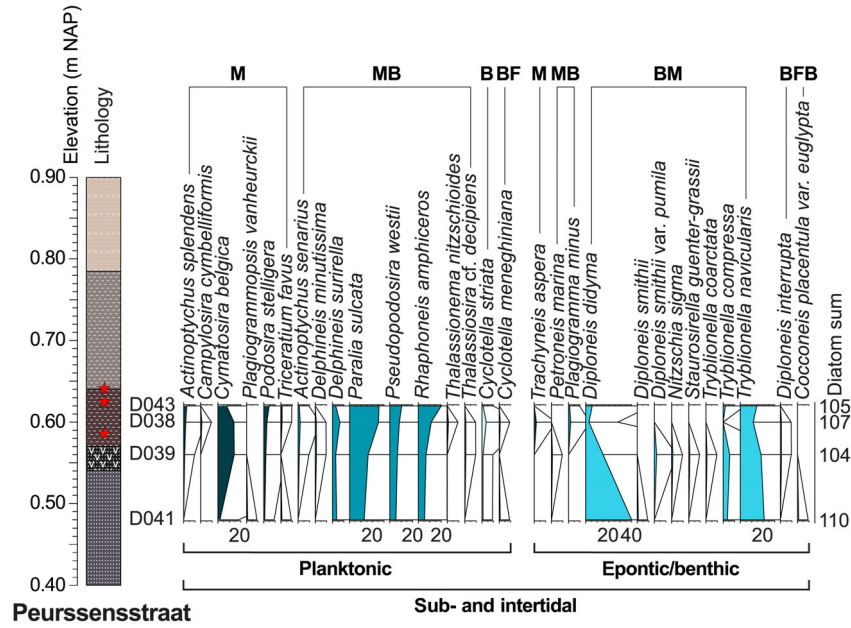


Fig. 8. Percentage diatom diagram reconstructing the aquatic palaeoenvironment at Peursensstraat (exaggeration $\times 10$, lithology key Fig. 5, selected taxa). M = marine; B = brackish; F = freshwater. The taxonomy follows Witkowski *et al.* (2000), Krammer & Lange-Bertalot (2008) and Bey & Ector (2013). The current accepted names were verified according to Algaebase (Guiry & Guiry 2022).

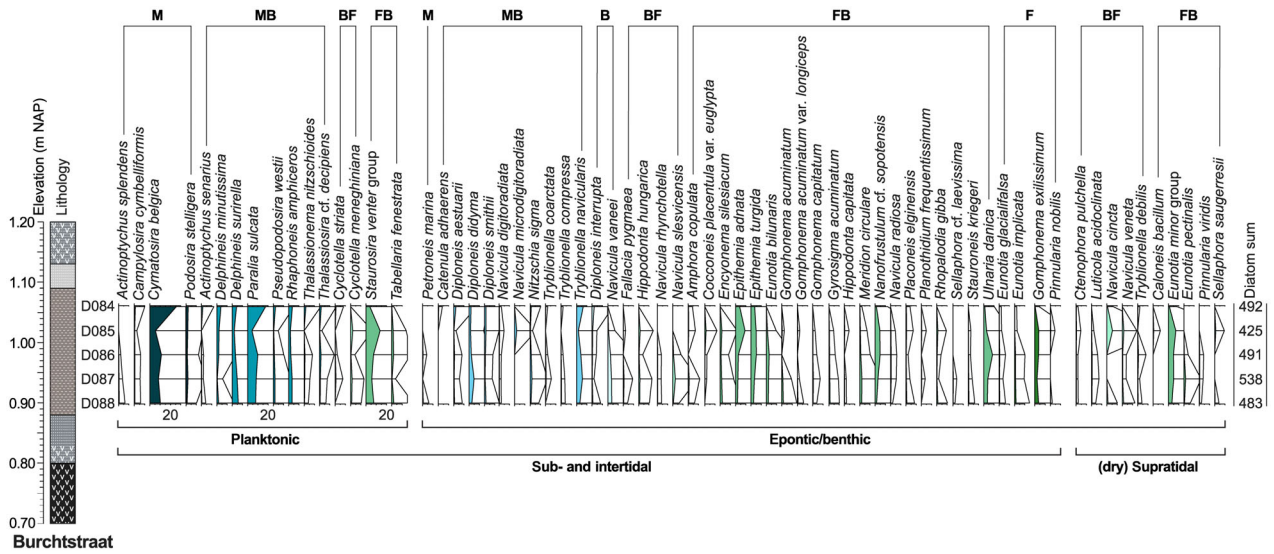


Fig. 9. Percentage diatom diagram reconstructing the aquatic palaeoenvironment at Burchtstraat (exaggeration $\times 10$, lithology key Fig. 5, selected taxa). M = marine; B = brackish; F = freshwater. The taxonomy follows Witkowski *et al.* (2000), Krammer & Lange-Bertalot (2008) and Bey & Ector (2013). The current accepted names were verified according to Algaebase (Guiry & Guiry 2022).

that grow on disturbed soil (e.g. *Chenopodium album*) but also for example species from salt marsh environments. The high values in the top of the zone suggest the presence of the halophytic taxa, growing locally or at a very close location to the settlement. Plumbaginaceae are found at the same levels. The presence of other marine palynomorphs such as acritarchs, dinoflagellate cysts and HdV-116 (*Cymatiosphaera* spores), strengthens the

assumption of Chenopodiaceae pollen being from halophytes. On the other hand, the freshwater palynomorphs *Pediastrum* spp., HdV-128 (Algae?), HdV-314 (*Zygnema* spores), HdV-315 (*Spirogyra* spores) and HdV-901 (*Botryococcus braunii*) most probably result from river run-off or a local freshwater pond or reworked material. The presence of reworked dinoflagellate cysts confirms input from reworked material.

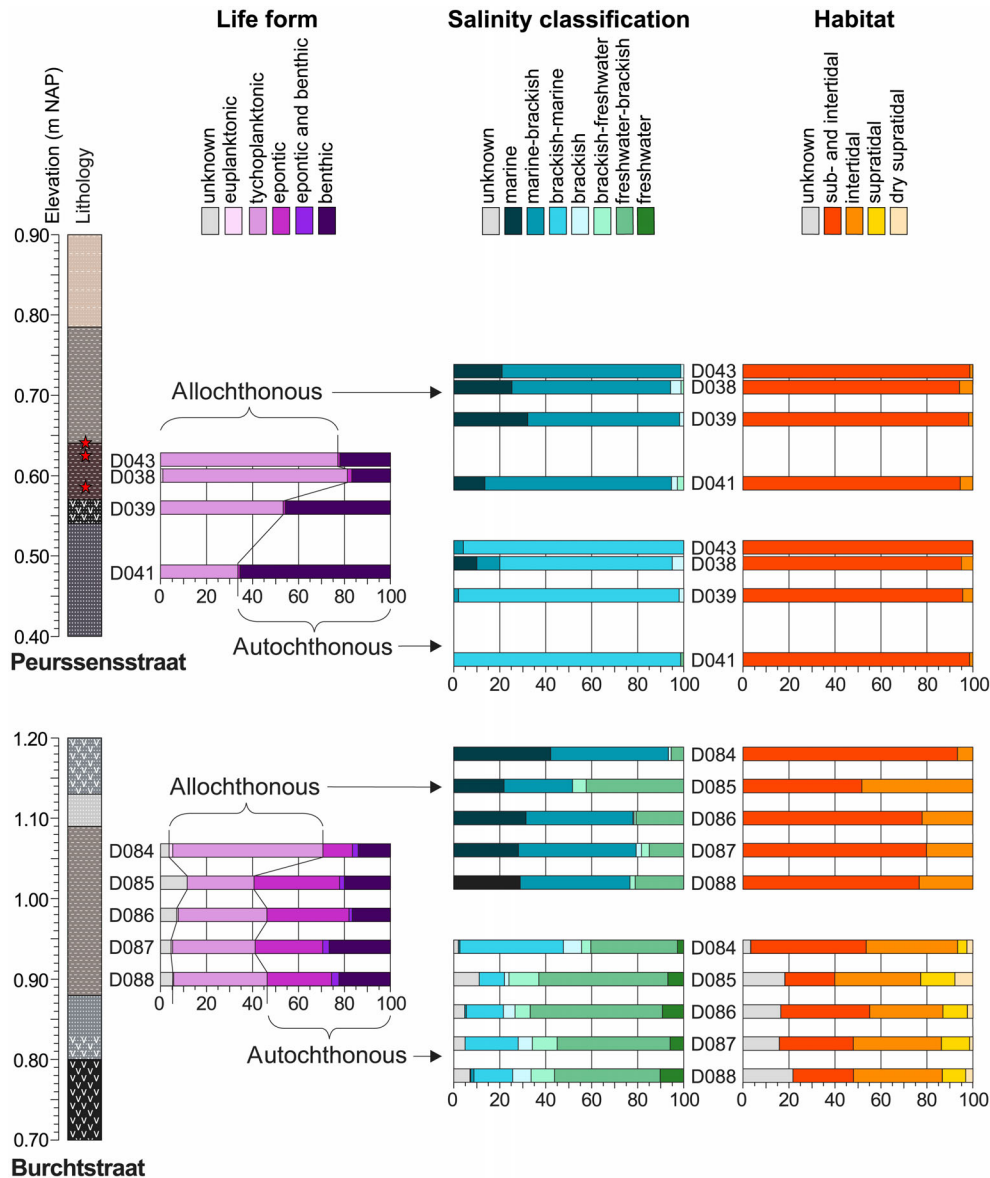


Fig. 10. Percentage diagram of ecological parameters (life form, salinity classification and habitat) for allochthonous and autochthonous diatoms at Aardenburg.

Peaks of *Sphagnum*, approximately three times the amount of pollen, and of Filicales, up to ~55%, are recorded around 0.64 and 0.70 m NAP. *Pteridium aquilinum*, *Polypodium vulgare* and heathland shrubs exhibit similar peaks at lower percentages, i.e. inferior to ~5%. These taxa were most certainly growing on a relatively nutrient-poor peat surface.

Zone Pe3. – Subsample P042 at 0.76 m NAP belongs to the marine clay layer while the three upper subsamples (P041–P039) are part of the non-marine silt layer between 0.78 and 0.90 m NAP (Fig. 5). The trees and shrubs decrease from ~61 to ~39% from the base to the top of zone Pe3 (Fig. 6). The AP composition remains

roughly the same as in Zone Pe2, except for *Pinus sylvestris*, which decreases. The NAP (Non Arboreal Pollen) is mostly dominated by Poaceae which rise to ~41%. Ruderals taxa are also frequent with Asteraceae–Liguliflorae (~10%) as well as some Brassicaceae and *Senecio* type and some rarer taxa (Behre 1981; Storme *et al.* 2020). Cerealia type is continuously present (~3%), and together with the ruderal herbs, points to anthropogenic influence.

Halophytic Chenopodiaceae remain common at 0.76 m NAP and decline towards the top (from ~9 to ~4%). *Sphagnum* and Filicales exhibit a similar pattern, whereas *Pteridium aquilinum* and *Polypodium vulgare* remain low. Both marine and freshwater NPPs also

decline except for HdV-128 (Algae?), which remains frequent and attains ~13% at 0.76 m NAP. Cyperaceae are also noticeable at this depth, indicating wetland conditions.

Palynological analysis – Burchtstraat

Zone Bu1. – Between 0.70 and 0.88 m NAP, the two lower subsamples (P114 and P113) are part of a peat layer while P112 and P111 are from fine-grained sand with peat detritus (Fig. 5). The pollen reflects a regional vegetation composed of trees and shrubs (~76%), with *Corylus* and *Alnus* dominating, followed by *Quercus* (Fig. 7). Dryland trees such as *Betula*, *Pinus*, *Tilia* and *Ulmus* are consistently present, although in lower percentages. The regional signal, as previously inferred from the Peurssensstraat analysis, is dominated by trees and shrubs growing in both dryland and wetland habitats and depicts a woodland-dominated landscape. In contrast, the proportion of herbs is minor (~12%) and is mostly represented by Poaceae. Chenopodiaceae are constantly recorded in low percentages (~2%), reflecting the presence of the coastal plain in the surroundings. The *in situ* peat holds relatively high abundances of *Sphagnum* (~16%) and *Calluna vulgaris* (~16%), indicative of an ombrotrophic bog. Part of the Filicales was also possibly growing in the peat.

Zone Bu2. – Five subsamples (P110–P106) were taken between 0.88 and 1.07 m NAP in the clay while a sixth subsample P105 was taken at 1.10 m NAP in the sand just below the high medieval waste layer (Fig. 5). The AP is dominated by the same taxa (Fig. 7), but the values are somewhat lower compared with zone Bu1 (~60%). *Pinus sylvestris* becomes more frequent (up to ~10%) together with other saccate pollen while low percentages of *Carpinus betulus*, *Fagus sylvatica*, *Taxus baccata* and *Salix* appear in this zone. Although scarce owing to its low pollen production and dispersal (Storme et al. 2017), the wetland *Salix* occurs exclusively in this zone and is today frequently observed along rivers, where it can withstand floods. *Calluna vulgaris* remains frequent with ~7%. The lower AP percentages are more probably related to an increase in local input than to forest decline. The total amount of NAP is higher than in zone Bu1 and mostly consists of Poaceae (~25%). Asteraceae–Liguliflorae, Brassicaceae and Cerealia type are continuously present. Furthermore, halophytic taxa, mostly Chenopodiaceae, become abundant together with the wetlands Cyperaceae, *Sparganium* type and *Potamogeton* type. Thus, a mixed signal from both marine and freshwater environments is also recorded. A proportion of the dryland herbs might also belong to these two environments, such as the Poaceae, which might have originated from salt marshes (e.g. *Puccinellia maritima*) or freshwater habitats (e.g. *Phragmites australis*) (Storme et al. 2020).

Sphagnum is largely dominant (~39%) and Filicales are abundant (~15%) while *Pteridium aquilinum* and *Polypodium vulgare* are rarer in the clay layer. In addition, several NPPs also from both marine and freshwater environments were recorded. The marine input is dominated by dinoflagellate cysts, followed by lower numbers of foraminifera linings and HdV-115 (acritarch *Micrhystridium*). The freshwater input is dominated by HdV-128 (Algae?) and *Pediastrum* spp. while HdV-61 (*Mougeotia* cf. *gracillima*), HdV-62 (Zygnemataceae), HdV-341b (Algae?) and HdV-901 (*Botryococcus braunii*) are sporadically present. Reworked dinoflagellate cysts are occasionally present and the fungus HdV-207 (*Glomus* chlamydo-spores), which is only present in the sand at the top of the zone, also points to soil erosion and the presence of reworked material.

Zone Bu3. – The two subsamples P103 and P104 (1.13 and 1.20 m NAP) were taken in the high medieval waste layer mostly consisting of sand and peat detritus (Fig. 5). The AP (~73%) and *Calluna vulgaris* (~10%) increase again (Fig. 7). *Corylus*, *Alnus* and *Quercus* remain the dominant taxa. *Pinus sylvestris* decreases while other saccate pollen and *Salix* become absent. Poaceae are likewise declining, yet they account for the bulk of herbs whereas Cerealia type is the only NAP increasing (~4%). Furthermore, the characteristic wetland herbs and algae from zone Bu2 quasi disappear. The same trend holds true for the Filicales, whereas *Sphagnum* diminishes but remains frequent (~14%).

Diatom analysis – Peurssensstraat

Only four subsamples (D041, D039, D038 and D043) from sample box Peurssensstraat yielded diatoms (Fig. 5). D041 originates from the Pleistocene sand, D039 from the peat, and D043 and D038 from the Roman waste layer. The sample box Peurssensstraat was collected above the current groundwater level, and this explains the low concentration and the high degradation of diatoms in the four subsamples through oxidation and probably because the pH was above 7.5–8.0 (Denys 1999). Additionally, given the fact that patches of oxidised iron were recorded in the coastal marine sediments overlying the Roman waste layer, the complete lack of diatom frustules there is also presumably caused by oxidation. Because of the low diatom content only 100 valves were counted in each subsample and 29 species belonging to 21 genera were identified. All diatoms are in general robust taxa with a high to moderate preservation potential (Denys 1991). Most of the valves are broken except for small forms such as *Cymatosira belgica* (Figs 6–10).

The two lower subsamples D041 and D039 are dominated by autochthonous diatoms, whereas the two upper subsamples D038 and D043 are mostly composed

of allochthonous diatoms (Fig. 10). The allochthonous diatoms are dominated by tychoplanktonic marine-brackish species (e.g. *Paralia sulcata* and *Cymatosira belgica*, Fig. 8) and the autochthonous diatoms are mostly represented by epontic/brackish-marine species (e.g. *Diploneis didyma* and *Tryblionella navicularis*). All the diatoms live in sub- and intertidal environments and reflect a mudflat that is flooded daily. The tychoplanktonic species were possibly brought in via tidal inlets or tidal channels (Vos & de Wolf 1988). The higher percentages of these tychoplanktonic diatoms recorded in the two upper subsamples (D038 and D043) might suggest that the area was flooded more often.

Diatom analysis – Burchtstraat

Diatoms were recorded in five subsamples (D088–D084) from the clay layer (Fig. 5). A total of at least 500 valves were counted in each subsample and 112 species belonging to 53 genera were identified. The five subsamples contain valves with a known moderate to high preservation potential while very fragile valves are entirely absent (Denys 1991). Most of the valves are highly fragmented in every subsample.

The four lower subsamples (D088–D085) are dominated by autochthonous diatoms and the upper subsample D084 by allochthonous diatoms (Fig. 10). A new species taxonomically described for the first time as *Pseudostaurosira ellipticolanceolata* (André *et al.* 2023), whose ecology remains so far unknown, is abundant in subsample D085. The allochthonous species are dominated by ~52–93% of tychoplanktonic marine-brackish species (e.g. *Cymatosira belgica* and *Paralia sulcata*, Fig. 9) living in sub- and intertidal environments. Thus, the ditch received a marine influence, most probably through a tidal channel. The higher portion of these tychoplanktonic marine-brackish species in the uppermost subsample D084 might reflect an increase in the tidal influence. *Staurosira venter* group is often found in freshwater ditches (Vos & de Wolf 1988) and makes up most of the tychoplanktonic freshwater-brackish diatoms, which are usually found between ~5 and 21% and are more common in D085 (~42%). Thus, the ditch also received freshwater, most probably originating from more inland. The autochthonous diatoms in the four lower subsamples (~46–58%) are dominated by epontic/benthic brackish-freshwater taxa such as *Eunotia minor* group, *Ulnaria danica*, *Epithemia turgida* and *Epithemia adnata*, which slightly decrease in subsample D084 (~38%). The two latter species are epiphytes (Vos & de Wolf 1993). Epontic/benthic brackish-marine diatoms (e.g. *Tryblionella navicularis* and *Diploneis didyma*) are relatively low (<23%) in the four lower subsamples and are dominant in subsample D084 (~45%). The presence of epiphytic and benthic diatoms indicates a permanently submerged environment with moderate hydrodynamic conditions

where aquatic plants could grow (Vos & de Wolf 1997). Diatoms living in the sub- and intertidal zone make up the majority of the autochthonous diatoms (~59–90%). The (dry) supratidal diatoms present in lower percentages (~<23%) are mostly represented by *Eunotia minor* group, while *Navicula cincta* is only abundant in subsample D085. The (dry) supratidal conditions possibly indicate that the highest parts at the edge of the ditch were not often submerged. Finally, acidophilous species in the *Eunotia* genus possibly lived in the coastal peat bogs (Baltrunas *et al.* 2013; Carballeira & Pontevedra-Pombal 2020) and were eroded and transported via tidal channel activity into the infill of the ditch.

Discussion

Middle Holocene peat (after c. 3500 BC)

Sphagnum and *Calluna vulgaris* dominate the peat in the base of the Burchtstraat sample box (Fig. 7) and indicate a raised bog growing locally. This corresponds to the top of the Middle Holocene peat layer (after c. 3500 BC), which evolved from a carr peat (e.g. *Betula* and *Alnus*) into an ombrotrophic bog (e.g. *Sphagnum* and *Calluna vulgaris*), when the peat that developed high enough became less connected with the groundwater and received less nutrients (Allemeersch 1991; Deforce & Bastiaens 2007).

Woodland before and during Roman occupation

Besides a Middle Holocene bog, a woodland signal is also recorded (Fig. 11). The ‘siliciclastic’ peat observed below the Roman waste layer in Peurssensstraat most probably reflects a soil that became humid at a certain moment; possibly it can be considered as the lateral equivalent of the peat in the Burchtstraat. *Alnus* may have grown locally in this soil while *Corylus* and *Quercus* were growing on dryer areas in the surroundings. The pollen spectrum of a dryland forest is however not contemporaneous with the Late Pleistocene Weichselian ice age of the investigated sand layer (Verbruggen *et al.* 1996). The original palynomorphs were not preserved in the sand deposited during the Late Pleistocene since they remained exposed to atmospheric conditions for thousands of years. A rise of the groundwater level led to the development of a Holocene peat overlying the Pleistocene top soil, from which pollen was preserved. It is thus highly probable that the relatively high percentages of Holocene arboreal pollen infiltrated from the superjacent peat into the underlying Pleistocene sand (Bottema 1975; Beyens & Denys 1982; Van Mourik 2003).

During the early Roman times, a densely forested landscape in the general area of the sandy coastal hinterland was also described by Caesar (De Bello

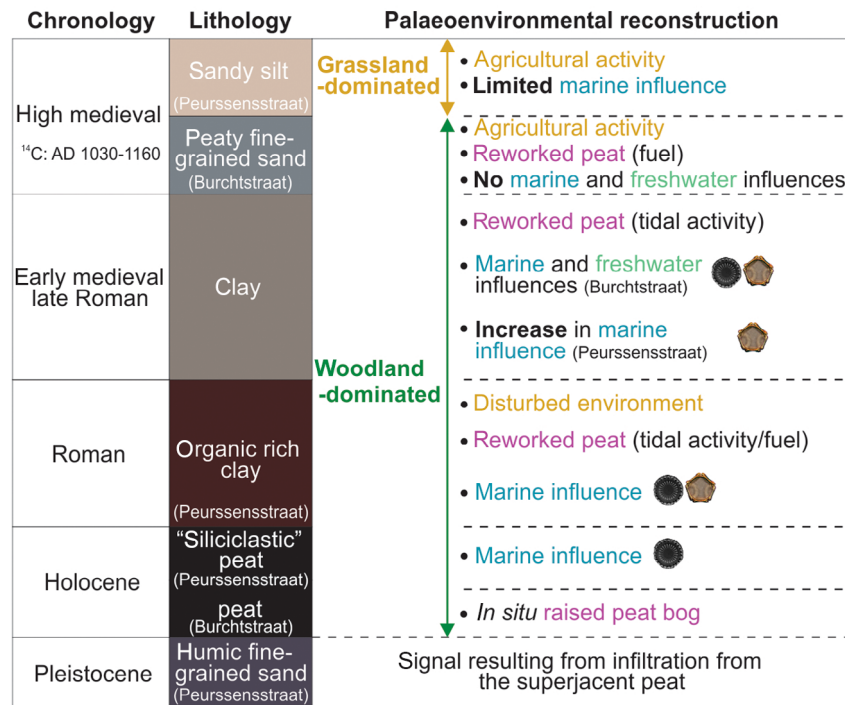


Fig. 11. Chronological evolution of the palaeolandscape from the Holocene to the high medieval time at Aardenburg. The colours follow the colours of the pollen diagram (dark green = trees and shrubs; yellow = dryland herbs; pink = heathland shrubs and spores, blueish = marine and freshwater input). The grey image relates to diatoms and the coloured image relates to palynomorphs.

Gallico, IV, 38, 3), as well by Strabo (Geographica, 3. 4–5), who referred to half-wild boars raised in woodlands. The pollen spectrum from the Roman waste layer also indicates a regional woodland-dominated vegetation characterised by *Alnus*, *Corylus* and *Quercus*. A similar regional vegetation was recorded at the Roman fort at Oudenburg (Vanhoutte *et al.* 2016). The latter site lies 32 km to the west of Aardenburg in the northern coastal plain of Belgium and is also located on higher Pleistocene ground bordering the coastal plain (Fig. 1). The mosses tucked on the joints of a Roman well at Oudenburg were collected in woodland dominated by *Quercus*, *Fagus* and *Carpinus* while the filling of the well (dated after at least c. AD 200) indicated a regional signal dominated by *Corylus*, *Alnus* and *Quercus*.

Pollen analysis at Aardenburg (and Oudenburg) suggests the presence of woodland bordering the coastal plain area during the Roman period (Fig. 6). However, a decrease in woodland was expected in this layer since the Romans had a significant impact on the forests (Meylemans *et al.* 2022). Large areas were deforested as a result of population and economic growth, with the need for additional arable land and pasture, as well as the supply of firewood and construction timber (Haneca *et al.* 2005; Deforce *et al.* 2020). The decline of woodland during the early and/or middle Roman period was followed by woodland regeneration during the late Roman and early

medieval period. This seems to have occurred on a large scale, as it has been widely reported throughout northwestern Europe, including the inland sandy area of northern Belgium (Deforce *et al.* 2020).

Roman waste layer

The decline in trees and shrubs in the upper Roman waste layer at Peurssensstraat (Fig. 6) is more linked to the observed differential preservation of the pollen than a signal of deforestation. The high abundance of the anthropogenic indicator Asteraceae–Liguliflorae points to a disturbed environment linked to the presence of the Romans. The macrobotanical analysis also recorded the presence of ruderal plants (e.g. *Plantago major* and *Urtica urens*) in the Roman well (Kooistra & de Man 1995). Grasslands with disturbed areas were also present in the vicinity of the *castellum* at Oudenburg during the Roman period (Vanhoutte *et al.* 2016).

Coastal environment

Apart from the woodland and settlement signal, the pollen spectrum also reflects a signal of the coastal environment already at the base of the Roman waste layer, but increasing significantly in the upper clay layer and reflecting thus the closer proximity of the intertidal zone in the latter parts of the Roman period (Figs 6, 11).

The observed diatom flora confirms the marine influence and the presence of a mudflat as early as the peat underlying the Roman waste layer (Figs 8, 11). Like pollen, the presence of diatoms in the Pleistocene sand results most probably from infiltration from the superjacent 'siliciclastic' peat. However, no diatoms were preserved in the upper clay layer. The macrobotanical analysis also recorded the coastal environment (e.g. *Armeria maritima* and *Triglochin maritima*) in the Roman sample (Kooistra & de Man 1995). The *castellum* at Oudenburg was also located near a salt marsh during the Roman period, according to mite and diatom studies (Schelvis & Ervynck 1992; Demiddele & Ervynck 1993).

The increase in marine influence at Aardenburg during the (late) Roman period reflects the increased marine activity and the large-scale tidal extension on the peat landscape in the coastal areas of Zeeland (Vos & Van Heeringen 1997; Vos 2015). As stated by Rippon (2000), the marine incursions that occurred in several sites located in the coastal wetlands of NW Europe during late to post-Roman times are no longer solely attributed to the simplistic concept of the synchronous 'Dunkirk II' transgression, a concept that has been refuted. The latter author furthermore advances that these marine transgressions in the coastal areas, and the eventual subsequent abandonment of settlements, were not synchronous events. There is a need for local palaeoenvironmental studies, such as at Aardenburg, to understand the development of the coastal areas along the North Sea on a wider scale.

At Aardenburg, the increase in the marine influence does not seem to be correlated with a sudden climate event. On the contrary, the climate has remained rather warm and stable for the last 8000 years in the region (Vos 2015). However, the coastal landscape evolution of The Netherlands was highly linked to the availability of accommodation space, which was first driven by a relative sea-level rise during the Early and Middle Holocene. Relative sea-level rise became relatively small (on average 5 cm per century) during the past 2000 years and human activities played a significant role in the development of the coastal landscape during the Late Holocene (Vos 2015). It has long been assumed that occupation of the dynamic coastal plain was temporary during the Roman period (Ervynck *et al.* 1999). Recent archaeological research supports the idea that permanent habitation was not only possible on a higher sandy ridge like at Aardenburg, but also for the first time in history intensively expanded in the coastal plain itself on desiccated peat surface or on artificially raised dwelling mounds (De Clercq 2011; Nieuwhof *et al.* 2019; Verwerft *et al.* 2019). Next to habitation also salt-making, sheep herding, peat extracting and arable farming involving local drainage of the landscape developed (Vos 2015; Dekoninck *et al.* 2022a). For the first time in the region, humans were involved in the evolution of the coastal landscape via reclamation, occupation and adaptation to

higher water levels, leading to the drainage of the landscape by ditches and local extraction of peat areas, which eventually subsided and became more vulnerable to the dynamics of the sea. By AD 350, the excavated peat areas were submerged and uninhabitable, while the drowning of the wider peatland in the whole of Zeeland continued until AD 800 (Vos 2015).

Reworked peat

The Roman waste layer contains high percentages of *Sphagnum* and Filicales (Fig. 6), probably growing in the Middle Holocene coastal peat (cf. supra). This observation can be linked to the Romans digging out the peat for fuel. Peat was conveniently accessible on the coastal plain and provided excellent fuel for cooking and heating the habitations already during the Iron Age (e.g. Vlaarding, The Netherlands; Braadbaart *et al.* 2012, 2017). Moreover, Dekoninck *et al.* (2022b) suggested that peat was also used in salt production at Aardenburg in the early- and middle Roman period. Excavation of the peat for fuel was common in the coastal plain, especially during the medieval times (Deforce & Bastiaens 2007; Deforce *et al.* 2007; Jongepier *et al.* 2011), but also during the Roman period (de Boer 2006; Vos 2015; Baeteman 2018). The macrobotanical analysis of the Roman well at Hof Buize II shows traces of reworked peat with *Erica*, *Calluna vulgaris* and *Betula pubescens* (Kooistra & de Man 1995), while the peat lump from the Roman well at Oudenburg is also predominantly formed from *Calluna vulgaris* and *Sphagnum* (Vanhoutte *et al.* 2016).

Finally, high percentages of Filicales and *Sphagnum* are also recorded in the marine clay overlying the Roman waste layer at Peurssensstraat as well as in the clay layer underlying the high medieval waste layer at Burchtstraat (Figs 6, 7). In both layers, as well as a proportion of the spores within the Roman layer, the surface peat and consequently the spores were eroded and transported via the tidal channels. At Burchtstraat, the presence of acidophilous diatoms might also reflect species living in the peat.

Local environment in the ditch

As mentioned before, the sediments in the Burchtstraat sample box were deposited via the nearby late 3rd century defensive ditch of the fort. Both palynomorphs and diatoms reveal the presence of both marine and freshwater species, indicating that the ditch probably received saline water from a tidal channel and more fresh water from another source, possibly the River Ee, leading from the inland to the coast. During the Roman occupation, the small River Ee, originally debouching into a depression 8 km to the south, was most likely rerouted towards a natural channel near the fort (De Clercq 2009). Several branches attached to this system

cut through the sand ridge at Aardenburg, but their exact course is only partially known.

Medieval waste layer

The marine and freshwater signals from pollen and algae disappear in the 11th- to 12th-century waste layer in the Burchtstraat sample box (Figs 7, 11), indicating that the area was no longer impacted by marine influence. The macrobotanical analysis at Hof Buize II also suggests that the salt marsh indicators most probably originate from a greater distance away from the settlement during the high Middle Ages (Kooistra & de Man 1995). Instead, macro remains of riparian plants (e.g. *Eleocharis* and *Thysselinum palustre*) suggest a fresh, most likely shallow body of open water in the vicinity. The diatom analyses at Oudenburg also indicate that the sea did not reach the *castellum* anymore during the 11th and 12th centuries (Demiddele & Ervynck 1993). The decrease in the marine influence reflects the silting up of the area. Furthermore, large parts of the coastal plains in northwestern Europe were reclaimed and embanked between the 11th and 13th centuries (Allen 1997; Rippon 2000; Tys 2013; Soens *et al.* 2014). The decline in marine influence recorded at Aardenburg can be linked to the gradual embankment of the coastal plain. From the 10th century onwards, the Counts of Flanders and some powerful abbeys started to reclaim and embank the area for political and economic reasons, which resulted in the transformation of the salt marshes into polders (Tys 2013).

The crop signal recorded in the high medieval waste layer can result from local cereal cultivation, but also from the threshing of the grains or from consumption waste. The detection of barley and chaff in the macrobotanical analysis indicates that the grain was grown locally in summer fields (Kooistra & de Man 1995). Finally, the high medieval waste layer is dominated by trees and shrubs, reflecting a woodland-dominated landscape at that time. The palynomorphs recorded a (reworked) peat, most probably excavated for fuel.

(Post-)medieval cultural land

The increase in anthropogenic indicators on top of the marine clay at Peurssensstraat is accompanied by a change in lithology from clay to sandy silt (Figs 5, 6). This interval must be carefully interpreted, as no dating exists and it underlies the recent plough layer, which might have been reworked. The pollen spectrum indicates that the marine influence was very limited, so the sampled location was mostly outside the tidal reach. The deforestation of the hinterland at Aardenburg might have resulted in soil erosion and surface run-off, causing silt deposition. The silt layer was either deposited in a high salt marsh environment that was only rarely flooded or the zone was already embanked. It is only from the

11th and 12th centuries AD onwards that there is evidence of more robust and protective dykes north of Aardenburg (de Ruijsscher 2023). From then onwards the medieval settlement grew into an important medieval town, with the area of the former *castellum* at its centre. The combination of pollen from grasses, ruderals and crops points to agriculture with meadows and arable fields in an open landscape. Their exact location, however, remains uncertain. Cerealia pollens do not disperse far from their source (Vuorela 1973; Hall 1989), which might reflect the cultivation or threshing of grain on site.

Conclusions

By integrating palynological and diatom analysis with sedimentology and archaeology, the landscape evolution of an important Roman and medieval centre located at the interface between the coast and inland was demonstrated. Our results revealed the presence and evolution of multiple palaeoenvironments at Aardenburg (Fig. 11). In general, woodland dominated the landscape in the Middle Holocene peatlands. This peat which later formed the base of the Roman occupation was covered with tidal deposits and changed into a more grassland-dominated landscape towards the high medieval times. In addition to a woodland-dominated landscape, a disturbed environment was also reflected during the Roman period. Peat excavation for fuel occurred in many coastal areas of the North Sea during the Roman period, including Aardenburg, where peat was particularly used in salt production. Furthermore, the marked increase in marine influence during the Roman period and early medieval times at Aardenburg is possibly partly due to human reclamation and occupation activities in the coastal plain, as referred to in adjacent regions. In addition to the marine influence, the ditch at Burchtstraat also received a freshwater influence, possibly from the River Ee. A further palaeogeographical reconstruction of the past channel and river systems can help test this hypothesis. The increase in marine influence was followed by the silting up of the landscape, which could then be used to cultivate crops locally. The area was most probably embanked since large-scale embankments took place during the 11th and 13th centuries in northwestern Europe.

Acknowledgements. – This research was carried out in the framework of the UGent CRA GOA- project ‘High Tide, Low Tide’. The input of the archaeologists Dieter Demey (Oudland Archeologie), Frederik D’Hondt (Artefact) and Marcel de Koning (Bodac) is acknowledged. We are grateful for the technical assistance by Sabine Van Cauwenberghé for the maceration of the subsamples. The discussions with Thomas Wong-Hearing (Ghent University, Department of Geology) and Koen Sabbe (Ghent University, Department of Biology) are appreciated. We acknowledge both reviewers for their constructive comments which considerably improved the manuscript.

Author contributions. – The research project was designed by WDC and SL. WDC and DdR provided the sample boxes. CA carried out the palaeoecological analyses and wrote the initial draft of the manuscript

with guidance from SL, DdR and AS. BVdV assisted with the diatom identification. FB provided the sedimentological analysis. CA and DdR produced the figures. AS, DdR, WDC and CA discussed the results and interpretation of the research.

References

- Allemeersch, L. 1991: Peat in the Belgian eastern coastal plain. *Wetlands in Flanders. Aardrijkskundige Mededelingen* 6, 1–54.
- Allen, J. R. L. 1997: The geoarchaeology of land-claim in coastal wetlands: a sketch from Britain and the north-west European Atlantic-North Sea coasts. *Archaeological Journal* 154, 1–54.
- André, C., Sabbe, K. & Van de Vijver, B. 2023: *Pseudostaurosira ellipticolanceolata*, a new araphid diatom (Bacillariophyta) from Flanders, Belgium. *Phytotaxa* 591, 83–86.
- Baeteman, C. 2005: How subsoil morphology and erodibility influence the origin and pattern of late Holocene tidal channels: case studies from the Belgian coastal lowlands. *Quaternary Science Reviews* 24, 2146–2162.
- Baeteman, C. 2007: De laat holocene evolutie van de Belgische kustvlakte: Sedimentatie-processen versus zeespiegelschommelingen en Duinkerke transgressies. *Geo- and Bioarchaeological Studies* 8, 1–17.
- Baeteman, C. 2013: History of research and state of the art of the Holocene depositional history of the Belgian coastal plain. In Thoen, E., Borger, G. J., de Kraker, A. M. J., Soens, T., Tys, D., Vervaeke, L. & Weerts, H. J. T. (eds.): *Landscapes or Seascapes? The History of the Coastal Environment in the North Sea Area Reconsidered*, 11–29. Brepols Publishers, Turnhout.
- Baeteman, C. 2018: The coastal plain of Belgium, joint product of natural processes and human activities. In Demoulin, A. (ed.): *Landscapes and Landforms of Belgium and Luxembourg*, 313–334. World Geomorphological Landscapes, Springer, Cham.
- Baltrunas, V., Šeiriene, V., Molodkov, A., Zinkute, R., Katinas, V., Karmaza, B., Kisieliene, D., Petrošius, R., Taraškevičius, R., Piličiauskas, G., Schmölcke, U. & Heinrich, D. 2013: Depositional environment and climate changes during the late Pleistocene as recorded by the Netiesos section in southern Lithuania. *Quaternary International* 292, 136–149.
- Battarbee, R. W. 1986: Diatom analysis. In Berglund, B. E. (ed.): *Handbook of Holocene Palaeoecology and Palaeohydrology*, 527–570. John Wiley, Chichester.
- Behre, K.-E. 1981: The interpretation of anthropogenic indicators in pollen diagrams. *Pollen et Spores* 23, 225–245.
- Beug, H. J. 2004: *Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete*. 542 pp. Friedrich Pfeil, München.
- Bey, M.-Y. & Ector, L. 2013: *Atlas des diatomées des cours d'eau de la région Rhône-Alpes. Tome 1. Centriques, Monoraphidées. Tome 2. Araphidées, Brachyraphidées. Tome 3. Naviculacées: Naviculoidées. Tome 4. Naviculacées: Naviculoidées. Tome 5. Naviculacées: Cymbelloidées, Gomphonématoidées. Tome 6. Bacillariacées, Rhopalodiacees, Surirellacées*. 1182 pp. Direction régionale de l'Environnement, de l'Aménagement et du Logement Rhône-Alpes, Lyon.
- Beyens, L. & Denys, L. 1982: Problems in diatom analysis of deposits: allochthonous valves and fragmentation. *Geologie en Mijnbouw* 61, 159–162.
- de Boer, G. 2006: Het fysisch-geografisch onderzoek en de ontstaansgeschiedenis van westelijk Zeeuw-Vlaanderen een status quaestionis. *Tijdschrift Voor Waterstaatsgeschiedenis* 14, 48–58.
- Bottema, S. 1975: The interpretation of pollen spectra from prehistoric settlements (with special attention to Liguliflorae). *Palaeohistoria* 17, 17–35.
- Braadbaart, F., Poole, I., Huisman, H. D. J. & van Os, B. 2012: Fuel, Fire and Heat: an experimental approach to highlight the potential of studying ash and char remains from archaeological contexts. *Journal of Archaeological Science* 39, 836–847.
- Braadbaart, F., van Brussel, T., van Os, B. & Eijsskoot, Y. 2017: Fuel remains in archaeological contexts: experimental and archaeological evidence for recognizing remains in hearths used by Iron Age farmers who lived in peatlands. *Holocene* 27, 1682–1693.
- Brown, A. & Dumolyn, J. 2018: *Medieval Bruges: c. 850-1550*. 549 pp. Cambridge University Press, Cambridge.
- Carballeira, R. & Pontevedra-Pombal, X. 2020: Diatoms in paleoenvironmental studies of Peatlands. *Quaternary* 3, 1–12.
- De Clercq, W. 2009: *Lokale gemeenschappen in het Imperium Romanum: transformaties in de rurale bewoningsstructuur en de materiële cultuur in de landschappen van het noordelijk deel van de civitas Menapiorum (Provincia Gallia-Belgica, ca. 100 v. Chr.–400 n. Chr.)*. Ph.D. thesis, Ghent University, 559 pp.
- De Clercq, W. 2011: Roman rural settlements in Flanders. Perspectives on a 'non-villa' landscape in extrema Galliarum. In Roymans, N. & Derks, T. (eds.): *Villa Landscapes in the Roman North: Economy, Culture and Lifestyles*, 235–253. Amsterdam University Press, Amsterdam.
- De Vries, D. 1968: The early history of Aardenburg to 1200. *Berichten van de Rijksdienst voor het Oudheidkundig Bodemonderzoek* 18, 227–260.
- Deforce, K. & Bastiaens, J. 2007: The Holocene history of *Taxus baccata* (yew) in Belgium and neighbouring regions. *Belgian Journal of Botany* 140, 222–237.
- Deforce, K., Bastiaens, J. & Ameels, V. 2007: Peat re-excavated at the abbey of Ename (Belgium): archaeobotanical evidence for peat extraction and long distance transport in Flanders around 1200 AD. *Environmental Archaeology* 12, 87–94.
- Deforce, K., Bastiaens, J., Crombé, P., Deschepper, E., Haneca, K., Laloo, P., Van Calster, H., Verbrugge, G. & De Clercq, W. 2020: Dark Ages woodland recovery and the expansion of beech: a study of land use changes and related woodland dynamics during the Roman to Medieval transition period in northern Belgium. *Netherlands Journal of Geosciences* 99, e12, <https://doi.org/10.1017/njg.2020.11>.
- Dekoninck, M., de Ruijsscher, D. & De Clercq, W. 2022a: Heated crafts on the Roman shore. Revisiting the debate on the exploitation of coastal wetlands. The case of Roman Aardenburg (Zeeland, The Netherlands). *Latomus* 81, 788–818.
- Dekoninck, M., Goemaere, E., Dewaele, S., De Grave, J., Leduc, T., Vandenberghe, D. & De Clercq, W. 2022b: Geochemical and mineralogical characterisation of vitrified waste material discovered in large quantities on Roman salt production sites along the southern North Sea coast. *Journal of Archaeological Science* 146, 105665, <https://doi.org/10.1016/j.jas.2022.105665>.
- Demiddele, H. & Ervynck, A. 1993: Diatomieën als ecologische indicatoren in de Vlaamse archeologie: Romeins en middeleeuws Oudenburg (prov. West-Vlaanderen). *Archeologie in Vlaanderen* 3, 217–231.
- Denys, L. 1991: A check-list of the diatoms in the Holocene deposits of the western Belgian coastal plain with a survey of their apparent ecological requirements, vol I. Introduction, ecological code and complete list. *Belgian Geological Survey* 246, 1–41.
- Denys, L. 1999: A diatom and radiocarbon perspective of the palaeoenvironmental history and stratigraphy of Holocene deposits between Oostende and Nieuwpoort (Western Coastal Plain, Belgium). *Geologica Belgica* 2, 111–140.
- Dhaeze, W. 2021: *The Roman North Sea and Channel Coastal Defence: Germanic Seaborne Raids and the Roman Response*. 341 pp. UNIVERSA, Wetteren.
- van Dierendonck, R. M., Vos, W. K., Besuijen, G. P. A., Kriek, M. & Ridderhof, B. 2013: *De Romeinse agglomeratie Aardenburg. Onderzoek naar de ontwikkeling, structuur en datering van de Romeinse castella en hun omgeving, opgegraven in de periode 1955-heden*. 365 pp. Hazenberg Archeologie, Middelburg.
- Ervynck, A., Baeteman, C., Demiddele, H., Hollevoet, Y., Pieters, M., Schelvis, J., Tys, D., Van Strydonck, M. & Verhaege, F. 1999: Human occupation because of a regression, or the cause of a transgression? A critical review of the interaction between geological events and the human occupation in the Belgian coastal plain during the first millennium AD. *Probleme der Künstenforschung im südlichen Nordseegebiet* 26, 97–121.

- Flower, R. J. 1993: Diatom preservation: experiments and observations on dissolution and breakage in modern and fossil material. In van Dam, H. (ed.): *Twelfth International Diatom Symposium: Proceedings of the Twelfth International Diatom Symposium, Renesse, The Netherlands, 30 August–5 September 1992*, 473–484. Springer, Netherlands.
- van Geel, B. 1972: Palynology of a section from the raised peat bog 'Wietmarscher moor', with special reference to fungal remains. *Acta Botanica Neerlandica* 21, 261–284.
- van Geel, B. 1978: A palaeoecological study of Holocene peat bog sections in Germany and The Netherlands, based on the analysis of pollen, spores and macro- and microscopic remains of fungi, algae, cormophytes and animals. *Review of Palaeobotany and Palynology* 25, 1–120.
- van Geel, B., Bohncke, S. J. P. & Dee, H. 1980: A Palaeoecological study of an upper late glacial and Holocene sequence from 'de Borchert', The Netherlands. *Review of Palaeobotany and Palynology* 31, 367–448.
- Grimm, E. C. 1987: CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers and Geosciences* 13, 13–35.
- Grimm, E. C. 2019: *Tilia for Windows: Pollen Spreadsheet and Graphics Program. Version 2.6.1*. Illinois State Museum, Research and Collections Centre, Springfield.
- Guiry, M. D. & Guiry, G. M. 2022: AlgaeBase. World-wide electronic publication. National University of Ireland, Galway. Available at: <https://www.algaebase.org> (accessed 14.10.2022).
- Hall, V. A. 1989: A study of the modern pollen rain from a reconstructed 19th century farm. *The Irish Naturalists' Journal* 23, 82–92.
- Haneca, K., Van Acker, J. & Beeckman, H. 2005: Growth trends reveal the forest structure during Roman and Medieval times in Western Europe: a comparison between archaeological and actual oak ring series (*Quercus robur* and *Quercus petraea*). *Annals of Forest Science* 62, 797–805.
- Heusser, L. & William, L. B. 1977: Pollen distribution in the Northeast Pacific Ocean. *Quaternary Research* 7, 45–62.
- Jongepier, I., Soens, T., Thoen, E., Van Eetvelde, V., Crombé, P. & Bats, M. 2011: The brown gold: a reappraisal of medieval peat marshes in Northern Flanders (Belgium). *Water History* 3, 73–93.
- Kooistra, L. I. & de Man, R. 1995: *Botanische resten uit de Romeinse tijd en de Middeleeuwen van Aardenburg-Hof Buize*. 2 pp. ROB, Amersfoort.
- Krammer, K. & Lange-Bertalot, H. 2008: *Die Süßwasserflora von Mitteleuropa 2. Teil 1–4*. Springer Spektrum, Munich.
- de Melker, B. R. 1987: *De ontwikkeling van de stad Aardenburg en haar bestuurlijke instellingen in de middeleeuwen*. 212 pp. Scriptiereeks Commissie Regionale Geschiedbeoefening Zeeland 3, Middelburg.
- Meylemans, E., Bastiaens, J., Bogemans, F., Clerbaut, T., Debruyne, S., Deforce, K., Eryvynck, A., Lentacker, A., Perdaen, Y., Storme, A., Vanholme, N. & Van Neer, W. 2022: The environment and its exploitation along the lower Scheldt river during the Roman period (Wichelen, Belgium—Late 1st to 3rd Centuries AD). *Environmental Archaeology*, 1–19. <https://doi.org/10.1080/14614103.2022.2108305>.
- Miola, A. 2012: Tools for non-pollen palynomorphs (NPPs) analysis: a list of Quaternary NPP types and reference literature in english language (1972–2011). *Review of Palaeobotany and Palynology* 186, 142–161.
- Moore, P. D., Webb, J. A. & Collison, M. E. 1991: *Pollen Analysis*. 216 pp. Blackwell Science, Oxford.
- Nieuwhof, A., Bakker, M., Knol, E., de Langen, G. J., Nicolay, J. A. W., Postma, D., Schepers, M., Varwijk, T. W. & Vos, P. C. 2019: Adapting to the sea: human habitation in the coastal area of the northern Netherlands before medieval dike building. *Ocean and Coastal Management* 173, 77–89.
- Ovaa, I. 1957: *De bodemgesteldheid van Westelijk Zeeuws-Vlaanderen*. 59 pp. Stiboka, Wageningen.
- Pals, J. P., Van Geel, B. & Delfos, A. 1980: Paleoecological studies in the klokkevel bog near hoogkarspel (prov. Of Noord-Holland). *Review of Palaeobotany and Palynology* 30, 371–418.
- Rippon, S. 2000: *The Transformation of Coastal Wetlands: Exploitation and Management of Marshland Landscapes in North West Europe during the Roman and Medieval Periods*. 332 pp. Oxford University Press, Oxford.
- de Ruijscher, D. 2023: Oppidum dardenbourg et portum ipsius. Aardenburg's high medieval marine connection with the Zwin: a status quaestionis. In De Clercq, W., Trachet, J., Dumolyn, J. & Poulain, M. (eds.): *Ad Brudgias Portum: Bruges' Medieval Port System as a Maritime Cultural Landscape*. Brepols Publishers, Turnhout.
- van Rummelen, F. F. F. E. 1965: *Bladen Zeeuwsch-Vlaanderen west en oost. Geologische kaart van Nederland*. 79 pp. Rijks Geologische Dienst, Haarlem.
- Schelvis, J. & Eryvynck, A. 1992: Mijten (Acari) als ecologische indicatoren in de archeologie. Onderzoek op de Romeinse vindplaats Oudenburg (prov. West-Vlaanderen). *Archeologie in Vlaanderen* 2, 175–189.
- Soens, T., Tys, D. & Thoen, E. 2014: Landscape transformation and social change in the North Sea polders, the example of Flanders (1000–1800 AD). *Siedlungsforschung: Archäologie, Geschichte, Geographie* 31, 133–160.
- Storme, A., Bastiaens, J., Crombé, P., Cruz, F., Louwye, S., Verhegge, J. & Deforce, K. 2020: The significance of palaeoecological indicators in reconstructing estuarine environments: a multi-proxy study of increased Middle Holocene tidal influence in the lower Scheldt river, N-Belgium. *Quaternary Science Reviews* 230, 106113, <https://doi.org/10.1016/j.quascirev.2019.106113>.
- Storme, A., Louwye, S., Crombé, P. & Deforce, K. 2017: Postglacial evolution of vegetation and environment in the Scheldt Basin (northern Belgium). *Vegetation History and Archaeobotany* 26, 293–311.
- Trachet, J., Delefortrie, S., Dombrecht, K., Dumolyn, J., Leloup, W., Thoen, E., Van Meirvenne, M. & De Clercq, W. 2015: Turning Back the Tide: the Zwin debate in perspective. A historiographical review of the medieval port system northeast of Bruges. *Revue du Nord* 413, 305–321.
- Trimpe Burger, J. A. 1985: Aardenburg-Rodanburg-Burg aan de Rudannā. *Naamkunde* 17, 335–346.
- Tys, D. 2013: The medieval embankment of coastal Flanders in context. In Thoen, E., Borger, G. J., de Kraker, A. M. J., Soens, T., Tys, D., Vervaeke, L. & Weerts, H. J. T. (eds.): *Landscapes or Seascapes? The History of the Coastal Environment in the North Sea Area Reconsidered*, 199–239. Brepols Publishers, Turnhout.
- Van Dam, H., Mertens, A. & Sinkeldam, J. 1994: A coded checklist and ecological indicator values of freshwater diatoms from The Netherlands. *Netherlands Journal of Aquatic Ecology* 28, 117–133.
- Van Mourik, J. M. 2003: Life cycle of pollen grains in mormoder humus forms of young acid forest soils: a micromorphological approach. *Catena* 54, 651–663.
- Vanhoutte, S., Dhaeze, W., Deforce, K., Demeyer, H., Eryvynck, A., Haneca, K., Lentacker, A. & Stieperaere, H. 2016: Een romeinse waterput met een vlechtwerkmand uit de vicus van Oudenburg. *Relicta* 14, 173–204.
- Verbruggen, C., Denys, L. & Kiden, P. 1996: Belgium. In Berglund, B. E., Birks, H. J. B., Ralska-Jasiewiczowa, M. & Wright, H. E. (eds.): *Palaeoecological Events during the Last 15000 Years: Regional Syntheses of Palaeoecological Studies of Lakes and Mires in Europe*, 553–574. John Wiley, Chichester.
- Verwerft, D., Mikkelsen, J. & De Clercq, W. 2019: Curbing the tide: the discovery of a Roman terp along the Heistlaan in Ramskapelle (Knokke-Heist). In Deák, J., Ampe, C. & Mikkelsen, J. (eds.): *Soils as Records of Past and Present. From Soil Surveys to Archaeological Sites: Research Strategies for Interpreting Soil Characteristics*, 243–257. Raakvlak, Bruges.
- Vos, P. 2015: *Origin of the Dutch coastal landscape. Long-term landscape evolution of The Netherlands during the Holocene, described and visualized in national, regional and local palaeogeographical map series*. Ph.D. thesis, Utrecht University, 372 pp.
- Vos, P. C. & de Wolf, H. 1988: Methodological aspects of paleoecological diatom research in coastal areas of The Netherlands. *Netherlands Journal of Geosciences/Geologie en Mijnbouw* 67, 31–40.

- Vos, P. C. & de Wolf, H. 1993: Diatoms as a tool for reconstructing sedimentary environments in coastal wetlands; methodological aspects. *Hydrobiologia* 269, 285–296.
- Vos, P. C. & de Wolf, H. 1997: Palaeo-environmental diatom study of the Holocene deposits of the Province of Zeeland (SW Netherlands). In Fischer, M. M. (ed.): *Holocene Evolution of Zeeland (SW Netherlands)*, 111–141. Mededelingen Nederlands instituut voor toegepaste geowetenschappen TNO, Haarlem.
- Vos, P. C. & Van Heeringen, R. M. 1997: Holocene geology and occupation history of the province of Zeeland. In Fischer, M. M. (ed.): *Holocene Evolution of Zeeland (SW Netherlands)*, 1–109. Mededelingen Nederlands instituut voor toegepaste geowetenschappen TNO, Haarlem.
- Vuorela, I. 1973: Relative pollen rain around cultivated fields. *Societas pro Fauna et Flora Fennica* 102, 1–27.
- Witkowski, A., Lange-Bertalot, H. & Metzeltin, D. 2000: Diatom flora of marine coasts I. In Lange-Bertalot, H. (ed.): *Iconographia Diatomologica* 7, 925 pp. ARG Gantner Verlag KG, Ruggell.

Supporting Information

Additional Supporting Information to this article is available at <http://www.boreas.dk>.

Table S1. Radiocarbon date.