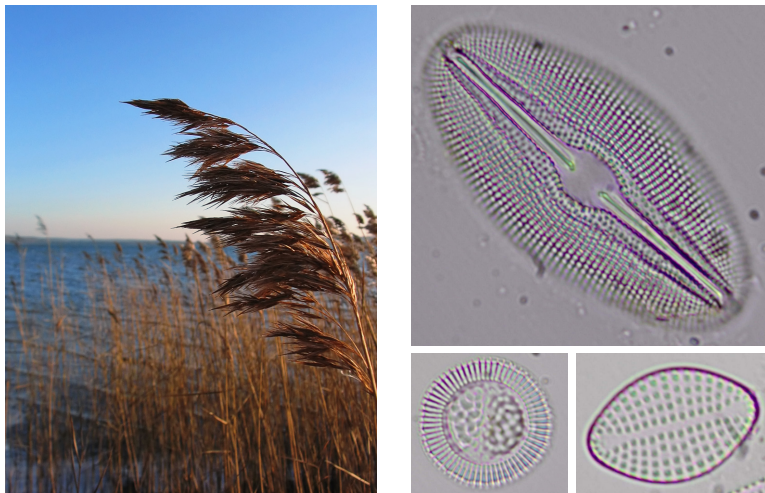


# Tidal peatlands

**A diatom study in the Old Rhine estuary, The Netherlands,  
revealing the role of reed peat in mid-Holocene landscape transitions**



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March, 2020

Master thesis Earth Sciences (37.5 ECTS)

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## Preface and Acknowledgements

It has been quite the journey. The Masterthesis that lies before you is the culmination of many months of hard work under difficult circumstances, delving into the puzzling world of diatoms. Working with diatoms is complex, and the extent of the task only became clear when the project was well underway. There were many (practical) hurdles to overcome and I owe several people gratitude for their efforts during the process.

Firstly, the first period of fieldwork and laboratory work. Planning days in the field was challenging, not in the least because we had to take into account the height of the grass at the coring locations. Fieldwork had to be conducted during the small windows outside the high grass season (5-week cycle) due to the mowing regime for hay harvest. The farmers at the Galgweg and Broekweg locations and Staatsbosbeheer are thanked for kindly letting us into their fields and take a small core. Many thanks to Wim Hoek, Harm Jan Pierik, Jelle Moree and Tim Winkels for their contributing efforts to the coring, without you the fieldwork would not have been possible.

The laboratory work was subject to an equally difficult planning, as the opening of the brand-new Earth Simulation Lab was delayed, and the samples had to be prepared elsewhere. Many thanks to Kees Nooren for teaching me laboratory procedures and helping me on hard days. Giovanni Dammers is acknowledged for his advice.

Another hurdle was diatom identification and obtaining their environmental characteristics. Literature on coastal and brackish diatom species is sparse, and despite repeated efforts, the majority of specialised sources was unfortunately unavailable to me. This made it nearly impossible to identify some of the diatom species. I am very thankful that Natasha Barlow and Geurt Verweij were willing to help with the identification of the more difficult species, although some still remain elusive. Thanks to Aleksandra Cvetkoska for teaching me the counting procedures and helping with the identification of several diatom species. To Timme Donders, for his help and advice. And to Peter Vos, Cathy Stickley and Peter Esselink for their advice on literature and other sources.

Thanks also to my supervisors. Harm Jan Pierik for the useful brainstorm discussions. Wim Hoek for instructing part of the laboratory work and especially the talks. Maarten Kleinhans for offering me yet another high diving board to jump off of into the deep. Despite the deep waters, I love the scientific challenge.

Many, many thanks to my parents, not only for your support during this project. I have no words.

Karianne

## Abstract

During the evolution of tidal basins, the dynamic equilibrium between accommodation space and inflow may shift, leading to the closure of the tidal basin. Closure occurs commonly due to one or a combination of two mechanisms: silting up of the tidal basin as terrestrialisation outpaces sea level (rise) or closing off of the tidal basin by beach barrier development. Recently, vegetation has been put forward as a possible promotor of terrestrialisation, but its role as driver mechanism in tidal basin closure has not yet been investigated.

Silting up, barrier formation and vegetation development all acted in the South-Holland tidal basin during the mid-Holocene, when the coastal area transitioned from tidal basin to peat landscape. The common palaeographical explanation at the final tipping point of tidal basin closure is that beach barriers closed and the back-barrier basin subsequent freshened, which facilitated peat formation. The basin-freshening explanation was tested, using diatoms for reconstructing salinity conditions around the lithological contact between marine clays and reed peat in the Old Rhine estuarine area within the South Holland basin. Did vegetation and peat formation play a role in “pushing out” the tidal influence?

Diatom analysis from two cores showed that open connections with the sea remained until peat formation commenced under brackish conditions in an intertidal environment. Marine flooding still occurred while peat developed. There are no signs of a freshwater environment in the marine clays nor in the peat, so the beach barriers did not close off the back-barrier basin completely before peat formation started.

The tidal landscape transitioned to peatland due to an interplay between silting up, beach-barrier development, and terrestrialisation by vegetation expansion. At the tipping point of the landscape transition, the development of reed fields and peat played a prominent role in pushing out marine influence of the back-barrier area. Terrestrialisation by peat formation could outpace mid-Holocene sea level rise. Importantly, peat is not only a consequence, but also a driving force of landscape transition.

The fact that reed peat formed under brackish conditions is contrary to the current lithostratigraphic definition of Holland peat, that classifies all peat as fresh. Revision of this definition as to types of peat and genesis would improve reconstructions of palaeoenvironments and especially transitions of palaeolandscapes. Other proxies such as diatoms have proven to be a valuable and necessary addition to lithology in palaeogeographic reconstructions.

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## 1. Introduction

Tidal embayments and estuaries have formed all over the world under a combination of different factors including relative sea level rise, sediment and flow dynamics, inherited topography and interactions with biotic agents (e.g. Pritchard, 1967; Beets et al., 1992, 1996; De Haas et al., 2018a). Inundated coastal areas may develop into tidal embayments with open connections to the sea (e.g. Beets et al., 1996, Vos, 2015), lagoons behind closed barrier systems (e.g. Oertel et al., 1998), or estuaries when fluvial influx is present (e.g. Pritchard, 1967; De Haas et al., 2018a). The dynamic equilibrium in tidal basins is in the first place defined by the size of the tidal basin (tidal prism), that controls the amount of flow into the basin. The cross-sectional area of the inlet is proportional to the size of the tidal prism (Jarett, 1976; Masselink et al., 2011). If one changes, the other will adjust. For example, a reduced size of the tidal prism alters the flow regime and thereby decreases the cross-sectional area of the tidal inlet, allowing beach barriers to grow (Beets et al., 1992). Tidal basins commonly cease to exist due to one or a combination of two mechanisms: silting up of the tidal basin as terrestrialisation outpaces sea level (rise), or closing off of the tidal basin by beach barrier development. Tidal basins are usually temporary systems, but if the creation of accommodation space in the basin exceeds infilling, for example in case of relative sea level rise, tidal embayments can remain open for much longer (De Haas et al., 2018a).

Biotic agents or eco-engineering species such as vegetation and peat development have recently been suggested as promoters of terrestrialisation processes within tidal basins (Pierik et al., 2017; De Haas et al., 2018). Vegetation is an intricate part of tidal basins, prominently exemplified by the presence of marshlands (Redfield, 1965; Oertel et al., 1998). Peat may also form in tidal basins, in intertidal to high marsh environments (Redfield, 1965), and can be used as an indicator of terrestrialisation. Despite its terrestrialisation potential, the role of vegetation and peat formation in tidal basin closure has not yet been investigated. This thesis aims to shed light on driver mechanisms acting in a tidal basin that transitioned to peatland at the time of basin closure.

Driver mechanisms for tidal basin closure can be derived from reconstructing the history of tidal basins, that is preserved in sediment deposits and peat layers in the subsurface. Sequences of marine clays and peat are common indicators of emerging (regressive) phases and are thus relevant for investigating tidal basin closure. Different factors may be involved in the formation of peat and terrestrialisation in regressive phases, and are thereby possible drivers for tidal basin closure. In the the Onnetoh estuary in Japan (Sawai et al., 2002) and the River Bann estuary in Ireland (Wilson & McKenna, 1996), (glacio)tectonic activity is responsible for the alternation of peat and sediment layers in the subsurface. Beach barrier formation is indicated to be the main driver for closure of the South Holland coast (e.g. Beets et al., 1996; Hijma, 2009; Vos, 2015). Cyprien et al. (2004) also mention beach ridge formation as a possible driver of the developing peat lands in a regressive phase in the Loire basin (France) during the mid-Subboreal, but they do not go into the process of landscape transition. Frouin et al. (2010) relate upstream peat formation in an aggrading Seine estuary during the Subboreal to local hydrological conditions. In the Oder lagoon (Baltic Sea), beach barriers had closed off the lagoon from marine influence during the Subboreal, and peat formation commenced under brackish conditions after a lacustrine phase (Müller, 2001).

The closing process of embayments and lagoons may take some time. De Wolf & Cleveringa (2006) pose that it took ~1000 years for the early prograding beach barriers along the South Holland coast to close whereafter peat could start to develop, with the remark that this hypothesis requires further discussion and research. The Albufera de València lagoon in Spain experienced several phases in which the lagoon was temporarily or partially closed off from marine influence, before the final closure of the beach ridges. The lagoon was brackish during the closing process, with infrequent marine influence. When several high magnitude flooding events supplied much extra sediment for deposition at the beach ridges, the lagoon was closed off definitively. The lagoon freshened after that, and when infilling had progressed enough, peat could grow and terrestrialisation took over (Carmona et al., 2016).

Studies into estuarine and tidal basin peat formation used peat as an indicator of water level fluctuations in order to reconstruct the general evolution of the tidal basin (Wilson & McKenna, 1996; Sawai et al., 2002; Cyprien et al., 2004; Frouin et al., 2010; Carmona et al., 2016), or as an indicator of freshening (e.g. Pruissers & De Gans, 1986; Baeteman et al., 1999; Donselaar & Geel, 2007; Hijma, 2009; Vos, 2015). None of these examples so far have gone into the details of driver mechanisms when the landscape transition involves beach barrier closure and terrestrialisation of the back-barrier basin.

Development of vegetation, terrestrialisation by peat, and known driver mechanisms *silting up* and *beach barrier closure* all acted in the South Holland tidal basin during the mid-Holocene, and this area therefore provides a suitable environment for studying tidal basin closure mechanisms. In the late Atlantic, the South Holland coast evolved from open tidal basin into a closed coastline with (high) beach barriers and back barrier peatlands (e.g. Van der Valk., 1995; Beets et al., 1996; Hijma 2009). The transition from tidal system to peat landscape is clearly visible in the subsurface, where thick layers of the Holland peat Member (Nieuwkoop Formation) lie sharply on top of marine clays of the Wormer Member (Naaldwijk Formation). Other studies have mapped out the spatial pattern of this transition and when it took place (e.g. Roep et al., 1991; Van der Valk, 1995; Beets et al., 1996; Beets & Van der Spek, 2000; Hijma & Cohen, 2011; Vos, 2015; De Haas et al., 2018b), but the landscape transition itself has never been studied in detail. Driver mechanisms that so far have been assumed to be involved in basin closure are *silting up* of the tidal basin and *closure of the beach barriers* with subsequent back-barrier basin freshening. The latter is presumed to be the main driver at the tipping point of tidal basin closure. This basin-freshening-explanation is based on the assumption that peat grows under freshwater conditions and rising groundwater tables. The presence of peat would therefore indicate an absent, or at least strongly restricted, marine influence and thereby closed beach barriers (Raven & Kuijper, 1981; Roep et al., 1991; Beets et al., 1996; Beets & Van der Spek, 2000; Berendsen & Stouthamer, 2000; Beets et al., 2003; De Wolf & Cleveringa, 2006; Hijma & Cohen, 2011; Vos, 2015; De Haas et al., 2018b) (see also chapter 2).

Key to unravelling the cause-consequence sequence of events at the time of tidal basin closure, and thereby to deduce driver mechanisms, are the (palaeo-)salinity conditions in the back-barrier area. Relying on peat as indicator of a freshwater environment is insufficient, because brackish peat can also be found in estuaries and coastal environments (e.g. Redfield, 1965; Bell, 2002; Sawai et al., 2002). Therefore, salinity cannot unequivocally be deduced from only lithology. A most useful proxy for salinity is the occurrence of diatoms, single-celled algae that are widely spread in aquatic environments and whose silicon skeletons are preserved in subsurface sediment (e.g. Batterbee, 1986; Batterbee et al., 2001; Juggins, 1992). Each species has specific requirements for their habitat (e.g. Vos & De Wolf, 1993; Stowa, 2014). The assemblage of diatom species found in sedimentary facies thus points to specific environmental conditions and can be used in paleogeographic reconstructions (Denys, 1985; Vos & De Wolf, 1988, 1993; Juggins, 1992) (see also chapter 3).

Diatoms from two cores of the back-barrier area were analysed and compared to the lithology around the clay-peat contact. Identification of basin closure driver mechanisms requires a fieldwork area that experienced influence from both marine and freshwater sources. The Old Rhine estuary was therefore chosen within the South Holland basin for its proximity to tidal inlets and the Old Rhine river branch.

The palaeo-salinity conditions were reconstructed from diatom assemblages to shed light on the question what the main driver for the mid-Holocene tidal basin closure was. Was it the closing of the beach barriers, as is the current palaeogeographic explanation, or did vegetation (peat formation) “push out” the influence of the tide? And additionally, does the basis of the Holland peat indicate a freshwater environment? If so, did this transition occur as abruptly as the lithological contact suggests?

The outline of this thesis is as follows. In the next chapter, the development of the study area in the Old Rhine estuary and the wider Holland coast is described to provide the context in which the landscape transition took place. It also incorporates the palaeogeographical knowledge into the processes of landscape development and driver mechanisms in this area so far. An introduction into the characteristics and use of diatoms in palaeoenvironmental research is provided in chapter 3, to get acquainted with the particulars and challenges of working with diatoms. The subsequent chapters focus on the research methods and results, leading to a more detailed environment reconstruction of the evolution of the back-barrier area around the time of the mid-Holocene landscape transition. From this environment reconstruction, the drivers of the closure of the South Holland tidal basin can be uncovered. Following from the results of this study, the implications for the methodology and underlying assumptions of palaeogeographical and palaeoenvironmental research are discussed.

## 2. Tidal basin evolution in the study area and driver mechanisms

This chapter provides the context in which the mid-Holocene landscape transition from tidal basin to peatland took place along the South Holland coast, and particularly in the Old Rhine area. The general landscape evolution includes several tipping points related to driver mechanisms. The state of knowledge regarding palaeogeographical reconstructions and driver mechanisms of tidal basin closure are discussed.

The tidal basin at the South Holland coast differs from that of the North Holland coast (and elsewhere along the Dutch coast), in that there were river channels debouching into the southern tidal basin during the Atlantic. The river system (Rhine branches) not only imported sediment into the system that accelerated infilling, but also flushed out sediment to sea and helped keeping parts of the basin open. The southern part of the South Holland tidal basin therefore silted up and in the northern part, where the main Rhine branch (Old Rhine) avulsed to, an estuary developed in the late Atlantic and Subboreal (Beets et al., 1996; De Haas et al., 2018a, b).

The Old Rhine river was active between 6500 - 1000 cal yr BP<sup>1</sup> (De Haas et al., 2018b) and became the main branch of the river Rhine for the majority of this period (Berendsen & Stouthamer, 2000). The Old Rhine estuary was located near present day Leiden and Katwijk along the southern Holland coast (figure 1). The estuary stretched inland to present-day Bodegraven, as can be derived from the extent of estuarine deposits in the subsurface (Dinoloket database), and evolved from tidal basin to estuary to small outlet during its lifespan (De Haas et al., 2018b). A schematic overview is provided in figure 2.

The development of the estuary is strongly linked to that of the wider area and coastline, the Rhine-Meuse delta and Holland coast, and is summarised below following the outline of the Holland coast evolution. The evolution of the Holland coast, Old Rhine and Rhine-Meuse delta during the Holocene have been reconstructed and described in detail in other works, to which the reader is referred for more information (e.g. Beets et al, 1996; Berendsen & Stouthamer 2000, 2001; Gouw & Erkens, 2007; Hijma, 2009; Vos, 2015; Pierik et al., 2017; De Haas et al., 2018a, 2018b).

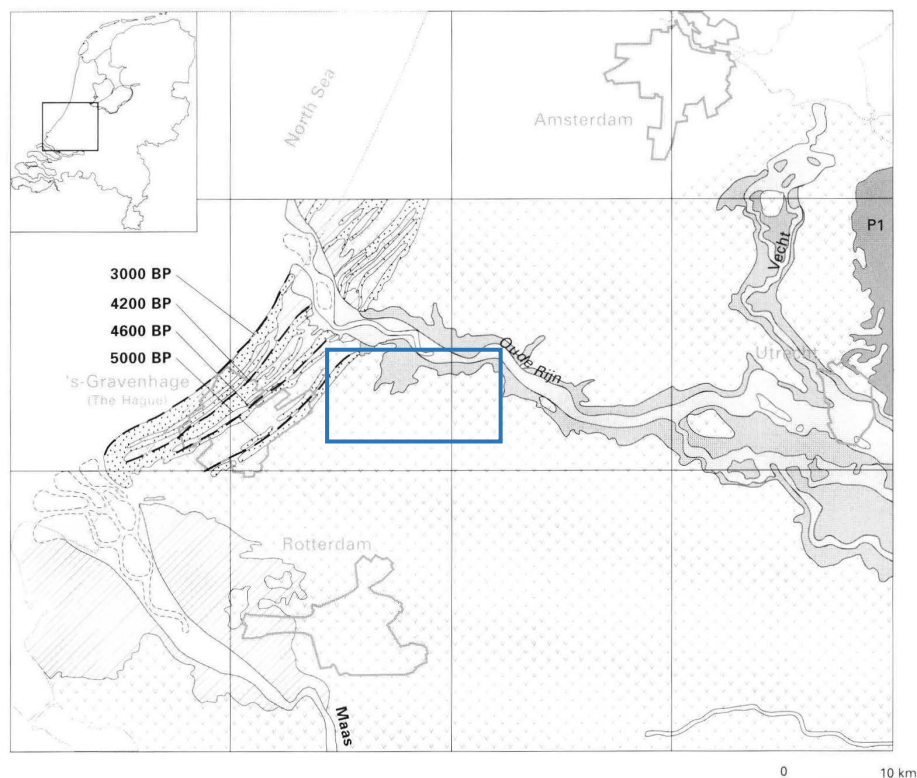


Figure 1: Location of the Old Rhine in the southern Holland basin (ages in <sup>14</sup>C years BP, source: Beets et al., 1996). Blue box shows the study area.

<sup>1</sup> Radiocarbon ages were calibrated using Calib rev. 7.0.4 and the Intcal13 curve. In cases where only a <sup>14</sup>C age without uncertainty range was available, an uncertainty of +/- 100 years was used.



## 2.1 The Holland Coast and back-barrier area

### 2.1.1 Atlantic > 6500 cal yr BP – Transgression

The Holland coast comprises the majority of the western Dutch coastline, of present-day provinces North Holland and South Holland. In the beginning of the Holocene, post-glacial sea level rise had inundated the vast low lying Weichselian alluvial plains created by braided river systems and aeolian deposits (Beets et al., 1996). At the onset of the Atlantic ~8ka in the middle Holocene, sea level was rising about 1 m per century (Hijma, 2009; Hijma & Cohen, 2019). The entire Holland coast had developed into a large interconnected tidal system that could support at least six major tidal inlets in between the Meuse delta in the south and the inlet to the Wadden Sea south of Texel to the north (Roep et al., 1991; Beets et al., 1992) (figure 2, map 6800 yr BP).

Sediment transport from marine origin was mainly directed cross-shore (Hijma, 2009), but the majority of sediment deposited in the tidal basin was supplied by the Rhine-Meuse rivers (Van der Valk, 1995; Hijma, 2009). Riverine deposits of different channel systems intersected the tidal basin. Sand and fine-grained sediment was deposited in the back-barrier basin, layered between clayey deposits of marine origin (Van der Valk, 1995). Infilling was able to keep pace with sea level rise due to the vast supply of (fluvial) sediments (Beets et al., 1996). Because of the presence of a large river system, marine influence in the Rhine-Meuse delta (South Holland) protruded less far inland than in the northern Holland coast.

Beach barrier formation occurred with a retreating shoreline up to 3-5 km landward under early Atlantic sea level rise (Van der Valk, 1995). Hijma & Cohen (2011) showed that the Holland coastline in the area of the Old Rhine estuary rapidly receded between 7500-6800 cal yr BP, with a tidal range increasing to 1.8m and relative sea level rising to -7.5m below NAP, at 0.3-0.5 m/century (Dutch Ordnance Datum) (figure 2 maps 6800 and 6300 yr BP). In the central and southern Holland coast, beach barriers islands of an estimated 8-10 km long started to develop, separating several tidal inlets among which was the Old Rhine estuary. Sediment was supplied by longshore transport in the North Sea and by ebb-tidal deltas (Hijma & Cohen (2011)). The majority of riverine sands of the Rhine/Meuse system were deposited in the tidal basin and further upstream, and therefore did not contribute to beach barrier formation (Beets et al., 1992; Van der Valk, 1995).

### 2.1.2 Late-Atlantic 6500-5500 cal yr BP – Silting up: change in coastal sediment fluxes

When the tidal basins had filled up to a critical extent in the Late Atlantic, a tipping-point in the coastal evolution was reached ~ 6300 cal yr BP (figure 2). This can be considered an early stage of gradual tidal basin closure, with *silting up* as the main driver mechanism. Even though the tidal basin had not filled in completely, sedimentation had reduced the tidal prism enough to influence sediment transport fluxes in favour of beach barrier formation. Longshore transport became dominant (Beets et al., 1992; Van der Valk, 1995; Hijma, 2009). Sea level rise was considerably lower than in the early Atlantic, with 0.2-0.3 m per century (Hijma, 2009).

The early barriers were relatively low and the system typically resembled a beach plain with cheniers, which is much different from the high present-day dunes. The maximum thickness of 5-7 meter of cheniers sand deposits indicates that the North Sea was relatively shallow compared to current conditions (Van der Valk, 1995). The Rijswijk-Zoetermeer system at the southern Holland coast became an extensive tidal system when the Rhine branch to this tidal inlet was rerouted to the north as the Old Rhine formed (Berendsen & Stouthamer 2000; Hijma & Cohen, 2011) (fig. 2 map 6300 yr BP). The southern Rhine branch and its part of the basin silted up quickly after abandonment. The Rijswijk-Zoetermeer system was the last active tidal basin along the South Holland coast and its southern inlet started to close ~6.1 ka (Hijma & Cohen, 2011). The coastline reached its maximum landward position ~5850 cal yrs BP (Vos, 2015) and from then on, coast had transitioned from retrogradation to progradation (fig. 2 map 5700 yr BP).

Silting up and terrestrialisation of the back-barrier basin continued in the mid-Holocene. At the same time, clastic deposits of marine incursions on top of peat caused compaction of peat layers in the tidal basin (Van der Valk, 1995). The consequent subsidence created new accommodation space that facilitated new incursions. Back and forth terrestrialisation and inundation in different areas eventually tipped in favour of net silting up of the back-barrier basin (Beets et al., 1992; Beets & Van der Spek, 2000; Van Heteren et al, 2011). Additionally, the coastal regime changed from mixed-energy to more wave-

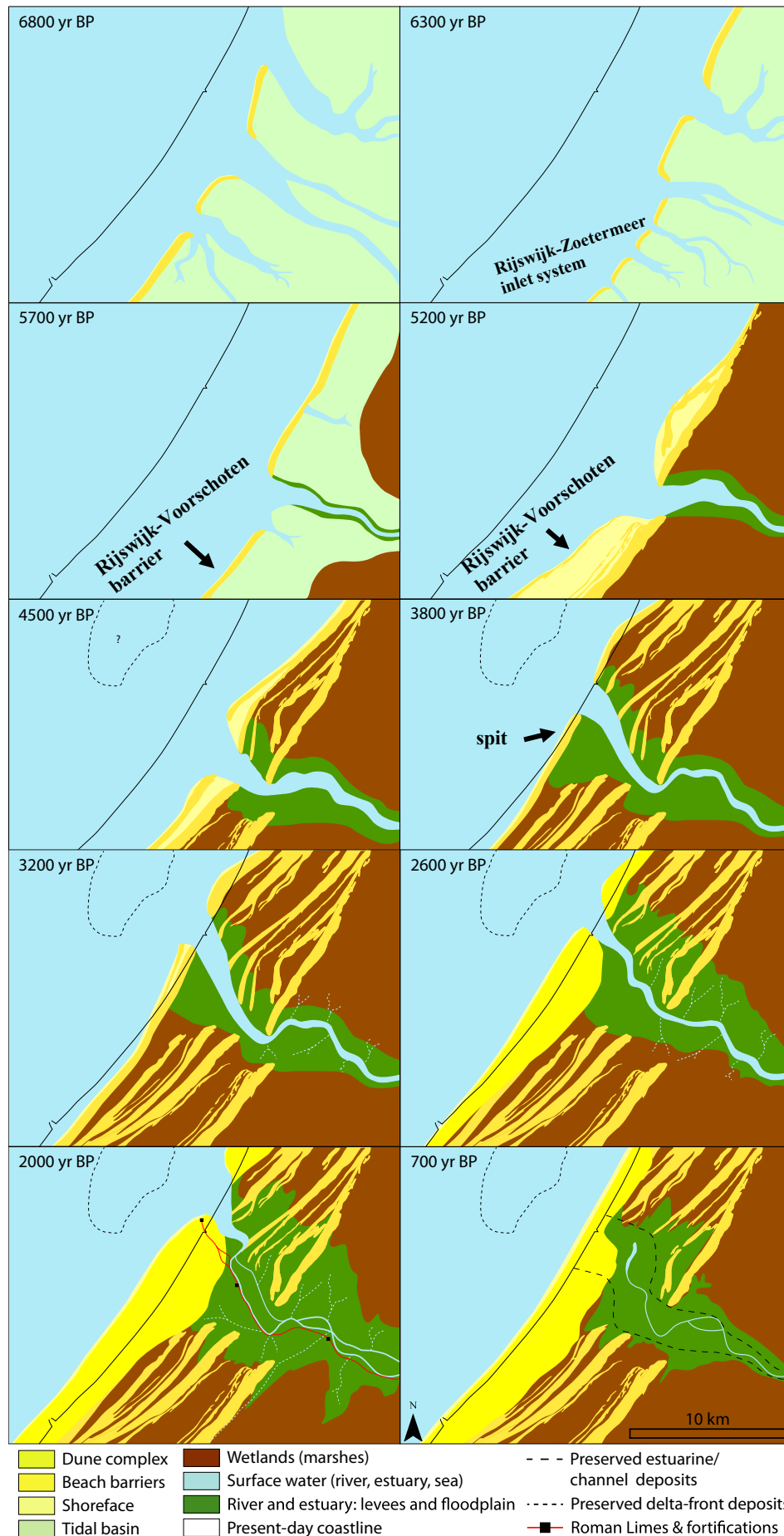


Figure 2: Schematic overview of the Holocene development of the Old Rhine estuary (ages in cal yr BP) (adapted from De Haas et al. 2018b).

dominated. This could have added to the shifting balance of accommodation space in and sediment supply to the back-barrier basin, possibly accelerating the closing of the tidal inlets (Van Heteren et al., 2011).

### **2.1.3 Subboreal <5500 cal yr BP – Beach barrier development and closing inlets**

The next step in tidal basin closure following the decreasing accommodation space during the Atlantic, is adjustment of the inlets, as both are related in tidal basin dynamics (see chapter 1). *Closing off* by beach barrier formation is considered to be the main driver in the final stage of tidal basin closure along the South Holland coast. Beach barrier remains from the time the coast started prograding are preserved in the subsurface, and the development of the beach barrier system is known in detail (e.g. Van der Valk, 1995). However, the role of beach barriers as closing mechanism is inferred from the presence of peat in the back-barrier area. Peat is assumed to have formed under freshwater conditions. The general palaeogeographical explanation is therefore that the back-barrier basin freshened as marine influence was excluded by the closed beach barriers, whereafter peat could form in the back-barrier basin (Raven & Kuijper, 1981; Roep et al., 1991; Beets et al., 1996; Beets & Van der Spek, 2000; Berendsen & Stouthamer, 2000; Beets et al., 2003; De Wolf & Cleveringa, 2006; Hijma & Cohen, 2011; Vos, 2015; De Haas et al., 2018b)

By the time of the early Subboreal around 5ka, sea level rise slowed down to 0.1-0.2 m per century (Hijma, 2009). Riverine sediments reached the coast through the infilling tidal basins and added to the ample sediment supply that was available for barrier formation (Beets & Van der Spek, 2000). Beach barriers grew and closed off several tidal inlets, marking the end of the tidal inlets into the back-barrier basin (fig. 2 map 5300 yr BP). Around 4500 cal yr BP, the Old Rhine estuary was the only remaining tidal inlets along South Holland coast (fig. 2 map 4500 yr BP). In North Holland, the Oer-IJ and Alkmaar-Bergen inlets also remained open, but the latter inlet silted up soon after that.

Younger beach ridges developed seaward of older barriers, wave action became more dominant still in shaping the Holland coast (Beets et al., 1992). During the Subboreal, progradation extended the central Holland coastline in seaward direction by almost 10km (Beets & Van der Spek, 2000). The early Subboreal also brought the first riverine flood plain deposits into the northern part of the tidal basin by the Old Rhine branch (Van der Valk, 1995).

After ~4000 cal yrs BP, progradation occurred in deeper water, steepening the coastal barriers (Roep et al., 1991). The southern Holland coast moved 1 km seaward, near Katwijk and the Old Rhine estuary, the position of the coastline remained more or less the same (Van der Valk, 1995) (figure 2 map 3800 yr BP). Coastal erosion and retrogradation started to prevail over progradation in the beginning of the Subatlantic, when sediment supply diminished and the sands of the steepened barriers were out of reach of the waves for reworking and redistribution (Van Heteren et al., 2011). The so-called “Younger Dunes” developed on top of the beach ridges (“Older Dunes”) and the Old Rhine and Oer-IJ inlets were closed off (Roep et al., 1991).

## **2.2 Back-barrier peatlands**

Two periods of peat formation can be distinguished in the wider Holland coast area during the Holocene. Firstly, Basal Peat developed on top of the Pleistocene deposits under influence of rising groundwater levels due to post-glacial sea level rise in the early Holocene, generally before 7500-7000 cal yr BP (De Haas et al., 2018b), and in the Old Rhine area near Hazerswoude ~7850 cal yr BP (Van de Plassche, 1982) (near fieldwork location GW, chapter 4 figure 6). The North Sea area was barely inundated in the early Holocene, and groundwater level was rising inland in accordance with sea level. The “Holland coastline”, or its predecessor, was located in the North Sea area at considerable distance of the inland areas where Basal peat grew (Hijma, 2009). Basal peat is indicative of a transgressive or “drowning” system. Further development of Basal peat was halted when the sea transgressed and flooded the tidal basin. The second period of peat formation, Holland peat, commenced in the subsequent regressive phase and is relevant for the present study.

Peat formed diachronically from the landward edges of the Holland coast tidal basins from ~8000-7700 cal yr BP, as inland peatlands had formed under rising groundwater levels and expanded in coastward direction (Van der Valk, 1995). The tidal basins behind the beach ridges gradually silted up from the Mid-Atlantic, and as more inlets closed (Hijma, 2009), the tidal range in the back-barrier area decreased and

slightly elevated parts of the basin fell dry. It has been posed that groundwater levels rose along with the relative sea level and together with a surplus in precipitation, this caused the drainage of the area to become increasingly problematic (Pruissers & De Gans, 1986), which would facilitate peat growth (Holland peat Member) in the tidal basin. Peat became widespread from the Late-Atlantic ~6.5ka, which has been related to the decreased drainage of the area (Pruissers & De Gans, 1986; Beets et al., 1996; Hijma, 2009) (figure 2 map 5700 yr BP). The peat generally comprised reed peat in the vicinity of the beach barriers and the former beach plains (Pruissers & De Gans, 1986), and gytija where water was stagnant in ponds or lakes (Hijma, 2009).

At the same time, sea level was still rising and creating more accommodation space in parts of the tidal basin. Marine ingressions interrupted peat growth locally, and the subsurface of the southern Holland tidal basins therefore contains layers of Holland peat at different depth in different locations. The clastic sediments deposited by these ingressions caused compaction of underlying peat layers (Van der Valk, 1995; Beets et al., 1996).

In places where terrestrialisation could progress, the eutrophic fen peat was succeeded by fen-wood peat in areas close to rivers or streams such as the Old Rhine, by mesotrophic peat (Dutch: zeggeveen, broekveen) on the lower beach plains (Pruissers & De Gans, 1986), or by oligotrophic peat, that would form extensive elevated bogs during the course of the Subboreal and Subatlantic. The first raised bog in the tidal basin already started forming ~ 4500 cal yrs BP in the middle of the peatlands near Zoetermeer (Van der Valk, 1992). As the beach barriers grew and tidal inlets closed, peat formation intensified under poor drainage conditions (figure 2 map 5200 yr BP and later). Raised bogs are fed by precipitation but also require high groundwater levels to grow upwards. The maximum thickness of the raised bogs (4-5m) was probably reached ~2000 cal yrs BP. By then, relative sea level rise had become so small that it could not support higher groundwater levels needed for the bogs to rise any further (Van der Valk, 1995).

Most of the peat was excavated for turf fuel, starting on a small but organised scale in the Middle Ages. In the 17<sup>th</sup> – 19<sup>th</sup> centuries AD, the peat cushions were drained to also make use of the turf below groundwater level. In Hazerswoude (near fieldwork location GW, see figure 6 in section 4.1), small scale peat production even extended well into the 20<sup>th</sup> century AD. Nearly all peat was excavated in the Holland provinces, and the remainder has compacted or oxidised. In places, tidal deposits on which the Holland peat Member had developed are now lying at the surface. Consequently, the majority of the area currently lies below sea level (Van der Valk, 1995).

## 2.3 The Old Rhine river and estuary

### 2.3.1 Atlantic >5700 cal yr BP – Establishment of the Old Rhine channel belt

The history of the Old Rhine started with the first of two avulsions near Wijk bij Duurstede around ~7300 cal yrs BP, the second occurred at a location nearby around 6500 cal yrs BP. The river Rhine left the Benschop channel belt and tidal basin near Rijswijk, that had been the outlet in the early Holocene, and took a more northern course to the North Sea (Berendsen & Stouthamer, 2000; Hijma & Cohen, 2011; De Haas et al., 2018b) (figure 2 map 6800 yr BP). The new Rhine branch became the main course of the river from 6100 cal yrs BP during the following millennia (Berendsen & Stouthamer, 2000; De Haas et al., 2018b). Other branches that avulsed upstream convulsed again to the Old Rhine, and this channel belt was active for much longer than previous and later branches of the Rhine system (Berendsen & Stouthamer, 2000).

After its avulsion from the large tidal inlet near Rijswijk, the Old Rhine connected to a tidal channel of the inlet near Leiden (Roep et al., 1991), that would eventually evolve into the Old Rhine estuary. Wetlands developed on abandoned floodplains and the Old Rhine channel belt affirmed its new northern course into the tidal back-barrier landscape and prograded.

Near the mouth of the Old Rhine behind the beach barriers, the estuary consisted of one or two branching channel systems in the late Atlantic. The Zoeterwoude channel system was located in the south of the Old Rhine outlet and did not incise far into the subsurface. Sandy deposits with fluvial characteristics slightly northward under Leiden point to the presence of a second channel system, that would have been active simultaneously with the Zoeterwoude tidal channels (Van der Valk, 1995).

### **2.3.2 Subboreal 5700-2200 cal yr BP – Beach barrier development**

The beach barrier Wateringen-Rijswijk-Voorburg-Voorschoten south of the Old Rhine estuarine mouth, settled on its definitive position ~5700 cal yrs BP. This coincides with the “establishment phase” that De Haas et al. (2018b) distinguished for the evolution of the Old Rhine, when the estuary had taken its definitive place and a truncated shape could start to develop (figure 2 maps 5700 and 5200 yr BP). Detailed reconstructions about barrier development around the Old Rhine estuary are available. The beach barrier systems north and south of the Old Rhine prograded at different speeds and at different times.

The barrier north of the estuary (later known as the Warmond barrier) did not develop until 5200 cal yrs BP (Van der Valk, 1995; De Haas, 2018b). A few centuries after its initial formation, the northern barrier prograded very fast, 3.5km in just over 500 years (Van der Valk, 1995). Natural levees developed along the river and kept the channels in place. The back-barrier area became increasingly isolated from the estuary, which enabled extensive peat swamps to develop along the Old Rhine in the hinterland of the former tidal basin. The peat itself attributed to stabilising the position of the channels as well (De Haas et al., 2018b). Van der Valk (1995) also defined an area in between the hinterland and beach barriers where fresh and saltwater conditions alternate, until peat development intensified from 4400 cal yr BP and inundation occurred sporadically, the river becoming the main source.

Between 4600-3700 cal yr BP, a long spit formed at the southern rim of the estuary mouth (Van der Valk, 1995; De Haas, 2018b) as a result of increased longshore SSW-NNE transport combined with estuarine outflow (Van der Valk, 1995) (figure 3 map 3800 yr BP). The beach ridges grew outwards towards the North Sea (Roep et al., 1991), and this was correlated to an increased accumulation in the Old Rhine delta around 3800-3300 cal yrs BP by Van Heteren & Van der Spek (2008). The delta presumably extended to 8km off the present coastline. Deposits have most likely been eroded by longshore currents or reworked (Van Heteren & Van der Spek, 2008; Hijma et al., 2009). All that remains in the subsurface is a relatively thin layer of 2m deltafront deposits (Van Heteren & Van der Spek, 2008). The mouth of the Old Rhine estuary on the landward side of the spit consisted of a branching channel network of ~8-10m deep (Roep et al., 1991; Van der Valk, 1995, De Haas et al., 2018b). The northern part of the estuary was less sheltered by beach barriers and subject to marine influence especially during storms.

When northward longshore sediment transport increased between 4000-3200 cal yrs BP as the older Rotterdam delta eroded, the developing spit in front of the Old Rhine estuary forced the mouth of the Old Rhine to move northward by 4.4m/yr (Van der Valk, 1995; De Haas et al., 2018b). The boundary of marine-perimarine conditions stagnated well east of Leiden from ~3200 cal yrs BP, and large areas of peat developed directly behind the spit under freshening of groundwater and increasingly wetter conditions (Van der Valk, 1995). By 2200 cal yrs BP, the southern channel had moved to present-day Katwijk (Roep et al., 1991), where it remained (figure 2 map 2000 yr BP). Deposits of marine origin of around this age indicate that the estuary mouth probably was more open at the onset of the Subatlantic, which could be the first signs of upstream changes in the direction of main flow of the Rhine system (Van der Valk, 1995). Other branches of the Rhine became more important for the main flow from 2200 cal yrs BP onwards, following a series of southward avulsions towards the Meuse around this period 2850-1500 cal yrs BP (Berendsen & Stouthamer, 2001; De Haas et al, 2018b).

### **2.3.3 Subatlantic <1500 cal yr BP – Final phase of the Old Rhine**

Fluvial clay deposits near Leiden indicate that the Old Rhine was still active in the Middle Ages, albeit with lesser discharge because of upstream avulsions (Van Dinter et al., 2017). Around ~800 AD, peat formation commenced again in the area of the Old Rhine estuary, under more moist conditions. This was a period of higher wind activity and the barrier sands were blown inland, causing a widening of the barrier system. Landward of the barrier, groundwater levels were higher (Van der Valk, 1995).

The Old Rhine started to silt up since ~1050 AD (Berendsen & Stouthamer, 2000). The last marine deposits in the Old Rhine estuary date back to the 12<sup>th</sup> century AD, inhabitants of the area attempted to keep out the sea from the estuary by constructing dikes (Van der Valk, 1995). The river finally ceased to exist when this branch was dammed near Wijk bij Duurstede in the year 1122 AD (Berendsen & Stouthamer, 2000) and aeolian deposits closed off the estuary mouth within a hundred years (Van der Valk, 1995) (figure 3 map 700 yr BP). The Old Rhine river branch existed for an unusually long period of millennia because of favourable conditions including upstream tectonics and the coastal configuration and extensive peat areas, preventing avulsion (Berendsen & Stouthamer, 2000). In 1807 AD, a new “river mouth” was dug directly south of the original Old Rhine mouth, to connect the hinterland to the North Sea and improve drainage of the Rhineland area. This area had long experienced problems with drainage during winters and many plans had been made in the previous centuries to create a passage through the beach

barriers to sea. The plans either failed (Mallegat near Katwijk aan Zee, 1572 AD) or were never executed, until the successful connection in the early 19<sup>th</sup> century (Van der Valk, 1995).

## 2.4 Human occupation

The morphology of the river and estuary made part of the landscape suitable for building early settlements. Although human occupation is of later time than the landscape transition investigated here, the archaeological interest in the Old Rhine channel belt is of such importance, that a description of the study area would not be complete without a brief mention of the matter.

The oldest archaeological finds in the region are of Neolithic age (Moree, 2019). Human occupation dates back to the Iron Age (2800-2000 BP) and intensified from the Roman Age (Van der Valk, 1995). During the first century AD, the Romans advanced westward along the Rhine. The majority of the landscape in the middle Netherlands was covered in extensive thick peat and therefore uninhabitable, but natural levees and crevasse splays along the river, if only half a meter above floodplain level, proved suitable for building forts. The forts along the Rhine were military structures that together eventually comprised the northwestern border of the Roman Empire, or “limes”. The forts at Valkenburg (founded in ~40 AD) and near Katwijk were located most westward. Fort Bittenburg near Katwijk would currently be located off the coast, but it has been lost as the coastline retrograded since (Van Dinter, 2013). Other Roman structures in the Old Rhine estuary include roads, mainly on levees, and canals (Van Dinter, 2013; Vos, 2015). The remains of the limes can be found in the subsurface and are subject of archaeological research (Van Dinter, 2013).

During the Middle Ages, some agricultural activity was even undertaken in the middle of the peatlands near Zoetermeer. Clayey deposits at the surface were partly excavated in the past few centuries for the brick industry and tileries (Van der Valk, 1995).

### 3. Diatoms

Investigating the salinity conditions around the time of closure of the South Holland tidal basin and the onset of peat formation requires a suitable proxy in addition to lithology (see chapter 1), and to this end, diatoms were analysed. In order to support the diatom analysis and interpretation of the results, it is useful to first get acquainted with these algae, their characteristics, diatom life and diatom use as a proxy. This provides important background information for both dealing with the complications that can arise when identifying species in a sample, and for the interpretation of the (palaeo)environment in which diatom remains are found.

#### 3.1 Diatom life

##### 3.1.1 Morphology and taxonomy

Diatoms are single-celled eukaryotic algae, that are classified under the Bacillariophyta and come in a wide variety of shapes and sizes, ranging from < 5 micron to 1 mm. An individual diatom is made up of an exoskeleton of silica, the frustule, with a yellow-brownish substance inside it (Stowa, 2014). The frustule consists of two valves with girdles (together called thecae), that overlap to form a small box (figure 3). The smaller valve is called hypovalve, the larger one epivalve (figure 4). The morphology of the valve can be recognised by its shape, its capitate and different structures on the valve. In some species, the epivalve and hypovalve are morphologically different, this is called hypovalvy. General morphological shapes are provided in appendix I.

The most general classification of shapes for subdivision are centric (centricae, symmetric) or linear (pennate). The capitate refers to the pole of the valves. The valve itself is decorated with a variety of structures including one or more of the following: raphe (slit from pole to pole), areolae (pores), costae (elongated thickening of the valve), striae (lines), spines, etc. (Database Diatoms of North America). Some of the features are only visible in electron microscopy images, and if these are not available, distinction between otherwise similar looking species becomes impossible. This occasionally happens, as illustrated by the examples in figure 5. Indecisive identification is especially problematic if the species candidates have different environmental characteristics, but in these cases, a list of encountered species from other studies at locations nearby or in similar environments may provide a good indication for identification.

Diatom taxonomy is an ever-changing field. Over 2000 different species have been identified in the Netherlands and it is estimated that the total number of species is 10-100 times higher worldwide (Stowa, 2014). Regularly, a species is moved to another genus or higher order, if more data on its characteristics become available, if there are new insights into the relations between diatom species or if two formerly considered different species turn out to be the same. The name of a species may therefore change through time, making it more difficult to compare different studies. For example, *Coscinodiscus excentricus* (older literature) and *Thalassiosira eccentrica* (younger literature) are one and the same diatom species (see appendix II-B). Databases such as WoRMS, Diatoms of North America and Algaebase keep track of most taxonomic changes, and the current name of a diatom species can usually be found there.



Figure 3: Example of diatom valves of *Diploneis interrupta*. Left: plan view, right: girdle view that shows the two valves of a frustule (images: K.M. van der Werf).

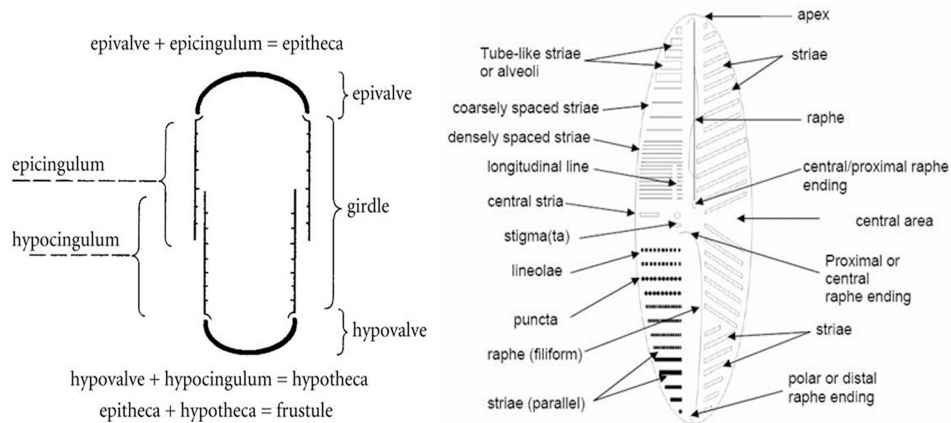


Figure 4: Schematic view of a diatom frustule (left) and the structures that can be encountered on a diatom valve (right) (images provided by A. Cvetskoska).

### 3.1.2 Life cycle

When a diatom reproduces, the two valves split and each valve of the mother cell forms the epivalve of the daughter cell, that in turn grows a new hypovalve to close the box. Vegetative cell division is the main form of reproduction among diatoms, and because the two valves are not similar in size, the daughter formed by the hypovalve will be smaller than its parent. This way, the size of offspring may become smaller still, until a critical small size is reached. Then, diatoms may revert to sexual reproduction, merging two cells into an auxospore from which a larger cell develops. This larger cell is able to reproduce vegetatively again and the reproduction cycle starts from the beginning (Batterbee et al., 2001; Stowa, 2014). Diatom remains of individuals of the same species that are found in deposits therefore greatly vary in size, which may lead to confusion with other smaller or larger species in the identification process. Rates of reproduction are very high, up to several times a day, which means that diatoms are abundant and that communities of species can adapt rapidly to changing environments (Stowa, 2014).

Diatoms live in aquatic environments, solitary or in colonies when individual algae are linked together by strands or pads into long chains. Most species are non-motile, but some are able to propel themselves slightly (Batterbee et al., 2001). Different species have different life forms. Planktonic species float in the water column, tychoplanktonic species float close to the substrate, littoral species live along a shore and benthic species reside in the substrate. Epipelon species live in the substrate and can move through it. Diatoms can also live attached to other materials such as plants (epiphyte), sand grains (epipsammon) and rock surfaces (epilithic) (Juggins, 1992; Batterbee et al., 2001). Aerophilous diatoms can temporarily withstand exposure to air, for example when a tidal flat falls dry. Species can be sensitive to different environmental conditions and water chemistry, such as temperature, pH, salinity, nutrient concentrations and organic materials, water depth, oxygen, and energetic conditions (Vos & De Wolf,

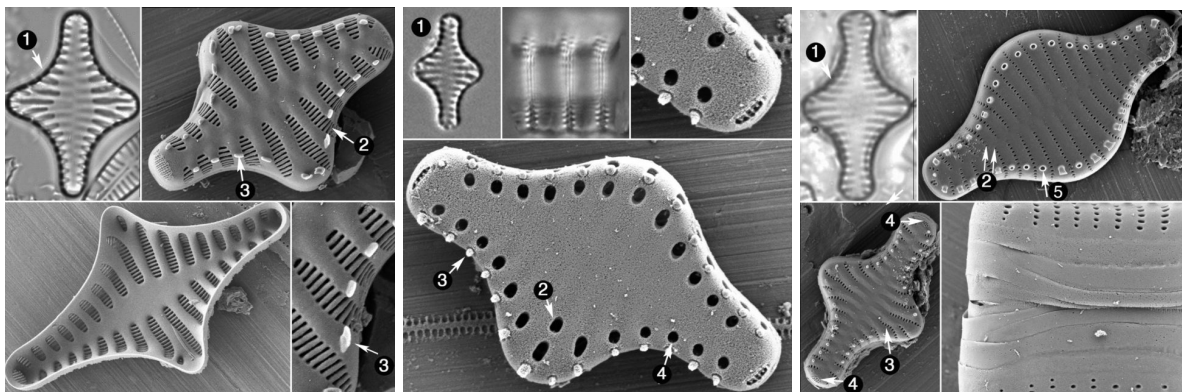


Figure 5: Similar looking diatom species *Staurosirella leptostauron* (left), *Pseudostaurosira pseudoconstruens* (middle) and *Staurosira constuens* (right). Light microscope images (top left corners (1)) and electron microscope images. Conclusive identification requires electron microscope imagery to see the details (source: Diatoms of North America species database).



1988; Batterbee et al., 2001; Stowa, 2014). Diatoms that thrive in saline (marine) waters are indicated as polyhalobous, species that live in brackish to saline waters are mesohalobous, species that have a salinity optimum in slightly brackish waters are oligohalobous or halophilous, and species with optimum in freshwater but also tolerant of brackish water are called oligohalobous indifferent (Walker et al., 1998). Because diatoms are so ubiquitous in waters worldwide and different species specialise in specific conditions, the species composition at a certain location gives a good indication of the type of aquatic environment (Stowa, 2014).

## 3.2 Using diatoms in palaeo-environmental research

Their environmental requirements, distinct morphology and preservation in the subsurface make diatoms a very useful proxy for palaeogeographic and palaeoenvironmental reconstructions (Batterbee, 1986; Batterbee et al., 2001). Diatoms can also be used for present-day water quality assessments (Stowa, 2014).

### 3.2.1 Preservation of diatom valves

When a diatom dies, its insides decay but its skeleton is very resistant and can therefore be buried and preserved in the sediment. The frustules of diatoms that lived in the water column are deposited in the upper few millimetres of the substrate, together with those of autochthonous species that live inside the substrate, and diatoms therefore give a very direct signal of the environmental conditions at the time of deposition (Juggins, 1992). Especially in locations where algae thrive, in algae blooms, the concentration of valves in the sediment can be very high. The fast response to changes in environments allows for high resolution reconstructions (Batterbee et al., 2001).

The exact composition of the palaeoflora of diatoms will probably not be encountered in analysing the diatom remains in a sample. Not all diatom species living in an environment may be incorporated in the sediment, and those that do may not all be preserved. Dissolution is a common cause of lack of preservation. The degree of dissolution depends on the chemistry of the sedimentary environment and the silicification of the frustules (Batterbee, 1986; Batterbee et al., 2001). De Wolf (1986a, b) suggests that reed might be such a big consumer of silica, that it expedites valve dissolution.

Furthermore, fracturing may damage valves to such an extent that identification or counting becomes problematic. Large and less heavily silicified species are especially prone to fracturing (Juggins, 1992). The amount of broken valves present in a sample of substrate can be an indicator for long-distance transport (Vos & De Wolf, 1988), but also of the energetic conditions of the environment (Juggins, 1992), chemical leaching, diagenesis, compaction, (fluctuations of) maximum temperature exposure, treatment of samples, predation, silicification properties of the diatom species or the shape of the valve (Vos & De Wolf, 1988). The specific processes in an estuarine environment are therefore in favour of more heavily silicified species that can endure the energetic conditions (Vos & De Wolf, 1993, 1994; De Wolf & Cleveringa, 2011).

In energetic environments (any non-stagnant or non-isolated waters), it is important to distinguish between autochthonous diatoms, that lived at the site of deposition, and allochthonous (inwash) species. Especially planktonic species are easily transported and therefore often allochthonous in these environments. Benthic species are often autochthonous and considered more useful for environmental reconstructions (Vos & De Wolf, 1988). However, the provenance and occurrence of washed-in diatoms can be put to good use in, for example, reconstruction of storm events. In coastal environments, the highly energetic storm waves may transport tycho plankton inland, that otherwise would have remained floating near the shoreface (Vos & De Wolf, 1994, De Wolf & Cleveringa, 2011).

### 3.2.2 Diatoms in estuarine deposits

Diatoms are frequently used to study estuarine deposits. Salinity transitions can be deduced from the diatom assemblage at different depths or stratigraphic levels, although there are some interpretation difficulties pertaining to post-mortem transport and allochthonous flora in estuarine environments (Juggins, 1992). Information on the method of sampling and the choice for sample depth is often not provided, but sampling in these studies usually occurs for support of the lithological data, where locations are chosen

within a lithological unit (e.g. De Wolf 1981; Wilson & McKenna, 1996; Vos & De Wolf, 1997; De Wolf & Cleveringa, 2006; Cremer, 2008), or it occurs at set intervals, sometimes regardless of the distance to lithological contacts (e.g. Denys, , 1985, 1999; Walker et al., 1998; Fukumoto, 2011). In this way, it is clear that the environment changes through time, but how these changes could occur cannot be deduced from the data. The sampling strategy is therefore very important, as is the choice of location (see also chapter 4).

## 4. Methods

### 4.1 Fieldwork

The Old Rhine estuary in the South Holland tidal basin was chosen as fieldwork area, because of its potential for investigating driver mechanisms related to marine and freshwater influence of tidal inlets and a river (see also chapter 1). Within the fieldwork area, the specific locations need to provide a regional signal of the evolution of the back-barrier basin and terrestrialisation process, rather than a local signal of, for example, the banks of a channel that stood in direct connection with the river. The paleoenvironment therefore needed to be sufficiently connected to main channels to minimise a lag in the exchange of water between river, tide, and back barrier area, and far away enough from the river and sea inlets, but not too far inside the saltmarsh area.

Additionally, requirements for diatom analysis needed to be taken into account, as to the particular environments that diatoms reside in and the potential for preservation of their silicon skeleton remains (see also section 3.2). In high energy environments, the scour and shear forces inhibit preservation of the silicon skeletons (Juggins, 1992; De Wolf & Cleveringa, 2011), and turbid conditions inhibit diatom growth (De Wolf & Cleveringa, 2011). Locations near the former river mouth, near the sea inlet, in crevasses and channels are therefore excluded. Any storm events are assumed to sufficiently flood the estuary. Locations with compacted peat in the surface were preferably avoided because of difficulties of retrieving cores for analysis.

Palaeogeographical maps, soil maps, subsurface data and elevation maps of the region were studied (AHN; DINOLOket; Van der Valk, 1995; Hijma, 2009; Moree, 2019) to find an area that met the requirements. The Leiden-Alphen aan den Rijn area south of the Old Rhine river was chosen because  $^{14}\text{C}$  ages, lithology and lithofacies descriptions were available (De Jong, 1977; Moree, 2019; Pierik et al., in prep), and for the connection to the influence of the Zoetermeer sea inlet. In this area, only a few locations lived up to the requirements of the paleoenvironment mentioned above. The farmers owning the fields were contacted, but some owners were untraceable or would not allow coring in their fields. Some potentially suitable locations were therefore not accessible for fieldwork.

Two fieldwork campaigns were undertaken at three coring locations in fields at the Galgweg (GW, inland location), Broekweg (BW, seaward location, for which  $^{14}\text{C}$  dates were available), and Weipoortse Vliet (WV) (figure 6). An Edelmann corer and gouge were used for boring, and the cores were described in the field according to the classification systems of De Bakker & Schelling (1966) (later adapted by Verbraeck (1984) and Berendsen & Stouthamer (2001)). Calcium content was assessed by spraying a 10% HCl solution onto the substrate.

Based on the lithology of the core, the depth for taking sample cores with the piston corer was decided upon. These sample cores were taken to the laboratory for further analysis and diatom sampling. The Weipoortse Vliet location proved unusable for sampling because of compacted peat in the subsurface that would not allow for the use of the piston corer. At the other two locations, a new hole was bored next

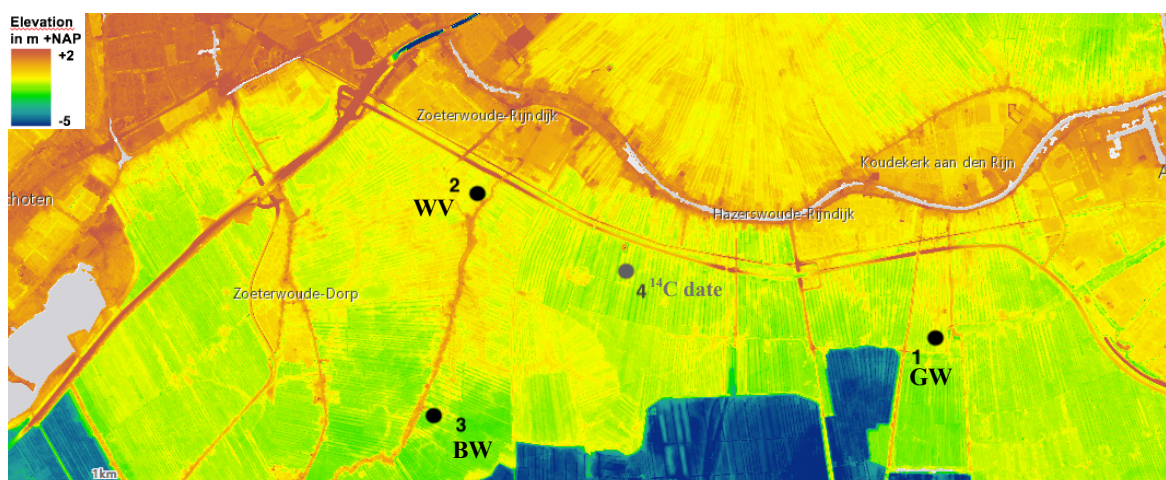


Figure 6: Elevation map (derived from AHN) of the southern area of the Old Rhine estuary with fieldwork locations 1 (Galgweg), 2 (Weipoortse Vliet) and 3 (Broekweg), and location 4 of the radiocarbon date of De Jong (1977). North is up. See also figure 1.

to the described core (at decimetres distance) using a wider auger until the desired depth, at which the piston corer was deployed. One metre sample cores were taken with a piston corer. This metre included at least the transition from Wormer to Holland peat, and preferably some additional small clay layers above this transition, if present. BW I hit an obstacle in the subsurface (wood), that prevented coring at lower depths. For BW II and BW III, a new core was taken a small distance (cm-dm) away from the BW I core, and BW II therefore shows some overlap with BW I.

## 4.2 Analysis

### 4.2.1 Organic matter content

Loss On Ignition (LOI) was performed on all retrieved cores (GW and BWI, II, III) to obtain the organic matter content for support of lithological interpretation and to clarify the possible presence of peat, reed or other vegetation. Processing occurred according to Heiri et al. (2001). Thus, samples of approximately 1cc were taken every centimetre, except where large chunks of wood impeded sampling (upper BW I core). Whenever there was a sharp transition in substrate within the centimetre of sample, smaller samples were taken for representation of the abrupt changes in organic matter content. All samples were dried at 105 °C, subsequently heated to 550 °C, and were weighed before and after each step. The heated samples were kept and stored for experimental analysis of salt content (see section 4.2.7).

### 4.2.2 Diatom sampling

Samples for diatom analysis were taken from all retrieved cores (GW and BWI, II, III) using a 0.3cc mini-corer. The sample depths were chosen based on lithology, presence of reed and colour of the substrate. The GW core was sampled first (table 1). This batch of samples was processed first and used as a diatom training set. Preliminary microscope analysis of the first batch provided a bigger picture of the variety of diatom assemblages with depth. Based on the location of major transitions in diatom assemblages, more samples were taken at high resolution, especially above the clay-peat contact (1 to 2 cm resolution). In the second round of sampling, the BW core was also included. In the BW core, samples were taken right below and above a lithological contact between clay, peat or gyttja. Because of time constraints, the GW core was sampled and analysed in detail and the BW core was analysed for support.

### 4.2.3 Diatom sample preparation

Processing of the first batch of samples occurred according to instructions as follows. Samples were each put into a test tube with 1ml 10% HCl and stirred using a mechanical device. 2 ml 30% H<sub>2</sub>O<sub>2</sub> was added to each tube and left overnight. Next, the tubes were placed in larger beakers with demi-water, that were heated to 50 °C for 3 hours and 140 °C for 1 hour. The tubes were stirred at 1600 rpm using a mechanical device and left to cool. The following day, the pH was increased to >5 by filling the tubes with

Table 1 Diatom samples from cores GW and BW. The samples of the first batch are indicated with \*

Core GW		Core BW	
3.66* (too few countable valves)	Reed peat	2.885	Peat
3.69 (too few countable valves)	Reed peat	2.905	Clay
3.72	Reed peat	3.08	Gyttja
3.74*	Reed peat	3.11	Clay
3.75	Reed peat		
3.76	Reed peat		
3.77	Reed peat		
3.78*	Reed peat		
3.80*	Clay		
3.89*	Clay		
3.99*	Clay		
4.02	Clay		
4.05*	Clay		
4.28*	Clay		

demi-water, centrifuging at 2200 rpm for 5 minutes and draining, repeated until pH >5. The pH was measured with litmus test strips when the tubes were topped off with demi-water. When pH was sufficient, the residue at the bottom of the tubes was brought back into suspension by shaking the tube manually, and after a few seconds when the larger particles had settled, 2ml of each sample was sprayed in a Batterbee tray. The trays were prepared by filling with demi-water and placing four microscope glasses of 20mm diameter dipped in acetone, into each tray. The samples in the trays were left to settle and dry overnight. The next day, paper straps were hung from the trays to aid evaporation of the fluid. When dry, one microscope glass per tray was selected for the microscope slide, based on most even distribution and enough, but not too dense coverage. The glasses were mounted on the slides using Naphrax®.

#### **4.2.4 Adjustments during the preparation process**

When analysing the first batch of microscope slides, two important features became apparent, based on which the preparation process of the second batch was adjusted. Firstly, tremors in the laboratory caused ripples on the microscope glasses, and the Batterbee trays of the second batch were therefore moved to a different location with a quieter environment for a more even spreading and settling. Secondly, the mechanical stirring and high centrifuge setting caused additional breaking and damage of the diatoms, especially in larger species (Batterbee, 1986). The procedure was adjusted in accordance with Renberg (1990). The second batch of samples (BW and remainder of GW samples, see table 1) were not mechanically stirred. Before heating, 1ml of 30% HCl was added. Heating occurred for 1 hour at 50 °C, 1 hour at 85 °C and 1 hour at 140 °C, and centrifuging was performed for 5 minutes at 1200 rpm. Centrifuging at 1000 rpm was tested first, but settlement was not deemed satisfactory.

The slower centrifuge treatment resulted in a larger share of attached valves in the counts, and in some cases, small colonies of diatoms were found attached to each other. It is possible that in samples centrifuged at higher rpm, some diatoms were fractured that could otherwise be counted. Based on observations in all samples combined with the consistency of the results, it was deemed that no correction was necessary, although it is good to be aware of the differences. The slower centrifuge treatment did make it easier to identify species and, moreover, the resulted attached valves provided important supporting information about allochthonous and autochthonous species.

On four left-over microscope glasses from the Batterbee trays of the second batch, a new mounting medium was tried out to see if it could replace Naphrax®. Glue4Glass is indicated to have the same refractive index as glycerine (RI index 1.47). The glue hardens under UV exposure and easier (and said to be healthier) to use than Naphrax®. For diatoms, a high refractive index of 1.65-1.75 is recommended (Batterbee, 1986; Batterbee et al., 2001; Stowa, 2014) to be able to distinguish the details necessary for species identification. Glue4Glass does not meet this criterion, and preliminary analysis of the slides under the microscope confirmed that this mounting medium is insufficiently suitable for the purpose. However, slide preparation with glue is much easier and faster than the standard Naphrax® procedure. The use of a different optical glue with a higher refractive index is a very interesting option for preparation of diatom slides in future studies.

#### **4.2.5 Diatom identification and species characteristics**

The first batch of diatom slides were used to make an inventory of the species that were encountered in the Old Rhine estuary. Identification of non-freshwater species mainly relied upon the overview of Dutch diatom flora by Van der Werff & Huls (1974). Other sources were literature of Van Heurck (1885), Cleve (1893), Hustedt (1939), Round et al. (1990), Krammer & Lange-Bertalot (1991), Morales (2001), De Stefano et al. (2008), Lange-Bertalot et al. (2011), online database Diatoms of North America, and expert judgement of dr. A. Cvetkoska, dr. G. Verweij and dr. N. Barlow. These sources mainly provided identification characteristics. Additionally, the following sources were used for classification of salinity characteristics: diatom studies from De Wolf (1981a,b,c, 1986a,b, 1989a,b, 1990), Juggins (1992), Van Dam et al. (1994), Vos & De Wolf (1993, 1994, 1997), Walker et al. (1998), Sawai et al., (2002), Cremer (2006) and Warnock et al. (2018), and online databases Algaebase, Diatom new taxon file, Florida coastal everglades longterm results and WoRMS. The vast majority of literature for identification focusses on marine and freshwater diatom species. There are only few literature sources that provide data on the particular species residing in coastal-marine and brackish waters (e.g. Snoeijs, 1993; Witkowski et al., 2000). These specialised sources are limited and were not accessible, some life-form and environmental characteristics of coastal and brackish species could therefore not be determined.

Identification of some individuals to species level was not possible due to unclear imagery, time-constraints and/or lack of identification sources, but identification of diatoms is often difficult in any case. The diatomist relies on the quality of the microscope imagery to see enough details, which is not always sufficient (see also section 3.1.1). Species within some genera “look alike” more than others, e.g. *Cocconeis* sp., *Navicula* sp. and *Nitzschia* sp., and taking more species under only the genus name in the counts is almost inevitable. In this study, some difficult or unidentifiable species had to be taken together under “unidentified/miscellaneous” because identification was not feasible for lack of time or literature sources. Each of those species had a maximum relative abundance of <1%, amounting to <5% unidentified in the samples of the GW core, which is acceptable. For the BW core, this comes to <6% of miscellaneous species, and additionally there is an unknown species (U41) that occurs <7% at depths of 3.08m and above. Much effort was put into trying to identify this particular diatom, but unfortunately even the consulted experts could not identify this species. Considering the miscellaneous group and the results of the count, the unidentified species are not likely to be of such influence that they would have led to significantly different results.

Regarding the identification of *Diploneis smithii*, some characteristic specimens were found in the samples that support correct identification, but there are also the *Diploneis* cf. *smithii* specimens that differed slightly (see appendix II-B). The characteristic smithii-structure between the striae appears to be absent or invisible, but the specimens also are not alike other *Diploneis* species. The consulted experts could not conclusively identify this diatom species. As it occurs in considerable numbers in the peat samples, it would be interesting to study this particular diatom in future research to find out more about its taxonomy. Its close resemblance to *D. smithii* and the accompanying assemblages point to habitat preferences similar to *D. smithii*.

#### 4.2.6 Diatom counting

Valves were counted under a Leica DM LB2 light microscope using 63x (times 1.5x) magnification and oil immersion. Per slide ~250 valves were counted, this number is sufficient for a statistically sound representation of the diatom assemblage (Stowa, 2014). Only diatoms with valves more than 70% intact, including the centre and characteristic features, were counted. If a complete frustule was encountered, the valves were counted separately (Batterbee et al., 2001). Valves orientated on their side (girdle view) were not counted, because identification was not conclusive, unless these valves were stacked with a valve near the end of the stack that was properly oriented for identification. Resting spores of *Chaetoceros* species were combined into one category (CRS), as identification to species level is not possible.

In practice, the count of 250 valves per slide is enough to make a reconstruction of the environment. However, some species occur in such abundance, that they can cloud the signal of species that are less abundant, while these do give important information about the habitat. This is especially the case when the over-abundance pertains to allochthonous diatoms (e.g. *Cymatosira belgica*) or diatoms with less specific habitat requirements. The differences in size may also affect representation in the counts, as was the case for the large diatom *Campylodiscus clypeus*. More rare species may not be discovered when counting only 250 valves. When scanning the samples before counting, a specimen of *Triceratium* was encountered, but this species was not present in the section of the slide that was counted. Counting 600-1000 valves per slide better incorporates rare species in the count (Batterbee, 1986), but this is obviously a very time-consuming labour and also unnecessary for the purpose of environmental reconstruction.

Furthermore, finding 250 valves per slide that are intact enough to identify and count is sometimes a challenge in itself when the valve density is low, for example in peat (De Wolf, 1986a,b, 1989, 1990; Vos & De Wolf, 1997; Denys, 1999; Sawai et al., 2002). Dissolution was the main challenge in peat samples, fracturing occurred in both peat and clay (see also section 3.2). Large (>150 micron) and elongated diatom valves (e.g. *Bacillaria paradoxa*) were mostly fractured in the samples, sometimes in more than two pieces, therefore these species might be underrepresented in the counts.

#### 4.2.7 Diatom classification and environment reconstruction

The identified diatom species were classified by salinity characteristics in five categories: Marine, Marine-Brackish, Brackish, Brackish-Fresh, Fresh. Some species have a wider tolerance for salinity, these were assigned to their preferred or most commonly mentioned habitat conditions based on several literature sources. In the case of *Liradiscus ellipticus*, salinity data was inconclusive. *Chaetoceros* spores do not occur in freshwater environments and CRS were therefore grouped under the Marine-category (Warnock et

al., 2018 and references therein). If literature sources disagree, a written account is preferred over a digital database. If written accounts disagree, the youngest account is preferred. Life-form data were not available for all identified species (see also section 4.2.5). Consequently, a full analysis of life-form for all species (e.g. benthic versus planktonic assemblages), which is useful for environmental reconstructions (e.g. Vos & De Wolf, 1993, 1994, 1997; Marco-Barba et al., 2019), could not be performed but life-form characteristics of individual species were taken into account in the analysis and interpretation of the results, whenever available.

Of some diatom species, the environmental requirements are not known or could not be found. They are grouped under “undefined” in the salinity analysis. This group varies between <2% (4.02m) and 11% (3.77m) in the GW core and between <5% (3.11m) and 18% (2.905m) in the BW core. The salinity signal in the cores is so strong, that the environment reconstruction is assumed to be largely correct, in spite of the unknowns. The interpretation of the clay layer at BW 2.905 could become more detailed if species U41 would be identified. The sample resolution in the cores is high enough to provide a very good image of the palaeoenvironment and the gradual transition in the landscape, owing to the varied diatom flora.

There may be several species with similar environmental requirements but each occurring in low numbers. It has been suggested during the early stages of this research to only focus on counting the occurrence of a few (previously determined) species that are expected to be indicative of an environment. If less frequent species were discarded because each only makes up 1% of relative abundance, an important part of the signal would be ignored. It is therefore not advisable to make assumptions on the flora beforehand and let that determine the counting process. Less abundant diatoms were also taken into account in interpretation of the results, as they can be a valuable addition and bring more specific details about the palaeoenvironment, for example water depth indicators.

#### ***4.2.8 Additional salinity analysis of the sediment using electric conductivity***

Obtaining estimates of salinity of the paleoenvironment by means of diatom analysis is effective, but time consuming. Taking advantage of studying the cores at high resolution, an experimental procedure was tried out to see if a salinity signal could be obtained directly from the sediment, to support the findings of the diatom analysis. Salt minerals deposited with marine clays can be preserved in the subsurface and marine clays can be recognised as such. Allochthonous minerals in clays can reside in the pore fluid or on the adhesive complex of clay minerals (Gillott, 1968). Common procedures to measure salt content include squeezing out the pore fluid and measure the electric conductivity of the pore fluid (Rieke & Chilingarian, 1974), drying of samples and re-hydration with a fluid of choice (Di Maio et al., 2004) or rinsing the clay with neutral ammonium acetate to replace all minerals in the adhesive complex of clay minerals and measure the amounts of minerals in the rinsed out fluid (Mathew & Rao, 1997).

The cores of the present study were taken from shallow depths and it is very likely that fresh groundwater has rinsed out salt minerals in the millennia after deposition. However, the low conductivity of clays slows down the transport of fresh water through clay layers, and salts may still reside in the minerals and even some in the pore fluid. Tasting of the sediment during fieldwork in some occasions revealed a distinguishable salty taste, especially several decimetres below the top of the Wormer Member.

After LOI analysis, the samples of the GW core were used to experiment with direct salinity analysis on the sediment. The original volume of all samples was ~1cc before LOI analysis. It was assumed that the minerals that resided in the pore water and in the organic matter, were left behind in the clastic post-LOI samples.

Each sample was crushed and grinded to a powder. The sample was then dissolved in 20ml demi-water and given 40 stirs before measuring electric conductivity and salinity with an EC-meter. The EC-value increased during measurements, indicating that dissolution was ongoing. When the value settled sufficiently, the measurement was noted. After each sample, the sensor was thoroughly wiped clean and rinsed in three beakers of demi-water. Calibration of the sensor was checked after every 10<sup>th</sup> sample, by rinsing in two beakers of 0.01M KCl solution and measuring electric conductivity in a third beaker KCl. The procedure was adjusted during the first five measurements, and these are therefore left out of account in the results.

The obtained EC-values were standardised to 1 gram using the dry weight of the samples (including the organic matter) for the electric conductivity of the substrate, and using the weight of moisture in the sample for the electric conductivity of the pore water.

## 5. Results

### 5.1 Lithology and organic matter content

All three cores contain the transition from marine clays to peat, indicating an estuarine or tidal environment with subsequent terrestrialisation. Gytja was found at the base of the peat in core BW. The peat is interrupted by clay layers in cores WV and BW. The lithology of the three cores is outlined in the next sections, this includes organic matter content of cores GW and BW. Depths are given in meters below ground level (Dutch Ordnance Datum, see also appendix III).

For visual support, results of retrieved cores of GW and BW are also depicted in a set of graphs and photos. Detailed results of LOI and lithology are provided in figures 7 (LOI), 8 and 9 (core photos). The combined results of lithology, LOI and diatoms are depicted in figures 10 and 11. Locations of the cores are indicated in figure 6 (chapter 4). Full lithological descriptions of all three cores are provided in appendix III.

#### 5.1.1 Core Galgweg (GW)

See figures 7, 8 and 9. The lower part of the core consists of marine clays, with a clear and sudden transition to peat at 3.78m. Groundlevel is 2m below NAP.

The marine clays belong to the Wormer Member (Naaldwijk Formation), indicating an estuarine or tidal environment. The lower part of the clays consists of grey silty clay loam that contains calcium (5.90-4.60m). There are occasional fragments of reed, and layered reed remains rooted the sediment around 5.20-5.10m, indicating that reed would have grown in situ at the time of clay deposition. In places, the marine clays contain black spots (5.90-5.30m and 5.00-4.30m) and thin black oxidation layers (4.74m and 4.47m). Further upwards, the clay is strongly ripened (4.70-4.30m), and around 4.50m it transitions into silty clay, that becomes humic from 4.20m upwards. This blue-grey clay is unconsolidated (Dutch: *slappe klei*) and contains reed. The roots of the reed extends downward until 5.00m. Ripening of the clay, increasing humic content and reed are indications or precursors of soil formation. However, organic matter content still remains low ~10% (figure 7). Above 4.30m the calcium content is negligible. An in-situ taste test of the sediment returned qualitative initial salinity results of some saline clays around 4.50-4.40m, and a fresher substrate around 4.10m. The organic matter content starts to rise from 4.00m when it peaks above 20%, in the zone with some reed remains in the clay, and the colour of the clays turns grey with a brownish hue.

At 3.78m a marked and sharp transition to reed peat is visible in the core, coinciding with a sudden increase in organic matter content to 40%. This is the lower boundary of a very thick pack of peat that was recognised as Holland peat (Nieuwkoop Formation), and can be stratigraphically correlated with a location ~3 km westward, for which De Jong (1977) has dated the base of Holland peat at  $5486 \pm 92$  cal yr BP (see figure 6). In the lower decimetre of the peat, the organic matter content wiggles and lowers slightly, after which the values increase from <30% to >60% within a few centimetres (3.76-3.70m). LOI remains above 50% in the peat higher in the core. The peat extends to the surface and is only interrupted by a pulse of silty clay (3.20-3.10m) and a layer of clay (1.90-1.60m) that transitions smoothly to and from the surrounding peat. The brown reed peat contains some black oxidation layers (3.77-3.30m). From 3.00m upwards the peat transitions gently from reed to wood peat, with only some reed remains below the surface.

#### 5.1.2 Core Weipoortse Vliet (WV)

Core WV comprises of marine clays in the lower part and a transition to compacted peat with thick layers of clay. Groundlevel is 1.74m below NAP. The compacted peat prevented retrieving a core for further analysis, therefore, only lithology is described for this location (see also appendix III).

The marine clays of the lower part of the core is slightly humic and silty, rooted with reed (Wormer Member, 5.00-4.60m). Horizontal layering of reed over a few decimetres' depth can be found at 4.70m and higher.

At 4.60m, the lithology transitions to reed peat of the Hollandveen Member. The peat is occasionally slightly clayey and with intercalated clay layers at 4.30m and 4.10-4.00m. The peat is layered and heavily compacted with some oxidised layers (4.10m and 3.70-3.40m) and black spots (3.10m).

The upward part of the core (<3.30m) consists of clay, that is silty at the downward boundary before it transitions to silty clay loam. Wood remains can be found throughout the silty clay loam up to



0.90m, and the substrate is occasionally humic (3.20-3.00m and 2.60-2.10m). In the latter part the silty clay loam also contains shell fragments and thus calcium. At 1.20m, a piece of alder wood (*Alnus*) was found.

### 5.1.3 Core Broekweg (BW)

See figures 7, 9 and 11. Core BW extends to lesser depth (3.80m) than the other cores and has more alternations between clay and peat, but similarly, silty clay loam of the Wormer Member (Naaldwijk Formation) makes up the lower part of the core. Groundlevel is 2m below NAP.

The lower marine deposits consist of silty clay loam that is blue-grey, calcareous and unconsolidated (Dutch: slap). The in-situ taste test indicated saline or brackish substrate. At 3.30m, the substrate contains more silt, and this is also the lower boundary of a zone with flat layers of reed, indicating in-situ growth of reed. The organic matter content is low (<10%).

A very sharp transition to gyttja marks the lower boundary of the Hollandveen Member at 3.16m, visible in both the core (figure 9) and the LOI results (figure 7), with a strong increase of organic matter content to 34%. Gyttja is a deposit from a local infilling pool and contains seeds, glimmering fragments and small clay pulses (millimetres to centimetres thick). As the gyttja transitions to unconsolidated reed peat (~2.80m), organic matter content remains fairly constant, and peaks to 65% in the lower parts of the reed peat.

Small intercalated clay layers can be found in the gyttja and peat, corresponding to minima in LOI values (17% at 2.88m and <10% at 2.75m). Centimetre thick clay pulses could be interpreted as storm or flood beds. Above 2.69m, the organic matter content of the peat wiggles between >50% and lows of 30-40%, with a maximum 75% (2.41m) (figure 7). A black oxidation layer occurs at 2.30m.

A sharp boundary to slightly humic and calcareous silty clay loam with reed and wood remains occurs at 2.00m, supported by a plummeting organic matter content to ~20%. This transition was dated 4144 ± 42 cal yr BP and the clayey facies was interpreted as levee deposits from a crevasse connected to the Old Rhine river by Pierik et al. (in prep). The clay is in parts very humic with wood remains (1.80-1.70m and 1.00-0.70m), in between lies peat with wood remains and a piece of alder wood (*Alnus*, 1.60m). The clays from 2.00m upward are presumed to belong to the Walcheren Member of the Naaldwijk formation (Moree, 2019). Peat is intercalated (<0.60m), in parts black and oxidised. The upper decimetres of the core consist of clay to silty clay with iron stains.

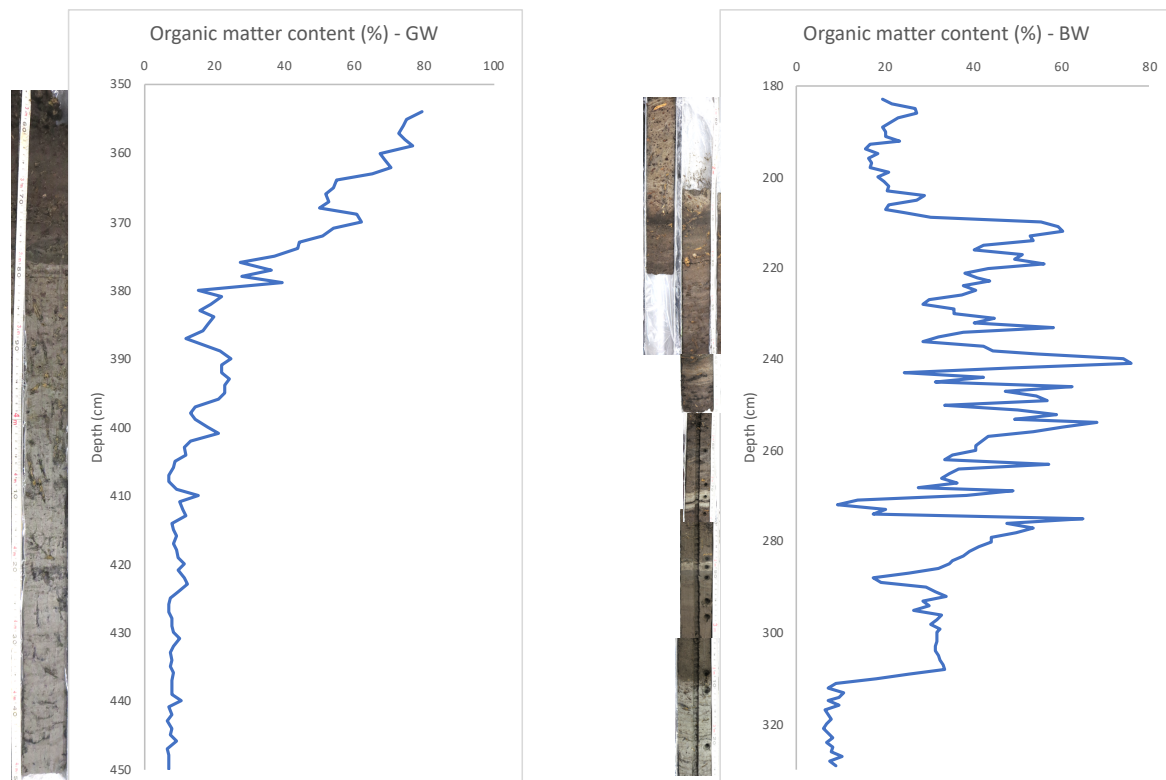


Figure 7: Detailed LOI results for cores GW (left) and BW (right). Photos of cores GW and BW are provided for reference (photos by W.Z. Hoek and K.M. van der Werf). An overview of all results can be found in figures 10 and 11.



Figure 8: Lithology of core GW containing marine clays (bottom) and peat (top) (image by W.Z. Hoek and K.M. van der Werf).



Figure 9: Lithology of core BW I&II (left) and BW III (right). From bottom to top: marine clay, gyttja, clay, peat, clay, peat, clay (images by W.Z. Hoek and K.M. van der Werf).

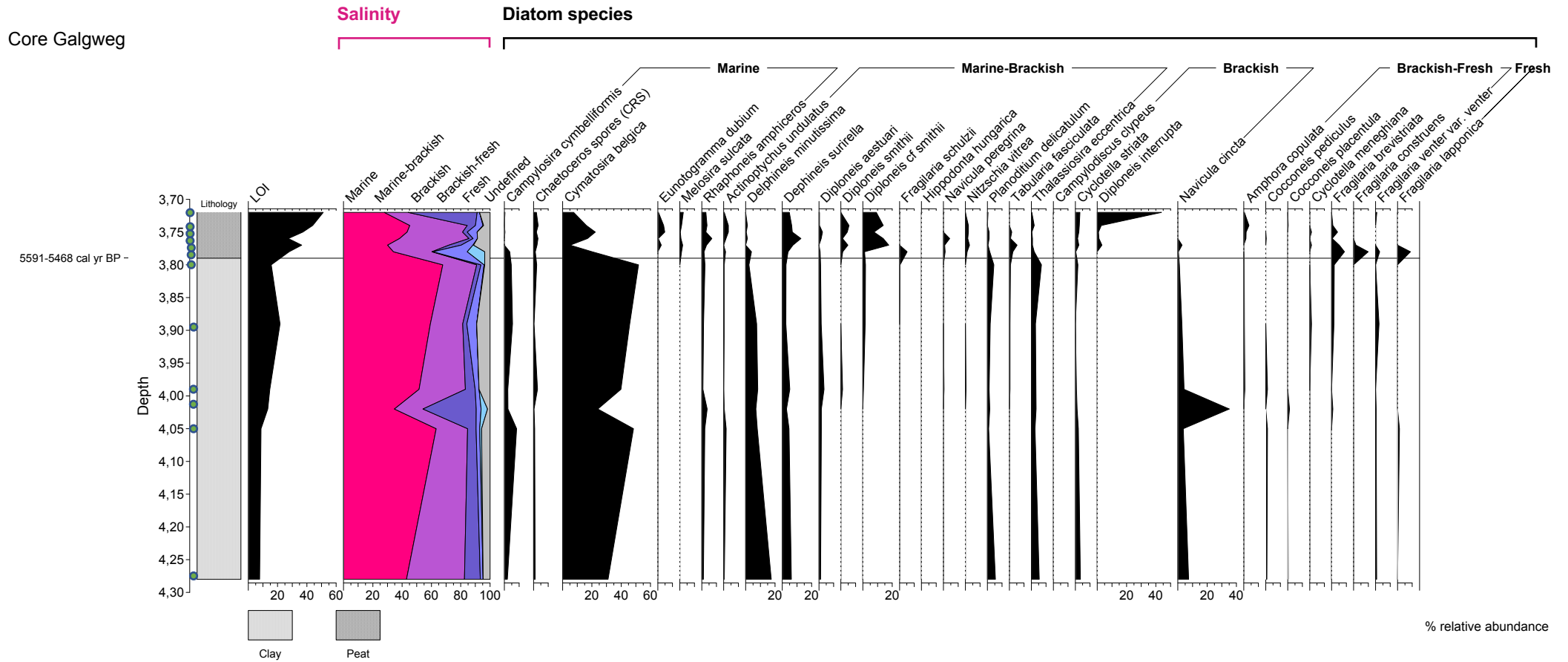


Figure 10: Analysis of core GW. Left: data for environmental reconstruction including salinity conditions in colour. Right: Diatom species with relative abundance >3% including *C. clypeus* and *N. vitrea*. Samples are indicated with green dots, samples at 3.66m and 3.69m are omitted for lack of countable valves, see also table 1. Date of basis of peat after De Jong (1977) (locations see figure 6).

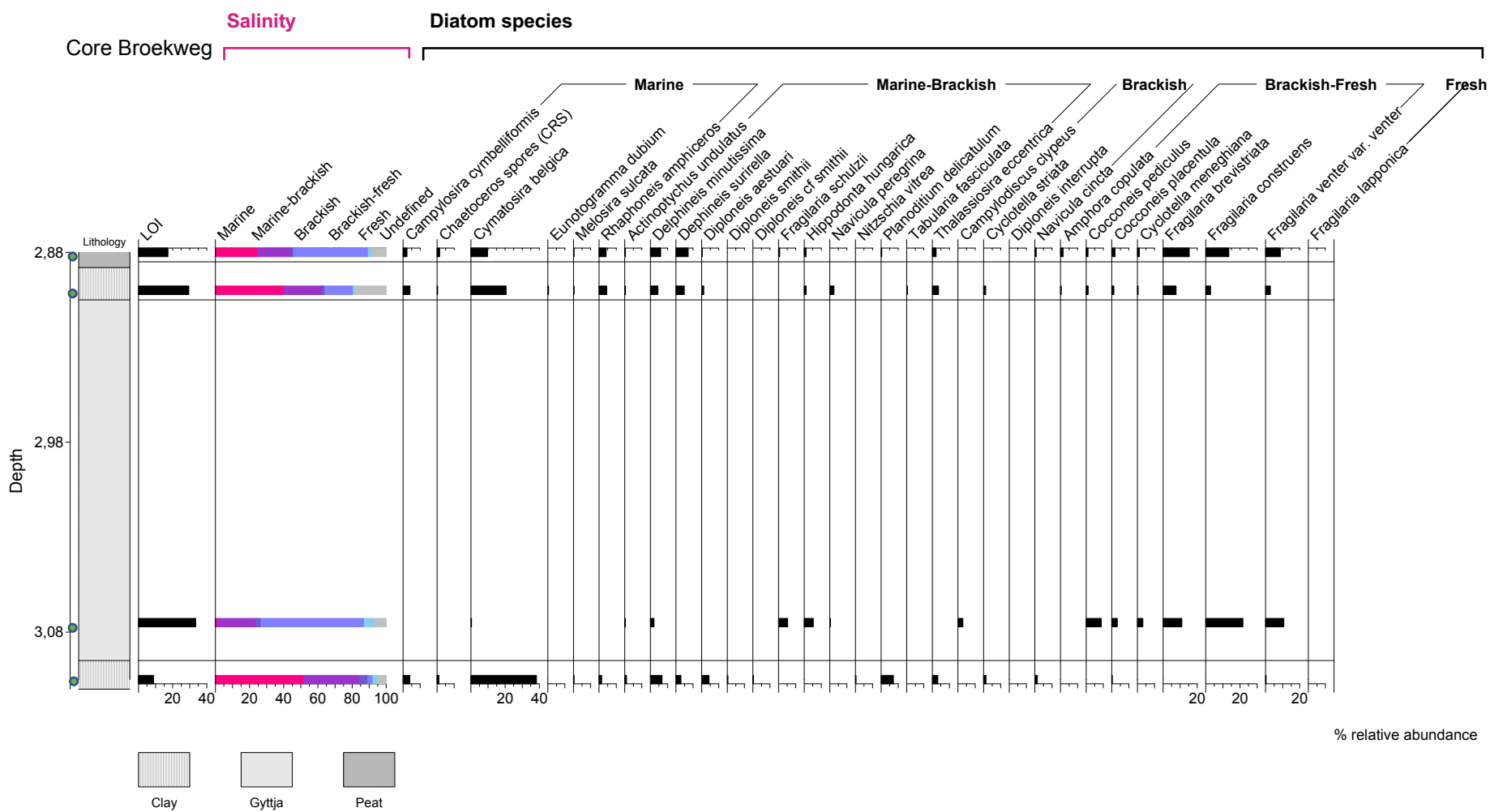


Figure 11: Analysis of core BW. Because fewer samples were analysed, the data is depicted as bar graphs to prevent distortion of the signal. Left: data for environmental reconstruction including salinity conditions in colour. Right: Diatom species with relative abundance >3% including *C. clypeus* and *N. vitrea*. Samples are indicated with green dots, see also table 1 (fieldwork location see figure 6).

## 5.2 Diatoms – Characteristic species and salinity

Over one hundred species of diatoms were found in the 14 samples of core GW and 4 samples of core BW. The occurrence of diatoms with relative abundance >3% is shown in figure 10 and 11 (right part of the graph). The subdivision of encountered species by salinity requirements is summarised in table 2, some important life-form and environment characteristics can also be found there. The salinity of the substrate as inferred from the diatoms is depicted in colour in the left part of figures 10 and 11.

### 5.2.1 Core GW

See figure 10. Below the transition of marine clay to reed peat at 3.79m, core GW is dominated (>50%) by marine species *Campylosira cymbelliformis* and *Cymatosira belgica*, and marine-brackish species such as *Delphineis minutissima*, *Delphineis surirella*, *Planothidium*, *Raphoneis amphiceros* and *Thalassionema excentrica*. At 4.28m and 4.02m, marked minima in marine diatom abundance occur, respectively 43% and 36%. At the same moment, occurrence of marine-brackish species (4.28m) and brackish species (4.02m) is relatively high, of which the sudden peak of *Navicula cincta* is most prominent. Fresh species are absent in this zone, except for a small peak of 4% at 4.02m and a 1% abundance leading up to this peak. This particular peak needs to be interpreted with caution, as there is some uncertainty regarding the identification of species responsible for it (*Gyrosigma* cf. *obtusatum* and *Nitzschia* cf. *palea*). Species of higher estuarine flats where vegetation starts to grow appear briefly and sparsely at 3.99m. *Cyclotella striata*, a characteristic species of estuaries with fluvial influence, only appears in low numbers.

Above the lithological transition to peat at 3.79m, the density of valves in the sample decreases, in the shallower peat samples over ten times less than in the marine clays. The relative abundance of the most polyhalobian species declines, prominently indicated by *C. belgica*. The sample of 3.78m, directly above the contact of marine clays to reed peat, shows a marked change in the diatom signal. The occurrence of *Diploneis smithii* (Marine-Brackish species, up to 22% relative abundance) in the peat is exemplary. This species is marine-brackish epipelon (Vos & De Wolf, 1997), but also attributed to lower marshes and tidal flats (Sawai et al., 2002). The combined Fresh and Brackish-Fresh species relative abundance is 35% at 3.78m, but they are virtually absent again above this depth.

A few centimetres into the peat, characteristic brackish diatom of intertidal flats *Diploneis interrupta* (Vos & De Wolf, 1997) makes its first appearance at 3.77m. *Fragilaria construens* and *Fragilaria lapponica* make a brief appearance of 10% and 9% to indicate a pulse of Brackish to Brackish-Fresh influence or stagnating waters (Denys, 1989; Vos & De Wolf, 1997). *Fragilaria brevistriata* has its maximum abundance at this depth. Characteristic estuarine species (*Diploneis aestuarii*, *Cyclotella striata*) reach a minimum. Other important indicators are *Nitzschia vitrea*, that is linked to brackish environments where terrestrialisation is in progress (De Wolf, 1981c), *Nitzschia navicularis* that lives on higher parts of mudflats with sparse vegetation, and *Navicula peregrina*, that occupies the highest (vegetated) parts of estuarine flats (De Wolf, 1986).

The marine influence appears to be increasing again directly after, at 3.76m, when marine-brackish (3.76m) species reach their maximum occurrence. The Marine diatom species that are encountered are slightly different than in the marine clays and contain relatively more planktonic species (e.g. *Melosira* sp.). This could be because the planktonic species are more easily transported than tychoplankton, or because the overall amount of diatoms has decreased and planktonic species stand out more while their exact numbers have remained constant. Based on the process of counting, it is likely a combination of the two (see also section 5.4.1). *C. striata* is present in increasing numbers upwards in the peat. Brackish diatoms reach their maximum occurrence at 3.72m, almost entirely due to *D. interrupta* (44% relative abundance).

Of note for the GW core is furthermore, that the lower decimetre of peat shows an upward trend of more dissolved diatom valves. Samples at 3.69m and 3.66m did not contain enough countable valves (1 and 8 valves respectively) for further analysis. Samples from the marine clays (lower part of the core, see section 5.1.1) show a lot of “rubble” containing broken diatom valves in the background. This indicates an energetic environment and reworked sediment.

### 5.2.2 Core BW

See figure 11. Core BW shows very strong fluctuations in the occurrence of especially the Marine species and Brackish-fresh species. In the marine clays in the lower part of the core, Marine species

(mainly *C. belgica*) occur >50%. Characteristic estuarine species *C. striata* and *D. aestuari* are present, as well as *Navicula digitoradiata* that indicates intertidal environments.

After the transition to gyttja, polyhalobous species are almost entirely replaced by Brackish-Fresh species (>60%), e.g. *Cocconeis pediculus*, *F. brevistriata*, *F. construens*, *Fragilaria venter* var. *venter*.

Some diatom species that occur in smaller numbers are characteristic for the gyttja. The appearance of *Hippodonta hungarica* (5.3%) and particularly, a bloom of *Campylodiscus clypeus*, which are considered to be autochthonous. The very large (>200 micron) *C. clypeus* is underrepresented at only 2.8% in the counts due to its size, but present in large numbers in the sample and therefore worth mentioning (see also section 4.2.6). Broken remains and fragments (too fragmented to count, but recognisable) of *C. clypeus* were found in the clay layer above the gyttja. Striking is also the absence of Marine species *C. cymbelliformis* and *C. belgica* in the gyttja. Fresh species reach their maximum occurrence in the gyttja at 3.08m, albeit only 6%.

The share of Marine-Brackish species remains fairly constant between 20-33% throughout the core. Fresh species and Brackish species do not exceed 7%. Peat and gyttja layers (*Fragilaria* species) alternate in diatom flora with clay layers (*C. belgica* and other Marine species).

### 5.3 Salinity analysis of the sediment by electric conductivity

The standardised electric conductivity of the dry substrate and the pore water was measured for core GW, the results are depicted in figure 12. Higher salinity would be expressed in higher EC-values. For comparison, tapwater has an EC-value of 346  $\mu\text{S}/\text{m}$  and seawater has an EC-value of  $5 \cdot 10^6$   $\mu\text{S}/\text{m}$ . The standardised substrate values show marked differences between the clays (>3.80m) and the peat (<3.79m), with a sharp increase at the lithological contact towards the peat (3.79m) (figure 12, left). The standardised EC-values of the porewater are erratic but show an overall decreasing trend (figure 12, right). From 3.65m upward the EC-values become slightly lower, which could indicate a decreasing salinity.

From the diatom analysis, it is clear that the palaeoenvironment was brackish throughout the core. However, the standardised measured EC-values of the substrate show an opposite trend (figure 12, left). The conditions during deposition of the clays would have been brackish or stronger saline than in the peat, indicated by the diatom assemblages. The EC-values would therefore be expected to show similar or higher

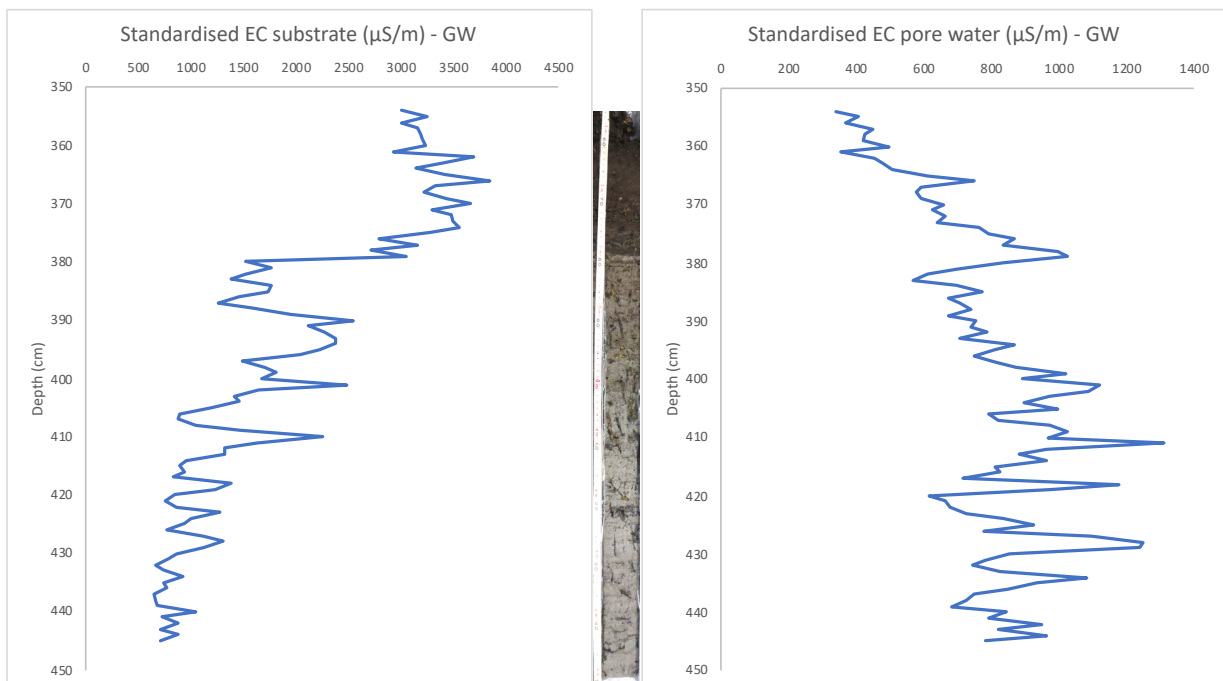


Figure 12: Standardised electric conductivity of the GW core measured on LOI samples, for substrate (left) and pore water (right). A photo of core GW is inserted for reference (photo by W.Z. Hoek and K.M. van der Werf).

values in clay samples compared to peat. In this regard, only the porewater EC-results matches slightly with the results of the diatom analysis, but the lack of diatom data above 3.65m prevents clear conclusions.

It was noted during the experiment that samples with more metallic minerals (dark orange coloured, indicating the presence of e.g. iron minerals) had slightly higher EC-values than greyer coloured samples. This suggests that electric conductivity not only indicates the presence of salt minerals, but is most likely a combination of dissolved salt and other minerals, with the latter giving the stronger signal. The signal of other minerals is especially apparent in the electric conductivity of the substrate.

Although the procedure was experimental, and the method would benefit from extra time to allow for a more fully dissolved sample, it appears that electric conductivity is not very suitable as a proxy for palaeosalinity conditions. If future research would opt to use and improve the EC-method, analysing porewater would probably be more appropriate than dry substrate.

## 5.4 Environment reconstruction

### 5.4.1 Core GW – landward location in the back-barrier basin

#### Pre 5600 cal yr BP – Open connections with the sea

At the time of deposition of marine clays, before 5591-5468 cal yr BP (De Jong, 1977), the landward part of the basin stood in open connection with the North Sea indicated by coastal marine tychoplankton (*C. cymbelliformis*, *C. belgica*, *D. minutissima*, *D. surirella*) (De Wolf, 1981b). *Campylosira cymbelliformis* is considered most indicative for the marine conditions, as this littoral-pelagic species lives further away from the coast than other species of this assemblage, and only occurs in the marine clays, not in the peat (Van der Werff & Huls, 1974). The Marine assemblage is therefore not considered as allochthonous as they would have been in a more closed estuarine environment. This is supported by the share of attached valves of the marine tychoplankton species in the counts and the vast majority of marine tychoplankton in the diatom flora.

The area could have experienced a sudden influx of fresh river water because of the occurrence of halophilous and brackish species, in particular *Navicula cincta*. This diatom is difficult to classify, because studies differ in attributing salinity characteristics to *N. cincta*, such as fresh to brackish habitats (Van der Werff & Huls, 1974; Hassan et al., 2006), but also as (marine-)brackish epipelon (e.g. Walker et al., 1998) and salt-marsh diatom (Sawai et al., 2018). What is more likely, is that the water depth around the GW core site was lower at that time, or even fell dry occasionally. *N. cincta* can tolerate dryer environments (De Wolf, 1981c), and so does the aerophilous *Raphoneis ampiceros*, that is present in low numbers throughout most of the core but shows a small peak at this depth. The anomalous occurrence of shallower water species at depths of 4.05-3.99m in the GW core coincides with the first occurrence of flat reed roots and a slight but increase in organic matter content. Perhaps reed patches were becoming denser or terrestriation was about to set in around this time of deposition but could not persist, as shown by the return of marine species. Moreover, other terrestrophile species that would be expected in such environments are only present in very low numbers, e.g. *Diploneis didyma*, that appears briefly and *Diploneis aestuarii*, that is present and peaks slightly later.

The environment can therefore best be considered subtidal with occasional fluctuations towards intertidal, i.e. a dynamic tidal basin. Fluvial influence is minimal, only indicated by the presence of *Cyclotella striata* that occurs in estuarine environments in the vicinity of a river mouth (De Wolf, 1986a). Apart from characteristic estuarine species, no distinct fluvial influence can be detected.

#### 5500 cal yr BP – a sudden change in environment

The sharp lithological contact between marine clay and reed peat indicates a sudden change in environment, and this is reaffirmed by the diatom flora. The Marine and Marine-Brackish assemblages reach their maximum occurrence just before reed peat starts to develop. During the first stages of reed peat development, the marine influence in the area decreases as marine diatom species show a marked decline, but the connection with the sea is not cut off completely. *Fragilaria* species (*F. construens*, *F. lapponica*, *F. nitzschioides*, *F. schulzii*) make a brief but strong appearance at a combined 24%. These are not all freshwater species, but indicate brackish stagnating shallowing waters (De Wolf, 1986b; Denys, 1989). An increased occurrence of *Fragilaria* assemblages is sometimes indicative of a relative increase of reed

habitat as opposed to mud habitat (Marco-Barba et al., 2019). The environment remains brackish, but the characteristic estuarine dynamics decline and the environment is less energetic.

#### Post ~5400 cal yr BP – a brackish estuarine environment and terrestrialisation

Reed peat develops under brackish estuarine conditions. Characteristic estuarine diatoms (*Diploneis* sp, *Navicula peregrina*, *Navicula digitoradiata*, *Nitzschia vitrea*) inhabit an intertidal environment (Vos & De Wolf, 1988, 1993; Sawai et al., 2002), also occupied by reed. Terrestrialisation occurs gently but steadily as an environment of mudflats and tidal channels develops at the site, ushered in by the prominent expansion of epipelagic *Diploneis smithii*. The environment evolves into a saltmarsh indicated by an abundance of *D. interrupta* a few centimetres higher into the peat (3.72m) (Vos & De Wolf, 1997). Terrestrialisation progressed and peat growth raised the area above mean high water, but still in the range of storm surge floods (De Wolf, 1981b).

The open connections with the North Sea and coastal environment had ceased, illustrated by the disappearance of *C. cymbelliformis*. The more modest presence of *C. belgica* compared to the period before 5500 cal yr BP suggest that this diatom and its fellow coastal marine species can now be regarded as inwash. Marine influence is still present and there is a significant share of clay in the reed peat (section 5.2). Diatom assemblages suggest that marine influence appears to occur in pulses, for example by marine incursions or storm surges.

Shortly before the saltmarsh conditions took over at the site, there was one more significant marine incursion in the area. The process of terrestrialisation probably continued after that. The organic matter content of >50% indicates that the environment is less often flooded, or that the reed field has become denser and more extensive. Fine particles settle quickly when flow enters dense vegetation (Boechat Albarnaz, in prep.), and clay deposits would therefore be thinner inside a reed field.

The lack of diatoms higher up in the peat could be indicative of a dry environment, but it is also possible that the supratidal saltmarsh conditions prevailed for longer and the absence of diatoms is due to preservation issues. Dissolution of valves strongly increases in samples deeper in the reed peat. The silica consumption of reed probably caused the dissolution of diatom remains (De Wolf, 1986a,b).

#### **5.4.2 Core BW – seaward location in the back-barrier basin**

##### Tidal environment

Indicated by the marine clays of the BW core below the transition to gyttja, a marine tidal environment occurred at the time of deposition. There are signs of an open connection with the sea, as there were at the GW site, but the transition to peaty substrate (gyttja) at the BW site occurred at much shallower depth. Given that this location is closer to the coast, and assuming that any differential compaction differences between the sites would not exceed 60 cm, it is likely that the BW site was at a topographically higher position. Water depth would have therefore been lower compared to the GW site, even though open connections with the sea might have existed (indicated by *C. cymbelliformis* and also *C. belgica*, *Planolithidium delicatulum*, *Thalassiosira eccentrica*). It can probably be characterised as an estuarine environment, given the presence of estuarine species, but many of the species associated with tidal flats and salt marshes are lacking. The environment and water depth are likely subtidal but shallow. Similar to the GW site, the presence of a river in the area can be deduced from *C. striata* (De Wolf, 1986a), but fluvial influence is minimal.

##### Quiet pond

Next, the site was completely cut off from the surrounding waters and a stagnant pond developed, illustrated by the disappearance of Marine assemblages and the rise of diatom species that prefer calm waters, such as *C. clypeus*, *H. hungarica*, *Navicula salinarum*, *Fragilaria ulna* and the erratic occurrence of *Eunotia tenella*. This matches the lithology, as gyttja is a deposit of stagnant waters. The organic matter content is clearly higher than in the marine clays.

The pond freshened to some extent (e.g. *Amphora ovalis*, *Cocconeis pediculus*, *Cocconeis placentula*, *F. brevistriata*, *F. construens*), for example due to precipitation, but was not fresh, as the increased occurrence of (Marine-) Brackish species *F. schulzii*, *H. hungarica*, *N. salinarum* and *Tabularia tabulata* show. The *Fragilaria* assemblage and *T. tabulata* are characteristic for a shallow fresh to brackish environment (De Wolf, 1989b, 1990). Epiphytic diatoms indicate the presence of water plants in the pond.



Marine influence and peat development

Marine influence increased again with the deposition of a clay layer and the return of characteristic marine species such as *C. belgica*, *Delphineis* sp., *R. amphiceros*, *T. eccentrica*. These species remain present as reed peat develops in the area. Here again, the reed peat formed under brackish conditions. The diatom flora indicates flowing waters with marine influence or inwash and the presence of a river mouth, but no distinct freshwater influence. Terrestrialisation is not clearly visible here. Diatom species of intertidal environments are few, and the absence of most *Diploneis* and *Navicula* species compared to the GW site is striking. The environment is therefore difficult to classify. Return of a subtidal environment or flooding are possible, as is intertidal if inwash of marine species clouds the autochthonous signal, although some characteristic intertidal diatom species are lacking.

Transition to fluvial environment

The site is frequently flooded, illustrated by several clay layers in the core. At first, these floods are of marine origin, but river floods might have taken over through time. By 4000 cal yr BP, channels had developed through the peat, that flooded around 4100 cal BP by levee breach and left crevasse splay deposits at the site (Moree, 2019). This is either fresh water or possibly brackish water, if the backwater effect and saltwater intrusion still extended far eastward in the, by then smaller, estuary.

Table 2: List of diatom species encountered in the GW and BW cores, subdivided by salinity characteristics. Additional life-form characteristics are provided for some species.

**Diatom species salinity groups****Marine species**

*Biddulphia aurita*<sup>2</sup>  
*Biddulphia rhombus*<sup>1</sup>  
*Biddulphia smithii*<sup>1</sup>  
*Caloneis westii*  
*Campylosira cymbelliformis*<sup>1</sup>  
*Chaetoceros spores*  
*Cocconeis costata*  
*Coscinodiscus apiculatus*  
*Coscinodiscus marginatus*  
*Coscinodiscus radiatus*  
*Cymatosira belgica*<sup>1</sup>  
*Eunotogramma dubium*<sup>1</sup>  
*Eunotogramma marinum*  
*Grammatophora oceanica*<sup>4</sup>  
*Melosira sulcata*  
*Melosira westii*<sup>1</sup>  
*Navicula distans*<sup>3</sup>  
*Nitzschia panduriformis*<sup>1</sup>  
*Plagiogramma laeve*  
*Plagiogramma vanheurckii*<sup>1</sup>  
*Podosira stelligera*<sup>1</sup>  
*Rhabdonema minutum*<sup>1,3,4</sup>  
*Rhaphoneis amphiceros*<sup>1,2,5</sup>  
*Rhaphoneis surirelloides*  
*Synedra nitzschioides*<sup>1</sup>

**Brackish species**

*Campylodiscus clypeus*  
*Cyclotella striata*  
*Diploneis interrupta*  
*Navicula cincta*<sup>3</sup>  
*Pseudostaurosira perminuta*  
*Rhopalodia musculus*<sup>4</sup>

**Brackish-Fresh species**

*Amphora copulata*<sup>4</sup>  
*Bacillaria paradoxa*  
*Cocconeis pediculus*<sup>4</sup>  
*Cocconeis placentula*<sup>4</sup>  
*Cyclotella meneghiana*  
*Diploneis ovalis*  
*Eunotia tenella*  
*Fragilaria brevistriata*<sup>2,5</sup>  
*Fragilaria construens*<sup>2</sup>  
*Fragilaria venter* var. *venter*<sup>2</sup>  
*Nitzschia tryblionella* var. *Levidensis*<sup>3</sup>  
*Nitzschia tryblionella* var. *Victoriae*<sup>3</sup>  
*Opephora martyi*<sup>5</sup>  
*Rhoicosphenia abbreviata*  
*Staurosirella pinnata*

Table 2 continued.

### Marine-Brackish species

*Achnanthes brevipes*  
*Achnanthes delicatula*<sup>5</sup>  
*Actinoptychus undulatus*<sup>1</sup>  
*Caloneis formosa*<sup>3</sup>  
*Catenula adhaerens*<sup>5</sup>  
*Cocconeis peltoides*<sup>5</sup>  
*Cocconeis scutelloides*<sup>4</sup>  
*Cocconeis scutellum*<sup>4</sup>  
*Delphineis minutissima*<sup>2</sup>  
*Delphineis surirella*<sup>2</sup>  
*Dimeregramma minor*<sup>5</sup>  
*Diploneis aestuari*  
*Diploneis bombus*<sup>1,3</sup>  
*Diploneis didyma*<sup>1,3</sup>  
*Diploneis fusca*  
*Diploneis smithii*<sup>3</sup>  
*Fragilaria schulzi*<sup>5</sup>  
*Hippodonta hungarica*<sup>3</sup>  
*Navicula digitoradiata*<sup>3</sup>  
*Navicula gracilis* var. *Schizonemoides*<sup>3</sup>  
*Navicula peregrina*<sup>3</sup>  
*Navicula salinarum*<sup>1,3</sup>  
*Nitzschia bilobata*<sup>3</sup>  
*Nitzschia circumscuta*  
*Nitzschia navicularis*<sup>3</sup>  
*Nitzschia punctata*<sup>3</sup>  
*Nitzschia tryblionella*<sup>3</sup>  
*Nitzschia vitrea*  
*Opephora pacifica*<sup>1,4,5</sup>  
*Plagiogramma staurophorum*<sup>5</sup>  
*Planothidium delicatulum*<sup>5</sup>  
*Stauroneis gregori*<sup>3</sup>  
*Surirella gemma*<sup>3</sup>  
*Tabularia fasciculata*  
*Tabularia tabulata*  
*Thalassiosira eccentrica*<sup>1</sup>

### Fresh species

*Amphora ovalis*<sup>3</sup>  
*Diploneis elliptica*<sup>3</sup>  
*Epithemia turgida*<sup>4</sup>  
*Fragilaria lapponica*  
*Fragilaria ulna*  
*Gomphonema minutum*  
*Gyrosigma* cf. *obtusatum*  
*Navicula* cf. *cryptotenella*  
*Nitzschia* cf. *palea*  
*Pseudostaurosira trainorii*  
*Tabularia fenestra*

### Undefined/unknown

*Amphora* sp  
*Caloneis* sp  
*Cocconeis* cf. *neodiminuta*  
*Cocconeis* sp  
*Diploneis* sp  
*Eunotogramma* sp  
*Fragilaria/Fragilariaforma* group  
*Liradiscus ellipticus*  
 Miscellaneous unknowns  
*Navicula* sp  
*Nitzschia* sp  
*Planothidium* sp  
*Tabularia* sp  
 U41

### Life-form characteristics

- 1) Littoral
- 2) Tychoplanktonic
- 3) Epipelon
- 4) Epiphyte
- 5) Epipsammon

## 6. Discussion

The driver mechanisms that have so far been known to induce closure of the South Holland tidal basin, are *silting up* and *closing off* (see chapter 2). During the Atlantic, the tidal basin *silted up* under delivery of sediment from both the river branches and landward transport by tides, tipping the balance between tidal prism and tidal inlets and changing offshore currents and sediment delivery. Beach barriers formed as offshore delta deposits were eroded by longshore currents and deposited along the shore, eventually *closing off* tidal inlets. At the final tipping point to definitive closure of the basin, *closing off* was considered the main driver. This followed from the basin-freshening explanation based on the assumption of peat as indicator of freshwater conditions (Raven & Kuijper, 1981; Roep et al., 1991; Beets et al., 1996; Beets & Van der Spek, 2000; Berendsen & Stouthamer, 2000; Beets et al., 2003; De Wolf & Cleveringa, 2006; Hijma & Cohen, 2011; Vos, 2015; De Haas et al., 2018b).

The results from diatom analysis of the Old Rhine estuary within the former South Holland basin show that brackish conditions prevailed around the mid-Holocene landscape transition from tidal landscape to peatland, instead of basin-freshening. The findings shed new light on the commonly known driver mechanisms acting at the time of tidal basin closure. In this chapter, the environment reconstructions at the fieldwork locations are put in the context of other palaeogeographical reconstructions, for a more detailed account of the final stages of back-barrier basin evolution than has been known so far. Subsequently, a new addition to driver mechanisms and insights into the role of peat in tidal basin evolution are discussed, as well as the implications for palaeogeographic research.

### 6.1 Synthesis – development of the back-barrier basin

#### 6.1.1 Atlantic > 5500 cal yr BP – open connections with the sea

The back-barrier basin stood in open connection with the North Sea. Estuarine conditions prevailed and marine influence reached far inland. There are no clear signs of a preserved intertidal environment. The diatom assemblages of core GW indicate that the water depth at this location fell from time to time, but was mainly subtidal. De Wolf (1981c) also found that areas in the brackish estuarine landscape could occasionally periodically fall dry (or dryer) based on diatom assemblages indicating terrestriation in the marine clays at a location near Waddinxveen, which is further landward than the GW location. The temporary lowering of the water depth could be caused by the sedimentation and erosion dynamics within the estuarine subtidal to intertidal environment. However, characteristic diatom species of intertidal environments are lacking. It is possible that more periods of shallow conditions are discovered if the marine clays (Wormer Member) are sampled at higher resolution. Before the shallow areas could silt up further and develop into salt marshes, these locations were possibly eroded because the diatom assemblages show a return of marine-estuarine conditions and there are no signs of further soil formation or salt marsh vegetation development, as would be expected on silted up flats that fall dry more frequently. Reed was probably already present in the system, hinted by some findings of horizontally oriented reed remains in the marine clays, but was sparse.

The presence of a river nearby can be deduced from the occurrence of characteristic estuarine diatoms, but the fluvial influence is limited to making the waters less saline or brackish, rather than a fresh water influence. The back-barrier basin may therefore be classified as an estuarine tidal basin

By 6211-6000 cal yr BP the Voorschoten beach barrier had started to develop (dating of shells in barrier sands at a more southern location near The Hague, Van der Valk, 1995), and from 5657-5598 cal yr BP the barrier had taken position near Leiden (Van der Valk, 1995) (see figure 2 map 5700 BP). This would mean that the Voorschoten barrier was already present before reed peat started to form near the GW location (5591-5468 cal yr BP, De Jong, 1977), based on the calibrated dates (Calib 7.1, for 1 $\sigma$ ).

If the current palaeogeographical view of closing beach barriers and freshening back-barrier basin (see chapter 2) is correct, the GW core would have to show signs of freshening below the reed peat. The time elapsed between the onset of deposition of the barrier sands and the formation of peat would be 7-189 years based on the aforementioned dates for 1 $\sigma$ . The onset of barrier formation refers to the barrier having taken position, but not necessarily being continuous or high enough to keep out the sea. However, for the basin-freshening explanation, the barrier would have to be closed.

Closed tidal basins can freshen quite quickly, especially if a river is present. Lake IJssel in the Netherlands was fresh within 40 years, after it was closed off from the Wadden Sea in 1932 AD (Brocades

Zaalberg, 1985). However, the diatom assemblages right below the reed peat (GW sample 3.80, BW sample 3.11) clearly show large marine influence and open connections with the North Sea and no freshwater species, this is supported by the assemblage from the BW core. The Voorschoten barrier therefore had to have been discontinuous (or perhaps of very low height), because the sea was easily able to reach the back-barrier basin.

The calibrated ages of the Voorschoten barrier and back-barrier peat are so close, that it is difficult to pinpoint which of the two events happened first. Looking at two standard deviations of the calibrated ages, it is even possible that peat started to form *before* the Voorschoten barrier near Leiden developed (and well before tidal inlets closed).<sup>2</sup> If this is indeed the case, it would further support the role of peat as a driver for the landscape transition. The calibrated dates put a new perspective on the cause-consequence relation in the southern Holland basin compared to the <sup>14</sup>C dates<sup>2</sup>, but what is clear, is that marine influence still occurred after peat formation had begun, and that the beach-barriers were not completely developed yet, regardless of whether a (small) barrier was present near Leiden, or of any previous barriers that may not have been preserved due to earlier retrogradation.

### 6.1.2 Subboreal <5500 cal yr BP – brackish conditions, peat and beach barriers

Around 5500 cal yr BP, widespread peat formation commenced in the area south of the Old Rhine estuary. Importantly, this occurred under brackish conditions. Even though the study area was relatively close to the Old Rhine palaeochannel, there is no distinct freshwater signal in the diatom assemblages of the reed peat (nor in the marine clays). It is possible that the Old Rhine river was not yet at its full capacity.

The diatom flora indicates terrestrialisation and the silting up of the estuarine subtidal environment. Salt marshes with reed (*Phragmites*) vegetation developed on the flats. On topographically (relatively) elevated areas stagnant ponds developed. There is no distinguishable phase of intertidal conditions in this part of the back-barrier basin in the classic sense of intertidal flats. Rather, reed and peat are part of the intertidal environment as terrestrialisation proceeded.

Terrestrialisation probably occurred quickly, assuming that the accumulation rate is constant and that there is no hiatus. The reed peat is not very compacted and the change in diatom flora to supratidal conditions took place within 6 cm in the GW core. For an indication of the time it took for the palaeoenvironment to silt up to supratidal level, it is recommended that a radiocarbon age of the GW core at 3.72m depth is obtained and compared with an age at 3.78m (and with the Nieuw Groenendijk location of De Jong, 1977).

The Voorschoten beach barrier did not yet seal off the back-barrier basin from marine influence, shown by the diatom assemblages. The decrease in marine tycho planktonic diatom species compared to marine planktonic species indicates that the beach barriers were closing and the sea could enter the back-barrier basin less easily. The barriers had grown, but sea ingressions could still occur regularly and bring saltwater with marine diatoms into the basin. This happened frequently enough that the back-barrier basin could not turn into a freshwater environment. It is likely that there were small inlets through the beach ridges, or possibly that there was also marine inflow through the mouth of the Old Rhine estuary that could reach the back-barrier basin. In any case, the marine ingressions were strong enough to extent kilometres into the tidal basin, because they can be traced to the inland (GW) fieldwork location. Van der Valk (1995) found crevasse deposits of a few meters thick behind the beach barrier near Leidschendam. The age is not known, but it supports the argument that the sea could still enter the back-barrier basin, in this case by overwash or barrier breach.

The BW core shows clay layers with Marine-Brackish diatom assemblages. It is not clear if these clays were deposited by marine ingressions breaking through or overstepping the beach barriers, or by flooding from the estuary. Clay deposits on top of (now compacted) peat in the vicinity show that at some point a large branched channel and crevasse system breached the levees of the Old Rhine river or estuary and entered the Zoeterwoude area (core Weipoortse Vliet, see section 5.1.2; DINOLOKET; Moree, 2019). Further research is recommended to investigate the nature of the clay deposits, importantly salinity characteristics to determine fluvial or marine origin e.g. via diatom analysis (including other cores), and the timing of the flood phases in the peat by dating the peat just below the clay layers of the BW core.

<sup>2</sup> The calibrated dates for two standard deviations are 5719-5589 cal yr BP for the Voorschoten barrier near Leiden (4910 ±40 <sup>14</sup>C yr BP), and 5609-5444 cal yr BP (0.8) or 5413-5324 cal yr BP (0.2) for the peat in the Old Rhine estuary near the GW location (4780 ±60 <sup>14</sup>C yr BP) (Calib, Intcal13 curve).

Comparing the BW and GW cores suggests that the BW (seaward) location gives a local signal, whereas the GW (landward) location gives a regional signal of environmental conditions in the back-barrier basin.

The reed fields expanded quickly into a dense marshland, as inferred from the organic matter content of the GW peat (decreasing clay deposition, see section 5.5.1), still under brackish conditions. This would have rapidly reduced the accommodation space in the back-barrier basin. According to tidal basin dynamics, it is very likely that the expansion of vegetation and peat formations would have contributed to “pushing” the marine influence out of the back-barrier basin.

The early tidal peatlands around the time of the landscape transition were likely a landscape of extensive reed vegetation, possibly in various stages of maturation depending on local topography, and scattered with small shallow lakes and ponds. The beach ridges were not closed or continuous, but had small inlets or crevasses from marine overwash. A conceptual representation of the South Holland tidal basin at the time of basin closure  $\sim 5500$  cal yr BP is depicted in figure 13. Important differences with other research (figure 2 maps 5700 and 5200 cal yr BP) are that the beach barriers are not completely closed and that peat occurs in an intertidal environment. Detailed palaeogeographic maps of the landscape transition requires further research into the spatial pattern and extent of reed fields and ponds, as well as the location of the inlets and overwash sites.



Figure 13: Conceptual map of tidal peatlands in a closing tidal basin with estuarine influence, as an example of the South Holland tidal basin  $\sim 5500$  cal yr BP.

## 6.2 Tidal peatlands: the role of reed peat and vegetation in tidal basin closure

Reed was already present in the open tidal basin, but expansion and peat formation could apparently not yet occur until a certain point in the evolution of the tidal basin. The reconstruction of the environment and salinity conditions in the final stages of tidal basin closure revealed that basin freshening is not a prerequisite for reed and peat growth. What did induce it, requires a closer look at the occurrence of reed in a tidal environment. Peat is the most prominent vestige of the extent of reed vegetation in palaeoenvironments, but at the time of formation, reed vegetation itself would have also been an important aspect of the palaeolandscape. The characteristics of reed vegetation therefore provide insight into the way reed settles and expands in tidal basins, in order to understand the role of reed peat as a driver mechanism in tidal landscape transitions.

### 6.1.1 Reed in a tidal basin

The challenges for reed in a coastal environment are not necessarily the salinity conditions, but initial settlement and water level fluctuations. Reed (*Phragmites australis*) is known to be able to grow under brackish to slightly saline conditions (Weeda et al., 1991). The plant deploys self-facilitating mechanisms such as osmotic adjustment in order to cope with salinity stress (Reijers et al., 2019), allowing it to tolerate waters with salinity up to 2/3 of the concentration of marine waters (P. Esselink, pers. comm.).

In Denmark, coastal reed fields exist in brackish conditions of up to 15‰ salinity (which is ~45% of the salinity of sea water), although the optimum for the plant is <5-10‰ salinity (Lissner & Schierup, 1997). Reed can reproduce in multiple ways, by seed dispersal, rhizomes (expanding root system) or (horizontal) shoots above ground (Weeda et al., 1991), and may enter a new water system via seed dispersal. Seeds usually sprout in fresher water provided by precipitation, for example in small pools (P. Esselink, pers.comm.), but in tidal environments, reed principally reproduces by rhizomes or shoots because seeds are washed away by (high) tide (Weeda et al., 1991). Additionally, juvenile reed plants are less tolerant to saline conditions than reed plants growing from rhizomes. Strong wind action, waves (Lissner & Schierup, 1997) and fluctuating water levels due to tides (Weeda et al., 1991; Lissner & Schierup, 1997) limit the expansion of reed in coastal areas. Young shoots stand the risk of drowning if water levels fluctuated to strongly (Weeda et al., 1991; Van der Werf, 2017).

Settlement of reed in the South Holland tidal basin did not necessarily require a (fluvial) freshwater pulse. Reed already occurred deeper in the marine clays at the GW site (5.1.1), and became slightly more prominent a few decimetres below the lithological transition to peat, when the organic matter content of the clay increased and diatom assemblages showed a pulse of species tolerant of brackish to fresh waters, but more importantly, these species prefer shallow conditions (see also sections 5.2.1 and 5.4.1). Lissner & Schierup (1997) mention that Danish coastal reed fields in dryer habitat expand much more quickly than reed fields in water. Shallowing conditions were also proposed by Denys (1989) as suitable palaeoenvironments for the development of reed marsh and peat in a tidal environment. In the South Holland basin, shallowing conditions could have allowed reed to expand further into the tidal basin via rhizomes, after initial settling had already occurred elsewhere. Seed sprouting could have occurred in elevated ponds, such as the one of the BW site, but in any case, reed was already present at the fringes of the tidal basin (e.g. Van der Valk, 1995; Hijma, 2009; Vos, 2015) and could have colonised the wider area from there if water depths were sufficiently shallow. Reed is known to grow in water depths of up to one metre in the Netherlands (Weeda et al., 1991). Colonisation of an area via rhizomes can proceed quite quickly, with speeds of 10-25 meter per year (P. Esselink, pers.comm.).

At the onset of peat formation, reed growth apparently exponentially increased but analysis of the GW does not give a straightforward answer as to the reason why. It is possible that a threshold for salinity was crossed, that the back-barrier basin turned less saline (strong brackish) due to a decreasing marine influence as the barriers grew, so that the habitat became more suitable for reed to expand. However, the presence of estuarine diatom species in the marine clays showed that the salinity of waters in the southern Holland tidal basin was probably already lower than marine waters and in range of the salinity tolerance of reed. This is illustrated by presence of reed remains in the marine clays, salinity conditions sufficed for reed growth, although they may not have been optimal.

Another explanation is that the beach barriers had developed enough to significantly reduce the tidal amplitude within the basin. The *Fragilaria* assemblage that is distinctive in the sample above the lower boundary of reed peat (GW sample 3.78) does point to quieter conditions and shallower waters, but could also indicate some freshwater influx, although the species can tolerate brackish conditions. Given the accompanying diatom assemblages and especially the lack of other freshwater species and the presence of aerophilous brackish diatoms, the more important facilitators of peat development were likely reduction of the tidal amplitude, quieter hydrodynamic conditions or less frequent inundation. The process of developing and closing beach barriers likely caused feedback mechanisms. The reduction of water level fluctuations and perhaps decreasing salinity due to a relative increase of precipitation and fluvial inflow compared to marine inflow, gradually improved conditions for reed towards a more optimal habitat, allowing reed vegetation (and eventually peat) to develop ever further under increasingly suitable conditions.

### 6.2.2 Reed peat and vegetation as a driver mechanism

The fact that Holland peat in the back-barrier basin developed under brackish conditions, and that it formed *before* the tidal basin was closed off from marine influence, puts peat forward as an additional driver for tidal basin closure. Denys (1999) also indicated reed marsh development (and silting up) as feedback mechanisms for terrestrialisation in the western Belgian coastal plain, rather than beach-barrier closure. Going back to the mechanisms described in chapter 2, the *closure* of the beach barriers and *silting up* of the basin, there is an important extension to add. So far, the closing of the beach barriers was considered the most important driver of final closure, after the basin had silted up under sediment delivery and the tidal prism was reduced (e.g. Van der Valk, 1995; Hijma, 2009; De Haas, 2018a, b). It can now be

proposed that there is an additional mechanism responsible for the closure of the southern Holland basin: *terrestrialisation by vegetation and peat development*.

The way that vegetation and peat operated as drivers for tidal basin closure can be explained as follows. During the final stages of barrier closure along the South Holland coast, the expansion of reed vegetation in the area and the accumulation of peat (the organic equivalent of “silting up”) further reduced the accommodation space in the back-barrier basin. Boechat Albernaz (in prep.) showed that, as soon as dense vegetation fringes estuaries, marine ingressions into an estuarine basin are halted as flow experiences resistance from the stems it encounters. In the South Holland basin, expanding reed vegetation hindered marine inflow far into the basin while the beach barriers grew. This induced feedback between abiotic aspects of tidal prism dynamics, i.e. beach barrier closure and reduction of accommodation space that reduced the tidal amplitude, and vegetation growth, that could expand and accelerate as habitat conditions became increasingly suitable. The mechanism for tidal basin closure is therefore an interplay between silting up (reduction of tidal prism), closing of the beach barriers (narrowing of inlets, restricted/inhibited inflow), and vegetation expansion (further reduction of the tidal prism) (see figure 14). The role of reed peat is a combination of being an indicator of the presence of dense reed vegetation, and a means of terrestrialisation by accumulation of organic material that raises the ground above water level.

Moreover, reed vegetation could have already influenced tidal basin closure before peat formation started. The first signs of reed growth were found half a meter into the marine clays of the GW site (section 5.1.1), and reed was probably present in the tidal basin when marine-estuarine conditions prevailed. Even though the reed fields would not have been as dense as at the time of peat formation, the vegetation could nevertheless have contributed to the resistance of flow in the tidal basin.

The effectiveness of reed peat formation as a terrestrialisation mechanism is demonstrated in the mid-Holocene South Holland back-barrier basin. Reed (peat) development was not only able to keep pace with sea level rise, but also outrun it in the terrestrialisation process. At the onset of the Subboreal, sea level was still rising ~0.2m per century (Hijma, 2009). In the present century, the predicted rates of sea level rise due to climate change are a concern for the inundation of low-lying areas. Reed vegetation (and peat formation) may offer a terrestrialisation mechanism for areas in the face of inundation to keep up with sea level rise to a certain extent, although climate models predict rates of sea level rise that may far exceed the rates during the Early Subboreal (IPCC, 2019).

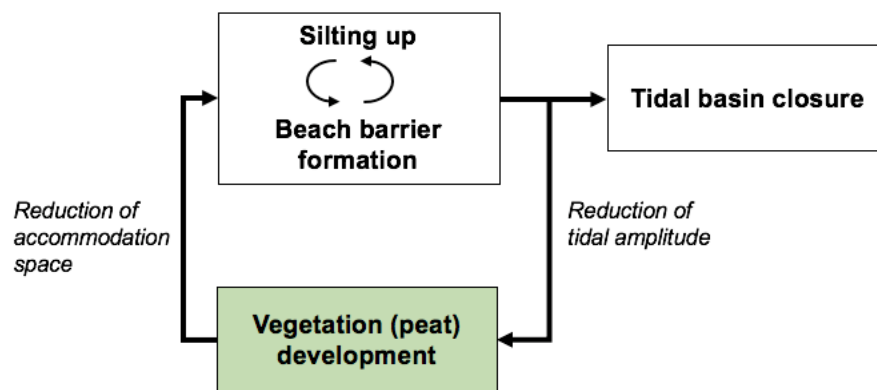


Figure 14: Schematic representation of the driver mechanisms in tidal basin closure, and the addition of the role of vegetation and peat as driver by terrestrialisation.

### 6.3 Reed peat in palaeogeographic reconstructions

The role of reed peat in tidal basin closure is a novel finding in palaeogeographic research. The main reason why reed peat has not been recognised before as driver mechanism lies in the assumptions on the characteristics of peat, that are discussed below. Several previous palaeogeographic studies already acknowledged that reed can grow under brackish conditions (e.g. Hijma, 2009; Vos, 2015), but this knowledge so far was not applied in reconstructions. Reed peat was still classified as a freshwater environment, following the lithostratigraphic definition of peat.

### 6.3.1 Peat in Dutch lithostratigraphy

There are two different lithostratigraphical units of peat in the Dutch classification system, the Basal peat Bed and the Holland peat Member, both belonging to the Nieuwkoop Formation. Both are ascribed to the same environmental facies “peat developed under rising groundwater levels in the coastal plains” (Weerts et al., 2000). Thus, all peat is considered to be fresh. However, there is a large difference in genesis of the two peat units. Basal peat formed in the early Holocene, when North Sea area was barely inundated in the early Holocene and groundwater level was rising inland in accordance with sea level, while Holland peat formed during the transgressive phase in the Atlantic and later.

At the time of Basal peat development, the “Holland coastline”, or its predecessor, was located in the North Sea area at considerable distance of the inland areas where Basal peat grew (Hijma, 2009). The assumption of fresh conditions may therefore be justified and Basal peat can be considered to originate in the wider context of a transgressive phase and a drowning landscape. Although some care must be taken here, because the relative sea level is reconstructed from the occurrence of Basal peat, a chicken and egg situation.

When Holland peat formed later in the Holocene, the sea had transgressed inland before coastal progradation and silting up of the area started. The coastline was positioned near its current stand and the North Sea was already a few meters deep (Hijma, 2009). The conditions in the wider area were therefore more or less saline during local peat formation and before widespread peat formation. This is supported by research of Delsman et al. (2014), who modelled that groundwater below the Holland basin was mainly brackish to saline up to 35 km inland and 0-250m depth in the late Atlantic-Early Subboreal as a result of the marine transgression, and that a freshwater lens developed below the sandy beach ridges (not in the back-barrier basin) during the Subboreal. Holland peat thus formed in the context of an emerging landscape and decreasing marine influence, as opposed to the “drowning landscape”-context of Basal peat. The many intercalations of Holland peat at different depths within the marine clays of the Wormer Member further illustrate that peat would have already developed in coastal-marine (saline or brackish) conditions rather than in local freshwater areas. Brackish peat intercalations also correspond better with the occurrence of this peat right along intertidal areas and salt marshes than freshwater peat intercalations.

### 6.3.2 Classification of environments based on lithostratigraphy

How equating all types of peat have been under the same type of deposit for lithostratigraphic purposes affects palaeogeographic reconstructions, is illustrated by the categorisation of environments. Hijma & Cohen (2011) classify environments Upper-estuary, fluvial-tidal basin and wetlands (peat, gyttja, extensive *Phragmites-Carex* fields) as fresh to slightly brackish in their description of palaeoenvironments that they have mapped out for the early-mid Holocene Rhine-Meuse delta. *Phragmites* stands at the edges of intertidal areas in the tidal basin are also assumed to be fresher. De Haas et al. (2018b) mapped “wetland

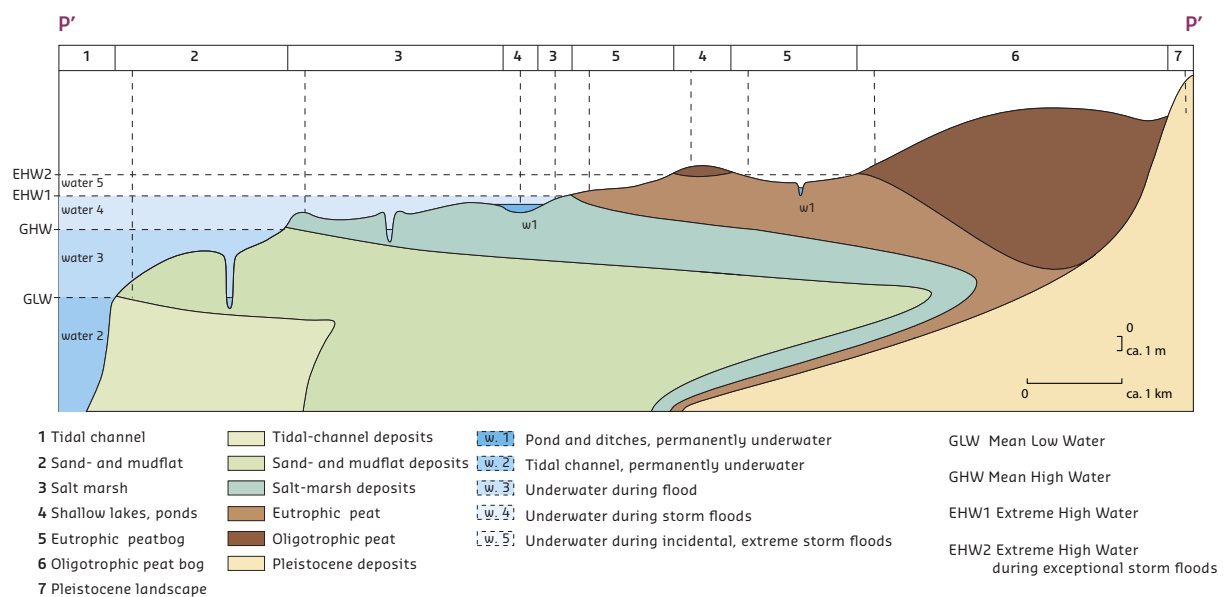


Figure 15: An example of a palaeoenvironmental reconstruction that takes peat as indicator for rarely submerged areas (source: Vos, 2015).



(marsh) complex” environments as fresh, Vos (2015) only considers peat as part of freshwater tidal or fluvial deposits and holds the occurrence of reed peat as the indicator for rarely submerged areas (see figure 14). Donselaar & Geel (2007) assume all Holland peat deposits to be fresh in their lithofacies classification.

The classification of environments relies on the assumption of all peat being fresh. This means that reed peat could not be regarded a salt marsh deposit, because peat and salt marsh deposits are assigned to different facies and stratigraphic units, and salt marshes are thus presumed to precede peat growth in the terrestrialisation process. The terrestrialisation sequence based on the stratigraphic position would therefore include the following habitats: subtidal estuarine environments and channels → intertidal environment and flats → supratidal salt marsh → peatland, according to Walther’s law (see figure 14). For example, Vos (2015) inferred intertidal environments indirectly from a presumed position between tidal channels and reed, because all peat including reed is considered to be a supratidal deposit, and this position in between peat and channels was subsequently mapped as intertidal.

The results from the present study suggest a different terrestrialisation sequence. Perhaps the terrestrialisation happened so fast that no intertidal morphology was able to form, implying that not all steps of may need to be taken (the data show no signs of a hiatus at this level). However, the majority sequence was probably still abided, with the addition that reed peat formation could already occur in an intertidal environment. A conceptual view of the palaeoenvironment within a tidal basin is depicted in figure 16.

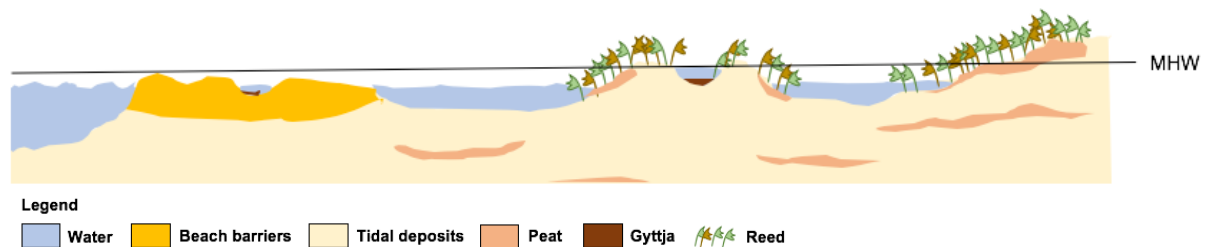


Figure 16: Conceptual cross-sectional view of a closing tidal basin with reed vegetation and peat. Peat formation also occurs in an intertidal environment and salt marshes. MHW = mean high water

## 6.4 New insights and recommendations for palaeogeographical research

The occurrence of reed peat in brackish environments shows that distinguishing between different kinds of peat is necessary when making landscape reconstructions. If peat is generalised and reed peat is not separated from other types of peat such as fen-wood peat (Dutch: bosveen) and *Sphagnum* peat, which formed vast raised peat bogs during the Subboreal and Subatlantic, and if stratigraphic classification boundaries are interpreted in a strict manner, it may become very difficult to accurately reconstruct palaeoenvironments. Consequently, important drivers for landscape transition may remain undiscovered. It is therefore recommended that the lithostratigraphic definition of Holland peat is revised as to the genesis, subdivision between different types of peat, and distinction from Basal peat.

Diatom analysis has proven to be a valuable addition to lithology in palaeoenvironmental reconstructions, as it has revealed a new driver mechanism that interacted with *silting up* and *closing off* the basin by beach barriers in the South Holland coastal area: terrestrialisation by vegetation and peat development. For future studies into (palaeo)landscape development and the infilling of basins, it would be recommended to take vegetation development and peat formation into account not only as a consequence of a landscape transition, but also as driver and terrestrialisation mechanism in tidal basin closure.

## 7. Conclusion

Diatoms of two cores from the Old Rhine estuarine area were analysed to reconstruct salinity conditions in the South Holland tidal basin during the mid-Holocene landscape transition, in order to shed light on the driver mechanisms of tidal basin closure. An abrupt transition in environment is visible in the lithology as a sharp contact of reed peat on top of marine clays. Diatom assemblages from the marine clays indicate that open connections between the back-barrier basin and the North Sea prevailed in the late Atlantic. There are no clear signs of a preserved intertidal environment leading up to the terrestrialisation process. At the onset of peat formation ~5500 cal yr BP, conditions were brackish with shallow water levels, indicated by characteristic intertidal and saltmarsh diatom assemblages in the lower decimetre of Holland peat. Marine influence was reduced but still present, and so the beach barriers were not completely closed at the onset of peat formation. The sea could still reach the back-barrier basin by small inlets, overwash and/or barrier breach. The reduced tidal range likely facilitated the expansion of reed in the back-barrier area. The influence of the Old Rhine river in the tidal basin is limited to contributing to the brackish estuarine conditions, there is no distinct freshwater signal in the marine clays or peat.

The fact that reed peat formation at the time of tidal basin closure occurred under brackish conditions, is contrary to the commonly assumed basin-freshening explanation of tidal basin closure along the South Holland coast. So far, closing of the beach barriers has been regarded as the main processes responsible for the (final) landscape transition from tidal basin to peat landscape, with silting up and barrier development leading up to the final tipping point of basin closure. The driver mechanism *closing off by beach barriers* was previously deduced from the assumption that all peat grows under freshwater conditions, based on the lithostratigraphic definition of Holland peat. The back-barrier basin would thus have had to freshen after beach barrier closure in order to facilitate peat growth. The present research has revealed a different cause-consequence relationship and a new driver mechanism for tidal basin closure.

The findings of brackish reed peat, put peat and reed vegetation forward as a driver mechanism of landscape transitions in tidal basins, rather than being only a consequence. Tidal basin closure was driven by an interplay between *silting up*, *closing of the beach barriers*, and *terrestrialisation by vegetation expansion* as new addition. The definitive driver at the tipping point of the landscape transition is vegetation, reed fields that formed peat and reduced accommodation space in the back-barrier basin. It can therefore be posed that vegetation “pushed out” the tide before the back-barrier basin was finally closed off. The leading role of reed expansion in the ending of marine influence in the back-barrier area under mid-Holocene sea level rise shows the potential of reed vegetation as terrestrialisation mechanism, which can be of interest for regions that face present-day sea level rise.

Diatoms have proven to be a valuable and effective proxy for palaeogeographic reconstructions in addition to lithology. High resolution sampling for diatoms around the clay-peat contact provided a detailed view on palaeoenvironmental conditions and has shed light on the role of driver mechanisms. Different factors (flow, deposition, vegetation) and environments (aquatic, terrestrial; marine, brackish, fluvial) interact with each other in a natural system, and lithostratigraphic classification alone is unable to provide a suitable reconstruction, especially in transitions of palaeolandscapes. The lithostratigraphic definition of Holland peat can be improved as to the genesis and the subdivision between different types of peat to more accurately represent palaeoenvironments, because reed peat in coastal areas not only occurs in fringe marshes, but is also an intricate part of the brackish intertidal and salt marsh environment within the tidal basin.

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Left: Reed - *Phragmites australis* (source: Wikipedia)

Right: Diatom lightmicroscope images (by K.M. van der Werf) of species *Diploneis* cf. *smithii* (top), *Cyclotella striata* (left) and *Delphineis surirella* (right). For scale see appendix II

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### Online sources and databases

Actueel Hoogtebestand Nederland  
[www.ahn.nl](http://www.ahn.nl)

AlgaeBase  
[www.algaebase.org](http://www.algaebase.org)

Calib (radiocarbon calibration)  
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Diatoms of North America  
[www.diatoms.org](http://www.diatoms.org)

Diatom New Taxon File, Academy of Natural Sciences, Drexel University  
<http://symbiont.ansp.org>

DINOloket, Data en Informatie van de Nederlandse Ondergrond  
[www.dinoloket.nl](http://www.dinoloket.nl)

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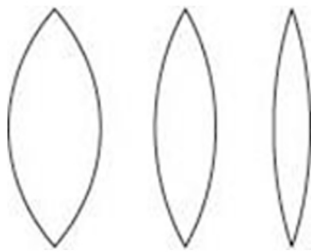


## Appendix I

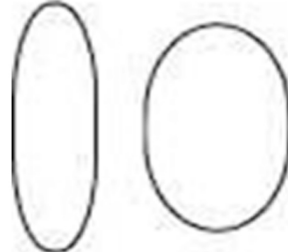
### Morphological shapes of diatom valves

(Images provided by dr. A. Cvetkoska)

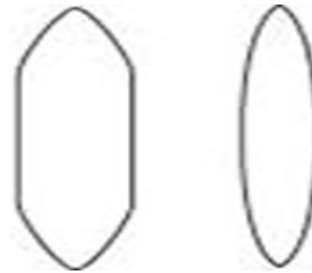
#### Valve morphology



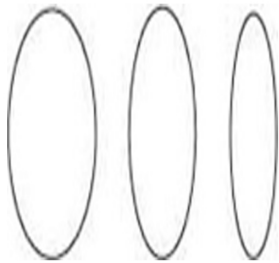
1-3. Lanceolate



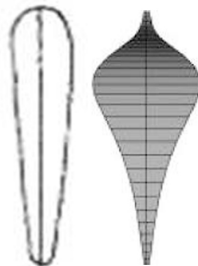
4,5. Linear-elliptical



6,7. Linear-lanceolate



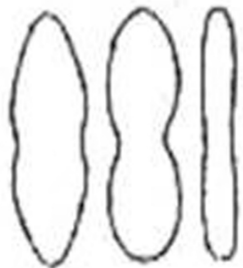
8. Elliptical



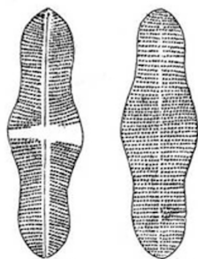
9, 10. Clavate



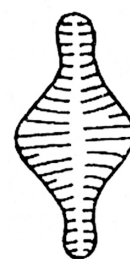
11. Oval



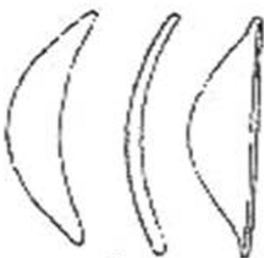
12-14. Panduriform



15, 16. Stauroform



17. Cruciform



18-20. Lunate

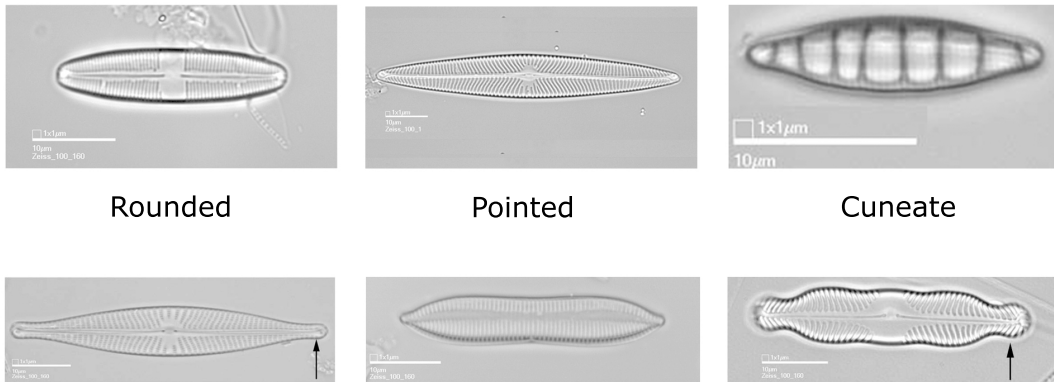


21, 22. Rhombic



23-25. Sigmoid

Apices of diatom valves



Rounded

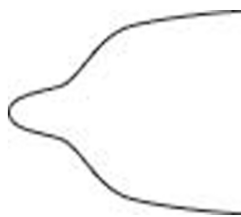
Pointed

Cuneate

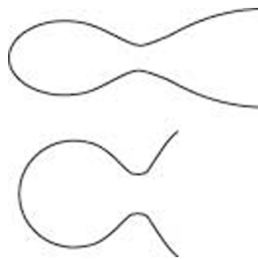
Protracted (drawn out)

Shape of poles deviates from overall valve outline

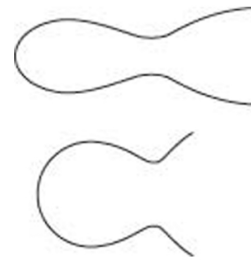
If protracted:



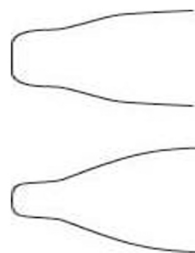
Apiculate



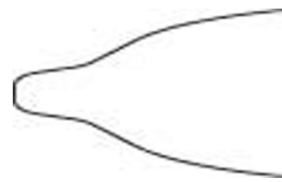
Capitate



Sub-capitate

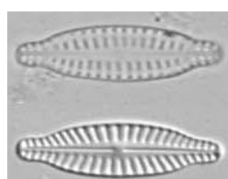


Rostrate

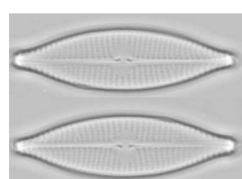


Sub-rostrate

Hypovalvy



Present



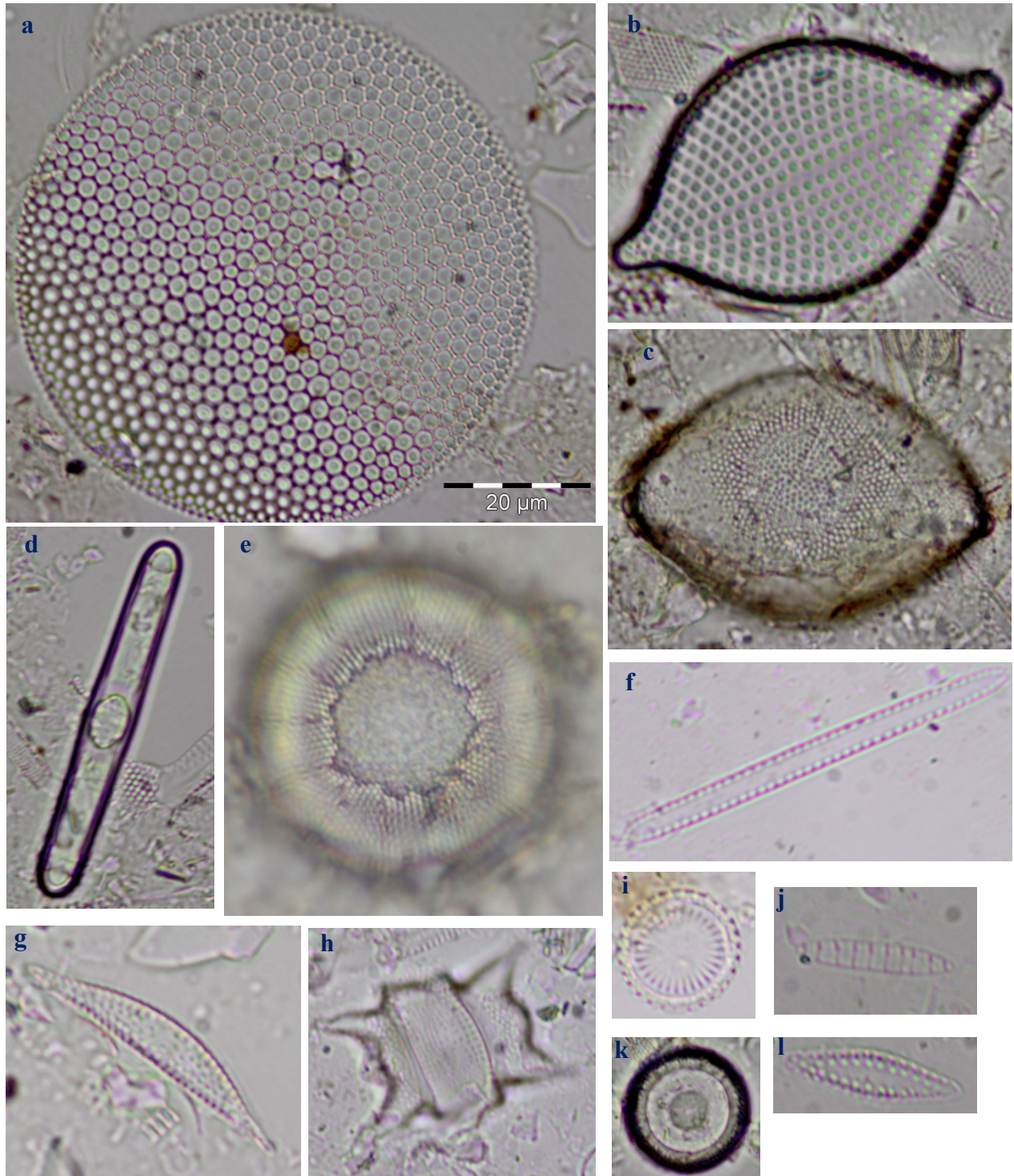
Absent

## Appendix II

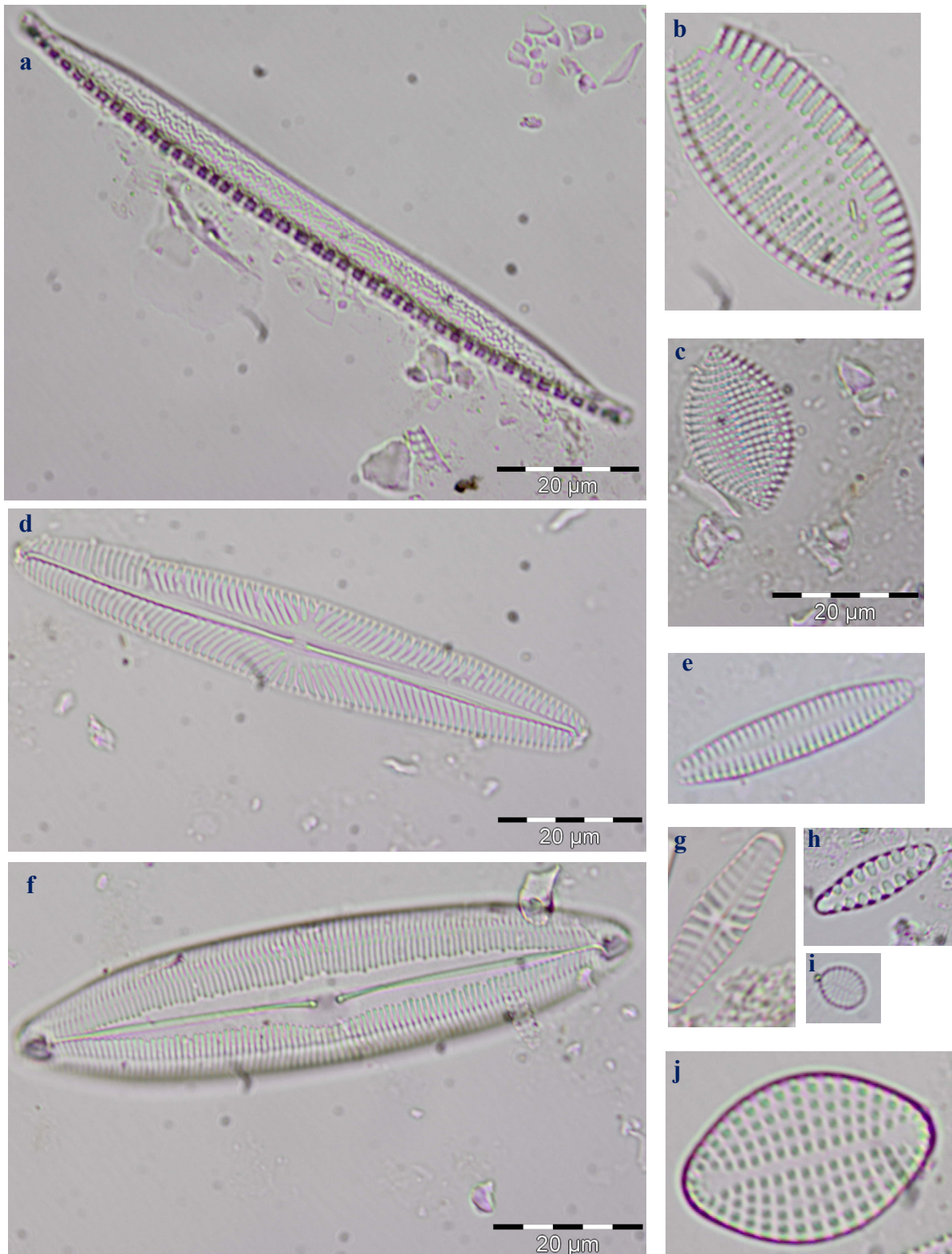
### Image gallery of a variety of diatom species encountered in cores GW and BW

Diatom species are subdivided in salinity groups. Diatom sizes are to scale, relative to each other (except for *Campylodiscus clypeus*). Size range between individuals encountered in samples may vary. Scale bar provided in each group (all images by K.M. van der Werf).

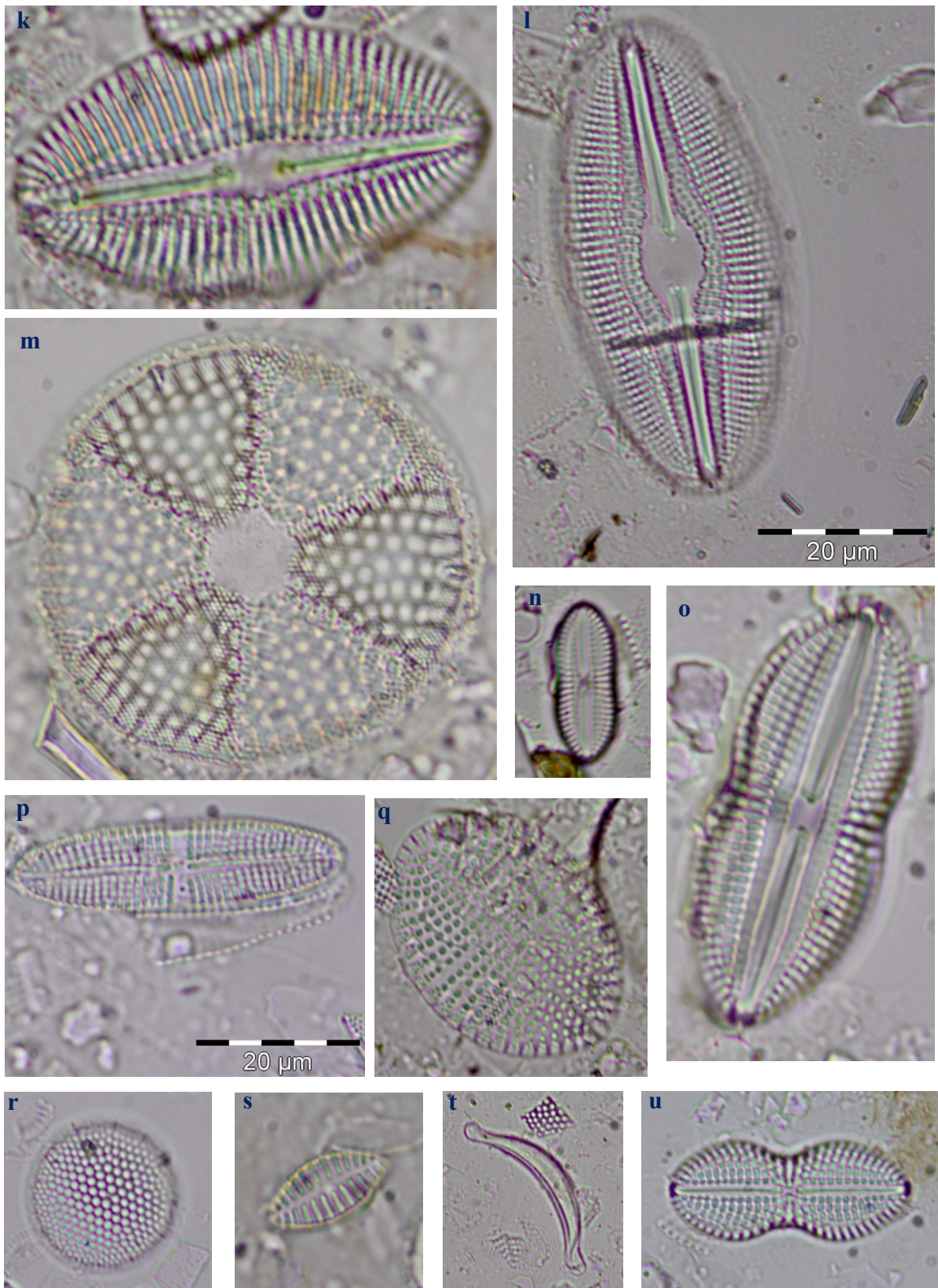
#### Marine species



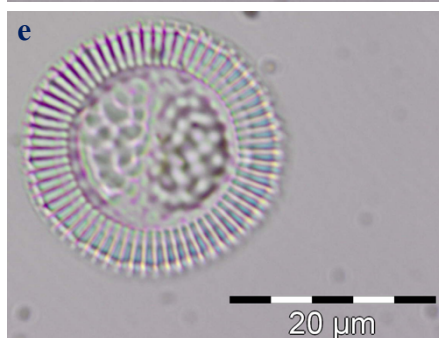
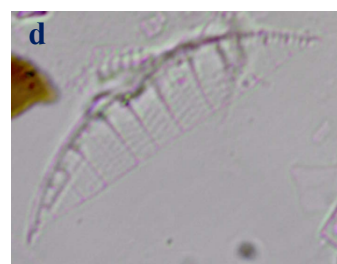
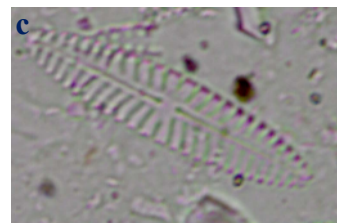
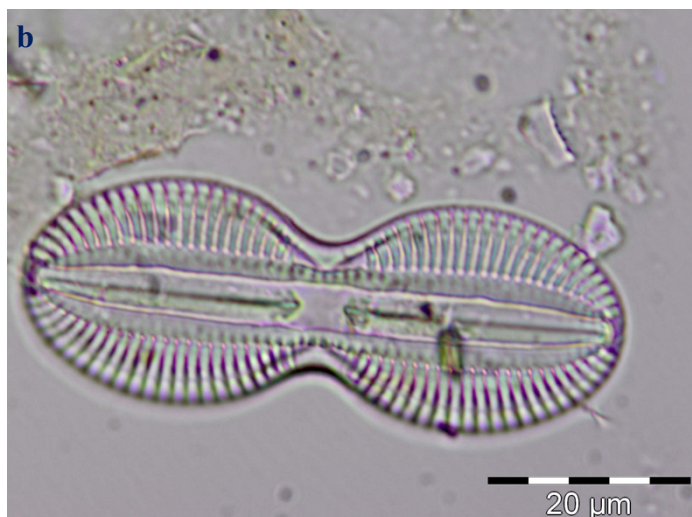
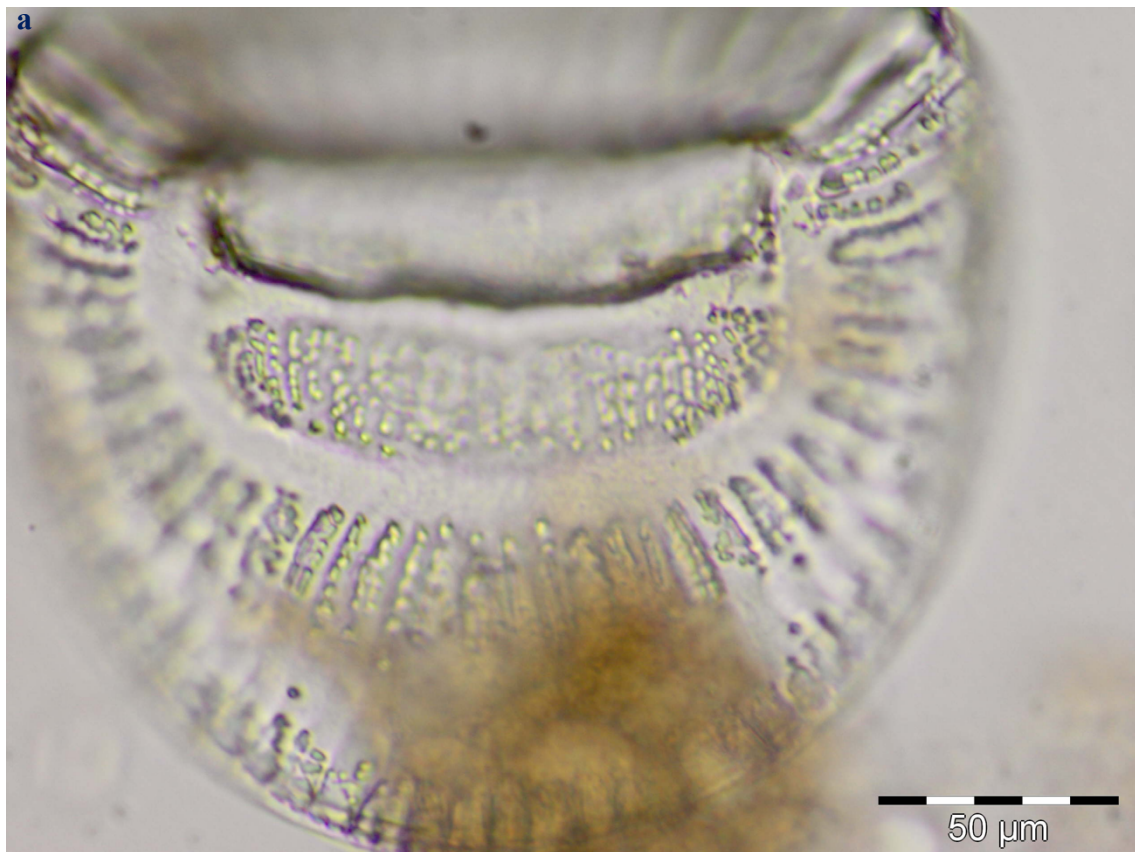
**II-A Marine species:** a) *Coscinodiscus radiatus*, b) *Raphoneis amphiceros*, c) *Biddulphia rhombus*, d) *Grammatophora oceanica*, e) *Podosira stelligera*, f) *Synedra nitzschoides*, g) *Campylosira cymbelliformis*, h) *Biddulphia aurita*, i) *Melosira sulcata*, j) *Eunotogramma marinum*, k) *Melosira westii*, l) *Cymatosira belgica*

**Marine-Brackish species**

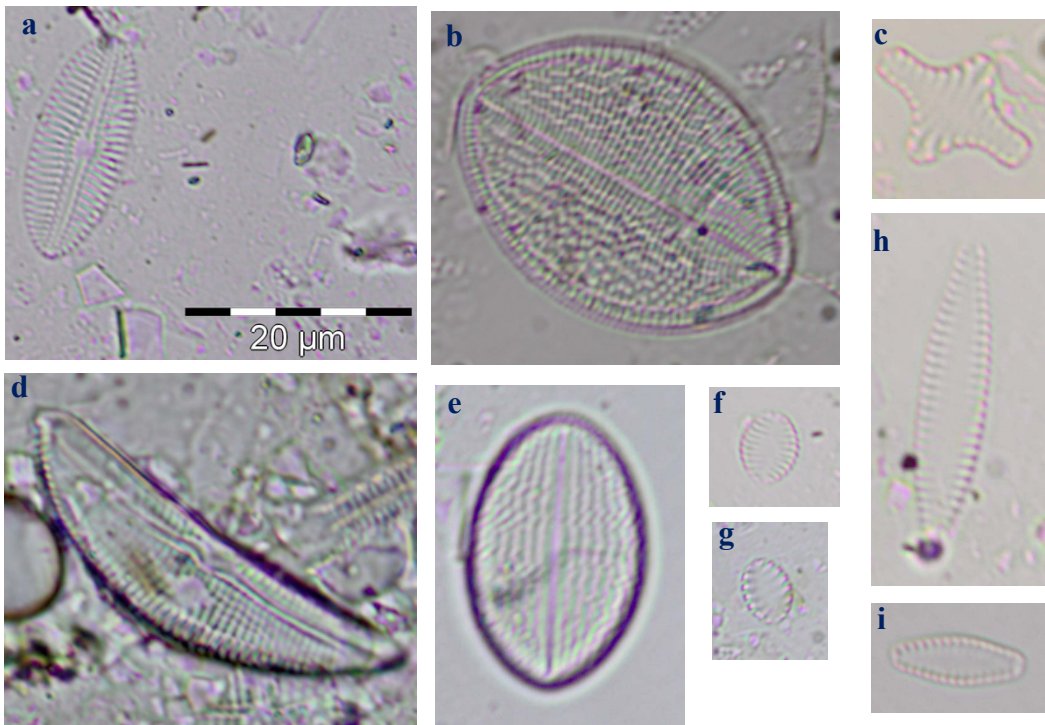
**II-B Marine-Brackish species:** a) *Nitzschia vitrea*, b) *Nitzschia navicularis*, c) *Nitzschia punctata*, d) *Navicula digitoradiata*, e) *Tabularia fasciculata*, f) *Caloneis formosa*, g) *Hippodonta hungarica*, h) *Opephora pacifica*, i) *Delphineis minutissima*, j) *Delphineis surirella*.



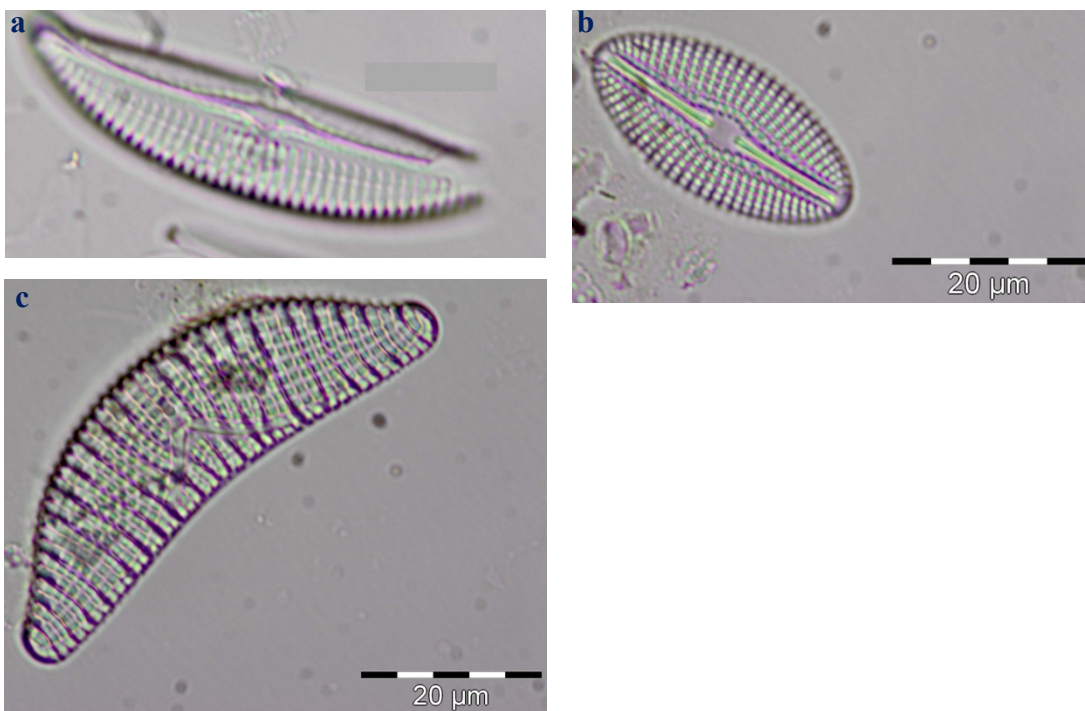
**II-B Marine-Brackish species (continued):** k) *Diploneis smithii*, l) *Diploneis* cf. *smithii*, m) *Actinoptychus undulatus*, n) *Diploneis aestuarii*, o) *Diploneis didyma*, p) *Achnanthes brevipes*, q) *Cocconeis scutelloides*, r) *Thalassiosira eccentrica*, s) *Planothidium delicatulum*, t) *Catenula adhaerens*, u) *Diploneis bombus*.

**Brackish species**

**II-C Brackish species:** a) *Campylodiscus clypeus* (note: different scale), b) *Diploneis interrupta*, c) *Navicula cincta*, d) *Rhopalodia musculus*, e) *Cyclotella striata*.

**Brackish-Fresh species**

**II-D Brackish-Fresh species:** a) *Diploneis ovalis*, b) *Cocconeis placentula*, c) *Fragilaria construens*, d) *Amphora copulata*, e) *Cocconeis pediculus*, f-g) *Fragilaria venter* var. *venter*, h-i) *Fragilaria brevistriata*.

**Fresh species**

**II-E Fresh species:** a) *Amphora ovalis*, b) *Diploneis elliptica*, c) *Epithemia turgida*.

## Appendix III

## Core logs from fieldwork locations Galgweg (GW), Weipoortse Vliet (WV) and Broekweg (BW)

Boorpunt: 201914001		Namen: KvdW, WH, HJP, JM		Jaar: 2019	Groep: 14	Datum: 17-4-2019
Coördinaten		Hoogte	Diepte	KAARTEENHEID	Geomorfogenetische kaart:	
Xco	Yco	Z [m]	[cm]	Geologische kaart:	Grondwatertrap:	
101097	458887	-2	590	Begroeiingskaart: gras	Bodemkaart:	

Galgweg 6, Zoeterwoude. Naast sloot, iets lager gelegen dan rest van weiland vanwege ploegen. Proefboring tbv diatomeeën onderzoek. Sample GW met pistoncorer 350-450cm.  
Maaiveld -2m tov NAP

Diepte	Textuur	Org	Plr	Kleur	Redox	Grind	M50	Ca	Fe	GW	M	LKL	Strat	Bijzonderheden
10		V2		br	or									Geroerd
20		V2		br	or									Geroerd
30		V2		br	or									Geroerd
40		V2		br	or									Geroerd
50		V2		br	or									
60		V1	r	grbr	r									
70		V1	rh	grbr	r									
80		V1	rh	grbr	r									
90		V2	h	br	r					GW				zwavelgeur 90 en dieper
100		V2	h	br	r									
110		V2	h	br	r									
120		V2	h	br	r									
130		V2	h	br	r									
140		V2	h	br	r									
150		V2	h	br	r									
160	ZK	H1	h	gr	r									geleidelijke overgang (5-10cm)
170	ZK	H1	h	gr	r									(niet zout)
180	ZK	H1	h	gr	r									
190	ZK	H1	h	gr	r									
200		V2	h	br	r									geleidelijke overgang (5-10cm)
210		V2	h	br	r									
220		V2	h	br	r									
230		V2	h	br	r									
240		V2	h	br	r									bosveen
250		V2	h	br	r									
260		V2	h	br	r									
270		V2	h	br	r									
280		V2	h	br	r									
290		V2	h	br	r									
300		V2	h	br	r									geleidelijk
310	MK	H1	r	gr	r									siltig, rietklei
320	MK	H1	r	gr	r									geleidelijk
330		V2	r	br	r									mm zwarte oxidatielagen
340		V2	r	br	r									mm zwarte oxidatielagen
350		V2	r	br	r									rond 367 2cm zwartig
360		V1	r	brgr	r									tot 365 geleidelijk
370	MK	H1	r	gr	r									op 367cm scherpe overgang
380	MK	H1	r	gr	r									360-390 iets gelaagd
390	MK	H1	r	gr	r									slap
400	MK	H0	r	blgr	r									slap
410	MK	H0	r	blgr	r									slap, zoetig
420	MK	H0	r	blgr	r									slap
430	MK			gr	r			2						zout, rietdoor tm 500
440	MK			gr	r			2						bladrest, zout
450	MK			gr	r			2						447 zwarte lijn, zout
460	LK			gr	r			2						gelaagd zwarte vlek 430-500
470	LK			gr	r			2						430-470 stevig gerijpt
480	LK			gr	r			2						474cm zwarte lijn, stuk riet
490	LK			gr	r			2						
500	LK			gr	r			2						
510	LK			gr	r			2						gelaagd riet, doorworteld
520	LK			gr	r			2						gelaagd riet, doorworteld
530	LK			gr	r			2						530-590 zwarte vlekken
540	LK			gr	r			2						
550	LK			gr	r			2						
560	LK			gr	r			2						
570	LK			gr	r			2						
580	LK			gr	r			2						
590	LK			gr	r			2						rietrest

Einde boring: 201914001



Boorpunt: 201914002      Namen: KvdW, WH, HJP, JM      Jaar: 2019      Groep: 14      Datum: 17-4-2019

Coördinaten		Hoogte	Diepte	KAARTENHEID	Geomorfogenetische kaart:	
Xco	Yco	Z [m]	[cm]	Geologische kaart:	Grondwatertrap:	
96302	460598	-1,74	510	Begroeiingskaart: gras	Bodemkaart:	

strook gras aan rand van terrein Weipootsevlief van SBB. Naast sloot enkele meters noord van klein molentje/sluisje in sloot. Proefboring voor diatomeeën onderzoek. Bleek ongeschikt voor piston corer ivm gecompacteerd veen.

Diepte	Textuur	Org	Plr	Kleur	Redox	Grind	M50	Ca	Fe	GW	M	LKL	Strat	Bijzonderheden
10														
20	LK			brgr	o									zandig erin
30	LK			brgr	o									
40	LK			brgr	o									
50	LK			brgr	o									
60	LK			brgr	or									
70	LK			brgr	or									
80	LK			brgr	or									
90	LK		h	brgr	or					GW				
100	LK			brgr	or									
110	LK		h	gr	r									
120	LK		h	gr	r									stuk Els
130	LK		h	gr	r									
140	LK		h	gr	r									
150	LK		h	gr	r									
160	LK		h	gr	r									
170	LK		h	gr	r									
180	LK		h	gr	r									
190	LK		h	gr	r									
200	LK		h	gr	r									
210	LK	H1	h	dgr	r									schelpen
220	LK	H1	h	dgr	r			2						schelpen
230	LK	H1	h	dgr	r			2						schelpen
240	LK	H1	h	dgr	r			2						schelpen
250	LK	H1	h	dgr	r			2						schelpen
260	LK	H1	h	dgr	r									schelpen
270	LK		h	gr	r									
280	LK		h	gr	r									
290	LK		h	brgr	r									
300	LK	H1	h	brgr	r									
310	LK	H1	h	brgr	r									zwarte vlekjes, spikkels
320	LK	H1	h	brgr	r									veenbrokje
330	MK			dgr	r									
340		V2	r	grbr	r									340-370 gelaagd, zeer compact
350		V2	r	grbr	r									340-370 verkolde laagjes
360		V2	r	grbr	r									
370		V2	r	grbr	r									
380		V2	r	grbr	r									
390		V2	r	br	r									
400	ZK	H1	r	gr	r									395 geleidelijk naar klei
410	ZK	H1	r	brgr	r									zwart laagje
420		V2	r	grbr	r									
430	ZK	H1	r	brgr	r									
440		V2	r	grbr	r									iets kleiig rietveen
450		V1	r	br	r									
460	MK	H0		gr	r									455 scherpe overgang
470	MK	H0		gr	r									470 en paar dm hoger hor riet
480	MK	H0		gr	r									470 losgescheurd
490	MK	H0		gr	r									460-500 doorgroeid riet
500	MK	H0		gr	r									brak
510														

Einde boring: 201914002

Boorpunt: 201914003

Namen: KvdW, WH, HJP, TW

Jaar: 2019

Groep: 14

Datum: 4-6-2019

Coördinaten		Hoogte	Diepte	KAARTEENHEID	Geomorfogenetische kaart:
Xco	Yco	Z [m]	[cm]	Geologische kaart:	Grondwatertrap:
95817	458051	-2	380	Begroeiingskaart: gras	Bodemkaart:

Broekweg 2, Zoeterwoude. In weiland naast kreekkrug achter boerderij. Proefboring voor diatomeen. BW= Zoeterwoude boring van JM. Piston corer samples: BW I: 1.70-2.28, (nieuw gat) BW II: 2.20-2.50, BWIII: 2.50-3.30m

Diepte	Textuur	Org	Plr	Kleur	Redox	Grind	M50	Ca	Fe	GW	M	LKL	Strat	Bijzonderheden
10	Z-MK			grbr	o				1					ijzervlekjes
20	Z-MK			grbr	o				1					ijzervlekjes
30	Z-MK			grbr	o				1					
40		V2		zw	o				1					geoxideerd veen
50		V2		zw	o				1					geoxideerd veen
60		V1		grbr	o				1					
70	ZK	H2		grbr	o				1					
80	ZK	H2	h	grbr	r									
90	ZK	H2	h	brgr	r									
100	ZK	H2	h	brgr	r									
110		V1	h	grbr	r					GW				
120		V1	h	grbr	r									
130		V1	h	grbr	r									
140		V1	h	grbr	r									
150		V1	h	grbr	r									
160		V1	h	grbr	r									els
170	ZK	H2	h	brgr	r									
180	ZK	H2	h	brgr	r									
190	LK	H0	hr	brgr	r			2						
200	LK	H0	hr	brgr	r			2						scherpe overgang
210		V2	r	br	r									
220		V2	r	br	r									cm kleibandje
230		V2	r	br	r									cm kleibandje, zwart bandje
240		V2	r	br	r									cm kleibandje
250		V2	r	br	r									
260		V2	r	br	r									
270		V1	r	grbr	r									rietveen slap
280		V1	r	grbr	r									rietveen slap
290		V2		grbr	r									GY, mm+cm kleiband, zwart band
300		V2		grbr	r									GY, 290-310 zaadjes, glimmers
310		V2	r	grbr	r									GY
320	LK	H0	r	gr	r			1						316 messcherp overgang
330	LK		r	blgr	r			2						310-330 gelaagd, plat riet
340	LK			blgr	r			2						330 relatief veel silt
350	LK			blgr	r			2						320-380 NaWo, ziltig
360	LK		plr	blgr	r			2						
370	LK		plr	blgr	r			2						slap
380	LK			blgr	r			2						slap

Einde boring: 201914003