From dust till drowned: the Holocene landscape development at Norderney, East Frisian Islands

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Abstract

Within the multidisciplinary WASA project, 160 cores up to 5 m long have been obtained from the back-barrier area and off the coast of the East Frisian island of Norderney. Thirty-seven contained basal peats on top of Pleistocene sands of the former *Geest* and 10 of them also had intercalated peats. Based on 100 acclerator mass spectrometry (AMS) ^{14}C dates and analyses of botanical as well as zoological remains from the peats, lagoonal sediments and the underlying sands, a variety of distinct habitats have been reconstructed. On the relatively steep slopes north of the present island, a swampy vegetation fringe several kilometres wide with carrs of alder (*Alnus glutinosa*) moved in front of the rising sea upwards of the *Geest* as it existed then until roughly 6 ka, when the sea level reached the current back-barrier region of Norderney at around −6 m NHN (German ordnance datum). From then on for nearly 4000 years a changing landscape with a mosaic of freshwater lakes and fens existed within this area. It was characterised by various stands of *Cladium mariscus* (fen sedge), alternating with brackish reed beds with *Phragmites australis* (common reed) and salt meadows with *Aster tripolium* (sea aster), *Triglochin maritima* (sea arrowgrass), *Juncus gerardii* (saltmarsh rush) as well as mudflats with *Salicornia europaea* (common glasswort). As far as shown by our cores, this highly diverse, and for humans potentially attractive landscape was at least some 4 km wide and followed the coast for about 10 km. Before the rising sea caused diversification of habitats, wet heath as well as dry and dusty sand areas existed. In the course of time, parts of the wet heath turned into raised *Sphagnum* bogs under an oceanic precipitation regime before this diverse landscape was drowned by the rising sea and finally covered by marine sediments, while the earlier sediments and peats were partly eroded and redeposited.

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Introduction

The German coast is rich in *Geest*, a landform of sands, gravels and tills from the Pleistocene. With the melting of the continental ice sheets since the end of the Last Glacial Maximum about 20,000 years ago, the global sea level rose about 130 m until today (Lambeck et al., 2002). After the rising sea had filled the North Sea basin and advanced up the slopes of the *Geest*, various kinds of coastal fens developed due to the rising groundwater level and deposited peat there. When the sea reached the fens, muddy lagoonal and later sandy marine sediments were deposited on top of the peat (Streif, 2004). This was not a continuous process, but interrupted by phases of reduced marine influence, allowing the accumulation of fen peats once more on previously deposited lagoonal sediments (Behre, 2007). Such recurring phases of peat formation left intercalated layers of different ages (Streif, 2004). Hence, the lower slopes of the *Geest* in the Wadden Sea and the currently embanked hinterland are covered by several metres of Holocene peat, clay and sand layers, surmounted over by the *Geest* heights. The exact timing, rates and progress of sea-level rise are still under debate (Bungenstock et al., 2021) and of crucial importance for any projections of landscape change under a predicted sea-level rise as a result of global warming (Golledge et al., 2019). The WASA (The Wadden Sea as an archive of landscape evolution, climate change and settlement history: exploration – analysis – predictive modelling) interdisciplinary joint project emphasises the reconstruction of the late Quaternary development of the German Wadden Sea (see also Bittmann et al., 2021). Here we focus on the wide ecological consequences and profound habitat changes driven by sea-level change during the past few millennia, offering a variety of natural resources for early human inhabitants for hunting, fishing and gathering in the Wadden Sea area (Bazelmans et al., 2012; Becker and Siegmüller, 2021).

Study area, materials and methods

The study area covers most of the back-barrier area and a few marine sites northwest of the East Frisian island of Norderney and within the UNESCO World Heritage-listed Wadden Sea area.

The intertidal flats of the back-barrier area drain twice a day with the ebbing of the tide, while deeper channels and the sites further from the island are permanently flooded. The tidal range is about 2.4 m (Behre, 2003) but may have been less in the past (Franken, 1987). Cores were drilled on the tidal flats at low water using a vibrocorer system with 6 m long aluminium tubes with an inner diameter of 8 cm. All other cores were obtained from a research vessel with a ship-based vibrocorer system using a steel tube with inner plastic liners of 5 m length and 10 cm inner diameter. Liners and aluminium tubes were cut on site into 1.0 to 1.2 m long sections, sealed and stored in a cold room. Before laboratory analyses, they were split longitudinally, recorded and macroscopically described (Bulian et al., 2019; Elschner et al., 2021).

Of 160 cores collected by the WASA team, 37 contained peat layers. These were mostly from the back-barrier tidal flats of Norderney, four of them northwest of the island. They reached from about +1 m NHN (German ordnance datum) down to about −16 m NHN. In seven cores a second peat was intercalated in lagoonal, or on top of lagoonal sediments overlain by marine deposits. About 180 slices, each 1–2 cm thick, were taken from the cores for dating and palaeoecological analyses mainly from the peats, some from lagoonal sediments and occasionally from the underlying sands including tree roots. About 130 selected slices were treated in a 10% potassium hydroxide (KOH) solution and were wet-sieved on a 63 μm mesh, their botanical (and zoological) remains handpicked and identified using reference collections of the NIhK and literature sources (e.g. Grosse-Brauckmann, 1964, 1972, 1974; Körber-Grohne, 1967; Behre, 1976; Grosse-Brauckmann & Streitz, 1992). If seeds of rushes were numerous, about 20 randomly picked seeds were identified in detail (Körber-Grohne, 1964).

One hundred selected botanical fractions were AMS ^{14}C-dated. The dated horizons concentrate on the start of marine influence, so the top of the basal peats and the base of the overlying lagoonal sediments as well as the intercalated peats were dated. For dating, the botanical remains of a sample were divided into up to eight species-specific fractions, depending on the amount of material and state of preservation (waterlogged, charred). Fruits of *Cladium mariscus* (fen sedge) and sclerenchyma spindles of *Eriophorum vaginatum* (cotton grass) in particular yielded enough material for dates of single species, as well as alder wood and sclerotia of *Cenococcum geophilum*. Also, waterlogged or charred twigs and leaves of *Calluna vulgaris* (common heather) and *Erica tetralix* (bell heather) were used, either separately or together. Where necessary, assemblages of taxa, charred stems mostly of grasses or the residual <63 μm bulk fine fraction, cleaned in KOH, were used. In case of material shortage, two adjacent samples were combined and treated together. To test the reliability of the various materials, additional fractions (charred, uncharred, different taxa etc.) were dated in parallel.

The dating was done at the Poznań Radiocarbon Laboratory (Goslar & Czernik, 2000). Calibration was done with OxCal v. 4.3 (Bronk Ramsey, 2009) including deposition models (Bronk Ramsey, 2008; Bronk Ramsey & Lee, 2013). Combined ages were calculated for all parallel fractions of potentially the same context, but disregarded if the ages of the fractions were not similar within the 95% probability of the OxCal χ^2 test. Data in the text refer to mean ages with 2σ intervals (Bronk Ramsey, 2009).

The description of the successive landscape stages in the area around Norderney is based on the temporary and spatial past occurrences of ecologically indicative plant groups. To discover the influence of salinity, we mapped the appearance of fruits and seeds of plants characteristic of salt meadows and salt marshes like *Aster tripolium*, *Triglochin maritima* (sea arrowgrass), *Juncus gerardii* and *Salicornia europaea*, in addition to linings of foraminifers (Shumilovskikh et al., 2016). We also applied the Ellenberg indicator values (EIV) (Ellenberg et al., 2001; Leuschner & Ellenberg, 2017), an approach also often used by archaeobotanists (e.g. Willerding, 1979; Hill, 1999; Rösch et al., 2002; Schepers et al., 2013; Bogaard et al., 2016) to identify differences in soil quality. For the most reliable results when using this actualistic approach, we have considered plants with clear ecological needs (EIV 8 and EIV 9) and therefore low synecological variance. Moreover, we use indicator species, as phytosociological syntaxa may have changed over time and modern analogues may be sparse or missing.

Results

The peat-bearing cores generally consisted, from bottom to top, of Pleistocene *Geest* sands with some early Holocene modifications, followed by basal peats covered by lagoon and marine deposits and locally intercalated peats. Seeds, fruits and vegetative plant remains of about 125 taxa were identified, when possible to species level (see table in the Supplementary Material available online at https://doi.org/10.1017/njg.2021.4). The locations of all cores containing peat are shown in Figure 1. Based on the dates, sediment and peat analyses, the most widespread habitats in the buried former wetlands of the present-day Wadden Sea area around Norderney are reconstructed in the following subsections, including aspects of dynamic landscape changes.

Before arrival of the sea

With the exception of a few charred remains, the vegetation before the start of deposition of the basal peats is hardly preserved at all. Charred twigs and leaves of *Erica tetralix* and *Calluna vulgaris* from the top of the sand of the former *Geest* at the bottom of the basal peat layer dated to 8750–8450 cal BP (core VVC15) and 8980–8580 cal BP (core W3). They formed here a few centuries after the beginning of the middle Holocene in the Atlantic period, which started at around 9200 cal BP (Barckhausen & Müller, 1984; Dörfler et al., 2012), and a several hundred years after their early Boreal spread on the *Geest* slopes around −30 m NHN at about 10,700 cal BP (Wolters et al., 2010). The early Holocene is represented only by a tiny, unidentified charcoal fragment dated to around 9700–9520 cal BP (core N71).

The records of *E. tetralix* and *C. vulgaris* point to the establishment of a wet heath dominated by *E. tetralix* on the Pleistocene sands, at the latest after the climatic amelioration of the Atlantic period, and long before any pronounced human influence. This predates by about three millennia the formation of wet heath as previously suggested by Menke (1963) and underlines its natural origin that has long been debated (Firbas, 1937; Tüxen, 1978). As some of these wet heath communities did not include *Sphagnum* mosses (Leuschner & Ellenberg, 2017), they did not form peat archives of this early phase of landscape development. In contrast to this Atlantic wet heath, the *Calluna*-dominated dry inland heathlands with *Juniperus communis* (juniper) result from human activities (Menke, 1963; Behre, 1999b; Karg, 2008).

On lower-situated slopes of the former *Geest*, as proved by Grohne (1957) for the regions around the recent islands of Juist and Baltrum, the peats are older and *E. tetralix* has grown here since the early Holocene (Preboreal), forming a kind of *Sphagnum*-rich wet heath in the Boreal at the latest. In higher places around Juist and Baltrum, *E. tetralix* was not found before the
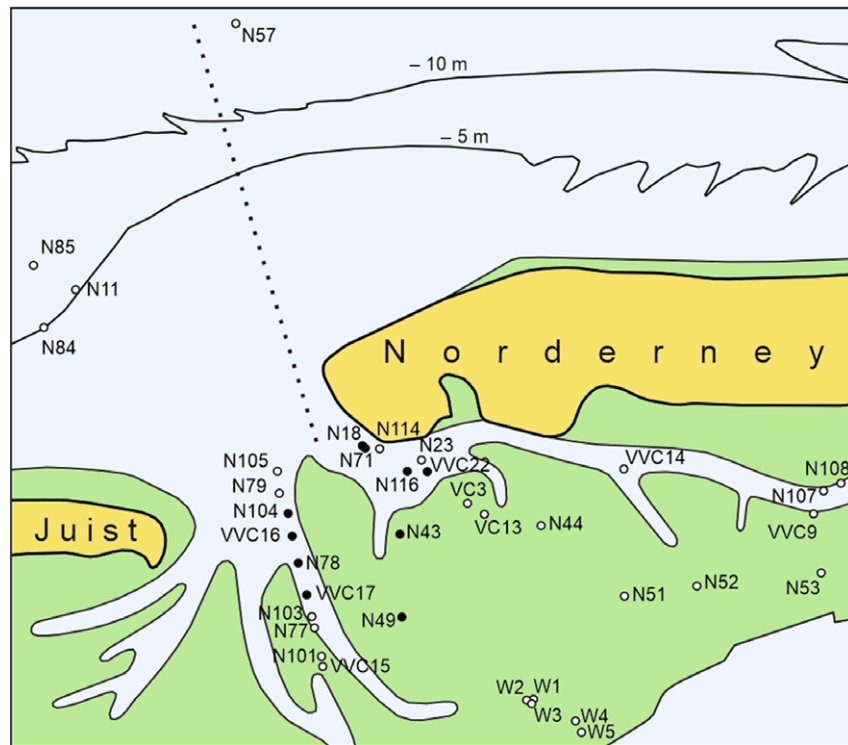
Fig. 1. Positions of cores with basal peats (white circles) and cores with basal and intercalated peats (black). Tidal flats (*Watt*) in green, islands in yellow, diked hinterland in the southeast. Depth counters given for north of the islands. Here and in some of the following maps overlapping core symbols are rearranged for clarification; the transect given in Figure 4 is shown as a stippled line.

Atlantic period either, and *C. vulgaris* dominated on the sands together with *Sphagnum* spp. but without *Juniperus* (Grohne, 1957). The vegetation fixed the unstable *Geest* surface, and recognisable input of aeolian material like sand and dust ceased, but only by the beginning of the Atlantic period (Grohne, 1958) or, as demonstrated by sand layers in core W1, even after 6500 cal BP. Lake sediments as described for the Preboreal and the preceding late glacial Younger Dryas period (Grohne, 1957, 1958) were not recognised.

A fringe of alder carrs facing the rising sea

In pollen records, the strong increase of *Alnus* around 9200 cal BP usually marks the change from the Boreal to the warmer Atlantic period (Barckhausen & Müller, 1984; Dörfler et al., 2012). Our oldest records of alder, from site N57 at a depth of −16.6 m NHN, date to 7930 cal BP and are therefore much younger. Core N57 also marks the earliest peat accumulation in our data set, starting probably several hundred years before the top of the 42 cm thick peat layer was formed. Further samples, one more with alder fruits and three samples of alder roots, tend to be younger with increasing elevation towards the *Geest* (Fig. 2).

Cenococcum geophilum is a mycorrhizal fungus on tree roots which forms sclerotia, lumps of hardened mycelium. Such sclerotia from the top of the peat in core N71 and alder roots from the underlying sand are of the same age according to the χ^2 test. The occurrence of sclerotia at the top of the peat shows that this combined age of around 7190 cal BP probably represents the last trees there. *Cenococcum* sclerotia near the bottom of this peat dated to 7270 cal BP point to tree growth about 100 years earlier, but it is uncertain if the trees were there earlier. This phase of peat with alder and sclerotia as recorded in the present study lasted until about 5700 BP. For practical reasons of landscape reconstruction, the dates of alder roots from sands in this study are related to the middle level of the overlying basal peats, in case of core N71 to the

level with the *Cenococcum* sclerotia of the same age. As no wood of other trees appeared in those samples, *Cenococcum* was most probably growing on the alder roots.

Taking the dated uppermost peat layers as sea inundation marker points, the flooding of the basal carr peat reflects an increasingly slower sea-level rise. Estimates for peat compression vary widely from, for instance, 25% (Linke, 1979), 40% in a few centuries (van Asselen et al., 2010) up to 80–90% (Bennema et al., 1954). If the compaction was 50%, the rate of sea-level rise would have decreased nearly by a factor of ten, from about 10.1 mm a^{-1} around 8 ka ago, to about 1.1 mm a^{-1} around 6 ka (Table 1). The initially rapid rise in sea level, its quick slowing down and the height of the reconstructed sea level are in good agreement with earlier results from the southern North Sea (Behre, 2007; Bungenstock and Schäfer, 2009; Meijles et al., 2018) (Fig. 3).

The dates from the bulk fine material of sand layers below the basal peats probably show the beginning of accumulation and preservation of plant material, most probably roots of wet heath plants, due to the start of waterlogged conditions from increasing soil moisture at a given site. This indicates groundwater levels near the sand surface and predates the later groundwater discharge and start of peat accumulation by an unknown but most probably short time interval. This indirect influence of the sea level took place about 500 (490, >570, 600) or even 900 years before a site was inundated. The duration of this period in core N78 seems to be much overestimated, due to dating charred material which probably derived from an earlier stage of landscape development.

Considering the initial rapid sea-level rise, the interval of organic accumulation at site N11 points to a sea level about 5 m below the later carr site, when paludification started. Here the swampy fringe facing the sea was about 3 km wide at the beginning. These magnitudes may also hold true for the lower parts of the *Geest* slope which are not included in the present study. The marsh
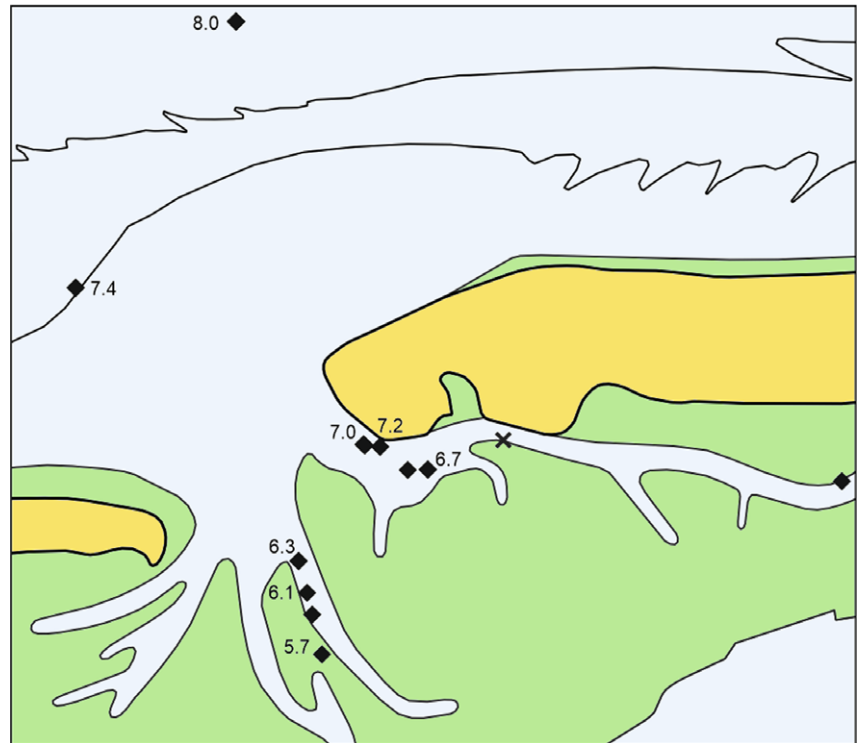
Fig. 2. Sites with alder carr peat and ages of dated *Alnus* remains in ka cal BP. X = tree roots in the *Geest* sand without basal peat (core N27). For explanations, see Figure 1. In place of 8.0 read 7.9 here and hereinafter.
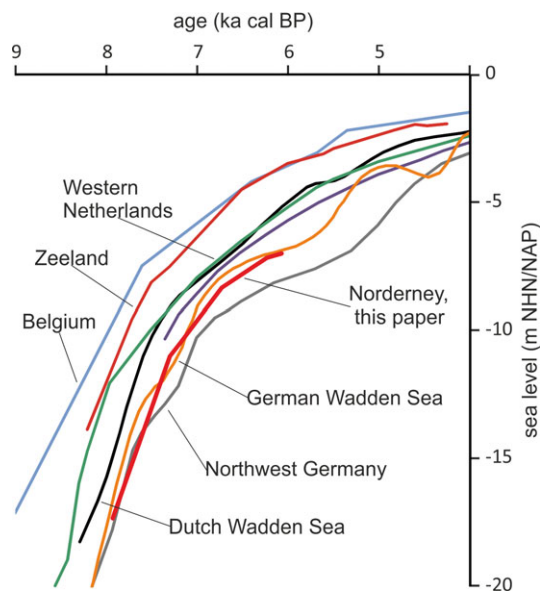

Fig. 3. Early sea-level change at Norderney based on alder carr flooding (this paper) in comparison with reconstructions from other sources and interpretations mostly following Meijles et al. (2018). Other sources: Belgium (Denys and Baeteman, 1995), Zeeland, Netherlands (Kiden, 1995; Vink et al., 2007), Western Netherlands (Hijma & Cohen, 2010), Dutch Wadden Sea (Meijles et al., 2018), Northwest Germany (Vink et al., 2007), German Wadden Sea (Behre, 2007).

formation which followed at site N71 started shortly afterwards. Due to the gentle *Geest* slope north of site N71, the swampy fringe doubled in width (Fig. 4).

The situation changed considerably when the sea, by then only slowly rising, flowed into the flat today back-barrier area about 6500 years ago. The alder carr at site VVC22 started to grow when the sea level was already close to its own level. Here, the rate of peat accumulation kept up with the average sea-level rise for some time (Behre & Streif, 1980; Streif, 1982). This implies a situation of very strong freshwater discharge which prevented permeation by salt water. Possibly the site received extra fresh water through a channel running across the former *Geest* (Streif, 1990). This could also explain a peat thickness twice as high compared to carrs located lower on the steep slope and the occurrence of the second thickest carr peat within the same channel (core N108, 43 cm). The rising sea may have created a situation like an estuary. Roots of alder in the *Geest* sand at −7.9 m NHN indicate an older carr nearby in a lower-situated channel to the east (core N27).

As the sea level rose, so did the local drainage system and the associated groundwater table, until freshwater discharge enabled carr development on the *Geest* slope. With this strong causal link to sea-level rise, the carr peats in our investigation area can be classified as *Basistorfe* (lower peats) in terms of Lange & Menke (1967). As macro remains demonstrate, the widespread alder was accompanied by *Betula* (birch) and also *Pinus* (pine). *Quercus* (oak) grew probably together with *Corylus* (hazel) on drier sites on higher land above the wet carrs (Behre, 2004), but they were found only sporadically (see Supplementary Material available online at https://doi.org/10.1017/njg.2021.4).

Halophytes after the alder carrs and later

With the increasing marine influence from the approaching sea, typical plants of salt meadows spread. Fruits and seeds of the halophytes *Aster tripolium*, *Triglochin maritima* and *Salicornia europaea* occurred in several samples and *Ruppia maritima* in one. *S. europaea* is an annual pioneer on mud and sand especially of the intertidal zone, while *A. tripolium* and *T. maritima* are also typical plants there and on salt meadows at higher elevations (Fig. 5). *R. maritima* grows, for instance, in brackish pools (Clapham et al., 1942; Davy & Bishop, 1991; Dijkema, 1994; Davy et al., 2001; Freund et al., 2004). These species, with indicator values (EIV) for

Table 1. Cores with dated alder carr including ages, depths and calculated rates of sea-level change. To compensate for an estimated compression of 50% (see text) the heights of the tops of the carr peats were increased by adding the peat thickness (1). For integration with Figure 4 the recent MTHW height of about 1.13 m above NHN for Norderney was subtracted (Behre, 2003), uncertain data in italics.

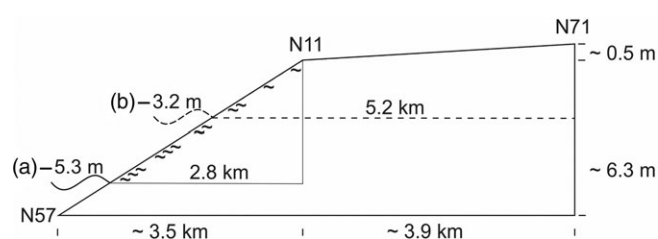| Core | Peat | | | | | Sea level | | |
| | Thickness in core (1) | Period | 'Accumulation' | Altitude plus thickness (=1) | Age of top | Increase | Time | Rate of increase |
ID	(m)	(a)	(mm a⁻¹)	(m NHN)	(cal BP)	(m)	(a)	(mm a⁻¹)
VVC22	0.59	570	1.04	−5.88	6070	0.17	160	1.1
N78	0.29	*1550*	*0.19*	−6.05	6230	1.17	500	2.3
N18	0.21	900	0.23	−7.22	6730	2.12	450	4.7
N71	0.16	600	0.27	−9.34	7180	0.54	120	4.5
N11	0.25	490	0.51	−9.88	7300	6.34	630	10.1
N57	0.42			−16.22	7930			

Fig. 4. Diagram showing the approximate relative altitudinal position of the sea level and the width of the zone with groundwater discharge around the time when paludification (~) started at (a) core N11 and additionally for (b) core N71. The height differences between the tops of the carr peat and the contemporary sea level are given in Table 1; approximate distances between core sites and the (former) coast along the transect are shown in Figure 1.
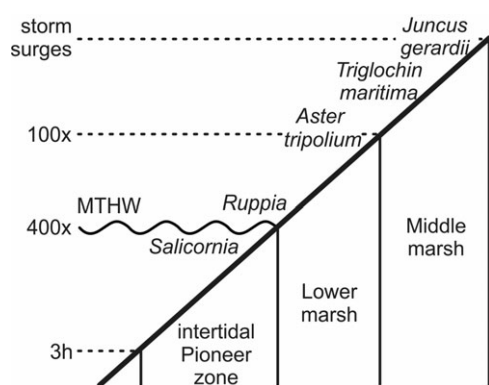

Fig. 5. Schematic zonation of the tidal marshes and times of inundation (h, hours per tide; x, tides per year; there are two tides a day). *Salicornia europaea* grows around the mean tide high water (MTHW) and below it to where the tidal flat is inundated up to about 3 hours per tide. *Ruppia maritima* grows in small brackish pools, *Aster tripolium* in the frequently flooded lower marsh area. *Triglochin maritima* and *Juncus gerardii* grow up to where regular storm surges commonly reach (after Erchinger, 1986; Streif, 1990; Vos & Gerrets, 2005).

salt of 8 to 9, indicate sites with the highest salinity (Leuschner & Ellenberg, 2017).

The first occurrences of these halophytes are noted at the lowest level (core N77) at around 7600 cal BP (Fig. 6). The next finds are from further up the *Geest* slope and with decreasing ages with height. From our dates, sites came under salt influence a few hundred years after the first occurrence of trees. Some halophytes may

have been growing directly on the seawater-soaked peats, as can be observed today at Jadebusen near Sehestedt. This rapid succession and the associated gradient to younger ages going up the *Geest* show the strict relationship of alder carr formation with rising sea level, not only at its beginning but also its end.

As indicated by the wide distribution of halophytic herbs, the development of mud flats and salt meadows exceeded the area of alder carr in the flat back-barrier area but remained restricted to south of the tidal channel between Norderney and the island of Juist, and was absent from the eastern back-barrier area. Nevertheless, linings of foraminifers in the top layers of the peat indicate marine influence in the eastern part of the study area already around 5.5 ka, which is long before the overall disappearance of the halophytic herbs. Obviously, time and salt did not limit the halophyte expansion but probably the geomorphological conditions as discussed below.

As well as these herbs, the salt-tolerant *Juncus gerardii* (EIV S7) also occurred, which is a typical perennial rush on the upper parts of the salt meadows. Despite an expected extensive spread of the small and light seeds (0.55–0.75 mm) by water, wind or birds, their distribution is quite similar to that of the halophytic herbs. The diaspores (seeds, fruits) of all these five halophytes consistently reflect the former distribution of salt meadows with intertidal salt marshes closer to the sea. South of the area with *J. gerardii* and at probably slightly higher elevations, the less salt-tolerant *J. subnodulosus* (EIV S2) indicates less marine-influenced habitats.

J. gerardii appeared in the eastern back-barrier area (core N108, 6090 cal BP, core VVC9, 5500 cal BP) accompanied by *Atriplex* (saltbush, orache) and *Chenopodium* (goosefoot), showing the existence of salt-tolerant vegetation which grew on top of the basal peats (core N107, core N108), as well as brackish lagoonal conditions before flooding by seawater (core VVC9). Today, *Atriplex littoralis* and *A. hastata* (*A. littoralis/hastata* type; Körber-Grohne, 1967; Behre, 1976) grow along drift lines. Together with other Chenopodiaceae, they may have grown together with *J. gerardii* at higher levels that were reached by seawater only sporadically during spring tides or storm surges, possibly on small erosional cliffs. The absence of frequently inundated stable slopes may have limited the expansion of the salt meadow herbs *Aster tripolium* and *Triglochin maritima* to the east. At several sites south of the area with *J. gerardii*, seeds were found of *J. subnodulosus*, indicative of less salt-influenced but moist conditions with percolating water, as in fens or communities of large sedges. This may again be evidence for the importance of groundwater from the *Geest* in opposing marine influence, for instance from occasional storm surges.
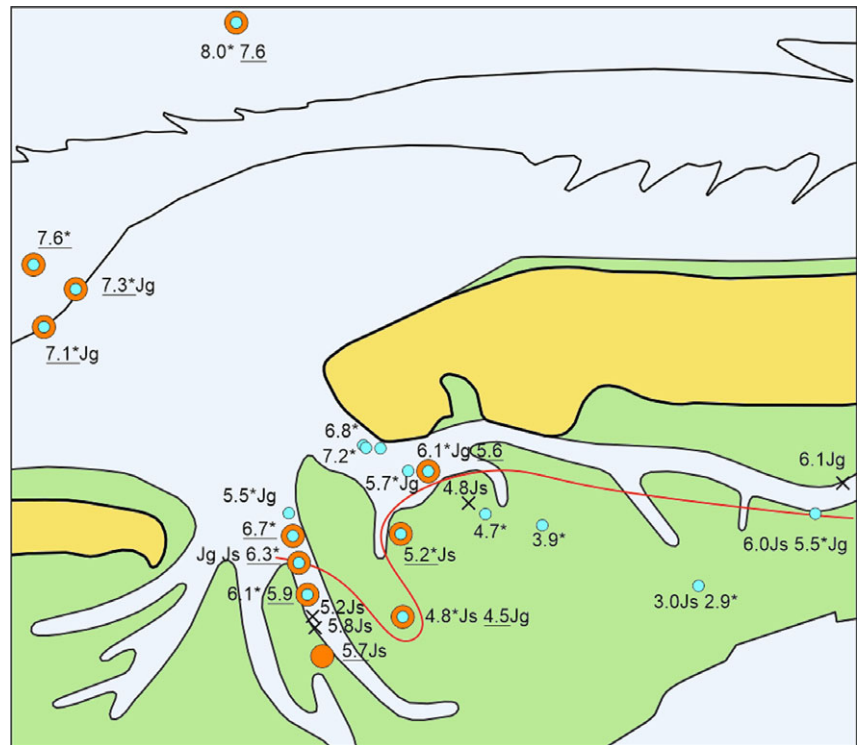
Fig. 6. Salt influence. Sites with halophytic herbs, *Aster tripolium*, *Triglochin maritima*, *Salicornia europaea* and *Ruppia maritima* (red filled circles), linings of foraminifers (blue dots) and seeds of *Juncus gerardii* (Jg) and *J. subnodulosus* (Js). Sample ages in ka cal BP, for halophytic herbs underlined, for foraminifers with an asterisk; Jg and Js follow the sample age if they are present. The red line denotes the border between the dominances of *J. gerardii* and *J. subnodulosus*; its lobe to the south follows the palaeochannel of the Hilgenrieder Rinne (Streif, 1990). For explanations, see Figure 1.

At some sites *J. subnodulosus* is followed after a few centuries by *J. gerardii* (cores N49, VVC9) and herbaceous halophytes (core N49), reflecting a succession driven by a rising sea level. Within the wide distribution of species of *Juncus* (rushes), the short wings were found from individuals of the rush-feeding plant hopper *Conomelus anceps* (Delphacidae) (van Geel et al., 1983), the only lowland representative of the genus (Kunz et al., 2011).

Phragmites australis *and the question of brackish lagoons*

Phragmites australis (common reed) occurred in nearly every microscopically analysed core, mostly represented by rhizome fragments occasionally accompanied by fruits. Its well-preserved rhizomes can easily be identified with the naked eye and are one of the most commonly mentioned botanical remains in core descriptions. The perennial grass can form over 3 m high, nearly monospecific stands with dense rhizome masses in the ground up to several decimetres thick. Common reed is widespread in shallow freshwater habitats like lake shores, swamps and carrs as well as in the saline conditions of saltmarshes and brackish lagoons (Packer et al., 2017). In contrast to its wide former distribution range (Streif, 1990), it is rather restricted along the diked coast today. Under experimental conditions, *Phragmites* benefits from some salt but reacts to near-marine salt concentrations with plant heights of less than 0.5 m (Achenbach et al., 2013). Populations of common reed in Jadebusen on the southern North Sea coast are found at present on soils with a maximum salinity of nearly a third of that of seawater (Scheer, 1953). It is expected to have grown in the former Wadden Sea in brackish conditions of nearly half sea-water salinity (Gerdes et al., 2003), which is the limit for the start of dieback on the coast of Denmark today (Lissner & Schierup, 1997). From North America, *Phragmites* is reported from soil salinities of about nearly two-thirds of that of seawater (Burdick et al., 2001). When salinity decreases from reduced

influence of tides, reed populations can spread vegetatively by up to 1 m a^{-1} into adjacent salt meadows (Burdick et al., 2001). The establishment of new stands from fruits or rhizome fragments seems to be largely restricted to salinities below one-third of seawater (Scheer, 1953; Chambers et al., 2003). In the widely diked brackish Jadebusen the few observed stands of *P. australis* were found from +0.7 m to −0.3 m MTHW (mean tide high water) (Scheer, 1953).

As reed rhizomes can penetrate downwards into peat, they may be younger than the surrounding peat or sediment (Streif, 1971; Törnqvist et al., 1992). To face this problem, additional fractions like charred stalk remains (probably grasses) and waterlogged leaf fragments of the *Thelypteris palustris* (marsh fern) were dated as well as some of the waterlogged rhizomes. Except for a *c.*300 years older charred control specimen, the others gave statistically robust combined ages from the X^2 test. The remaining single *P. australis* ages fit into the time successions of the related depositional sequences. A reason for this generally good agreement might be the relatively high accumulation rate of *P. australis* peat at about 1 mm a^{-1} (Törnqvist et al., 1992). Nevertheless, caution is needed and ages of other fractions of peats and sediments might be older than the rhizomes (Sindowski, 1979). It is important to note that the starting point of a rhizome runner is rarely detectable in a core and *P. australis* is recognised by some authors as a secondary constituent of peat (Grosse-Brauckmann, 1972).

The oldest reed beds are reflected by rhizomes and fruits in the carr peat of core N57 (−16.6 m NHN, 7930 cal BP). Younger *P. australis* finds from higher up on the *Geest* are directly dated rhizomes from the end of the formation of local basal peat (core N85, −10.3 m NHN, 7140 cal BP; core N84, −9.9 m NHN, 7060 cal BP; core N49, −4.3 m NHN, 4750 cal BP). *P. australis* rhizomes from the top of lagoonal sediments mark the end of brackish conditions caused by increased marine influence and date to 7620 cal BP (core N57, −16.3 m NHN), 5500 cal BP (core VVC09, −5.8 m NHN) and

3560 cal BP (core N44, −2.9 m NHN). The marine transgression was not a continuous process, but was interrupted by freshwater phases shown by fen and wood peats with *P. australis* rhizomes at their base at around 6500 cal BP (core N18, core N71) and 4200 cal BP (core N49). The youngest peat with reed remains is about 2900 years old (core N52).

Over a long timespan and in a wide ecological range from freshwater fens, swamps and carrs to brackish lagoons, *Phragmites* reed beds were a long-lasting part of the landscape in various appearances from about 7950 to 2850 cal BP.

Despite the common macroscopic and microscopic records of *P. australis* rhizomes, the ecological significance of their occurrence and the dates from the rhizomes are ambiguous. Aboveground remains of ecologically more restricted plants are better suited for dating and environmental reconstructions.

Fertile soils and freshwater conditions

Besides salinity, the availability of nutrients and the soil pH, particularly the base status, are important ecological factors. As demonstrated by the presence of *Erica* and *Calluna*, the original sandy soils of the *Geest* slopes were acidic and barren. The available substrate qualities changed radically with the rising sea. Since the earliest alder carr formation (core N57), nitrophilous aquatic plants such as *Alisma plantago-aquatica* (water-plantain) and the swamp plants *Eupatorium cannabinum* (hemp agrimony) and *Sonchus oleraceus* (common sow thistle) occurred, indicating the release of nutrients by decay of the previously accumulated organic material. With the accumulation of carr and fen peat caused by the rising sea level, a nutrient-rich fringe of vegetation with highly nutrient-demanding plants (Table 2) moved up the *Geest* slope (Fig. 7). The occurrence of nitrophilous *Atriplex littoralis/hastate* type indicates fertile marine substrates in connection with lagoonal conditions. Sources for the nutrients would have been, for instance, redeposited peat, seaweed as well as animal corpses and faeces (Liebezeit et al., 2008).

The previously mentioned nitrophilous *Sonchus oleraceus* requires a high base supply as well as high nitrogen and is, along with *Berula erecta* (lesser water-parsnip), one of the earliest species in this indicator group to appear, both found in the oldest carr peat (core N57) at latest around 7930 years ago (Fig. 8). As the *Geest* sands would have been poor in carbonates and other basic compounds, extra sources must be considered. Possibly the groundwater feeding the carr carried base-rich minerals from the Lauenburg clay, which contains 10% carbonate (Meyer, 2017) or the more widespread glacial tills of the *Geest*. Both sources exist below the western area of Norderney at about −10 m NHN (Streif, 1990), from where the ancient channel of the Hilgenrieder Rinne passes towards site N57 (Sindowski, 1973). The geological situation may be the reason why no calcicole plants were found from the higher and more westerly sites (core N11, core N84 and core N85). Within the today tidal-flat back-barrier area, base-demanding plants spread soon after about 7000 cal BP, with the latest occurrences at 2900 cal BP, which is contemporary with slowly rising to stationary or even falling sea level, but increased tidal ranges (Franken, 1987), together offering sites rich in carbonates. As most plants are intolerant of salt, the calcareous marine sediments must have been fed by precipitation or fresh groundwater.

Cladium mariscus (fen sedge, Fig. 8) depends strongly on calcareous substrates and is strictly limited to fresh water (Conway, 1942; Hill, 1999; Leuschner & Ellenberg, 2017). It may have dominated, or formed together with *Phragmites australis*, dense reed

Table 2. Ellenberg indicator values (EIVs) of taxa found in the WASA cores with high requirements for nutrients (EIV N 8–9), bases (EIV R 8–9) or salt tolerance (EIV S 8–9), and information about their annual (a) or perennial (p) life forms (Ellenberg & Leuschner, 2010). EIVs vary or are unknown within the species aggregate *Salicornia europaea*; defined salt values range from 7 to 9

	N	R	S	a/p
Alisma plantago-aquatica	8	x	0	p
Andromeda polifolia	1	1	0	p
Aster tripolium	7	7	8	a/p
Atriplex hastata	9	x	0	a
Atriplex littoralis	9	x	7	a
Berula erecta	6	8	1	p
Brassica nigra	7	8	0	a
Calluna vulgaris	1	1	0	p
Carex flava agg.	2	8	0	p
Cladium mariscus	3	9	0	p
Erica tetralix	2	1	0	p
Eriophorum vaginatum	1	2	0	p
Eupatorium cannabinum	8	7	0	p
Juncus gerardii	x	7	7	p
Juncus subnodulosus	3	9	2	p
Ranunculus sceleratus	9	7	2	a
Ruppia maritima	?	8	9	p
Salicornia europaea agg.	—	—	7–9	a
Schoenoplectus tabernaemontani	6	9	3	p
Scirpus maritimus	7	8	2	p
Solanum dulcamara	8	x	0	p
Sonchus oleraceus	8	8	0	a
Triglochin maritima	5	x	8	p
Urtica dioica	9	7	0	p
Urtica urens	8	x	0	a

and sedge beds along lake shores, also including *Sparganium erectum*, *Typha sp.* and *Alisma plantago-aquatica*. In swampy areas and fens, *Cladium* could have grown together with *Hydrocotyle vulgaris*, *Lythrum salicaria*, *Filipendula ulmaria* (meadowsweet), *Eupatorium cannabinum* and *J. subnodulosus*, which were also found (Conway, 1942; Garve, 2007). The existence of freshwater lakes or ponds is shown by numerous statoblasts of freshwater bryozoans (Wood, 2005; Wöss, 2005). *Cladium* is nowadays restricted to small spots on the westernmost East Frisian Island of Borkum and the northern Jadebusen near Hooksiel (Bettinger et al., 2013). In contrast, this sedge was widespread along the entire German Wadden Sea coast in the past (Grohne, 1957; Wiermann, 1962; Menke, 1968). South of Norderney, stands of this sedge characterised the landscape for over 4000 years (6750–2850 cal BP). Locally, the alder carr already included pools with bryozoans and with increasing wetness turned into *Cladium*-dominated reed beds.

Climate as a controlling factor?

The climatic needs of some of the more common taxa in terms of minimum average July temperatures are listed in Table 3. As
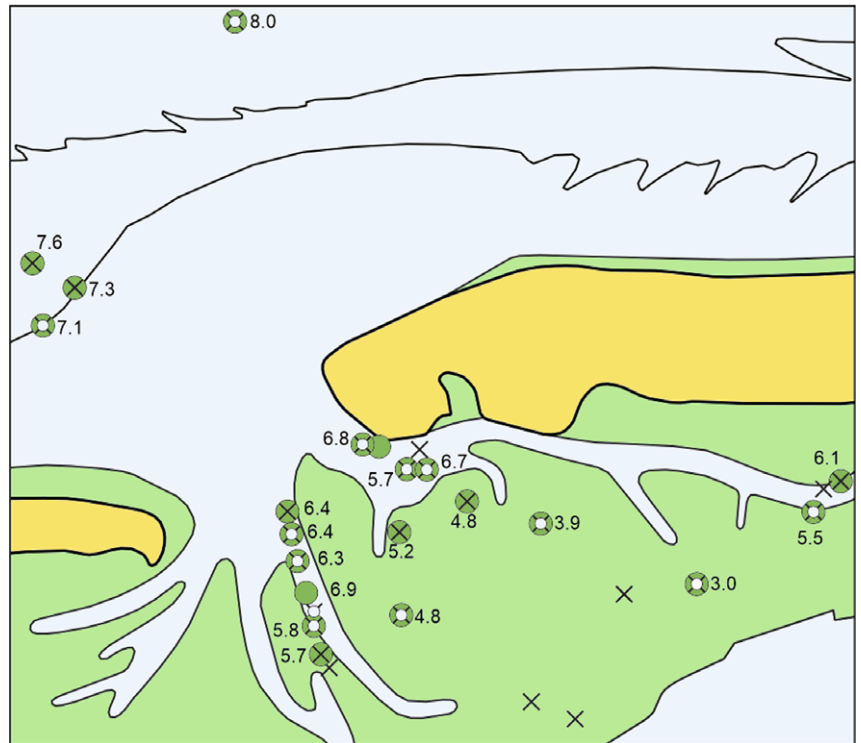
Fig. 7. Records of nitrophilous plant taxa (EIV N 8–9, green circles) with oldest ages (ka cal BP). All sites with seeds of any *Juncus* species (X) and with *Conomelus anceps* wings (white dots) are marked. For explanations, see Figure 1.
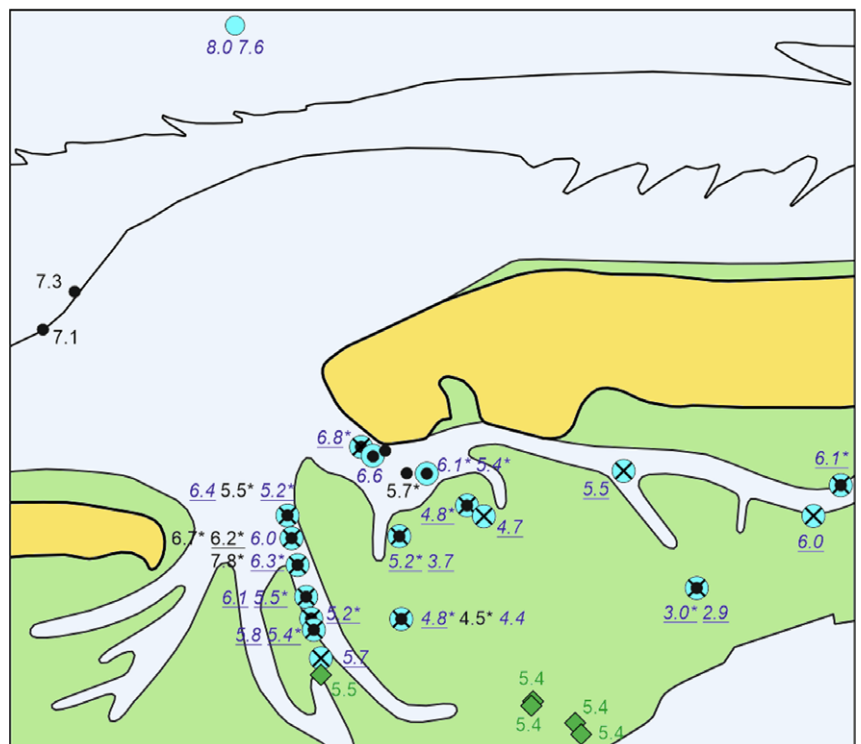

Fig. 8. Calcareous soils, freshwater swamps, lakes and raised *Sphagnum* bogs. Finds of calcicole plant taxa (EIV R 8–9, blue filled circles), *Cladium mariscus* (X), freshwater bryozoans (black dots) and *Sphagnum* bogs (green diamonds). Ages in ka cal BP, occurrences of calcicole plants shown in blue italics, *C. mariscus* underlined, bryozoans asterisked, and tops of the eroded *Sphagnum* peats in green. For explanations, see Figure 1.

demonstrated by the reconstructions of Zagwijn (1994) for instance, they occur sometime later or even long after their listed temperature requirements would have been reached or already exceeded by the Holocene climate amelioration. Therefore, the sea was the dominating factor for the observed changes in vegetation composition. The same holds true for trees like Alnus (alder), *Betula* sp. (birch), *Pinus sylvestris* (pine) and *Quercus* sp. (oak) as

well as *Corylus avellana* (hazel). They spread in northern Germany (long) before they occupied the newly emerging vegetation belt facing the rising sea at Norderney (Behre, 1967; Giesecke et al., 2016, 2017). In contrast, precipitation played an important role. The large amount of precipitation caused swampy conditions and led to the development of carrs on the *Geest* slopes several metres above the rapidly rising sea level and it then maintained the

Table 3. The earliest occurrence of selected species in WASA cores and their requirements for minimum middle July temperatures at their recent distribution limits and for middle January and middle July temperatures at their centres of distribution, from probability density function analyses (Brinkkemper et al., 1987; Aalbersberg and Litt, 1998; Kühl et al., 2002)

	Occurence (cal BP)	Min. July (°C)	Middle Jan./July (°C)
Calluna vulgaris	8750	8	
Cladium mariscus	6750	15.5	
Empetrum nigrum	~5 ka	7,7	
Eriophorum vaginatum	6850	7	
Filipendula ulmaria	7950	8	
Frangula alnus	6350	13	−4.1/18.6
Hydrocotyle vulgaris	7600	11.5	
Menynathes trifoliata	5400	8	
Moeringia trinerva	6650		−3.1/18.4
Pinus sylvestris	>8 ka	>12	
Ranunculus flammula	5400	8.5	
Solanum dulcamara	6750	13	
Typha angust./lapathif.	>8 ka	13.5	
Urtica dioica	7600	8	

freshwater conditions inside the back-barrier area, and the moist oceanic climate also led to the formation of raised bogs.

Podzols before raised Sphagnum bogs on the Geest

Independent of the sea level, but resulting from the high precipitation from an oceanic climate, the wet heath turned into a complex of rain-fed raised *Sphagnum* bogs on some higher slopes in the south (Fig. 8). The complex of bogs spread up the *Geest* for some kilometres into the now diked hinterland and about 15 km into the western back-barrier region of the neighbouring island, Juist, where *Sphagnum* peats have been described by Körber-Grohne (Grohne, 1957, 1958). In some cores, the Pleistocene sands of the *Geest* are coloured black like the overlying organic material and so caution is needed when identifying the exact start of peat formation (van de Plassche et al., 2010). Below this black layer, caused by infiltration of humic colloids, several centimetres of sand was bleached to a lighter greyish colour (as already reported by Grohne, 1957) suggesting the existence of a deep downwards bleached podzolic soil before the start of *Sphagnum* peat formation. Analyses of the humic layer lying directly on the sand revealed an extraordinarily large number of local and wind-transported pollen grains containing dark-coloured fungal hyphae (Fig. 9). Such fungal decayed pollen is a result of increased fungal metabolic activity during relatively dry phases and was first described by Shumilovskikh et al. (2015) from several bogs in northern Germany. Sewell (1959) identified dark-coloured fungal mycelia as a common component in all kinds of investigated heathlands. Therefore, the appearance of such fungal decayed pollen on the *Geest* sands seems to represent raw humus accumulation on heathland preserved by the subsequent *Sphagnum* peat formation. Raw humus is a characteristic accumulation on podzols under poorly decomposable heath vegetation. Due to aeration, the layers directly

on the sands yielded no well-preserved material. Dates of the sand/humus contact had to be done using charred vegetative remains of *Erica tetralix*, *Calluna vulgaris* and *Eriophorum vaginatum*, and for the sands also with fine bulk organic material. *Sphagnum* peat dates used the same species but both charred and waterlogged and also as fine bulk material. One date is from sclerotia of *C. geophilum*, one of the fungi with dark-coloured mycelia (Gadd et al., 2007). Paired charred and waterlogged fractions of the bog slices revealed statistically identical ages, indicating continuous *Sphagnum* peat deposition without significant vertical shift or entry of external material.

The earliest dates from charred plant material from the sands (core W3, 8750 cal BP, core VVC15, 8590 cal BP) indicate a wet heath on the *Geest* about a millennium before water accumulation by *Sphagnum* mosses led to the preservation of biological material in the ground (fine bulk material, 7560 cal BP, 7670 cal BP, 7380 cal BP). The stratigraphically lowest dates from a bog peat layer are from its centre and revealed a combined age of 5940 cal BP. The top of the *Sphagnum* peat from five cores provided up to three parallel dates, such as 5480 cal BP, 5410 cal BP, 5400 cal BP, 5400 cal BP and 5360 cal BP. The peats exhibited an uneven eroded surface, perforated by mussel shells and borings filled up with lagoon sediments containing reworked peat debris, but filled with marine sediments at the lowest site (core VVC15).

Due to its height above the contemporary sea level and peat loss by abrasion, the marine flooding of the bogs most probably happened significantly later than 5400 cal BP. A climatically driven ending of bog growth long before the flooding can be excluded. The bogs further up the *Geest* kept on growing and new ones even started to develop on the nearby *Geest* (Grohne, 1957) and in the north German lowland (Petzelberger, 2000; Gerdes et al., 2003). Moreover, in the whole North Atlantic realm a strong increase in bog formation is reported to have started shortly after about 5400 cal BP (Franzén and Cropp, 2007; Kylander et al., 2018).

Intercalated layers of marine clay in the present bog peats indicate breakages of the peat layers and floating of the top layers during flooding by storm surges, leaving a secondary intercalated clay deposited there, *Klappklei* (Grohne, 1957; Behre, 2004; Bruns et al., 2015). The marine origin of the clay is shown by characteristic microscopic remains of marine organisms like *Pterosperma* cf. *reticulosa* and dinoflagellate cysts (Fig. 9). The breakages of the peat layers are linked to density contrasts and weaknesses of their inner structure, for instance a burnt layer in core W1.

Climate changes at the turn from the Atlantic to the Subboreal (~5600 cal BP) possibly caused alterations in the *Sphagnum* species composition and/or a looser peat structure from rapid growth, as seen later at the change from the Subboreal to the Subatlantic (Grohne, 1957; Overbeck, 1963). A previously reduced peat growth with decomposition could have increased the peat density in favour of later colonisation by mussels. Abrupt changes in the growth of *Sphagnum* bogs are described as recurrence surfaces in the older literature and the oldest recognised surface is dated by archaeological finds to roughly 5600 cal BP (van Zeist, 1955). During storm surges thousands of years later, the upper peat layer could split horizontally along the structural interface and drift away (Behre & Kučan, 1999). As nearby bog developments were terminated by sea transgression around 2200 cal BP (Grohne, 1957), about 3000 years of Subboreal *Sphagnum* peat formation was lost by such displacement and abrasion at our study sites, corresponding to about 80 cm of peat in that area (Grohne, 1957). Rhizomes of *Phragmites* in the upper centimetres of the *Sphagnum* peat (cores VVC15, W4, W5) indicate that following
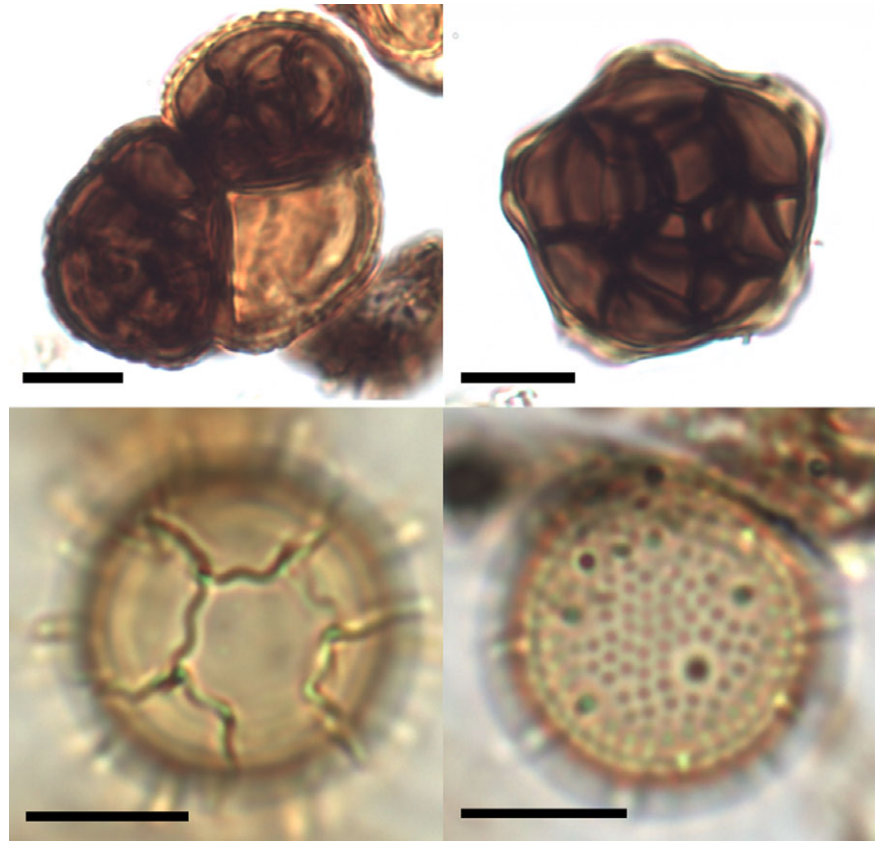
Fig. 9. Palynomorphs from core W1, clockwise from upper left. A pollen tetrad of *Calluna vulgaris* with two compartments filled with dark-coloured fungal hyphae and an infected five-pored pollen grain of alder, infection most probably after transportation to the site by wind (cf. Shumilovskikh et al., 2015). Both from the same wet-heath raw humus layer on top of the *Geest* sands. Marine non-pollen palynomorphs *Micrhystridium* (echinate) and *Pterosperma* (reticulate) as indicators of marine influence in peats (http://nonpollenpalynomorphs.tsu.ru, Bakker & van Smeerdijk, 1982; Tomas & Hasle, 1997). Scale bar 10 μm.

the removal of peat a fen or lagoonal deposit developed, which is otherwise not preserved in the sedimentary record.

Hunting, fishing, gathering and staying

The changing landscape of the *Geest* slopes provided over time various habitats with a wide range of opportunities for hunting, fishing and gathering. The coast offered mussels and saltwater fish. The kilometre-wide swampy vegetation fringe with carr provided natural habitats for a variety of animal and plant resources like hazelnuts until around 6 ka. Freshwater fish and waterfowl would have inhabited the then spreading lakes and lagoons. Edible plants like *Salicornia europaea*, *Triglochin maritima* or *Sonchus oleraceus* and others are popular for salads up to the present. The rhizomes of *Typha* and *Alisma plantago-aquatica* are a rich source for carbohydrates. The wet heath and bogs offered berries of *Empetrum nigrum* (black crowberry), *Vaccinium oxycoccos* (small cranberry) (Grohne, 1957) and possibly other *Vaccinium* species. Leaves of *Mentha aquatica/arvensis* (mint) and other Lamiaceae may have been used as herbs. *Filipendula ulmaria* (meadowsweet) is edible, can sweeten drinks (mead, for instance), hence its common name, and it could have provided a remedy for headaches due to its content of salicylic acid (Behre, 1999a; Düll and Kutzelnigg, 2016). In addition, other potential drugs and poisons were available such as *Solanum nigrum* (black nightshade) or *Ranunculus sceleratus* (celery-leaved buttercup). The vegetation could also have supplied material for making shelters or for firewood and tinder, such as *C. mariscus*. The cored material, however, did not offer any artefacts or other direct evidence of human activities.

Conclusions

The large number of ^{14}C dates and botanical analyses in the present study illustrates the development of the Wadden Sea around the East Frisian island of Norderney with particular attention to the detailed suitability of the landscape for providing natural resources for early humans. Our reconstructions go further back in time, add many details to earlier reviews (Goldhammer & Karle, 2015; Vos & Knol, 2015) and expand the detailed but spatially restricted analyses of Körber-Grohne (Grohne, 1957, 1958) into the back-barrier region and in the area northwest of Norderney. The sea-level index points and rates of sea-level rise derived from flooded alder carrs are in good agreement with previous results from the southern North Sea (Behre, 2007; Meijles et al., 2018). With our new data, the sea-level reconstruction of upcoming WASA publications is extended back to around 8000 cal BP and therefore to the inundation of the oldest peat analysed in the project.

An important but so far quite neglected landscape element of the early stage was a kilometre-wide swampy vegetation fringe including alder carr, fed by groundwater discharge from the *Geest* slopes facing the fast-rising sea. With flooding of the today tidal-flat back-barrier area by a then slowly rising sea and an unchanging or even decreasing marine influence, a vast zone of brackish reed beds and lakes arose. The widespread *Cladium mariscus* and freshwater bryozoans confirm freshwater conditions. On the higher slopes of the *Geest*, *Sphagnum* raised bogs developed under a moist oceanic climate. This highly diverse landscape offered a variety of habitats with animals, fish and numerous wild plants potentially usable by people for various purposes. This hospitable environment disappeared some 2000 years ago (Grohne, 1957), and freshwater conditions ended in the back-barrier area

already 3000 years ago. Today, comparable landscape elements still exist, but only in fragments, partly because of the silting-up of the back-barrier areas and partly because of the building of dikes.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/njg.2021.4.

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