Netherlands Journal of Geosciences — Geologie en Mijnbouw |94 – 2 | 157–183 | 2015 doi:10.1017/njg.2015.4

Holocene landscape reconstruction of the Wadden Sea area between Marsdiep and Weser

Explanation of the coastal evolution and visualisation of the landscape development of the northern Netherlands and Niedersachsen in five palaeogeographical maps from 500 BC to present

P.C. Vos[1,*] & E. Knol[2]

1 Deltares, Department of Applied Geology and Geophysics, PO Box 85467, 3508 AL Utrecht, the Netherlands
2 Groninger Museum, PO Box 90, 9700 ME, Groningen, the Netherlands
* Corresponding author: Email: peter.vos@deltares.nl

Manuscript received: 7 August 2014, accepted: 12 January 2015

Abstract

This paper describes the background of five palaeogeographical maps between the Marsdiep and the Weser River, and discusses the natural and anthropogenic processes driving the coastal changes during the last part of the Holocene. Before 2500 BC, during the first half of the Holocene, tidal basins were formed in the lower lying Pleistocene valley system as a result of the Holocene sea-level rise. The tidal basins were filled during the second half of the Holocene and on the deposits from the Pleistocene in the hinterland large coastal peat bogs developed. These peat bogs were vulnerable and sensitive to marine ingressions when the peat surface subsided due to drainage, compaction and erosion. During the Subatlantic (450 BC to present), the different ingression systems in the coastal area between Marsdiep and Weser had their own histories in timing and evolution. The ingressions were naturally caused by lateral migration of coastal barrier and tidal-inlet systems or by changes in the natural drainage system in the hinterland. From the Late Iron Age onwards, humans started to be the major cause of ingressions. By reclaiming and cultivating the seaward margins of coastal peat bogs, these areas subsided significantly and were flooded by high storm surges. When coastal areas were embanked during the historical period, the situation for the lower lying peat lands became more dramatic. When the sea dikes breached, the peat land was flooded, leading to casualties and huge material damages and loss of land. Drowning of the peat lands of the Jade and Dollard in the 14th and 15th centuries are examples of such catastrophes.

Keywords: Holocene geology, long-term coastal evolution, peat subsidence, auto-compaction, ingressions

Introduction

Recently a visual reconstruction has been made of the development of the coastal landscape of the northern Netherlands and Niedersachsen. This was done in the framework of the exhibition *Het verdronken land is vruchtbaar* (The drowned land is fertile) in the Groninger Museum (21 October 2013 to 9 February 2014). For this exhibition five palaeogeographical maps were compiled of the area between the Marsdiep tidal inlet and Weser Estuary (Vos & Knol, 2014). The exhibition was part of the EU programme INTERREG IVa, a Dutch–German cross-border cooperation project.

Geological, geomorphological, archaeological and historical information of the coastal area of the northwestern Wadden Sea (Fig. 1) was used for designing these map reconstructions, reflecting the dynamic evolution of the coastal landscape of the Wadden Sea since 500 BC. The maps are indispensable for understanding the prehistoric occupation of the undiked salt marshes of the Wadden Sea. Human occupation of the marsh areas of northwest Germany and the Netherlands began in the Late Bronze Age and Early Iron Age (Taayke, 1996; Strahl, 2005). The background of the compilation of the map series and the main driving mechanisms responsible for the coastal evolution will be discussed. A major research topic of this

Fig. 1. Locations of the Wadden Sea study area between the Marsdiep and the River Weser.

paper is the role humans played in the transformation of the peat landscape by inducing large ingression systems in the coastal area.

Origins of tidal basins and ingression systems

Geological processes and human interventions induced major changes in the Holocene coastal landscape. As a result of the global Holocene sea-level rise, after the last glacial period (the Weichselian) the Pleistocene landscape of the northern Netherlands and northwest Germany changed into a marine environment. Tidal channels locally eroded the subsoil and the lower parts of the Pleistocene valleys were flooded. These valley systems turned into tidal basins and where large rivers such as the Eems and Weser debouched into the sea they became estuaries (Fig. 2). The sea-level rise also led to a groundwater-table rise in the higher Pleistocene areas close to the expanding marine domain. Thus peat started to grow in the transitional Pleistocene areas.

The Early Holocene Wadden Islands, tidal basins and estuaries migrated landward as a result of ongoing sea-level rise (van der Spek, 1994a,b; Flemming & Davis, 1994; Oost, 1995; Chang et al., 2006; Kosian, 2009). In the last half of the Holocene the sea-level rise decreased sharply and the tidal basins silted up for the major part (Vos & van Kesteren, 2000; Vos & Knol, 2005; Vos & de Langen, 2008, 2010). The change from a drowning and retreating coastal area to a seaward expanding coastal area took place between about 5000 and 4250 BC (Cleveringa, 2000; Bungenstock & Schäfer, 2009) because from that period onwards the sediment supply to the basins outpaced the sea-level rise (Beets & van der Spek, 2000). Because of the deteriorating natural drainage the peat area in the hinterland expanded strongly, in combination with the silting up of the tidal basins the salt-marsh area along or at the margins of the basins prograted seaward.

This study shows that from the Subatlantic onwards new sea branches intruded on the salt marshes and coastal peat bogs (Fig. 3). These ingressions may have a natural or an anthropogenic origin or a combination of both. One natural cause of new ingression systems was drowning of the coastal peat area when a protective natural coastal defence was lost, for instance by the lateral shift of a barrier and tidal-inlet system (N1; Fig. 4). The salt marshes became sensitive to erosion because of increases in the wave attacks on the salt-marsh coastline. When the protective salt marsh disappeared, the peat area behind became vulnerable to erosion. Because of the high water content of peat, it is very sensitive to compaction and subsidence. When peat was eroded, hardly any sediment (organic material) remained behind. The new accommodation space led to an increase in the tidal prism. As a consequence, the tidal channels and tidal inlet increased in size because of the linear relationship between the tidal volume and the (wet) cross-sectional area of the tidal channels (Sha & de Boer, 1991; Oost, 1995; van der Spek, 1994b). The increased tidal prism caused an increase in tidal range and maximum storm surge level (extreme high water, EHW). More and larger tidal channels improved the natural drainage, oxidation and subsidence of the drained peat. When the subsiding peat surface was flooded during storms, clay was deposited on top of it, which meant that the sediment load increased. Because of the weight of the clay the peat subsided further. This process is known as auto-compaction: subsidence of wetland peat by the gravitational pressure of newly deposited

https://doi.org/10.1017/njg.2015.4 Published online by Cambridge University Press

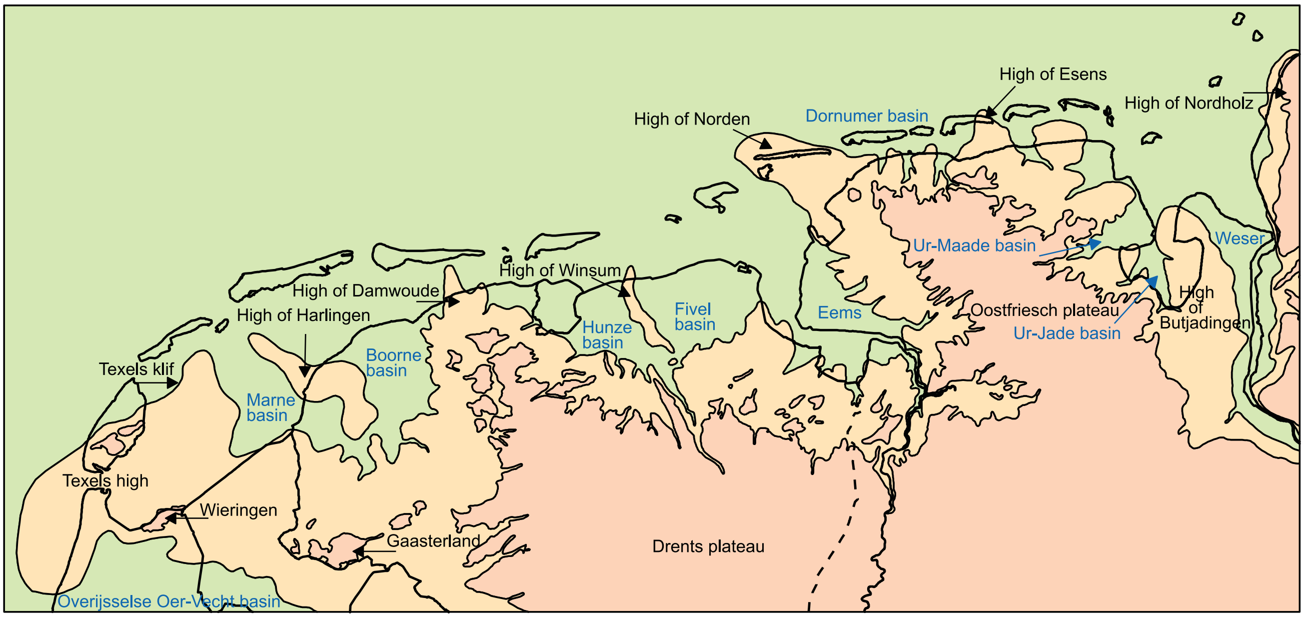

Fig. 2. Location of the Early Holocene tidal basins in the northern Dutch and northwestern German coastal areas.

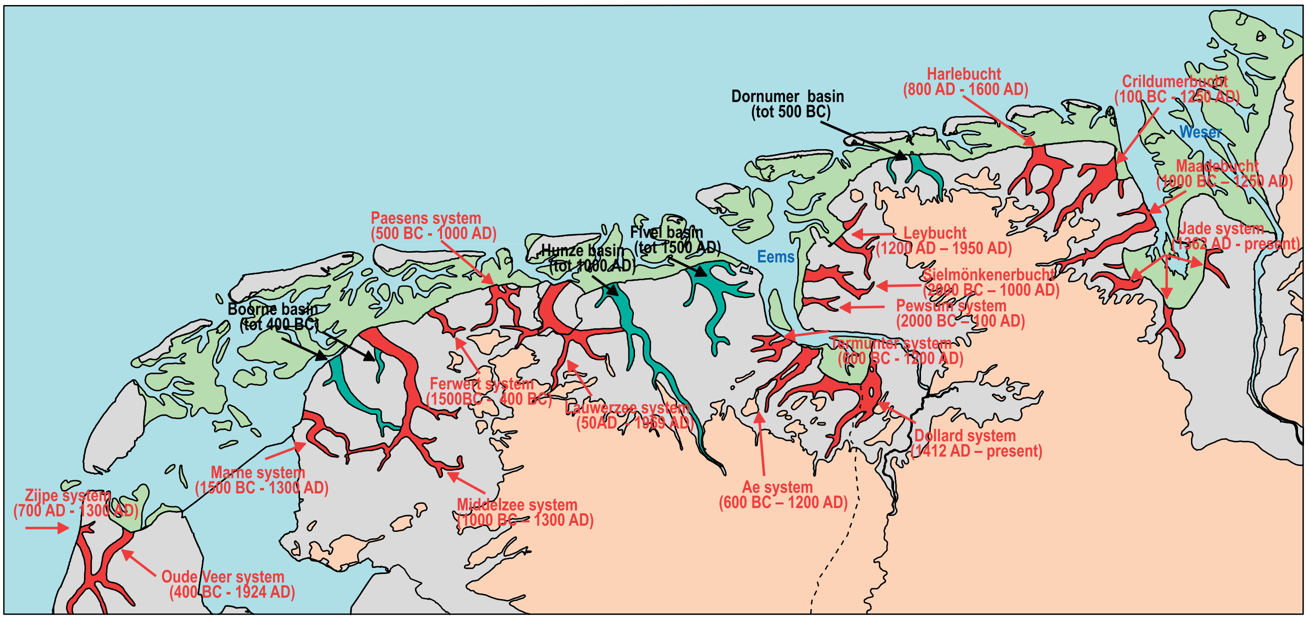

Fig. 3. Locations of the active tidal systems in the northern Dutch and northwestern German coastal areas during the Subatlanticum. Green: tidal channels belonging to the old tidal basins which at the time had not yet silted up completely and where the tidal channel was still active (date indicates the last time at which the tidal basin system was still functioning). Red: locations of the ingression channels (dates indicate the active period of the ingression system).

and infiltrated clay on and in the peat (Allen, 1999; Long et al., 2006). This favoured the self-reinforcing process of peat drowning.

Ingressions were also enhanced by the silting-up of the basin margins, forcing drainage from the peat to the lower lying (more compacted) hinterland, from where a new outlet was needed. Thus new outlets in the coastal system were created, implying a local transgressive development (N2; Fig. 5).

Since the late Iron Age/Roman Period humans have played an important role in the self-reinforcing processes by artificially draining the margins of the coastal peat landscape. This has led to a significant lowering and drowning of the inhabited peat land, leading to new ingressions (A1; Fig. 6). From the Late Medieval Period, when the salt marsh and peat lands were diked on a large scale, subsidence in the embanked coastal peat lands further increased. This led to catastrophic situations when

https://doi.org/10.1017/njg.2015.4 Published online by Cambridge University Press

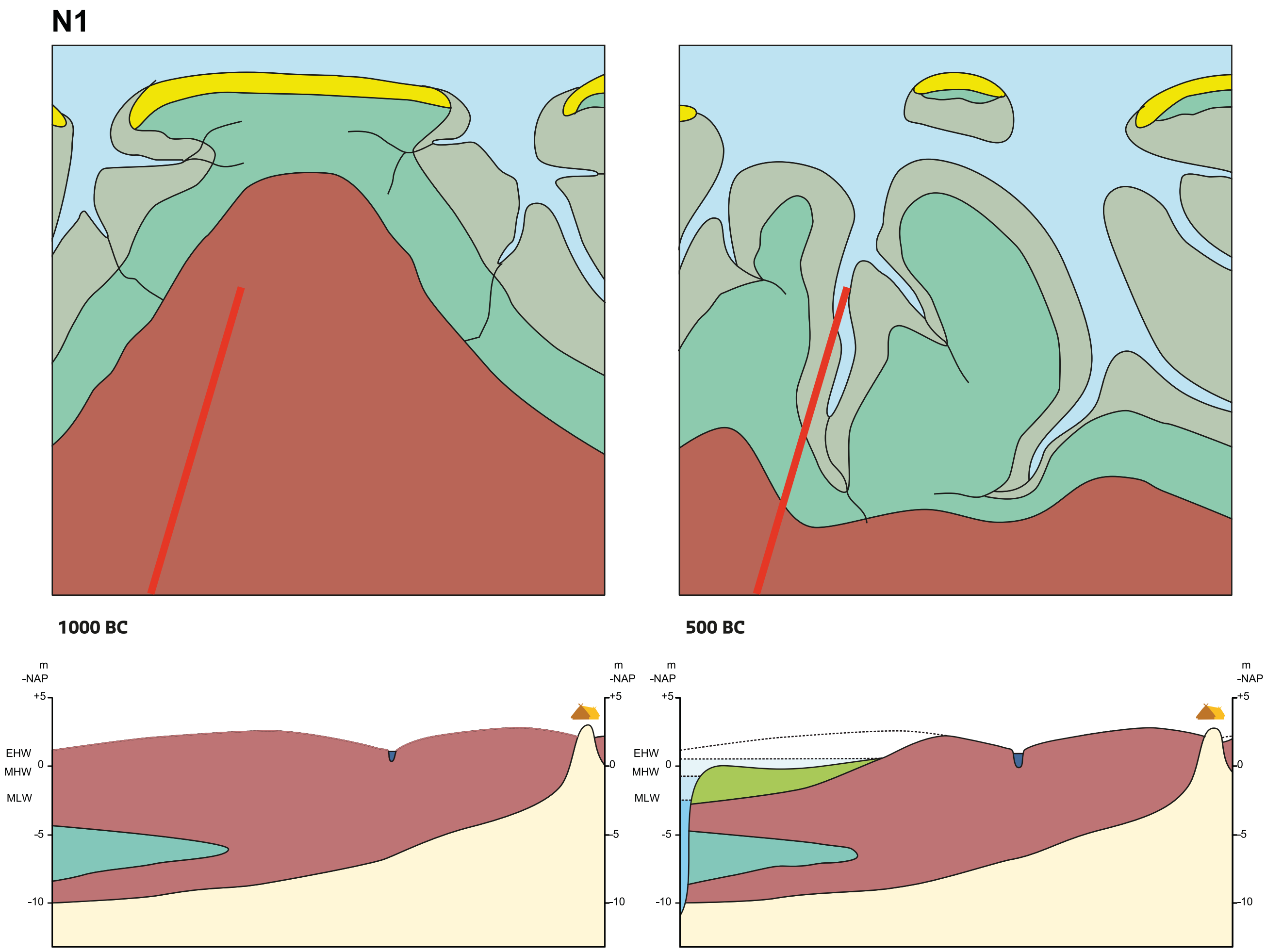

Fig. 4. Schematic reconstruction of a naturally drowning peat landscape, before 100 BC, induced by erosion of the protecting coastal barriers and salt-marshes by tidal inlet and channel migration. This led to the drowning and formation of channels and creeks in the peat landscape, which resulted in subsidence of the peat surface caused by auto-compaction and drainage of groundwater via the channel system. The reconstruction is inspired by the Peasens ingression system. For map legend see Figs 8–12; for cross-section legend see Fig. 13.

dikes collapsed during storms, leading to large land losses (A2; Fig. 7).

Relevance of palaeogeographic maps

Landscape evolution with many ingressions and reclamations in the past can be used as a sounding board for studies related to coastal protection and future long-term development of the northern Dutch and German coastal zone and for prospective archaeological research. The reconstruction maps for the different archaeological periods indicate where habitation was possible and where it was not. Intertidal flat environments with semi-daily tides were unfit for habitation but highly silted-up salt marshes were suitable if settlements were built on dwelling mounds. The high biological productivity of this area made this tidal landscape very attractive for habitation. Not the whole salt-marsh area was suitable for occupation. The lowest parts, the pioneer zones, were not suitable because of frequent inundations. Geoarchaeological research in Friesland has revealed that salt marshes were inhabited only if the cover of salt-marsh clay had reached a minimum thickness of about 80 cm (Vos, 1999). By then the marsh had been silted up to the middle marsh level and it flooded less than about 50 days per year (Vos & Gerrets, 2004). Regional palaeogeographic maps, which display these depositional environments, can thus be used as prospective maps. By linking this knowledge to geological layer information it can be assessed at which depth archaeological finds may be expected.

A future development in palaeogeographic mapping would be to add the subsurface (depth) to the two-dimensional map images such that three-dimensional landscape models can be constructed. By adding the time dimension to these models even 4D landscape reconstructions are possible. With advanced spatial palaeolandscape models, mid- and long-term

https://doi.org/10.1017/njg.2015.4 Published online by Cambridge University Press

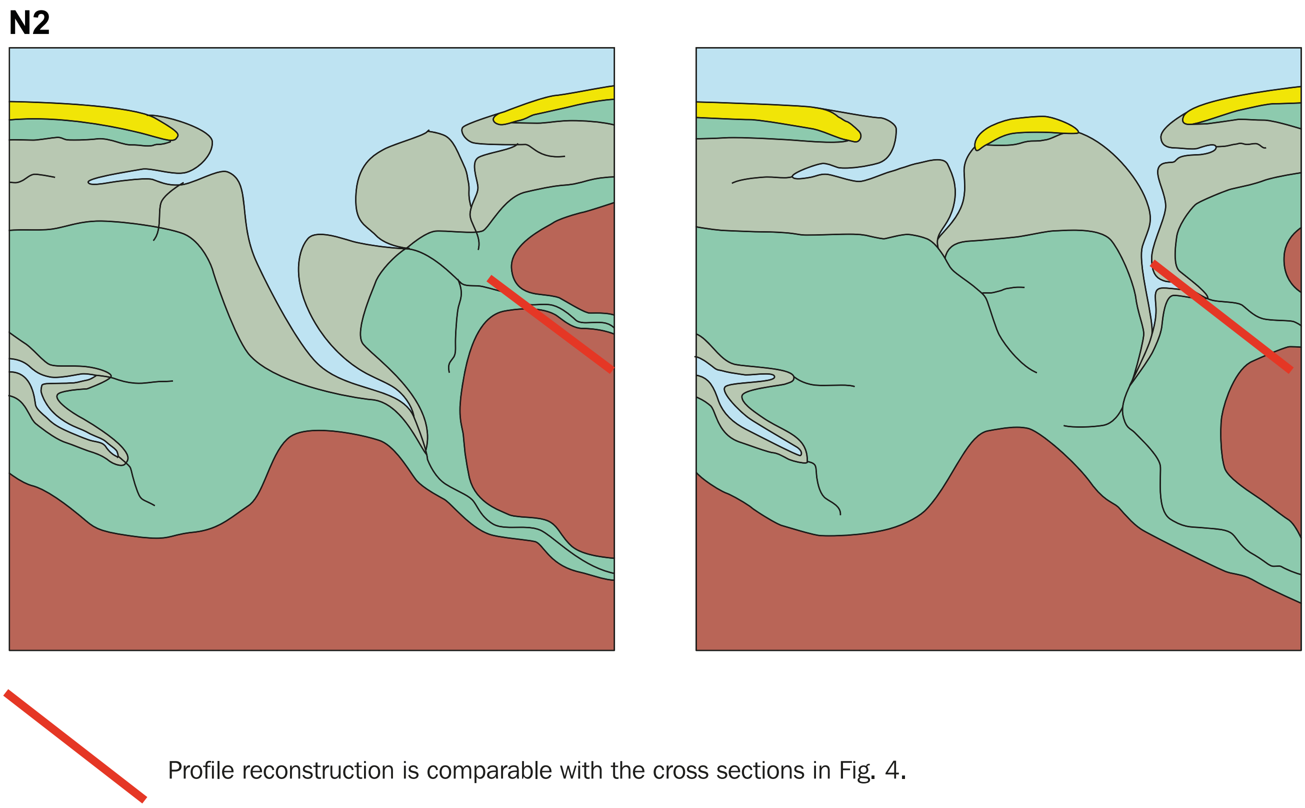

Fig. 5. Schematic reconstruction of a naturally drowning peat landscape, before 100 BC, caused by changing and migrating natural drainage systems in the hinterland. The driving processes of the subsidence of the peat surface were the enlargement of the new channel system, auto-compaction by deposition of a clay layer on top of the peat in that area, drainage of groundwater and oxidation due to natural drainage by the newly formed channels and creeks. The reconstruction is inspired by the Middelzee ingression system. For map legend see Figs 8–12; for cross-section legend see Fig. 13.

morphodynamics can be better understood and forecast: the past as a key to the future, and an opportunity for future palaeogeographic research.

History of Holocene landscape reconstructions

Long tradition of landscape reconstruction in the Netherlands

In the Netherlands there is a long tradition of composing palaeogeographic maps. The manuscript map of the Roman period by Arnoldus Buchelius (1565–1641) is the oldest known reconstruction map of the Netherlands. It is based on Roman writers such as Tacitus and Pliny. In 1574, Jacob van der Mersch made a reconstruction map of the drowned and lost lands in the Dollard following similar Flemish maps of the drowned lands along the Westerschelde and Oosterschelde (Knottnerus, 2013). Later historians investigated the courses of former rivers such as the Fivel in Groningen and lateral migrations of the Wadden Islands (van Veen, 1930; Isbary, 1936).

In the 1950s Pons and co-workers began the first map reconstructions of the Dutch coastal area based on the geological data of Noord-Holland and Flevoland, and subsequently of the whole of the Netherlands (Pons & Wiggers, 1959, 1960; Pons et al., 1963). In the 1970s and 1980s regional studies of Groningen and Friesland were done (Roeleveld, 1974; Griede, 1978; Griede & Roeleveld, 1982) and it became clear that before the Middle Ages large parts of the western and northern Netherlands were covered with an extensive peat bed that in many places has almost or completely disappeared. This peat bed covered West Friesland and the lower parts of Friesland and Groningen (Borger, 2007; Slofstra, 2008). This finding changed the palaeogeographic map picture dramatically as compared to the previous palaeogeographic maps of Zagwijn (1986).

The idea of an extensive peat cover on the sandy areas of Oostergo, Westergo and the Groninger Wold, confirmed by several observations below cemeteries, was quickly embraced by archaeologists and historical geographers. It agrees with the fact that there are hardly any archaeological observations in the time span between Late Neolithic and Bronze Age finds on the one hand, and Medieval finds on the other. The medieval colonisations and their consequences for the peat area were the

https://doi.org/10.1017/njg.2015.4 Published online by Cambridge University Press

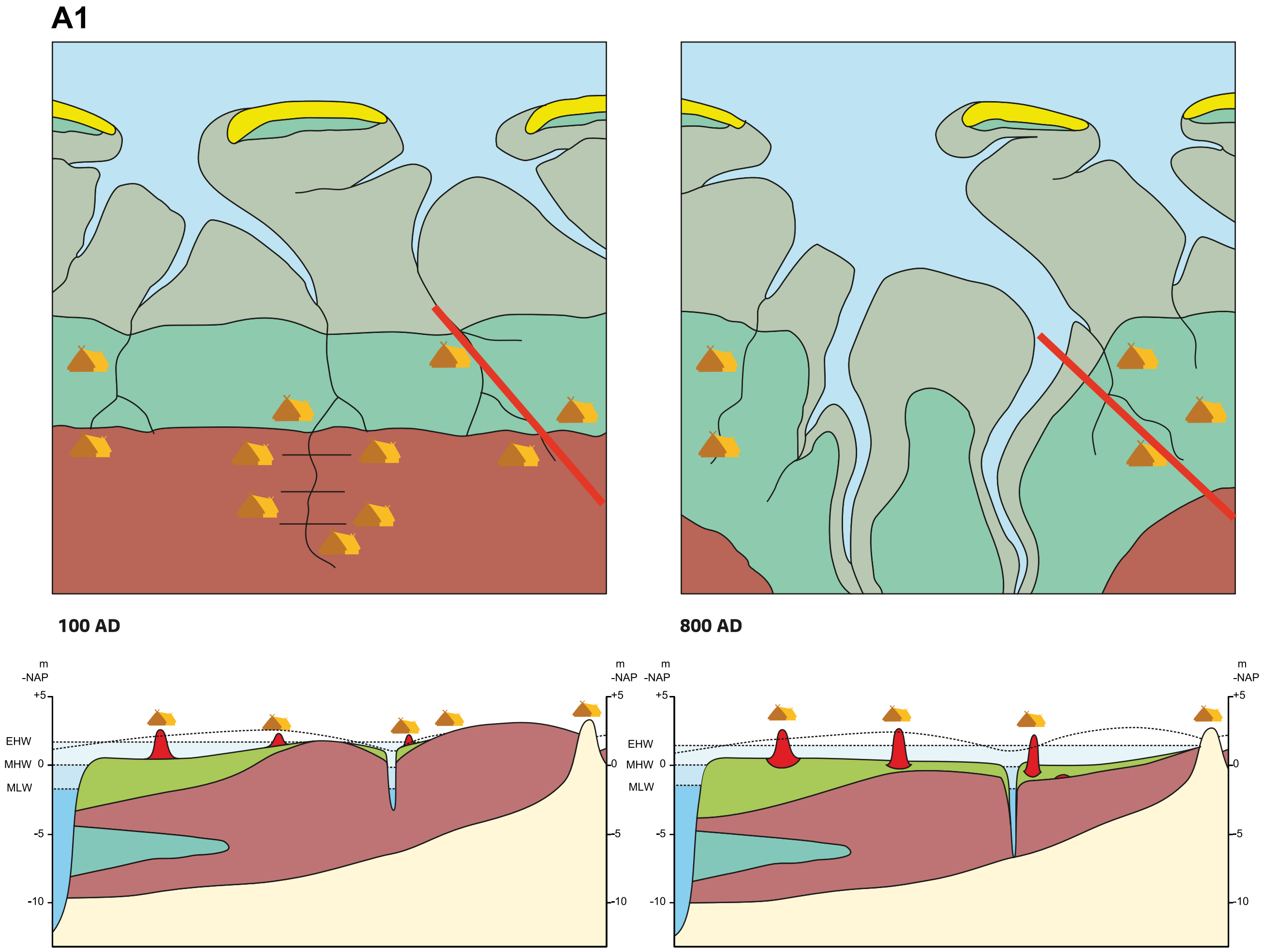

Fig. 6. Schematic reconstruction of an anthropogenically drowning peat landscape, after 100 BC, as a result of reclamation and cultivation of the marginal zone of the coastal peat bog. The driving processes of the subsidence of the peat surface were drainage of groundwater, inundation of the peat land and enlargement of the tidal channels, auto-compaction by deposition of a clay layer on top of the peat and oxidation due to artificial drainage. The reconstruction is inspired by the Lauwerszee and Harlebucht ingression systems. For map legend see Figs 8–12; for cross-section legend see Fig. 13.

subject of many archaeological and historical studies: Wassermann (1985), Mol et al. (1990), Casparie & Molema (1990), Groenendijk & Schwarz (1992), de Langen (1992), Knol (1993), Fokkens (1998), Schwarz (2004, 2005), Ligtendag (1995), Knottnerus (2005, 2008), Bakker (2001, 2002, 2003), Brinkkemper et al. (2006), Spek (2008), Groenendijk & Bärenfänger (2008), van den Broek (2011) and Kortekaas (2013).

Many subregional reconstructions were made during previous decades, often with an archaeological background, of the IJsselmeer (or former Zuiderzee area; Lenselink & Koopstra, 1994; Lenselink & Menke, 1995), the Lauwerszee region (Vos, 1992; Groenendijk & Vos, 2002), Westergo (Vos, 1999; Vos & Gerrets, 2004), the northern Dutch coastal area (Vos & Knol; 2005; Vos & Bungenstock, 2013; Vos & Knol, 2013), Oostergo (Vos & de Langen, 2008) and the Eems-Dollard (Vos, 2011).

Elsewhere, regional palaeogeographical maps were produced of Zeeland (Vos & van Heeringen, 1997), the Oer-IJ (Vos et al., 2010) and the Kop van (northern part of) Noord-Holland (Lambooij, 1987; Woltering et al., 1999). The Nationale Onderzoeksagenda Archeologie (National Research Agenda Archaeology; Vos, 2006) was an incentive for constructing new palaeogeographic maps of the Netherlands resulting in the *Atlas van Nederland in het Holoceen* (Atlas of the Netherlands in the Holocene; Vos et al., 2011). An update of these maps (version 2.0) has been made in Vos (2013a). Amongst other features, in this new version a distinction is made between intertidal flats (flooded twice daily) and salt marshes (flooded only during spring tide and/or storm surges), and the reconstructed peat expansion of the 100 and 800 AD maps has been modified significantly based on new data from the area to the northeast of the town of Schagen (Vos, 2012). The distinction between mudflats and salt marshes on the new maps makes clear where people could settle (salt marshes) in the tidal area and where they could not (sand and mudflats). It provides an insight into the occupation possibilities in the past and the opportunity of finding archaeological sites.

https://doi.org/10.1017/njg.2015.4 Published online by Cambridge University Press

A2

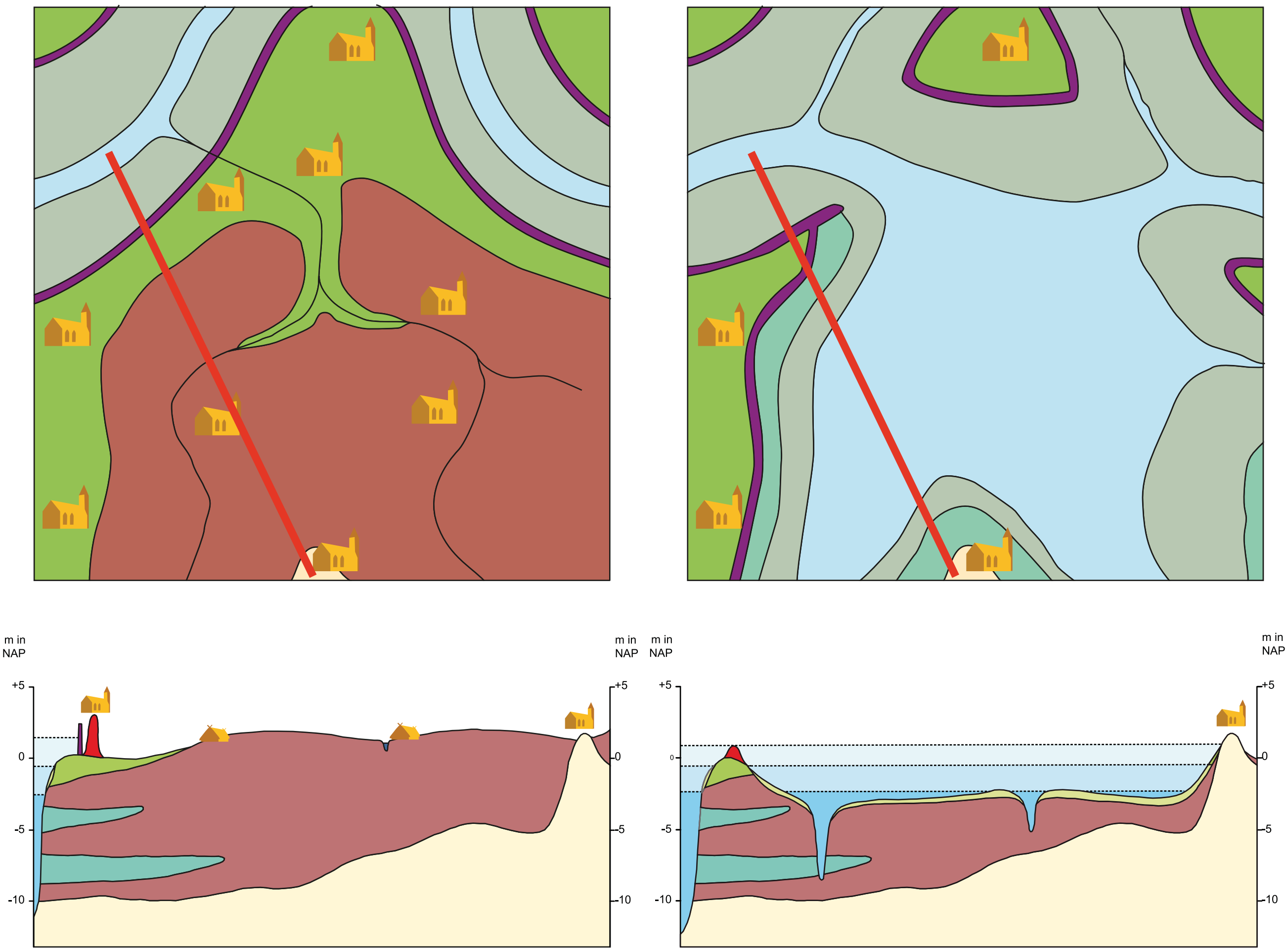

Fig. 7. Schematic reconstruction of an anthropogenically forced drowning of the peat landscape, after 1200 AD, caused by diking of the salt-marsh area and peat landscape and by artificial drainage of the land via sluices. The driving processes of the subsidence of the peat surface were drainage of groundwater, oxidation due to artificial drainage, catastrophic inundation of the peat land and erosion of the peat surface, and disappearance of the peat out of the system by floating and drifting peat islands. The reconstruction is inspired by the Dollard and Jade ingression systems. For map legend see Figs 8–12; for cross-section legend see Fig. 13.

Coastal reconstructions in Germany

Unlike in the Netherlands, palaeogeographic reconstructions in northwestern Germany have mainly been made by historians and archaeologists, and focus in particular on coastline development. In 1909, Ramaer compiled a series of maps from the late Middle Ages (1250 AD) up to the present in which the evolution of the Eems–Dollard region in both countries was reconstructed. A map of this area in 1000 AD was compiled by Wasserman (1985). A detailed study of the mouth of the Eems based on ancient nautical maps is also available (Lang, 1955, 1958).

In 1943 a series of reconstructions of the Ostfriesische islands from 1623 onwards was made by Backhaus. Sketches of the original locations of Langeoog Island, from the 8th to the 2nd century BC and from the 1st and 13th centuries AD, were compiled by Barckhausen (1969).

Linke's (2001) study of the geology of Neuwerk Island is useful for reconstructing the landscape there. Rough sketch maps of the coastal evolution from 7500 and 6500 BC to 800 AD were published by Flemming & Davis (1994). Homeier (1969, 1977) reconstructed the successive coastlines and made a regional reconstruction of northwestern Germany around 800 AD. He rightly suggested a major expansion of peat areas in the higher Pleistocene sandy areas. Behre (1999) reconstructed the coastlines of the marsh areas in the northwestern German coastal area for 1500 and 1800 AD. For the Reiderland, Behre (1986a) made detailed landscape reconstructions. As part of his sea-level studies, he also proposed palaeo-coastlines. The study of the Jade–Weser area resulted in a number of palaeogeographic maps for the beginning of the Christian era and for the years 800 AD and 1362 AD (Behre, 1999; 2004, 2005). Palaeogeographic maps of the area around the Jadenbusen and Weser were made by Behre (2012) for the time slices around the birth of Christ,

https://doi.org/10.1017/njg.2015.4 Published online by Cambridge University Press

and 800, 1300, 1362 and 1520 AD. The peat land extension on these maps was derived from geological map data and did not change in these reconstructions.

Laser altimetry data of the ground level (Actueel Hoogtebestand Nederland (AHN) in the Netherlands, Digitale Geländmodelle (DGM) in Germany, Light Detection And Range (LIDAR in the UK) up to now have hardly been used in geo- and archaeo-landscape research of Niedersachsen. The study of Heinze (2013) of the area around Bensersiel was one of the first.

Methods of palaeogeographical map reconstruction

Data and scale

The main depositional environments in the coastal system are tidal channels, sand- and mudflats, salt marshes and peat bogs. Information about the extent of these environments in the past has been derived from geological, geomorphological and pedological map data and observations. Using dating techniques, archaeological data and historical sources, the palaeosedimentary environments have been reconstructed. The level of detail of the palaeolandscape maps depends on the scale of the mapping programme (national, regional or local), and the available geological and archaeological data.

The Marsdiep–Weser reconstructions have been made at a working scale of 1:100.00 and thus they are between the 'regional' and 'national' mapping scales, which are compiled at scales of 1: 25.000/50.000 and 1: 500.000/1.500.000, respectively.

The most important basic data for the map reconstructions are from geological and pedological mappings, geoarchaeological research and elevation data of the present-day surface. This is especially the case for the maps of 500 BC, 100 AD and 800 AD, whereas the maps for 1500 and 2000 AD rely heavily on historical and recent topographical data, the AHN elevation maps. Pedological maps provide insight into the extent of the peat and clay cover, and the occurrence of palaeochannel fills at the surface. The geological maps supply data about the Holocene units in the deeper subsurface and the top of the Pleistocene deposits (see references to Dutch and German geological and pedological maps in the appendix). For the new lithostratigraphy of the Netherlands see de Mulder et al. (2003), and for the adjusted lithostratigraphy of the Northern Netherlands see Vos (2013b). For the background to the geological mapping of the coastal area of Niedersachsen see Streif (1989a).

On the AHN surface elevation maps the deposition patterns of the last phase of sedimentation are well illustrated. In many places the marine sedimentation stopped in the Late Medieval period, when large parts of the coastal area were diked. Morphological surface structures recognised on the elevation maps are, for example, salt-marsh ridges. For the determination of the age of these landscape forms ^{14}C and OSL methods have been used to date the deposits of the coastal landscapes, and geoarchaeological information from excavations has been used in dating the ages of the different palaeo-environments. The geoarchaeological research carried out within the framework of the archaeological key sites in the Northern Netherlands is documented in Vos (1999, 2001a,b, 2002a,b, 2004, 2007, 2011, 2012), Vos & Groenendijk (2005), Vos & de Vries (2009, 2011, 2012), Vos et al. (2010), Theunissen et al. (2005), Lubbers & Osinga (2007), Waldus & Vos (2006), Waldus et al. (2005) and Dresscher & Vos (2010). The use of archaeological data for the coastal reconstruction of the Northern Netherlands is described in Vos & Gerrets (2004).

Landscape reconstruction of the Dutch part

The Dutch part of the map reconstructions are based on the second-generation Atlas maps of the Netherlands (Vos, 2013a). As mentioned above, a large number of recent regional reconstructions was available, allowing great regional detail. In the new maps the tidal areas have been subdivided into mudflats and salt marshes, with the (relatively) high-lying salt marshes and tidal levee systems indicated separately. The ridges formed along the former salt marsh and tidal creeks and are up to several decimetres high. These morphological features can be easily recognised on the AHN elevation map. In the dating of these ridges archaeology contributed to a large extent (e.g. Vos & Gerrets, 2004).

Landscape reconstruction of the German part

The landscape reconstruction of the German part of the survey area relied heavily on the geological maps of Niedersachsen (1:25.000). From these, an overview map of the top of the Pleistocene surface has been made (Holozän basis; GHBK25, see appendix). From the geological surface maps (GK25) the extent of the peat and clay layers near the surface could be determined and the patterns of large tidal channel systems could be copied. The periods during which tidal channels were active in the coastal region of Niedersachsen have been derived from the coastline reconstructions and maps of Behre (1999, 2001, 2004, 2012). These maps supply important data for the expansion of channel systems and the timing of salt-marsh losses.

For the dating of peat, ages have been used as indicated by Streif (2004) in five coastal geological cross-sections between the Eems and Weser. For the reconstruction of peat bogs on higher Pleistocene grounds, the *Campsche Karte von Ostfriesland (Camp's map of Ostfriesland)* from 1806 was very valuable (Willem Camp, 1761–1855; republished by Henninger et al., 2005). On this map, the high moorlands and low fens which were still widespread at the beginning of the 19th century are

https://doi.org/10.1017/njg.2015.4 Published online by Cambridge University Press

indicated. Based on this and other historical information, the Landesamt für Bergbau, Energie und Geologie compiled a map of the original distribution of moors in the Niedersächsisches Bodeninformationsystem (NIBIS). This information is used for map reconstructions from 500 BC to 1500 AD.

Much of the reconstructed original peat cover has disappeared since the 20th century. The remainder, depicted on the map of 2000 AD, has been derived from the geological map of Niedersachsen. The older the reconstruction maps (1500 and 800 AD), the more the extent of the peat bogs, compared with the *Campsche Karte* and moor reconstructions of the NIBIS.

It is assumed that already between the 9th and 19th centuries parts of the peat disappeared due to human activities (land reclamation and peat extraction). In the maps of 500 BC, 100 AD and 800 AD, the extent of the peat and the river courses in the higher Pleistocene area have been kept the same, an arbitrary choice.

The DGM map images have been used particularly to reconstruct the watercourses in the higher Pleistocene sand areas. The DGM elevation data were available only in a raw form through the internet, therefore the morphological surface structures in the coastal areas (salt-marsh ridges and tidal levee systems) could not be mapped in Germany with the same accuracy as in the Dutch part.

In the oldest maps (500 BC–800 AD), the Ostfriesische Wadden Islands have been located between the reconstructed main tidal channel systems, somewhat more to the north than the current coastline of the Wadden Islands as the islands have moved landward (Flemming & Davis, 1994). For the position of the islands on the map of 1500 AD the reconstructions by Backhaus (1943) and Barckhausen (1969) and the map of Waghenaer from 1575 are important guidelines. For the reconstructions up to 1500 AD the locations of the islands have a large degree of uncertainty.

Landscape reconstruction from the Bronze Age onwards

In Figs 8–12 the landscape evolution of the Dutch and northwestern German Wadden Sea region is visualised after the Bronze Age (2000–650 BC), the period when the colonisation of the coastal areas began. The settlers lived on higher parts of the salt-marsh area. Some finds from the Late Bronze Age (Strahl, 2005) suggest that locally humans lived in the marshes but not on a large scale. This is remarkable since from a landscape perspective the salt-marsh area was suitable for habitation if settlements were raised artificially. Apparently, there was little need for the Bronze Age humans to settle in the Wadden Sea coastal area. The occupancy of the higher, dry – and not peat covered – Pleistocene soils was sufficient. Around 600 BC pioneers from the margins of the German estuaries migrated to the Dutch salt marshes, soon followed by people from Drenthe (Taayke, 1996). Humans constructed dwelling mounds in these marshes to be safe during storm flood inundations. In Friesland these dwelling mounds are called *terpen*, in Groningen *wierden* and in Germany *Wurten* or *Warften*.

700–100 BC (Fig. 8)

In the Early Iron Age (650–0 BC), the Dutch tidal basins were still open to a great extent, and the salt marshes of the German part were located mainly within the current Wadden Sea. In subsequent periods, the northern Dutch tidal basins silted up more and more, and became salt-marsh land, whereas in large parts of the northwest German coast the salt marshes were subject to erosion and retreated because of the exposed position to the sea.

Around 500 BC parts of the ancient tidal basins of the Boorne, Hunze, Fivel and Ur-Jade were still open, and the Zuiderzee had not yet come into existence. Two large Flevo lakes were present in the IJsselmeer region. The Overijsselse Vecht River flowed into the northern Flevo Lake, which was connected with the Wadden Sea. Through this outlet, marine influence was noticeable in the surroundings of Medemblik (Vos et al., 2011).

As a result of ingressions in the northern and southern Flevo lakes around 400 BC, the Zuiderzee came into existence (Vos et al., 2011). In this period the Oer-IJ stopped draining the southern Flevo Lake and the Utrechtse Vecht River started to silt up. Since then the peat area around the Zuiderzee and the Utrechtse and Overijsselse Vecht rivers discharged into the Wadden Sea. Through the enlarged outlet the sea penetrated more and more, resulting in further erosion and flooding of the peat area. Observations at the location Schagen de Nes, northeast of Schagen (Vos, 2012), show that already in the Middle Iron Age clay was deposited on the peat along the draining channels. The drowning of the peat in this region continued into the Middle Ages (450–1500 AD). It is likely that humans played a role in this drowning because in the northern part of Noord-Holland many traces of Roman and medieval peat reclamations occur.

Around 500 BC the salt-marsh area in the tidal basins of the Boorne, Hunze and Fivel rivers had expanded strongly as the result of a continued silting-up. With the silting of the Boorne tidal basin the drainage systems of the Marne and Middelzee became the outlet for the hinterlying peat area and they increased in size and became ingression systems. The expansion of the Middelzee in western Oostergo began around 1200–1000 BC. In the first stage this was a natural ingression that continued until Roman times, when marine influence of the expanding channels of the Middelzee became increasingly noticeable in the region around Sneek (Vos, 2007; Vos & de Vries, 2009, 2011).

In the eastern part of Oostergo, the area between the Boorne and the Hunze basins, large-scale marine flooding took place in the peat area present at that time (Griede, 1978). This ingression channel is named after the local Paesens River, which

https://doi.org/10.1017/njg.2015.4 Published online by Cambridge University Press

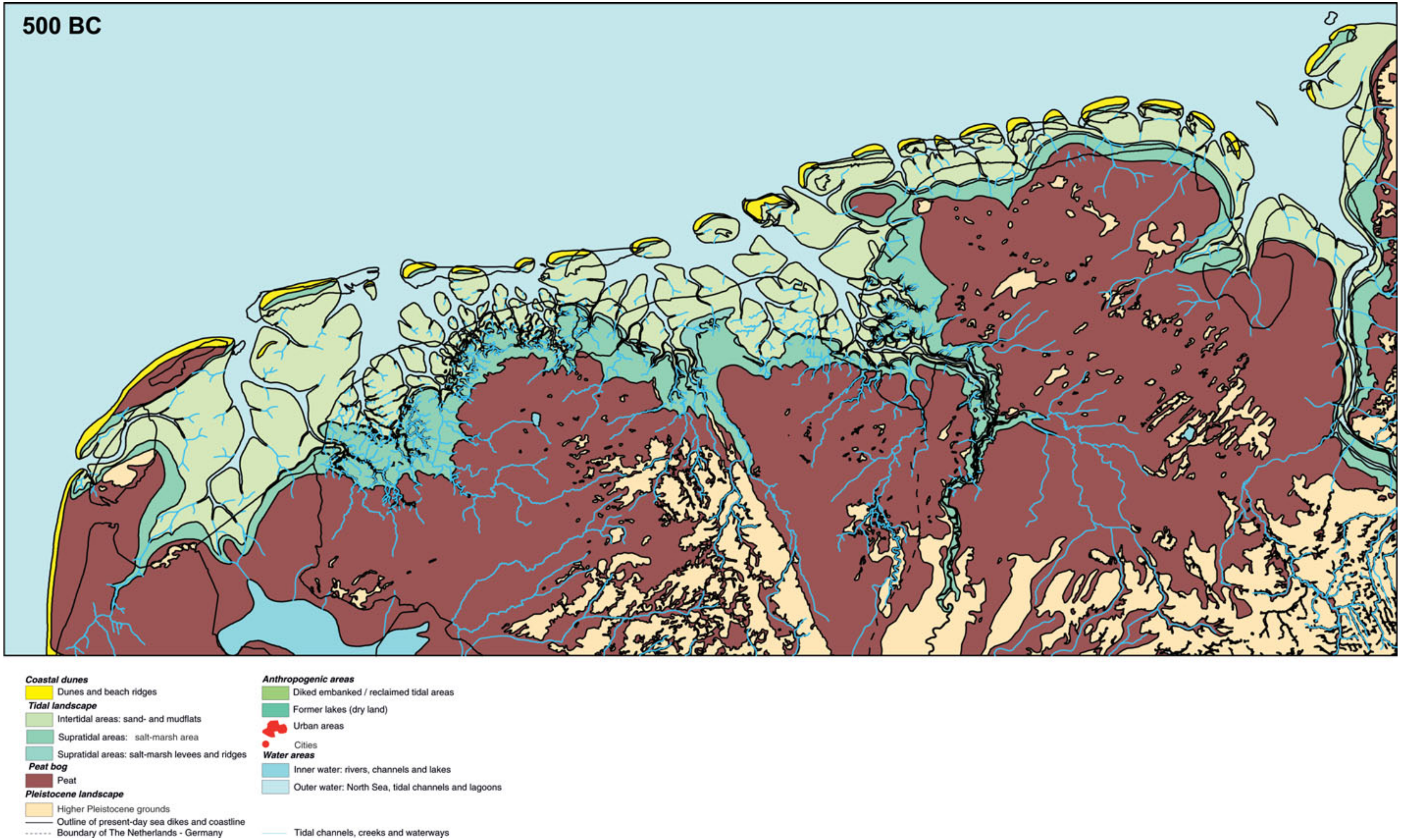

Fig. 8. Palaeogeographic map of the study area around 500 BC.

https://doi.org/10.1017/njg.2015.4 Published online by Cambridge University Press

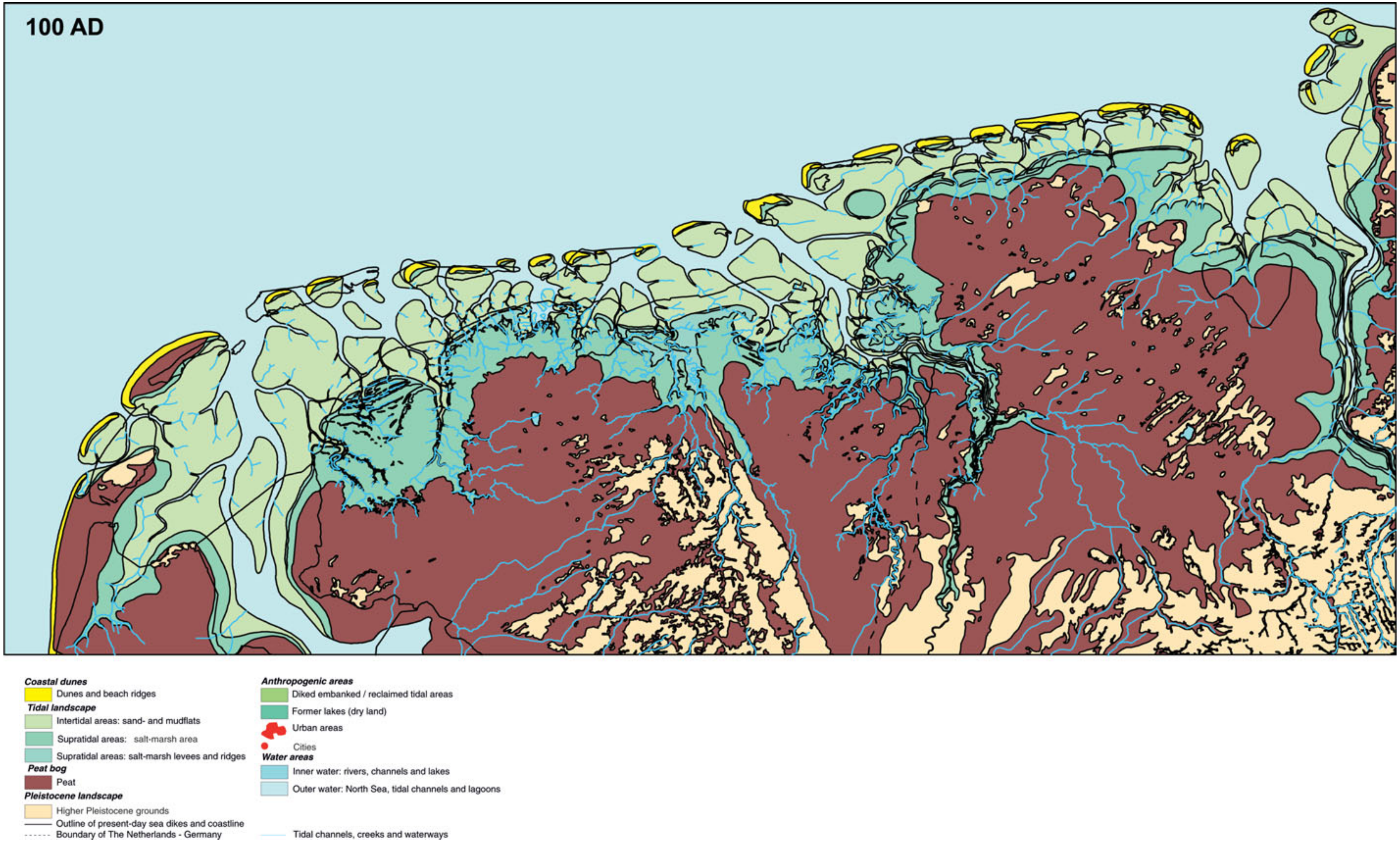

Fig. 9. Palaeogeographic map of the study area around 100 AD.

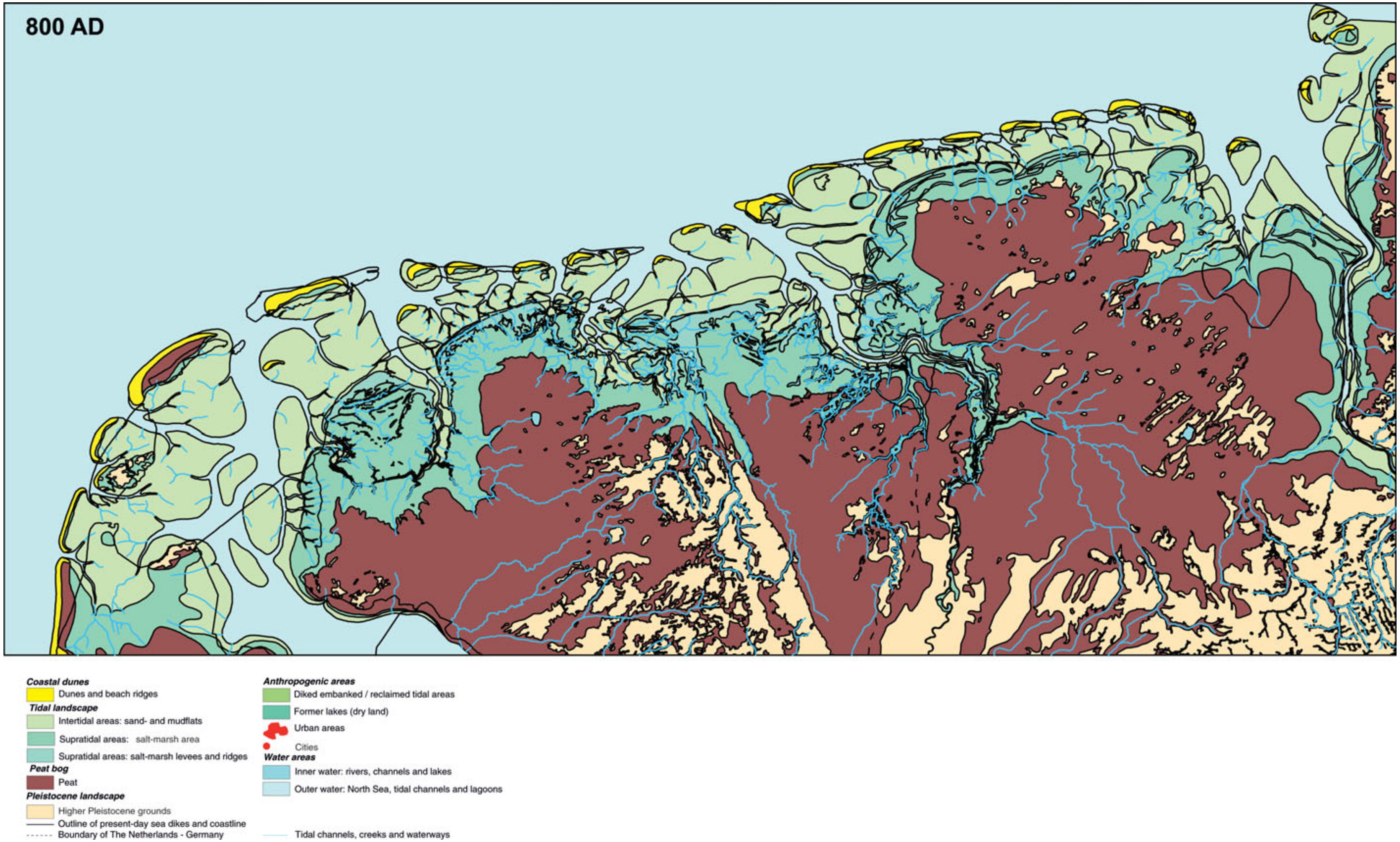

Fig. 10. Palaeogeographic map of the study area around 800 AD.

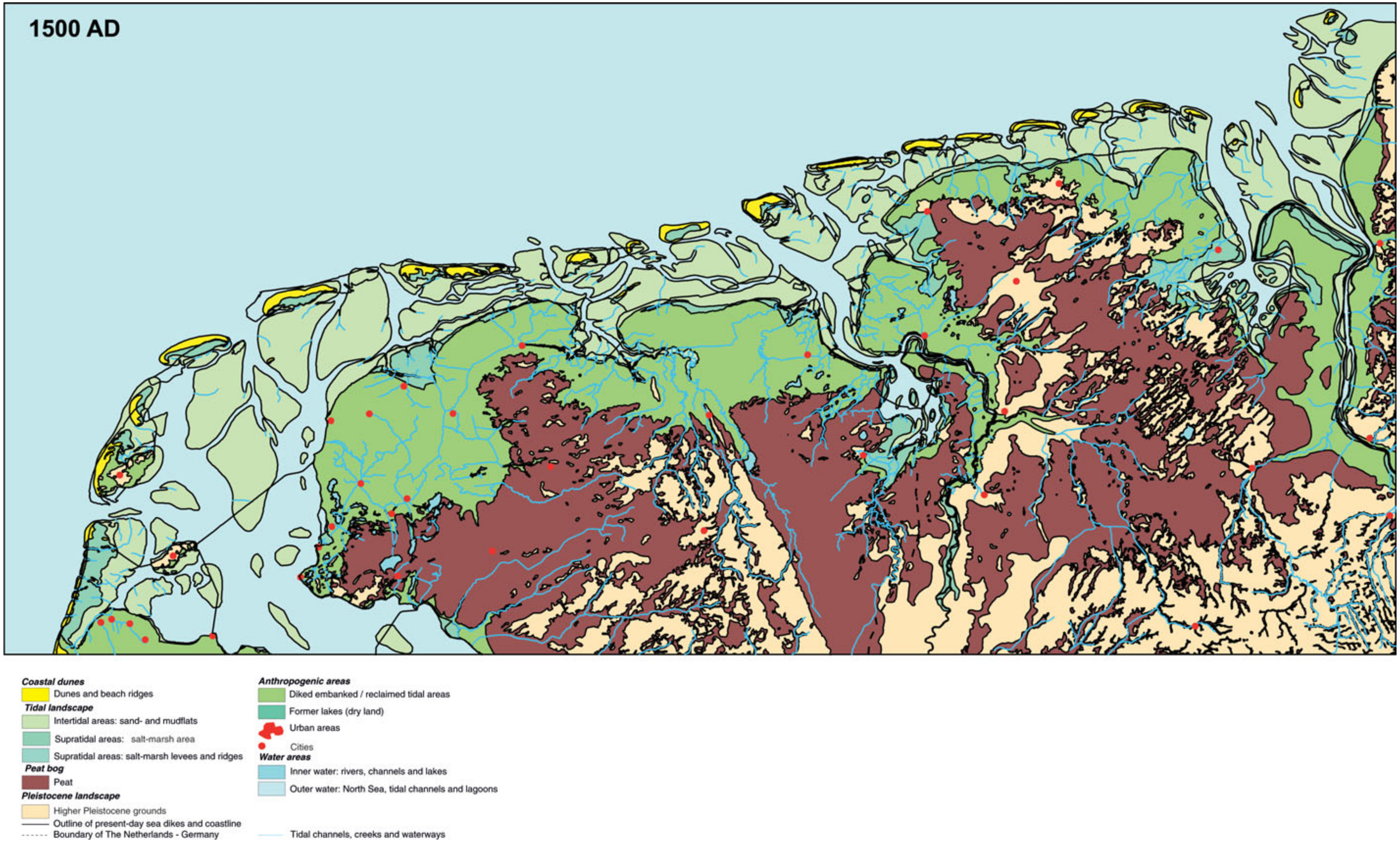

Fig. 11. Palaeogeographic map of the study area around 1500 AD.

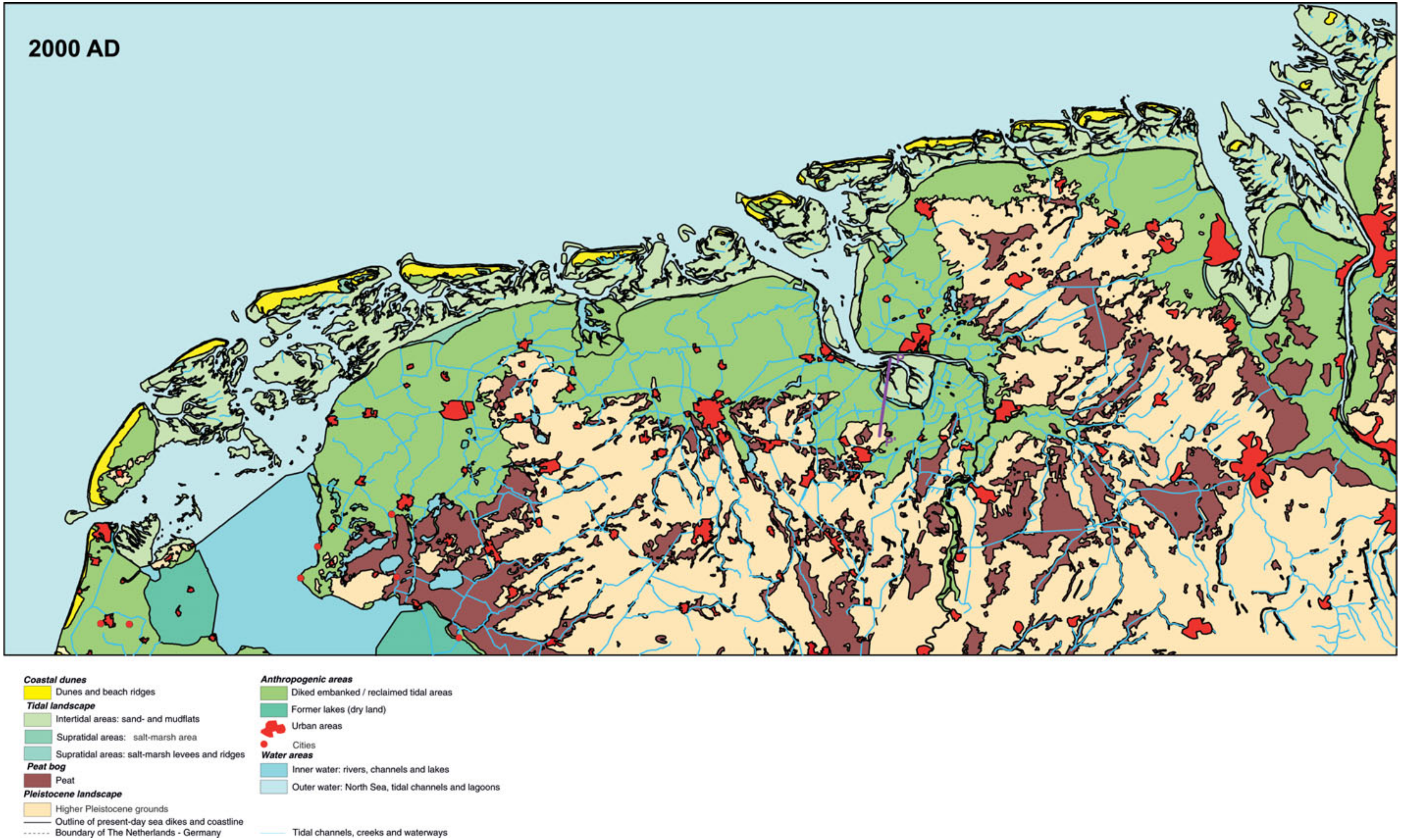

Fig. 12. Palaeogeographic map of the study area at 2000 AD.

https://doi.org/10.1017/njg.2015.4 Published online by Cambridge University Press

continued until Engwierum. On both banks of this palaeochannel clay was deposited on the peat. The development of the Paesens system did not have an anthropogenic cause because humans did not yet inhabit this part of the coastal area on a large scale. The ingression of the Paesens system into the peat area of De Kolken is related to the opening of the coastline east of Ameland. In the first half of the Holocene the coastal area there protruded into the sea for a long time. This headland in the coastline was related to the Pleistocene High of Damwoude in the subsurface, a continuation of the Drents Plateau. It is assumed that due to the straightening and retreat of the coastline near Ameland the coastal barrier to the east was eroded. The hinterlying peat area was not protected anymore, and subsequently a self-reinforcing peat drowning process started, resulting in the Paesens ingression system.

The silting-up of the Hunze and Fivel basins continued gradually after 500 BC. The enlargement of the salt marshes in these areas has been archaeologically dated on the basis of the ages of dwelling mounds (*terpen*), which become younger seaward (Vos & Knol, 2005).

Around 500 BC, the main channel in the Eems estuary was located near the current dike between Emden and Greetsiel. In the Iron Age and Roman Period (0–450 AD) this channel migrated towards the area between Bierum and the Punt van de Reide. There, this led to a landward (transgressive) shift of the mudflat/salt-marsh border and clay deposition on the adjacent peat area (Theunissen et al., 2005). These deposits are referred to as the Eems Clay (de Smet, 1960, 1962). In contrast, on the German side of the Eems silting-up occurred as a consequence of the diversion of the main channel and the marshes expanded seaward, and tidal channels, such as the Sielmönkener Bucht, gradually silted up (see map reconstructions in Vos & Bungenstock, 2013 and Vos & Knol, 2013).

Northwest of Norden a Pleistocene high, the continuation of the Oldenburger-Ostfriesland Plateau, was oriented in the direction of the island of Juist. This Pleistocene headland, the High of Norden, is comparable to the Damwoude High. Around 500 BC a salt-marsh area called Bant was present at this high. This salt-marsh area gradually disappeared due to continuing erosion and the enlargement of the tidal flat area (Lang, 1951; Haarnagel, 1979). The tidal-flat/salt-marsh coastline between Esens and Wangerooge was located in the current Wadden Sea (Heinze, 2000; Niederhöfer, 2013), and the inland coastal peat-bog had reached its northernmost position. Only small peat-draining rivers like the Benser, Harle and Crildumer debouched into the Wadden Sea. At that time no large ingression had yet developed in this region.

The Ur-Jade (the forerunner of the current Jadebusen) and the Maadebucht together formed a tributary of the Weser estuary with its mouth between Butjadingen and Cuxhaven (Behre, 2012). The Ur-Jade and Ur-Maade were drainage rivers of the hinterlying peat area.

In the course of the Iron Age, in both the German and Dutch parts of the Wadden Sea, occupation intensity increased. This is evidenced by the increase in the number of mounds in these areas. Also the border zone of the peat bogs adjacent to the coastal area was more and more intensively occupied, amongst others, between Leeuwarden and Sneek (Lubbers & Osinga, 2007) and along the seaward margin of the former peat bog northwest of Bensersiel (Heinze, 2000). Thus humans played an increasingly important role in shaping the rural landscape from Roman times onwards (Behre, 2012). In the salt marshes and the adjacent peat zone, ditches and trenches were dug on a large scale. In all archaeological excavation sites from that period artificial drainage structures have been encountered. The ditches were connected to natural drainage systems, so that drainage of the area was improved artificially.

As a result of the digging of the ditches, tidal water could be transported easier and faster from the Wadden Sea to the hinterland through the dug ditches and canals. The drainage pattern of natural channels and creeks was artificially changed so that channel systems could cannibalise others, and the groundwater level in the drained area was lowered, allowing oxygen to penetrate the soil so that peat material decomposed (also below the clay cover) and disappeared, particularly at the seaward margin of the peat lands. Grey, organic and humus-poor clays were formed because the plant material of the marsh surface was oxidised completely.

Particularly along the seaward margin of the peat the effects of anthropogenic interventions were extensive because artificial drainage there resulted in strong subsidence. Large-scale man-made parcellation patterns from that time occur, amongst others, in Schagerbrug (west of Schagen), Hempens (south of Leeuwarden; Waldus, 1999) and near Kolken (Nicolay, 2010). The palaeolandscape research at the archaeological site of Arkum (south of Bolsward) showed that the grey clay cover was deposited from the (tidal) ditches that had been dug there, since major tidal creeks were lacking in the area. Those ditches drained the area well and the groundwater level in the marsh was lowered. From about 100 AD onwards no organic matter was retained in the salt-marsh clay anymore and a grey, humus-poor clay was deposited. Also east of Arkum (near Sneek) the seaward margin of the peat area was silted over after the Late Iron Age and a clay layer was deposited. There too, it is plausible that the digging of ditches played an important role in the silting over. It is likely that the Middelzee tidal channel north of Sneek was a ditch or canal initially. Its straight course and the fact that this channel cuts through a Pleistocene ridge in the subsoil support this view. The incision of the channel to a depth of about 10 m –NAP is explained by the fact that this 'anthropogenic channel' has taken over part of the discharge of the Marne (Vos & de Vries, 2011). This expansion of the tidal storage area of the Middelzee resulted in strong tides and thus to an enlargement and deepening of the man-made ditch.

https://doi.org/10.1017/njg.2015.4 Published online by Cambridge University Press

Small-scale dike structures were already made in the Late Iron Age and Roman Period. Remnants of these dike structures have been found during excavations in the dwelling mounds of Wijnaldum, Dongjum, Peins-Oost and Anjum (Bazelmans et al., 1999; Nicolay, 2010). They were primarily intended to protect the farmlands around the dwelling mounds (*terps)*.

100 BC–400 AD (Fig. 9)

During the Late Iron Age and Roman times, at increasingly more locations in the northwestern Dutch and German Wadden Sea, marine sedimentation in the marginal peat lands took place. Clay deposits from that time on the marginal peat bed have been found in the northern part of Noord-Holland (Vos, 2012), in the region around Sneek (Lubbers & Osinga, 2007) and east of Leeuwarden near Wartena in the central and eastern part of Groningen (Wold area and vicinity of Appingedam; de Smet, 1960, 1962), and in the coastal area between Norden and Esens (Streif, 2004). This is striking because in the tidal basins of the rivers Boorne (Westergo) Hunze, Fivel (Vos, 1999; Vos & van Kesteren, 2000) and east of the Eems estuary between Emden and Greetsiel (Behre, 1999) the development of the salt marshes was largely regressive. Subsidence in the border zones of the peat areas – caused by human reclamations – is likely to have played a role all around the northwestern Wadden Sea. However, more factors may have played a role in the drowning of the border zones of peat areas. The continuous sea-level rise will certainly have contributed to the inundation during major floods. The average sea level rose by about 5–10 cm per century (Kiden et al., 2002, 2008). In addition, specific regional factors may have played a role, such as an increase in the tidal inlet system, by which the maximum storm surge levels in the tidal hinterland could rise.

In the northeastern part of Groningen, the southwestward migration of the Eems Channel certainly had an impact on the drowning of the peat in the hinterland during the Late Iron Age and the Roman period.

In this period, in Wangerland, west of the Weser estuary, the sea intruded into the peat area and the Crildumerbucht ingression system developed (Behre, 1999, 2004, 2012). Datings of the top of the peat – below the covering clay layer – indicate, however, that landward of the ingression system peat development continued until the Roman period (Streif, 2004). It is not clear whether the ingression of the Crildumerbucht system had a natural cause (erosion of the protecting coastal barrier), an anthropogenic origin or a combination of both. The more southerly Maadebucht system was further enlarged in the Iron Age ('Duinkerke I deposits', cf. Behre, 1999). At that time the Jadebusen remained free from major flooding and stayed a (high) peat moor area until the Late Middle Ages (1000–1500 AD).

400–1000 AD (Fig. 10)

During the Migration Period (400–500 AD) the occupation intensity in the salt-marsh area of the northwestern Wadden Sea reduced sharply and so did the reclamation activities. In Friesland, at a few locations near Sneek and Wartena, a very thin peat layer developed in the clay cover, the Layer of Tinga (Vos, 2001a). The Layer of Tinga is associated with decreasing anthropogenic activity during the Migration Period. As a result, the man-made drainage deteriorated and peat growth recovered locally (Vos & de Langen, 2008).

The occupancy of salt marshes at the seaward margin of the peat area in the northern Netherlands and northwestern Germany increased strongly again during the Early Middle Ages when the large-scale peat reclamations started, leading to full cultivation of the coastal peat bog and the adjacent peat-moor area on the Pleistocene soils. They caused a significant subsidence in the surface of the seaward margin of the peat area. Because of subsidence the seaward margin of the peat area was flooded during storms and as a result the clay cover expanded strongly in all coastal regions of the northwestern Wadden. Concomitantly the tidal currents to the hinterland strengthened, which in turn led to an enlargement of the tidal channels. Consequently, the Middelzee increased further and the drainage of the Marne River was reactivated.

The Lauwerszee reached its maximum extent in the Early Middle Ages. It is likely that this ingression system had grown already in the Roman Period (Vos & de Langen, 2010). In contrast, the Peasens ingression system silted up even more. The drainage function of the Peasens system was taken over by the man-dug Dokkumer Grootdiep, which discharged into the Lauwerszee system. The subsidence resulting from peat reclamation enabled the tidal system of the Lauwerszee to enlarge. Near Stroobos, in the seaward margin of the system, the first marine influence has been dated around 700 AD (Vos & Groenendijk, 2005). Between 700 and 1000 AD the system expanded further and large parts of the coastal peat area in this region were covered with a grey clay layer. The Lauwerszee also took over the drainage of the Hunze River by means of a new channel between Zoutkamp and Ezinge, and the noticeable bend in the Hunze River, known as Reitdiep, originated. Previously the Hunze flowed to the Wadden Sea through the northern part of Hunsingo. Humans probably contributed to the coming into existence of the Reitdiep by digging a connecting canal between the Lauwerszee system and the Hunze River, a canal comparable with the Dokkumer Grootdiep. Because of the strong current, the Lauwerszee channel started meandering in this area. These meanders are much larger than those in the Dokkumer Grootdiep. The new course of the Hunze – through the Lauwerszee ingression system – caused the old mouth of the Hunze tidal basin to be silted up definitively to salt-marsh level.

https://doi.org/10.1017/njg.2015.4 Published online by Cambridge University Press

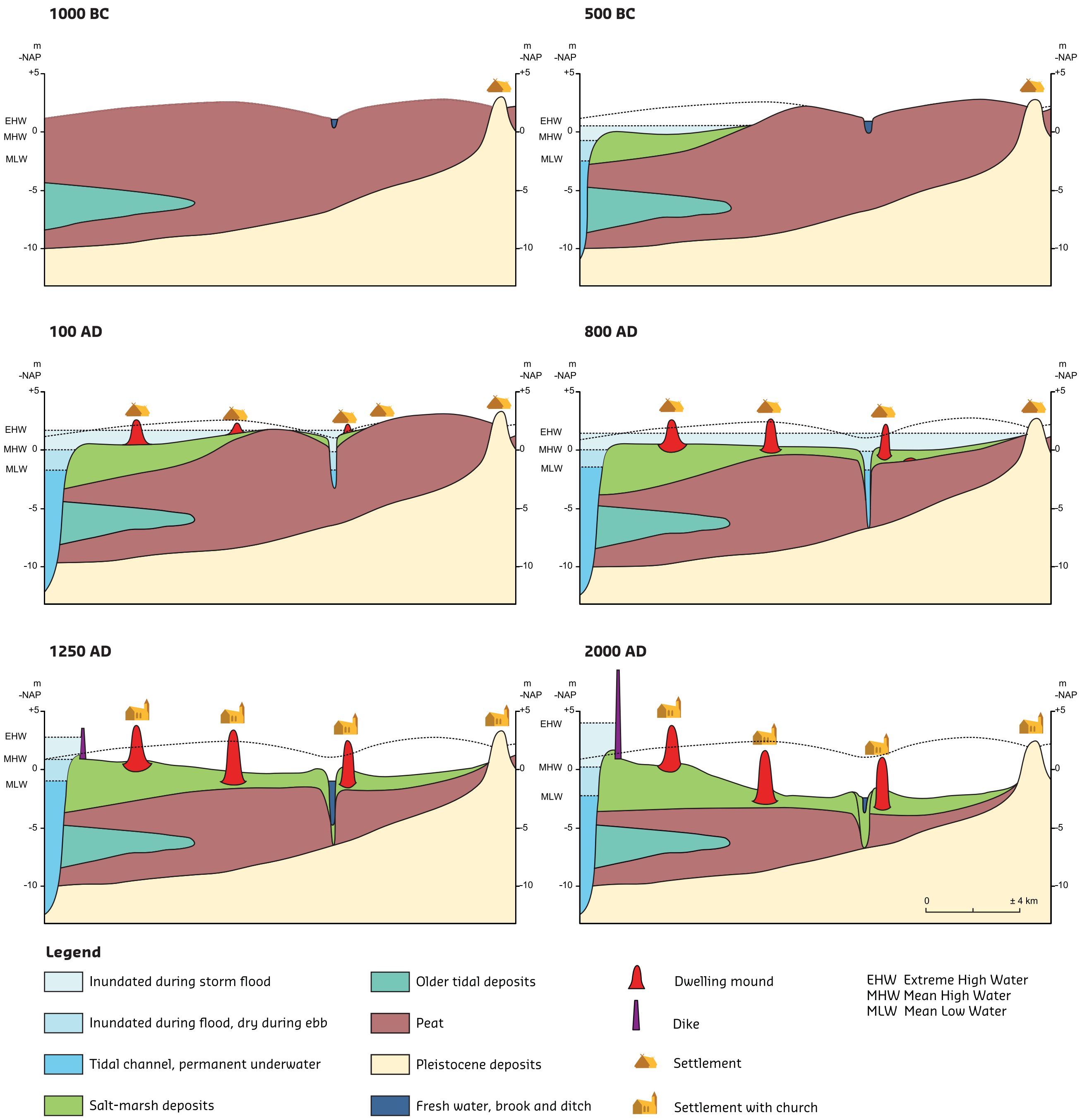

Fig. 13. Schematic cross-section reconstructions through the coastal area of the northern Netherlands (north–south orientation) between 1000 BC and 2000 AD.

In the Early Middle Ages (450–1000 AD), probably before 800 AD, also in the northwestern German coastal area a new ingression system, the Harlebucht, developed in the peat bog in which the Harle River discharged (Behre, 1999). The loss of a protective coastal defence due to the migration of the islands of Spiekeroog and Wangerooge, and the emergence of a large tidal inlet are considered to be the main causes (Streif, 1989b). This transgressive coastal development is very similar to that of the Paesens ingression system. In the formation of the Harlebucht system – just like in the Lauwerszee area – the anthropogenic lowering of the peat surface also played a role in the drowning process (Fig. 6; Fig. 13). South of the Harlebucht, the Crildumerbucht and Maadebucht ingression systems also increased in size due to flooding of the hinterlying coastal peat area. Anthropogenic subsidence effects in the Late Middle Ages are mentioned in the German literature and are particularly associated with salt-mining activities or 'selnering' (Bantelmann, 1967; Behre, 2004).

East of the Eems estuary no major marine ingressions occurred in the Early Medieval period. The protective coastal

https://doi.org/10.1017/njg.2015.4 Published online by Cambridge University Press

barrier consisting of salt-marsh deposits and the relatively minor human interventions are explanatory of this. The same reasons apply also to the Dollard and Jade areas, where no major marine ingressions occurred in this period.

Parts of the Dutch and German Wadden Sea area silted up during the Early Middle Ages. This was the result of sediment supply, which enabled the salt-marsh shorelines to expand (e.g. the Peasens system, the old Hunze tidal-basin system, Fivel Bay, the Sielmönkener Bucht and the salt-marsh shorelines near Butjadingen and near Land Wursten). In the northern part of Noord-Holland large-scale erosion occurred in the Early Middle Ages, as is evidenced by the formation of mudflat deposits in the former peat area. The protective coast was breached to a great extent and the remaining parts of the coastal barrier moved landward (Schoorl, 1999). A big ingression in the Zijpe occurred in the Early Middle Ages.

1000–1500 AD (Fig. 11)

The Zuiderzee enlarged during the Middle Ages (Ente, 1986; Ente et al., 1986; Lenselink & Koopstra, 1994), erosion during major storms playing a major role. For example, during the great storm of 1170 AD a large piece of land, seaward of the current dike at Stavoren, was lost (Schoorl, 1999) and the Marsdiep came into existence (Schoorl, 1973). As the inland sea increased in size, wave attack on the shorelines became stronger because of the increasing fetch. The Marsdiep tidal inlet became increasingly important during the Middle Ages (Sha & de Boer, 1991). However, only in the 15th century was the watershed between North Sea and Wadden Sea (on the line Texel-Schagen) broken and a large channel offered a direct connection with the Zuiderzee (Schoorl, 1999).

The effects of anthropogenic interventions in the coastal landscape became dramatic in the Late Middle Ages, when the major part of the northern Dutch and northwestern German salt-marsh area was embanked. In the course of the 11th century the construction of dikes had become necessary in areas with strong subsidence. In the previous periods the water flowed back to the sea in a natural way after a flood. However, after the artificial subsidence of the land, water remained present and could only be discharged to the sea during low water through a system of dikes and sluices. The Wolddijk around the strongly subsided peat land near Bedum is an example. The dike had already been constructed there for the reclamation of the seaward salt-marsh area. In the following centuries, the entire coastal area of northern Groningen was diked (Knol, 2010, 2013a). In this way almost the entire marsh area of the northwestern Wadden Sea area of the Netherlands and Germany was diked between 1200 and 1300.

As a result of this diking water could no longer be stored in the salt marshes during storms, leading to the impoundment of water against the dikes and an increase in maximum storm water levels in the Wadden Sea. The increase of storm-surge level and the lowering of the soil surface behind the dikes due to drainage created ideal conditions for major catastrophes. When dikes broke, water plunged into the low-lying polders with disastrous consequences for humans and animals.

Inundations were not only the result of extreme high seawater levels. In areas where the ground level had dropped sharply, the water in these polders could not discharge easily anymore to the sea. Particularly during periods of heavy rainfall during winter, this resulted in stagnant ponds in the lowest areas. Where the surface level of the area dropped below the mean low water (MLW) level, the discharge during low water through a system of sluices did not work anymore and the low-lying polders could only be kept dry by artificial drainage techniques such as mills.

In diked (peat) areas where strong subsidence had taken place, permanent damage could occur in the form of permanent loss of land when it was hit by a flood disaster. Examples are the peat lands in the western and central part of the Jadebusen (Wartenberg & Freund, 2012; Wartenberg et al., 2013) and Dollard (Vos & Knol, 2013). These areas have in common that in the subsurface Pleistocene valley systems are present and in these valleys a very thick package of peat had developed. This peat package in the Jadebucht and Dollard made these areas highly vulnerable to oxidation of the top layer and soil subsidence when they were artificially drained. Before the dikings and reclamations in the Late Middle Ages, the peat surface there was a few metres above sea level and was protected against coastal erosion by a salt-marsh zone, a natural barrier. After the embankments, the peat surface dropped significantly, even to below mean high water (MHW) level. If a dike broke, water flowed into the peat area during every tide and created large and deep channels that could not be closed by humans anymore (Figs 7 and 14). In contrast, in the lateral located embanked salt marsh areas – with a clay-sandy subsoil – the permanent loss of land after a dike breakthrough was very limited. The surface level of these marsh areas was still above the MHW level at that time because the subsidence, caused by artificial drainage, was relatively small. After the breakthrough, the dikes around these areas could easily be repaired because they fell dry again after the storm flood inundation.

The disastrous Marcellus flood in 1362 was responsible for the great drowning of the peat lands of the Jadebusen (Behre, 1999), and the entire low-lying peat area was permanently lost. Also, open water connections arose between the Jade and Weser River through the Heete and the Lockfleth, which some 150 years later in the 16th century was diked again. These openings did not become large tidal channels because they occurred in the watershed area between the Jadebusen and the Weser estuary. The relatively low current velocities here resulted into a rapid silting-up of these openings.

In the profile reconstruction of Fig. 14 the drowning of the Dollard between 1000 and 2000 AD is shown. The Dollard was lost only in the 15th century (Knottnerus, 2013) when quarrels

https://doi.org/10.1017/njg.2015.4 Published online by Cambridge University Press

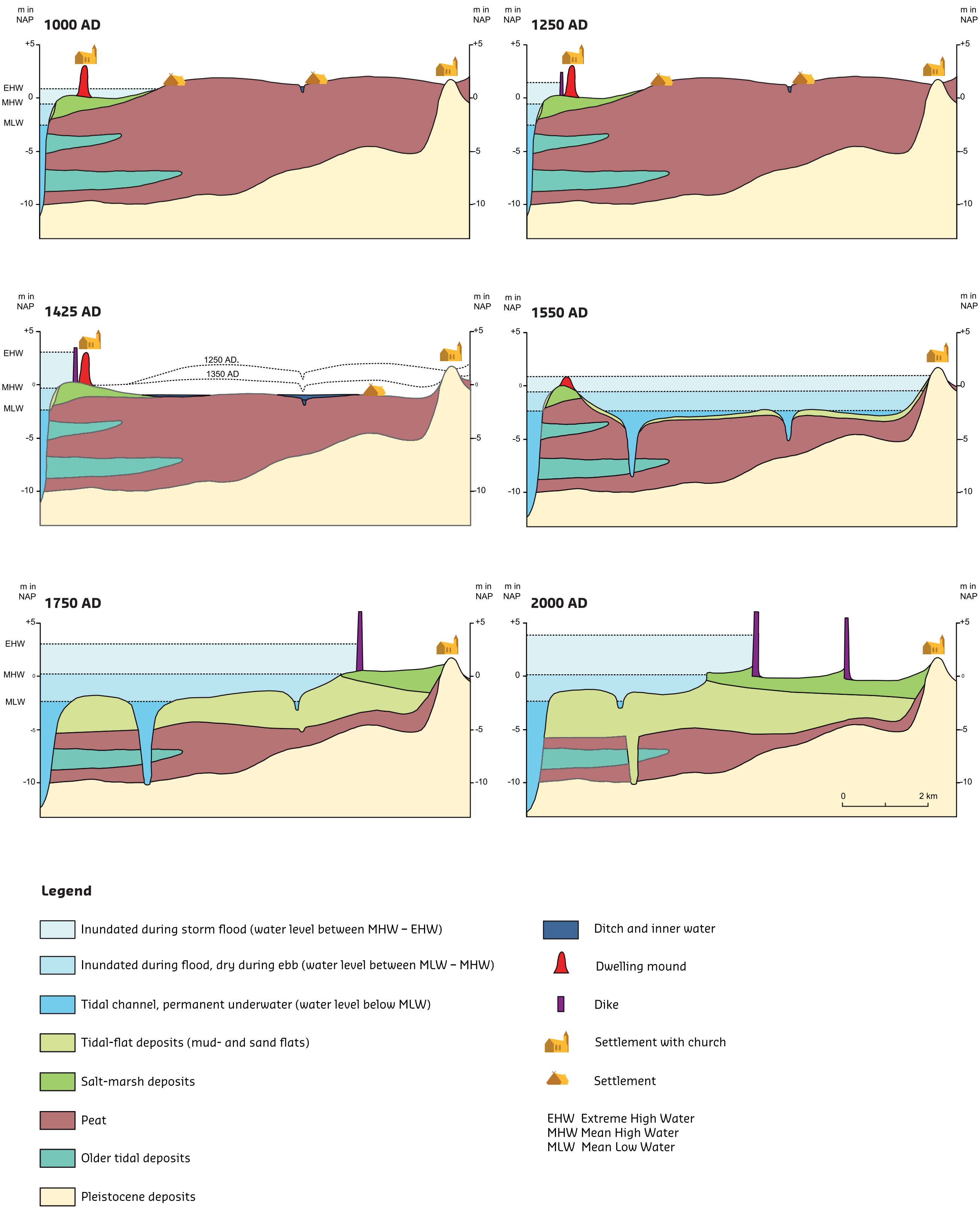

Fig. 14. Schematic north–south cross-section reconstructions of the Dollard area between 1000 and 2000 AD.

https://doi.org/10.1017/njg.2015.4 Published online by Cambridge University Press

about maintenance led to a deterioration of the dikes and the 1412 Cecilia flood caused drowning of large parts of the eastern part of the Dollard. An ingression of the west side of the Eems meander in front of the city of Emden turned Nesserland into a peninsula. The western part of the Dollard area was at that time still protected by an emergency dike between Reide and Finsterwolde, but was lost in the great Cosmas and Damianus flood of 1509. This flood also breached the eastern levee of the Eems meander and Nesserland became an island, which, together with the Punt van Reide, forms the remainder of the tidal levees of the Eems (Knol, 2008; Knol, 2013a,b). Because of erosion and drifting away of large lumps of peat after the inundations (floating peat islands), an inland sea arose with the deepest parts below 4–5 m –NAP. The origin of the Dollard and Jade was ascribed especially to the behaviour of the local elite who, in their feuds, mutually destroyed dikes and sluices (Acker Stratingh & Venema, 1855; Ramaer, 1909; Breuer, 1965).

The ingression of the Leybucht east of the Eems estuary between Greetsiel and Norden is comparable to that of the Jade and Dollard. A low-lying peat area was also flooded, to be diked again in the course of the subsequent centuries as it silted up for the major part. It is different, however, in that no deep inland sea developed. Probably the Leybucht developed in the 12⁻/13th centuries and the floods of 1362 and 1374 further enlarged the ingression in the peat hinterland (Behre, 1999). Also in case of the Leybucht, humans undoubtedly played a major role in the subsidence of the soil resulting from peat reclamations, a low surface level and lakes being the result (Schwarz, 2004, 2005). Behre (1999, 2004) assumes a link between the origin of the Leybucht and the erosion of the salt-marsh island of Bant in the Wadden Sea, northwest of Norden. This would have caused the loss of the natural coastal defence, making the hinterland vulnerable. However, the former marsh island was located at a certain distance north of the Leybucht system (Figs 10 and 11). More likely it was mainly the low surface of the peat that enabled the sea to penetrate far inland and led to the creation of the Leybucht and a large tidal channel. The development of the large channel of the Leybucht promoted erosion of the Bant. The wave attack on the island was enhanced due to a larger sea opening to the hinterland. In any event, the exposure of Bant to the sea in combination with anthropogenic peat extraction for salt production was harmful (Behre, 1999). The last remnant of the Bant was lost permanently to the sea after 1780 (Behre, 1999).

Its namesake, the island of Bant in northeast Frisia, was lost permanently after 1500. The cause of the disappearance was the lateral shift of the Lauwersgeul (Vos, 1992). Until the 14th century the tidal channel of the Lauwers discharged east of Schiermonnikoog. In the course of the 14th century the channel broke through the mudflat between Schiermonnikoog and the mainland of northeast Friesland. A large new inlet evolved, comprising the Westgat and the Zoutkamperlaag. Thus wave attack from the sea on the northeastern coast of Friesland increased strongly. The dike northeast of Wierum had to be rebuilt more inland as the result of strong coastal erosion and the graveyard, located on the seaside of the old dike, disappeared.

1500–2000 AD (Fig. 12)

After 1500 AD the land loss was more than compensated for by the accretion of new land. The northern part of Noord-Holland silted up strongly and the silted-up salt marshes were diked in stages. The same holds true for the Middelzee, the Fivel system, the Leybucht and the Harlebucht.

After the great floods in the Jadebusen and Dollard rapid sedimentation took place in the newly formed inland seas. The landward areas of these inner seas quickly silted up to salt-marsh levels and were diked in stages. Over last 60 years deepening and dredging of the tidal channels have changed the hydrodynamic conditions in the Eems estuary. The Eems-Dollard mudflats and salt marshes have been silting up over the last few centuries, but since the 1980s – the large Eems fairway deepening – erosion and deposition alternate and no clear net sedimentation occurs anymore (Commissie voor de Milieueffectrapportage, 2014). This intervention in the tidal system has led, amongst other things, to an increase in estuarine turbidity levels, which strongly affect the ecosystem of the estuary (Bos et al., 2012; de Jonge et al., 2014).

From the 19th century onwards the intertidal coastal zone along the embanked mainland has also been reclaimed using wooden structures along the dike in which silt was trapped. When such reclamation areas had silted up to the level of the salt marsh they were diked.

In the 20th century the Zuiderzee and the Lauwerszee were cut off from the Wadden Sea by large dikes. Thus the Wadden Sea area has been reduced. In particular, the salt-marsh areas are only a fraction of what they once were. After 1500 AD the peat area also decreased considerably. The coastal peat and the peat areas on the higher Pleistocene grounds (Groenendijk, 1997; Spek, 2004) have largely disappeared due to large-scale peat-cutting for fuel (*turf*) and salt, and by oxidation of peat due to exploitation.

Discussion of the Subatlantic genesis of the Wadden Sea area

Forcing factors and processes

The driving mechanisms of the coastal evolution of the northern Dutch and German landscapes since 500 BC have much in common (mechanisms visualised in Figs 4–7), but each ingression system had its own specific development (Fig. 3).

The ingressions in the coastal peat areas of Paesens and Harlebucht have the disappearance of a protective coastal barrier in common, and the sea penetrated far into the hinterlying

https://doi.org/10.1017/njg.2015.4 Published online by Cambridge University Press

peat area. However, the timing was different. The Paesens system evolved in the Early/Middle Iron Age and silted up in the course of the Middle Ages, whereas the Harlebucht was only formed in the Early Middle Ages and silted up (and was diked) in the Modern Age.

The evolution and geometry of the Dollard and the Jadebusen are also very similar and related to a thick peat layer developed in former Pleistocene valley systems. These diked peat areas were very vulnerable to subsidence due to reclamations. Because of their low elevation these areas were permanently lost after major flood disasters in the Late Middle Ages, the Jadebusen in 1362 AD and the Dollard in 1412 and 1509 AD.

The course of tidal channels was likely affected by humans digging ditches. The straight Middelzee channel north of Sneek was formed in Roman times, probably due to the digging of a ditch or canal between the ingression systems of the Marne and the Middelzee. A dug water connection probably also ensured that the Reitdiep near Zoutkamp, the connection between the Hunze and Lauwerszee, evolved in the Early Middle Ages, such that the Hunze Valley silted up completely in the subsequent period. There are also similarities between the losses of the islands named Bant in the Dutch and German Wadden Sea. Both islands were lost in the Late Middle Ages and Modern Age as a result of the channel diversion exposing the islands to strong wave attack.

Similarly to the genesis of the landscape, the occupation histories of the Dutch and German coastal areas also shows strong similarities. The colonisation of salt marshes – directly on the marsh soil (*Flachsiedlungen*) and/or dwelling mounds (*wierden* and *terpen*) – took place on a large scale from the Early Iron Age onwards. The creation of artificial dwelling mounds continued until the diking of the salt-marsh areas in the Late Middle Ages.

The prehistoric occupations of the seaward margins of the peat areas of the Netherlands and Germany also show similarities, for instance the former seaward margins of the peat between Leeuwarden and Sneek, and those seaward of the dike near Bensersiel. There the occupation began in the Middle/Late Iron Age in fens which were silted over by salt-marsh clays in the Late Iron Age/Roman Period, indicating a (relative) increase in the maximum storm surge level. However, the subsequent development of the landscape in these regions was different due to the location of the areas relative to the open sea. The seaward margins of the peat areas near Leeuwarden–Sneek had a sheltered position in the hinterland of the silting-up Boorne tidal basin, whereas the area at the seaward side of the dike near Bensersiel was exposed and was eroded by the sea after the Middle Ages.

Sea-level fluctuations and coastal development

The Subatlantic sea-level rise – about 15 to 5 cm per century (Kiden et al., 2002, 2008) – played a role in the drowning of the coastal peat lands but was not the major driving mechanism determining the development of the ingression systems. Natural or anthropogenic subsidence of coastal peat bogs on a vertical scale of decimetres to metres was the main cause (Figs 4–7). This view is in contrast with earlier views (Ter Wee, 1976; de Groot et al., 1987; Streif, 1989b; Behre, 1999). The evolution of the ingression systems (Duinkerke 0, 1, 2 and 3) was earlier explained by cyclical sea-level fluctuations. Periods of (alleged) rapid sea-level rise were linked to transgression phases and marine sedimentation, and periods of declining sea-level rise (or even falling sea level) to regression phases and peat formation (Roeleveld, 1974; Griede, 1978; van de Plassche, 1985; Menke, 1988; Behre, 1999, 2001, 2003), a view now regarded as outdated (e.g. Vos & van Heeringen, 1997; Beets et al., 1994; Beets & van der Spek, 2000; Vos & van Kesteren, 2000; Bungenstock & Schäfer, 2009). The evolution of tidal systems after 500 BC shows that the coastal development within those systems was not cyclical and that each system has its own history. Prograding and retrograding (salt-marsh) coastlines may occur at the same time within one and the same system, determined by local factors (e.g. compare the Boorne tidal basin and the Middelzee). Also in the Eems tidal area opposite developments occurred from the Iron Age until into the Middle Ages at the two sides of the estuary. Southwestward migration of the Eems channel between Delfzijl and Reiderland caused erosion at the Dutch side and coastal expansion at the German side.

The Holocene sea-level curves for the Dutch coastal area show a smooth arc shape (e.g. Jelgersma, 1966; Kiden et al., 2002, 2008) while the curves for the German coast – in particular those of the last half of the Holocene – show strong fluctuations (Behre, 1986b, 2001, 2003; Menke, 1988). The recent sea-level curve (Behre, 2003) has aroused much international criticism (Bungenstock & Weerts, 2010; Baeteman et al., 2011), focusing on the unreliability of peat layers and archaeological materials as palaeo-sea-level indicators and the fact that sea-level index points were taken all over the southern North Sea. In the southern North Sea, the subsidence is not the same everywhere due to differences in glacio-isostasy so that each region has its own relative sea-level curve. The post-500 BC index points used by Behre consist largely of archaeological observations from settlements in salt marshes in the German coastal area. These archaeological index points provide information about the maximum or extreme palaeo-storm surge level in a region (EHW) – humans lived above this level – but are not good indicators of the palaeo-mean sea level (MSL) or palaeo-MHW level since there is no linear relation between the MSL along the coast and the EHW level on the salt marshes.

Conclusions

The main driving factors in the long-term coastal evolution of the northwestern Dutch–German Wadden Sea region were

https://doi.org/10.1017/njg.2015.4 Published online by Cambridge University Press

relative mean sea-level rise in the first part of the Holocene and subsidence of the coastal peat bogs in the Late Holocene when the peats were intensively drained by humans.

In the Early Holocene the fast relative sea-level rise induced drowning of the Pleistocene valley systems, which led to formation of tidal basins (Fig. 2). As a consequence of a decreasing rate of sea-level rise the tidal basins were filled with sediment and silted up for a large part in the Middle Holocene. In the marginal zone of the basins towards the higher Pleistocene sand area, large salt marshes and coastal peat bogs came into existence.

From the Subatlantic period marine ingressions into the coastal peat bogs occurred (Fig. 3).

Natural and/or anthropogenic drainage of the peatlands – and subsequent compaction and oxidation – was the main cause of this drowning. Natural causes were the development of new tidal channels, which could develop in the tidal hinterland when a protective sea wall was eroded (such as the Paesens system; Fig. 4) or when a main tidal channel, which drained the hinterland, found a watercourse (such as the Boorne/Middelzee system; Fig. 5).

From the Late Iron Age humans started to drain the marginal area of the coastal bogs by digging ditches on a large scale. The result of these reclamations was that the cultivated peat lands subsided significantly, these areas were drowned during storm tides and a clay layer was formed on top of the peat. This resulted in an auto-compaction process that enhanced the subsidence of the peat (e.g. the Middelzee/Marne system near Sneek; schematic profile reconstructions of Figs 6 and 13).

From the Late Medieval Period onwards, when the saltmarsh areas were embanked and the adjacent peatlands were exploited, the subsidence was dramatic. When the protecting dikes breached, this led to catastrophes and permanent losses of the low-lying peat lands (e.g. the Dollard area; schematic profile reconstructions of Figs 7 and 14).

The moderate sea-level rise of about 5–10 cm per century from the Iron Age onwards enhanced drowning of the coastal peat lands but was not the major driving force of the Subatlantic ingression systems because the Subatlantic subsidence of the drained and drowned peat bog areas had a vertical scale of decimetres to metres.

The landscape reconstruction of the Wadden Sea area between Marsdiep and the Weser (Fig. 3, Figs 8–12) shows that each ingression system has its own history, that humans played a significant role in the drowning process and that no natural cyclic trans- and regression mechanism can be held responsible for this.

Acknowledgement

The research for this study was carried out within the framework INTERREG IV A-programme Deutschland-Nederland and we thank the European Regional Development Fund, the Ministerie für Arbeit, Wirtschaft und Verkehr Niedersachsen and the provinces Groningen, Drenthe and Friesland for their financial support in the project. The Waddenacademie in Leeuwarden is thanked for its financial contribution to make this publication possible. We appreciate the advice and data source references of our German colleagues Friederike Bungenstock and Martina Karle of the Niedersächsisches Institut für historische Küstenforschung (NIhK) and Holger Freund of the Institut für Chemie und Biologie des Meeres (ICBM), which allowed us to compile the reconstructions of the area of Niedersachsen. We thank the members of the Terpen Project (a cooperation of Groningen University and the province of Friesland), Gilles de Langen, Johan Nicolay, Marco Bakker and Theun Varwijk, and Hennie Groenendijk (province of Groningen) for their cooperation in landscape reconstruction of the coastal area of the northern Netherlands. Sieb de Vries is thanked for drafting the map figures, Roel Savert for drawing the profiles (both Deltares) and Hans Smit for improving the English text in the first draft of the manuscript. We are grateful to the reviewers Poppe de Boer, Cecile Baeteman and Kees Kasse, and the associate editor Geert-Jan Vis, whose criticism and advice improved the manuscript significantly.

Supplementary material

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/njg.2015.4

References

Acker Stratingh, G. & ***Venema, G.A.***, 1855. De Dollard of Geschied-, Aardrijks- en Natuurkundige beschrijving van dezen Boezem der Eems. Groningen, XVI: 333 pp.

Allen, J.R.L., 1999. Geological impacts on coastal wetland landscapes: some general effects of sediment auto-compaction in the Holocene of northwest Europe. The Holocene 9: 1–12.

Backhaus, H., 1943. Die ostfriesischen Inseln und ihre Entwicklung. Provinzial-Institut für Landesplanung und Niedersächsische Landes- und Volksforschung, Reihe AI, Band 12.

Baeteman, C., ***Waller, M.*** & ***Kiden, P.***, 2011. Reconstructing middle to late Holocene sea-level change: A methodological review with particular reference to 'A new Holocene sea-level curve for the southern North Sea' presented by K.-E. Behre. Boreas: Volume 1–16.

Bakker, G., 2001. Het ontstaan van het Sneekermeer in relatie tot de ontginning van een laagveengebied 950–1300. Tijdschrift voor Waterstaatsgeschiedenis 10: 54–66.

Bakker, G., 2002. Echten en Oosterzee, ontginning en vervening, bijna duizend jaar maaiveldverlaging. It Beaken 64(2): 129–160.

Bakker, G., 2003. Veenontginningen in Wymbritseradeel en Doniawerstal vanuit Goënga, Sneek, IJlst, Oosthem en Abbega 900–1300. It Beaken 65(3/4): 87–124.

Bantelmann, A., 1967. Die Landschaftsentwicklung an der schleswig-holsteinischen Westküste. Offa-Bücher 21, Neumünster 1967. XX pp.

Barckhausen, J., 1969. Entstehung und Entwicklung der Insel Langeoog. Geologisches Jahrbuch 68: 239–281.

Bazelmans, J., ***Gerrets, D.A.***, ***Koning, J. de*** & ***Vos, P.C.***, 1999. Zoden aan de dijk. Kleinschalige bedijking van akker- en hooiland in de late prehistorie en protohistorie van noordelijk Westergo. De Vrije Fries 79: 7–74.

Beets, D.J., ***van der Spek, A.J.F.*** & ***van der Valk, L.***, 1994. Holocene ontwikkeling van de Nederlandse kust, Rijks Geologische Dienst, Rapport 40.016 (Haarlem): 1–53.

Beets, D.J & ***van der Spek, A.F.***, 2000. The Holocene evolution of the barrier and back barrier basins of Belgium and the Netherlands as a function of relative sea level rise, late Weichselian morphology and sediment supply. Netherlands Journal of Geosciences 79: 3–16.

Behre, K.E., 1986a. Ackerbau, Vegetation und Umwelt im Bereich früh- und hochmittelalterlicher Siedlungen im Flussmarschgebiet der unteren Eems. Probleme der Küstenforschung in südlichen Nordseegebiet 16. Verlag August Lax, Hildesheim: 9–63.

Behre, K.E., 1986b. Meeresspiegelverhalten und Beschiedlung während der Zeit um Christi Geburt in den Nordseemarschen. Sonderdruck aus: Offa 43: 45–53.

Behre, K.E., 1999. Die Veränderung der niedersächsischen Küstenlinien in den letzten 3000 Jahren und ihre Ursachen. Probleme der Küstenforschung in südlichen Nordseegebiet, Band 26. Isensee Verlag, Oldenburg: 9–33.

Behre, K.E., 2001. Holozäne Küstenentwicklung, Meeresspiegelbewegungen un Siedlungsgeschehen an der südlichen Nordsee. Bamberger Geographischer Schriften, Band 20: 1–28.

Behre, K.E., 2003. Eine neue Meeresspiegelkurve für die südliche Nordsee. Transgressionen und Regressionen in den letzten 10.000 Jahren. Probleme der Küstenforschung in südlichen Nordseegebiet, Isensee Verlag, Oldenburg: 9–63.

Behre, K.E., 2004. Coastal development, sea-level change and settlement history during the late Holocene in the Clay District of Lower Saxony (Niedersachsen), northern Germany. Quaternary International 112: 37–53.

Behre, K.E., 2005. Das Moor von Sehestedt. Landschaftgeschichte am östlichen Jasenbusen. Oldenburger Forschungen, Neue Folge Band 21: 148 pp.

Behre, K.E., 2012. Die Geschichte der Landschaft um den Jadebusen. Wilhelmshaven: 280 pp.

Borger, G.J., 2007. Het verdwenen veen en de toekomst van het landschap. Amsterdam: 83 pp.

Bos, D., ***Büttger, H.***, ***Esselink, P.***, ***Jager, Z.***, ***de Jonge, V.***, ***Kruckenberg, H.***, ***van Maren, B.*** & ***Schuchardt, B.***, 2012. Programma Naar Een Rijke Waddenzee. Altenburg & Wymenga, Leeuwarden/Veenwouden.

Bosch, J.H.A., 1990. Toelichtingen bij de Geologische Kaart van Nederland 1:50.000. Blad Assen West (12W) en Blad Assen Oost (12), Geologische Dienst (Haarlem): 188 pp.

Breuer, H., 1965. Dollart und Eems. Die Folgen der Dollartbildung für das Gebiet der unteren Eems. Jahrbuch der Gesellschaft für bildende Kunst und väterlandische Altertümer zu Emden 45: 11–90.

Brinkkemper, O., ***Bijkerk, W.***, ***Brongers, M.***, ***Jager, S.***, ***Kosian, M.***, ***Spek, T.*** & ***van der Vaart, J.***, 2006. Biografie van de mieden. Landschapsgeschiedenis van de miedengebieden bij Buitenpost, Surhuizum en Zwaagwesteinde (Noordoost-Friesland), Amersfoort/Leeuwarden/Veenwouden. Rapport i.o. van Staatsbosbeheer Noord, deel I Tekstdeel en deel II.

Bungenstock, F. & ***Schäfer, A.***, 2009. The Holocene relative sea-level curve for the tidal basin of the barrier island Langeoog, German Bight, Southern North Sea. Global and Planetary Change 66: 34–51.

Bungenstock, F. & ***Weerts, H.J.T.***, 2010. The high-resolution Holocene sea-level curve for northwest Germany: global signals, local effects or data-artefacts? International Journal of Earth Science 99: 1687–1706.

Casparie, W.A. & ***Molema, J.***, 1990. Het middeleeuwse veenontginningslandschap bij Scheemda. Palaeohistoria 32: 271–289.

Chang, T.S., ***Flemming, B.W.***, ***Tilch, E.***, ***Bartholomä, A.*** & ***Wöstmann, R.***, 2006. Late Holocene stratigraphic evolution of a back-barrier tidal basin in the East Frisian Wadden Sea, southern North Sea: transgressive deposition and its preservation model. Facies 52: 329–340.

Cleveringa, J., 2000. Reconstruction and modelling of Holocene coastal evolution of the western Netherlands. PhD thesis, University of Utrecht. Geologica Ultraiectina 200: 198 pp.

Commissie voor de Milieueffect rapportage (MER), 2014. Verruiming vaargeul Eemshaven – Noordzee. Toetsingadvies over het geactualiseerde milieueffectrapport en de aanvulling daarop. MER, rapportnummer 1826–250 (Utrecht): 1–11.

de Groot, T.A.M., ***van Adrichem Boogaert, H.A.***, ***Fischer, M.M.***, ***Klijnstra, B.***, ***van Montfrans, H.M.***, ***Uil, H.***, ***ter Wee, M.W.***, ***van Weperen, M.J.***, ***Zanstra, J.G.***, 1987. Toelichtingen bij de Geologische Kaart van Nederland 1:50.000, Blad Heerenveen West en Oost (11 W en 11 O), Rijks Geologische Dienst (Haarlem): 251 pp.

de Jonge, V.N., ***Schuttelaars, H.M.***, ***van Beusekom, J.E.E.***, ***Talke, S.A.*** & ***de Swart, H.E.***, 2014. The influence of channel deepening on estuarine turbidity levels and dynamics, as exemplified by the Eems estuary. Estuarine, Coastal and Shelf Science 139: 46–59.

de Langen, G.J., 1992. Middeleeuws Friesland. Groningen: 395 pp.

de Mulder, E.F.J., ***Geluk, M.C.***, ***Ritsema, I.***, ***Westerhoff, W.E.*** & ***Wong, T.E.***, 2003. De ondergrond van Nederland, Nederlands Instituut voor Toegepaste Geowetenschappen TNO (Utrecht): 379 pp.

de Smet, L.A.H., 1960. Die holozäne Entwicklung des niederländischen Randgebietes des Dollarts und der Eems. Verhandelingen Koninklijk Nederlands Geologisch en Mijnbouwkundig Genootschap GS XIX: 15–23.

de Smet, L.A.H., 1962. Het Dollardgebied, bodemkundige en landbouwkundige onderzoekingen in het kader van de bodemkartering. De Bodemkartering van Nederland, Verslagen Landbouwkundig Onderzoek, 67.16. 's-Gravenhage.

Dresscher, S.J. & ***Vos, P.C.***, 2010. De prehistorische geul bij Goutum (Provincie Friesland). Geoarcheologisch booronderzoek naar de loop van de prehistorische getijdengeul in het gebied tussen Wergea en Goutum, uitgevoerd in het kader van de planontwikkeling van het gebied De Zuidlanden (gemeente Leeuwarden). Deltares-rapport, kenmerk 1202574-000-BGS-0003: 18 pp.

Ente, P.J., 1986. Het ontstaan van het Marsdiep en de Zuiderzee, lezing gehouden te Amsterdam op 25-3-1983, met aanvullingen. Werkdocument Rijksdienst voor de IJsselmeerpolders, 1986-102abw (Lelystad): 22 pp.

Ente, P.J., ***Koning, J.*** & ***Koopstra, R.***, 1986. De bodem van oostelijk Flevoland. Rijksdienst voor de IJsselmeerpolders, Flevobericht, nr. 258 (Lelystad): 178 pp.

Flemming, B.W. & ***Davis, R.A.***, 1994. Holocene Evolution, Morphodynamics and Sedimentology of the Spiekeroog Barrier Island System (Southern North Sea). Senckenbergiana Maritima 24: 117–155.

Fokkens, H., 1998: Drowned landscape: the occupation of the western part of the Frisian-Drentian Plateau, 4400 BC–AD 500 (Amersfoort): 183 pp.

Griede, J.W., 1978. Het ontstaan van Frieslands Noordhoek, Ph. D. thesis, Vrije Universiteit (Amsterdam): 186 pp.

Griede, J.W. & **Roeleveld, W.**, 1982. De geologische en paleogeografische ontwikkeling van het noordelijk zeekleigebied. K.N.A.G. Geografisch Tijdschrift XVI, nr 5: 439–455.

Groenendijk, H.A., 1997. Op zoek naar de horizon, het landschap van Oost-Groningen en zijn bewoners tussen 8000 voor Chr. en 1000 na Chr. Ph.D.Tthesis, REGIO–Project Uitgevers (Groningen): 314 pp.

Groenendijk, H. & **Bärenfänger, R.**, 2008. Gelaagd landschap, veenkolonisten en kleiboeren in het Dollardgebied. Bedum: 96 pp.

Groenendijk, H. & **Schwarz, W.**, 1992. Mittelalterliche Besiedlung der Moore am Dollart-Rand. *In*: **Knottnerus, E.A.** (ed.): Rondom Eems en Dollard/Rund um Eems und Dollart. Groningen-Leer: 84–97.

Groenendijk, H.A. & **Vos, P.C.**, 2002. Outside the terpen landscape: Detecting drowned settlements by using the geo-genetic approach in the coastal region of Grijpskerk (Groningen, The Netherlands). Berichten Rijksdienst voor het Oudheidkundig Bodemonderzoek 45: 57–80.

Haarnagel, W., 1979. Burcana. Reallexikon der germanischen Altertumskunde 4: 114–117.

Heinze, A., 2000. Archäologische Funde im ostfriesischen Watt. Jaarverslagen van de Vereniging voor Terpenonderzoek 76–82: 76–97.

Heinze, A., 2013. Das unbekannte Gesicht der Marsch, in hochauflösenden Höhenkarten. Museum Leben am Meer (Esens): 31 pp.

Henninger, W., **Kappelhoff, B.** & **Schumacher, H.**, 2005. Die grosse handgezeichnete Campsche Karte von Ostfriesland von 1806, herausgegeben und eingeleitet. Verlag Hahnsche Buchhandlung (Hannover): 72 pp.

Homeier, H., 1969. Der Gestaltwandel der ostfriesischen Küste im Laufe der Jahrhunderte, ein Jahrtausend ostfriesischer Deichgeschichte. *In*: Ohling, J. (ed.): Ostfriesland im Schütze des Deiches 4: p. 3–75 & Karte: 1–31.

Homeier, H., 1977. Einbruch und weitere Entwicklung des Dollart bis um 1600, Jahresbericht 1976 der Forschungsstelle für Insel- und Küstenschutz der Niedersächsischen Wasserwirtschaftsverwaltung. Nordeney 39–81 & B 2 Anlage 1–16.

Isbary, G., 1936. Das Inselgebiet von Ameland bis Rottumeroog. Morphologische und hydrographische Beiträge zur Entwicklungsgeschichte der friesischen Inseln. Archiv der Deutschen Seewarte Hamburg 56(3): 1–55.

Jelgersma, S., 1966. Holocene sealevel changes during the last 10,000 years. Proceedings of the International Symposium on World Climate from 8000 to 0 BC. Royal Metrological Society London: 54–71.

Kiden, P., **Denys, L.** & **Johnston, P.**, 2002. Late Quaternary sea-level change and isostatic and tectonic land movements along the Belgian-Dutch North Sea coast: geological data and model results. Journal of Quaternary Science 17: 535–546.

Kiden, P., **Makaske, B.** & **van de Plassche, O.**, 2008. Waarom verschillende zeespiegelreconstructies voor Nederland? Grondboor & Hamer 62, nrs. 3/4 (special: Kustontwikkeling): 54–61.

Knol, E., 1993. De Noordnederlandse kustlanden in de Vroege Middeleeuwen, Ph.D. thesis, Vrije Universiteit (Amsterdam): 271 pp.

Knol, E., 2008. Nessereiland, de oostelijkste punt van Reiderland, Groninger Historisch Jaarboek Groningen: 20–35.

Knol, E., 2010. Het verleden van kwelders, wierden en dijken, werk voor natuurwetenschappers, *In:* Borger, G.J., Breuker, P. & de Jong, H. (eds): Van Groningen tot Zeeland. Geschiedenis van het cultuurhistorisch onderzoek naar het kustlandschap. Hilversum: 11–27, 65–68, 145–149.

Knol, E., 2013a. Moorkolonisation und Deichbau als Ursache von Flutkatastrophen – das Beispiel der nördlichen Niederlande. Siedlungs- und Küstenforschung im südlichen Nordseegebiet/Settlement and Coastal Research in the southern North Sea Region 36: 157–170.

Knol, E., 2013b. Nooit verdwenen Dollardland. In: Essink, K. (ed.) Stormvloed 1509 –Geschiedenis van de Dollard. Stichting Verdronken Geschiedenis (Groningen): 117–126.

Knottnerus, O.S., 2005. Fivelboezem, de erfenis van een verdwenen rivier. Bedum: 99 pp.

Knottnerus, O.S., 2008. Natte voeten, vette klei. Oostelijk Fivelingo en het water. Bedum: 96 pp.

Knottnerus, O.S., 2013. Dollardgeschiedenis(sen)- Mythe en realiteit. *In:* Essink, K. (ed.): Stormvloed 1509 –Geschiedenis van de Dollard. Stichting Verdronken Geschiedenis (Groningen): 95–116.

Kortekaas, G., 2013. Leeg land. Een laatmiddeleeuwse krimpregio langs de Hondsrug. Hervonden stad 2013: 83–94.

Kosian, M., 2009. Historic Maritime Maps in GIS. MACHU Report 2. Educom Publishers (Rotterdam): 26–28.

Lambooij, H.T.M., 1987. Getekend land: nieuwe beelden van Hollands. Hoogheemraad Noordhollands Noorderkwartier (Alkmaar): 160 pp.

Lang, A.W., 1951: Der Untergang der Insel Bant. Ostfreesland ein Kalender für Jedermann 34: 37–44.

Lang, A.W., 1955. Das Juister Watt. Schriften der wirtschaftswissenschaftlichen Gesellschaft zum Studium Niedersachsens. Neue Folge, Bd. 57. Bremen-Horn: 98 pp.

Lang, A.W., 1958. Gestaltungswandel des Eemsmündungstrichters. Schriften der wirtschaftswissenschaftlichen Gesellschaft zum Studium Niedersachsens. Neue Folge, Bd. 58. Bremen-Horn: 153 pp.

Lenselink, G. & **Koopstra, R.**, 1994. Ontwikkeling in het Zuiderzeegebied; van Meer Flevo, via de Almere-lagune, tot Zuiderzee. *In*: Rapporl, M. & Soonius, C.M. (eds): In de bodem van Noord-Holland, Lingua Terrae: 129–140.

Lenselink, G. & **Menke, U.**, 1995. Geologische en bodemkundige atlas van het Markermeer. Blad 1, Toelichting. Directoraat Rijkswaterstaat Directie IJsselmeergebied, Lelystad.

Ligtendag, W.A., 1995. De Wolden en het water. Regio-project (Groningen): 368 pp.

Linke, G., 2001. Die Entstehung der Insel Neuwerk – unter Berücksichtigung der Verhältnisse bei Scharhörn. Probleme der Küstenforschung im südlichen Nordseegebiet 27: 11–37.

Long, A.J., **Waller, M.P.** & **Stupples, P.**, 2006. Driving mechanisms of coastal change: Peat compaction and the destruction of late Holocene coastal wetlands. Marine Geology 225: 63–84.

Lubbers, N. & **Osinga, M.**, 2007. Archeologisch onderzoek De Hemmen te Sneek. Inventariserend veldonderzoek d.m.v. proefsleuven. Grontmij Archeologische Rapporten 237: 35 pp.

Menke, B., 1988. Die holozäne Nordseetransgression im Küstenbereich der südöstlichen Deutschen Bucht. *In:* Müller-Wille e.a., M., Higelke, B., Hoffmann, D., Menke, B., Brande, A., Bokelmann, K., Saggau, H.E. & Kühn, H.J. (eds): Landschaftsentwicklung und Siedlungsgeschichte im

https://doi.org/10.1017/njg.2015.4 Published online by Cambridge University Press

Einzugsgebiet der Norderhever (Nordfriesland). Offa-Bücher 66. Studien zur Küstenarchäologie Schleswig-Holstein: 117–137.

Mol, J.A., ***Noomen, P.N.*** & ***van der Vaart, J.H.P.***, 1990. Achtkarspelen-Zuid/Eestrum, een historisch-geografisch onderzoek voor de landinrichting. Leeuwarden: 107 pp.

Nicolay, J.A.W. (ed.), 2010. Terpbewoning in oostelijk Friesland. Twee opgravingen in het voormalige kweldergebied van Oostergo. Barkhuis, Eelde (Groningen): 321 pp.

Niederhöfer, K., 2013. Archäologische Fundstellen im ostfriesischen Wattenmeer – Siedlungsgeschichte einer untergegangenen Landschaft bis 1570. PhD thesis Hamburg, https://dl.dropboxusercontent.com/u/54969631/Diss_KN_Band01.pdf.

Oost, A.P., 1995. Dynamics and sedimentary development of the Dutch Wadden Sea with emphasis on the Frisian Inlet. A study of barrier islands, ebb-tidal deltas, inlets and drainage basins. Geologica Ultraiectina, no 126: PhD thesis: 455 pp.

Pons, L.J. & ***Wiggers, A.J.***, 1959–60. De holocene wordingsgeschiedenis van Noordholland en het Zuiderzeegebied. Tijdschrift van het Koninklijk Nederlands Aardrijkskundig Genootschap. Tweede Reeks 76: 104–152.

Pons, L.J. & ***Wiggers, A.J.***, 1960. De holocene wordingsgeschiedenis van Noordholland en het Zuiderzeegebied. Tijdschrift van het Koninklijk Nederlands Aardrijkskundig Genootschap. Tweede Reeks 77: 3–57.

Pons, L.J., ***Jelgersma, S.***, ***Wiggers, A.J.*** & ***de Jong, J.D.***, 1963. Evolution of the Netherlands coastal area during the Holocene. In: de Jong, J.D. (ed.): Verhandelingen van het Koninklijk Nederlands Mijnbouwkundig Genootschap, geologische serie deel 21–2, Transactions of the Jubilee Convention, Part 2: 197–208.

Ramear, J.C., 1909. De vorming van den Dollard en de terpen in Nederland, in verband met de geographische geschiedenis van ons polderland. Tijdschrift van het Aardrijkskundig Genootschap 26: 161 & Kaart: I–II.

Roeleveld, W., 1974. The Holocene evolution of the Groningen marine clay district. PhD thesis, Vrije Universiteit (Amsterdam): 1–132. Also in: Berichten van de Rijksdienst voor het Oudheidkundig Bodemonderzoek, 24 supplement: 132 pp.

Schokker, J., 2010. Geologische overzichtskaart van Nederland. TNO Bouw en Ondergrond (Utrecht).

Schoorl, H., 1973. Zeshonderd jaar water en land. Bijdrage tot de historische geo- en hydrografie van de kop van Noord-Holland in de periode ± 1150–1750 (Groningen).

Schoorl, H., 1999. De Convexe Kustboog Texel–Vlieland–Terschelling. Bijdragen tot de kennis van het westelijke Waddengebied en de eilanden Texel, Vlieland en Terschelling. Deel I. Schoorl: 186 pp.

Schwarz, W., 2004. Mittelalterliche Funde am und im Grossen Meer, Landkreis Aurich, Archäologische Mitteilungen aus Nordwestdeutschland 26: 63–113.

Schwarz, W., 2005. Morsaten, Moorsiedler im frühmittelalterlichen Norder- und Brokmerland. *In*: Schmid e.a., H. (ed.): Tota Frisia in Teilansichten, Hajo van Lengen zum 65. Geburtstag, Aurich: 13–40.

Sha, L.P. & ***de Boer, P.L.***, 1991. Ebb-tidal delta deposits along the west Frisian Islands (The Netherlands): processes, facies architecture and preservation. Journal Clastic Tidal Sedimentology. Canadian Society of Petroleum Geologists Memoir 16: 199–218.

Slofstra, J., 2008. De kolonisatie van de Friese veengebieden. *In:* Huisman, K., Bekkema, K., Bos, J., de Jong, H., Kramer, E. & Salverda, R. (eds): Diggelgoud, 25 jaar Argeologysk Wurkferbân: archeologisch onderzoek in Fryslân. Leeuwarden: 206–230.

Spek, T., 2004. Het Drentse esdorpen-landschap, een historisch geografische studie, deel 2. Uitgeverij Matrijs (Utrecht): 500–1100.

Spek, T., 2008. De verdwijning van het hoogveen en het ontstaan van het woudenlandschap in de Zuidoosthoek van Friesland. *In:* Huisman, K., Bekkema, K., Bos, J., de Jong, H., Kramer, E. & Salverda, R. (eds): Diggelgoud, 25 jaar Argeologysk Wurkferbân: archeologisch onderzoek in Fryslân. Leeuwarden: 231–241.

Strahl, E., 2005. Die jungbronzezeitliche Siedlung Rodenkirchen- Hahnenknooper Mühle, Ldkr. Wesermarsch – Erste Bauern in der deutschen Marsch. *In:* Endlich, C. & Kremer, P. (eds): Kulturlandschaft Marsch. Natur, Geschichte, Gegenwart, Oldenburg. Schriftenreihe des Landesmuseums für Natur und Mensch 33: 52–59.

Streif, H., 1989a. Die Geologische Küstenkarte von Niedersachsen 1:25.000 – eine neue Planungsgrundlage für die Küstenregion. Zeitschrift für angewandte Geologie 44: 183–194.

Streif, H., 1989b. Barrier islands, tidal flats and coastal marshes resulting from a relative rise of sea level in East Frisia on the German North Sea coast. Proceedings KNGMG Symposium 'Coastal Lowlands, Geology and Geotechnology'. Kluwer Academic Publishers (Dordrecht): 213–223.

Streif, H., 2004. Sedimentary record of Pleistocene and Holocene marine inundations along the North Sea coast of Lower Saxony, Germany. Quaternary International 112: 3–28.

Taayke, E., 1996. Die einheimische Keramik der nördlichen Niederlande, 600 v.Chr. bis 300 n.Chr. Thesis, Rijksuniversiteit Groningen. Also: Berichten Rijksdienst Oudheidkundig Bodemonderzoek 40 (1990): 101–222; 41 (1991), 9–102; 42, 9–208.

Ter Wee, M.W., 1976. Toelichtingen bij de Geologische Kaart van Nederland 1:50.000, Blad 11 Blad Sneek (10 W, 10 O), Rijks Geologische Dienst (Haarlem): 131 pp.

Theunissen, E.M., ***van Doesburg, J.***, ***Vos, P.*** & ***Laarman, F.***, 2005. Archeologische begeleiding van het uitgraven van een bouwput op het wettelijk beschermd monument dorpswierde Oling (gemeente Appingedam). Rapportage Archeologische Monumentenzorg 128: 61 pp.

van de Plassche, O., 1985. Time-limit assessment of some Holocene transgressive and regressive periods in the Northern Netherlands. Eiszeitalter und Gegenwart 35: 43–48.

van den Broek, J. 2011. Een kronkelend verhaal. Nieuw licht op de oude Hunze. Assen.

van der Spek, A., 1994a. Holocene depositional sequences in the Dutch Wadden Sea south of the island of Ameland, Large-scale evolution of Holocene tidal basins in the Netherlands. PhD thesis, Universiteit of Utrecht: 29–73.

van der Spek, A., 1994b. Reconstruction of tidal inlet and tidal channel dimensions in the Frisian Middelzee, a former tidal basin in the Dutch Wadden Sea, large-scale evolution of Holocene tidal basins in the Netherlands, PhD thesis, University of Utrecht: 97–128.

van Veen, J., 1930. De Fivel en hare verzanding bewerkt uit nagelaten aanteekeningen van P.M. Bos. Tijdschrift van het Koninklijk Nederlandsch Aardrijkskundig Genootschap, 2e reeks 47: 673–691, 773–800.

Vos, P.C., 1992. Paleogeografische reconstructie van het Lauwersmeergebied. Rijks Geologische Dienst – Distrikt Noord, Oosterwolde: 22 pp.

https://doi.org/10.1017/njg.2015.4 Published online by Cambridge University Press

Vos, P.C., 1999. The Subatlantic evolution of the coastal area around the Wijnaldum-Tjitsma terp. *In:* Besteman, J.C. et al. (eds): The Excavation near Wijnaldum, Reports on Friesland in Roman and Medieval Times 1, University of Amsterdam: 33–73.

Vos, P.C., 2001a. Geologisch onderzoek opgraving Sneek-Tinga. TNO-rapport, NITG 01-124-B: 13 pp.

Vos, P.C., 2001b. Tracébegeleiding Vierhuizen. Resultaten geoarcheologische tracébegeleiding bij de aanleg van de afvalwaterpijplijn ten westen van Vierhuizen (NW Groningen), uitgevoerd in september/oktober 2001. TNO-rapport, NITG 01-236-B: 27 pp.

Vos, P.C., 2002a. Geologisch onderzoek opgraving Sneek-Pasveer. TNO-rapport, NITG 02-119-B: 19 pp.

Vos, P.C., 2002b. Geologisch onderzoek opgraving Leeuwarden-Bullepolder. TNO-rapport, NITG 02-118-B: 18 pp.

Vos, P.C., 2004. Geoarcheologisch vooronderzoek Lauwerzijl-NAM locatie. TNO-rapport, NITG 04-192-B: 17 pp.

Vos, P., 2006: Toelichting bij de nieuwe paleogeografische kaarten van Nederland, Nationale Onderzoeksagenda Archeologie 25 (versie 1.0), (www.noaa.nl), 1–15, kaarten 1–8.

Vos, P.C., 2007. Geolandschappelijk onderzoek Boazum. TNO-rapport 2007-U-R1231/B: 31 pp.

Vos, P.C., 2011. Verfijning van de archeologische verwachtingskaart voor het pilotgebied Kantens – Stitswerd (Noord Groningen). Deltares-rapport, kenmerk 1204018-000-BGS-0004: 30 pp.

Vos, P.C., 2012. Kort verslag van het veldbezoek op 3 augustus 2012 aan de midden ijzertijd site in Schagen, gelegen in het nieuwbouw terrein aan de Nes. Intern rapport Deltares (Utrecht).

Vos, P.C., 2013a. www.Archeologieinnederland.nl, <http://www.Archeologieinnederland.nl.

Vos, P.C., 2013b. Lithostratigrafie van de Holocene kustafzettingen in Noord Nederland. Deltares-rapport, kenmerk 1208302-000-BGS-0008: 23 pp.

Vos, P.C. & ***Bungenstock, F.***, 2013. Abriss der Landschafts- und Küstenentwicklung/Schets van de ontwikkeling van het kustlandschap. *In*: Kegler, J.F. (ed.): Land der Entdeckungen. Die Archäologie des friesischen Küstenraums. Ostfriesische Landschaft (Aurich): 60–69.

Vos, P.C. & ***de Langen, G.J.***, 2008. Landschapsgeschiedenis van Noordwest-Friesland in kaartbeelden. *In:* Huisman, K. et al. (eds): Diggelgoud. 25 jaar Argeologysk Wurkferbân: archeolgisch onderzoek Fryslân. Leeuwarden: 310–323.

Vos, P.C. & ***de Langen, G.J.***, 2010. Geolandschappelijk onderzoek: de vorming van het landschap voor en tijdens de terpbewoning en het ontstaan van de Lauwerszee. *In:* Nicolay, J.A.W. (ed.): Terpbewoning in oostelijk Friesland. Twee terpopgravingen in het voormalige kweldergebied van Oostergo. Groningen Archaeological Studies (Groningen): 63–94.

Vos, P.C. & ***de Vries, S.***, 2009. Samenstelling van de verwachtingskaart voor de gemeenten Sneek en Wymbritseradiel, betreffende het gebied gelegen tussen de RD-coördinaten 165/560 en 180/570. Deltares-rapport, 0907-0205: 46 pp.

Vos, P.C. & ***de Vries, S.***, 2011. Aanvulling op het geoarcheologische rapport 0907-0205 Sneek – Wymbritseradiel. Archeologische verwachtingszonekaart, geologische en paleolandschappelijke basiskaarten en profielen van de gemeenten Sneek en Wymbritseradiel; Deltares-rapport, kenmerk 1202841-000-BGS-0003: 17 pp.

Vos, P.C. & ***de Vries, S.***, 2012. Geoarcheologisch onderzoek op het terrein van het voormalige schoolgebouw op het Oud Kerkhof in Sneek. Geologisch en archeolandschappelijk veldonderzoek door middel van handboringen en profielopnamen in de bouwput van de kelder in het voormalige schoolgebouw aan het Oud Kerkhof nr. 13 in Sneek. Deltares-rapport, kenmerk 1202841-000-BGS-0003: 23 pp.

Vos, P.C. & ***Gerrets, D.A.***, 2004. Archaeology, a major tool in the reconstruction of the coastal evolution of Westergo (The Northern Netherlands). Quaternary International 133–134: 61–75.

Vos, P.C. & ***Groenendijk, H.A.***, 2005. Geolandschappelijk en archeologisch onderzoek Stroobos. Geoarcheologische begeleiding van een nieuw gegraven bermsloot, die aangelegd is in het kader van de bochtverruiming van het Van Starkenborgkanaal bij Stroobos in de zomer van 2003 (provincie Groningen). TNO-rapport NITG-05-073-A: 57 pp.

Vos, P.C. & ***Knol, E.***, 2005. Wierden ontstaan in een dynamisch getijdenlandschap. *In*: Knol e.a., E. (ed.): Professor Van Giffen en het geheim van de wierden. Groninger Museum: 119–135.

Vos, P.C. & ***Knol, E.***, 2013. De ontwikkelingsgeschiedenis van het Dollardlandschap: natuurlijke en antropogene processen. *In:* Essink, K. (ed.): Stormvloed 1509 – Geschiedenis van de Dollard. Stichting Verdronken Geschiedenis (Groningen): 31–43.

Vos, P.C. & ***Knol, E.***, 2014. Paleogeographische kaarten van het Waddengebied tussen Marsdiep en Weser, 500 v. Chr. – heden. Brochure van het Groninger Museum (Groningen).

Vos, P.C. & ***van Heeringen, R.M.***, 1997. Holocene geology and occupation history of the Province of Zeeland (SW Netherlands). Mededelingen Nederlands Instituut voor Toegepaste Geowetenschappen TNO 59: 5–109.

Vos, P.C. & ***van Kesteren, W.P.***, 2000. The long-term evolution of intertidal mudflats in the Northern Netherlands during the Holocene; natural and anthropogenic processes. Continental Shelf Research 20: 1687–1710.

Vos, P.C., ***Bunnik, F.***, ***Cremer, H.*** & ***de Vries, S.***, 2010. Geologisch onderzoek naar de afzettingen van de Ges binnen het plangebied Houkepoort. Deltares rapport, kenmerk 1202000-000-BGS-0002: 33 pp.

Vos, P.C., ***Bazelmans, J.***, ***Weerts, H.J.T.*** & ***van der Meulen, M.J.***, 2011. Atlas van Nederland in het Holoceen. Prometheus (Amsterdam): 94 pp.

Waldus, W.B.,1999. Vergraven en Verdronken. Het archeologisch onderzoek van een overslibde nederzetting uit de late ijzertijd en Romeinse tijd bij de Vinex-locatie Hempens-Teerns direct ten zuiden van Leeuwarden. Doctoraalscriptie Archeologie (Leiden): 96 pp.

Waldus, W.B. & ***Vos, P.C.***, 2006. Uitzicht over de Middelzee: de opgraving van een 12e en 13e eeuwse terp- en vlaknederzetting bij Beetgumermolen (gemeente Menaldumadeel). Met bijdragen van M. Schabbink (HBS-VU), H. van Haaster, (BIAX consult) & C. Nooijen. ADC, ArcheoProjecten Rapport 650: 63 pp.

Waldus, W.B., ***Vos, P.C.*** & ***van der Heijden, F.J.G.***, 2005. Tussen veengebied en Middelzee, een geoarcheologisch onderzoek bij Scharnegoutum. ADC, ArcheoProjecten Rapport 324: 33 pp.

Wartenberger, W. & ***Freund, H.***, 2012. Late Pleistocene and Holocene sedimentary record within the Jade Bay, Lower Saxony, Northwest Germany – New aspects for the palaeo-ecological record. Quaternary International 251: 31–41.

Wartenberger, W., ***Vött, A.***, ***Freund, H.***, ***Halder, H.***, ***Frechen, M.***, ***Willershäuser, T.***, ***Schnaidt, S.***, ***Fischer, P.*** & ***Obrocki, L.***, 2013. Evidence of isochronic transgressive surfaces within the Jade Bay tidal flat area, southern German

https://doi.org/10.1017/njg.2015.4 Published online by Cambridge University Press

North Sea coast – Holocene event horizons of regional interest. Zeitschrift für Geomorphologie, Supplementary Issue: 1–18.

Wasserman, E., 1985. Auf Strecksiedlungen in Ostfriesland: ein Beitrag zur Erforschung der mittelalterlichen Moorkolonisation. Aurich. (Abhandlungen und Vorträge zur Geschichte Ostfrieslands 61): 179 pp.

Woltering, P.J., ***Besteman, J.C***, ***van Regteren Altena, J.F.*** & ***Hallewas, D.P.***, 1999. Early Medieval North Holland Surveyed: The Hollands Noorderkwartier Sheet: Early Middle Ages of the Archaeological Map of the Netherlands. Berichten van de Rijksdienst voor het Oudheidkundig Bodemonderzoek 43: 361–370 and map.

Zagwijn, W.H., 1986. Nederland in het Holoceen. Geologie van Nederland, 1, Rijks Geologische Dienst (Haarlem): 46 pp.

Appendix

Maps used for this study

Pedological maps 1:50,000 of the northern Netherlands

- *STIBOKA, 1971–1991. Bodemkaarten van Nederland, Stichting voor Bodemkartering, Wageningen.*
- *Bodemkaart van de Waddeneilanden Vlieland, Terschelling, Ameland en Schiermonnikoog (1986)*
- *Bodemkaart van Nederland, Blad 3 West Uithuizen en Blad 3 Oost Uithuizen (1987)*
- *Bodemkaart van Nederland, Blad 5 West Harlingen en 5 Oost Harlingen (1976)*
- *Bodemkaart van Nederland, Blad6 West Leeuwarden, 6 Oost Leeuwarden en het vasteland van de kaartbladen 2 West en 2 Oost (1981)*
- *Bodemkaart van Nederland, Blad 7 West Groningen (1973)*
- *Bodemkaart van Nederland, Blad 7 Oost Groningen en Blad 8 Nieuwerschans (1986)*
- *Bodemkaart van Nederland, Blad 10 West Sneek en 10 oost Sneek (1974)*
- *Bodemkaart van Nederland, Blad 11 West Heerenveen (1976)*
- *Bodemkaart van Nederland, Blad 11 Oost Heerenveen (1971)*
- *Bodemkaart van Nederland, Blad 12 West Assen (1991)*

Geological maps 1:50,000 of the northern Netherlands

- *Toelichtingen bij de Geologische Kaart van Nederland 1:50,000. Blad Assen West (12W) en Blad Assen Oost (12)*; Bosch,1990.
- *Toelichtingen bij de Geologische Kaart van Nederland 1:50,000, Blad Heerenveen West en Oost* (*11 W, 11 O*); de Groot et al., 1987.
- *Geologische overzichtskaart van Nederland. TNO Bouw en Ondergrond, Utrecht;* Schokker, 2010 (www.dinoloket.nl).
- *Toelichtingen bij de Geologische Kaart van Nederland 1:50,000, Blad 11 Blad Sneek (10 W, 10 O)*; Ter Wee, 1976.

German maps

- *Campsche Karte von Ostfriesland*; Henninger et al., 2005.
- *Geologische Karten von Niedersachsen; Geologische Holozän Basis Karte* (GHBK25) *und Geologische Karte* (GK25) *von des Landesamts für Bergbau, Energie und Geologie von Niedersachsen*; www.lbeg.niedersachsen.de.
- *Bodenübersichtskarte 1:200,000* (BÜK 200); www.bgr.bund.de.
- Peat reconstruction maps of the Niedersächsisches Bodeninformationsystem (NIBIS) of the Landesamt für Bergbau, Energie und Geologie; http://nibis.lbeg.de/cardomap3/?TH=541#.
- Background to the *Geologische Karten von Niedersachsen*; Streif, 1989a.