

Landscape history of the Oer-IJ tidal system, Noord-Holland (the Netherlands)

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Abstract

The prehistoric Oer-IJ tidal system in the coastal area of Noord-Holland, between Castricum, Uitgeest, Velsen and Amsterdam, was the successor of the Haarlem tidal system when this was silted up around 3000 BC and large peat bogs formed in the Zaanstreek and Haarlemmermeer areas. Since then the Oer-IJ has been the natural outlet to the sea, draining the peat hinterlands. About 800 BC the Oer-IJ system was connected to the fluvial system of the Utrechtse Vecht and became the northern branch of the river Rhine. During the Late Iron Age, when the Flevo lakes in the IJsselmeer region and the Utrechtse Vecht were connected with the Wadden Sea, the Oer-IJ lost its discharge function. The tidal area silted up and was closed between 200 and 100 BC by a barrier ridge. The settlement history of the Oer-IJ system and the archaeological heritage in the subsurface is closely related to the geological and hydrological development throughout the ages. The shape and location of the continuously migrating outlet determined the opportunities for human settlements and activities. The best locations were beach ridges, higher, silted-up salt marshes and marginal zones of the peatland. In the Late Iron Age the sand flats also became habitable since tidal activity had stopped. In the Early Roman period there was no direct connection from the harbour of Castellum Flevum at Velsen to the North Sea, but ships could navigate from the Oer-IJ channel between Velsen and Amsterdam, through the Flevo lakes and the Utrechtse Vecht to the Wadden Sea, and to the Roman border (Limes) along the Oude Rijn. Here the data used for the palaeogeographic landscape reconstruction of the Oer-IJ are presented and explained, and the most important landscape-forming processes, which led to the emergence and closure of the Oer-IJ, are described. The landscape reconstructions give a new perspective on the migration of the main tidal channel and the formation of the tidal-inlet system near Castricum, which was the result of the progradation of the beach ridges south and north of the Castricumerpolder (Binnendelta according to De Roo, 1953). The geological and archaeological observations in the Binnendelta prove that the Oer-IJ was closed from the open sea in the early Late Iron Age.

Keywords: Holocene geology, geoarchaeology, palaeogeography, coastal landscape evolution, Oer-IJ region

Introduction

The Oer-IJ tidal system

Güray (1952) introduced and defined the Oer-IJ as the prehistoric tidal system between Castricum–Uitgeest, Beverwijk–Assendelft and Velsen–Amsterdam that was the forerunner of the IJ-Lake (Fig. 1). It was the successor of the Haarlem tidal system that had developed between Haarlem and Amsterdam in the early and middle Holocene (Van der Valk, 1992). Owing to the rapid Holocene sea-level rise, the western Netherlands had

developed into one large tidal area in the Early Holocene, connected with the North Sea through a dozen tidal inlets (Beets et al., 1994).

Between 4000 and 3000 BC the rate of sea-level rise decreased significantly (e.g. see the sea-level curve of Van de Plassche, 1982), the tidal area in the western Netherlands filled up and large parts were transformed into peat bogs. The back-barrier part of the tidal inlet of the Haarlem system, which had moved northward over time (Van der Valk, 1992, 1996), was bounded on both sides by newly formed peatlands. After 3000 BC, when the main tidal channel was surrounded by peat bogs,

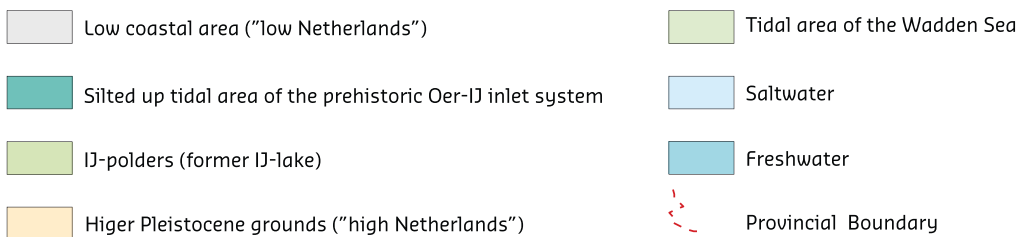


Fig. 1. *T* Location maps with the topographic names mentioned in the text. A. The northwestern part of the Netherlands, with the location of the former IJ-lake and the silted-up tidal area of the Oer-IJ inlet system; B. Location map of the Oer-IJ region.

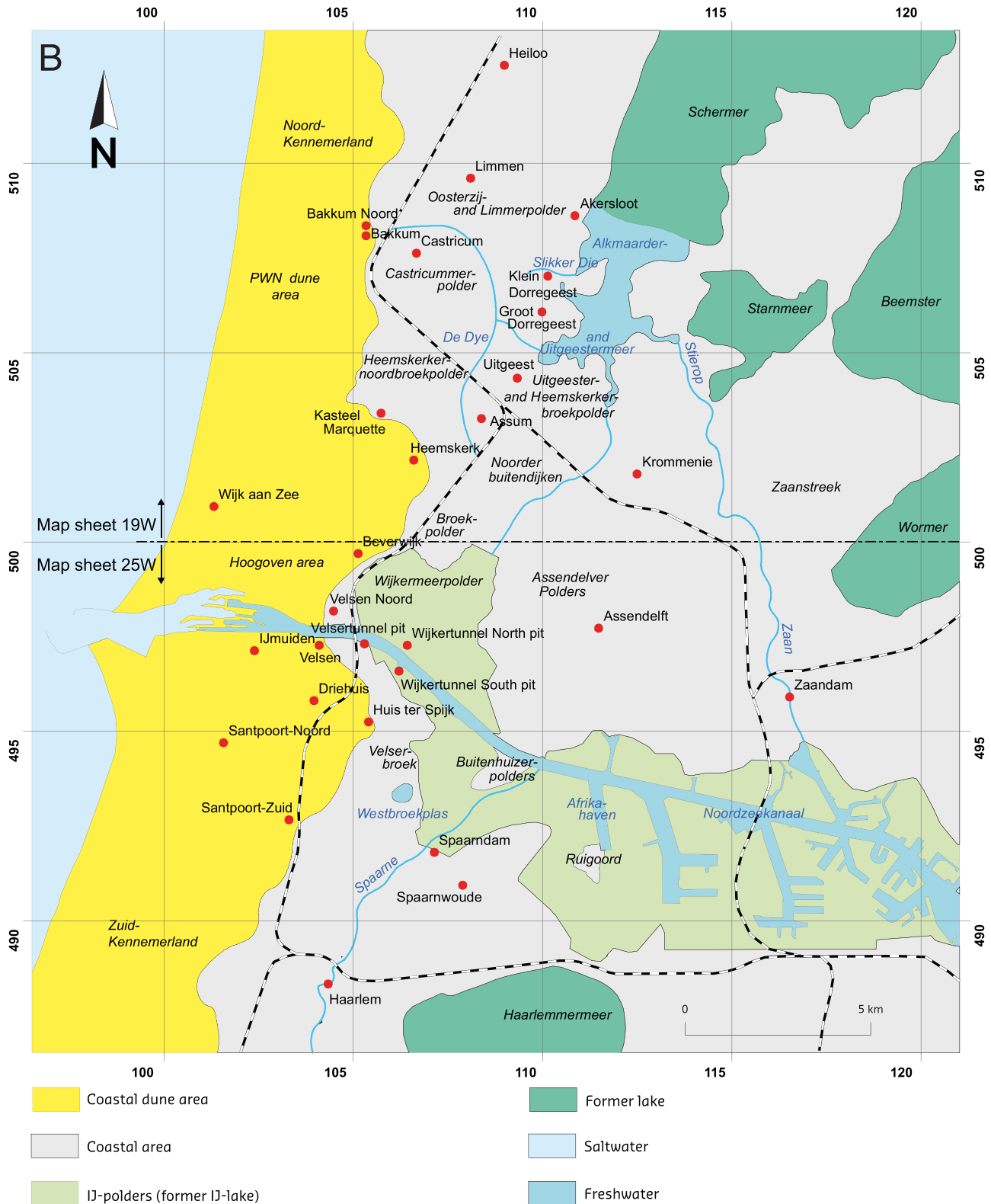


Fig. 1. Continued.

the system changed in characteristic. The well-defined channels of this so-called Oer-IJ system drained the peatlands of Noord-Holland, the peat lakes of Flevoland (the area of the IJsselmeer, Markermeer, Flevopolder and Noordoostpolder, Fig. 1;

Lenselink & Koopstra, 1994) and those along the Eem River. Following the end of the Late Bronze Age (about 800 BC), the system was connected to the Rhine river farther south through the Utrechtse Vecht (Bos, 2010). Through this connection, the

Oer-IJ became the northernmost branch of the Rhine, changing into an estuary (the *Oer-IJ Estuary*) (Zagwijn, 1971a).

Earth scientific surveys and palaeogeographic reconstructions

After the Second World War, extensive regional earth scientific surveying was carried out in the Oer-IJ area. First, soil scientists mapped the areas Noord-Kennemerland (De Roo, 1953), southern Noord-Holland (Kloosterhuis, 1954; Pons & Kloosterhuis, 1955) and IJ-Lake (Güray, 1952). Later in the 1950s, the National Geological Survey (RGD) started its systematic mapping, based primarily on coring surveys. Surficial-geological map sheets 19 West and East were published by Westerhoff et al. (1987). Map sheets 25 West and East were never completed, and only a concept surficial-geological map compiled by De Gans (RGD, unpubl.) is available for the associated area. This latter map was used by Blokzijl et al. (1995) for the popular-scientific geological map of Haarlem.

Within the framework of the geological mapping, palaeobotanical/palynological research by Zagwijn (1971b) and De Jong (1987a), and various geochronologic studies have produced valuable age control (see Appendices A1–A6). Useful information on the lateral variability of identified units has been obtained by studying temporary exposures of different dimensions. Large pits made for the construction of the Velsertunnel and Wijkertunnel (Van Straaten, 1957; Beets et al., 1996, 2003) were invaluable in understanding the sedimentary mechanisms behind the Oer-IJ deposits. Much smaller exposures in the dunes and beach plains of Kennemerland, including key sites in the Hoogovens area, enabled Jelgersma et al. (1970) to identify stages of dune formation, providing a context for preserved archaeology in the dune deposits. The most recent large-scale geo-landscape/geoarchaeological research in this area is based on observations in medium-sized pits (tens of metres) created during removal of redundant buildings and pumping stations in the dune area of the Water Supply Company Noord-Holland (PWN) in 2001 and 2002 (Vos et al., 2010).

The first palaeogeographic maps of Noord-Holland, compiled on the basis of geological data, date back to the late 1950s and early 1960s, and were made by Pons and Wiggers (1959, 1960). Zagwijn (1971a) studied the origin of the Oer-IJ and produced five additional palaeogeographic maps, largely based on the geological map of the coastal area between Bergen and Monster, farther south in Zuid-Holland (Jelgersma et al., 1970), in which the mouth of the Oer-IJ was projected near Egmond. The palaeogeographic reconstructions of the Oer-IJ by Vos from 1983 also located the tidal outlet near Egmond, specifically during the Late Iron Age. From the geological mapping of sheet 19W it has appeared, however, that the mouth of the Oer-IJ was, in its final phase, located near Castricum–Bakkum (Westerhoff et al., 1987). In his shoreline reconstructions Westerhoff also suggested that the Oer-IJ inlet formed between Uitgeest and

Heemskerk around 2400 BC (between 4000 and 3500 ¹⁴C years BP). In coastal reconstructions of the earliest period of the Oer-IJ, Van der Valk (1992) showed that the Oer-IJ evolved from the earlier tidal inlet system of Haarlem between 3000 and 2400 BC.

More recent palaeogeographic maps of the Oer-IJ area (Vos, in Lange et al., 2004 and Kok, 2008; Vos et al., 2010) are updates of the maps by Vos (1983). The protocol followed in creating these maps, including scientific methods and expert considerations, has not been addressed, however, and an overview of the abundant multidisciplinary data used has not been provided. This paper fills that gap.

Palaeolandscape and archaeology

The prehistoric Oer-IJ region is particularly relevant from an archaeological perspective because it was one of the main settlement centres in the Netherlands (e.g. Meffert, 1998; Lange et al., 2004; Kok, 2008). Abundant natural water courses made the coastal area easily accessible and kept it well drained. Elevated barrier ridges and dunes were suitable for permanent occupation. The upper, silted-up parts of salt marshes and the margins of adjacent higher lying peatland were periodically inhabited.

The favourable palaeolandscape conditions explain the presence of humans and the multitude of archaeological remains in the shallow subsurface of the Oer-IJ area. Site-specific archaeological research was conducted in the Oer-IJ region, with Roman harbour works being surveyed in Velsen (Van Straaten, 1957; Morel, 1986, 1988), being addressed in the peaty marshlands of Assendelpolders (near Assendelft; Brandt & Van der Leeuw, 1987), and Iron Age and Roman settlements being discovered in salt marsh deposits excavated in Velsbroek (Therkorn & Oversteegen, 1994) and the nearby Broekpolder (Therkorn et al., 2009). Highlights included the discovery of the early Medieval church of Assendelft on post-Roman peatland (Besteman & Guiran, 1987) and a canoe on the bottom of a tidal creek at Uitgeest-De Kleis (De Koning & Vos, 2007). Many archaeological studies provided key evidence used to improve and refine palaeolandscape reconstructions (see Appendices B1–B10). In the context of archaeological research, geological/palaeo-environmental studies by RGD, TNO and Deltares provided geoarchaeological information for palaeolandscape reconstructions and for understanding the relationship between habitation and landscape history. Key sites in the coastal dune area were the pits in the PWN dune area west of Bakkum/Castricum (Vos et al., 2010) and in the Middensluiseland Dam of the sluice complex in IJmuiden (Vos, 2008). Beach-ridge sediments were exposed in excavations and construction pits of Klein Dorregeest (Vos, 2007a; Müller et al., 2008), Limmen-De Krocht (De Dijkstra et al., 2006), and Assum and Waldijk (De Koning, 2007; Williams, 2012). The pits of Castricum-De Zanderij (Vos, 2007) and Uitgeest-Benes (De Koning & Vos, in prep.) provided

valuable palaeolandscape information for the last marine phase of the Oer-IJ tidal area (for locations, see Fig. 1 and Fig. App. A).

For basic descriptions of the archaeology from the Late Neolithic up to the Late Middle Ages in the Oer-IJ area we refer, for example, to Lange et al. (2004), De Koning (2007), Williams (2012), Müller et al. (2008), Vos et al. 2010, Therkorn et al. (2009) and the dissertations of Therkorn (2004) and Kok (2008).

Methods

Geomorphology, subsurface geology and archaeology are the main pillars of palaeolandscape reconstruction for the Oer-IJ region, each with its own spatial and temporal strengths and weaknesses. Concerning the subsurface, a litho- and chronostratigraphic framework provides the context, whereas geological mapping uses the stratigraphic framework in creating logical and consistent visualisations of the distribution of stratigraphic units.

All landscape reconstructions presented in this paper are founded on combining a thorough, pre-existing geological framework with digital terrain models created using LIDAR images, with relevant information from key archaeological sites, and with absolute ^{14}C (radiocarbon) and optically stimulated luminescence (OSL) age control. The geological map (Fig. 2) and LIDAR images of the Oer-IJ region (Fig. 3) constrain the spatial extent of geological features at and below the surface. Using absolute and relative (archaeological) age control on these features, the palaeolandscape was reconstructed in series of palaeogeographic maps. Absolute ages, available from publications and reports, are presented in Appendices A1–A6 (Fig. App. A) and the palaeolandscape information of the key sites in Appendices B1–B9 (Fig. App. B).

Lithostratigraphy

The Holocene coastal deposits of the Netherlands are divided hierarchically into formations, members and layers. Clastic coastal deposits as dune, beach and tidal facies all belong to the Naaldwijk Formation (Westerhoff et al., 2003; Fig. 4). The organic deposits accumulated in coastal-peat bogs belong to the Nieuwkoop Formation. The peat layer at the base of the Holocene coastal sequence – directly on top of the Pleistocene substrate – is called Basal Peat (Doppert, 1975; Westerhoff, 2003). Peat layers underlain by Holocene clastic tidal deposits are called Holland Peat. On the landward side of the Oer-IJ system, a particularly thick layer of Holland Peat occurs. At its base, this peat is eutrophic (reed peat and reed-sedge peat). In the central parts of the area marked by thick Holland Peat, oligotrophic peat with recognisable remains of heather, peat moss

and cotton grass covers the eutrophic peat. Woody peats have not been found in the Holland Peat around the Oer-IJ. However, twigs of shrubs are locally preserved. Myrtle, occurring in mesotrophic to oligotrophic peat, is one of the species identified. In the Assendelpolders there is evidence that the peat was partly dehydrated as a result of the activity of prehistoric humans.

In the study area, the following clastic members are distinguished within the *Naaldwijk Formation* (Fig. 4), from base to top:

Wormer Member: Tidal deposits between the Basal Peat and the Holland Peat, or between separate Holland Peat layers. Humic and lagoonal clays at the base of this unit are assigned to the *Velsen Layer* (Bennema, 1954).

Walcheren Member: Tidal deposits above the uppermost Holland Peat layer or, in the absence of Holland Peat, the Basal Peat (Vos, 2015).

Zandvoort Member: Beach sands, usually below the dune sands of the *Schoorl Member*.

Schoorl Member: Coastal dune deposits with thin peat layers, including any humic soils.

Within the *Schoorl Member*, the classical distinction between *Younger* and *Older Dunes* (Doppert, 1975) has been kept in the new classification. The *Younger Dunes* consist of parabolic dunes with more relief than the *Older Dunes*. They locally exceed 10 m +NAP (the Dutch ordnance level, around mean sea level) and were formed largely after 1000 AD. The *Older Dunes*, generally not exceeding 6 m +NAP, contain (peat) soils and ancient culture layers in many places.

In this paper, the tidal sediments of the Oer-IJ system are referred to as *Oer-IJ deposits*. They belong to the *Walcheren Member*. Within the Oer-IJ deposits, different sub-units are distinguished on the basis of their sedimentary characteristics (lithofacies):

Subtidal channel and tidal-inlet deposits include sandy channel sediments formed below mean low water (MLW). They are layered and contain varying amounts of shells (partially in layers), (peat) detritus and clay (partially in laminae). The shell assembly consists largely of an open marine fauna, of which *Spisula subtruncata* (cut through shell) is the most important one.

Intertidal-flat deposits are dominated by sandy sediments, deposited between mean low and mean high water (MHW) levels. In their upper parts, these tidal-flat deposits are commonly slightly clayey and homogenised owing to bioturbation (mixing) by tidal-flat organisms. Downward the sands may be laminated with clay. The main shell species preserved in these facies and commonly found in life position are *Scrobicularia plana* (peppery furrow shell), *Macoma balthica* (Baltic tellin), *Cerastoderma edule* (common cockle) and *Peringia ulvae* (Laver spire shell; ‘*Hydrobia*’, in the older geological literature).

Upper-intertidal salt-marsh creek and supratidal-levee deposits are composed mainly of clays with some fine laminae

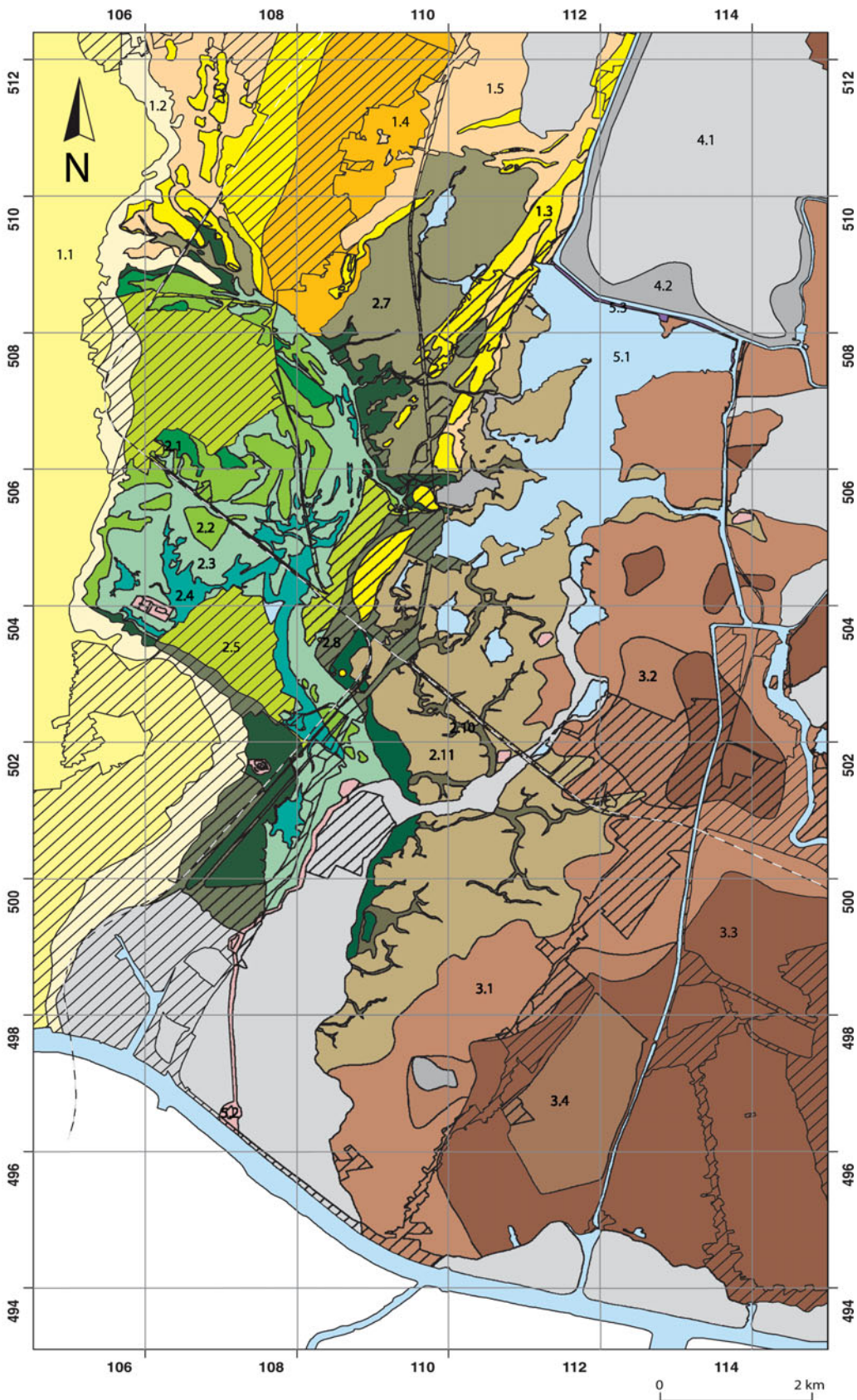


Fig. 2. Geological map of the northern part of the Oer-IJ region (from Kok, 2008). Numbers on the grid stand for kilometres in a national coordinate system (RD, Rijksdriehoek coordinates).

1. Coastal dune, beach ridge and beach plain landscape

- 1.1 Thick dune sand, above 1 m +NAP
- 1.2 Thick dune sand, below 1 m +NAP
- 1.3 Beach-ridge sediments
- 1.4 Thin aeolian sand on top of beach plain deposits, with a peat layer in between
- 1.5 Thin aeolian sand on top of beach plain deposits, without a peat layer in between

2. Oer-IJ tidal landscape

- 2.1 Intertidal deposits near the surface, relatively high elevation
- 2.2 Intertidal deposits near the surface, relatively moderate elevation
- 2.3 Intertidal deposits near the surface, relatively low elevation
- 2.4 Intertidal deposits near the surface, lowest elevation in basins
- 2.5 Intertidal deposits near the surface, undifferentiated
- 2.6 Salt-marsh-ridge deposits, on top of tidal deposits
- 2.7 Salt-marsh-plain deposits, on top of tidal deposits
- 2.8 Salt-marsh deposits, on top of tidal deposits, undifferentiated
- 2.9 Salt-marsh-ridge deposits, on top of peat
- 2.10 Salt-marsh-creek and levee deposits, incised in peat (inversion ridges)
- 2.11 Salt-marsh- plain deposits, on top of peat deposits

3. Peat landscape

- 3.1 Eutrophic peat deposits (mainly reed – sedge peat)
- 3.2 Mesotrophic peat deposits (a.o. with bog myrtle and birch shrubs)
- 3.3 Oligotrophic peat deposits (o.a with peat moss and heath)
- 3.4 Reclaimed and partly excavated peat

4. Former lake landscapes

- 4.1 Lake deposits, on older tidal deposits
- 4.2 Lake deposits with peat remains on older tidal deposits

5. Other landscape elements

- 5.1 Water, (lakes and canals)
- 5.2 Historical infrastructure
- 5.3 Dikes
- Non mapped area
- Built-up area and large infrastructure

Fig. 2. Continued.

of detritus and sand and/or silt. These deposits are sandier than adjacent salt-marsh deposits.

Supratidal salt-marsh deposits consist of grey organic clays, with the clastic component deposited at spring tides and/or during storms. Towards the peatlands of the Zaansteek, salt-marsh deposits become more humic ('peaty') and intensely rooted by reed. The salt-marsh clays fringing the coastal barrier, however, are lighter coloured and contain more silt and sand.

The names used for the various lithofacies are combined with the depositional system responsible for their accumulation (Oer-IJ), for example Oer-IJ channel deposits and Oer-IJ salt-marsh deposits.

The *IJ-Lake deposits* of the post Roman IJ-Lake between Amsterdam and Velsen include the fills of channels incised into Oer-IJ deposits, consisting of heavy humic clay and partially decayed organic material (peat chunks and peat detritus), and the clayey and sandy lake bottom lateral of channel fills. The sandy lake-bottom sediments in the vicinity of Velsen often contain peat detritus and are called the *Dirty Sands* (Bennema & Pons, 1957; Bosman, 2011).

Geological map and LIDAR images

Existing geological maps of Westerhoff et al. (1987) and Blokzijl et al. (1995) were supplemented and refined using LIDAR images of the land surface from the digital terrain model *Actueel Hoogtebestand Nederland* (AHN). On LIDAR images, the present-day surface expression of prehistoric Oer-IJ landscapes such as former main tidal channels and creeks in the clay-on-peatland (peat area covered thin clay layer of max. 0.5 m) can be recognised. Despite the intensive urbanisation, the morphological features are still visible over a large area (Fig. 3). Even the silted-up, closed sea-arm west of Bakkum, which was covered by *Younger Dunes* in the Middle Ages, is recognisable as these overlying dunes are lower here than to both the north and south.

Age control

Numerous samples from building pits, excavations, trenches of gas pipes and boreholes have been dated using ^{14}C (on plant and shell material) and OSL (on silt and sand) (Fig. App. A). In one case (building excavation De Kleis in Uitgeest), dendrochronological analysis of an oak canoe found at the base of a tidal-channel fill was used for dating. An overview of hundreds of ^{14}C dates and dozens of OSL dates, including their relevance to the palaeogeographic reconstruction of the Oer-IJ region, is given in Appendices A1–A6.

Archaeologically constrained ages are an important addition to absolute ages. Pottery provides an indication of the archaeological period in which it was manufactured, and offers the possibility of corroboration.

Palaeolandscape evolution

Using geological, morphological and archaeological information, the evolution of the Oer-IJ landscape is visualised in palaeogeographic maps at supra-regional and regional levels. At the supra-regional level, the maps (Fig. 5) show the entire Holocene coastal evolution of the northwestern Netherlands down to the Oude Rijn estuary in the lower-left corner. Regional maps of the Oer-IJ between Heiloo in the north and

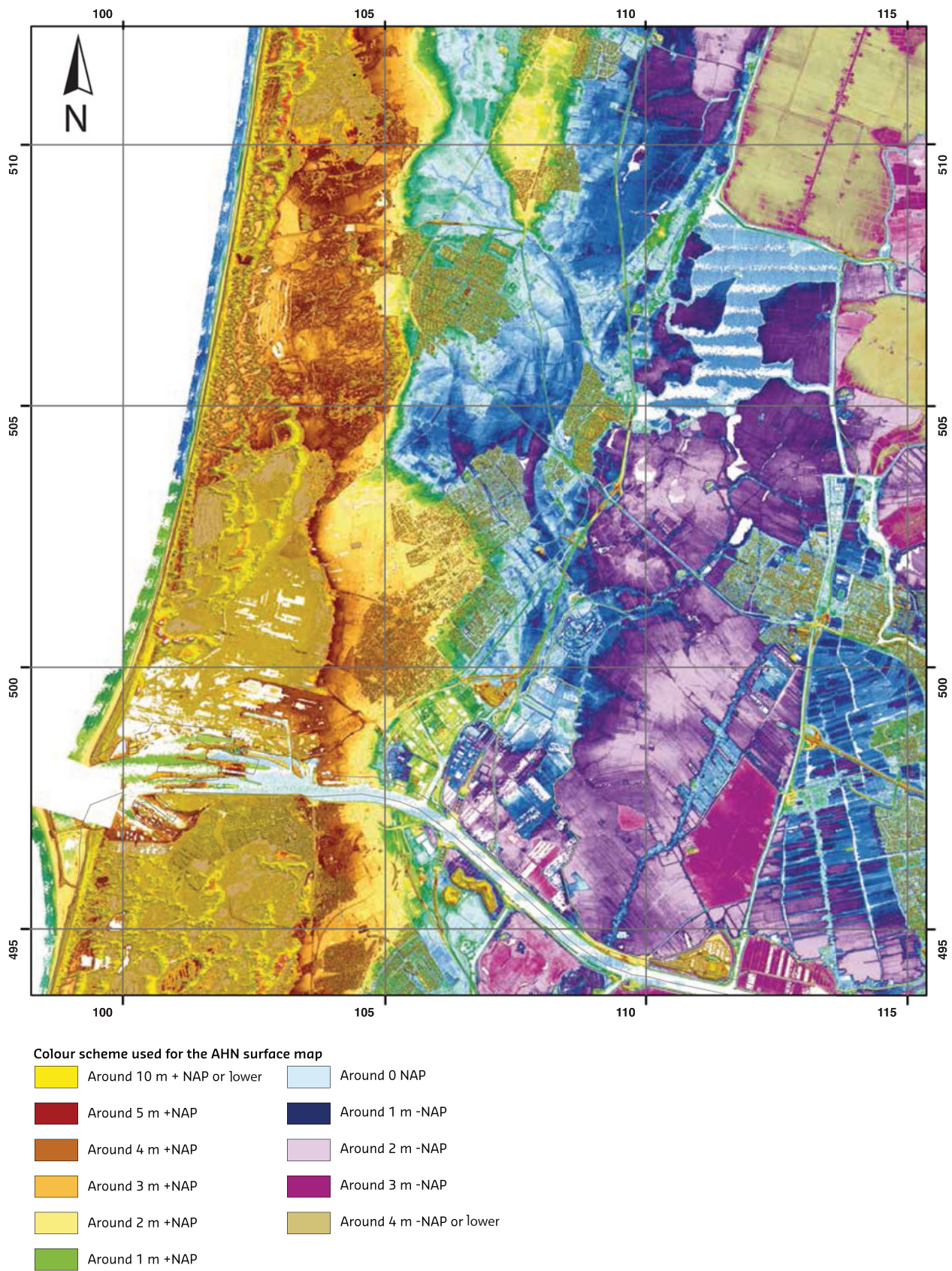


Fig. 3. LIDAR-generated elevation map (AHN) of the Oer-IJ region.

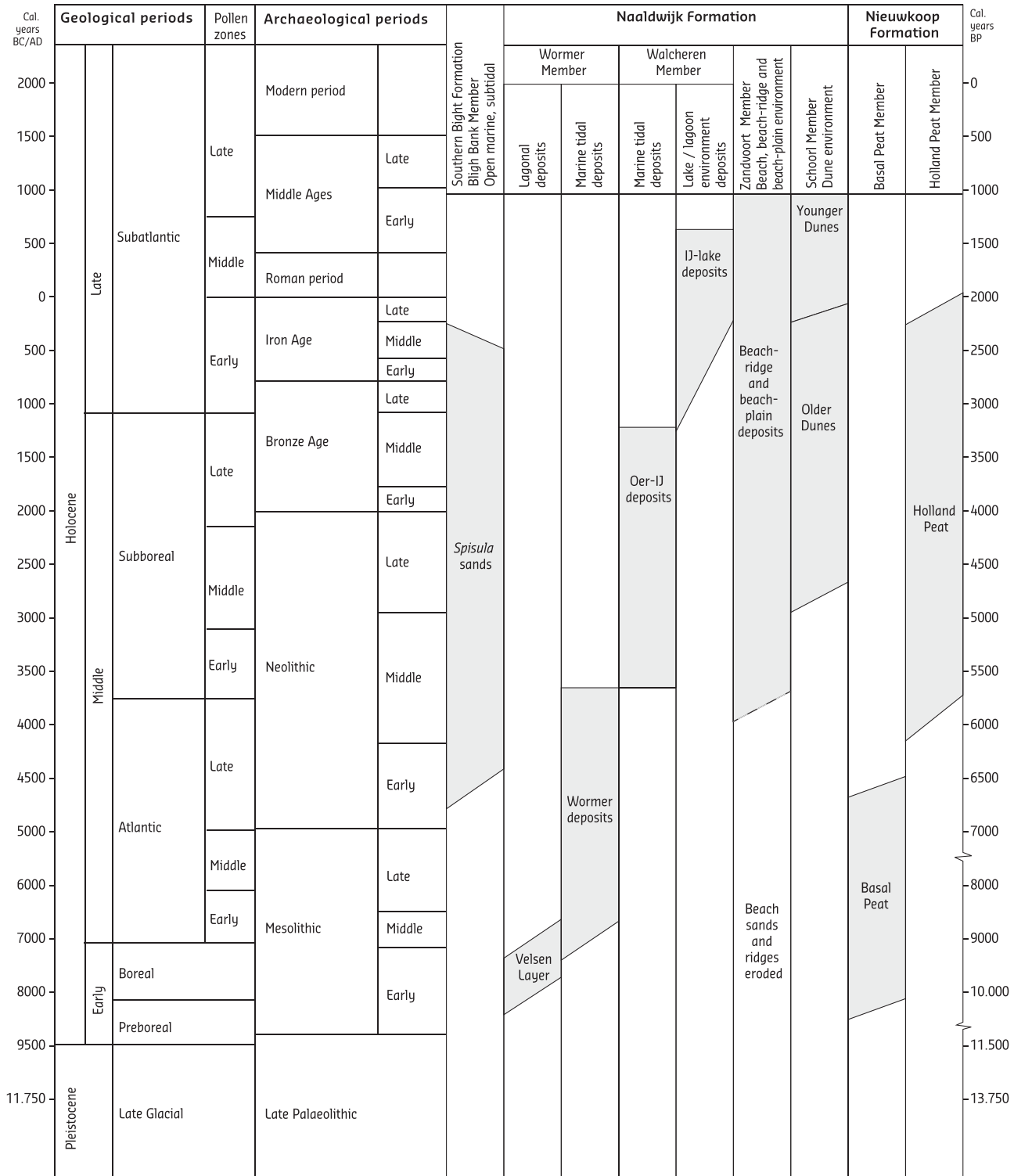


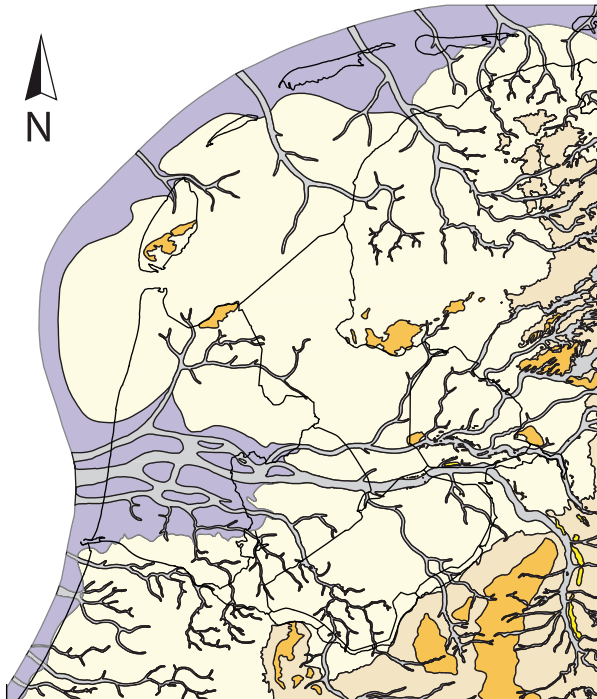
Fig. 4. Holocene chrono- and lithostratigraphy of the coastal deposits in the subsurface of the Oer-IJ region.

Velsen in the south (for extent, see Fig. 1) cover the period 2500 BC to 1000 AD (Fig. 6), and show the landscapes in and around the Oer-IJ from its inception to its final silting-up, as well as the formation of the IJ-Lake (Fig. 6). A reconstruction of beach ridge and dune progradation in the Oer-IJ region between 3500 BC and 500 AD, drawn on the basis of these maps, is shown in Fig. 7.

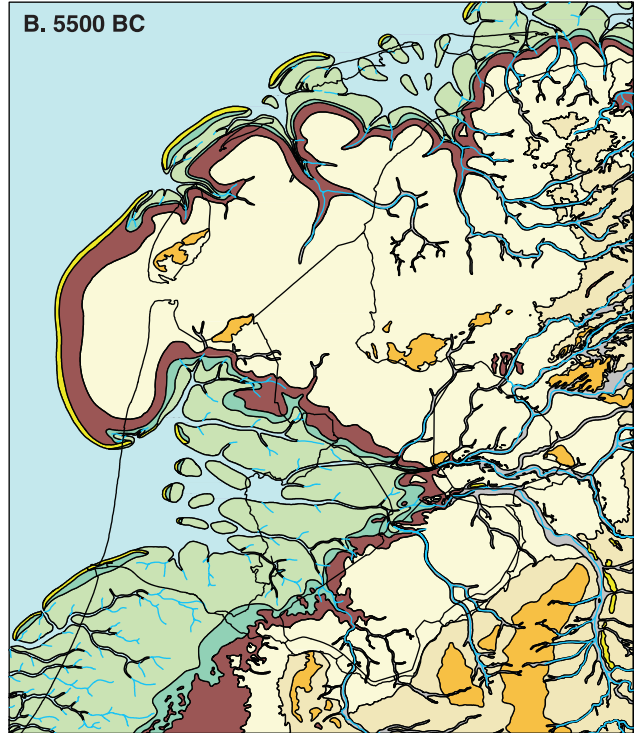
The history of the Oer-IJ system from a long-term supra-regional perspective

In the early Holocene sea level was around 35 m -NAP. The present-day Dutch coastal area and a large part of what is now the bottom of southern North Sea were dry (cf. Beets & Van der Spek, 2000). A remnant of the Overijsselse Oer-Vecht Valley

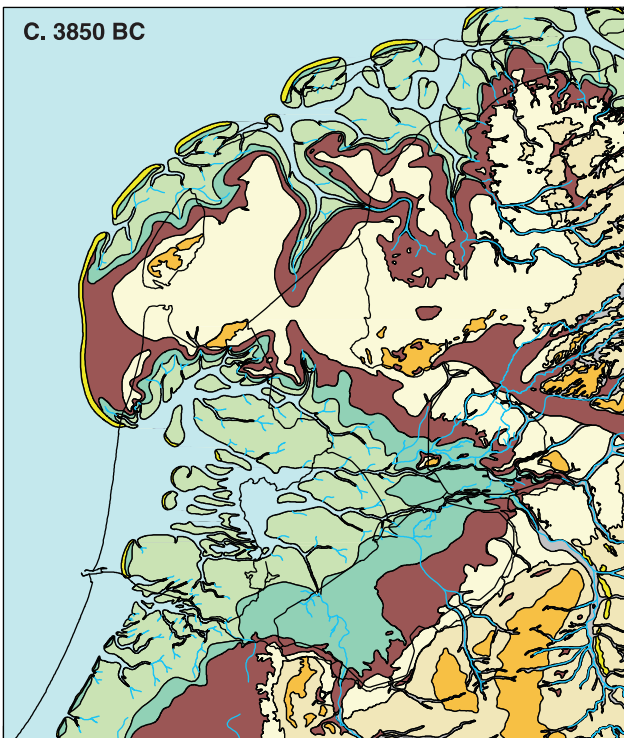
A. 9000 BC



B. 5500 BC



C. 3850 BC



D. 2750 BC

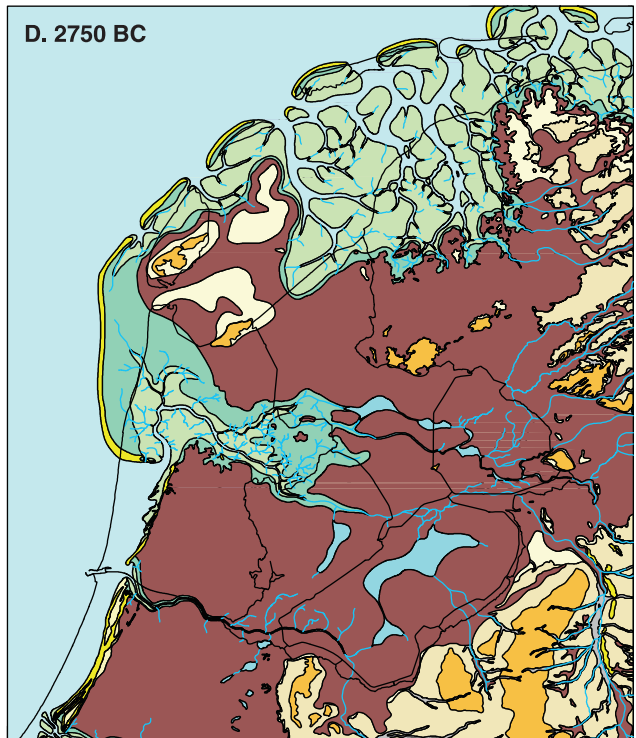


Fig. 5. Palaeogeographical maps of the northwestern Netherlands between 9000 BC and present (revised after Vos et al., 2011).

in the middle of Noord-Holland (Fig. 5A) represents an ancient course of the Rhine River during the Saale ice age. Earlier the Rhine ran in a northwesterly direction to the North Sea, but the Saale ice front along the Wieringen–Gaasterland line deflected the course of the river westward. South of the ice front a new river valley formed and low contemporary sea level allowed

the Rhine and its tributaries to deepen the valley significantly (Busschers, 2008). During the subsequent Eem interglacial and Weichsel glacial the primeval valley was partly filled with marine and terrestrial deposits (Westerhoff et al., 1987). In the early Holocene, the Overijsselse Vecht, draining the eastern part of the Netherlands and part of Germany, debouched into

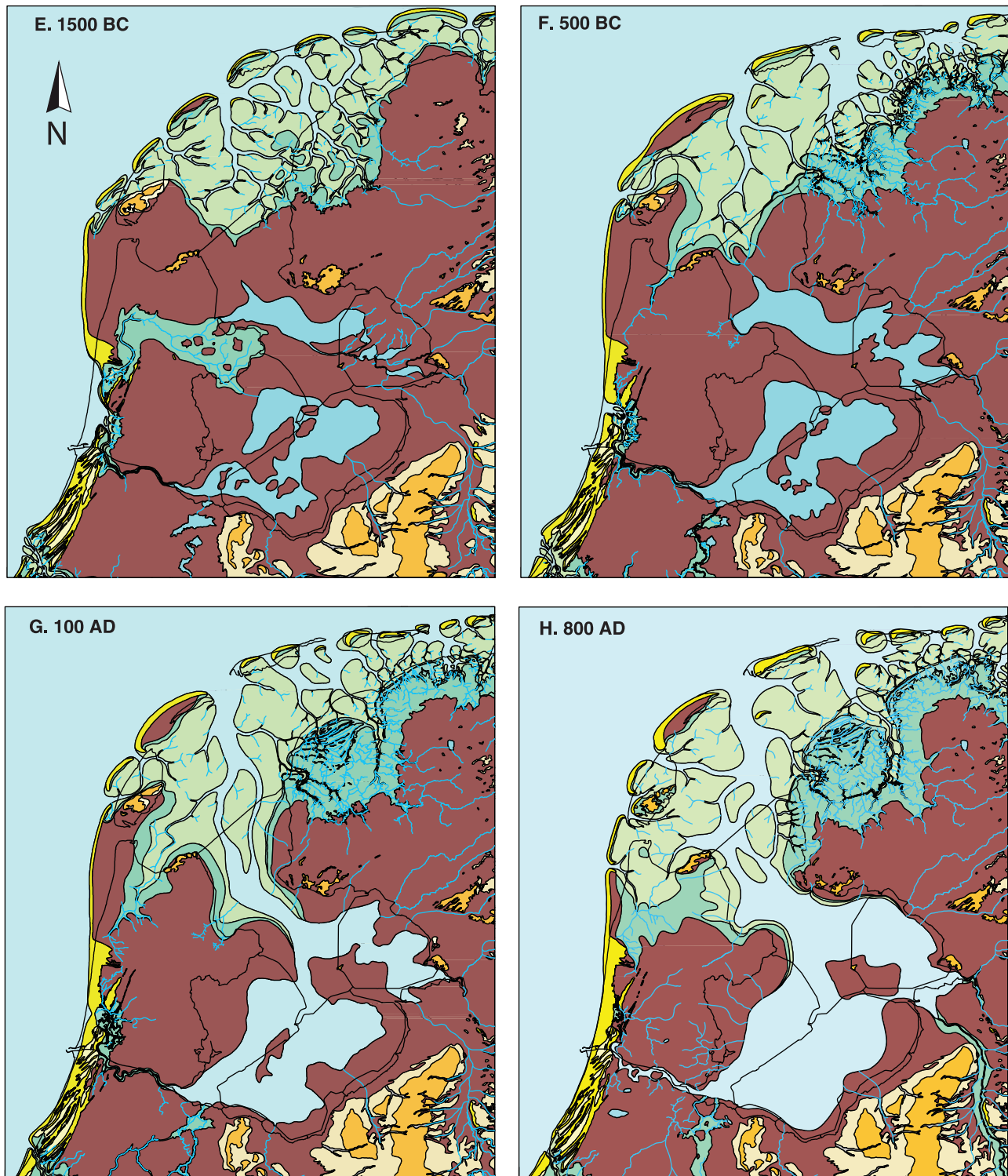


Fig. 5. Continued.

this still considerable oversized valley, with the much larger Rhine following a more southerly course towards the Maas Estuary near Rotterdam (e.g. Busschers, 2008). The deepest part of the valley in the central part of Noord-Holland at the beginning of the Holocene was ~ 25 m $-NAP$. The later Oer-IJ was located along the southern edge of this valley. Here, the top of

the Pleistocene surface, where it is not eroded by younger tidal channels, lies between 23 and 16 m $-NAP$ (Westerhoff et al., 1987).

Late Palaeolithic and Mesolithic hunters and gatherers likely encamped in this area, and archaeological remains possibly occur in the upper part of Pleistocene deposits, where not eroded

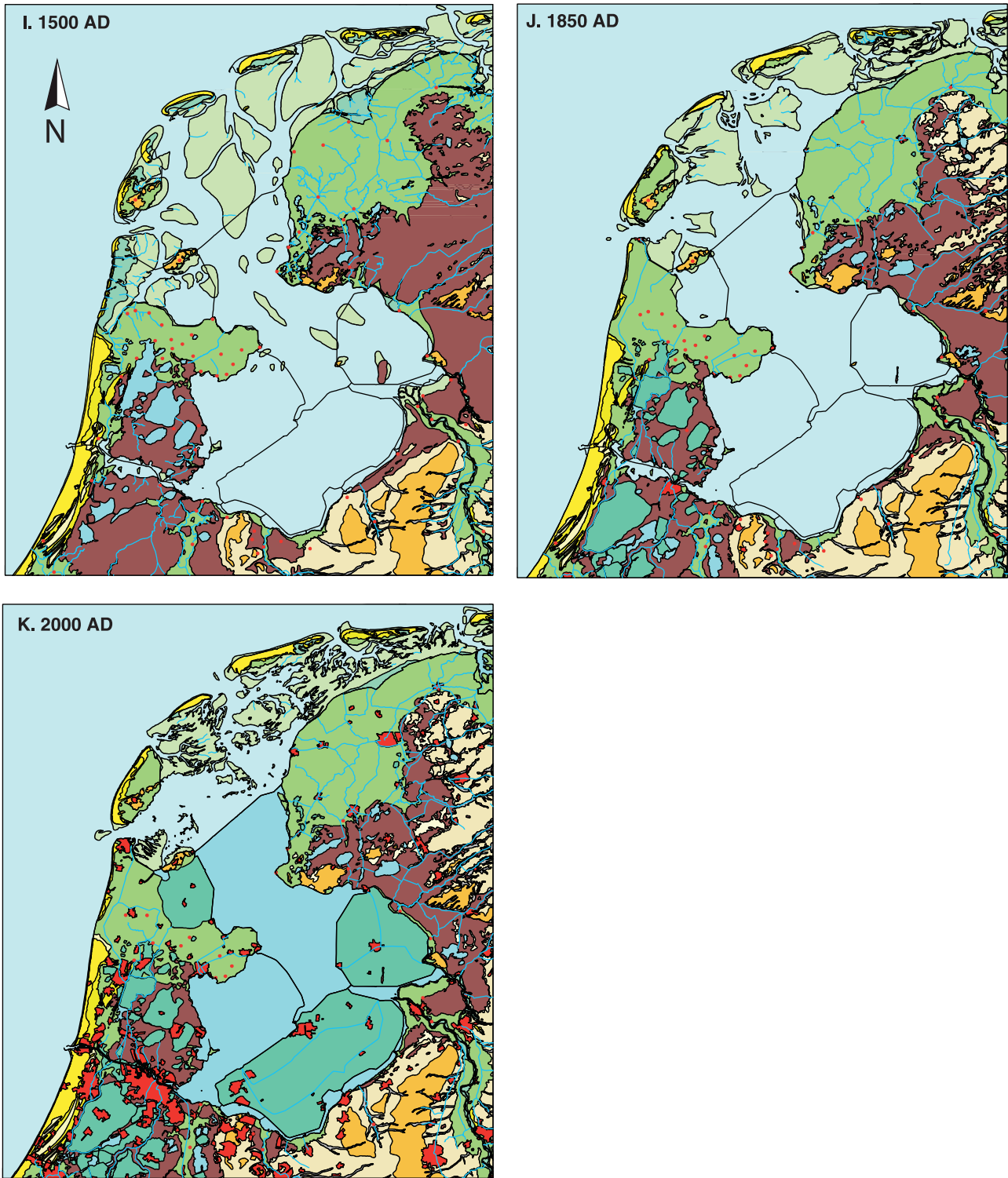


Fig. 5. Continued.

by younger Holocene tidal channels (Van Heeringen & Theunissen, 2001).

The geometry of the valley system had a strong influence on the drowning of Noord-Holland during the Holocene. The rapid sea-level rise in the early Holocene (Jelgersma, 1996; Van de Plassche, 1982; Kiden, 2002) raised the water table in this

palaeovalley, resulting in *Basal Peat* formation in a zone that showed an overall landward shift in time together with the landward-expanding open-water tidal basin (deposition of the *Wormer Member*) seaward of the peat landscape. In the PWN dune area, peat formation began around 7535 BC at about 23 m -NAP (B945-7; Table A3.20).



Fig. 5. Continued.

With continued sea-level rise, the peat area in the lowest part of the valley (25–20 m -NAP) was drowned around 7500 BC. Stratified humic clays of the lagoonal *Velsen Layer* continued to be formed in the PWN dune area, at least up to about 6720 BC (B45–6; Table A3.20). Near the Velsertunnel construction pit, where the top of the Pleistocene sand is at around 16 m -NAP, the Basal Peat was formed later, around 6085 BC (VT-5 and 6; Table A4.7); until shortly before that time lagoonal accumulation had taken place near the nearby located borehole Beverwijk-Wijkerbroek (WIJ-3; Table A4.8). The lagoons and coastal marshes were unsuitable for residential sites and camps, but fishing and hunting by Stone Age humans may well have been possible in these environments. No archaeological evidence of human presence in Noord-Holland during the early Holocene has been found yet. Artefacts found buried in the Maasvlakte area of the Port of Rotterdam (18.5–20 m -NAP), farther south, show that humans were present in the Dutch coastal lowlands during the early Holocene (Moree & Sier, 2014).

Around 6500 BC the southern and northern North Sea became connected and the North Sea had grown to about its present size. The deepening of the North Sea and other changes in its bathymetry led to an increase in tidal amplitude along the Dutch coast (Van der Molen & De Swart, 2001; Hijma & Cohen, 2011). In the drowning Overijsselse Oer-Vecht system, increased tidal forces stimulated the formation of large tidal channels. At drilling locations B43 (B43–7; Table A3.18; Fig. App. A) and Wormer (BW-7 and 8; Table A1.2; Fig. App. A) the bases of channel fills date to around 5800–5700 BC. In the first half of the Atlantic, sedimentation could not keep up with rapid sea-level rise (Fig. 8), and an embayment arose, with tidal flats and associated tidal channels toward the landward basin margin (Van der Spek, 1994; Beets & Van der Spek, 2000; Beets et al., 2004; Fig. 5B).

Around 3850 BC the Overijsselse Oer-Vecht tidal basin had reached its maximum extent, enveloping almost all of Flevoland (Ente, 1986; Lenselink & Koopstra, 1994), while the location of the later Oer-IJ tidal system was still largely seaward of the contemporary coastline (Fig. 5C). To its south the tidal-inlet system of Haarlem extended all the way to present-day Amsterdam. The expansive tidal-basin landscape dominated by channels and sand flats was not suitable for habitation; unsurprisingly, no archaeological remnants have been found in the lower and middle part of the tidal deposits of the *Wormer Member*. Along the landward margins of this large tidal basin there is some evidence of occupation and habitation (5000–3400 BC) on creek ridges and Pleistocene sand outcrops near, amongst others, location P14 in the Noordoostpolder and near Swifterbant in the Flevopolder (Deckers et al., 1980; Raemaekers et al., 2010; Ten Asscher, 2012).

After 3850 BC the embayment silted up gradually. Sediment from the sea and from rivers began to catch up and even exceed the accommodation space created by decelerating sea-level rise, resulting in a reduction of the tidal prism and a decrease in channel size and back-barrier tidal range (Van der Spek, 1994; Beets & Van der Spek, 2000). With the reduction of the tidal prism (the volume of water flowing into and out of the tidal basin during each tidal cycle) the wet cross-sectional area of the associated tidal inlet decreased (Oost & De Boer, 1994). As less sediment became needed to fill newly created space in the back-barrier environment, the landward migration of the shoreline stopped and the barrier started to prograde through beach-ridge formation (cf. Cleveringa, 2000). More and more of the tidal hinterland silted up to salt-marsh level (Vos & De Wolf, 1988, 1994), falling dry for prolonged periods and enabling vegetation to colonise the surface. In Westfriesland and the Wieringermeer this salt-marsh landscape was inhabited (e.g. De Weerd, 1965; Van Heeringen & Theunissen, 2001; Kleijne et al., 2013). Neolithic remains in the Amstel River deposits, found during the excavation of the North–South Metro Line in the old town of Amsterdam, are reworked and probably originate from this salt-marsh landscape as well.

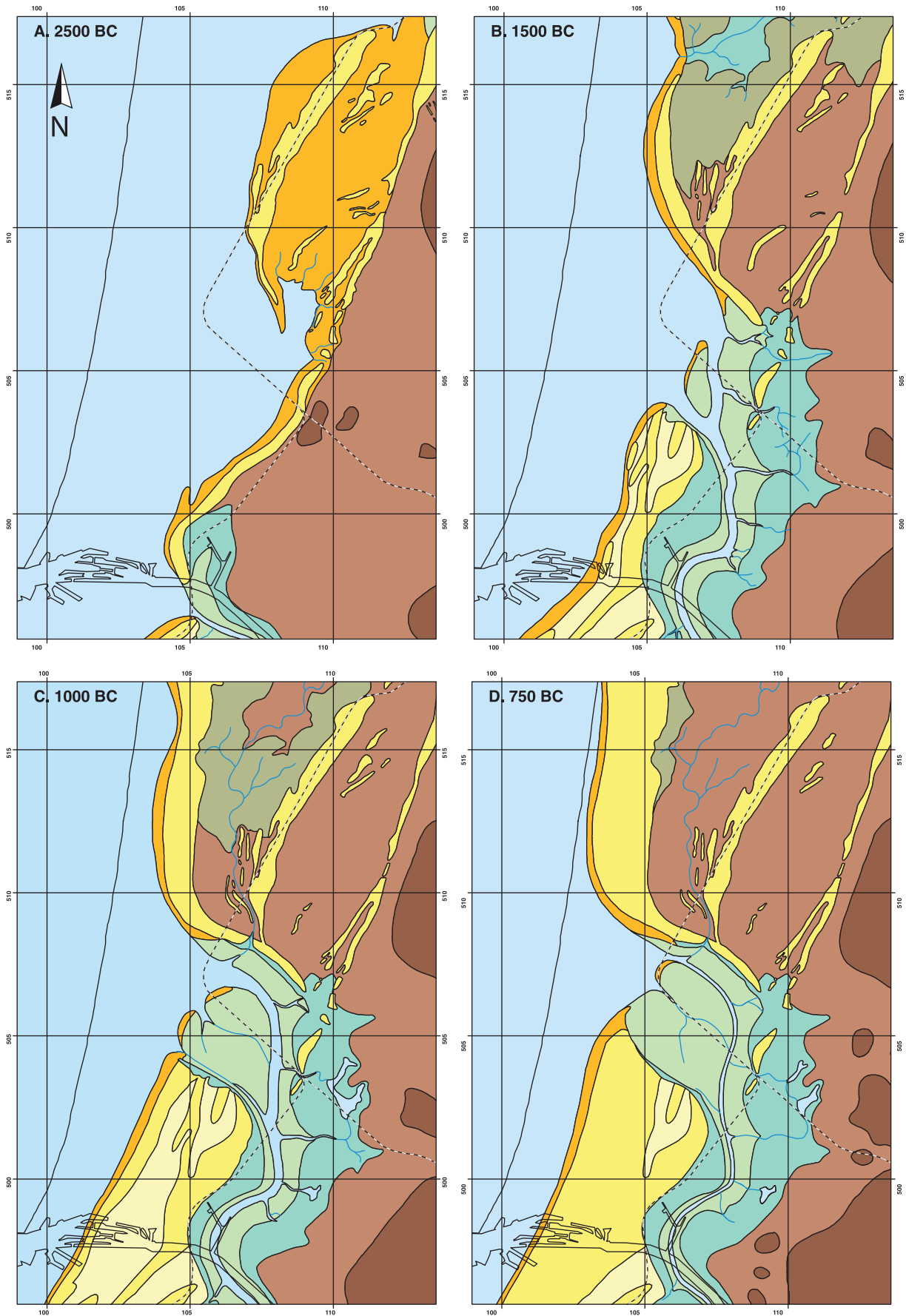


Fig. 6. Palaeogeographical maps of the Oer-IJ region between 2500 BC and 1000 AD (revised after Vos et al., 2010).

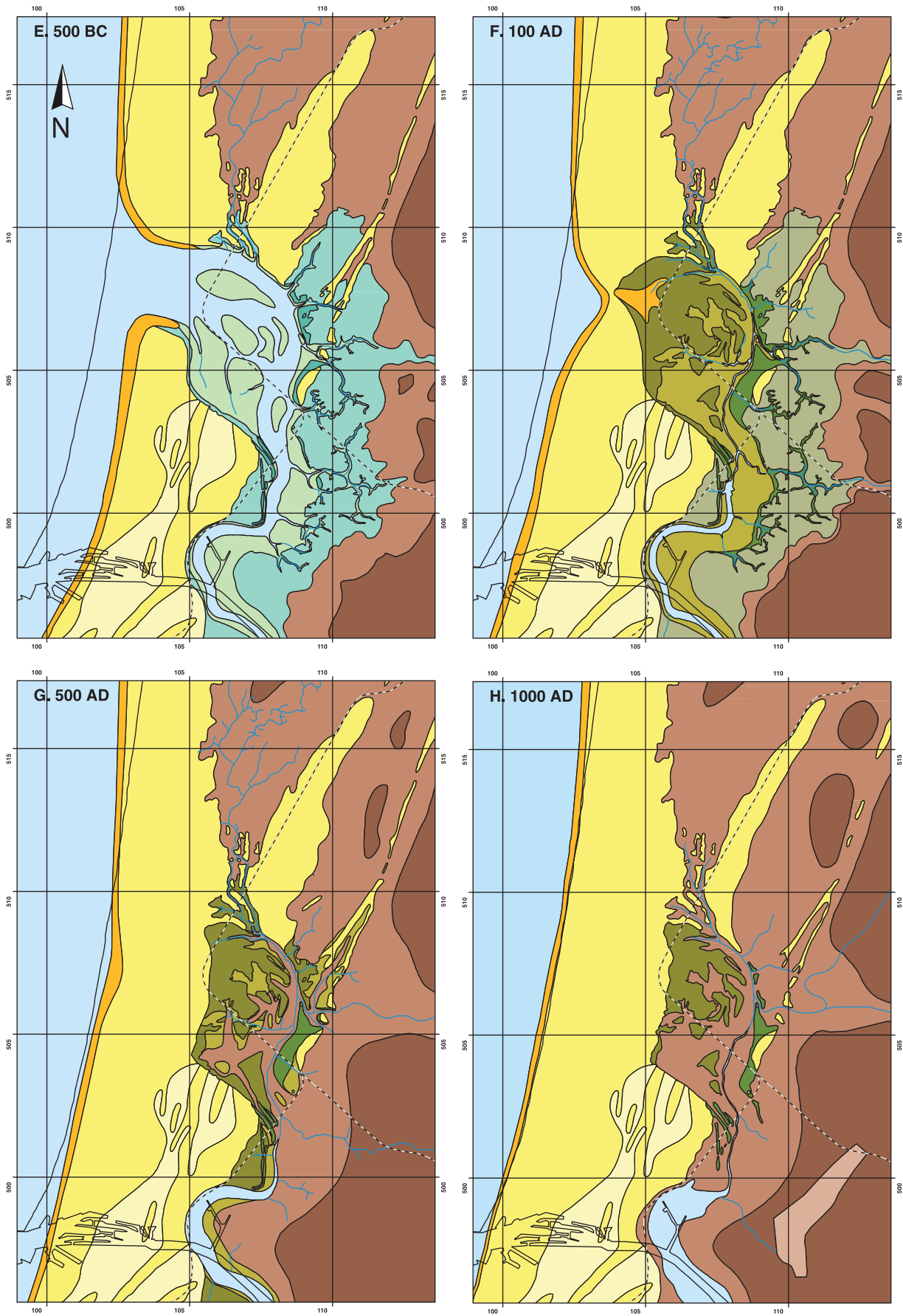









Fig. 6. Continued.


Tidal landscapes*Subtidal area*
 North Sea, tidal channels, lagoons
Intertidal area
 Mud and sand flats
Inter- / supratidal tidal area
 Beaches and washovers
Terrestrial landscapes*Supratidal area*
 Salt-marsh plains

 Salt-marsh ridges and levees
Dune landscape
 Higher dune areas

 Lower dunes and dune valleys, partly filled up with peat
Peat landscape
 Eutrophic peatlands

 Meso- and oligotrophic peatlands

 Reclaimed, formerly drowned peatlands
Former tidal landscape, permanently dry
 Former mud and low sand flats, permanently dry

 Former high sand flats and washovers, permanently dry

 Former salt marsh ridges and levees, permanently dry

 Former salt-marsh plains, permanently dry
Line symbols
 Creeks and other small water courses

 Present coastline and Noordzeekanaal

 Railway

Fig. 6. Continued.

The gradual silting-up of the embayment's tidal inlets and the infill of tidal channels strongly deteriorated the natural drainage of the hinterland, which became waterlogged and started to enable large-scale peat development between 3200 and 2500 BC (BN-2, Table A1.1; BW-2, Table A1.2; OM-1, Table A1.6; BK-1, Table A1.7; HO-1, Table A1.8; BH-1, Table A1.9; BII-1, Table A1.10 and MD-1, Table A1.11; for locations, see Fig. App. A). The central parts of the peatland became completely isolated from the sea, nutrient-rich water was no longer supplied, and oligotrophic peat formation and accumulation started. Near locations Neck (BN) and Wormer (BW) the oligotrophic peat formation began between 3000 and 2750 BC (BN-1, Table A1.1; BW-1, Table A1.2).

Around 3000 BC a relatively small tidal channel subdivided the large peatland that included both the Zaanstreek in the

north and the Haarlemmermeer area in the south. The tidal system associated with this channel, known as Oer-IJ, continued to have an open connection to the sea because it provided the natural drainage of the surrounding peatland, including several peat lakes in the low-lying peat depressions in Flevoland (Lenselink & Koopstra, 1994) and the Eem River (Fig. 5D).

After 2750 BC (Fig. 5D) the Oer-IJ drained all of the southern Flevoland peat hinterland and later – around 800 BC (Bos, 2010) – also the Utrechtse Vecht region. The IJsselmeer area and the Noordoostpolder drained through the much larger Westfrieze inlet system farther north, which formed the main remnant from the Oer-Vecht tidal basin. The two inlet-related tidal systems became separated completely by peatland (Lenselink & Koopstra, 1994).

During the following centuries the progradation of the coastline accelerated, causing marine influence in the hinterland to dwindle even further. The reduced influence of the sea made Late Neolithic and Bronze Age settlement possible on the highest salt-marshes (Roep & Van Regteren Altena, 1988). Around 1750 BC, the Westfrieze tidal system was still active (Vos et al., 2013), but after about 1500 BC the inlet silted up and the shrinking tidal basin was cut off from the sea upon complete barrier closure (Roep et al., 1979; Beets et al., 1996; Fig. 5E (note that these two publications report ages in non-calibrated ^{14}C years BP, about 250 years younger than the calibrated ^{14}C ages BC). As a result of the closure, the natural drainage of the Westfrieze tidal system to the sea was impeded, the groundwater level rose in the area and large-scale peat growth started at the cost of a salt-marsh area that became increasingly saturated with water. The replacement of supratidal environments with peat bogs significantly reduced the possibilities for settlement in the Late Bronze Age and Early Iron Age.

As a result of the silting-up and closure of the Westfrieze tidal basin after 1500 BC, a series of beach ridges developed between Limmen and Bergen, forcing the coastline to migrate seawards beyond its present position. The Middle Holocene embayment silted-up (Figs 5C–F) and due to this infilling also between Velsen and Beverwijk the beach ridges and dunes show a pattern of seaward coastal accretion (Fig. 7). The progradation of the coastline on both sides of the contemporary Oer-IJ mouth led to the development of a sandy tidal-flat area (the area between Castricum and Uitgeest), interpreted as an inner or flood-tidal delta by De Roo (1953).

The connection with the Rhine River through the Utrechtse Angstel–Vecht system only emerged after 800 BC, when the peat lakes in the Vecht region became interconnected (avulsion process) and a continuous waterway between the Rhine and the Flevo lakes was created (Bos, 2010). From south to north, the smaller lakes in the Vecht region were filled one by one with fluvial Rhine deposits. Through the new, northern connection, the Rhine eroded channels, incising the previously formed lake

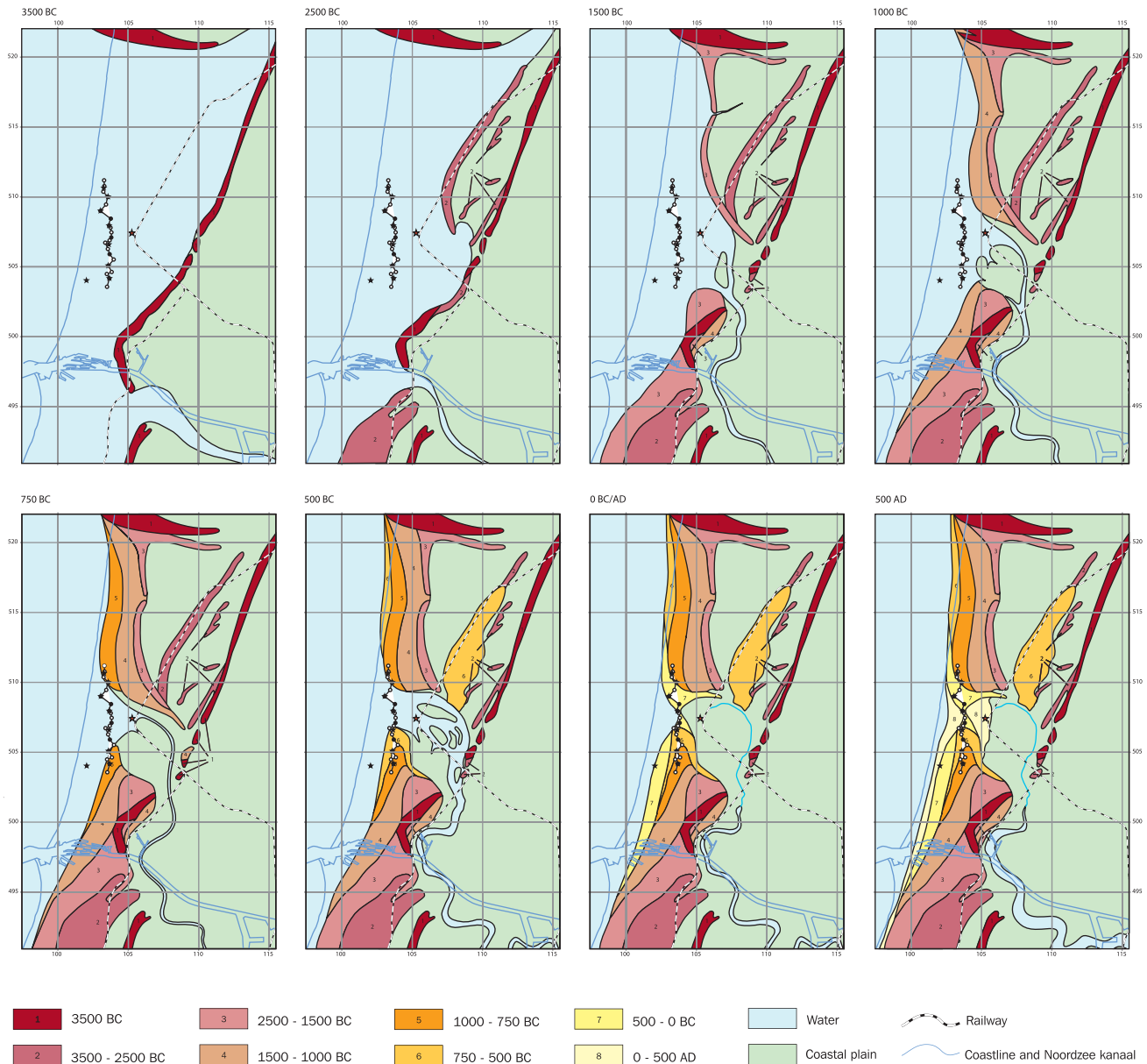
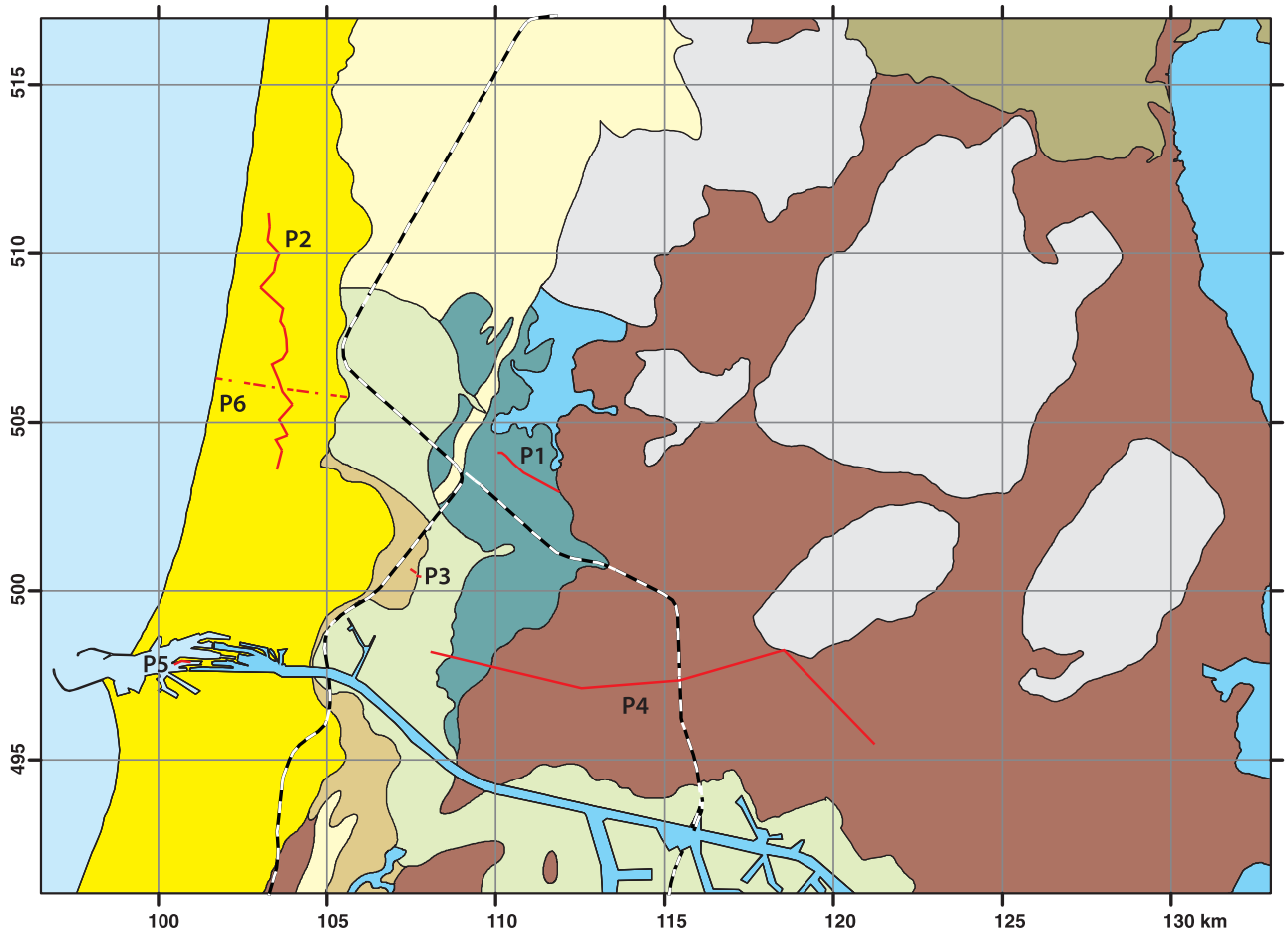


Fig. 7. Beach-ridge and dune formation in the Oer-IJ region between 3500 BC and 500 AD. For geological profile, see Fig. 10.

deposits and other underlying sediments, on its way to the Flevo lakes (Fig. 5F).

During that same period, West Friesland, the northern Flevo lake and the Overijsselse Vecht probably drained through a separate opening between the northern Flevo lake and the Wadden Sea. A ‘peat barrier’ separated the northern and southern Flevo lakes (Fig. 5F) until about 400 BC. The creation of a connection between the northern and southern Flevo lakes is considered to be the primary factor causing the silting-up of the Oer-IJ tidal area at that time. As a result all Flevo lakes and the rivers draining the Utrechtse Vecht region started to discharge through the new natural waterway towards the Wadden Sea. Now deprived of much of its water supply, the main channel

of the Oer-IJ lost its discharge function. An abundant supply of marine sand by waves and tides drove the gradual closure of the Oer-IJ inlet (Vos et al., 2010). This process was finalised between 200 and 100 BC when the barrier closed, thus isolating what remained of the Oer-IJ tidal system. Late Iron Age settlements in the former intertidal area between Castricum and Uitgeest (Castricummer Polder; Fig. 1) strongly suggest that there was no tidal activity anymore in this area at that time (Fig. 5G) and that the hinterland of the Oer-IJ system became fresh. The natural drainage direction reversed, with water moving through the channel of the Oer-IJ from Beverwijk to Amsterdam and onward into the newly formed Zuiderzee (Fig. 5G).



Type areas of the dated sites reported in Appendices A1-A6

- A1. Peatlands
- A2. Beach-ridge and beach-plain area
- A3. Coastal-dune area
- A4. Oer-IJ tidal area and IJ-polders
- A5. Salt-marsh area, adjacent to peatlands
- A6. Salt-marsh area, adjacent to the coastal dune area

Others

- Wormer Deposits at the surface
- Reclaimed former lakes, former Holland Peat eroded or oxidized; Wormer deposits at the surface
- Canals and lakes
- North Sea

- Location profiles
- Location schematic profile (Fig. 15)

Fig. 8. Geographical subdivision of the Oer-IJ region, with the location of the geological profiles p1 to p6.

Increasing wave erosion and human activity along the old Oer-IJ channel during the Middle Ages led to the disappearance of marginal peatlands and to the creation of the IJ-Lake (De Gans & Bunnik, 2012; Fig. 5H). With the diking of the sur-

rounding peatlands after 1300 AD, the enlargement of the lake was stopped (Fig. 5I, J). Sedimentation in the lake filled the part between Beverwijk and Assendelft. In 1872 the remaining parts of the lake were reclaimed and the IJ-Polders were

created. The construction of the Noordzeekanaal in 1876 shortened the shipping route between Amsterdam and the North Sea, traversing the relatively narrow dune belt near IJmuiden (Fig. 5K).

— Landscape and settlement history of the Oer-IJ region

The Oer-IJ existed for some 2800 years, from its inception around 3000 BC to the closure of its inlet around 200 AD. The landscape history of the region is visualised for eight successive periods (Fig. 6A–H), defined on the basis of coastal developments, marine activity and large-scale human interventions. Along with the maps, the most important palaeolandscape data (sample ages and relevant information from key sites in Appendices A and B) are discussed in light of the settlement history.

— Formation of the Oer IJ: 3000–2000 BC (Fig. 6A)

The Oer-IJ tidal system is the successor to the Haarlem–Amsterdam system and developed around 3000 BC, when the tidal basins in Holland silted up. Because of the infilling the coastal-peat bog extended and the inlet system was sandwiched between the new peatlands to the north (Zaanstreek) and south (Haarlemmermeer area).

Around 3000 BC the mouth of the Oer-IJ system was located near Velsbroek (Van der Valk, 1992). Subsequently – due to the infill of the embayment of the central part of Holland and longshore currents – the associated tidal inlet shifted to the north, with low coastal dunes developing in the beach-ridge plain near Westerbroeksterplas (south of Velsbroek) (Bosman & Van Eerden, 2009). About 2500 BC, the inlet and main tidal channel of the system were located just south of the present Noordzeekanaal – between Driehuis and Velsen-Zuid – as constrained from tidal-flat deposits near Huis ter Spijk (HS-1; Table A6.2; Fig. App. A) and at the Velsertunnel construction pit (VT-4 Table A4.7; Fig. App. A). At the location of the Wijkertunnel construction pits, salt marshes were present (Beets et al., 2004). Northeast of the northern pit of the Wijkertunnel, a peat layer is still present on top of the Wormer salt-marsh deposits, pointing to a sheltered environment at the margin of the tidal system. The formation of freshwater peat in the whole area north of the Noordzeekanaal (A17 II-4; Table A5.7; Fig. App. A) indicates that at that time a beach ridge stretching from Velsen-Noord to Uitgeest–Akersloot protected this area, which allowed peat formation in this area.

Before 3000 BC a beach ridge had formed about 500 m farther west than the preserved landward-most beach ridge of Uitgeest.

Peat formation in construction pit site Uitgeest-De Kleis at that time (Appendix B1; Fig. App. B) – on top of tidal deposits of the Wormer Member and below beach-ridge sediments of Uitgeest – point to a sheltered position and thus to the presence of a protecting barrier seaward of this location. The base of this peat layer dates from 3365 BC at De Kleis (UK-6; Table A2.1a) and from 3455 BC at the nearby gas pipe of Uitgeest (UG-1; Table A5.1). The top of the peat layer was formed at about 3040 BC (UK-5; Table A2.1a), providing a maximum age for the beach ridge at De Kleis. The landward side of the beach ridge is covered by a second peat layer that formed between 2530 BC and 2020 AD (UK-3 and 4; Table A2.1a).

Around 3000 BC openings in the beach barrier south of Uitgeest were still present, as witnessed by a clay layer (3455 BC, UG-1 and Table A5.1, to 3315 BC, BU-2 and Table A5.2) at the base of the Holland Peat in the western part of the Uitgeester- and Heemskerkerbroekpolders (Fig. 9). The age of the clay wedge in the western part of the Uitgeesterbroekpolder indicates that there was active exchange of tidal water between the North Sea band and the tidal basin until about 2600 BC. Fine sediment was supplied through small breaches in the Heemskerker–Assum–Uitgeest barrier. After 2600 BC, the barrier at this location was closed (Fig. 6A), with oligotrophic peat beginning to form (Fig. 9) in complete isolation from the sea.

Breaches were also present north of Uitgeest. In prehistoric times the associated channel systems, such as the Stierop channel between Uitgeest and Groot Dorregeest, and the Slikker-Die channel between Klein Dorregeest and Akersloot, remained partially open. They played an active role in the drainage of the adjacent peatlands. The southern side of the beach ridge along the Slikker-Die palaeochannel was overgrown by peat (Müller et al., 2008), which was formed between 2680 and 1615 BC (KF-3 and 4; Table A2.7).

Between 3000 and 2500 BC the orientation of the coastline changed. The beach ridge south of Uitgeest migrated landward over the Holland Peat of the site De Kleis while north of Uitgeest, the beach plain between Akersloot and Limmen expanded seaward. Bivalves from this prograding intertidal area, collected in the upper part of beach sands near Heiloo, Kooibrug and Nijenburgerviaduct, gave ages of 2375 BC (HO-1; A2.10), 2765 BC (KB-1; Table A2.11) and 2915 BC (NV-1; Table A2.12). Here, the aeolian sands covering the beach ridges started to accumulate between ~2500 and 2250 BC.

The beach ridge of Uitgeest–Akersloot was inhabited during this period, as witnessed by Bell Beaker finds (2500–2000 BC) on the eastern flank of the beach ridge near Klein Dorregeest (Appendix B2; Müller et al., 2008). Near the Hoogdorperweg in Heemskerk, Late Neolithic/Early Bronze Age plough traces are present in the top of the beach-ridge unit (Appendix B3; Vaars, 2004). South of the Oer-IJ tidal inlet near Velsen, the beach-ridge area – with small sand dunes – near the

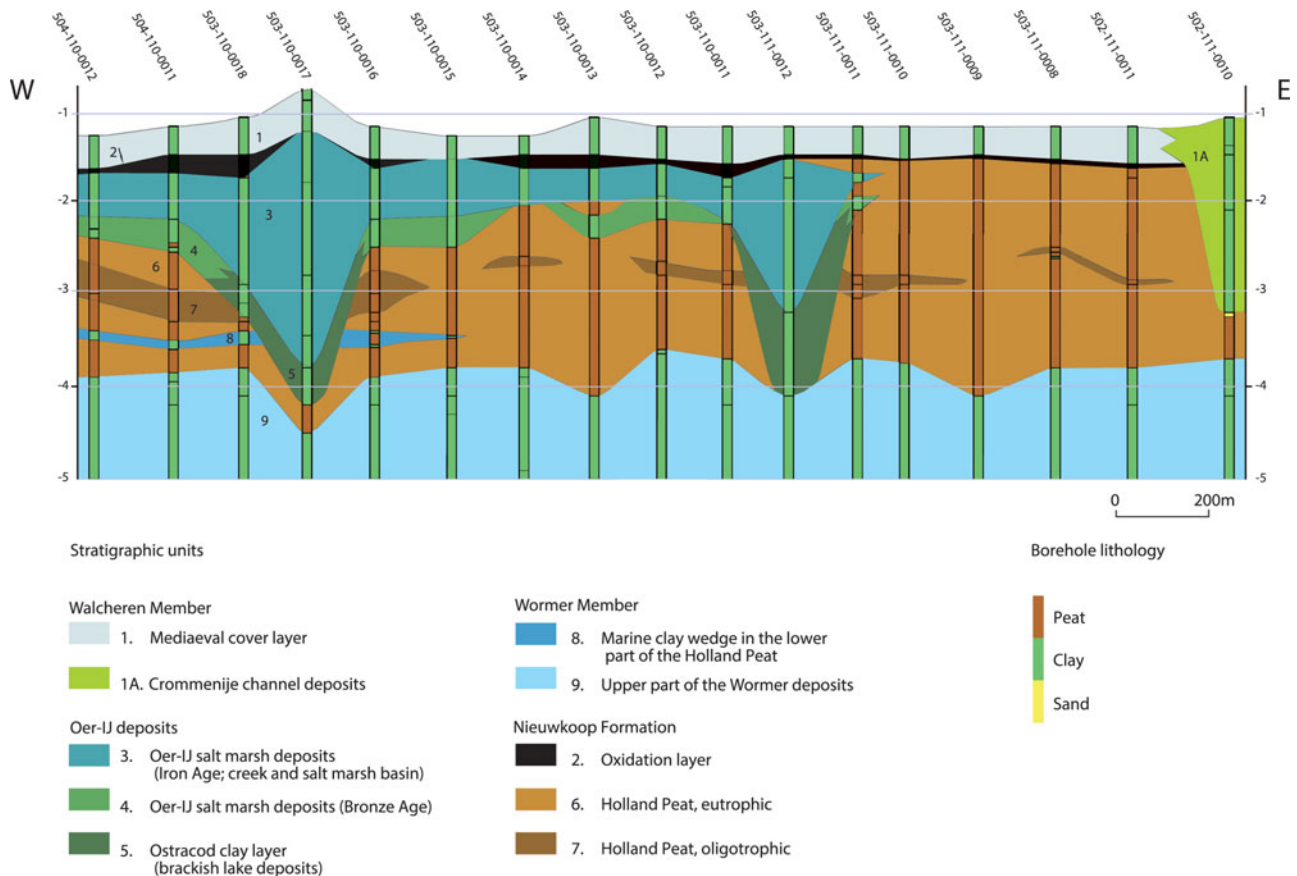


Fig. 9. Geological cross-section through the Uitgeesterbroekpolder, based on borehole descriptions from the DINO database of TNO. The profile demonstrates that the Early Age Creek deposits were formed in Bronze Age lake deposits (Ostracod clay). For the location of the profile see Fig. 8 (P1).

Westerbroeksterplas (Velsbroekpolder) was also inhabited from the late Neolithic Period (Bosman & Soonius, 1990).

Neolithic people were active in the tidal marshes along the main Oer-IJ tidal channel, as evidenced by a flint scraper and a sharpened pole found in the top of *Wormer* deposits at location Afrikahaven (below the Holland Peat; AH-4, around 3195 BC, Table A4.9).

Ingression of a tidal inlet south of Assum and formation of the 'gooseneck' tidal channel in the Noorderbuitendijken: 2000–1500 BC (Fig. 6B)

Shortly after 2000 BC, the continuous beach ridge between Heemskerk and Uitgeest was breached south of Assum. The changing coastline orientation had eroded and weakened the beach ridge at this location, as indicated by the formation of overwash sands in this area. The oldest overwash sands at site Waldijk II, linked to this breach, were deposited around 1950 BC (WA-02; Table A2.3b). The washover may have acted as a sand source for contemporaneous and subsequent

dune formation at Assum-Waldijk I (Appendix B4; De Koning, 2007).

The large, permanent ingression in the beach ridge, south of location Assum-Waldijk I, captured the tidal prism of the soon-to-be-abandoned inlet near Velsen-Zuid, creating a new Oer-IJ inlet about 10 km farther north and changing the course of the main tidal channel. This large channel incised into the (former) peatland of the Noorderbuitendijken area between Beverwijk-Heemskerk and the Assendelverpolders. It is likely that the breach formed during a major storm, linking to a drainage pattern that was already present in the peatland behind the beach ridge Beverwijk-Uitgeest. Owing to this ingression, around 2000–1900 BC, the main tidal channel of the Oer-IJ got its characteristic curved shape ('gooseneck'), partly parallel to the North Sea coastline (Fig. 6B). Peatlands east of the channel were covered by Bronze Age clay layers. The old inlet (between Velsen Zuid and Noord) silted up shortly after the new breach formed. The tops of the beach sands at locations Velsen-Noordzeekanaal (VIa-1; Table A3.26b) and Velsen-PEN Noorderweg (VP-1; Table A3.23) are from about 2315 BC and 1700 BC, respectively. These dates indicate that the area of the old inlet filled up rapidly and dune formation started here.

Differential progradation of the coastline and development of the Oer-IJ Estuary: 1500–650 BC (Fig. 6C, D)

In this period, the coastline migrated seaward both north and south of the newly formed Oer-IJ tidal inlet. At the southern side, at the location of Hoogoven IV, the base of the dune sands – covering beach sands – had an age shortly before 875 BC (HIV-3; Table A3.21c). At that time the zone of beach ridges and dunes fronting the coast-parallel stretch of the Oer-IJ Estuary had already broadened to some 4 km and had extended northward to Kasteel Marquette in Heemskerk.

North of the new Oer-IJ inlet, between Limmen and Bakkum-Noord, the beach ridge and dune area migrated seaward as well, following the silting-up and closure of the Westfriese Inlet after 1500 BC. The Middle Holocene embayment of the coast of Noord-Holland was filled completely for this area between 1500 and 500 BC (Fig. 5C–E).

Owing to the coastal progradation south and north of the mouth of the Oer-IJ, the tidal area in between became larger, lengthening in a cross-shore direction. As the inlet shifted to Bakkum/Castricum, a large tidal-flat area developed in the Castricumerpolder around 1000 BC. This flood-tidal delta (De Roo, 1953), fronted by low storm ridges, was not the result of a passive marine transgression as assumed before (Pons & Wiggers, 1959/1960), but of increasingly strong tidal currents through the lengthening inlet (De Groot et al., 1996).

The meandering Oer-IJ channel between Amsterdam and Velsen-Zuid deeply incised into the subsurface (De Gans, 2012) in the period that the tidal prism of the basin increased. Near Amsterdam, the base of the main channel fill is located at about 16 m –NAP. The maximum fill depth increases to about 24 m –NAP toward Spaarndammerpolder, and then decreases in the direction of the tidal inlet near Bakkum/Castricum. Near the construction pits of the Wijker- and Velsertunnel (Van Straaten, 1957; Beets et al., 2004) the inlet-proximal channel depth never exceeded 15 m –NAP. Close to the estuary mouth, in the PWN area near Castricum, it only reached max. 11 m –NAP (1000 BC time line in Fig. 10B; Vos et al., 2010). Here, the channel was wider.

The varying depth of the channel base is explained by subsurface lithology. Between Amsterdam and Spaarndammerpolder, the tidal deposits along the Oer-IJ channel were clayey and peaty, and much more cohesive than the sandy and therefore easily erodible layered deposits of the *Wormer Member* below the channel. In this area, the channel deepened rather than widened in response to increased tidal prism. Towards the inlet, the channel had sandy levees and widened rather than deepened. The history of this deepening and widening is unclear owing to a lack of data. Sediment fills from that period have been poorly preserved and few observations have been made.

In the transition zone, humic and peaty clays accumulated mostly under spring-tide and storm conditions in the supratidal

reach. The humic peaty layers encountered in several Velsbroek cores have ages between 3525 BC and 85 AD (V2–1–6 and V3–1–3; Tables A6.3 and A6.4), showing that locally this zone remained in place for a long time.

North and northeast of the Oer-IJ channel, the transition zone between the salt-marsh area and the peatlands was located near the Buitenhuis- and Assendelver Polders, and near Uitgeester- and Heemskerkerbroek. Peat formation in the Assendelver Polders began around 2775 BC (A17 II-4; Table A5.7) and continued until the Early Iron Age.

A salt-marsh clay wedge of a couple of decimetres in the Holland Peat 200 m south of location Q is estimated to have been deposited around 1500–1000 BC (Bronze Age). On top of the clay, eutrophic reed peat and oligotrophic peat was formed. The latter accumulated between 845 and 800 BC (AQ-4 and AQ-3; Table A5.10), associated with the temporary decrease in marine activity. A Bronze Age clay wedge of tidal deposits – covering the Holland Peat layer and deposited after the tidal-inlet ingress south of Assum around 1900 BC – is also found farther north in the Wijkermeerpolder, the Noorderbuitendijken and in the Uitgeester- and Heemskerkerbroekpolders. In these latter polders, a layer of eutrophic reed peat, several decimeters thick, is present between the Bronze Age clay (layer 4) and oligotrophic peat (layer 7; Fig. 9). The eutrophication of the peat and Bronze Age clay deposition are thus related to the breach of the beach ridge in this area.

Together with sea-level rise (10–15 cm/century), autocompaction of the peat under the weight of the newly formed clay layer certainly played a role in the temporary drowning of the peatlands in the Noorderbuitendijken, Uitgeester- and Heemskerkerbroekpolder.

Bowl-shaped depressions in the Bronze Age clay layer in the western part of the Uitgeester and Heemskerkerbroekpolders and Assendelverpolders (near site P; Vos, 1998) contain humic ‘ostracod’ clay (Fig. 9), marked by abundant ostracods and *Hydrobia* snails. These depressions, with an erosive base, were brackish lakes in the transition zone between the tidal area and the peatlands. They were enlarged and deepened by wind-wave erosion. *Hydrobia* snails from site P have an age of 1310 BC (AP-1; Table A5.9).

Around 700–600 BC, the lakes had been filled to salt-marsh level. A reed level at the top of the Bronze Age clay layer formed around 685 BC (UB-1; Table A5.4.). More evidence that the lakes were fully filled by 650–600 BC is provided by the dated fills of salt-marsh creeks incised into the underlying ostracod clay (Fig. 9) during the subsequent phase of renewed marine influence.

From 850 to 650 BC marine activity in the Oer-IJ tidal system decreased and channels likely became shallower. Changes in tidal activity are distilled from observations in the transition zone between the tidally influenced landscape and the peatlands, such as around the Broekpolder and the Assendelver Polders. Oligotrophic peat at site Q (AQ-4 and AQ-3; Table A5.10)

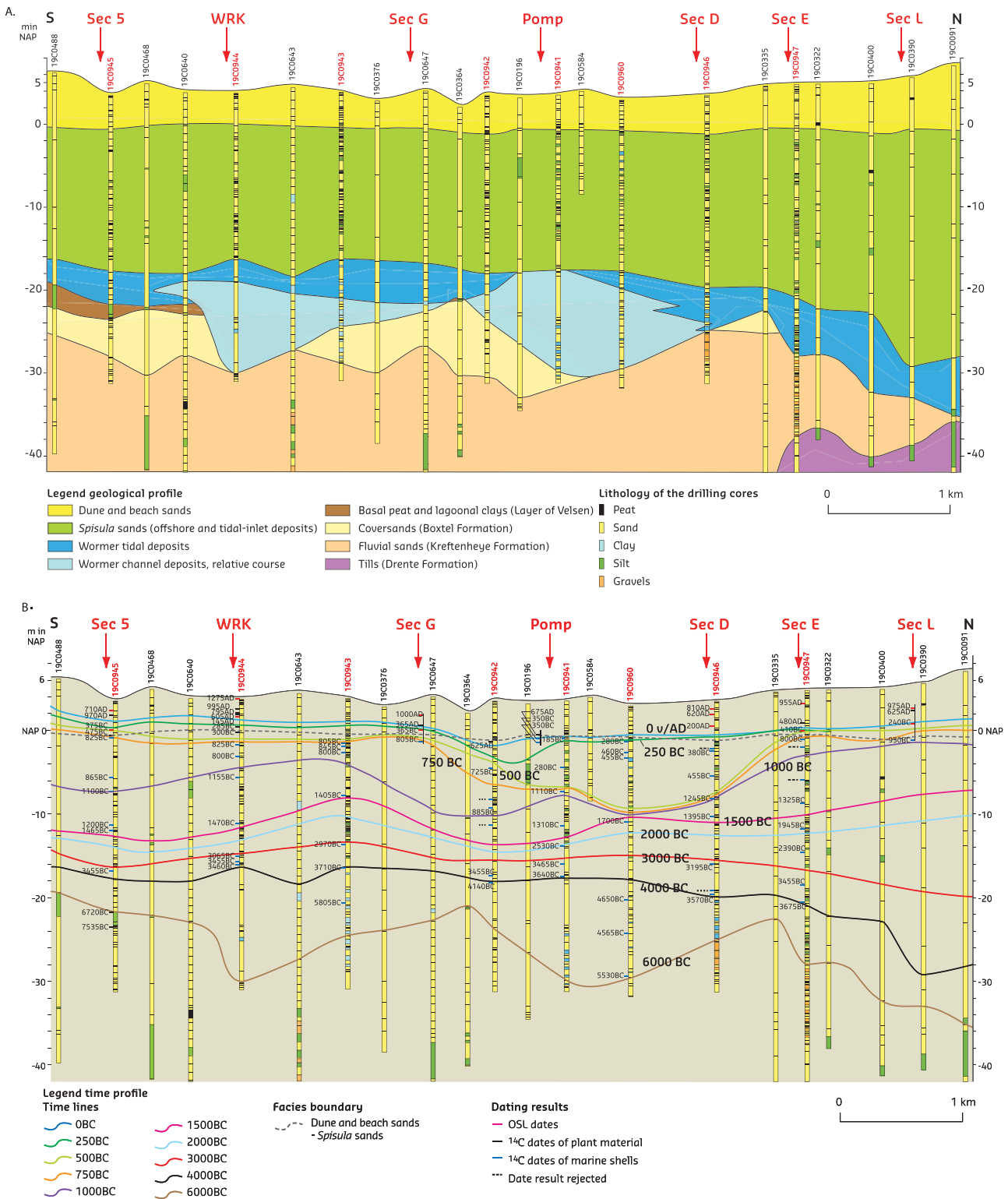


Fig. 10. Cross-section through the mouth of the Oer-IJ system in the PWN dune system, after Vos et al. (2010). For the location of the profile, see Fig. 8 (P2). Key sites and boreholes in red are the new data from Vos et al. (2010). A. Geological profile (S–N) of the PWN dune area. B. Reconstruction of the time lines, based on ¹⁴C and OSL dates. The results of the dates are presented in Appendix A3.

indicates that at least this marginal peat zone was no longer flooded by marine nutrient-rich water in the Late Bronze Age. Contemporary maximum flood levels in the tidal system had either decreased or the peat had grown to above extreme high water (EHW, or maximum stormflood level). Relatively limited marine activity during this time (lower EHW) is also reflected in the nature of pollen assemblages more north in the peatland of the Assendelpolders at site A17 (De Jong, 1989). A period of decreased marine influence in the peatland, separating two periods of more prominent marine influence as represented by a local vegetation component with high amounts of *Cheneopodiaceae* (or goosefoot family): Chen. 3a peak of De Jong (1989) around 1230 BC (A17 I-3; Table A5.7) and Chen. 4 peak around 525 BC (A17 II-2; Table A5.7).

In the Broekpolder, the temporary reduction in tidal influence between 850 and 650 BC enabled humans to populate the area. Plough marks from the Late Bronze Age (Therkorn et al., 2009) in salt-marsh deposits (layer III, Fig. 11; Appendix B5) date from around 790 BC (BP-7; Table A6.1). Land snails in this unit are an indicator of prolonged dry conditions (Vos, 2000).

In the Assendelver Polders the Early Iron Age settlement of site Q on top of the oligotrophic peat top (Therkorn, 1987) dates the end of this peat formation and has an age of about 650 BC (AQ-1 and 2; Table A5.10).

It is difficult to explain the decrease in tidal activity in the Oer-IJ area during the Late Bronze Age. The changing dimensions of the Oer-IJ basin may have favoured dampening of the tidal amplitude, but the seemingly most important changes to its configuration took place well before the temporary reduction in marine influence. The flood-tidal delta between Castricum and Assum/Uitgeest that may have provided increased resistance to the incoming tide around 1000 BC, and the 'gooseneck structure' of the main channel between the Castricumerpolder and Velsen-Zuid, which might have slowed down the tidal activity (Kleinhans, pers. commun.), had been in existence since about 2000 BC. Positive feedback of peat development in intertidal areas is an alternative explanation, but there is no preserved evidence of this mechanism. Whatever the reason, lower tidal levels improved the living and working conditions in the higher margins of the main channel, as testified by the increased presence of humans during this relatively quiet period.

Active marine phase in the Oer-IJ Estuary: 650–400 BC (Fig. 6E)

Marine activity in the hinterland of the Oer-IJ increased once again in the Early Iron Age. Estuarine clay was deposited on top of oligotrophic peat along the eastern edge of the Uitgeester and Heemskerkerbroekpolders, and in the Assendelpolders. A clay layer overlying the settlement at site Q (Vos, 1983) and the surrounding area indicates that drowning took place after

650–600 BC (AQ 1 and 2; Table A5.10). In addition, the lateral side of the beach ridge of Assum was covered with an Early Iron Age to early Middle Iron Age salt-marsh clay layer (layer Z3 in profile Fig. App. B4; De Koning, 2007).

On the northern side of the Assendelpolders (site A17) a dated *Cheneopodiaceae* peak in a sample from the marginal zone of the peatland indicates an increase in marine activity around 525 BC (Chen. 4; A17 II-2; Table A5.7). In the Broekpolder, Early/Middle Iron Age intertidal-flat deposits on top of salt-marsh units of the Late Bronze Age form another direct indication of increased marine activity (layer II, Fig. 11; Appendix B5). *Scrobicularia plana* shells from the tidal-flat sediments were formed between 600 and 345 BC (BP-2/6; Table A6.1). The widespread presence of Early Iron Age intertidal deposits on top of slightly older supratidal deposits indicates a regional increase in the MHW level (layer II, Fig. 11; Appendix B5). Other bivalve shells in the intertidal flat deposits formed next to the contemporary main channel also date from this period (WP-3, Table A4.4; NS-1, Table A4.5; BP-2 to BP-7, Table 6.1), confirming that the Oer-IJ was an open and active marine tidal system at that time.

The clearest indication that the tidal activity increased after 650 BC is the formation of creeks in the salt marshes in Uitgeester and Heemskerkerbroek, and in the Assendelpolders. These creeks incised into the Wormer tidal deposits below, and their sediment fill consists of clays with thin sand layers. The hollowed-out oak canoe found at location Uitgeest-De Kleis at the base of the creek fill was made of wood that formed between 617 and 600 BC (UK-a1 to 4; Table A2.1b; outer and youngest part of the tree; Appendix B1). Assuming a maximum lifetime of the canoe of 25–50 years, the sediments directly below the canoe date from 550–590 BC. The minimum age of the creek incision – the beginning of the active marine period – therefore is estimated to be about 625–590 BC.

During the active marine period, the main tidal channel in the flood-tidal delta extended to the northern side of this area, near the present course of the De Dye (a remnant of the former tidal channel; Appendix B6), and by lateral migration of the channel the north bank of the Oer-IJ was eroded between Bakkum-Noord, Limmen and Uitgeest. The released overbank sands by channel erosion – in addition to aeolian activity due to reclamation activities (disturbance of the vegetation) of the adjacent beach ridges of Limmen – may have been the cause of the great sand drift east of the beach ridge of Limmen-Heiloo. The minimum available age of this event is around 765 BC (LK-6; Table A2.8), but there is probably a time hiatus between the end of the peat growth and the start of the sand drifts of about 150 years). Between Limmen and Heiloo sand was deposited over a large area on top of coastal peat that had formed in the beach-ridge plain at the present Oosterzij- and Limmerpolder.

During the increase in marine activity in the tidal hinterland of the Oer-IJ, the coastline on both sides of the tidal inlet

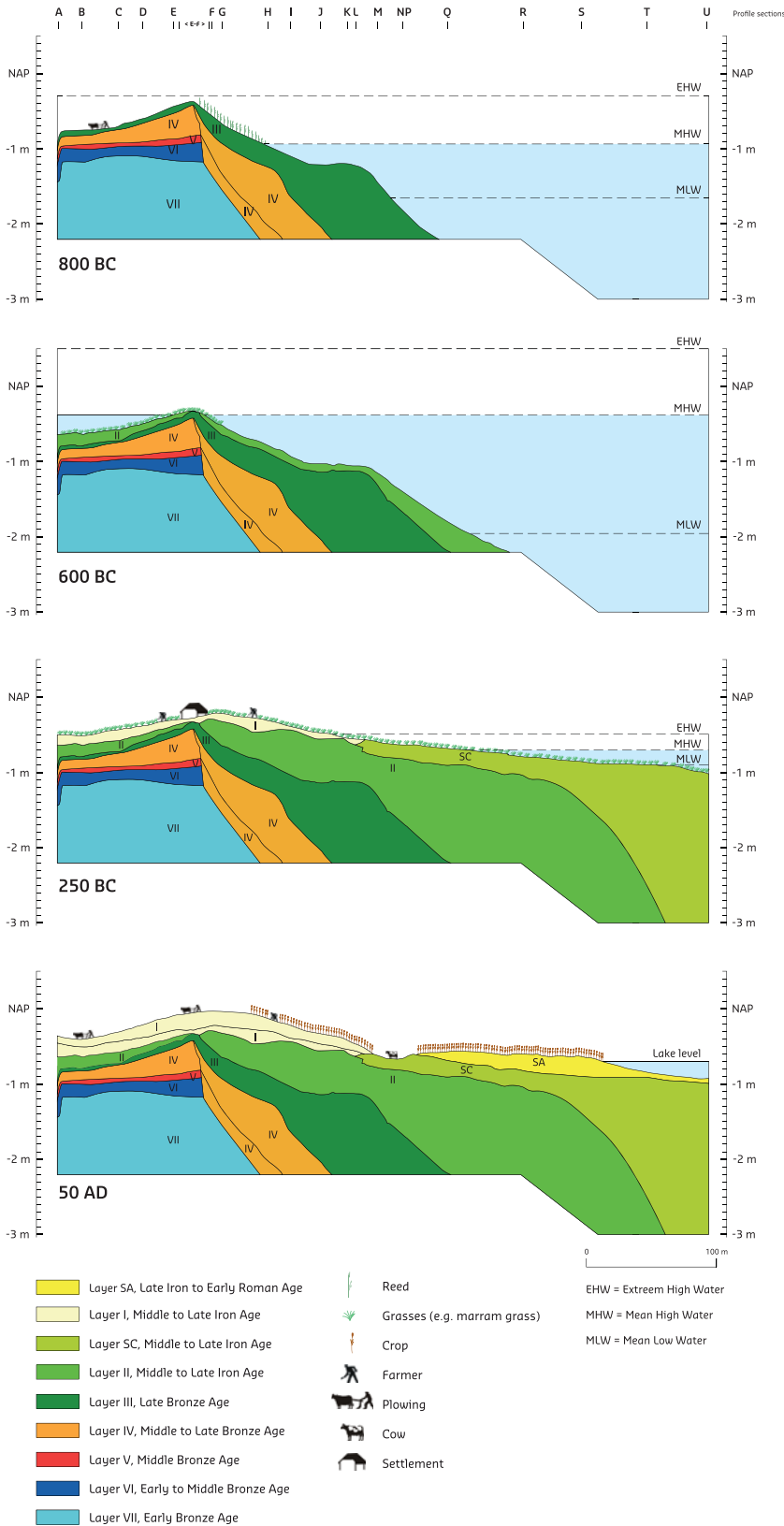


Fig. 11. Profile reconstruction of the salt-marsh ridge, west of the main tidal channel of the Oer-IJ, Broekpolder location. For the location of the profile, see Fig. 8 (P3) and Fig. App. B5. For the description of the layers see Appendix B5.

continued to migrate seaward (Figs 6 and 7). South of the mouth, near Secundair 5, dune formation along the moving coastline began around 475 BC (S5-02; Table A3.11b; Fig. App. B7) and north of the mouth, at Secundair E, starting around 410 BC (SE-02; Table A3.6b).

There are different explanations for the increase in marine influence in the area of the Uitgeester and Heemskerkerbroekpolders, the Assendelpolders and the Broekpolder after 650 BC, but none of them is fully satisfactory. A driving factor may have been the greatly increased fluvial discharge from the hinterland after the Utrechtse Vecht had become the northern branch of the River Rhine. The origin of the northern Rhine and Oer-IJ connection has been dated to around 800 BC (Bos, 2010).

Amplified fluvial flow would have enlarged the tidal inlet and main channel of the Oer-IJ. Because of the wider opening of the inlet the friction effect decreased and this led to an increase in the tidal range in the estuary. An increase in the tidal range caused an enlargement of the tidal prism and this led again – a self-reinforcing process – to larger tidal channels and a decline in the friction effect at the mouth of the system.

Drainage of the peatlands of the Assendelpolders during the Early Iron Age, through dug ditches, could have lowered the surface by peat oxidation and consequent subsidence. However, there is no evidence of intensive occupation of the area during the Early Iron Age.

Autocompaction, combined with some sea-level rise (approximately 10 cm per century at that time), is the most plausible explanation for creating accommodation space in the tidal system of the Oer-IJ. Deposition of clay on top of the peatlands during extreme high water would have triggered positive feedback, accelerating peat compaction under the weight of the clay cover. The subsequent increase in tidal volume would have enlarged the tidal channel, allowing the tide to penetrate farther into the estuary. In this self-reinforcing process of drowning, tidal flats and open water would have increased at the expense of supratidal peatlands.

— **Silting-up and final closure of the Oer-IJ system: 400 BC–250 AD (Fig. 6F)**

Marine activity in the Oer-IJ Estuary decreased gradually after about 400 BC, when the self-reinforcing drowning in the Oer-IJ region ended and a reverse development started. Once sedimentation and peat formation took place faster than the creation of new accommodation space by relative sea-level rise, tidal channels were reduced in size, and peak tidal and storm-surge levels decreased. This process started around 400 BC, when the Flevo lakes became interconnected, thus linking the Oer-IJ region with the Wadden Sea. The ensuing reduction in the drainage function of the Oer-IJ formed the prelude to the closure of its North Sea inlet.

The pollen assemblage in the peat below the Roman settlement of site A17 in the Assendelpolders (top peat formed at about 45 BC; A17 II-1; Table A5.7) and above the peat with the *Cheneopodicaea* 4 peak (signifying strong marine influence; formed around 525 BC; A17 II-2; Table A5.7) indicates that oligotrophic peat was being formed in the immediate vicinity (Therkorn et al., 1997) around this time. Humans took immediate advantage of reduced marine activity in the transition zone between the salt marsh and the peatland, as evidenced by the archaeological finds in the fill of a salt-marsh creek at site N (bone dating back to about 380 BC; AN-1, Table A5.8) and at location 9805-eastside in the northern part of the Assendelpolders (RW III/G3a pottery type, which was in use between 400 and 250 BC; Van Roon, 2000).

As the Oer-IJ silted up over the course of several centuries, its mouth (located in the PWN dune area) became significantly narrower and shallower. Radiocarbon and OSL dates from cores and pits in a north–south cross-section (Fig. 10) traversing the former mouth show that by 400 BC the southern part of the estuary up to Sec. G had already been cut off from the sea by a beach ridge (see Tables A3.5/A3.20; Appendix B7).

Around 200 BC the Oer-IJ system definitively lost its westward connection to the sea when the frontal beach ridges bounding the estuary merged to form a continuous barrier. Tidal activity in the former inlet fully ceased during the last half of the Late Iron Age and the whole area, including the sandy flood-tidal delta of the Castricum Polder, became permanently habitable. The Late Iron Age sites (settlements) found on top of the youngest Oer-IJ tidal deposits in this polder are testament to this change (Appendix B6). At sites Uitgeest-Benes (Fig. App. B6; De Koning, in prep.), Castricum-Grote Ven, locations A and B (Woltering, 1977; De Koning, 2013), Late Iron Age pottery and traces of settlements were found in archaeological trenches and newly dug ditches. The Iron Age pottery found is typical for the period between 200 BC and 50 AD. At site Uitgeest-Benes, the sand layers in which the settlement and ditches were constructed were dated. A storm layer (sand with open-marine shell species, including *Spisula subtruncata*) and an overlying aeolian sand layer – directly on top of it – have overlapping ¹⁴C-age intervals. Both formed around 220 BC (UB-01 and 2; Table A4.11b). The upper part of the underlying intertidal sand-flat deposits was dated using two specimens of the bivalve *Scrobicularia plana*, which provided ages of about 390–285 BC (UB-3 and 4; Table A4.11a). These tidal-flat deposits were formed during the active marine phase of the Oer-IJ, as to be expected, and the aeolian cover sand layer was formed in the first half of the Late Iron Age. The age of the dune sand (the last non-aquatic sedimentation at this location) fits well with the associated Late Iron Age occupation.

Late Iron Age settlements were also present in the dry salt marsh and marginal peatlands along the beach ridge of Uitgeest (Helderman, 1970; De Koning, 2003, 2012) and salt-marsh areas in the Uitgeester- and Heemskerkerbroekpolders (Therkorn,

2004), in the Assendelver Polders (Brandt et al., 1987; Therkorn et al., 1997) and in the Broekpolder (Therkorn, 2009). In the margins of the peatlands, peat growth stopped near Late Iron Age settlements because of drainage and exploitation of the land, while at some distance from these sites peat growth continued. Because the peat was no longer inundated by nutrient-rich water, oligotrophic *Sphagnum* peat began to dominate. This peat was extracted in the Roman Period in elongated strips (Therkorn et al., 1997) and used as fuel and building material.

Around 0 AD the seaward edge of the closed barrier between IJmuiden and Egmond was still located well landward of the present coastline (Fig. 7), but seaward of the Hoogovens construction pits. Here, 3 km landward of the present-day coastline, the start of dune formation on the beach sands took place some time between 875 and 545 BC, around the transition from the Bronze Age to the Early Iron Age (HIII-6; Table A3.21b; and HIV-3; Table A3.21c).

In the Early Roman Period the lower parts of the barrier were still occasionally flooded during extreme storms, with large amounts of overwash sands and shells being deposited behind gaps in the frontal dune. These storm deposits were found at the locations Pompgebouw and Castricum-Zanderij. OSL ages of sand layers above and below the storm unit at Castricum-Zanderij indicate that the overwash deposit formed at the end of the second century AD (CZ-01 and 2; Table A4.3b; Appendix B8).

On barrier closure during the Late Iron Age, the Oer-IJ Estuary could no longer drain directly to the sea. Between Velsen and Amsterdam the main Oer-IJ channel remained open (time of the beginning of the infilling of the channel/IJ-Lake formation) as the natural drainage was forced in the opposite direction to the Flevo lakes (early Zuiderzee) and Wadden Sea area (Fig. 5G). Because the waterway between Velsen and Amsterdam still existed at 50 AD, the Roman harbour at Velsen maintained a good connection with the Oude Rijn, the Roman border (*Limes*) at that time, through the Amstel and Utrechtse Vecht rivers.

As a result of the long water-discharge route through the Flevo lakes to the Wadden Sea, the drainage of the Oer-IJ area deteriorated, and the groundwater level in the silted-up salt marshes of the Uitgeester- and Heemskerkerbroek and Assendelverpolders rose. In the second and third centuries AD people adjusted to the rising water table by constructing plank bridges between their houses. As wetlands expanded, widespread post-Roman peat growth started, and people abandoned the area at the end of the third century AD.

Coastal progradation and peat formation in the Oer-IJ hinterland: 250–950 AD (Fig. 6G, H)

After 250 AD, large-scale peat development took place in much of the Oer-IJ region behind a widening belt of dunes, reflecting

continued deterioration of the natural and artificial drainage. In the Broekpolder, west of the abandoned main tidal channel (BP-1; Table A6.1), newly developed peat in the lower parts of the former tidal area was eutrophic. In the former peatland areas of the Uitgeester- and Heemskerkerbroek Polders and Assendelverpolders predominantly oligotrophic peat developed (AR-1 up to 5; Table A5.5; Fig. 12). Because of the large-scale peat formation, the habitation opportunities in these areas decreased markedly, and no archaeological remains from the late third to the 10th century have been found here.

Peat formation continued into the Early Middle Ages, and the central parts of peat domes reached elevations of at least 3–4 m +NAP (Fig. 12). In the 10th century the first peat extraction in central Noord-Holland began along the ditch known as The Kaaik, which is located west of the present village of Assendelft (Besteman & Guiran, 1987). A simple wooden church made Assendelft the first parish in the Zaanstreek (Fig. 13).

In the Assendelverpolders, post-Roman peat is still present below the site of the 10th-century church of Assendelft (Figs 12 and 13). The weight of the church compacted the post-Roman peat, preserving the overlying culture layer. The age of the peat directly below the culture layer indicates that peat formation continued until the ninth century (A0-1; Table A5.6).

Post-Roman peat was also found below the IJ-Polder clay near Ruigoord, where peat development also continued certainly into the ninth century (RZ-1; Table A1.3) and possibly even longer since the original top has been eroded (Veerkamp, 2001).

In the Castricum- and Heemskerker Noordbroekpolder eutrophic peat was formed during the Early Middle Ages in depressions and silted creeks (*Delgronden*; De Roo, 1953). The highest sand flats and lower dunes in this area were probably never covered by peat. Habitation was likely limited to these higher locations (e.g. Uitgeest-Benes; App. B6; De Koning, in prep.), where humans were present during the Early Middle Ages. Settlements from this period have also been found on higher sandy areas in the PWN dune area (Duinker, 1955; Deelen, 1962; Van Regteren Altena; 1970; Vos et al., 2010), and on the beach ridges of Limmen–Heiloo (Dijkstra et al., 2006; Dijkstra & Verhoeven, 2013) and Akersloot–Dorregest–Uitgeest–Assum (De Koning, 1992, 2003, 2007/2012).

The abandoned deep Oer-IJ channel between Amsterdam and Velsen was oversized for local drainage. As a result, clay was deposited in the channel thalweg starting in Roman times (Cleveringa, 1988). The channel fill postdating 800 BC contains much organic material, even as blocks of peat (De Gans, 2008), indicating that peat was eroded along the channel margins. As part of this process, the channel became both shallower and wider. An elongated lake began to form, the early phase of the later IJ-Lake. Continued erosion caused the lake to expand in time.

In the meantime, the coastal dune area widened. Periods of local sand drift, contributing to the formation of the *Older*

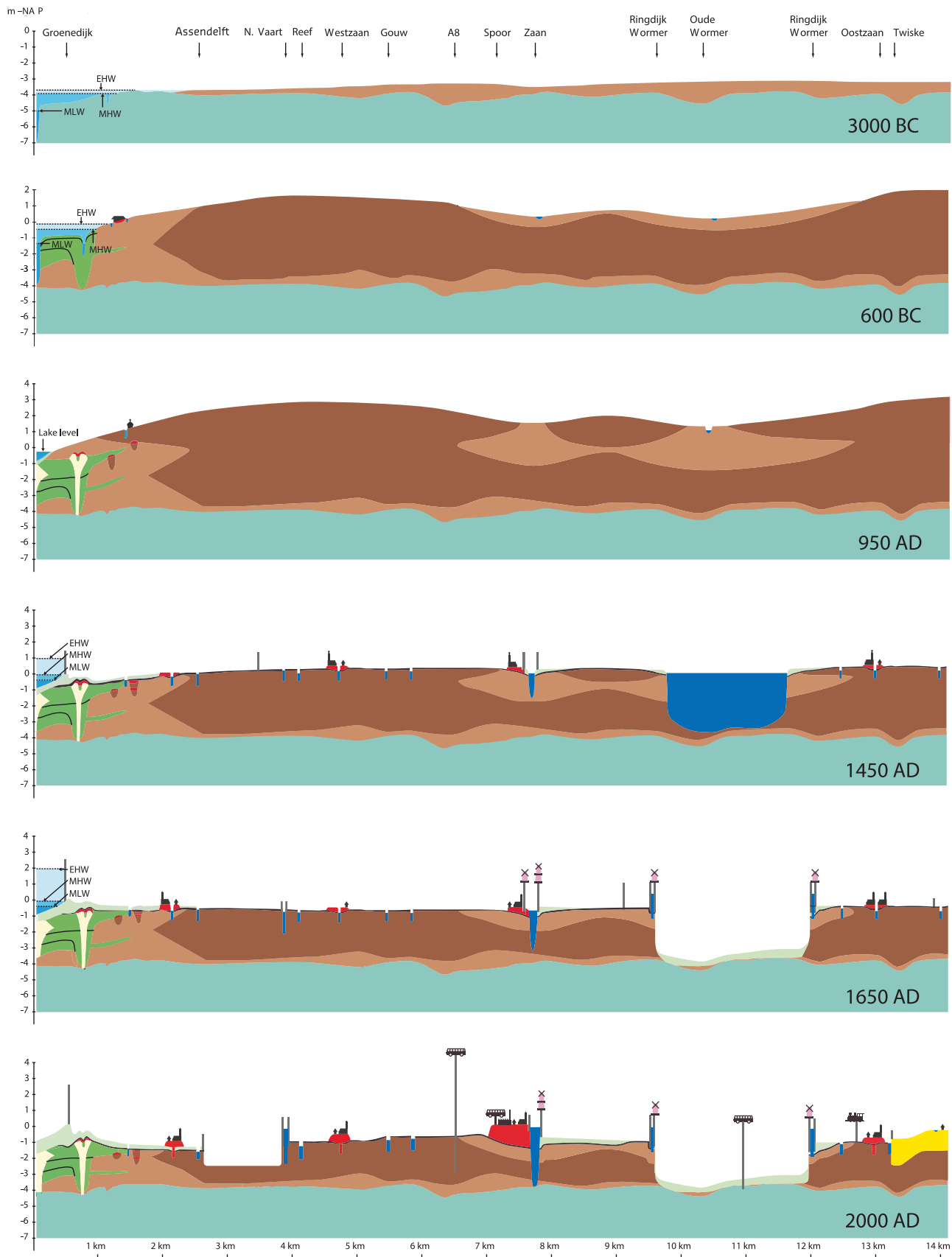
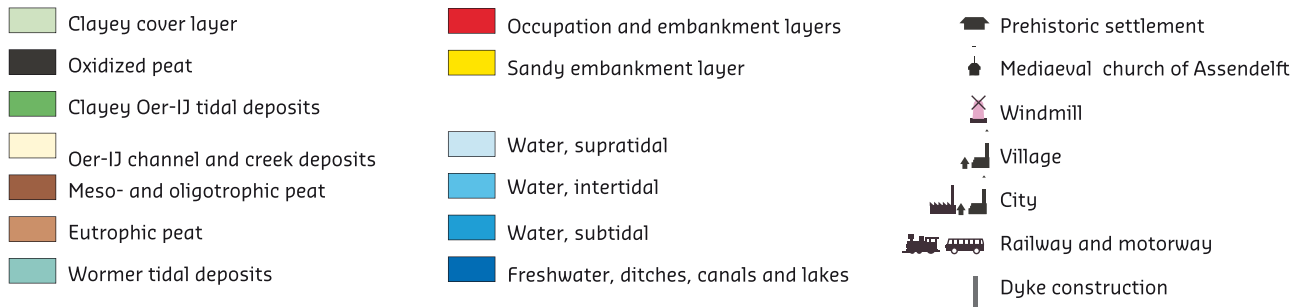


Fig. 12. Profile reconstruction of the rise and decline of the peat land in the Assendelpolders and Zaanstreek. For the location of the profile, see Fig. 8 (P4).



EHW = Extreem High Water

MHW = Mean High Water

MLW = Mean Low Water

Fig. 12. Continued.

Dunes, alternated with periods of vegetation and soil formation. Generally, the dunes were several metres high, with a maximum elevation of about 6 m +NAP. In the studied pits and trenches in the PWN dune area (Appendix B7), and at the Hoogoven location (Jelgersma et al., 1970) and Middensluis-eiland (Appendix B9), the exposed dune profiles show one or more light brown to black palaeosols, with thicknesses varying from a few centimetres to a couple of decimetres. These soils are humic to very humic or even peaty. Even the peaty soils are sandy or contain thin sand layers, indicating that some aeolian sand transport continued in the area during periods of vegetation. Plough marks and hoof imprints of cows occur in many places in the palaeosols (Appendices B7 and B9). Anthropogenically reworked soils are termed ‘culture layers’.

Multiple organic-rich layers were especially well-developed at sites Secundair 5, Secundair G and WRK in the PWN dunes (Tables A3.9–A3.11; Appendix B7) and at Middensluis-eiland (Table A3.4; Appendix B9; Fig. 14), separating sand-drit units formed as little as a century apart. The palaeosols are intensively ploughed, suggesting that the disturbance of the vegetation by humans was a major factor in the local sand drift and dune formation. Only in the dune profile of pit Secundair 3 was no organic palaeosol found. This site is located in the convex cove of the former Oer-IJ mouth where the formation of *Older Dunes* started relatively late.

The *Older Dunes* landscape became intensively populated and used as soon as it was formed, as testified by many archaeological indicators and artefacts from the pits and trenches in the Hoogoven (Van Regteren Altena, 1970) and PWN dune areas (e.g. Secundair E, Secundair D, Secundair G, WRK gebouw and Secundair 5; Vos et al., 2010). The *Older Dunes* are mostly covered by *Younger Dunes* sand accumulated during the next phase, keeping the greater part of the incorporated archaeological heritage both ‘invisible’ and preserved.

Formation of the Younger Dunes and large-scale reclamation of the peatlands: 950–1800 AD

From the 11th century onwards the whole peat area of the Zaanstreek was reclaimed, and peat villages such as Westzaan, Oostzaan and Zaandam arose (De Cock, 1980). For these reclamations peat was drained on a large scale, lowering bog surfaces significantly through oxidation and compaction. High-lying, well-drained peat areas remained arable until about 1400 AD. By 1450 AD the surface level had become so low that drainage problems arose. It became increasingly difficult to discharge excess water into the IJ-Lake, and the area turned into a wetland suitable for livestock only. Peat lakes began to form along bog streams such as the Wormer peat river during the Late Middle Ages. Owing to wave-governed shore erosion and extensive peat extraction by humans, many of these lakes expanded quite rapidly. The IJ-Lake also increased in size, reaching its maximum extent in this period. Continued drainage caused the surface level of the remaining peatlands to be lowered further and they sank around or below the 0 NAP level (Figs 12D, E). Thus, at high tide the open water of the IJ-Lake stood at a higher level than the peat surface. Dikes protecting the area against flooding broke repeatedly. At each breach location erosion pits were scoured and clay was deposited on the adjacent peat. Clay was also deposited by ‘inland water’ (water inundations in the polders behind the sea dike) when low parts of the embanked areas were flooded. Sluicing excess water during low tide in order to keep the polders dry became more and more difficult as the difference between polder levels and open water, such as the IJ-Lake, increased. From the 17th century onwards windmills had to be used. They also became instrumental in reclaiming peat lakes such as the Wormer.

In the dune area of the western Netherlands, the mode of aeolian sand transport changed drastically between 950 and 1050 AD. Enormous quantities of sand went adrift, forming large



Fig. 13. Mediaeval church of Assendelft from the 10th century AD in its 10th-century AD environment. A. Image from Mienke van Gogh of the wooden church of Assendelft; B. Remnants of the graveyard around the excavated mediaeval church of Assendelft. Below the 0.4 m thick clay cover only the bottom plates of the coffins were preserved. About 1.2 m of peat has disappeared by oxidation. The height of the coffins was ~ 0.4 m and the depth of the grave ~ 1.2 m.

parabolic Younger Dunes. In the PWN dune area they reached up to 25 m +NAP. Ages of peat and sand from pits and trenches at Middensluiseiland and in the PWN area confirm that the formation of the Younger Dunes in this region began at the end of the 10th and the beginning of the 11th centuries (ME-3 and 4, Table A3.4a; SE-01, Table A3.6b; WRK-1; Table A3.10a; S5-1, Table A3.11a), in line with the regional timing (Jelgersma et al., 1970). Possible driving mechanisms were sand availability in response to strong coastal erosion (Van Straaten, 1965; Jelgersma et al., 1970; Van der Valk, 1992), changing climate

(increasing storm activity, e.g. Ehlers, 1986) and human influence (Van den Berg, 2013). Palynological and faunal proxies provide evidence for relatively warm and dry conditions around 1000 AD (Klijn, 1981; Van den Berg, 2013), which would have promoted aeolian sand transport. Increased storm frequency (Ehlers, 1986) was another relevant climatic change. Observations in the pits of Middensluiseiland (Vos, 2008) and the PWN dune area (Vos et al., 2010) show that human interference in the dune landscape was large (e.g. ploughing) and definitely played an important role in aeolian sand transport. At the end

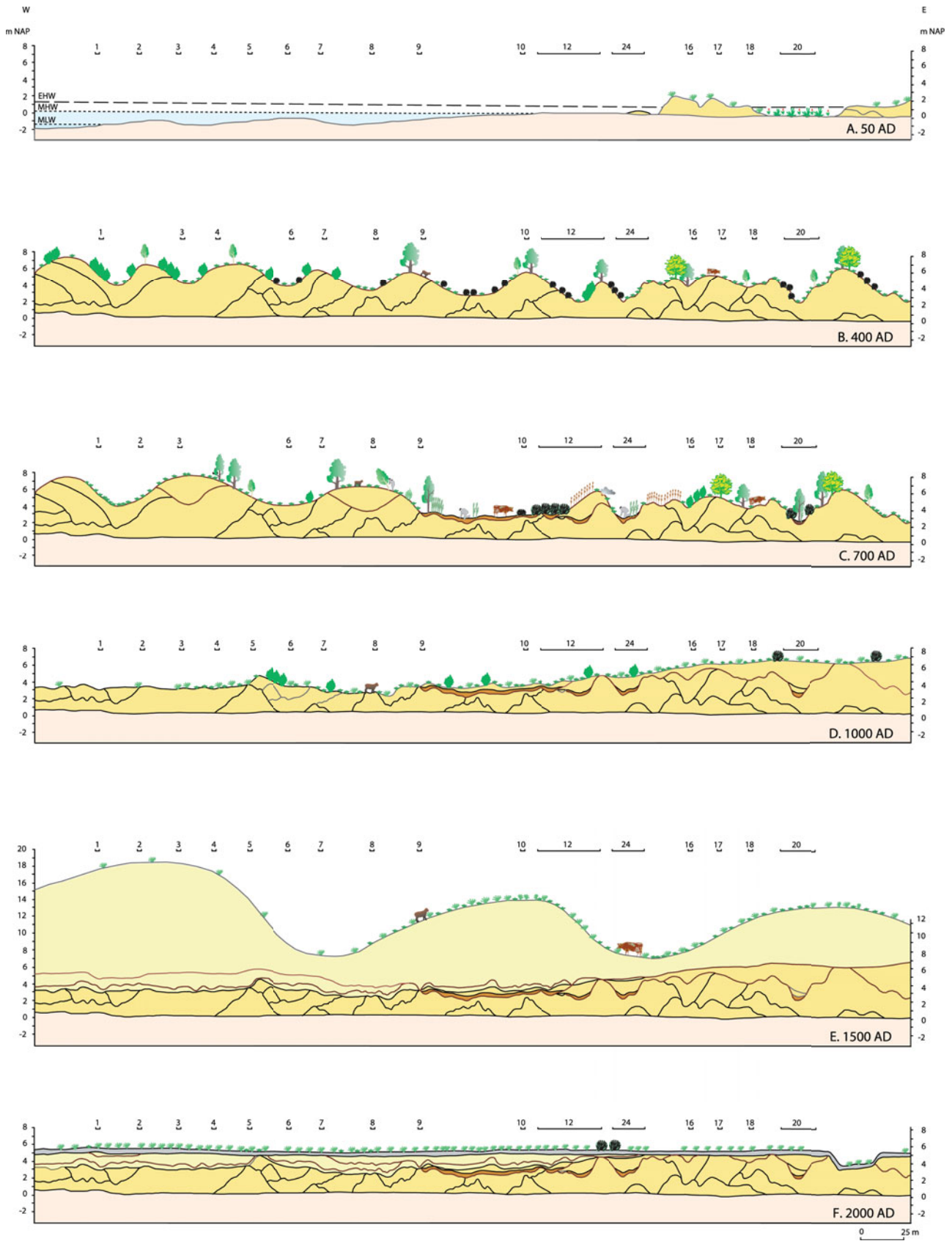


Fig. 14. Landscape reconstruction for profile Middensluiseiland. For the location of the profile, see Fig. 8 (P5) and Fig. App. B9. The vertical exaggeration of the profile is 5. For the location of the profile sections 1 to 20, see Fig. App. B9.

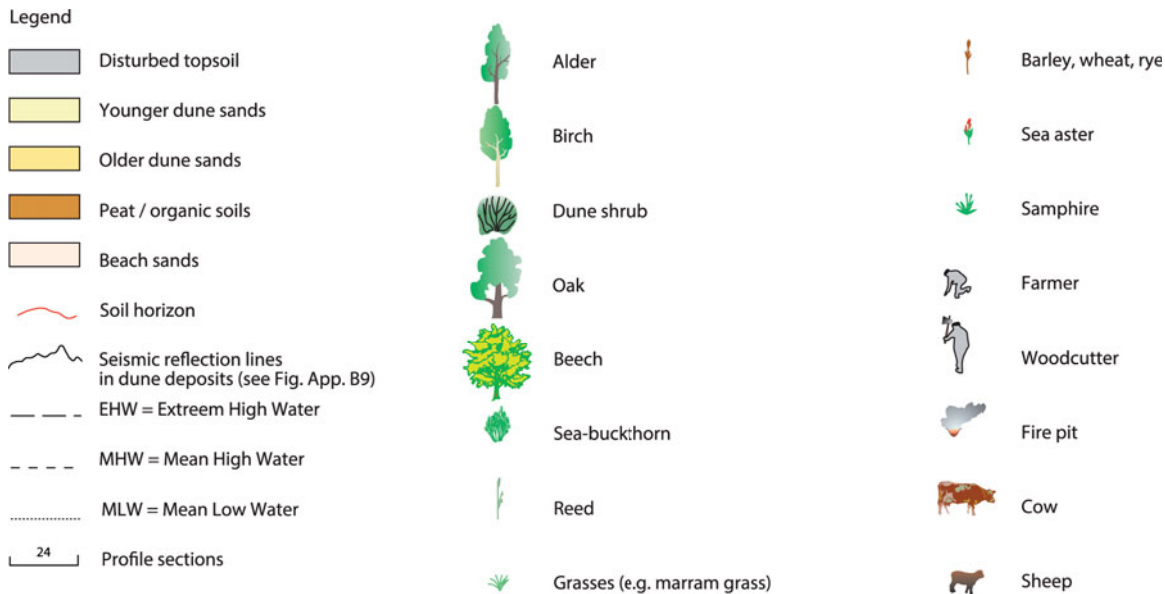


Fig. 14. Continued.

of the Early Medieval Period humans disturbed the vegetation on a large scale, at least helping to set off a self-enhancing process of aeolian sand transport that culminated in the formation of large parabolic dunes (Klijn, 1981). The importance of each of these processes and the ultimate driving (decisive) factor in the formation of the *Younger Dunes* remains a point of discussion.

Below the highly accented parabolic dunes, horizontally layered aeolian deposits level the former relief of the *Older Dunes*. As the parabolic dunes (also known as 'walking dunes') migrated, the tops of the *Older Dunes* were flattened by wind erosion ('equalisation phase'; Jelgersma et al., 1970; Pruijssers et al., 1991; Van der Valk, 1992) and many of the intermediate dune valleys were filled with aeolian sand (Fig. 14C–E). In the predominantly horizontal deposits from this equalisation phase some thin organic beds occur locally, formed in the broad plains between the parabolic dunes. At Secundair 5 and near the WRK building such thin organic layers were found to have formed around 970 AD (S5-1; Table A3.11a; WRK-1; Table A3.10a). The overall pattern of the parabolic dunes dates for the major part from before the 16th century. In subsequent times, local sand drift has still taken place, but the general dune morphology, as seen on the AHN elevation map (Fig. 3; yellow parabolic shapes), has not changed since then.

The AHN terrain map shows clear evidence for migration to the northeast, reflecting prevailing southwesterly winds. In light of this parabolic orientation of the dunes (indicative for SW–NE aeolian transport), it is likely that the present-day Papenberg dune migrated over the site of the construction pits at Secundair 5, the WRK Building and Secundair G, and equalised the former relief of the *Older Dunes* in the process, during the transition from the Early to the Late Middle Ages.

The *Younger Dunes* buried Early Medieval settlements in the area. Humans continued to be present in the dune area but the habitation was increasingly concentrated in villages along the landward side of the widening dune belt. Archaeological traces or materials have not been found in deposits from the equalisation phase, and are few and far between in the sand forming the *Younger Dunes*.

Urbanisation and formation of a 'sand dike' in the coastal zone: 1800 AD–present

Before 1800 AD the frontal dunes fringing the contemporary coastline were still highly mobile, reflecting their parabolic origin. Intermittent lows were prone to flooding during major storms, locally transforming into ephemeral or permanent tidal inlets (known locally as *sluifers*). Since the 19th century the coastline has changed strongly. For coastal defence, sand transported along the coastline was captured with fences, and the captured sand was fixed by planting marram grass (Klijn, 1981). The most seaward interdune areas were filled with wind-blown sand, creating a single frontal dune. The current coastline of the western Netherlands is fringed by a high and straight, commonly vegetated dune ridge. Because of its anthropogenic genesis, it is frequently referred to as a 'sand dike' (Fig. 15D, E).

In the 19th century the major change in the landscape behind the dunes was the reclamation of the IJ-Lake, immediately followed by the construction of the Noordzeekanaal (Fig. 5K), traversing the new IJ-Polder and the dune belt to connect Amsterdam with the North Sea. The reclamation and drainage of the IJ-Polder and other polders by engine-driven pumping stations

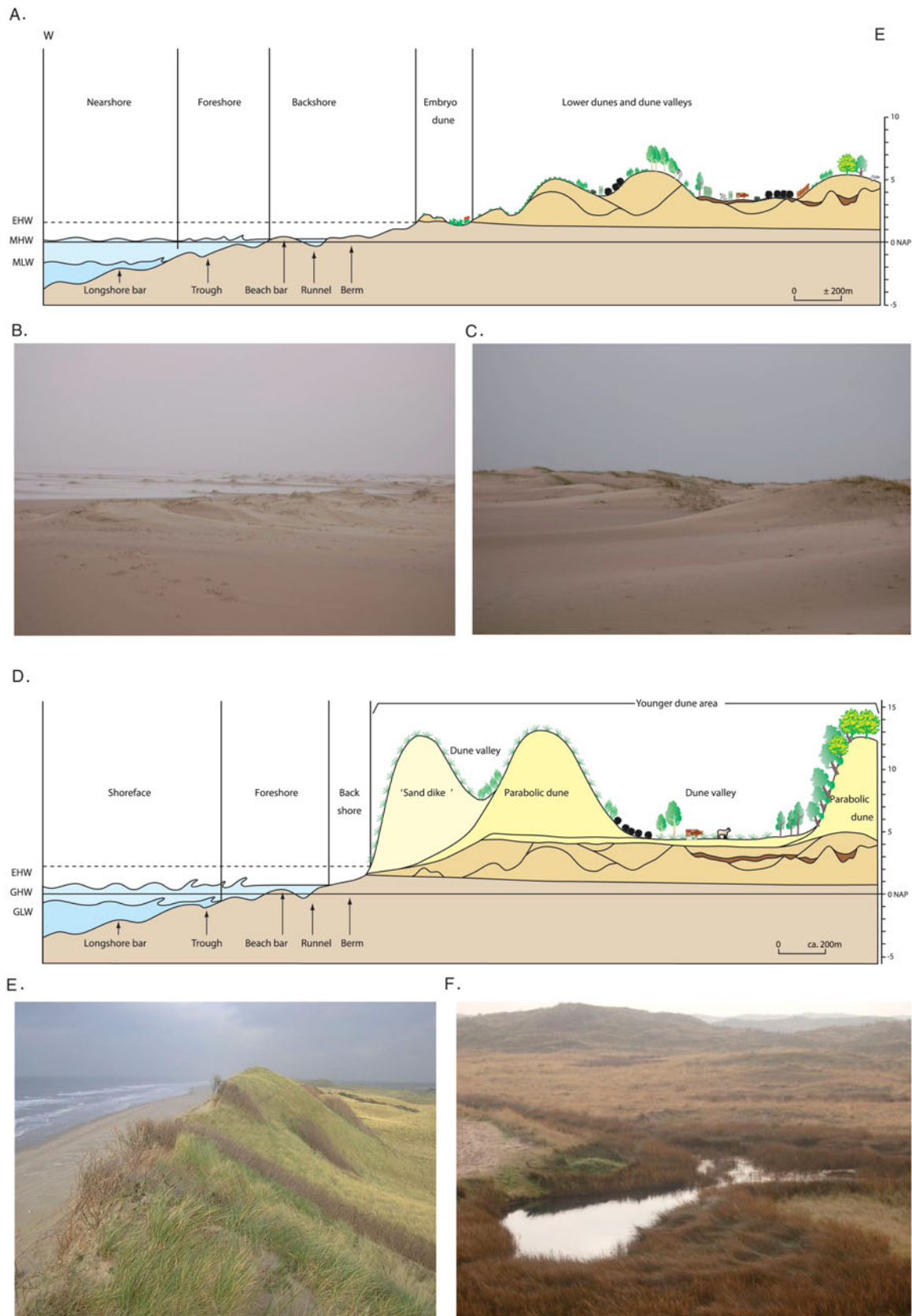


Fig. 15. Landscape reconstruction for the profile through the PWN dune area and present-day examples of the reconstructed features. The vertical exaggeration of the profile is about 60. A. Reconstruction for the Roman Period; B. Embryo-dune formation (De Hors, Texel; photo Laura Vonhögen); C. Lower-dune formation (De Hors, Texel; photo Laura Vonhögen). D. Present situation; E. 'Sand dike' (Heemskerker beach; photo Marcel Bakker); F. Vegetated parabolic dunes in the Younger Dune area (De Hors, Texel).

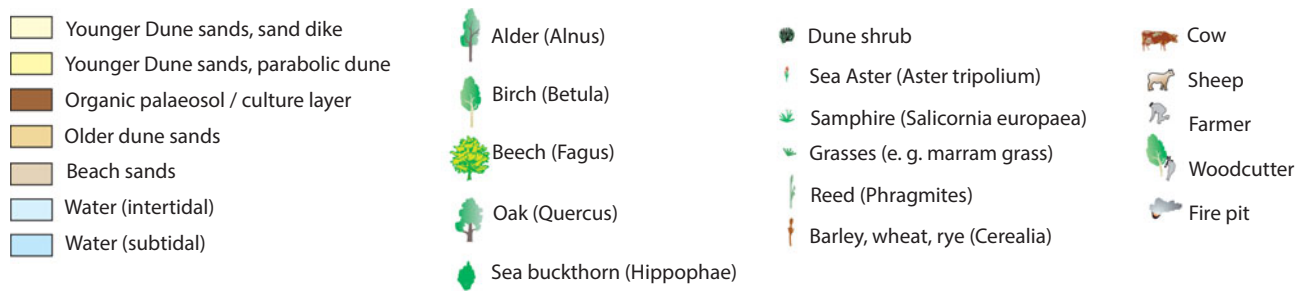


Fig. 15. Continued.

has gradually lowered the surface level of the peat polders to 1–2 m –NAP (Fig. 12; reconstructions 1650 and 2000 AD).

Large-scale urbanisation in the 20th century rapidly changed the landscape in the Oer-IJ region. Although these changes have obscured and obliterated more and more of the natural landscape, they have also allowed geo-archaeologists to study former landscapes and their inhabitants in unprecedented detail (key-site information and AHN elevation map; Fig. 3).

Discussion

New insights into key events

Our research confirms that the change in the position of the Oer-IJ tidal inlet was not caused by gradual migration driven by longshore currents, as was suggested in the reconstructions by Vos (2004) and Vos et al. (2010), but rather the result of a breakthrough event, as indicated in the reconstruction of Van der Valk (1992, 1996). The associated ingress was created around 2000–1900 BC, some 500 years later than suggested in these latter publications.

There has been disagreement on the timing of the development of the Zuiderzee. In his palaeogeographic maps, Zagwijn (1986) placed it not before the Early Medieval period (after 400 BC). Pons & Wiggers (1960), Ente et al. (1986), and Westerhoff et al. (2003), however, concluded that the connection of the Zuiderzee with the Wadden Sea was established in the Early Roman period (about 50 AD). They based their opinion on landscape descriptions by the Roman writers Tacitus and Plinius, and on the assumption that the other opening to the sea – the Oer-IJ – would have silted up simultaneously (Ente, 1986). Lenselink (in Lenselink & Koopstra, 1994; Menke et al., 1998) proposed a narrow connection between the Flevo lakes and the Wadden Sea in the Late Iron Age (before 0 AD).

Here, we argue that the connection of the Flevo lakes and the Wadden Sea was established even earlier, in the Middle Iron Age. Silting up of the Oer-IJ started around 400 BC, caused in part by the creation of the Zuiderzee opening.

The common opinion (e.g. Zagwijn, 1986; Morel, 1988; Bosman, 1997) was that in the Early Roman period the Oer-

IJ still had an open connection to the North Sea. Between 15 and 50 AD Roman ships could supposedly still navigate from the port of Castellum Flevum to the open sea. However, geological and archaeological evidence argues against such a late open connection. Dated Oer-IJ sediments in the former mouth and tidal hinterland indicate that the opening had been already closed in the Late Iron Age. Just landward of the mouth of the Oer-IJ, the base of dune sands on top of marine tidal deposits dates from around 220 BC. Nearby, Late Iron Age settlement traces were found on top of Oer-IJ-tidal deposits. Clearly, the Oer-IJ system had been cut off from the sea by a coastal barrier at that time. In the Roman period this barrier was flooded only during extreme storms, and shell-rich overwash sediments were deposited on the backside of temporary breaches.

Unresolved issues

Since deepening and widening of the main Oer-IJ channel are erosive processes that do not leave a sedimentary record, it is likely that their timing will never be fully resolved. Nevertheless, it may be possible to shine some indirect light on these processes, analysing the deepest parts of the channel fill and using hydrodynamic models to reconstruct channel behaviour as a function of subsurface lithological characteristics.

Hydrodynamic modelling can also help to understand how and to what degree changing tidal-inlet and -basin configurations affected the tidal influence in the region, including high- and low-tide levels. At present, several explanations of observed geological and archaeological evidence call on very significant changes in tidal amplitude and particular mean high water (e.g. key site Broekpolder, Appendix B5 and Fig. 11). Confirmation through independent evidence would strengthen this argument, whereas refutation would focus our attention on alternative hypotheses.

Finally, it is still unclear which factor(s) triggered the formation of the *Younger Dunes*. To answer this question, the spatial and temporal resolution of our knowledge of dune development needs to be improved. OSL dating has proved to be a very useful addition to the suite of dating methods available to the geo-archaeologist and should be used extensively to time dune initiation, maturation and migration on a regional scale.

Supplementary material

To view supplementary material for this article, please visit <http://dx.doi.org/10.1017/njg.2015.27>

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References

- Abbinck, A.A.**, 1999. Make it and break it: the cycles of pottery. A study of the technology, form, function, and use of pottery from settlements at Uitgeest-Groot Dorregeest and Schagen-Muggenburg: 1, Roman period, North-Holland, the Netherlands. *Archaeological Studies Leiden University* 5.
- Allen, J.R.L.**, 1999. Geological impacts on coastal wetland landscapes: Some general effects of sediment autocompaction in the Holocene of northwest Europe. *The Holocene* 9: 1–12.
- Bazelmans, J.G.A.**, 2009. The early-medieval use of ethnic names from classical Antiquity: The case of the Frisians. *In: Derks, T. & Roymans, N. (eds): Ethnic Constructs in Antiquity. The Role of Power and Tradition.* Amsterdam University Press (Amsterdam): 321–338.
- Bazelmans, J., Dijkstra, M.F.P. & De Koning, J.**, 2001. Holland in het eerste millennium. *In: De Nijs, T. & Beukers, E. (eds): De Geschiedenis van Holland. Deel I, tot 1572. Verloren (Hilversum):* 20–68.
- Beentjes, R.A. & De Koning, J.**, 2000. Nabij de monding van het voormalige Oer-IJ. *Westerheem* 49: 46–52.
- 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.
- Beets, D.J., Van der Valk, L. & Stive, M.J.F.**, 1992. Holocene evolution of the coast of Holland. *Marine Geology* 103: 423–443.
- Beets, D.J., Van der Spek, A.J.F. & Van der Valk, L.**, 1994. Holocene ontwikkeling van de Nederlandse kust. Report no. 40.016. Rijks Geologische Dienst (Haarlem): 1–53.
- Beets, D.J., Roep, Th.B. & Westerhoff, W.E.**, 1996. The Holocene Bergen Inlet: Closing history and related barrier progradation. *In: Beets, D.J. et al. (eds): Coastal studies on the Holocene of the Netherlands. Mededelingen Rijks Geologische Dienst* 57: 97–113.
- Beets, J., De Groot, T.A.M. & Davies, H.A.**, 2003. Holocene tidal back-barrier development at decelerating sea-level rise: A 5 millennia record, exposed in the western Netherlands. *Sedimentary Geology* 158: 117–144.
- Bennema, J.**, 1954. Bodem- en zeespiegelbewegingen in het Nederlandse kustgebied. Boor en Spade 7. PhD thesis. Wageningen University (Wageningen): 1–96.
- Bennema, J. & Pons, L.J.**, 1957. The Holocene deposits in the surroundings of Velsen and their relations to those in the excavation. *In: Van Straaten, L.M.J.U. & de Jong, J.D. (eds): The Excavation at Velsen. A Detailed Study of Upper Pleistocene and Holocene Stratigraphy. Verhandelingen van het Geologisch-Mijnbouwkundig Genootschap. Geologische Serie* 17: 199–218.
- Besteman, J.C.**, 1990. North Holland AD 400–1200: Turning tide or tide turned? *In: Besteman, J.C., Bos, J.M. & Heidinga, H.A. (eds): Medieval Archaeology in the Netherlands. Van Gorcum (Assen):* 91–120.
- Besteman, J.C. & Guiran, A.J.**, 1987. An early peat bog reclamation area in medieval Kennemerland. *In: Brandt, R.W., Groenman-Van Waateringe, W. & Van der Leeuw, S.E. (eds): Assendelver Polder Papers I (Cingula 10) (Amsterdam):* 297–332.
- Bloemers, J.H.F. (ed.)**, 1988. Archeologie en Oecologie van Holland tussen Rijn en Vlie. *Studies in Prae- en Protohistorie* 2. Van Gorcum (Assen).
- Bloemers, J.H.F. & Therkorn, L.L.**, 2003. Wisselende seizoenen en verborgen landschappen. *Wetland archeologie in de Velslerbroek. Provincie Noord-Holland (Haarlem):* 40 pp.
- Blokzijl, J., Dubelaar, C.W., De Gans, W. & De Jong, J.**, 1995. Vereenvoudigde geologische kaart van Haarlem en omgeving. Rijks Geologische Dienst (Haarlem).
- Bos, I.J.**, 2010. Distal Delta-Plain Successions. Architecture and Lithofacies of Lake Fills and Organics in the Holocene Rijn–Maas Delta, The Netherlands. PhD thesis. Utrecht University (Utrecht): 208 pp.
- Bos, I., Busschers, F.S. & Hoek, W.Z.**, 2012. Organic-facies determination: A key for understanding facies distribution in the basal peat layer of the Holocene Rhine-Meuse delta, The Netherlands. *Sedimentology* 59: 676–703.
- Bosman, A.V.A.J.**, 1997. Het Culturele Vondstmateriaal van de Vroeg-Romeinse Versterking Velsen 1. PhD thesis. Universiteit van Amsterdam (Amsterdam).
- Bosman, W.J.**, 2011. Dirty Sands. Concept-rapportage Velsen 2. Onderzoek naar de Vroeg Romeinse basis in de periode 1945–2005, kortlopende project in het kader van het door NWO gefinancierde Odyssee programma. Bosman (Santpoort-Zuid).
- Bosman, M. & Calkoen, H.J.**, 1967. Een Karolingische woonplaats bij Wijk aan Zee, gemeente Beverwijk. *Westerheem* 15 (5): 224–231.
- Bosman, W.J. & Soenius, C.**, 1990. Bronstijdboeren met hun schaaapjes op het droge in Velsen. *Westerheem* 39: 1–6.
- Bosman, W.J. & Van Eerden, R.A.**, 2009. Sporen onder het zand. *In: Roos, R. (ed.): Duinen en Mensen Kennemerland. Stichting Natuurmedia, Amsterdam:* 28–45.
- Brandt, R.W. & Van der Leeuw, S.E.**, 1987. Conclusions. *In: Brandt, R.W., Groenman-Van Waateringe, W. & Van der Leeuw, S.E. (eds): Assendelver Polder Papers I (Cingula 10) (Amsterdam):* 297–332.
- Brandt, R.W., Van der Horst, G.J. & Stolp, J.J.** (eds), 1983. De Zaanstreek archeologisch bekeken. Speciale uitgave in de Westerheem-reeks. Awn (Zaanstad).
- Busschers, F.S.**, 2008. Unravelling the Rhine. Response of a fluvial system to climate change, sea-level oscillation and glaciation. PhD thesis. Vrije Universiteit (Amsterdam).
- Calkoen, H.J.**, 1967. Velsen, grepen uit de geschiedenis van een oude woonplaats in Kennemerland. Report Awn-IJmuiden.
- Cleveringa, P.**, 1988. Pollenanalytisch onderzoek van boring Beverwijk/Wijkerbroek en enige boringen in het aangrenzende deel van de Noordzee voor de kust bij IJmuiden. Report no. 1055. Afdeling Paleobotanie Kenozoicum, Rijks Geologische Dienst (Haarlem).
- Cleveringa, J.**, 2000. Reconstruction and modelling of Holocene evolution of the western Netherlands. PhD thesis. Utrecht University (Utrecht): 197 pp.

- Cordfunke, E.H.P.**, 1969. Roman and early-medieval pottery from Limmen, Prov. North Holland. *Berichten van de Rijksdienst voor het Oudheidkundig Bodemonderzoek* 19: 291–298.
- De Bont, C.**, 2009. Middeleeuws veen en middeleeuwse veenboeren. *Grondboor & Hamer* 63 (3/4): 85–114.
- De Cock, J.K.**, 1980. Bijdrage tot de Historische Geografie van Kennemerland in de Middeleeuwen op Fysisch-Geografische Grondslag. Gysbers & Van Loon (Arnhem): 289 pp.
- De Gans, W. & Bunnik, F.**, 2012. Ruigoord en het Oer-IJ. *Grondboor & Hamer* 66 (6): 462–468.
- De Gans, W., Bunnik, F. & Van Wirdum, G.**, 2010. Het Naardermeer: Een bijzondere en complexe ontstaansgeschiedenis. *Grondboor & Hamer* 64 (1): 2–12.
- De Jong, J.**, 1980. C14-bepaling van schelpen afkomstig uit een ontsluiting in het waterwingebied van de P.W.N. te Castricum. Report no. 872. Afdeling Paleobotanie Kenozoicum, Rijks Geologische Dienst (Haarlem).
- De Jong, J.**, 1983. Uitkomsten C14-dateringen te Uitgeest-Dorreegeest. Report no. 932. Afdeling Paleobotanie Kenozoicum, Rijks Geologische Dienst (Haarlem).
- De Jong, J.**, 1984. Gegevens ingezonden materiaal voor experimentele C14-ouderdomsbepaling door middel van de Van de Graaff tandemversneller. Report no. 945. Afdeling Paleobotanie Kenozoicum, Rijks Geologische Dienst (Haarlem).
- De Jong, J.**, 1986a. Veldgegevens verkregen in een bouwput op het terrein van de PWN te Heemskerk en uitkomsten van een tweetal bij het onderzoek verkregen C14-bepalingen. Report no. 995. Afdeling Paleobotanie Kenozoicum, Rijks Geologische Dienst (Haarlem).
- De Jong, J.**, 1986b. Uitkomsten C14-ouderdomsbepalingen aan het Hollandveen bij Wormer. Report no. 999. Afdeling Paleobotanie Kenozoicum, Rijks Geologische Dienst (Haarlem).
- De Jong, J.**, 1986c. Uitkomsten C14-ouderdomsbepalingen aan materiaal verkregen uit een gassleuf te Uitgeest. Report no. 1005. Afdeling Paleobotanie Kenozoicum, Rijks Geologische Dienst (Haarlem).
- De Jong, J.**, 1986d. Uitkomsten van C14-ouderdomsbepalingen, verricht aan boringen uit de omgeving van Akersloot. Report no. 1006. Afdeling Paleobotanie Kenozoicum, Rijks Geologische Dienst (Haarlem).
- De Jong, J.**, 1987a. Palynology of two cored sections at Assendelft 17. In: Brandt, R.W., Groenman-Van Waateringe, W. & Van der Leeuw, S.E. (eds): *Assendelfter Polder Papers I* (Cingula 10) (Amsterdam): 39–48.
- De Jong, J.**, 1987b. Uitkomsten van C14-ouderdomsbepalingen aan schelpen uit de boring De Woude (19D/269). Report no. 1026. Afdeling Paleobotanie Kenozoicum, Rijks Geologische Dienst (Haarlem).
- De Jong, J.**, 1987c. Uitkomsten C14-ouderdomsbepalingen aan materiaal afkomstig uit de Uitgeesterbroekpolder. Report no. 1036. Afdeling Paleobotanie Kenozoicum, Rijks Geologische Dienst (Haarlem).
- De Jong, J.**, 1987d. Palynology of two core sections at Assendelft 17 In: Brandt, R.W., Groenman-Van Waateringe, W. & Van der Leeuw, S.E. (eds): *Assendelfter Polder Papers I* (Cingula 10) (Amsterdam).
- De Jong, J.**, 1988a. Uitkomsten van een drietal C14-ouderdomsbepalingen aan schelpen, afkomstig uit de voormalige Wijkermeer. Report no. 1047. Afdeling Paleobotanie Kenozoicum, Rijks Geologische Dienst (Haarlem).
- De Jong, J.**, 1988b. Onderzoek van een tweetal boringen in en voor de monding van de Westerschelde. Internal report no. 1056. Afdeling Paleobotanie Kenozoicum, Rijks Geologische Dienst (Haarlem): 7 pp.
- De Koning, J.**, 1992. Het aardewerk van de vroegmiddeleeuwse nederzetting Uitgeest-De Dog. Doctoraalscriptie, IPP (Amsterdam).
- De Koning, J.**, 2003. Why did they leave? Why did they stay? On continuity versus discontinuity from Roman times into the early Middle Ages in the western coastal area of the Netherlands. In: Grünwald, T. & Seibel, S. (eds): *Kontinuität und Diskontinuität. Germania inferior am Beginn und am Ende der Römischen Herrschaft. Beiträge des Deutsch-Niederländischen Kolloquiums in der Katholieke Universiteit Nijmegen* (27. bis 30.06.2001) (Berlin, New York): 53–82.
- De Koning, J.**, 2007. 3000 jaar bewoning bij Assum, Nederzettingssporen uit de late Bronstijd/vroege IJzertijd, midden IJzertijd, Romeinse tijd en late Middeleeuwen bij Uitgeest Waldijk en de Assummervaart. Met bijdragen van: P. Vos (Geologie), T. Vernimmen (Archeobotanie) en L. de Vries (Archeozoölogie). *Hollandia-reeks* no. 199.
- De Koning, J.**, 2011. Onder het duinzand. Verstoven vroegmiddeleeuwse nederzettingen in het nationaal park Zuid-Kennemerland bij Bloemendaal. De opgravingscampagnes Groot Olmen 2005, 2006 en 2007. Met bijdragen van W. Bosman, F. Bunnik, S. Knippenberg, J. Matser, O. Odé, T. Vernimmen, Y. Sablerolles, L. De Vries en P. Vos. *Hollandia-reeks* no. 400: 576 pp.
- De Koning, J.**, 2012a. De betekenis van Noord-Holland binnen vroegmiddeleeuws Frisia. In: *Sporen van het Fries en de Friezen in Noord-Holland. Taalkundige en historische evidentie* (Symposium 12 en 13 november 2010). *It Beaken* 74 (1/2): 3–31.
- De Koning, J.**, 2012b. Castricum project stichting Hooge Weide: Grote Ven en Oude Venne (DO). Evaluatierapport *Hollandia* archeologen (Zaandijk).
- De Koning, J. & Hogendijk, T.**, 2012. Een proefsleuvenonderzoek (IVO-P) op twee locaties langs de Schulpvaart in Castricum. *Hollandia-reeks* no. 442.
- De Koning, J. & Vos, P.**, 2007. De opgraving van een prehistorische boomstamkano in Uitgeest, Met bijdragen van L. Koehler, E. Hanraets, T. Vernimmen, E. Jansma, O. Brinkkemper en C. Vernimmen. *Hollandia* reeks no. 170: 58 pp.
- De Mulder, E.F.J. & Bosch, J.H.A.**, 1982. Holocene stratigraphy, radiocarbon datings and paleogeography of central and northern Noord-Holland (the Netherlands), *Mededelingen Rijks Geologische Dienst* 36 (3): 135–148.
- 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 Roo, H.C.**, 1953. De bodemgesteldheid van Noord-Kennemerland. De kartering van Nederland, deel XIV, *Verslagen van Landbouwkundige onderzoekingen*, no 59.3. Directie van den Landbouw's-Gravenhage: 1–202.
- De Weert, M.D.**, 1987. The medieval logboat. In: Brandt, R.W., Groenman-van Waateringe, W. & Van der Leeuw, S.E. (eds): *Assendelfter Polder Papers I* (Cingula 10) (Amsterdam): 265–284.
- Diederik, F.**, 2002. Scherven gericht. Een onderzoek naar inheems aardewerk uit de late 3^e en 4^e eeuw in de kop van Noord-Holland. *AWN* reeks no. 3: 168 pp.
- Dijkstra, M.F.P. & Verhoeven, A.A.A.**, 2013. Heiloo Zandzoom/Zuiderloo. In: *De Archeologische Kroniek van Noord-Holland: Provincie Noord-Holland, Haarlem. Kroniek* 57–60.
- Dijkstra, M.F.P., De Koning, J. & Lange, S.**, 2006. Limmen–De Krocht. De opgraving van een middeleeuwse plattelandnederzetting in Kennemerland. Publicatie no. 41. Projectbureau AAC (Amsterdam): 256 pp.
- Doppert, J.W.Ch., Ruegg, G.H.J., Van Staalduinen, C.J. & Zagwijn, W.H.**, 1975. Formaties van het Kwartaire en Boven Tertiaire in Nederland. In: *Zagwijn, W.H.*

- & Van Staaldunin, C.J. (eds): Toelichtingen bij de Geologische Overzichtskarten van Nederland. Rijks Geologische Dienst (Haarlem): 11–56.
- Duinker, P.L.**, 1955. Het watervlak. (typescript). Dienst der terreinen, Internal report. PWN.
- Ehlers, J.**, 1986. The morphodynamics of the Wadden Sea. Balkema (Rotterdam): 397 pp.
- Ente, P.J., Koning, J. & Koopstra, R.**, 1986. De bodem van oostelijk Flevoland. Flevovericht no. 258. Rijksdienst voor de IJsselmeerpolders (Lelystad): 178 pp.
- Güray, A.R.**, 1952. De bodemgesteldheid van de IJ-polders. Boor en Spade 5: 1–28.
- Hagers, J.K. & Sier, M.M.**, 1999. Castricum-Oosterbuurt, bewoningssporen uit de Romeinse tijd en middeleeuwen. Rapporten Archeologische Monumentenzorg no. 53. Rijksdienst voor het Cultureel Erfgoed (Amersfoort).
- Hallewas, D.P.**, 1981. Archaeological cartography between Marsdiep and IJ. Berichten van de Rijksdienst voor het Oudheidkundig Bodemonderzoek 31: 219–272.
- Hallewas, D.P.**, 1987. The geology in relation to the record of occupation and settlements. In: Brandt, R.W., Groenman-Van Waateringe, W. & Van der Leeuw, S.E. (eds): Assendelver Polder Papers I (Cingula 10) (Amsterdam): 23–38.
- Heidinga, H.A.**, 1997. Frisia in the first millennium. An outline. Uitgeverij Matris (Utrecht).
- Helderman, E.J.**, 1970. Nieuwe vondsten te Uitgeest. Grondspoor 32.
- Helderman, E.J.**, 1971. Archeologische activiteiten te Uitgeest. Grondspoor 33.
- Jelgersma, S., De Jong, J., Zagwijn, W.H. & Van Regteren Altena, J.F.**, 1970. The coastal dunes of the western Netherlands: Geology, vegetational history and archaeology. Mededelingen Rijks Geologische Dienst, Nieuwe Serie, 21: 93–167.
- Jelgersma, S., Stive, M.J.F. & Van der Valk, L.**, 1995. Holocene storm surge signatures in the coastal dunes of the western Netherlands. Marine Geology 125: 95–110.
- Kleijne, J.P., Brinkkemper, O., Lauwerier, R.C.G.M., Smit, B.I. & Theunissen, E.M.**, 2013. A matter of life and death at Mienakker (The Netherlands). Late neolithic behavioural variability in a dynamic landscape. Nederlandse Archeologische Rapporten (NAR) 45 (Amersfoort).
- Klijn, J.A.**, 1981. Nederlandse kustduinen. Geomorfologie en bodems. Centrum voor Landbouwpublikaties en landbouwdocumentatie (Wageningen): 188 pp.
- Kloosterhuis, J.C.**, 1954. Bodemkundige verkenningsskaart, Provincie Noord-Holland (Zuidelijk deel). Concept bodemkaart van de Stichting voor Bodemkartering (Wageningen).
- Koene, B., Morren, J. & Schweitzer, F.**, 2003. Midden-Kennemerland in de Vroege en Hoge Middeleeuwen. Het Land, de Bewoners en hun Heren tussen 700 en 1300. Uitgeverij Verloren (Hilversum).
- Kok, M.S.M.**, 2008. The Homecoming of Religious Practice. An Analysis of Offering Sites in the Wet Low-Lying Parts of the Landscape in the Oer-IJ Area (2500 BC–AD450). PhD thesis. Universiteit van Amsterdam (Amsterdam): 264 pp.
- Kootker, L.M. & Altena, E.**, 2010. Bioarcheologisch onderzoek van de menselijke resten uit Castricum-Oosterbuurt. Report no. 2010–07. Instituut voor Geo- en Bioarcheologie, Vrije Universiteit Amsterdam (Amsterdam).
- Lange, S., Besselsen, E. & Van Londen, H.**, 2004. Het Oer-IJ estuarium. Archeologische Kennis Inventarisatie (AKI). Publicatie Projectbureau AAC 12: 124.
- Lenselink, G. & Koopstra, R.**, 1994. Ontwikkeling in het Zuiderzeegebied; van Meer Flevo, via de Almere-lagune, tot Zuiderzee. In: Rappol, M. & Soonius, C.M. (eds): In de Bodem van Noord-Holland. Lingua Terrae (Amsterdam): 129–140.
- 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.
- Meffert, M.**, 1998. Ruimtelijke relaties in het Oer-IJ-estuarium in de Romeinse IJzertijd met nadruk op de Assendelver polders. PhD thesis. Universiteit van Amsterdam (Amsterdam).
- Modderman, P.J.R.**, 1960. De Spanjaardsberg; voor- en vroeghistorische boerenbedrijven te Santpoort. Berichten Rijksdienst voor het Oudheidkundig Bodemonderzoek 10: 210–263.
- Moree, J.M. & Sier, M.M.**, 2014. Twintig meter diep. Mesolithicum in de Yangtze-haven – Maasvlakte te Rotterdam. Landschapontwikkeling en bewoning in het Vroeg Holoceen. B00Rrapporten.
- Morel, J.M.A.W.**, 1986. The Early Roman defended harbours at Velsen, North Holland. In: Unz, C. (ed.): Studien zu den Militärgrenzen Roms 3, 13. International Congress of Roman Frontier Studies, British Archaeological Reports Int. Ser. 71 (Oxford): 475–494.
- Morel, J.M.A.W.**, 1988. De Vroeg-Romeinse Versterking te Velsen. Fort en Haven. PhD thesis. Universiteit van Amsterdam (Amsterdam).
- Müller, A., Van Bergeijk, G., Drenth, E., Vos, P.C. & Van Heeringen, R.M.**, 2008. Akersloot-Klein Dorregeest. Een vindplaats van de klokbekercultuur in de gemeente Castricum, provincie Noord-Holland. Rapportage Archeologische Monumentenzorg 159 (Amersfoort).
- Pons, L.J. & Kloosterhuis, J.L.**, 1955. Rapport van de verkenning van de bodemgesteldheid van het zuidelijke gedeelte van de provincie Noord-Holland. Report no. 409. Stiboka (Wageningen).
- Pons, L.J. & Van Oosten, M.F.**, 1974. De Bodem van Noord-Holland. Toelichting bij Blad 5 van de Bodemkaart van Nederland, schaal 1:200.000. Stiboka (Wageningen): 193 pp.
- Pons, L.J. & Wiggers, A.J.**, 1959. De holocene wordingsgeschiedenis van Noordholland en het Zuiderzeegebied; deel 1. Tijdschrift Koninklijk Nederlands Aardrijkskundig Genootschap, Tweede Reeks 76: 104–152.
- Pons, L.J. & Wiggers, A.J.**, 1960. De holocene wordingsgeschiedenis van Noordholland en het Zuiderzeegebied; deel 2. Tijdschrift 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 KNGMG: transactions of the jubilee convention – part two 21: 197–207.
- Pruissers, A.P., Vos, H.H. & Van der Valk, L.**, 1991. De geologische en landschappelijke ontwikkeling van het Breesaapduingebied. Holland – Regionaal-Historisch Tijdschrift 23 (3): 117–138.
- Roep, Th.B. & Beets, D.J.**, 1988. Sea-level rise and paleotidal levels from sedimentary structures in the coastal barriers in the western Netherlands since 5600 BP. Geologie & Mijnbouw 67: 53–60.
- Roep, T.B. & Van Regteren Altena, J.F.**, 1988. Paleotidal levels in tidal sediments (3800–3635 BP); compaction, sea-level rise and human occupation (3275–2620 BP) at Bovenkarspel, NW Netherlands. In: De Boer, P.L. et al. (eds): Tide-influenced sedimentary environments and facies. Reidel (Dordrecht): 215–231.

- Roep, T.B., Beets, D.J. & De Jong, J.**, 1979. Het zeegat tussen Alkmaar en Bergen van ca. 1900 tot 1300 jaar v. Chr. Alkmaarse Historische Reeks, deel III: 9–35.
- Roep, Th.B., Van der Valk, L. & Beets, D.J.**, 1991. Strandwallen en inletsystemen langs de Hollandse kust. *Grondboor & Hamer* 45:115–124.
- Taayke, E.**, 1997. Die einheimische Keramik der nordlichen Niederlande, 600 v. Chr. bis 300 n. Chr. PhD thesis. Groningen Institute of Archaeology (Groningen).
- Ten Anscher, T.J.**, 2012. Leven met de Vecht. Schokland-P14 en de Noordoostpolder in het Neolithicum en de Bronstijd. Hoofdstuk 27: Landschap en bewoning in de Noordoostpolder. PhD thesis. Universiteit van Amsterdam (Amsterdam): 507–536.
- Therkorn, L.L.**, 2004. Landscaping the Powers of Darkness & Light. 600 v. Chr. – 350 AD Settlements Concerns of Noord-Holland in a Wider Perspective. PhD thesis. Universiteit van Amsterdam (Amsterdam).
- Therkorn, L.L. & Abbink, A.A.**, 1987. Seven levee sites: B, C, D, G, H, F, and P. *In: Brandt, R.W., Groenman-Van Waateringe, W. & Van der Leeuw, S.E. (eds): Assendelver Polder Papers I (Cingula 10) (Amsterdam): 115–167.*
- Therkorn, L.L. & Oversteegen, J.F.S.**, 1994. Velsen: Velsersbroek, site B6. *In: Hagers, J.K. & Hessing, W. (eds): Archeologische Kroniek van Holland 1993. Holland – Regionaal-Historisch Tijdschrift 26: 389–392.*
- Therkorn, L.L., Brandt, R.W., Pals, J.P. & Taylor, M.**, 1984. An Early Iron Age farmstead: Site Q of the Assendelver Polders Project. *Proceedings of the Prehistoric Society* 50: 351–373.
- Therkorn, L., Besselsen, E.A. & Oversteegen, J.F.S.**, 1998. Assendelver Polders Revisited: excavations 1997. Faculty for Environmental Sciences, University of Amsterdam (Amsterdam): 1–59.
- Therkorn, L.L., Besselsen, E., Diepeveen-Jansen, M., Gerritsen, S., Kaarsemaker, J., Kok, M., Kubiak-Martens, L., Slopsma, J. & Vos, P.**, 2009. Landscapes in the Broekpolder, Excavations around a Monument with Aspects of Bronze Age to the Modern (Beverwijk & Heemskerk, N-H), vol. 1. AAC/Projectenbureau, University of Amsterdam (Amsterdam): 228 pp.
- Vaars, J.P.L.**, 2004. Archeologisch opgravingen aan de Hoogdorperweg te Heemskerk. *Hollandia reeks* 24: 17 pp.
- Van Deelen, D. & Schermer, A.** 1963. Middeleeuws akkerland onder de Castricummer duinen. *Westerheem* 12: 136–144.
- Van de Plassche, O.**, 1982. Sea-level change and water-level movements in the Netherlands during the Holocene, *Mededelingen Rijks Geologische Dienst* 36 (1): 1–93.
- Van de Plassche, O. & Roep, T.**, 1989. Sea-level changes in the Netherlands during the last 6500 years: Basal Peat vs. coastal barrier data. *In: Scott, D.B. et al. (eds): Late Quaternary Sea-Level Correlation and Applications. Kluwer Academic Publishers (Dordrecht): 41–56.*
- Van der Leeuw, S.E.**, 1987. Outline of the project and first results. Assendelver Polders. *In: Brandt, R.W., Groenman-Van Waateringe, W. & Van der Leeuw, S.E. (eds): Assendelver Polder Papers I (Cingula 10) (Amsterdam): 1–21.*
- Van der Spek, A.**, 1994. Mid-Holocene evolution of a tidal basin in the western Netherlands: A model for future changes in the northern Netherlands under conditions of accelerated sea-level rise? PhD thesis. University of Utrecht (Utrecht): 75–95.
- Van der Valk, L.**, 1992. Mid- and Late Holocene Coastal Evolution in the Beach Barrier Area of the Western Netherlands. PhD thesis. Vrije Universiteit (Amsterdam): 235 pp.
- van der Valk, L.**, 1994. Rapportage veldgegevens Castricum PWN Infiltratievlak. Rijks Geologische Dienst, District West (OP 60191).
- Van der Valk, L.** 1996. Coastal barrier deposits in the central Dutch coastal plain. *In: Beets, D.J. et al. (eds): Coastal Studies on the Holocene of the Netherlands. Mededelingen Rijks Geologische Dienst nr. 57: 133–199.*
- Van der Valk, L.** 2007. Environmentally controlled, transgressive ‘younger’ coastal dunes along the Dutch coast. R&D 2007, Annual Report, Deltareas (Delft): 2–8/2–29.
- Van Eerden, R. (ed.)**, 2004. Behoud en beheer van archeologische vindplaatsen in het Oer-IJ-gebied. Provincie Noord Holland (Haarlem).
- Van Gijn, A.**, 1987. Site N. *In: Brandt, R.W., Groenman-Van Waateringe, W. & Van der Leeuw, S.E. (eds): Assendelver Polder Papers I (Cingula 10) (Amsterdam): 91–113.*
- Van Heeringen, R.M.**, 1992: The Iron Age in the Western Netherlands. PhD thesis. University of Amsterdam (Amsterdam); also: *Berichten van de Rijksdienst voor het Oudheidkundig Bodemonderzoek* 39: 7–67, 69–155, 157–267.
- Van Heeringen, R.M. & Theunissen, E.M. (eds)**, 2001. Kwaliteitsbepalend onderzoek ten behoeve van duurzaam behoud van neolithische terreinen in West-Friesland en de Kop van Noord-Holland. *Nederlandse Archeologische Rapporten* 21. Deel 2 Site-dossiers (Amersfoort).
- Van Raaij, M.**, 1993. Limmen: Zuidkerkenlaan I en II. *In: Woltering, P.J. & Hagers, J.K.A. (eds): Archeologische kroniek van Holland over 1992. Holland – Regionaal-Historisch Tijdschrift 25: 315–320.*
- Van Regteren Altena, J.F.**, 1970. The coastal dunes of the western Netherlands; geology, vegetational history and archaeology, Chapter V, *Archeology. Mededelingen Rijks Geologische Dienst, Nieuwe Serie* 21: 133–167.
- Van Roon, C.J.**, 2000. Boerderijen uit de midden- en late ijzertijd. Grondsporen: Veertig jaar archeologisch onderzoek in de Zaanstreek, 1960–2000. Afdeling Zaanstreek-Waterland en Omstreken van de Archeologische Werkgemeenschap Nederland (AWN) in samenwerking met de Stichting Uitgeverij Noord-Holland: 76–83.
- Van Smeerdijk, D.G.**, 1989. A palaeoecological and chemical study of a peat profile from the Assendelver Polder (The Netherlands). *Review of Palaeobotany and Palynology* 58: 231–288.
- Van Staalduinen, C.J.**, 1977. Geologisch onderzoek van het Nederlandse Waddengebied; inclusief Bijlagen I–V. Rijks Geologische Dienst (Haarlem): 77 pp.
- Van Staalduinen, C.J.**, 1979. Toelichting bij de Geologische Kaart van Nederland 1:50.000; Blad Rotterdam West (37 W). Rijks Geologische Dienst (Haarlem): 140 pp.
- Van Straaten, L.M.J.U.**, 1957. The Holocene deposits. *In: Van Straaten, L.M.J.U. & De Jong, J.D. (eds): The excavation at Velsen. A detailed study of Upper Pleistocene and Holocene stratigraphy. Verhandelingen van het Geologisch-Mijnbouwkundig Genootschap, serie 17: 93–218.*
- Van Straaten, L.M.J.U.**, 1965. Coastal barrier deposits in South- and North-Holland in particular in the areas around Scheveningen and IJmuiden. *Mededelingen van de Geologische Stichting* 17: 41–75.
- Veerkamp, J.**, 2001. Afrikahaven, een mammoet in Amsterdam. *Archeologische begeleiding ontgraving Afrika-Haven. Archeologische Rapporten Serie Amsterdam (ARSA) 01–02, Amsterdam: 1–21.*
- Verbraeck, A.**, 1974. The genesis and age of the riverdunes (donken) in the Alblasserwaard. *Mededelingen Rijks Geologische Dienst, Nieuwe Serie*, 25 (1): 1–8.

- Verhagen, M.**, 1985. Velsen Hoogovens. Een inheems-Romeinse nederzetting in het duingebied. Doctoraalscriptie. IPP (Amsterdam).
- Vos, P.C.**, 1983. De relatie tussen de geologische ontwikkeling en de bewoningsgeschiedenis in de Assendelver polders vanaf 1000 voor Chr. *In*: Brandt, R.W., Van der Horst, G.J. & Stolp, J.J. (eds): De Zaanstreek archeologisch bekeken (Zaanstad): 6–32.
- Vos, P.C.**, 1998. 10 Profiel reconstructies door de Zaanstreek tussen Groenedijk en Twiske (3000 v. Chr. - heden) t.b.v. de tentoonstelling 'De dubbele bodem' van het Zaanse museum, Aanvullende geologische informatie. TNO-Report NITG 98-136-B: 37 pp.
- 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, no. 1. University of Amsterdam (Amsterdam): 33–73.
- Vos, P.C.**, 2000. Geo-archeologisch profiel Broekpolder 1999. TNO rapport NITG 00-113-B.
- 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.**, 2007a. Geo-archeologische rapportage van de vondstmeldingen Castricum Zanderij en Klein Dorregeest. TNO-Report 2007-U-R0327/B: 25 pp.
- Vos, P.C.**, 2007b. Inventariserend bureauonderzoek Middensluiseland. TNO-Report 2007-U-R0014/B: 15 pp.
- Vos, P.C.**, 2008. Geo- en archeolandschappelijk onderzoek bij het archeologisch proefsleufonderzoek op Middensluiseland. Tweeduizend jaar duingehiedenis van het voormalige havenhoofd tussen de Midden- en Noordersluis in IJmuiden. TNO-Report 2008-U-R1200/B: 77 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 Report (Deltares).
- Vos, P.C.**, 2013. Lithostratigrafie van de Holocene kustafzettingen in Noord Nederland. Deltares-Report, kenmerk 1208302-000-BGS-0008: 23 pp.
- Vos, P.C.**, 2015. Origin of the Dutch coastal landscape. Long-term landscape evolution of the Netherlands during the Holocene, described and visualized in national, regional and local palaeogeographical map series. Barkhuis (Groningen): 359 pp.
- Vos, P.C. & De Wolf, H.**, 1988. Paleo-ecologisch diatomeeën onderzoek in de Noordzee en provincie Noord-Holland in het kader van het kustgenese project, Taakgroep 5000. Report no. 500. Afdeling Paleobotanie Kenozoïcum Diatomeeën, Rijks Geologische Dienst (Haarlem).
- Vos, P.C. & Kiden, P.**, 2005. De landschapsvorming tijdens de Steentijd. *In*: Deeben, J. et al. (eds), De Steentijd van Nederland. Archeologie 11/12: 7–37.
- Vos, P.C. & Knol, E.**, 2005. Wierden ontstaan in een dynamisch getijdenlandschap. *In*: Knol, E. et al. (eds): Professor Van Giffen en het geheim van de wierden. Groninger Museum (Groninger): 119–135.
- Vos, P.C. & Soenius, C.**, 2004. Het Oer-IJ estuarium, Archeologische Kennisinventarisatie (AKI), 4. Oude landschappen. *In*: Lange, S. et al. (eds): Het Oer-IJ estuarium, Archeologische Kennisinventarisatie (AKI). Amsterdams Archeologisch Centrum: 30–40.
- Vos, P.C. & Van Heeringen, R.M.**, 1997. Holocene geology and occupation history of the Province of Zeeland (SW Netherlands). *In*: Fischer, M.M. (ed.): Holocene evolution of Zeeland (SW Netherlands). Mededelingen NITG-TNO, no. 59 (Haarlem): 5–109.
- Vos, P.C., Bunnik, F.P.M. & De Wolf, H.**, 2005. Geolandschappelijk onderzoek bij het archeologisch proefsleufonderzoek Hoekpolder (Rijswijk, Z-H). TNO-Report NITG-05-170-B: 27 pp.
- Vos, P.C., Van Eerden, R.A. & De Koning, J.**, 2010. Paleolandschap en archeologie van het PWN duingebied bij Castricum. Rapportage van een multidisciplinair onderzoeksprogramma, uitgevoerd naar aanleiding van geologische en archeologische veldopnamen in acht bouwputten gelegen binnen het duinwaterwingebied van PWN bij Castricum. Deltares-Report, kenmerk 0912-0242: 110 pp.
- Vos, P.C., Bazelmans, J.G.A., Weerts, H.J.T. & Van der Meulen, M.J.** (eds), 2011. Atlas van Nederland in het Holoceen. Prometheus (Amsterdam): 94 pp.
- Vos, P.C., Van der Heide, M. & Stuurman, E.**, 2013. Archeolandschappelijk onderzoek bij de bronstijdvindplaats in het gebied De Druppels, Geestemerambacht. Deltares-Report, kenmerk 1204816-000-BGS: 41 pp.
- Wallinga, J. & Voskuilen, E.**, 2014. OSL dateringen Uitgeest Benes. Luminescentiedateringsrapport NCL-6114 (Delft).
- Westerhoff, W.E.**, 2003. Hoofdstuk 3. Opbouw van het Paleogeen. *In*: Mulder, E.F.J., de, Geluk, M.C., Ritsema, I., Westerhoff, W.E., & Wong, T.E. (eds): De ondergrond van Nederland. Nederlands Instituut voor Toegepaste Geowetenschappen TNO (Utrecht): 283–352.
- Westerhoff, W.E., De Mulder, E.F.J. & De Gans, W.**, 1987. Toelichtingen bij de Geologische Kaart van Nederland 1:50.000; Bladen 19 W en 19 O (Alkmaar west en Alkmaar oost). Rijks Geologische Dienst (Haarlem).
- Williams, G.L.** (ed.), 2012. Waldijk II te Uitgeest. Report no. 1785. ADC Archeo-Projecten (Amersfoort): 103 pp.
- Witte, H.J.L. & Van Geel, B.**, 1985. Vegetational and environmental succession and net organic production between 4500 and 800 B.P. reconstructed from a peat deposit in the western Dutch coastal area (Assendelver Polder). *Review of Palaeobotany and Palynology* 45: 239–300.
- Woltering, P.H.**, 1977. Castricum. Archeologische Kroniek van Noord-Holland over 1976: 194–196.
- 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.**, 1971a. De ontwikkelingen van het 'Oer-IJ' estuarium en zijn omgeving. *Westerheem* 20: 11–18.
- Zagwijn, W.H.**, 1971b. Pollenanalytisch en C-14 onderzoek van boringen in de Velsbroekpolder. Report no. 594. Afdeling Paleobotanie Kenozoïcum, Rijks Geologische Dienst (Haarlem).
- Zagwijn, W.H.**, 1984. The formation of The Younger Dunes on the west coast of The Netherlands (AD 1000–1600). *Geologie en Mijnbouw* 63: 225–336.
- Zagwijn, W.H.**, 1992. Onderzoek van lagen uit het Oude Duin I in de omgeving van het Noordzeekanaal. Report no. 1175. Afdeling Paleobotanie Kenozoïcum, Rijks Geologische Dienst (Haarlem).
- Zagwijn, W.H.**, 1997. Een landschap in beweging: De duinen van Holland sinds het Neolithicum. *In*: Hallewas, D.P., Scheepstra, G.H. & Woltering, P.J. (eds): Dynamisch Landschap; Archeologie en Geologie van het Nederlandse kustgebied. Van Gorcum, Assen/ROB (Amersfoort): 93–129.
- Zagwijn, W.H. & Van Staalduinen, C.J.**, 1975. Toelichting bij Geologische Overzichtskaarten van Nederland. Rijks Geologische Dienst (Haarlem): 1–134.