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Quaternary

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ABSTRACT

During the Quaternary (last 2.58 Myr) polycyclic and progressive climate shifts controlled depositional systems in the southern North Sea region and shaped today's Dutch landscapes. Continuous sediment supply from surrounding regions and strong basin subsidence resulted in thick depositional sequences that recorded information on successive regional climate conditions, glaciations, tectonic movement, landscapes and ecosystems.

During the Early Pleistocene, the Baltic River System acted as the principal sediment source for the Southern North Sea Basin, which was rapidly filled and consequently progressively shallowed. During the last 1 Myr the glacial climatic cycles intensified significantly, ushering in a mode of stronger and longer Fennoscandian ice-sheet expansion. This caused the demise of the Baltic River System, which in turn allowed the Rhine-Meuse River System to expand. As the Middle Pleistocene progressed, the Fennoscandian ice sheets repeatedly reached far into the North Sea region. During glaciation maxima in the Elsterian (ca. 450 ka) and Saalian (ca. 160 ka) land ice even covered northern parts of the onshore Netherlands. Along the ice-sheet fronts, ice and meltwater widely eroded, reworked and deformed pre-existing substrates and created a diverse topography that controlled river-valley courses and transgressive pathways, both in glacial and postglacial times. Across the southwestern shoulder of the North Sea Basin, an erosional connection with the English Channel was established that progressively deepened over time. Late Pleistocene (Weichselian) glacial advances were confined to the northern Dutch North Sea. Postglacial transgression, culminating in the present highstand, resulted in laterally extensive Holocene coastal-deltaic onlap.

Marine and terrestrial life in the region changed composition throughout the Quaternary: modern marine faunal and terrestrial floral assemblages emerged during the Mid-Pleistocene Revolution (from 1.2 to 0.8 Ma). Terrestrial faunas underwent spectacular turnovers, culminating in the Late Pleistocene megafaunal extinction. Humans became a dominant force in the last few millennia, in the heavily water-managed Holocene coastal plain and in inland areas of Pleistocene sediments.

<< Holocene transgression as exposed in a 20-m-deep construction pit (Kruisplein, Rotterdam). Lowstand fluvial succession (Kreftenheye Formation) with soil formation, overlain (near knife) by gyttja/basal peat and topped by estuarine clay. Photo: Geert-Jan Vis.

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The Quaternary research tradition of the Netherlands

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For many centuries, the challenges that come with living in a low-lying delta with unconsolidated sediments have provided a motivation to explore and understand the subsurface. As early as 1605, in search of high-quality water to brew beer, Pieter Pieterszn Ente managed to drill a borehole to a depth of 73 m in the centre of Amsterdam in only twenty-one days. Unfortunately, just brackish water was encountered, but the recovered sediment samples were described in considerable detail. The associated report contains one of the oldest borehole descriptions to such depth known worldwide. In those same early days, foundation demands for increasingly large stone buildings on Amsterdam's soft soil triggered the need to collect further information on the shallow subsurface. In 1655, for example, the Amsterdam City Hall (presently the Royal Palace) was founded on 13,659 wooden piles, all resting on Pleistocene sand at 12 m below NAP (the Dutch ordnance datum, about MSL).

In the nineteenth century, the search for potable groundwater in Dutch cities intensified. Pieter Harting, professor of natural history, noticed that shell-rich sediments were present at considerable depths below the surface in multiple cities in the central and western Netherlands. The uppermost shell-rich bed contained a shallow-marine molluscan association with species that now occur in the Bay of Biscay. He concluded that the North Sea must once have reached further inland, at a time when climate was warmer than today. To denote the shell-rich sediments at this stratigraphic level he introduced the term Eemian (Harting, 1874, 1875), named after the river Eem in the central part of the country, which marks the landward margin of the shell bed. Internationally, the term is still widely used to denote the Last Interglacial (equating to Substage 5e in the global marine isotope stratigraphy; Lisiecki & Raymo, 2005).

In the mid-twentieth century the well-preserved Dutch Quaternary record became subject to intensifying research efforts. At its location just south of the maximum extent of the most extensive Pleistocene glaciations and sufficiently north to document strong climatic, paleogeographic and biotic changes throughout the Quaternary, the Netherlands region appeared ideal for emerging integrated climato-, chrono- and biostratigraphic approaches. The work of various prominent researchers of that time, including I.M. van der Vlerk, F. Florschütz and W.H. Zagwijn (see photo below) coincided with the establishment of a whole range of new research methods, including palynology and radiocarbon dating, and led to a wealth of new information. Van der Vlerk & Florschütz (1950, 1953) presented a subdivision of the Pleistocene, based on floral and faunal associations (Hooghiemstra & Richards, 2022). Zagwijn (1960, 1961, 1963) further expanded and detailed this scheme. It combines the climatostratigraphic research, mainly based on palynology, and mineralogical analyses that have formed the basis for a chronostratigraphic subdivision (Hooghiemstra & Hoek, 2019). The glacial and interglacial periods that Zagwijn defined were subsequently adopted in large parts of Europe and were tied to the paleomagnetic and marine isotope record (e.g. Zagwijn, 1985; Van Kolfschoten & Gibbard, 1998; Zagwijn, 1998). Their names still appear on modern regional and global correlation charts (Cohen & Gibbard, 2019).

Following pioneering work (e.g. Oele, 1969), the number of studies addressing the Dutch offshore stratigraphic record increased in the 1980s and 1990s, profiting from improving and expanding seismic-surveying capabilities (e.g. Cameron et al., 1986; Laban, 1995). Up to today, however, correlation of the offshore and onshore Quaternary stratigraphy and records remains challenging (Fig. 10.1).

Waldo H. Zagwijn in quarry Maalbeek in 1992 (Hooghiemstra & Hoek, 2019).

Introduction

Following a lengthy period of obliquity-forced, 41-kyr climatic cycles alternating between relatively warm and temperate phases, northwestern Europe first started to experience very deep glacial minima between 2.6 and 2.4 Ma (e.g. Lisiecki & Raymo, 2005; Fig. 10.1). The first occurrence of such a cold glacial minimum in the global marine isotope record roughly coincides with the Gauss-Matuyama magnetic reversal at 2.58 Ma. It marks the onset of the Quaternary Period or the Pleistocene Epoch. Ample evidence of ice-sheet development over Fennoscandia at this time comes from iceberg scour marks in marine sedimentary records of northwestern Europe, easily recognisable on time slices of 3D seismic surveys (Ruddiman et al., 1986; Sosdian & Rosenthal, 2009; Rea et al., 2018). Although the onset of large-scale glaciation in the Northern Hemisphere was driven by a complex interconnected set of (conditional) factors and feedback mechanisms, global oceanographic change resulting from closure of the Panama isthmus in the latest Pliocene is regarded a critical factor (Mudelsee & Raymo, 2005).

The Dutch terrestrial record of the onset of the Quaternary shows evidence of phases with steppe-like vegetation (Zagwijn, 1957, 1960; Donders et al., 2018), large-scale faunal turnover (Meloro et al., 2008) and massive increases in sediment supply by the dominant river systems of the time. It also marks the beginning of the disappearance of many thermophile species that dominated the area before the Quaternary. Following continuing alternations of temperate and cold climatic phases after 2.4 Ma, the intensity of cold-climate conditions strongly increased from about 1.2 million years ago onwards, the start of the Mid-Pleistocene Revolution. At the same time, cycles of ice build-up in the Northern Hemisphere lengthened (Fig. 10.1) shown by the spacing of the Marine Isotope Stages (MIS). This resulted in periods of ice-sheet advance into previously temperate latitudes of the Northern Hemisphere, including the present-day Dutch territory, and large changes in sea level.

Under intensively varying climatic conditions of the Quaternary, a thick, complex succession of marine, deltaic, fluvial and glacigenic sediments accumulated in the Dutch part of the North Sea Basin (Fig. 10.2). This succession reflects the evolution of several terrestrial sedimentary systems and their associated coastal and shallow-marine equivalents, with clear evidence for cyclic landward and seaward shifts of the coastline. It also contains a wealth of information on the development of ecosystems and biota. Vast parts of the succession were deposited by the Baltic River System, which had been functioning since the Miocene. By the time of the Pliocene and Early Pleistocene, its depocentre was just offshore the northern Netherlands (Ottesen et al., 2018). Once it terminated as a river system at the end of the Early Pleistocene, the Rhine-Meuse River and episodically functioning depositional systems of the Fennoscandian ice-sheet margin became the main sedimentary drivers in the Netherlands and its offshore region. This new situation characterized the remainder of the Pleistocene and Holocene.

The exceptional near-surface preservation of the Quaternary sediments has generated a great deal of interest from both applied and fundamental scientific fields. Geoscientific study started as early as the seventeenth century, evolved into various disciplinary branches and has helped answer many applied questions, for example on building material, groundwater resources and the surface stability of soft soils. The Dutch Quaternary record has hence been subject to intense mapping and research efforts, particularly during the second half of the twentieth century (see Textbox 1).

With its technological and digital progress, the 21st century heralded a new phase for Quaternary research. Greatly increased amounts of accumulated and newly collected data, a focus on multidisciplinary core analysis, improved seismic acquisition and a broadening suite of dating techniques have upgraded the insight into the depositional evolution and its tectonic, geographic and paleoenvironmental contexts. Diverse scientific studies of the Quaternary were, among others, spawned from increased activities regarding exploration for aggregate and groundwater resources, for thermal energy storage in aquifers, for transportation and energy-transition infrastructure (e.g. tunnels, windfarms), for coastal safety (nourishments), and for legally required archeological prospection and investigation related to plans that will disturb the geologic record. The decision within the Geological Survey of the Netherlands to move to nationwide digital mapping and modelling, and its increasing involvement in cross-border mapping collaborations, also brought considerable new research impetus (Van der Meulen et al., 2013). Academic research output increased manyfold and involved inter-institutional collaboration. Herein, global marine isotope stratigraphy has provided an essential framework for referring to and discussing the particular age of regionally recognized stratigraphic units, events and stages. As such, traditionally established regional chronostratigraphic naming schemes remain. They are applied in parallel with international nomenclature, with alignments and correlations from time to time re-evaluated. With the raised awareness of ongoing global climate change and issues of biodiversity loss, the Quaternary archive is more than ever used to assess past conditions and responses to climate and environmental change that can be relevant to address projected sea-level rise and the development of sustainable energy sources. These issues are expected to be a major

Table 10.1. Codes for lithostratigraphic units used by TNO-GDN (status 2024).

Code	Stratigraphic unit
NUAA	Anthropogenic deposits
NUAAES	Plaggen soil
NUAAOM	Reworked ground
NUAAOP	Made ground
NUAP	Appelscha Formation
NUAPWE	Weerdinge Member
NUAU	Aurora Formation
NUBB	Brown Bank Formation
NUBE*	Beegden Formation
NUBERO	Rosmalen Bed
NUBEWY	Wijchen Bed
NUBG	Brielle Ground Formation
NUB*	Breda Subgroup
NUBV	Batavier Formation
NUBX	Boxtel Formation
NUBXBS	Best Member
NUBXDE	Delwijnen Member
NUBXKO	Kootwijk Member
NUBXLM	Liempde Member
NUBXSC	Schimmert Member
NUBXSI	Singraven Member
NUBXTI	Tilligte Member
NUBXWI	Wierden Member
NUDB	Dogger Bight Formation
NUDBBC	Botney Cut Member
NUDBBO	Bolders Bank Member
NUDBDB	Dogger Bank Member
NUDBVO	Volans Member
NUDBWG	Well Ground Member
NUDN	Drachten Formation
NUDR	Drente Formation
NUDRGI	Gieten Member
NUDRSC	Schaarsbergen Member
NUDRUI	Uitdam Member
NUDRUIOO	Oosterdok Bed
NUEC	Echteld Formation
NUEE	Eem Formation
NUEG	Egmond Ground Formation
NUHS	Holset Formation
NUHT	Heijenrath Formation
NUIE	Inden Formation
NUKI*	Kieseloolite Formation
NUKK	Kreekrak Formation
NUKR	Kreftenheye Formation
NUKROC	Ockenburg Member
NUKRTW	Twello Member
NUKRWE	Well Member
NUKRWY	Wijchen Bed
NUKRZU	Zutphen Member
NUKW	Koewacht Formation
NUMH	Markhams Hole Formation
NUMS	Maassluis Formation
NUNA	Naaldwijk Formation
NUNASC	Schoorl Member
NUNAWA	Walcheren Member
NUNAWAAL	Almere Bed
NUNAWAYE	IJe Bed
NUNAWAYS	IJsselmeer Bed
NUNAWAZU	Zuiderzee Bed
NUNAWO	Wormer Member
NUNAWOBE	Bergen Bed
NUNAWOVE	Velsen Bed
NUNAZA	Zandvoort Member
NUNI	Nieuwkoop Formation
NUNIBA	Basisveen Bed
NUNIFL	Flevomeer Bed
NUNIGR	Griendtsveen Member
NUNIHO	Hollandveen Member
NUOO*	Oosterhout Formation
NUOS	Outer Silver Pit Formation
NUPE	Peelo Formation
NUPENI	Nieuwolda Member
NUPZ	Peize Formation
NUPZBA	Balk Member
NUSB	Southern Bight Formation
NUSBBL	Bligh Bank Member
NUSBBU	Buitenbanken Member
NUSBIG	Indefatigable Grounds Member
NUSBTB	Terschellinger Bank Member
NUSK	Smith's Knoll Formation
NUST	Sterksel Formation
NUSY	Stramproy Formation
NUSYHO	Hoogcruts Member
NUUA	Urania Formation
NUUAWH	Well Hole Member
NUUAWM	Western Mud Hole Member
NUUR	Urk Formation
NUURLI	Lingsfort Member
NUURTY	Tijnje Member
NUURVE	Veenhuizen Member
NUVI	Ville Formation
NUWA	Waalre Formation
NUWAHO	Hoogerheide Member
NUWATE	Tegelen Member
NUWAWO	Woensdrecht Member
NUWB	Woudenberg Formation
NUWG	Westkapelle Ground Formation
NUWS	Winterton Shoal Formation
NUYG	IJmuiden Ground Formation
NUYR	Yarmouth Roads Formation
NUYRAL	Alkaid Member

* Subdivision not indicated

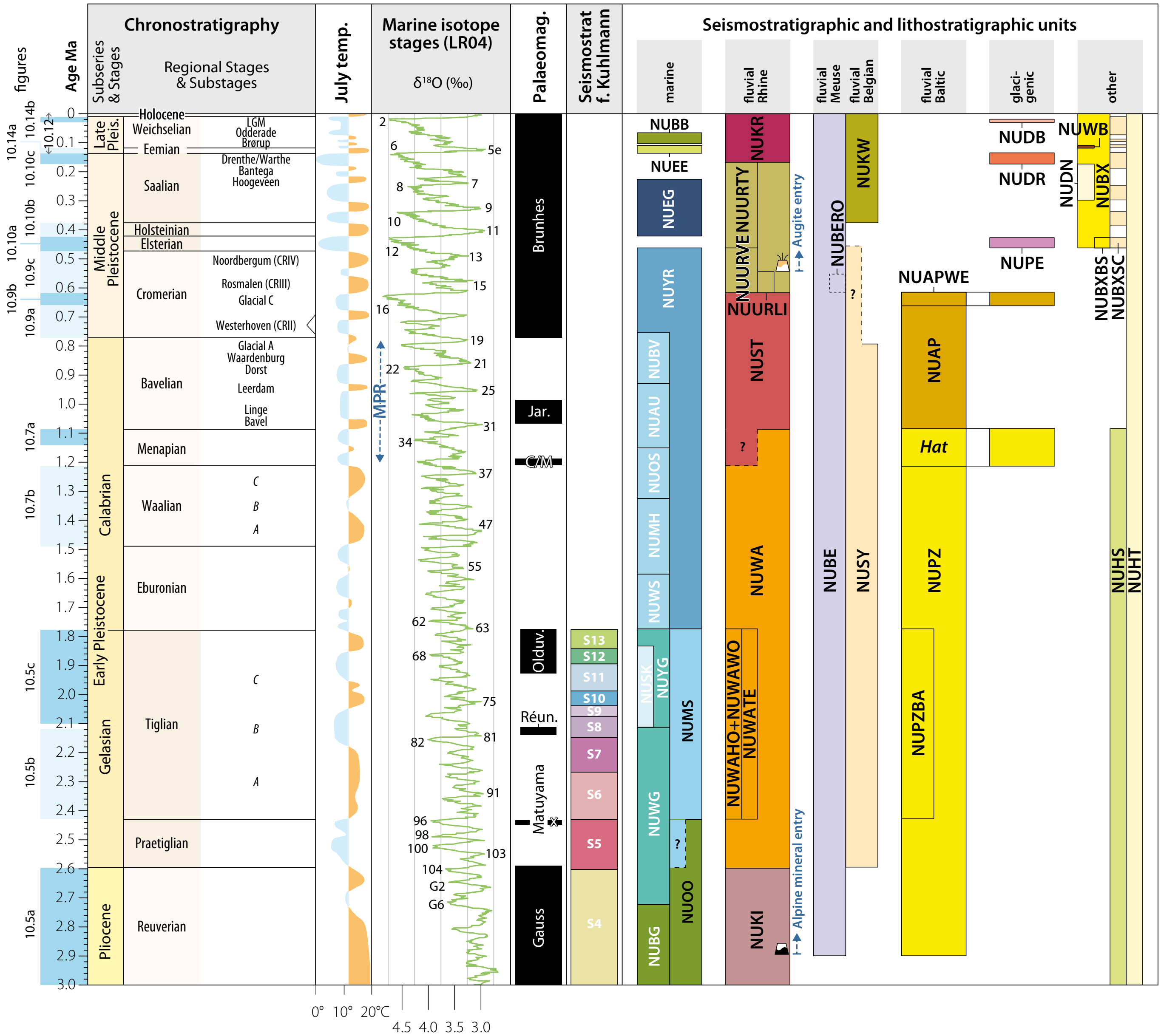


Figure 10.1. *Subdivision of the latest Pliocene and Pleistocene with, from left to right, chronostratigraphic subseries and stages (Cohen & Gibbard, 2019; complemented with stages and substages from regional schemes for northwestern Europe), pollen-based July temperature curve (Zagwijn, 1992, 1998; age model partly revised), deep-ocean oxygen isotope sequence (Marine Isotope Stages – MIS; Lisiecki & Raymo, 2005), paleomagnetic record (Channell et al., 2016), offshore seismostratigraphic scheme (Kuhlmann & Wong, 2008), and formally defined stratigraphic units in the on- and offshore domains of the Netherlands (TNO-GDN, 2023d). Age ranges of seismostratigraphic units were taken from Sha et al. (1991), Cameron et al. (1992), Gatliff et al. (1994), Stoker et al. (2011) and Westerhoff et al. (2003). Age ranges of lithostratigraphic units were primarily taken from Zagwijn (1996b), Westerhoff et al. (2003), Westerhoff et al. (2020), Busschers et al. (2007, 2008), Schokker et al. (2005), and Kars et al. (2012), but some changes to these ages are presented in this chapter. Although the figure suggests uniform ages and continuity between minimum and maximum ages, diachroneity and hiatuses occur throughout the sedimentary sequences. Late Pleistocene and Holocene (not indicated here) units are shown in Fig. 10.12. See Table 10.1 for lithostratigraphic codes. Paleo-magnetic abbreviations: Jar. = Jamarillo; C/M = Cobb Mountain Event; Olduv. = Olduvai; Réun. = Réunion Event; X = X Event. Other abbreviations: MPR = Mid-Pleistocene Revolution; Hat = Hattem beds (informal).*

driver for further geological research in the forthcoming decades.

The next sections describe the state-of-the-art knowledge on the Quaternary geology of the southern North Sea region. The initial focus is on the general depositional setting, as controlled by tectonics, sediment sources and processes. Stage-wise overviews of the temporal evolution then follow for the Early Pleistocene, Middle Pleistocene, Late Pleistocene and Holocene. In these overviews, we explore the interaction between terrestrial, marine and glacigenic depositional systems in the study area, as well as their external drivers.

Setting of the southern North Sea region

Regional tectonics

The Netherlands is situated in the south-southeastern sector of the North Sea Basin (Ziegler, 1994). The modern neotectonic situation became established in the Early Miocene. Fairly strong subsidence in the North Sea Basin has characterized much of the Neogene-Quaternary phase and is consistent with widespread uplift around this region (e.g. Ardennes/Rhenish Shield, Britain and southwestern Scandinavia). While Alpine orogeny-related plate-tectonic stress fields are endogenic drivers of the subsidence and uplift (Michon et al., 2003), considerable further vertical movement of the lithosphere has been caused by isostastic adjustments (Kooi et al., 1998). Increased rates of sediment supply from surrounding uplands, attributed to the intensified cold-climatic swings from the onset of the Early Pleistocene (Fig. 10.1), outpaced tectonic and isostasy-driven subsidence rates and thus facilitated progradational basin fill (Arfai et al., 2018; Ottesen et al., 2018). The main offshore Quaternary depocentre, labelled here as Dogger Basin, is confined to a relatively narrow zone that is orientated north-northwest to south-southeast (Lamb et al., 2018; Ottesen et al., 2018). In this basin, which corresponds to the Mesozoic Step Graben, Dutch Central Graben and Terschelling Basin (De Jager et al., 2025, this volume, their Fig. 1.1), Quaternary sediments reach a maximum thickness of 1150 to 1250 m (Figs 10.2, 10.3a). A secondary depocentre, labelled here as the Southern Bight Basin, extends offshore westward from the coast of Holland to the boundary with the British continental shelf (Fig. 10.2). In this basin, which occupies roughly the same area as the Mesozoic Broad Fourteens Basin, Quaternary sediments reach a maximum thickness of 800 to 900 m (Fig. 10.2). Further southwest and also in landward directions, the Quaternary gradually thins.

Onshore, subordinate depocentres are the Zuiderzee Basin in the northwestern Netherlands and the Roer Valley Rift System in the southern Netherlands and northeastern Belgium, the latter connecting to the Lower Rhine Graben in Germany. A maximum Quaternary sediment thickness of 200 to 300 m is reached in the central part of the Roer Valley Graben (RVG in Fig. 10.3d). Vertical motions of structural blocks of the Roer Valley Rift System are controlled by normal faulting, mainly along the Feldbiss and Peel Boundary Fault Zones that bound the Roer Valley Graben to the south and north, respectively. These active fault zones have a geomorphological scarp expression and record historic earthquake activity. The most recent major earthquake (Mw 5.4) in the Peel Boundary Fault Zone occurred in 1992 (see Dost et al., 2025, this volume). Paleoseismology revealed evidence of larger earthquakes (Mw ca. 6.8) at the end of the Last Glacial, attributed to contemporaneous glacio-isostatic adjustment of the crustal-stress regime (Van Balen et al., 2019, 2021, 2024). Fluvial deposition interacted with the regional subsidence and uplift dynamics of the graben and its shoulder blocks, leading to repeated shifts of valley positions and preservation of terrace flights (see Textbox 2). Throughout the Quaternary, this has controlled the routing, preservation and erosion of sediment produced in the Rhine and Meuse hinterland through the hinge zone of the North Sea Basin towards northwestern depocentres (Van Balen et al., 2005; Boenigk & Frechen, 2006). Since the end of the Last Glacial, fault-zone activity and glacio-isostatically enhanced subsidence have also modified paleovalley gradients, thus controlling sedimentation as well as preservation of Rhine and Meuse fluvial deposits and morphology (Cohen et al., 2002; Van Balen et al., 2005; Busschers et al., 2007; Woolderink et al., 2019).

Sediment sources, transport agents and stratigraphy

Two major fluvial systems supplied sediment to the Dutch part of the North Sea Basin during the Quaternary. These are the Baltic (or Eridanos) River System sourced from the east-northeast, and the Rhine-Meuse System sourced from the south. The Baltic River System was by far the largest sediment supplier for most of the Quaternary. Small-scale fluvial (Scheldt and other systems), fluvioperiglacial and eolian sediments only make up a small part of the sediment record but are highly significant in the shallowest, youngest part of the succession and in basin areas temporarily vacated by the larger rivers. Glacigenic sediments occur at distinct levels in the record of the North Sea Basin. Although subglacial erosion (valleys) and glaciotectonic structures had a major impact on landscape evolution, glacigenic sediments are of lesser importance in terms of sediment volume. Tidal and open-marine processes have reworked the fluvial and glacigenic record to varying degrees.

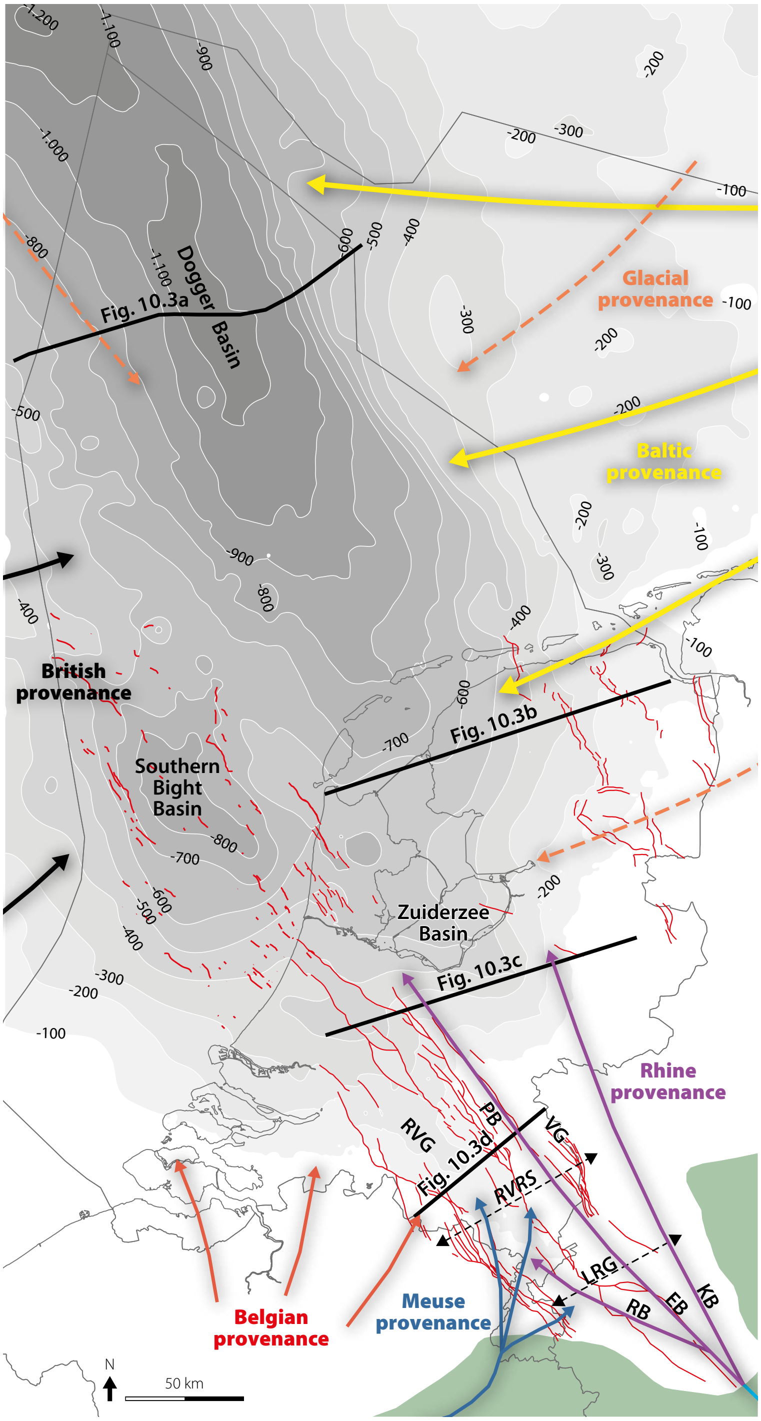
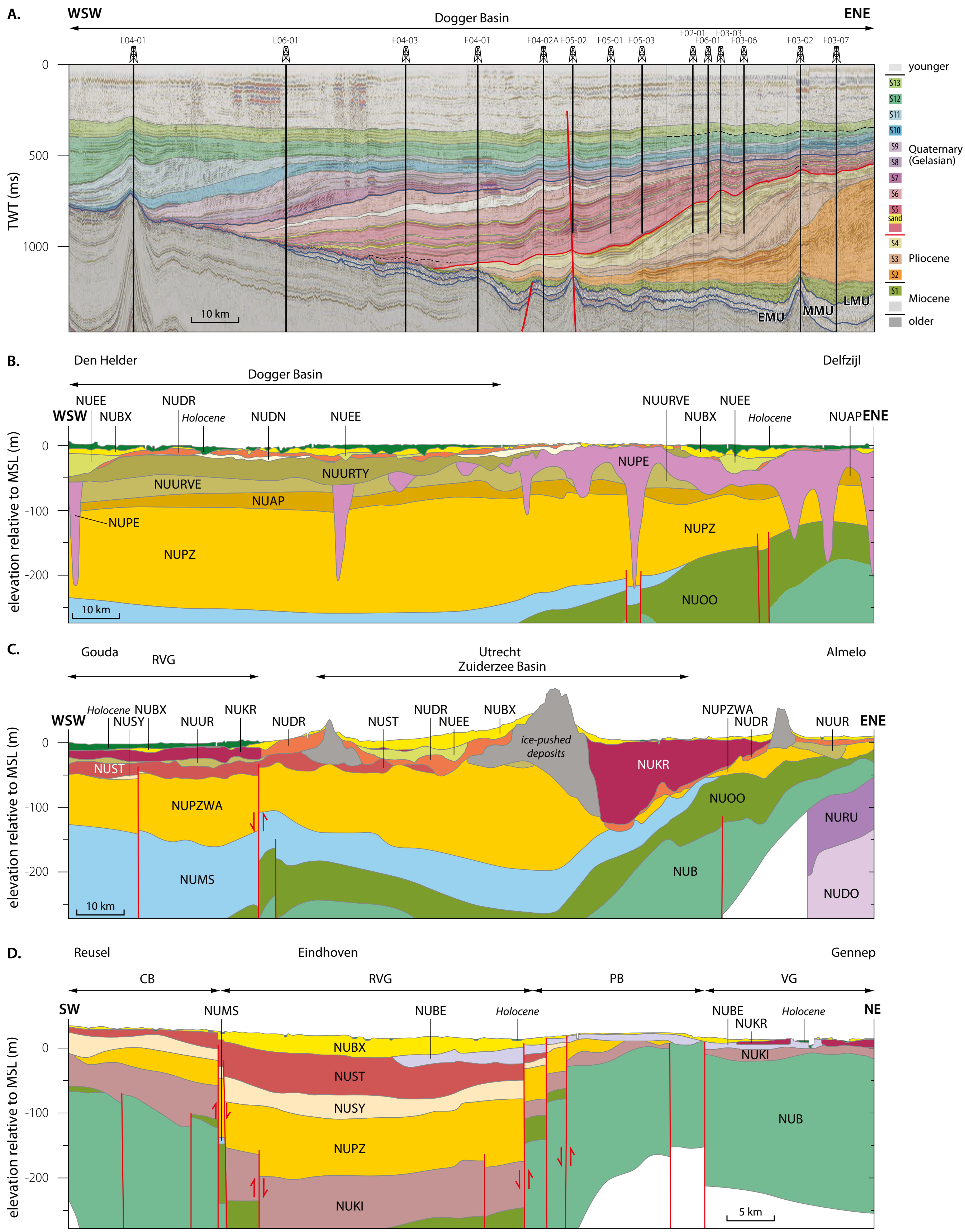


Figure 10.2. *Depth map of the base of the Quaternary (isolines: depth below modern MSL) with main tectonic elements, faults (in red) sediment-transport pathways (Kooi et al., 1998; Van Balen et al., 2005; Westerhoff, 2009; Cohen et al., 2022; TNO-GDN, 2023b). Depths above -100 m MSL not indicated. LRG = Lower Rhine Graben, RB = Roer Block, EB = Erft Block, KB = Köln Block, RVRS = Roer Valley Rift System, RVG = Roer Valley Graben, PB = Peel Block, VG = Venlo Graben.*

Baltic River System

The Baltic River System had a large source area east-northeast of the Netherlands (Fig. 10.2). From the Late Miocene onwards until the early Middle Pleistocene, this river system supplied vast amounts of sediment to the eastern part of the North Sea Basin (Peize and Appelscha formations and their offshore equivalents; Figs 10.1, 10.3). Its source area comprised two major domains: (I) the Baltic region and (II) the Central Uplands of Germany including the Harz, Erzgebirge, Teutoburger and Thüringer Wald, Bohemia and the northern Carpathians. Quaternary Baltic River formations in the Netherlands reach thicknesses of 50 to 200 m onshore (TNO-GDN, 2023c) and up to 900 m in the offshore region (Overeem et al. 2001; Kuhlmann et al., 2006a,b; Arfai et al., 2018). Offshore, seismic data have revealed 100 to 300 m thick sets of clinothems that represent prograding shelf-edge delta fronts of the Baltic River System (Fig. 10.3a; Kuhlmann et al., 2006a,b; Patruno et al., 2020).

The onshore Baltic River sediments are composed most-


A.
WSW
Dogger Basin
ENE
E04-01
E06-01
F04-03
F04-01
F04-02A F05-02
F05-01 F05-03
F02-01 F06-01
F03-03 F03-06
F03-02 F03-07
TWT (ms)
0
500
1000
10 km
EMU
MMU
LMU
younger
S13
S12
S11
S10
S9
S8
S7
S6
S5
sand
S4
S3
S2
S1
Quaternary (Gelasian)
Pliocene
Miocene
older
B.
Den Helder
Dogger Basin
Delfzijl
WSW
ENE
NUEE
NUBX
NUDR
Holocene
NUDN
NUURVE
NUAP
NUPE
NUPZ
NUURTY
NUOO
elevation relative to MSL (m)
0
-100
-200
10 km
C.
Gouda
RVG
Utrecht
Zuiderzee Basin
Almelo
WSW
ENE
Holocene NUBX
NUSY
NUUR
NUKR
NUDR
NUST
NUEE
NUBX
ice-pushed deposits
NUPZWA
NUUR
NUMS
NUOO
NUB
NURU
NUDO
elevation relative to MSL (m)
0
-100
-200
10 km
D.
Reusel
Eindhoven
Gennep
CB
RVG
PB
VG
SW
NE
NUMS
NUBE
Holocene
NUKR
NUBX
NUST
NUSY
NUPZ
NUKI
NUB
elevation relative to MSL (m)
0
-100
-200
5 km

← ***Figure 10.3.*** *Four sections (a-d) representative of the Quaternary stratigraphic succession of the North Sea region in the on- and offshore areas of the Netherlands (see Fig. 10.2 for section locations and Table 10.1 for explanation of lithostratigraphic codes). a) Interpreted composite seismic time section (modified from Ten Veen et al., 2020) through the Dogger Basin in the northern part of the Dutch North Sea illustrating westward-prograding seismostratigraphic units S1 to S13 (Kuhlmann & Wong, 2008) belonging to the Pliocene-Pleistocene shelf-edge delta of the Baltic River System. Units S1-S4 represent the Upper Miocene-Pliocene part of this system, directly overlying the Late Miocene Unconformity (LMU; see also Munsterman et al., 2025, this volume). Units S5-13 represent the Gelasian sequence. Seismostratigraphic units S5-13 are tentatively correlated to the Westkapelle and IJmuiden Ground formations (Fig. 10.1). The top of the interpreted part of the sequence is of Eburonian age (unit S13; Kuhlmann & Wong, 2008) and is marked by a major unconformity. b) Section showing lithostratigraphy of the southernmost part of the Dogger Basin and adjacent basin-marginal zone in the northern Netherlands (DGM model; TNO-GDN, 2023c). Volumetrically, the stratigraphy is dominated by Baltic sediments (NUPZWA) and by an alternation of Rhine sediments (NUURVE, NUURTY) with glacigenic sediments from the Elsterian (NUPE) and Saalian (NUDR) glaciations. The presence of Elsterian tunnel valleys, here reaching depths more than 200 m, is striking. Marine sediments and sediments of local origin are present on top of the Saalian and locally Elsterian glacigenic series. c) Section showing lithostratigraphy of the central Netherlands (DGM model; TNO-GDN, 2023c). The section crosses the northwestern part of the Roer Valley Rift System (west) and the southeastern part of the Zuiderzee Basin (centre), terminating on the basin margin (east). Aside from Rhine, marine and local stratigraphic units, this section contains the southernmost occurrence of Baltic sediments (here included in units NUPZ and NUWA). Also visible is a strong imprint of erosion and deposition associated with the Saalian glaciation (e.g. subglacial formation and postglacial infill of the IJssel Valley glacial basin with sediments of unit NUKR), as well as glaciotectonic ice-pushed deposits. d) Section showing lithostratigraphy of the Roer Valley Rift System in the southeastern Netherlands (DGM model; TNO-GDN, 2023c). A thick stack of Quaternary Rhine, Meuse, Belgian and local fluvial units, overlying Pliocene and Miocene shallow marine units, is present in the Roer Valley Graben. The Quaternary sediment thickness on the adjacent blocks is limited.*

ly of whitish, non-calcareous sand, commonly gravelly and rich in transparent quartz. In the basin, sediments primarily consist of fine-grained sand and silt. Large-scale glaciation of the Baltic area at the end of the Early Pleistocene beheaded the Baltic drainage basin (Bijlsma, 1981; Hall & Van Boeckel, 2020), significantly reducing its size. Its northern domain became restricted to the Baltic depression (today's Baltic Sea, including the Finnish and Bothnian Gulfs). Ice-rafted erratics derived from Fennoscandia (Hattem beds), embedded in the uppermost part of Baltic River sediments, mark the onset of this change (Fig. 10.1). A shrunken fluvial system remained, in which precursors of the Oder, Elbe and Weser Rivers drained westward towards the North Sea Basin. Their sediments differ from those of their earlier Baltic counterparts thanks to a much larger share of gravel components sourced from the central German uplands (e.g. lydite) and by topaz from Bohemia in the heavy-mineral fraction.

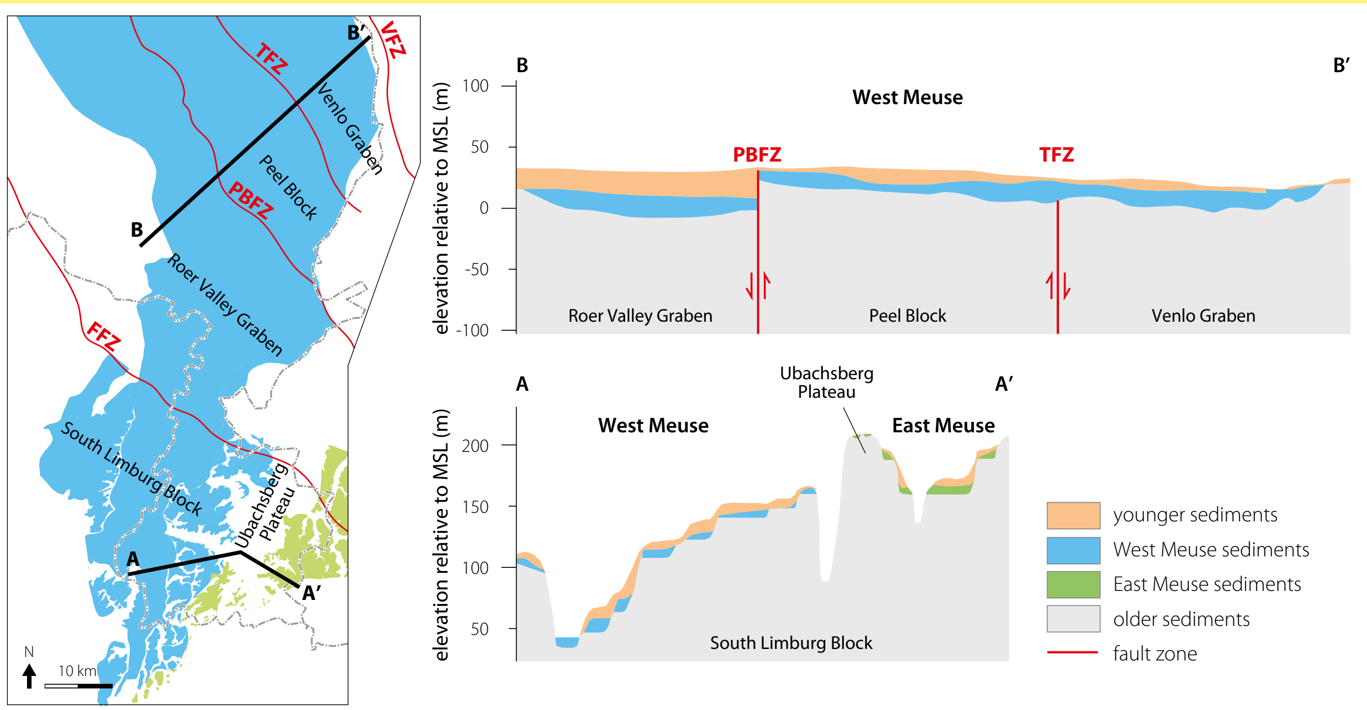
Rhine-Meuse River System

Late Miocene uplift of the Rhenish Massif instigated progradation of the proto-Rhine fluvial-deltaic Inden Formation and the overlying latest Tortonian Kieseloolite Formation into Germany and the southeastern Netherlands (Schäfer et al., 2005; Munsterman et al., 2019, 2025, this volume). The Rhine-Meuse River System expanded its catchment considerably in the period immediately preceding the Early Pleistocene, capturing Upper Rhine Graben and Alpine headwater reaches that have proven to be critical to the hydrological regimes, sediment composition and magnitude of supply throughout the Quaternary. Its deposits are contained in terrace flights at the basin margin, stacked fluvial successions at the basin rim and estuarine/deltaic successions in the basin proper (Waalre, Sterksel, Urk, Kreftenheye and Beegden formations and offshore equivalents; Figs 10.1, 10.3). The combination of lowland topography with little dividing relief, differential tectonic motions (grabens and shoulders), and increasing base-level fluctuations (due to intensification of glacial-interglacial climate and sea-level cycles) allowed the Rhine-Meuse System to shift in the basin, feeding several depocentres. Pre-Quaternary Rhine and Meuse sediments had been primarily derived from the strongly weathered sediment cover of the Rhenish Shield and Ardennes (Boenigk, 2002). This is evident from quartz-rich gravels and coarse sands with stable heavy-mineral components and low carbonate contents (Kieseloolite Formation; Figs 10.1, 10.3). The expansion of the system altered the Rhine sediment mineralogy, adding an unstable heavy-mineral assemblage characterized by dominant epidote, green hornblende and garnet (Westerhoff, 2009; Hülscher et al., 2018; Fig. 10.1), and also changed zircon fission-track data towards a spectrum dominated by Cenozoic cooling ages (Tatzel et al., 2015). Furthermore, carbonate and mica-flake content increased. The gradual increase of iron-stained sands and quartzitic gravel through the course of the Pleistocene reflects accelerating bedrock incision into the Rhenish Shield and Ardennes where they were

The Meuse terrace sequence

2

The Meuse River originates in the northeastern part of the Paris Basin in France, crosses the Ardennes in Belgium, and converges with the Rhine in the Netherlands. Younger courses merge with the Rhine in the central Netherlands, whereas Early and Middle Pleistocene courses were confluent further south. The paleogeographic and incisional history of the Meuse is heavily affected by tectonic uplift of the Ardennes-Rhenish Massif and by rifting in the Roer Valley Rift System.



Distribution of deposits from the East Meuse (green) and West Meuse (blue) and composite Meuse terrace sequence. Schematized cross-sections illustrate differences between a tectonically uplifting (terraced) area in the south (A-A') and tectonically stable and subsiding areas in the north (B-B'). Abbreviations: FFZ = Feldbiss Fault Zone; PBFZ = Peel Boundary Fault Zone; TFZ - Tegelen Fault Zone; VFZ = Viersen Fault Zone.

crossed by Rhine and Meuse rivers. These proximal Ardennes and Rhenish Shield clasts (e.g. 'Taunus' quartzite) dominate the gravel fraction. While Alpine fine sand fractions (including heavy minerals) reached the North Sea Basin, Alpine gravels did not since they were not abraded during fluvial transport but became trapped upstream in the Upper Rhine Graben.

Rhine sediments younger than about 500 kyr (halfway through the Middle Pleistocene) are enriched in volcanic minerals such as clino-pyroxenes ('augite') and brown hornblende, introduced into the system by increased Eifel eruptions during that time (Zagwijn, 1985; Van den Bogaard & Schmincke, 1990; Boenigk & Frechen, 2006; Gallant et al., 2014; Fig. 10.1). The occurrence of these minerals is of marked stratigraphic benefit in separating older from younger depositional units (Van Kolfschoten & Turner, 1996; Zagwijn, 1996b; Fig. 10.1). Deposits that are exclusive to the Meuse River (i.e. upstream from its confluence with the Rhine) are found in the extreme south of the country, concentrated along an Early Pleistocene East Meuse Valley (which extended into Germany) and the younger West Meuse Valley (see Textbox 2). These sediments lack the Alpine and Eifel-volcanic Rhine components but share stable heavy-mineral components of the Ardennes-Rhenish Shield and Vosges bedrock hinterlands (Zonneveld, 1974; Westerhoff, 2008). The Meuse sediments are relatively gravelly, rich in flints and Ardennes-specific indicator gravels (e.g. 'Revinian' quartzite). Downstream of the confluence of the Rhine and Meuse, the Meuse signature, which is dominated by stable minerals, is entirely diluted by the Rhine sediment contribution with its high concentrations of unstable heavy minerals

In between the Ardennes s.s. and the Feldbiss Fault Zone of the Roer Valley Rift System, on the South Limburg Block, the Meuse Valley has a well-developed terrace staircase consisting of ca. 31 levels (Zonneveld, 1974; Felder & Bosch, 1989; Van den Berg, 1996; Van den Berg & Van Hoof, 2001). Individual levels are vertically separated by 4 to 9 m. The oldest levels probably date back to the Pliocene. The terraces formed in response to climatic oscillations, but they have been preserved because of tectonic uplift causing long-term incision. During cold climatic conditions, the Meuse was an aggrading braided river with high peak discharges and high sediment loads. During temperate conditions it took on a meandering style and during warm periods the river was likely stable, like at present. The incisional steps were formed during cold-warm and warm-cold transitions, reflecting a temporary imbalance of discharge and sediment load (Vandenberghe, 2015). Terraces were formed first along the East Meuse Valley course, and later, following a capture, along the West Meuse Valley course. For most of the Quaternary, the confluence with the Rhine was located in the subsiding Roer Valley Graben in between the Feldbiss Fault Zone and the Peel Boundary Fault Zone, where sediments accumulated as a buried stack. In the middle Saalian (250 ka; MIS 8), the Meuse started to shift its course away from the graben. From the late Saalian onward (150 ka; MIS 6), it formed terraces along its current course on the uplifting Peel Block and Venlo Graben, north of the Peel Boundary Fault Zone. Here, relatively small terraces were formed during post-LGM climatic oscillations and associated river style changes (Woolderink et al., 2019).

One of the first-dated terrace remnants was at Maastricht-Belvédère, an important Paleolithic hominin site. Using thermoluminescence dating of burnt flint artefacts, an age of ca. 250 ka (MIS 7) was established for the Caberg-3 terrace level (Huxtable & Aitken, 1985; Vandenberghe, 1993). This terrace is the first in which the heavy-mineral assemblage lacks Vosges hornblende. Its absence is attributed to the loss of the Upper Moselle tributary to the Rhine system (Losson & Quinif, 2001). Paleomagnetic analyses, U-Th dating of cements, pollen biostratigraphy, luminescence dating, cosmogenic isotope dating, and up- and downstream correlations have provided increasingly precise local age control for terraces on the South Limburg Block (Van Balen et al., 2000; Schaller et al., 2004; Van Balen et al., 2021; Da Silva Guimarães et al., 2024). The Meuse terraces have been used to determine uplift rates of the South Limburg Block (Van Balen et al., 2000; Van den Berg & Van Hoof, 2001) and displacement rates on the major fault zones (Houtgast et al., 2002; Van Balen et al., 2021).

from the Alps and Upper Rhine Graben. (Busschers et al., 2007).

Glacigenic systems

Sediments belonging to Quaternary glacigenic systems occur in the northern half of the Netherlands and below the Dutch part of the North Sea (Van den Berg & Beets, 1987; Laban & Van der Meer, 2011). These sediments comprise tills, fluvioglacial outwash and glaciolacustrine fines, which are thickest in infills of subglacial valleys and glacial basins (Peelo, Drente and Dogger Bight formations and in those upper parts of the Peize and Appelscha formations that have glacigenic input; Figs 10.1, 10.3). The glacial sediments are primarily derived from erosion and reworking of older sediments and are mixed with Fennoscandian gravel (crystalline fragments, flints and chalk) and other reworked elements. As a whole, glacigenic systems may not have left large sediment volumes in the North Sea Basin, but they did have a severe impact on the evolution of landscapes and depocentres in the form of subglacial erosion (i.e. tunnel valleys and glacial basins), glaciotectonic deformation and sedimentation (i.e. push moraines and sandurs; Van den Berg & Beets, 1987; Bakker & Van der Meer, 2003). This strongly affected the evolution of the pathways and positions of successive fluvial and marine systems.

Evidence for grounded ice sheets in the northern and central North Sea dates back as far as MIS 100 (2.53 Ma) while the Fennoscandian and British ice sheets first became confluent ca. 1.9 Ma ago (Bendixen et al., 2018; Rea et al., 2018). In the on- and offshore part of the northern Netherlands, at least five levels of glacial evidence have been identified to date (Fig. 10.1), each marked by a set of erosional, sedimentary and/or glaciotectonic features.

Small-scale fluvial, fluvioperiglacial and eolian systems

Small-scale fluvial, fluvioperiglacial and eolian sedimentary systems produced deposits (primarily belonging to the Stramproy, Drachten, Koewacht and Boxtel formations) that are intercalated with, and overlie sediment left by the larger-scale 'main' depositional systems (Figs 10.1, 10.3). These deposits are dominated by medium- and fine-grained sands, loam and local peat strata. Mainly they lack carbonate and contain a heavy-mineral spectrum that is more stable than the mineralogy of the Rhine sediments. The sediments were primarily deposited under periglacial climatic conditions in areas beyond the limits of the Rhine-Meuse activity at the time (Westerhoff, 2009). The thickest record of these sediments occurs in the Roer Valley Graben (Schokker et al., 2005; Westerhoff, 2009), as infills of glacially eroded topography (Kasse et al., 2022), directly below the late Saalian till (Zagwijn, 1973) and as infills of some Late Pleistocene river valleys (for example the Scheldt Valley; Kiden, 2006; De Clercq et al., 2018; Kasse et al., 2020). In major parts of the on- and offshore Netherlands, the uppermost section of the Quaternary sediment sequence is formed by a 1- to 2-m-thick eolian sand sequence, referred to as 'coversands' (Kasse et al., 2007). In Limburg, this upper Quaternary sequence is primarily represented by loess that is part of the northwestern fringe of the European loess belt (Meijs et al., 2013; Lehmkuhl et al., 2021).

Reworking by tidal and open-marine systems

The North Sea Basin is mostly portrayed as a sink that has trapped riverine and glacially transported sediment produced under terrestrial conditions north and east of the basin. Extensive shelf-edge deltaic units, formed especially in the Early Pleistocene, predate the major glaciations. The Dutch marine realm was farthest away from source areas. It was a place where, once deposited, such terrestrial sediments were reworked during transgressive and highstand conditions. Where rapid subsidence quickly moved sediment to depths beyond the reach of marine erosive processes, reworking was limited to single highstands. Farthest south, close to the basin edge, repeated reworking during successive highstands has resulted in a fragmentary and highly discontinuous stratigraphy. Open-marine transport and deposition, causing some of the reworking, were dominated by tidal and wave processes. Sand-wave fields and other large-scale marine bedforms displace sands over large areas but small distances, and transgressive surfaces typically leave coarse wave-formed lags. Marine muds indicate a strongly mixed provenance far away from modern-day river mouths. They are derived in part from eroding British cliffs and from seabed scouring of Belgian Paleogene clay (especially in the Late Pleistocene and Holocene). All of these fines are tidally circulated in the North Sea and are relevant to both the nearshore and offshore realms (Beets & Van der Spek, 2000; Rijsdijk et al., 2005).

Closer to continuously migrating shorelines, tidal currents have caused local but volumetrically more significant erosion and (re)deposition. Because of rapidly reorganising and partly cyclical coastal landscapes, stacked generations of channel sediments are common (Van der Spek, 1994). Although tidal and other coastal units dominate the Holocene record, their preservation potential has typically been limited. Pre-Eemian coastal deposits are rare.

Evolution of southern North Sea sedimentary systems and landscapes

Early Pleistocene Subseries, Gelasian Stage (2.58-1.8 Ma)

Climate, sea level, ice sheets and biota

Stable-isotope records of North Atlantic planktonic foraminifers, further referred to as the marine oxygen isotope record, show that the chronostratigraphic Gelasian Stage was characterized by an obliquity-forced cyclicity (41 kyr) of alternating relatively warm (to temperate) and cool climatic phases (Fig. 10.1). Very low $^{18}O/^{16}O$ isotope values indicate that several cycles were characterized by very cold climatic conditions (or glacial minima). Although average temperatures were generally lower than in the preceding Pliocene, the markedly higher frequency of these very cold climatic conditions makes the Gelasian critically different. The earliest phase of this stage (2.6-2.4 Ma) is characterized by a distinct triplet of such glacial minima (MIS 100, 98 and 96; Fig. 10.1), also known as the Praetiglian Regional Stage in northwestern Europe (Zagwijn, 1998; Cohen & Gibbard, 2019; Fig. 10.1). This interval is marked by the first extensive development of steppe-like vegetation (Zagwijn, 1957, 1960) and faunal turnover (Meloro et al., 2008) and was accompanied by extensive ice-sheet development over Fennoscandia and associated North Sea iceberg-rafting events (Rea et al., 2018; Løseth et al., 2022). It effectively marks the onset of the ice-age period.

Fossil pollen records indicate that for most of the following Tiglian Regional Stage, vegetation patterns changed from boreal forest during cool climatic phases, periodically with permafrost (e.g. the Beerse Glacial of Kasse, 1993; Kasse & Bohncke, 2001), to deciduous forest during the more temperate phases. Even during these warmer times, many thermophile species that existed in the area during the Pliocene did not return or became incrementally regionally extinct (Zagwijn, 1998; Donders et al., 2018; Westerhoff et al., 2020). The deciduous forests were characterized by a diverse arboreal vegetation that included exotic taxa such as *Eucommia, Tsuga* and *Pterocarya* (Westerhoff et al., 2020; Fig. 10.4).

The climate variations of the Tiglian Regional Stage are also reflected in successions of warm temperate to arctic palynological and molluscan assemblages in marine sediment (Meijer et al., 2006; Donders et al., 2018). Turnover events (including extinction/extirpation) were frequent, leading to overall impoverishment of the fauna. At the

Figure 10.4. Artist impression of the Tegelen landscape and biota along the Rhine River, with rich floodplain forests including thermophile taxa such as the Tegelen macaque (Macaca sylvanus florentina). *Drawing E.J. Bosch, Naturalis.*

same time, the proportion of species with a Pacific origin increased (Slupik et al., 2007; Preece et al., 2020).

On the basis of extensive work near the Tiglian type locality in the Venlo Graben and in the Roer Valley Graben in the southeastern Netherlands (see also Textbox 1), Zagwijn (1963, 1992) suggested that during the Tiglian only two cold intervals occurred, which he referred to as 'Tiglian B' and 'Tiglian C4' (Fig. 10.1). This vision was formally incorporated into the chronostratigraphic subdivision and is still widely used as a standard throughout northwestern Europe. Westerhoff et al. (2020), however, showed that the Tiglian record in the Roer Valley Rift System includes more cold-climate intervals, reflected in peaks of non-arboreal pollen or 'Tiglian B' associations, than had hitherto been identified. The mismatch between the number of observed Tiglian climate oscillations in the terrestrial record (given the meaning of incorporated information) and the many more isotopic oscillations that are reported from the ocean-floor, as well as the link to periods of grounded icebergs that are observed in marine records from the North Sea Basin (Rea et al., 2018), make this interval a focus of ongoing study.

Sedimentary systems and paleogeography

As in the Late Pliocene situation (Fig. 10.5a), the Gelasian North Sea was an embayment open to the Atlantic Ocean to the northwest, but without a marine passage towards the southwest (Fig. 10.5b,c). The Baltic River System entered the marine area from the east, while the Rhine-Meuse System entered from the south. As a result of the marked increase in climate-driven sediment supply, the early Gelasian, and in particular the Tiglian Regional Stage (Fig. 10.5b), was dominated by extensive deposition of fluvial sediments in the present onshore region (Peize and Waalre formations) and large-scale progradation of their equivalent shelf-delta complexes in the offshore (upper part of the Oosterhout Formation; Maassluis, Westkapelle Ground and IJmuiden Ground formations; Fig. 10.1; Overeem et al., 2001; Arfai et al., 2018). The deeper parts of the contemporaneous North Sea had initial water depths up to 300 m but became rapidly filled by shelf deposits arranged in amalgamated clinothems (Fig. 10.3a; Arfai et al., 2018; Lamb et al., 2018; Rea et al., 2018). As a consequence of the associated progradation (Fig. 10.5), the marine depositional area decreased in size and became shallower, while depositional rates increased by an order of magnitude compared to the preceding Neogene period (Kooi et al., 1998; Knox et al., 2010). The Gelasian Stage can be regarded as a period of under-accommodation as clinoform progradation resulted in rapid basin infill. As a result, the depocentre and the coastlines shifted towards the north to northwest (Funnell, 1996; Ottesen et al., 2018).

During the Gelasian, the Rhine followed alternate courses through the Roer Valley Graben, over the Venlo Graben and through the Lower Rhine Graben (Kieseloolite and Waalre formations; Fig. 10.1). Towards the late Gelasian, the southern Roer Valley Graben was abandoned and deposition was concentrated in the northern part of the Roer Valley Graben and in an adjacent area towards the west (Fig. 10.5c). Abandonment of the southern Roer Valley Graben initiated a period of deposition of the Campine River System (which gradually extended northward during latter periods of the Early Pleistocene). Extensive floodplains and meandering channels characterized the fluvial systems during the warm(er) climatic intervals of the Gelasian (Fig. 10.6). These environments graded into estuarine and shallow-marine settings to the west and northwest (Kasse, 1988; Westerhoff, 2009; Fig. 10.5b,c). Towards the end of the Gelasian, continued progradation of the Baltic fluviodeltaic system to the west-southwest resulted in interfingering with the Rhine-Meuse System in the central Netherlands, as reflected in spatio-temporal alternations of the Waalre and Peize formations. Throughout the Gelasian, the Meuse (Beegden Formation) flowed through the East Meuse valley (Fig. 10.5b,c; Textbox 2).

Figure 10.5. *Paleogeography during the Late Pliocene (a), early Gelasian (b) and late Gelasian (c). The successive paleogeographic maps show 1) a gradual increase in size of the Baltic River system, 2) development of a Baltic – Rhine-Meuse convergence zone in the central Netherlands ('Bunnik Rijn'), and 3) activity of the Campine River System and East Meuse River in the south. Primary sources: Kasse (1988), Westerhoff (2009) and TNO-GDN (2023c).*

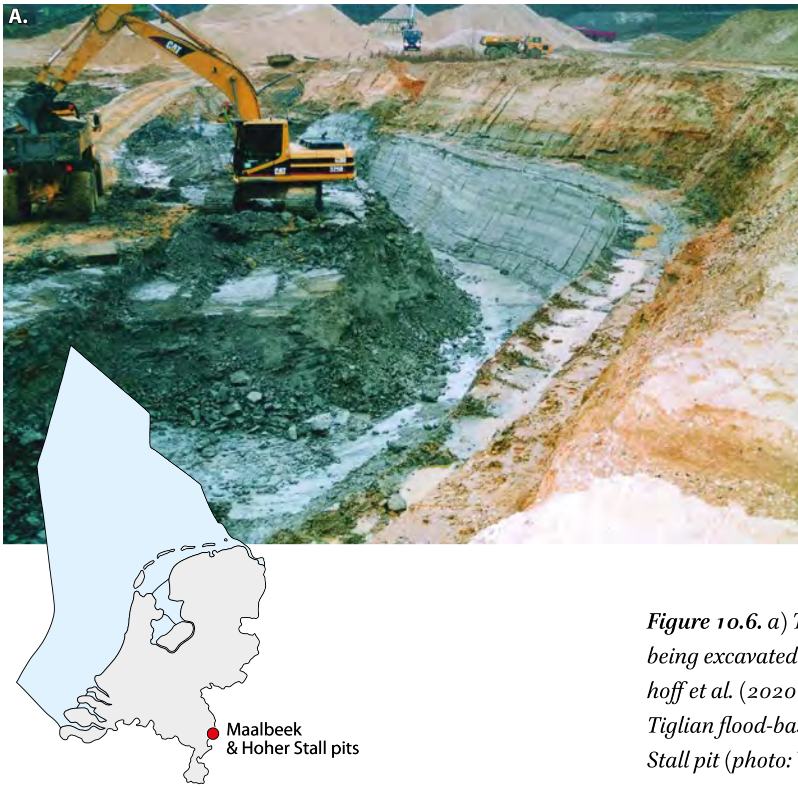


Figure 10.6. *a) Tiglian oxbow lake fill with bedded clay being excavated in the Maalbeek pit reprinted from Westerhoff et al. (2020) with permission from Elsevier. b) Detail of Tiglian flood-basin clay (Waalre Formation) in the Hoher Stall pit (photo: W. de Weger).*

Early Pleistocene Subseries, Calabrian Stage (1.8-0.8 Ma)

Climate, sea level, ice sheets and biota

Like the earlier Gelasian, the Calabrian Stage was globally characterized by glacial-interglacial cycles (Fig. 10.1). However, from the onset of the Calabrian by ca. 1.8 Ma, particularly cold glacial minima occurred more frequently than before. Phases with steppe-like vegetation and cryoturbation, indicating temporal permafrost conditions, left their mark in the terrestrial record. In the regional chronostratigraphy (Fig. 10.1), the resulting glacial complex is known as the Eburonian. Provisional correlation with the marine isotope record aligns this complex with the minima MIS 54 to 46, for which evidence of iceberg rafting and grounding has been observed in marine sequences of the North Sea Basin (Rea et al., 2018). In the terrestrial record, the Eburonian is succeeded by a generally warmer period, referred to as the Waalian Regional Stage, with pollen indicative of forest cover. It is provisionally aligned to MIS 47 to 37 and lasted until about 1.2 Ma (Fig. 10.1).

During the last 400 kyr of the Calabrian Stage (ca. 1.2-0.8 Ma), the periodicity of the Earth's glacial-interglacial climate cycle began to change significantly, a phenomenon known as the Mid-Pleistocene Revolution or the Early-Middle Pleistocene Transition (Head & Gibbard, 2005; Maslin & Ridgwell, 2005; Berends et al., 2021; Head, 2021). This time interval saw intensification of cold periods and cycles of ice-sheet growth and decay lengthening to 100 kyr. The cold intervals were characterized by gradual cooling and contrasting rapid terminations (Fig. 10.1), mirrored in global sea-level minima some 100-140 m lower than at present, and maxima up to ca. 10 m above present sea level. The Mid-Pleistocene Revolution is the first post-Gelasian phase during which major ice-sheet expansion occurred in the North Sea region, although the extents of these ice sheets are not well-constrained (Ottesen et al., 2018; Rea et al., 2018; Hughes et al., 2020). In the terrestrial record onshore and in the regional stratigraphic scheme, the onset of the Mid-Pleistocene Revolution is provisionally correlated to MIS 34 (Margari et al., 2023; Fig. 10.1) and associated with the Menapian Regional Stage, which has intervals characterized by a non-arboreous palynology (Zagwijn, 1960; Zagwijn & De Jong, 1984; De Jong, 1988).

The marine oxygen isotope record shows that this phase was followed by pronounced alternations of very warm interglacials and colder climatic phases (Bavelian Regional Stage; Fig. 10.1). Owing to their intensity, some of these interglacials are referred to as 'super-interglacials' (e.g. MIS 31; Oliveira et al., 2017; Tzedakis et al., 2017). In the onshore record, three warm phases are reported within this period: the Bavel, Leerdam and Waardenburg interglacials. Originally, Zagwijn (1996b) considered the latter to be part of the Mid-Pleistocene Cromerian Regional Stage. In light of the international decision to align the onset of the Middle Pleistocene with the Brunhes-Matuyama reversal

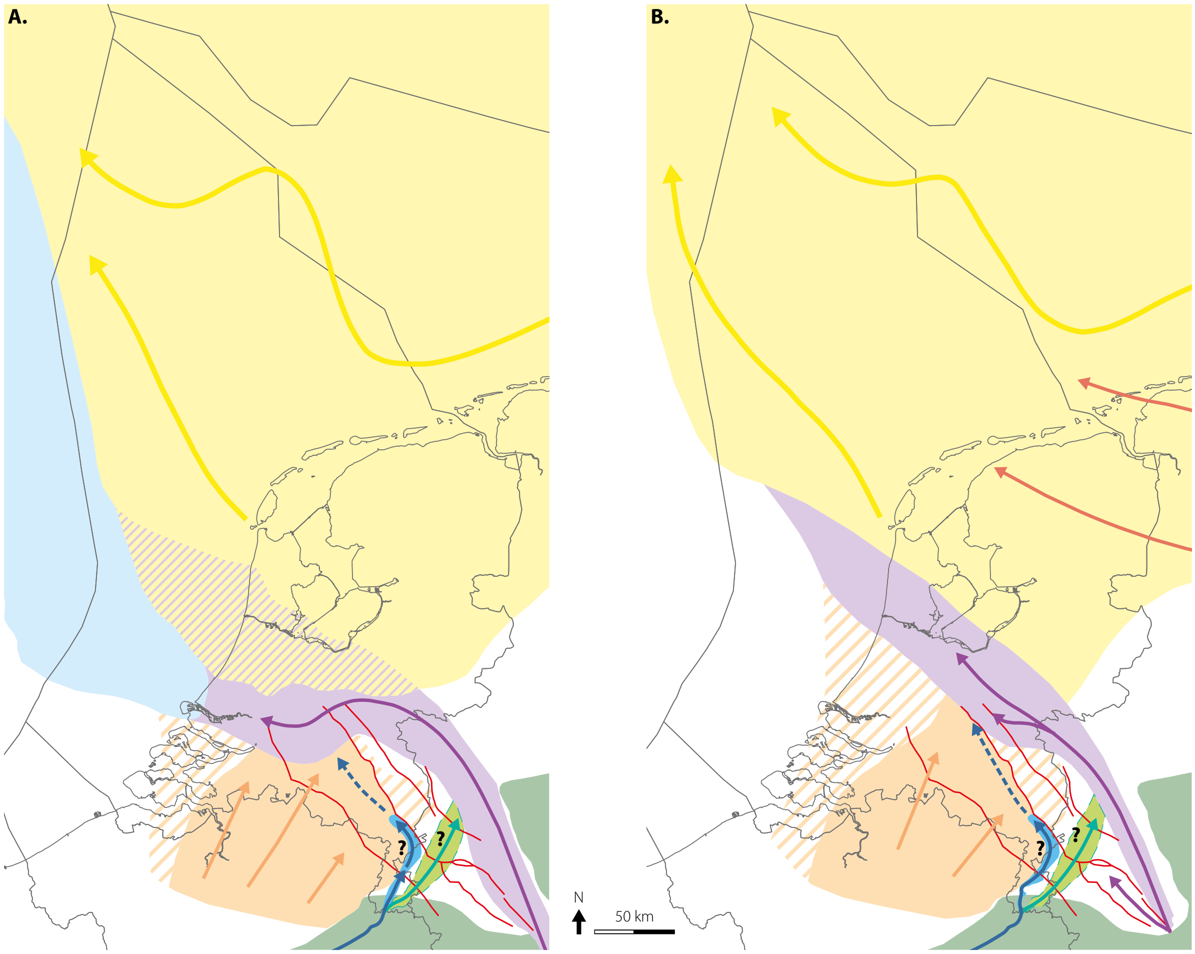


Figure 10.7. Paleogeography during a) the middle Calabrian (Waalian Regional Stage) and b) late Calabrian Stage (Menapian to earliest Bavelian Regional Stages). The successive paleogeographic maps show 1) a gradual demise of the Baltic River System, 2) first evidence of Fennoscandian influence, and 3) expansion of the Campine River System into the Roer Valley Rift System (see Fig. 10.5 for legend). Primary sources: Kasse (1988), Westerhoff (2009) and TNO-GDN (2023c).

(e.g. Chibanian Global Boundary Stratotype Section and Point; Suganuma et al., 2021), our preference is to reassign the Waardenburg interglacial and its overlying 'Glacial A' to the Bavelian (Fig. 10.1). Current insight favours correlation of the Bavel interglacial to MIS 31, Leerdam to MIS 25 and Waardenburg to MIS 21 (Fig. 10.1). Palynologically, these interglacials are the last to have assemblages that include the 'typical' Early Pleistocene taxa *Eucommia* and *Tsuga* (Zagwijn & De Jong, 1984; De Jong, 1988; Preece & Parfitt, 2012). Contemporaneously, critical turnovers (extinctions and arrivals of new species) in molluscan assemblages took place (Meijer, 1988, 1991), along with immigration of Eurasian mammal species (Van Kolfschoten, 2001).

Sedimentary systems and paleogeography

At the onset of the Calabrian, the southern North Sea had shallowed considerably compared to the beginning of the Pleistocene, following major sediment infill (Kuhlmann et al., 2006a,b; Ottesen et al., 2018). At the same time, increasingly accentuated glacial-interglacial sea-level cycles deepened lowstand levels. This combination set the stage for major change in terms of landscape development and fluvial-marine configurations (Fig. 10.7a,b).

During the cold-climate Eburonian (Fig. 10.1), marine influence was absent from the present-day Dutch onshore, but during the Waalian, marine conditions returned to the western Netherlands (Zagwijn, 1975; Kasse, 1988; Fig. 10.7a). The Rhine repositioned itself eastwards to the Lower Rhine Graben, largely abandoning the Roer Valley Rift System (Westerhoff, 2009), and continuing its convergence with the Baltic River System in the central Netherlands. This led to the subsequent expansion of the Campine River System (Stramproy Formation). Contradicting views exist on the position of the Meuse during this period. Westerhoff et al. (2008) suggested the East Meuse Valley was still an active branch during this phase and correlations to the Holzweiler Formation in Germany point to active deposition up to the early Bavelian Regional Stage (Boenigk, 2002; Boenigk & Frechen, 2006). Other age

Figure 10.8. Artist impression of a typical Mid-Pleistocene interglacial landscape with rich floodplain forests where early humans (Homo heidelbergensis) *lived alongside thermophile taxa such as forest elephant, rhinoceros and hippopotamus. Drawing E.J. Bosch, Naturalis.*

models suggest that the East Meuse Valley was abandoned earlier, around the Gelasian-Calabrian transition (Zagwijn, 1975; Kuyl, 1980; Kasse, 1988; Van den Berg & Van Hoof, 2001). As new dating of the East Meuse sediments is needed to solve this puzzling issue, both scenarios are presented in the paleogeographic reconstruction for this period (Fig. 10.7a).

The intensified periodic glaciation of Fennoscandia during and following the Mid-Pleistocene Revolution triggered major reorganization of sediment delivery and depositional system interactions in the North Sea area at large (Bijlsma, 1981; Gibbard, 1988). Basin shallowing in the northern and central North Sea facilitated the expansion of Scandinavian and British-Irish ice sheets onto the North Sea shelf (Sejrup et al., 1995; Batchelor et al., 2019). The northern Danish subsurface bears sedimentary-stratigraphic indications that the Fennoscandian ice sheet first extended that far south by ca. 1.2-1.0 Ma (Houmark-Nielsen, 2004), correlating to the Menapian periglacial indicators in the Netherlands. Seismic records from the northern and central North Sea feature the Crenulate Marker, attributed to shelf glaciation at this time (Buckley, 2017; Ottesen et al., 2018). Sejrup et al. (1995) and Ottesen et al. (2014) suggested that initiation of the Norwegian Channel Ice Stream at the northern fringe of the basin could be of the same age, but more recent results point to a likely younger initiation around 0.8 Ma (Løseth et al., 2022).

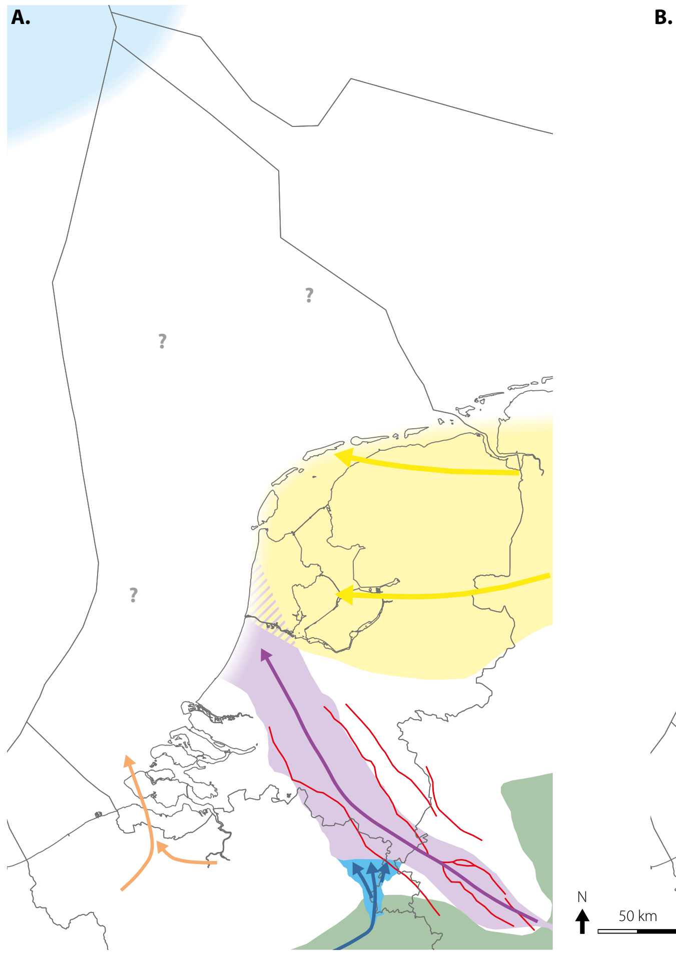
The Fennoscandian ice-sheet expansions transformed the hinterland of the Baltic River drainage basin. This upstream change is reflected in reworked erratics in the top of Baltic River units in the Netherlands (Hattem beds, Peize Formation; Zandstra, 1971; Fig. 10.1), suggesting proximity of an ice sheet during the Menapian glaciation (Fig. 10.7b). Remnant tributaries of the Baltic River System (the Weser and Elbe Rivers) draining Central Germany and Bohemia remained active as sediment suppliers from the east (Appelscha Formation), but with strongly reduced sediment supply. During the Menapian, the Rhine remained in its position outside of the Roer Valley Rift System. Towards the northwest the Rhine-Meuse System started to dominate the shrinking Baltic River System (Fig. 10.7b). Shallow-marine deposition was restricted to the northwestern offshore (just northwest of the map domain of Fig. 10.7b; Outer Silver Pit and/or Aurora formations; Fig. 10.1).

At the end of the Menapian or in the early Bavelian, the Rhine-Meuse System reestablished a course through the Roer Valley Graben (Zagwijn, 1985; Kasse, 1988; Fig. 10.7b; Zagwijn, 1996b). From this moment onwards, the Rhine-Meuse deposits show considerable coarsening (Sterksel Formation; Kasse, 1988). This trend is attributed to a combination of frost weathering and intensified periglacial processes in hinterland and valleys, which favoured the production of coarse sediment during the cold climatic phases that are reported for this period (Linge, Dorst and Glacial A glacials; Fig. 10.1). Increased uplift rates in the Rhenish Massif and Ardennes were fluvially countered by bedrock incision (Van Balen et al., 2000; Meyer & Stets, 2002; Rixhon & Demoulin, 2018) and further added to bedload reaching the Netherlands. Vast volumes of coarse-grained sand and gravel ended up in the fluvial domains.

Mid-Pleistocene Subseries (773-130 ka)

Climate, sea level, ice sheets and biota

The North Atlantic isotope record shows that during the Middle Pleistocene (0.78-0.13 Ma) climatic cyclicity was dominated by 100-kyr periodicity, with an overprint of shorter obliquity- and/or precession-paced warm to cool climatic phases (Fig. 10.1). In general, each 100-kyr cycle began with a very warm interglacial phase followed by stepwise cooling (alternating interstadials and stadials) that culminated in a very cold glacial minimum, of which MIS 16, 12 and 6 were the most pronounced. The marine oxygen isotope record shows that MIS 19 and 11c were the most strongly developed interglacials (Gibbard & Lewin,



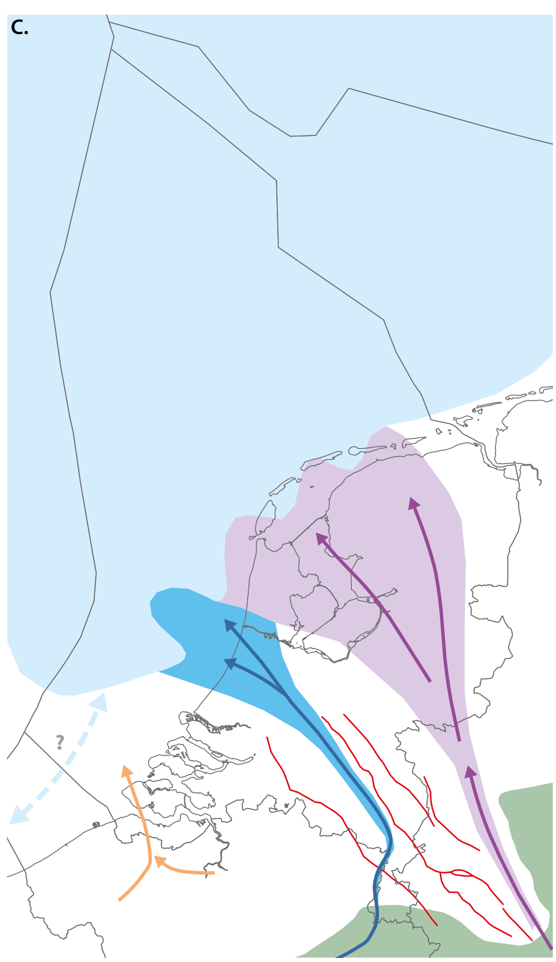


Figure 10.9. *Paleogeography during the Cromerian Regional Stage: a) early Cromerian (MIS 19-17), b) Cromerian Glacial C (MIS 16) and c) Cromerian III to IV (MIS 15-13). The successive paleogeographic maps show 1) termination of the Baltic River System and ice-sheet proximity, 2) re-entry of the Rhine into the Roer Valley Graben, and 3) expansion of the Rhine-Meuse System towards the northwest (see Fig. 10.5 for legend). Primary sources: Zagwijn (1975), Busschers et al. (2008), Beerten et al. (2018), Heyse & Demoulin (2018), Batchelor et al. (2019), TNO-GDN (2023c,d).*

2009; Tzedakis et al., 2017). Sea level oscillated semi-synchronously with the glacial-interglacial cycles, producing interglacial highs within metres of modern-day levels and sea-level drops of more than 100 m during glacial minima.

On the basis of pollen analysis of fine-grained sediments in fluvial and estuarine sequences of the Sterksel, Urk and Beegden formations, Zagwijn & Zonneveld (1956), Zagwijn et al. (1971) and Zagwijn (1996b) defined several Middle Pleistocene interglacial and glacial intervals (Fig. 10.1). The pollen records indicate that the warmest phases were characterized by deciduous forest vegetation. During cooler conditions, boreal forest and/or steppe-like vegetation dominated the region (Zagwijn, 1996b; Fig. 10.8).

Within the Cromerian three interglacials are recognized (Fig. 10.1). A critical difference with older interglacial periods is that their pollen spectra lack the thermophile tree taxa *Eucommia* and *Tsuga*. Details of vegetation successions into the interglacials differ considerably between the interglacials (Zagwijn, 1996b; Westerhoff et al., 2003). The Cromerian was followed by the Elsterian glacial (MIS 12) and Holsteinian interglacial (MIS 11). Holsteinian pollen spectra are the last to include the thermophile taxon *Pterocarya*. The longer Saalian complex (MIS 10-6) completes the Middle Pleistocene, with three glacials and two interglacials dominated by boreal forest (Fig. 10.1).

The coldest climatic phases were characterized by open vegetation types and/or polar desert conditions, development of continuous permafrost, and extensive ice-sheet advance. Known advances of the Fennoscandian and British ice sheets close to or into Dutch territory took place during the Cromerian Glacial C (MIS 16), the Elsterian (MIS 12) and the late Saalian (MIS 6) (Van den Berg & Beets, 1987; Laban & Van der Meer, 2011; Batchelor et al., 2019; Hughes et al., 2020). In the central and northern North Sea multiple advances of the Middle Pleistocene ice sheets led to the formation of a marked glacigenic unconformity (Upper Regional Unconformity; Ottesen et al., 2014, 2018).

Sedimentary systems and paleogeography

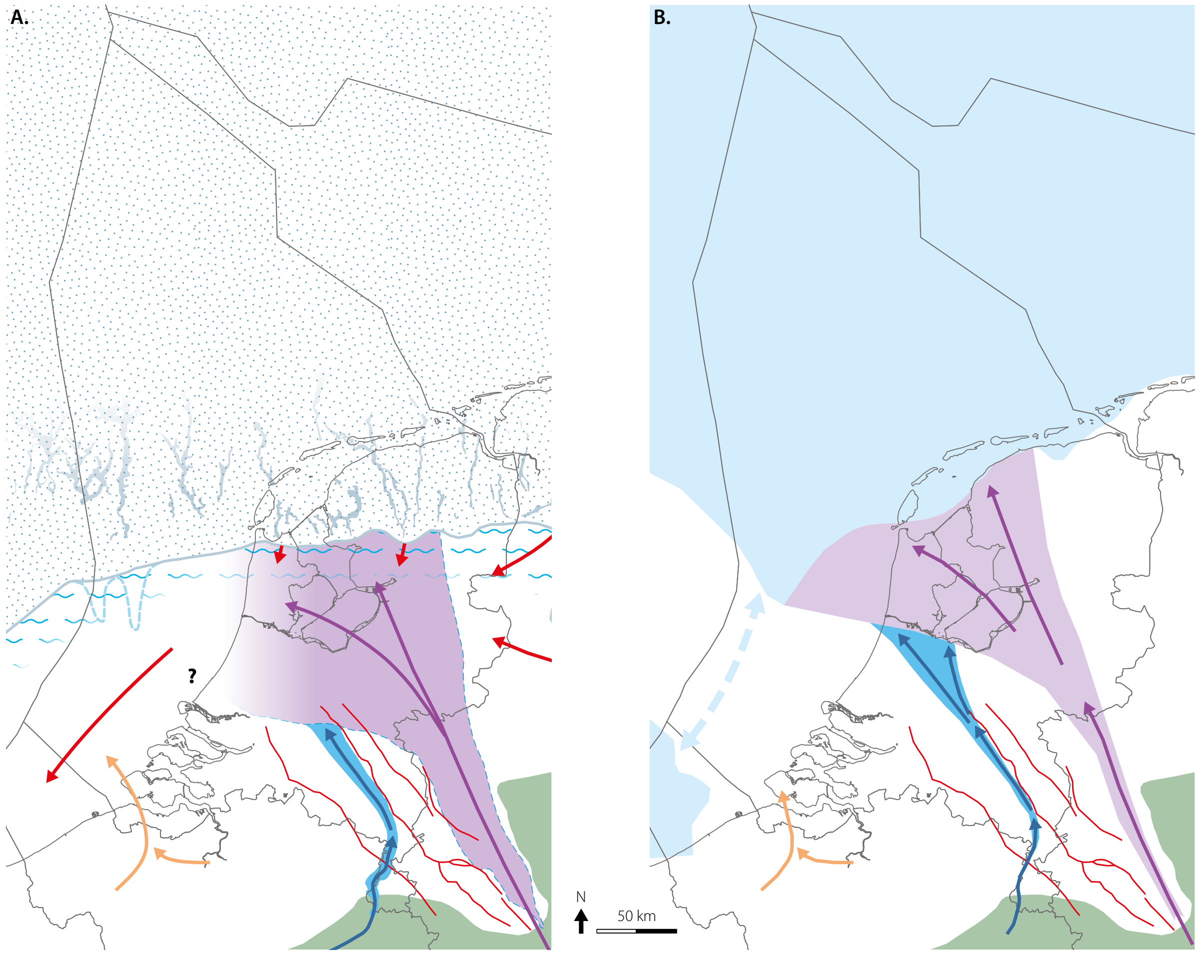
Middle Pleistocene up to the Elsterian (773-478 ka)

During the earliest Cromerian, the Rhine was positioned in the Roer Valley Graben (Sterksel Formation) (Fig. 10.9a). The Meuse and Rhine converged in the southern part of the graben. Towards the northwest, the Rhine appears to have merged with remaining easterly rivers (Appelscha Formation) and their depositional systems jointly extended into the marine realm (Yarmouth Roads and Batavier formations). The southwest of the Netherlands and adjacent parts of Belgium began to be incised by local river systems, while the Scheldt and its tributaries started developing the Flemish Valley in the uplifting Campine Block (Heyse & Demoulin, 2018; Fig. 10.9a).

For Glacial C (MIS 16) in the middle of the Cromerian (Fig. 10.9b), specific information comes from fluvioglacial deposits (Weerdinge Member, Appelscha Formation) exposed in the Emmerschans quarry in the northeastern Netherlands (Ruegg & Zandstra, 1977; Zagwijn, 1985). The Weerdinge Member is regarded as a glacial outwash and ice-marginal river product, indicating a contemporaneously active ice front to the northeast in northern Germany and its offshore area that predates more prominent glaciation of the same area during the Elsterian (MIS 12). The Rhine deposited significant volumes of coarse-grained sediments in the Roer Valley Graben and Venlo Graben (Sterksel Formation, Fig. 10.9b). Their compositional signature matches key levels in Rhine terrace flights in the German part of the Roer Valley Rift System record (Boenigk, 1978; Zagwijn, 1985), for which age constraints point to MIS 16 (Upper Terrace 3, cf. Boenigk & Frechen, 2006). A similar age correspondence follows from recent cosmogenic dating (Beerten et al., 2018; Vandermaelen et al., 2022) of morphostratigraphically equivalent terrace levels along the Meuse in Belgian borderland (Gullentops et al., 2001). During MIS 16 Glacial C, the Rhine-Meuse System of the southern and west-central Netherlands and the ice-marginal outwash river of the northeast were likely confluent in the northwestern Netherlands (Fig. 10.9b).

During or shortly after Glacial C, the Rhine part of the depositional system abandoned the Roer Valley Graben, although the Meuse System kept using this route for the remainder of the Cromerian (Fig. 10.9b,c). Late Cromerian interglacial depositional evidence is available both from Meuse deposits in the Roer Valley Graben (Rosmalen Member, Beegden Formation) and from Rhine deposits traced through the central and northern Netherlands (Veenhuizen Member, Urk Formation). These areas host the respective palynological type sites for Cromerian III and Cromerian IV (Zagwijn, 1985, 1996b), correlated to MIS 15 and MIS 13 respectively (Fig. 10.1). A minor cold period in between explains the compositional differences between the associated units. A review of geological mapping evidence indicates that no major glacial interval separates the two interglacials, in contrast to the suggestion of Zagwijn (1985, 1996b). Therefore, both the Weerdinge Member ('Glacial C' of Zagwijn, 1986, 1996b) and the upper part of Sterksel Formation ('Glacial B' of Zagwijn, 1986, 1996a), are attributed to a single major northwest European glaciation episode, for which the name 'Glacial C' is retained and the correlation to MIS 16 upheld (Fig. 10.1).

In the late Cromerian (MIS 15-13), the Rhine followed a relatively easterly course through the central Netherlands (Veenhuizen Member; Zagwijn, 1975; Busschers et al.,



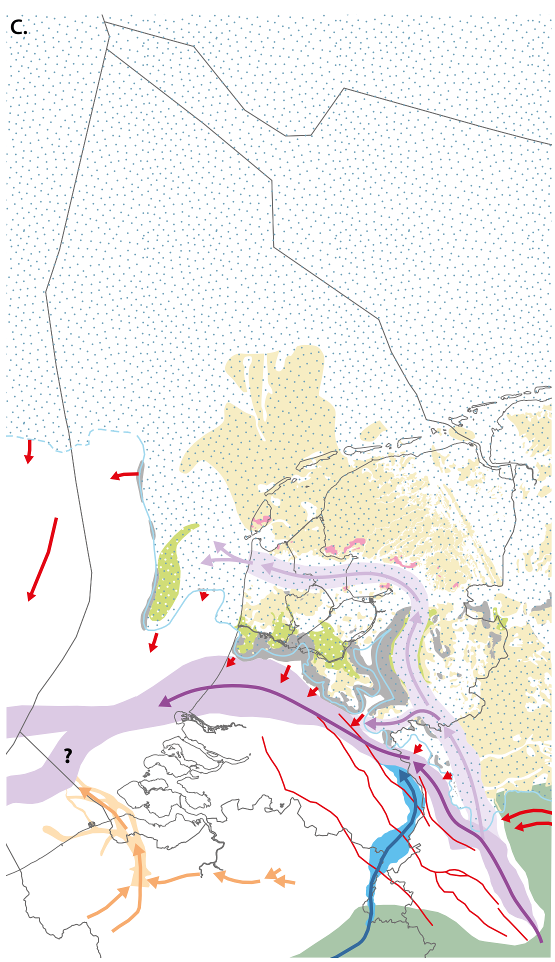
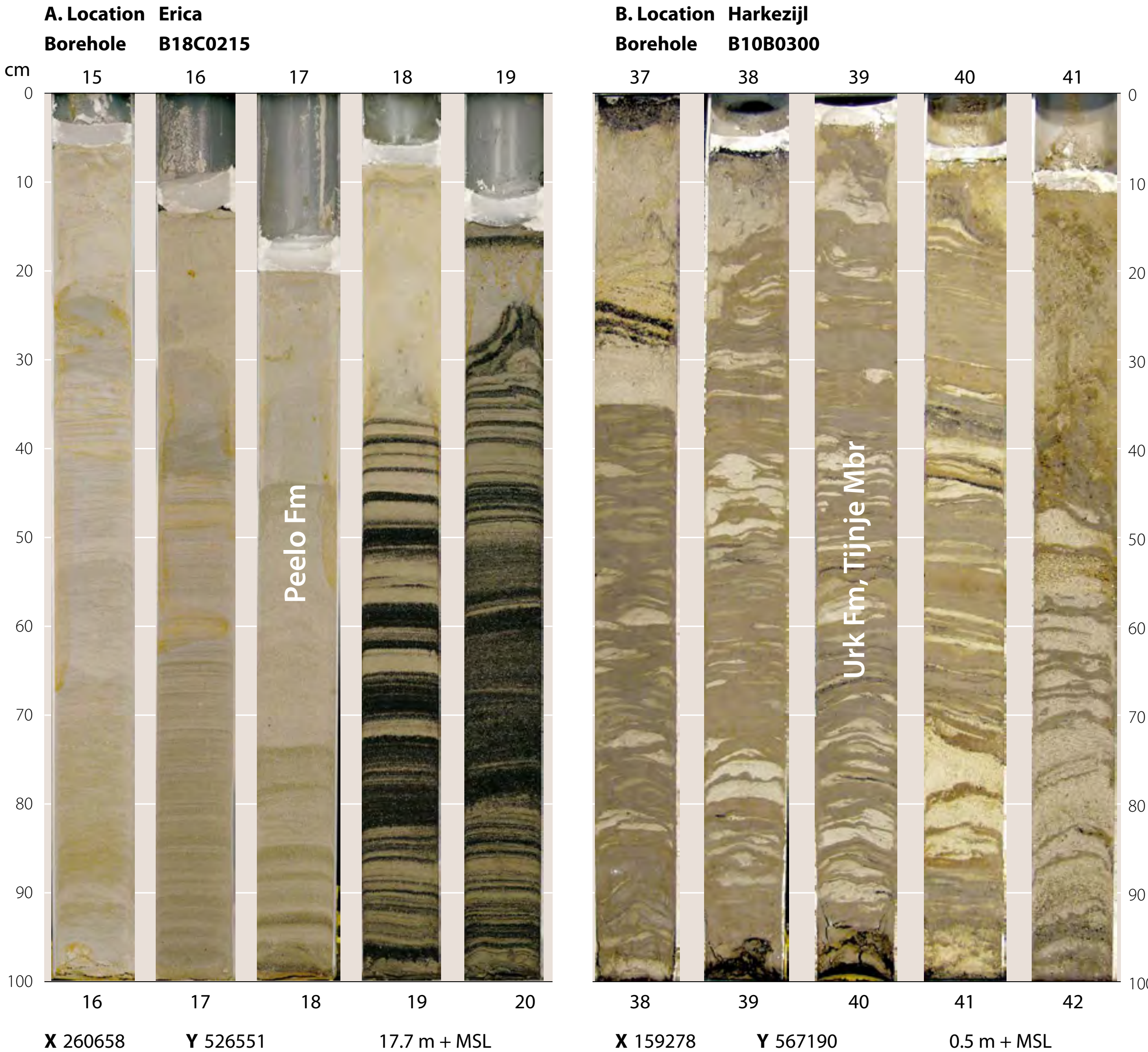


Figure 10.10. Paleogeography during a) the Elsterian glaciation (MIS 12), b) Holsteinian interglacial (MIS 11) and c) Saalian glaciation (MIS 6). The successive paleogeographic maps show 1) periods of large-scale glaciation of both the on- and offshore sector, 2) major (glaciation-controlled) changes in landscape topography and position of depocentres, and 3) fluvial and marine exchange between the North Sea Basin and the Channel area. Late Saalian (c) position of the Rhine near question mark and the dotted ice-sheet position in the west are uncertain. Primary sources: Zagwijn (1975), Laban (1995), Busschers et al. (2008), Moreau et al. (2012), Batchelor et al. (2019), Cartelle et al. (2021), Breuer et al. (2023), TNO-GDN (2023c) and TNO-GDN (2023d).



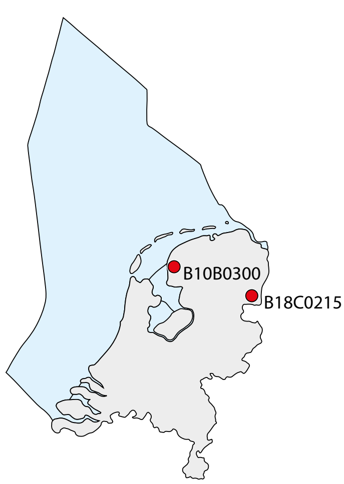


Figure 10.11. *a) Elsterian glaciolacustrine sands with parallel lamination and climbing ripples in a core from the northeastern Netherlands (Peelo Formation). The base of the core shows high concentrates of organic fragments reworked from underlying peat layers of the Urk Formation (Veenhuizen Member). b) Holsteinian tidal sediments (heterolithic bedding) in a core from the northern Netherlands (Tijnje Member, Urk Formation). Coordinates in Rijksdriehoeksstelsel. Core photos: TNO-GDN, 2023d.*

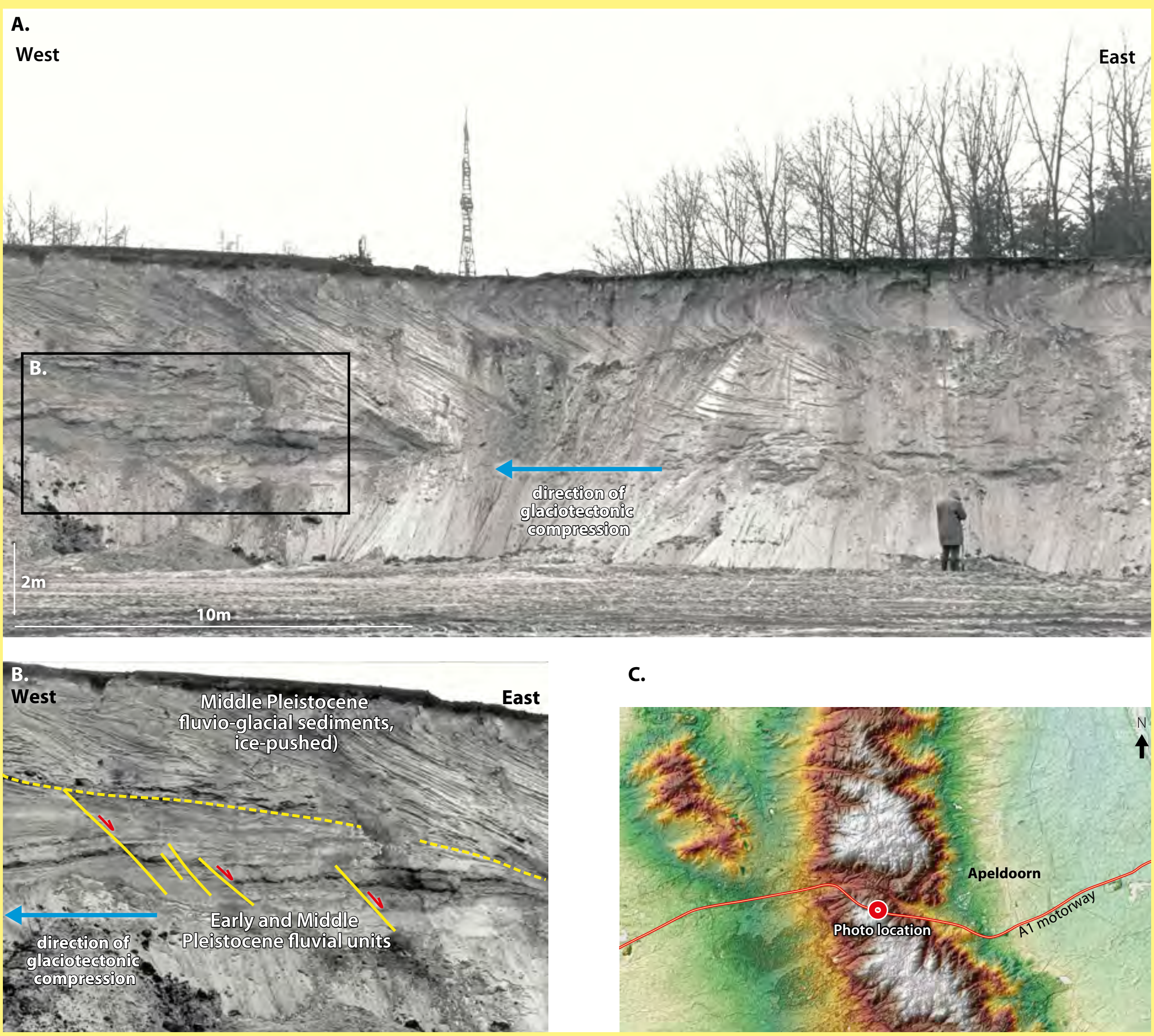
2008), widening into a coastal-deltaic plain with estuarine mouths aligned northwest, grading into shallow-marine deposits (Fig. 10.9c) and continuing as part of the Yarmouth Roads Formation in the offshore domain (Zagwijn, 1996b). Interglacial mollusc assemblages from the coastal and estuarine levels have a Lusitanian signature suggesting early marine exchange between the North Sea and English Channel (Wesselingh et al., 2023). The MIS-13 attribution of Cromerian-IV interglacial sites within the Veenhuizen Member is corroborated by the presence of clino-pyroxene (augite) in the sediments: a heavy mineral released by Eifel volcanic systems active since around 0.5 Ma (Fig. 10.1). Dating of the entry of augite was established using tephra layers in sequences bearing assemblages of small mammal species along the Middle Rhine in Germany (Van Kolfschoten, 1990; Van Kolfschoten & Turner, 1996; Gallant et al., 2014).

Late Saalian glacial landforms and sediments

3

Glacial deposits of the late Saalian glaciation (Drente Formation), show variable compositions and landforms. Till sheets formed in the northern part of the Netherlands (Gieten Member) and the adjacent part of the offshore sector as the ice advanced over fine-grained sediments (Fig. 10.10c). Thicker accumulations of till are limited to standstill and terminal locations where ice-marginal deposition and the formation of small-scale glaciotectonic ridges took place. Elongated, parallel ridges of up to 70 km length developed in the northeastern Netherlands, consisting of till and deformed preglacial material. This major geomorphological feature is known as the Hondsrug megaflute complex, formed below an ice stream that drained the ice sheet from the northwest (Van den Berg & Beets, 1987).

In the central Netherlands, the ice sheet advanced over coarse-grained fluvial sediments. Meltwater drainage from the permeable glacier bed resulted in coupling of the ice sheet with the substrate, and in the formation of large ice-pushed ridges (or push moraines) and associated glacial basins (Fig. 10.10c). The ice-pushed ridges consist of stacked (thrust) sheets of preglacial and fluvioglacial sediments (see figures a and b below). In the central Netherlands and the North Sea, these are mainly Pleistocene gravelly sands with few clay and loam beds. In the eastern Netherlands, Neogene units have been glaciotectonised as well. Fluvioglacial outwash was deposited prior to and during



a) Exposure of glaciotectonized sediments visible during construction of the A1 motorway west of Apeldoorn in 1970 (photo taken by Van der Veen; archive TNO-GDN). b) Close-up of glaciotectonic sequence with low-angle thrusts and relaxation structures (photo taken by Van der Veen; archive TNO-GDN). c) Lidar DTM (AHN4) of the Veluwe ice-pushed ridge with the location of the exposure shown in a and b.

the formation of ice-pushed ridges (Schaarsbergen Member). Till patches are present in the glacial basins, on the proximal flanks of the ice-pushed ridges and partly in ice-pushed position. During deglaciation, the initial infill of the glacial basins comprised fine-grained glaciolacustrine sediments and coarser-grained mass-flow deposits (Uitdam Member), the latter originating from the steep slopes, flanking ice-pushed ridges (Van Leeuwen et al., 2000; Beets & Beets, 2003).

After deglaciation, the remaining lows formed depositional sinks for marine, coastal and estuarine sediments of Eemian age and fluvial and eolian sediments of Weichselian age, respectively (e.g. Fig. 10.15). Currently the basins are completely filled, their remnants buried in the subsurface. This is also true for the toes of the ice-pushed ridges in the east and the lower half of the ice-pushed ridges in the central Netherlands. From Amsterdam westward and further below the North Sea (Fig. 10.10c), the ice-pushed ridges are entirely covered by younger sediments. Geophysical data show that postglacial denudation has lowered the crests of the ice-pushed ridges by about 15 m. The eroded sediments have been redistributed in the basins and on the ridge flanks as alluvial fans (Boxtel Formation; Busschers et al., 2007). Other preserved features related to the Saalian glaciation include drumlins, eskers, buried tunnel valleys and deposits of ice-dammed lakes, including kettle-hole fills.

Artefacts found in ice-pushed sediments testify to the late Middle Pleistocene presence of early humans (Stapert, 1987). Aligned series of hand-dug pits on the ice-pushed ridges themselves are relicts of early medieval iron industry. These pits follow outcrops of iron-bearing concretions and reflect the strike of the ice-pushed strata. Currently the ice-pushed ridges provide major groundwater reserves. Hydrogeological aspects include a marked anisotropic character of the aquifers arising from their specific structural architecture.

Middle Pleistocene from Elsterian to Mid-Late Pleistocene Transition (478-130 ka)

The Elsterian (MIS 12) was a glacial period that began with severe cooling and sea-level lowering, followed by far-reaching Fennoscandian ice-sheet advance (Fig. 10.10a). Eventually, this ice sheet covered the northern Netherlands and all but the southernmost parts of the Dutch and English sectors of the North Sea, while coalescing with British ice cover over East Anglia (Anglian glaciation in the British scheme). This arguably most extensive glaciation to ever cover the North Sea region left a vast network of subglacial tunnel valleys that cut deeply into the substrate (Fig. 10.3b). Towards the east, they are marked by considerable outwash deposits at their southern terminations. The irregular network geometry and ups and downs in thalweg depth indicate that overpressured meltwater was the main agent responsible for tunnel-valley formation, with steady-state conditions and catastrophic outbursts fed by supra- and englacial meltwater as key mechanisms (Praeg, 2003; Benvenuti et al., 2018; Kirkham et al., 2024).

Sediments of the Elsterian glaciation are grouped into the Peelo Formation (Fig. 10.1). Usually, the tunnel-valley infill has an erosional lag at the base. It consists of a heterogeneous unit of gravel, sand and diamicton that may contain rock fragments of Neogene to Cretaceous age. The lag is overlain by sandy deposits. Seismic imagery commonly shows characteristic northward-dipping clinoforms. Their precise mode of origin is debated, but they likely were formed synchronously with headward erosion of the valleys during or immediately following ice-front recession (Huuse & Lykke-Andersen, 2000; Praeg, 2003; Moreau & Huuse, 2014). Subsequently, glaciolacustrine conditions prevailed, during which glacial clay ('pottery clay') and fine-grained sands were deposited preferentially in the tunnel valleys and other topographic lows. The clay can be very stiff, reflecting postdepositional dewatering and overcompaction from loading by the younger late Saalian ice sheet.

In the Dutch onshore and offshore, the southern limit of Elsterian glaciation is effectively defined by the southernmost extent of tunnel valleys. In and around the Netherlands, it maps out as a remarkably straight ice-sheet margin (Fig. 10.10a), linking up to more irregular British and German ice-front maxima constrained from tunnel-valley tips and patchy tills (Batchelor et al., 2019; Breuer et al., 2023). Along the Dutch Elsterian margin, glaciotectonic deformation appears to be rare, which is in sharp contrast to the Dutch Saalian margin. This may indicate that it was bounded and held up by a large freshwater body, with a calving ice front and tunnel valleys releasing abundant sediment-laden subglacial water. In the east of the country, remnants of thick glaciolacustrine outwash complexes of Elsterian age have been identified (Peelo Formation, Fig. 10.11a). Erosion during subsequent times makes it difficult, however, to reconstruct the situation westward and to demonstrate lateral continuity of lakes bounded by the ice front. Exceptionally large proglacial lake systems have been suggested, with tentatively projected shoreline positions in the southern Netherlands, but the absence of positively identifiable glaciolacustrine facies in the central Netherlands (e.g. in Saalian ice-pushed complexes), makes it more likely that Elsterian glacial lakes were restricted to zones closer to the ice front. Whether or not spillage of ice-lake waters initiated strong erosion in the Dover Strait, and to what degree it explains cliff and erosional seafloor features over there, is also still a matter of debate (e.g. Gibbard, 1995; Gupta et al., 2007; Hijma et al., 2012; Gupta et al., 2017).

The Elsterian Rhine River System must have merged with easterly proglacial drainage systems some distance south of the ice front in the central Netherlands. It built out coarse-grained braidplain deposits that comprise parts of the Urk Formation (Fig. 10.10a). The exact extent of this braidplain is unknown. From the south, the Meuse braidplain (Beegden Formation) merged with the Rhine ice-marginal system. South of the Rhine braidplain, eolian and fluvio-eolian deposition prevailed (Best Member, Boxtel Formation; Schokker et al., 2005, 2007; Kars et al., 2012; Meijs et al., 2013).

During the Holsteinian interglacial (MIS 11), the Rhine ran a northward course (Fig. 10.10b) towards estuarine and shallow-marine areas in the northern Netherlands (Tijnje Member, Urk Formation). Here, the Rhine record has a complex architecture comprising alternating channel sands and flood-basin clays and peats, (Fig. 10.11b; Bosch, 1990; Lee et al., 2012), analogous to the Holocene coastal prism (see section on the Holocene). This complex holds a palynological record of several warm phases associated with interglacial deciduous forests. The earliest and most widespread of these has been linked to interglacial MIS 11 on the basis of relative intensity and duration as well as the match with traditional Holsteinian pollen spectra (Ehlers, 2011; Stephan, 2014; Tzedakis et al., 2022). A second warm level, although originally less widespread or less well preserved than the basal level, occurs higher in the complex. It is separated from the basal level by coarse-grained cold-stage Rhine sands suggesting that it might correlate to MIS 9. Offshore, this ensemble passes into estuarine and shallow-marine facies of the Egmond Ground Formation (Zagwijn, 1983; Laban, 1995). During the Holsteinian, the Meuse maintained a course through the Roer Valley Graben (Schokker et al., 2005), with estuarine reaches projected in the northwestern Netherlands (Busschers et al., 2008).

During cooling phases following the Holsteinian, the Rhine-Meuse System adopted a new course through the central Netherlands (Fig. 10.10c). Early to middle Saalian (MIS 10-7) Rhine deposits (Urk Formation) are encountered in areas that later were glaciotectonised during the Drenthe glaciation (ca. 160-150 ka, within MIS 6; Busschers et al., 2008). These deposits contain intervals bearing Paleolithic artefacts assigned to MIS 7 and early MIS 6 ('Rhenen industry'; Stapert, 1987; Van Balen & Busschers, 2010; Niekus et al., 2023). Paleolithic human presence during MIS 7 (243-190 ka) is also evident from the Meuse Valley upstream (Maastricht Belvédère, on the Caberg-3 Terrace; see Textbox 2). Estuarine and shallow-marine sediments were deposited in the northwestern Netherlands and offshore area during MIS 9 and possibly MIS 7 (Tijnje Member and Egmond Ground Formation; Meijer et al., 2021).

Saalian sediments belonging to local depositional systems are widespread both in the north and the south of the country. In the north, the Drachten Formation (Fig. 10.1) comprises fluvial, fluvioperiglacial and eolian sands with organic intercalations, overlying the aforementioned Rhine complex of the Urk Formation. Two organic levels record the periodic return of boreal forest during the Hoogeveen and Bantega interstadials (Fig. 10.1), which likely correlate to MIS 7e (ca. 240 ka) and MIS 7c (ca. 215 ka), respectively. Luminescence dating of quartz grains from the upper parts of the Drachten Formation gave an age of ca. 170 ka (Kars et al., 2012) corresponding to MIS 6, just prior to glaciation of the area. In the southern Netherlands, a similar package of fluvial, fluvioperiglacial and eolian sands that accumulated in the Roer Valley Graben along with lacustro-eolian silts, stretches further back in time (Boxtel Formation; Schokker et al., 2005, 2007; Kars et al., 2012). Multiple involuted intercalations encountered in the Boxtel Formation indicate multiple freezing and thawing cycles. The depositional sequence in the Roer Valley Graben holds several peaty beds with pollen assemblages attributed to Holsteinian and early Saalian interglacials (MIS 11 and 9), and to the Hoogeveen and Bantega interstadials (MIS 7) also encountered farther north. Even farther south, loess blanketing of the landscape occurred repeatedly during Saalian stadials (in MIS 10, 8 and 6) alternating with soil formation during interglacials and interstadials (in MIS 9 and 7; Meijs et al., 2013).

Towards the end of the Saalian, during the Drenthe glaciation (MIS 6, ca. 170-140 ka), a major sector of the Fennoscandian ice sheet extended into the Netherlands. The glaciation had a major influence on the paleogeographic developments, sedimentary records and landforms (also see Textbox 3). The lobate ice front advanced from the northeast and eventually covered the northern and central Netherlands (Van den Berg & Beets, 1987). As it overcame temporal stillstands, the ice sheet overrode and deformed its own proglacial outwash and associated ice-marginal river deposits. Once the ice reached basin-rim areas with their coarser-grained substrate of earlier Rhine-Meuse and easterly river formations, it glaciotectonised, froze up and bulldozed that substrate into a series of pronounced ice-

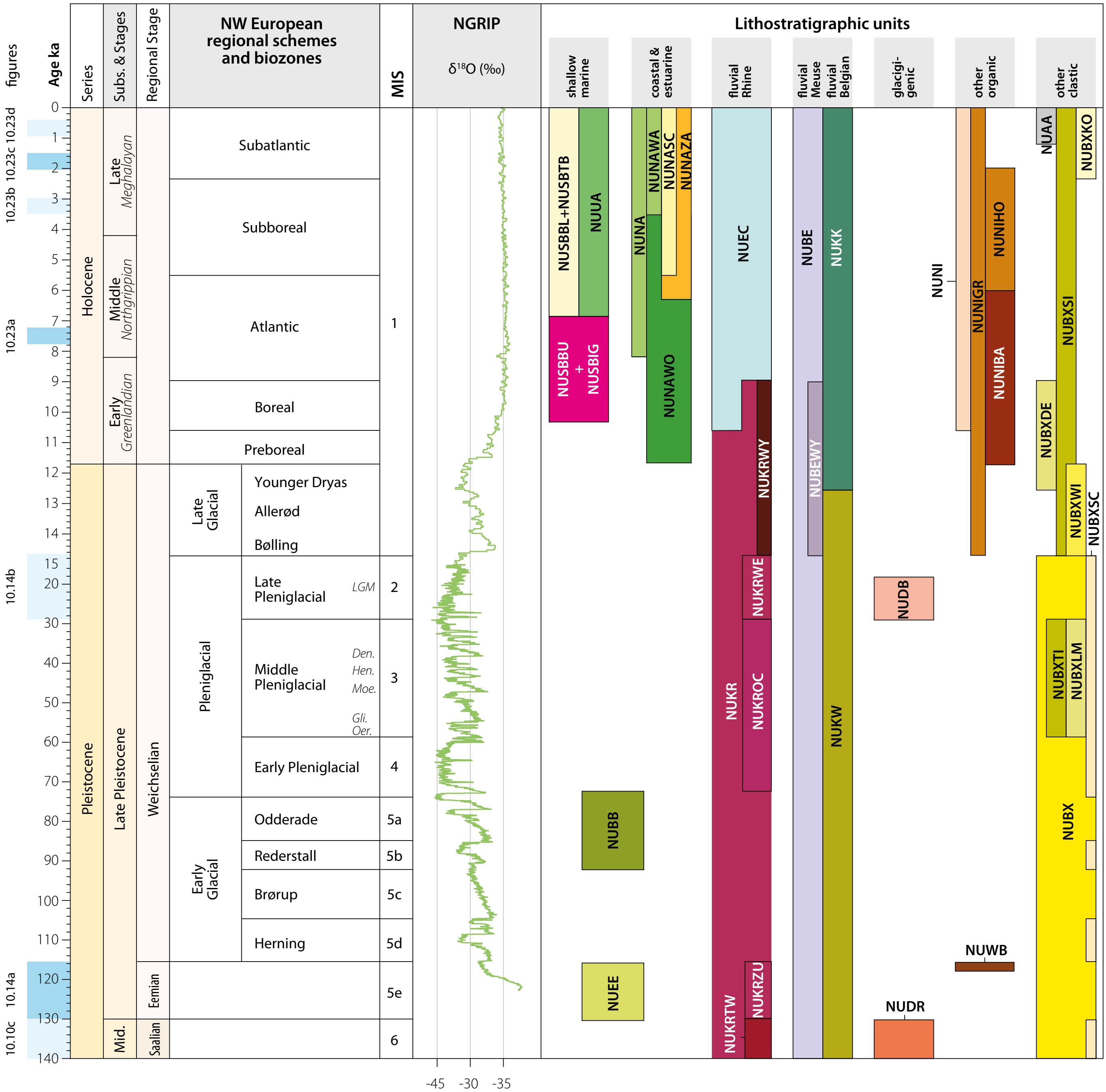


Figure 10.12. Subdivision of the Late Pleistocene and Holocene, with from left to right chronostratigraphic subseries and stages (Cohen & Gibbard, 2019) complemented with regional (northwest European) stages and substages, northwest European regional schemes and biozones, deep-ocean oxygen isotope stages (Lisiecki & Raymo, 2005), NGRIP oxygen isotope record (North Greenland Ice Core Project members, 2004), and formally defined stratigraphic units in the on- and offshore domains of the Netherlands (TNO-GDN, 2023d). See Table 10.1 for explanation of lithostratigraphic codes. Age ranges indicate minimum and maximum ages of each unit; diachroneity and hiatuses, present throughout the stratigraphic column, are not shown.

pushed ridges (Van der Wateren, 1995; Bakker & Van der Meer, 2003; Fig. 10.10c) and associated glacial basins. The ridges are especially well developed in the central Netherlands where they form the Utrechtse Heuvelrug and Veluwe push-ridge complexes (see also Textbox 3).

By ca. 160 ka (Busschers et al., 2008), the ice sheet had reached it southernmost extent in the central Netherlands, continuing into Germany as well as the Netherlands offshore area (Laban, 1995; Moreau et al., 2012; Cartelle et al., 2021; Fig. 10.10c). The topographic prominence of the ridge complex forced the Rhine-Meuse System to adopt a westward proglacial course. During the final stage of the glaciation, major incision and dissection occurred by the ice-marginal Rhine-Meuse River System (Busschers et al., 2008; Rijsdijk et al., 2013). This is the first incised lowstand valley of the Rhine-Meuse System that can be positively traced westward to the Dover Strait (Fig. 10.10c).

During ice-sheet disintegration (ca. 150-140 ka), series of (interconnected) lakes developed in the newly exposed glacial basins. The Rhine shifted its course to a position north of the glaciotectonic ridge complexes and began depositing sequences of fine-grained fluviolacustrine sediments (Twello Member, Kreftenheye Formation) in the largest glacial basin in the east (IJssel glacial basin; Fig. 10.10c). These fine sediments were gradually buried by coarse-grained sands. Through time, the lake transformed into a river valley. Via the IJssel glacial basin, the Rhine continued westward through the central Netherlands, shaping a deeply incised valley partly filled with fluvial sand of the Kreftenheye Formation (Peeters et al., 2016). The position of the offshore continuation of this valley is still unknown (Fig. 10.10c).

Late Pleistocene Subseries (130-11.7 ka)

Climate, sea level, ice sheets and biota

The Late Pleistocene marks the final, full interglacial-glacial cycle of the Quaternary (Fig. 10.1). It started with the Eemian interglacial (ca. MIS 5e), when temperatures and global MSL reached slightly higher values than those of today (Medina-Elizalde, 2013; Long et al., 2015; Spratt & Lisiecki, 2016). The Eemian vegetation succession is different from that of the Holocene, especially in the later part of the Eemian (Zagwijn, 1961, 1996a; Helmens, 2013). The pollen assemblages, particularly the presence of *Taxus*, indicate that temperatures during the peak Eemian climate were slightly higher than during the Holocene climatic optimum. The Eemian interglacial was followed by the Weichselian Early Glacial with a succession of cool to temperate interstadials (notably Brørup and Odderade; Fig. 10.12) with *Betula-Pinus-Picea* forests, and cold stadials characterized by tundra vegetation and discontinuous permafrost (Zagwijn, 1961; Van der Meer et al., 1984; Behre, 1989; Helmens, 2013; Kasse et al., 2022). During the warmer phases of the Weichselian Early Glacial, global MSL was positioned ca. 10-20 m below the present-day level during interstadials and even lower during stadials (Medina-Elizalde, 2013; Spratt & Lisiecki, 2016).

Rapid and severe cooling, accompanied by extreme sea-level lowering, occurred at the onset of the Weichselian Early Pleniglacial (MIS 4), with polar desert conditions becoming established. This interval also saw extensive Fennoscandian ice sheet expansion, but it was more limited than during the latest part of the Weichselian. The Early Pleniglacial also marked the transition from the diverse warm-temperate faunas to the mammoth fauna that flourished during the Middle Pleniglacial (MIS 3). During the Middle Pleniglacial the climate was generally milder than in the Early Pleniglacial, with tundra- and steppe-dominated landscapes and common but non-pervasive permafrost (Van Huissteden et al., 2003; Busschers et al., 2007). Coeval ice-sheet build-up over Fennoscandia was limited at this time (Mangerud et al., 2011; Batchelor et al., 2019) and sea level was positioned several tens of metres lower than that of the Weichselian Early Glacial (MIS 5d-a).

The Greenland ice sheet recorded repeated alternations of very cold stadials and cool-temperate interstadials (Dansgaard-Oeschger events), which particularly affected the North Atlantic and northwest European regional climate strongly (Fig. 10.12). In the Dutch Weichselian sequence, these interstadials (e.g. Moershoofd, Hengelo and Denekamp interstadials) are evident from peat beds that are dominated by tundra vegetation (Zagwijn, 1961; Van der Hammen & Wijmstra, 1971; Van der Meer et al., 1984; Van Huissteden, 1990; Vandenberghe & Van der Plicht, 2016). Botanical macrofossil research indicates that *Betula nana* and *Salix polaris* were common in the tundra landscapes. For the duration of the Pleniglacial, closed boreal forests were unable to return to the Netherlands. For extensive periods, stadial-interstadial vegetation cover was dominated by abundant grasses, sedges and some herbaceous vegetation. The southern North Sea region formed part of a mammoth-steppe ecosystem that supported a wealth of smaller and larger mammals. Large grazers (mammoth, horse, bison, woolly rhinoceros) were particularly common while hyena was abundant and other predators such as cave bear and cave lion were also present (Fig. 10.13).

Modern humans may have first arrived in the region during this time (Higham et al 2011). Through the course of MIS 3, megafaunal species began to disappear. The ranges of their typical habitats contracted mostly towards the northern Asian realm before they ultimately became extinct (see Textbox 4).

The cooling that followed MIS 3 culminated in the Weichselian Late Pleniglacial (MIS 2), when the Netherlands and North Sea floor experienced polar desert conditions. This phase includes the Last Glacial Maximum (LGM), ca. 21 ka (Fig. 10.12). Between 29 and 23 ka, Fennoscandian and British ice-sheet sectors advancing across the North Sea reached local maximum extents, forming the now submerged Dogger Bank glaciotectonic ridge in the central North Sea (Laban, 1995; Roberts et al., 2018; Emery et al., 2019). In regions further south, polar desert conditions prevailed. After about 19 ka and accelerating from 14.7 ka onwards, warming caused the land ice to recede. Newly exposed terrain was rapidly occupied by tundra to taiga ecosystems. The warming continued into the early Holocene, preceded by the Younger Dryas Stadial

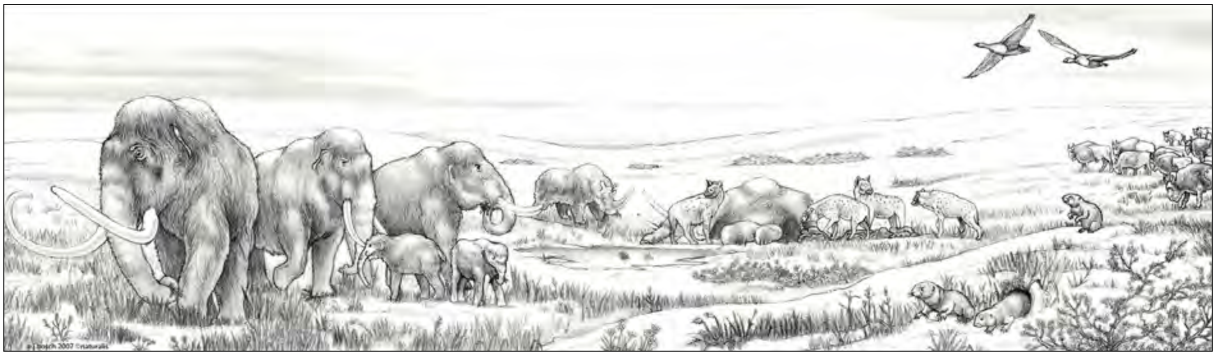


Figure 10.13. *Artist impression of the MIS 3 mammoth steppe, a dry periglacial landscape home to a typical ice-age megafauna including mammoths, whooly rhinoceros and hyenas. Drawing E.J. Bosch, Naturalis.*

(12.9-11.7 ka), when a North American meltwater pulse disrupted the North Atlantic meridional overturning and subarctic conditions returned briefly.

Sedimentary systems and paleogeography

Eemian and Weichselian Early Glacial (MIS 5)

At the onset of the Eemian interglacial, the rising sea level of the North Sea encountered a diverse topography with ice-pushed ridges and deep glacial basins that strongly affected the inundation history (Fig. 10.14a). The coastline configuration of the Eemian sea was different from the present one, with peninsular promontories as well as embayments extending far inland. The Rhine flowed northward through today's IJssel Valley, triggering extensive floodplain deposition (Zutphen Member, Kreftenheye Formation; Fig. 10.12; Busschers et al., 2007; Peeters et al., 2016). It debouched into a shallow-marine embayment (Fig. 10.14a). The Meuse River broadly followed its modern course and discharged into the North Sea tens of kilometres further inland than its present-day mouth.

During the Eemian highstand, which was coeval with pollen zone E5 (*Carpinus* zone; Zagwijn, 1983; Long et al., 2015; Cohen et al., 2022; Kasse et al., 2022; late MIS 5e), coastal marine conditions prevailed in large parts of the northern and western Netherlands, including the Amsterdam and Amersfoort basins (Fig. 10.14a). These basins became filled with generally shell-rich shallow-marine and lagoonal deposits of the Eem Formation (Fig. 10.15). The topography resulting from the previous Saalian glaciation provided varied habitats (Cleveringa et al., 2000; Van Leeuwen et al., 2000). A species-rich nearshore fauna with common warm seagrass-associated mollusc species lived in embayments that experienced different salinity regimes depending on basin configuration and the spatiotemporally varying amount of river inflow. As a consequence of the warm-temperate conditions, vegetation on land was lush, the landscape stabilized and extensive soil formation took place. Organic-rich units attributed to the Boxtel Formation were formed in peat bogs that developed in areas with a high groundwater table (Schokker et al., 2004).

At the end of the Eemian (pollen zone E6), regression enabled peat of the Woudenberg Formation to form along the coast in more protected areas (Fig. 10.15). As a result of ongoing and severe climate cooling as well as sea-level fall at the end of the Eemian, the North Sea probably became disconnected from the English Channel region, with a single ocean connection in the northern North Sea remaining. This oceanic connection drove strong cooling of marine habitats in the North Sea even though summer temperatures on land may have remained moderately high. This created a setting somewhat comparable to today's Hudson Bay (Waajen et al. 2024). Cold, boreal marine faunas, with walrus and beluga, dominated the southern North Sea at the time.

During this period, the Rhine continued to follow a course through the IJssel Valley and the province of Noord-Holland in the northwest, forming an extensive deltaic and prodeltaic depositional complex centred below the present day coast (Kreftenheye Formation; Busschers et al., 2007; Hijma et al., 2012; Peeters et al., 2016). The Meuse remained approximately in the same position as during the Eemian, although later erosion has fragmented its depositional record (Busschers et al., 2007). Seismic data and shallow vibrocores from the North Sea demonstrate that deposition farther offshore was dominated by fine-grained sand and clay under alternating shallow-marine and lagoonal conditions (Brown Bank Formation; Fig. 10.12; Laban, 1995; Busschers et al., 2007; Hijma et al., 2012; Eaton et al., 2020; Missiaen et al., 2021; Waajen et al., 2024).

Beyond the major river valleys, alternations between small-scale fluvial, fluvioperiglacial, lacustrine and peat strata dominate Early Glacial successions, reflecting transitions between warmer and cool to cold climatic phases (Zagwijn, 1961; Van den Berg & Den Otter, 1993; Kasse et al., 2022). Closer to the Saalian ice-pushed ridges, the imprints of these MIS 5 climatic variations are also visible

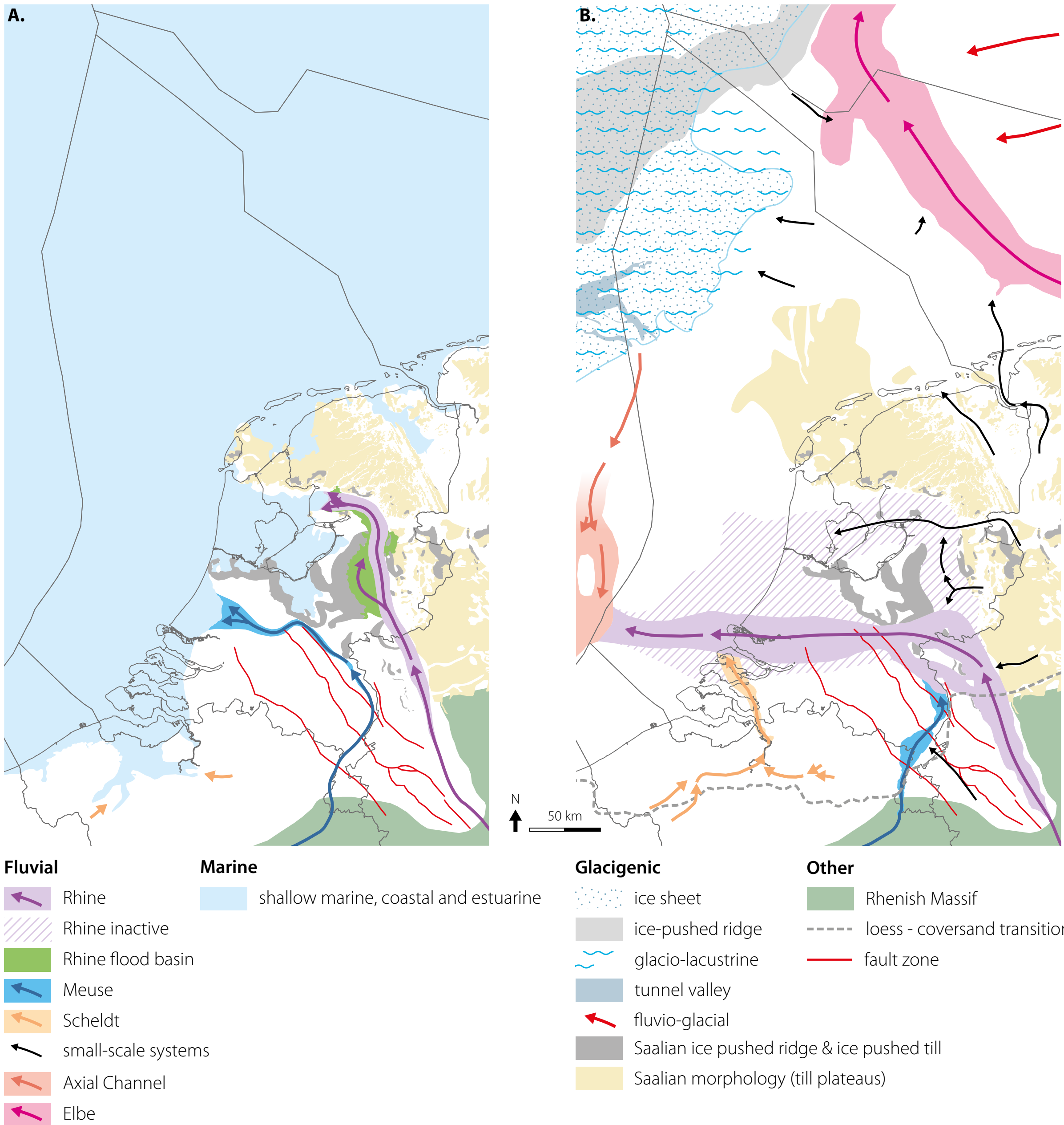


Figure 10.14. *Paleogeography during a) the Eemian (MIS 5e) and b) the Weichselian Late Pleniglacial (MIS 2). The successive maps show 1) a complex of Eemian marine embayments and protruding capes, in the central and northern Netherlands strongly affected by inherited glacial relief (a), 2) initial separation and eventual joining of Rhine and Meuse (b), and 3) glaciation of the northern offshore sector towards the end of the Late Pleistocene (b). Primary sources: Busschers et al. (2007), Hijma et al. (2012); Peeters et al. (2016, De Clercq et al. (2018), Batchelor et al. (2019), Hepp et al. (2019), Cartelle et al. (2021), Lehmkuhl et al. (2021), Cohen et al. (2022), TNO-GDN (2023c) and TNO-GDN (2023d).*

in alluvial fan deposits as alternations between coarse-grained sediments, eolian sands, loess and peat horizons (Van der Meer et al., 1984; Palstra et al., 2021).

Weichselian Early and Middle Pleniglacial (MIS 4-3)

During the Weichselian Early Pleniglacial, climate cooling and sea-level lowering resulted in incision and large-scale reworking of Eemian and Weichselian Early Glacial marine sediments in the valleys of the Rhine-Meuse (Kreftenheye Formation) and other smaller rivers (Koewacht and Boxtel formations; Van Huissteden et al., 2003; De Clercq et al., 2018). These valleys largely followed the same courses as during the preceding interglacial but extended their downstream ranges onto the dry North Sea floor, becoming confluent towards Dover Strait (Busschers et al., 2007; Hijma et al., 2012; Peeters et al., 2016). Extremely cold and dry conditions towards the end of the Weichselian Early Pleniglacial resulted in a phase of large-scale eolian transport and deposition of sand (Schokker & Koster, 2004) and, in the southeasternmost province of Limburg, of loess (Meijs, 2011). Large ice-wedge casts in sediments from this period testify to the presence of continuous permafrost at a time of very low temperatures (Huijzer & Vandenberghe, 1998; Fig. 10.16).

Halfway through the Middle Pleniglacial, major changes in the course of the Rhine occurred. As a result of avulsion in the upstream part of the IJssel Valley, related to ongoing climate-driven aggradation and a strong gradient advantage, the Rhine adopted a new course to the south of the ice-pushed ridges of the central Netherlands (Fig. 10.14b). Here the river became confluent with the Meuse. By ca. 38 ka, the northern route was fully abandoned, possibly also in response to initial glacio-isostatic uplift resulting from the advance of the growing Fennoscandian and British ice sheets (Busschers et al., 2007; Peeters et al., 2016).

The precursor of the Scheldt ran northward and merged with the Rhine-Meuse close to today's harbour city of Rotterdam (Slupik et al., 2013; Koewacht Formation). The Rhine-Meuse System resumed its course into the present-day southern North Sea (Kreftenheye Formation), where it connected with the Thames and was deflected southward through Dover Strait into the Channel River System (Toucanne et al., 2010; Hijma et al., 2012). The latter debouched into the Atlantic Ocean near the present-day shelf break between Brittany and southern Ireland. Severe seasonality, with massive meltwater pulses during the spring, resulted in strong sediment supply and redeposition.

Outside the realm of the large rivers, sediments from MIS 3 filled glacial basins in the central Netherlands as well as subsiding areas in the south where they have been well-studied. In the Nordhorn and Hengelo Glacial Basins, up to 20-m-thick sequences of small-scale fluvial sediments and organic deposits occur (Tilligte Member, Boxtel Formation). These sediments provide information on paleoclimate, paleoecological conditions and changes in fluvial styles (Van der Hammen & Wijmstra, 1971; Van Huissteden, 1990; Berrittella, 2017). The sedimentary sequence in the Roer Valley Graben forms a complex alternation of small-scale fluvial, wet-eolian and lacustrine deposits. Grain-size distribution, sedimentary structures and malacological content of thick calcareous loam beds (Liempde Member, Boxtel Formation; Schokker et al., 2007) indicate the presence of shallow pools filled with loess-like sediments in a sub-arctic climate. The sedimentary sequence in this area testifies to generally wet, tundra-like conditions with repeated cryoturbation phases (Deeben et al., 2010).

Weichselian Late Pleniglacial (MIS 2)

Extreme climate cooling at the onset of the Weichselian Late Pleniglacial resulted in major expansion of the Fennoscandian and British ice sheets. The ice sheets advanced into the central North Sea, creating the Cleaver Bank and Dogger Bank highs through glaciotectonics (Laban, 1995; Roberts et al., 2018; Emery et al., 2019), as well as into the southwestern Baltic (Batchelor et al., 2019). The southernmost ice-margin positions were obtained between 27 and 21 ka (Figs 10.1, 10.14b).

Ice-pushed ridges and outwash complexes formed along maximum and recessional ice margins. Some of these are evident from seafloor topography and from subsurface features visible in shallow seismics. Additional evidence comes from Dogger Bank cores. The subsurface features are mapped as the Dogger Bight Formation (Fig. 10.12), which includes the Bolders Bank Member (till), the Well Ground Member (sandy outwash deposits) and the Dogger Bank Member (clayey glaciolacustrine deposits). Northeast of the Dutch sector the Elbe established a southeast-northwest oriented incised valley (Hepp et al., 2019; Fig. 10.14b). In the northwest of the Dutch Sector, a British ice lobe advanced farthest south, leaving tunnel valleys such as Outer Silver Pit (Fig. 10.14b) and Botney Cut. These valleys were partially infilled during deglaciation (Botney Cut and Volans members) and still receive fine sediment from suspension today. In general, modern high-resolution bathymetric charts reveal many well-preserved details of the last glacial action in the region (lineations, fields of boulder-sized erratics), overprinted to varying degrees by shallow-marine bedform fields formed by subsequent Holocene tidal and wave action.

During the Weichselian Late Pleniglacial, the Rhine-Meuse System followed an east-west orientated course (Fig. 10.14b) and deposited coarse-grained sands and gravel (Kreftenheye and Beegden formations; Fig. 10.12). The Scheldt joined with the Rhine-Meuse System close to the present-day coastline. Further west, the joint Rhine-Meuse-Scheldt System coalesced with the north-south orientated Axial Channel (Fig. 10.14b). The Axial Channel also received copious amounts of meltwater from the ice front to the north (Cohen et al., 2014; De Clercq et al., 2018). It connected with the Thames and was deflected southward through Dover Strait into the Channel River System (Toucanne et al., 2010; Hijma et al., 2012; García-Moreno, 2017; De Clercq et al., 2018).

In its peripheral position relative to the Fennoscandian and British ice-mass centres, the southern parts of the North Sea Basin experienced glacio-isostatic uplift (forebulge updoming). The northern Netherlands was part of the main centre of uplift, which temporarily inverted the general subsidence regime of the Netherlands depocentre (Kiden et al., 2002; Busschers et al., 2007). Because the uplift occurred during the cold-period sea-level lowstand, its effect was mainly reflected in the changing behaviour of fluvial drainage systems like the Rhine-Meuse, notably as southward deflections away from the uplift centre and as a dominance of incision (Busschers et al., 2007). During deglaciation (ca. 25-11 ka), glacio-isostatic adjustment led to enhanced subsidence (forebulge collapse). This is recorded in the Rhine-Meuse System by marked coarse-grained aggradation in a widening active braidplain (ca. 18-15 ka) and eventually (ca. 13-10 ka) by a northward lateral deflection (Busschers et al., 2007; Hijma et al., 2009). Coevally, forebulge collapse also led to an increase in paleoseismic activity in the Roer Valley Rift System (Van Balen et al., 2019, 2021). At diminishing rates, glacio-isostatic subsidence continued into the Holocene, as is evident from south-to-north differences in postglacial relative sea-level rise (Kiden et al., 2002).

Beyond the active rivers, polar desert conditions prevailed between 29 and 16 ka. As a consequence of the extremely cold and dry climatic conditions, the vegetation cover was very limited and wind became an impor-

Constraining the age of Europe's megafaunal extinction

4

The southern North Sea is globally renowned for its very rich Quaternary vertebrate faunas. Many of the numerous fossils have been recovered during bottom trawling, a common fishing practice. In recent decades, they have also been dredged from offshore sand-extraction pits. Sand from these pits has been used for coastal reinforcements (nourishments) and for construction. Sand nourishments are an increasingly popular faunal resource to a large and active community of citizen scientists. The richest beach trajectories include those of Maasvlakte and Maasvlakte 2, two Rotterdam harbour extensions, and the Sand Motor mega-nourishment (21.5 million m^3) slightly further north. Most fossils (and Paleolithic artefacts) found there come from the Late Pleistocene Kreftenheye Formation (Amkreutz & Van der Vaart-Verschoof, 2022).

The majority of vertebrate faunal elements shown in the photo below are typical of the mammoth steppe and include species such as mammoth, woolly rhinoceros, hyena, horse and deer (Mol et al., 2006). Cold marine vertebrate taxa such as walrus, bearded seal and beluga are rare, but ecologically compatible. Fossil mollusc taxa, such as the boreal *Astarte*, are frequently found. Warm-temperate terrestrial taxa originating from interglacial Eemian intervals, such as forest elephant, rhinoceros and hippo, are poorly represented, but thermophilous marine mollusc species, including *Acanthocardia tuberculata* are common. Finally, Early and Middle Pleistocene faunas, rare on the beaches, have been trawled from the Eastern Scheldt and from some offshore areas, making the North Sea one of the most productive fossil-rich regions worldwide.

The continued collection of fossils and artefacts is contributing majorly to our understanding of late Quaternary landscapes, biotic evolution and hominin occupation of the Southern North Sea Basin (Amkreutz & Van der Vaart-Verschoof, 2022). However, difficulties of age constraining hamper detailed understanding of biotic successions. The ongoing debate on the timing and causes of the mammal extinction around the end of the last ice age invokes rapid climate deterioration and/or human overkill as primary drivers (Stuart, 2021). According to the present consensus, the timing of extinction of many taxa within western Eurasia was not sudden but spanned the entire Late Pleistocene and Early Holocene, making a single climatic driver untenable. However, direct and indirect evidence for extensive demise related to hominid hunting is extremely scarce and fails to match observed extinction patterns. Erecting a detailed and correct chronostratigraphic framework for the occurrence and disappearance of the ice-age fauna is a prerequisite to improve the understanding of the drivers of the demise of many great mammals. For this, the southern North Sea fossil record provides many opportunities.

Photo: P. Wildschut, D. Mol.

tant sediment-transport agent. In a broad area known as the European Sand Belt, sand sheets and dune fields were formed (Wierden Member, Boxtel Formation; Figs 10.12, 10.16, 10.17). These so-called coversands have been studied in detail, focussing on stratigraphic, sedimentological and palynological aspects, and have also been dated extensively by luminescence and radiocarbon methods (Kasse et al., 2007; Kolstrup, 2007; Vandenberghe et al., 2013; Bazelmans et al., 2021; Van Hateren et al., 2022). In areas farther south, including Belgium, Germany and neighbouring regions of France, loess deposits (Schimmert Member, Boxtel Formation) rather than coversands accumulated as wind-blown sediment blankets that successively colluviated (Fig. 10.4b; Meijs, 2011; Lehmkuhl et al., 2021). Pockets of loess are also known from the flanks of the central Netherlands ice-pushed ridges.

Weichselian Late Glacial (onset MIS 1)

The Late Glacial stage comprises the last interstadial and stadial of the Weichselian (14.7-11.7 ka; Fig. 10.12). The transition from full glacial conditions to warmer ones is recorded in the coversand sequence, at various well-described sites, notably those of Lutterzand (Van der Hammen & Wijmstra, 1971; Van Huissteden, 1990; Kasse, 2002; Fig. 10.17) and Usselo (e.g. Van Geel et al., 1989; Kolstrup, 2007).

These coversand records reflect both eolian deposition during cold and/or dry phases and organic beds and associated soils (with charcoal fragments) representing warmer and/or wetter times. The Usselo Soil is a characteristic Late Glacial Allerød marker horizon. It is typified by the presence of dung-beetle burrow casts (Fig. 10.18a), indicating that herds of large herbivores roamed the landscape. In wet low-lying areas, including pingo remains, organic deposits from the same age accumulated. Where preserved, they show a dominance of open vegetation with mainly herbs and grasses, and *Betula* as well as *Pinus* in favourable places. Recently, remains from a Late Glacial stand of pine forest have been uncovered in Leusden in the central Netherlands (Fig. 10.18b). Dated wood samples have Allerød and early Younger Dryas ages, suggesting that the trees did not survive the abrupt climatic and environmental shift from the mild Allerød into the cold and dry Younger Dryas Stadial (Bazelmans et al., 2021). During the second part of this last cold interval, before the onset of the Holocene, large fields of low, eolian dunes developed (upper part of the Wierden Member). These dunes are characteristic elements in the modern landscape of the eastern and southern Netherlands.

The climatic amelioration that marked the end of the Late Glacial and onset of the Holocene (ca. 15-9 ka) had a strong influence on channel styles and floodplain terraces. It is also reflected in paleosols belonging to the river valleys upstream of the Rhine-Meuse delta and those buried beneath the delta itself. In Late Pleniglacial times (up to 15 ka), the river style had been braided, with active multichannel beds up to a few kilometres wide. These saw high spring regimes of meltwater discharge generated by a hinterland with frozen subsoils, little vegetation and plenty of sediment input. Through the Late Glacial (ca. 15-12 ka), climate conditions improved overall. The permafrost disintegrated, the discharge regime changed from peaked to more regular, vegetation could become established in hinterland and floodplains, and sediment loads decreased. Most notably, the active width of riverbed reduced and the channel style was transformed from braided to meandering (Kasse, 1995; Vandenberghe, 1995; Hoek et al., 2017; Fig. 10.17). Abandoned stretches of braidplain became floodplain terrace. They silted up in a fluvial system that was increasingly meandering in nature (Wijchen Bed in the Kreftenheye and Beegden formations). Newly formed terraces stabilized after regular flooding events ceased.

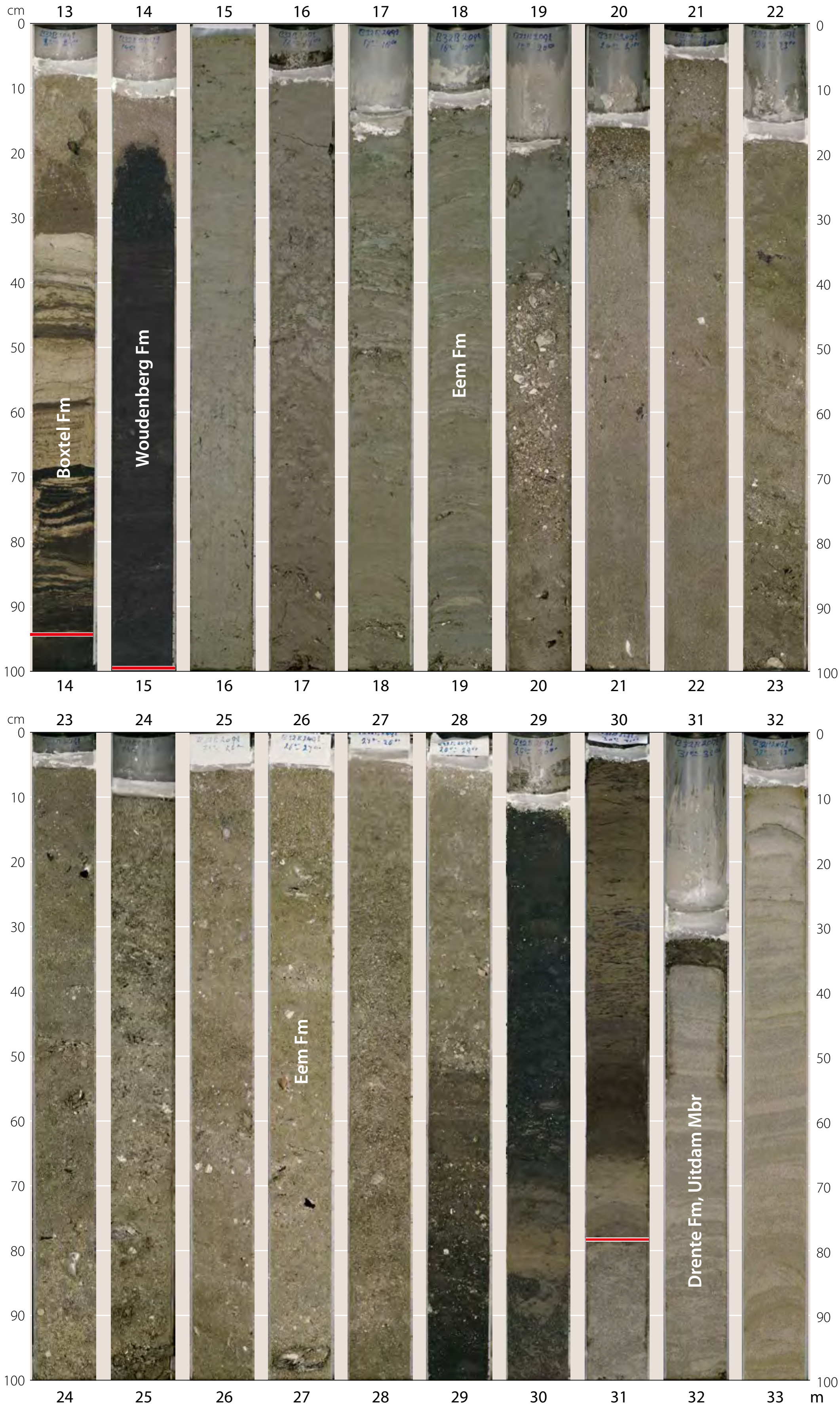
The Younger Dryas cold period (12.9-11.7 ka) initiated a temporal return to seasonally frozen subsoils, which interrupted the transformation from braided to meandering conditions, temporarily widening riverbeds that failed to reach the widths of Pleniglacial times (Fig. 10.17). These wider beds enabled wind to pick up sediment, creating inland dune systems along the rivers. Following this short break, during the onset of Early Holocene warming, the transformation to a single-thread narrow channel with a meandering style resumed (Fig. 10.17) and floodplain forests returned. The latter influenced the formation of soils on terraces and accelerated the maturation of floodplain dunes. They also contributed to further narrowing of the river course into a single channel. This situation was reached by 10.5 ka in the southeastern Netherlands Meuse Valley (Woolderink et al., 2019) and by 9.5 ka in the Rhine-Meuse Valley of the western Netherlands (Hijma et al., 2009; 2011). By that time, the Holocene was in full swing.

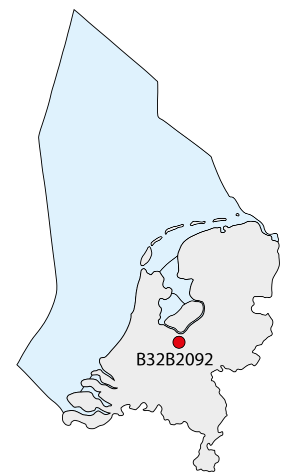
Holocene Series (11.7 ka – present)

Climate, sea level and human influence

The current, Holocene Series is a relatively stable, warm and humid interglacial that followed the cold Younger Dryas Stadial that marked the end of the Pleistocene. In and around the Netherlands, rising temperatures had a profound effect on sea level (Fig. 10.19), groundwater tables, vegetation, indigenous fauna and, importantly, the human population. Abundant evidence of this effect and of the associated changes in paleogeography has been preserved in the shallow Dutch subsurface record, both onshore and offshore.

Early on in the Holocene (Preboreal biozone, 11.7-10.6 ka, Fig. 10.12), warming was rapid. Through glacio-





Location **Amersfoort**
Borehole **B32B2092**

X 157127 **Y** 463605

2.9 m + MSL

← ***Figure 10.15.*** *Latest Saalian, Eemian and Weichselian succession in the Amersfoort glacial basin (core B32B2092; Kasse et al., 2022). Meltwater sand of late Saalian age (Drente Formation) at the base of the core is overlain by an organic unit (gyttja/peat; Eem Formation) reflecting early Eemian lacustrine situation with rising water table owing to nearby sea-level rise. The organic deposits are partly reworked and are covered by a coarsening-upward sequence of loam and fine sand, indicating a brackish to salt-water subtidal environment (the embayment shown in Fig. 10.14a). This is followed by 8 m of shell-bearing coarse-grained sand deposited under highly energetic shallow-marine conditions during the Eemian highstand. The shelly sand is separated from overlying loam and clay by a sharp boundary at 19.4 m that formed in response to shallowing or partial closure of the marine basin. The lithological transition from clay at the top of the Eem Formation to peat of the Woudenberg Formation witnesses a gradual climate cooling and the onset of sea-level fall. The subsequent change to fully terrestrial conditions at ca. 14 m depth (sandy and loamy, partly organic-rich deposits; Boxtel Formation) marks major climate cooling at the onset of the Weichselian Early Glacial. Coordinates in Rijksdriehoeksstelsel. Core photos: TNO-GDN, 2023d.*

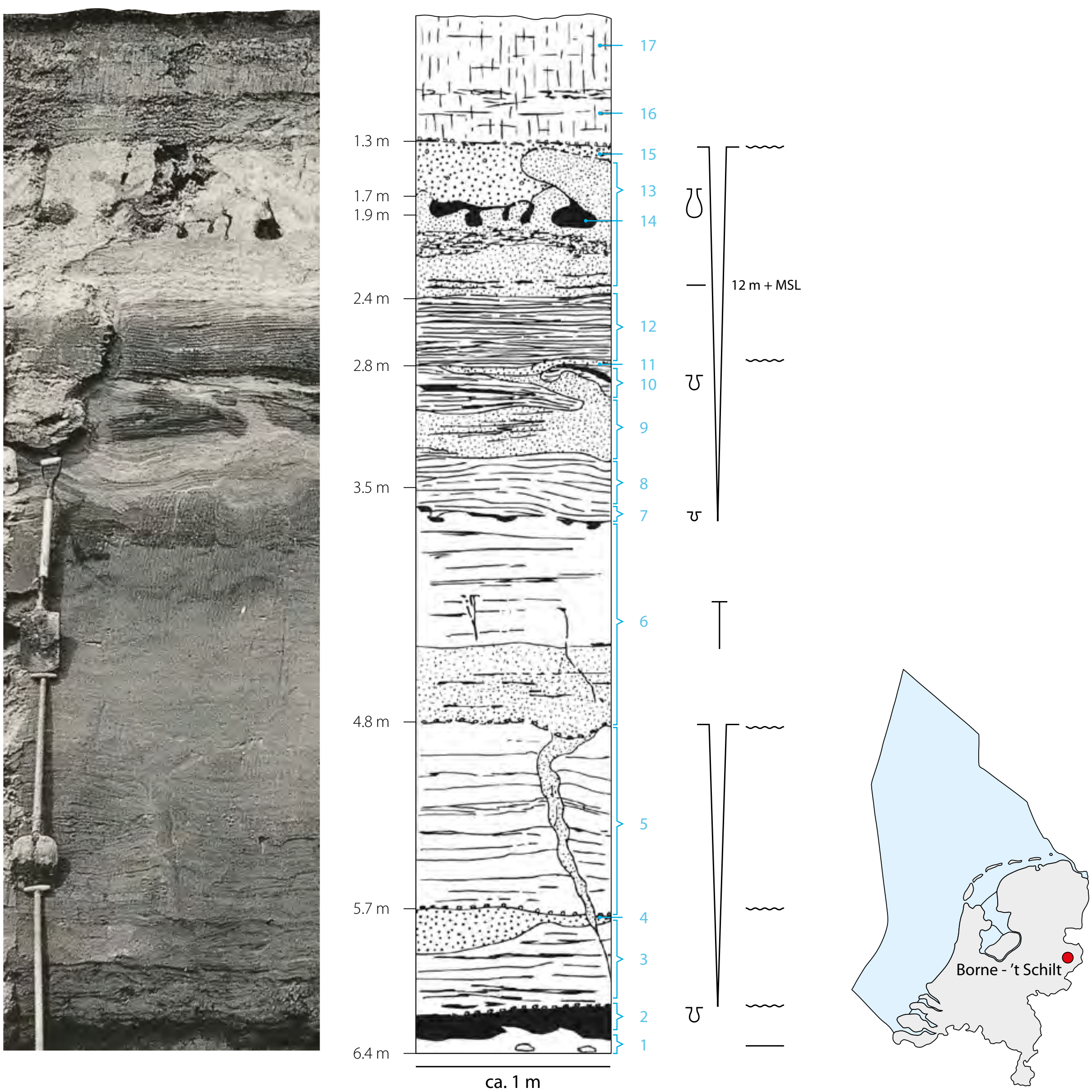


Figure 10.16. *Weichselian sedimentary sequence and associated ice-wedge casts, frost cracks and involutions in outcrop Borne-'t Schilt in the eastern Netherlands (Van den Berg & Den Otter, 1993). Left: outcrop photo; right: interpreted sedimentary log. Layer 1: Saalian glacial diamicton; 2: Eemian peat; 3-5: Early Glacial fluvial and lacustrine deposits; 6-14: Middle-Pleniglacial fluvio-eolian and lacustrine deposits; 15: Late Pleniglacial fluvial deposits, capped by a desert pavement; 16: Late Glacial eolian deposits; 17: Holocene brook deposits. Two levels with large ice-wedge casts and involutions (unit 5 and units 13-15) indicate periods of permafrost degradation at the end of MIS 4 and MIS 2, respectively.*

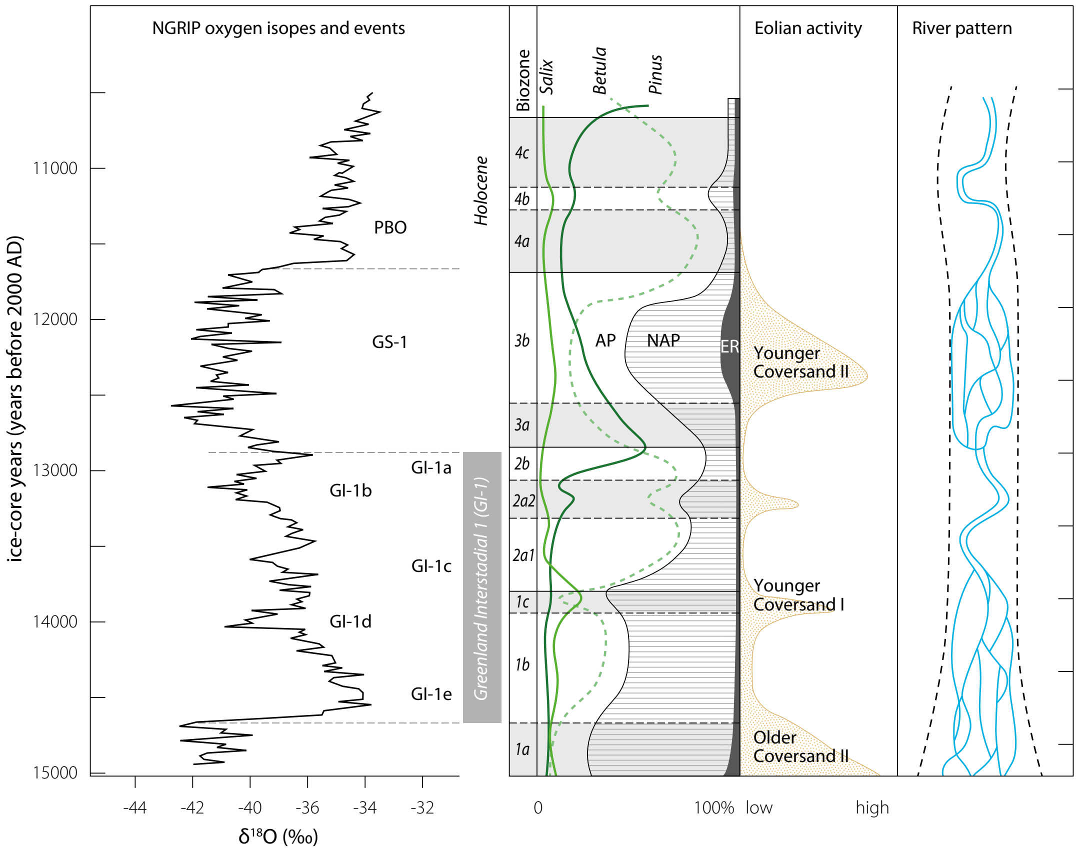


Figure 10.17. Schematic overview of Weichselian Late Glacial coversand deposition and river style changes in relation to climate and vegetation development (Hoek & Bohncke, 2002; Lowe et al., 2008; Hoek et al., 2017). NGRIP oxygen isotope record from North Greenland Ice Core Project members (2004). Biozonation according to Hoek & Bohncke (2002). GS-1 = Younger Dryas, GI-1 = Bølling / Allerød, AP = Arboreal Pollen, NAP = Non-Arboreal Pollen, ER = Ericales. Younger Coversand I + II equal the Wierden Member of the Boxtel Formation. © Cambridge University Press, reproduced with permission.

eustasy and glacio-isostatic subsidence, climate-driven deglaciation caused regional relative sea level to rise tens of metres at rates well exceeding 1 m per century. This sea-level change is recorded in basal peats that cap the Pleistocene paleosurface in many locations offshore and below the near- and onshore coastal plain. The lowest such areas of the Pleistocene landscape, more than 60 m below present-day MSL, were submerged soon after the Younger Dryas ended. By 9.2 ka (Boreal biozone, Fig. 10.12), the sea had flooded vast parts of the present marine basin, creating ample accommodation space in areas that had been erosional or non-depositional before. By 8.5 ka (early Atlantic biozone, Fig. 10.12), when relative sea level had risen to 15-20 m below current MSL, the North Sea shoreline had moved to positions close to its modern one, even landward from it at some places (Vos, 2015). The Holocene succession offshore and onshore shows effects of short-lived events superimposed on the main long-term trend: relative sea level (Hijma & Cohen, 2010) that was still rising about 1 m per century. Around 7 ka, only a few Pleistocene promontories remained along a gradually straightening coastline. By then, Doggerland, with its fertile lowlands occupying the North Sea during times of low sea level, was drowned.

The regional climate of northwestern Europe and the North Atlantic Ocean reached its natural temperature optimum by 7-6 ka (middle of Atlantic biozone, Fig. 10.12). Lowland organic deposits (e.g. lake muds), fine-grained Rhine-Meuse channel fills and buried paleosols as well as upland peat bogs provide spatially consistent records of climate change impacting shallow groundwater systems as well as surficial drainage (e.g. Hoek & Bohncke, 2002; Makaske & Maas, 2023).

By 6 ka, climate-driven deglaciation had ceased and climate variability as such stopped being a major factor in landscape and depositional change. With eustatic sea-level rise no longer a principal influence, only tectonic subsidence and compaction continued to affect regional sea level. Decelerating but persistent relative sea-level rise, governed mainly by remnant glacio-isostasy remained to drive the establishment of the Dutch coastal plain. Its indirect influence on sediment supply, especially from the eroding shoreface, explains the south-to-north diachronic turnovers between transgressive and regressive phases in coastal behaviour. As inlets opened and closed, and tidal basins expanded and filled, adjacent coastlines adjusted accordingly. An anastomosing network of meandering and straight river branches supplied sediment on the landward side of these tidal basins, repeatedly triggering avulsions (Törnqvist, 1993; Hijma et al., 2011; Stouthamer et al., 2011). Extensive peatlands covered ever larger tidal and fluvial areas with poor drainage conditions. Seaward of the steepening shoreface, fully marine processes became dominant, with tidal ridges and sand waves occupying extensive areas of residual sand transport.

Around 5 ka (early Subboreal biozone, Fig. 10.12), the rate of relative sea-level rise had dropped to 0.15 m per century. A further reduction to just a few centimetres per century followed in the Late Holocene. This overall deceleration is reflected in the depositional record of the onshore coastal prism (Fig. 10.19): a wedge-shaped sediment body that extends from the lower shoreface to the landward edge of marine or lowland fluvial (Rhine-Meuse and Scheldt) influence and is typically thickest near the present-day coastline. Along with spatiotemporally varying sediment supply and human influence, even this modest sea-level change has been an influential driver of sedimentation and erosion.

Agriculture and the associated deforestation commenced in the Netherlands by 7.5 ka (Neolithization, Louwe Kooijmans, 2005), spreading westward from the eastern and southeastern entry points of Rhine and Meuse. It influenced flow regimes and riverbank vegetation along distributaries that formed and decayed in response to avulsions. By 5 ka, agriculture was also practiced close to the contemporaneous coastline, on innermost beach ridges and in the lowland delta plain. Along small-scale rivers, it even spread northeast into extensive upland with less fertile substrate. After 3.5 ka (Bronze Age), when forest clearing intensified and ploughing was introduced in the Rhine-Meuse hinterlands, sediment loads of these main rivers began to increase. Around 2 ka (Roman times), they carried twice as much suspended sediment compared to their natural states before (Hoffmann et al., 2007), dramatically increasing deposition in estuaries and along rivers, and triggering major channel-network alteration downstream and upstream in the delta (Stouthamer et al., 2011; Pierik et al., 2017b; 2018b). Simultaneously, digging of ditches to drain coastal-plain bogs and reclaim peatland for agriculture increased (Van Bergen & Kosters, 2025, this volume). This resulted in peat loss, in the coastal plain as well as inland. Part of the deforestation-related mud ended up covering depressions that formed by excavation and oxidation of peat. Around 1 ka (medieval times), people started to construct interconnected dykes along the rivers, tidal inlets and lagoon shores. This strategy fixed the channel network of the delta and its tidal river mouths and stopped deposition in large former flood-basin areas. Relatively narrow embanked floodplains remained along the delta rivers. Greater volumes of mud were carried fur-

Figure 10.18. a) Usselo soil at a key site in Doorn (Photo: J. Schokker). b) Excavation trench in Leusden-Den Treek with exceptionally well-preserved Late Glacial pine-tree remnants (Bazelmans et al., 2021). Photo: RCE/J. Bazelmans. The pine-tree remnants are covered by eolian sediments (Younger Coversand II; see Fig. 10.17). See inset map for locations.

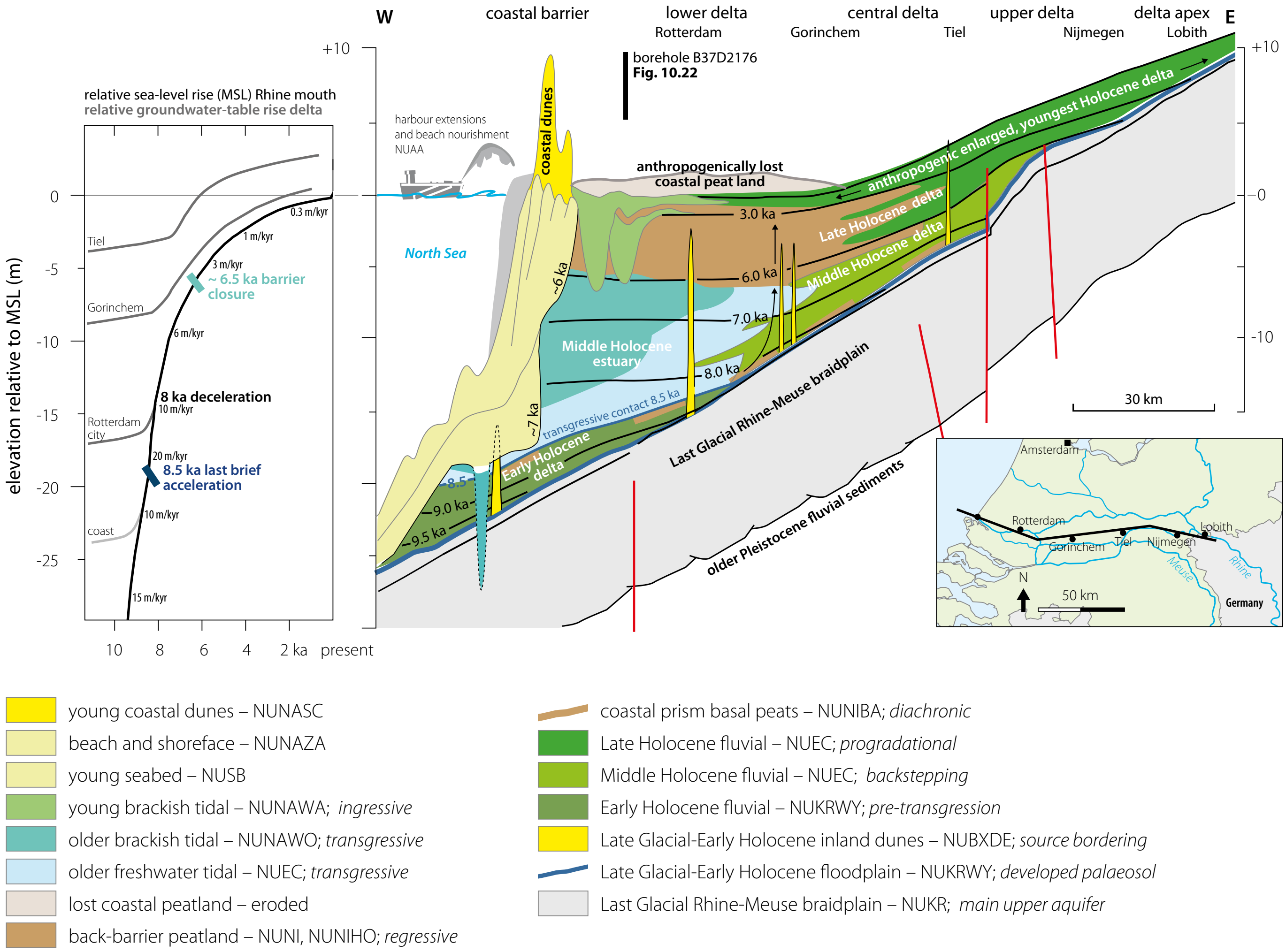


Figure 10.19. Longitudinal architecture of the Holocene coastal prism, showing the infill of the main fluvial basin in response to changes in relative sea-level rise. Left panel plots Holocene relative sea-level rise at the Rhine mouth and coeval groundwater-table rise in the delta inland (modified from Hijma & Cohen, 2011). Because the seaward reaches of shoreface sediments (NUNAZA) are difficult to distinguish from young seabed sediments, they are denoted in the same colour.

ther downstream than before and were delivered to estuarine reaches where the fine sediment settled in narrow zones between channels and dykes. Since the twentieth century, man-managed volumes of relocated sediment (dredging, nourishment, building) in the urbanized lowlands and its waters have grown substantially, outweighing natural sediment transport.

Sedimentary systems and paleogeography

To describe and explain the preserved Holocene record, we subdivided the Dutch Holocene sequence into three domains with differing lithostratigraphic sequence types, Pleistocene topography and substrate lithology: the offshore, onshore lowland/coastal, and onshore upland (Fig. 10.20). This tripartition is clearly visible on the recently published Geological map of the Netherlands (TNO-GDN, 2023d).

The offshore domain is dominated by open-marine units that are part of the Southern Bight and Urania formations. They occur either directly on top of Pleistocene or older sediments, or are separated from these sediments by a mostly reworked tidal sequence (Naaldwijk Formation) with a local peat bed (Basisveen Bed, Nieuwkoop Formation). See Figures 10.12 and 10.19 to 10.22.

The lowland/coastal domain is dominated by a very large Middle- to Late Holocene coastal prism that extends across roughly half of the country (Naaldwijk, Nieuwkoop, Echteld and Kreekrak formations; Fig. 10.12). The coastal prism can be further divided into a southwestern (Zeeland province), central (Holland coast and back-barrier areas including the Rhine-Meuse delta and central Netherlands lagoon) and northern part (Wadden Sea and coastal plain). Its predominantly wave-formed and tidal sediments (Naaldwijk Formation) cover and alternate with

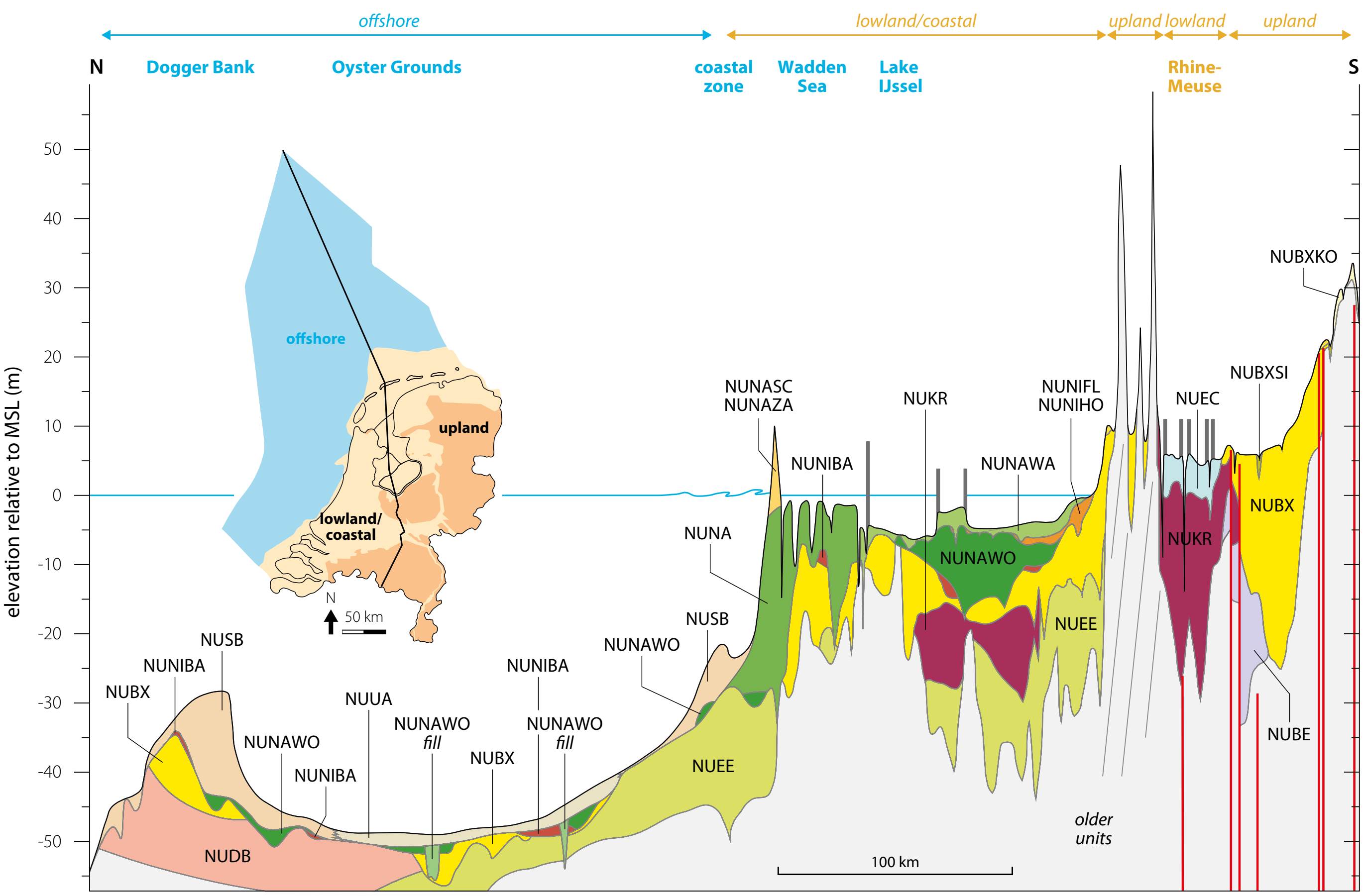


Figure 10.20. Section from the northernmost point in the Dutch part of the North Sea to the Pleistocene upland at the south-central border with Belgium (see inset map for location). It shows a bipartition of depth settings for the Nieuwkoop and Naaldwijk formations between the offshore and lowland/coastal zones. In places such as below the Wadden Sea, where the Wormer and Walcheren members are directly stacked and the Hollandveen Member is missing, these clastic tidal units are grouped in the Naaldwijk Formation (undifferentiated). See Table 10.1 for explanation of lithostratigraphic codes.

extensive horizons of peat (Nieuwkoop Formation). Near the coast, fluvial influence is mostly limited to indirect, estuarine imprints. Moving inland, the prevalence of riverine deposits (Echteld Formation of Rhine-Meuse origin; Kreekrak Formation of Scheldt origin) increases, but their total volume is an order of magnitude smaller than that of the Naaldwijk Formation (Figs 10.19, 10.20).

The Holocene depositional volumes in the upland domain are minor compared to the offshore and lowland/coastal domains. They comprise sediments of brook valley systems (Singraven Member, Boxtel Formation) and sand drifts (Kootwijk Member, Boxtel Formation), the Rhine-Meuse System (youngest parts of Beegden and Kreftenheye formations), and inland peats formed by blanket bogs (Griendtsveen Member, Nieuwkoop Formation; Fig. 10.12). Because they contain abundant organic indicators of climate and paleoenvironment, easily datable soils and paleosols are an especially informative part of the Holocene geological record (TNO-GDN, 2023a).

Onshore, the subsurface record is complete enough to enable high-resolution paleogeographic mapping (Berendsen & Stouthamer, 2001; Vos et al., 2020 ; Fig. 10.23) and detailed reconstruction of the changing depositional settings (Beets et al., 1996a). Offshore, the Holocene succession is more fragmentary and is dominated by open-marine units that overlie heavily eroded coastal deposits or Pleistocene substrate.

Early Holocene (Greenlandian: 11.7-8.2 ka)

Aside from inland depositional activity independent of rising base level, the first unit that started developing in the Early Holocene was the Basisveen Bed, reflecting a rising water table. It was soon followed by the Wormer Member (Naaldwijk Formation) with its early lagoonal clay (Velsen Bed), heterogeneous tidal-channel fills and muddy tidal-flat deposits. Offshore, these units are located as deep as 65 m below MSL. They cap terrestrial surfaces of land where hunter-gatherer populations lived, known as Doggerland, where a hunter-gatherer population lived (Coles, 1998; Amkreutz & Van der Vaart-Verschoof, 2021). This was the first area in present-day Dutch territory to be affected by postglacial transgression. In just a few thousand years, 11.7-8.5 ka, the expanding North Sea left a transgressive record of extremely rapid water-table and sea-level rise (Figs 10.19, 10.20, 10.21).

In seaward parts of the coastal lowland, the Early Holocene sequence indicates that incipient aggradation was being initiated as base level started to rise, even before the sea reached this area (Fig. 10.19). As they flooded, four Weichselian drainage basins of different size (from south to north: Lower Scheldt, Rhine-Meuse, Vecht and Boorne-Hunze areas) began to fill up. Intact sections of the sloping Pleistocene paleosurface are capped by peat (Basisveen Bed). Profiting from its diachronous nature, this peat has been dated to reconstruct water-level rise and marine submergence (e.g. Van de Plassche, 1982; Hijma & Cohen, 2019). Its compositional variability is used to distinguish brackish, freshwater and rainwater-fed environments in paleogeographic mapping. Commonly thick tidal facies of the Wormer Member (including Velsen Bed; Fig. 10.20), with alternating sand and mud, overlie and incise much of this peat as well as some of the Pleistocene underlying it.

The fluvial lowland record further inland is mostly limited to the Rhine-Meuse Valley (Berendsen & Stouthamer, 2001; Hijma & Cohen, 2011). The Late Glacial transition in river style, with its width reduction and regime change, continued. It was completed in the Early Holocene and the eventual meander belts occupy only a small area of the ice-age braidplain width (Hijma et al., 2009; Woolderink et al., 2019). Multiple immature paleosols are part of a fine-grained floodplain succession associated with the newly established meandering channel system (Wijchen Bed; Figs 10.12, 10.19, 10.22; see also photo at beginning of this chapter). Deeper than ca. 5 m below MSL, this unit is typically capped by the Basisveen Bed (Figs 10.19-10.22). The basal peats of the Rhine-Meuse delta are woody and clayey and formed in the freshwater-dominated flood basins of rivers. Eutrophic reed peats and mesotrophic sedge peats are dominant further away from contemporaneous channel systems (Bos et al., 2012).

The uplands underwent little activity limited to small rivers and brook systems (Singraven Member , Boxtel Formation), aside from soil formation at the undulating Late Pleistocene surface.

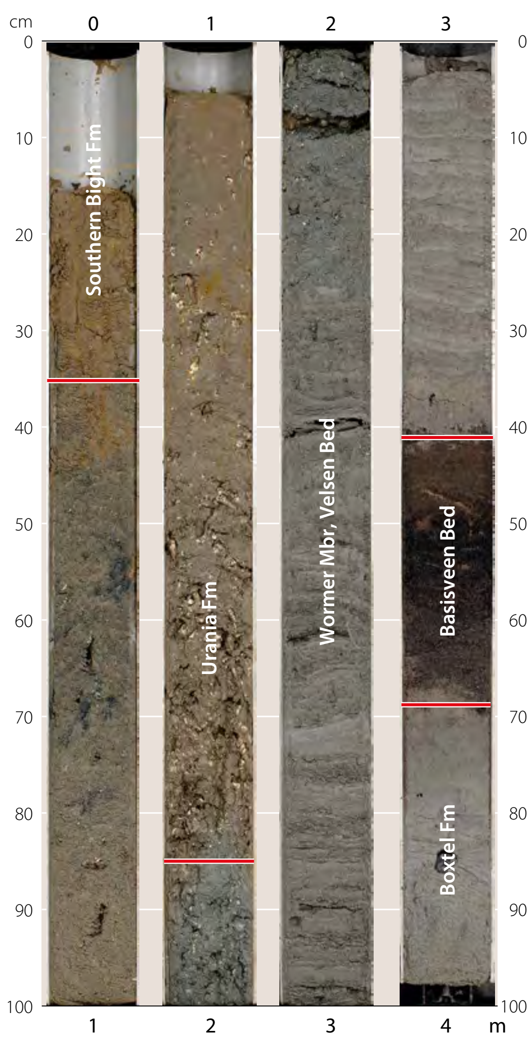
Middle Holocene (Northgrippian: 8.2-4.2 ka)

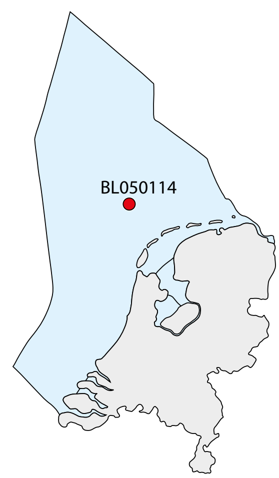
Offshore, the Middle Holocene was dominated by ravinement through wave and tidal action impacting the drowned Pleistocene land surface. Many of the Early Holocene sediments were reworked along with the top of the underlying Pleistocene (Fig. 10.20). This process left a spatially variable lag deposit enriched with shell and local gravels, depending on the nature of the eroded sediment. Gravel-rich lags (Indefatigable Grounds Member, Southern Bight Formation) overlie glacigenic units at the Cleaver Bank and offshore Texel, the southernmost Wadden island. Gravel-bearing lags rich in shells and shell fragments (Buitenbanken Member, Southern Bight Formation) occupy a southwest-northeast belt extending from the Belgian sector up to the Rhine-Meuse mouth, indicating reworking of Late Pleistocene Rhine-Meuse deposits. Shelly lags with local peat and clay pebbles (base of the Bligh Bank and Terschellinger Bank members of the Southern Bight Formation), widespread elsewhere, represent reworking of both Pleistocene sands and gravel and Early Holocene transgressive clay, sand and peat. As the North Sea bathymetry and tidal circulation approached their highstand equilibrium, by 6 ka, large parts of these lag deposits were being covered in turn by open-marine sand with a much lower shell content (Bligh Bank and Terschellinger Bank members). Ever since their formation, the variable thickness of these units has been a function of sand-wave and megaripple migration in response to (residual) tidal transport and combined wave-current flow.

In the lowland/coastal domain, an extensive coastal prism grew by 9.0-8.0 ka during Middle Holocene time (Beets & Van der Spek, 2000; De Haas et al., 2019), in the southwestern and central sectors, and by ca. 7.0 ka in the north (Kiden et al., 2002; Hijma & Cohen, 2011; Vos, 2015; Meijles et al., 2018). Incipient barrier shorelines and back-barrier plains developed from 8.5 ka onward (Rieu et al., 2005; Fig. 10.19). The general succession for this phase – seen in all transgressed drainage systems and the southwest, centre and north alike – was that of a landward-migrating transition from incipient, freshwater-dominated terrestrial wetlands with low-energy conditions (fens, fringes of inland lagoons: with formation of Basisveen Bed) to increasingly dynamic inter- and subtidal environments in brackish and saline estuaries and tidal basins. These basins were connected to tidal inlets with direct marine influence (Wormer Member). In the lower Rhine-Meuse, a phase of tidally influenced freshwater conditions left transgressive subaqueous muds (Echteld Formation) wedged between wetland peats at its base and brackish estuarine clastics on top (Figs 10.19, 10.20). Near the coastal barrier, Middle Holocene tidal basins were deepest, and tidal channels developed where tidal sediment import was largest, allowing development of fully saline tidal-flat sand and mud complexes (Wormer Member; Figs 10.19-10.22, 10.23a). Because of growing tidal prisms, partly associated with increasing tidal range, the share of sand in these deposits increased. Simultaneously, the barrier complex matured into widening and lengthening barrier spits, no longer backstepping and with modest eolian dune capping. The narrow oldest preserved beach barriers of this stage mark the inland fringe of the Holland coastal barrier complex (central sector). They may have had counterparts in the southwest but the latter have been lost to Late Holocene erosion. It is likely that counterparts in the north never existed. Under continued transgression, this part of the barrier coast matured into an island chain rather than an elongated amalgamated barrier complex.

In the millennia that followed the initial establishment of the barrier complex, adjacent beach-dune sections and associated back-barrier areas underwent complex diachronous development, with different architectural outcomes. In the southwestern and central sectors, back-barrier accommodation space had filled with tidal and fluvio-tidal sediments by 6.0-4.0 ka: sediment supply was rapidly catching up with decelerating sea-level rise. This occurred contemporaneously with a switch from retrogradational to progradational shoreline behaviour. Accretion of beach ridges widened the barrier complex (Zandvoort Member, Naaldwijk Formation). The transition from transgressive to stabilized and regressive overall conditions affected the barrier and back-barrier areas and was not a synchronous event. It dates back to 7.0-6.5 ka in the southwest and the Rhine-Meuse mouth (Figs 10.19, 10.23b), and to 4.0 ka in northwest-central (Bergen inlet) section. A switch between transgression and regression never materialized in the northern sector (Wadden Sea), which ended up being stabilized by man.

In the central sector, the accreting barrier complex widened to several kilometres and thickened to some 20 m between 7.0 and 4.0 ka (Fig. 10.19). The cross-sectional areas of tidal inlets decreased in response to an interplay with tidal-prism reduction and the associated filling of tidal basins (youngest parts of the Wormer Member). Upon tidal-inlet closure through spit accretion, tidal basins transformed into increasingly sheltered salt marshes and freshwater coastal-plain peatlands, favouring development of the Hollandveen Member (Nieuwkoop Formation; Fig. 10.22; Beets & Van der Spek, 2000; see also Van Bergen & Kosters, 2025, this volume). Aided by poor drainage, peat gradually grew to about 1 m above contemporaneous mean high-tide level. Eutrophic and mesotrophic reed and sedge peat had the upper hand early on, but over time, woody peat started to develop in areas of the lower Rhine-Meuse delta and the central delta interior (Fig. 10.19), as





Location **Oyster Grounds**
Borehole **BL050114**
X 598814 **Y** 5955857 39.6 m - MSL

Figure 10.21. *Core from the Oyster Grounds in the offshore domain, showing the Basisveen Bed followed by lagoonal clay of the Velsen Bed, indicating Early Holocene submergence of the Pleistocene surface (top Boxtel Formation). Coordinates in UTM31-WGS84. Core photos: TNO-GDN, 2023d.*

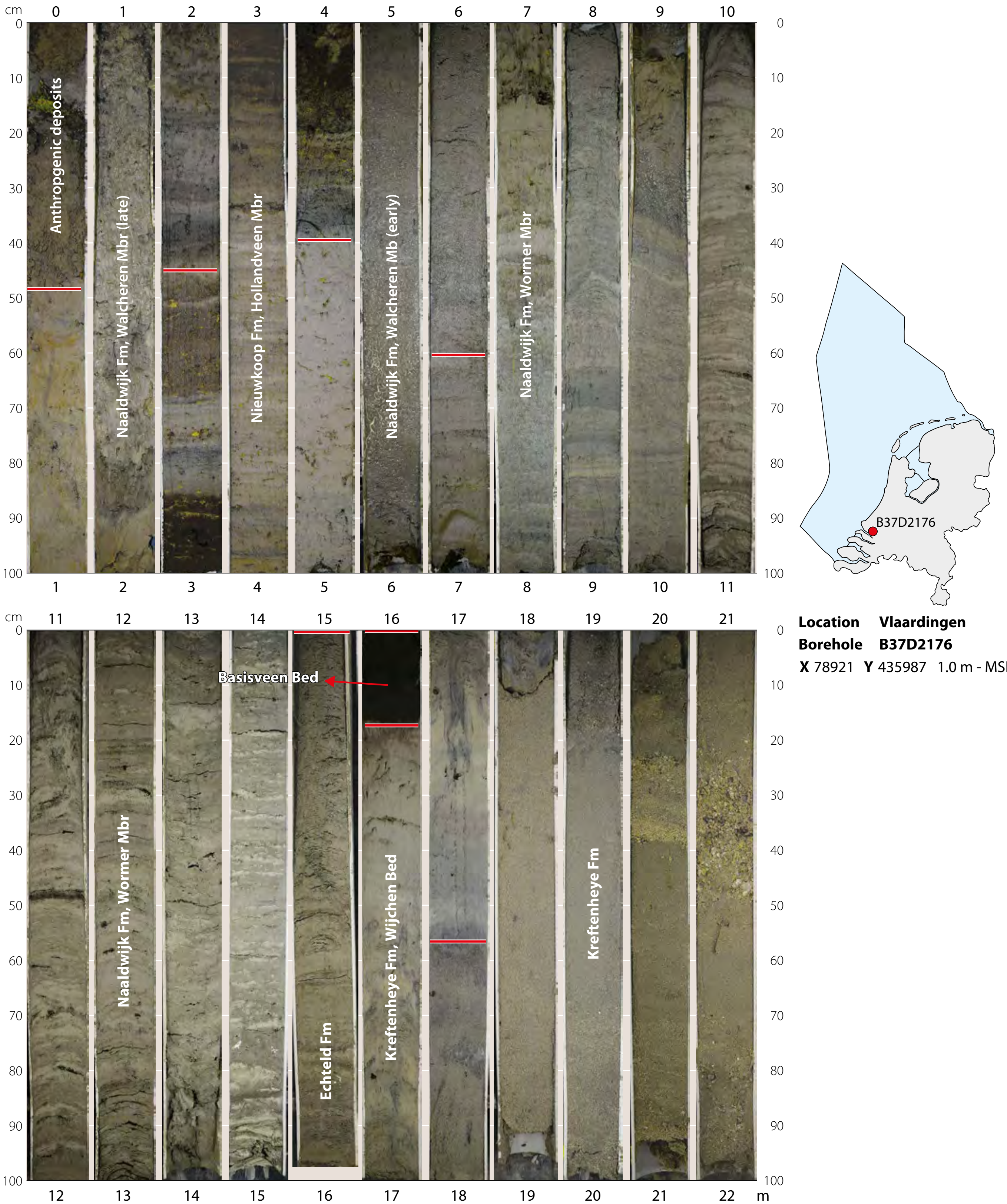


Figure 10.22. Core from the central coastal lowland, showing the Basisveen Bed that marks submergence of the Pleistocene upland (Kreftenheye Formation). The overlying Naaldwijk Formation shows distinct phases in Holocene tidal-basin development. Coordinates in Rijksdriehoeksstelsel. Core photos: TNO-GDN, 2023d.

arboreal wetlands replaced reed marsh and sedge fens (Van Asselen et al., 2017). Sizable fen-rimmed, peat-calving lakes also developed, particularly in the north-central Netherlands (Pons & Wiggers, 1960). Part of the eroded material accumulated nearby as organic detritus (Flevomeer Bed, Nieuwkoop Formation).

The barrier-island chain and large tidal basin of the Wadden Sea shows that the northern shoreline did not become regressive. When by 5.0 ka sea-level rise reduced to background rates (higher in the Wadden Sea than farther south because of differential subsidence regimes), the island chain occupied a position just a few kilometres north of its current position (Oost et al., 2012). Cyclic sediment exchanges between open sea and tidal basin have since kept most inlets open. Barrier configuration has been governed by longshore as well as ebb- and flood-tidal currents and storm-related overwash, and was constrained by inlet positions, island heads and tails (a function of substrate lithology and paleotopography). Continuously rejuvenating islands shifted slowly to their current positions (Fig. 10.23b). Rather than changing into ubiquitous peatland, the Wadden Sea back-barrier tidal basin remained open. In the Late Holocene, it would even increase in size in the northwest.

Early in the Middle Holocene (8.5-6.0 ka), development of the Rhine-Meuse delta was characterized by repeated backstepping, with an important role for avulsions triggered by downstream sea-level rise (channel belts in the Echteld Formation). Thereafter, backstepping lessened and was replaced by nodal avulsion (6.0-3.0 ka), in response to decelerating sea-level rise and coastal barrier development (Stouthamer et al., 2011). Longitudinally, the inland apex of the delta established itself in the east-central Netherlands (Fig. 10.19). In both planform and cross-section, the avulsions left an anastomosing mosaic of cross-cutting channel-belt units embedded in flood-basin clay and woody peat (Törnqvist, 1993). Local lacustrine gyttja and sandy crevasse splays formed as well (Echteld Formation). A major avulsion, commencing at 6.3 ka, shifted the main Rhine branch from its original southerly mouth that was shared with the Meuse to an independent one with a more northerly position (Fig. 10.23a,b). This new branch steadily developed into a progradational tidal river mouth, with sandy promontory beach ridges adhering to the originally linear coastal barrier, and a small pro-deltaic muddy body forming just offshore (Naaldwijk Formation). Throughout the delta, the assemblage of sandy channel systems, clayey proximal overbanks and peaty intercalated beds has been radiocarbon-dated extensively. Extensive ^{14}C-dating has documented the activation and deactivation of avulsing channels through time (Cohen et al., 2012). It has enabled a separate characterization of developments in main river-trunk channels and secondary distributaries. The excellent dating record has also been crucial in the development of similarly constrained chronologies for flood-basin environmental evolution and prehistoric occupancy (Berendsen & Stouthamer, 2001; Louwe Kooijmans, 2005; Toonen et al., 2012; 2015; Van Asselen et al., 2017).

Beyond the coastal plain and the Rhine-Meuse floodplain, above the contemporaneous mean high tide and independent of sea level, extensive fenlands and bogs blanketed the Pleistocene topography in areas of poor drainage, groundwater seepage and early deforestation. Mesotrophic sedge peat formed in the lowest parts of brook valleys and in seepage zones, oligotrophic moss peat accumulated on topographic sills in the inherited Pleistocene relief (Griendtsveen Member, Nieuwkoop Formation). The few remnants of peat developed in these wet upland environments are much less widespread than fluvial deposits of local streams (Singraven Member) from the same Middle Holocene times.

Late Holocene – the dawn of human impact (Meghalayan: 4.2-1.5 ka)

Onshore in the lowland, tidal-inlet evolution continued to have a strong influence on erosion and deposition in the northwest and north, while from about 3 ka onwards avulsions and estuarine development altered the Rhine-Meuse delta network majorly once again. Fluvial and tidal channel systems tend to be wider than their Middle Holocene counterparts, owing to relative longevity at a time of stable sea level. Peat continued to accumulate, both in the coastal plain and in the upland. At its peak, almost half of the Netherlands was peatland. In the back-barrier area of the southwestern, western and northwestern plain, freshwater wetland thrived, especially in areas away from established main channels and behind a seaward-growing coastal barrier that impeded the landward flow of saline groundwater (Fig. 10.23b,c). Reed and sedge peat formed mainly in tidal basins and estuaries, woody peat in riverine environments, and moss peat where groundwater had no influence. Domes of this oligotrophic peat, with local stands of oak, reached up to 3 m above regional water level. In the north, peatlands were formed inland from the Wadden Sea and were separated from intertidal back-barrier areas by a brackish supratidal salt-marsh zone (Vos, 2015; Vos & Knol, 2015).

From about 2.5 ka onward, intensifying human presence and especially peatland cultivation started to leave its mark in the coastal record (Van Bergen & Kosters, 2025, this volume). Swamp forests situated on peaty substrates and separating freshwater-dominated tidal rivers from boggy coastal-plain interiors, were cleared for timber and fuel, while ditches were dug to drain these lands for agriculture (Van Dinter, 2013; Pierik et al., 2018b). With the natural levees cultivated and cleared of forests, and dykes not yet in place, floodwaters could invade the cleared and drained lands deeper and more frequently than before. This resulted in the blanketing of fringes of Middle- to Late Holocene coastal and deltaic peatlands with clays: brackish tidal in the west (Walcheren Member, Naaldwijk Formation) and fluvial in the central delta (Echteld Formation) (Figs 10.19, 10.22). Feedback processes involving intruding tidal channels and retrograding lakeshores, as well as human peat extraction for salt and fuel, eroded and removed considerable parts of Late Holocene peat stock and this was further exacerbated by later land use in polders.

The progradational shoreface and beach-ridge system of the Holland coastline in the western Netherlands reached a width of more than 10 km during the Late Holocene (Fig. 10.23c). Radiocarbon dating of shells in beach and shoreface facies has made it possible to reconstruct this growth in detail (Beets et al., 1992; Cleveringa, 2000). Early during the progradation phase, marine scouring was able to remobilize sand from a wide zone of drowned, gently sloping Pleistocene substrate that was still well within reach of waves. As the coastline migrated seaward, this zone of erodible sediment became narrower and shoreface slopes steepened. Because of later erosion, older parts of the regressive wedge have been preserved more completely than younger and thus more seaward ones. The sequence is dominated by shoreface facies but also includes associated beach facies, both belonging to the Zandvoort Member (Figs 10.19, 10.20) and an eolian cap (Schoorl Member, Naaldwijk Formation). It is particularly complete and informative at the mouth of the Middle to Late Holocene Rhine that was gradually abandoned and simultaneously sanded up between 2.0 and 1.0 ka (Van de Plassche, 1982; Beets & Van der Spek, 2000; De Haas et al., 2019). In between subparallel supratidal beach ridges that mimic former coastlines, linear swales accommodated marshes that filled the lows with clayey tidal deposits and peat.

Barrier widening affected the width of remaining tidal inlets downdrift to the north (Fig. 10.23c). There, previously large tidal basins shrunk and silted up, and adjacent coastal peatland expanded across increasingly vegetated tidal flats (Pons & Wiggers, 1960; Beets et al., 1996b; Vos, 2015). Closure of the originally major Bergen inlet occurred around 3.5 ka, as is evident from barrier-spit remnants and a clayey tidal-inlet fill (Bergen Bed, part of the Wormer Member). After this, the only remaining interruptions of the Holland coastal barrier were the outlets of Meuse and Rhine and the Oer-IJ inlet west of Amsterdam. This latter inlet formed a western connection between lowland lakes and small rivers in the central Netherlands and the North Sea. Other local rivers with catchments in the eastern Netherlands had rerouted northward to the Wadden Sea when the Bergen inlet just north of the Oer-IJ began closing. They drained into the North Sea through the Vlie tidal inlet just north of Texel. From 3.0 ka onward, this inlet gradually increased its influence, servicing a tidal basin that enlarged into the central Netherlands (Fig. 10.23c), thus tapping into the lagoon-like peat-fringed freshwater lakes that had been depositing organic detritus (Flevomeer Bed; Fig. 10.20). Around 2.0 ka, the Oer-IJ inlet closed off naturally, its demise being expedited when the central peat lakes connected to the Vlie inlet captured discharge. From 3.0 to 2.0 ka, these lakes had grown and become interconnected, receiving water and sediment from a minor Rhine branch (Angstel-Vecht, ca. 2.6 ka; Bos, 2010). From 2.0 ka onwards (Vos, 2015), freshwater lacustrine conditions made way for increasingly brackish circumstances (Fig. 10.23d) with deposition of fine silts and humic clays (Almere Bed, Naaldwijk Formation).

Also around 2.0 ka, barrier erosion and shoreline retreat commenced along the Holland coastline of the central sector, following an earlier shift towards transgression in the southwest (Beets & Van der Spek, 2000). This new behaviour stood in marked contrast to the barrier widening observed over millennia before. Shoreface deepening and steepening narrowed the source area where wave-base orbitals could harvest Pleistocene sand, while decreases in the efficiency of longshore sediment supply were an additional cause for the change. In the southwest, the shoreline has been set back the strongest (Fig. 10.23cd), with no surviving direct evidence for prior prograding barriers (Vos, 2015). Pleistocene sand sources below the shoreface in the southwest were reworked and exhausted earlier than in the central sector, and the Middle to Late Holocene barrier system may have been a comparatively narrow complex anyway. More importantly, southwesterly shoreface sands were gradually cannibalized by northward-directed longshore currents to supply the more prominent Holland barrier, adding to sediment brought along by local waves and by the Rhine and Meuse. Despite this barrier cannibalization and retreat, the southwestern coastal plain was continuously protected by a narrow barrier from 4.2 to 1.5 ka, with just a single small river outlet of the Scheldt (Fig. 10.23c). A vast back-barrier peatland produced enormous volumes of organic deposits (Hollandveen Member) up to ca. 1.5 ka (Vos, 2015; Pierik et al., 2017a).

In the north, the Wadden Islands system matured during the Late Holocene, migrating landward (Zandvoort Member) over a Middle Holocene back-barrier depositional substrate (Naaldwijk Formation; Fig. 10.20). Crescentic complexes of coastal dune ridges also form a substantial part of the barrier islands (Schoorl Member). The back-barrier tidal basin continued to grow as the northwesterly Vlie inlet reached southward and connected to more and more peat lakes in the central Netherlands (Fig. 10.23c). Other Wadden Sea inlet systems also developed ingressions into coastal-plain fenlands, in part eroding and in part burying their peat with clastics (Walcheren Member). Dwelling mounds show that this development was coeval with human settlement and cultivation of supratidal terrain (Vos & Knol, 2015).

With respect to avulsion history and sedimentation, Late Holocene development of the Rhine-Meuse delta and estuaries contrasted with the Middle Holocene (Gouw & Erkens, 2007; Stouthamer et al., 2011). Up to 3.0 ka, avulsions mainly affected short-lived secondary channels in the central delta. These secondary channels rejoined established tidal outlets of the northerly Rhine and southerly Meuse, and did not affect the main discharge routing. Between 3.0 and 1.5 ka, the frequency of avulsions increased. First, central-delta avulsions created Rhine distributaries (Linge and Merwede Rivers) that connected to the Meuse estuary (Rotterdam), and upper-delta avulsions (Nederrijn River) stepped back the delta apex (Fig. 10.19) to the modern position (Fig. 10.23c,d). This development is associated with volumetrically doubled deposition of fine sediment in response to increased anthropogenic hinterland supply. Consequently, the deltaic Rhine-Meuse deposition (Echteld Formation) expanded downstream *and* upstream, as did estuarine deposition in the Meuse estuary (Walcheren Member). After 2.0 ka a second wave of avulsions created three further Rhine connections to the Rotterdam estuary (central delta: Waal; lower delta: Lek and Hollandse IJssel) and a new northward one (delta apex: Gelderse IJssel). Of these avulsions, the ones in the lower delta were due to pre-embankment human impacts in the lower and central delta itself (Pierik et al., 2018b). Avulsions in the central delta and apex are attributed to increased sedimentation, with additional influence of flooding regime and inherited topography (Cohen et al., 2009; Pierik et al., 2017b). They strongly diminished discharge to the former Rhine outlet, and its promontory of beach ridges eroded quickly.

The sandy uplands of the Late Holocene were gradually deforested. The terrain was turned into arable land (Celtic Fields). Upon exhaustion, it was either abandoned to let secondary forests appear, or was left overgrazed to develop short-lived dune fields of drift sand (Kootwijk Member; Pierik et al., 2018a), heaths and peat bogs. Once established, these mossy peat bogs (Griendtsveen Member) tended to expand gradually across larger plateaus and drainage divides (Quik et al., 2023), but little remains today. Sedge peats were topographically more constrained, accumulating locally over seepage areas and in overgrown brook valleys, as well as more regionally along the rim of the coastal plain. Paleoenvironmental key records contained within remnant bog peats indicate that climate became cooler and wetter around 2.8 ka (Van Geel et al., 1980).

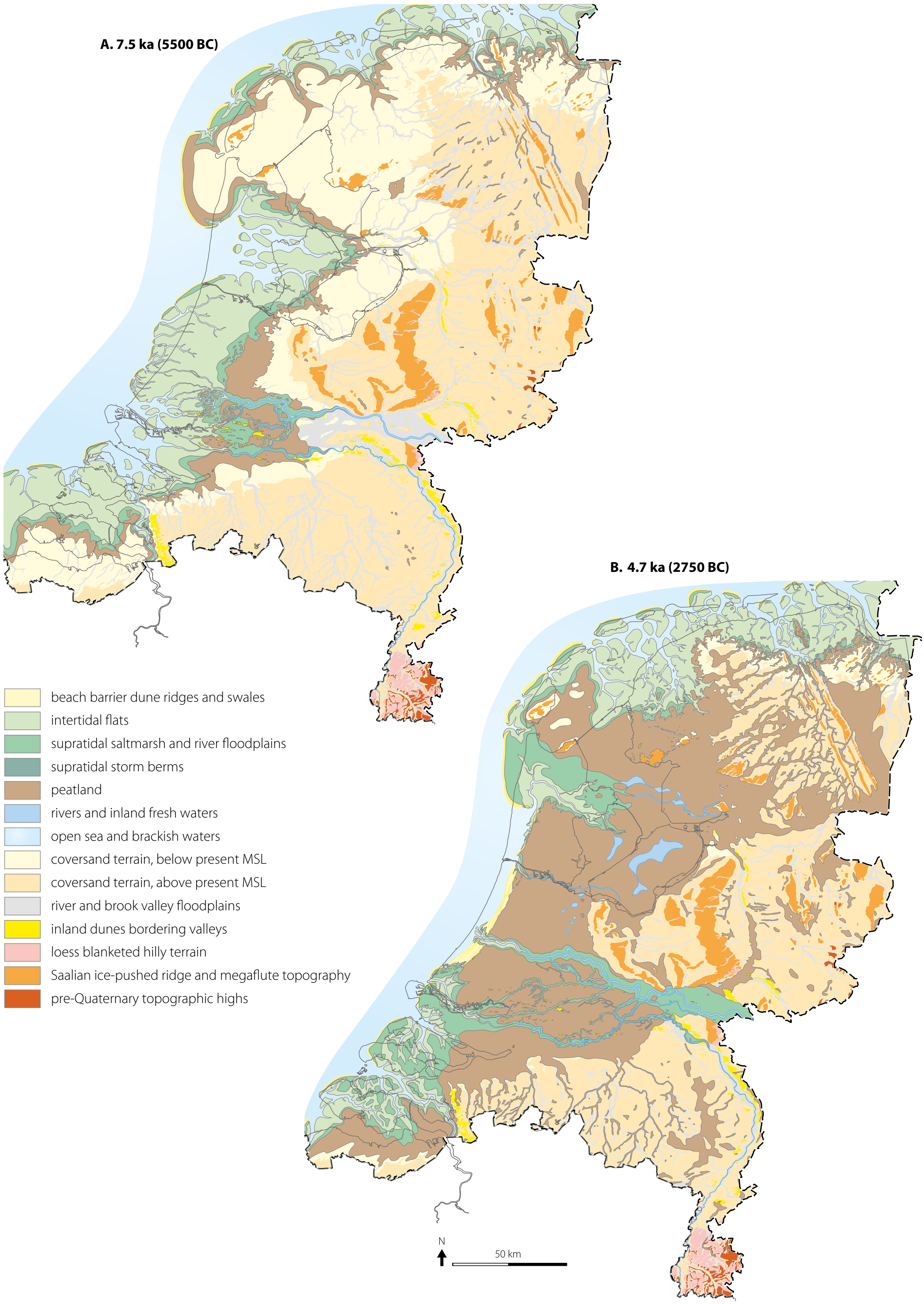
Late Holocene, youngest millennia with abundant human impacts (1.5 ka – present)

From ca. 1.5 ka onward, human-induced deposition and erosion strongly affected lowland and upland landscapes, starting to exceed natural processes in extent and magnitude (Pierik et al., 2017b). The first such human action drove increased tidal incursion into peaty back-barrier areas in the southwestern Netherlands and the Rhine-Meuse estuary (Vos, 2015), the central Netherlands lagoon (Pons & Wiggers, 1960; Van Popta et al., 2020) and the northeastern Netherlands (Dollard; Vos & Knol, 2015). Between 1.5 and 0.5 ka, erosion created new estuarine and lagoonal water bodies (Fig. 10.23d) in which considerable sub-, inter- and supratidal deposition took place (Walcheren Member).

Storm surges started to breach coastal barriers, creating new inlets that were further enlarged by subsequent extreme events. Depletion of sediment supply from lower-shoreface erosion inhibited the natural ability of barrier systems to fix such event-based damage. More importantly, human activities in the peaty coastal plain created circumstances and feedback mechanisms (like those in the Meuse estuary around 2.0 ka) that accelerated marine incursion. Over time, tidal erosion reached progressively further inland, commonly into areas with highly vulnerable organic substrate. Most of the Late Holocene southwestern peat was eroded, surviving only where it was buried under tidal mud (Fig. 10.22, upper metres). Following land loss during storm surges, areas marked by rapid accretion turned into salt marshes, many of which were successfully reclaimed from 0.8 ka onwards.

In the southwest, successive storm surges between 1.5 and 0.6 ka created four new main estuarine sea arms, servicing the Scheldt and Rhine-Meuse systems. They were interconnected through numerous tie channels. In the northwest, a series of storm surges between 1.5 and 0.2 ka enlarged the connection between the Wadden Sea and the central Netherlands lagoon (allowing a second inlet to connect to it) and made the lagoon itself bigger as well while turning it increasingly brackish (Almere, Zuiderzee and IJe beds of the Walcheren Member). In the northeast, several incursions were created during storm surges and then silted up again between 0.5 and 0.2 ka. As in the southwest, the Ems estuary at the German border was especially prone to such changes.

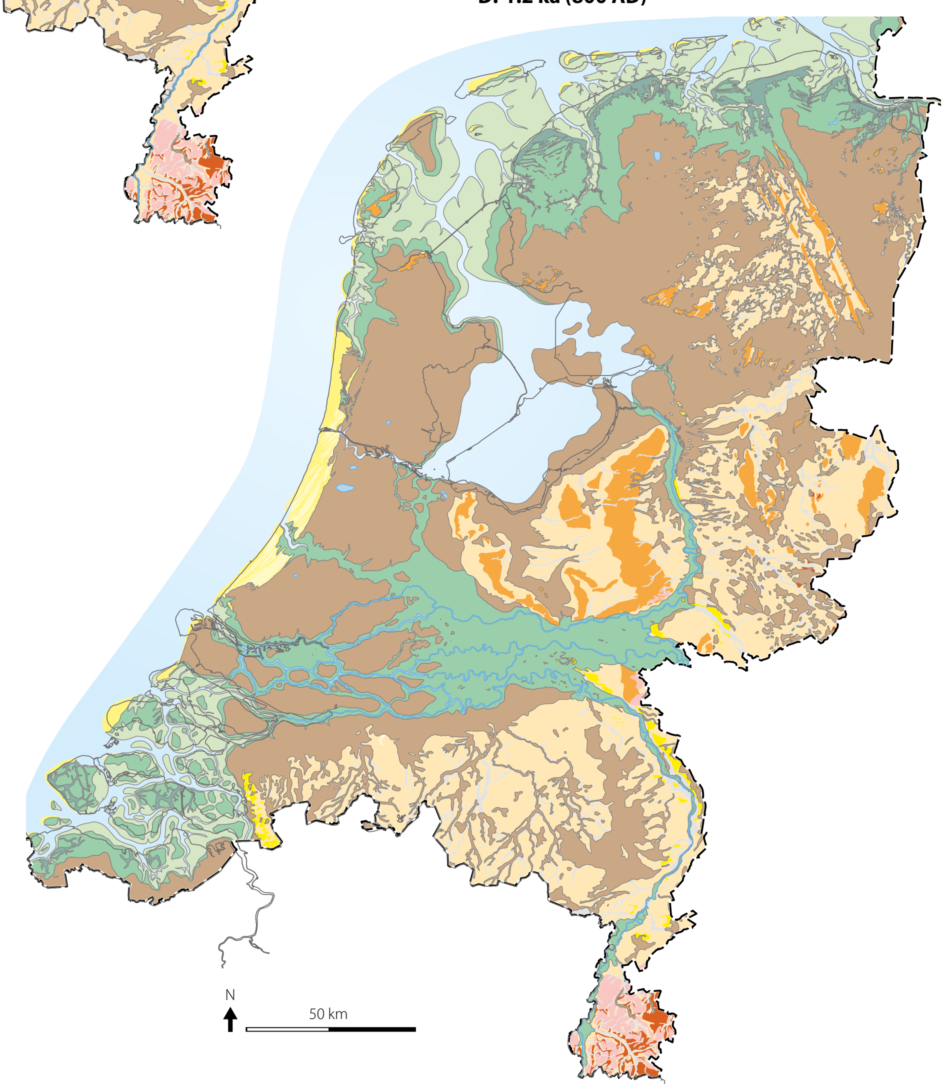
The presence and actions of humans affected lowland and waterbodies of the central and northern coastal plains as well. To minimize the loss of lowland to erosion, many dykes were built along vulnerable parts of the coastal plain and along rivers. These early structures, dating mostly from 1.3 to 0.8 ka, protected peatland. The strategy of raising dykes was particularly successful in the lower Rhine-Meuse delta, where the channel network


A. 7.5 ka (5500 BC)
B. 4.7 ka (2750 BC)
beach barrier dune ridges and swales
intertidal flats
supratidal saltmarsh and river floodplains
supratidal storm berms
peatland
rivers and inland fresh waters
open sea and brackish waters
coversand terrain, below present MSL
coversand terrain, above present MSL
river and brook valley floodplains
inland dunes bordering valleys
loess blanketed hilly terrain
Saalian ice-pushed ridge and megaflute topography
pre-Quaternary topographic highs
N
50 km

C. 2.5 ka (500 BC)

Figure 10.23. *Paleogeography during the a) Holocene middle Atlantic (7.5 ka), b) late Subboreal (4.7 ka), c) early Subatlantic (2.5 ka) and d) late Subatlantic (1.2 ka). The main developments shown are submergence of the Pleistocene landscape, closure of tidal basins, peatland expansion, inland-lake formation and growth, and barrier breaching and tidal-basin expansion. Modified from Vos et al. (2020).*

D. 1.2 ka (800 AD)



became essentially fixed. Further engineering measures between 0.3 and 0.1 ka also stopped meandering, removed mid-channel bars and shoals, fixed and deepened navigable channels, and regulated discharge division.

While human society protected vast parts of the lowlands against flooding and erosion with dykes and other defences (groynes, revetments, stone armouring) from medieval times onwards, they also dug into this protected land as part of cultivation and resource use. This has lowered the surface elevation to well below original levels of regular inundation, such as those associated with daily high tide or seasonal flooding. In the fifteenth to eighteenth century, Late Holocene peat (Hollandveen Member) was extracted to its base (top of Wormer Member) and water filled the resulting depressions in the west-central coastal plain. Wave-driven downwind shore erosion made the resulting lakes grow through time. Where technically possible, they were pumped dry after 0.4 ka, introducing a new form of land reclamation.

In addition to surface lowering, a lack of sediment accretion increased lowland vulnerability to flooding. Geologically, polder segmentation and widespread embankment turned extensive parts of the lowland into non-depositional areas at a time when the Rhine-Meuse system was at its muddiest (Gouw & Erkens, 2007; Cohen et al., 2009; Toonen et al., 2015; Pierik et al., 2017b). Instead of dispersing across floodplains, much of the suspended fluvial mud was now carried further downstream and delivered to tidal river and estuarine reaches. Upstream, sedimentation became restricted to zones between the river channel and flanking dykes, where rapidly accumulating clay was being extracted. Illustrative of the vulnerability of embanked areas, the St. Elizabeth's Flood in the fifteenth century helped earlier formed incursions to break poorly maintained dykes of the lower delta and turn a large and populated medieval polder into a tidal water body. With it, direct inner-estuarine connections established themselves between Rhine-Meuse System and the estuarine sea arms farther southwest. A century later, another another major storm surge (St. Elizabeth's Flood) established the Western Scheldt. This new, dominant sea arm owes its name to rerouting of the Scheldt, triggered as a large embanked inland area was lost.

In the upland, medieval agriculture altered the relief by interfering with small river systems, by creating raised fields that capped the nutrient-poor natural surface with manure-fertilized sediment, and by overgrazing that induced sand drifts (Kootwijk Member). Other human impact involving the geological record includes gravel, sand and clay mining (in quarries) as well as peat extraction (superficially). Their intensity increased gradually up to the twentieth century.

In the twentieth century, reclamation of lakes would take on a new dimension, extending to the enormous Zuiderzee lagoon. In 1916, a deadly storm surge impacted the central coastal lowland, triggering extensive modifications that shaped the land as we know it today. Construction of a closure dam between the Wadden Sea and Zuiderzee, finalized in the 1930s, turned the latter into a large freshwater lake and its deposits represent the youngest lithostratigraphic unit (IJsselmeer Bed, Walcheren Member). In the absence of tides, a substantial area of lagoon floor could be reclaimed, turning land that had been lost over previous millennia into fertile agricultural soil.

In today's lowland polders with peaty substrate and ditches, man-managed land subsidence occurs at rates that are an order of magnitude greater than Late Holocene natural subsidence rates (Fokker et al., 2025, this volume). Oxidation, consolidation and compaction have left their mark. Because natural sedimentation is excluded from these low-lying polder areas, substantial areas of raised ground have been created for infrastructure and urban development (anthropogenic deposits; Fig. 10.22). They are needed to allow the population to live and move around in areas as low as 7 m - MSL.

From present to future

The management of land and water continues today, and intensifies with lengthening human presence. Owing to ongoing climate change and accelerating sea-level rise, storm surges and floods are expected to become increasingly severe and frequent. To limit their negative impact on society, two strategies have been deployed. First, triggered by the 1916 event and even more by the storm-surge disaster that hit the southwest in 1953, hard protective engineering structures have been built in the southwest and northwest at unprecedented scales. These constructions drastically modified patterns of erosion and deposition in tidal basins that were allowed to stay open, such as the Western Scheldt, as well as in partly or fully enclosed counterparts. The second strategy sees the seabed, shoreface and beach-dune complex as important linked assets that need to be managed in an adaptive way. During millennia of coastal erosion, southwestern and central coastal sections became straightened, developing a prominent beach-parallel foredune in many places. This foredune, fronting either a belt of parabolic dunes (Schoorl Member) or low-lying polders, has been increasingly managed by man to keep it high and continuous enough. Here and elsewhere, the protection afforded by this dune system has been increasingly compromised over the twentieth century as sand sources for semi-natural maintenance dried up. Since the 1990s, large-scale sand nourishments have become common practice. In nourishing the upper shoreface and the beaches, this soft engineering measure mimics the natural process of sand supply from inner shelf to shoreface to beach and dune that had been in play until well into the Late Holocene, but which was no longer functioning. Every year, this requires some 12 million m³ of sand dredged from extraction pits 2 to 6 m into the seabed, beyond the 20 m depth contour. The nourished beaches now form a rich source of stray Quaternary fossils, including hominin remains, and artefacts (Textbox 4; Amkreutz & Van der Vaart-Verschoof, 2021; Niekus et al., 2023). Sand has also been extracted for raising, consolidating and levelling of construction sites onshore. The recent Maasvlakte 2 harbour extension required extraction (Fig. 10.19) from seabed pits as deep as 20 m, reaching well into Pleistocene units. Material dredged for harbour maintenance follows the opposite route, ending up in offshore dumping areas. In total, about one billion m³ of North Sea sand has been displaced so far.

Onshore, quarry-based gravel, sand and clay extraction as well as peat mining have been reduced, either due to exhaustion of resources or for environmental reasons. Sand and gravel extraction was relocated downriver. Along lowland sections of the main rivers and in the central Netherlands lagoon, subaqueous sand and gravel mining has multiplied since the middle of the twentieth century, reshaping landscapes and modifying sediment-transport regimes. Because of upstream weirs and dams in hinterland tributaries and due to reforestration, the twentieth century has seen a dramatic drop in fluvial suspended-sediment load, which was returned to values equal to those before prehistoric impacts. Depleted of sediment, the trunk channel Waal in the upper delta is geologically deepening itself. Socio-economically, this is felt during summer droughts as it lessens discharge in other Rhine-Meuse branches. Intensifying high-discharge events in the Rhine and Meuse during the late twentieth century have necessitated dyke upgrades and modifications, including relocations to increase room for the river between the dykes. This is designed to keep peak flooding levels below nationally defined maximum threshold risk levels.

Humans have left their marks in various, sometimes surprising kinds of ways. They have changed, for example, geochemical signatures of riverine sand and clay, estuarine mud and the active seabed, and have also introduced new particle types. In the Southern Bight and Urania formations offshore, the active layer from the twentieth and twenty-first century can now be identified by looking at pollutants and microplastics.

During the past century alone, humans have completely reshaped sedimentary landscapes and environments in the Netherlands and had as much influence as during the thousand years before that. By doing so, they have strongly modified how depositional and erosional processes can respond to sea-level and climate changes, in the parts of the landscape where man allows so. Human intervention has been inducing severe and rapid changes in the coastal and fluvial systems well beyond the natural thresholds seen during the Quaternary.

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Digital map data

Spatial data of figures in this chapter for use in geographical information systems can be downloaded here: https://doi.org/10.5117/aup.28163615.

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