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Paleogene – Neogene

Dirk K. Munsterman, Timme H. Donders, Alexander J.P. Houben, Johan H. ten Veen & Frank P. Wesselingh

*Corresponding author: dirk.munsterman@tno.nl

ABSTRACT

During the late Danian-Selandian Laramide phase, open-marine carbonate deposition of the Late Cretaceous and earliest Paleocene was replaced by clastic sediment infill of the Southern North Sea Basin. The Laramide phase, associated with domal uplift and subsidence of Mesozoic grabens, led to a break in sedimentation and reworking of Upper Cretaceous carbonates into marls. Consequently, Paleogene marine deposits are condensed in most areas. Late Paleocene to earliest Eocene uplift of basin margins caused major sand influxes into marginal marine environments with restricted circulation. In the North Sea area, global Paleogene warming culminated in near-tropical conditions and associated biota. Under maximum temperature conditions and differential subsidence, deltaic and submarine-fan sand deposition continued into the early Eocene. Cenozoic sediment input changed from the northwest during the Eocene, through northeastern sources in the Oligocene and Miocene, to dominantly southeastern and southern sources during the Pliocene and Pleistocene. The Paleocene-Eocene transition was interrupted by major volcanism, resulting in widespread ash layer deposition from volcanoes on the Greenland-Scotland ridge. From the middle Eocene onwards, regional subsidence interrupted by uplift phases led to transgression/regression patterns at the basins margins.

In the North Sea Basin, a major discontinuity formed due to the Pyrenean inversion phase that occurred just before Antarctic ice cap growth and global cooling at the onset of the Oligocene. From late Eocene to Mid Miocene, the basin experienced warmer and cooler phases, developing a rich, mostly endemic North Sea marine biota. In the early Oligocene, much of the Southern North Sea Basin drowned, and outer-neritic marine clays of the Rupel Formation (Boom Member) were deposited. During the late Oligocene through Pliocene, shallow marine sedimentation was balanced by subsidence resulting in monotonous sequences of marine clays and silts. During the Miocene Climate Optimum, peat formation was widespread at the southern margin of the North Sea Basin, followed by large-scale fluvial-deltaic deposition with local peatbogs as the climate cooled in the Late Miocene. The Upper Pliocene and Lower Pleistocene deposits are dominated by marine silty and sandy clays with ice-rafted debris, marking the first strong Northern Hemisphere glaciations, grading into shallow marine and fluvial sands towards the margins. These are overlain by predominantly sandy Pleistocene fluvial deposits. This chapter is structured around the varying tectonic and climatic factors that determined the structures of the North Sea Basin and its heterogeneous Paleogene-Neogene basin fill.

<< Laminated clay of the Belgian Boom Formation (quarry of Wienerberger in Rumst, west Belgium), equivalent to the Rupel Formation in the Netherlands. The laminations reflect Milankovitch driven sea-level fluctuations related to early Antarctic glaciations. Photo: Patrick Kiden.

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Paleogene and Neogene time scale

Giovanni Arduino was a mining specialist who was the first to use the term 'Tertiary' in 1760. Based on observations in the Alps of northern Italy, Arduino proposed a subdivision of geological time into Primary, Secondary, and Tertiary periods. Later a fourth period, the Quaternary, was added. Although widely used, the 'Tertiary' was no longer recognized as a formal unit by the International Commission on Stratigraphy in the 1990s. Until 2010 the Paleogene and Neogene referred to the span of time between 65 and 1.8 million years ago (Fig. 9.1). Later, the 'dawn' of the Quaternary was put at the start of the Gelasian at 2.58 Ma (Gibbard et al., 2010).

The name Cenozoic (originally Cainozoic) Era is derived from the new (*kainos*) biota, compared to those of the Mesozoic Era (Phillips, 1841). The Cenozoic Era comprises the Paleogene (*palaios* = old, *genos* = birth), Neogene, and Quaternary periods. The subdivision of the Paleogene (66-23 Ma) and the Neogene (23-2.58 Ma) periods was originally based on the different relationship with modern fauna in marine deposits. In the Eocene, for example, only 3% of 'modern' (still extant) species are present, whereas in the Pliocene this percentage had risen to 90% (Lyell, 1833; Simmons, 2018). The Paleogene Period is subdivided into three epochs: the Paleocene, Eocene, and Oligocene, again referring to the evolution of biota (*eos* = dawn, *oligos* = little). The three Paleogene epochs are formally subdivided into nine ages. The Paleocene Epoch consists of the Danian, Selandian, and Thanetian ages, the Eocene Epoch of the Ypresian, Lutetian, Bartonian, and Priabonian ages and the Oligocene Epoch comprises the Rupelian and Chattian ages (Speijer et al., 2020). The Neogene Period presently includes the Miocene and Pliocene epochs. The Miocene includes the Aquitanian and Burdigalian (*Lower Miocene*), Langhian and Serravallian (*Middle Miocene*) and Tortonian and Messinian (*Upper Miocene*). With the recent transfer of the Gelasian to the Quaternary, the Pliocene now consists of the Zanclean (*Lower Pliocene*) and Piacenzian (*Upper Pliocene*) ages (Raffi et al., 2020). Orbital tuning of sedimentary cycles, calibrated to geomagnetic polarity- and biostratigraphic time scales has improved the resolution of the Paleogene and Neogene time scale over the last two decades (Raffi et al., 2020; Speijer et al., 2020). Astronomical age control is provided for almost all geomagnetic polarity reversals.

Introduction to the Paleogene and Neogene Southern North Sea Basin

The contours of the primordial North Sea became established in the Paleogene-Neogene (Fig. 9.2). The present-day Netherlands is located in the southern sector, but originally was positioned on the western edge of the Eurasian continent, at the approximate latitude of the Iberian Peninsula today. Over the past 60 My, the Southern North Sea Basin (SNSB) has migrated from 42° to 52° northern latitude, passing through a range of climatic zones from tropical to temperate (Van Hinsbergen et al., 2015). Throughout the Cenozoic, the Dutch part of the SNSB was located at the boundary between land and sea environments and the coastal zone was mainly located around the present province of South Limburg.

The exact position of the coastline and the types of depositional environments represented at the earth's surface are controlled by the long- and short-term interplay of change in accommodation space and sediment supply. Both accommodation changes and sediment supply responded, directly or indirectly, to the interaction of tectonics and climate. These responses are recorded in the sedimentary record by vertical variations in sedimentary facies, reflecting lateral shifts in depositional systems and the dynamic development of the paleo-landscapes.

Ongoing post-rift thermal subsidence since mid-Cretaceous times and the progressive opening of the northern Atlantic Ocean and African-European collision drove the evolution and origin of the North Sea Basin. These factors resulted in regional uplift of the British Isles, Fennoscandian Shield, Ardennes, Rhenish and Bohemian massifs around the Netherlands during the Paleogene-Neogene. These developments were responsible for the opening and closure of seaways which, together with climatic cooling, caused shifts in biotic provinces and the increasing importance of boreal elements in both fauna and flora. The developing geographic isolation of northwest Europe from southern Europe, caused by Alpine uplift and closure of epicontinental seaways, created a climatological and biological divide that precipitated extinctions and development of glacial landforms (Knox et al., 2010). As a result, the SNSB contains an almost complete geological archive of Paleogene and Neogene climate, landscape and biotic evolution, although the record is mostly contained within the subsurface. Isolated Paleogene-Neogene deposits between 200 and 1600 m thick (Fig. 9.3) crop out in restricted areas in the eastern and southern Netherlands and dip towards the Central North Sea Basin depocentre, where siliciclastic Cenozoic deposits reach over 2500 m thick (Kuhlmann et al., 2006a,b). The Cenozoic record of terrestrial environmental change is considerably more fragmented than that of the marine realm, and ages are often poorly constrained (Utescher et al., 2011).

Stable oxygen and carbon isotope records provide insight into trends in paleoclimate and carbon cycling (Zachos et al., 2008; Westerhold et al., 2020). These reveal a long-term global warming trend that started in the mid-

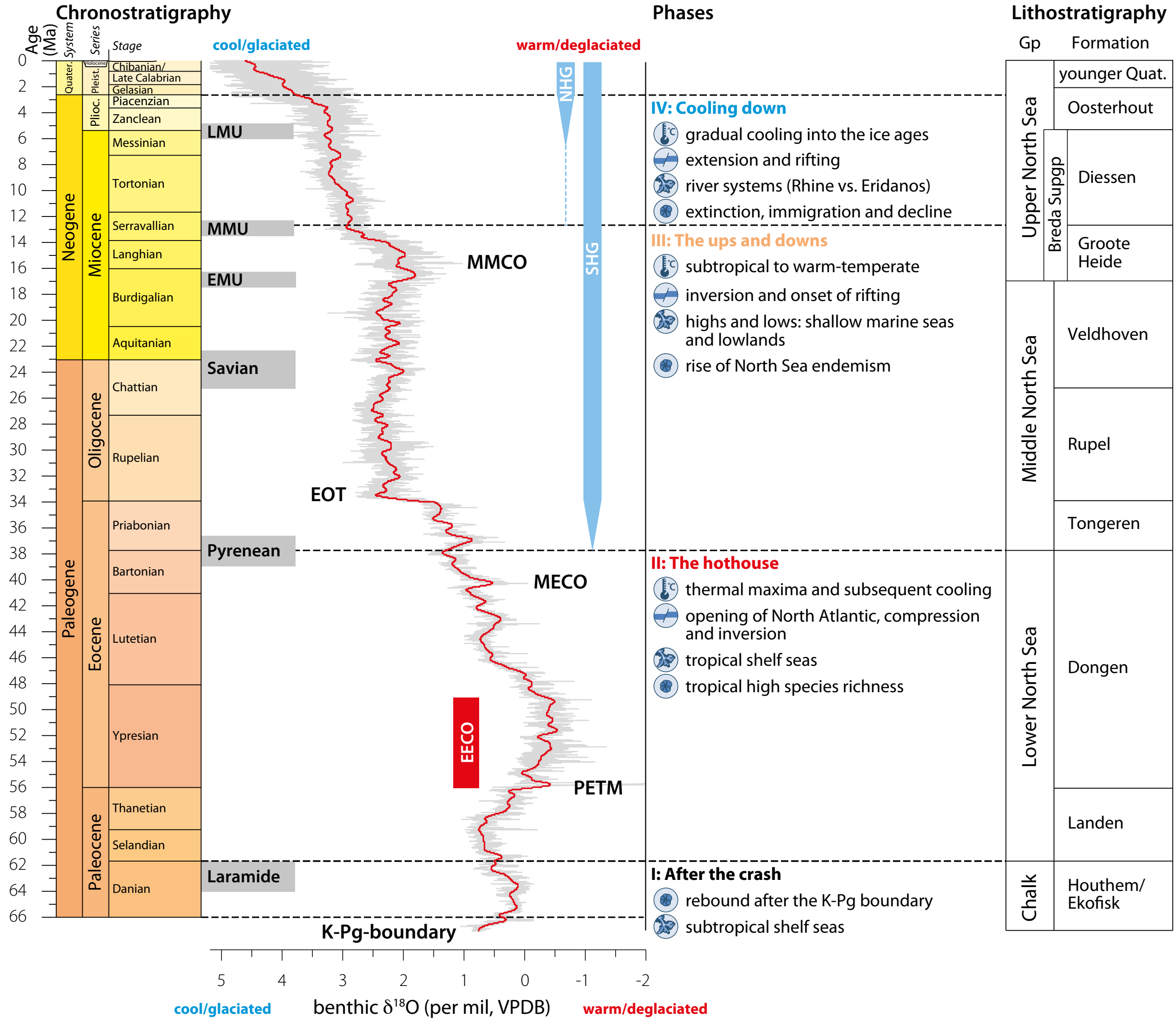


Figure 9.1. Paleogene-Neogene tectonic, climate and lithostratigraphic framework. The grey bars represent regionally recognized tectonic phases and/or unconformities. EMU – Early Miocene Unconformity, MMU – Mid-Miocene Unconformity, LMU – Late Miocene Unconformity. Phases I-IV correspond to distinct tectonic-climatic phases described in the text. The climatic framework is provided by the deep-sea benthic foraminiferal oxygen isotope compilation after Westerhold et al. (2020). Heavy (more positive) values correspond to cooler deep-sea temperatures and/or the development of continental glaciations. K-Pg = Cretaceous-Paleogene boundary; PETM = Paleocene-Eocene Thermal Maximum; EECO = Early Eocene Climatic Optimum; MECO = Middle Eocene Climatic Optimum; EOT = Eocene-Oligocene Transition; MMCO = Mid-Miocene Climatic Optimum.

dle Paleocene and culminated in the early Eocene. After peak warmth in the early Eocene this trend reversed and developed as a stepwise cooling from greenhouse to ice-house conditions, starting with the appearance of ephemeral ice-sheets on Antarctica across the Eocene-Oligocene transition (Zachos et al., 1992; Hutchinson et al., 2021). Northwest Europe and the SNSB started to cool as part of the global development of steeper and spatially more heterogeneous latitudinal climate gradients during the Cenozoic (Bijl et al., 2009; Liu et al., 2009). During the Oligocene and Miocene, numerous short-term isotope excursions mark a high degree climatic variability, largely driven by an interplay of solar insolation and oceanographic reorganizations (Palike et al., 2006; Jakobsson et al., 2007, Steinthorsdottir et al., 2021a). Progressive long-term cooling eventually culminated in the Pliocene establishment of permanent ice-sheets in the northern hemisphere, which expanded significantly at the start of the Pleistocene (Lisiecki & Raymo, 2005; Head & Gibbard, 2015).

Tectonic and depositional setting

Since the mid-Cretaceous (Van Lochem et al., 2025, this volume), the North Sea Basin has been almost continuously subsiding between the Fennoscandian Shield in the

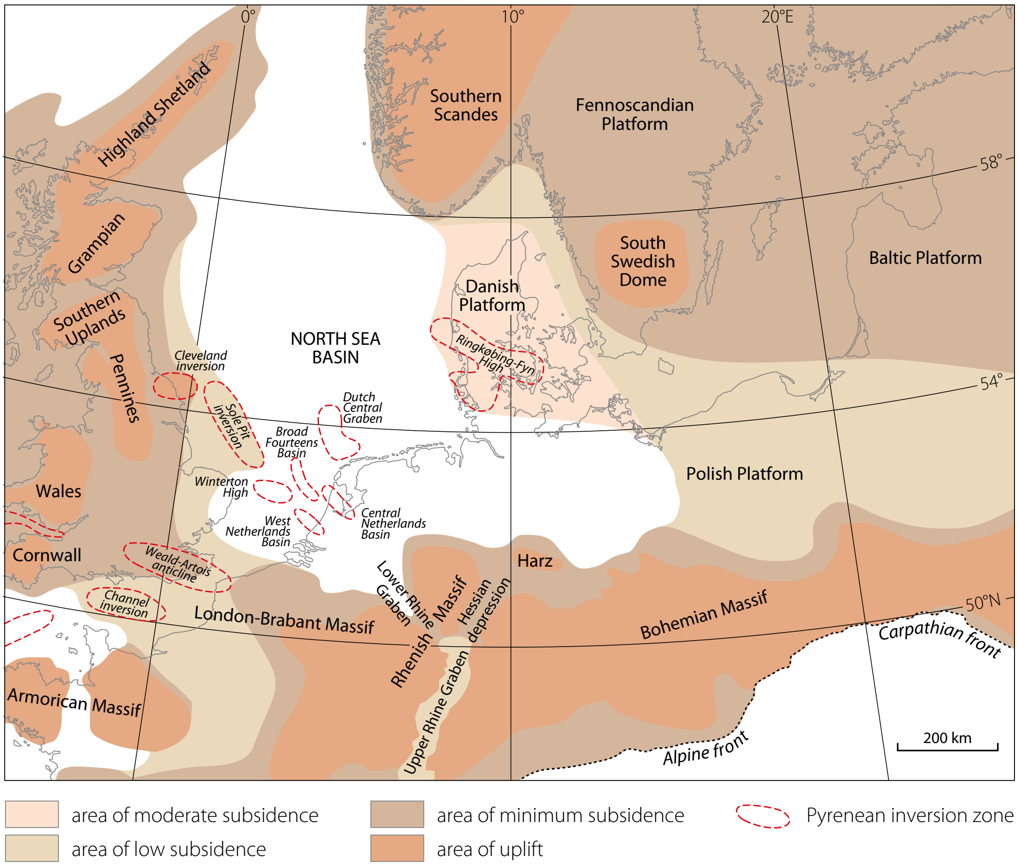


Figure 9.2. Paleogene and Neogene structural elements in the North Sea region. Modified after Knox et al. (2010) *and Gibbard & Lewin* (2016).

north, the European mainland in the south and the British Isles in the west. New seismic techniques and data have led to the realization that the predominantly subsiding post-rift thermal sag basin developed in response to gradual lithospheric cooling of underlying deeper Jurassic rift dome structures (Ziegler, 1990). Its central axis lies to the west of the Dutch Central Graben. The connection between the southern North Sea via the Channel to the Atlantic shelves of France and Ireland was opened intermittently by flooding or breaching of the Melantois-Artois High throughout the Cenozoic (Van Vliet-Lanoë et al., 1998; Gibbard & Lewin, 2003; Ziegler & Dèzes, 2007). The North Sea Basin region evolved during fragmentation of the Eurasian-North American plate and Alpine and Pyrenean orogenies. These forces caused repeated fluctuations in the magnitude and orientation of the intraplate stress field and related subtle reactivations of pre-Cenozoic structural elements (Knox et al., 2010).

The most important fracture system in the Netherlands in this regard is the approximately 1100 km long complex European Cenozoic Rift System (ECRIS; Fig. 9.4) which extends from the Southern North Sea Basin, through the Lower Rhine Graben (also called Basin or Embayment), via the Jura, Saône Graben as far as the Valencia Trough (Zagwijn, 1989; Ziegler, 1992). The Roer Valley Graben is the main tectonic feature in the Lower Rhine Graben (Geluk et al., 1994; Ziegler, 1994; Michon et al., 2003; Van Balen et al., 2005), which is bordered by the Rhenish Massif in the east and south and by the Brabant Massif in the southwest. It started to develop in the Alpine foreland and propagated northwards (and southwards) to accommodate the stress from the Alpine-Mediterranean orogenic system. During the Rupelian, the rifting progressively moved northward and the Rhine and Leine grabens developed a narrow seaway between the Alpine foredeep and the North Sea Basin (Vinken, 1988). The development of this rift system was also influenced by mantle-plume related volcanic activity, which intensified during the Oligocene and Miocene and contributed, by thermal thinning of the lithosphere, to the uplift of the Ardenno-Rhenish Massif and – in part – the Bohemian Massif (Ziegler & Dèzes, 2006, 2007).

Extensional tectonics in the Eurasian Plate attributed to the separation of North America away from Eurasia during the Paleogene resulted in the Danian Laramide phase. By latest Paleocene to earliest Eocene times, ridge-push forces exerted by the opening of the North Atlantic led to crustal separation between Greenland and Europe. This was

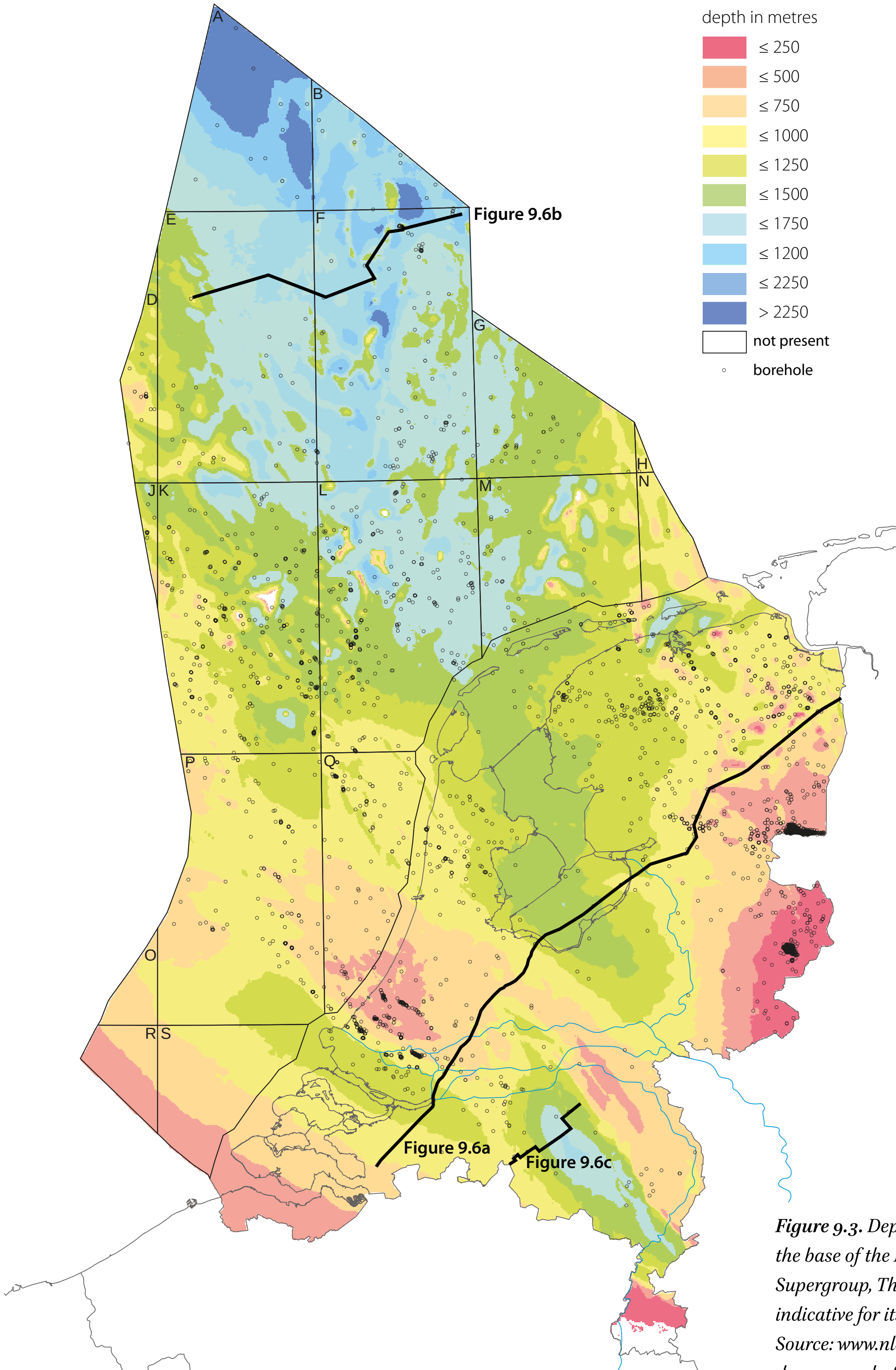


Figure 9.3. Depth map of the base of the North Sea Supergroup, The map is also indicative for its total thickness. Source: www.nlog.nl/en/dgm-deep-v5-and-offshore

accompanied by major extrusive volcanism in the Norwegian Sea (Abdelmalak et al., 2016; Horni et al., 2017), which is represented by tuffaceous sediments in the Netherlands (De Wijk Member of the Dongen Formation).

In the southwestern part of present-day Europe, the Iberian Plate pushed against the southern part of France, which led to the exhumation of the Pyrenees (Pyrenean tectonic phase) in the middle to late Eocene. During this

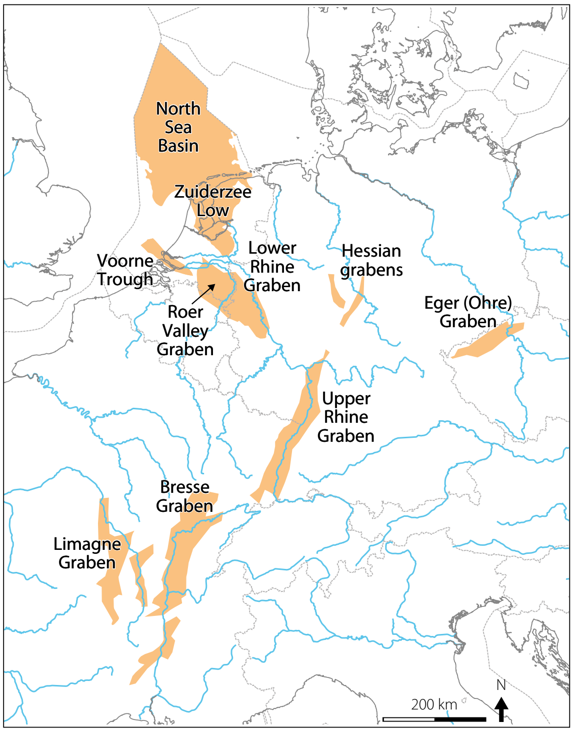


Figure 9.4. *Depocentres (grabens, basins, troughs, and lows) of the European Cenozoic Rift System (ECRIS) in northwestern Europe.*

Pyrenean inversion, roughly north-south directed compression is recognisable on seismic data in the southern North Sea (Nalpas et al., 1995) where a marked angular unconformity is seen in the Sole Pit area, close to the Eocene-Oligocene boundary (De Jager, 2007). This tectonic pulse caused widespread inversion (approximately 300 m) in the Mesozoic West and Central Netherlands basins, becoming less towards the Broad Fourteens Basin (Knox et al., 2010). Uplift of the Roer Valley Graben increased in southeastern direction (Deckers et al., 2016). It was estimated that the Weald Basin was uplifted by up to 1500 m during its late Eocene to Miocene inversion (Simpson et al., 1989). Massive erosional processes occurred in most of the inverted parts of the West and Central Netherlands basins. The Pyrenean phase ended in the earliest Oligocene and was followed by a widespread shallow marine transgression that even crossed the current Ardennes (Vandenberghe, 2017). An intermittent marine connection between the North Sea and the Upper Rhine Graben possibly existed via the Hessian Seaway (Berger et al., 2005; Sissingh, 2006) in the early Oligocene. In addition, a connection in the early Oligocene probably existed between the Tethys Ocean and the Atlantic via the Loire Seaway (Knox et al., 2010). Uplift and sea-level fall resulted in emergence of the Fennoscandian Platform (Knox et al., 2010). Large areas became subaerially exposed and forced the rivers seaward.

Absence of major sediment influx from the western North Sea Basin margin during the late Oligocene indicates that the land area maintained a low relief (Gibbard & Lewin, 2003, 2016). A marine connection via a Channel Seaway between the North Sea and the Atlantic is evidenced by mollusc faunas (Janssen & Gürs, 2002); coeval Lower Miocene deposits in the Paris Basin are non-marine. This implies that any threshold generated by inversion of the Central Channel and Weald basins must have been substantially reduced before the Burdigalian transgression, possibly due to the Savian tectonic phase.

During the Neogene, multiple unconformities developed due to uplift and inversion and interacted with eustatic sea-level variations. Rotational movements of the African and Iberian Plates against the Eurasian Plate led to closure of the Tethys Ocean in the Oligocene-Miocene. The related Early Miocene compression drove the orogeny of the Alps, Apennines and Jura. It was accompanied by rotational movement of the Adriatic (or Apulian) Plate on which Italy is situated and, at the same time, continued opening of the North Atlantic Ocean that enhanced regional uplift of the Fennoscandian Shield.

This interplay of plate-tectonic events resulted in an uplift and inversion phase that is referred to as the Savian phase (end Chattian-earliest Aquitanian). At the base of the Miocene, the Savian Unconformity represents a gap separating Chattian from early Aquitanian or younger deposits (Köthe, 2007). Next to its plate-tectonic origin, the Savian Unconformity corresponds to a glacio-eustatic event at the end of the Oligocene (Miller et al., 2008). The Savian Unconformity, though widespread, is less distinct in the eastern part of the North Sea Basin than in the west. Increased sediment supply in the eastern part during this time was associated with the development of a major Baltic River System, which drained a large area of Fennoscandia, the German lowlands, northern Carpathians and western Russian Platform (Gibbard & Lewin, 2016). The Baltic River flowed westwards along the present-day southern Baltic Sea (Cameron et al., 1992). Coastal progradation also took place in active basin settings such as the Lower Rhine Graben. Increased uplift in the West Netherlands Basin (De Jager, 2007), in the northern Campine Block (Munsterman & Deckers, 2020), on the Ringkøbing-Fyn High and Central Graben in the Danish sector (Rasmussen, 2009), and in the Mesozoic Sole Pit, Weald and Cleveland basins of the UK sector (Whittaker, 1985) are all related to the Savian phase, but the unconformity seems to be less well-developed in other parts of the Netherlands and Germany (Knox et al., 2010). Following the Savian phase, sedimentation recommenced and a Lower Miocene sequence of glauconite-bearing sands was deposited in the Sourthern North Sea Basin (Rasmussen & Dybkjær, 2014).

This sequence has a late Burdigalian, or possibly early Langhian age (Munsterman et al., 2019).

A eustatic sea-level rise associated with the Mid-Miocene Climatic Optimum (MMCO; Steinthorsdottir et al., 2021a) resulted in widespread transgression, characterized by sediment onlap on tectonic highs (marked by the Early Miocene Unconformity - EMU) and thick prograding sequences along the basin margins. In the late-middle Miocene a distinct change in the tectonic regime affected the SNSB. Accelerated uplift of Fennoscandia and Britain marked the culmination of the plate-tectonic regime that started in the Oligocene, possibly driven by mantle processes (Cloetingh et al., 2005). The uplift, coupled with a cooling in climate (Sangiorgi et al., 2021) and associated eustatic sea-level fall, led to widespread erosional processes and formation of the large-scale Mid-Miocene Unconformity (MMU). The uplift of Fennoscandia forced progradation of the fluvial-deltaic Baltic system into the southeastern embayment of the North Sea and its river system reached the Danish part of the southern North Sea in the Late Miocene (Knox et al., 2010; Rasmussen & Dybkjær, 2014; Thöle et al., 2014). In the Dutch northern offshore, time-equivalent, post-MMU, deposits are represented by a condensed sequence of Tortonian fine grained marine siliciclastics. This sequence represents toe-of-slope deposits that correspond to the distal parts of the sedimentary system that started to be deposited onto the MMU (Kuhlmann & Wong, 2008). The MMU is one of the main regional (seismic) horizons and is always characterized by stratal onlap. In the Roer Valley Graben, for instance, the MMU is expressed as a downlap surface of west-prograding clinoforms (Munsterman et al., 2019). A large-scale incision into the Paleogene successions indicates that the MMU is an erosional unconformity in the western North Sea (Cameron et al., 1992). The MMU is also associated with channel erosion at the base of the Diest Formation in Belgium (e.g. Vandenberghe et al., 2005).

Due to widespread and increasingly strong subsidence during the Neogene, the onshore Lower Rhine-Roer Valley Graben and offshore North Sea Basin became major depocentres (Munsterman et al., 2019). The timing of accelerated subsidence as well as the geometry of the depocentres could suggest that this was due to lithospheric folding under northwest-directed Alpine compression (Deckers & Louwye, 2020). During Pliocene and Pleistocene times, the central North Sea Basin also experienced accelerated subsidence, probably due to the same process of lithospheric downfolding (Van Wees & Cloetingh, 1996). This reflects the continuity of the Southern North Sea Basin as part of the Alpine foreland, together with the Ardennes and the northeastern part of the Paris Basin, which were also folded at this time (Bourgeois et al., 2007; Stoutham-er et al., 2023). Two of the three connections between the Atlantic Ocean and the Mediterranean closed completely at the end of the Miocene (~5.96-5.33 Ma) due to tectonic uplift (Ryan et al., 1973; Flecker et al., 2015; Krijgsman et al., 2018), resulting in the Messinian Salinity Crisis (Ryan, 1973; Roveri et al., 2014) and associated erosion expressed as the Late Miocene Unconformity (LMU). Seismic studies in the Roer Valley Graben (e.g. of the transect between wells Goirle and Heeswijk) show that topsets are missing and that an angular unconformity exists (Munsterman et al., 2019).

By the end of the Pliocene, plate-tectonic reorganization resulted in the Eurasian and North American landmasses to start surrounding the shallow marine polar basin and the gradual closure of the Isthmus of Panama (e.g. Keigwin, 1982; Bacon et al., 2015), linking North and South America. These gateway closures intensified Atlantic Gulf Stream circulation and set off a cascade of climatic feedbacks that ultimately led to the extensive Northern hemisphere glaciation in the Quaternary.

Stratigraphy and geological history

The stratigraphy and geological history of the Paleogene-Neogene in the Netherlands can be divided in four major phases bounded by tectonic events, described below in detail (Fig. 9.1). These phases, the late early to mid-Paleocene Laramide phase, the late Eocene Pyrenean phase and the late Middle Miocene phase (MMU) are separated by three major unconformities relevant for the Netherlands. The Savian phase strongly effected the proximal settings of the Southern North Sea Basin, including the southwestern part of the Netherlands, resulting in a Chattian-Early Miocene hiatus. More distally however, the MMU is the most prominent feature on seismic sections. In addition, an obvious trend break in climate development towards more consistent cooling is associated with the MMU. The importance is such that it led to a recent subdivision of the former Breda Formation into the Miocene Groote Heide and Diessen formations (Munsterman et al., 2019), grouped in the Breda Subgroup.

The Paleogene-Neogene successions are subdivided into a lowermost calcareous part (the Danian part of the Chalk Group) and predominately siliciclastic rocks of the Lower, Middle and Upper North Sea groups. Lithostratigraphically, the Cenozoic phases are represented by the Lower North Sea Group (interval between Laramide and Pyrenean tectonic events), the Middle North Sea Group (in between Pyrenean phase and EMU) and Upper North Sea Group (post-EMU). The alternation of mainly clay and sand and to a lesser extent marls and gravels near the southern margin of the North Sea Basin forms the basis

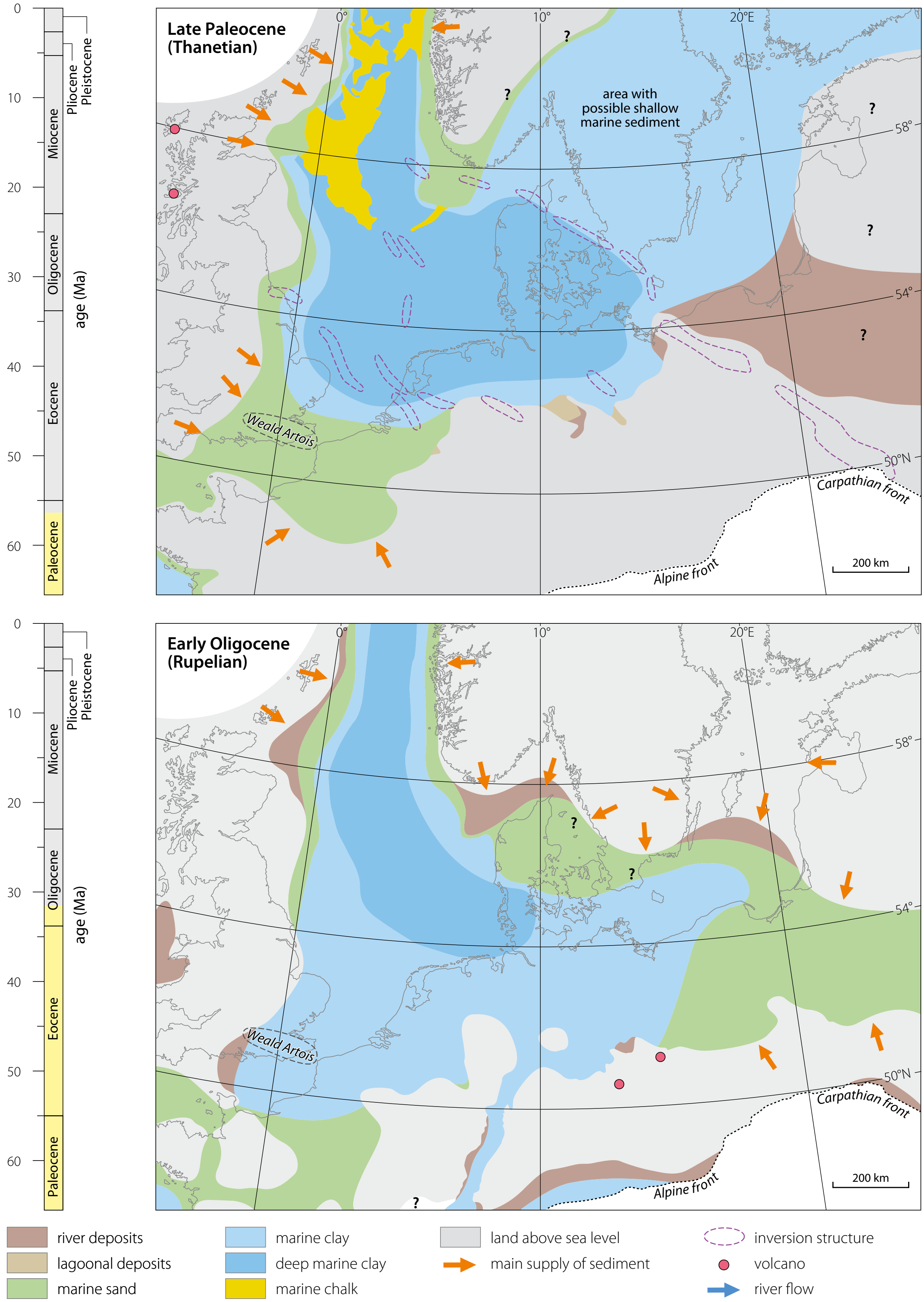
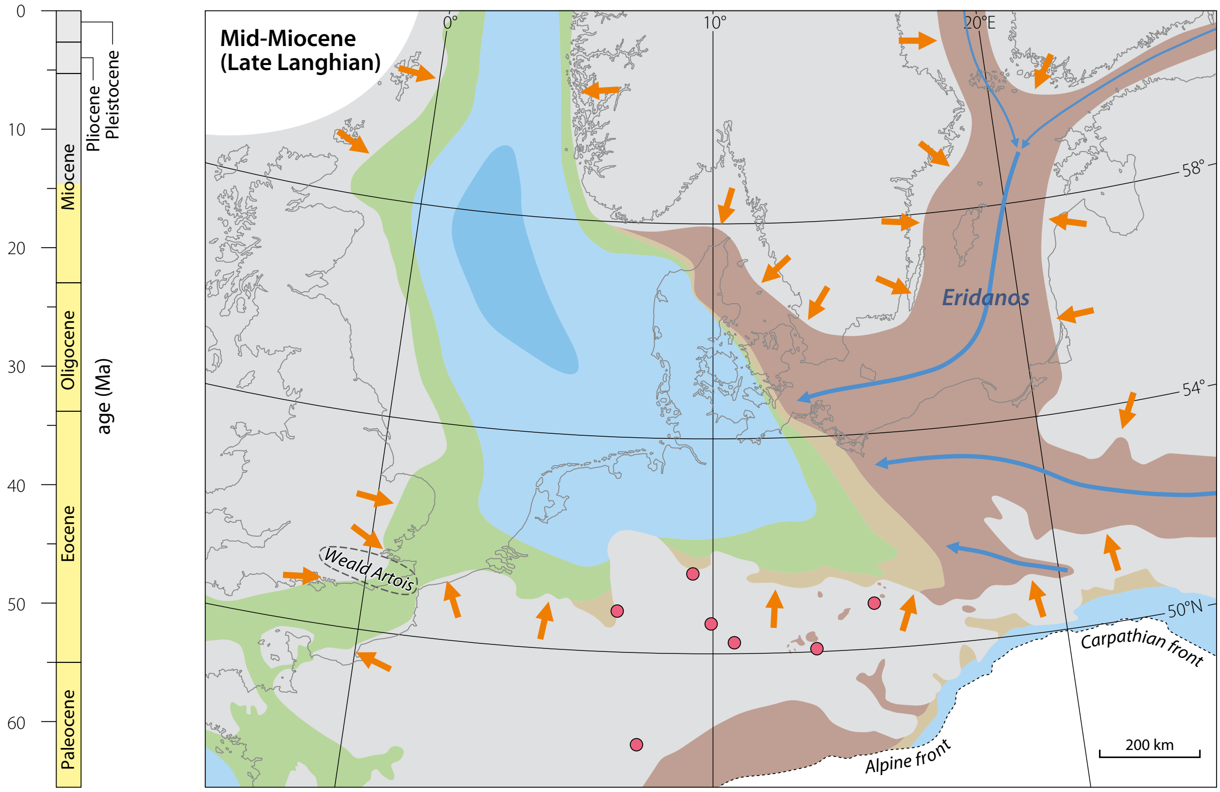
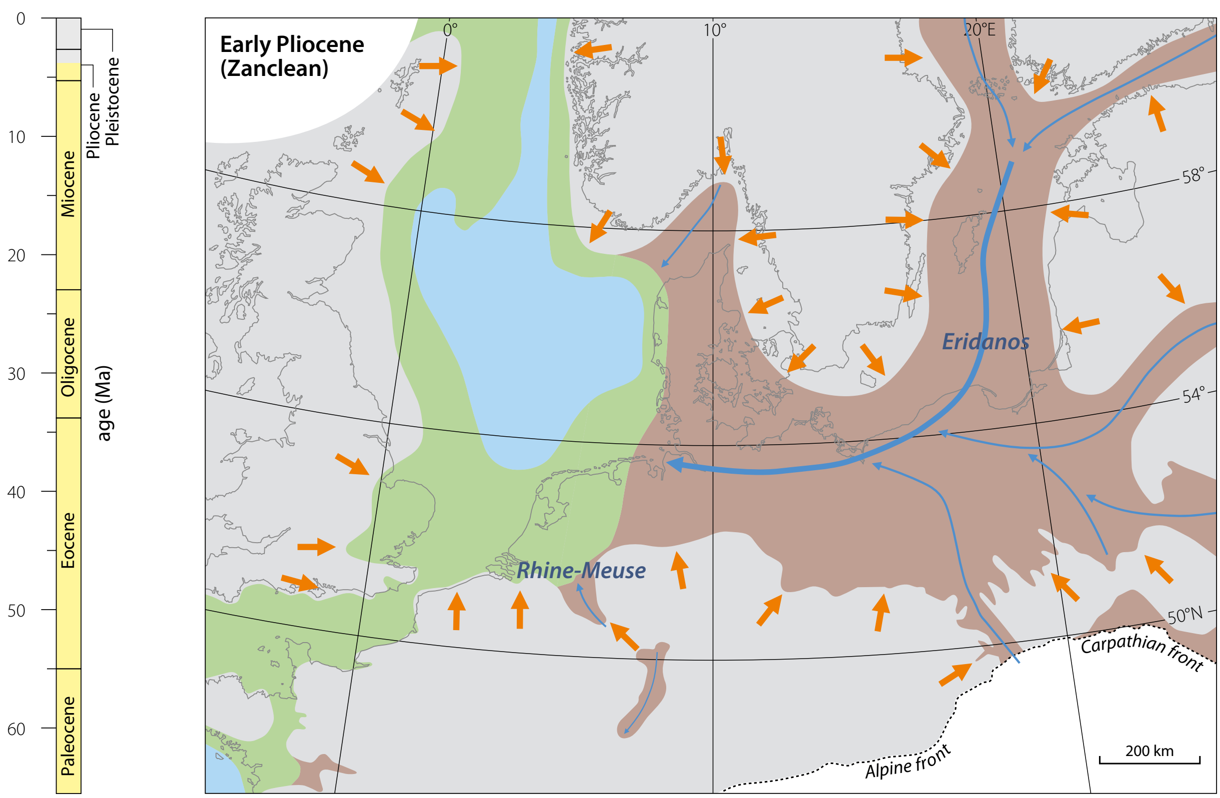


Figure 9.5. Paleogeographic maps for a) the late Paleocene, b) the early Oligocene, c) Middle Miocene, and d) Early Pliocene. Modified after Knox et al. (2010) and Gibbard & Lewin (2016).





of the subdivision into formations and members. The description of the phases includes separate sections focusing on regional tectonics, climate, depositional systems, landscape, ecosystem evolution and lithostratigraphic development (Fig. 9.5).

Phase I – After the impact and Sub-Hercynian inversion (Danian, 66-62 Ma)

The Yucatan asteroid impact at 66 Ma (formerly known as the K-T event) marked the catastrophic end of the dinosaur world at the end of the Cretaceous and saw the almost instant demise of typical Mesozoic biota such as ammonites, rudists and inoceramid molluscs. The impact shell-shocked the shallow-marine tropical biota and also affected plankton groups, such as calcareous nannofossils and dinoflagellates. This was, however, followed by a rapid (partial) recovery. The early Paleocene North Sea Basin almost immediately returned to the limestone deposition that characterized the Late Cretaceous. The rapid recovery of carbonate ecosystems has been ascribed to calcium oversaturation resulting from the Yucatan impact and its aftermath (Bralower et al., 2020).

In terms of lithostratigraphy, the Paleocene chalk-type deposits are included in the Ekofisk Formation (offshore) and the Houthem Formation (onshore) of the Chalk Group (see Van Lochem et al., 2025, this volume). Deposition occurred under relatively stable, low-energy conditions in carbonate-shelf to upper bathyal environments. The sediments predominantly consist of pelagic biogenic remains, which settled from suspension with only very limited detrital input.

Life on land had a full reset with the loss of the dominant sauriid groups and the emergence of mammal dominated communities. In the Netherlands, the main paleontological record for the onset of the Paleogene is found in the marine Houthem Formation, of which a very good section used to be exposed in the Curfs quarry near Berg en Terblijt in South Limburg (Jagt et al., 2013). Rich marine faunas from the NE North Sea Basin, including the Faxe area (Denmark) and terrestrial faunas from the Mons Basin in Belgium (De Bast & Smith, 2016) provide a regional view on the ecosystem and biotic development. Top marine Mesozoic mosasauriid predators became replaced by sharks and crocodiles during the onset of the Paleocene. However, several other Mesozoic groups, including

Fossil marine mammals from the Neogene

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The southern part of the North Sea Basin, including particular sites of the Western Scheldt and sandpits of Mill and Liessel, conceal large fossil treasures. Until approximately a decade ago, these treasures were hidden in buried seafloor sediments, but were revealed by recent sand extraction and trawling. The faunal association of marine vertebrates from the Late Miocene Diessen Formation revealed dozens of fossil taxa that were little or not known. Unique for the Netherlands and Europe!

Recent studies of these fossils show that the composition of Late Miocene whale faunas is radically different from the current ones (e.g. Post & Peters, 2023). The extant marine mammal fauna is dominated by a few species of fin whales, several dolphin species, the harbour porpoise and the grey- and harbour seal. The large sperm whale and two members of the beaked whale family are less common.

The whale faunas of the Late Miocene were even richer in genera and species than recent pendants. The former were dominated by many species of relatively small and basal fin whales (Cetotheriidae), small true fin whales, which are the ancestors of the enormous recent fin whales (Balaenopteridae), sperm whales of all shapes and sizes, with rows of extremely sharp teeth in the lower and upper jaws (Physeteroidea), a range of species of longirostral beaked whales, some of which hunted their epipelagic prey in large groups in shallow waters (Ziphiidae), and small 'river' dolphins (Pontoporiidae). These faunas also included up to half a dozen of pinniped taxa (large and small) and a seacow.

During the Pliocene, and especially by the end of the Pliocene, the highly varied Miocene faunas were replaced by faunas with a reduced number of taxa, which included the direct ancestors of the present-day North Sea fauna. Fossils of these Pliocene faunas are extremely rare worldwide, although some taxa have been described from the Oosterhout Formation (Post & Kompanje, 2010; Post & Bosselaers, 2017).

Skull with mandibles and cervical vertebrae of a yet undescribed species of beaked whale of approximately 4-5 metres body length from the Western Scheldt (collection Natuurhistorisch Museum-Natural History Museum, Rotterdam; NMR 12016).

some ammonoid and inoceramid- and trigonoid bivalve taxa briefly lingered on into the earliest Paleocene before their final extinction (Jagt et al., 2013). Echinoderms and molluscs experienced a major extinction of (sub-) tropical communities followed by rapid recovery through immigration from the northern Atlantic (Jagt, 2000; Vellekoop et al., 2019). The Houthem Formation fossils indicate shallow (sub-)tropical conditions with common algal firmgrounds. The Danian marine biota have much in common with those from the northern Paris Basin and from Denmark/southern Sweden, and indicate that the North Sea Basin at the time was an embayment of the North Atlantic (Jagt et al., 2013). During the Danian, lowland coastal habitats existed near the southern border of the Netherlands. A very rich fauna retrieved from Hainin (Belgium) represents an early Paleocene assemblage dominated by small mammals of primitive groups and insectivores that lived in forested environments with dense undergrowth at the southern margin of the North Sea Basin (De Bast & Smith, 2016). Rare fossils of *Thalassotaenia* seagrass foliage from the earliest Danian represent the first Cenozoic plants remains found in the Netherlands (Van der Ham et al., 2007).

The change from Late Cretaceous and early Paleocene chalk deposition to Paleocene-Eocene clastic deposition occurred around the transition from early-middle Paleocene (late Danian/Selandian boundary) (Steurbaut & Sztrákos, 2008). This transition has been linked to the Laramide phase and is regionally correlated with the Atlantean and Near Base Paleogene unconformities (Patruno et al., 2021). The change in sediment supply is attributed to widespread regional uplift (Knox et al., 2010) that lead to enhanced erosion and sediment supply. Hypotheses on the reason for the uplift include relaxation inversion (Nielsen et al., 2005, 2007), lithospheric folding (Deckers, 2015; Deckers & Matthijs, 2017), the Iceland mantle plume (Gale & Lovell, 2018) and a combination of these factors (e.g. Hillis et al., 2008). The uplift led to subaerial exposure of land-masses, such as the British Isles and the Brabant Massif, to the west and south of the Netherlands (Knox et al., 2010; Deckers & Matthijs, 2017), as well as in Mesozoic grabens in the Netherlands, such as the Vlieland and West Netherlands basins (Deckers & Van der Voet, 2018). Simultaneously, other areas such as the Central Netherlands Basin, Roer Valley Graben, Voorne Trough and local areas of the Broad Fourteens Basin experienced subsidence of depocentres that were filled with latest Danian continental deposits and/or Selandian greensands and marls (Deckers & Van der Voet, 2018). These marls consist mainly of reworked Cretaceous nannofossils from the Chalk Group (Steurbaut, 1998; Vandenberghe et al., 1998) that were probably eroded from the nearby highs. During the Laramide phase, the southern part of the Dutch Central Graben was an area of non-deposition (Van Lochem, 2018) or shallow marine environments, whereas the northern part was covered by marly clays of the deep marine (outer shelf to bathyal) Danish Våle Formation (Deckers & Munsterman, 2019).

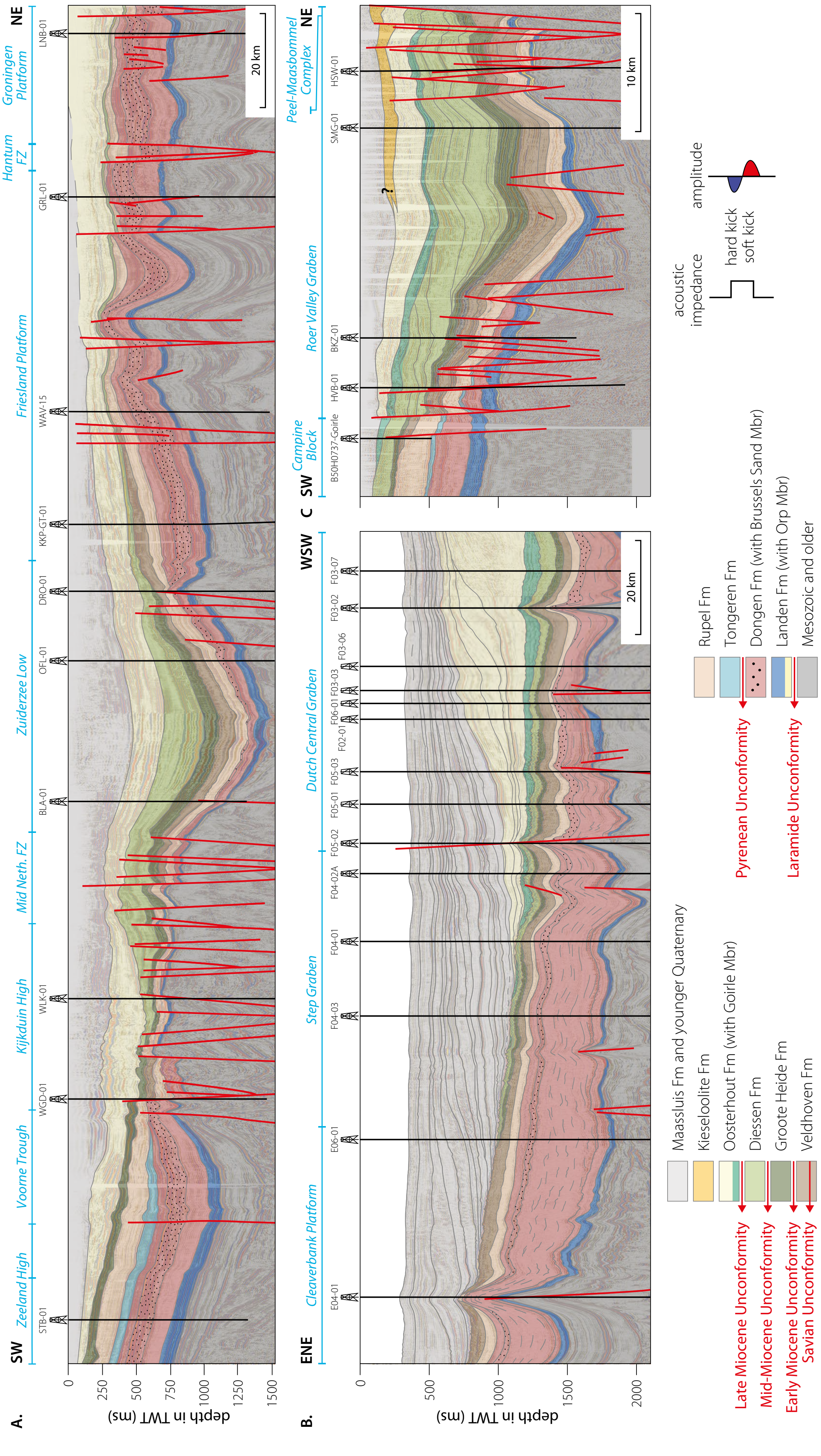
Paleoclimate- and sea-level reconstructions suggest global cooling and a progressive sea-level fall through the late Paleocene (Miller et al., 2020; Speijer et al., 2020; Hollis et al., 2021). Regional biotic and/or environmental data are very limited, but the abrupt regional disappearance of the hyposaline *Braarudosphaeracea* nannofossils in conjunction with the shift from carbonate to clastic deposition suggests a reaction to reduced precipitation (Steurbaut & Sztrákos, 2008). This could be a basin-specific response to the long-term climatic developments. The contact between the Chalk Group and North Sea Supergroup is unconformable across much of the onshore Netherlands, but is quasi conformable in the deepest parts of the offshore North Sea Basin.

Phase II – Hothouse times (Paleocene-Eocene, 62-38 Ma)

Regional tectonics and paleogeography

During the Paleocene-Eocene, tectonic regimes in NW Europe were mostly driven by progressive opening and widening of the North Atlantic Ocean that led to episodic compression and inversion pulses. By early late Paleocene times, the SNSB was marginally connected to the Paris Basin to the south, but connections became severed and only a northern Atlantic connection remained (Knox et al., 2010). At the Paleocene-Eocene transition, the inception and intensification of a mantle plume between Scotland and Iceland caused extensive regional uplift across the British Isles and the SNSB (Maclennan & Jones, 2006). Volcanoclastic remnants are well documented in the North Sea Basin (Morton & Knox, 1990; Watson et al., 2017; Van Bergen et al., 2025). In the Netherlands these are known as the De Wijk Member of the Dongen Formation (previously known as the Dongen Tuffite Member).

Over the course of the Eocene, broad thermal subsidence led to voluminous clastic-dominated deposition. In addition to the offshore SNSB, other major Paleocene-Eocene depocentres include the Voorne Trough, the Zuiderzee Low (Fig. 9.6a) and the Lauwerszee Trough. The Voorne Trough is a basin located on the southern flank of the inverted part of the West Netherlands Basin referred to as the Kijkduin High (Duin et al., 2006). The origin of the Voorne Trough is linked to the Laramide phase. A seismic profile (Duin et al., 2006) shows that the Kijkduin High is a Pyrenean inversion structure that determined the cut-off and distribution of Paleogene-Eocene deposits (and is expresed as an unconformity between the Dongen and


A.
SW
NE
Zeeland High
Voorne Trough
Kijkduin High
Mid Neth. FZ
Zuiderzee Low
Friesland Platform
Hantum FZ
Groningen Platform
STB-01
WGD-01
WLK-01
BLA-01
OFL-01
DRO-01
KKP-GT-01
WAV-15
GRL-01
LNB-01
depth in TWT (ms)
0
250
500
750
1000
1250
1500
20 km
B.
ENE
WSW
Cleaverbank Platform
Step Graben
Dutch Central Graben
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
depth in TWT (ms)
0
500
1000
1500
2000
20 km
C
SW
NE
Campine Block
Roer Valley Graben
Peel-Maasbommel Complex
B50H0737-Goirle
HVB-01
BKZ-01
SMG-01
HSW-01
10 km
?
Maassluis Fm and younger Quaternary
Kieseloolite Fm
Oosterhout Fm (with Goirle Mbr)
Diessen Fm
Groote Heide Fm
Veldhoven Fm
Late Miocene Unconformity
Mid-Miocene Unconformity
Early Miocene Unconformity
Savian Unconformity
Rupel Fm
Tongeren Fm
Dongen Fm (with Brussels Sand Mbr)
Landen Fm (with Orp Mbr)
Mesozoic and older
Pyrenean Unconformity
Laramide Unconformity
acoustic impedance
hard kick
soft kick
amplitude

Rupel formations). Their original distribution was linked to the Laramide phase and thus more widespread. This cut-off can also be seen in the Voorne Trough (see Fig. 6 of Deckers & Van der Voet, 2018).

The Lauwerszee Trough is delineated by north to northwest and east to northeast trending faults that were reactivated during the Cenozoic (De Jager, 2007). It is a distinct and long-lived feature, which is clearly expressed in the pre-Permian subcrop pattern and the increased thicknesses of the Rotliegend. Thickness trends in Lower Cretaceous and Paleogene deposits are primarily due to withdrawal of Zechstein salt into flanking salt walls associated with the eastern and western (Hantum Fault Zone) boundary faults, which grew significantly during Early Cretaceous and Cenozoic times (De Jager, 2007). The Paleogene succession in this basin is up to 1000 m thick and the whole Cenozoic succession totals more than 1750 m (see Fig. 9.3).

Regional climate

Following the abrupt environmental change and ecosystem turnover at the Cretaceous-Paleogene boundary, the Paleocene was a period of relative climatic stability, not marking a major contrast with the Late Cretaceous. Polar climates were temperate and largely ice-free (Westerhold et al., 2020). The late Paleocene is characterized by a transition towards a cooler climate. Carbon-isotope data suggest that this was a phase of excess organic-burial, perhaps related to extensive uplift and consequent development of coastal swamps during the Laramide phase (Kurtz et al., 2003). The cooling trend reversed and across the Paleocene-Eocene boundary a major change in the climate occurred. The boundary coincides with the Paleocene-Eocene Thermal Maximum (PETM), the first of a series of transient warming-events that were associated with an injection of CO_2 into the ocean-atmosphere system (Dunkley Jones et al., 2013; Westerhold et al., 2020). Current hypotheses for the sources for CO_2 include the destabilization of marine methane hydrates (Dickens et al., 1995) and/or the thermogenic release associated with contemporaneous North Atlantic volcanism (Svensen et al., 2004). The carbon cycle perturbation that characterizes the PETM is also recorded in shelf environments from the North Sea (e.g. in borehole Woensdrecht-1; Sluijs et al., 2008). These so-called hyperthermal events were superimposed on a longer time-scale increase in temperature, labelled the Early Eocene Climatic Optimum (EECO). Reconstructions of atmospheric CO_2-concentrations (Rae et al., 2021) suggest that this warmest phase of the Cenozoic is associated with a coeval maximum in CO_2 concentration that lasted for most of the early Eocene (Ypresian).

The earliest well-preserved Cenozoic floras are known only from the Paleocene in Belgium (Gelinden Member) and the climatic interpretation of these floras indicates mean annual temperatures of around 16°C and high precipitation (Tanrattana et al., 2020). Comparison with floras from France show a long-term Paleocene warming trend analogous to marine-based reconstructions of temperature. Lipid paleothermometry data from early Eocene lignites from Germany and the UK (Inglis et al., 2017; Naafs et al., 2018) show warm mean annual temperatures (MAT) of up to 23-28°C, reflecting the temperature optimum at that time. The Messel Pit, near Frankfurt is a world-famous locality providing insights into the flora and fauna of the early middle Eocene (48 Ma, Lenz et al., 2015) of NW-Europe. Quantitative analyses of the vegetation composition at Messel indicate a MAT of approximately 22°C and annual precipitation rates about three times as high as at the present-day (2540 mm/yr; Grein et al., 2011). The remainder of the Eocene experienced a gradual cooling trend (e.g. Cramwinckel et al., 2018) that was only interrupted by the Middle Eocene Climatic Optimum (MECO) (Bohaty & Zachos, 2003; Bijl et al., 2010). The long-term early Eocene warmth and subsequent cooling are generally ascribed to a change from a net-excess of CO_2 outgassing from Tethyan subductive volcanism vs. CO_2-capture due to silicate weathering (Kent & Muttoni,

← ***Figure 9.6.*** *Interpreted seismic sections across the Netherlands, illustrating the distribution of Cenozoic lithostratigraphic units in various structural elements (blue italic text) as discussed in text. Key wells (mostly energy exploration wells) used for lithostratigraphic correlation are indicated. Note that (only) vertical scales are equal. a) NE-SW section crossing the main structural elements onshore the Netherlands, illustrating how the presence, thickness and internal arrangement of the Paleogene-Neogene units was strongly controlled by several phases of subsidence and inversion of the main sedimentary basins. b) Seismic section in the northern offshore E and F blocks, showing eastward thinning and truncation of the pre-Eocene section (with internal stratal arrangement indicated with dashed lines), a relatively thin sequence of Eocene-Miocene rocks, and the strong progradational stratigraphic arrangement of seismic sequences S1-S13 (after Kuhlmann & Wong, 2008) belonging to the Pliocene-Pleistocene Eridanos shelf-edge delta system. The lower boundary of the Eridanos interval is the Mid-Miocene Unconformity (MMU sensu Kuhlmann, 2004). Note that the upper/younger part of this system continues into the Pleistocene and is discussed in Busschers et al. (2025, this volume). c) Seismic section across the Roer Valley Graben, showing the relatively thick development of Paleogene and Neogene sequences. The Diessen Formation shows several stacked clinoform sets that were deposited in a time of strong differential vertical movements that resulted in considerable deepening of the graben in Miocene times.*

2008). Over the course of the Eocene, CO_2-concentrations declined to levels that eventually allowed for full-scale Antarctic glaciation across the Eocene-Oligocene Transition (DeConto & Pollard, 2003; Pearson et al., 2009).

Depositional systems, landscape and ecosystem evolution

After the Danian the shallow marine carbonates were replaced by siliciclastic deposits. Most of the time the Southern North Sea Basin was a subtropical-tropical shelf sea bordered by coastal areas in the southern Netherlands and Belgium. Low diversity North Atlantic marine faunas from the middle Paleocene eventually gave way to the rich tropical marine biota of the middle Eocene. At the same time, life on land diversified and very rich tropical to subtropical lowland biota emerged around the southern shores of the North Sea Basin in the early to middle Eocene. During the PETM, the warming and accompanying hydrological changes caused the shallow seas of the SNSB to experience widespread anoxia (Kender et al., 2012).

For this time interval sparse and exclusively marine fossils have been recorded from outcrops and boreholes in Twente and Zeeuws-Vlaanderen as well as from some coal mine shafts in Limburg. Furthermore, Eocene fossils deposited from Quaternary rivers draining the Flemish hinterland have been found on beaches in Zeeland. In adjacent regions, such as northern Belgium, Denmark and the eastern UK, an extensive sedimentary record provides detailed insights into the regional biotic- and ecosystem evolution through this hothouse phase.

In the Paleocene Gelinden flora, mostly thermophilic *Fagaceae* and *Lauraceae* made up the evergreen forest with palms and a few conifers. Terrestrial mammal faunas diversified as did bird faunas. Along the shores of the southern North Sea large flightless birds filled the vacant niches of the large terrestrial predators, while arboreal birds diversified together with the diversification of forests (Mayr & Smith, 2019). The late Paleocene exchange with North American terrestrial biota shaped the subsequent faunas.

The early Eocene tropical climate supported coastal mangrove forests with (*Nypa*) palms and tropical ferns (*Acrostichum*). There is no direct evidence from the Netherlands, but mangrove fossils known from Belgium and Southern England reveal a very rich lowland flora (Kvaček, 2010). From the London Clay in the southern UK over 350 species of plants have been identified. Fossil forest remains from Hoegaarden (Belgium) show that swamp forests with cypress trees, so typical of Neogene lignites, were already present in the lowlands of the SNSB during the EETM (Fairon-Demaret et al., 2003)).

Benthic marine communities during the Selandian-Thanetian (mid-late Paleocene) were relatively species-poor in the Southern North Sea Basin, which at that time extended into the northern Paris Basin. The Ypresian (early Eocene) saw the rise of rich tropical marine and terrestrial biota. The presence of nummulitids (larger foraminifera that host endosymbionts) in the Ieper Group of Belgium indicate very warm shallow marine conditions and most likely some connection towards more southerly Atlantic basins. A very widespread transgression resulted in the almost entire drowning of the North Sea Basin and the Netherlands must have been fully overlain by sea.

The early Lutetian is represented by the fossiliferous lower part of the Brussels Sand Member in the shallow subsurface of Zeeuws-Vlaanderen. In the region between Gent and Brugge this unit is known as the Oedelem Member and crops out extensively. Fossil shells and shark teeth eroded from this formation are well known from beaches such as at Cadzand. Truly tropical marine faunas occurred in the middle Eocene (Lutetian-Bartonian) as shown for example by the occurrence of very large *Campanile* gastropods in western Belgium and the Dutch offshore sector (Wesselingh et al., 2013). During the Bartonian, marine ecosystems in the Netherlands were dominated by fine-grained sandy and clayey sea floors and little of the fauna was preserved here. The middle to late Eocene floras regionally show a decline in diversity due to climatic cooling (Kvaček, 2010), but they are not preserved in the Netherlands.

Lithostratigraphy

The interacting climate, tectonic and depositional regimes resulted in the formation of a series of units that are most distinct in the coastal regions, but which shale-out towards the central North Sea where they become amalgamated within the Lower North Sea Group. The lithological succession of the Lower North Sea Group consist of an alternation of predominantly marine grey sands, sandstones and clays. The total thickness is up to ~650 m. In large parts of the LNSG the lower boundary is characterized by an unconformity (Laramide tectonic phase), expressed as a sharp lithologic break marking the top of the calcareous Chalk Group. Elsewhere, the group rests with a distinct unconformity on even older deposits. The upper boundary is defined by unconformably overlying deposits of the Middle North Sea Group or younger units and corresponds to the Pyrenean tectonic phase. The Lower North Sea Group comprises the Landen and Dongen formations.

Landen Formation

In the southern part of North Brabant and in Limburg (basin fringe), the Landen Formation (Fig. 9.7) starts with dark green-grey, fine-grained glauconitic sand (Orp Member) followed upward by light-grey marl (Gelinden Member) with dark green-grey clay at its base (Liessel Member). These become less limey and more sandy up-

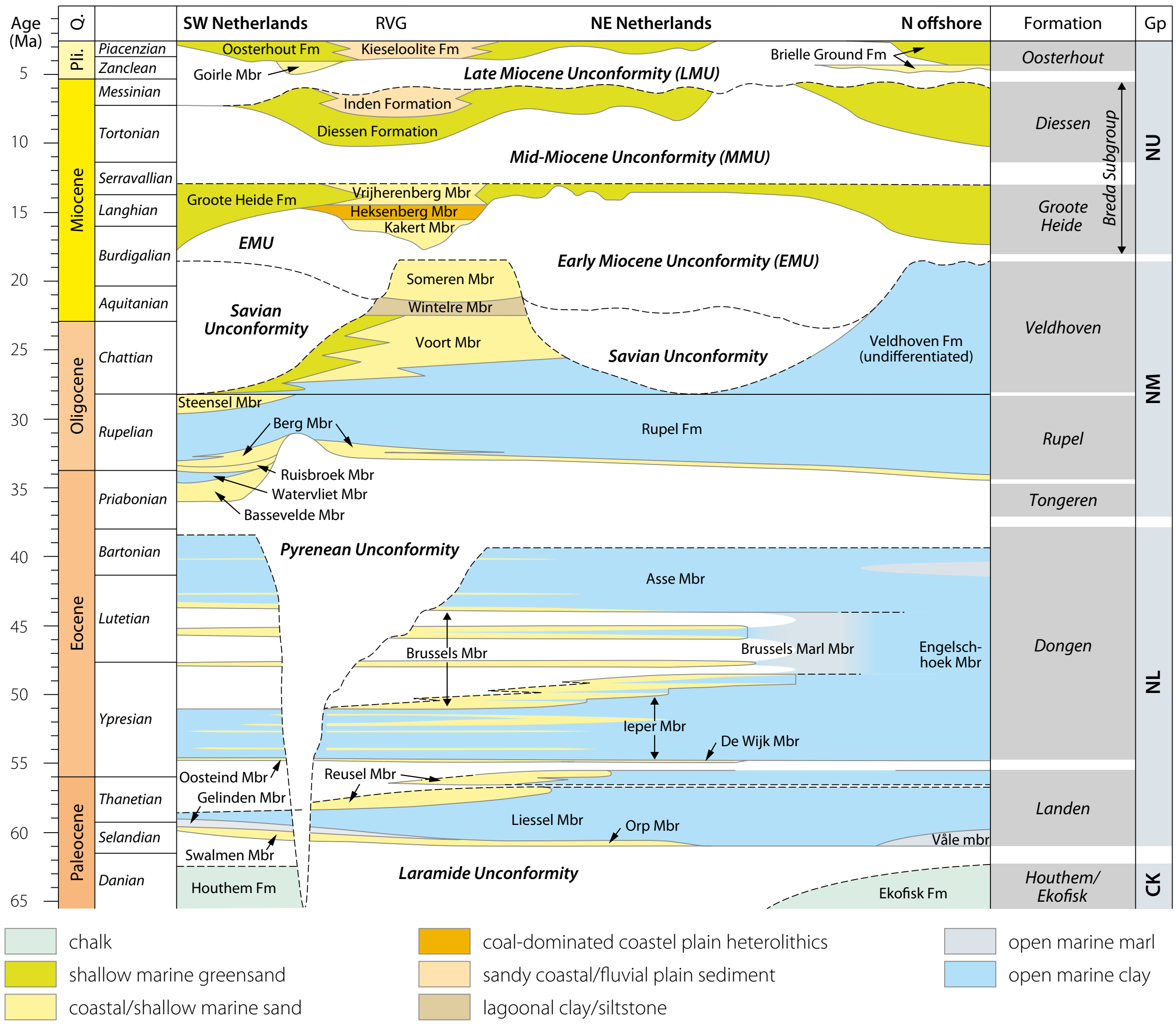


Figure 9.7. *Stratigraphic scheme (Wheeler diagram) of the Lower (NL), Middle (NM) and Upper (NU) North Sea groups in the Netherlands (with exception of the Quaternary interval). The scheme corresponds to seismic lines shown in Fig. 9.6. Hiatuses are linked to major unconformities as discusses in text. The figure is partly based on Van Adrichem Boogaert & Kouwe (1997) and De Mulder et al. (2003). Stratigraphic codes are conform the Dutch Stratigraphic Nomenclator (www.dinoloket.nl). CK = Chalk Group; RVG = Roer Valley Graben.*

wards and in turn are overlain by sandy clay with fine-grained sandy intercalations (Reussel Member). Locally, in the north of Limburg, variegated clay and minor sand occur. Further north (more distally), the formation consists exclusively of grey to greenish-grey clays with local marl intercalations (Liessel Member), particularly in the basal part. Initially, the overall depositional setting was shallow-marine and later changed to open-marine conditions. The maximum water depth may have reached several hundreds of metres in the central parts of the basin. An exception is the Swalmen Member at the base of the Landen Formation that is locally present in the south of the Netherlands and possibly in the Central Netherlands Basin (Deckers, 2015) and which was deposited in a lagoonal, brackish to non-marine environment. The upper part of the formation consists of mid-late Paleocene regressive sands up to 300 m thick, probably related to NW-SE oriented prograding deltaic lobes, which locally led to brackish conditions.

Recently the Våle member, as lateral equivalent of the Våle Formation in Denmark and Norway and the Maureen Formation in the UK, was proposed to represent the basal late Danian-Selandian interval of the Landen Formation (Deckers & Munsterman, 2019; Fig. 9.8). In an area that spans over 100 km in the northernmost offshore Netherlands, marly claystones to marlstones form a transitional interval up to over 30 metres thick, sandwiched between the calcareous coccolithic mudstones of the Ekofisk Formation and the claystones of the Liessel Member (Landen Formation). The latest Danian and Seelandian successions in the North Sea Basin contain significant amounts of reworked Cretaceous fossils, due to the erosional effects of the Laramide phase (Clemmensen & Thomsen, 2005). At the southern margin of the SNSB, abundant reworked fossils are recorded in the Gelinden Member (Vandenberghe et al., 1998). The newly named Våle member is the lateral, deep marine equivalent of the shallow marine Orp and Gelinden members (Fig. 9.8). The Landen Formation unconformably overlies the chalks of the Ekofisk and Houthem formations or older units. The lower boundary is expressed as a sharp break in lithology and log signature. The upper boundary is marked by the transition to the sand-prone Oosteind or De Wijk members of the Dongen

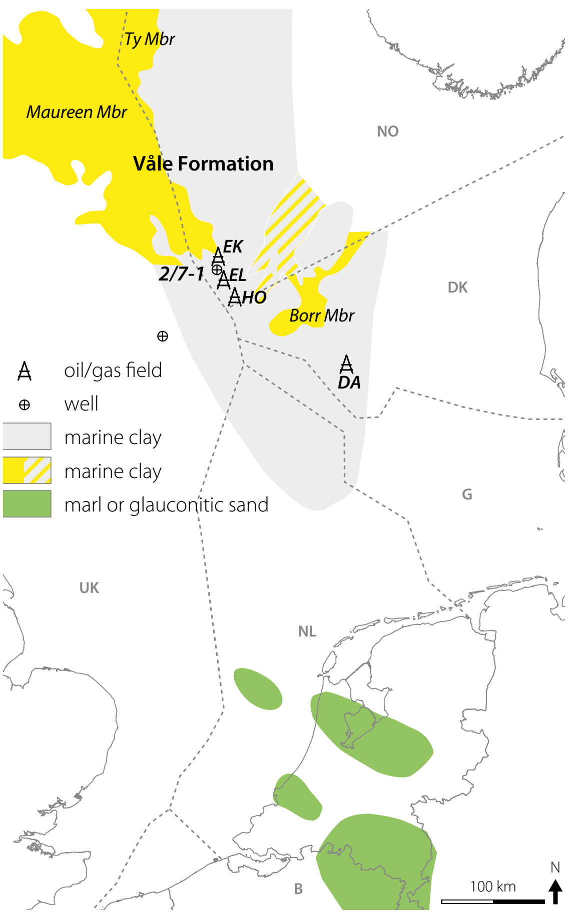


Figure 9.8. The North Sea Basin with the middle Paleocene distal Våle Formation and the more proximal Orp and Gelinden members. In the Dutch northern offshore, the marine clay (grey color) is proposed to represent the Våle member within the Landen Formation. The location of the sandy members of the Våle Formation is indicated in yellow and based on Brunstad et al. (2013). The geographic extents of the middle Paleocene sandy units in the Netherlands units were taken from Deckers & Van der Voet (2018).. The location of several of the major hydrocarbon fields in the Chalk Group (EK= Ekofisk, EL=Eldfisk, Ho=Hod, DA= Dan) and reference well 2/7-1 are indicated.

Formation, which overlie the clays of the Landen Formation with a sharp contact. In the southern Netherlands, the boundary is less evident because sands of the Reussel Member are intercalated with sands of the Oosteind Member (Dongen Formation) and a distinction can only be made on biostratigraphical grounds. Particularly southeast of the Tilburg-Den Bosch area, the Dongen Formation is absent below the Pyrenean Unconformity. Here, the Landen Formation is unconformably covered by sandy deposits of the Tongeren Formation or the Rupel Formation.

Dongen Formation

The lowermost part of this formation is represented by the De Wijk Member, which consists of tuffaceous clays and silts that grade into fine-grained sands in more proximal positions of the middle and southern parts of the Netherlands. The depositional setting is inner to outer neritic with a transgressive basal part of glauconitic fine sands (Oosteind Member). The Ieper Member comprises dark-grey, green and brown, slightly calcareous clays, with intercalated glauconitic sands. Distally these sands grade into marly sediments. Apart from near-shore and inner-neritic conditions also estuarine conditions are interpreted for the Lutetian Brussels Sand Member Above the Brussels Sand, dark greenish-grey and blue-grey clays of the Asse Member indicate a return to full marine conditions. In a more proximal setting, the Maldegem Formation, the Belgian lateral equivalent of the Asse Member, includes sandy intercalations. In distal settings the Brussels Sand Member is absent and a continuous sequence of marine clays exists (Engelschhoek Member). The age of the Dongen Formation is early-middle Eocene and its thickness is up to 850 m.

Generally, the lowermost boundary is characterized by a sharp transition from the clay of the Liessel Member to the sandy or tuffaceous base of the Dongen Formation. The latter appears to be synchronous with the PETM, during which significant flooding occurred through thermal expansion of sea-water, and which can be recognized by the acme of the dinoflagellate cyst *Apectodinium* (Sluijs et al., 2008). Outside the major depocentres, the PETM is manifested as a thin (1-2 m thick) but distinct clay layer that rests on top of the Landen Formation, but in the major depocentres, the lithological signature of the PETM flooding is less prominent due to a combined increase in accommodation space and sediment supply. Also, in the southern Netherlands, where the underlying Landen Formation has a regressive sandy top, the boundary is less clear. In the easternmost parts of the provinces of Gelderland and Overijssel, the formation unconformably overlies Mesozoic deposits. In areas where the succession is virtually complete, the upper boundary of the formation is marked by an usually clear transition from its upper argillaceous part (Asse Member) to the unconformably overlying sands of the Berg Member of the Rupel Formation. Around the eroded Kijkduin High and its north-western extension into the North Sea, an unconformable contact with the overlying formations exists. Locally the Asse Member may be absent and calcareous sands of the Brussels Sand Member are directly overlain by slightly calcareous to non-calcareous sands of the Berg Member (Rupel Formation; Fig. 9.7). Due to erosion during the Pyrenean phase, multiple lithostratigraphic units may be missing. Northward increase of erosion towards the Roer Valley Graben (Deckers et al., 2015) is shown by progressive removal of the Asse and Brussels Sand members and eventually erosion down into Cretaceous successions (Fig. 9.6). Similar erosion can be seen on the southern edge of West Netherlands Basin. In those areas where the Berg Member is absent, the Boom Member rests directly on the clays of the Asse Member (Dongen Formation) and in these cases, determination of the boundary on lithological grounds may be difficult. However, on wire-line logs the Boom Member shows a somewhat higher gamma-ray response compared to clays of the Lower North Sea Group.

Phase III – Ups and downs of the middle Cenozoic (late Eocene-Middle Miocene, 38-12 Ma)

Regional tectonics and paleogeography

Phase III is bounded by the Pyrenean and MMU tectonic phases. The Pyrenean inversion affected the West and Central Netherlands basins, the southern part of the Broad Fourteens Basin (Van Wijhe, 1987) and the Roer Valley Graben (Deckers, 2015) and was restricted to the southern North Sea (Michon et al., 2003). The Pyrenean inversion caused broad basin uplift. Most of the inverted parts of the West and Central Netherlands basins were subjected to erosion during the late Oligocene Savian inversion as well. Uplift and erosion associated with the Pyrenean inversion is in the order of 400 m, whereas the effects of the Savian inversion are approximately 100 m. Broad uplift of the West Netherlands Basin occurred at the Mid-Netherlands Fault Zone, forming the Kijkduin High in the late Eocene. The Savian inversion, which is very conspicuous in the West Netherlands Basin (De Jager, 2007; Fig. 9.6), barely influenced the Broad Fourteens Basin and had no effect in the Roer Valley Graben (Munsterman & Deckers, 2022). The strong inversion of the Mesozoic West and Central Netherlands basins during the Pyrenean and Savian phases leaves a preserved Cenozoic succession of 500 m maximally, i.e. far less compared to the 1000 m in the northern part of the non-inverted Broad Fourteens Basin (Knox et al., 2010).

The Roer Valley Rift System (RVRS) developed from the late Oligocene onward and consists of several structural elements (Geluk et al., 1994). To the northwest, the rift system steps over to the West Netherlands Basin. At a regional scale, the Roer Valley Rift System is delineated by NW-SE and NNW-SSE faults that represent reactivated Variscan structures (e.g. Ziegler, 1990). Blocks of intermediate subsidence or uplift flank the central Roer Valley Graben on both sides. In the southwest, these areas are the Eastern and Western Campine Blocks, while the Venlo, Peel and Köln Blocks are recognized in the northeast (Geluk et al., 1994). The Campine Block is separated from the subsiding Roer Valley Graben by the Feldbiss Fault System (Dusar et al., 2001). The deepest part of the Venlo-Peel Block is often referred to as the Venlo Graben (Van den Berg, 1994). The Peel Block has been uplifted ~1000 m along the NW-SE oriented Peel Boundary Fault. The Tegelen Fault separates the Peel Block from the Venlo Block (Van Adrichem Boogaert & Kouwe, 1997). The Viersen Fault is the principal displacement zone that separates the Venlo Block from the Krefeld Block to the northeast. Before rifting started, the Roer Valley Rift System area subsided uniformly until it was interrupted by middle-late Eocene inversion movements and erosion related to the Pyrenean tectonic phase (Letsch & Sissingh, 1983). In the Chattian, rifting became evident in the southern Netherlands (Demyttenaere, 1989; Geluk et al., 1994) and resulted in differential subsidence of the various blocks in the Roer Valley Rift System (Michon et al., 2003; Munsterman & Brinkhuis, 2004). The rifting was accompanied by sinistral strike-slip faulting that led to a southeastward translation of the Roer Valley Graben relative to the Peel Block (Geluk et al., 1994). A strong eustatic sea-level drop apparently occurred at the Rupelian-Chattian transition (e.g. Hardenbol et al., 1998; Van Simaeys et al., 2004) and led to substantial erosion of the top sets of the latest Rupelian highstand system tracts.

Śliwinska et al. (2014) showed that the base of the Chattian is synchronous with the Oxygen index-2a cooling event around 28.3 Ma (Vis et al., 2016). Hence the recorded unconformity at the base of the Chattian deposits in the North Sea Basin is not related to a glacio-eustatic sea-level fall linked to the Oi-2b cooling event, because calcareous nannofossils indicate a younger (early Chattian) age for this cooling (Van Adrichem Boogaert & Kouwe, 1993; Clausen et al., 2012; Śliwinska et al., 2014). Following the base-Chattian tectonic event, a progressive, probably eustatic, sea-level rise led to widespread marine transgression. Warm-water faunas with affinities to those of both the Atlantic and Tethys oceans (Janssen, 1979) indicate renewed connections with the marine domain to the west and south. Connection with the Tethys Ocean via the Upper Rhine Graben can be ruled out, as paralic and non-marine environments prevailed in the graben throughout Chattian times (Sissingh, 2006). However, a connection with the eastern Paratethys via the eastward

Moravian Seaway seems possible, as sediments of Chattian age in southwest Poland consist of marine glauconitic sands (Knox et al., 2010). The Roer Valley Graben and the Lower Rhine Graben developed as nearshore depocentres during the Chattian (Figs 9.7, 9.9). In the northern, western and eastern parts of the Netherlands, the marine Chattian (Voort Member) is believed to be largely absent, either due to non-deposition, synsedimentary uplift or later erosion (Zagwijn, 1989; Fig. 9.7). In large parts of the western Campine area, most of the (upper) Chattian and Aquitanian strata have been removed during both the Savian and EMU phases and sometimes only a single gravel bed remains at the base of the Miocene (Louwye, 2005; Munsterman & Deckers, 2020). This hiatus is known from large parts of the North Sea Basin and is related to the Savian tectonic phase (Utescher et al., 2000; Wong et al., 2001; Verbeek et al., 2002; Munsterman & Brinkhuis, 2004; Knox et al., 2010; Rasmussen et al., 2010; Eidvin et al., 2014; Dybkjær et al., 2020). Around the Oligocene/Miocene boundary a glacio-eustatic sea-level fall coupled with the Savian phase (e.g. Beddow et al., 2018; Miller et al., 2020; Steinthorsdottir et al., 2021b) was most likely responsible for development of restricted marine conditions in the strongest subsiding areas. Non-deposition or erosion occurred in the surrounding highs such that isolated (sub)basins were created. The younger EMU is mainly seen as a regional onlap/baselap surface and represents a small hiatus that covers the mid-Burdigalian (Munsterman et al., 2019). Outside the main depocentres, the EMU is often combined with the Savian Unconformity and the hiatus spans the Chattian-Early Miocene period. In the Achterhoek, for instance, the Miocene sequence directly overlies the Rupel Formation. During the subsequent Burdigalian-Langhian sea-level rise, the area of marine sedimentation increased compared to the Chattian. Marginal to shallow marine successions of the Groote Heide Formation were deposited over most of the Netherlands except the southwesternmost parts. During the Neogene, progressive uplift of the Ardennes and the Rhenish and Bohemian massifs resulted in increased clastic influx into the North Sea Basin.

Regional climate

Global climate in this period changed from a warm, 'greenhouse' world with very little ice towards an 'icehouse' world characterized by significant ephemeral Antarctic ice-sheets and sea-level fluctuations (Zachos et al., 2008; Westerhold et al., 2020). In the early Oligocene, the first substantial Cenozoic ice build-up on Antarctica caused shallow marine and lowland areas to experience notable orbitally-controlled glacioeustatic sea-level oscillations. These led to distinct and laterally persistent metre-scale alternations of shallow marine silt- and claystones in the Rupelian deposits at the southern margin of the SNSB (Abels et al., 2006). The early Oligocene temperature decline is reflected in the paleobotanical record of western Europe by a ~2.5°C cooling and increased seasonal contrast (Utescher et al., 2015). Chattian pollen-based data and $\delta^{18}O$ values of fossil bivalve shells and shark teeth show further evidence for cooling in both the marine and terrestrial environments (Walliser et al., 2016), as well as some evidence for associated precipitation decline (Utescher et al., 2015). Towards the Miocene, climate experienced a renewed warming phase.

At the end of the late Eocene-Middle Miocene phase III, a prominent period of global warmth named the Miocene Climatic Optimum (MCO) occurred. This period lasted from 17 to 14.5 Ma. The MCO world became 7-8°C warmer than present day with atmospheric CO_2 concentrations of ~500-600 parts per million (Steinthorsdottir et al., 2021a,b), possibly even more. Most regional and local climate information is based on fossil assemblages but few recent studies use microbial cell membrane lipids to reconstruct surface water temperatures. Such 'lipid paleothermometer' data, for instance, have been used in reconstructions from the west coast of Ireland and suggest sea surface temperatures of over 26°C during the MCO (Sangiorgi et al., 2021). Records from the Danish North Sea (Herbert et al., 2020) also suggest that Miocene sea surface temperatures were 11-20°C higher than modern mean annual temperatures at ~55°N. Terrestrial climate reconstructions from marginal marine deposits in the SE Netherlands show equally high temperatures (Donders et al., 2009). A MCO record from Denmark based on plant fossil data suggests that maximum mean annual temperatures varied mostly between 17-20°C and that there was little or no winter frost (Larsson et al., 2011). These temperatures are much higher than at present but remain significantly lower than the lipid-based estimates, which only show some indication for a bias to the summer season (Sangiorgi et al., 2021). Precipitation was generally high, exceeding 1200 mm/year (Larsson et al., 2011). All available records show that long-term temperature decline started at about 14 Ma and that, within the age uncertainties, several cooling phases were associated with increases in Antarctic ice build-up and global-scale reorganization of carbon cycling and ocean circulation. Despite such cooling events, the stratigraphic records in the southern Netherlands (Deckers & Munsterman, 2020) and Denmark (Rasmussen, 2004) indicate renewed transgression of the margins of the North Sea Basin after the MCO in the Serravallian.

Depositional systems, landscape and ecosystem evolution

During the Priabonian-Rupelian the preceding rich tropical marine faunas were entirely replaced by lower diverse communities. From the Chattian onwards, an increasingly rich and endemic marine North Sea biota evolved that culminated in the very rich 'paratropical' middle Miocene faunas. Subtropical lowland swamp ecosystems started to develop in the Lower Rhine Graben to the east of Limburg (Huhn et al., 1997; Utescher et al., 2021). Important sites covering this phase in the Netherlands are isolated occurrences of the Goudberg Member around Valkenburg and Rupel Formation outcrops near Meerssen (Limburg) and Winterswijk (Herngreen et al., 2005). The middle Miocene is particularly well known from outcrops near Winterswijk. Important regional information on the Priabonian-Rupelian comes from extensive outcrops in northern Belgium. Mine shafts around Krefeld (Germany) have disclosed important marine Chattian successions. Miocene terrestrial and coastal deposits are found in the lignite mines of Nordrhein-Westfalen, while extensive fossiliferous marine localities are known from the Antwerp region and from isolated outcrops and boreholes in northern Germany and Denmark (Schwarzhans, 2010; Larsson et al., 2011; Utescher et al., 2015).

The Priabonian-Rupelian transition in the Southern North Sea Basin is marked by a series of Milankovitch related transgressions and regressions culminating in widespread outer-shelf marine settings of the Boom Clay covering the entire Netherlands. Initially, an intermediate diverse para-tropical biota (Marquet, 2016) reminiscent of the earliest Oligocene faunas developed. It is found in the Belgian Grimmertingen Sands (a lateral equivalent of the Dutch Tongeren Formation), which are preserved in some of the mine shafts in Limburg. In overlying deposits, diversity levels drop (Marquet & Herman, 2012) and successions contain low diverse near-shore communities with intermittent tropical cerithiid snail communities dominating the brackish coastal zone (Fairon-Demaret et al., 2003; Marquet, 2016). During the Rupelian, much of the Southern North Sea Basin drowned and extensive deeper marine clays of the Rupel Formation (Boom Member) were deposited that contain mollusc, fish and microfossil assemblages representing neritic environments. Faunas were not particularly diverse (Marquet & Herman, 2012). During this interval, most of the Netherlands became covered by the Rupel Sea. A major terrestrial faunal transition known as the 'grand coupure' extinction phase, took place around 33.5 Ma when endemic European mammal species became extinct and new groups immigrated from Asia. It is preserved in the famous Hoogbutsel locality in the Belgian province of Brabant (Smith & Smith, 2003). Forested coastal wetlands existed at that time around the North Sea with a wealth of fish, reptilians and amphibians, birds and mammals.

The Rupelian-Chattian boundary marks a major shift in ecosystems and biota. In general, it is represented by a regional unconformity that is attributed to renewed tectonic activity coupled with a glacially induced sea-level fall (Oi-2a event of Miller et al., 2008). The cooler conditions of the Chattian are reflected in more drought-tolerant taxa and an overall decline in evergreen broadleaved elements. From the Chattian to the Middle Miocene, extensive coastal lowland swamp ecosystems developed at times in the Lower Rhine Graben in Nordrhein-Westfalen, and some isolated *Taxodium* macrofossils are known from isolated outcrops in the Sittard area. Following the base Chattian tectonic event, a progressive – probably eustatic – sea-level rise led to a marine transgression. Warm-water faunas with affinities to those of both the Atlantic and Paratethys (Janssen, 1979) indicate renewed connections with marine waters to the west and south. A connection of the SNSB to the eastern Paratethys via the Moravian Seaway seems possible. Widespread shelfs developed with very rich shallow marine algal, seagrass and soft bottom communities that included a rich endemic North Sea marine mollusc fauna (Welle, 1997; 1998) as well as Sirenians and archaic whales (Diedrich, 2012). The rich subtropical marine assemblages with their very diverse endemic invertebrate and fish lineages continued through the Early Miocene into the Middle Miocene when they diversified even further (Janssen, 1984; Schwarzhans, 2010). During the Burdigalian stage additional tropical marine groups (molluscs, fish) that originated from more southerly Atlantic regions such as the Aquitaine Basin in France appeared in the North Sea Basin, suggesting a possible direct marine connection to the south (Janssen, 2001; Schwarzhans, 2010). Rare Paratethyan fish species in these Middle Miocene faunas imply limited connection with the Middle Miocene (Badenian) Paratethyan seas, yet no evidence for large scale faunal exchange exists. The Middle Miocene marine biota were very species rich: in the famous locality of Miste near Winterswijk, over 500 species of molluscs are found (Janssen, 1984).

Later in the Burdigalian, a coastal lowland system with freshwater marshes and swamps (Ville Formation) prograded from Germany into the Netherlands and preserves the remains of rich assemblages of subtropical and warm temperate plants and animals, including straight-tusked elephants and tapirs. The subsidence of extensive wetlands resulted in thick lignite deposits in the Lower Rhine Graben that extend into the southeast of the Netherlands. Near Kerkrade in South Limburg, Middle Miocene browncoals of the Ville Formation contain a rich palynoflora (Manten, 1958), but most information in the Netherlands comes from boreholes. The peat-forming taxa included wetland forest trees that are presently limited to SE Asia and the SE USA. The lowland swamp environments were dominated by cypress (*Glyptostrobus* and *Taxodium* species) and umbrella pine (*Sciadopitys*, currently confined to

Japan) together with other extant conifer taxa and diverse angiosperm shrubs and trees such as ash and oaks (Figueiral et al., 1999; Utescher et al., 2017, 2021; Mosbrugger et al., 2022). From the German lignite mines extensive flora and fauna has been collected that show a lowland subtropical swamp biota with intermittent shallow marine species such as dolphins (Mörs, 2002). The lignite swamp forests were inhabited by diverse fish, amphibians and reptiles including aquatic and terrestrial crocodiles and turtles, as well as very diverse mammal communities that included a range of small mammals, commonly beavers, but also larger-sized groups such as primates, carnivores, deer, horses and elephants.

Lithostratigraphy

Phase III is delimited by the Pyrenean tectonic phase and the Middle Miocene Unconformity (MMU) and is represented by the entire Middle North Sea Group and the lower part of the Upper North Sea Group. This interval includes the Tongeren, Rupel, Veldhoven, and Groote Heide formations (Figs 9.1, 9.7). The thickness of this interval is minimally 700 m and decreases towards the northwest, i.e. the centre of the Southern North Sea Basin.

The Tongeren Formation

The new Dutch Stratigraphic Nomenclature Online (Dinoloket, 2021) integrated two earlier versions for the deep (Van Adrichem Boogaert & Kouwe, 1997) and shallow subsurface (Rijsdijk et al., 2005) of the Geological Survey of the Netherlands. The distribution of the Tongeren Formation was originally restricted to the southern part of the province of Limburg (SE Netherlands) but has been extended to the southern part of the province of Zeeland (SW Netherlands). The depositional setting of the Tongeren Formation is interpreted successively as a shallow-marine and lagoonal to coastal-plain. In the SE part of the Netherlands the formation is split into the Klimmen Member (clayey sands) followed by the Goudsberg Member (clays). In the southwestern part of the Netherlands a tripartition into the Bassevelde (grey sands), Watervliet (clays) and Ruisbroek (green-grey glauconitic sands) members is made. The Tongeren Formation unconformably overlies the Dongen Formation or older deposits. The upper boundary is sharp when overlain by fluvial sands and gravels or eolian sediments of the Upper North Sea Group, but gradual when overlain by transgressive sands and clays of the Rupel Formation. The thickness is up to 60 m and the age is Priabonian to earliest Rupelian. In the southwestern part of the Netherlands, the unit contains reworked middle Eocene sediments suggesting that the Tongeren Formation developed during the Pyrenean tectonic phase, south of the main inversion axis of the Kijkduin High. Also in Belgium just to the southwest of the Netherlands, Priabonian sands were deposited during the Pyrenean inversion as supported by changes in clay mineral associations (Saeys et al., 2004).

Rupel Formation

The Rupel Formation has recently been updated and revised (see www.dinoloket.nl). The lithology is described as heavy, dark brown-grey silty clays, rich in pyrite and relatively glauconite-poor. Towards both base and top, the clays grade into silts and rather abruptly into sands along the southern basin margin (Vis et al., 2016). The basal sands are transgressive (Berg Member). In Flanders, the Berg Member passes northwestwards into the Belsele-Waas Member, which is silty. This may explain the local occurrence of the Berg Member at the base of the Rupel Formation, where flint pebbles and phosphorite nodules commonly occur. In the SE part of the Netherlands these sands are followed by laminated clays (Kleine Spouwen Member) and white sands with clay layers (Waterval Member). The clayey Boom Member contains septarian carbonate concretions often documented from Belgian quarries (De Craen et al., 1999). Middle to outer neritic marine conditions are interpreted for the clays (water depths over 200 m). At the top of the formation an alternation of sands and silty clays grade upward into sands (Steensel Member). The latter unit is of shallow to marginal marine origin. The thickness of the formation is up to 125 m and the age is early Oligocene (Rupelian). The Rupel Formation unconformably overlies the Tongeren Formation, the Dongen Formation or older sediments. In those areas where the sandy development at the base is missing, the clays of the Rupel Formation rest directly on the Asse or Engelsche Hoek members, which complicates definition of the boundary. However, on wire-line logs, the Rupel clays show a somewhat higher gamma-ray response compared to the clays of the Lower North Sea Group. Biostratigraphic data may assist in establishing this lower boundary. In the central and eastern Netherlands, and in parts of the northeastern offshore the Rupel Formation is conformably (or mildly unconformably) overlain by the sands and silty clays of the Veldhoven Formation. In the southern Netherlands the latter has a typical, thin clay interval at its base. The upper limit is usually sharp in those parts of the Netherlands where the Rupel Formation is partly eroded (e.g. on the Middle Netherlands High between the cities of Nijmegen and Leiden) and is overlain by the Groote Heide Formation.

Veldhoven Formation

The Veldhoven Formation overlies either the Steensel Member or Boom Member of the Rupel Formation with a minor unconformity. The base of the formation is marked by a distinct clay layer. It is overlain by the Groote Heide

Formation from which it is separated by the Early Miocene Unconformity. Outside the Roer Valley Graben and the Venlo Block, the EMU represents a distinct and sometimes angular unconformity that encompasses the late Burdigalian (Munsterman et al., 2019). The age of the Veldhoven Formation is Chattian-Early Miocene. The thickness may reach over 400 m. In the Roer Valley Graben the formation predominantly comprises light grey to green grey, very fine-grained, micaceous sand (Voort Member) followed by (dark) green-grey sandy clay (Wintelre Member) that coarsens upward into sands (Someren Member). In general, the depositional setting was shallow-marine. In contrast to earlier interpretations, the increase in clay of the Wintelre Member (formerly Veldhoven Clay) is now attributed to a shallowing towards restricted marine conditions instead of an increase in sea-level. Munsterman & Deckers (2022) claim that these clays can be distinguished from clays intercalated in the Voort Member by a higher concentration of shells, as is recorded in the lithological description of the Groote Heide borehole. Dinoflagellate cyst assemblages are here dominated by a single genus indicating extreme depositional environments, with salinities that deviate from normal marine conditions, most probably due to periodic minor connection to the Atlantic Ocean. The glacioeustatic sea-level fall of 50-70 m around the Oligocene/Miocene boundary most likely limited sea coverage to the strongest subsiding areas, where deposition of the Wintelre Member took place. Non-deposition or erosion occurred in the surrounding highs, hence creating an isolated (sub)basin (e.g. Miller et al., 2020; Steinthorsdottir et al., 2021b). The most recent depositional interpretation places the Wintelre Member around the Oligocene/Miocene boundary as a restricted marine facies related to this sea level fall in concert with the Savian inversion tectonics (Dybkjær & Rasmussen, 2007; Dybkjær et al., 2012; Munsterman & Deckers, 2022). This is in accordance with the eustacy based model of Hager et al. (1998) and disproves the sedimentological 'dynamic' infill model put forward by Schäfer et al. (2005) and Wong et al. (2007). The North Sea Basin probably became a (semi-)enclosed basin during the latest Oligocene-earliest Miocene, with a narrow connection to the North Atlantic Ocean between the Shetland Isles and Norway (Rasmussen et al., 2008; Knox et al., 2010).

Groote Heide Formation

The recognition of an intraformational hiatus within the former Breda Formation (known as the Mid-Miocene Unconformity) led to a decision to split the formation. As a result, the Breda Formation was promoted to Subgroup, of which the part between the EMU and MMU was defined as the Groote Heide Formation and the part between the MMU and LMU as the Diessen Formation (Munsterman et al., 2019; Figs 9.1, 9.7). The age of the Groote Heide Formation is late Burdigalian-Serravallian and the thickness is up to 200 m. The formation comprises greyish to blackish green silts and very fine to medium sands that can be (very) glauconitic, calcareous, and locally micaceous or organic. Sandy to moderately silty clays are also present. The presence of glauconite is very characteristic of the formation, except for the deposits that developed in coastal settings. In the province of Zeeland and in the western part of North Brabant, moderately fine- to moderately coarse-grained glauconite-rich sands occur. On the Peel Horst, i.e. the northern rift shoulder of the Roer Valley Graben, the deposits are generally fine-grained and include mica flakes. Within the Roer Valley Graben and Venlo Slenk the formation also contains organic material. In the eastern part of the Netherlands the formation has sand-clay alternations with varying glauconite content and goethite and phosphorite concretions. In the offshore centre of the North Sea Basin, the Middle Miocene sequences are often very condensed into glauconitic clays (Rasmussen & Dybkjær, 2014).

The Groote Heide Formation was deposited in a shallow-marine environment, except at its easternmost edges where (near)coastal sedimentary facies occur. The glauconitic content of this coastal facies is markedly lower than in the remainder of the formation. In the southeastern part of the Netherlands shallow marine fine sands of the Kakert Member form the base of the formation. In the northern part of the Roer Valley Graben and in the Venlo Graben, the gravelly Elsloo Bed (Zagwijn & Van Staalduinen, 1975; Kuyl, 1980) marks the transition of the Someren Member to the Kakert Member and represents a winnowed interval corresponding to the EMU. In the Achterhoek, the base of the Miocene is represented by the Miste Bed that unconformably overlies the Rupel Formation and contains reworked phosphoritic pebbles and nodules and contains Chattian and Early-to-middle Middle Miocene reworked taxa (Janssen, 1984). In the Limburg area, the Kakert Member is succeeded by pure quartz sands of the Heksenberg Member (locally known as 'silver sands') that were deposited in a coastal setting. At the lower boundary of the member, sandy coastal prisms with thin lignite layers are locally present that correlate with the Morken Seam of the Ville Formation (Fig. 9.9). The Belgian Genk Sands are considered equivalent to the Dutch Heksenberg sands (Vandenberghe et al., 1998) and both are laterally equivalent to regionally widespread lignite seams of the Frimmersdorf Seam (Van Adrichem Boogaert & Kouwe, 1997). Following the Serravallian transgression, the Heksenberg Member passes up into brownish-yellow to green-grey fine sands and silts that belong to the Vrijherenberg Member, laterally equivalent to the Neurath Sand in Germany (Prinz et al., 2017). In the

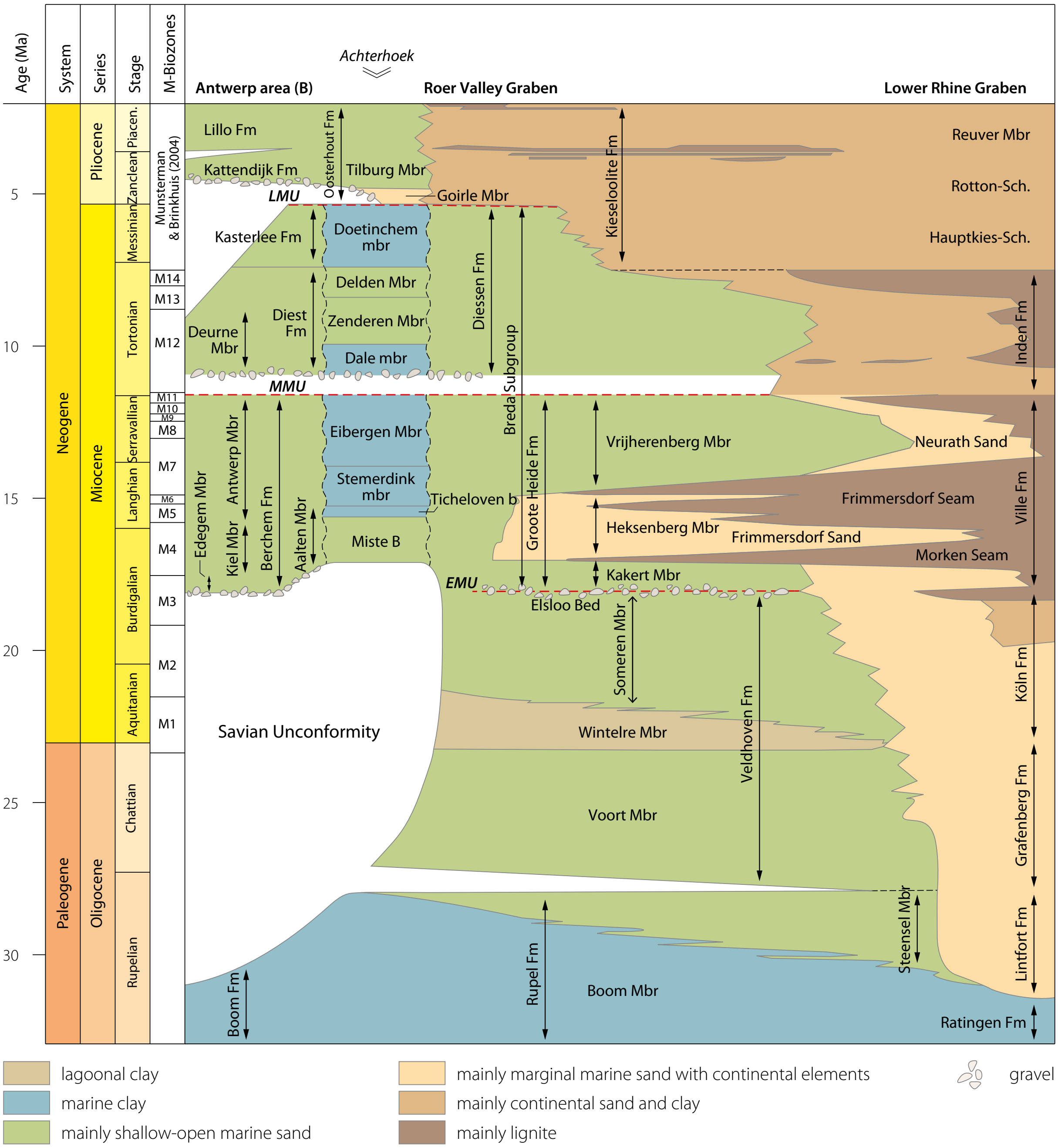


Figure 9.9. *Stratigraphic scheme (Wheeler diagram) of the Oligocene-Early Pliocene of the Antwerp area (Belgium), the Achterhoek, the Roer Valley Graben (the Netherlands) and its continuation into the Lower Rhine Graben (Germany). The litho-stratigraphy is modified from Van Adrichem Boogaert & Kouwe (1997), Deckers & Louwye (2019), Munsterman et al. (2019), Vandenberghe & Louwye (2020), and Everaert et al. (2020). Everaert et al. (2020), and Munsterman et al. (2024). EMU = Early Miocene Unconformity; MMU = Mid-Miocene Unconformity; LMU = Late Miocene Unconformity.*

central part of these sands a maximum flooding surface is interpreted, which is rich in shells and glauconite, and is expressed by a gamma-ray peak (Deckers & Munsterman, 2020).

The distribution of sedimentary facies in combination with foreset-bottomset geometries observed on seismic data suggest a delta plain (east) to delta front (west) setting. An unconformity (EMU) is usually present at the base of the unit. On the relatively high margins of the Roer Valley Rift System, such as the Peel-Maasbommel High and the Campine area, the formation truncates the Veldhoven and Rupel formations (mainly Boom Member) or older deposits. The gamma-ray log shows lower values at the base of the formation, due to the low concentration of glauconite. In the Peel region and in part of the Roer Valley Graben the lower boundary of the formation is difficult to establish due to the gradual transition of the slightly glauconitic beds of the Veldhoven Formation (Someren Member) into the greensands of the Groote Heide Formation (Deckers & Munsterman, 2020). Above the basal interval, an upward decrease in glauconite content is compensated by an upward increase in clay content within the Groote Heide Formation, which masks the upward reduction in gamma-ray values that is observed elsewhere. The MMU marks the top of the Groote Heide Formation and is characterized in all wells by a very distinctive positive gamma-ray log shift immediately followed by a sharp decrease, presumably reflecting reworking of glauconite. This gamma-ray spike suggests that the MMU represents a late-Middle Miocene hiatus after which sedimentation resumed in the early Tortonian. In Belgium, basal gravels are deposited at this time. In the centre of the Roer Valley Graben the upper boundary of the Groote Heide Formation is associated with a shift in colour of the glauconitic clays from dark green to greenish-grey. In more proximal settings, the MMU is associated with a lithological change from strong sandy loam to silty fine-grained sands. The formation is present in most of the Dutch subsurface. In the eastern part of the Netherlands (Achterhoek), the Groote Heide Formation is divided into the Aalten (sands passing into clays), Stemerdink (silty layered brownish-grey clay) and Eibergen (stiff blackish clays) members (Munsterman et al., 2024). However, it is absent in small areas in the extreme eastern, southeastern and southwestern parts of the country, on the Kijkduin High (Fig. 9.6a) and in the northwestern offshore.

Phase IV – Late Neogene cooling (Late Miocene-Early Pleistocene, 12-2.5 Ma)

Regional tectonics and paleogeography

The onset of phase IV is constrained by a distinct change in the tectonic regime of the North Sea area. Regional tectonic movements led to an increased tilting of the Fennoscandian Platform and accelerated uplift of Britain (Japsen et al., 2002; Anell et al., 2010). This resulted in divergence of the Baltic river system, which started to feed a large-scale delta stretching from the present-day Baltic region into the Dutch part of the North Sea Basin. The entire fluvio-deltaic system is referred to as the Eridanos (Overeem et al., 2001) or Southern North Sea delta (SNS). It supplied large amounts of freshwater and sediment into the shelf sea during the Neogene and Early Pleistocene (Overeem et al., 2001). In the Late Miocene the delta was located along the southern Norwegian and Danish shore. Western progradation continued with a lateral shift of depocentre towards the Dutch northern offshore during the Pliocene-Pleistocene (De Bruin et al., 2017). Whereas during the Miocene sediments laid down in the Danish North Sea sector were predominantly sourced from Fennoscandia, in the Pliocene this was overtaken by Central European sources (Rasmussen & Dybkjær, 2014). The southwestward Eridanos extention during the Gelasian is clearly discernible from seismic data that show progradational sigmoidal and oblique shelf-prism clinoforms that downlap onto the MMU (Ten Veen et al., 2018; Busschers et al., 2025, this volume). Hence, in this phase the eastern boundary of the North Sea Basin shifted westwards and the depositional basin considerably narrowed. The SNSB became separated from a shallow basin to the southeast known as the East German-Polish Basin, which closely represents the present-day configuration. Locally, fast-growing salt diapirs surrounded by rim synclines likely contributed to failure of delta slopes and mass transport deposition and an irregular seafloor topography (Benvenuti et al., 2012; Thöle et al., 2016).

The Mid-Miocene Unconformity forms the lower (seismo)stratigraphic boundary of the Eridanos delta. With the exception of the Danish offshore section, the central axis of the Roer Valley Graben and the Venlo Graben in the Netherlands, it represents a hiatus covering a substantial part of the Serravallian. In Denmark, a 3 m thick condensed section composed of deeper marine hemipelagic clays spans the several million years that coincide with the MMU elsewhere (Rasmussen & Dybkjær, 2014). In the Venlo Graben the MMU time span is represented by a thick coarsening upward sequence dominated by a coastal to restricted-marine facies of the latest Serravallian-earliest Tortonian age (Munsterman et al., 2019).

In the Serravallian, uplift of the London-Brabant Massif resulted in non-deposition and formation of erosional channels with basal gravels and rounded flints in the southernmost North Sea Basin (Demyttenaere, 1989; Wouters & Vandenberghe, 1994; Van Vliet-Lanoë et al., 2002; Louwye & Laga, 2008). Massive reworking of Middle Miocene Antwerp Sands in the Late Miocene Diest Formation is recorded in the Campine area (Vandenberghe et al., 2014). Uplift along the Weald-Artois Axis (Fig. 9.2) led to closure of the Channel Seaway (Knox et al., 2010) that linked the SNSB to the eastern Atlantic, further isolating the basin during the Late Miocene and ending the few indications for direct southern connections in the late Burdigalian and Langhian. Compared to the Groote Heide Formation, the Diessen Formation is much thicker on the southern margin of the North Sea Basin. Deckers & Louwye (2020) suggested that this might be explained by the start of Late Miocene lithospheric folding in that area that continued into Pliocene-Pleistocene times (Van Wees & Cloetingh, 1996). In addition to folding, upward mantle flows resulted in uplift of the Rhenish Massif during the Late Miocene (Garcia-Castellanos et al., 2000; Van Balen et al., 2000). After the Middle to Late Miocene transition, this uplift instigated the progradation of the proto-Rhine fluvial-deltaic Inden Formation (Schäfer et al., 2005) and the overlying latest Tortonian Kieseloolite Formation (Munsterman et al., 2019) from Germany into the southeastern Netherlands. The Inden Formation passes westwards into the shallow marine Diessen Formation. On seismic data, the latter is characterized by multiple stacked clinoforms that indicate a westward shelf-delta progradation into the Roer Valley Graben/Lower Rhine Graben during the Late Miocene and Early Pliocene. Similar progradational geometries are observed in the time-equivalent Diest Formation in the Campine Basin (Vandenberghe et al., 2014). These observations suggest that the proto-Rhine delta front became the most important contributor of sediment here. Additionally, the Eridanos system was a source for background sedimentation here, albeit with a rather small contribution (Verhaegen, 2019). The input of southerly-sourced sediments (Meuse-Ardennes and proto-Rhine) strongly increased from the Early Miocene to the Late Miocene and Pliocene (Adriaens, 2015; Verhaegen et al., 2019). During the Late Miocene, besides the Roer Valley Graben, the Zuiderzee Low (Fig. 9.4; Duin et al., 2006) developed as a second depocentre. A direct connection to the Alpine forelands was established in the Late Pliocene and is traceable in unstable mineral associations with a proto-Rhine origin (Kemna & Westerhoff, 2007).

In many seismic profiles through the Netherlands it is evident that topset beds of clinoforms of the Diessen Formation are missing and are directly overlain by either parallel or downlapping (inclined and concave-downward) strata of the Oosterhout Formation (Fig. 9.6c). This angular unconformity is defined as the LMU (Munsterman et al., 2019) and is inferred to represent a hiatus due to considerable erosion.

Regional climate

Following the MCO, strengthening of the North Atlantic Current caused divergent climate developments on either side of the Atlantic Ocean since the Late Miocene. Long-term Miocene cooling and humidity decrease were clearly stronger in NW Europe (Donders et al., 2009; Sangiorgi et al., 2021) than at similar latitudes along the Atlantic coast of North America (Kotthoff et al., 2014) and the east of Eurasia (Utescher et al., 2015). Climate reconstructions based on plant macrofossils from German basins place the most pronounced cooling between 12 and 10 Ma. The diversity decrease of subtropical plants most likely reflects decline of winter temperature minima, due to their sensitivity of frost. The plant macrofossil records further indicate a decline in Neogene precipitation in response to long-term cooling that seems to lag behind the major temperature transitions (Mosbrugger et al., 2005; Utescher et al., 2011). In the Netherlands, the only quantitative reconstruction of Miocene terrestrial climate is based on analysis of the Groote Heide borehole in the Venlo Graben. Here, integrated marine and terrestrial microfossil and lipid-based paleothermometry analyses record a clear cooling phase between 12 and 11.2 Ma followed by a relatively stable period and a gradual cooling trend between 9.5 and 7.4 Ma. The quantitative reconstructions suggest a 3-5°C mean annual temperature decline during each of these cooling phases, associated with impoverishment of the terrestrial flora (Donders et al., 2009).

The Pliocene Climatic Optimum (3.26-3.0 Ma) is characterized by global temperatures that were 2-4°C higher compared to the present (Haywood et al., 2013). Locally, lipid paleothermometry indicates that the SNSB was 1-2°C warmer on land, with marine anomalies of up to 10°C (Dearing Crampton-Flood et al., 2018, 2020). This optimum was followed by 'precursor' Northern Hemisphere glaciations that resulted in variable sedimentary facies in the SNSB. The tectonically-driven isolation of the Arctic Ocean and intensification of the North Atlantic Current, increased moisture distribution northward (Haug & Tiedemann, 1998). This led to an enhanced fresh water budget in the Arctic Ocean. The additional fresh water is thought to have facilitated the formation of sea ice, causing a positive ice-albedo feedback. In turn, Arctic waters flowing back into the North Atlantic could have become less cold and salty, hence interrupting and slowing the Ocean Conveyor belt as a global heat pump to North Atlantic regions (Haug et al., 2004). The resulting globally cooler conditions and initiation of Northern Hemisphere ice-sheet growth during the Late Pliocene (Bintanja & Wal, 2008) developed into periodic glaciations covering large parts of the Northern Hemisphere during the Middle and Late Pleistocene (De Schepper et al., 2014). The M2 glacial at 3.3 Ma is globally the most pronounced early glaciation and is associated with a regional unconformity in the shallow marine deposits in the onshore western Netherlands (Dearing Crampton-Flood et al., 2020). Coupled records of such marine and terrestrial environments show contemporaneous floral extinction and climate cooling with marine ingressions of arctic water masses during this and subsequent glacial periods (Kuhlmann et al., 2006a; Donders et al., 2018, 2009).

Depositional systems, landscape and ecosystem evolution

During the second half of the Neogene, the progressive disappearance of (sub)tropical and endemic taxa drove declining marine and terrestrial biodiversity levels, while the occurrence of Pacific immigrants in the Pliocene shaped the modern marine faunas. Macrofossils from terrestrial biota have been dredged from the Liessel and Langenboom localities and small outcrops in the Venlo area in Limburg, and are extensively exposed in lignite mines of adjacent Nordrhein-Westfalen, such as the well-known Hambach locality. Most microfossil data rely on mixed samples from airlift boreholes and there are very few continuously cored intervals.

The presence of palm fossils in the Lower Rhine Graben shows that frost conditions were still rare during the Miocene (Van der Burgh, 1984). Pollen records from the Miocene seams include many so-called 'form' taxa for which the exact botanical affinity is not known. Most of these taxa disappeared during the Miocene cooling events, suggesting that they have tropical and subtropical affinities (Donders et al., 2009). In comparison, Pliocene lignite seams contain an essentially modern flora but, compared to today, have higher quantities of angiosperm wetland taxa such as poplar (*Populus* spp.), tupelo (*Nyssa*) and sweetgum (*Liquidambar*), characteristic of present-day hardwood swamps in the southeastern United States (Zagwijn, 1960; Westerhoff et al., 2020). Upland vegetation from outside the wetland areas is much less known but analyses from shallow marine deposits show that conifers were surprisingly common regionally (Larsson et al., 2011; Dearing Crampton-Flood et al., 2020). Many conifer taxa like pine (*Pinus*), spruce (*Picea*) and fir (*Abies*) but also hemlock (*Tsuga*) – which presently is confined to North America – are today characteristic of cooler, mountainous regions. Leached, acidic soils that formed during extended warm periods might explain the abundance of conifers that are more tolerant to such conditions. Other 'cool' vegetation elements like birch (*Betula*) and heath (*Ericaceae*) are indeed rare in the Neogene and increased in abundance only in the Early Pleistocene (Donders et al., 2018).

Marine fossils from the Late Miocene-Pliocene time interval are known from a number of outcrops and extraction sites in the Netherlands, including Langenboom and Liessel in North Brabant (Peters, 2009; Peters & Peters, 2013) and from boreholes throughout the country (e.g. Sliggers & Leeuwen, 1987). Rich fossil faunas are known from beaches and dredged samples in the Westerschelde area (Moerdijk et al., 2010; Post & Reumer, 2016). As with the flora, faunas during the Late Miocene-Early Pliocene were warm-temperate in character. Most of the truly tropical taxa that flourished in the Middle Miocene – such as conids and cowries – had disappeared. Endemic mollusc and fish lineages continued to dominate the marine biota and there was an increase of transatlantic fish species during the Tortonian, indicating oceanic dispersal (Schwarzhans, 2010), but overall diversity was considerably lower than during the Middle Miocene. Rich marine mammal and fish (including shark) faunas have been recovered from Upper Miocene sediments at Liessel and the Westerschelde (Marx et al., 2016, 2019; Post et al., 2018; Bisconti et al., 2019, 2020; Peters et al., 2021; Bosselaers & Munsterman, 2022) The occurrence of very large whales indicates that shallow to open marine conditions extended over the southern and southeastern Netherlands during the Tortonian. Dinoflagellate cyst assemblages indicate nutrient-rich water, associated with prograding fluvial deltaic river systems (Inden and Kieseloolite formations) from the southeast. During Early Pliocene times shallow to open marine conditions persisted well towards the east as is shown by cetacean and marine bird assemblages (including albatross) recovered from the Langenboom locality (Wijnker et al., 2008). The arrival of Pacific immigrant species such as clams (*Macoma*), whelks (*Neptunea*) and mussels (*Mytilus*) started to shape the modern faunas. Proposed connections through the Channel region during Late Miocene and Pliocene (Van Vliet-Lanoë et al., 2002) are not in agreement with the largely endemic and northern faunas represented in the North Sea Basin, which at that time probably was an embayment of the North Atlantic. During the Late Pliocene a progressive loss of species around cooling events, most notably thermophilous and endemic taxa, drove a strong decline in marine diversity, analogous to changes on land. Invertebrate faunas became dominated by species of Pacific origin.

Lithostratigraphy

Sediments deposited during tectonic phase IV include the Diessen, Inden, Kieseloolite and Oosterhout formations. Figure 9.9 shows a summary of these post-MMU sediments in the Netherlands.

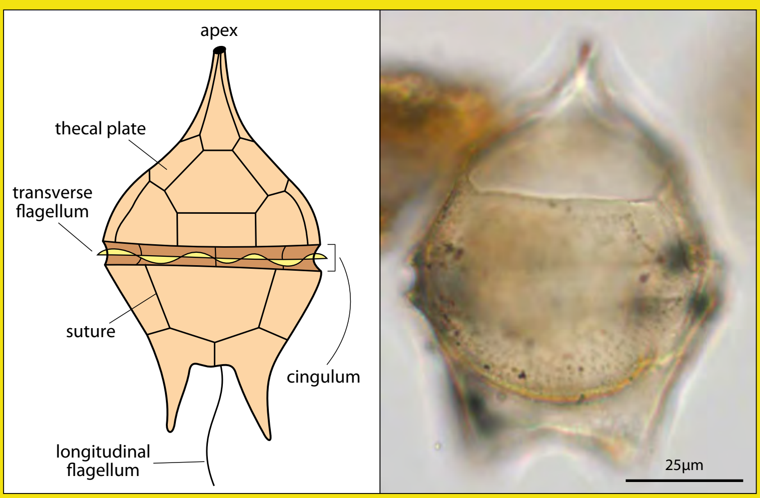
Diessen Formation

The Diessen Formation is placed in between the MMU and LMU and is Tortonian to Messinian in age. With the LMU as upper boundary, locally the upper part of the former Breda Formation was assigned to the newly defined Goirle Member of the Oosterhout Formation. The lithology of the Diessen Formation changes from sandy loam at its base into silty fine-grained sand upwards and has a moderate glauconite content. This coarsening upward trend is associated with colours shifting from green-grey to grey as the concentration of mica increases upward. Traces of molluscs and sea urchin spines are present. Coincident with a shift to lower grain size there is a sharp increase in epidote and amphibole relative to tourmaline and metamorphic minerals. Upwards, the heavy mineral composition again becomes increasingly rich in tourmaline and metamorphic minerals. The succession in the deepest part of the Roer Valley Graben (well Sint Michielsgestel-1) consists of grey-greenish clays with glauconite. The sediments were deposited in the prodeltaic environment of a fluvio-deltaic system and reach a thickness up to 500 m. On seismic data the base is detectible as widespread downlap surface

2

Dinoflagellate cysts

Dinoflagellates are free-living, single-celled organisms that inhabit aquatic environments. The name is derived from the Greek word *dinos* (rotation) and the Latin word *flagellum* (small whip). Their food strategy may be autotrophic or heterotrophic, i.e. indicating that their energy is obtained by photosynthesis or from organic material, respectively. Mixture of endosymbiosis and parasitism also occurs. Dinoflagellates are particularly common in marine nearshore and neritic settings and populations are most varied in shallow to open marine conditions. The organism is characterized by the presence of a swimming (motile) cell with two flagella: a transverse flagellum that encircles the cell and is ribbonlike, and a longitudinal flagellum that is cylindrical and trails the cell posteriorly (left figure). Combined actions of the flagella move motile cells through water in a corkscrew manner. Most living dinoflagellate cells range in diameter from 5 to 100 µm. The life cycle of many dinoflagellates includes at least one cyst stage, during which the organism is dormant/resting and life processes are suspended. Some produce long-term resting cysts (hypnozygotes) of which the wall is composed of a fossilizable organic material (dinosporin), calcium carbonate or, very rarely, silica (Fensome & Munsterman, 2020). These cysts can be well-conserved in sediments and occur frequent in the rock record. Cyst fossils go back to the Middle Triassic and can be used to study the evolution of dinoflagellates. The intricate Jurassic to Cenozoic organic-walled cyst taxonomy allows a refined marine biostratigraphy (right figure). Fossil cyst analysis is an excellent application tool in marine geology for age assessment, reconstruction of paleoenvironment and paleoclimatic evolution.



Left: General morphology of a motile dinoflagellate cell showing the position of the two flagella. Right: Light microscope photograph of a **Deflandrea phosphoritica** *cyst, which in the Dutch North Sea Basin is an age-diagnostic taxon for the top of the late Oligocene.*

of the overlying clinoforms, which corresponds to a gamma-ray peak in log data. This suggests that the MMU can be interpreted as unconformity (or disconformity). The arrangement of clinoforms on seismic profiles in the Roer Valley Graben is indicative for multiple phases and directions of progradation and/or avulsion of a large fluvio-deltaic system. In the Goirle borehole, marine dinoflagellate cysts become very rare to absent at the top of the Diessen Formation, indicating an upward shallowing to marginal marine and possibly even subaerial conditions. Based on foraminiferal analysis in well Sint Michielsgestel-1, infra- to epineritic conditions (water depths between less than 100 m at the base and ca. 10-30 m at the top of this unit) were interpreted (Doppert et al., 1975). The LMU spans a period equal to at least all of the missing topset beds of the Diessen Formation clinoforms. Despite the fact that a hiatus cannot be identified on the basis of palynological criteria, across the unconformity all Miocene dinoflagellate cyst marker taxa disappeared from the assemblages. In the Oud-Turnhout borehole (Belgium) a hiatus is recorded as the Lower Pliocene Kattendijk Formation is missing and the Upper Pliocene (Piacenzian) directly overlies the Upper Miocene Diest Formation (Louwye & De Schepper, 2010). In the southeastern part of the Netherlands the formation interfingers with the mainly continental deposits of the Inden and Kieseloolite formations. These transitions are marked by erosional scours and shifts to more coarse-grained deposits. In the northeastern part of the country the Diessen Formation is in lateral contact with the nearshore to continental beds of the Peize Formation. In the eastern part of the Netherlands (Achterhoek) it is divided into four units (Munsterman et al., 2024): the informal Dale member (dark grey-green clayey silts and silty clays), followed by the Zenderen Member (green glauconitic fine sands), the Delden Member (sharp increase in coarse-grained sands) and, finally the informal Doetinchem member (loam, sandy, silty clays).

Inden Formation

The Inden Formation is described as dark grey medium to very coarse sand, locally gravelly, with minimal calcareous content and dark grey to brown clay, which is slightly sandy and silty. In the Rur Block (Germany) interbedded, locally clayey lignite seams compose the Tortonian Upper Seam that reaches up to 30 m in thickness (Schafer et al., 2005). The depositional environment is interpreted as coastal lowland (proto-Rhine), including swamp (lignite), meandering channel (sand), residual channel (clay), crevasse (sand) and floodplain (clay) sub-environments (Boersma et al., 1981; Abraham, 1994; Schäfer et al., 2004, 2005). The lower boundary is defined at a sharp contact with finer glauconitic shallow-marine sand and clay of the Diessen Formation. The upper boundary commonly shows a thick clay layer and a sharp contact with overlying coarser fluvial sand and gravel (Waubach Member, Kieseloolite Formation). The age is early late Miocene (Tortonian) and the thickness reaches up to 140 m. The distribution is limited to the eastern part of the Roer Valley Graben.

Kieseloolite Formation

The depositional conditions were fluvial (proto-Rhine and -Meuse) (Boenigk, 1978; Gliese & Hager, 1978; Westerhoff, 2009), including floodplain and swamp to tidally influenced coastal plain with back-barrier areas and beach ridges. Sediments were sourced from the Ardennes and Lower Rhine Graben. The lithology comprises whitish to brownish grey, very fine to very coarse sand (quarzitic) and gravel (granules to boulders) together with thick intercalated clay beds and associated peat/lignite layers. The formation is split into the Brunssum Member (stiff greyish brown to dark brown clay, slightly sandy to very silty, with intercalated layers of fine to medium sand and lignite) and the Waubach Member (white to light grey medium to very coarse sand, very gravelly, partially lithified in coarsening-upward sequences with poorly developed clay layers). The lower boundary is a sharp contact with either fine, glauconitic shallow-marine sand of the Diessen Formation or dark grey medium to very coarse and gravelly sand of the Inden Formation. Laterally, it is transitonal to glauconitic shallow-marine sand with marine molluscs of the Oosterhout Formation. The upper boundary is generally a transition into micaceous fluvial sands (Waalre Formation), but may be sharp where this fluvial unit overlies the Reuver Member clay beds. There is a conformable, gradual transition into very fine to fine eolian and local river sand of the Stramproy Formation, which has thinner clay beds and a locally sharp contact with coarse gravelly fluvial sand of the Kreftenheye and Beegden formations. The age is Late Miocene to Pliocene and the thickness is up to 200 m. Distribution is limited to the southeastern part of the Netherlands (the province of Limburg and eastern part of Brabant).

Oosterhout Formation

The recently redefined base of the Oosterhout Formation is now located at an angular unconformity defined as the LMU (Munsterman et al., 2019). In some parts of the Netherlands the LMU is directly overlain by parallel-layered sands of the Goirle Member of the Oosterhout Formation. In these instances, the unconformity is marked by a sharp decrease in gamma-ray readings. The Goirle sands were previously assigned to the former Breda Formation. Sands in the upper levels of the Diessen Formation are relatively enriched in glauconite and the sudden lower gamma-ray values are due to waning concentrations of glauconite in the Goirle Member. This change can be seen in the colour of the sands, which changes from green into light grey and/or white. These lightly coloured sands are followed by dark green-grey, glauconitic, slightly silty sands including clays, defined as Tilburg Member, and interpreted as a marine flooding surface. In the Antwerp area and by extension probably also in the neighbouring parts of Dutch Zeeland, Deckers & Louwye (2020) described a >10 m deep gully incision at the base of the Belgian Kattendijk Formation which is the lateral equivalent to the Tilburg Member.

In general, the lithology of the Oosterhout Formation consists of light grey-green very fine to medium sand rich in shells and can locally be clayey and glauconitic. At the top, dark grey to greyish-brown silty or sandy clays occur. At this level several shell banks (crags) are present. Locally, yellow to reddish-brown medium grained fossiliferous sands are encountered that are partly cemented by iron(hydr)oxides. The depositional setting is shallow-marine and includes estuarine, deltaic, beach and nearshore facies. Landward, to the southeast the formation is transitional to and interfingers with coastal-plain and fluvial deposits of the Kieseloolite Formation. The exact transition of the Oosterhout Formation into the overlying Maassluis Formation is a subject of ongoing study that focuses on depositional systems and biotic evolution at the Pliocene-Pleistocene transition.

The Phase IV sedimentary succession of the Dutch northern offshore onlaps onto the MMU (Fig. 9.6b). Above the latter a toe-of-slope facies of the early Eridanos (mid-Late Miocene; Kuhlmann et al., 2006a) and a relatively thick Pliocene-Pleistocene late Eridanos shelf-edge delta sequence (De Bruin et al., 2017; Busschers et al., 2025, this volume) corresponds to the Diessen and Oosterhout formations, respectively. In this area, the Brielle Ground and Westkapelle Ground formations (Rijsdijk et al., 2005) which have a slightly more distal depositional setting (shelf to slope) compared to the Oosterhout Formation, denote the Pliocene part of the westward prograding Eridanos interval. Offshore the western part of the Netherlands, the Brielle Ground Formation also shows influences from the Rhine/Meuse system. Further to the east, the formation has a sharp contact with coarser fluvial and coastal sand and gravel (Waalre and Peize formations) or passes gradually into eolian or local river sand (Stramproy Formation). The thickness is up to 150 m and the age is Pliocene.

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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.28163597.

References

Á Horni , J., Hopper, J.R., Blischke, A., Geisler, W.H., Stewart, M., McDermott, K. & Árting, U., 2017. Regional distribution of volcanism within the North Atlantic Igneous Province. Geological Society, London, Special Publications 447(1): 105-125. DOI: 10.1144/SP447.18

Abdelmalak, M.M., Meyer, R., Planke, S., Faleide, J.I., Gernigon, L., Frieling, J. & Myklebust, R., 2016. Pre-breakup magmatism on the Vøring Margin: Insight from new sub-basalt imaging and results from Ocean Drilling Program Hole 642E. Tectonophysics 675: 258-274. DOI: 10.1016/j.tecto.2016.02.037

Abels, H.A., Van Simaeys, S., Hilgen, F.J., De Man, E. & Vandenberghe, N., 2006. Obliquity-dominated glacio-eustatic sea level change in the early Oligocene; evidence from the shallow marine siliciclastic Rupelian stratotype (Boom Formation, Belgium). Terra Nova 19(1): 65-73. DOI: 10.1111/j.1365-3121.2006.00716.x

Abraham, M., 1994. Untersuchungen zur sedimentologischen Entwicklung der fluviatilen Deckschichten (Miozän, Pliozän) der Rheinischen Braunkohle. Bonner Geowissenschaftliche Schriften 15: 1-27.

Adriaens, R., 2015. Neogene and Quaternary clay minerals in the southern North Sea. PhD thesis KU Leuven (Belgium), 47 : 273 pp.

Anell, I., Thybo, H. & Stratford, W., 2010. Relating Cenozoic North Sea sediments to topography in southern Norway: The interplay between tectonics and climate. Earth and Planetary Science Letters 300: 19-32. DOI: 10.1016/j.epsl.2010.09.009

Bacon, C.D., Silvestro, D., Jaramillo, C., Smith, B.T., Chakrabarty, P. & Antonelli, A., 2015. Biological evidence supports an early and complex emergence of the Isthmus of Panama. Proceedings of the National Academy of Sciences 112(19): 6110-6115. DOI: 10.1073/pnas.1423853112

Beddow, H.M., Liebrand, D., Wilson, D.S., Hilgen, F.J., Sluijs, A., Wade, B.S. & Lourens, L.J., 2018. Astronomical tunings of the Oligocene-Miocene transition from Pacific Ocean Site U1334 and implications for the carbon cycle. Climate of the Past 14(3): 255-270. DOI: 10.5194/cp-14-255-2018

Benvenuti, A., Kombrink, H., Ten Veen, J.H., Munsterman, D.K., Bardi, F. & Benvenuti, M., 2012. Late Cenozoic shelf delta development and Mass Transport Deposits in the Dutch offshore area – results of 3D seismic interpretation. Netherlands Journal of Geosciences 91(4): 591-608. DOI: 10.1017/S0016774600000391

Berger, J.-P., Reichenbacher, B., Becker, D., Grimm, M., Grimm, K., Picot, L., Storni, A., Pirkenseer, C., Derer, C. & Schaefer, A., 2005. Paleogeography of the Upper Rhine Graben (URG) and the Swiss Molasse Basin (SMB) from Eocene to Pliocene. International Journal of Earth Sciences 94(4): 697-710. DOI: 10.1007/s00531-005-0475-2

Bijl, P.K., Houben, A.J., Schouten, S., Bohaty, S.M., Sluijs, A., Reichart, G.J. & Brinkhuis, H., 2010. Transient Middle Eocene atmospheric CO_2 and temperature variations. Science 330(6005): 819-821. DOI: 10.1126/science.1193654

Bijl, P.K., Schouten, S., Sluijs, A., Reichart, G.J., Zachos, J.C. & Brinkhuis, H., 2009. Early Palaeogene temperature evolution of the southwest Pacific Ocean. Nature 461(7265): 776-779. DOI: 10.1038/nature08399

Bintanja, R. & Wal, R.S.W., 2008. North American ice-sheet dynamics and the onset of 100,000-year glacial cycles. Nature 454(7206): 869-872. DOI: 10.1038/nature07158

Bisconti, M., Munsterman, D.K., Fraaije, R.H.B., Bosselaers, M.E.J. & Post, K., 2020. A new species of rorqual whale (Cetacea, Mysticeti, Balaenopteridae) from the Late Miocene of the Southern North Sea Basin and the role of the North Atlantic in the paleobiogeography of Archaebalaenoptera. PeerJ 8(8315). DOI: 10.7717/peerj.8315

Bisconti, M., Munsterman, D.K. & Post, K., 2019. A new balaenopterid whale from the late Miocene of the Southern North Sea Basin and the evolution of balaenopterid diversity (Cetacea, Mysticeti). PeerJ 7(6915). DOI: 10.7717/peerj.6915

Boenigk, W., 1978. Gliederung der altquartären Ablagerungen in der Niederrheinischen Bucht. Fortschritte in der Geologie von Rheinland und Westfalen 28: 135-212.

Boersma, J.R., Van Gelder, A., De Groot, T.A.M. & Puigdefabregas, C., 1981. Formen fluviatiler Sedimentation in neogenen und jungeren Ablagerungen im Braunkohlentagebau Frechen (Niederrheinischen Bucht). Fortschritte in der Geologie von Rheinland und Westfalen 29: 275-307.

Bohaty, S.M. & Zachos, J.C., 2003. Significant Southern Ocean warming event in the late middle Eocene. Geology 31(11): 1017-1020. DOI: 10.1130/G19800.1

Bosselaers, M. & Munsterman, D.K., 2022. The discovery of a Balaenomorpha (Persufflatius renefraaijeni n. gen., n. sp.) from the upper Miocene of the Netherlands sheds new light on the cranial anatomy of archaic rorqual relatives. Geodiversitas 44(30): 933-973. DOI: 10.5252/geodiversitas2022v44a30

Bourgeois, O., Ford, M., Diraison, M., Veslud, C.L.C.D., Gerbault, M., Pik, R. & Bonnet, S., 2007. Separation of rifting and lithospheric folding signatures in the NW-Alpine foreland. International Journal of Earth Sciences 96(6): 1003-1031. DOI: 10.1007/s00531-007-0202-2

Bralower, T.J., Cosmidis, J., Heaney, P.J., Kump, L.R., Morgan, J.V., Harper, D.T. & Vajda, V., 2020. Origin of a global carbonate layer deposited in the aftermath of the Cretaceous-Paleogene boundary impact. Earth and Planetary Science Letters 548: 116476. DOI: 10.1016/j.epsl.2020.116476

Brunstad, H., Gradstein, F., Lie, J.E., Hammer, Ø., Munsterman, D.K., Ogg, G. & Hollerbach, M., 2013. Stratigraphic guide to the Rogaland group, Norwegian North Sea. Norwegian North Sea 46(2): 137-286.

Busschers, F.S., Cohen, K., Wesselingh, F.P., Schokker, J., Bakker, M., Van Balen, R. & Van Heteren, S., 2025. Quaternary. In: J.H. Ten Veen, G.-J. Vis, J. De Jager, J. & Th.E. Wong (eds): Geology of the Netherlands, second edition. Amsterdam University Press (Amsterdam): 333-391. DOI: 10.5117/9789463728362_ch10

Cameron, T.D.J., Crosby, A., Balson, P.S., Jeffery, D.H., Lott, G.K., Bulat, J. & Harrison, D.H., 1992. United Kingdom offshore regional reports: the geology of the southern North Sea. HMSO (London) for the British Geological Survey: 152 pp.

Clausen, O.R., Śliwińska, K.K. & Gołędowski, B., 2012. Oligocene climate changes controlling forced regression in the eastern North Sea. Marine and Petroleum Geology 29: 1-14. DOI: 10.1016/j.marpetgeo.2011.10.002

Clemmensen, A. & Thomsen, E., 2005. Palaeoenvironmental changes across the Danian-Selandian boundary in the North Sea Basin. Palaeogeography, Palaeoclimatology, Palaeoecology 219(3-4): 351-394. DOI: 10.1016/j.palaeo.2005.01.005

Cloetingh, S.A.P.L., Ziegler, P.A., Beekman, F., Andriessen, P.A.M., Matenco, L., Bada, G. & Sokoutis, D., 2005. Lithospheric memory, state of stress and rheology: neotectonic controls on Europe's intraplate continental topography. Quaternary Science Reviews 24(3-4): 241-304. DOI: 10.1016/j.quascirev.2004.06.015

Cramwinckel, M.J., Huber, M., Kocken, I.J., Agnini, C., Bijl, P.K., Bohaty, S.M. & Sluijs, A., 2018. Synchronous tropical and polar temperature evolution in the Eocene. Nature 559(7714): 382-386. DOI: 10.1038/s41586-018-0272-2

De Bast, E. & Smith, T., 2016. The oldest Cenozoic mammal fauna of Europe: implication of the Hainin reference fauna for mammalian evolution and dispersals during the Paleocene. Journal of Systematic Palaeontology 15(9): 741-785. DOI: 10.1080/14772019.2016.1237582

De Bruin, G., Geel, K., Houben, S., Munsterman, D., Verweij, H., Smit, J., Janssen, N., Kerstholt-Boegehold, S. & Vandeweijer, V., 2017. MMU Unravelling the stratigraphic and structural development of the strata found underneath and above the Mid-Miocene unconformity. TNO (Utrecht), Report No. R10425: 104 pp.

De Craen, M., Swennen, R., Keppens, E., Macaulay, C.I. & Kiriakoulakis, K., 1999. Bacterially mediated formation of Carbonate concretions in the Oligocene Boom Clay of Northern Belgium. Journal of Sedimentary Research 69(5): 1098-1106. DOI: 10.2110/jsr.69.1098

De Jager, J., 2007. Geological development. In: Wong, Th.E., Batjes, D.A.J. & De Jager, J. (eds): Geology of the Netherlands. Royal Netherlands Academy of Arts and Sciences (KNAW, Amsterdam): 5-26.

De Mulder, E.F.J., Geluk, M.C., Ritsema, I., Westerhoff, W.E. & Wong, Th.E., 2003. De ondergrond van Nederland. Wolters-Noordhof (Groningen): 379 pp.

De Schepper, S., Gibbard, Ph.L., Salzmann, U. & Ehlers, J., 2014. A global synthesis of the marine and terrestrial evidence for glaciation during the Pliocene Epoch. Earth-Science Reviews 135: 83-102. DOI: 10.1016/j.earscirev.2014.04.003

Dearing Crampton-Flood, E., Noorbergen, L.J., Smits, D., Boschman, R.C., Donders, T.H., Munsterman, D.K., Ten Veen, J.H., Peterse, F., Lourens, L. & Sinninghe Damsté, J.S., 2020. A new age model for the Pliocene of the southern North Sea basin: a multi-proxy climate reconstruction. Climate of the Past 16: 523-541. DOI: 10.5194/cp-16-523-2020, 2020

Dearing Crampton-Flood, E., Peterse, P., Munsterman, D. & Sinninghe Damsté, J.S., 2018. Using tetraether lipids archived in North Sea Basin sediments to extract North Western European Pliocene continental air temperatures. Earth and Planetary Science Letters 490: 193-205. DOI: 10.1016/j.epsl.2018.03.030

Deckers, J., 2015. The Paleocene stratigraphic records in the Cen-

tral Netherlands and close surrounding basins: Highlighting the different responses to a late Danian change in stress regime within the Central European Basin System. Tectonophysics 659: 102-108. DOI: 10.1016/j.tecto.2015.07.031
Deckers, J. & Louwye, S., 2020. Late Miocene increase in sediment accommodation rates in the southern North Sea Basin. Geological Journal 55(1): 728-736. DOI: 10.1002/gj.3438
Deckers, J. & Louwye, S., 2019. A reinterpretation of the ages and depositional environments of the lower and middle Miocene stratigraphic records in a key area along the southern margin of the North Sea Basin. Geological Magazine 156(3): 525-532. DOI: 10.1017/S0016756817000991
Deckers, J. & Matthijs, J., 2017. Middle Paleocene uplift of the Brabant Massif from central Belgium up to the southeast coast of England. Geological Magazine 154(5): 1117-1126. DOI: 10.1017/S001675681600073X
Deckers, J. & Munsterman, D., 2019. Introducing the Våle Formation in the southern central North Sea Basin, offshore Netherlands. Marine and Petroleum Geology 101: 512-518. DOI: 10.1016/j.marpetgeo.2018.12.032
Deckers, J. & Munsterman, D., 2020. Middle Miocene depositional evolution of the central Roer Valley Rift System. Geological Journal 55(9). DOI: 10.1002/gj.3799
Deckers, J. & Van der Voet, E., 2018. A review on the structural styles of deformation during Late Cretaceous and Paleocene tectonic phases in the southern North Sea area. Journal of Geodynamics 115: 1-9. DOI: 10.1016/j.jog.2018.01.005
Deckers, J., Vandenberghe, N., Lanckacker, T. & de Koninck, R., 2016. The Pyrenean inversion phase in northern Belgium: an example of a relaxation inversion? International Journal of Earth Sciences 105(2): 583-593.
DeConto, R.M. & Pollard, D., 2003. Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO2. Nature 421(6920): 245-249. DOI: 10.1038/nature01290
Demyttenaere, R., 1989. The Post-Paleozoic geological history of north-eastern Belgium. Mededelingen van de Koninklijke Academie Voor Wetenschappen, Letteren En Schone Kunsten van België 51(4): 51-81.
Dickens, G.R., O'Neil, J.R., Rea, D.K. & Owen, R.M., 1995. Dissociation of oceanic methane hydrate as a cause of the carbon isotope excursion at the end of the Paleocene. Paleoceanography 10(6): 965-971. DOI: 10.1029/95PA02087
Diedrich, C.G., 2012. Eocene (Lutetian) Shark-Rich Coastal Paleoenvironments of theSouthern North Sea Basin in Europe: Biodiversity of the Marine Fürstenau Formation Including Early White and Megatooth Sharks. International Journal of Oceanography: 1-22. DOI: 10.1155/2012/565326
Donders, T.H., Van Helmond, N.A.G.M., Verreussel, R., Munsterman, D., Ten Veen, J., Speijer, R.P., Weijers, J.W.H., Sangiorgi, F., Peterse, F., Reichart, G., Sinninghe Damste, J.S., Lourens, L., Kuhlmann, G. & Brinkhuis, H., 2018. Land–sea coupling of early Pleistocene glacial cycles in the southern North Sea exhibit dominant Northern Hemisphere forcing. Climate of the Past 14(3): 287. DOI: 10.5194/cp-14-397-2018
Donders, T.H., Weijers, J.W.H., Munsterman, D.K., Kloosterboer-van Hoeve, M.L., Buckles, L.K., Pancost, R.D., Schouten, S., Sinninghe Damste, J.S. & Brinkhuis, H., 2009. Strong climate coupling of terrestrial and marine environments in the Miocene of northwest Europe. Earth and Planetary Science Letters 281(3-4): 215-225. DOI: 10.1016/j.epsl.2009.02.034
Doppert, J.W.C., Ruegg, G.H.J., Van Staalduinen, C.J., Zagwijn, W.H. & Zandstra, J.G., 1975. Formaties van het Kwartair en Boven Tertiair in Nederland. In: Zagwijn, W.H. & JVan Staalduinen, J.C. (eds): Toelichting bij de geologische overzichtskaarten van Nederland. Rijks Geologische Dienst (Haarlem) 1: 11-56.
Duin, E., Doornenbal, J.C., Rijkers, R.H.B., Verbeek, J.W. & Wong, Th.E., 2006. Subsurface structure of the Netherlands; results of recent onshore and offshore mapping. Netherlands Journal of Geosciences 85(4): 245-276. DOI: 10.1017/S0016774600023064
Dunkley Jones, T., Lunt, D.J., Schmidt, D.N., Ridgwell, A., Sluijs, A., Valdes, P.J. & Maslin, M., 2013. Climate model and proxy data constraints on ocean warming across the Paleocene–Eocene Thermal Maximum. Earth-Science Reviews 125: 123-145. DOI: 10.1016/j.earscirev.2013.07.004
Dusar, M., Rijpens, J., Sintubin, M. & Wouters, L., 2001. Plio-Pleistocene fault pattern of the Feldbiss fault system (southern border of the Roer Valley Graben, Belgium) based on high resolution reflection seismic data. Netherlands Journal of Geosciences 80(3/4): 79-94.
Dybkjær, K., King, C. & Sheldon, E., 2012. Identification and characterisation of the Oligocene–Miocene boundary (base Neogene) in the eastern North Sea Basin — based on dinocyst stratigraphy, micropalaeontology and δ13C-isotope data. Palaeogeography, Palaeoclimatology, Palaeoecology 363-364: 11-22. DOI: 10.1016/j.palaeo.2012.08.007
Dybkjær, K. & Rasmussen, E.S., 2007. Organic-walled dinoflagellate cyst stratigraphy in an expanded Oligocene-Miocene boundary section in the eastern North Sea Basin (the Frida-1 well, Denmark) and correlation from basinal to marginal areas. Journal of Micropalaeontology 26(1): 1-17. DOI: 10.1144/jm.26.1.1
Dybkjær, K., Rasmussen, E.S., Eidvin, T., Grøsfjeld, K., Riis, F., Piasecki, S. & Śliwińska, K.K., 2020. A new stratigraphic framework for the Miocene – Lower Pliocene deposits offshore Scandinavia: a multiscale approach. Geological Journal 56(3): 1699-1725. DOI: 10.1002/gj.3982
Eidvin, T., Riis, F. & Rasmussen, E.S., 2014. Oligocene to Lower Pliocene deposits of the Norwegian continental shelf, Norwegian Sea, Svalbard, Denmark and their relation to the uplift of Fennoscandia: A synthesis. Marine and Petroleum Geology 56: 184-221. DOI: 10.1016/j.marpetgeo.2014.04.006
Everaert, S., Munsterman, D.K., De Schuiter, P.J., Bosselaers, M., Van Boeckel, J., Cleemput, G. & Bor, T.J., 2020. Stratigraphy and palaeontology of the lower Miocene Kiel Sand Member (Berchem Formation) in temporary exposures in Antwerp

(northern Belgium). Geologica Belgica 23(3-4): 167-198. DOI: 10.20341/gb.2020.025

Fairon-Demaret, M., Steurbaut, E., Damblon, F., Dupuis, C., Smith, T. & Gerrienne, P., 2003. The in situ Glyptostroboxylon forest of Hoegaarden (Belgium) at the Initial Eocene Thermal Maximum (55 Ma). Review of Palaeobotany and Palynology 126(1): 103-129. DOI: 10.1016/S0034-6667(03)00062-9

Fensome, R.A. & Munsterman, D.K., 2020. Dinoflagellates. In: Gradstein, F.M., Ogg, J.G., Schmitz, M.D. & Ogg. G.M. (eds): The Geological Time Scale 2020. Elsevier Science Publishing (Amsterdam) 1: 99-108. DOI: 10.1016/C2020-1-02369-3

Figueiral, I., Mosbrugger, V., Rowe, N.P., Ashra, A.R., Utescher, T. & Jones, T.P., 1999. The Miocene peat-forming vegetation of northwestern Germany: an analysis of wood remains and comparison with previous palynological interpretations. Review of Palaeobotany and Palynology 104(3-4): 239-266. DOI: 10.1016/S0034-6667(98)00059-1

Flecker, R., Krijgsman, W., Capella, W., de Castro Martíns, C., Dmitrieva, E., Mayser, J.P. & Yousfi, M.Z., 2015. Evolution of the Late Miocene Mediterranean–Atlantic gateways and their impact on regional and global environmental change. Earth-Science Reviews 150: 365-392. DOI: 10.1016/j.earscirev.2015.08.007

Gale, A.S. & Lovell, B., 2018. The Cretaceous–Paleogene unconformity in England: Uplift and erosion related to the Iceland mantle plume. Proceedings of the Geologists' Association 129(3): 421-435. DOI: 10.1016/j.pgeola.2017.04.002

Garcia-Castellanos, D., Cloetingh, S. & Van Balen, R., 2000. Modelling the Middle Pleistocene uplift in the Ardennes–Rhenish Massif: thermo-mechanical weakening under the Eifel? Global and Planetary Change 27(1-4): 39-52. DOI: 10.1016/S0921-8181(01)00058-3

Geluk, M.C., Duin, E.J.T., Dusar, M., Rijkers, R.H.B., Van den Berg, M.W. & Van Rooijen, P., 1994. Stratigraphy and tectonics of the Roer Valley Graben. Geologie En Mijnbouw 73(2-4): 129-141.

Gibbard, P.L. & Lewin, J., 2003. The history of major rivers of southern Britain during the Tertiary. Journal of the Geological Society 160(6): 829-845. DOI: 10.1144/0016-764902-137

Gibbard, P.L. & Lewin, J., 2016. Filling the North Sea Basin: Cenozoic sediment sources and river styles. Geologica Belgica 19(3/4): 1-17. DOI: 10.20341/gb.2015.017

Gibbard, P.L., Head, M.J. & Walker, M.J.C., 2010. Formal ratification of the Quaternary System/Period and the Pleistocene Series/Epoch with a base at 2.58 Ma. Journal of Quaternary Science 25(2): 96-102. DOI: 10.1002/jqs.1338

Gliese, J. & Hager, H., 1978. On brown coal resources in the Lower Rhine Embayment (West Germany). Geologie En Mijnbouw 57(4): 517-525.

Grein, M., Utescher, T., Wilde, V. & Roth-Nebelsick, A., 2011. Reconstruction of the middle Eocene climate of Messel using palaeobotanical data. Neues Jahrbuch Fur Geologie Und Palaontologie-Abhandlungen 260(3): 305-318. DOI: 10.1127/0077-7749/2011/0139

Hager, H., Vandenberghe, N., Van den Bosch, M., Abraham, M., Von der Hocht, F., Rescher, K., Laga, P., Nickel, E., Verstraelen, A., Leroi, S. & Van Leeuwen, R.J.W., 1998. The geometry of the Rupelian and Chattian depositional bodies in the Lower Rhine district and its border area: implications for Oligocene lithostratigraphy. Bulletin of the Geological Society of Denmark 45: 53-62.

Hardenbol, J., Thierry, J., Farley, M.B., Jacquin, T., De Graciansky, P.-C. & Vail, P.R., 1998. Mesozoic and Cenozoic sequence chronostratigraphic framework of European basins. In: Graciansky, P.-C., Hardenbol, J., Jacquin, T. & Vail, P.R. (eds): Mesozoic and Cenozoic Sequence Stratigraphy of European Basins. (Tulsa) 1: 3-13.

Haug, G.H. & Tiedemann, R., 1998. Effect of the formation of the Isthmus of Panama on Atlantic Ocean thermohaline circulation. Nature 393(6686): 673-676.

Haug, G.H., Tiedemann, R. & Keigwin, L.D., 2004. How the Isthmus of Panama put ice in the Arctic. Oceanus 42: 94-97.

Haywood, A.M., Hill, D.J., Dolan, A.M., Otto-Bliesner, B.L., Bragg, F., Chan, W.L. & Zhang, Z., 2013. Large-scale features of Pliocene climate: results from the Pliocene Model Intercomparison Project. Climate of the Past 9(1): 191-209. DOI: 10.5194/cp-9-191-2013

Head, M.J. & Gibbard, P.L., 2015. Early–Middle Pleistocene transitions: linking terrestrial and marine realms. Quaternary International 389: 7-46. DOI: 10.1016/j.quaint.2015.09.042

Herbert, T.D., Rose, R., Dybkjær, K., Rasmussen, E.S. & Śliwińska, K.K., 2020. Bihemispheric Warming in the Miocene Climatic Optimum as Seen From the Danish North Sea. Paleoceanography and Paleoclimatology 35(10): e2020PA003935. DOI: 10.1029/2020PA003935

Herngreen, G.F.W., Van Konijnenburg-Van Cittert, J.H.A. & Oosterink, H.W., 2005. New geological data (Middle Triassic, Rhaetian-Liassic and Oligocene) of the Winterswijk quarry, the eastern Netherlands. Netherlands Journal of Geosciences 84 (4): 409-413. DOI: 10.1017/S0016774600021223

Hillis, R.R., Holford, S.P., Green, P.F., Doré, A.G., Gatliff, R.W., Stoker, M.S., Thompson, K., Turner, J.P., Underhill, J.R. & Williams, G.A., 2008. Cenozoic exhumation of the southern British Isles. Geology 36(5): 371-374. DOI: 10.1130/G24699A.1

Hollis, C.J., Naeher, S., Clowes, C.D., Naafs, B.D.A., Pancost, R.D., Taylor, K.W.R., Dahl, J., Li, X., Ventura, G.T. & Sykes, R., 2021. Late Paleocene CO2 drawdown, climatic cooling, and terrestrial denudation in the southwest Pacific. Climate of the Past Discussion 18:1295-1320. DOI: 10.5194/cp-18-1295-2022.

Huhn, B., Utescher, T., Ashraf, A.R. & Mosbrugger, V., 1997. The peat-forming vegetation in the Middle Miocene Lower Rhine Embayment, an analysis based on palynological data. Mededelingen Nederlands Instituut voor Toegepaste Geowetenschappen TNO.

Hutchinson, D.K., Coxall, H.K., Lunt, D.J., Steinthorsdottir, M., Boer, A.M., Baatsen, M. & Zhang, Z., 2021. The Eocene–Oligocene transition: a review of marine and terrestrial proxy data, models and model–data comparisons. Climate of the Past 17(1): 269-315. DOI: 10.5194/cp-17-269-2021

Inglis, G.N., Collinson, M.E., Riegel, W., Wilde, V., Farnsworth, A., Lunt, D.J., Valdes, P., Robson, B.E., Scott, A.C., Lenz, O.K., David, B., Naafs, A. & Pancost, R.D., 2017. Mid-latitude continental temperatures through the early Eocene in western Europe. Earth and Planetary Science Letters 460: 86-96. DOI: 10.1016/j.epsl.2016.12.009

Jagt, J.W.M., 2000. Late Cretaceous-Early Palaeogene echinoderms and the K/T boundary in the southeast Netherlands and northeast Belgium-Part 5: Asteroids. Scripta Geologica 121: 377-503.

Jagt, J.W.M., Van Bakel, B.W.M., Cremers, G., Deckers, M.J.M., Dortangs, R.W., Van Es, M., Fraaije, R.H.B., Kisters, P.J.M., Van Knippenberg, P.H.M, Lemmens, H., Nieuwenhuis, E., Severijns, J. & Stroucken, J.W., 2013. Het Vroeg Paleoceen (Danien) van zuidelijk Limburg en aangrenzend gebied – nieuwe fauna's en nieuwe inzichten. Afzettingen 34: 198-230.

Jakobsson, M., Backman, J., Rudels, B., Nycander, J., Frank, M., Mayer, L. & Moran, K., 2007. The early Miocene onset of a ventilated circulation regime in the Arctic Ocean. Nature 447(7147): 986-990. DOI: 10.1038/nature05924

Janssen, A.W., 1979. Over de molluskenfauna van de Nuculaklei en de relatieve ouderdom van enkele midden-oligocene afzettingen in Belgisch Limburg. Afzettingen 1:10-18.

Janssen, A.W., 1984. Mollusken uit het Mioceen van Winterswijk - Miste. Stichting Uitgeverij Koninklijke Nederlandse Natuurhistorische Vereniging 36.

Janssen, A.W., 2001. The age of the North Sea Basin Hemmoorian (Miocene); holoplanktonic molluscan evidence. Aardkundige Mededelingen 11: 45-50.

Janssen, A.W. & Gürs, K., 2002. Notes on the systematics, morphology and biostratigraphy of fossil holoplanktonic Mollusca, 12. On the identity of Hyalea perovalis Von Koenen, 1882 (Mollusca, Gastropoda, Euthecosomata) from the Early Miocene of the North Sea Basin. Basteria 66(4/6): 143-148.

Japsen, P., Bidstrup, T. & Lidmar-Bergström, K., 2002. Neogene uplift and erosion of southern Scandinavia induced by the rise of the South Swedish Dome. In: Doré, A.G., Cartwright, J.A., Stoker, M.S., Turner, J.P. & White, N. (eds): Exhumation of the North Atlantic margin: timing, mechanism and implications for petroleum exploration. Geological Society of London, Special Publications 196: 183-207.

Keigwin, L., 1982. Isotopic paleoceanography of the Caribbean and East Pacific: role of Panama uplift in late Neogene time. Science 217(4557): 350-353.

Kemna, H.A. & Westerhoff, W.E., 2007. Remarks on the palynology-based chronostratigraphical subdivision of Pliocene terrestrial deposits in NW-Europe. Quaternary International 164: 184-196. DOI: 10.1016/j.quaint.2006.10.017

Kender, S., Stephenson, M.H., Riding, J.B., Leng, M.J., Knox, R.W.B., Peck, V.L. & Jamieson, R., 2012. Marine and terrestrial environmental changes in NW Europe preceding carbon release at the Paleocene–Eocene transition. Earth and Planetary Science Letters 353: 108-120. DOI: 10.1016/j.epsl.2012.08.011

Kent, D.V. & Muttoni, G., 2008. Equatorial convergence of India and early Cenozoic climate trends. Proceedings of the National Academy of Sciences 105(42): 16065-16070. DOI: 10.1073/pnas.0805382105

Knox, R.W.O.B., Bosch, J.H.A., Rasmussen, E.S., Heilmann-Clausen, C., Hiss, M., De Lugt, I.R., Kasińksi, J., King, C., Köthe, A., Słodkowska, B., Standke, G. & Vandenberghe, N., 2010. Cenozoic. In: Doornenbal, J.C. & Stevenson, A.G. (eds): Petroleum geological atlas of the Southern Permian Basin area. EAGE Publications b.v. (Houten): 211-223.

Köthe, A., 2007. Cenozoic biostratigraphy from the German North Sea sector (G-11-1 borehole, dinoflagellate cysts, calcareous nannoplankton). Zeitschrift Der Deutschen Gesellschaft Fur Geowissenschaften 158(2): 287-327. DOI: 10.1127/1860-1804/2007/0158-0287

Kotthoff, U., Greenwood, D.R., McCarthy, F.M.G., Müller-Navarra, K., Prader, S. & Hesselbo, S.P., 2014. Late Eocene to middle Miocene (33 to 13 million years ago) vegetation and climate development on the North American Atlantic Coastal Plain (IODP Expedition 313, Site M0027). Climate of the Past 10(4): 1523-1539. DOI: 10.5194/cp-10-1523-2014

Krijgsman, W., Capella, W., Simon, D., Hilgen, F.J., Kouwenhoven, T.J., Meijer, P.T. & Flecker, R., 2018. The Gibraltar corridor: Watergate of the Messinian salinity crisis. Marine Geology 403: 238-246. DOI: 10.1016/j.margeo.2018.06.008

Kuhlmann, G., Langereis, C.G., Munsterman, D., Van Leeuwen, R.-J., Verreussel, R., Meulenkamp, J.E. & Wong, Th.E., 2006a. Chronostratigraphy of Late Neogene sediments in the southern North Sea Basin and paleoenvironmental interpretations. Palaeogeography, Palaeoclimatology, Palaeoecology 239: 426-455. DOI: 10.1016/j.palaeo.2006.02.004

Kuhlmann, G., Langereis, C.G., Munsterman, D., Van Leeuwen, R.-J., Verreussel, R., Meulenkamp, J.E. & Wong, Th.E., 2006b. Intergrated chronostratigraphy of the Piocene-Pleistocene interval and its relation to the regional stratigraphical stages in the southern North Sea region. Netherlands Journal of Geosciences 85 (1): 19-35. DOI: 10.1017/S0016774600021405

Kuhlmann, G. & Wong, Th.E., 2008. Pliocene paleoenvironment evolution as interpreted from 3D-seismic data in the southern North Sea, Dutch offshore sector. Marine and Petroleum Geology 25: 173-189. DOI: 10.1016/j.marpetgeo.2007.05.009

Kurtz, A.C., Kump, L.R., Arthur, M.A., Zachos, J.C. & Paytan, A., 2003. Early Cenozoic decoupling of the global carbon and sulfur cycles. Paleoceanography 18: 1090. DOI: 10.1029/2003PA000908

Kuyl, O.S., 1980. Toelichting bij de geologische kaart van Nederland 1 : 50.000, Blad Heerlen (62 W oostelijke helft, 62 O westelijke helft). Rijks Geologische Dienst (Haarlem): 206 pp.

Kvaček, Z., 2010. Forest flora and vegetation of the European early Palaeogene – a review. Bulletin of Geosciences 85(1): 63-76. DOI: 10.3140/bull.geosci.1146

Larsson, L.M., Dybkjær, K., Rasmussen, E.S., Piasecki, S., Utescher, T. & Vajda, V., 2011. Miocene climate evolution of northern Europe: A palynological investigation from Denmark. Palaeogeography, Palaeoclimatology, Palaeoecology 309(3-4): 161-175. DOI: 10.1016/j.palaeo.2011.05.003

Lenz, O.K., Wilde, V., Mertz, D.F. & Riegel, W., 2015. New palynology-based astronomical and revised 40Ar/39Ar ages for the Eocene maar lake of Messel (Germany). International Journal of Earth Sciences 104(3): 873-889. DOI: 10.1007/s00531-014-1126-2

Letsch, W.J. & Sissingh, W., 1983. Tertiary stratigraphy of The Netherlands. Geologie En Mijnbouw 62(2): 305-318.

Lisiecki, L.E. & Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic δ18O records. Paleoceanography 20(PA1003). DOI: 10.1029/2004PA001071

Liu, L., Yu, L., Pearl, D.K. & Edwards, S.V., 2009. Estimating species phylogenies using coalescence times among sequences. Systematic biology 58(5): 468-477. DOI: 10.1093/sysbio/syp031

Louwye, S., 2005. The Early and Middle Miocene transgression at the southern border of the North Sea Basin (northern Belgium. Geological Journal 40(4): 441-456. DOI: 10.1002/gj.1021

Louwye, S. & De Schepper, S., 2010. The Miocene–Pliocene hiatus in the southern North Sea Basin (northern Belgium) revealed by dinoflagellate cysts. Geological Magazine 147(5): 760-776. DOI: 10.1017/S0016756810000191

Louwye, S. & Laga, P., 2008. Dinoflagellate cyst stratigraphy and palaeoenvironment of the marginal marine Middle and Upper Miocene of the eastern Campine area, northern Belgium (southern North Sea Basin). Geological Journal 43(1): 75-94. DOI: 10.1002/gj.1103

Lyell, C., 1833. Principles of Geology, being an attempt to explain the former changes of the earth's surface, by reference to causes now in operation. London (John Murray): 398 pp.

Maclennan, J. & Jones, S.M., 2006. Regional uplift, gas hydrate dissociation and the origins of the Paleocene–Eocene Thermal Maximum. Earth and Planetary Science Letters 245(1-2): 65-80. DOI: 10.1016/j.epsl.2006.01.069

Manten, 1958. Palynology of the Miocene browncoal mined at Haanrade (Limburg, Netherlands. Acta Botanica Neerlandica 7(3): 445-488.

Marquet, R., 2016. A revision of the gastropod fauna of the Boom Clay Formation (Rupelian, Early Oligocene) in Belgium, 1. Vetigastropoda and Caenogastropoda to Eulimoidea. Cainozoic Research 16(1): 13-33.

Marquet, R. & Herman, J., 2012. Reinvestigation of the invertebrate fauna of the Boom Clay Formation and the Ruisbroek Sand Member (Oligocene, Rupelian) of Belgium, with the description of a new lithostratigraphic unit: the Sint Niklaas Phosphorite Bed. Cainozoic Research 9(1): 101-120.

Marx, F.G., Bosselaers, M.E.J. & Louwye, S., 2016. A new species of Metopocetus (Cetacea, Mysticeti, Cetotheriidae) from the Late Miocene of the Netherlands. PeerJ 4(1572). DOI: 10.7717/peerj.1572

Marx, F.G., Post, K., Bosselaers, M. & Munsterman, D.K., 2019. A large Late Miocene cetotheriid (Cetacea, Mysticeti) from the Netherlands clarifies the status of Tranatocetidae. PeerJ 7(6426). DOI: 10.7717/peerj.6426

Mayr, G. & Smith, T., 2019. New Paleocene bird fossils from the North Sea Basin in Belgium and France. Geologica Belgica 22(1-2): 35-46. DOI: 10.20341/gb.2019.003

Michon, L., Van Balen, R.T., Merle, O. & Pagnier, H., 2003. The Cenozoic evolution of the Roer Valley rift system integrated at a European scale. Tectonophysics 367 (1-2): 101-126. DOI: 10.1016/S0040-1951(03)00132-X00132-X

Miller, K.G., Browning, J.V., Aubry, M.P., Wade, B.S., Katz, M.E., Kulpecz, A.A. & Wright, J.D., 2008. Eocene–Oligocene global climate and sea-level changes: St. Stephens Quarry, Alabama. Geological Society of America Bulletin 120 (1-2): 34-53.

Miller, K.G., Browning, J.V., Schmelz, W.J., Kopp, R.E., Mountain, G.S. & Wright, J.D., 2020. Cenozoic sea-level and cryospheric evolution from deep-sea geochemical and continental margin records. Science Advances 6(20): 1346.

Moerdijk, P.W., Janssen, A.W., Wesselingh, F.P., Peeters, G.A., Pouwer, R., Nieulande, F.A.D. & Ter Poorten, J.J., (eds) 2010. De fossiele schelpen van de Nederlandse kust. Nederlands Centrum voor Biodiversiteit Naturalis (Leiden): 332 pp.

Mörs, T., 2002. Biostratigraphy and paleoecology of continental Tertiary vertebrate faunas in the Lower Rhine Embayment (NW-Germany). Netherlands Journal of Geosciences 81(2): 177-183. DOI: 10.1017/S0016774600022411

Morton, A.C. & Knox, R.O.B., 1990. Geochemistry of late Palaeocene and early Eocene tephras from the North Sea Basin. Journal of the Geological Society 147(3): 425-437. DOI: 10.1144/gsjgs.147.3.0425

Mosbrugger, V., Gee, C.T., Belz, G. & Ashraf, A.R., 2022. Three-dimensional reconstruction of an in-situ Miocene peat forest from the Lower Rhine Embayment, northwestern Germany—new methods in palaeovegetation analysis. Palaeogeography, Palaeoclimatology, Palaeoecology 110(3-4): 295-317. DOI: 10.1016/0031-0182(94)90089-2

Mosbrugger, V., Utescher, T. & Dilcher, D.L., 2005. Cenozoic continental climatic evolution of Central Europe. Proceedings of the National Academy of Sciences 102(42): 14964-14969.

Munsterman, D.K. & Deckers, J., 2020. The Oligocene/Miocene boundary in the ON-Mol-1 and Weelde boreholes along the southern margin of the North Sea Basin, Belgium. Geologica Belgica 23(3-4). DOI: 10.20341/gb.2020.007

Munsterman, D.K., Ten Veen, J.H., Menkovic, A., Deckers, J., Witmans, N., Verhaegen, J., Kerstholt-Boegehold, S.J., Van de Ven, T. & Busschers, F.S., 2019. An updated and revised stratigraphic framework for the Miocene and earliest Pliocene strata of the Roer Valley Graben and adjacent blocks. Netherlands Journal of Geosciences 98(8). DOI: 10.1017/njg.2019.10

Munsterman, D.K., Van den Bosch, M., Wesselingh, F.P., Helwerda, M. & Busschers, F.S., 2024. A proposal for an updated and revised stratigraphical framework of the Miocene in the

Achterhoek (eastern Netherlands). Netherlands Journal of Geosciences 103(7). DOI: 10.1017/njg.2024.3
Munsterman, D.K. & Brinkhuis, H., 2004. A southern North Sea Miocene dinoflagellate cyst zonation. Netherlands Journal of Geosciences 83(4): 267-285. DOI: 10.1017/S0016774600020369
Munsterman, D.K. & Deckers, J., 2022. Biostratigraphic ages and depositional environments of the upper Oligocene to lower Miocene Veldhoven Formation in the central Roer Valley Rift System (SE Netherlands-NE Belgium). Netherlands Journal of Geosciences 101(6). DOI: 10.1017/njg.2022.3
Naafs, B.D.A., Rohrssen, M. & Inglis, G.N., 2018. High temperatures in the terrestrial mid-latitudes during the early Palaeogene. Nature Geosciences 11: 766-771.
Nalpas, T., Le Douaran, S., Brun, J.P., Unternehr, P. & Richert, J.P., 1995. Inversion of the Broad Fourteens Basin (offshore Netherlands), a small-scale model investigation. Sedimentary Geology 95 (3-4): 237-250. DOI: 10.1016/0037-0738(94)00113-9
Nielsen, S.B., Stephenson, R. & Thomsen, E., 2007. Dynamics of Mid-Palaeocene North Atlantic rifting linked with European intra-plate deformations. Nature 450: 1071-1074. DOI: 10.1038/nature06379
Nielsen, S.B., Thomsen, E., Hansen, D.L. & Clausen, O.R., 2005. Plate-wide stress relaxation explains European Paleocene basin inversions. Nature 435(7039): 195-198. DOI: 10.1038/nature03599
Overeem, I., Weltje, G.J., Bishop-Kay, C. & Kroonenberg, S.B., 2001. The Late Cenozoic Eridanos delta system in the Southern North Sea Basin: a climate signal in sediment supply? Basin Research 13: 293-312. DOI: 10.1046/j.1365-2117.2001.00151.x
Palike, H., Norris, R.D., Herrle, J.O., Wilson, P.A., Coxall, H.K., Lear, C.H. & Wade, B.S., 2006. The heartbeat of the Oligocene climate system. Science 314(5807): 1894-1898. DOI: 10.1126/science.1133822
Patruno, S., Kombrink, H. & Archer, S.G., 2021. Cross-border stratigraphy of the Northern, Central and Southern North Sea: a comparative tectono-stratigraphic megasequence synthesis. Geological Society of London, Special Publications 494 (1): 13-83. DOI: 10.1144/sp494-2020-228
Pearson, P.N., Foster, G.L. & Wade, B.S., 2009. Atmospheric carbon dioxide through the Eocene–Oligocene climate transition. Nature 461(7267): 1110-1113 .
Peters, N., (ed.) 2013. Van reuzenhaai tot Chalicotherium. Fossielen uit Mill-Langenboom. Oertijdmuseum De Groene Poort (Boxtel): 158 pp.
Peters, N., Munsterman, D.K. & Post, K., 2021. A late Miocene balaenopterid petrotympanic from Liessel (The Netherlands). Cainozoic Research 21(2): 165-172
Peters, N. & Peters, H., (eds) 2009. Brabant tussen walvissen en mastodonten: fossielen uit Liessel. Nationaal Beiaard- en Natuurmuseum (Asten) & Oertijdmuseum De Groene Poort (Boxte)l: 111 pp.
Phillips, J., (ed.) 1841. Figures and Descriptions of the Palaeozoic Fossils of Cornwall, Devon and East Somerset. Longman, Brown, Green and Longmans (London): 231 pp.
Post, K. & Bosselaers, M., 2017. Cetacean fossils from a 1961 expedition at the Schelde estuary, province of Zeeland, the Netherlands. Cainozoic Research 17(1): 11-21.
Post, K. & Kompanje, E.J.O., 2010. A new dolphin (Cetacea, Delphinidae) from the Plio-Pleistocene of the North Sea. Deinsea 14: 1-12
Post, K., Munsterman, D.K., Peters, M.E., Hille, P. & Reumer, J., 2018. Lederschildpadden, reuzenhaaien en La Plata dolfijnen zwommen ooit in het zuidelijk deel van het Noordzeebekken (Nu: Westerschelde. Cranium 35(2): 37-42
Post, K. & Peters, N., (eds) 2023. De fossiele zeezoogdieren van Nederland. GBU (Urk): 112 pp.
Post, K. & Reumer, J.W., 2016. History and future of paleontological surveys in the Westerschelde Estuary (Province of Zeeland, the Netherlands. Deinsea 16: 1-9.
Prinz, L., Schäfer, A., McCann, T., Utescher, T., Lokay, P. & Asmus, S., 2017. Facies analysis and depositional model of the Serravallian-age Neurath Sand, Lower Rhine Basin (W Germany). Netherlands Journal of Geosciences 96(3): 211-231. DOI: 10.1017/njg.2016.51
Rae, J.W., Zhang, Y.G., Liu, X., Foster, G.L., Stoll, H.M. & Whiteford, R.D., 2021. Atmospheric CO2 over the past 66 million years from marine archives. Annual Review of Earth and Planetary Sciences 49: 609-641.
Raffi, I., Wade, B.S. & Palike, H., 2020. The Neogene Period. In: Gradstein, F.M., Ogg, J.G., Schmitz, M.D. & Ogg, G.M. (eds): The Geologic Time Scale 2020. Elsevier (Boston) 2: 1141-1215. DOI: 10.1016/B978-0-12-824360-2.00029-2
Rasmussen, E.S., 2009. Neogene inversion of the Central Graben and Ringkobing-Fyn High, Denmark. Tectonophysics 465(1-4): 84-97. DOI: 10.1016/j.tecto.2008.10.025
Rasmussen, E.S., 2004. The interplay between true eustatic sea-level changes, tectonics and climatic changes: what is the dominating factor in sequence formation of the Upper Oligocene - Miocene succession in the eastern North Sea Basin, Denmark. Global and Planetary Change 41(1): 15-30. DOI: 10.1016/j.gloplacha.2003.08.004
Rasmussen, E.S. & Dybkjær, K., 2014. Patterns of Cenozoic sediment flux from western Scandinavia: discussion. Basin Research 26(2): 338-346. DOI: 10.1111/bre.12024
Rasmussen, E.S., Heilmann-Clausen, C., Waagstein, R. & Eidvin, T., 2008. The Tertiary of Norden. Episodes 31(1): 66-72. DOI: 10.18814/epiiugs/2008/v31i1/010
Rasmussen, E.S., Dybkjær, K. & Piasecki, S., 2010. Lithostratigraphy of the Upper Oligocene – Miocene Succession of Denmark. Geological Survey of Denmark and Greenland Bulletin 22: 92.
Rijsdijk, K.F., Passchier, S., Weerts, H.J.T., Laban, C., Van Leeuwen, R.J.W. & Ebbing, J.H.J., 2005. Revised Upper Cenozoic stratigraphy of the Dutch sector of the North Sea Basin: towards an integrated lithostratigraphic, seismostratigraphic and al-

lostratigraphic approach. Netherlands Journal of Geosciences 84(2): 129-146. DOI: 10.1017/S0016774600023015

Roveri, M., Flecker, R., Krijgsman, W., Lofi, J., Lugli, S., Manzi, V. & Stoica, M., 2014. The Messinian Salinity Crisis: Past and future of a great challenge for marine sciences. Marine Geology 352: 25-58. DOI: 10.1016/j.margeo.2014.02.002

Ryan, W.B., Dewey, J.F., Pitman, W.C. & Bonnin, J., 1973. Plate tectonics and the evolution of the Alpine system. Geological Society of America Bulletin 84(10): 3137-3180. DOI: 10.1130/0016-7606(1973)84<3137:PTATEO>2.0.CO;2

Ryan, W.B.F., 1973. Geodynamic implications of the Messinian crisis of salinity. In: Drooger, C.W. (ed.): Messinian events in the Mediterranean. North-Bolland Publishing Company (Amsterdam): 26-38.

Saeys, R., Verheyen, A. & Vandenberghe, N., 2004. A rapid clay-mineral change in the earliest Priabonian of the North Sea Basin? Netherlands Journal of Geosciences 83(3): 179-185. DOI: 10.1017/S0016774600020242

Sangiorgi, F., Quaijtaal, W., Donders, T.H., Schouten, S. & Louwye, S., 2021. Middle Miocene temperature and productivity evolution at a Northeast Atlantic shelf site (IODP U1318, Porcupine Basin): Global and regional changes. Paleoceanography and Paleoclimatology 36(7): e2020PA004059. DOI: 10.1029/2020PA004059

Schäfer, A., Utescher, T., Klett, M. & Valdivia-Manchego, M., 2005. The Cenozoic Lower Rhine Basin – rifting, sedimentation, and cyclic stratigraphy. International Journal of Earth Sciences 94: 621-639. DOI: 10.1007/s00531-005-0499-7

Schäfer, A., Utescher, T. & Mörs, T., 2004. Stratigraphy of the Cenozoic Lower Rhine Basin, northwestern Germany. Newsletters in Stratigraphy 40(1-2): 73-110. DOI: 10.1127/0078-0421/2004/0040-0073

Schwarzhans, W., (ed.) 2010. The otoliths from the Miocene of the North Sea Basin. Backhuys Publishers (Leiden) & Margraf Publishers (Weikersheim): 352 pp.

Simmons, M.D., 2018. Sir Charles Lyell. In: Simmons, M.D. (ed.) Great geologists. (Abington): 39-41.

Simpson, I.R., Gravestock, M., Ham, D., Leach, H. & Thompson, S.D., 1989. Notes and cross-sections illustrating inversion tectonics in the Wessex Basin. Geological Society, London, Special Publications 44: 123-129.

Sissingh, W., 2006. Syn-kinematic palaeogeographic evolution of the West European Platform: correlation with Alpine plate collision and foreland deformation. Netherlands Journal of Geosciences 85(2): 131-180. DOI: 10.1017/S0016774600077933

Sliggers, B.C. & Leeuwen, R.J.W., 1987. Mollusc biozonation of the Miocene in the south-eastern Netherlands and correlation with the foraminiferal biostratigraphy. Mededelingen van de Werkgroep voor Tertiaire en Kwartaire Geologie 24(1-2): 41-57.

Śliwinska, K.K., Heilmann-Clausen, C. & Thomsen, E., 2014. Correlation between the type Chattian in NW Europe and the Rupelian–Chattian candidate GSSP in Italy. STRATI 2013, Springer: 283-286. DOI: 10.1007/978-3-319-04364-7_57

Sluijs, A., Brinkhuis, H., Crouch, E.M., John, C.M., Handley, L., Munsterman, D.K. & Dickens, G.R., 2008. Eustatic variations during the Paleocene-Eocene greenhouse world. Paleoceanography 23(4). DOI: 10.1029/2008PA001615

Smith, T. & Smith, R., 2003. Terrestrial mammals as biostratigraphic indicators in upper Paleocene-lower Eocene marine deposits of the southern North Sea Basin. Geological Society of America Special Papers 369: 513-520.

Speijer, R.P., Pälike, H., Hollis, C.J., Hooker, J.J. & Ogg, J.G., 2020. The Paleogene Period. In: Gradstein, F.M., Ogg, J.G., Schmitz, M.D. & Ogg, G.M. (eds): Geologic time scale 2020. Elsevier (Amsterdam): 1088-1140. DOI: 10.1016/B978-0-12-824360-2.00028-0

Steinthorsdottir, M., Coxall, H.K., Boer, A.M., Huber, M., Barbolini, N., Bradshaw, C.D., N.J., B., Feakins, S.J., Gasson, E., Henderiks, J., Holbourn, A.E., Kiel, S., Kohn, M.J., Knorr, G., Kürschner, W.M., Lear, C.H., Liebrand, D., Lunt, D.J., Mörs, T., Pearson, P.N., Pound, M.J., Stoll, H. & Strömberg, C.A.E., 2021a. The Miocene: The Future of the Past. Paleoceanography and Paleoclimatology 36(4): e2020PA004037. DOI: 10.1029/2020PA004037

Steinthorsdottir, M., Jardine, P.E. & Rember, W.B., 2021b. Near-future pCO2 during the hot Mid Miocene Climatic Optimum. Paleoceanography and Paleoclimatology 36(1): e2020PA003900. DOI: 10.1029/2020PA003900

Steurbaut, E., 1998. High-resolution holostratigraphy of Middle Paleocene to Early Eocene strata in Belgium and adjacent areas. Palaeontographica 247(5-6): 91-156.

Steurbaut, E. & Sztrákos, K., 2008. Danian/Selandian boundary criteria and North Sea Basin–Tethys correlations based on calcareous nannofossil and foraminiferal trends in SW France. Marine Micropaleontology 67(1-2): 1-29. DOI: 10.1016/j.marmicro.2007.08.004

Stouthamer, E., Cohen, K.M. & Hoek, W.Z., (eds) 2023. De vorming van het land. Geologie en geomorfologie. Perspectief Uitgevers (Bilthoven) 9: 448 pp.

Svensen, H., Planke, S., Malthe-Sørenssen, A., Jamtveit, B., Myklebust, R., Rasmussen Eidem, T. & Rey, S.S., 2004. Release of methane from a volcanic basin as a mechanism for initial Eocene global warming. Nature 429(6991): 542-545. DOI: 10.1038/nature02566

Tanrattana, M., Boura, A., Jacques F.M., B., Villier, L., Fournier, F., Enguehard, A., Cardonnet, S., Voland, G., Garcia, A., Chaouch, S. & Franceschi, D., 2020. Climatic evolution in Western Europe during the Cenozoic: insights from historical collections using leaf physiognomy. Geodiversitas 42(11): 151-174. DOI: 10.5252/geodiversitas2020v42a11

Ten Veen, J., De Bruin, G., Donders, T., Verweij, H. & Geel, K., 2018. Shallow gas traps in the Cenozoic Southern North Sea delta, offshore Netherlands. First Break 36: 30-36.

Thöle, H., Gaedicke, C., Kuhlmann, G. & Reinhardt, L., 2014. Late Cenozoic sedimentary evolution of the German North Sea – A seismic stratigraphic approach. Newsletters on Stratigraphy

47(3): 299-329. DOI: 10.1127/0078-0421/2014/0049
Thöle, H., Kuhlmann, G., Lutz, R. & Gaedicke, C., 2016. Late Cenozoic submarine slope failures in the southern North Sea–Evolution and controlling factors. Marine and Petroleum Geology 75: 272-290. DOI: 10.1016/j.marpetgeo.2016.04.028
Utescher, T., Ashraf, A.R., Kern, A.K. & Mosbrugger, V., 2021. Diversity patterns in microfloras recovered from Miocene brown coals of the lower Rhine Basin reveal distinct coupling of the structure of the peat-forming vegetation and continental climate variability. Geological Journal 56: 768-785. DOI: 10.1002/gj.3801
Utescher, T., Bondarenko, O.V. & Mosbrugger, V., 2015. The Cenozoic Cooling—Continental signals from the Atlantic and Pacific side of Eurasia. Earth and Planetary Science Letters 415: 121-133. DOI: 10.1016/j.epsl.2015.01.019
Utescher, T., Bruch, A.A., Micheels, V., Mosbrugger, V. & Popova, S., 2011. Cenozoic climate gradients in Eurasia — a palaeo-perspective on future climate change? Palaeogeography, Palaeoclimatology, Palaeoecology 304(3-4): 351-358. DOI: 10.1016/j.palaeo.2010.09.031
Utescher, T., Erdei, B., Hably, L. & Mosbrugger, V., 2017. Late Miocene vegetation of the Pannonian Basin. Palaeogeography, Palaeoclimatology, Palaeoecology 467: 131-148. DOI: 10.1016/j.palaeo.2016.02.042
Utescher, T., Mosbrugger, V. & Ashraf, A.R., 2000. Terrestrial climate evolution in Northwest Germany over the last 25 million years. Palaios 15(5): 430-449. DOI: 10.1669/0883-1351(2000)015<0430:TCEING>2.0.CO;2
Van Adrichem Boogaert, H.A. & Kouwe, W.F.P., 1993. Stratigraphic nomenclature of The Netherlands, revision and update by RGD and NOGEPA. Mededelingen Rijks Geologische Dienst 50: 1-24.
Van Adrichem Boogaert, H.A. & Kouwe, W.F.P., 1997. Stratigraphic nomenclature of the Netherlands, revision and update by RGD and NOGEPA. Mededelingen Rijks Geologische Dienst (Haarlem) 50: 1-39.
Van Balen, R.T., Houtgast, R.F. & Cloetingh, S.A.P.L., 2005. Neotectonics of The Netherlands: a review. In: Cloetingh, S.A.P.L. & Cornu, T.G.M. (eds): Neotectonics and Quaternary fault-reactivation in Europe's intraplate lithosphere. Quaternary Science Reviews 24: 439-454. DOI: 10.1016/j.quascirev.2004.01.011
Van Balen, R.T., Houtgast, R.F., Van der Wateren, F.M., Vandenberghe, J. & Bogaart, P.W., 2000. Sediment budget and tectonic evolution of the Meuse catchment in the Ardennes and the Roer Valley Rift System. Global and Planetary Change 27 (1-4): 113-129. DOI: 10.1016/S0921-8181(01)00062-5
Van Bergen, M.J., Vis, G.-J., Sissingh, W., Koornneef, J. & Brouwers, I., 2024. Magmatism in the Netherlands: expression of the north-west European rifting history. In: Ten Veen, J.H., Vis, G.-J., De Jager, J. & Wong, Th.E. (eds): Geology of the Netherlands, second edition. Amsterdam University Press (Amsterdam): 393-455. DOI: 10.5117/9789463728362_ch11
Van den Berg, M.W., 1994. Neotectonics of the Roer Valley rift system; style and rate of crustal deformation inferred from syn-tectonic sedimentation. Geologie En Mijnbouw 73: 143-156.
Van der Burgh, J., 1984. Some palms in the Miocene of the Lower Rhenish Plain. Review of Palaeobotany and Palynology 40: 359-374.
Van der Ham, R.W.J.M., Konijnenburg-van Cittert, J.A.H. & Indeherberge, L., 2007. Seagrass foliage from the Maastrichtian type area (Maastrichtian, Danian, NE Belgium, SE Netherlands. Review of Palaeobotany and Palynology 144(3-4): 301-321. DOI: 10.1016/j.revpalbo.2006.07.008
Van Hinsbergen, D.J.J., De Groot, L.V., Van Schaik, S.J., Spakman, W., Bijl, P.K., Sluijs, A., Langereis, C.G. & Brinkhuis, H., 2015. A paleolatitude calculator for paleoclimate studies. PLoS ONE 10(6): e0126946. DOI: 10.1371/journal.pone.0126946
Van Lochem, H., 2018. F17-Chalk: new insights in the tectonic history of the Dutch Central Graben. Geological Society, London, Special Publications 468: 537-558. DOI: 10.1144/SP469.17
Van Lochem, H., Vis, G.-J. & Jagt, J.W.M., 2025. Late Cretaceous. In: Ten Veen, J.H., Vis, G.-J., De Jager, J. & Wong, Th.E. (eds): Geology of the Netherlands, second edition. Amsterdam University Press (Amsterdam): 253-291. DOI: 10.5117/9789463728362_ch09
Van Simaeys, S., De Man, E., Vandenberghe, N., Brinkhuis, H. & Steurbaut, E., 2004. Stratigraphic and Paleoenvironmental Analysis of the Rupelian and Chattian in the Type Region : evidence from dinoflagellate cysts, foraminifera and calcareous nannofossils. Palaeogeography, Palaeoclimatology, Palaeoecology 208: 31-58. DOI: 10.1016/j.palaeo.2004.02.029
Van Vliet-Lanoë, B., Laurent, M., Hallégouët, B., Margerel, J.P., Chauvel, J.J., Michel, Y., Moguedet, G., Trautman, F. & Vauthier, S., 1998. Le Mio-Pliocène du Massif armoricain. Données nouvelles. Comptes Rendus de l'Académie des Sciences - Series IIA - Earth and Planetary Science 326(5): 333-340. DOI: 10.1016/S1251-8050(98)80303-0
Van Vliet-Lanoë, B., Vandenberghe, N., Laurent, M., Laignel, B., Lauriat-Rage, A., Louwye, S., Mansy, J.-L., Mercier, D., Hallégouët, B., Laga, P., Laquement, F., Meilliez, F., Michel, Y., Moguedet, G. & Vidier, J.-P., 2002. Palaeogeographic evolution of northwestern Europe during the Upper Cenozoic. Geodiversitas 24(3): 511-540.
Van Wees, J.-D. & Cloetingh, S.A.P.L., 1996. 3D flexure and intraplate compression in the North Sea basin. Tectonophysics 266 (1-4): 343-359.
Van Wijhe, D.H., 1987. Structural evolution of inverted basins in the Dutch offshore. Tectonophysics 137: 171-219. DOI: 10.1016/0040-1951(87)90320-9
Vandenberghe, N., 2017. Tectonic and climatic signals in the Oligocene sediments of the Southern North-Sea Basin. Geologica Belgica 20(3-4): 105-123. DOI: 10.20341/gb.2017.007
Vandenberghe, N., Harris, W.B., Wampler, J.M., Houthuys, R., Louwye, S., Adriaens, R., Vos, K., Lanckacker, T., Matthijs, J.,

Deckers, J., Verhaegen, J., Laga, P., Westerhoff, W. & Munsterman, D., 2014. The implications of K-Ar glauconite dating of the Diest Formation on the paleogeography of the Upper Miocene in Belgium. Geologica Belgica 17(2): 161-174. DOI: 10.20341/gb.2020.010

Vandenberghe, N., Laga, P., Louwye, S., Vanhoorne, R., Marquet, R., De Meuter, F., Wouters, K. & Hagemann, H.W., 2005. Stratigraphic interpretation of the Neogene marine – continental record in the Maaseik well (49W0220) in the Roer Valley Graben, NE Belgium. Memoirs of the Geological Survey of Belgium 52: 1-39.

Vandenberghe, N., Laga, P., Steurbaut, E., Hardenbol, J. & Vail, P.R., 1998. Tertiary sequence stratigraphy at the southern border of the North Sea Basin in Belgium. In: De Graciansky, P.-C., Hardenbol, J., Jacquin, T. & Vail, P.R. (eds): Mesozoic and Cenozoic Sequence Stratigraphy of European Basins. SEPM, Special Publications (Claremore) 1(60): 119-154. DOI: 10.2110/pec.98.02.0119.

Vandenberghe, N. & Louwye, S., 2020. An introduction to the Neogene stratigraphy of northern Belgium: present status. Geologica Belgica 23(3-4): 97-112. DOI: 10.20341/gb.2020.008

Vellekoop, J., Woelders, L., Sluijs, A., Miller, K.G. & Speijer, R.P., 2019. Phytoplankton community disruption caused by latest Cretaceous global warming. Biogeosciences 16(21): 4201-4210. DOI: 10.5194/bg-16-4201-2019

Verbeek, J.W., De Leeuw, C.S., Parker, N. & Wong, Th.E., 2002. Characterisation and correlation of Tertiary seismostratigraphic units in the Roer Valley Graben. Netherlands Journal of Geosciences 81(2): 159-166. DOI: 10.1017/S0016774600022393

Verhaegen, J., 2019. Quantitative sediment provenance and volumetric reconstruction: application to the Miocene of the Southern North Sea Basin (PhD study KU Leuven.).

Verhaegen, J., Weltje, G.J. & Munsterman, D., 2019. Workflow for analysis of compositional data in sedimentary petrology: provenance changes in sedimentary basins from spatio-temporal variation in heavy-mineral assemblages. Geological Magazine 156(7): 1111-1130. DOI: 10.1017/S0016756818000584

Vinken, R., 1988. The Northwest European Tertiary Basin. Results of the IGCP Project No. 124. Geologisches Jahrbuch A100: 508.

Vis, G.-J., Verweij, J.M. & Koenen, M., 2016. The Rupel Clay Member in the Netherlands: towards a comprehensive understanding of its geometry and depositional environment. Netherlands Journal of Geosciences 95 (3): 221-251. DOI: 10.1017/njg.2016.25

Walliser, E.O., Lohmann, G., Niezgodzki, I., Tütken, T. & Schöne, B., 2016. Response of Central European SST to atmospheric pCO2 forcing during the Oligocene—A combined proxy data and numerical climate model approach. Palaeogeography, Palaeoclimatology, Palaeoecology 459: 552-569. DOI: 10.1016/j.palaeo.2016.07.033

Watson, D., Schofield, N., Jolley, D., Archer, S., Finlay, A.J., Mark, N. & Watton, T., 2017. Stratigraphic overview of Palaeogene tuffs in the Faroe–Shetland Basin, NE Atlantic margin. Journal of the Geological Society 174(4): 627-645. DOI: 10.1144/jgs2016-132

Welle, J., 1997. Oligozäne Mollusken aus dem Schacht 8 der Bergwerksgesellschaft Sophia Jacoba bei Erkelenz (Niederrheinische Bucht). Teil 1: Lamellibranchia und ScaphopodaLamellibranchia und Scaphopoda 4: 1-137.

Welle, J., 1998. Die Molluskenfauna des Rupeltons im Tagebau Amsdorf westlich von Halle, Systematik und Paläoökologie. Münstersche Forschungen zur Geologie Paläontologie 85: 137-187.

Wesselingh, F., Janse, A.C., Vervoenen, M. & Van Nieulande, F.A.D., 2013. New records of giant campanilid gastropods (Mollusca) from the southern North Sea Basin: implications for Eocene and Quaternary palaeogeography. Netherlands Journal of Geosciences 92(2-3): 159-164. DOI: 10.1017/S0016774600000093

Westerhoff, W.E., 2009. Stratigraphy and sedimentary evolution - The Lower Rhine-Meuse system during the Late Pliocene and aerly Pleistocene (southern North Sea Basin). PhD thesis Vrije Universiteit Amsterdam (the Netherlands): 168 pp.

Westerhoff, W.E., Donders, T.H., Trabucho Alexandre, N. & Busschers, F.S., 2020. Early Pleistocene Tiglian sites in the Netherlands: A revised view on the significance for quaternary stratigraphy. Quaternary Science Reviews 242: 106417. DOI: 10.1016/j.quascirev.2020.106417

Westerhold, T., Marwan, N., Drury, A.J., Liebrand, D., Agnini, C., Anagnostou, E. & Zachos, J.C., 2020. An astronomically dated record of Earth's climate and its predictability over the last 66 million years. Science 369(6509): 1383-1387. DOI: 10.1126/science.aba6853

Whittaker, A., (ed.) 1985. Atlas of onshore sedimentary basins in England and Wales: Post-Carboniferous tectonics and stratigraphy. Blackie, Glasgow & London: 71 pp.

Wijnker, E., Bor, T.J., Wesselingh, F.P., Munsterman, D.K., Brinkhuis, H., Burger, A.W., Vonhof, H.B., Post, K., Hoedemakers, K., Janse, A.C. & Taverne, N., 2008. Neogene stratigraphy of the Langenboom locality (Noord-Brabant, the Netherlands). Netherlands Journal of Geosciences 87(2): 165-180. DOI: 10.1017/S0016774600023209

Wong, T.E., De Lugt, I.R., Kuhlmann, G. & Overeem, I., 2007. Tertiary. In: Wong, Th.E., Batjes, D.A.J.& De Jager, J. (eds): Geology of the Netherlands. Royal Netherlands Academy of Arts and Sciences (KNAW, Amsterdam): 151-172.

Wong, Th.E., Parker, N. & Horst, P., 2001. Tertiary sedimentary development of the Broad Fourteens area, the Netherlands. Netherlands Journal of Geosciences 80(1): 85-94. DOI: 10.1017/S0016774600022186

Wouters, L. & Vandenberghe, N., 1994. Geologie van de Kempen. Division of Geology, KU Leuven, Belgium.

Zachos, J.C., Breza, J.R. & Wise, S.W., 1992. Early Oligocene ice-sheet expansion on Antarctica: Stable isotope and sedimentological evidence from Kerguelen Plateau, southern Indian Ocean. Geology 20(6): 569-573.

Zachos, J.C., Dickens, G.R. & Zeebe, R.E., 2008. An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics. Nature 451: 279-283. DOI: 10.1038/nature06588

Zagwijn, W.H., 1989. The Netherlands during the Tertiary and the Quaternary: A case history of Coastal Lowland evolution. In: Van der Linden, W.J.M., Cloetingh, S.A.P.L., Kaasschieter, J.P.K., van de Graaff, W.J.E., Vandenberghe, J. & van der Gun, J.A.M. (eds): Coastal Lowlands: Geology and Geotechnology. Springer Netherlands (Dordrecht): 107-120. DOI: 10.1007/978-94-017-1064-0_6

Zagwijn, W.H., 1960. Aspects of the Pliocene and Early Pleistocene vegetation in the Netherlands. PhD thesis Leiden University. Mededelingen van de Geologische Stichting, Serie C-III-1 5: 78 pp.

Zagwijn, W.H. & Van Staalduinen, C.J., 1975. Toelichting bij geologische overzichtskaarten van Nederland, met bijbehorende 5 kaarten (1 : 600 000) en 3 overzichtsprofielen. Rijks Geologische Dienst (Haarlem): 134 pp.

Ziegler, P.A., (ed.) 1990. Geological Atlas of Western and Central Europe. Shell Internationale Petroleum Maatschappij (Den Haag) & Geological Society Publishing House (Bath) 2: 239 pp.

Ziegler, P.A., 1992. European Cenozoic rift system. Tectonophysics 208 (1-3): 91-111. DOI: 10.1016/0040-1951(92)90338-7

Ziegler, P.A. & Dèzes, P., 2006. Crustal evolution of Western and Central Europe. Geological Society of London, Memoirs 32: 43-56. DOI: 10.1144/GSL.MEM.2006.032.01.03

Ziegler, P.A., 1994. Cenozoic rift system of western and central Europe: an overview. Geologie En Mijnbouw 73(2-4): 99-127.

Ziegler, P.A. & Dèzes, P., 2007. Cenozoic uplift of Variscan Massifs in the Alpine foreland: Timing and controlling mechanisms. Global and Planetary Change 58(1-4): 237-269. DOI: 10.1016/j.gloplacha.2006.12.004