

8 Late Cretaceous

Henk van Lochem, Geert-Jan Vis & John W.M. Jagt*

*Corresponding author: j.h.vanlochem@argo-geoscience.com

ABSTRACT

The Upper Cretaceous is one of the rare stratigraphic intervals in the Netherlands that can be studied in outcrop. The quarrying of chalky limestone and interbedded chert nodules in South Limburg has contributed to the study of these rocks and their notable fossil content. During the Late Cretaceous, a transgression which had started in the Jurassic resulted in a complete flooding of the current extent of the Netherlands. A fairly uniform succession of marine marls and limestones of the Texel and Ommelanden formations of the Chalk Group developed. This period of calm sedimentation was locally interrupted by the Sub-Hercynian (Santonian-Campanian) and Laramide (Paleocene) tectonic inversion phases. The resulting erosion removed much of the Cretaceous succession, especially in areas of the former Jurassic basins. However, deposition continued unabated in the previous Jurassic high areas, resulting in significant sediment thicknesses of more than 1800 m. The biostratigraphy and paleoenvironments of the Upper Cretaceous can be studied in detail in outcrop in South Limburg, including the Cretaceous-Paleogene boundary.

<< Fine-grained limestone with rhythmic chert layers of the Gulpen Formation overlain by the massive calcarenitic Maastricht Formation (abandoned ENCI quarry, southeast Netherlands).
Photo: Geert-Jan Vis.

Introduction

Previous research

As Upper Cretaceous strata are virtually the only rocks that crop out in the Netherlands, they have attracted human interest quite early. Already during the Stone Age, Upper Cretaceous limestones in what is currently known as South Limburg (southeast Netherlands), were put to practical use. Neolithic people used intricate mining techniques to extract flint (chert) from the subsurface, which they used for knapping tools. They clearly had an understanding of the geology of the Upper Cretaceous since they preferentially mined intervals with a high chert content. In the mine field of Rijckholt-St. Geertruid this was flint level 10 of the Lanaye Member (upper Gulpen Formation; Rademakers, 1998).

From Roman times onwards these limestones have been used as building material (Engelen, 1989). For this application the miners preferred intervals of relatively soft rock, which contained only few chert nodules and which could be cut by chisels and saws. In the well-known 'caves' of Mount Saint Peter (Sint Pietersberg) for over centuries rectangular blocks of limestone were cut from the Maastricht Formation (Felder & Bosch, 2000).

The mining activities in the Mount Saint Peter also resulted in the find of the famous mosasaur jaws (Camper, 1786), which set off more scientific studies into Late Cretaceous paleontology and geology. In 1849, the 'système maestrichtien' was introduced when Dumont (1849) defined the highest stage of the Cretaceous in the Maastricht area, the only formal, international stage named after a Dutch location. In 1859, Binkhorst van den Binkhorst, published his standard work on the geology of the Cretaceous of South Limburg. A year later, part two of Staring's (1860) book 'De Bodem van Nederland' appeared, which contained a lithostratigraphic subdivision of the Cretaceous.

W.M. Felder (1975) formalized the lithostratigraphy of the Upper Cretaceous of South Limburg, while NAM & RGD (1980) defined a less detailed lithostratigraphy for the Chalk Group for that part of the Netherlands where the Upper Cretaceous is only known from boreholes. The latter subdivision was later revised in the lithostratigraphic nomenclature compiled by Van Adrichem Boogaert & Kouwe (1994), while the former was illustrated in more detail by W.M. Felder & Bosch (2000).

In South Limburg the late Felder brothers, Werner (1930-2008) and Peter Jozef ('Sjeuf'; 1928-2009), contributed much to our understanding of the stratigraphy of the Upper Cretaceous, while others have since continued to build on their legacy (Jagt et al., 2011).

Ongoing exploration for oil and gas has yielded more subsurface information on the Upper Cretaceous inter-

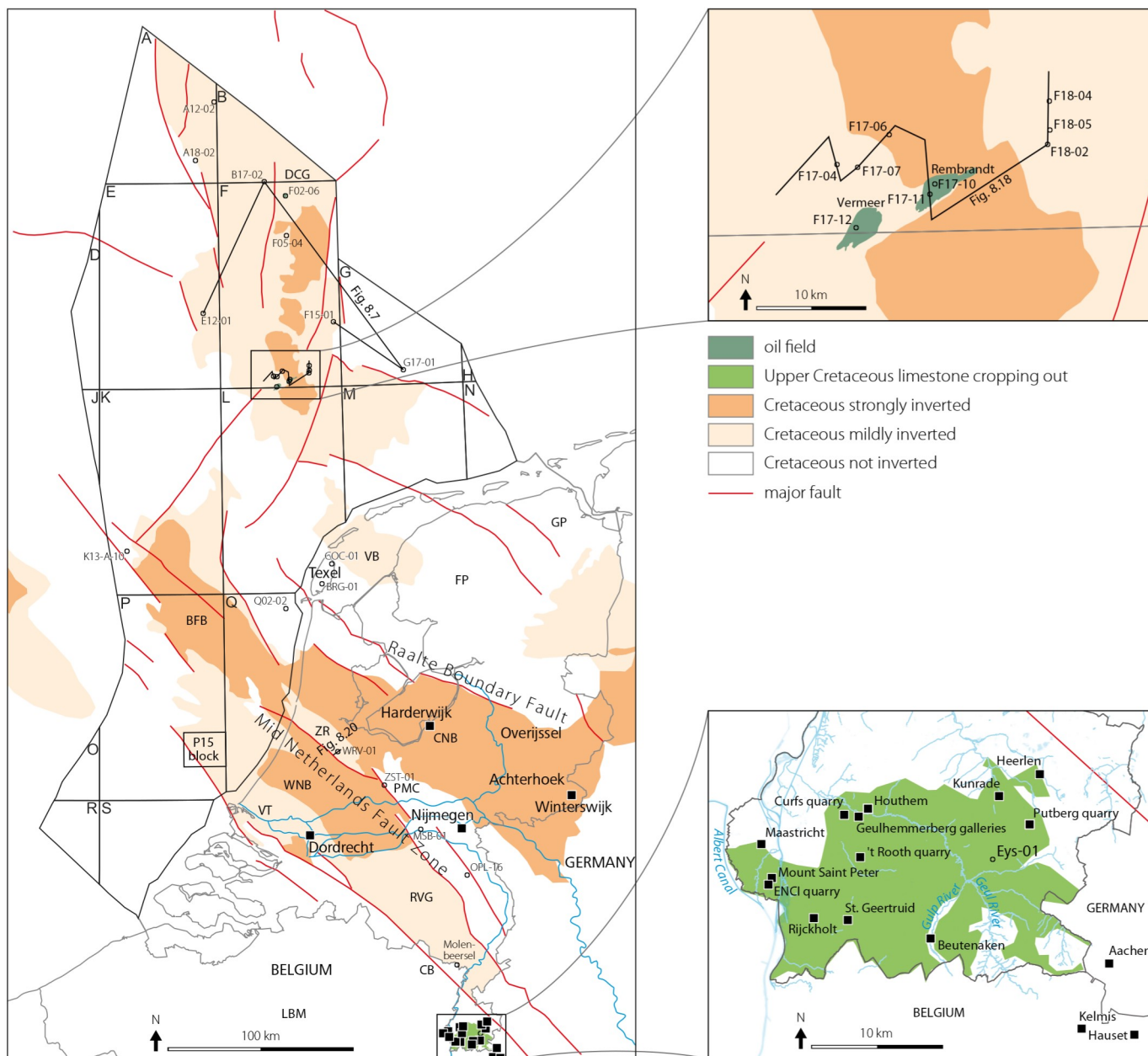
val. Tectonic inversion (Fig. 8.1) in particular, during or just after the Late Cretaceous, has been and is an important topic of studies (see e.g. Van Wijhe, 1987a,b; Burgers & Mulder, 1991; Dronkers & Mrozek, 1991; Van Lochem, 2018). Duin et al. (2006) and Kombrink et al. (2012) presented a compilation of subsurface maps based on results obtained during more than 50 years of oil and gas exploration (Figs 8.2, 8.3). Vejbaek et al. (2010) placed all mapping efforts of the Cretaceous strata of the Southern Permian Basin, including the Netherlands, into a single atlas chapter.

Oil and gas exploration in Upper Cretaceous reservoirs in the Netherlands did not match the great successes of the Norwegian Ekofisk field or the Dan field in the Danish sector (Surlyk et al., 2003). Consequently, the Dutch oil industry and research institutions did not spend much time and effort on the Upper Cretaceous, aside from ongoing studies in South Limburg. Far more work was done in the Danish, Norwegian and UK sectors of the North Sea Basin. A notable exception is the PhD thesis by Van der Molen (2004), who introduced the use of seismic stratigraphy for the Chalk Group in the Dutch offshore, which yielded a better understanding of the internal structure of this group and of the timing of tectonic movements during the Late Cretaceous.

Regional geological setting

All Upper Cretaceous sedimentary rocks in the Netherlands are attributed to the Chalk Group. However, this unit also includes the Ekofisk and Houthem formations of Danian age (Van Adrichem Boogaert & Kouwe, 1994). For this reason, the present chapter on the Upper Cretaceous also includes Danian strata, the first stage of the Paleocene Epoch (Fig. 8.4). The whole interval discussed in the present chapter covers a time period of 38.8 Myr (Gale et al., 2020).

The Late Cretaceous world was utterly different from the Quaternary world (Skelton et al., 2003; MacLeod et al., 2011; Hu et al., 2012; Huber et al., 2018). While for the last three million years the earth's climate has seen an alternation of ice ages and interglacials, the Late Cretaceous can be characterized as a 'greenhouse' world. Global temperatures were much higher than today's, especially extending to higher latitudes (Frakes, 1999; Hay & Floegel, 2012; O'Brien et al., 2017). The long-term eustatic sea level was significantly higher than the current level (Haq, 2014) with the highest level (~250 m) reached during the Turoonian Stage and slowly decreasing to around 200 m above the present-day level during the Danian. In general, the CO₂ content of the atmosphere was high, in the range of 500-1000 ppmv (Wang et al., 2014). Ice sheets were virtually absent, although cooling has been demonstrated at the end of the Late Cretaceous (Linnert et al., 2014, 2018).



Acronym	Full name	Acronym	Full name
BFB	Broad Fourteens Basin	PMC	Peel-Maasbommel Complex
CB	Campine Basin	RVG	Roer Valley Graben
CNB	Central Netherlands Basin	VB	Vlieland Basin
DCG	Dutch Central Graben	VT	Voorne Trough
FP	Friesland Platform	WNB	West Netherlands Basin
GP	Groningen Platform	ZR	Zandvoort Ridge
LBM	London-Brabant Massif		

Figure 8.1. Inverted basins in the Netherlands. In the mildly or non inverted basins, the Upper Cretaceous chalk is thin as a result of erosion and/or limited deposition. In the strongly inverted basins, no chalk has been preserved. Locations and geological features mentioned in the text are indicated. Inverted basins modified from Kombrink et al. (2012). Eys-01 = B62B4547.

The present-day Netherlands was located at a latitude of around 45 degrees north in the Northern Mid-Latitude Warm Humid Belt according to paleoclimatic maps by Chumakov et al. (1995) and Hay & Floegel (2012).

During the Late Cretaceous the North Atlantic Ocean continued to open between West Africa and North America, while, albeit at a slower pace, the Norwegian Sea rifted between Greenland and Norway (Scotese, 2001; Pharaoh

et al., 2010; Hopper et al., 2014). Meanwhile, Italy and the Balkans moved north in the Tethys Ocean and at the end of the Cretaceous started to collide with the southern margin of the European continent.

A large sea covered most of Europe (Vejbæk et al., 2010) during the Late Cretaceous (Fig. 8.5). While in western and central Europe the sea was relatively shallow and epicontinental, to the south the Tethys Ocean was consider-

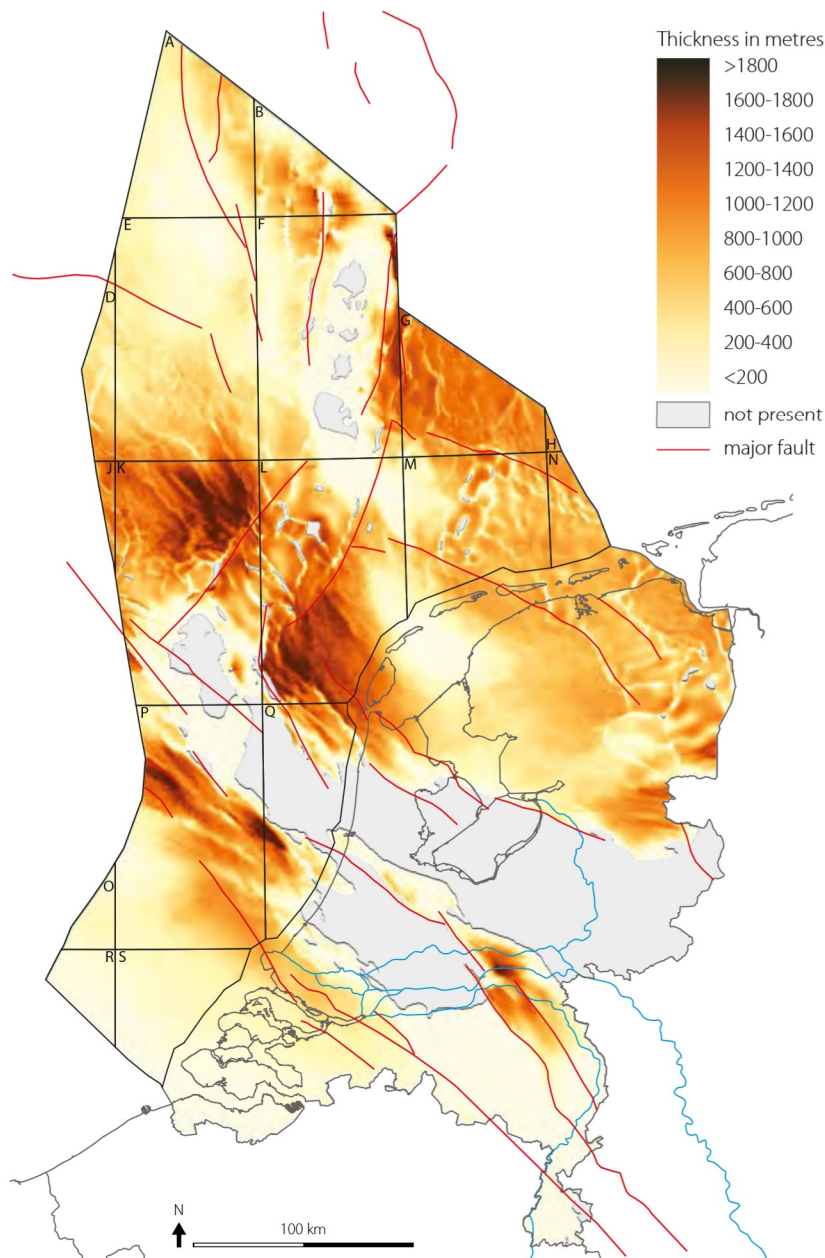


Figure 8.2. Isochore map of the Chalk Group. Data: DGM-deep v5, www.nlog.nl (2020).

ably deeper and in part was underlain by oceanic crust. The nearest continental landmass was Eurasia, including the Fennoscandian High and Baltic Shield, situated to the north and east. In the Late Cretaceous sea several exposed islands were present (Fig. 8.5): to the southeast lay the Mid-European Island (Wilmsen et al., 2014) which stretched from the Rhenish Massif to the Bohemian Massif, to the southwest (Bretagne) the Armorican Massif and to the west the Cornish Massif, Welsh High, Grampian High and Shetland Platform. The lack of continental sediment source areas limited the influx of siliciclastic sediments into the sea. Only locally, around the landmasses and islands, were siliciclastic, shallow-marine sediments deposited, while the largest part of the basin was filled with very fine-grained calcareous nannofossil ooze, which

turned into calcareous mudstone due to lithification. In and around the Netherlands these deposits are called 'chalk' (Scholle, 1977), which consists for the largest part of the tests of coccolithophorid algae settled out of suspension, which makes these carbonate rocks very different in facies and lithology from platform and reef limestones.

During the Late Jurassic to Late Cretaceous, a large southwardly directed transgression inundated the present-day territory of the Netherlands. At the start of the Late Cretaceous, the coastline extended approximately from Dordrecht to Nijmegen, as evidenced by the presence of the shallow-marine Texel Greensand Member to the north of this line. During the Late Cretaceous (Fig. 8.5), transgression in the south continued and by Maastrichtian time the

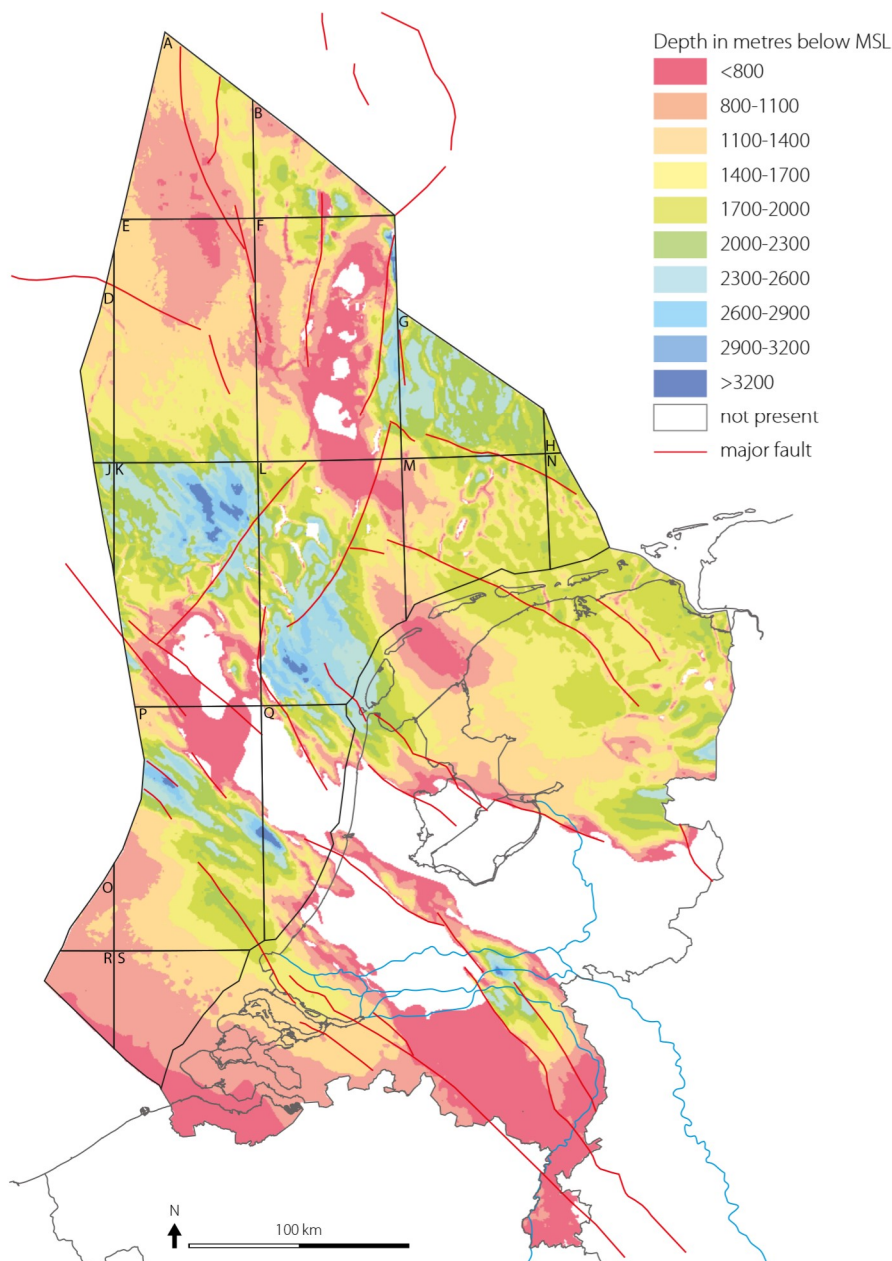


Figure 8.3. Depth map of the base of the Chalk Group. Data: DGM-deep v5, www.nlog.nl (2020).

sea had flooded the entire London-Brabant Massif (Dusar & Lagrou, 2007).

On a global scale at the Cenomanian-Turonian boundary, organic carbon-rich deposits can be found with a concomitant positive shift in carbon-isotope values (Tsikos et al., 2004). The Plenus Marl found at this boundary represents an Oceanic Anoxic Event (OAE) (Schlanger & Jenkyns, 1976), also identified as the OAE-2 or Bonarelli Event after the Livello Bonarelli, the characteristic black shales found in the central part of the Apennines in Italy. The OAE-2 represents a worldwide sea level high-stand, coupled with a rise of the oxygen-minimum zone and large-scale organic carbon deposition and burial. It occurred during an episode of global greenhouse conditions when large amounts of organic matter entered the marine

sedimentary record, probably triggered by increased availability of nutrients for planktic biota. Globally widespread carbon burial and silica weathering have both been identified as important mechanisms for drawing down levels of atmospheric carbon dioxide that caused the Plenus Cold Event (Jenkyns et al., 2017).

The Cretaceous-Paleogene (K-Pg) boundary mass extinction was one of the most devastating events in the Phanerozoic history of life, both on land and in the oceans (Alvarez et al., 1980; Smit & Hertogen, 1980; Speijer et al., 2020). This is now widely acknowledged to be related to the impact of an asteroid with an estimated diameter of ~10 km at Chicxulub, Yucatán Peninsula, Mexico (Kring, 2007; Schulte et al., 2010). The impact was followed by a so-called 'impact winter', the result of the injection of

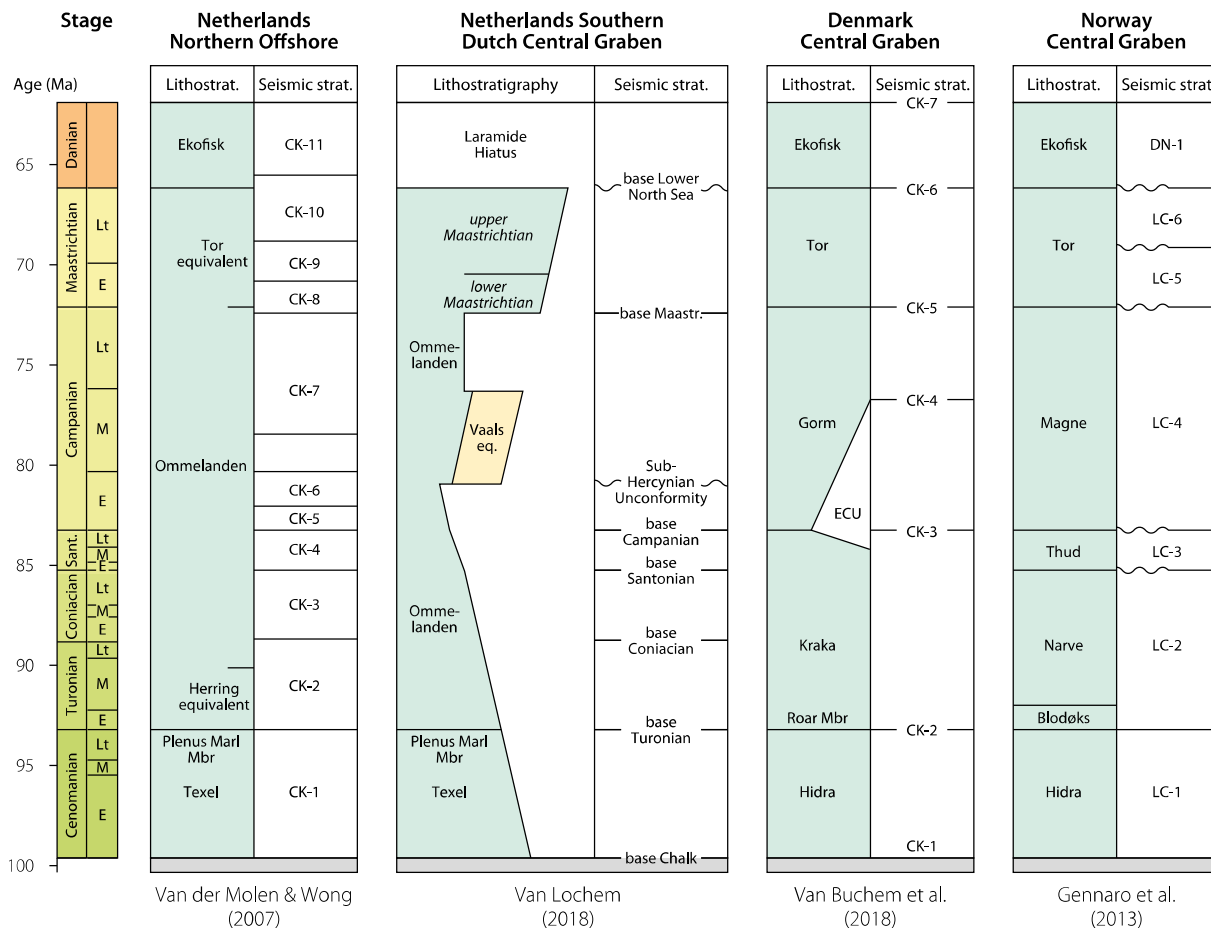


Figure 8.4. Stratigraphic scheme of the Chalk Group in the Dutch (after Van der Molen & Wong, 2007; Van Lochem, 2018), Danish (Van Buchem et al., 2018), and Norwegian (after Gennaro et al., 2013) sectors presenting (informal) lithostratigraphic units and interpreted seismic sequences. Numerical ages are from Cohen et al. (2013; updated). Modified from Van Lochem (2018). ECU = Early Campanian Unconformity.

large amounts of dust and aerosols into the stratosphere, which significantly reduced incoming solar radiation for decades. Therefore, this phase will have been a key contributory element in the extinctions of many biological clades, including most species of planktic foraminifera and many coccolithophorids but also of larger marine taxa such as ammonites and reptiles, in addition to non-avian dinosaurs and flying reptiles (Vellekoop et al., 2014; Fischer et al., 2015; Landman et al., 2015). Strata deposited just after the impact are often enriched in the element iridium (Ir), which points to an extra-terrestrial origin of the K-Pg event (Alvarez et al., 1980). The mass extinction of marine life and the deposition of impact-related sediments can also be studied in the chalk of South Limburg (Smit & Brinkhuis, 1996).

In large parts of the North Sea Basin the Danian Stage of the lower Paleocene sedimentary record consists of calcareous nannofossil mudstone that is quite similar to strata formed just prior to the K-Pg boundary. However, the fossil

content of these superficially identical rocks differs significantly from that of the Upper Cretaceous levels (Hansen, 2019; Schröder & Surlyk, 2020). Following the Danian, during the Selandian, the sedimentary development of the North Sea Basin completely changed from a carbonate system to a siliciclastic-dominated system, resulting from the Paleocene Laramide tectonic phase.

During the early Late Cretaceous (Cenomanian-Turonian) the tectonic development of the present-day Netherlands was characterized mainly by post-rift thermal subsidence, since the North Sea rift had abated in Albian times (Pharaoh et al., 2010). The lithosphere of northwest Europe was subjected to compressional intraplate stresses starting in the late Turonian-Coniacian, when extensional and transtensional Mesozoic basins began to experience tectonic inversion (Fig. 8.1; De Jager et al., 2025, this volume). Older normal faults were reactivated as reverse faults and much of the inverted basin fills were eroded.

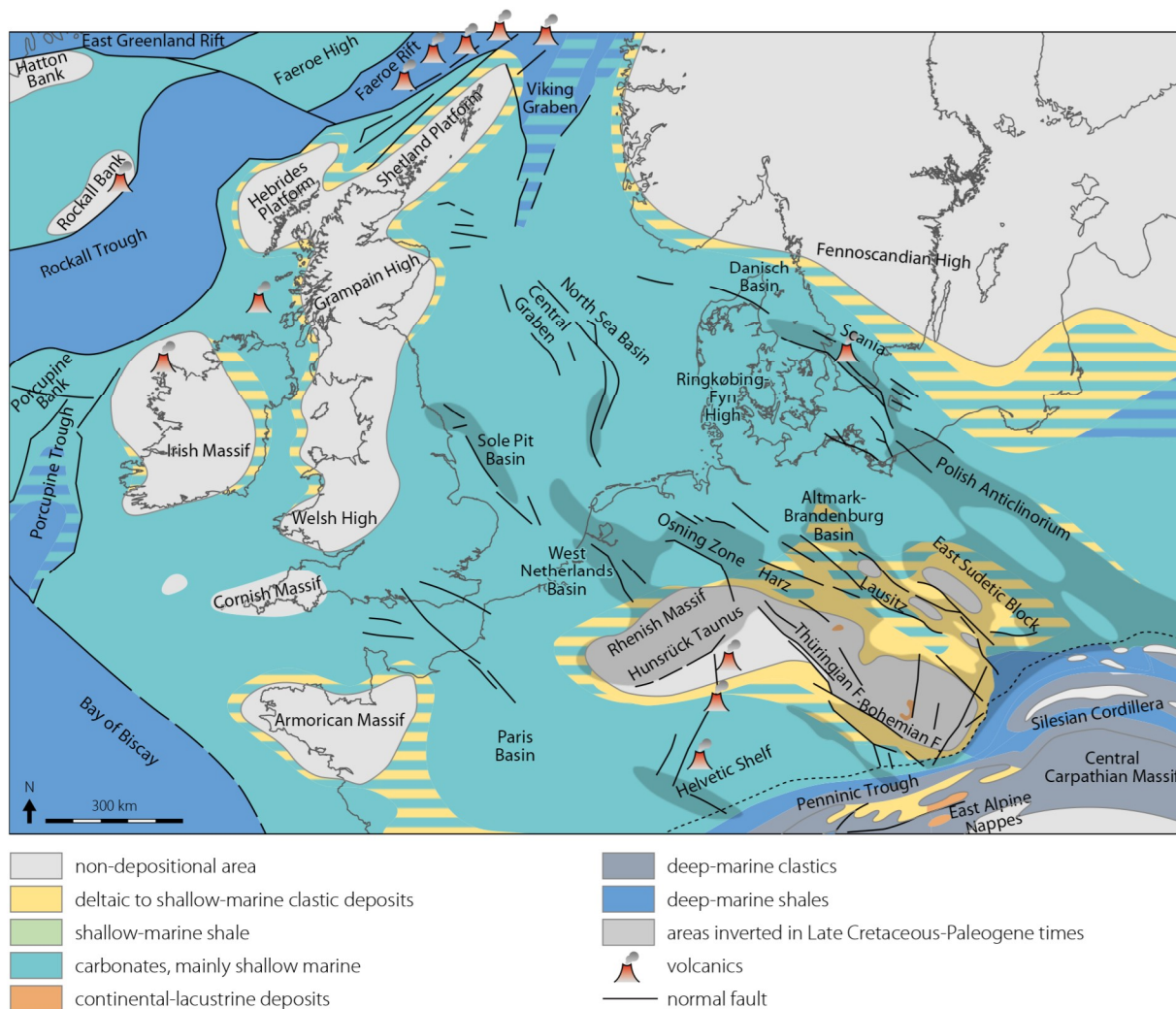


Figure 8.5. Central European paleogeography in Cenomanian to Danian times (modified from Ziegler, 1982; from Vejbaek et al., 2010).

Stratigraphy

Chalk Group

The Chalk Group consists of a succession of marine, predominantly bioclastic and in part marly limestones or calcareous mudstones (Fig. 8.6). In the southwest and southeast of the Netherlands, deposits of this group unconformably overlie strata of Paleozoic age. The stratigraphy in the southeast, in the region of South Limburg where these rocks partly crop out, follows a separate subdivision with six lithostratigraphic units which are of Santonian to Danian age (Fig. 8.6; Felder, 1975; Felder & Bosch, 2000).

Biostratigraphic interpretations of offshore sections rely on analyses of calcareous nannoplankton, planktic and benthic foraminifera and dinoflagellates in borehole cuttings and cores; data on macrofossil groups are very limited (Van Buchem et al., 2018; Eldrett et al., 2021). Ranges of key index microfossil species and, more specifically,

their first and last appearance datums (FAD, LAD) can be used for correlations to other offshore and onshore sections. On the basis of foraminifera, dinoflagellates, calcareous nannofossils and diatoms Gradstein et al. (2016) distinguished 19 microfossil zones (NCF1-19) and more than one hundred events. They also used literature data to link Dinoflagellate Cyst Zones (DCZ) to these NCF zones. In all, 11 dinoflagellate zones and 39 subzones were recognized for the marine Cretaceous succession in the North Sea.

Thus, microfaunal analyses of borehole cores have yielded a robust correlative framework. Overall, depositional conditions for strata penetrated in wells may be assumed not to have differed in any significant respect from onshore sections around the North Sea (e.g. Surlyk et al., 2006, 2013; Anderskov et al., 2007; Voigt et al., 2008; Niebuhr et al., 2011; Jelby et al., 2014; Mortimore & James, 2015; Mitchell, 2019; Wilmsen et al., 2019). In cores of the Chalk Group, ichnofossils (reflecting benthic macrofaunal activity) and skeletal elements of certain macrofossil

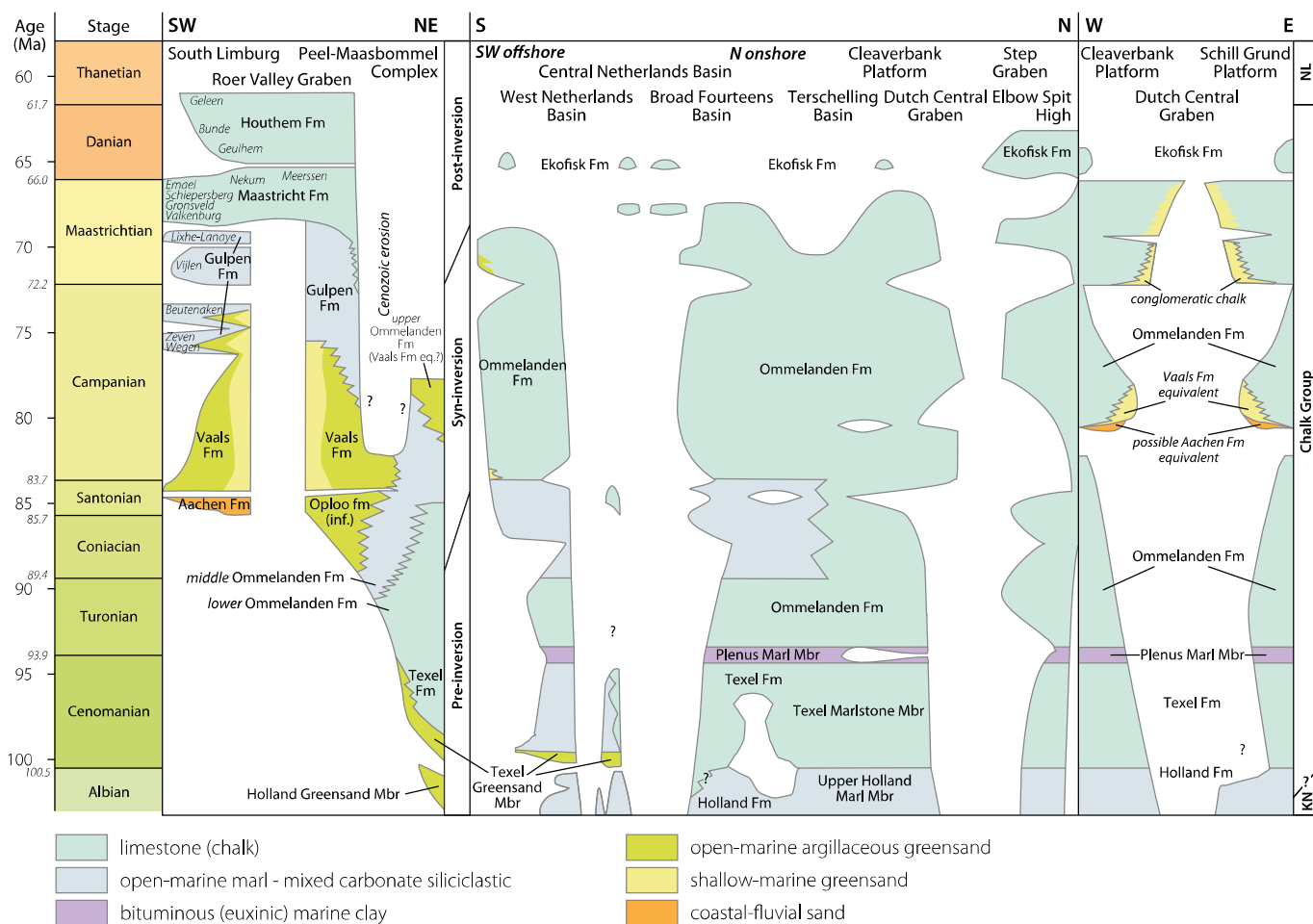


Figure 8.6. Lithostratigraphic scheme of the Upper Cretaceous succession of the Netherlands, based on Van Adrichem Boogaert & Kouwe (1994), Gras & Geluk (1999), Jagt (1999a,b), Map sheet XIII+XIV (NITG-TNO, 2001), Vellekoop et al. (2022) and Gale et al. (2023). Lithostratigraphy of the Dutch Central Graben (right panel) after Van Lochem (2018). KN = Vlieland Group; NL = Lower North Sea Group

groups are occasionally noted. Key index macrofossil taxa such as ammonites, belemnites, inoceramid bivalves, brachiopods, echinoids and crinoids are also known from some observations in core and cuttings.

Texel Formation

The Texel Formation usually comprises light grey to beige and white limestones and marly chalks with some marl intercalations. Near the southern edge of its distribution, i.e. the southern part of the West Netherlands Basin and along the Peel-Maasbommel Complex, greensands form the base of the formation (Fig. 8.6). Elsewhere, in the central part of the West Netherlands Basin, and in the Central Netherlands and Broad Fourteens basins, the formation becomes increasingly marly and, in a more offshore setting north of these basins, it develops into pure limestones. The formation's thickness varies between 50 and 70 m in the northern and eastern Netherlands (Vlieland Basin, Friesland Platform, Groningen Platform and the east of the

province of Overijssel) and increases southwards to 300 m (borehole Q02-02). The formation is locally exposed in the Achterhoek and is well developed in adjacent parts of Germany (Hiss et al., 2018). The sediments of this formation were deposited in a transgressive setting of relatively deep water and have been dated as Cenomanian on the basis of benthic and planktic foraminifera (Table 8.1). The formation comprises sequence CK1 of Van der Molen & Wong (2007) (Fig. 8.7).

The Texel Greensand Member (Fig. 8.6) is a highly glauconitic, calcareous sandstone with intercalated marls. It occurs only along the southern fringe of the West Netherlands Basin. The Texel Marlstone Member consists of white

Table 8.1. Index taxa for Upper Cretaceous units, arranged by groups available online at:
DOI: 10.5117/aup.27108772.

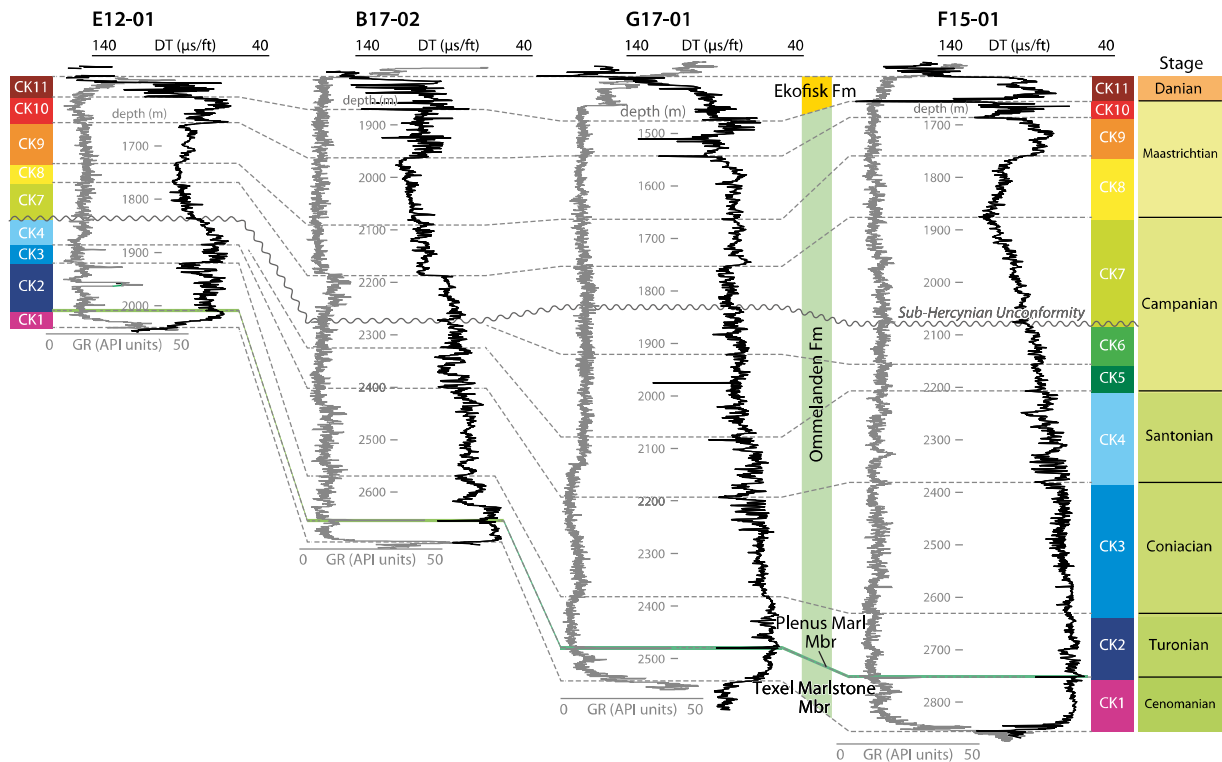


Figure 8.7. Well-log correlation panel with gamma-ray- and sonic logs of wells E12-01, B17-02, G17-01 and F15-01 (for location see Fig. 8.1). Intra-chalk seismic sequences CK1 to CK11 were tied to the wells using synthetic seismograms. The seismic sequences were subsequently dated with biostratigraphic data available in a selection of wells (modified from Van der Molen & Wong, 2007, Fig. 7). Note that the Plenus Marl Member clearly stands out in the gamma-ray and sonic logs.

to light-grey limestones and marly chalks in the northern Netherlands and of marls with marly chalks south of the Broad Fourteens Basin and in the western part of the West Netherlands Basin. The Plenus Marl Member is a dark grey, locally black, calcareous, laminated, bituminous claystone of widespread distribution. The marl represents an Oceanic Anoxic Event (OAE-2). Its thickness is usually some decimetres to a few metres and it is easily recognized on wireline logs by the characteristic high(er) gamma-ray and resistivity, and lower sonic readings (Fig. 8.7). The age of the member straddles the Cenomanian-Turonian boundary.

Ommelanden Formation

A succession of white to yellowish-white or light olive-grey, fine-grained, and in places argillaceous limestones characterizes this formation (Fig. 8.8a,b; Fig. 8.9a-d). Layers of chert nodules are locally common in its Campanian to Maastrichtian part. Along the basin edge coarse-grained, bioclastic limestones and wedges of sandstone and glauconitic sandstone occur (Gras, 1995; Gras & Geluk, 1999; Van Lochem, 2018). The formation comprises mainly hard, dense limestones (as result of compaction and cementation), but in its upper part, it tends to be softer and more chalky in texture (Fig. 8.10a). The sediments

were deposited under relatively stable, low-energy conditions in carbonate-shelf and upper bathyal settings and range in age from early Turonian to Late Maastrichtian. They comprise sequences CK2-CK10 of Van der Molen & Wong (2007). The age assignment relies primarily on benthic foraminifera (genera *Stensioeina*, *Gavelinella* and *Bolivinoidea*; see Table 8.1). The LADs of the planktic foraminifera *Racemiguembelina fruticosa* and *Pseudotextularia elegans* date sequence CK10 as Late Maastrichtian, but in some places, it extends into the early Danian, where the index *Globoconusa daubjergensis* has been noted.

North of the Peel-Maasbommel Complex the formation has informally been subdivided into three units (Fig. 8.6), although recent ongoing work casts doubt on this subdivision. The lowermost Turonian interval is a whitish, hard, dense limestone with high sonic readings. It is overlain by a more marly succession of Coniacian to Campanian age (NITG-TNO, 2001). The uppermost unit is less marly and, in its lower part, consists of consolidated calcarenites, grading upwards into massive chalk with abundant chert nodules.

Thicknesses up to 1500 m are reached in the offshore K and L quadrants. The thickness is greatly influenced by inversion movements whereby former Mesozoic depocentres were uplifted, resulting in a thin cover of Chalk

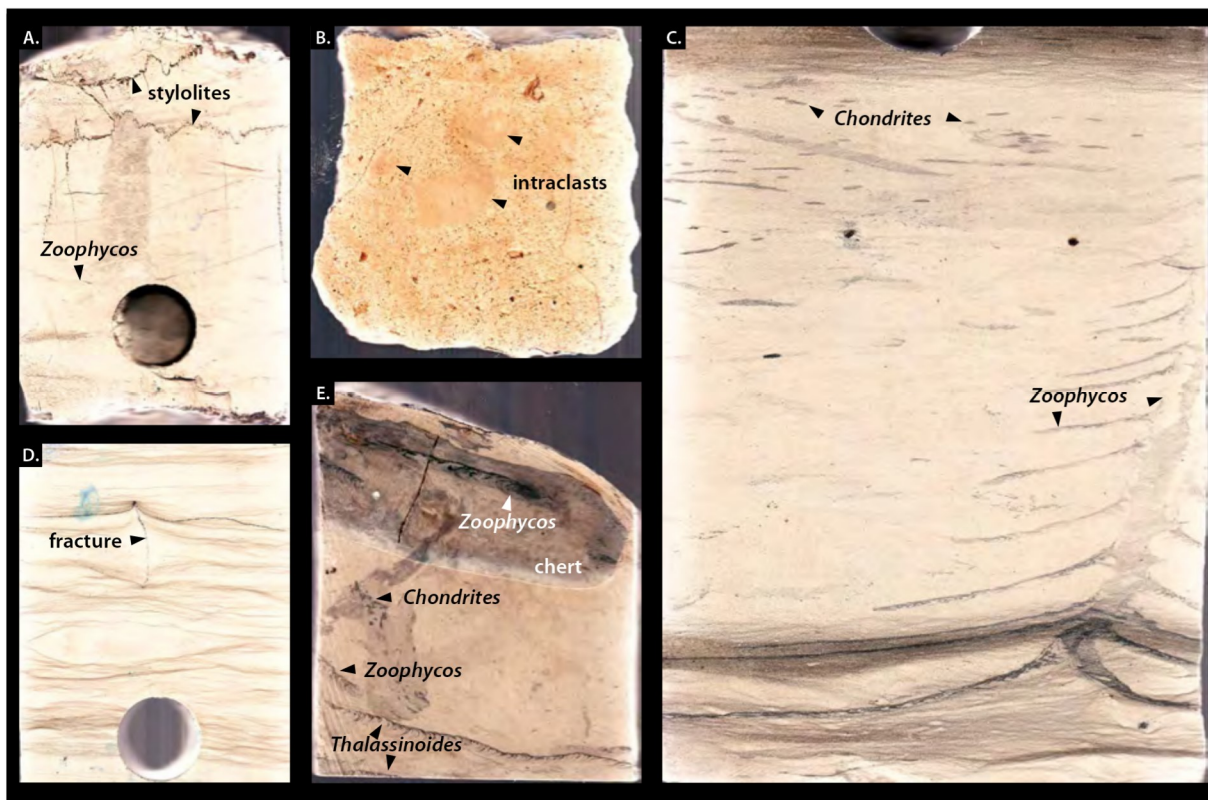
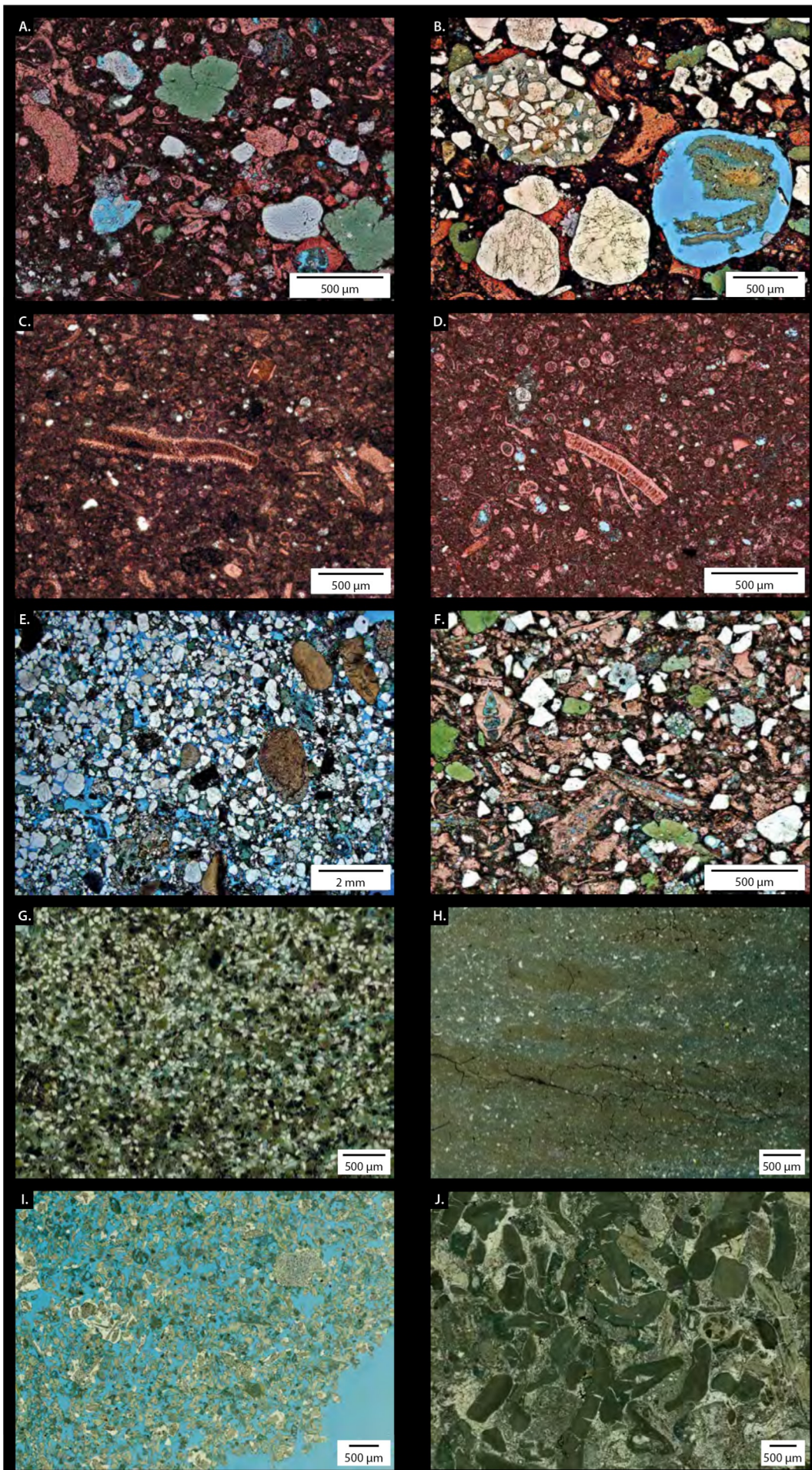


Figure 8.8. Core photographs (from Ineson et al., 2014). a) Chalk Mudstone Association (FA-1): chalk mudstone, bio-mottled, stylolitic; note the curved concave-up Zoophycos traces and the discontinuous open fractures emanating from the stylolites. Ommelanden Formation, Maastrichtian (A12-02, Core 4, 2040.6 m, core width ca. 9 cm; note that Core 4 is probably inverted and is shown here in the inferred correct way-up). b) Skeletal Wackestone-Packstone Association (FA-3): skeletal packstone containing chalk mudstone intraclasts, Ommelanden Formation, lower Maastrichtian (F05-04, Core 3, 1358.75 m, core width ca. 7 cm). c) Marly Chalk Association (FA-2): slightly marly chalk showing a cross-section of the axial tube of a Zoophycos system (right) and Chondrites (top left). Ekofisk Formation, Danian (A12-02, Core 3, 2022.6 m, core width ca. 10 cm). d) Marly Chalk Association (FA-2): marly chalk showing nodular fabric produced by abundant anastomosing solution seams. Note compaction effects over an early calcite-filled discontinuous fracture. Ekofisk Formation, Danian (A12-02, Core 3, 2018.8 m, core width ca. 10 cm). e) Marly Chalk Association (FA-2): slightly marly chalk mudstone with well-defined burrows of Thalassinoides, Zoophycos and Chondrites. Note virtually uncompacted Zoophycos in the chert nodule. Ekofisk Formation, Danian (A18-02, Core 2, 1947.0 m, core width ca. 10 cm).

→ **Figure 8.9.** Microphotographs of thin sections of Chalk Group sedimentary rock taken in plain polarized light (PPL). a) Ommelanden Formation (Lower Maastrichtian) sandy chalk (F17-11, 1467.6 m; Van Lochem, 2018). b) Ommelanden Formation (Lower Maastrichtian) conglomeratic chalk (F17-11, 1469.9 m; Van Lochem, 2018). c) Ommelanden Formation (Upper Maastrichtian) clean chalk (F17-10, plug number: S14A core depth: 1387.85 m; Petrea & Goldberg (2013). d) Ommelanden Formation (Upper Maastrichtian) clean chalk (F17-11, 1432.6 m; Van Lochem, 2018). e) Vaals Formation equivalent (late Campanian) sandstone (F17-11, 1474.1 m; Van Lochem, 2018). f) Vaals Formation equivalent (late Campanian) sandstone (F17-12, 1437.0 m; Van Lochem, 2018). g) Vaals Formation: very fine to fine-grained glauconitic sandstone with sponge spicules and planktonic foraminifera (Eys-01 (B62B4547), 109.50 m). h) Gulpen Formation (Lixhe Member): bioclastic wackestone with planktonic foraminifera (ENCI quarry). i) Lower Maastricht Formation: highly porous bioclastic grainstone, with syntaxial overgrowth of echinoderms. The main bioclasts are echinoderms, bivalves, foraminifera, gastropods, and bryozoans (ENCI quarry). j) Houthem Formation: red algae grainstone to boundstone with bryozoans, foraminifera, and echinoderms (borehole Molenbeersel (Belgium), 1235.10 m). Images g-j kindly provided by Mateus Kroth of Utrecht University.



Group strata. Strong subsidence of the adjacent highs resulted in so-called marginal troughs with very thick successions. Biostratigraphic and log-correlation studies in places have identified several unconformities within the succession, which can be related to the different inversion pulses (Van Wijhe, 1987b; Herngreen et al., 1996; De Jager, 2003, 2007; Van der Molen, 2004).

Ekofisk Formation

This formation comprises white, chalky limestones with rare nodular and bedded chert layers (Fig. 8.8c-e) and thin, grey to green clay laminae; glauconite may occur in its basal part. The formation displays a characteristic gradual upward increase in transit time log readings, resulting from an increase in porosity (Fig. 8.7). The Cretaceous/

Paleogene (K-Pg) boundary is placed either at a rarely observed gamma-ray peak representing the Cretaceous/Paleogene (K-Pg) boundary clay (Herngreen & Wong, 2007), or at a negative excursion in $\delta^{13}\text{C}$ values or at an interval with 'disaster taxa' among calcareous nannofossils (Eldrett et al., 2021). Near this boundary a hardground, overlain by a glauconite-rich bed, occurs locally. This boundary equates with the Fish Clay in eastern Denmark (e.g. Christensen et al., 1973; Schmitz et al., 1992; Surlyk et al., 2006) and the base of subunit IVF-7 (Meerssen Member) in South Limburg (Smit & Brinkhuis, 1996; Herngreen et al., 1998).

The sediments of this formation were deposited under relatively stable, low-energy marine conditions in carbonate-shelf and upper bathyal environments. Local coral growth has been observed on submarine highs such as in the core of well Fo2-06 (Ineson et al., 2014). The Ekofisk Formation corresponds to sequence CK11 of Van der Molen & Wong (2007) and is dated as Danian based on foraminiferal evidence. It is not clear, however, when the onset of deposition of its sediments occurred.

The Ekofisk Formation is found in the northern and southern parts of the Dutch North Sea sector and is the equivalent of the Houthem Formation. By definition, the name Ekofisk Formation is reserved to offshore occurrences. Its thickness attains maximum values of 140 m.

Chalk Group in the (south)eastern Netherlands

In the onshore sections, both micro- and macrofaunal assemblages permit more detailed paleoenvironmental interpretations than in the offshore. From the Winterswijk area (eastern Netherlands), typical early middle Cenomanian ostracods (Witte et al., 1992) and early Cenomanian ammonites (Jagt & Oosterink, 2012) have been recorded from the so-called 'Kottense Kalk', which belongs to the Texel Formation. There are no outcrops of strata of middle Cenomanian to late Coniacian age in the Netherlands.

In the southeast of the Netherlands strata of Santonian to Danian age are present and six formations are defined (Fig. 8.6). Their lateral distribution is not clearly defined, but currently is limited to the area of South Limburg and adjacent regions, where most of these formations are found in outcrop. In general, the sedimentary rock of the Chalk Group of South Limburg has a coarser texture than its equivalents in the present-day North Sea area (Figs 8.9 h-j, 8.10, 8.11). Most formation names used in the Netherlands for this region are adopted by neighbouring Belgium and Germany. The formations have been subdivided into members (Fig. 8.6) separated by (marker) horizons (Felder, 1975; Felder & Bosch, 2000). The field characteristics on which these formations and members are subdivided is questionable (Bless et al., 1986), however, as the

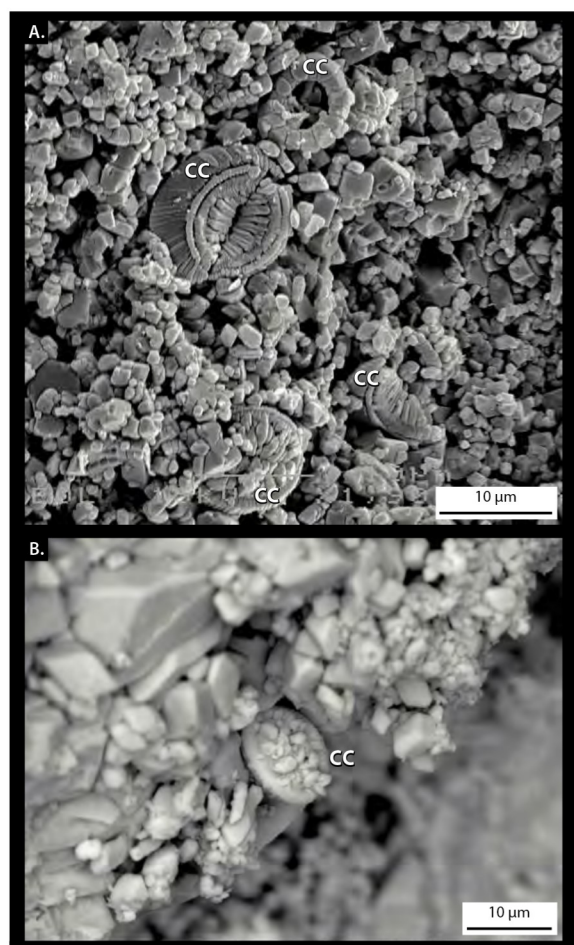


Figure 8.10. SEM images, both with the same level of magnification. a) Exceptionally well-preserved coccoliths (CC) from the Ommelanden Formation in the North Sea. Note that most of the grains derive from disintegrated coccoliths (well F17-10, plug number: S11A core depth: 1386.81 m, source Petrea & Goldberg, 2013). b) The only coccolith found in a sample from the Meerssen Member (former ENCI quarry, Maastricht). Note the much larger calcite crystals compared to the chalk mudstone from well F17-10.

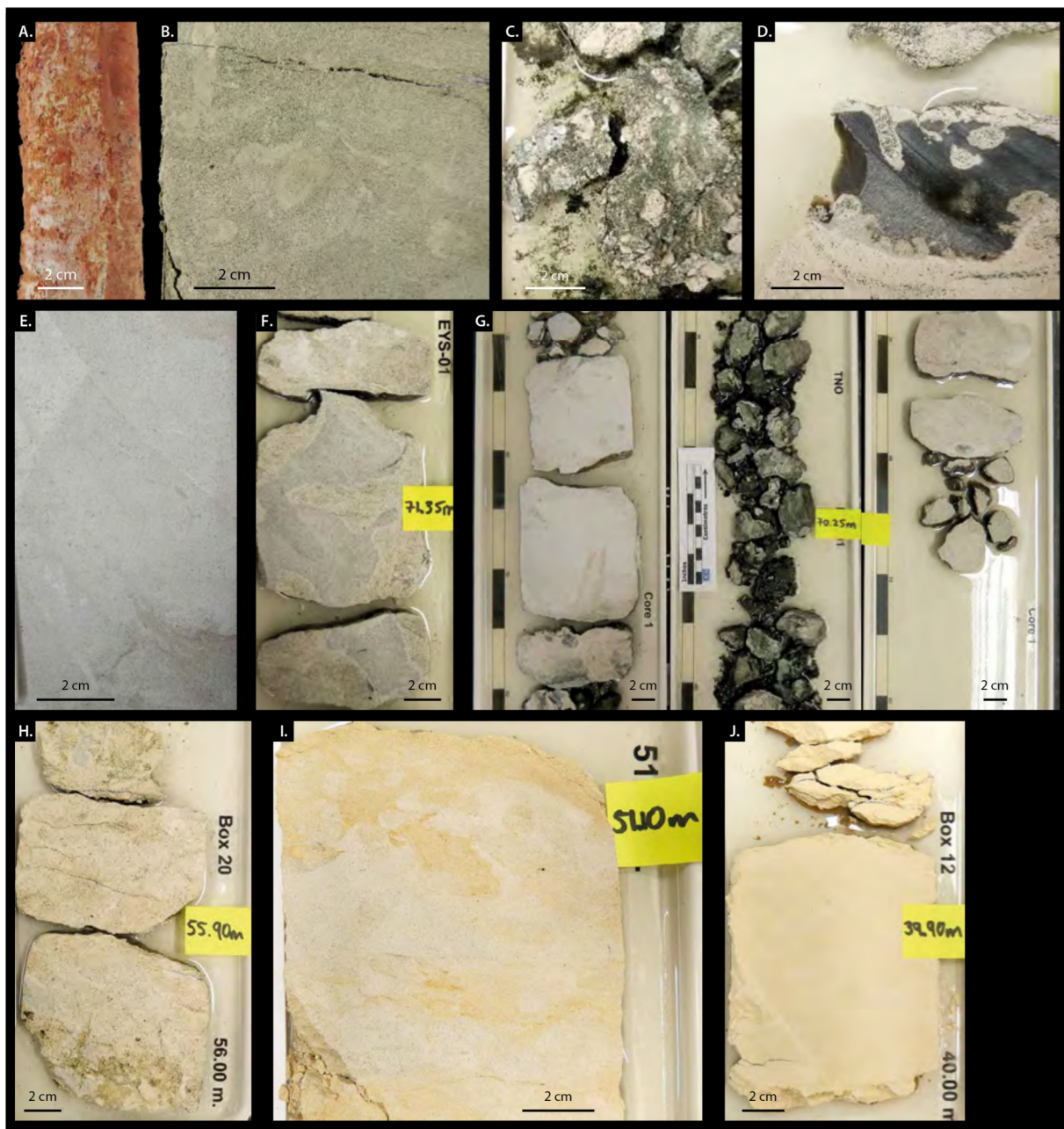


Figure 8.11. Core photographs from well Eys-01 (B62B4547, Gutteridge & Thompson, 2019). a) Aachen Formation: soil formation in smectitic Hergenrath Clay (178.6 m). b) Vaals Formation: bioturbated argillaceous sandstone with ?*Teichichnus* cemented by calcite (108.45 m). c) Gulpen Formation: basal clastic-rich limestone; peloidal glauconite, comminuted bioclasts and up to mm-sized detrital quartz grains (102.20 m). d) Gulpen Formation: bioturbated grainstone with bored hardground on chert nodule (100.58 m). e) Gulpen Formation: bioturbated calcarenitic limestone (78.85 m). f) Gulpen Formation: reworked lithified limestone in glauconitic limestone (71.35 m). g) Gulpen Formation: fine-grained glauconitic sandstone interval embedded in limestone (70.25 m). h) Maastricht Formation: sandy glauconitic limestone with reworked lithified burrow fills (55.90 m). i) Maastricht Formation: bioturbated calcarenitic limestone with firm ground at the top (51.10 m). j) Maastricht Formation: bioturbated calcarenitic limestone (39.90 m).

3D-stratigraphic architecture is more complex than previously recognized. As an ongoing PhD study is likely to shed new light on the Upper Cretaceous succession in South Limburg, we limit ourselves here to presenting only the formations and noteworthy details at smaller stratigraphic

scales. For reference, the members are indicated in Fig. 8.6 in *italics*.

For the Maastrichtian type area (South Limburg), no formal micro- or macrofaunal biozones have been proposed to date. However, certain taxa serve as proxies in correla-

tions with biozones in the Boreal white chalk succession of northern Germany. In addition, the sequence-stratigraphic calibrated ecozonation can be used as proposed by Keutgen (2018); see also Felder (1994, 1995).

Aachen Formation

This formation has a smectitic clay unit at its base, known as the Hergenrath Clay (Fig. 8.11a). This clay was deposited as fluvial overbank deposit as evidenced by the presence of brown coal layers, root horizons and soils (Fig. 8.11a), while marine incursions with bioturbation have been recognized towards the top. The clay is overlain by a succession of well-sorted, fine-grained quartz sands, with multi-directional cross bedding, known as the Aachen and Hauset sands (Fig. 8.12). These sands are difficult to distinguish especially in small outcrops and borehole data. They are interpreted to have been deposited in a shallow-marine setting. The unit reaches a thickness of up to 60 m. The formation is rich in terrestrial plant fossils, examples being on display in Museum Valkenburg. Deposits of the Aachen Formation crop out in now disused quarries in northeast Belgium. Well-known former quarries are those of Flög (Bingeberg, near Hauset), Schampelheide and Käskorb near Kelmis (La Calamine).

The lowest part of the Aachen Formation is dated primarily on spores, pollen and dinoflagellate cysts, indicating a middle to late Santonian age (Batten et al., 1987, 1988; Knobloch et al., 1993). Very little is known of the marine fauna in this unit, as all calcareous material has been dissolved. However, in places bioturbation by decapod crustaceans is common.

Oploo formation (informal)

This informal formation is probably time-equivalent to the upper part of the Aachen Formation (Fig. 8.6) and can be found on the Peel-Maasbommel Complex (Gras & Geluk, 1999; NITG-TNO, 2001). This formation differs from the Aachen Formation by its purely marine nature. The lower part consists of a cyclic alternation of glauconitic and argillaceous sandstones, grading into bioclastic limestones. The upper part consists of fine-grained, locally argillaceous sandstones. Towards the north, the sandstones of the Oploo formation grade into marls and chalks of the Ommelanden Formation. The formation represents a marine basin-edge facies, reaches a thickness of more than 300 m and is of Coniacian to Santonian age. The geographic distribution of this unit has not been well established yet. The formation has only been penetrated in well Oploo-16 (OPL-16).

Vaals Formation

The Vaals Formation consists predominantly of partly decalcified, yellow to greyish green, fine-grained glauconitic



Figure 8.12. Cross-bedded sandstone from the Aachen Formation with multiple clay drapes and possible tidal bundles in the lowermost set, indicating marine influence. Käskorb Quarry, Kelmis (Belgium). Source: RGD (photo PAR0014054, 1994). Estimated vertical scale: ca. 150 cm.

ic and moderately to well-sorted argillaceous sandstone occasionally showing trough cross bedding (Fig. 8.11b). Intervals with strong bioturbation occur, with occasional mud-lined burrows. Bioclasts include echinoid spines, bivalves, bryozoans, monaxon sponge spicules and planktic foraminifera, while just across the border in Germany mosasaurid remains were found (Sachs et al., 2018). In South Limburg, the formation passes into calcareous, glauconitic silty clay to the west and northwest (Felder & Bosch, 2000). Masses of marine shelly fossils and glauconite grains are concentrated in channel fills. When complete, the succession starts with a 0.25 to 0.5 m thick basal conglomerate on top of the bioturbated Aachen Formation (Hauset Sand). The sediments were deposited mainly in a shallow-marine environment which is thought to have been interrupted by tectonic movements causing submarine erosion of major parts of the formation. Due to the syn-sedimentary movements and post-depositional erosion the thickness varies strongly but may reach up to 150 m.

Age assignment of the Vaals Formation is based mainly on belemnites and ammonites (Table 8.1) that yield an (early) Campanian age (Albers, 1976; Christensen & Schmid, 1987; Kennedy & Jagt, 1995). Faunal assemblages are comparatively diverse, with infaunal and epifaunal groups (echinoids, lobsters, molluscs and echinoderms) represented in addition to ichnotaxa. The upper levels of this succession have produced early late Campanian ammonites (Fig. 8.13a), hinting at correlation with the Zeven Wegen Member (Gulpen Formation) elsewhere, as do benthic foraminifera, belemnites and crinoids (see Gale, 2018).

The Vaals Formation has received little attention since the study by Albers (1976). This formation crops out in various roadcuts in the southeast of South Limburg. Close to the now abandoned and protected Putberg quarry, near the historic farm De Dael, sand of this formation crops out below the Maastricht Formation. Deposits equivalent in age and composition to the Vaals Formation have been found in the offshore F quadrant as erosional products near Sub-Hercynian inversion highs (Figs 8.6, 8.14b-d; Van Lochem, 2018).

Gulpen Formation

The Gulpen Formation sees the onset of carbonate deposition in South Limburg. This formation is dominated by mixed siliciclastic and carbonate sediments. The basal unit is a clean white chalk (Zeven Wegen Member; Fig. 8.6). The layers above show increasing but varying amounts of glauconite, siliciclastic sediment and chert (Figs 8.9h, 8.11c-g). Towards the top of the formation, the glauconite content diminishes, but the chert content increases further into organized layers of black chert, occurring every 0.5–1.5 m (see photo at the beginning of this chapter). In the top of the lower part of the formation, the Vijlen Member (Fig. 8.6) represents the infill of erosional channels (Felder & Bless, 1994; Felder, 1997) which scoured into the top of the Carboniferous bedrock in South Limburg in two zones with a NW-SE-trending orientation. Therefore, the base of the Vijlen Member represents an unconformity. The top of the Gulpen Formation (Lanaye Member) is a clean limestone consisting of a more than 95% pure coccolithic, bioclastic silty packstone. Bioturbation is omnipresent in this formation, as are several hardgrounds. A transitional facies of the Gulpen Formation, characterized by glauconitic marls, was identified by Felder et al. (1985) in the eastern Campine area and the westerly Roer Valley Graben border zone in Belgium. These facies are provisionally indicated as 'Pre-Valkenburg strata' by these authors.

The lowermost unit of the Gulpen Formation yields typically late Campanian ammonites, belemnites, pectinid bivalves, echinoderms and brachiopods (Jagt, 1999a,b, 2000a-d; Simon & Owen, 2001; Jagt & Jagt-Yazykova, 2019), illustrating links with northern Germany, southern Belgium and eastern England. The uppermost Campanian-lowermost Maastrichtian (i.e. Beutenaken and Vijlen members) is still poorly understood, despite the fact that several key belemnite species (e.g. *Belemnella obtusa*) have been recorded. However, condensed sections and ubiquitous reworking blur the overall picture.

For the Maastrichtian succession of the Gulpen Formation (Vijlen Member and younger), ammonites and belemnites are prime index taxa (Felder & Bless, 1994; Jagt et al., 1999; Christensen et al., 2005; Keutgen et al., 2010), in addition to inoceramid bivalves and echinoids. Inoceramids

include key index taxa that allow correlation with Europe, North America and South Africa (Walaszczyk et al., 2010), just prior to their extinction. The Lanaye Member represents the uppermost member of the Gulpen Formation and sees the transition from a north-temperate (Boreal) to a Tethyan setting, as documented by diverse 'newcomers' among echinoids, crinoids (Fig. 8.13c), brachiopods, chelonid turtles and mosasaurs. These include taxa (Table 8.1) that have close relatives in North America (Atlantic Plain and Gulf Coast) and North Africa (Jagt, 1999a,b, 2000a-d, 2005; Mulder, 1999; Phillips et al., 2014).

The sediments of this formation were deposited under fully marine conditions. The formation reaches a thickness of up to 175 m. Hiatuses occur within it (Fig. 8.6) and the top of the formation is separated by a hiatus of some 0.7 Myr from the base of the overlying Maastricht Formation (Vandenbergh et al., 2004; Keutgen, 2018; Vellekoop et al., 2022). In the east of South Limburg, the Gulpen Formation can be found in some road cuttings and disused quarries, such as the Habets quarry east of the village of Beutenaken in the Gulp River valley. In the west, the formation is exposed in the now abandoned ENCI quarry south of Maastricht (see photo at the beginning of this chapter) and in the incision of the Belgian Albert Canal.

Maastricht Formation

The Maastricht Formation is less variable in lithology than the underlying Gulpen Formation and consists mainly of carbonate deposits (Fig. 8.9i). It has been informally subdivided into the Maastricht limestone facies and the Kunrade limestone facies (see for an early reference e.g. Umbgrove, 1925). In the Kunrade-Heerlen area (eastern part of South Limburg), the Kunrade limestone facies ('Kunrader Kalk') is an alternation of hard and soft light-grey, fine-grained limestone beds without chert nodules. It is considered to be the lateral, shallower and more onshore equivalent of the Maastricht limestone facies, with macrofaunas reflecting a range of sea floor conditions from firm grounds (regular echinoids, crinoids) to less consolidated substrates (echinoids). The most detailed correlation attempt to date is that of Felder & Bless (1989), who equated the 'Kunrader Kalk' with the middle Lanaye Member (Gulpen Formation) and the lower portion of the Maastricht Formation (basal Nekum Member), dating it as late Maastrichtian (Fig. 8.13l). In Belgium the 'Kunrader Kalk' has recently been raised to the rank of formation for the Campine area (see ncs.naturalsciences.be).

The Maastricht limestone facies is found in the southwestern part of South Limburg, and consists of soft, coarse-grained limestone of a yellow-whitish colour with 5 to 12% chert (Fig. 8.11h-j). Felder & Bosch (2000) identified an intermediate development between the Maastricht

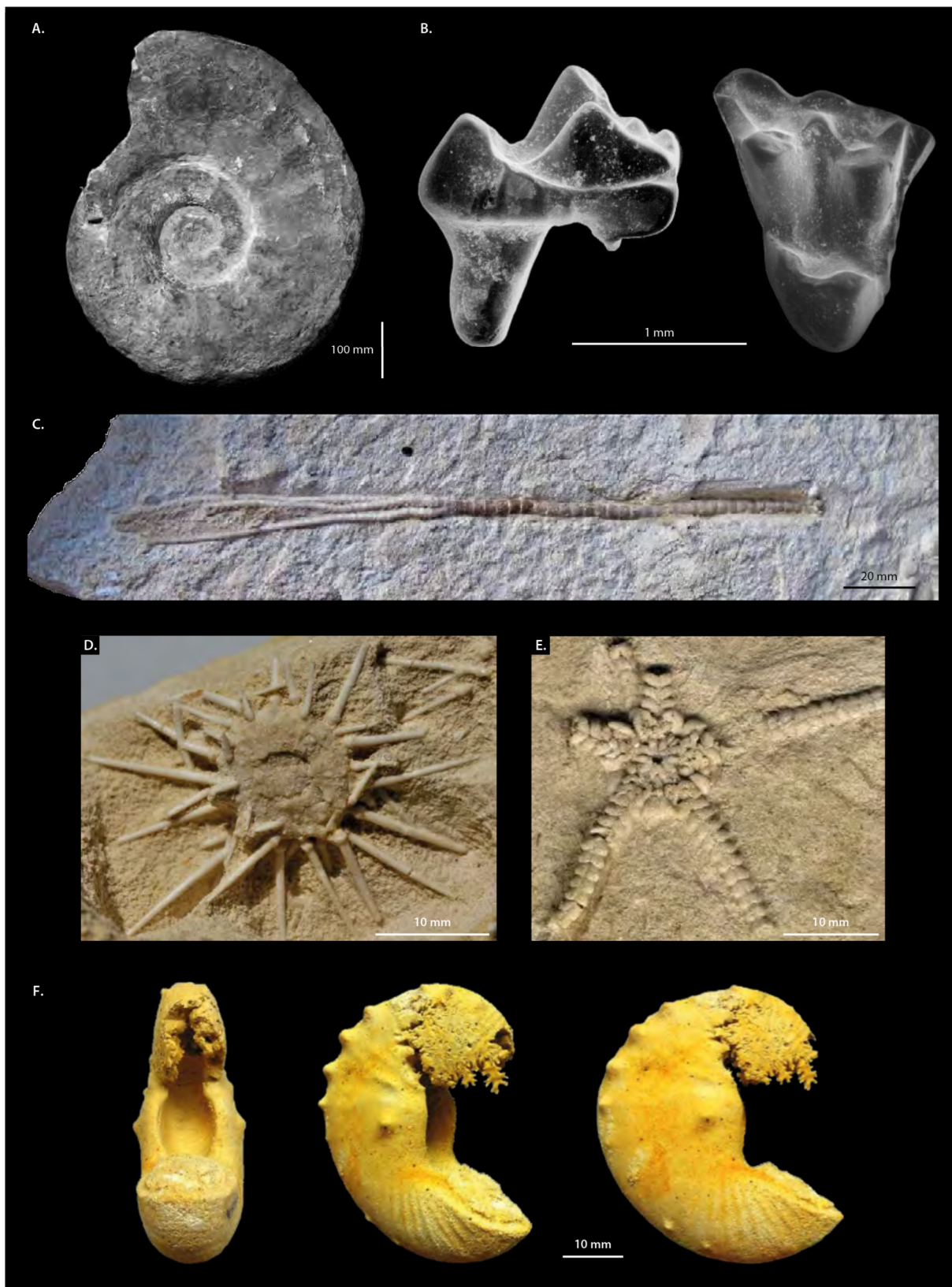
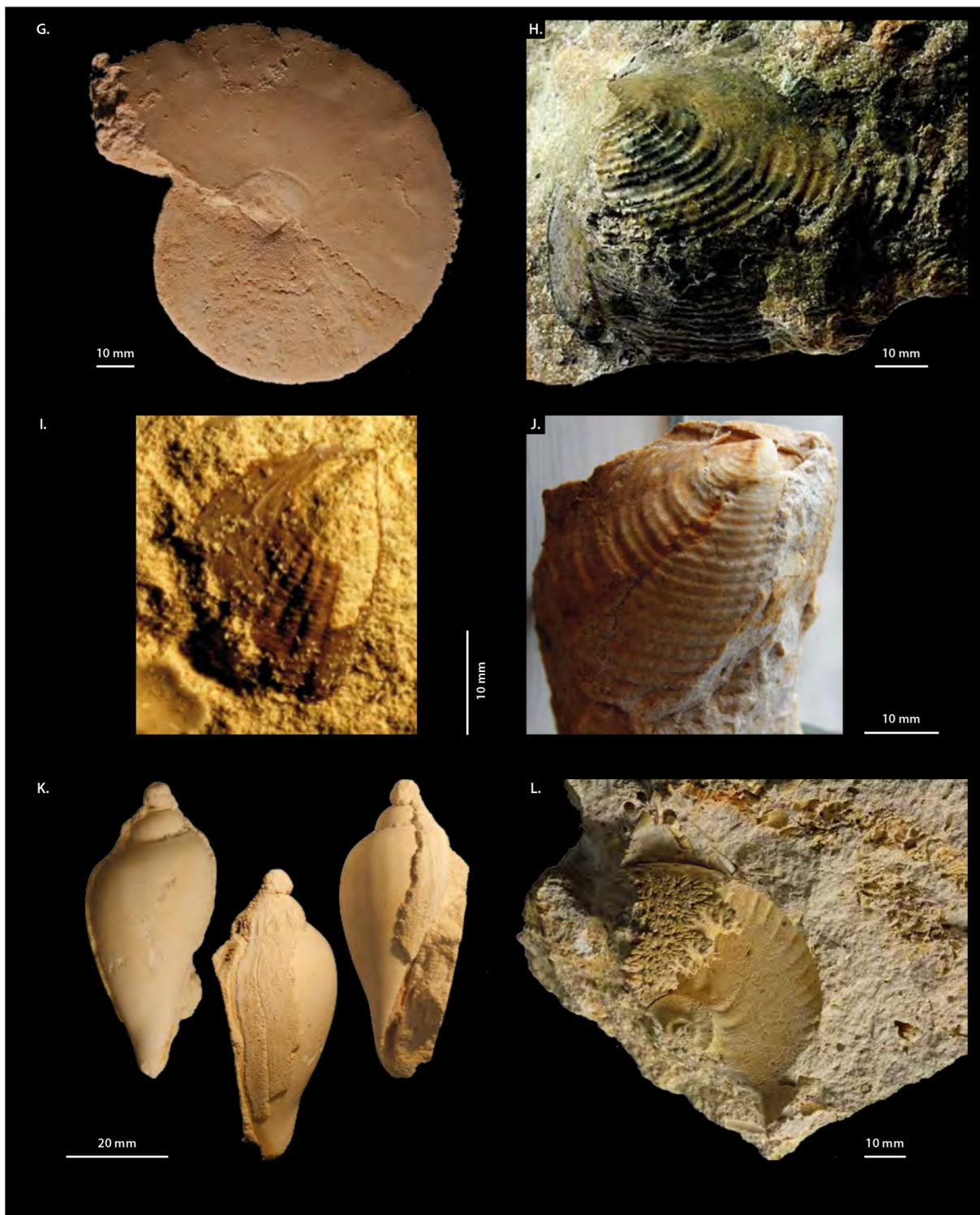


Figure 8.13. Characteristic macrofossils from the Upper Cretaceous of South Limburg. a) *Patagiosites stobaei*, an ammonite from the Benzenrade Member which documents the lateral equivalence of that unit with the Zeven Wegen Member (late Campanian). b) Type specimen of the late Maastrichtian mammal (a small marsupial), *Maastrichtidelphys meurismeti*, from the abandoned ENCI quarry (Maastricht); a direct North American link (Martin et al., 2005). c) The stalked crinoid, *Dunnocrinus aequalis* (collection Oertijdmuseum, Boxtel), from the abandoned ENCI quarry (Maastricht), allows correlation with the upper Maastrichtian of Mississippi (US Gulf Coast). d) Regular echinoid, *Gauthieria* gr. *radiata*, with full complement of spines, apical disc and lantern,



testifying to storm-generated obrution events during the latest Maastrichtian. e) vagile bottom fauna, such as this brittle star, is typical of all members of the Maastricht Formation. f) The heteromorph ammonite, *Hoploscaphites constrictus johnjagti*, defines the uppermost Maastrichtian in Boreal settings of northwest and eastern Europe (Machalski, 2005). g) The ammonite *Sphenodiscus binckhorsti* from the uppermost Meerssen Member, directly below the K-Pg boundary at the abandoned Curfs quarry, Geulhem. h-j) The 'tegulated' inoceramid key index, *Spyridoceras tegulatus*, typical of the Vijlen to Nekum members; this is replaced by *Tenuipteria argentea* in the uppermost Meerssen Member (Jagt & Jagt-Yazykova, 2018). k) The carnivorous snail, *Volutospina aff. deperdita*, from the Meerssen Member illustrates precursors of post-Cretaceous (Paleogene) gastropod faunas. l) The ammonite *Pachydiscus gollevillensis* allows correlation of the basal Nekum Member (Maastricht Formation) with the upper part of the Kunrade facies (middle Lanaye Member). Photo (c): Oertijdmuseum Boxtel, with permission; remaining photos by Natural History Museum Maastricht.

and Kunrade limestone facies which they named the limestone of Schaelsberg (informal).

Towards the top of the formation, chert becomes rare, bioclastic grain size increases and large-scale trough cross bedding can be found (Brinkhuis & Smit, 1996; Zijlstra et al., 1996; Lagrou & Dreesen, 2005). The uppermost part of the formation, the Meerssen Member (Figs 8.6, 8.10b), is characterized by numerous detrital fossil layers full of algae, bryozoans, corals, etc. above hardgrounds, and does not contain chert. Lagrou & Dreesen (2005) reported mudstone to wackestone textures for the Gulpen and Maastricht formations sampled in boreholes in Belgium, indicating that deeper-marine and more offshore settings were developed towards the northwest.

The general shallowing trend in the upper Maastrichtian succession is concomitant with an increase in biodiversity at all levels reflected in seagrass meadow microhabitats and decapod crustacean burrows (Villain, 1977; Liebau,

1978; Sprechmann, 1981; Bless, 1989; Zijlstra, 1994; Schiøler et al., 1997). The lower Maastricht Formation is characterized by some obrution levels ('Lagerstätten', predominantly with echinoderms; Fig. 8.13d), testifying to severe storm activity. In addition, there was riverine/eolian input of terrestrial plants, mammals (Fig. 8.13b) and birds (Martin et al., 2005; Van der Ham et al., 2010; Field et al., 2020).

In the upper Maastricht Formation omission surfaces and hardgrounds (bored and encrusted) are present and the impact of periodic storms is visible in coquinas or lumachelles at several levels, composed mostly of serpulid worms, bivalves and gastropods (Fig. 8.13d,e). Bioherm-like structures of scleractinian corals, rudists and bryozoans became established in some places. Ammonites comprise an admixture of Boreal and Tethyan forms (Table 8.1; Fig. 8.13f, g), while the cold-water belemnite *Neobelemnella* gr. *kazimiroviensis* first appears in the Meerssen

Feathered dinosaurs from the Maastrichtian type area

Until recently, there were no records of avian dinosaurs (or birds) from the Upper Cretaceous biocalcarenes in the Maastricht region. This changed some years ago with the description of two incomplete specimens from a quarry along the southern margin of the Mount Saint Peter, south of Maastricht. One of these, *Janavis finalidens*, named by Benito et al. (2022), had been recovered from the basal Valkenburg Member (Maastricht Formation) already in 1999, but following high-resolution CT scanning at the University of Cambridge (England), it became clear how special this specimen actually was. Although the skull is not preserved, a single bone from the palate (pterygoid) is. Partly on the basis of this, it proved possible to define a new genus and species for it, closely related to the piscivorous genus *Ichthyornis* from the lower Upper Cretaceous of North America, but attaining a considerably larger size, with an estimated wingspan of 1.5 metres. *Janavis finalidens* is of great importance in constituting the youngest known toothed bird worldwide. It demonstrates that, during the late Maastrichtian, around one million years prior to the Cretaceous-Paleogene boundary, toothed birds ('stem group' birds) co-existed with very early 'modern' birds ('crown' birds) such as the partridge-sized wading bird, *Asteriornis maastrichtensis*, or 'wonderchicken' (Field et al., 2020). The type specimen of that form, recovered in the year 2000, originates from the same stratigraphic level as *Janavis finalidens*. It includes a well-preserved skull, lacking teeth, and is interpreted to have been close to the most recent common ancestor of present-day land and water fowl (chicken- and duck-like birds, or Galloanserae).



Reconstruction of the smaller-sized wading bird *Asteriornis maastrichtensis* and the gull-like, tooth-bearing *Janavis finalidens* (artwork by Phillip Krzeminski).

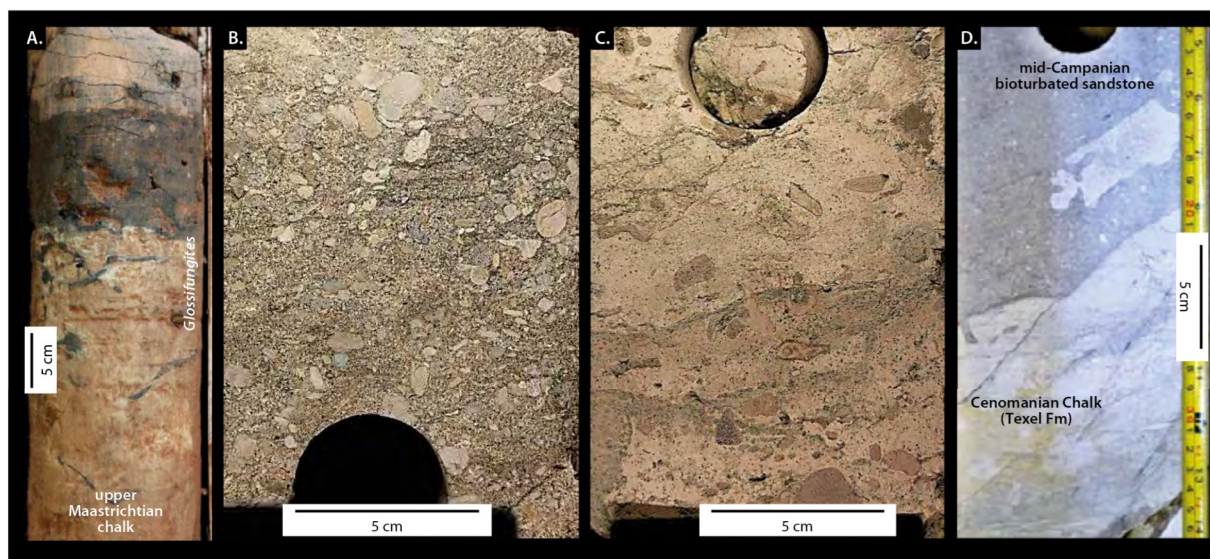


Figure 8.14. Core photographs (Van Lochem, 2018). a) Well F17-11 (measured depth (MD) 1420.0 m): contact between the Landen Formation and upper Maastrichtian chalk of the Ommelanden Formation. Note the *Glossifungites* ichnofossils in the chalk. b) Well F17-11 (MD 1469.8 m): clast-supported conglomerate with a chalk matrix. c) Well F17-11 (MD 1468.7 m): matrix-supported conglomerate. d) Well F17-12 (MD 1450.9 m): the Sub-Hercynian Unconformity is between the upper Campanian bioturbated sandstone (Vaals Formation equivalent) and the fractured Cenomanian chalk of the Texel Formation.

Member (Fig. 8.6) and ranges to the K-Pg boundary (Keutgen et al., 2017).

The Maastricht Formation has yielded sharks, rays, chelonid turtles, mosasaurs (Fig. 8.15), plesiosaurs and crocodiles (Mulder et al., 2016; Schulp et al., 2017), as well as rich associations of endo- and epibenthic invertebrates (8.13h-j,k), all indicative of clear, well-oxygenated waters. The highest part of the formation (i.e. Meerssen Member, subunit IVf-7) is now considered to be of earliest Danian (early Paleocene) age, the K-Pg boundary being equated with the Bergen Terblijt Horizon, rather than at the Vroenhoven Horizon, which is situated some three metres higher (Fig. 8.17).

In the Maastricht Formation bioturbation is omnipresent. Cryptocrystalline quartz concretions (chert) of varying sizes, morphology and abundance are concentrated mainly in layers but also occur in isolation (Zijlstra, 1987, 1994). The thickness of the formation ranges between 45 and 90 m. Sediments accumulated in a shallow-marine environment (Zijlstra, 1994). Well-known sites where this formation crops out include the disused quarries of ENCI, south of Maastricht (see photo at the beginning of this chapter), and 't Rooth, east of Maastricht near Bemelen. The transition to the overlying Houthem Formation is exposed in the abandoned Curfs quarry, northeast of Maastricht.

Houthem Formation

This formation consists of soft, light grey to beige, fine- to coarse-grained limestones with intercalated hardgrounds

and indurated limestone concretions (Fig. 8.9j). The lowermost part of the formation is characterized by the occurrence of glauconite. It occurs mainly in the south of the Netherlands and is by definition only found onshore and is considered to be the lateral equivalent of the Ekofisk Formation (Fig. 8.6). The lower boundary of the Houthem Formation is the Vroenhoven Horizon, a conspicuous hardground with bioturbation at the top of the Maastricht Formation. In ascending order, this unit is subdivided into the Geulhem, exposed at the abandoned Curfs quarry (Herngreen et al., 1998; Felder & Bosch, 2000), the Bunde and the Geleen members. The latter two are known only from boreholes and mine shafts. They comprise coarse-grained, yellowish white limestone with hard bands and very coarse-grained, probably cyclic, limestones respectively.

Sediments of this formation were deposited in carbonate-shelf and upper bathyal environments. The rocks consist essentially of pelagic biogenic remains, which settled from suspension. The sedimentary rocks of the formation may locally reach a thickness of more than 100 m and are of Danian and possibly Selandian/Thanetian age. The formation crops out near the village of Houthem, northeast of Maastricht (e.g. abandoned Curfs quarry and Geul River valley).

Onshore Cretaceous-Paleogene (K-Pg) boundary

In the South Limburg area, carbonate deposition continued across the K-Pg boundary. The early Danian date of subunit IVf-7 is based on palynomorphs, calcareous



Figure 8.15. Large marine reptiles from the Maastricht area. a) Partial skull of *Mosasaurus hoffmanni*, nicknamed ‘Curfske’, from the abandoned Curfs quarry (Geulhem; Meerssen Member, upper part of subunit IVf-6). b) The type specimen of *Prognathodon saturator* from the upper Lanaye Member (Gulpen Formation; Dortangs et al., 2002) at the former ENCI quarry, now residing on the inner square of the Natuurhistorisch Museum Maastricht. Photos by Natural History Museum Maastricht.

nannoplankton and foraminifera (Brinkhuis & Schiøler, 1996; Kuhnt, 1996; Romein et al., 1996; Smit & Zachariasse, 1996; Witte & Schuurman, 1996), which indicate that it can be correlated with the basal Danian Po planktic foraminifer zone, while the overlying Geulhem Member yields planktic foraminifera that tie in with the type-Danian (Moorkens, 1982). Macrofaunal elements with a link to the type-Danian (Stevns Klint and Faxe, Denmark) include echinoderms (Gravesen, 1993; Jagt, 1999a,b, 2000a-d), cirripedes, sharks and rays (Adolfssen & Ward, 2014, 2015). Vagile benthic molluscs from subunit IVf-7 and the overlying Geulhem Member include numerous taxa in common with the middle Danian (‘Montien’) of southern Belgium (Bignot, 1993; Jagt et al., 2013; Vellekoop et al., 2020).

The combined sections of the former Curfs quarry (Geulhem) and Geulhemmerberg galleries (Fig. 8.16) nearby constitute the most complete K-Pg boundary interval in the South Limburg area (Fig. 8.17). A 0.2–0.3 m thick, heavily indurated level capping subunit IVf-7 yielded diverse molluscan assemblages, including heteromorph ammonites (Landman et al., 2014, 2015). Numerous bivalves are still articulated or in butterfly position, and baculitid ammonites often preserve intact apertures, providing evidence that these assemblages are *in situ*. Based on

gastropod faunas, Vellekoop et al. (2020) suggested that a rapid recovery followed the K-Pg extinction event.

For the K-Pg section in the Geulhemmerberg galleries, Smit & Brinkhuis (1996) presented a total picture, based on sedimentology, biostratigraphy, geochemistry and paleomagnetism. The undulating hardground (Berg en Terblijt Horizon) at the base of subunit IVf-7 (Fig. 8.17), with depressions up to 1.5 m in depth, cut into heavily

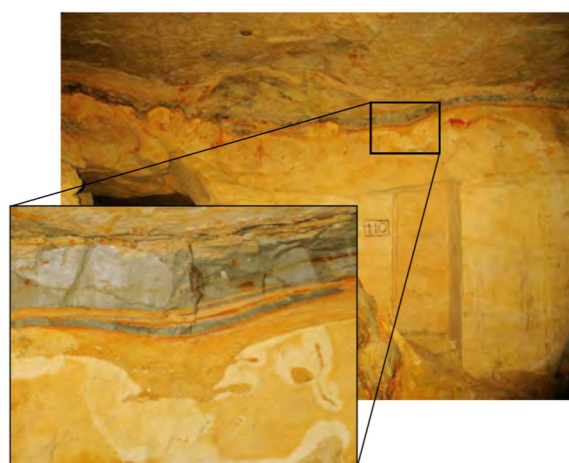
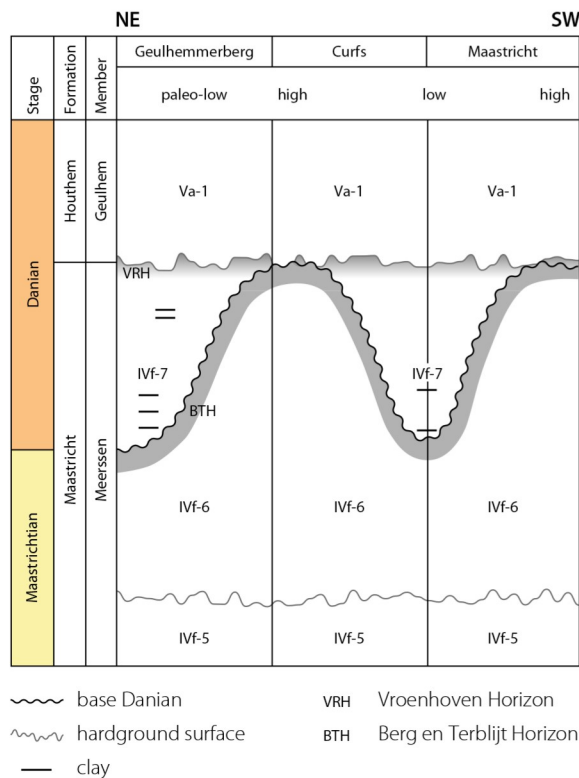


Figure 8.16. The K-Pg boundary section in the underground galleries of the Geulhemmerberg. The irregular erosion surface in the top of the Maastricht Formation is overlain by bioclastic sand and grey clay layers (IVf-7 in Fig. 8.17). Inset photograph represents 0.4 m vertically. Photos: courtesy of Rudi Dortangs.



bioturbated IVf-6 calcarenites and mark a brief period of non-deposition in the Meerssen Member. Above this, the initially coarse-grained sediments filling the paleorelief depressions represent a thinning-up and fining-up sequence, culminating in a 0.1-0.15 m thick clay level, the so-called E clay. The infilling process is inferred to have been episodic, involving decreasing storm-wave activity in waters deepening to *c.* 20 to 40 m, or alternatively a changeover to a more 'shielded' situation. The clay layers could have formed only during low-energy conditions. Just below the Berg en Terblijt Horizon, very low, yet slightly elevated iridium (Ir) contents have been observed (Smit & Brinkhuis, 1996). The time span between IVf-6 and IVf-7 sediments involved the deposition of latest Maastrichtian calcarenites, followed by K-Pg storm- or hypercane-related 'washing' of the paleoshelf and erosion of uppermost Maastrichtian and lowermost Danian sediments, inclusive of an Ir-bearing layer.

Geological history

Structural development

Chalk Group strata were deformed at various times and different scales. The earliest deformation took place during deposition. Van der Molen et al. (2005) and Van der Voet et al. (2018) recorded local slump structures in the Dutch Central Graben, while Back et al. (2011) documented a large number of gravity-driven structures like slumps

Figure 8.17. Stratigraphic relationships in the K-Pg boundary interval in South Limburg (modified from Herngreen et al., 1998 and Vellekoop et al., 2020). Codes (IVf-5, 6, 7 and Va-1) were introduced by Felder (1975).

and slides, which developed due to syn-depositional tectonics in the southern Danish North Sea. Smit (2018) also noted frequent fluid escape structures in this area. In comparison to the Danish sector fewer syn-sedimentary deformation structures have been found in the Dutch sector. This may in part be due to the lesser number of studies performed on the Dutch chalk interval, but it may also be linked to the shallower nature of the chalk sea in the Dutch sector (Ineson et al., 2014) which led to lower sea floor relief and, concomitantly, gravity-driven structures with a smaller lateral extent.

Syn-depositional tectonics

An important syn-depositional tectonic event was the Sub-Hercynian inversion phase, which peaked during the Campanian. Pre-inversion intervals were folded, tilted and locally faulted by this tectonic event, preferentially above pre-existing Mesozoic grabens (Van Wijhe, 1987a; Dronkers & Mrozek, 1991; De Jager, 2003). Outside these inversion areas sedimentation continued almost without interruption, leading to a continuous, horizontally stratified Cretaceous succession. In the inversion areas, islands emerged in the chalk sea due to the tectonic uplift and were subsequently eroded (Van Lochem, 2018). The pre-inversion chalk intervals, which may not have been completely lithified, may have eroded quite rapidly without leading to recognisable erosional material, as chalk easily disintegrates into its original constituent material (Buls et al., 2015). Eroded clay-rich material may also have been diluted into the surrounding chalk sea, leading to more marly chalk intervals. Siliciclastic-rich erosional material has been found around some inversion structures in the Netherlands, most being assigned to the Vaals Formation (Figs 8.4, 8.6).

In the Dutch Central Graben, seismic data show a clear unconformity between pre- and post-inversion chalk sections (Clark-Lowes et al., 1987; Van der Molen, 2004; Van der Voet et al., 2018; Van Lochem, 2018). Van Lochem (2018) presented a cored section of the Sub-Hercynian Unconformity in well F17-12, where upper Campanian sandstones overlie a fractured and eroded Texel Formation chalk section (Fig. 8.14d). 3D-seismic interpretation (Van Lochem, 2018) demonstrates that the Dutch Central Graben inversion structure has the shape of a north-south-striking anticline with, towards its core, progressively older intervals subcropping below the Sub-Hercynian Unconformity (Fig. 8.18). On the Sub-Hercynian Unconformity

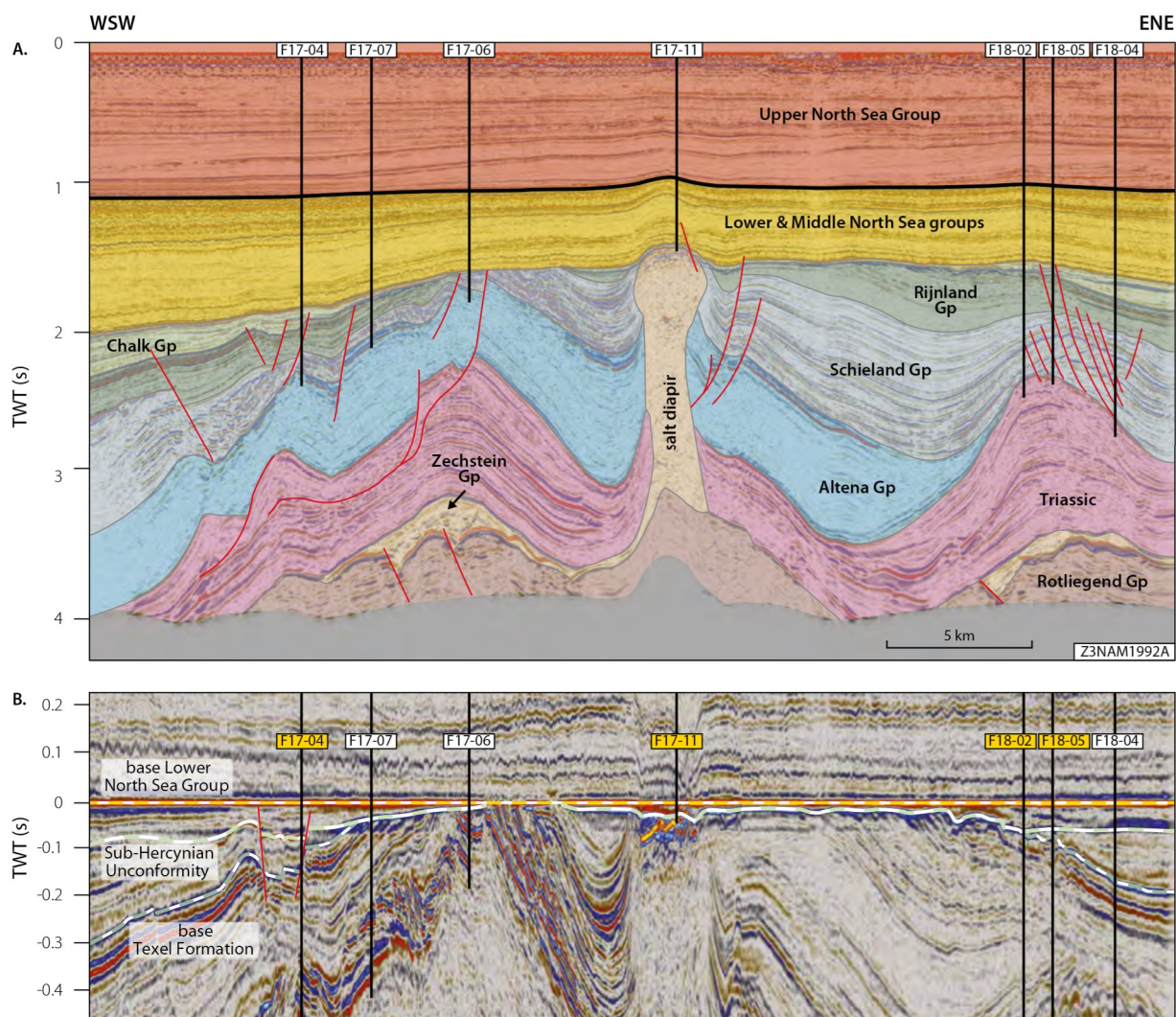


Figure 8.18. a) Interpreted seismic time section across the inverted Dutch Central Graben in blocks F17 and F18. The Upper Cretaceous is present over much of the section but is not visible at this scale. b) Same section flattened on the base Lower North Sea Group and stretched vertically to show the chalk interval. Wells indicated in yellow have a Campanian sandstone above the Sub-Hercynian Unconformity. Note that the morphology of the Sub-Hercynian Unconformity represents a fault-bounded graben at F17-04, a depression above the salt dome near F17-11, and a channel shape with a rapidly thickening succession on top near F18-02. Maastrichtian chalk is absent east of well F17-06 where highly reflective Upper Jurassic sandstone, claystone and coal beds subcrop below the base Cenozoic (from Van Lochem, 2018). For location see Fig. 8.1

surface onlapping levels of late Campanian and Maastrichtian age are found, demonstrating that most of the inversion movements had come to a halt here during the late Campanian. In the southern part of the Dutch Central Graben, the upper Maastrichtian is conformably overlain by Selandian and Thanetian deeper marine claystones of the Landen Formation. This contact was cored in well F17-11 (Fig. 8.14a); it shows a burrowed interval of Maastrichtian chalk, which can be interpreted as a marine hard-ground, overlain by a 0.1 m thick, glauconitic-rich claystone (Van Lochem, 2018).

The NW-SE-striking Broad Fourteens Basin (Fig. 8.1) has been the subject of several inversion-related studies

during the last decades (Van Wijhe, 1987b; Hooper et al., 1995; Naplas, 1994; Bouw & Oude Essink, 2003a,b; Deckers & Van der Voet, 2018). An important difference with the Dutch Central Graben is the fact that existing Mesozoic graben faults were reactivated as reversed faults or locally as thrust faults. Zechstein salt acted as decollement surface and facilitated the formation of several low angle thrust faults (Nalpas et al., 1996). Hooper et al. (1995) estimated the shortening by inversion of the Broad Fourteens Basin at 10% and the total uplift along the inversion axis at 3500 m. The erosion that followed this uplift completely removed the Chalk Group from the centre of the Broad Fourteens Basin. At the basin's edges partially

eroded sections of chalk are unconformably overlain by a chalk section of Maastrichtian age (e.g. well K13-A-10). A thin unconformable Maastrichtian and/or potentially Danian cover can be traced from the western flank towards the centre of the basin, overlying older Mesozoic sedimentary rocks (Deckers & Van der Voet, 2018). Bouw & Oude Essink (2003a,b) modelled the hydrogeological evolution of the Broad Fourteens Basin during the inversion. Fresh meteoric water infiltrated into the eroded outcropping Mesozoic sedimentary rocks and may have influenced the biodegradation of Lower Cretaceous oil fields there.

Inversion in the West Netherlands Basin is limited to the northern part of this Jurassic basin. In the southern half, which partly coincides with the Paleogene Voorne Trough, a complete and uneroded chalk succession is present (NITG-TNO, 2002). A burial study by Worum & Van Wees (2017) has shown that the maximum thickness of the Chalk Group in the centre of the basin at any moment during the Late Cretaceous was around 300 m. This figure is much smaller than the total preserved thickness of the chalk in the Voorne Trough, indicating that continuous syn-inversion sedimentation occurred there, while non-deposition or slight erosion characterized the centre of the basin, which was inverting. Thinning of the Heers Formation from the Voorne Trough in the direction of the West Netherlands Basin and truncation of the top of the Chalk Group in the same direction suggests that the basin was also inverted during the Paleocene Laramide phase (Deckers & Van der Voet, 2018). Doornenbal et al. (2019) recognized NE-SW oriented intra-chalk runoff channels, which may be related to uplift in the northeast part of offshore block P15.

The fault zone between the West Netherlands Basin and the Central Netherlands Basin to the north is characterized by reverse faulting and overthrusting of the Mesozoic succession (NITG-TNO, 2002). Directly north of this fault zone there is a ridge which has been referred to as the Zandvoort Ridge, which contains an eroded chalk section of Cenomanian to Coniacian age. Compared to the adjacent inverted basins this ridge was buried less deeply and aquifers in this structural feature may have preserved more favourable reservoir parameters due to less intense diagenesis (Pluymaekers et al., 2012). North of the Zandvoort Ridge, no chalk has been preserved in the Central Netherlands Basin, except for a thin development of the Danian-aged Houthem Formation in the area around Harderwijk (NITG-TNO, 2004) near the axis of the basin. The preservation of Danian carbonates shows that Late Cretaceous basin-wide inversion had significantly slowed down or even ended prior to the Danian and that the Central Netherlands Basin did not experience strong erosion during the Laramide phase at the end of or just after the Danian (Deckers & Van der Voet, 2018). The northeastern

boundary of the Central Netherlands Basin is determined by the Raalte Boundary fault, which is a large, pre-existing Paleozoic normal fault that was reversed during Late Cretaceous inversion (NITG-TNO, 2004).

During the Cenomanian to Coniacian the Roer Valley Graben and the adjacent Campine Basin (Belgium) as well as the southern part of the Peel-Maasbommel Complex were exposed above sea level (Luijendijk et al., 2011). During this period the coastline was located on the northern part of the Peel-Maasbommel Complex in the area of Nijmegen (Gras & Geluk, 1999). During the Santonian to Campanian, a southward transgression took place. On the borders of the Peel-Maasbommel Complex, the Campine Basin and the London-Brabant Massif shallow-marine siliciclastics of the Oploo and Vaals formations accumulated. These sedimentary rocks are erosional products of the inverting Roer Valley Graben, which formed a positive feature during the Sub-Hercynian Phase (Kuyt, 1983; Bless et al., 1987; Gras, 1995; Gras & Geluk, 1999; NITG-TNO, 1999; NITG-TNO, 2001). During the Maastrichtian, the strata became more carbonate-rich as the Roer Valley Graben gradually lost its importance as a source area. Finally, during the Danian, also the Roer Valley Graben was inundated and the marine Houthem Formation formed a blanket over most of the south of the Netherlands (NITG-TNO, 2001). During the Laramide Phase a broad domal uplift of the London-Brabant Massif removed the Danian and part of the Maastrichtian successions (Deckers & Van der Voet, 2018).

In the Vlieland Basin two inversion phases can be recognized as well. Herngreen et al. (1996) concluded that thickness changes in the Coniacian to Campanian sections in wells Den Burg-1 (BRG-01) and De Cocksdorp-1 (COC-01) on the Isle of Texel could be related to the Sub-Hercynian inversion of the adjacent Vlieland Basin. The missing parts of the Maastrichtian and truncation of the Cretaceous strata reflect erosion during the Laramide Phase.

Not only did inversion tectonics have an impact on the thickness distribution of the Chalk Group, also halokinetic movements played an important role. The Chalk Group is often thinned over rising salt domes, while next to the salt structure in subsiding rim synclines the group is clearly thickened (RGD, 1993; Van der Voet et al., 2018).

Post-depositional tectonics

Following deposition, deformation of the Chalk Group continued. Due to the brittle nature of chalk extensive fracture networks can often be found. Welch et al. (2015) studied fracture geometries in chalk outcrops in the UK, while Koestler & Ehrmann (1986, 1991) mapped faults and fractures in quarries in northern Germany (Hamburg area), where chalk was pushed upwards by underlying salt

diapirs (Niebuhr, 2006; Voigt et al., 2008). The development of these fractures is very important for any fluid (oil) flow to take place in the chalk, as chalk matrix permeability is generally too low (typically <10 mD) for any commercially interesting flow quantities. Van Rooijen (1989) noted that in South Limburg the ground water abstraction rates from chalk reservoirs were highly influenced by the presence of fractures.

In the North Sea Basin salt doming is the most important deformation mechanism that contributes to the creation of fracture networks in the chalk. The main chalk oil fields in the Norwegian, UK and Danish sectors rely on these fracture networks for production (Surlyk et al., 2003). In the Dutch Central Graben, where the Chalk Group lies above major salt domes and diapirs (Remmelts, 1996; Van Winden et al., 2018), fractured chalk is the reservoir of several oil fields. For the Hanze oil field average permeabilities of 200-780 mD were modelled in the course of a 3D-permeability modelling exercise, taking into account the intense macroscopic fracturing (0.8-1.2 fractures/m), as well as the microscopic fracture network and well injectivity results (Hofmann et al., 2002). For the Rembrandt and Vermeer chalk oil fields, Wang et al. (2018) built a discrete fracture network model using 3D-seismic attributes by mapping small-scale faults and lineaments, while Beller et al. (2019) used diffraction im-

aging to improve the fault and fracture models of these fields. Van Gent et al. (2010) used small-scale, intra-chalk faults, confined to the brittle Chalk Group, to provide a way to estimate paleostress from seismic data for specific time intervals. Based on the orientation and position and on a thickness analysis, it was concluded that these faults were formed due to the tectonic reactivation of salt structures during the latest Cretaceous.

Other large faults cutting through the Chalk Group are related to the Roer Valley Graben and the Mid-Netherlands Fault Zone. A large number of these faults may have been active up to recent times (Van Balen et al., 2005). These faults mainly have a normal-slip mode, which is in accordance with the present-day orientation of the maximum horizontal stress and the vertical orientation of the maximum stress (Van Balen et al., 2005). In and near these fault zones open fracture systems may be expected in the Chalk Group.

Karstification

Fresh water from the surface with dissolved organic acids percolating through limestone causes dissolution of the limestone. This process is called (meteoric) karstification and results in a plethora of dissolution features (Gilli, 2015). In South Limburg these features are known from quarries, boreholes and occasional sinkholes. The most

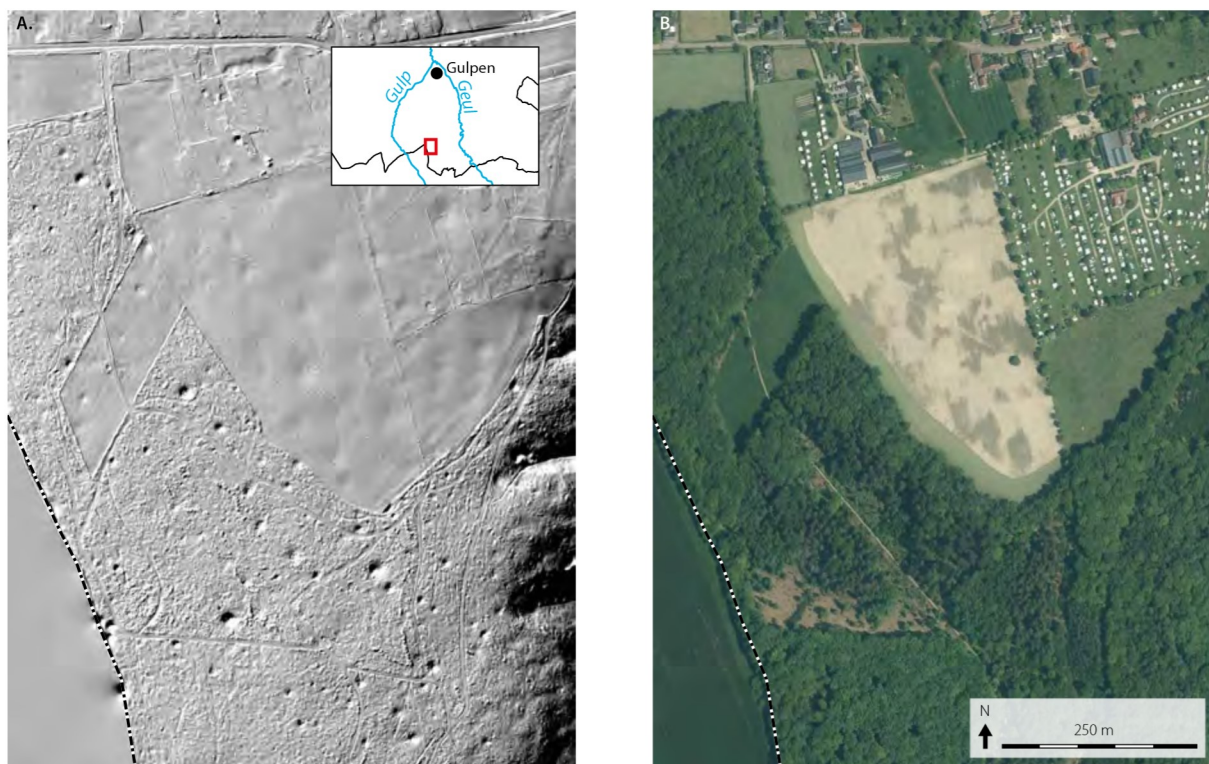


Figure 8.19. Suffosion dolines on the plateau between the rivers Gulp and Geul in South Limburg. a) LIDAR image with shaded relief effect shows pronounced and smooth dolines (AHN v3). b) Aerial photograph of the same area showing that smooth dolines are located in farmland.

commonly observed features are solution pipes, which are often filled with gravel and loess. However, in most cases they lie below a thick sedimentary cover and their presence cannot be demonstrated. In the southeast of South Limburg, the sedimentary cover is thin enough (8–20 m) to permit a topographic expression of the underlying chalk. Depressions in the sediment overlying limestone, called *suffusion dolines* can be observed using publicly available Laser Imaging Detection and Ranging data (LIDAR). A distinction can be made between dolines with a pronounced expression and those with a smooth expression (Fig. 8.19). The difference is probably the result of land-use as smooth dolines are found in farm land where ploughing and filling tend to level the dolines. Dolines with a more pronounced expression are found in forested areas.

The distribution of dolines and the underlying solution pipes in the landscape is often linked to the occurrence of fractures and cracks, as is often the case with hard, compact limestone (Jennings, 1985). In the soft and coarse-grained limestone of South Limburg, however, the dolines seem to occur more randomly, without control by fractures or cracks. This observation is also supported by several publications that state that in the Upper Cretaceous limestones of northwest Europe (chalk), solution pipes unconnected to fractures occur (Kirkaldy, 1950; Rodet, 1992; Mouriau, 1998). In the Romontbos quarry south of Maastricht, solution pipes are frequently found under the gravelly deposits of the Meuse River, while under clayey sands in the west of the quarry, no solution pipes are observed in the limestone (Juvigné & Renard, 1992; Willems et al., 2007). The presence of solution pipes seems to correlate with the presence of permeable deposits on top of the limestone.

The age of solution pipes and dolines in South Limburg is unknown and no research has been published on the subject. The frequency with which dolines form is also largely unknown, but observations of sinkholes are regularly reported from the area. The dissolution of limestone probably started tens of millions of years ago when the limestones were lifted above sea level. Data from borehole Molenbeersel in the Belgian Campine region suggest that karstification occurred shortly after the end of the Cretaceous (Swennen & Dusaer, 1997). Solution pipes observed in the former ENCI quarry show that the backfill consists of thick layers of loess, which indicates that there was already a depression during the Pleistocene (2.58–0.01 Ma) when the loess was deposited.

Outside South Limburg karst features have been observed in the subsurface on the Zandvoort Ridge (Fig. 8.20), where the partially eroded chalk section shows dissolution and collapse structures. Near well Waverveen-1 (WRV-01), two 200 to 500 m wide dolines can be observed on seismic data. This karstification predates the Oligocene

to lower Miocene Rupel Formation, which overlies the chalk of the Coniacian Ommelanden Formation. Wells Waverveen-1 and Zeist-1 (ZST-01) (Fig. 8.1) encountered significant losses while drilling the chalk, indicating the presence of open fractures and karst cavities. During the Cretaceous, karstification also affected the lower Carboniferous (Dinantian) limestones exposed along the London-Brabant Massif (see Vis et al., 2025, this volume).

Offshore chalk sedimentology and facies

Most geologists who do not work on the Chalk Group would consider this interval to rank amongst the most monotonous with respect to facies and sedimentology. While the bulk of the Chalk Group consists of white carbonate mudstones with few apparent sedimentological features other than interbedded chert layers or nodules, more can be said about its subtle variations. Although the Chalk Group crops out in southern South Limburg and is therefore relatively easy to study, only a few detailed sedimentological and paleoecological studies have been carried out (Zijlstra, 1994; Roep & Smit, 1996; Zijlstra et al., 1996; Lagrou & Dreesen, 2005). As work is underway to fill this knowledge gap, we here limit the description of sedimentological details and facies to the offshore Chalk Group.

The study of offshore chalk relies on rock cores for detailed sedimentological facies analysis. However, due to the lack of hydrocarbon discoveries in the Chalk Group, the core coverage is low. Preferentially, the uppermost intervals of the chalk have been cored, which has led to a bias towards study of Danian- and Maastrichtian-aged successions. Following the discovery of the Rembrandt oil field, Wintershall Noordzee B.V. and its partners commissioned a study of all released chalk cores in the Dutch offshore, as well as some onshore cores (Ineson et al., 2014). Identification of the main facies associations and the environmental model are reproduced here, with permission, from this confidential report.

Eight facies associations (Figs 8.8, 8.21) have been recognized in the cores of the Ekofisk and upper part of the Ommelanden formations, with 95% of the cored interval consisting of the Chalk Mudstone Association (FA-1; 30%), the Marly Chalk Association (FA-2; 37%) and the Skeletal Chalk Wackestone-Packstone Association (FA-3; 28%). The remaining five facies associations record more local conditions.

The Chalk Mudstone Association (Fig. 8.8a) consists of fine-grained carbonate, primarily reflecting a pelagic setting. The ubiquitous bioturbation indicates an oxygenated sea floor environment and relatively low accumulation rates, allowing for wholesale biogenic reworking of the carbonate ooze. Although the well-known, deeper-water, low-energy trace fossil assemblage *Chondrites-Planolites-Zoophycos* typifies this association, certain sections

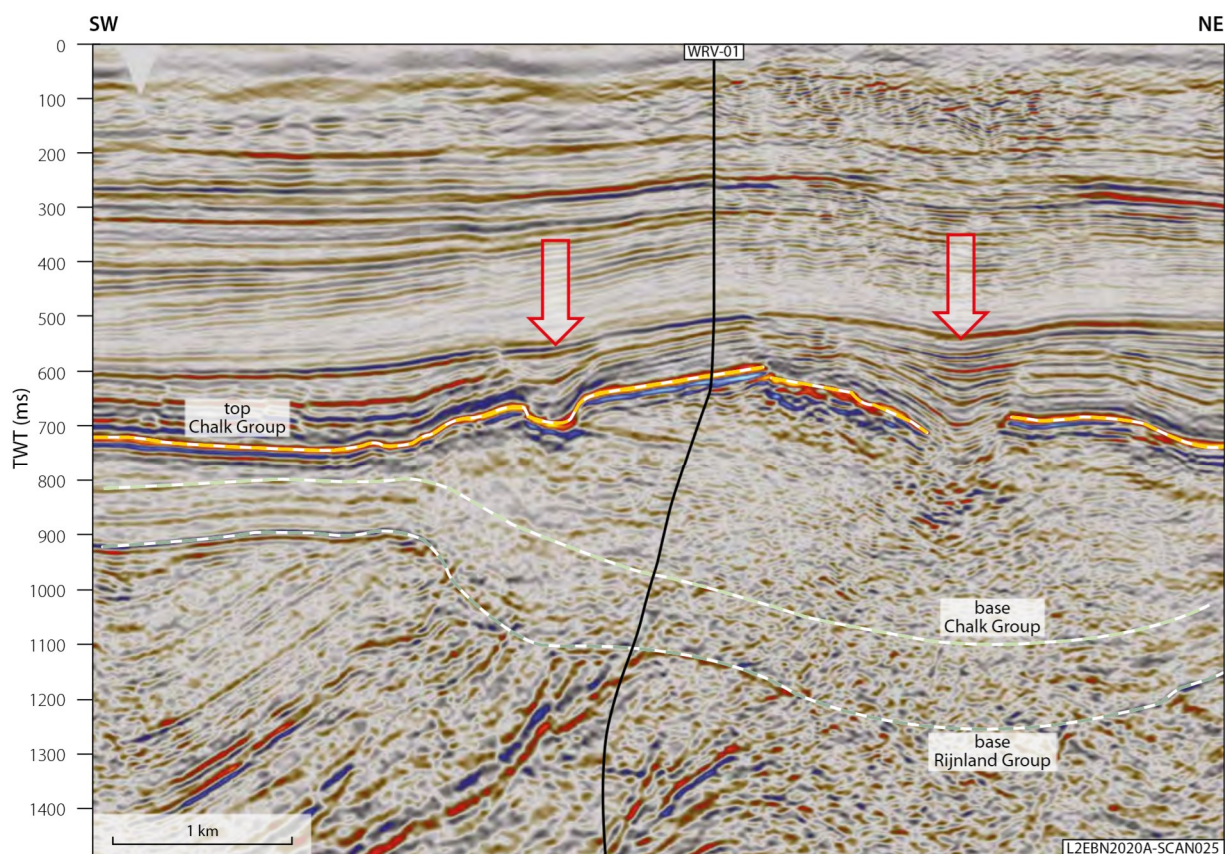


Figure 8.20. Seismic time section showing collapse structures (arrows) at the top of the Chalk Group near well Waverveen-1 (WRV-01; for position see Fig. 8.1) on the Zandvoort Ridge.

show well-developed *Thalassinoides* fabrics, probably indicating shallower, more hospitable conditions.

The Marly Chalk Association (Fig. 8c-e) is common in the logged cores; it is characterized by an alternation of burrowed, variably marly chalk mudstones and marlstones. It is commonly rich in chert. Two assemblages have been distinguished in this association, both named after the dominant trace fossil: the deeper-water *Zoophycos* assemblage and the more proximal *Thalassinoides* assemblage.

The Skeletal Chalk Wackestone-Packstone Association (Fig. 8.8b), with common to abundant occurrences of skeletal remains together with a predominance of *Thalassinoides*-dominated trace fossil assemblages, suggests a relatively shallow, nutrient-rich setting with moderate energy levels. Interbeds of dense bioclastic packstone suggest periodic higher-energy levels induced by increased velocity of bottom currents or possibly by deep-reaching storm waves. Accordingly, the depositional position of this facies association is interpreted to have been along submarine highs with reduced marly input and/or in intermediate shelf/ramp positions.

The remaining facies associations are related to local shallow-water or emergent conditions. It should be noted

that mass-flow deposits are very rarely recognized in the cored sections.

Ineson et al. (2014) proposed two stages to explain the spatial relationships between the observed depositional environments (Fig. 8.21). Phase A depicts a distally steepened ramp environment in which a deep shelf-basinal setting is characterized by coccolith-dominated chalks with a deeper-water, *Zoophycos*-dominated trace fossil assemblage. The clay content in this setting varies temporally, controlled by regional climatic/tectonic factors. Shorewards, the chalk sea shallows to mid-shelf and becomes more nutrient-rich; the benthic fauna increases and, as the environment shifts from oligotrophic to mesotrophic calcispheres become important. This skeletal chalk belt grades into a *Thalassinoides*-burrowed more marly chalk facies, with siliciclastic mud being derived from the regional shoreline or from locally emergent highs.

Stage B (Ineson et al., 2014) schematically illustrates the effect of inversion/salt-induced uplift on the facies belts; with increasing shallowing, the developing structural high will have formed a favourable habitat for benthic invertebrates, potentially culminating in local bryozoan/coral mound development (e.g. the Hanze diapir). Further shallowing will have exposed the high area to current

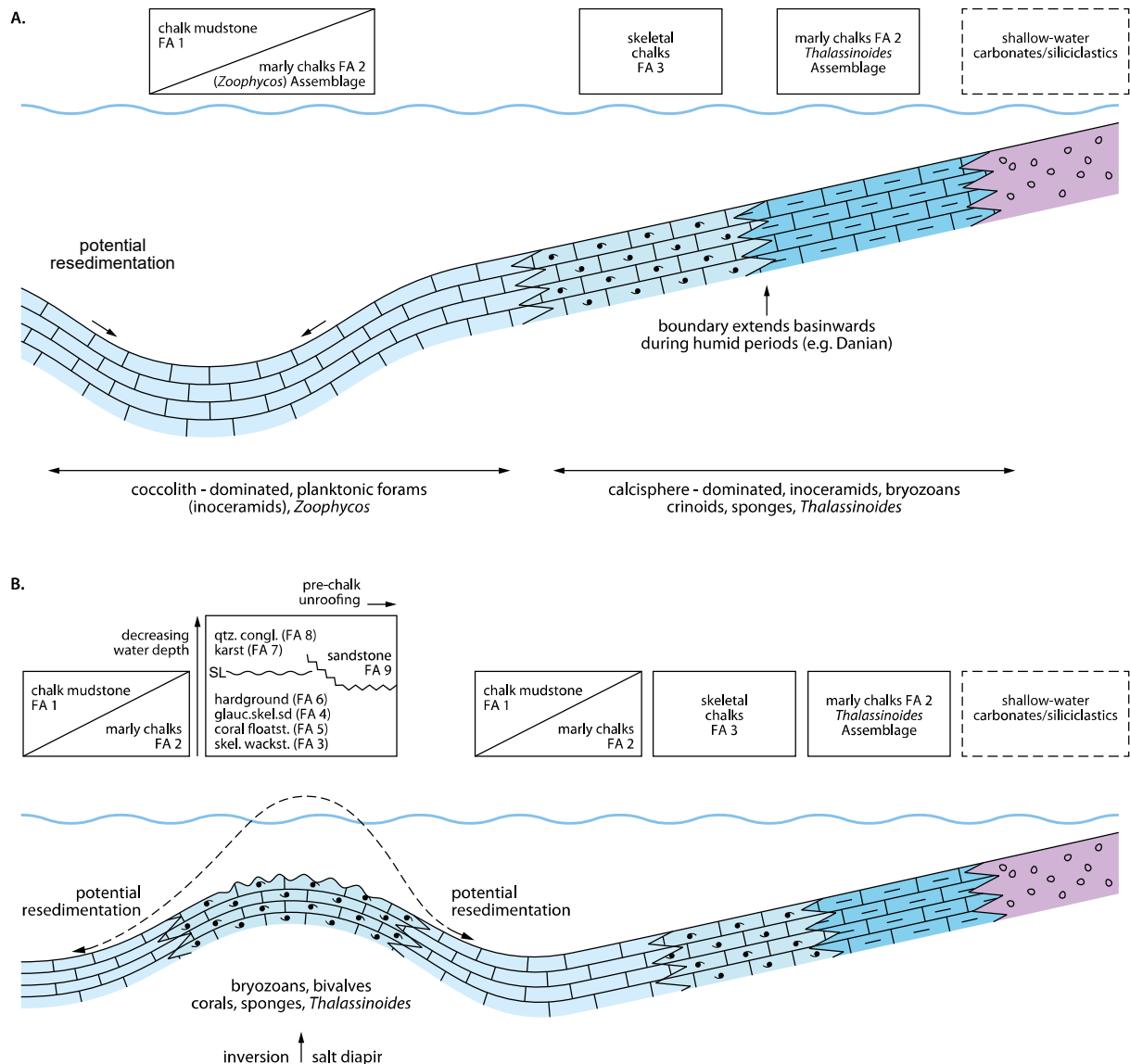


Figure 8.21. Sketches showing stages A and B for the inferred spatial relationships between depositional environments (Facies Associations (FA) 1-8) during (a) Periods of regional subsidence (Cenomanian-Santonian) and (b) Following late Campanian-Danian localized structural inversion uplift (from Ineson et al., 2014).

winnowing, concentration of skeletal sands and potentially also to hardground development. Local exposure of the high also may have resulted in karstification.

In the cores of the Chalk Group several typical, small-scale sedimentological features can be recognized (Fig. 8.8). Often intense bioturbation and discrete trace fossils are observed, the latter of which may be indicative for specific depositional environments. Anastomosing solution seams, also called horsetail structures, and horizontal stylolites indicate dissolution of limestone due to overburden pressure, whereby darker non-dissolving material is concentrated on the solution surfaces. In addition, chert nodules are often present, which occasionally follow burrow structures and are sometimes deposited in rhythmic

vertical successions, which may be related to Milankovitch cycles (Zijlstra, 1994). The formation of these chert nodules or levels is thought to have been governed by early diagenetic bacterial redox reactions concentrating the silica particles present in the chalky sediment (Zijlstra, 1987). Chert is more common in the upper part of the Ommelanden Formation (Campanian-Maastrichtian) and in the Ekofisk Formation than in the lower part of the Ommelanden Formation and the Texel Formation (Herngreen et al., 1996).

Microfacies analyses (Fig. 8.9c) of samples from the cored upper Maastrichtian section of well F17-10 show mud-supported, bioturbated, heterogeneous wackestone textures, the sediment consisting of 97-99% calcite (Pe-

trea & Goldberg, 2013). The main detrital components are coccoliths, foraminiferal tests (mostly planktic), calcispheres, bivalves (in particular inoceramids) and brachiopod shell fragments, ostracods, echinoderm ossicles and fragments, bryozoan colonies, calcareous sponges and sponge spicules. The main authigenic components are overgrowths on original calcite mud components and rare to common calcite sparite cements. Herrngreen et al. (1996) described similar microfacies from the cores of the Den Burg-1 (BRG-01) well on Texel. These samples are from chalk of a Cenomanian to early Campanian age that formed at water depths of approximately 50-150 metres.

In well F17-10 SEM and BSEM images of the chalk (Petrea & Goldberg, 2013) document that complete or nearly complete coccolith tests are rare (Fig. 8.10a). Mostly, coccoliths are disarticulated into individual platelets, which form the bulk of this micrite mud, which is neither compacted nor cemented very well, resulting in high porosities. However, the pore throats of the micrite mud typically range between 0.5 and 2.0 μm , resulting in a low matrix permeability of 1-5 mD. Pure chalk mudstone can have a porosity of up to 45%, while admixture of bioclastic and siliciclastic material tends to decrease the total porosity in chalk wackestones in this area to 25-35% (Van Lochem & Beller, 2018).

In areas close to emergent landmasses, siliciclastic facies are present in the Chalk Group, often in the form of glauconite-rich 'greensands'. The oldest of these greensands is the Cenomanian Texel Greensand, present mainly on the southern fringe of the West Netherlands Basin and further east in well Maasbommel-1 (MSB-01) (Gras, 1995). In the Dutch Central Graben area, Van Lochem (2018) documented the presence of upper Campanian marine conglomerates and glauconitic sandstones that overlie the Sub-Hercynian Unconformity and grade upwards into lower Maastrichtian sandy chalk (Fig. 8.14b-d). The sandstone facies in this area formed when fluvial incised valleys were flooded during a transgressive phase. These valleys were eroded into emerging highs during uplift subsequent to the Sub-Hercynian tectonic phase (Fig. 8.18).

Van Lochem (2018) and Van Lochem & Beller (2018) have shown that in offshore block F17 in the interval just above the Sub-Hercynian Unconformity there is a higher content of siliciclastic material and, to a lesser degree, an increased number of skeletal grains. The siliciclastic grains comprise very fine- to medium-grained, quartz and glauconite/green clay grains (Fig. 8.9a,b,e,f) that are either dispersed through the carbonate mud matrix or concentrated within burrows, along laminae of more coarsely grained material or as component of tests of agglutinated foraminifera.

A large north-south-trending channel system was described by Van der Molen (2004) on the Schill Grund High

and on the Ameland Block in the Maastrichtian and Danian interval. Surlyk et al. (2008) mapped the continuation of this feature to the north into the German offshore area. They documented channels that were filled laterally, obliquely, or longitudinally by chalk drifts and proposed that the main channel system was eroded by powerful contour-parallel bottom currents (contourites) flowing towards the southeast. Large-scale evidence for channelling due to ocean bottom currents in the chalk was found by Surlyk & Lykke-Andersen (2007) in the Danish Basin and by Hübscher et al. (2019) in the southern Baltic Sea.

Geophysical studies

Well-log correlation within the Chalk Group is quite difficult without the help of micropaleontology and/or seismic interpretation (Fig. 8.7). The gamma-ray log typically shows a continuous low value, while only the high values in the thin Plenus Marl Member stand out. The gamma-ray log readings often increase towards the base of the Texel Formation, at the transition with the underlying Rijnland Group. A clearer trend can be seen in the sonic-log with transit-times decreasing and velocities increasing from the top to the bottom of the Ommelanden Formation. It is often the interval of Turonian age which shows the highest velocity, higher than the underlying Texel Formation. Where present, also the base of the Ekofisk Formation often shows a slightly higher velocity than the underlying Ommelanden Formation.

Van der Molen (2004) used spectral frequency analyses of well logs to conclude that specific wavelength ratios between 5-7 m and 2-3 m represent Milankovitch 100-kyr eccentricity and 40-kyr obliquity cycles, respectively. From this he derived average net accumulation rates in the chalk of about 5 to 7 cm/kyr. However, it should be noted that sufficiently detailed biostratigraphic control was absent and these estimates could therefore not be corroborated. Arts (2017) recognized a 15-22 m cycle in the well-log records, which he interpreted to correspond to the 405-kyr eccentricity cycle.

Seismic stratigraphy is a powerful tool to unravel the sedimentary and large-scale tectonic development of the Chalk Group. For it to be successful a good biostratigraphic framework is needed next to high-quality seismic data. Van der Molen (2004) and Van der Molen & Wong (2007) subdivided the Chalk Group of the Dutch offshore into eleven seismic sequences (CK1-CK11; Figs 8.4, 8.7) and mapped these sequences on 2D-seismic data over most of the Dutch offshore area. In general, the seismic facies of the chalk are characterized by parallel and continuous reflections of varying amplitudes. Two megasequences were recognized, the first includes the Cenomanian to lower Campanian interval, which is separated from the second megasequence (upper Campanian to Danian) by a

large uplift and erosion phase that predates the deposition of the upper Campanian. In a more detailed study by Van der Molen et al. (2005) on two 3D-seismic surveys seven sequences were mapped. They found that most of the Chalk Group is characterized by parallel and continuous reflections, indicative of pelagic sedimentation under relatively quiescent tectonic conditions. Where deposition of the Chalk Group coincided with intense tectonic activity, discontinuous and irregular seismic reflections are found. Such reflection configurations indicate reworking of sediment.

Van der Voet et al. (2018) performed a 3D-seismic sequence-stratigraphic study of the northern E and F quadrants in the Dutch sector, covering the Elbow Spit Platform, the Step Graben and the northern and central part of the Dutch Central Graben. In their study the Chalk Group was subdivided into the seven chronostratigraphic stages of the Late Cretaceous plus the Danian.

Van Lochem (2018) published the results of a seismic-stratigraphic study of the Chalk Group in the central and southern part of the Dutch Central Graben. The interpreted markers coincide with the boundaries of the stages of the Upper Cretaceous and, in addition, to the Sub-Hercynian Unconformity surface. This interpretation resulted in a subcrop map of the Sub-Hercynian Unconformity. The results of these studies in the Dutch North Sea compare well with studies in the Norwegian (Gennaro et al., 2013) and Danish (Van Buchem et al., 2018) sectors (Fig. 8.4). In the Danish sector the only inversion event is referred to as the Early Campanian Unconformity (Van Buchem et al., 2018) and is equivalent in timing and tectonic character to the Sub-Hercynian Unconformity in the Dutch sector.

For the Dutch onshore area the only study to make use of seismic stratigraphy was conducted by Gras & Geluk (1999). These authors subdivided the Chalk Group of the Peel-Maasbommel Complex into three seismic facies. The lowermost seismic facies I, which has a transparent character with few and discontinuous reflections, represents the sandy, shallow-marine Oploo and Vaals formations of Santonian to Campanian age. Towards the north, it grades into seismic facies II and becomes less transparent, marking a lithofacies change from siliciclastic sediments into chalk and marls of the Ommelanden Formation. Unconformably overlying is seismic facies III, which shows a fairly constant thickness of 60–80 m. This seismic facies comprises several continuous high-amplitude reflectors, parallel to the overlying Paleogene succession, representing the Gulpen, Maastricht and Houthem formations, which were deposited in a shallow-marine chalk environment.

Other types of seismic evaluations have been successfully applied to the Chalk Group, especially where 3D-seismic

data are available. Since chalk is a monomineralic rock it is ideal for rock physical and seismic inversion studies to understand the acoustic properties as a function of porosity. Seismic inversion and spectral decomposition studies in the Danish sector show slump and fluid escape structures and also diagenetically altered areas (Smit, 2018). In the Dutch offshore sector seismic inversion, spectral decomposition and PaleoScan™ interpretation studies in the chalk yielded promising results (Van Lochem, personal observation), but this work has not been published yet.

The chalk has been the subject of geophysical velocity studies (Van der Molen, 2004; Van Dalfsen et al., 2006), which is of particular interest as its velocity is often clearly higher than in underlying rocks, while the velocity also increases significantly with burial depth. Van der Molen (2004) used the observed velocity changes in the chalk to estimate burial anomalies. Especially in the Dutch Central Graben the velocities proved to be lower than expected at the present burial depth, indicating that the sequence is under-compacted. This under-compaction can be related to overpressure and reduced dewatering (Verweij, 2006).

Acknowledgements

Wintershall Noordzee B.V. and its partners are thanked for releasing the information from their offshore core report (Ineson et al., 2014). Allard van der Molen provided useful suggestions for the improvement of an earlier typescript. Dominik Mock and Marie Klose of the Institute of Mineralogy of Leibniz Universität Hannover are acknowledged for producing SEM images of limestone from South Limburg. Nik Trabucho Alexandre is thanked for drawing a number of figures and we are grateful to Mateus Kroth for valuable discussion on the Upper Cretaceous stratigraphy of South Limburg and for providing images of thin sections. We appreciate our reviewers Nora Witmans and Eva de Boever of TNO – Geological Survey of the Netherlands for their valuable comments on a first draft of the manuscript.

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.28163312>.

References

- Adolfsson, J.S. & Ward, D.J., 2014. Crossing the boundary: an elasmobranch fauna from Stevns Klint, Denmark. *Palaeontology* 57: 591–629. DOI: [10.1111/pala.12079](https://doi.org/10.1111/pala.12079)

- Adolfsson, J.S. & Ward, D.J., 2015. Neoselachians from the Danian (early Paleocene) of Denmark. *Acta Palaeontologica Polonica* 60: 313-338. DOI: [10.4202/app.2012.0123](https://doi.org/10.4202/app.2012.0123)
- Albers, H.J., 1976. Feinstratigraphie, Faziesanalyse und Zyklen des Unterampans (Vaalser Grünsand = Hervien) von Aachen und dem niederländisch-belgischen Limburg. *Geologisches Jahrbuch A34*: 3-68.
- Alvarez, L.W., Alvarez, W., Asaro, F. & Michel, H.V., 1980. Extra-terrestrial cause for the Cretaceous-Tertiary extinction. *Science* 208: 1095-1108. DOI: [10.1126/science.208.4448.1095](https://doi.org/10.1126/science.208.4448.1095)
- Anderskov, K., Damholt, T. & Surlyk, F., 2007. Late Maastrichtian chalk mounds, Stevns Klint, Denmark – Combined physical and biogenic structures. *Sedimentary Geology* 200: 57-72. DOI: [10.1016/j.sedgeo.2007.03.005](https://doi.org/10.1016/j.sedgeo.2007.03.005)
- Arts, M.C.M., 2017. Towards a cyclostratigraphic framework of the Upper Cretaceous Chalk Group in the Dutch offshore. MSc thesis Utrecht University (the Netherlands) (the Netherlands): 144 pp.
- Back, S., Van Gent, H., Reuning, L., Grötsch, J., Niederau, J. & Kukla, P., 2011. 3D seismic geomorphology and sedimentology of the Chalk Group, southern Danish North Sea. *Journal of the Geological Society* 168: 393-406. DOI: [10.1144/0016-76492010-047](https://doi.org/10.1144/0016-76492010-047)
- Batten, D.J., Streel, M., Duser, M. & Bless, M.J.M., 1987. Late Cretaceous palynomorphs from the boreholes Thermae 2002 (Valkenburg a/d Geul, the Netherlands) and 's-Gravenvoeren (Belgium). *Annales de la Société Géologique de Belgique* 110: 47-51.
- Batten, D.J., Dupagne-Kievits, J. & Lister, J.K., 1988. Palynology of the Upper Cretaceous Aachen Formation of northeast Belgium. In: Streel, M. & Bless, M.J.M. (eds): *The Chalk District of the Euregio Meuse-Rhine. Selected papers on Upper Cretaceous deposits*. Natuurhistorisch Museum Maastricht/Université d'État Liège: 95-103.
- Beller, M., Chaouch, N., Petri, V., Veeken, P., Landa, E., Kokoshin, E., Smirnov, K. & Paleari, C., 2019. Diffraction imaging: resolving subtle seismic geo-features in the Rembrandt and Vermeer Chalk oil fields, Dutch offshore. 81st EAGE Conference and Exhibition 2019, London: 1-5. DOI: [10.3997/2214-4609.201900935](https://doi.org/10.3997/2214-4609.201900935)
- Benito, J., Kuo, P.-C., Widrig, K.E., Jagt, J.W.M. & Field, D.J., 2022. Cretaceous ornithurine supports a neognathous crown bird ancestor. *Nature* 612: 100-105. DOI: [10.1038/s41586-022-05445-y](https://doi.org/10.1038/s41586-022-05445-y)
- Bignot, G., 1993. The position of the Montian Stage and related facies within the stratigraphic-palaeogeographic framework of NW Europe during the Danian. *Contributions to Tertiary and Quaternary Geology* 29: 47-59.
- Binkhorst van den Binkhorst, J.T., 1859. Esquisse géologique et paléontologique des couches Crétacées du Limbourg, et plus spécialement de la craie tuffeau. Première partie. Van Osch-America et Cie. (Maastricht): 268 pp.
- Bless, M.J.M., 1989. Event-induced changes in Late Cretaceous to Early Paleocene ostracode assemblages of the SE Netherlands and NE Belgium. *Annales de la Société géologique de Belgique* 112: 19-30.
- Bless, M.J.M., Felder, P.J. & Meessen, J.P.M.Th., 1986. Late Cretaceous sea level rise and inversion: their influence on the depositional environment between Aachen and Antwerp. *Annales de la Société géologique de Belgique* 109: 333-355.
- Bless, M.J.M., Bouckaert, J. & Paproth, E., 1987. Fossil assemblages and depositional environments: Limits to Stratigraphical Correlations. In: Miller, J., Adams, A.E. & Wright, V.P. (eds): *European Danian environments*. Geological Journal, Special Issue 12: 61-73.
- Bouw, L. & Oude Essink, G.H.P., 2003a. Development of a freshwater lens in the inverted Broad Fourteens Basin, Netherlands offshore. *Journal of Geochemical Exploration* 78-79: 321-325. DOI: [10.1016/S0375-6742\(03\)00113-4](https://doi.org/10.1016/S0375-6742(03)00113-4)
- Bouw, L. & Oude Essink, G.H.P., 2003b. Fluid flow in the northern Broad Fourteens Basin during Late Cretaceous inversion. *Netherlands Journal of Geosciences: Geologie En Mijnbouw* 82: 55-69. DOI: [10.1017/S0016774600022794](https://doi.org/10.1017/S0016774600022794)
- Brinkhuis, H. & Schiøler, P., 1996. Palynology of the Geulhemmerberg Cretaceous/Tertiary boundary section (Limburg, SE Netherlands). *Geologie en Mijnbouw* 75: 193-213.
- Brinkhuis, H. & Smit, J., 1996. The Geulhemmerberg Cretaceous/Tertiary boundary section (Maastrichtian type area, SE Netherlands); an introduction. *Geologie en Mijnbouw* 75: 101-293.
- Buls, T., Anderskov, K., Fabricius, I.L., Friend, P.L., Thompson, C.E.L. & Stemmerik, L., 2015. Production of calcareous nannofossil ooze for sedimentological experiments. *Journal of Sedimentary Research* 85: 1228-1237. DOI: [10.2110/jsr.2015.80](https://doi.org/10.2110/jsr.2015.80)
- Burgers, W.F.J. & Mulder, G.G., 1991. Aspects of the Late Jurassic and Cretaceous history of The Netherlands. *Geologie En Mijnbouw* 70: 347-354.
- Camper, P., 1786. Conjectures relative to the petrifications found in St. Peter's Mountain, near Maestricht. *Philosophical Transactions of the Royal Society of London* 76: 443-456. DOI: [10.1098/rstl.1786.0026](https://doi.org/10.1098/rstl.1786.0026)
- Christensen, L., Frejerslev, S., Simonsen, A. & Thiede, J., 1973. Sedimentology and depositional environment of Lower Danian Fish Clay from Stevns Klint, Denmark. *Bulletin of the Geological Society of Denmark* 22: 193-212.
- Christensen, W.K. & Schmid, F., 1987. The belemnites of the Vaals Formation from the C.P.L. quarry at Hallembaye in Belgium – taxonomy, biometry and biostratigraphy. *Geologisches Jahrbuch A94*: 37 pp.
- Christensen, W.K., Schmid, F. & Schulz, M.-G., 2005. Belemnitenla from the Upper Maastrichtian of Hemmoor, northwest Germany. In: Schmid, F. (ed): *Das Maastricht in Nordwestdeutschland – Fossilien aus der Schreibkreide von Hemmoor und Kronsmeer*. *Geologisches Jahrbuch A157*: 23-67.
- Chumakov, N.M., Zharkov, M.A., Herman, A.B., Doludenko, M.P., Kalandadze, N.N., Lebedev, E.L., Ponomarenko, A.G. & Rautian, A.S., 1995. Climatic belts of the Mid-Cretaceous time. *Strati-*

- graphy and Geological Correlation 3: 42-63.
- Clark-Lowes, D.D., Kuzemko, N.C.J. & Scott, D.A., 1987. Structure and petroleum prospectivity of the Dutch Central Graben and neighbouring platform areas. In: Brooks, J. & Glennie, K. (eds): Petroleum Geology of North-West Europe: Proceedings of the Third Conference. Graham & Trotman (London): 337-356.
- Cohen, K.M., Finney, S.C., Gibbard, P.L. & Fan, J.-X., 2013. The ICS International Chronostratigraphic Chart. Episodes 36(3): 199-204. DOI: [10.18814/epiugs/2013/v36i3/002](https://doi.org/10.18814/epiugs/2013/v36i3/002)
- De Jager, J., 2003. Inverted basins in the Netherlands, similarities and differences. Netherlands Journal of Geosciences 82(4): 339-349. DOI: [10.1017/S0016774600020175](https://doi.org/10.1017/S0016774600020175)
- 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 Jager, J., Van Ojik, K. & Smit, J., 2025. Geological development. In: J.H. Ten Veen, G.-J. Vis, J. De Jager & Th.E. Wong (eds): Geology of the Netherlands, second edition. Amsterdam University Press (Amsterdam): 21-51. DOI: [10.5117/9789463728362_ch01](https://doi.org/10.5117/9789463728362_ch01)
- 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](https://doi.org/10.1016/j.jog.2018.01.005)
- Doornenbal, J.C., Kombrink, H., Bouroullec, R., Dalman, R.A.F., De Bruin, G., Geel, C.R., Houben, A.J.P., Jaarsma, B., Juez-Larré, J., Kortekaas, M., Mijlneff, H.F., Nelskamp, S., Pharaoh, T.C., Ten Veen, J.H., Ter Borgh, M., Van Ojik, K., Verreussel, R.M.C.H., Verweij, J.M. & Vis, G.-J., 2019. New insights on subsurface energy resources in the Southern North Sea Basin area. In: Patruno, S., Archer, S.G., Chiarella, D., Howell, J.A., Jackson, C.A.-L. & Kombrink, H. (eds): Cross-border themes in petroleum geology I: The North Sea. Geological Society of London, Special Publications 494: 233-268. DOI: [10.1144/SP494-2018-178](https://doi.org/10.1144/SP494-2018-178)
- Dortangs, R.W., Schulp, A.S., Mulder, E.W.A., Jagt, J.W.M., Peeters, H.H.G. & De Graaf, D.Th., 2002. A large new mosasaur from the Upper Cretaceous of The Netherlands. Netherlands Journal of Geosciences 81: 1-8. DOI: [10.1017/S0016774600020515](https://doi.org/10.1017/S0016774600020515)
- Dronkers, A.J. & Mrozek, F.J., 1991. Inverted basins of The Netherlands. First Break 9: 409-418. DOI: [10.3997/1365-2397.1991019](https://doi.org/10.3997/1365-2397.1991019)
- Duin, E.J.T., 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: 245-276. DOI: [10.1017/S0016774600023064](https://doi.org/10.1017/S0016774600023064)
- Dumont, M.A., 1849. Rapport sur la carte géologique du Royaume. Bulletins de l'Académie Royale des Sciences, des Lettres et Des Beaux-Arts de Belgique 16: 351-373.
- Dusar, M. & Lagrou, D., 2007. Cretaceous flooding of the Brabant Massif and the lithostratigraphic characteristics of its chalk cover in northern Belgium. Geologica Belgica 10: 27-38.
- Eldrett, J.S., Vieira, M., Gallagher, L., Hampton, M., Blaauw, M. & Swart, P.K., 2021. Late Cretaceous to Palaeogene carbon isotope, calcareous nannofossil and foraminifera stratigraphy of the Chalk Group, Central North Sea. Marine and Petroleum Geology 124: 104789. DOI: [10.1016/j.marpetgeo.2020.104789](https://doi.org/10.1016/j.marpetgeo.2020.104789)
- Engelen, F.G.H., 1989. Vuursteenwinning en toepassing. Grondboor & Hamer 43: 207-210.
- Felder, P.J., 1994. Bioklasten in het Krijt uit boringen van West- en Oost-Vlaanderen. Belgische Geologische Dienst, Professional Paper 1994/3 (270). Drukkerij van het Ministerie van Economische Zaken (Brussel): 86 pp.
- Felder, P.J., 1995. Bioklasten-onderzoek van Boven-Krijt en Dano-Montiaan afzettingen uit boringen in de Belgische Kempen. Belgische Geologische Dienst, Professional Paper 1994/8 (275). Drukkerij van het Ministerie van Economische Zaken (Brussel): 240 pp.
- Felder, P.J., 1997. The Vijlen Chalk Member (Maastrichtian, Late Cretaceous) in the Meuse-Rhine Euregion. Annales de la Société Géologique de Belgique 119: 119-133.
- Felder, P.J. & Bless, M.J.M., 1989. Biostratigraphy and ecostratigraphy of Late Cretaceous deposits in the Kunrade area (South-Limburg, SE Netherlands). Annales de la Société Géologique de Belgique 112: 31-45.
- Felder, P.J. & Bless, M.J.M., 1994. The Vijlen Chalk (early Early to early Late Maastrichtian) in its type area around Vijlen and Mamelis (southern Limburg, the Netherlands). Annales de la Société Géologique de Belgique 116: 61-85.
- Felder, P.J., Bless, M.J.M., Demyttenaere, R., Dusar, M., Messen, J.P.M.Th. & Robaszynski, F., 1985. Upper Cretaceous to Early Tertiary deposits (Santonian - Paleocene) in northeastern Belgium and South Limburg (The Netherlands) with reference to the Campanian - Maastrichtian. Belgische Geologische Dienst, Professional Paper 1985/1 (214). Drukkerij van het Ministerie van Economische Zaken (Brussel): 1-151 pp.
- Felder, W.M., 1975. Lithostratigrafie van het Boven-Krijt en het Dano-Montien in Zuid-Limburg en het aangrenzende gebied. In: Zagwijn, W.H. & Van Staalduinen, C.J. (eds): Toelichting bij de geologische overzichtskaarten van Nederland. Rijks Geologische Dienst (Haarlem): 63-72.
- Felder, W.M. & Bosch, P.W., 2000. Krijt van Zuid-Limburg. Plantijn-Casparie (Rotterdam): 192 pp.
- Field, D.J., Benito, J., Chen, A., Jagt, J.W.M. & Ksepka, D.T., 2020. Late Cretaceous neornithine from Europe illuminates the origins of crown birds. Nature 579: 397-401. DOI: [10.1038/s41586-020-2096-0](https://doi.org/10.1038/s41586-020-2096-0)
- Fischer, V., Bardet, N., Benson, R.B.J., Arkhangelsky, M.S. & Friedman, M., 2015. Extinction of fish-shaped marine reptiles associated with reduced evolutionary rates and global environmental volatility. Nature Communications 7: 10825. DOI: [10.1038/ncomms10825](https://doi.org/10.1038/ncomms10825)
- Frakes, L.A., 1999. Estimating the global thermal state from Cretaceous sea surface and continental temperature data. In: Barrera, E. & Johnson, C.C. (eds): Evolution of the Cretaceous

- ocean-climate system. Geological Society of America, Special Paper 332: 49-57. DOI: [10.1130/0-8137-2332-9.49](https://doi.org/10.1130/0-8137-2332-9.49)
- Gale, A., Batenburg, S., Coccioni, R., Dubicka, Z., Erba, E., Falzoni, F., Haggart, J., Hasegawa, T., Ifrim, C., Jarvis, I., Jenkyns, H., Jurowska, A., Kennedy, J., Maron, M., Muttoni, G., Pearce, M., Petrizzo, M.R., Premoli-Silva, I., Thibault, N., Voigt, S., Wagreich, M. & Walaszczyk, I., 2023. The Global Boundary Stratotype Section and Point (GSSP) of the Campanian Stage at Bottaccione (Gubbio, Italy) and its Auxiliary Sections: Seaford Head (UK), Boceniec (Poland), Postalm (Austria), Smoky Hill, Kansas (U.S.A), Tepayac (Mexico). Episodes 46: 451-490. DOI: [10.18814/epiugs/2022/022048](https://doi.org/10.18814/epiugs/2022/022048)
- Gale, A.S., 2018. An integrated microcrinoid zonation for the lower Campanian chalks of southern England, and its implications for correlation. Cretaceous Research 87: 312-357. DOI: [10.1016/j.cretres.2017.02.002](https://doi.org/10.1016/j.cretres.2017.02.002)
- Gale, A.S., Mutterlose, J., Batenburg, S., Gradstein, F.M., Agterberg, F.P., Ogg, J.G. & Petrizzo, M.R., 2020. The Cretaceous period. In: Gradstein, F.M., Ogg, J.G., Schmitz, M.D. & Ogg, G.M. (eds): Geologic time scale 2020. Elsevier (Amsterdam): 1023-1086. DOI: [10.1016/B978-0-12-824360-2.00026-7](https://doi.org/10.1016/B978-0-12-824360-2.00026-7)
- Gennaro, M., Wonham, J.P., Gawthorpe, R. & Sælen, G., 2013. Seismic stratigraphy of the Chalk Group in the Norwegian Central Graben, North Sea. Marine and Petroleum Geology 45: 236-266. DOI: [10.1016/j.marpetgeo.2013.04.010](https://doi.org/10.1016/j.marpetgeo.2013.04.010)
- Gilli, É., 2015. Karstology. Karsts, caves and springs: Elements of fundamental and applied karstology. CRC Press (Boca Raton, FL, USA): 256 pp.
- Gradstein, F.M., Waters, C.N., Charnock, M., Munsterman, D.K., Hollerbach, M., Brunstad, H., Hammer, O. & Vergara, L., 2016. Stratigraphic guide to the Cromer Knoll, Shetland and Chalk Groups, North Sea and Norwegian Sea. Newsletters on Stratigraphy 49: 71-280. DOI: [10.1127/nos/2016/0071](https://doi.org/10.1127/nos/2016/0071)
- Gras, R., 1995. Late Cretaceous sedimentation and tectonic inversion, southern Netherlands. Geologie en Mijnbouw 74 (2): 117-127.
- Gras, R. & Geluk, M., 1999. Late Cretaceous – Early Tertiary sedimentation and tectonic inversion in the southern Netherlands. Geologie en Mijnbouw 78: 1-19. DOI: [10.1023/A:1003709821901](https://doi.org/10.1023/A:1003709821901)
- Gravesen, P., 1993. Early Danian species of the echinoid genus Tylocidaris (Cidaridae, Psychocidarinae) from eastern Denmark. Contributions to Tertiary and Quaternary Geology 30: 41-73.
- Gutteridge, P. & Thompson, S., 2019. Sedimentology and microfacies of the cored interval in well Eys-1, Limburg Province, the Netherlands. Cambridge Carbonates Ltd report: 39 pp.
- Hansen, T., 2019. Gastropods from the Cretaceous-Palaeogene boundary in Denmark. Zootaxa 4654: 1-196. DOI: [10.11646/zootaxa.4654.1.1](https://doi.org/10.11646/zootaxa.4654.1.1)
- Haq, B.U., 2014. Cretaceous eustasy revisited. Global and Planetary Change 113: 44-58. DOI: [10.1016/j.gloplacha.2013.12.007](https://doi.org/10.1016/j.gloplacha.2013.12.007)
- Hay, W.W. & Floegel, S., 2012. New thoughts about the Cretaceous climate and oceans. Earth-Science Reviews 115: 262-272. DOI: [10.1016/j.earscirev.2012.09.008](https://doi.org/10.1016/j.earscirev.2012.09.008)
- Herngreen, G.F.W. (ed), Eillebrecht, A.T.J.M., Gortemaker, R.E., Remmelts, G., Schuurman, H.A.H.M. & Verbeek, J.W., 1996. Upper Cretaceous Chalk Group stratigraphy near the isle of Texel, the Netherlands (a multidisciplinary approach). Mededelingen Rijks Geologische Dienst 56: 63 pp.
- Herngreen, G.F.W. (ed), Schuurman, H.A.H.M., Verbeek, J.W., Brinkhuis, H., Burnett, J.A., Felder, W.M. & Kedves, M., 1998. Biostratigraphy of Cretaceous-Tertiary boundary strata in the Curfs quarry, the Netherlands. Mededelingen Nederlands Instituut voor Toegepaste Geowetenschappen TNO 61: 57 pp.
- Herngreen, G.F.W. & Wong, Th.E., 2007. Cretaceous. 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): 127-150.
- Hiss, M., Niebuhr, B. & Teipel, U., 2018. Die Kreide in der Stratigraphischen Tabelle von Deutschland 2016. Zeitschrift der Deutschen Gesellschaft für Geowissenschaften 169: 247-266. DOI: [10.1127/zdgg/2018/0149](https://doi.org/10.1127/zdgg/2018/0149)
- Hofmann, A.P., Price, A., Kaffenberger, G., Godderij, R.R.G.G. & Simpson, M., 2002. Hanze chalk oil field—the Chalk pearl in the Dutch North Sea. cp-5-00405. 64th EAGE Conference and Exhibition 2002, Florence: 211. DOI: [10.3997/2214-4609-pdb.5.P211](https://doi.org/10.3997/2214-4609-pdb.5.P211)
- Hooper, R.J., Goh, L.S. & Dewey, F., 1995. The inversion history of the northeastern margin of the Broad Fourteens Basin. In: Buchanan, J.G. & Buchanan, P.G. (eds): Basin inversion. Geological Society of London, Special Publications 88, 307-317. DOI: [10.1144/GSL.SP.1995.088.01.17](https://doi.org/10.1144/GSL.SP.1995.088.01.17)
- Hopper, J. R., Funck, T., Stoker, M., Ártung, U., Péron-Pinvidic, G., Doornenbal, H. & Gaina, C. (eds), 2014. Tectonostratigraphic Atlas of the North-East Atlantic Region. Geological Survey of Denmark and Greenland (GEUS) (Copenhagen, Denmark): 339 pp.
- Hu, X., Wagreich, M. & Yilmaz, I.O., 2012. Marine rapid environmental/climatic change in the Cretaceous greenhouse world. Cretaceous Research 38: 1-6. DOI: [10.1016/j.cretres.2012.04.012](https://doi.org/10.1016/j.cretres.2012.04.012)
- Huber, B.T., MacLeod, K.G., Watkins, D.K. & Coffin, M.F., 2018. The rise and fall of the Cretaceous Hot Greenhouse climate. Global and Planetary Change 167: 1-23. DOI: [10.1016/j.gloplacha.2018.04.004](https://doi.org/10.1016/j.gloplacha.2018.04.004)
- Hübscher, C., Al Hseinat, M., Schneider, M. & Betzler, C., 2019. Evolution of contourite systems in the late Cretaceous Chalk Sea along the Tornquist Zone. Sedimentology: 1341-1360. DOI: [10.1111/sed.12564](https://doi.org/10.1111/sed.12564)
- Ineson, J., Bjerager, M. & Kristensen, L., 2014. Upper Cretaceous-Danian chalk of the Netherlands subsurface - Core descriptions, facies analysis, reservoir properties. Nationale Geologische Undersøgelser for Danmark og Grønland (GEUS) confidential report 2014/47: 90 pp. For Wintershall Noordzee, cited with permission.

- Jagt, J.W.M., 1999a. Late Cretaceous-Early Palaeogene echinoderms and the K/T boundary in the southeast Netherlands and northeast Belgium – Part 1: Introduction and stratigraphy. *Scripta Geologica* 116: 1–57.
- Jagt, J.W.M., 1999b. Late Cretaceous-Early Palaeogene echinoderms and the K/T boundary in the southeast Netherlands and northeast Belgium – Part 2: Crinoids. *Scripta Geologica* 116: 59–255.
- Jagt, J.W.M., 2000a. Late Cretaceous-Early Palaeogene echinoderms and the K/T boundary in the southeast Netherlands and northeast Belgium – Part 3: Ophiuroids (with a chapter on: Early Maastrichtian ophiuroids from Rügen (northeast Germany) and Møn (Denmark) by Manfred Kutschner & John W.M. Jagt). *Scripta Geologica* 121: 1–179.
- Jagt, J.W.M., 2000b. 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., 2000c. Late Cretaceous-Early Palaeogene echinoderms and the K/T boundary in the southeast Netherlands and northeast Belgium – Part 6: Conclusions. *Scripta Geologica* 121: 505–577.
- Jagt, J.W.M., 2000d. Late Cretaceous-Early Palaeogene echinoderms and the K/T boundary in the southeast Netherlands and northeast Belgium – Part 4: Echinoids. *Scripta Geologica* 122: 181–375.
- Jagt, J.W.M., 2005. Stratigraphic ranges of mosasaurs of Belgium and the Netherlands (Late Cretaceous) and cephalopod-based correlations with North America. *Proceedings of the First Mosasaur Meeting, Netherlands Journal of Geosciences* 84: 283–301. DOI: [10.1017/S0016774600021065](https://doi.org/10.1017/S0016774600021065)
- Jagt, J.W.M. & Jagt-Yazykova, E.A., 2018. Stratigraphical ranges of tegulated inoceramid bivalves in the type area of the Maastrichtian Stage (Belgium, the Netherlands). *Cretaceous Research* 87: 385–394. DOI: [10.1016/j.cretres.2017.05.022](https://doi.org/10.1016/j.cretres.2017.05.022)
- Jagt, J.W.M. & Jagt-Yazykova, E.A., 2019. Late Cretaceous and Cenozoic cephalopods from the southern North Sea Basin: stocktaking and future directions. *Vita Malacologica* 18: 1–33.
- Jagt, J.W.M. & Oosterink, H.W., 2012. Hypoturrilites uit het vroeg-Cenomanien van Winterswijk. *Staringia* 13: 199.
- Jagt, J.W.M., Kennedy, W.J. & Machalski, M., 1999. Giant scaphitid ammonites from the Maastrichtian of Europe. *Bulletin de l'Institut royal des Sciences naturelles de Belgique, Sciences de la Terre* 69: 133–154.
- Jagt, J.W.M., Jagt-Yazykova, E.A. & Schins, W.J.H., 2011. A tribute to the late Felder brothers – pioneers of Limburg geology and prehistoric archaeology; introduction. *Netherlands Journal of Geosciences* 90: 65–71. DOI: [10.1017/S0016774600001025](https://doi.org/10.1017/S0016774600001025)
- 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.
- Jelby, M.E., Thibault, N., Surlyk, F., Ullmann, C.V., Harlou, R. & Korte, C., 2014. The lower Maastrichtian Hvidskud succession, Møns Klint, Denmark: calcareous nannofossil biostratigraphy, carbon isotope stratigraphy, and bulk and brachiopod oxygen isotopes. *Bulletin of the Geological Society of Denmark* 62: 89–104. DOI: [10.37570/bgds-2014-62-05](https://doi.org/10.37570/bgds-2014-62-05)
- Jenkyns, H.C., Dickson, A.J., Ruhl, M. & Van den Boorn, S.H.J.M., 2017. Basalt-seawater interaction, the Plenus Cold Event, enhanced weathering and geochemical change: deconstructing Oceanic Anoxic Event 2 (Cenomanian–Turonian, Late Cretaceous). In: Robinson, S.A., Heimhofer, U., Hesselbo, S.P. & Petrizzo, M.R. (eds): *Mesozoic climate and oceans – a tribute to Hugh Jenkyns and Helmut Weissert*. *Sedimentology* 64: 16–43. DOI: [10.1111/sed.12305](https://doi.org/10.1111/sed.12305)
- Jennings, J.N., 1985. *Karst geomorphology*. Blackwell (Oxford, UK): 293 pp.
- Juvigné, E. & Renard, F., 1992. Les terrasses de la Meuse de Liège à Maastricht. *Annales de la Société Géologique de Belgique* 115: 167–186.
- Kennedy, W.J. & Jagt, J.W.M., 1995. Lower Campanian heteromorph ammonites from the Vaals Formation around Aachen, Germany, and adjacent parts of Belgium and The Netherlands. *Neues Jahrbuch für Geologie und Paläontologie - Abhandlungen* 197: 275–294. DOI: [10.1127/njgpa/197/1995/275](https://doi.org/10.1127/njgpa/197/1995/275)
- Keutgen, N., 2018. A bioclast-based astronomical timescale for the Maastrichtian in the type area (southeast Netherlands, northeast Belgium) and stratigraphic implications: the legacy of P.J. Felder. *Netherlands Journal of Geosciences* 97: 229–260. DOI: [10.1017/njg.2018.15](https://doi.org/10.1017/njg.2018.15)
- Keutgen, N., Jagt, J.W.M., Felder, P.J. & Jagt-Yazykova, E.A., 2010. Stratigraphy of the upper Vijlen Member (Gulpen Formation; Maastrichtian) in northeast Belgium, the southeast Netherlands and the Aachen area (Germany), with special reference to belemnite cephalopods. *Netherlands Journal of Geosciences* 89: 109–136. DOI: [10.1017/S0016774600000731](https://doi.org/10.1017/S0016774600000731)
- Keutgen, N., Remin, Z. & Jagt, J.W.M., 2017. The late Maastrichtian Belemnella kazimiroviensis group (Cephalopoda, Coleoidea) in the Middle Vistula valley (Poland) and the Maastricht area (the Netherlands, Belgium) – taxonomy and palaeobiological implications. *Palaeontologia Electronica* 20.2: 1–29. DOI: [10.26879/671](https://doi.org/10.26879/671)
- Kirkaldy, J.F., 1950. Solution of the Chalk in the Mimms Valley, Herts. *Proceedings of the Geologists' Association* 61: 219–224. DOI: [10.1016/S0016-7878\(50\)80028-7](https://doi.org/10.1016/S0016-7878(50)80028-7)
- Knobloch, E., Kvaček, Z., Bůžek, Č., Mai, D.H. & Batten, D.J., 1993. Evolutionary significance of floristic changes in the Northern Hemisphere during the Late Cretaceous and Palaeogene, with particular reference to Central Europe. *Review of Palaeobotany and Palynology* 78: 41–54. DOI: [10.1016/0034-6667\(93\)90016-N](https://doi.org/10.1016/0034-6667(93)90016-N)
- Koestler, A.G. & Ehrmann, W.U., 1986. Fault patterns in the calcareous overburden of a salt diapir: Laegerdorf, NW Germany.

- Neues Jahrbuch für Geologie Und Paläontologie, Monatshefte 1986: 555-569. DOI: [10.1127/njgpm/1986/1986/555](https://doi.org/10.1127/njgpm/1986/1986/555)
- Koestler, A.G. & Ehrmann, W.U., 1991. Description of brittle extensional features in chalk on the crest of a salt ridge (NW Germany). In: Roberts, A.M., Yielding, G. & Freeman, B. (eds): The geometry of normal faults. Geological Society of London, Special Publications 56: 113-123. DOI: [10.1144/GSL.SP.1991.056.01.0](https://doi.org/10.1144/GSL.SP.1991.056.01.0)
- Kombrink, H., Ten Veen, J.H. & Geluk, M.C., 2012. Exploration in the Netherlands, 1987-2012. Netherlands Journal of Geosciences 91: 403-418. DOI: [10.1017/S0016774600000317](https://doi.org/10.1017/S0016774600000317)
- Kring, D.A., 2007. The Chicxulub impact event and its environmental consequences at the Cretaceous-Tertiary boundary. Palaeogeography, Palaeoclimatology, Palaeoecology 255: 4-21. DOI: [10.1016/j.palaeo.2007.02.037](https://doi.org/10.1016/j.palaeo.2007.02.037)
- Kuhnt, W., 1996. Early Danian benthic foraminiferal community structures, Geulhemmerberg, SE Netherlands. Geologie en Mijnbouw 75: 163-172.
- Kuyl, O.S., 1983. The inversion of part of the southern border of the Central Graben in South Limburg during the Late Cretaceous. Geologie en Mijnbouw 62: 401-408.
- Lagrou, D. & Dreesen, R., 2005. Kartering en karakterisering (sedimentpetrografisch en petrofysisch) van de Krijtgesteenten in Vlaanderen. VITO (Mol, Belgium), Report 2005/MAT/R/0216: 104 pp.
- Landman, N.H., Goolaerts, S., Jagt, J.W.M., Jagt-Yazykova, E.A., Machalski, M. & Yacobucci, M.M., 2014. Ammonite extinction and nautilid survival at the end of the Cretaceous. Geology 42: 707-710. DOI: [10.1130/G35776.1](https://doi.org/10.1130/G35776.1)
- Landman, N.H., Goolaerts, S., Jagt, J.W.M., Jagt-Yazykova, E.A. & Machalski, M., 2015. Ammonites on the brink of extinction: diversity, abundance, and ecology of the Order Ammonoidea at the Cretaceous/Paleogene (K/Pg) boundary. In: Klug, C., Korn, D., De Baets, K., Kruta, I. & Mapes, R.H. (eds): Ammonoid paleobiology: from macroevolution to paleogeography. Topics in Geology 44. Springer (Dordrecht): 497-553. DOI: [10.1007/978-94-017-9633-0_19](https://doi.org/10.1007/978-94-017-9633-0_19)
- Liebau, A., 1978. Paläobathymetrische und paläoklimatische Veränderungen im Mikrofaunenbild der Maasrichter Tuffkreide. Neues Jahrbuch für Geologie und Paläontologie - Abhandlungen 157: 233-237. DOI: [10.1127/njgpa/157/1978/233](https://doi.org/10.1127/njgpa/157/1978/233)
- Linnert, C., Robinson, S.A., Lees, J.A., Bown, P.R., Pérez-Rodríguez, I., Petrizzo, M.R., Falzoni, F., Littler, K., Arz, J.A. & Russell, E.E., 2014. Evidence for global cooling in the Late Cretaceous. Nature Communications 5: 4194. DOI: [10.1038/ncomms5194](https://doi.org/10.1038/ncomms5194)
- Linnert, C., Robinson, S.A., Lees, J.A., Pérez-Rodríguez, I., Jenkyns, H.C., Petrizzo, M.R., Arz, J.A., Bown, P.R. & Falzoni, F., 2018. Did Late Cretaceous cooling trigger the Campanian-Maastrichtian Boundary Event? Newsletters on Stratigraphy 51: 145-166. DOI: [10.1127/nos/2017/0310](https://doi.org/10.1127/nos/2017/0310)
- Luijendijk, E., Van Balen, R.T., Ter Voorde, M. & Andriessen, P.A.M., 2011. Reconstructing the Late Cretaceous inversion of the Roer Valley Graben (southern Netherlands) using a new model that integrates burial and provenance history with fission track thermochronology. Journal of Geophysical Research 116: B06402: 1-19. DOI: [10.1029/2010JB008071](https://doi.org/10.1029/2010JB008071)
- Machalski, M., 2005. Late Maastrichtian and earliest Danian scaphitid ammonites from central Europe: Taxonomy, evolution, and extinction. Acta Palaeontologica Polonica 50: 653-696.
- MacLeod, K.G., Isaza Londoño, C., Martin, E.E., Jiménez Berrocoso, A. & Basak, C., 2011. Changes in North Atlantic circulation at the end of the Cretaceous greenhouse interval. Nature Geoscience 4: 779-782. DOI: [10.1038/NGEO01284](https://doi.org/10.1038/NGEO01284)
- Martin, J.E., Case, J.A., Jagt, J.W.M., Schulp, A.S. & Mulder, E.W.A., 2005. A new European marsupial indicates a Late Cretaceous high-latitude transatlantic dispersal route. Journal of Mammalian Evolution 12: 495-511. DOI: [10.1007/s10914-005-7330-x](https://doi.org/10.1007/s10914-005-7330-x)
- Mitchell, S.F., 2019. The Chalk Group (Upper Cretaceous) of the Northern Province, eastern England – a review. Proceedings of the Yorkshire Geological Society 62: 153-177. DOI: [10.1144/pygs2017-010](https://doi.org/10.1144/pygs2017-010)
- Moorkens, T.L., 1982. Foraminifera of the Montian stratotype and of subjacent strata in the "Mons Well 1969" with a review of Belgian Paleocene stratigraphy. Mémoires pour servir à l'explication des Cartes géologiques et minières de la Belgique 17: 186 pp.
- Mortimore, R. & James, L., 2015. The search for onshore analogues for the offshore Upper Cretaceous Chalk of the North Sea. Proceedings of the Geologists' Association 126: 188-210. DOI: [10.1016/j.jpeola.2015.01.008](https://doi.org/10.1016/j.jpeola.2015.01.008)
- Mouriaux, P., 1998. Phénomènes de karstification dans le Calcaire grossier lutétien du nord de l'Île-de-France et de la Picardie. Mémoires des actes du 1er Congrès franco-belge de spéléologie (Fromelennes, Ardennes): 47-69.
- Mulder, E.W.A., 1999. Transatlantic latest Cretaceous mosasaurs (Reptilia, Lacertilia) from the Maastrichtian type area and New Jersey. Geologie en Mijnbouw 78: 281-300. DOI: [10.1023/A:1003838929257](https://doi.org/10.1023/A:1003838929257)
- Mulder, E.W.A., Jagt, J.W.M. & Stroucken, J.W., 2016. New records of latest Cretaceous neosuchian crocodyliforms from the Maastrichtian type area (southern Limburg, the Netherlands). In: Sullivan, R.M. & Lucas, S.G. (eds): Fossil Record 5. New Mexico Museum of Natural History and Science Bulletin 74: 169-172.
- Nalpas, T., 1994. Inversion des grabens du sud de la mer du Nord. Données de sub-surface et modélisation analogique. PhD thesis Université Rennes (France), Mémoires de Géosciences 71: 246 pp.
- Nalpas, T., Richert, J.-P., Brun, J.-P., Mulder, T. & Unternehr, P., 1996. Inversion du « Broad Fourteens Basin » ou Graben de La Haye (sud de la Mer du Nord) apport de la sismique 3D. Bulletin des Centres de Recherches Exploration-Production Elf Aquitaine 20: 309-321.
- Nederlandse Aardolie Maatschappij & Rijks Geologische Dienst, 1980. Stratigraphic Nomenclature of the Netherlands. Verhandeligen van Het Koninklijk Nederlands Geologisch Mijnbouwkundig Genootschap 32: 77 pp.

- Niebuhr, B., 2006. Multistratigraphische Gliederung der nord-deutschen Schreiekreide (Coniac bis Maastricht), Korrelation von Aufschlüssen und Bohrungen. *Zeitschrift der deutschen Gesellschaft für Geowissenschaften* 157: 245-262. DOI: [10.1127/1860-1804/2006/0157-0245](https://doi.org/10.1127/1860-1804/2006/0157-0245)
- Niebuhr, B., Hampton, M.J., Gallagher, L.T. & Remin, Z., 2011. Integrated stratigraphy of the Krons Moor section (northern Germany), a reference point for the base of the Maastrichtian in the Boreal Realm. *Acta Geologica Polonica* 61: 193-214.
- NITG-TNO, 1999. Geological atlas of the subsurface of the Netherlands (1 : 250,000) - Explanation to Map sheet XV: Sittard-Maastricht. Netherlands Institute of Applied Geoscience TNO - National Geological Survey (Utrecht): 127 pp.
- NITG-TNO, 2001. Geological Atlas of the subsurface of the Netherlands (1 : 250,000) - Explanation to Map Sheets XIII and XIV: Breda-Valkenswaard and Oss-Roermond + Map Sheet XIII and XIV. Netherlands Institute of Applied Geoscience TNO (NITG-TNO, Utrecht): 149 pp.
- NITG-TNO, 2002. Geological Atlas of the subsurface of the Netherlands (1 : 250,000) - Explanation to map sheets VII and VIII: Noordwijk-Rotterdam and Amsterdam-Gorinchem. Netherlands Institute of Applied Geoscience TNO - National Geological Survey (Utrecht): 135 pp.
- NITG-TNO, 2004. Geological Atlas of the subsurface of the Netherlands (1 : 250,000) - Explanation to map sheet IX: Harderwijk. Netherlands Institute of Applied Geoscience TNO - National Geological Survey (Utrecht): 123 pp.
- O'Brien, C.L., Robinson, S.A., Pancost, R.D., Sinninghe Damsté, J.S., Schouten, S., Lunt, D.J., Alsenz, H., Bornemann, A., Bottini, C., Brassell, S.C., Farnsworth, A., Forster, A., Huber, B.T., Inglis, G.N., Jenkyns, H.C., Linnert, C., Littler, K., Markwick, P., McAnena, A., Mutterlose, J., Naafs, B.D.A., Püttmann, W., Sluijs, A., Van Helmond, N.A.G.M., Vellekoop, J., Wagner, T. & Wrobel, N.E., 2017. Cretaceous sea-surface temperature evolution: constraints from TEX86 and planktonic foraminiferal oxygen isotopes. *Earth-Science Reviews* 172: 224-247. DOI: [10.1016/j.earscirev.2017.07.012](https://doi.org/10.1016/j.earscirev.2017.07.012)
- Petrea, C. & Goldberg, T., 2013. Sedimentology and petrography of chalk samples from well F17-10. PanTerra Geoconsultants B.V. (Leiderdorp) report: 23 pp.
- Pharaoh, T.C., Dusa, M., Geluk, M.C., Kockel, F., Krawczyk, C.M., Krzywiec, P., Scheck-Wenderoth, M., Thybo, H., Vejbaek, O.V. & Van Wees, J.D., 2010. Tectonic evolution. In: Doornenbal, J.C. & Stevenson, A.G. (eds): *Petroleum geological atlas of the Southern Permian Basin area*. EAGE Publications b.v. (Houten): 25-57.
- Phillips, G.E., Nyborg, T. & Vega, F.J., 2014. Icriocarcinidae: a family of portunoid crabs from the Upper Cretaceous of North America. *Paläontologische Zeitschrift* 88: 139-158. DOI: [10.1007/s12542-013-0190-4](https://doi.org/10.1007/s12542-013-0190-4)
- Pluymaekers, M.P.D., Kramers, L., Van Wees, J.-D., Kronimus, A., Nelskamp, S., Boxem, T. & Bonté, D., 2012. Reservoir characterisation of aquifers for direct heat production: Methodology and screening of the potential reservoirs for the Netherlands. *Netherlands Journal of Geosciences* 91: 621-636. DOI: [10.1017/S001677460000041X](https://doi.org/10.1017/S001677460000041X)
- Rademakers, P.C.M. (ed.), 1998. De prehistorische vuursteenmijnen van Ryckholt - St. Geertruid. Nederlandse Geologische vereniging afdeling Limburg (Beek): 333 pp.
- Remmelts, G., 1996. Salt tectonics in the southern North Sea, the Netherlands. In: Rondeel, H.E., Batjes, D.A.J. & Nieuwenhuijs, W.H. (eds): *Geology of gas and oil under the Netherlands*. Royal Geological and Mining Society of the Netherlands, Kluwer Academic Publishers (Dordrecht): 143-158. DOI: [10.1007/978-94-009-0121-6_13](https://doi.org/10.1007/978-94-009-0121-6_13)
- RGD, 1993. Geological atlas of the subsurface of the Netherlands (1 : 250,000). Explanation to map sheet V Sneek- Zwolle. Rijks Geologische Dienst (Haarlem): 127 pp.
- Rodet, J., 1992. La craie et ses karsts. Thèse d'Etat Centre Normand d'étude du karst et des cavités du sous-sol. In: Elbeuf & Groupe Seine-CNRS (Caen): 560 pp.
- Roep, T.B. & Smit, J., 1996. Sedimentological aspects of the K/T boundary at Geulhemmerberg, Zuid Limburg, the Netherlands. *Geologie en Mijnbouw* 75: 119-131.
- Romein, A.J.T., Willems, H. & Mai, H., 1996. Calcareous nanoplankton of the Geulhemmerberg K/T boundary section, Maastrichtian type area, the Netherlands. *Geologie en Mijnbouw* 75: 231-238.
- Sachs, S., Hornung, J.J. & Scheer, U., 2018. Mosasaurid and plesiosaurian remains from marginal facies of the lower Campanian (Upper Cretaceous) Bottrop and Vaals formations of western Germany. *Cretaceous Research* 87: 358-367. DOI: [10.1016/j.cretres.2017.05.026](https://doi.org/10.1016/j.cretres.2017.05.026)
- Schiøler, P., Brinkhuis, H., Roncaglia, L. & Wilson, G.J., 1997. Dinoflagellate biostratigraphy and sequence stratigraphy of the Type Maastrichtian (Upper Cretaceous), ENCI Quarry, The Netherlands. *Marine Micropaleontology* 31: 65-95. DOI: [10.1016/S0377-8398\(96\)00058-8](https://doi.org/10.1016/S0377-8398(96)00058-8)
- Schlanger, S.O. & Jenkyns, H.C., 1976. Cretaceous Oceanic Anoxic Events: causes and consequences. *Geologie en Mijnbouw* 55: 179-184.
- Schmitz, B., Keller, G. & Stenvall, O., 1992. Stable isotope and foraminiferal changes across the Cretaceous-Tertiary boundary at Stevns Klint, Denmark: Arguments for long-term oceanic instability before and after bolide-impact event. *Palaeogeography, Palaeoclimatology, Palaeoecology* 96: 233-260. DOI: [10.1016/0031-0182\(92\)90104-D](https://doi.org/10.1016/0031-0182(92)90104-D)
- Scholle, P.A., 1977. Chalk diagenesis and its relation to petroleum exploration: oil from chalks, a modern miracle? *American Association of Petroleum Geologists Bulletin* 61 (7): 982-1009. DOI: [10.1306/C1EA43B5-16C9-11D7-8645000102C1865D](https://doi.org/10.1306/C1EA43B5-16C9-11D7-8645000102C1865D)
- Schröder, A.E. & Surlyk, F., 2020. Adaptive brachiopod morphologies in four key environments of the Late Cretaceous-Danian Chalk Sea of northern Europe: A comparative study. *Cretaceous Research* 107: 104288. DOI: [10.1016/j.cretres.2019.104288](https://doi.org/10.1016/j.cretres.2019.104288)

- Schulp, A.S., Janssen, R., Van Baal, R.R., Jagt, J.W.M., Mulder, E.W.A. & Vonhof, H.B., 2017. Stable isotopes, niche partitioning and the paucity of elasmosaur remains in the Maastrichtian type area. *Netherlands Journal of Geosciences* 96: 29–33. DOI: [10.1017/njg.2016.20](https://doi.org/10.1017/njg.2016.20)
- Schulte, P., Alegret, L., Arenillas, I., Arz, J.A., Barton, P.J., Bown, P.R., Bralower, T.J., Christeson, G.L., Claey, P., Cockell, C.S., Collins, G.S., Deutsch, A., Goldin, T.J., Goto, K., Grajales-Nishimura, J.M., Grieve, R.A.F., Gulick, S.P.S., Johnson, K.R., Kiessling, W., Koeberl, C., Kring, D.A., MacLeod, K.G., Matsui, T., Melosh, J., Montanari, A., Morgan, J.V., Neal, C.R., Nichols, D.J., Norris, R.D., Pierazzo, E., Ravizza, G., Rebolledo-Vieyra, M., Reimold, W.U., Robin, E., Salge, T., Speijer, R.P., Sweet, A.R., Urrutia-Fucugauchi, J., Vajda, V., Whalen, M.T. & Willumsen, P.S., 2010. The Chicxulub asteroid impact and mass extinction at the Cretaceous–Paleogene boundary. *Science* 327: 1214–1218. DOI: [10.1126/science.1177265](https://doi.org/10.1126/science.1177265)
- Scotese, C.R., 2001. Atlas of earth history, volume 1: Paleogeography. PALEOMAP Project (Arlington, Texas, USA): 52 pp.
- Simon, E. & Owen, E.F., 2001. A first step in the revision of the genus *Cretirhynchia* Pettitt, 1950. *Bulletin de l'Institut royal des Sciences naturelles de Belgique, Sciences de la Terre* 71: 53–118.
- Skelton, P.W., Spicer, R.A., Kelley, S.P. & Gilmour, I., 2003. The Cretaceous world. The Open University, Cambridge University Press: 360 pp.
- Smit, F.W.H., 2018. Integrated seismic geomorphological analysis of syn- and post-depositional fluid migration features in the Chalk Group of the Danish North Sea. PhD thesis Technical University of Denmark: 161 pp.
- Smit, J. & Brinkhuis, H., 1996. The Geulhemmerberg Cretaceous/Tertiary boundary section (Maastrichtian type area, SE Netherlands); summary of results and a scenario of events. *Geologie en Mijnbouw* 75: 283–293.
- Smit, J. & Hertogen, J., 1980. An extraterrestrial event at the Cretaceous–Tertiary boundary. *Nature* 285: 198–200. DOI: [10.1038/285198a0](https://doi.org/10.1038/285198a0)
- Smit, J. & Zachariasse, W.J., 1996. Planktic foraminifera in the Cretaceous/Tertiary boundary clays of the Geulhemmerberg (Netherlands). *Geologie en Mijnbouw* 75: 187–191.
- 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](https://doi.org/10.1016/B978-0-12-824360-2.00028-0)
- Sprechmann, P., 1981. Paleocommunities and paleobathymetry of Maastrichtian sublittoral benthonic foraminifera from western Europe. *Neues Jahrbuch für Geologie und Paläontologie – Abhandlungen* 162: 188–230.
- Staring, W.C.H., 1860. De bodem van Nederland. De zamenstelling en het ontstaan der gronden in Nederland ten behoeve van het algemeen beschreven. Deel II. A.C. Kruseman (Haarlem): 480 pp.
- Surlyk, F. & Lykke-Andersen, H., 2007. Contourite drifts, moats and channels in the Upper Cretaceous chalk of the Danish Basin. *Sedimentology* 54: 405–422. DOI: [10.1111/j.1365-3091.2006.00842.x](https://doi.org/10.1111/j.1365-3091.2006.00842.x)
- Surlyk, F., Dons, T., Clausen, C.K. & Higham, J., 2003. Upper Cretaceous. In: Evans, D., Graham, C., Armour, A. & Bathurst, P. (eds): *The Millennium Atlas: Petroleum geology of the central and northern North Sea*. The Geological Society (London): 212–233.
- Surlyk, F., Damholt, T. & Bjerager, M., 2006. Stevns Klint, Denmark: Uppermost Maastrichtian chalk, Cretaceous–Tertiary boundary, and lower Danian bryozoan mound complex. *Bulletin of the Geological Society of Denmark* 54: 1–48. DOI: [10.37570/bgscd-2006-54-01](https://doi.org/10.37570/bgscd-2006-54-01)
- Surlyk, F., Kolbye Jensen, S. & Engkilde, M., 2008. Deep channels in the Cenomanian–Danian Chalk Group of the German North Sea sector: Evidence of strong constructional and erosional bottom currents and effect on reservoir quality distribution. *AAPG Bulletin* 92: 1565–1586. DOI: [10.1306/07100808035](https://doi.org/10.1306/07100808035)
- Surlyk, F., Rasmussen, S.L., Boussaha, M., Schiøler, P., Schovsbo, N.H., Sheldon, E., Stemmerik, L. & Thibault, N., 2013. Upper Campanian–Maastrichtian holostratigraphy of the eastern Danish Basin. *Cretaceous Research* 46: 232–256. DOI: [10.1016/j.cretres.2013.08.006](https://doi.org/10.1016/j.cretres.2013.08.006)
- Swennen, R. & Dusa, M., 1997. Diagenesis of Late Cretaceous to Paleocene carbonates in the Rur Valley Graben (Molenbeersel borehole, NE-Belgium). *Annales de la Société Géologique du Nord* 5: 215–226.
- Tsikos, H., Jenkyns, H.C., Walsworth-Bell, B., Petrizzo, M.R., Foster, A., Kolonic, S., Erba, E., Premoli Silva, I., Baas, M., Wagner, T. & Sinninghe Damsté, J.S., 2004. Carbon-isotope stratigraphy recorded by the Cenomanian–Turonian Oceanic Anoxic Event: correlation and implications based on three key localities. *Journal of the Geological Society, London* 161: 711–719. DOI: [10.1144/0016-764903-077](https://doi.org/10.1144/0016-764903-077)
- Umbgrove, J.H.F., 1925. Bijdrage tot de kennis der stratigraphie, tektoniek en petrographie van het Senoon in Zuid-Limburg. *Leidse Geologische Mededelingen* 1–1: 254–332.
- Van Adrichem Boogaert, H.A. & Kouwe, W.F.P., 1994. Stratigraphic nomenclature of the Netherlands, revision and update by RGD and NOGPA, Section H. Upper Cretaceous and Danian (Chalk Group). *Mededelingen Rijks Geologische Dienst* 50: 1–20.
- 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](https://doi.org/10.1016/j.quascirev.2004.01.011)
- Van Buchem, F.S.P., Smit, F.W.H., Buijs, G.J.A., Trudgill, B. & Larsen, P.-H., 2018. Tectonostratigraphic framework and depositional history of the Cretaceous–Danian succession of the Danish Central Graben (North Sea)—new light on a mature area. In: Bowman, M. & Levell, B. (eds): *Petroleum Geology*

- of NW Europe: 50 Years of Learning – Proceedings of the 8th Petroleum Geology Conference. Geological Society of London: 9-46. DOI: [10.1144/PGC8.24](https://doi.org/10.1144/PGC8.24)
- Van Dalfsen, W., Doornenbal, J.C., Dortland, S. & Gunnink, J.L., 2006. A comprehensive seismic velocity model for the Netherlands based on lithostratigraphic layers. *Netherlands Journal of Geosciences* 85: 277-292. DOI: [10.1017/S0016774600023076](https://doi.org/10.1017/S0016774600023076)
- Vandenbergh, N., Van Simaey, S., Steurbaut, E., Jagt, J.W.M. & Felder, P.J., 2004. Stratigraphic architecture of the Upper Cretaceous and Cenozoic along the southern border of the North Sea Basin in Belgium. *Netherlands Journal of Geosciences* 83: 155-171. DOI: [10.1017/S0016774600020229](https://doi.org/10.1017/S0016774600020229)
- Van der Ham, R.W.J.M., Jagt, J.W.M., Renkens, S. & Van Konijnenburg-van Cittert, J.H.A., 2010. Seed-cone scales from the upper Maastrichtian document the last occurrence in Europe of the Southern Hemisphere conifer family Araucariaceae. *Palaeogeography, Palaeoclimatology, Palaeoecology* 291: 469-473. DOI: [10.1016/j.palaeo.2010.03.017](https://doi.org/10.1016/j.palaeo.2010.03.017)
- Van der Molen, A.S., 2004. Sedimentary development, seismic stratigraphy and burial compaction of the Chalk Group in the Netherlands North Sea area. PhD thesis Utrecht University (the Netherlands): 175 pp.
- Van der Molen, A.S. & Wong, Th.E., 2007. Towards an improved lithostratigraphic subdivision of the Chalk Group in the Netherlands North Sea area – a seismic stratigraphic approach. *Netherlands Journal of Geosciences* 86: 131-143. DOI: [10.1017/S0016774600023131](https://doi.org/10.1017/S0016774600023131)
- Van der Molen, A.S., Dudok van Heel, H.W. & Wong, T.E., 2005. The influence of tectonic regime on chalk deposition: examples of the sedimentary development and 3D-seismic stratigraphy of the Chalk Group in the Netherlands offshore area. *Basin Research* 17: 63-81. DOI: [10.1111/j.1365-2117.2005.00261.x](https://doi.org/10.1111/j.1365-2117.2005.00261.x)
- Van der Voet, E., Heijnen, L. & Reijmer, J.J.G., 2018. Geological evolution of the Chalk Group in the northern Dutch North Sea: inversion, sedimentation and redeposition. *Geological Magazine* 156 (7): 1265-1284. DOI: [10.1017/S0016756818000572](https://doi.org/10.1017/S0016756818000572)
- Van Gent, H., Back, S., Urai, J.L. & Kukla, P., 2010. Small-scale faulting in the Upper Cretaceous of the Groningen block (The Netherlands): 3D seismic interpretation, fault plane analysis and regional paleostress. *Journal of Structural Geology* 32: 537-553. DOI: [10.1016/j.jsg.2010.03.003](https://doi.org/10.1016/j.jsg.2010.03.003)
- Van Lochem, H., 2018. F17-Chalk: new insights in the tectonic history of the Dutch Central Graben. In: Kilhams, B., Kukla, P.A., Mazur, S., McKie, T., Mijnlief, H.F. & Van Ojik, K. (eds): *Mesozoic resource potential in the southern Permian Basin*. Geological Society of London, Special Publications 469: 537-558. DOI: [10.1144/SP469.17](https://doi.org/10.1144/SP469.17)
- Van Lochem, H. & Beller, M., 2018. Maastrichtian chalk reservoir quality in the Rembrandt and Vermeer oilfields, Dutch offshore block F17. *First Break* 36: 60-63.
- Van Rooijen, P., 1989. Grondwater in Limburg. *Grondboor & Hamer* 43: 377-386.
- Van Wijhe, D.H., 1987a. Structural evolution of inverted basins in the Dutch offshore. *Tectonophysics* 137: 171-219. DOI: [10.1016/0040-1951\(87\)90320-9](https://doi.org/10.1016/0040-1951(87)90320-9)
- Van Wijhe, D.H., 1987b. The structural evolution of the Broad Fourteens Basin. In: Brooks, J. & Glennie, K. (eds): *Petroleum Geology of North-West Europe*. Proceedings of the Third Conference. Graham & Trotman (London): 315-323.
- Van Winden, M., De Jager, J., Jaarsma, B. & Bouroullec, R., 2018. New insights into salt tectonics in the northern Dutch offshore: a framework for hydrocarbon exploration. In: Kilhams, B., Kukla, P.A., Mazur, S., McKie, T., Mijnlief, H.F. & Van Ojik, K. (eds): *Mesozoic resource potential in the Southern Permian Basin*. Geological Society of London, Special Publications 469: 99-117. DOI: [10.1144/SP469.9](https://doi.org/10.1144/SP469.9)
- Vejbæk, O.V., Andersen, C., Duser, M., Herngreen, G.F.W., Krabbe, H., Leszczyński, K., Lott, G.K., Mutterlose, J. & Van der Molen, A.S., 2010. Cretaceous. In: Doornenbal, J.C. & Stevenson, A.G. (eds): *Petroleum geological atlas of the Southern Permian Basin area*. EAGE Publications B.V. (Houten): 195-209.
- Vellekoop, J., Sluijs, A., Smit, J., Schouten, S., Weijers, J.W.H., Sinninghe Damsté, J.S. & Brinkhuis, H., 2014. Rapid short-term cooling following the Chicxulub impact at the Cretaceous–Paleogene boundary. *Proceedings of the National Academy of Sciences* 111: 7537-7541. DOI: [10.1073/pnas.1319253111](https://doi.org/10.1073/pnas.1319253111)
- Vellekoop, J., Van Tilborgh, K.H., Van Knippenberg, P., Jagt, J.W.M., Stassen, P., Goolaerts, S. & Speijer, R.P., 2020. Type-Maastrichtian gastropod faunas show rapid ecosystem recovery following the Cretaceous–Palaeogene boundary catastrophe. *Palaeontology* 63: 349-367. DOI: [10.1111/pala.12462](https://doi.org/10.1111/pala.12462)
- Vellekoop, J., Kaskes, P., Sinnesael, M., Huygh, J., Déhais, T., Jagt, J.W.M., Speijer, R.P. & Claeys, P., 2022. A new age model and chemostratigraphic framework for the Maastrichtian type area (southeastern Netherlands, northeastern Belgium). *Newsletters on Stratigraphy* 55: 479-501. DOI: [10.1127/nos/2022/0703](https://doi.org/10.1127/nos/2022/0703)
- Verweij, H., 2006. Dual hydraulic behaviour of the Chalk in the Netherlands North Sea. *Journal of Geochemical Exploration* 89: 405-408. DOI: [10.1016/j.gexplo.2005.11.013](https://doi.org/10.1016/j.gexplo.2005.11.013)
- Villain, J.-M., 1977. Le Maastrichtien dans sa région type (Limbourg, Pays-Bas). *Étude stratigraphique et micropaléontologique*. *Palaeontographica* A157: 1-87.
- Vis, G.-J., Houben, A.J.P., Debacker, T.N. & Geel, C.R., 2025. The geological foundation of the Netherlands: the early Carboniferous, Devonian and older. 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): 53-93. DOI: [10.5117/9789463728362_ch04](https://doi.org/10.5117/9789463728362_ch04)
- Voigt, S., Wagreich, M., Surlyk, F., Walaszczyk, I., Uličný, D., Čech, S., Voigt, T., Wiese, F., Wilmsen, M., Niebuhr, B., Reich, M., Funk, H., Michalik, J., Jagt, J.W.M., Felder, P.J. & Schulp, A., 2008. Cretaceous. In: McCann, T. (ed): *The Geology of Central Europe*. Volume 2: Mesozoic and Cenozoic. The Geological Society of London: 923-997. DOI: [10.1144/CEV2P.3](https://doi.org/10.1144/CEV2P.3)

- Walaszczyk, I., Jagt, J.W.M. & Keutgen, N., 2010. The youngest Maastrichtian 'true' inoceramids from the Vijlen Member (Gulpen Formation) in northeast Belgium and the Aachen area (Germany). *Netherlands Journal of Geosciences* 89: 147-167. DOI: [10.1017/S0016774600000755](https://doi.org/10.1017/S0016774600000755)
- Wang, Y., Huang, C., Sun, B., Quan, C., Wu, J. & Lin, Z., 2014. Paleo-CO₂ variation trends and the Cretaceous greenhouse climate. *Earth-Science Reviews* 129: 136-147. DOI: [10.1016/j.earscirev.2013.11.001](https://doi.org/10.1016/j.earscirev.2013.11.001)
- Wang, Z., Bachmann, R. & Pipping, J.C.P., 2018. F17 chalk fracture model. 80th EAGE Conference and Exhibition 2018, Copenhagen, Denmark: European Association of Geoscientists & Engineers (EAGE). DOI: [10.3997/2214-4609.201801486](https://doi.org/10.3997/2214-4609.201801486)
- Welch, M.J., Souque, C., Davies, R.K. & Knipe, R.J., 2015. Using mechanical models to investigate the controls on fracture geometry and distribution in chalk. In: Agar, S.M. & Geiger, S. (eds): *Fundamental controls on fluid flow in carbonates: Current workflows to emerging technologies*. Geological Society of London, Special Publications 406: 281-309. DOI: [10.1144/SP406.5](https://doi.org/10.1144/SP406.5)
- Willems, L., Rodet, J., Fournier, M., Laignel, B., Dusar, M., Lagrou, D., Pouclet, A., Massei, N., Dussart-Baptista, L., Compère, P. & Ek, C., 2007. Polyphase karst system in Cretaceous chalk and calcarenite of the Belgian-Dutch border. *Zeitschrift für Geomorphologie* 51: 361-376. DOI: [10.1127/0372-8854/2007/0051-0361](https://doi.org/10.1127/0372-8854/2007/0051-0361)
- Wilmsen, M., Uličný, D. & Košťák, M., 2014. Cretaceous basins of central Europe: deciphering effects of global and regional processes – a short introduction. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften* 165: 495-499. DOI: [10.1127/1860-1804/2014/0088](https://doi.org/10.1127/1860-1804/2014/0088)
- Wilmsen, M., Engelke, J., Linnert, C., Mutterlose, J. & Niebuhr, B., 2019. A Boreal reference section revisited (Kronsmoor, northern Germany): high-resolution stratigraphic calibration of the Campanian-Maastrichtian boundary interval (Upper Cretaceous). *Newsletters on Stratigraphy* 52: 155-172. DOI: [10.1127/nos/2018/0473](https://doi.org/10.1127/nos/2018/0473)
- Witte, L. & Schuurman, H., 1996. Calcareous benthic foraminifera across the Cretaceous/Tertiary boundary in the Geulhemmerberg (SE Netherlands). *Geologie en Mijnbouw* 75: 173-186.
- Witte, L., Lissenberg, Th. & Schuurman, H., 1992. Ostracods from the Albian/Cenomanian boundary in the Achterhoek area (eastern part of the Netherlands). *Scripta Geologica* 102: 33-84.
- Worum, G. & Van Wees, J.-D., 2017. High-resolution quantitative reconstruction of Late Cretaceous–Tertiary erosion in the West Netherlands Basin using multi-formation compaction trends and seismic data: implications for geothermal exploration. *Acta Geodaetica et Geophysica*: 243-268. DOI: [10.1007/s40328-017-0196-6](https://doi.org/10.1007/s40328-017-0196-6)
- Ziegler, P.A., 1982. *Geological atlas of western and central Europe*. Shell Internationale Petroleum Maatschappij B.V. (The Hague), distributed by Elsevier (Amsterdam): 130 pp.
- Zijlstra, H.J.P., 1987. Early diagenetic silica precipitation, in relation to redox boundaries and bacterial metabolism, in late cretaceous chalk of the Maastrichtian type locality. *Geologie en Mijnbouw* 66 (4): 343-355.
- Zijlstra, J.J.P., 1994. *Sedimentology of the Late Cretaceous and Early Tertiary (Tuffaceous) chalk of northwest Europe*. PhD thesis Utrecht University (the Netherlands), *Geologica Ultraiectina* 119: 192 pp.
- Zijlstra, J.J.P., Brouwers, M.H.M.P., Brinkhuis, H. & De Boer, P.L., 1996. Microfacies analysis of Cretaceous/Tertiary boundary sections in the quarries Geulhemmerberg and Curfs, SE Netherlands. *Geologie en Mijnbouw* 75: 133-151.

