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Late Jurassic – Early Cretaceous

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ABSTRACT

The sedimentary and structural development in the Late Jurassic-Early Cretaceous period in the Netherlands is largely governed by the Late Cimmerian rift phase and the subsequent post-rift. The rifting affected the Dutch Central Graben in the northern offshore first. East-west extension during the Callovian and Oxfordian activated the faults and salt structures that bordered the existing Triassic graben structure and created accommodation space. The basin was filled with siliciclastic non-marine and marginal marine sediments, interrupted by thick and basin-wide coal seams at the Callovian-Oxfordian boundary. In the Kimmeridgian, the extension regime changed to NE-SW and provoked the reactivation of Paleozoic NW trending faults in the subsurface of the Netherlands. As a result, accommodation space was created in several other basins and thick stacks of sediments accumulated in the hanging walls of these faults. This continued throughout the latest Jurassic until the earliest Cretaceous when movement along the faults slowed down or stalled and footwall erosion occurred in many places. During the ensuing post-rift thermal sag phase, deposition extended outside the basins onto the bordering platforms but the basins remained the most active depocentres accumulating hundreds of metres of sediment up until the Aptian. In the Aptian and Albian, the formerly prevailing siliciclastic depositional systems were gradually replaced by carbonate-dominated systems. By that time, the vast majority of the Netherlands had become fully marine.

<< Shallow marine sandstone with large concretions of the Grès de la Crèche Formation at Cap Grix-Nez (northern France), equivalent to the Terschelling Sandstone Member in the Netherlands.
Photo: Bart van der Kwaak.

DOI: 10.5117/9789463728362_ch07

Introduction

Upper Jurassic and Lower Cretaceous rocks occur in large parts of the subsurface of the Netherlands both onshore and offshore, but apart from one location in the town of Losser, eastern Netherlands, outcrops are nowhere to be found. The geology of the Late Jurassic-Early Cretaceous is complex: no less than four groups, three subgroups, seventeen formations and sixty-one members have been defined within this time interval in the subsurface of the Netherlands (Van Adrichem Boogaert & Kouwe, 1993; Munsterman et al., 2012; see also Table 7.1). The main reason for this complexity is the fact that the Late Cimmerian rift phase led to the development of several sub-basins, each with its own tectonic development and depositional history (Coward et al., 2003; see also Fig. 7.1). Further complexity resulted from salt tectonics (Ten Veen et al., 2012; Bouroullec et al., 2018; Bouroullec & Ten Veen, 2025, this volume). The oldest sediments that can be attributed to the Late Cimmerian rift phase in the Netherlands are found in the offshore Dutch Central Graben and are of Middle Jurassic (Callovian) age. Because most of the Cimmerian rift phase took place during Late Jurassic and Early Cretaceous times, the short title of this chapter 'Late Jurassic-Early Cretaceous', although justified is not entirely correct. During the rift phase and shortly afterwards, the basins were filled with up to 2200 metres of siliciclastic sediments, sourced from the bordering platforms and structural highs (De Jager, 2007). All the while, Zechstein salt was being re-mobilized, faults were moving, volcanoes were active and the climate was changing from warm and wet to cooler and dry and back to wet again (Abbink et al., 2001a; Bouroullec & Ten Veen, 2025, this volume; De Jager et al., 2025, this volume; Van Bergen et al., 2025, this volume). This resulted in a wide array of different depositional environments: fluvial, lagoonal, lacustrine, marginal marine, shallow marine and deep marine. The Upper Jurassic-Lower Cretaceous deposits contain coal, oil and gas

Table 7.1. Hierarchically arranged Upper Jurassic-Lower Cretaceous lithostratigraphic units with generalized lithologies and depositional environments. For detailed descriptions and formal definitions the reader is referred to the online stratigraphic nomenclature: dinoloket.nl/en/stratigraphic-nomenclature. For an explanation of the abbreviations of basin names: see Fig. 7.1.

Lithostratigraphy	Lithology	Depositional environment	Basin	TMS
Rijnland Group				
Holland Formation	Marl, claystone and greensand	Open marine	**all**	**5**
Vlieland Claystone Formation	Claystone	Open marine	**all**	**4**
Vlieland Sandstone Formation	Sandstone	Coastal to offshore marine	**all**	**4**
Niedersachsen Group				
Coevorden Formation	Brownish-grey marly claystone	Lacustrine, restricted marine, lagoonal	**LSB**	**3**
Weiteveen Formation	Conglomerate, anhydritic marl, limestone	Estuarine, lacustrine, marginal marine	**LSB**	**2, 3**
Scruff Group				
Lutine Formation	Claystones and bituminous claystone	Open marine and restricted marine	**DCG, TB**	**3**
Scruff Greensand Formation	Bioturbated glauconitic sandstone	Shallow marine, shoreface	**DCG, TB**	**3**
Skylge Formation	Sandstone and claystone	Shallow marine and coastal	**DCG, TB**	**2**
Kimmeridge Clay Formation	Silty claystone with dolomite streak	Offshore distal marine	**DCG**	**1, 2**
Schieland Group, Delfland Subgroup				
Zurich Formation	Volcaniclastic, sandstone, claystone, coal	Lacustrine, coastal and deltaic	**all but LSB**	**2, 3**
Breeveertien Formation	Sandstone, siltstone, claystone and coal	Fluvial plain and coastal plain	**BFB**	**2, 3, 4**
Nieuwerkerk Formation	Sandstone, siltstone, claystone and coal	Fluvial plain and coastal plain	**WNB**	**2, 3, 4**
Schieland Group, Central Graben Subgroup				
Upper Graben Formation	Sandstone and coal	Deltaic	**DCG**	**1**
Middle Graben Formation	Sandstone, siltstone, claystone and coal	Deltaic	**DCG**	**1**
Lower Graben Formation	Sandstone, siltstone, claystone and coal	Fluvial plain and coastal plain	**DCG**	**1**
Puzzle Hole Formation	Carbonaceous claystone thin sandstone	Deltaic	**DCG**	**1**
Friese Front Formation	Claystone, siltstone and sandstone	Fluvial plain	**DCG, TB**	**1, 2**
Igneous rock group (inf.)				
Zuidwal Volcanic Formation	Massive volcanic rock and brecciated volcanic agglomerate	N/A	**VB**	N/A

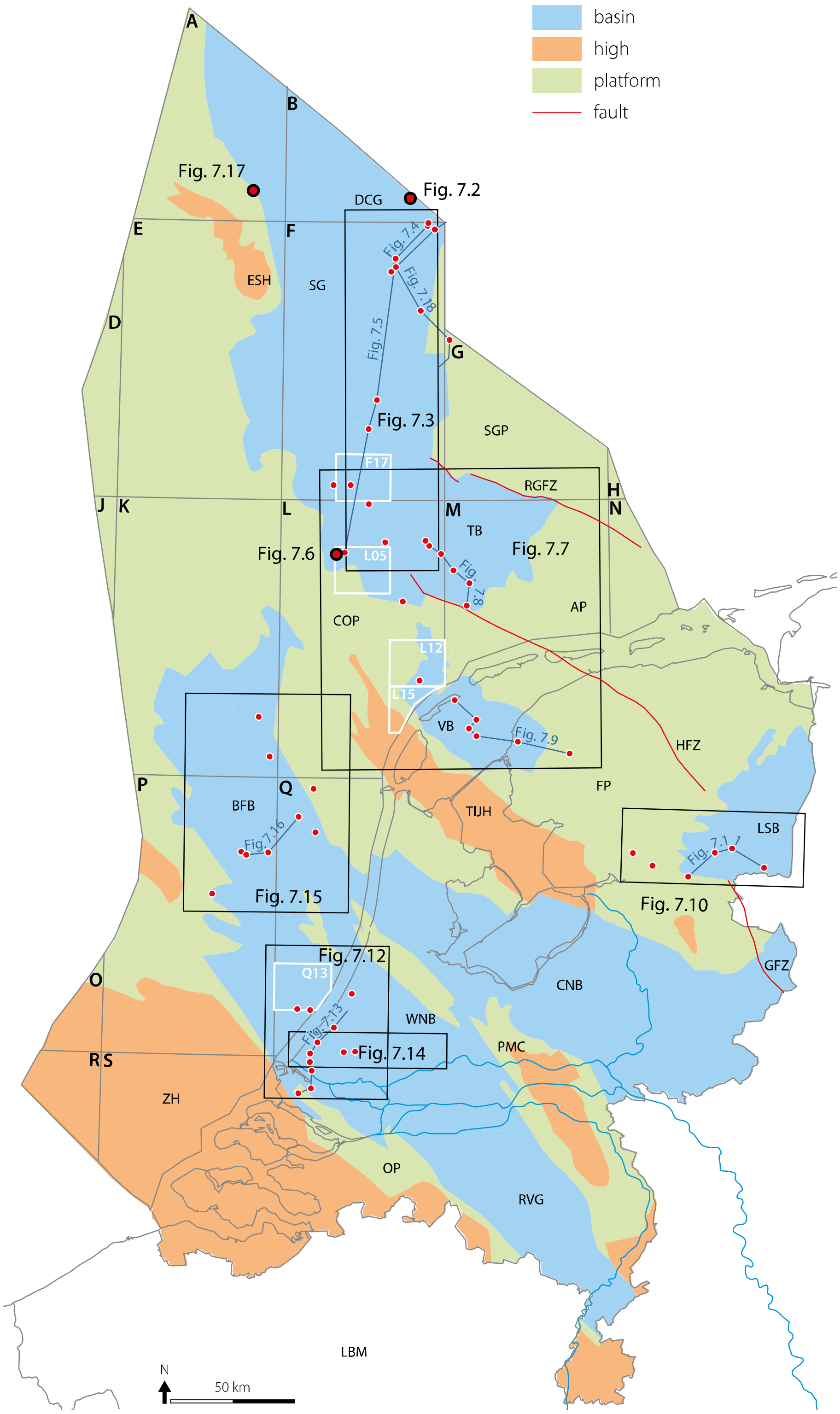


Figure 7.1. Map of the Dutch on- and offshore displaying the structural elements. The structural elements are after Kombrink et al. (2012). Basins: BFB = Broad Fourteens Basin, CNB = Central Netherlands Basin, DCG = Dutch Central Graben, LSB = Lower Saxony Basin, SG = Step Graben, TB = Terschelling Basin, VB = Vlieland Basin, WNB = West Netherlands Basin. Highs: ESP = Elbow Spit High, LBM = London-Brabant Massif, TIJH = Texel-IJsselmeer High, PMC = Peel-Maasbommel Complex, ZH = Zeeland High. Platforms: AP = Ameland Platform, COP = Central Offshore Platform FP = Friesland Platform, OP = Oosterhout Platform. Fault Zones: RGFZ = Rifgronden Fault Zone, HFZ = Hantum Fault Zone, GFZ = Gronau Fault Zone. Thin lines with small red bullets indicate the position of well correlation panels as shown in the indicated figures. Boxes with figure numbers show the area with Wheeler diagrams for the Dutch Central Graben, Terschelling, Vlieland, Broad Fourteens, West Netherlands and the Lower Saxony basins. Large red bullets indicate the position of wells for which core material is shown in the corresponding figures.

and have therefore been explored for these resources since the early 1960s. Most of the present-day knowledge is obtained from hydrocarbon exploration. From 2007 onward, geological characterization for geothermal energy in the Netherlands has taken off and this has resulted in renewed research activity on the Late Jurassic-Early Cretaceous interval of the onshore.

Many aspects of the Late Jurassic-Early Cretaceous geology of the Netherlands have been documented in the chapters on the Jurassic (Wong, 2007) and Cretaceous (Herngreen & Wong, 2007) in the previous edition of Geology of the Netherlands. The most comprehensive account, still very useful today, is in Van Adrichem Boogaert and Kouwe (1993). The lithostratigraphy of the interval established in Van Staalduinen et al. (1979) and Van Adrichem Boogaert and Kouwe (1993) was updated in Munsterman et al. (2012). Results of geological mapping programs were published in Duin et al. (2006) and Kombrink et al. (2012) and recent seismic intrepretation, biostratigraphic analyses, stratigraphic correlation, structural analyses and mapping results were published by Bouroullec et al. (2018), and Verreussel et al. (2018), who provide a robust tectonostratigraphic framework of the rift basins in the northern Dutch offshore.

The regional geology of the Late Jurassic-Early Cretaceous is documented in atlasses such as the Millennium Atlas (Evans et al., 2003) and the Southern Permian Basin Atlas (Doornenbal & Stevenson, 2010). Fraser et al. (2003) and Copestake et al. (2003) provided a comprehensive account of the petroleum geology of the Late Jurassic and Early Cretaceous from the central and northern North Sea and Coward et al. (2003) and Zanella and Coward (2003) described the tectonic evolution and structural framework in detail. Lott et al. (2010) and Vejbæk et al. (2010) discussed the regional development of the Jurassic to Cretaceous of the Southern Permian Basin, stretching from southeast England to Poland, while the geology of the Danish Jurassic was dealt with extensively in a series of papers in a special publication of the Geological Survey of Denmark and Greenland: Andsbjerg (2003), Andsbjerg & Dybkjaer (2003), Johannessen (2003). Verreussel et al. (2018) described the stepwise basin evolution during the Late Jurassic-Early Cretaceous and linked the geology of the Danish Upper Jurassic-Lower Cretaceous to that of the Dutch Central Graben. Jeremiah et al. (2010) provided a sequence stratigraphic framework and paleogeographic maps of the Lower Cretaceous from the southern North Sea and Patruno et al. (2021) integrated the stratigraphy of the entire northern, central and southern North Sea in a tectonostratigraphic framework. Another tectonostratigraphic framework was provided by Van Buchem et al. (2018), who described the depositional history of the Cretaceous-Danian of the Danish Central Graben in detail and compared it to that in the German and Dutch offshore sectors. Recently, publications on the geology of the German sector appeared, for example Arfai et al. (2014), Arfai & Lutz (2018) and Müller et al. (2023).

The role of salt movement in the depositional history of the Dutch Central Graben and surrounding areas has become much clearer in recent years with the recognition of e.g. turtle structures in the Dutch Central Graben and adjacent areas (Ten Veen et al., 2012; Bouroullec et al., 2018; Van Winden et al., 2018; Bouroullec & Ten Veen, 2025, this volume).

Publications focusing on biostratigraphy are primarily based on palynology: Abbink (1998); Abbink et al. (2001a, 2006); Herngreen and Wong (1989), Herngreen et al. (2000) and Verreussel et al. (2018), a Late Jurassic-Early Cretaceous ostracod stratigraphy was established in Witte and Lissenberg (1994), while nannofossil stratigraphy combined with palynology was established for the Late

Figure 7.2. *Photographs of macrofossils from the cored interval 2242-2260 m of well B18-02, northern part of the Dutch Central Graben. The cored section is part of the stratotype section (2225-2315 m) of the late Ryazanian Lutine Formation (Munsterman et al., 2012). a) Core piece from a depth of 2247.95 m showing the ammonite* Lynnia icenii *and the bivalve* Buchia volgensis *from the late Ryazanian icenii ammonite zone (from Janssen et al., 2022). b) Core piece from a depth of 2256.73 m showing two well-preserved specimens of the bivalve* Buchia volgensis *(from Janssen et al., 2022). Core diameter approximately 75 mm.*

Jurassic-Early Cretaceous of the West Netherlands Basin by Jeremiah et al. (2010). Rare ammonite occurrences in the Upper Jurassic-Lower Cretaceous strata of the Netherlands are described in Abbink et al. (2001a) and Janssen et al. (2022; see also Fig. 7.2)

Key publications dealing with geological aspects of the Late Jurassic-Early Cretaceous are often only limited to one of the Dutch sub-basins and include: Geluk et al. (1995) on the Roer Valley Graben, Den Hartog Jager (1996), DeVault and Jeremiah (2002), Donselaar et al. (2015), Racero-Baena and Drake (1996), Vondrak et al., (2018), Willems et al. (2017a,b,c), Willems et al. (2020); Mijnlieff (2020) on the West Netherlands Basin, Abbink et al. (2006); Bouroullec et al. (2018) on the Dutch Central Graben, Step Graben and Terschelling Basin, Abbink et al. (2001a) on the Terschelling Basin; Beha et al. (2008); Best et al. (1983) on the Horn Graben, Wolf et al. (2018) and Heim et al. (2013) on the Schill Grund Platform, Herngreen et al. (1991), on the Vlieland Basin and Vis et al. (2018) and Rutten et al. (2020) on the Lower Saxony Basin.

Publications focusing on petroleum geological aspects of the Late Jurassic-Early Cretaceous are De Jager et al. (1996), Verweij and Simmelink (2002), De Jager and Geluk (2007), and Doornenbal et al. (2019).

Regional setting

Tectonics

The assembly of Pangea in the Paleozoic was followed by Mesozoic break-up and the development of a large rift system in Northwest Europe (Ziegler, 1990a,b; Coward et al., 2003; Zanella & Coward, 2003). Rifting started in the Middle Triassic and resulted in large and relatively wide graben structures in the North Sea and in the Norwegian Sea that were filled with predominantly non-marine sediments (Geluk, 2007; McKie & Kilhams, 2025, this volume). During Triassic rifting, salt from the Zechstein became mobile and started to influence deposition of synrift sequences in the Netherlands (De Jager, 2007; Bouroullec & Ten Veen, 2025, this volume). After a period of relative quiescence, most rift structures were blanketed with fine-grained sediments of the Lower Jurassic Altena Group (Trabucho Alexandre & Wong, 2025, this volume). During much of the Middle Jurassic, thermal doming in the North Sea affected large areas of the Dutch onshore and offshore causing regional uplift and erosion (Underhill & Partington, 1993; Husmo et al., 2003), but deposition continued in the West Netherlands Basin as it was too far away from the thermal dome area to be affected (Wong, 2007).

By Late Jurassic-Early Cretaceous times, rifting resumed in the entire North Sea area. This phase, known as the late Cimmerian rift phase (Kombrink et al., 2012) ceased in the Early Cretaceous and never developed into ocean spreading in the North Sea area (Coward et al., 2003). A failed rift complex was established in the region, comprising three branches that diverge from a triple junction in the central North Sea (Zanella et al., 2003). The southernmost branch, referred to as the Central Graben, runs across the Danish and German offshore into the Dutch offshore where it terminates against the Central Offshore Platform in the L05 block (Bouroullec et al., 2018; Verreussel et al., 2018). The Late Cimmerian rift phase developed in discrete steps, which are related to changes in the tectonic regime. In the late Kimmeridgian, the extensional regime changed from E-W towards NE-SW, related to the opening of the North-East Atlantic (Zanella et al., 2003). This long-field change in the tectonic regime had a profound impact on the evolution of the Mesozoic basins in the North Sea area. In the Netherlands and Denmark for example, basins that inherited a NW-SE early Paleozoic structural grain became active and started to accumulate thick sequences of Upper Jurassic-Lower Cretaceous deposits (Verreussel et al., 2018). This phase was characterized by active faulting and, where Zechstein salt was present by halokinesis. Deep water sediments of e.g. the Kimmeridge Clay and Farsund formations occur in large parts of the Central Graben, including the Dutch Central Graben. The phase of maximum rift activity was succeeded by a phase of transition and readjustment at the Jurassic-Cretaceous boundary (late Volgian and Ryazanian). During this transitional phase, fault movement decreased, shoulders of rotated fault blocks were eroded and the remaining depocentres were filled up to sea level and rifting came to an end. This phase is characterized by widespread erosion, which led to hiatuses and unconformities. Subsidence however, continued in most basins due to thermal sag and thick accumulations of marine shales and shoreface complexes developed during the Valanginian to Barremian post-rift sag phase.

The Late Cimmerian rift phase was accompanied by active volcanism. Tuffaceous deposits occur in the Dutch Central Graben and the Vlieland, Broad Fourteens and West Netherlands basins, but not in the Lower Saxony Basin (Van Bergen et al., 2025, this volume). On seismic images, two structures have been unambiguously identified as volcanoes, one named Mulciber in block F16 (Bouroullec et al., 2016b , Vis, 2020; Van Bergen et al., 2025, this volume) in the Dutch Central Graben, the other named Zuidwal in the Vlieland Basin (Van Bergen et al., 2025, this volume). The latter volcano was discovered during exploration for oil and gas, well Zuidwal-1 (ZDW-01) having drilled right into the volcanic conduit (Van Bergen & Sissingh, 2007). Volcanism peaked in the Volgian-Ryazanian in the north and in the Valanginian-Hauterivian in the south (Van Bergen et al., 2025, this volume).

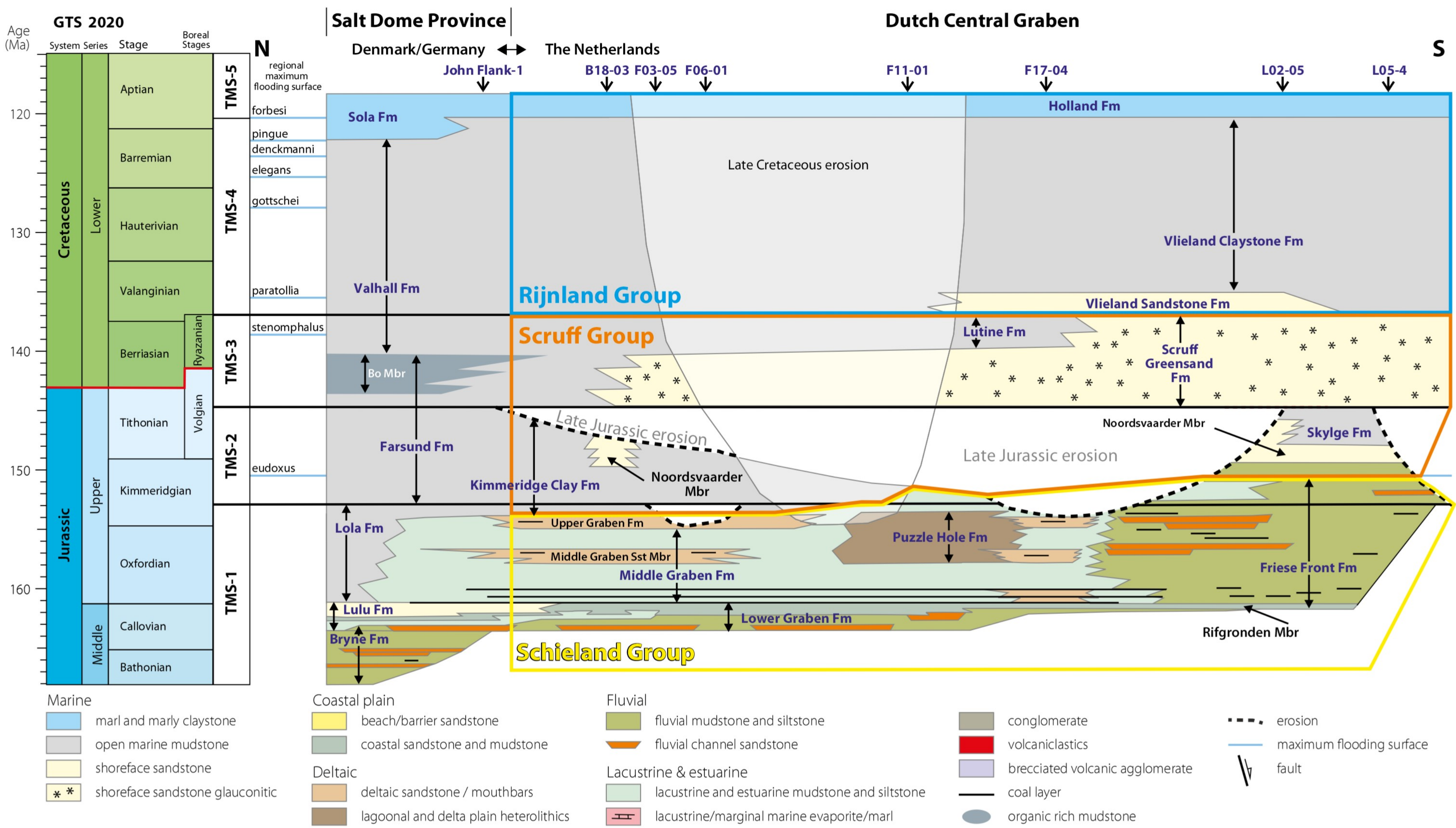


Figure 7.3. *Wheeler diagram along a N-S transect through the axis of the Dutch Central Graben and the southern tip of the Danish Salt Dome Province (see Fig. 7.1 for location). The diagram displays the generalized time and facies relationships of the Bathonian (Middle Jurassic) to Aptian (Lower Cretaceous) lithostratigraphic units. Formation names are indicated in blue, member names in black and lithostratigraphic groups are outlined in yellow, orange and blue. Relevant maximum flooding surfaces are displayed with blue lines. The black horizontal lines indicate tectonostratigraphic megasequences (TMS, see text for explanation). Key wells are shown at the top of the diagram.*

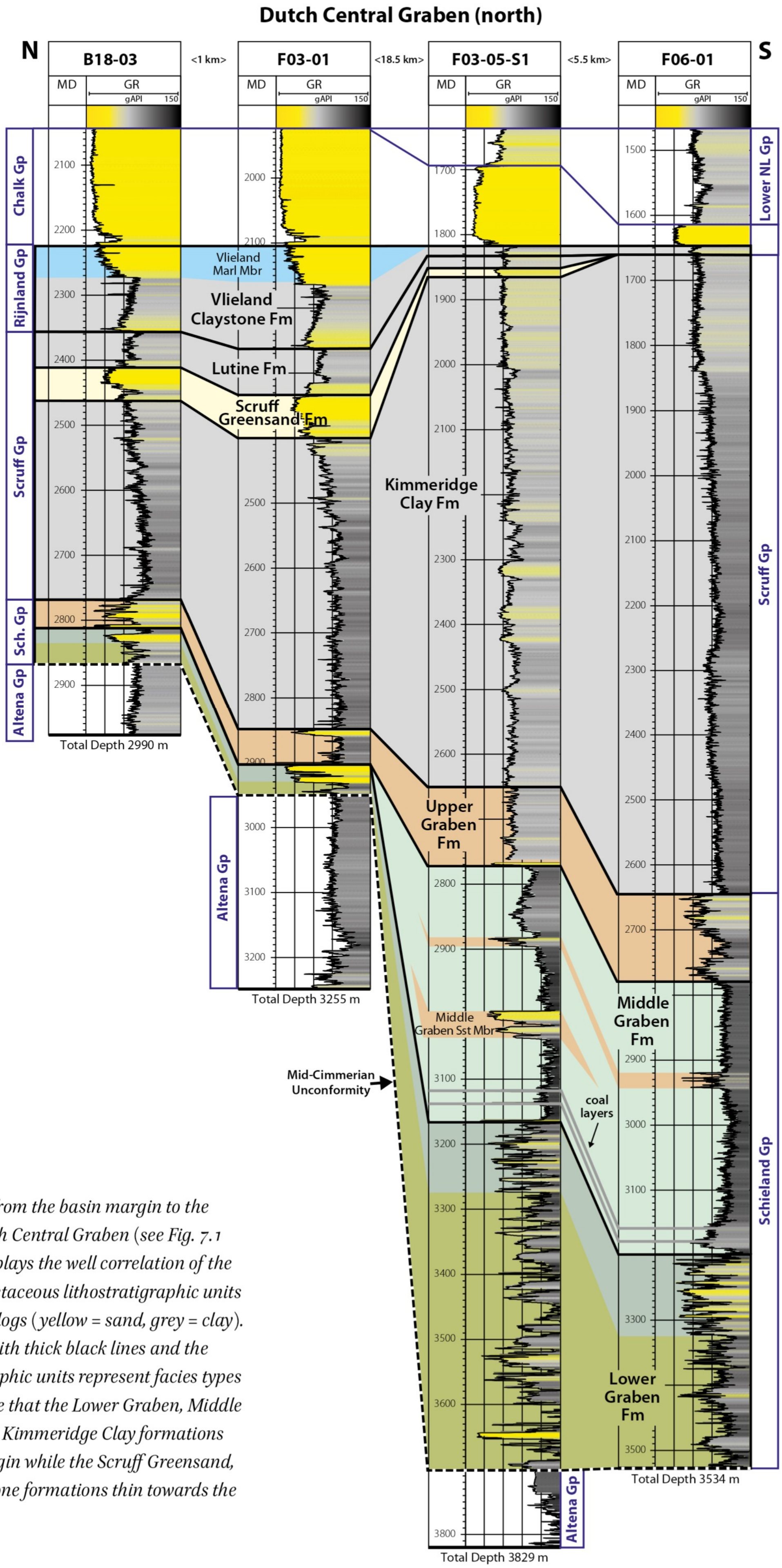


Figure 7.4. *N-S well panel from the basin margin to the centre of the northern Dutch Central Graben (see Fig. 7.1 for location). The panel displays the well correlation of the Upper Jurassic to Lower Cretaceous lithostratigraphic units based on gamma-ray (GR) logs (yellow = sand, grey = clay). Formations are indicated with thick black lines and the colours of the lithostratigraphic units represent facies types (see legend of Fig. 7.3). Note that the Lower Graben, Middle Graben, Upper Graben and Kimmeridge Clay formations thin towards the basin margin while the Scruff Greensand, Lutine and Vlieland Claystone formations thin towards the basin centre.*

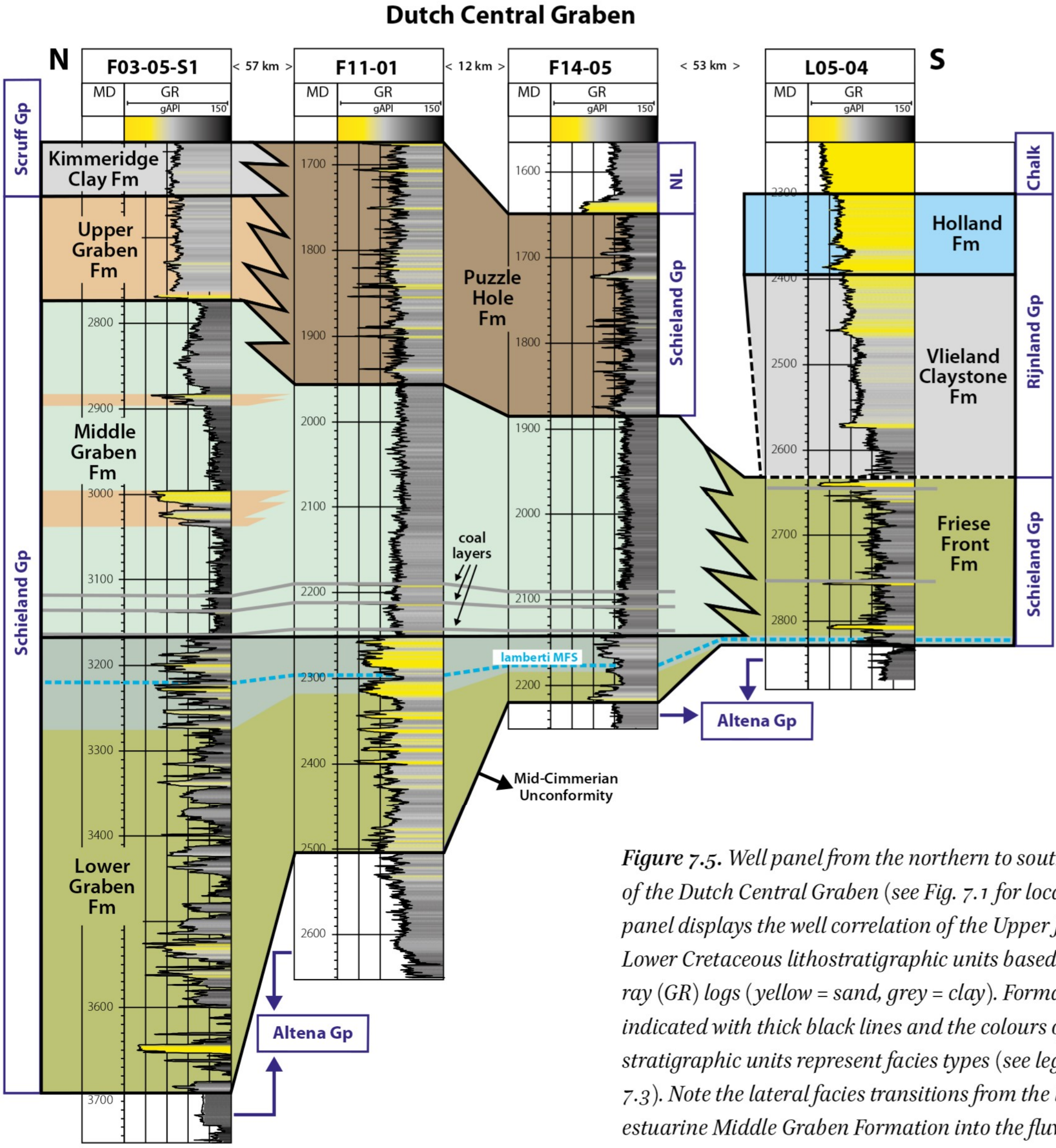


Figure 7.5. Well panel from the northern to southern part of the Dutch Central Graben (see Fig. 7.1 for location). The panel displays the well correlation of the Upper Jurassic to Lower Cretaceous lithostratigraphic units based on gamma-ray (GR) logs (yellow = sand, grey = clay). Formations are indicated with thick black lines and the colours of the lithostratigraphic units represent facies types (see legend of Fig. 7.3). Note the lateral facies transitions from the lacustrine/estuarine Middle Graben Formation into the fluvial Friese Front Formation and from the open marine Kimmeridge Clay Formation into the deltaic Puzzle Hole Formation. Also note the continuity of the three coal layers at the base of the Middle Graben Formation. NL = Lower North Sea Group.

Late Jurassic-Early Cretaceous basins

In the Netherlands, nine basins contain Upper Jurassic-Lower Cretaceous strata (Fig. 7.1). Four basins are located in the Dutch offshore: the Step Graben, the Dutch Central Graben, the Terschelling Basin and the Broad Fourteens Basin. Three basins are located onshore: the Lower Saxony Basin, the Central Netherlands Basin and the Roer Valley Graben, while the Vlieland and West Netherlands basins extend from the onshore into the offshore (Fig. 7.1). Each of the nine basins displays a distinct stratigraphy and basin fill history, but overall the basins share large scale eustatic, climatic and tectonic evolutionary trends.

The Dutch Central Graben

The Dutch Central Graben is located in the northern Dutch offshore (Fig. 7.1) and runs from the B quadrant through the F quadrant to the L quadrant, where it terminates against the Central Offshore Platform. It forms the southernmost extension of the Late Jurassic rift that runs from the Viking Graben in the northern North Sea via the Tail End Graben in the Danish offshore and the German Central Graben, to the Dutch Central Graben. The structural grain of the basin is inherited from Triassic graben structures and is narrow and elongated (40 by 160 km), bounded by N-S trending faults. These faults originated in the Triassic and are associated with salt diapirs and salt walls (Bouroullec & Ten Veen, 2025, this volume) that had a major impact on the structural style and sedimentary fill of the basin. The importance of salt tectonics in the evolution of the Dutch Central Graben is expressed by the widespread occurrence of turtle structures and rim synclines (Bouroullec et al., 2018; Bouroullec & Ten Veen, 2025, this volume). Sediments from the entire Late Jurassic-Early Cretaceous interval are represented in the stratigraphic record of the basin, in the form of non-marine, estuarine and deltaic deposits of the Schieland Group (Central Graben Subgroup), marine deposits of the Scruff Group and open marine deposits of the Rijnland Group (Figs 7.3-7.5). Claystones of the Altena Group, including the Posidonia Shale Formation, subcrop underneath the Upper Jurassic (Kombrink et al., 2012; see also Fig. 7.6), while the overlying Upper Cretaceous Chalk Group is very thin or absent due to mild inversion during the Late Cretaceous.

The Step Graben

The Step Graben (SG) is situated in the northern Dutch offshore along the western side of the Dutch Central Graben (Fig. 7.1). Despite its name and in contrast to the Dutch Central Graben, it never developed into an actively subsiding basin during the Late Jurassic-Early Cretaceous and should be considered a platform area instead. The basin configuration was inherited from the Triassic early rifting expressed by N-S trending salt structures and faults (Kombrink et al., 2012; Bouroullec & Ten Veen, 2025, this volume). The Step Graben terminates against the El-

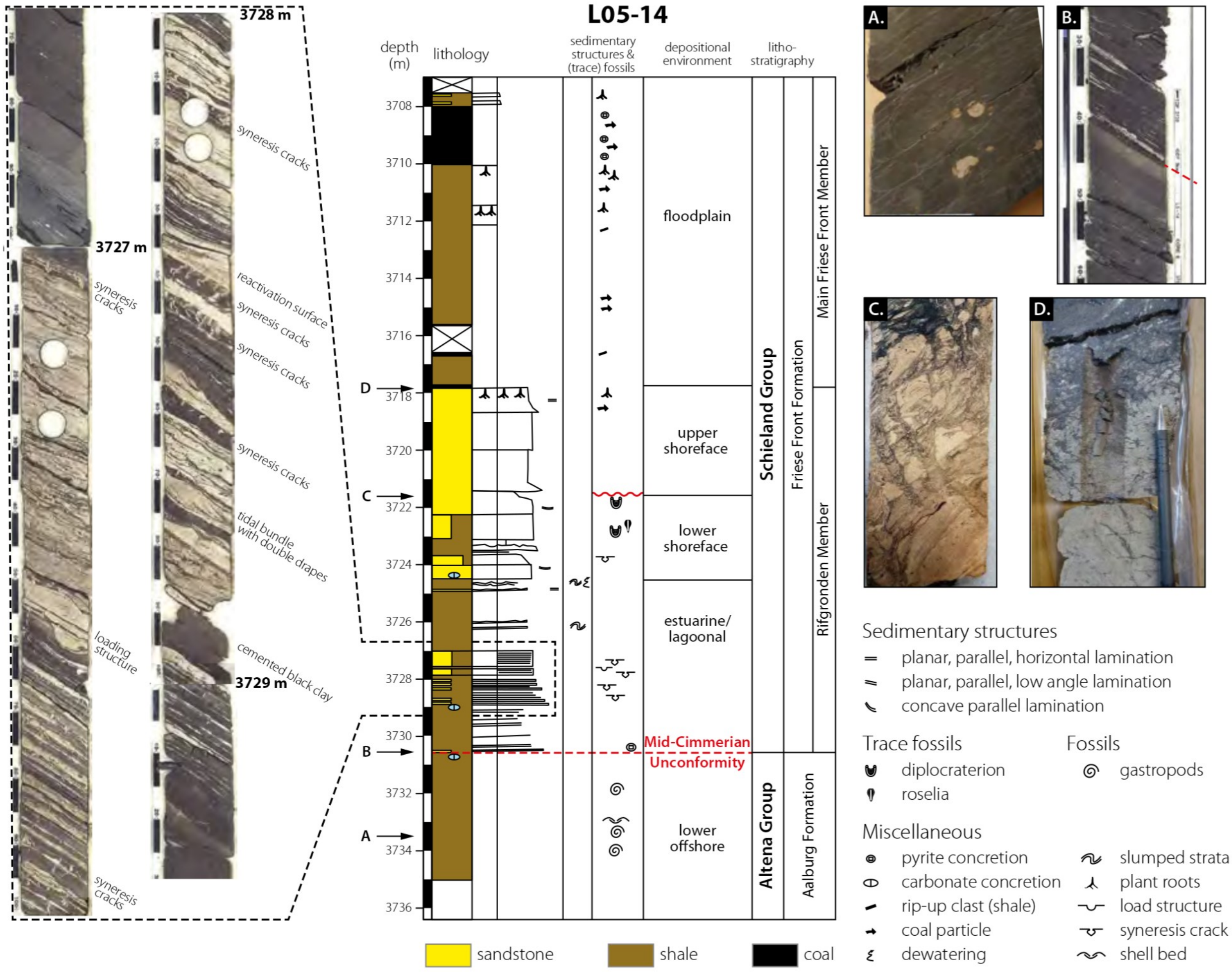


Figure 7.6. Lithological log of the cored interval 3608-3735 m of well L05-14 from the southern part of the Dutch Central Graben. The log displays the lithology, the observed sedimentary structures, the interpreted paleoenvironment and the lithostratigraphy. The far left shows a core photograph of interval 3726.65-3729.30 m with sedimentary structures annotated. To the right, more detailed core sections are shown (a-d) and their positions are indicated on the left-hand side of the lithological log. a) Cored section from a depth of 3733.6 m showing gastropod fossils within a matrix of laminated claystones from the Altena Group, b) Cored section showing the Mid-Cimmerian unconformity, indicated with a red dashed line at 3730.36 m. The unconformity separates the latest Callovian Rifgronden Member of the Friese Front Formation from the Lower Jurassic (Toarcian or older) Aalburg Formation of the Altena Group (see Trabucho-Alexandre & Wong, 2025, this volume), c) Core piece from a depth of 3721.5 m showing Diplocraterion ichnofossils. The vertical U-shaped burrows are characteristic for upper shoreface paleoenvironments, d) Core piece from a depth of 3717.9 m showing traces of plant rootlets. The rootlets indicate a transition from a marine upper shoreface paleoenvironment to a non-marine vegetated floodplain paleoenvironment.

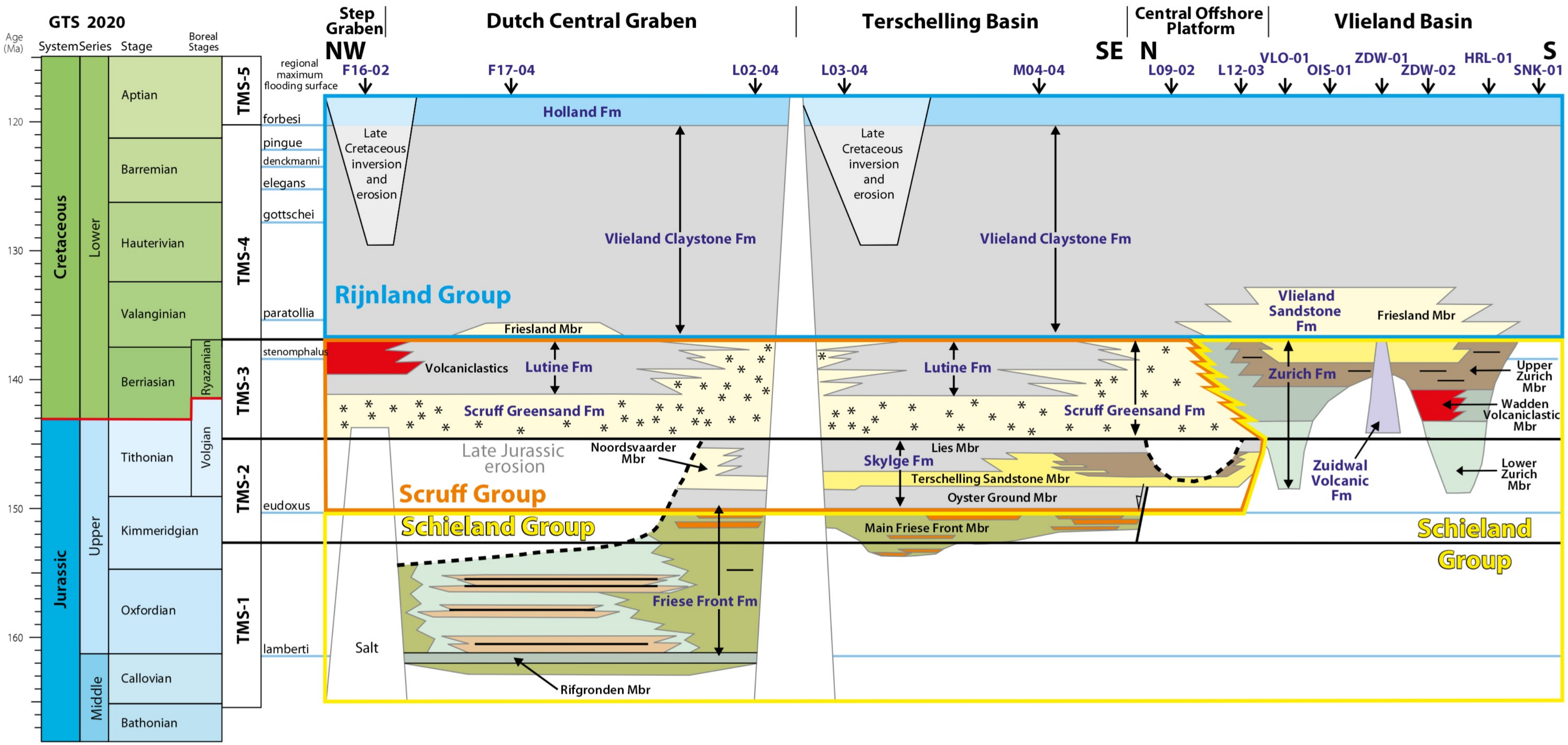


Figure 7.7. Wheeler diagram along a NW-SE transect through the southern Dutch Central Graben, the Terschelling Basin and the Vlieland Basin (see Fig. 7.1 for location). The diagram displays the generalized time and facies relationships of the Callovian (Middle Jurassic) to Aptian (Lower Cretaceous) lithostratigraphic units. Formation names are indicated in blue, member names in black and lithostratigraphic groups are outlined in yellow, orange and blue. Relevant maximum flooding surfaces are displayed with blue lines. The black horizontal lines indicate tectonostratigraphic megasequences (TMS, see text for explanation). Key wells are shown at the top of the diagram. For legend see Fig. 7.3.

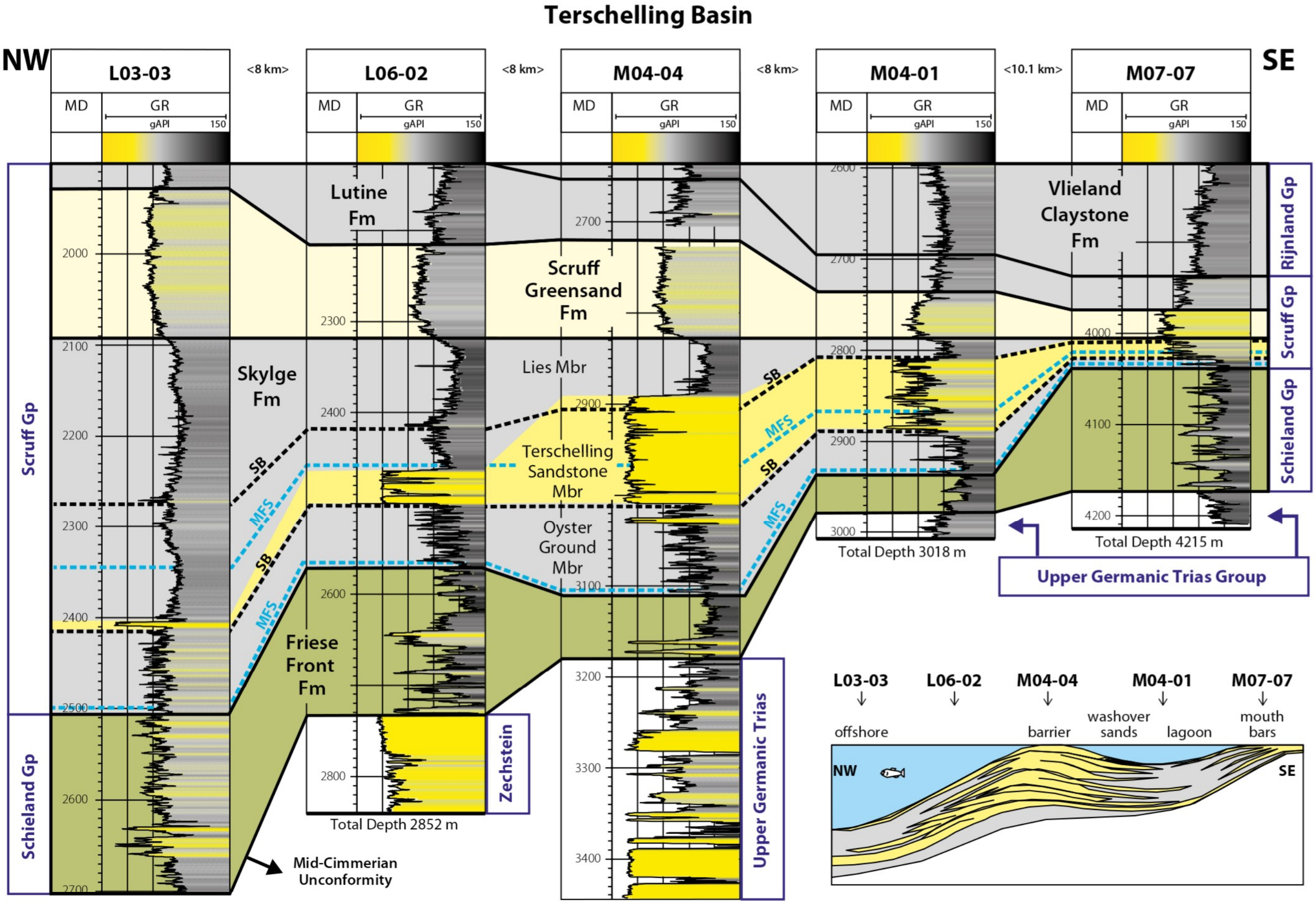


Figure 7.8. *NW-SE well panel through the Terschelling Basin (see Fig. 7.1 for location). The panel displays the well correlation of the Upper Jurassic to Lower Cretaceous lithostratigraphic units based on gamma-ray (GR) logs (yellow = sand, grey = clay). Formations are indicated with thick black lines and the colours of the lithostratigraphic units represent facies types (see legend of Fig. 7.3). The blue dashed lines represent maximum flooding surfaces (MFS) and the black dashed lines represent sequence boundaries (SB). The thick amalgamated sandstones of the Terschelling Sandstone Member in M04-04 are interpreted as a stacked shoreface succession, possibly representing a coastal barrier system. Towards the northwest, the upper part of the Terschelling Member shales out rapidly. Towards the southwest, the spikey gamma-ray trend of well M04-04 is interpreted as a heterolithic back-barrier lagoonal succession (see inset diagram).*

bow Spit High to the west and is connected to the Outer Rough Basin in the Danish offshore (Japsen et al., 2003) via the German Entenschnabel area (Müller et al., 2023). The Upper Jurassic-Lower Cretaceous sedimentary cover is thin due to a combination of limited accommodation space and erosion on the shoulders of the main rift system. The overlying Chalk Group is very thick (Van der Molen, 2004) because the Step Graben was not inverted during the Late Cretaceous. Below the Upper Jurassic-Lower Cretaceous, a relatively thin Upper Germanic Trias Group and a relatively thick Lower Germanic Trias Group are present (Kombrink et al., 2012). The Late Jurassic-Early Cretaceous Kimmeridgian to Ryazanian time interval is mainly represented by the Scruff Greensand and Lutine formations of the Scruff Group (Verreussel et al., 2015) with occasional presences of the Skylge Formation (Fig. 7.7).

The Terschelling Basin

The Terschelling Basin is situated in the northern L and M quadrants of the Dutch offshore (Fig. 7.1). The WNW-ESE basin trend is inherited from the middle Paleozoic (Wong, 2007). The Terschelling basin is bounded by two major fault systems; to the north by the Rifgronden Fault Zone and to the south by the Hantum Fault Zone (Duin et al., 2006; Fig. 7.1). The depocentre lies in the west, where the basin connects to the southern part of the Dutch Central Graben via a complex salt structure (Bouroullec et al., 2016a; see also Fig. 7.7). The basin is dissected by a number of NNE-SSW trending salt structures (McKie & Kilhams, 2025, this volume) and is mostly filled with sediments of late Kimmeridgian to Ryazanian age, consisting of non-marine deposits of the Schieland Group and marine deposits of the Scruff Group and the Rijnland Group (Figs 7.7, 7.8). Upper and Lower Germanic Triassic sed-

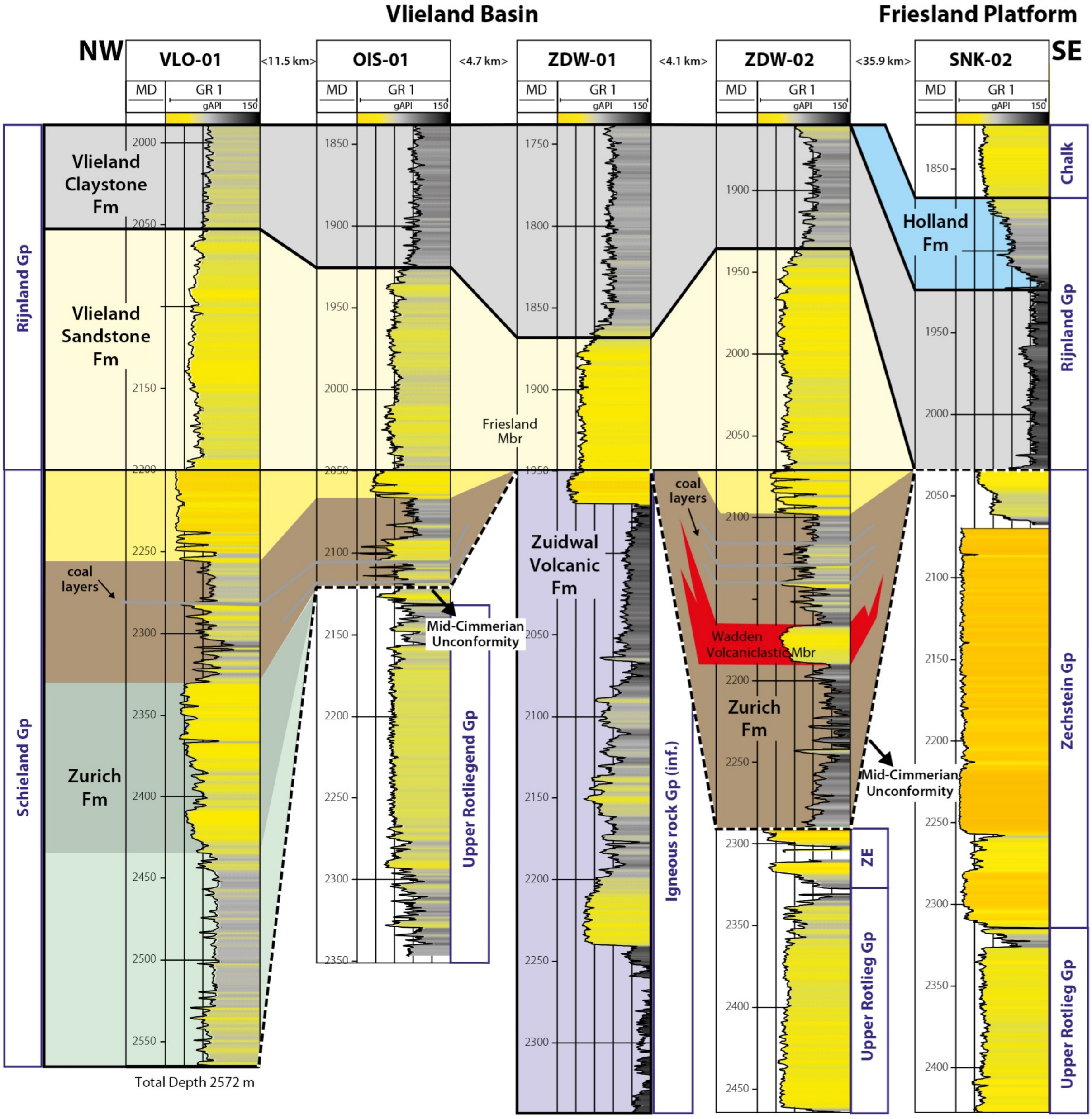


Figure 7.9. NW-SE well panel through the Vlieland Basin and on to the Friesland Platform (see Fig. 7.1 for location). The panel displays the well correlation of the Upper Jurassic to Lower Cretaceous lithostratigraphic units based on gamma-ray (GR) logs (yellow = sand, grey = clay). Formations are indicated with thick black lines and the colours of the lithostratigraphic units represent facies types (see legend of Fig. 7.3). Note that the Zurich Formation is characterized by many different facies types, including volcaniclastic sediments and coal layers.

iments lie below the interval and a thin cover of Upper Cretaceous chalk – a result of mild inversion – is situated on top (Bouroullec et al., 2016a).

The Vlieland Basin

The small Vlieland Basin trends WNW-ESE and runs from the offshore L12 and L15 blocks across the island of Vlieland via the Wadden Sea into the onshore province of Friesland (Fig. 7.1). The basin is separated from the Terschelling Basin by the Hantum Fault Zone and stands out from the other Late Jurassic-Early Cretaceous basins thanks to the prominent presence of a volcano right in its middle (Van Bergen et al., 2025, this volume; see also Fig. 7.7): The Zuidwal volcano was active in Late Jurassic-Early Cretaceous times and its tuffaceous deposits are widespread throughout the basin (Herngreen et al., 1991). The Upper Jurassic-Lower Cretaceous sequence is situated on top of the Zechstein or Upper Germanic Trias Group and is overlain by a thin cover of the Upper Cretaceous Chalk Group (Van der Molen, 2004; Duin et al., 2006; Kombrink et al., 2012). The basin is filled with predominantly marginal marine deposits of the Schieland Group associated with a thin section of the open marine Rijnland Group (Fig. 7.9).

The Lower Saxony Basin

The Lower Saxony Basin (LSB) is located onshore in the northeastern part of the Netherlands (Fig. 7.1). It trends WNW-ESE and extends into Germany where the bulk of the basin is situated, occupying an area of 300 by 80 km (Lott et al., 2010). In Germany, the basin is limited by the highs of the Pompeckj Block to the north and by the Rhenish Massif to the south (Seyfang et al., 2017) and in the Netherlands it is bordered by the Friesland Platform to the west. The Upper Jurassic-Lower Cretaceous deposits thin and wedge out onto this platform area (Fig. 7.11). Towards the south, the Gronau Fault Zone defines the boundary of the basin (Duin et al., 2006). The basin is filled with predominantly non-marine deposits of the Schieland and Niedersachsen groups and with marine deposits of the Rijnland Group (Figs 7.10, 7.11).

The Central Netherlands Basin

The Central Netherlands Basin (CNB) is a large WNW-ESE trending basin, located onshore in the central part of the Netherlands (Fig. 7.1). It was uplifted by an estimated 1500 metres during Late Cretaceous inversion (De Jager, 2003) and, as a result, the Upper Jurassic-Lower Cretaceous is only present as relatively thin erosional remnants (Duin et al., 2006) that are not discussed in detail here.

The Roer Valley Graben

The Roer Valley Graben (RVG) is a NW-SE trending basin, located onshore in the southern part of the Netherlands (Fig. 7.1). To the northwest it is connected with the West Netherlands Basin and towards Germany in the southeast it terminates against the Rhenish Massif (Kombrink et al., 2012). During Cenozoic times, the Roer Valley Graben was re-activated to connect with the Rhine Graben and it remains actively subsiding to the present day (Geluk et al., 1995; Peters & Van Balen, 2007). The basin was strongly inverted during the Late Cretaceous and as a result, most Upper Jurassic-Lower Cretaceous sediments were eroded (De Jager, 2003; Duin et al., 2006). Only in the northwestern part where the basin connects to the West Netherlands Basin, deposits from the Schieland Group are preserved.

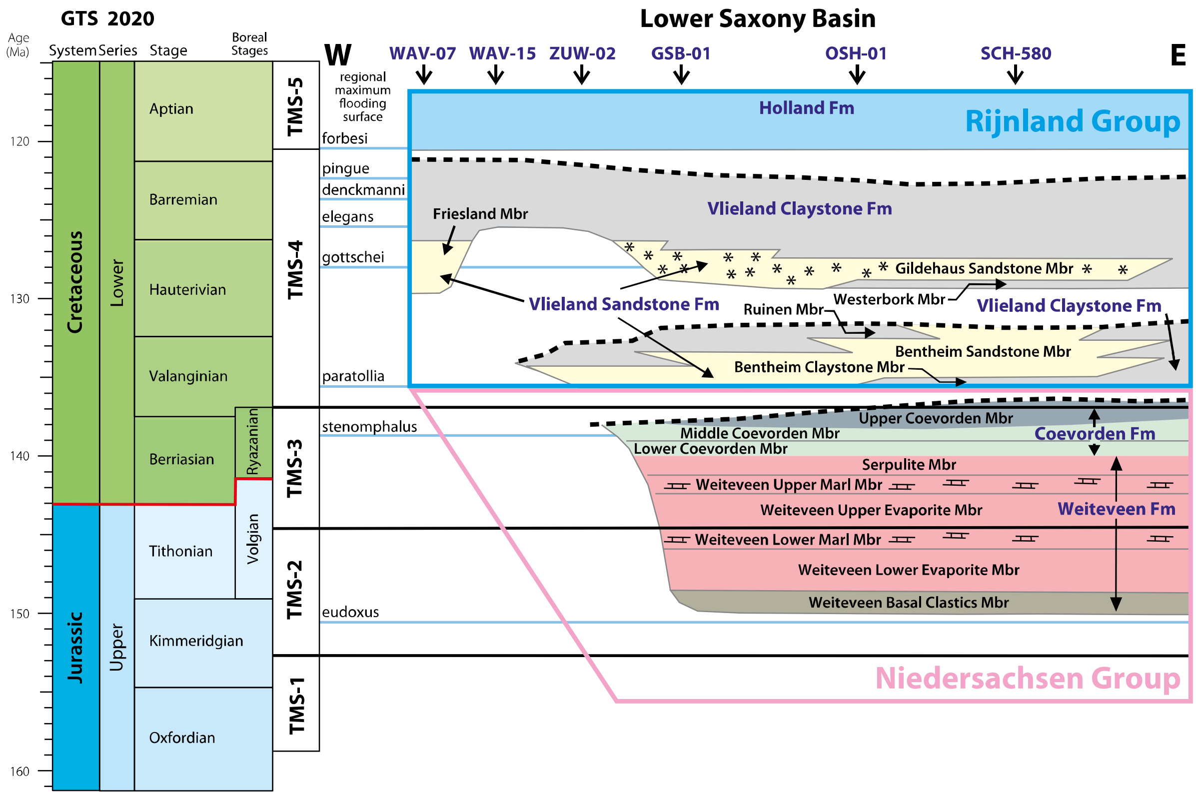


Figure 7.10. Wheeler diagram along a W-E transect through the Lower Saxony Basin (see Fig. 7.1 for location). The diagram displays the generalized time and facies relationships of the Kimmeridgian (Upper Jurassic) to Aptian (Lower Cretaceous) lithostratigraphic units. Formation names are indicated in blue, member names in black and lithostratigraphic groups are outlined in pink and blue. Relevant maximum flooding surfaces are displayed with blue lines. The black horizontal lines indicate tectonostratigraphic megasequences (TMS, see text for explanation). Key wells are shown at the top of the diagram. For legend see Fig. 7.3.

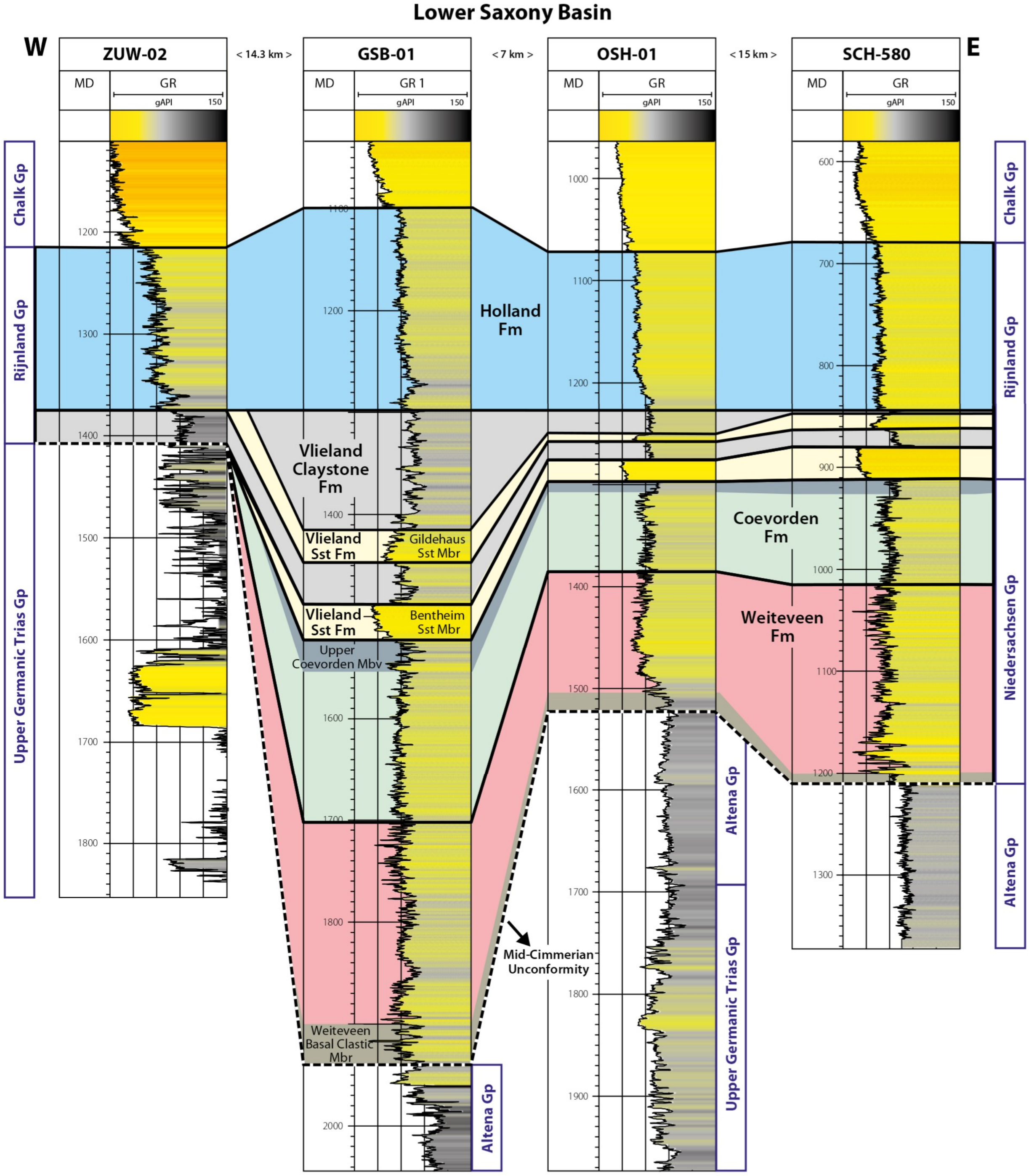


Figure 7.11. W-E well panel through the Lower Saxony Basin (see Fig. 7.1 for location). The panel displays the well correlation of the Upper Jurassic to Lower Cretaceous lithostratigraphic units based on gamma-ray (GR) logs (yellow = sand, grey = clay). Formations are indicated with thick black lines and the colours of the lithostratigraphic units represent facies types (see legend of Fig. 7.3). Two prominent sandstone units occur in the basin, the Bentheim and Gildehaus Sandstone members. The Bentheim Sandstone Member pinches out towards the west whereas the Gildehaus Sandstone Member is cut off by erosion.

The West Netherlands Basin

The West Netherlands Basin is a NW-SE trending basin that is located partially onshore and partially offshore, stretching from the provinces of Brabant and South Holland to the offshore P and Q quadrants (Fig. 7.1). The NW-SE structural grain was inherited from the Paleozoic (De Jager, 2007). The basin is virtually devoid of Zechstein Group salt (Duin et al., 2006). The basin ramps up via the intermediate Oosterhout Platform to the London-Brabant Massif in the SW and towards the NE, it is transitional into the Central Netherlands Basin. The West Netherlands Basin is dissected by an intricate pattern of faults trending

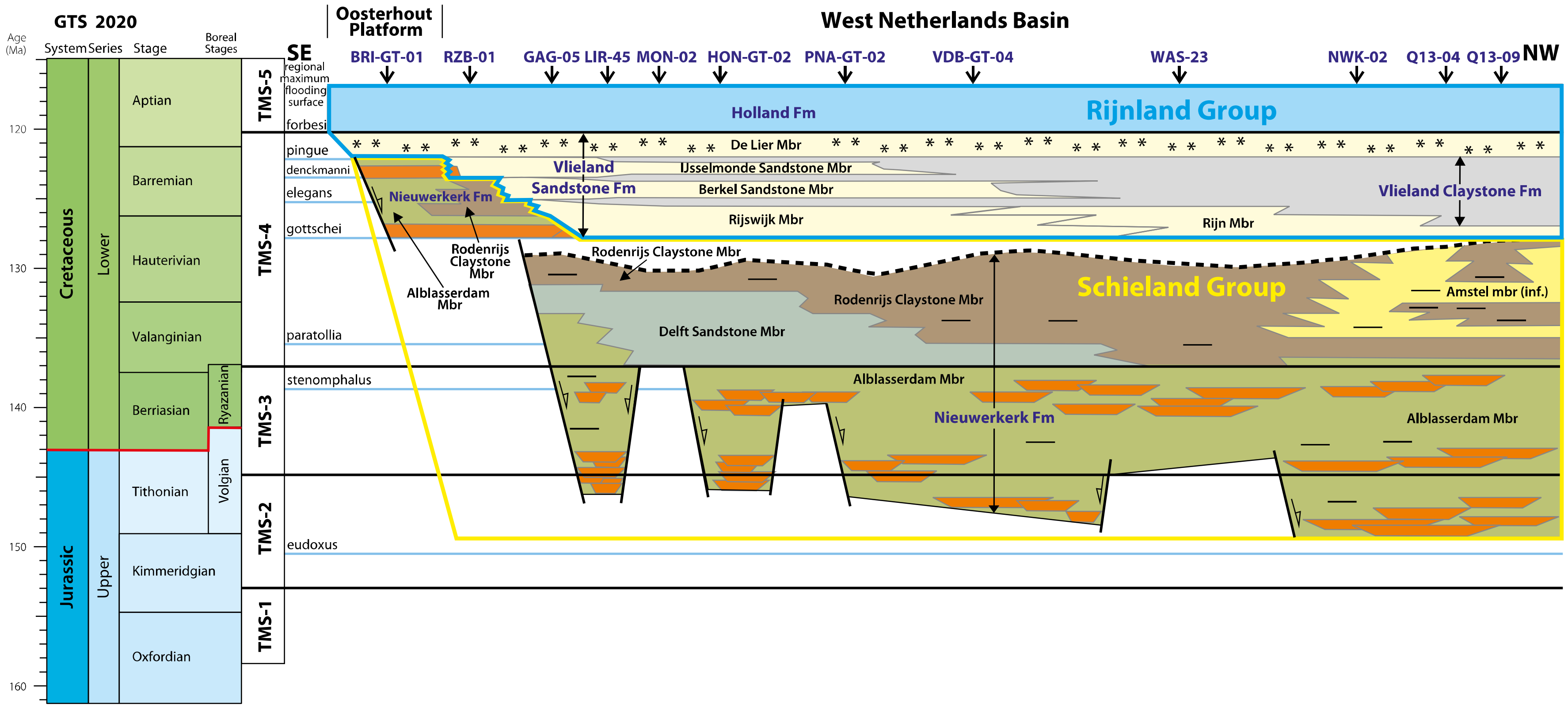


Figure 7.12. Wheeler diagram along a SE-NW transect through the West Netherlands Basin (see Fig. 7.1 for location). The diagram displays the generalized time and facies relationships of the Kimmeridigian (Upper Jurassic) to Aptian (Lower Cretaceous) lithostratigraphic units. Formation names are indicated in blue, member names in black and lithostratigraphic groups are outlined in yellow and blue. Relevant maximum flooding surfaces are displayed with blue lines. The black horizontal lines indicate tectonostratigraphic megasequences (TMS, see text for explanation). Key wells are shown at the top of the diagram. For legend see Fig. 7.3.

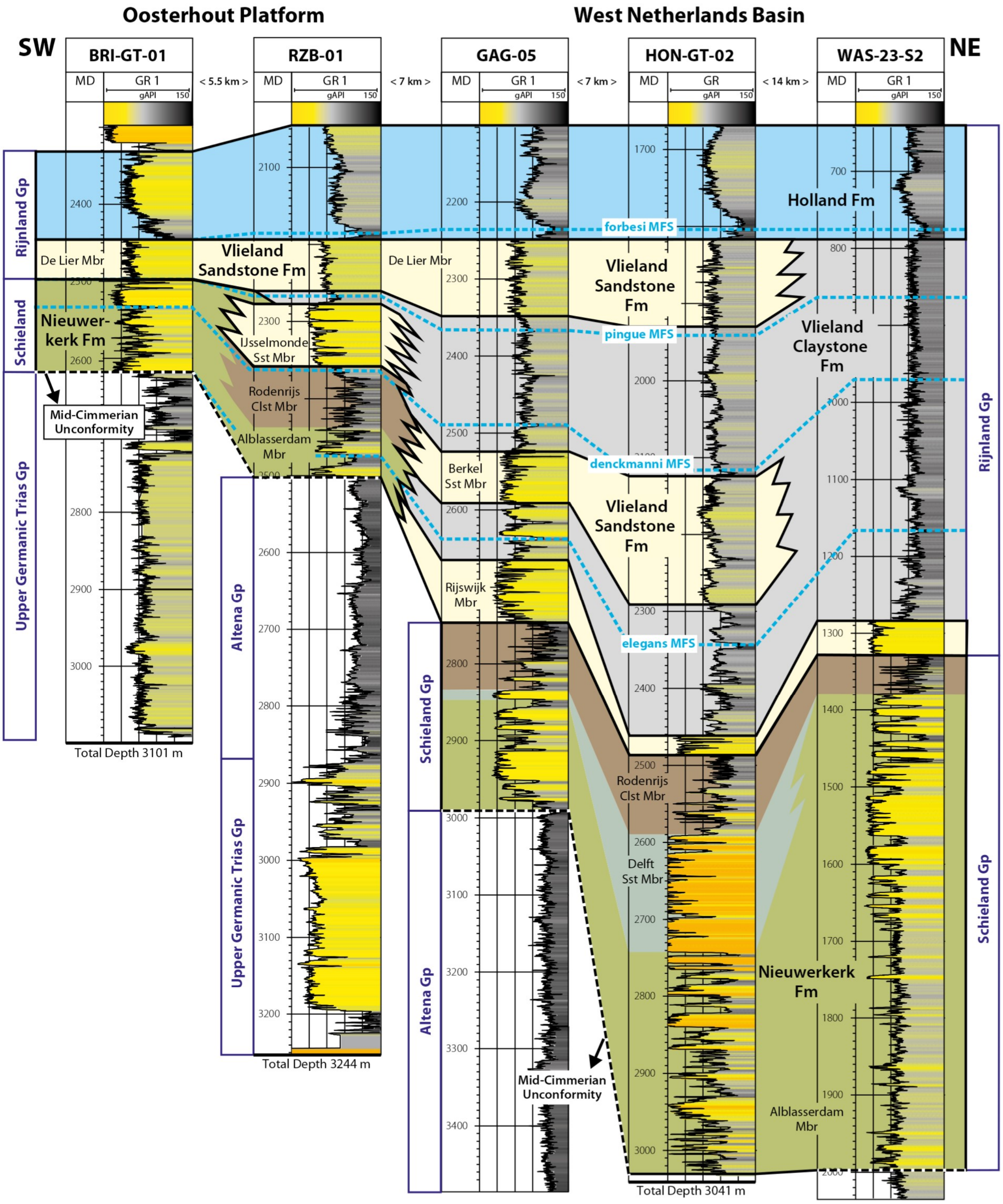


Figure 7.13. SW-NE well panel through the West Netherlands Basin (see Fig. 7.1 for location). The panel displays the well correlation of the Upper Jurassic to Lower Cretaceous lithostratigraphic units based on gamma-ray (GR) logs (orange = coarse sand, yellow = sand, grey = clay). Formations are indicated with thick black lines and the colours of the lithostratigraphic units represent facies types (see legend of Fig. 7.3). Relevant maximum flooding surfaces are displayed with blue dashed lines. Note the lateral transition of the non-marine Nieuwerkerk Formation to the marine Vlieland Sandstone and Vlieland Claystone formations. Also note the shaling out of the IJsselmonde and Berkel Sandstone members towards the basin axis.

NNW-SSE, NW-SE and ENE-WSW (Racero-Baena & Drake, 1996; Duin et al., 2006; also see Fig. 1.19 in De Jager et al., 2025, this volume). Due to inversion, the Upper Jurassic-Lower Cretaceous is in most parts of the basin capped by sediments of the Cenozoic North Sea Supergroup. The sequence is represented by the non-marine Schieland

Group and by the marine Rijnland Group (Figs 7.12, 7.13, 7.14).

The Broad Fourteens Basin

The Broad Fourteens Basin is located in the Dutch offshore K, L, P and Q quadrants (Fig. 7.1). Towards the south it connects to the West Netherlands Basin and towards the east, to the Central Netherlands Basin. The NNW-SSE trending structural grain of the basin is inherited from the Triassic (De Jager et al., 2025, this volume). The basin is bounded by faults and was strongly inverted in the Late Cretaceous (De Jager, 2003). As a result, much of the Upper Jurassic-Lower Cretaceous sequence has been removed by erosion from the former basin centre, where the inversion had the most profound impact (Duin et al., 2006). The thickest successions are now in the former marginal areas (De Jager, 2003). The Upper Jurassic-Lower Cretaceous succession comprises the non-marine Schieland Group and the marine Rijnland Group (Figs 7.15, 7.16).

Paleoclimate

While on a large scale, the depositional patterns of the Late Jurassic-Early Cretaceous were controlled by the tectonics of the Late Cimmerian rift phase, paleoclimate variations played an important role as well. The Jurassic Period is generally considered to have been a greenhouse world without any major glacial episodes (Jenkyns et al., 2012), but in the Middle Jurassic significantly cooler episodes, possibly including polar ice development occurred (Dera et al., 2011). Overall, the climate switched from relatively cool and humid (Callovian to Early Oxfordian) to relatively warm (middle Oxfordian to Kimmeridgian) to very warm and arid (latest Jurassic, Volgian to Early Ryazanian) and back to cool and humid again (late Ryazanian to Hauterivian) (Abbink et al., 2004a,b; Schneider et al., 2018a,b). The precise controls on these regional variations in temperature and humidity remain elusive, but the effects of both Tethyan and Boreal water-mass movements have repeatedly been considered (Dera et al., 2015; Vickers et al., 2020). In the Late Jurassic-Early Cretaceous sedimentary record of the Netherlands, continuous coal deposits developed during cooler and more humid phases. This is for instance the case for the Oxfordian Middle Graben and Friese Front formations in the Dutch Central Graben (Figs 7.3, 7.4). From the Volgian (Tithonian) onward, paleoclimate changes and warmer and more arid conditions were established. In the Lower Saxony Basin, these conditions led to strong contrasts in salinity, which are reflected in the presence of evaporites of the Weiteveen Formation (Van Adrichem Boogaert & Kouwe, 1993). In southern England, evaporites, limestones and freshwater deposits alternate in the Purbeck Formation (West, 1975). These indicate that warm and arid conditions were widespread around the Jurassic-Cretaceous boundary. In the Early Cretaceous Ryazanian (Berriasian), the warm and arid phase ended and humid conditions were established in the Netherlands and beyond (Schneider et al., 2018a,b). In the lithological record of the Broad Fourteens Basin, this is reflected by the occurrence of brackish, marginal marine and lagoonal deposits of the Bloemendaal and Neomiodon members of the Breeveertien Formation (Van Adrichem Boogaert & Kouwe, 1993).

Stratigraphy

Although the stratigraphy of the Upper Jurassic to Lower Cretaceous is complex thanks to the Late Cimmerian rift phase, many details of the stratigraphy have been revealed by biostratigraphic analyses of exploration wells drilled in the Netherlands. Biostratigraphic analyses on marine sediments generally return more precise and more reliable results than those on terrestrial sediments. As a consequence, the stratigraphy of the mostly marine middle and upper part of the Upper Jurassic-Lower Cretaceous succession is better constrained than the largely non-marine lower part. New stratigraphic methods that are independent from the fossil record, such as stable isotope- or chemo-stratigraphy, are currently being applied to counteract this shortcoming (Eldrett & Vieira, 2022; Houben et al., in prep).

Chronostratigraphy

The time interval presented in this chapter spans from the Bathonian (Middle Jurassic) to the Albian (Early Cretaceous) and consists of 11 stages, representing 68 million years of geological history according to the international Geological Time Scale GTS 2020 (100.5-168.3 Ma, Gradstein et al., 2020). For definition of the Jurassic-Cretaceous boundary, represented by the latest Jurassic Tithonian and earliest Cretaceous Berriasian stages, the international time scale is based on Tethyan reference sections and ammonite zones (Gale et al., 2020; Hesselbo et al., 2020). During that time interval, the Tethyan realm included French, Italian and southern German basins, but was isolated from the Boreal realm, which includes British, Danish and Dutch basins. As a consequence, provincialism among fossil groups was strong and it is often impossible to precisely correlate stratigraphic units across these realms. For that reason, the regional Volgian and Ryazanian stages are used for correlation purposes in the Dutch basins and in this chapter. Note that the base of the Cretaceous in the Boreal and Tethyan realms is temporally offset (Figs 7.3, 7.7, 7.10, 7.12, 7.15, 7.19). The base of the Berriasian Stage (by definition also the base of the Creta-

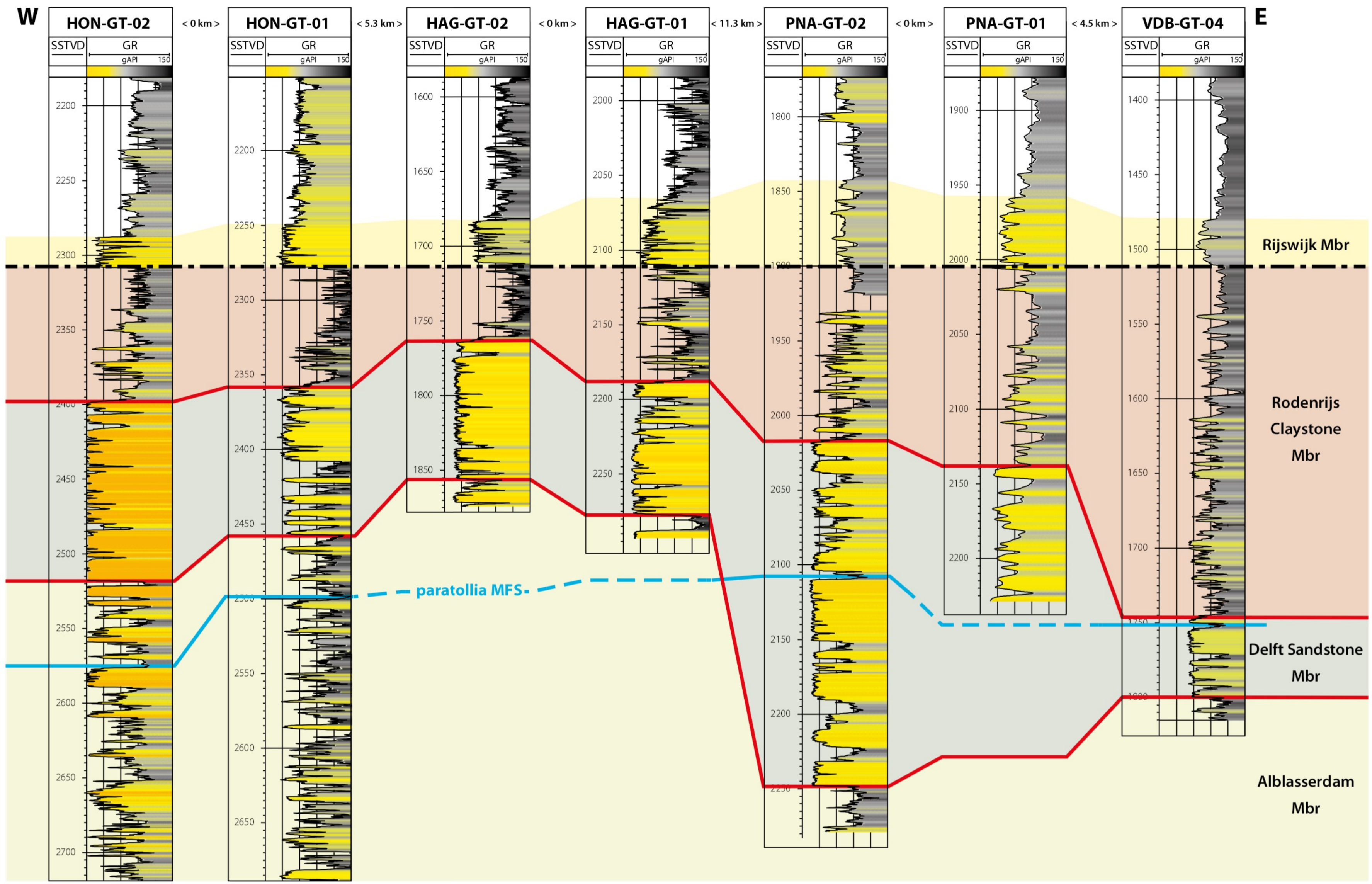


Figure 7.14. *W-E well panel displaying the correlation of the Delft Sandstone Member throughout the West Netherlands Basin based on gamma-ray (GR) logs (orange = coarse sand, yellow = sand, grey = clay).. The Delft Sandstone Member is an excellent aquifer that is targeted for geothermal energy. The Delft Sandstone Member has a diachronous relationship with both the Alblasserdam and the Rodenrijs members as is shown by its position relative to the paratollia maximum flooding surface. The correlation is based on palynological analyses (Willems et al., 2017a, 2020).*

ceous Period), is based on calpionellids, a group of calcareous microfossils. The First Appearance Datum of *Calpionella alpina,* marking the base of the *C. alpina* Subzone of the Calpionella Zone, has been selected by the Berriasian Working Group of the International Commission on Cretaceous Stratigraphy to mark the base of the Berriasian (Wimbledon et al., 2011; 2020a,b; Wimbledon, 2017; Gale et al., 2020; Hesselbo et al., 2020). This event correlates to the magnetic polarity Chron M19n.2n and corresponds to an age of 143.1 Ma. The base of the regional boreal Ryazanian Stage from the Russian Platform is defined by the base of the *ryasanensis* ammonite zone which correlates to the base of Polarity Chron M17 and corresponds to an age of 141.8 Ma (Gale et al., 2020; Hesselbo et al., 2020; Wimbledon et al., 2020a,b).

Biostratigraphy

Numerous consultancy and Geological Survey of the Netherlands reports provide detailed accounts on the age and paleoenvironments of Upper Jurassic-Lower Cretaceous deposits. Some of these reports can be found on the Netherlands Oil & Gas portal (www.nlog.nl), e.g. Bouroullec et al. (2016a,b), but the majority are not available in the public domain. Fortunately, an important part of the information derived from the studies has been incorporated in literature. The majority of the biostratigraphic information pertains to palynology (Abbink, 1998; Herngreen et al., 2000; Abbink et al., 2001a; Hoedemaeker & Herngreen, 2003; Abbink et al., 2006,Willems et al., 2017a; Verreussel et al., 2018). This discipline is ideally suited for the non-marine, marginal marine and shallow marine siliciclastic deposits that dominate the Upper Jurassic to lowermost Cretaceous of the Dutch subsurface. Palynomorphs such as dinoflagellate cysts, pollen and spores occur in a variety of environments and bridge the gap between the continental and marine realm (Jansonius & McGregor, 1996; see also Fig. 7.17). Consultancy studies on the more open marine and more calcareous deposits, such as the early Cretaceous Vlieland Sandstone Formation or the Holland Formation, have relied mostly on calcareous nannofossils. A synthesis based on this group was published in Jeremiah et al. (2010).

Sequence stratigraphy

The role of eustacy on the Upper Jurassic and Lower Cretaceous stratigraphy of the North Sea was recognized and promoted in the 1990s by authors such as Partington et al. (1993a,b) who developed a regional genetic sequence-stratigraphic framework for this time interval. Unit boundaries of their stratigraphic scheme were based on maximum flooding surfaces rather than on sequence boundaries and the stratigraphic sequences were calibrated against biostratigraphy (Partington et al., 1993b). The stratigraphic schemes were improved and further refined to fit application in specific areas such as the Outer Moray Firth (Duxbury et al., 1999; Kadolsky et al., 1999), the central and northern North Sea (Fraser et al., 2003) and the Danish Central Graben (Johannessen et al., 1996; Andsbjerg & Dybkjær, 2003). In the Netherlands, the role of eustacy is generally subordinate to the role of tectonics, but some eustatic trends are reflected in the lithological record. Within the latest Jurassic Tithonian Stage ongoing basin restriction led to an increase in provincialism that affected the evolution and distribution of environmentally sensitive fossil groups such as ammonites (Casey et al., 1977). A number of distinct maximum flooding surfaces can be recognized on wireline logs and seismic images and can be correlated across large distances. All maximum flooding surfaces are named after the ammonite zone in which they occur (Partington et al., 1993b).

The latest Callovian *Lamberti* maximum flooding surface (MFS) is reflected in the lithological record of the Dutch Central Graben by a marine flooding event near the top of the predominantly non-marine Lower Graben Formation. It heralds an overall change in depositional environment from the fluvial Lower Graben Formation to the lacustrine and estuarine Middle Graben Formation (Bouroullec et al., 2018; see also Figs 7.3, 7.5). In the southern part of the Dutch Central Graben, marine sediments of the Rifgronden Member onlap onto the partially eroded Middle Jurassic Altena Group (Fig. 7.5).

The late Kimmeridgian *Eudoxus* MFS can be traced regionally. In the Terschelling and Vlieland Basin, it marks the base of the marine Oyster Ground Member of the Skylge Formation and the estuarine/lacustrine Zurich Formation (Herngreen et al., 2000; Abbink et al., 2006; Munsterman et al., 2012; see also Figs 7.7, 7.8). In the Viking Graben and Danish Central Graben, the *eudoxus* MFS marks the transition towards the dysaerobic facies of the Kimmeridge Clay Formation (Fraser et al., 2003).

The late Ryazanian *stenomphalus* MFS is reflected in the lithological record of the Dutch Central Graben and the Terschelling Basin by the appearance of marine mudstones of the Lutine Formation (Munsterman et al., 2012; see also Figs 7.3, 7.7). In the Lower Saxony Basin, the *stenomphalus* MFS is associated with the organic-rich Upper Coevorden Member of the Coevorden Formation (Fig. 7.10) and in the Broad Fourteens Basin by the lagoonal Neomiodon Claystone Member of the Breeveertien Formation (Fig. 7.15).

The early Valanginian *paratollia* MFS more or less marks the base of the marine Rijnland Group in the Dutch Central Graben, the Terschelling Basin and the Broad Fourteens Basin (Figs 7.3, 7.7, 7.15). In the Lower Saxony Basin, the Bentheim Sandstone Member is associated with the *paratollia* MFS (Fig. 7.10). In the West Netherlands Basin, the diachronous Delft Sandstone Member of the Nieuwerkerk Formation is associated with this MFS (Willems et al., 2017a, 2020; see also Figs 7.12, 7.14).

The late Hauterivian *gottschei* MFS marks the base of the Rijswijk Member of the Vlieland Sandstone Formation in the West Netherlands Basin (Fig. 7.12).

The closely spaced early to late Barremian *Fissicostatum* and *elegans* MFSs are linked to the Berkel Sandstone Member of the Vlieland Sandstone Formation in the West Netherlands Basin (Jeremiah et al., 2010; see also Figs 7.12, 7.13). In the Danish Central Graben, the eustatic sea-level high is expressed in the organic-rich Munk Marl (Copestake et al., 2003) and in the German Lower Saxony Basin it is expressed in the bituminous Hauptblatterton (Mutterlose & Bornemann, 2000).

The *denckmanni* MFS is associated with the IJsselmonde Sandstone Member of the Vlieland Sandstone Formation in the West Netherlands Basin (Jeremiah et al., 2010; see also Figs 7.12, 7.13).

The late Barremian *pingue* MFS marks the base of the widespread De Lier Member of the Vlieland Sandstone Formation (Jeremiah et al., 2010; see also Figs 7.12, 7.13).

The early Aptian *forbesi* MFS marks the base of the Holland Formation in all basins (Figs 7.3, 7.7, 7.10, 7.12, 7.13, 7.15) and is easy to recognize on wireline logs and seismic images; the organic rich shales produce high gamma-ray readings and cause a strong contrast in acoustic impedance with the underlying sandstones. In the North Sea and Lower Saxony basins it is expressed in the organic-rich Fischshiefer (Copestake et al., 2003; Jeremiah et al., 2010). On a global scale, this maximum flooding surface is linked to the oceanic anoxic event OAE1a (Keller et al., 2011).

Lithostratigraphy

Because of the dynamic structural and climatic setting, a wide array of depositional environments developed in the Netherlands during the Late Jurassic and Early Cretaceous, including fluvial, lagoonal, lacustrine, deltaic, tidal, shoreface, offshore and deep marine environments. As a result, the stratigraphy is characterized by juxtapositions and lateral transitions. In general, the formations and members are grouped according to either the depositional setting (e.g. marine versus non-marine), the lithology (e.g.

Late Jurassic crocodile traces

When looking for Upper Jurassic or Lower Cretaceous rocks in the Netherlands you might be in for a surprise when you visit the city of Utrecht. Right at the bottom of the medieval Dom tower you will find a white limestone from the top of the Jurassic. The Dom tower is the highest church tower in the Netherlands and is mainly constructed of bricks, red sandstone and volcanic tuff from the Eifel region, but the base of the tower is clad with white oolitic limestone. The limestone is known as Portland stone and is derived from the isle of Portland in South England, where it has been quarried extensively for use as building stone. The isle also gave its name to the regional Portlandian Stage that represents the latest part of the Jurassic and earliest part of the Cretaceous. The transition from the Jurassic to the Cretaceous was characterized by a warm and arid climate and this is reflected in the rock record by the occurrence of limestones and evaporites that were deposited in shallow marine environments, often hypersaline lagoons. The characteristically abundant bivalves and oolites of the Portland stone match perfectly with such a depositional setting. Not only bivalves but also crocodiles and dinosaurs were roaming these lagoons looking for snacks and left their traces as footprints in the soft sediment. These footprints are perfectly preserved in the rocks that are now exposed in the many outcrops along the English and French coasts.

Inverted imprint of crocodile front legs from the Upper Jurassic Grés de la Crèche Formation near Boulogne-sur-Mer, northern France. The imprints are made by a crocodile belonging to a species that is characterized by five toes. The crocodile left the imprints in the soft silty sediments of a lagoon. Later, the imprints were filled with sand that was deposited on top of the partially cemented lagoon floor.

sandstone versus claystone-dominated sequences), or the geographic distribution (proximal versus distal). All major lithostratigraphic units that are defined for the Late Jurassic-Early Cretaceous are listed in Table 7.1 and the formal descriptions and definitions can be consulted online: dinoloket.nl/en/stratigraphic-nomenclature. For online listings of lithostratigraphic units from the countries bordering the Netherlands, reference is made to: litholex.bgr.de (Germany), webapps.bgs.ac.uk/lexicon/(United Kingdom) and ncs.naturalsciences.be (Belgium).

The following section provides a synopsis of the lithostratigraphic nomenclature for the Upper Jurassic and Lower Cretaceous. The lithostratigraphic units are described from old to young.

Schieland Group

The Schieland Group constitutes lithostratigraphic units that were deposited in non-marine to marginal marine depositional settings. Based on the geographic distribution, the Schieland Group is subdivided into two subgroups: the Delfland Subgroup is confined to the Vlieland, Broad Fourteens and West Netherlands basins and the Central Graben Subgroup is confined to the Dutch Central Graben and Terschelling Basin. The Schieland Group is the oldest unit of the Upper Jurassic-Lower Cretaceous succession in the Netherlands.

Delfland Subgroup

The Delfland Subgroup consists of three formations, the Zurich, the Breeveertien and the Nieuwerkerk formations (Table 7.1). The Zurich Formation is represented by non-marine deposits in the Vlieland Basin, while the Breeveertien and the Nieuwerkerk formations represent the non-marine to marginal marine base of the Upper Jurassic-Lower Cretaceous succession in the Broad Fourteens and West Netherlands basins respectively.

Zurich Formation

The Zurich Formation consists predominantly of sandy and silty claystones with thin intercalated sandstone and coal layers and includes a sequence of volcaniclastic sediments. Three members are distinguished, from old to young: the Lower Zurich, the Wadden Volcaniclastic and the Upper Zurich members. The Lower Zurich Member is dominated by claystones with few sandstone intercalations and displays weak marine influence (Herngreen et al., 2000), indicating an estuarine paleoenvironment. Based on pollen and spores, it has been assigned an early to middle Volgian age (Herngreen et al., 2000). The Wadden Volcaniclastic Member consists of variegated fine- to coarse-grained volcaniclastics with a grey tuffaceous matrix, embedded in red-brown and green clays. The Upper Zurich Member contains common coal and sandstone layers, indicative of a back-barrier lagoonal depositional setting (Van Adrichem Boogaert & Kouwe, 1993). A sandstone unit at its base in well Vlieland Oost-1 (VLO-01) may represent a lateral equivalent to (a part of) the Scruff Greensand Formation and to the Wadden Volcaniclastic Member (Figs 7.7, 7.9). The top of the Zurich Formation is often represented by more massive sandstones separated by thin claystone layers, indicating a foreshore to back-barrier depositional environment and is late Ryazanian (Herngreen et al., 2000) in age (Fig. 7.7, 7.9). The Zurich Formation reaches a thickness of more than 350 m and is limited to the Vlieland Basin. Isolated occurrences of volcaniclastic rocks are found in the Step Graben, Broad Fourteens and West Netherlands basins (Figs 7.7, 7.15, 7.16).

Breeveertien Formation

The Breeveertien Formation consists predominantly of claystones; sandstones occur mainly in the basal and the upper part of the formation. It is subdivided into seven members which are not always distinguishable. The Aerdenhout Member is the oldest and consists of claystones and channel sandstones, representing a fluvial to coastal depositional environment with an approximate late Kimmeridgian age (Van Adrichem Boogaert & Kouwe, 1993; see also Figs 7.15, 7.16). Succeeding the Aerdenhout Member are three members that share comparable depositional environments: the Fourteens Claystone Member, the Santpoort Member and the Driehuis Mottled Claystone Member. The claystone units consist predominantly of non-marine claystones with little to no marine influence which accumulated in lacustrine to estuarine depositional environments. The Santpoort Member consists of sandstones and claystones which exhibit weak marine influence, indicative of a coastal depositional environment. The age of these combined members is early to middle Volgian (Verreussel et al., 2015). At the top of the Breeveertien Formation, two partial lateral equivalents, the Bloemendaal Member and the Neomiodon Member (Figs 7.15, 7.16) occur. Palynological evidence suggests a marginal marine setting for the sandstone dominated Bloemendaal Member and a restricted marine setting for the claystone-dominated Neomiodon Member. The latter is characterized by abundant debris of the brackish water bivalve Neomiodon, indicating a lagoonal to back-barrier depositional environment (Van Adrichem Boogaert & Kouwe, 1993). The age of the Bloemendaal and Neomiodon members is late Ryazanian to earliest Valanginian (Van Adrichem Boogaert & Kouwe, 1993; Verreussel et al., 2015). Based on palynological studies, a hiatus is suggested between the Bloemendaal Member and the underlying Driehuis Mottled Claystone Member (Verreussel et al., 2015; see also Fig. 7.15). The Breeveertien Formation attains a maximum thickness of

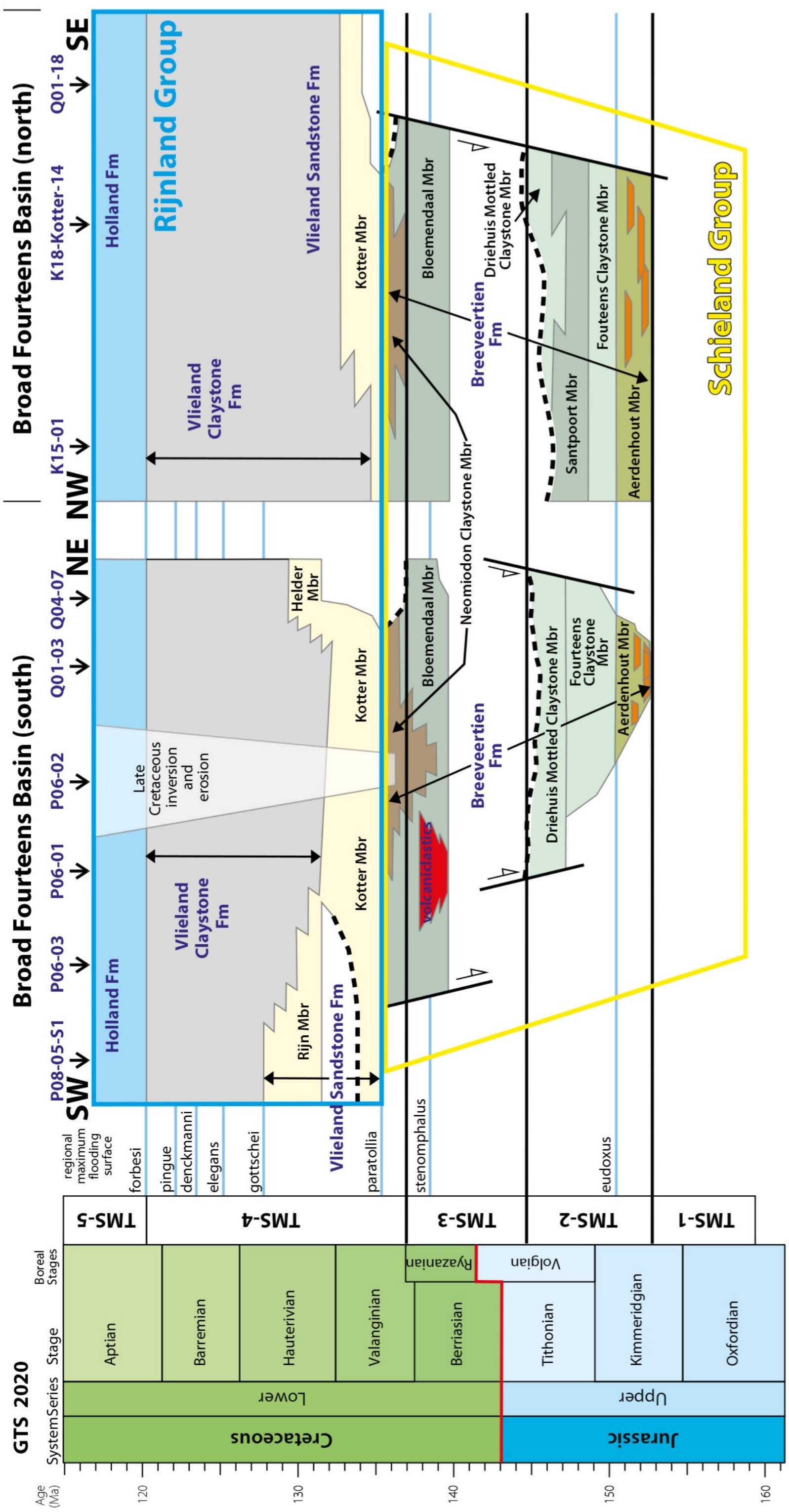


Figure 7.15. *Wheeler diagram along a SW-NE to NW-SE transect through the Broad Fourteens Basin (see Fig. 7.1 for location). The diagram displays the generalized time and facies relationships of the Kimmeridgian (Late Jurassic) to Aptian (Lower Cretaceous) lithostratigraphic units. Formation names are indicated in blue, member names in black and lithostratigraphic groups are outlined in yellow and blue. Relevant maximum flooding surfaces are displayed with blue lines. The black horizontal lines indicate tectonostratigraphic megasequences (TMS, see text for explanation). Key wells are shown at the top of the diagram.For legend see Fig. 7.3.*

640 m and is limited in distribution to the Broad Fourteens Basin.

Nieuwerkerk Formation

The Nieuwerkerk Formation consists predominantly of non-marine sandstones and variegated claystones and may attain a thickness of 1000 m (Van Adrichem Boogaert & Kouwe, 1993). The formation is limited in distribution to the West Netherlands Basin and can be considered as the slightly more proximal counterpart of the Breeveertien Formation from the Broad Fourteens Basin. Due to active faulting at the time of deposition, the age and stratigraphic thickness of the Nieuwerkerk Formation is very variable (Den Hartog Jager, 1996; Racero-Baena & Drake, 1996; DeVault & Jeremiah, 2002). For example on the Oosterhout Platform, the Hauterivian to Barremian Nieuwerkerk

Formation is juxtaposed against laterally equivalent shoreface sandstones of the Vlieland Sandstone Formation (Figs 7.12, 7.13). Three members are distinguished within the Nieuwerkerk Formation, from old to young these are the Alblasserdam Member, the Delft Sandstone Member and the Rodenrijs Member (Figs 7.13, 7.14). The Alblasserdam Member represents fluvial floodplain deposits with single and stacked channel sandstones and overbank fines. Its age is poorly known because age-diagnostic (micro-)fossils and palynomorphs are lacking, but based on its position between the underlying Brabant Formation (Trabucho Alexandre & Wong, 2025, this volume) and the overlying Delft Sandstone or Rodenrijs members, it must be younger than Oxfordian and older than Valanginian. The overlying Delft Sandstone Member is an important aquifer that is currently being targeted for geothermal energy (Mijnlieff, 2020; Willems et al., 2020; Mijnlieff et al., 2025, this volume). It consists of massive and closely spaced sandstones that probably represent meandering distributary channels in a coastal plain setting (Donselaar et al., 2015; Vondrak et al., 2018; Willems et al., 2020). The Rodenrijs Claystone Member consists of grey mudstones alternating with thin sandstones and associated coal layers. The depositional setting was coastal plain to lagoonal. In the West Netherlands Basin the Delft Sandstone Member is diachronous and may be a correlative equivalent to both the overlying Rodenrijs Member and the underlying Alblasserdam Member (Fig. 7.14). Its palynology-based age ranges from earliest Valanginian to earliest Hauterivian (Willems et al., 2017a, 2020) and it may attain a maximum thickness of 250 m. In the offshore Amstel Field in block Q13, barrier and back-barrier sandstones occur. These are likely a lateral equivalent of the Rodenrijs Member and are provisionally referred to as the informal Amstel member (Fig. 7.12).

Central Graben Subgroup

The Central Graben Subgroup includes five predominantly non-marine formations in the Dutch Central Graben and Terschelling Basin: the Lower Graben Formation, the Middle Graben Formation, the Upper Graben Formation, the Friese Front Formation and the Puzzle Hole Formation (Table 7.1). The Lower, Middle and Upper Graben formations are distributed in the middle and northern part of the Dutch Central Graben, the Puzzle Hole Formation is limited in its distribution to the middle part of the Dutch Central Graben and the Friese Front Formation occurs in the southern part of the Dutch Central Graben and in the bordering Terschelling Basin.

Friese Front Formation

The Friese Front Formation consists predominantly of carbonaceous claystones with intercalated coal beds and thin sandstones (Munsterman et al., 2012). A wide variety of depositional environments are represented, ranging from fluvial, coastal plain, fluvial channel, fluvial floodplain, estuarine and deltaic to shoreface, but on the whole, non-marine paleoenvironments prevail (Munsterman et al., 2012; Bouroullec et al., 2016b, 2018; Verreussel et al., 2018). Two members are developed, the Rifgronden Member and the main Friese Front member (Fig. 7.7). The Rifgronden Member occurs at or near the base of the formation in the southern Dutch Central Graben and displays a marine depositional environment that has been correlated to the regional J46 Lamberti maximum flooding surface in the latest Callovian (Abbink et al., 2001b; see also Fig. 7.6). The Main Friese Front Member is mostly non-marine. In block L05 at the southernmost tip of the Dutch Central Graben, it is characterized by coals and fluvial channel sands (Abbink, 1998; Abbink et al., 2006). In block F17 at the transition of the Dutch Central Graben to the Terschelling Basin, the member is characterized by three stacked sandstone units associated with coal (Fig. 7.7). These units resemble the deltaic mouth-bar sequences of the Middle and Upper Graben Formation and are possibly time equivalent, viz. Oxfordian in age (Bouroullec et al., 2016b). Within the Terschelling Basin, the main Friese Front member is characterized by fluvial channels and overbank fines and is younger than in the Dutch Central Graben: late Kimmeridgian (Verreussel et al., 2018). The Friese Front Formation is generally around 150 metres thick but may reach a maximum thickness of 480 metres.

Puzzle Hole Formation

The Puzzle Hole Formation consists of carbonaceous mudstones and siltstones, alternating with thin, fining upward sandstones and coal layers (Van Adrichem Boogaert & Kouwe, 1993). Combined with a general lack of marine indicators (Herngreen et al., 2000), a delta plain depositional environment is inferred. The formation occurs in the middle part of the Dutch Central Graben only. Towards the north, the Puzzle Hole grades into the deltaic mouthbars and estuarine claystones of the Middle and Upper Graben formations (Figs 7.3, 7.5). The Puzzle Hole Formation is limited in extent to the middle part of the Dutch Central Graben. The age of the formation is late Oxfordian to early Kimmeridgian (Verreussel et al., 2018).

Lower Graben Formation

The Lower Graben Formation is characterized by well-sorted sandstones and silty to sandy claystones, often carbonaceous with common coal layers (Van Adrichem Boogaert & Kouwe, 1993). Towards the top, the sandstones become more massive and marine influence increases (Bouroullec et al., 2018; see also Figs 7.4, 7.5). The depositional environment changed from a fluvial, quiet bay in the lower parts, to brackish lagoon and tidal shoals at

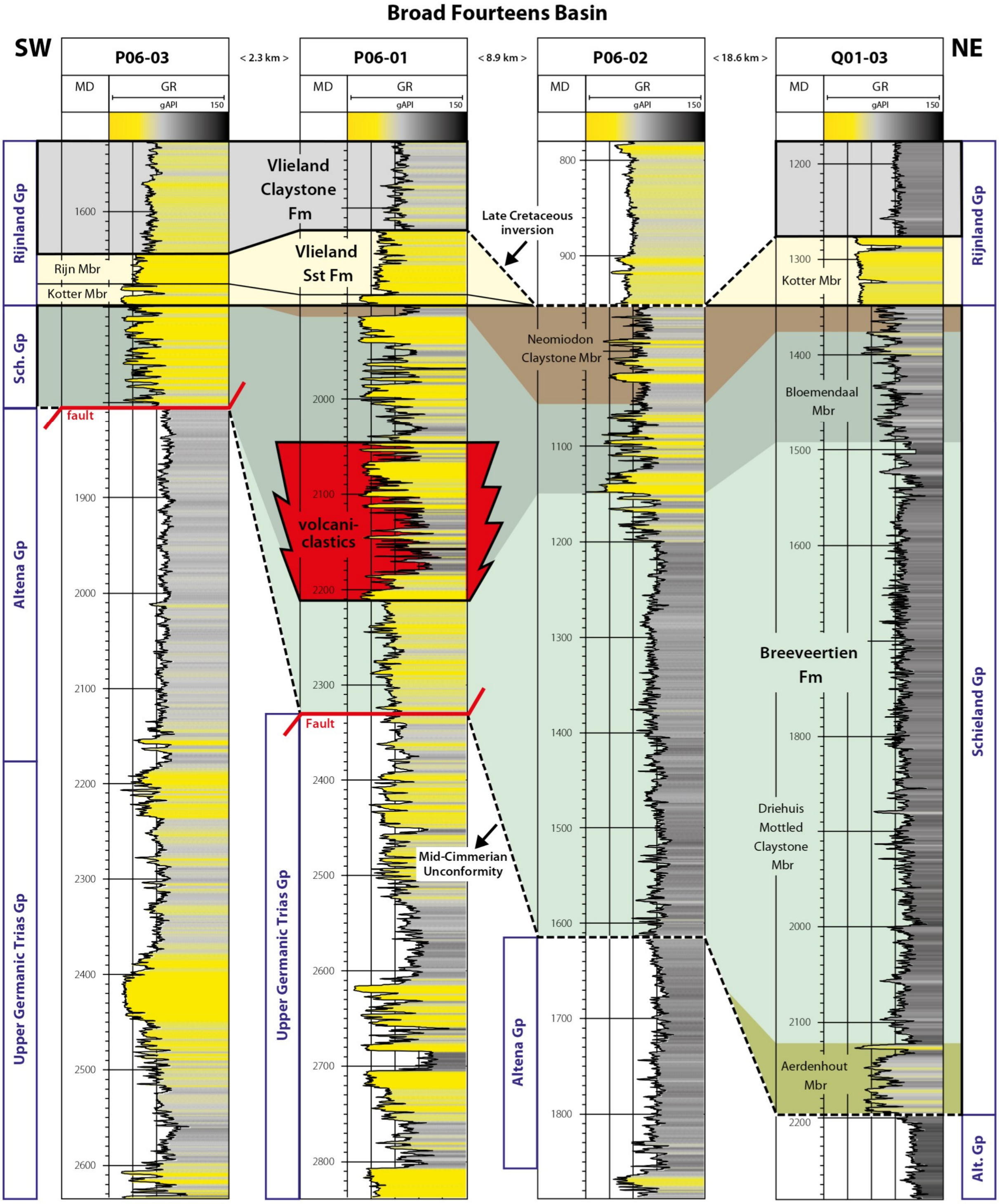


Figure 7.16. SW-NE well panel through the Broad Fourteens Basin (see Fig. 7.1 for location). The panel displays the well correlation of the Upper Jurassic to Lower Cretaceous lithostratigraphic units based on gamma-ray (GR) logs (yellow = sand, grey = clay). Formations are indicated with thick black lines and the colours of the lithostratigraphic units represent facies types (see legend of Fig. 7.3). Volcaniclastic sediments from the Zurich Formation in well P06-01 reveal the nearby presence of an active volcano. Note the large overall thickness of the non-marine Schieland Group in the basin.

the top of the formation. It reaches a maximum thickness of 500 m and is limited in its distribution to the northern and middle parts of the Dutch Central Graben. The age is middle to late Callovian and its top correlates to the Callovian-Oxfordian boundary (Verreussel et al., 2018).

Middle Graben Formation

The Middle Graben Formation is an up to 500 m thick unit that consists predominantly of carbonaceous claystones interrupted by two subordinate sandstone units (Fig. 7.14), the lower of which forms the Middle Graben Sandstone Member. These sandstones are very similar in lithology and architecture to those of the Upper Graben Formation, differing only in their more limited development. They were deposited as deltaic mouthbars in a marginal marine deltaic depositional environment, comparable to those of the Upper Graben Formation. Palynological associations from the claystones show a dominance of pollen and spores indicative of lacustrine to estuarine paleoenvironments (Herngreen et al., 2000). Three up to 3 metres thick coal seams, separated by up to 30 metres of claystone occur at the base of the formation (Figs 7.3-7. 5) and can be traced across the entire Dutch Central Graben. The thickest coal seam lies at the base and is visible as an excellent reflector on seismic images. A meandering channel feature identified within it has been attributed to a large fluvial system entering the basin from the east (Bouroullec et al., 2018). The age of the Middle Graben Formation is Oxfordian, the basal coal seam corresponds to the Callovian-Oxfordian boundary (Verreussel et al., 2018).

Upper Graben Formation

The Upper Graben Formation consists of two coarsening upward, relatively fine-grained carbonaceous sandstone units associated with coal layers, separated by fine-grained siliciclastics (Van Adrichem Boogaert & Kouwe, 1993). It is confined to the northernmost part of the Dutch Central Graben; towards the south the formation grades into the Puzzle Hole Formation (Figs 7.3, 7.4). The coarsening upward sandstone units with associated coals point to prograding mouthbars in a marginal marine deltaic depositional setting, and this is corroborated by the identification of small bird-foot deltas within the formation near the basin margin (Bouroullec et al., 2018). The age of the Upper Graben Formation is latest Oxfordian to earliest Kimmeridgian (Herngreen et al., 2000; Verreussel et al., 2018). It is succeeded by shallow marine to offshore claystones of the Kimmeridge Clay Formation (Fig. 7.4) and reaches a maximum thickness of 180 m.

Niedersachsen Group

The Niedersachsen Group differs from all other Upper Jurassic-Lower Cretaceous groups in that limestones and evaporites commonly occur. The Niedersachen Group includes two formations, the Coevorden Formation and the Weiteveen Formation and is limited in its distribution to the Lower Saxony Basin. It attains a maximum thickness of 600 m.

Weiteveen Formation

The Weiteveen Formation is characterized by anhydritic and marly claystones with halite and limestone intercalations. Coarse sands and conglomerates may occur at the base. The depositional environment is lacustrine to marginal marine. The predominance of evaporitic facies points to warm and arid climate conditions. The formation is subdivided into six members (Fig. 7.10), from old to young being the Weiteveen Basal Clastic Member (variegated conglomerates, sandstones and claystones), the Weiteveen Lower Evaporite Member (alternation of dolomitic claystones, anhydrites, halites and limestones), the Weiteveen Lower Marl Member (blue-grey marly, locally anhydritic or pebbly claystone succession), the Weiteveen Upper Evaporite Member (anhydrite, carbonate and halite), the Weiteveen Upper Marl Member (marly claystone unit with some sand, anhydrite and limestone intercalations) and the Serpulite Member (limestone-rich claystone interval, characterized by the common occurrence of fossil worm tubes known as serpulids). Towards the western and northern margins of the Lower Saxony Basin the Basal Clastic Member becomes less coarse-grained, while the Lower and Upper Evaporite members become thinner and eventually pinch out. The age of the top of the Weiteveen Formation is latest Volgian (earliest Berriasian, Hoedemaeker & Herngreen, 2003; Seyfang et al., 2017), but the base is not well established. Based on ostracods it is probably latest Kimmeridgian, (Van Adrichem Boogaert & Kouwe, 1993). The Weiteveen Formation is limited to the onshore Lower Saxony Basin and is equivalent to the Münder Formation in the German part of the basin (Erbacher et al., 2014; Schneider et al., 2018b).

Coevorden Formation

The Coevorden Formation mainly consists of marly claystones with occasional limestone beds. The depositional setting is fresh- to brackish-water lacustrine to marginal-marine lagoonal. The fresh water dominated depositional environment reflects the humid climate conditions characteristic for the earliest Cretaceous of NW Europe, often referred to as the 'Wealden' (after the comparable succession in the Weald Basin of southwest England, see e.g. Abbink et al., 2001b; Stollhofen et al., 2008). The formation is subdivided into three members, the Lower, Middle and Upper Coevorden members (Van Adrichem Boogaert & Kouwe, 1993; see also Fig. 7.10). The Lower Coevorden Member consists of grey, calcareous, occasionally sandy claystones. Limestone beds occur frequently in the basal part. The Middle Coevorden Member consists of grey, fossiliferous, silty claystones and is typically more calcareous than the other two members. The Upper Coevorden Member consists of brownish-grey, occasionally sandy claystones in which locally laminated organic-rich claystones occur, reflecting anaerobic bottom conditions (Figs 7.10, 7.11). These paper shales are the source rocks for the oil of the Schoonebeek Field (De Jager & Geluk, 2007). The age of the Coevorden Formation is late Ryazanian to earliest Valangian (Hoedemaeker & Herngreen, 2003) and it reaches a maximum thickness of 150 m. It is limited to the onshore Lower Saxony Basin and continues into Germany where the Isterberg Formation is its correlative equivalent (Erbacher et al., 2014).

Scruff Group

The Scruff Group contains lithostratigraphic units that were deposited in a marine depositional setting. It is divided into four formations: the Lutine, the Scruff Greensand, the Skylge and the Kimmeridge Clay formations (Van Adrichem Boogaert & Kouwe, 1993; Munsterman et al., 2012; see also Table 7.1). The Scruff Group is generally sandwiched between the underlying and predominantly non-marine Schieland Group and the overlying marine Rijnland Group. The Group ranges in age from late Oxfordian to late Ryazanian and units belonging to it are developed in the offshore Step Graben, Dutch Central Graben, Terschelling Basin and Vlieland Basin. It attains a maximum thickness of 850 m in the Dutch Central Graben. The deep-marine Kimmeridge Clay Formation reflects peak basin subsidence related to Late Cimmerian rifting.

Kimmeridge Clay Formation

The Kimmeridge Clay Formation consists mainly of claystones, which are siltier in its basal part. Stratigraphically up-section, dolomite streaks appear but they are less common near the basin margins. Based on the palynological content and on the predominance of claystones, an open marine offshore depositional setting has been determined (Munsterman et al., 2012). The age of the Kimmeridge Clay Formation is Kimmeridgian to middle Volgian (Verreussel et al., 2018) and it attains a maximum thickness of 1000 m. It is limited to the middle and northern part of the Dutch Central Graben and to isolated patches in the Step Graben, but does not extend into the Terschelling or Vlieland basins. The Kimmeridge Clay Formation conformably overlies the deltaic sandstones of the Upper Graben Formation (Figs 7.3, 7.4) and has correlative inter-

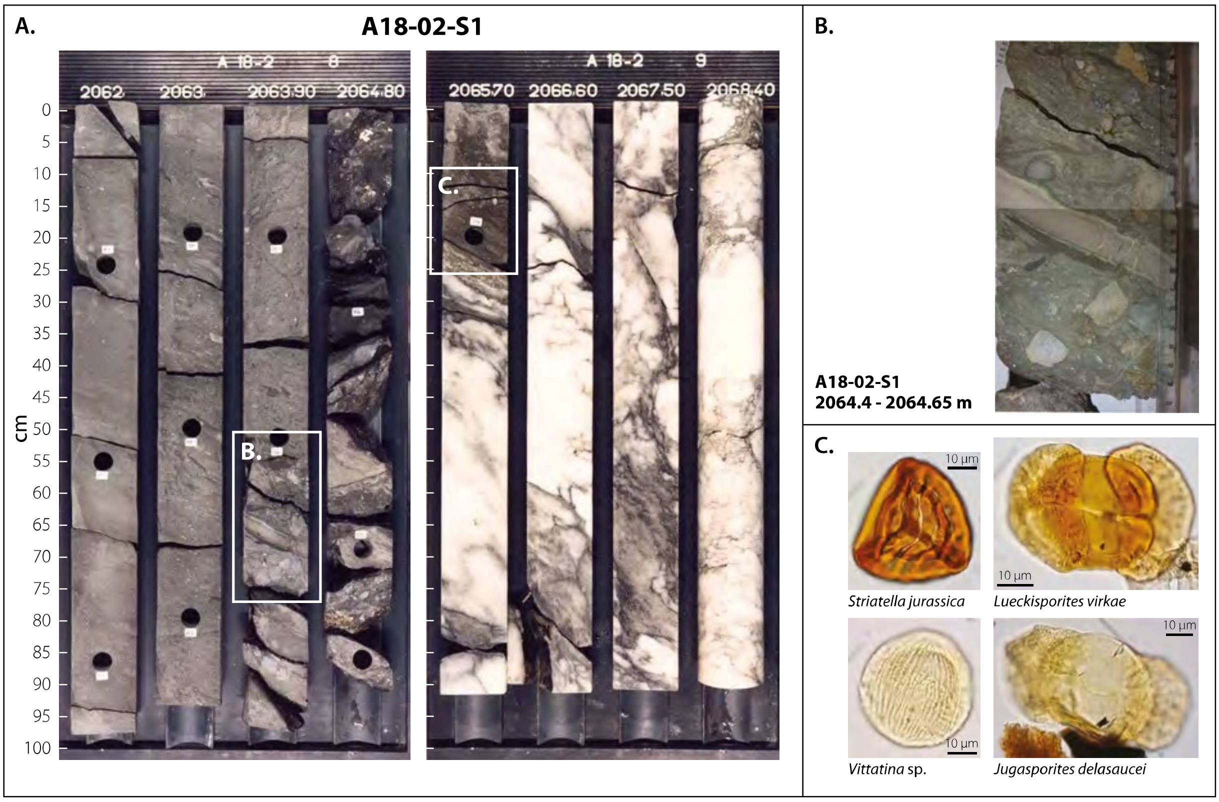


Figure 7.17. *a) Core photographs of interval 2062.0-2069.3m of well A18-02-S1 from the Step Graben in the northern Dutch offshore (see Fig. 7.1 for location; source: nlog.nl). The core displays the unconformable contact between the Permian Zechstein Group (white) and the Upper Jurassic Scruff Group (grey and black). Core photos from www.nlog.nl. b) The base of the Upper Jurassic Schieland Group is represented by sandstones and breccias of the Noordsvaarder Member. Among the large and angular clasts are limestones and dolomites from the Zechstein Group. The sandy matrix contains dinoflagellate cysts that indicate a Volgian age. c) The base of the Upper Jurassic sequence is a dark, laminated claystone that contains excellently preserved pollen and spores from the Permian, e.g.* Lueckisporites virkae, Vittatina sp. *and* Jugasporites delasaucei*, in combination with Jurassic spores such as e.g.* Striatella jurassica.

national equivalent units with widespread occurrence in the North Sea and adjacent basins, where they often display elevated total organic carbon content (Cooper et al., 1995; Van der Hoeven et al., 2022). Although the organic carbon content of the Kimmeridge Clay Formation in the Netherlands is somewhat elevated, it is not characterized as an oil-prone source rock (De Jager & Geluk, 2007; Remmelts et al., 2025, this volume).

Skylge Formation

The Skylge Formation includes the Upper Jurassic marine deposits below the Scruff Greensand Formation in the Terschelling Basin (Munsterman et al., 2012). The formation comprises discrete claystone and sandstone units which are ranked as members. These are the Oyster Ground Member, the Terschelling Sandstone Member, the Noordsvaarder Member and the Lies Member (Fig. 7.7). The early Volgian Oyster Ground Member lies at the base of the Skylge Formation in the basin centre of the Terschelling Basin and consists of parallel laminated claystones with numerous thin silty or sandy storm layers with abundant shell fragments, indicating a storm dominated lower shoreface depositional environment (Bouroullec et al., 2018; Verreussel et al., 2018). The succeeding Terschelling Sandstone Member consists of middle- to coarse-grained sandstones, often cross-bedded, with varying degrees of bioturbation. These sands mainly represent upper shoreface environments but also include back-barrier and tidal lagoon environments (Bouroullec et al., 2018) forming a stacked shoreface succession, likely representing a coastal barrier system with thick amalgamated barrier sandstone units organized in a belt. The upper sandstones thin towards the basin centre, while a more heterolithic unit represents the back-barrier lagoon (Fig. 7.8). The Heno Formation in the Danish offshore (Michelsen et al., 2003, Johannessen et al., 2010a,b) is considered to represent a correlative equivalent (Verreussel et al., 2018). The Terschelling Sandstone Member is of early Volgian to middle Volgian age (Verreussel et al., 2018), occurs in the southern part of the Terschelling Basin and reaches a maximum thickness of 150 m. The Noordsvaarder Member is time equivalent to the Terschelling Sandstone but is distributed mainly in the northern part of the Terschelling Basin and in the Dutch Central Graben. It consists of bioturbated glauconitic shoreface sandstones, comparable in composition and organization with the Scruff Greensand Formation. In the Step Graben, the Noordsvaarder Member is sometimes represented by a breccia or by an immature sandstone at the base of the Upper Jurassic sequence (Bouroullec et al., 2016b; see also Fig. 7.17). It reaches a maximum thickness of 310 m and is of early to middle Volgian age (Verreussel et al., 2018). In the northern part of the Terschelling Basin and in the southern part of the Dutch Central Graben, the Noordsvaarder Member is overlain by the Scruff Greensand Formation. Towards the centre of the Terschelling Basin, the top shales out into the Lies Member (Munsterman et al., 2012), which consists of claystones and siltstones that accumulated in a shallow marine depositional environment (Munsterman et al., 2012; see also Fig. 7.7). The age of the Lies Member is middle to late Volgian (Verreussel et al., 2018).

Scruff Greensand Formation

The Scruff Greensand Formation consists predominantly of intensely bioturbated greensands with a high glauconite content (Munsterman et al., 2012). Bedding, cross-bedding and other sedimentary features are rare, most having been obliterated by bioturbation. At the base of the formation sponge spicules are abundant and these intervals are sometimes referred to as the Scruff Spiculite Member. The sandstones were deposited in a lower shoreface to upper offshore environment (Bouroullec et al., 2018). The base of the formation is conformable in the Terschelling Basin, where it is characterized by a distinct coarsening trend following the fine-grained deposits of the underlying Lies Member of the Skylge Formation (Fig. 7.7). In other parts of the Dutch offshore the base is erosional and a hiatus separates the Scruff Greensand Formation from older units (Fig. 7.3). The Scruff Greensand Formation is often succeeded by claystones of the Lutine Formation and is limited to the northern part of the Dutch offshore, to the Step Graben, Dutch Central Graben, Terschelling Basin and the bordering platforms. The Scruff Greensand has no correlative equivalent in the German and Danish offshore as the formation shales out towards the north (Verreussel et al., 2018; see also Fig. 7.3). It reaches its maximum thickness of 180 m in the Terschelling Basin and is late Volgian to early Ryazanian in age (Verreussel et al., 2018).

Lutine Formation

The Lutine Formation consists of claystones. It is typically organic rich in the northernmost part of the Dutch offshore, where the organic-rich intervals are ranked as a separate member, the Clay Deep Member (Munsterman et al., 2012). The depositional environment is open marine, but with anoxic bottom conditions for the Clay Deep Member. The Lutine Formation is thin, with a maximum thickness of 150 m and its distribution is limited to the northern part of the Dutch offshore, the Step Graben, Dutch Central Graben and Terschelling Basin. The age of the Lutine Formation is uppermost Volgian to upper Ryazanian (Verreussel et al., 2018). The claystones of the Lutine Formation typically overlie sandstones of the Scruff Greensand Formation reflecting a regionally recorded basal Cretaceous flooding (Figs 7.3, 7.4, 7.7, 7.8). The Lutine Formation can be distinguished from the claystones of the succeeding

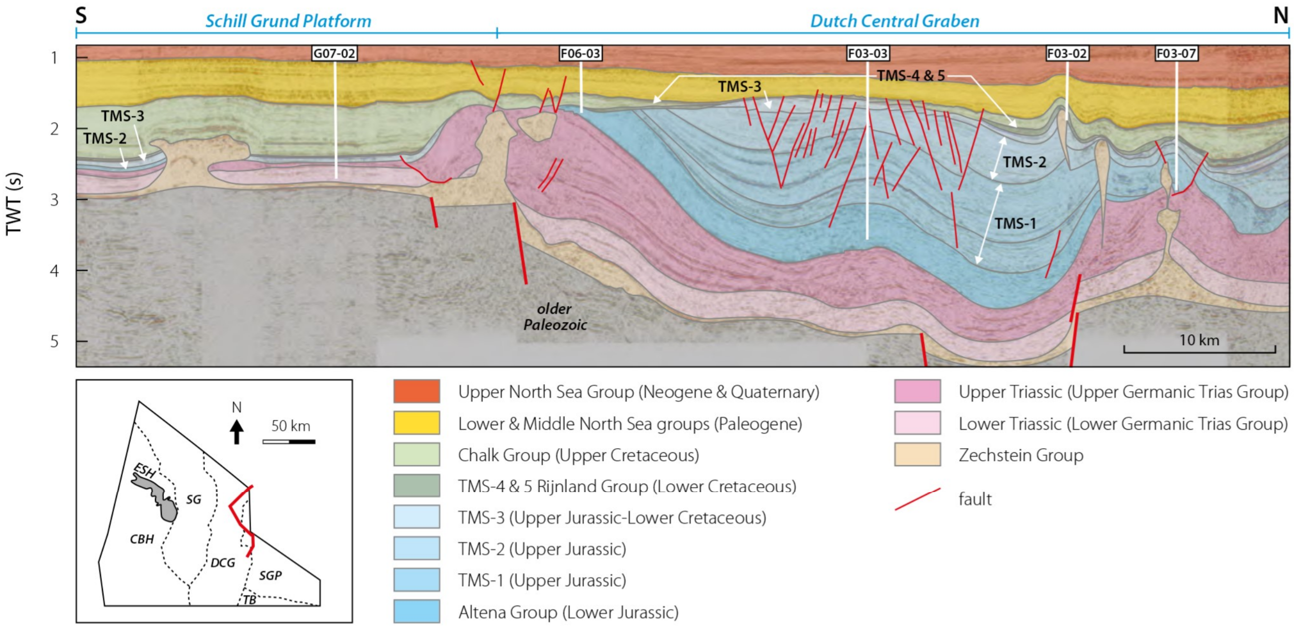


Figure 7.18. Seismic time section through part of the Schill Grund Platform and the Dutch Central Graben showing the prominent role of salt movement in the basin development. Due to the Late Cretaceous inversion, the Chalk Group is relatively thick on the Schill Grund Platform but is virtually absent in the Dutch Central Graben. Note that TMS-1, representing the initial phase of the Late Cimmerian rifting, is very expanded in the northern part of the Dutch Central Graben.

Vlieland Claystone Formation by a subtle kick on the wireline logs, coinciding the Base Cretaceous Unconformity (Ineson et al., 2022, see also Fig. 7.4).

Rijnland Group

All lithostratigraphic units belonging to the Rijnland Group were deposited in marine depositional environments and are of Early Cretaceous age. The Group is subdivided into one stand-alone formation, the Holland Formation, and one subgroup, the Vlieland Subgroup (Table 7.1). The Rijnland Group is widely distributed across all Mesozoic basins in the Netherlands and generally overlies other Upper Jurassic-Lower Cretaceous strata. It is stratigraphically overlain by the Upper Cretaceous Chalk Group (Van Lochem et al., 2025, this volume) and is Early Cretaceous, Valanginian to Albian in age. The Rijnland Group attains a maximum thickness of 1700 metres in the West Netherlands Basin. The widespread distribution and the predominance of layer cake type of internal organization reflects a relatively quiet tectonic phase with relative uniform subsidence following the Late Cimmerian rifting.

Holland Formation

The Holland Formation consists of marls, claystones and glauconitic sands (greensands), with locally thin layers of organic-rich shale. Greensands, represented by the Holland Greensand Member and the Spijkenisse Greensand Member, occur mainly in the West Netherlands Basin, while other members, including the Lower Holland Marl Member, Middle Holland Claystone Member and the Upper Holland Marl Member are widely distributed across all Mesozoic basins (Figs 7.3, 7.7, 7.10, 7.12, 7.15). The depositional setting was offshore marine. The age of the Holland Formation is Aptian to Albian (Jeremiah et al., 2010) and it is 100 to 500 metres thick.

Vlieland Subgroup

The Vlieland Subgroup consists of two partially laterally equivalent formations, the Vlieland Sandstone Formation and the Vlieland Claystone Formation (Table 7.1). These formations may be laterally equivalent, in which case they represent a trend in the depositional environment from proximal to distal, or they alternate stratigraphically, in which case they represent regressive-transgressive cycles. The formations may also alternate stratigraphically in which case the sandstone-claystone alternations represent regressive-transgressive cycles. These lateral and vertical facies trends are best illustrated in the West Netherlands Basin (Figs 7.12, 7.13). The age of the Vlieland Subgroup is Early Cretaceous, Valanginian to Barremian (Van Adrichem Boogaert & Kouwe, 1993).

Vlieland Claystone Formation

The Vlieland Claystone Formation consists predominantly of claystones, with subordinate marls, thin sandstones and siltstones. Eight members have been defined, mostly in order to distinguish claystone units that are intercalated within sandstone units. This is best illustrated in the Lower Saxony Basin where the Westerbork Member, Ruinen Member, Schoonebeek Member and the Bentheim Claystone Member define fine-grained lithological units associated with the Bentheim Sandstone and Gildehaus Sandstone members (Fig. 7.10). The age of the Vlieland Claystone Formation ranges from Valanginian to Barremian (Van Adrichem Boogaert & Kouwe, 1993) and the thickness varies between 200 and 600 metres. The Vlieland Claystone Formation is widely distributed across both the onshore and offshore basins.

Vlieland Sandstone Formation

The Vlieland Sandstone Formation is subdivided into thirteen members representing a wide variety of depositional environments and ages (Van Adrichem Boogaert & Kouwe, 1993). Most of the members are limited in their distribution to a single basin. For example, the Bentheim and Gildehaus Sandstone members are found only in the Lower Saxony Basin (Fig. 7.10). The Bentheim Sandstone Member is extensively exposed near the town of Bad Bentheim in Germany where it consists of massive and locally cross-bedded clean sandstones. In the subsurface of the Netherlands it consists of massive calcareous sandstones with abundant shell fragments and lignite particles. The sandstone was deposited in a coastal to offshore setting. The younger Gildehaus Sandstone Member consists of coarse-grained very glauconitic sandstones, often with abundant sponge spicules. The Friesland Member is found in the Terschelling Basin, the Broad Fourteens and Vlieland basins and on the margins of the Lower Saxony Basin (Figs 7.3, 7.7, 7.9, 7.10). The Friesland Member consists of bioturbated sandstones and represents shallow to open marine environments in a transgressive setting. In the Broad Fourteens Basin, the Vlieland Sandstone is represented by massive sandstone units like the Kotter and the Helder members, deposited in a shallow marine shoreface or barrier island depositional environment and by fining-upward transgressive sheet sandstones such as the Rijn Member. Along the southern and eastern margin of the West Netherlands Basin (Fig. 7.1) four members of the Vlieland Sandstone Formation are stacked as a series of successive shoreface complexes. From old to young these are: the Rijswijk, the Berkel Sandstone, the IJsselmonde Sandstone and the De Lier members (Figs 7.12, 7.13). The erosive base of the late Hauterivian to Barremian Rijswijk Member marks the base of the Rijnland Group in the West Netherlands Basin (Jeremiah et al., 2010). The glauconitic sandstones of the late Barremian De Lier Member cover a large part of the West Netherlands Basin and represent the top of the Vlieland Subgroup there (Jeremiah et al., 2010). The thickness of most members of the Vlieland Sandstone Formation is typically in the order of 50 to 100 metres and reaches a maximum of 200 metres for the IJsselmonde Sandstone and the Helder members in the West Netherlands and Broad Fourteens basins.

Igneous Rock

Zuidwal Volcanic Formation

The Zuidwal Volcanic Formation consists of massive volcanic rocks and brecciated volcanic agglomerates (Herngreen et al., 1991; Van Adrichem Boogaert & Kouwe, 1993). The formation is only recognized in well Zuidwal-01 (ZDW-01), which was drilled in the volcanic conduit of the Zuidwal volcano (Van Bergen et al., 2025, this volume; see also Figs 7.7, 7.9). No less than 1058 metres of the Zuidwal Volcanic Formation were penetrated until the well reached total depth at 3002 m.

Sedimentary and structural development

The geology of the Late Jurassic-Early Cretaceous interval in the Netherlands is governed to a large extent by the Late Cimmerian rift phase and salt tectonics (Bouroullec & Ten Veen, 2025, this volume). A major and widespread hiatus separates deposits of the Late Cimmerian rift phase from the underlying Middle Jurassic or older sediments (Kombrink et al., 2012). The rifting occurred in discrete steps which are reflected in the sedimentary record as genetically related accumulations of sediments or tectonostratigraphic megasequences (Bouroullec et al., 2018; Verreussel et al., 2018; see also Fig. 7.18). For each basin, the timing, style and intensity of rift activity differs, which is reflected in the stratigraphic thickness of the tectonostratigraphic megasequences and in the facies distribution, in particular in the occurrences of sandstone units (Figs 7.19, 7.20). The inherited structural grain of the basins plays an important role in the rift development and lingers on longest in the West Netherlands Basin. Five tectonostratigraphic megasequences are distinguished and described below.

TMS-1 Bathonian-early Kimmeridgian

TMS-1 represents the onset of the Late Cimmerian rift. The initial phase took place under an east-west extensional regime and had a pronounced effect on the Dutch Central Graben area (Figs 7.3, 7.4, 7., 7.7). The oldest deposits that can be ascribed to Late Cimmerian rifting in the Netherlands are middle Callovian (Verreussel et al., 2018) and are represented in the Dutch Central Graben by the Lower Graben Formation (Fig. 7.5). Hundreds of metres of sediments were deposited during TMS-1 (Verreussel et al., 2018; see also Figs 7.18, 7.20). In most other basins, such as the Terschelling Basin, the Vlieland Basin, the Lower

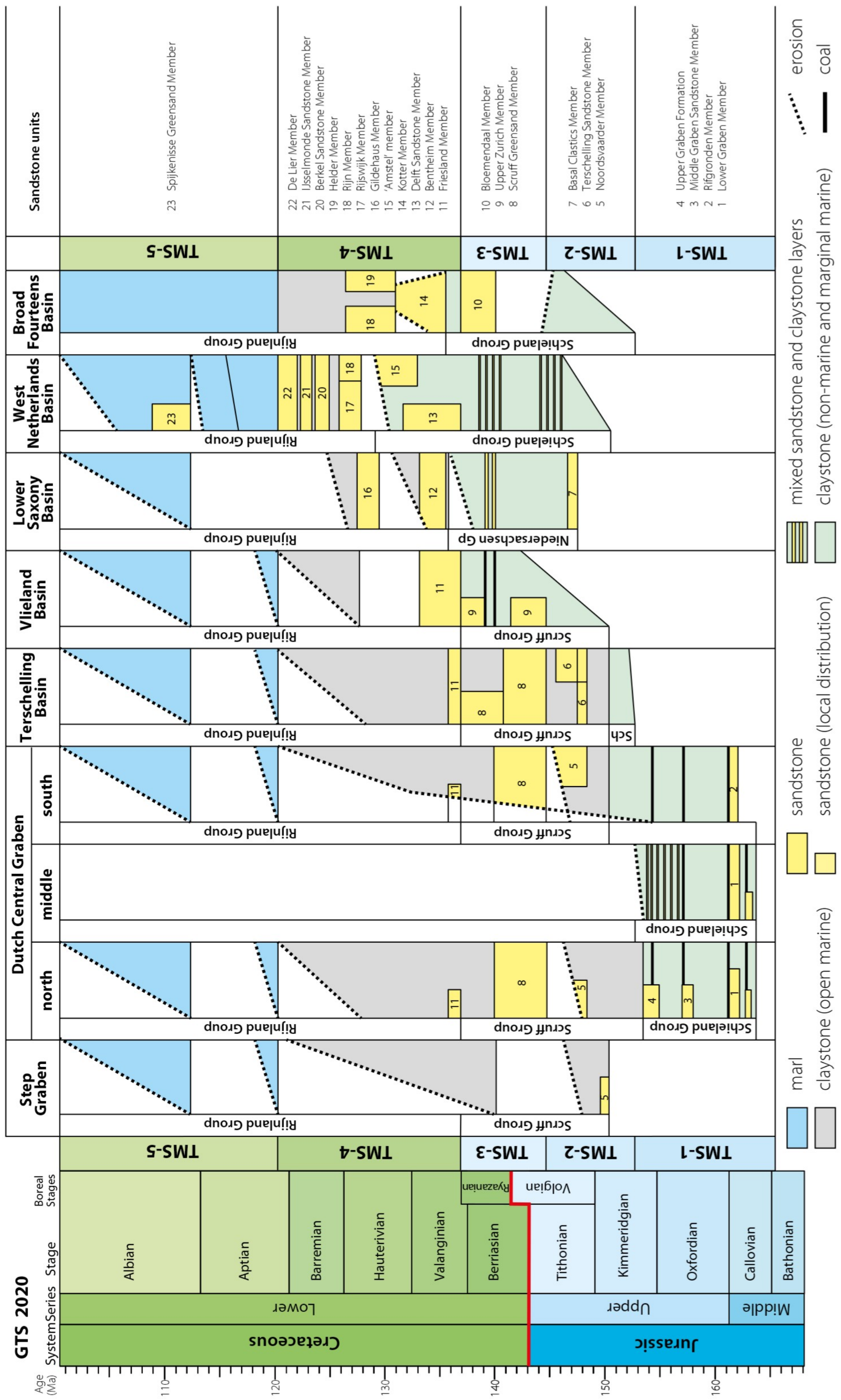


Figure 7.19. Generalized Wheeler diagram displaying simplified time and facies relationships of the Callovian to Albian for each of the basins discussed. The different facies types from the Wheeler diagrams and the well panels are summarized into five main categories: marl, open marine claystone, sandstone, mixed sandstone and claystone layers and non-marine to marginal marine claystone.

Saxony Basin and the Broad Fourteens Basin, Bathonian to early Kimmeridgian deposits are either missing or very thin (Wong, 2007; Van Adrichem Bogaert & Kouwe, 1993; see also Figs 7.7, 7.10, 7.12, 7.15, 7.19, 7.20).

In the Dutch Central Graben, the east-west extension triggered migration and withdrawal of Zechstein salt from the central parts of the basin towards its eastern and western margins and this led to the development of oval-shaped sub-basins that were initially disconnected from the German and Danish sectors of the Central Graben (Bouroullec et al., 2016b, 2018). Within these basins, fluvial and marginal marine sediments of the Lower Graben Formation accumulated (Fig. 7.3), the thickest accumulations of which are located in the middle and northern part of the Dutch Central Graben (Figs 7.4, 7.5). The upward transition to the deposits of the Middle Graben Formation occurred while eustatic sea level was rising and the paleoclimate was changing. This change corresponds to the Callovian-Oxfordian boundary and is marked by the occurrence of three thick and continuous coal layers, indicating that extensive swamps existed at the time (Verreussel et al., 2018; Bouroullec et al., 2018; see also Figs 7.3-7.5). During the Oxfordian, mainly claystones were deposited in lacustrine to restricted marine settings but the succession is interrupted multiple times by fluvial-deltaic sandstone units with associated coal layers, such as the Middle Graben Sandstone Member and the Upper Graben Formation (Figs 7.3-7.5). These coarsening upward units represent small-scale deltas prograding from the basin margins into the basin centre (Bouroullec et al., 2018). In the early Kimmeridigian, the Dutch Central Graben gradually developed into a deep marine basin, reflected by the organic-rich mudstones with dolomite streaks of the Kimmeridge Clay Formation. The deep marine setting continued across the boundary from TMS-1 to TMS-2.

In the Lower Saxony Basin uplift and subaerial exposure occurred during TMS-1 and led to development of a regional erosional unconformity, especially along the western and northern margins of the Lower Saxony Basin (Klassen, 1984; Betz et al., 1987).

In the West Netherlands Basin, sedimentation continued from the Bathonian to the Oxfordian without prolonged interruptions, as seen in the cyclic alterations of sand, sandy limestone and marls of the Brabant Formation (Van Adrichem Boogaert & Kouwe, 1993; Trabucho Alexandre & Wong, 2025, this volume). The Brabant Formation belongs to the Altena Group that genetically predates the Late Cimmerian rift phase (Trabucho Alexandre & Wong, 2025, this volume). The introduction of sand into the West Netherlands Basin during TMS-1 times may indicate increased erosion from the bordering highs in response to incipient tectonic activity related to the onset of Late Cimmerian rifting.

TMS-2 late Kimmeridgian-late Volgian

TMS-2 was the most active phase of the Late Cimmerian rift. All Mesozoic basins were affected and sediments accumulated in them (Figs 7.3, 7.7, 7.10, 7.12, 7.15, 7.19, 7.20). At the start of TMS-2 an important change in the extensional regime occurred; the E-W extension that characterized TMS-1 changed into an NE-SW extensional direction (Zanella & Coward, 2003; Verreussel et al., 2018). This change provoked the reactivation of fault systems that had inherited a NW-SE trending structural grain from the Paleozoic and had a profound effect on the Dutch basins. The Terschelling, Vlieland, West Netherlands and Broad Fourteens basins commenced to subside and accumulated large volumes of sediment (Figs 7.7, 7.10, 7.12, 7.15).

In the Step Graben, marine sediments of the Skylge Formation appeared for the first time in the late Kimmeridgian-early Volgian (Verreussel et al., 2015), but they are patchy and limited in extent. The same applies to the Schill Grund Platform (Fig. 7.1) on the eastern side of the Dutch Central Graben, where only thin stacks of sediment belonging to TMS-2 are found (Fig. 7.18). The base of the Upper Jurassic-Lower Cretaceous succession in the Step Graben is often represented by the Scruff Greensand or Lutine formations belonging to TMS-3 but sometimes by sandstones and breccias of the Noordsvaarder Member from TMS-2, as exemplified in a cored section from well A18-02-S1 (Fig. 7.17).

In the northern part of the N-S trending Dutch Central Graben, deep marine mudstones of the Kimmeridge Clay Formation continued to be deposited (Figs 7.3, 7.4), but the depocentres gradually shifted northward and a NW-SE trending branch of the graben developed into a more actively subsiding basin (Bouroullec et al., 2018). The basin development of the Dutch Central Graben is largely controlled by activity in the underlying salt, which is reflected in the development of turtle structures (Bouroullec & Ten Veen, 2025, this volume). At the early to middle Volgian transition, salt was evacuated from below the thick Upper Jurassic-Lower Cretaceous piles of sediment in the basin centre, with the resultant development of large-scale turtle structures (Bouroullec et al., 2018). With no more space for accommodation, these structures emerged and their tops became eroded. Alongside these turtles, for example in well L02-05, rapidly subsiding rim synclines developed and were filled in with sandy deposits of the Noordsvaarder Member (Fig. 7.3). The southernmost part of the Dutch Central Graben never developed into a deep marine basin and remained dominated by fluvial to marginal marine depositional environments (Abbink et al., 2006; see also Fig. 7.3). The NE-SW extensional regime invoked strike-slip movement on the N-S trending faults bordering the Dutch Central Graben (Peeters, 2016) which added to the complexity of the basin evolution.

In the Terschelling Basin, non-marine sediments of the Friese Front Formation lie at the base of the Upper Jurassic-Lower Cretaceous succession. These are succeeded by offshore marine mudstones of the Oyster Ground Member (Figs 7.7, 7.8). The arrival of marine sediments in the Terschelling Basin coincides with the *eudoxus* maximum flooding surface (Fraser et al., 2003; see also Fig. 7.7). On the northwestern side of the basin, erosion from the turtle structures in the Dutch Central Graben resulted in the deposition of a wedge of poorly sorted sandstones of the Noordsvaarder Member (Bouroullec et al., 2016a). On the

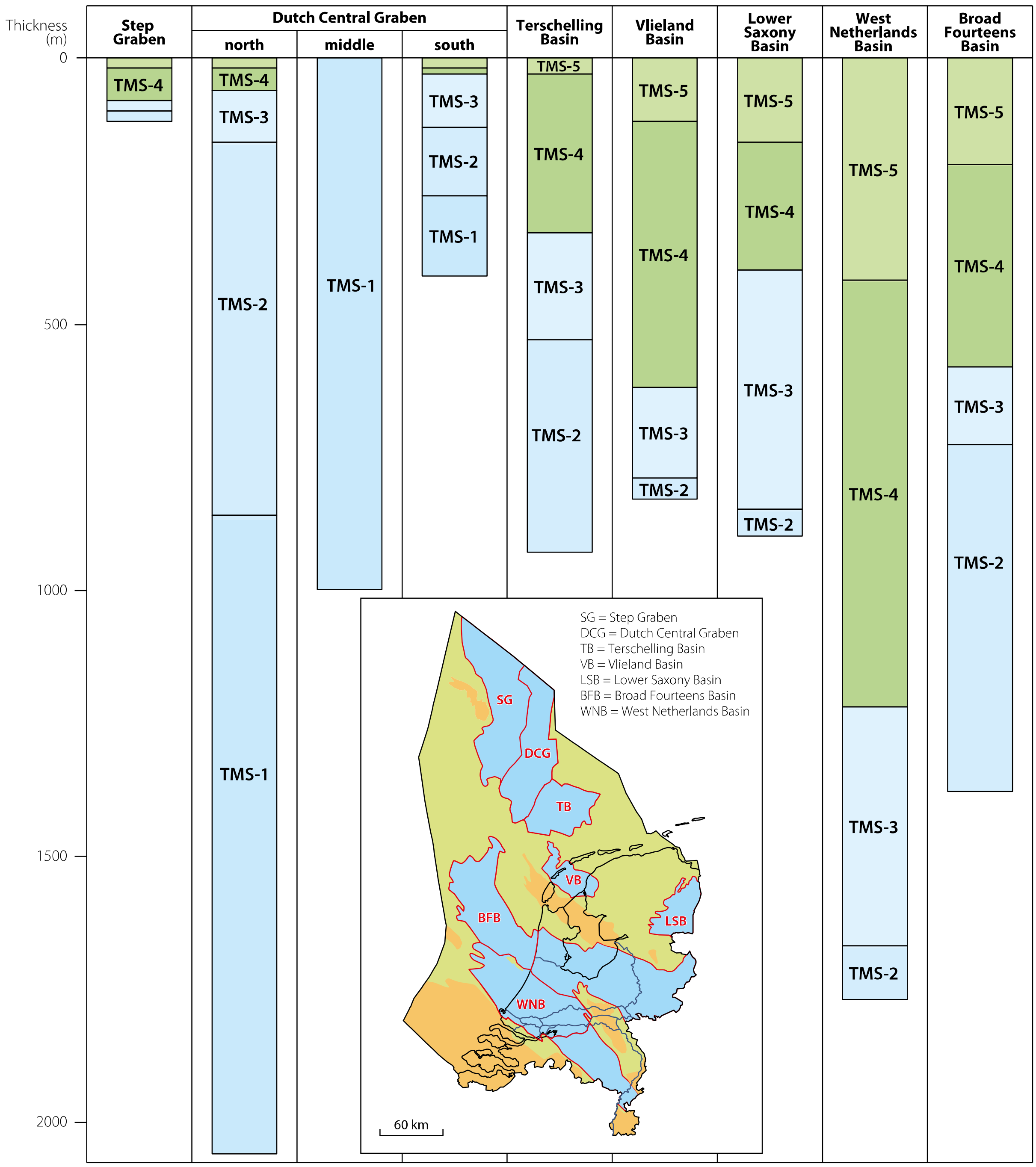


Figure 7.20. *Generalized thicknesses of tectonostratigraphic megasequences (TMS) per basin. The thicknesses provide an indication of the shift of depocentres through time.*

southeastern side of the basin close to the basin margin, log-character and palynological analyses indicate that a shoreface complex including barriers and back-barrier lagoons developed at around the same time. These sands are classified as the Terschelling Sandstone Member and onlap onto the Central Offshore Platform that borders the Terschelling Basin to the south (Figs 7.7, 7.8).

In the Vlieland Basin, the oldest sediments associated with the Late Cimmerian rift are Volgian marginal marine or estuarine claystones of the Zurich Formation (Figs 7.7, 7.9). The Hantum Fault Zone (Fig. 7.1) became an intermittent platform area with subsiding basins on both the northern (Terschelling Basin) and southern sides (Vlieland Basin). However, the accommodation space created during TMS-2 in the Vlieland Basin was considerably less (up to 100 m thick sequence) than that of the Terschelling Basin (Fig. 7.20).

In the Lower Saxony Basin, the oldest sediments associated with the Late Cimmerian rift are latest Kimmeridgian coarse-grained sandstones and breccias of the Basal Clastics Member of the Weiteveen Formation (Figs 7.10, 7.11, 7.19). At that time, the Lower Saxony Basin was isolated, which led to brackish marine conditions and eventually in the middle Volgian to the development of hypersaline conditions. Evaporites formed during this period show cyclic successions of carbonates, anhydrite, halite, and claystone (Betz et al., 1987). Warm and arid conditions and associated facies continued into the early Ryazanian, approximately halfway TMS-3 (Fig. 7.10). The general lack of siliciclastic sediments indicates that the tectonic setting was less dynamic than for instance in the Dutch Central Graben. The average thickness of TMS-2 deposits is estimated to be less than 100 m (Fig. 7.20).

In the Broad Fourteens and West Netherlands basins, the major bounding faults were re-activated in response to the E-W extension initiated at the start of TMS-2. In both basins thick Zechstein salt accumulations are absent and the basin evolution was primarily controlled by fault movements. The numerous intra-basinal faults in the West Netherlands Basin were subjected to oblique-slip faulting during TMS-2, which resulted in a series of fault blocks consisting of half-grabens, intermediate highs and relay ramps (Racero-Baena & Drake, 1996; see also Fig. 7.12). Differential subsidence acted on these fault blocks and caused large variations in the thickness of the non-marine and marginal marine units (Mijnlieff, 2020) of the Alblasserdam Member in the West Netherlands Basin (Figs 7.12, 7.13) and of the Aerdenhout, Fourteens Claystone and Driehuis Mottled Claystone members in the Broad Fourteens Basin (Figs 7.15, 7.16). Deposits of substantial thickness accumulated during TMS-2, especially in the Broad Fourteens Basin (Fig. 7.20). Note that the half-grabens were inverted into pop-up and flower structures during the Late Cretaceous inversion (Racero-Baena & Drake, 1996; De Jager, 2003; Duin et al., 2006).

TMS-3 late Volgian-Ryazanian

TMS-3 reflects the transition from the active Late Cimmerian rift phase to the post-rift sag phase and is characterized by hiatuses, unconformities and sandstone deposition (Bouroullec et al., 2018; Verreussel et al., 2018; see also Fig. 7.19).

In the Step Graben, an hiatus usually separates sediments corresponding to TMS-3 from the underlying Upper Jurassic interval (Fig. 7.19). TMS-3 is often represented by a thin succession of marine claystones of the Lutine Formation (Verreussel et al., 2015, 2018; see also Fig. 7.20). The flooding of the Step Graben and deposition of the Lutine Formation reflects a relative sea-level rise at that time.

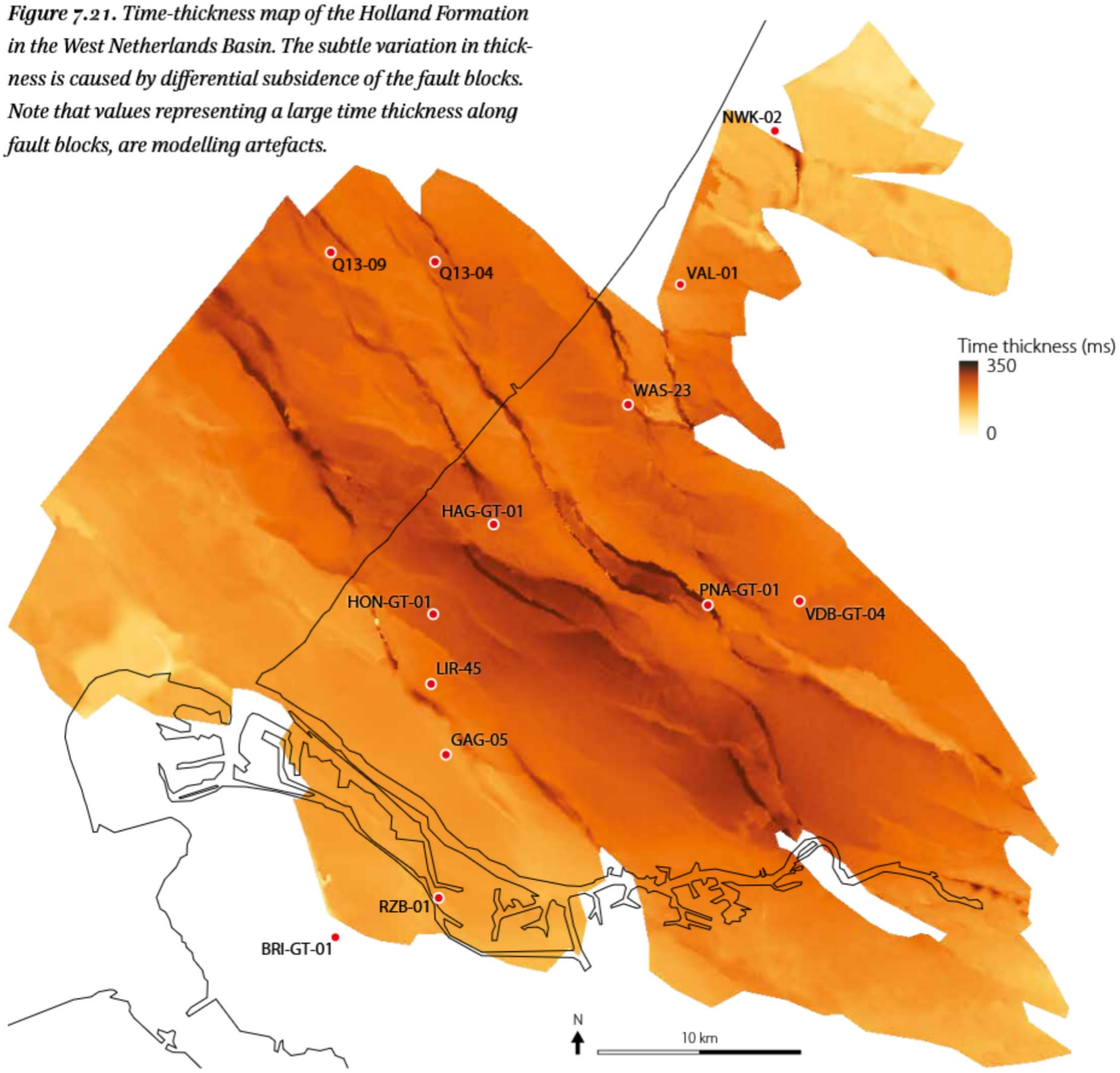
In the Dutch Central Graben the fault activity and salt movement that characterized TMS-2 gradually came to an end and the existing relief was flattened. The boundary between TMS-2 and TMS-3 is erosional and the base of the latter consists of glauconitic sandstones of the Scruff Greensand Formation (Figs 7.3, 7.4, 7. 7, 7.8). By the end of TMS-2, the Dutch Central Graben was characterized by a rugged landscape of emergent areas in a shallow sea, situated above turtle structures in the centre of the basin and shoulders and diapir crests near the basin margin. The sands derived from the erosion of these structures filled the remaining depressions in the existing relief. In the northern part of the Dutch Central Graben, for example in well B18-03 (Fig. 7.4), the Scruff Greensand is succeeded by open marine claystones of the Lutine Formation and TMS-3 reaches a thickness of 100 m (Fig. 7.20). The presence of open marine claystones reflects high eustatic sea levels at that time (Verreussel et al., 2018).

In the Terschelling Basin, the transition from TMS-2 to TMS-3 is conformable. This is one of the few areas in the Netherlands where the Jurassic-Cretaceous boundary interval is continuously marine and is not affected by erosion (Bouroullec et al., 2016a; see also Fig. 7.7). The Scruff Greensand Formation overlies the underlying Skylge Formation and reaches thicknesses in excess of 300 metres in the basin centre (Verreussel et al., 2018). The shale content of the Scruff Greensand Formation gradually increases upward, which is reflected in increasing gamma-ray values on well logs (see e.g. well L06-02 and M04-04 in Fig 7.8). Eventually, the sandstones were replaced by claystones of the Lutine Formation, indicating a more distal depositional setting.

In the Vlieland basin marine influence is recorded for the first time in TMS-3, represented by marginal marine sandstones and volcaniclastic sediments of the Wadden Volcaniclastic and Upper Zurich members (Fig. 7.7). The age of the volcaniclastic sedimentary rocks indicates that the Zuidwal volcano was active during TMS-3. The marine sediments are followed by non-marine claystones, thin sandstones and thick coal layers, indicating a back-barrier lagoonal setting and a regressive sea-level trend. The depositional cycle of TMS-3 ends with massive coastal sandstones of the Upper Zurich Member that reach a thickness of over 50 metres in well Vlieland Oost-1 (VLO-01) and signal the end of the most active rift phase (Fig. 7.9).

In the Lower Saxony Basin, the calcareous and evaporitic deposits of the Weiteveen Formation are replaced by marly claystones and limestone beds of the Coevorden Formation in TMS-3 (Figs 7.10, 7.11). The change from evaporitic to fresh water dominated depositional environments reflects the change to the humid climate conditions of the 'Wealden', which characterized the earliest Cretaceous of NW Europe (Abbink et al., 2001b; Stollhofen et al., 2008). TMS-3 ends with the organic-rich claystones of the Upper Coevorden Member that form the source rock for the oil of the Schoonebeek Field (De Jager & Geluk, 2007; Remmelts et al., 2025, this volume).

Figure 7.21. Time-thickness map of the Holland Formation in the West Netherlands Basin. The subtle variation in thickness is caused by differential subsidence of the fault blocks. Note that values representing a large time thickness along fault blocks, are modelling artefacts.



In the West Netherlands Basin, sedimentation of the non-marine Alblasserdam Member probably continued uninterruptedly throughout TMS-3 and filled the half-graben fault blocks (Fig. 7.12). However, based on the assumption that the fault activity decreased in the West Netherlands Basin during TMS-3 (Mijnlieff, 2020), it is conceivable that erosion occurred at this time and that parts of the Delft Sandstone and Rodenrijs Claystone members are separated by a time gap from the Alblasserdam Member, but so far unequivocal data to corroborate that scenario are lacking.

In the Broad Fourteens Basin erosion occurred during TMS-3 (Fig. 7.15). An hiatus separates the late Ryazanian Bloemendaal Member from the underlying Driehuis Mottled Claystone Member. Also in the Broad Fourteens Basin, a volcano must have been active at this time: volcanoclastic sediments occur in well P06-01 (Figs 7.15, 7.16; also see Van Bergen et al., 2025, this volume). The marine sandstones of the Bloemendaal Member interfinger with claystones and coals of the lagoonal Neomiodon Member. This coastal-lagoonal complex represents the transition from the active rift phase to the post-rift sag phase.

TMS-4 Valanginian-Barremian

TMS-4 represents the post-rift thermal sag following the Late Cimmerian rift and is represented by marine claystones and sandstones of the Rijnland Group that extend outside the basins onto the bordering platforms (Duin et al., 2006). In the Danish offshore, the base of TMS-4 is referred to as the Base Cretaceous Unconformity and is represented by bioturbated sandstones associated with slumped beds and with a water mass overturn from stratified and poorly oxygenated to oxygenated (Ineson et al., 2022). The slump features are linked by the authors to transgressive erosion and de-stabilization of the slopes along the basin margins.

On the Step Graben, TMS-4 is represented by a thin Vlieland Claystone Formation (Fig. 7.20). The absence of sandstones and the presence of a thin claystone unit indicates that subtle subsidence continued during TMS-4 in a relatively distal marine setting.

In the Dutch Central Graben, TMS-4 is either thin or missing due to erosion that took place during Late Cretaceous inversion (Figs 7.3, 7.4, 7.20). In wells B18-03 and F03-01, a kick in the gamma-ray log is observed at the base of the Rijnland Group, followed by a gradual increase (Fig. 7.4). This probably reflects erosion and a transgression and is equivalent to the Base Cretaceous Unconformity in the Danish offshore.

In the Terschelling Basin, claystones of the Vlieland Claystone Formation dominate TMS-4 and attain a thickness of 400 m or more (Figs 7.7, 7.20). Apparently, subsidence continued throughout the Valanginian, Hauterivian and Barremian without interruption and created substantial accommodation space. Often the distinction between the fine-grained Lutine and Vlieland Claystone formations is difficult to make, unless the thin Friesland Member of the Vlieland Sandstone Formation separates the two.

In the Vlieland Basin, the base of TMS-4 is characterized by the presence of the thick sandstone package of the Friesland Member (Figs 7.7, 7.9) which in well Vlieland Oost-1 (VLO-01) reaches a thickness of 150 metres, but which thins out rapidly towards the Terschelling Basin. The depositional setting of the Vlieland Basin was more proximal than that of the Terschelling Basin and sands coming from the Texel-IJsselmeer High accumulated there.

In the Lower Saxony Basin, TMS-4 is also characterized by a marine transgression in the Valanginian that established a shoreface complex in the area and resulted in the deposition of the Bentheim Sandstone Member (Figs 7.10, 7.11, 7.19), the main reservoir unit of the Dutch Schoonebeek oil field (De Jager, 2007) and which has also been extensively quarried in Germany for building stone (Dubelaar & Nijland, 2015). In the Hauterivian stage, a second shoreface complex developed, represented by the Gildehaus Sandstone Member. A small erosional gap is inferred between the Gildehaus Sandstone and the Bentheim Sandstone members (Vis et al., 2018; see also Figs 7.10, 7.19).

In the West Netherlands Basin, TMS-4 equivalent strata reach a thickness in excess of 700 meters and (Fig. 7.20), demonstrate that substantial TMS-3 subsidence continued for another 15 million years. There are, however, indications that the basin was affected by readjustment after TMS-3. An unconformity in the Hauterivan separates the Rijnland Group from the underlying Schieland Group (Figs 7.12, 7.14). The non-marine Alblasserdam Member that was deposited during TMS-2 and TMS-3 was succeeded by marginal marine deposits in the Valanginian. Deceleration of fault activity in TMS-3, a rise in base level and increasing marine influence led to the deposition of coastal sands of the Delft Sandstone Member, lagoonal claystones of the Rodenrijs Claystone Member and beach/barrier sandstones of the informal Amstel member. The stratigraphic relationships of these marginal marine units are complex, the Delft Sandstone Member for example is diachronous (Fig. 7.14) and the distinction between sandstones from the Delft Sandstone Member and sandstones from the Alblasserdam Member is not easy to establish based on wireline logs alone. The Schieland Group is succeeded by shallow marine sandstones of the Rijswijk and Rijn members, which are widely distributed across the basin and display erosive bases. These two members herald a change to marine conditions that persisted for the remainder of TMS-4. Note that the Oosterhout Platform, a narrow fault block near IJsselmonde and Ridderkerk (Fig. 7.1) remained in a non-marine environment for much longer (Figs 7.12, 7.13). Marine conditions reached the Oosterhout Platform in the latest Barremian when the De Lier Member onlapped onto the basin margin (Jeremiah et al., 2010; see also Figs 7.12, 7.13). The coastal sandstone units of TMS-4 display an onlapping pattern in the West Netherlands Basin. The occurrence and distribution of these units are mainly determined by eustatic sea-level variations (Jeremiah et al., 2010), but correlations between wells are not straightforward, as the marginal marine sandstones grade into finer grained sediments across short distances.

In the Broad Fourteens Basin, marine conditions were already reached at the base of TMS-4, where thick and massive sandstones of the Kotter and Helder members occur (Figs 7.15, 7.16). The provenance of these transgressive sands were probably the footwall shoulders of the large basin-bounding faults that were subjected to erosion after the active rift phase. The sandstones are succeeded by the open marine mudstones of the Vlieland Claystone Formation.

TMS-5 Aptian - Albian

In the North Sea area, TMS-5 marks the transition into the Late Cretaceous carbonate world. From a wider and more global perspective, the Aptian and Albian concluded the break-up of Pangea and paved the way for the next plate tectonic event, the alpine collision (De Jager, 2003). Large parts of the Netherlands had become fully marine by this time and the depositional areas were mostly located far away from major land masses.

In the Step Graben, the Dutch Central Graben, the Terschelling, Vlieland and Lower Saxony basins, TMS-5 is represented by thin successions of marls and claystones of the Holland Formation. A hiatus generally separates the Lower Holland Marl Member from the Albian Middle

Holland Claystone and Upper Holland Marl members (Van Adrichem Boogaert & Kouwe, 1993; see also Fig. 7.19). The hiatus has been ascribed to the Austrian tectonic phase (Herngreen & Wong, 2007) and is most evident in the Lower Saxony Basin where the entire Aptian is missing (Vis et al., 2018; see also Fig. 7.19).

In the Broad Fourteens and West Netherlands basins, the base of the Aptian is represented by the Lower Holland Marl Member, which displays very high gamma-ray readings at its base. The fossiliferous and organic-rich shale is time-equivalent to the Fischschiefer, a globally recognized black shale that reflects a regional maximum flooding (Jeremiah et al., 2010) and a global anoxic event (OAE-1a, Jenkyns, 2010). In the West Netherlands Basin, minor thickness variations in the Holland Formation can be seen on seismic images (Fig. 7.21), which indicates that differential subsidence still acted on the fault blocks within the basin.

Concluding remarks

The sedimentary rocks that were deposited during the Late Jurassic to Early Cretaceous are of economical and historical interest to Dutch society. For example, in 1648 the impressive Royal Palace of Amsterdam was constructed entirely out of the Lower Cretaceous Bentheim Sandstone, which was quarried just across the border in present day Germany. In the year 1943 oil was discovered in the small Dutch community of Schoonebeek from the same sandstone unit. For many years the Schoonebeek discovery was the largest onshore oil field in Western Europe. Not much later, Lower Cretaceous sandstones in and around Rijswijk in the western Netherlands proved oil bearing and, at the present-day, the Lower Cretaceous Delft Sandstone Member from the same area is being targeted for geothermal energy. Offshore, the Lower Cretaceous sandstones are considered for CO_2 storage.

Acknowledgements

Many current and former colleagues from the Geological Survey of the Netherlands and peers from academia contributed to knowledge of the Upper Jurassic-Lower Cretaceous geology, which is gratefully acknowledged. Industries stimulated and sponsored numerous biostratigraphic and integrated studies through which much of the present-day understanding of the Upper Jurassic-Lower Cretaceous geology came into being, which is also gratefully acknowledged. We thank Jochen Erbacher and Theo Wong† for providing helpful comments on earlier drafts 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.28163300.

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