Stepwise basin evolution of the Middle Jurassic–Early Cretaceous rift phase in the Central Graben area of Denmark, Germany and The Netherlands

R. M. C. H. VERREUSSEL1*, R. BOUROULLEC2, D. K. MUNSTERMAN1, K. DYBKJÆR3, C. R. GEEL2, A. J. P. HOUBEN1, P. N. JOHANNESSEN3 & S. J. KERSTHOLT-BOEGEHOLD2

1TNO Netherlands Organisation for Applied Scientific Research, Geological Survey of the Netherlands, Princetonlaan 6, 3584 CB Utrecht, The Netherlands
2TNO Netherlands Organisation for Applied Scientific Research, Applied Geosciences, Princetonlaan 6, 3584 CB Utrecht, The Netherlands
3GEUS Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350, Copenhagen, Denmark

*Correspondence: roel.verreussel@tno.nl

Abstract: This paper presents the results of a cross-border study of the Middle Jurassic–Early Cretaceous rift phase in the Danish–German–Dutch Central Graben area. Based on long-distance correlations of palynologically interpreted wells, a stepwise basin evolution pattern was determined. Four phases are defined and described as tectonostratigraphic mega-sequences (TMS). The TMS are governed by changes in the tectonic regime. TMS-1 reflects the onset of rifting, triggered by regional east–west extension. Rift climax was reached during TMS-1, reflected by thick mudstone accumulations. TMS-2 reflects a change in the tectonic regime from east–west to NE–SW extension. NW–SE-trending normal faults became active during this phase, switching the depocentres from the graben axis into adjacent basins. TMS-3 displays divergent basin development. In the Dutch Central Graben area, it is characterized by a basal unconformity and widespread sandstone deposition, indicating continued salt and fault activity. Organic-rich mudstone deposition prevails in the Danish and German Central Graben area, indicating sediment starvation and water-mass stratification. With TMS-4 the rift phase ended, reflected by regionally uniform mudstone deposition. The basin evolution model presented here coherently places the lithostratigraphic units occurring in a stratigraphic framework and provides a valuable basis for hydrocarbon exploration activities in the region.

Gold Open Access: This article is published under the terms of the CC-BY 3.0 license.

In this paper, a basin evolution model for the Middle Jurassic–Early Cretaceous rift phase of the cross-border Central Graben area in Denmark, Germany and The Netherlands is presented (Fig. 1). This study builds on earlier work from TNO (Netherlands Organisation for Applied Scientific Research) on the Dutch Central Graben (Herngreen & Wong 1989; Van Adrichem Boogaert & Kouwe 1993; Abbink et al. 2006; De Jager 2007; Lott et al. 2010; Munsterman et al. 2012) and from the Danish Geological Survey (GEUS) on the Danish Central Graben (Johannessen et al. 1996, 2010a; Andsbjerg & Dybkjær 2003; Johannessen & Andsbjerg 1993; Møller & Rasmussen 2003). Ideas and concepts from these papers have been refined and integrated into a single cross-border basin evolution model. This was achieved by detailed palynological analysis on approximately 230 exploration wells in the area. The palynological results allowed for the correlation of lithostratigraphic units across the various sub-basins and for the establishment of tectonic phase timing, such as the onset of fault or salt movement. It is apparent that the Middle Jurassic–Early Cretaceous basin evolution of the Central Graben area is mainly controlled by broad-scale changes in its tectonic history, in particular by a change in the extensional regime occurring during the Late Kimmeridgian (Møller & Rasmussen 2003; Zanella & Coward 2003). Absolute sea-level changes also played an important role, especially with respect to sediment and facies distribution (Andsbjerg & Dybkjær 2003; Abbink et al. 2006; Bouroullec et al. 2018).

This study confirms that this change in extensional direction led to a region-wide shift in the main depocentre position from basin axis to basin margin and later to the adjacent basins. In addition, it is demonstrated for the first time that the basin evolution of the Danish and Dutch Central Graben is
Fig. 1. Location map showing structural elements, well locations and correlation panels. The graben axis is indicated in the blue polygon, the basins adjacent to the graben axis are indicated in olive green polygons, the plateau areas in pale yellow fill and the structural highs in grey polygons. Principal faults are drawn in red. Parts of the offshore sectors of five countries are represented on the map: Norway (NO), Denmark (DK), Germany (GER), United Kingdom (UK) and The Netherlands (NL). The purple line indicates the maximum extent of the Middle Jurassic–Lower Cretaceous sediments. The blue line shows the position of the panel in Figures 5 and 16; the green line corresponds to Figures 6 and 17; the yellow line corresponds to Figures 7 and 18.
very similar in the initial phase of rifting, but diverges considerably in the last phase (latest Volgian and Ryazanian). Four tectonostratigraphic mega-sequences (TMS) and nine subordinate sequences (TS) are defined and described. Combined, these sequences capture the step-wise basin evolution of the Middle Jurassic–Early Cretaceous rift phase of the Central Graben area (Fig. 2). The numerous lithostratigraphic units from Danish and Dutch stratigraphic nomenclature that occur in the studied time interval are coherently placed and are displayed on Wheeler diagrams.

Geological setting

Tectonic setting

During the Mesozoic, a large rift system developed in the present-day North Sea area as a result of the break-up of Pangaea (Zanella & Coward 2003). The first rift phase took place around the Middle Jurassic and resulted in large and relatively wide graben structures filled with predominantly non-marine sediments. Zechstein salt was mobilized and, subsequently, influenced Triassic depositional patterns in the Northern and Southern Permian Basin (De Jager 2003; De Jager & Geluk 2007). After a period of relative quiescence and blanketing of the rift structures by fine-grained sediments during the Early Jurassic (Wong 2007), the area was affected by a regional uplift phase during the Middle Jurassic, also known as the North Sea Thermal Doming event (Partington et al. 1993; Husmo et al. 2003). This uplift and associated volcanism was caused by an active mantle plume in the triple junction area (Underhill & Partington 1993). During this uplift phase, deposition continued in small, fault-controlled sub-basins in the Danish Central Graben (Andsbjerg 2003; Mellere et al. 2016). The second and most intense rift phase took place during the Middle Jurassic–Early Cretaceous (Surylk & Ineson 2003; Zanella & Coward 2003), which is the subject of this study. Rifting activity ceased during the Early Cretaceous (Vejbaek et al. 2010); the resultant failed rift consists of three branches that meet in a triple junction, roughly situated 200 km east of Aberdeen (Coward et al. 2003). The Central Graben is the southern branch, which runs in a southeast direction from the triple junction to the Salt Dome Province in the Danish offshore and due south into the German and Dutch sectors. The Central Graben terminates against the Central Offshore Platform in Block L05 in the Dutch offshore (Fig. 1).

Middle Jurassic–Early Cretaceous eustasy

The Middle Jurassic–Early Cretaceous sedimentary succession in the Central Graben area is deposited in an active rift setting (Fraser et al. 2003; Zanella & Coward 2003). As a consequence, the effect of eustatic sea level on the distribution of sediments plays a subordinate role compared to the tectonic component. On a third-order scale, however, facies changes related to eustasy do occur and provide a basis for correlation.

After the publications of Partington et al. (1993a, b), this sequence stratigraphic approach was widely adopted in North Sea exploration (Andsbjerg & Dybkjær 2003). Partington et al. (1993a, b) introduced a sequence stratigraphic framework in which the J-sequences of Rattey & Hayward (1993) were further subdivided and in which the maximum flooding surfaces (MFS) were presented as correlative horizons, named after the ammonite chronozones these MFS were associated with. In later publications (Duxbury et al. 1999; Fraser et al. 2003), a nomenclature based on maximum abundances of dinoflagellate cysts was preferred. Regionally important MFS are the J46 in the latest Callovian, the J63 and J64 in the Late Kimmeridgian and the J76 in the Late Ryazanian (Partington et al. 1993a, b; Bouroullec et al. 2018, fig. 1).

Middle Jurassic–Early Cretaceous climate

The Jurassic Period is generally considered as a greenhouse world, devoid of major glacial episodes (Donnadieu et al. 2011). The start of the Jurassic might even be considered a super-wothhouse, with extreme high atmospheric CO2 levels as a result of volcanic outgassing associated with the Central Atlantic Magmatic Province (Korte & Hesselbo 2011). This generally warm phase, with periodic hyper-thermals, persisted until the end of the Early Jurassic Epoch (Hettangian, Sinemurian, Pliensbachian, Toarcian), with a possible minor cooling during the late Pliensbachian (Korte & Hesselbo 2011). Evidence for cooler climates and possibly even polar ice in the Middle Jurassic Epoch (Aalenian, Bajocian, Bathonian and Callovian) is widespread (Nunn & Price 2010; Dera et al. 2011; Dromart et al. 2003). An example of such a cooler phase is found in the palynological record of the latest Callovian to earliest Oxfordian from the Dutch offshore. Cored sections from the Lower Graben and Friese Front Formation of wells F03-05-S1, F06-01, F14-05, F17-04 and L05-04 (among others) show relatively cool and humid climates, reflected in the near-absence of the pollen type Classopolis (an indicator species for warm-arid conditions; e.g. Abbink 1998; Bonis & Kürschner 2012) and the overall dominance of Peripollenites (an indicator species for wet lowland habitats; Abbink et al. 2006). Interestingly, the thick coal occurrences at the base of the succeeding Middle Graben Formation also occur within this relatively cool and wet phase. An important climate
Fig. 2. Age calibration for the stratigraphic framework. The tectonostratigraphic mega-sequences (TMS-1–3) are aligned with the same numbering as the TNO dinoflagellate cyst zonation. The same colour coding to distinguish the three TMSs is used in all figures. The Geological Time Scale 2016 is used for the chronostratigraphic calibration (Ogg et al. 2016).
shift is observed during the Middle Oxfordian when relatively warmer and drier conditions were established (Price & Rogov 2009), reflected by a sudden decrease in the occurrence of *Perinopollenites* (Abbink 1998; Abbink et al. 2001). This event is known as the *densiplicatum* climate event (Abbink 1998), named after the *Densiplicatum* Chronozone it is calibrated to (Fig. 2). The climate changed again during the Early Volgian; this time increasingly warmer and arid conditions were established, reflected by the dominance of *Classopollis* (Abbink 1998). This change is referred to as the *scitulus* climate event by Abbink (1998), after the *Scitulus* Chronozone (Fig. 2). From the *Scitulus* Chronozone onwards, warm and arid conditions persisted throughout the rest of the Volgian and across the Jurassic–Cretaceous boundary. The Syltje Formation, sections of the Farsund Formation (including the Bo Member) as well as the Kimmeridge Clay Formation were deposited under these warm and arid climatic conditions. Note that in the Danish and Dutch subsurface, the entire period is characterized by siliciclastic sedimentation; in the UK, carbonates and evaporites of the Purbeck Formation characterize this arid phase. The warm and arid phase came to an end at the beginning of the Early Cretaceous Ryazanian Stage, reflected by the decrease of *Classopollis* concomitant with an increase of ornamented trilete spores such as *Cicatricosiporites* (Abbink 1998), indicating still warm but much more humid climate conditions. This climate event is referred to as the *kochi* climate event (Abbink 1998). Tropical and wet (humid) conditions were established during the Late Ryazanian and Valanginian, across a large area from the UK to Germany. This wet phase is reflected in the geological record of NW Europe by widespread fluvial and coastal sediments, rich in plant fossils (‘Wealden Facies’, Allen et al. 1998).

**Study area**

The area of interest is the southern part of the Middle Jurassic–Lower Cretaceous rift system and is loosely referred to as the Central Graben area (Fig. 1). The study area stretches 250 km from north to south, is 50 km wide on average, and includes the offshore territories of Denmark, Germany and The Netherlands. Three depositional domains are distinguished:

1. the primary graben axis, which runs from the boundary of Norway and Denmark all the way to its southernmost tip in the L05 Block in The Netherlands and includes the Søgne Basin, the Tail End Graben, the Salt Dome Province and the Northern Dutch Central Graben;

2. the basins adjacent to the graben, which include the Heno and Gertrud plateaus, the Feda Graben in Denmark and the Terschelling Basin in The Netherlands; and

3. the plateau areas which received little or no sediments during the Middle Jurassic–Early Cretaceous rift phase, including the Inge and Mads highs, the Outer Rough Basin, the Step Graben and the Schill Grund, Central Offshore and Cleaverbank platforms in The Netherlands.

Thicknesses of the Middle Jurassic–Lower Cretaceous sediment succession range from a couple of metres in the Step Graben (Bouroullec et al. 2018) to more than 2000 m in the Danish Tail End Graben (Andsbjerg & Dybkjær 2003). The graben axis can be characterized as an en echelon series of sub-basins (Japsen et al. 2003) with asymmetric wedge-shaped sediment fills (Møller & Rasmussen 2003). The Danish part of the graben axis roughly comprises the southern tips of the Norwegian/Danish Søgne Basin, the Tail End Graben and the Salt Dome Province. The Danish Graben axis is bound to the east by the Ringkøbing-Fyn High. In the Salt Dome Province, the Central Graben bends sharply to the SSW across the German Entenschnabel into the Dutch offshore. In the Dutch offshore the graben axis comprises the Dutch Central Graben, which is subdivided into northern, middle and southern areas. The Dutch Central Graben is bounded by the Schill Grund Platform to the east and the Step Graben and Cleaverbank Platform to the west. Note that the Step Graben belongs to the plateau domain, with only thin Middle Jurassic–Lower Cretaceous deposits present. The Dutch Central Graben axis pinches out against the Central Offshore Platform in the south. Across the Central Offshore Platform, the tip of two other Mesozoic basins are visible on the location map (Fig. 1): the Broad Fourteens and Vlieland basins. These basins have a NW–SE strike and have a shared tectonic history, but do not belong to the Central Graben area as such.

**Methodology**

The basin evolution model presented in this paper is primarily based on palynological analyses from exploration wells. Over a timespan of 20 years, approximately 230 wells were analysed and interpreted in terms of age and palaeoenvironment. From these 230 wells 32 wells are reported on in this paper, but palynological data are not provided at the detailed level of individual samples. A palynological zonation has been erected to facilitate correlations. The zonation is described in the section ‘Palynology’ (see also Fig. 2 and Table 1). Seismic interpretations, utilizing both 2D and 3D seismic data (Møller & Rasmussen 2003; De Jager 2007; Bouroullec et al. 2018), were also used as supporting information.
| Zone | Subzone | Age | Definition | Remarks |
|------|---------|-----|------------|---------|
| DCZ 1 | Bathonian–Early Kimmeridgian | 168–154.7 Ma | From LO Adnatosphaeridium caulleryi to HO Limbodinium ridingii | |
| DCSZ 1A | Bathonian–Callovian | 168–163.5 Ma | From FO Adnatosphaeridium caulleryi to HO Durotrigia filiplicata, Pareodinia prolongata and Lithodinia jurassica | FO Adnatosphaeridium caulleryi is calibrated to the Zigzag Chronozone (1); HO Durotrigia filiplicata, Pareodinia prolongata and Lithodinia jurassica are calibrated to the Lamberti Chronozone (2, 3, 4, 5, 6, 7, 8) |
| DCSZ 1B | Early Oxfordian | 163.5–161 Ma | From HO Durotrigia filiplicata, Pareodinia prolongata and Lithodinia jurassica to HO Wanaea spp. and HO common Rigaudella aemula | HO Wanaea spp. is calibrated to the Cordatum Chronozone (8); HO common of Rigaudella aemula is calibrated to the Cordatum Chronozone (7) |
| DCSZ 1C | Middle Oxfordian | 161–159.8 Ma | From to HO Wanaea spp. and HO common Rigaudella aemula to HO Trichodinium scarburghensis and Rigaudella aemula | HO Trichodinium scarburghensis is calibrated to the Plicatilis Chronozone; HO Rigaudella aemula is calibrated to the Pumilus Chronozone (1, 9, 10). Note that the densiplicatum Climate Shift occurs in DCSZ 1C (11, 29, 30). |
| DCSZ 1D | Late Oxfordian | 159.8–157.5 Ma | From HO Trichodinium scarburghensis and Rigaudella aemula to HO abundant Rhyncho diniospis cladophora | HO abundant Rhyncho diniospis cladophora and HO Stephaneleytron redcliffense are in the Pseudocordata Chronozone (7, 9, 12). HO Compositosphaeridium polonicum is in the Cautisignae Chronozone (13). |
| DCSZ 1E | Early Kimmeridgian | 157.5–154.7 Ma | From HO abundant Rhyncho diniospis cladophore to HO Limbodinium ridingii or HO Scriniodinium crystallinum | HO Limbodinium ridingii is calibrated to the Cymodoce Chronozone (8). HO Scriniodinium crystallinum is calibrated to the Baylei Chronozone (1, 2, 5, 6, 9, 10, 14, 15). |
| DCZ 2 | Late Kimmeridgian–Middle Volgian | 154.7–146.6 Ma | From HO Limbodinium ridingii or HO Scriniodinium crystallinum to HO Glossodinium dimorphum, Senonia asphaera jurassica and Dichadogonyaulax pannea | |
| DCSZ 2A | Late Kimmeridgian | 154.5–152.2 Ma | From HO Limbodinium ridingii or HO Scriniodinium crystallinum to HO Endoscrinium luridum | HO Endoscrinium luridum is calibrated to the Autissiodorensis Chronozone (1, 9, 15, 16). FO Dichadogonyaulax pannea and Corculodinium inaffectum is calibrated to the Mutabilis Chronozone (23, 15, 16, 17, 19). |
DCSZ 2B Early Volgian
152.2–149.8 Ma
From HO *Endoscrinium luridum* to HO
*Oligosphaeridium patulum*

**HO Oligosphaeridium patulum** is calibrated to the
Pectinatus Chronzone (15, 20, 21). HO abundant
*Oligosphaeridium patulum* is calibrated to the
Hadlestoni Chronzone (9, 19, 21). LO
*Gochtiodinia mutabilis* and *Criproperidinium
hansenii* are calibrated to the Scitulus Chronzone
(1, 2, 9, 23). HO of *Corculodinium inaffectum* and
*Corculodinium paeninosum* are calibrated to the
Wheatleyensis Chronzone (19). Note that the
scitulus Climate Shift occurs in DCSZ 2B (11, 29,
30).

DCSZ 2C Middle Volgian (p.p.)
149.8–148 Ma
From HO *Oligosphaeridium patulum* to HO
*Occisucysta balios*

**HO Occisucysta balios** is calibrated to the
Fittoni Chronzone (2, 23 24)

DCSZ 2D Middle Volgian (p.p.)
148–146.6 Ma
From HO *Occisucysta balios* to the HO
*Glossodinium dimorphum, Senoniasphaera
jurassica* and *Dichadogonyaulax pannaea*

**HO Glossodinium dimorphum, Senoniasphaera
jurassica* and *Dichadogonyaulax pannaea* are
calibrated to the Anguiformis Chronzone (2, 9, 15,
19, 21, 22). HO *Scriniodinium inritibile* is calibrated
to the Albani Chronzone (2, 15, 16).

**DCZ 3** Late Volgian–Late Ryazanian
146.6–139 Ma
From HO *Glossodinium dimorphum, Senoniasphaera
jurassica* and *Dichadogonyaulax pannaea* to HO
*Dingodinium spinosum*

**HO abundant *Criproperidinium hansenii* is calibrated
to the Primitivus Chronzone (8, 25). HO
*Egmontodinium polyplacophorum* is calibrated to the
Opressus or Primitivus Chronzone (2, 8, 9).

**DCSZ 3A** Late Volgian (p.p.)
147–146 Ma
From HO *Glossodinium dimorphum, Senoniasphaera jurassica* and *Dichadogonyaulax pannaea* to HO abundant *Criproperidinium hansenii*

**HO Rotosphaeropsis thula* and *Systematophora daveyi* are calibrated to the Kochi Chronzone (8, 15, 25,
26, 27). HO *Gochtiodinia virgula* and
*Egmontodinium expiratum* are calibrated to the
Runctoni Chronzone (2, 8, 9, 25). Note that the
kochi Climate Shift occurs in DCSZ 3B (11, 29,
30).

**DCSZ 3B** Late Volgian (p.p.)–Early Ryazanian
146–141 Ma
From HO abundant *Criproperidinium hansenii* to
HO *Rotosphaeropsis thula* and *Systematophora
daveyi*

**HO Dingodinium spinosum** and *Egmontodinium
arya* are calibrated to the Albidum Chronzone
(8, 9, 22, 28, 27). LO *Oligosphaeridium diluculum* is calibrated to the Icenii Chronzone Ammonite Zone
(2, 9). HO common *Oligosphaeridium diluculum* and HO of *Daveya boresphaera* are calibrated to the
Stenomphalus Chronzone (8, 22, 25, 32).

**DCSZ 3C** Late Ryazanian
141–139.5 Ma
From HO *Rotosphaeropsis thula* and
*Systematophora daveyi* to HO *Dingodinium
spinosum* and *Egmontodinium torynurn*

**DCZ 4** Valanginian–Early Barremian
139.5–129 Ma
From HO *Dingodinium spinosum* and
*Egmontodinium torynurn* to HO of
*Kleithriasphaeridium corrugatum* (Continued)
| Zone   | Subzone                        | Age               | Definition                                                                 | Remarks                                                                                       |
|--------|--------------------------------|-------------------|---------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|
| DCSZ 4A| Early Valanginian (p.p.)       | 139.5–139 Ma      | From HO Dingodinium spinosum and Egmontodinium torynum to HO of Tehamadium daveyi | HO Tehamadium daveyi and HO Endoscrinium pharo are calibrated to the Paratollia Chronozone (22, 15, 25, 27) |
| DCSZ 4B| Early Valanginian (p.p.)       | 139–138.5 Ma      | From HO of Tehamadium daveyi to HO Systematophora palmula                 | HO Systematophora palmula is calibrated to the Poyptychites Chronozone (22, 27)            |
| DCSZ 4C| Early (pars.) Valanginian–Late Valanginian | 138.5–134.5 Ma    | From to HO Systematophora palmula to HO Lagenorthytis delicatula           | HO Lagenorthytis delicatula is calibrated to the Amblygonium Chronozone (27, 31). LO Nelchinopsis kostromiensis is calibrated to the Dictomites Chronozone (27). |
| DCSZ 4D| Early Hauterivian–Late Hauterivian (p.p.) | 134.5–131.5 Ma    | From HO Lagenorthytis delicatula to HO Canningia cf. reticulata            | HO Canningia cf. reticulata is calibrated to the base Variabilis Chronozone (22, 27, 28, 31). HO Batioladinium varigranosum is calibrated to the Noricum Chronozone (27). LO Subtilisphaera perlucida is calibrated to the Speetonense Chronozone (27). LO Cribreroperidinium con fossus is calibrated to the Gottschei Chronozone (28, 33, 34). |
| DCSZ 4E| Late Hauterivian (p.p.)        | 131.5–131 Ma      | From HO Canningia cf. reticulata to HO Nelchinopsis kostromiensis          | HO Nelchinopsis kostromiensis and Cribreroperidinium con fossus are calibrated to the Variabilis Chronozone (28, 33, 34, 35). |
| DCSZ 4F| Early Barremian                | 131–129 Ma        | From HO Nelchinopsis kostromiensis to the HO Kleithriaspheeridium corrugatum | HO Kleithriaspheeridium corrugatum and Muderongia simplex are calibrated to the Elegans Chronozone (28, 35, 37). LO Odontochitina operculata is calibrated to the Rornocinctum Chronozone (27). |

References: (1) Riding & Thomas (1992); (2) Riding (1987); (3) Prauss (1989); (4) Riding & Bailey (1991); (5) Feist-Burkhardt & Wille (1992); (6) Woolam (1980); (7) Riley & Fenton (1982); (8) Herrgreen et al. (2000); (9) Partington et al. (1993b); (10) Fauconnier (1995); (11) Abbink (1998); (12) Kunz (1990); (13) Poulsen (1998); (14) Arfus et al. (1989); (15) Poulsen (1998); (16) Poulsen (1994); (17) Nohe-Hansen (1986); (18) Ioannides et al. (1988); (19) Riding & Thomas (1988); (20) Riley (1979); (21) Bailey et al. (1997); (22) Davey (1979a; b); (23) Barron (1989); (24) Münsterman et al. (2012); (25) Davey (1982a; b); (26) Riding & Davey (1989); (27) Costa & Davey (1992); (28) Duxbury (1977); (29) Abbink et al. (2001); (30) Abbink et al. (2006); (31) Heilmann-Clausen & Birkelund (1987); (32) Birkelund et al. (1983); (33) Harding (1990); (34) Kirsch & Below (1995); (35) Duxbury (2001); (36) Mutterlose & Harding (1987); (37) Duxbury (1980); and (38) Heilmann-Clausen & Thomsen (1995).
Attached to the graben axis are several other basins with relatively thick (100–1000 m) Middle Jurassic–Lower Cretaceous deposits. These basins are generally connected to the graben axis on one side and are typically bound by straight and up to 50 km long faults (Fig. 1). In the Danish offshore, west of the Tail End Graben these basins consist of a series of NW–SE-trending plateaus and half-grabens. The basins are connected to the graben axis to the east and bounded by the Mads and Inge highs and by the Outer Rough Basin to the SW. The Outer Rough Basin crosses the German Entenschnabel onto the A and B blocks in the Dutch offshore and contains relatively thin (less than 100 m) Middle Jurassic–Lower Cretaceous successions. In the Dutch offshore, east of the southern Dutch Central Graben, the Terschelling Basin is separated from the graben axis by a salt-filled fault. The Terschelling Basin thickens towards the graben axis and is confined by NW–SE-trending fault zones (Fig. 1).

**Palynology**

**Palynological processing**

The large number of samples (estimated to exceed 6000) was processed in different laboratories, but always according to standard palynological processing procedures. The standard processing routine includes treatment with hydrochloric acid to digest the carbonate and hydrofluoric acid, in order to destroy the silicate mineral bonds and release the acid-resistant organic matter. The organic matter is isolated by heavy liquid separation and concentrated by sieving. The remaining organic residue is mounted on glass slides for microscopic analysis.

**Palaeoenvironmental interpretation based on palynology**

Apart from dolomite stringers in the Farsund and Kimmeridge Clay Formation, the Middle Jurassic–Lower Cretaceous sedimentary succession of the Central Graben area is dominated by siliciclastic sediments (Van Adrichem Boogaert & Kouwe 1993; Andsbjerg & Dybkjær 2003; Lott et al. 2010). The depositional environments are known to exhibit strong variation over relatively short distances, due to the active tectonic setting and the relatively complex basin configuration (Johannessen et al. 2010a; Munsterman et al. 2012). The Dutch part of the study area is characterized by marine to non-marine deposits (Abbink et al. 2006; Bouroullec et al. 2018), while the Danish part, in particular the graben axis, is dominated by deep-marine deposits (Andsbjerg & Dybkjær 2003). In such a setting, palynology is a useful tool for age assessment and palaeoenvironmental interpretation; it provides information from both the marine realm, via the occurrences of dinoflagellate cysts, and the terrestrial realm, via the occurrences of pollen and spores (Abbink 1998). However, palaeoenvironmental interpretations based on palynology reflect generally supra-local to regional conditions and are not directly comparable to sedimentology-based interpretations, as these mainly reflect local conditions (Fig. 3).

Dinoflagellates exhibit a planktonic lifestyle and only the organic-walled cysts end up in the sedimentary record. Dinoflagellate cyst occurrences are not specifically related to palaeo-water depth, but may provide information on sea-surface temperature, productivity and salinity (Sluijs et al. 2005). As a rule of thumb, high diversity and low dominance indicates open-marine shelf environments, while low diversity and high dominance indicates restricted, usually marginal, marine conditions (Jansonius & McGregor 1996). Pollen and spore assemblages reflect the regional vegetation from land and, as such, provide information on the palaeo-climate (Abbink et al. 2001). As a rule of thumb, the ratio between the marine dinoflagellate cysts and terrestrial pollen and spores indicates the relative distance from shore (Donders et al. 2009). Hydrodynamic energy may be reflected in the amount of physical degradation of the organic constituents of the palynological assemblages; very small fragments point to high-energy conditions and intact specimens indicate low-energy conditions (Traverse 2007).

**Age calibration**

The Late Jurassic and the succeeding Early Cretaceous periods are relatively poorly constrained in a global chron stratigraphic sense. For example, there are no global boundary stratotype section and points (GSSPs) for the base of the Callovian, Oxfordian, Kimmeridgian, Berriasian and Valanginian (Wimbledon et al. 2011; Ogg et al. 2016). Furthermore, the Late Jurassic is characterized by strong provincialism, in particular with respect to the distribution of ammonites (Gradstein et al. 2012). This hampers the application of international standards to the sedimentary successions from the North Sea. Boreal chronostratigraphic schemes are generally applied in North Sea geology, in particular the Russian stages: Kimmeridgian, Volgian and Ryazanian (e.g. Fraser et al. 2003). For that reason, reference to Russian chronostratigraphy and to the Sub-Boreal Ammonite Zones is made in this paper (Fig. 2). For practical reasons, the target interval of this paper is loosely referred to as Middle Jurassic–Early Cretaceous although, strictly speaking, this should be late Middle Jurassic–early Early Cretaceous.
Fig. 3. Schematic overview of depositional environments occurring in the terrestrial and marine realm which are mentioned in the text. These environments form the bulk of the environments that occur in the Middle Jurassic–Lower Cretaceous in the Central Graben area. Note that palaeoenvironmental interpretations based on palynology generally reflect sub-regional to regional conditions, whereas palaeoenvironmental interpretations derived from sedimentology reflect local conditions.
Note that in Ogg et al. (2016) the absolute age spans of chronozones vary. For example, the Early Ryazanian Runcioni Chronozone plus the Late Volgian Lamplughii and Preplicomphalus chronozones together represent 4 Ma, whereas the seven chronozones below the Preplicomphalus represent less than 2 Ma. Based on our own observations, the marked difference in absolute age span between the Runcioni–Preplicomphalus and Primitivus–Albani chronozones is questioned.

**Palynological zonation**

Based on palynological analyses from exploration wells in the Danish and Dutch offshore, a regional dinoflagellate cyst zonation for the Middle Callovian–Barremian is established (Table 1, see also Fig. 2). The zonation includes 4 zones and 18 subzones.

The dinoflagellate cyst zones (DCZ) and subzones (DCSZ) are predominantly based on top occurrences of taxa, to accommodate for use in industry. For practical reasons, the numbering of the independently calibrated dinoflagellate zones has been synchronized with the numbering of the tectonostratigraphic mega-sequences (Fig. 2). The international geological timescale of Ogg et al. (2016) is used for chronostratigraphic calibration.

**Results**

Based on palynological analyses and observations from seismic and sedimentological analyses, the basin development of the Middle Jurassic–Lower Cretaceous from the Central Graben areas of Denmark, Germany and The Netherlands is demonstrated in detail. The basin evolution is seen to follow discrete phases with active depocentres and fault patterns changing through time (Fig. 4). These discrete phases in basin evolution are reflected in the sedimentary record as genetically related accumulations of sediments (Figs 5–7).

Four main phases in the basin evolution are distinguished, which are named tectonostratigraphic mega-sequences (TMS) and subordinate sequences (Fig. 4). The TMS are numbered 1–4, from old to young:

- **TMS-1 (168–154.7 Ma)**
  
  During the entire timespan of TMS-1 (Bathonian–Early Kimmeridgian) only the graben axis is subjected to major subsidence. Sediments of this age are rarely encountered away from the graben axis in the study area (Fig. 4).

  The first synrift deposits are fluviol–deltaic sediments of the Bryne Formation (Aalenian–Bajocian age), which are found in the Danish Søgne Basin and Tail End Graben (Andsbjerg 2003; Andsbjerg & Dybkjær 2003; Mellere et al. 2016). Towards the end of the Callovian, the entire graben axis was affected by subsidence. In the succeeding Oxfordian, subsidence related to rifting reached its maximum. Deposition within the graben axis was then dominated by mudstones of the Lola and Middle Graben formations (Fig. 5). In the Danish Graben axis (Søgne Basin, Tail End Graben, Salt Dome Province), the depocentres are situated close to the Coffee Soil Fault, emphasizing the asymmetric style of deformation within this area (Fig. 1). In the Dutch Central Graben axis, the structural style is different since the bounding faults are often overlain by remobilized Zechstein salt (e.g. Pharaoh et al. 2010; Bouroullec et al. 2018). Because of salt withdrawal, onlaps or truncations along the graben margins are predominant in the Dutch Central Graben (Bouroullec et al. 2018, figs 6–13). In the northern part of the Dutch Central Graben a total depositional thickness of 1500 m is observed for TMS-1 (F03 block), while in the southern part of the Dutch Central Graben thicknesses are limited to approximately 200 m (L05 block). This thinner succession is partially due to later erosion, but also related to lower initial accommodation. The thickness variation is accompanied by noticeable sedimentary facies changes. The southern Dutch Central Graben (F17, L02 and L05 Blocks) is characterized by predominantly non-marine, fluviol deposits of the Friese Front Formation (Figs 5–7), while the northern Dutch Central Graben (B18, F03, F05 and F06) displays a succession from
Fig. 4. Schematic representation of the stepwise basin evolution discussed in the text. The vertical bars represent the relative amount of basin subsidence (black) for the different structural domains. The relative amounts of subsidence are estimated from the thicknesses of the sedimentary succession. Timescale after (Ogg et al. 2016).

non-marine to marginal-marine sediments (Lower Graben, Middle Graben and Upper Graben formations; Bouroullec et al. 2018) to open-marine sediments at the top of TMS-1 (Kimmeridge Clay Formation). Based on these observations a stepwise, or gradual topographic gradient related to
Fig. 5. Wheeler diagram along a N–S transect through the axis of the Central Graben. The diagram displays the generalized time and facies relationships of the Middle Jurassic–Lower Cretaceous lithostratigraphic units. See Figure 1 for location of the panel.
Fig. 6. Wheeler diagram along a W–E transect through the Danish basins. The diagram displays the generalized time and facies relationships of the Middle Jurassic–Lower Cretaceous lithostratigraphic units. See Figure 1 for location of the panel.
Fig. 7. Wheeler diagram along a W–E transect through the Dutch Terschelling Basin. The diagram displays the generalized time and facies relationships of the Middle Jurassic–Lower Cretaceous lithostratigraphic units. See Figure 1 for location of the panel.
Fig. 8. Age reference for the Dutch Lower Graben, Middle Graben, Upper Graben, Kimmeridge Clay, Scruff Greensand and Lutine formations. Well F03-05-S1 is located in the northern part of the Dutch Central Graben. The wireline log on the left is the gamma ray (GR) and the log on the right is the sonic (DT). See Figure 1 for location and Figure 2 for abbreviations of palynological events.
Fig. 9. Age reference for the Dutch Lower Graben, Middle Graben and Puzzle Hole formations. Well F11-01 is located in the middle part of the Dutch Central Graben. Wireline logs as for Figure 8. See Figure 1 for location and Figure 2 for abbreviations of palynological events.
differences in subsidence, is proposed to have existed from south to north.

During TMS-1, basin infill occurred from multiple directions. There is no single, large-scale prograding delta system such as the Brent Delta (sensu Husmo et al. 2003) filling up the graben along its axis. For example, during the Aalenian–Bathonian, the Danish–Norwegian Sogne Basin was occupied by a tidally influenced delta system from the NE, but the drainage pattern was reversed in the

---

**Fig. 10.** Age reference for the Danish Heno, Lola and Farsund formations. Well Karl-1 is located in the Danish basins adjacent to the Central Graben axis. Wireline logs as for Figure 8. See Figure 1 for location and Figure 2 for abbreviations of palynological events.

| Depth (MD) | Tectono-stratigraphic (mega)-sequences | Dino cyst Subzones | Palynological events |
|------------|----------------------------------------|-------------------|---------------------|
| 4200m      |                                        |                   |                     |
| 4250m      |                                        |                   |                     |
| 4300m      |                                        |                   |                     |
| 4350m      |                                        |                   |                     |
| 4400m      |                                        |                   |                     |
| 4450m      |                                        |                   |                     |
| 4500m      |                                        |                   |                     |
| 4550m      |                                        |                   |                     |
| 4600m      |                                        |                   |                     |

| Depth (MD) | DT (US/F) | GR (gAPI) | Karl-1 |
|------------|-----------|-----------|--------|
| 0          | 240       | 200       |        |
| 4200m      | 40        |           |        |
| 4250m      |           |           |        |
| 4300m      |           |           |        |
| 4350m      |           |           |        |
| 4400m      |           |           |        |
| 4450m      |           |           |        |
| 4500m      |           |           |        |
| 4550m      |           |           |        |
| 4600m      |           |           |        |
Fig. 11. Age reference for the Dutch Friese Front, Skylge and Scruff Greensand formations. Well L06-03 is located in the Dutch Terschelling Basin, adjacent to the Central Graben axis. Wireline logs as for Figure 8. See Figure 1 for location and Figure 2 for abbreviations of palynological events.
Callovian (Bryne–Sandnes Formation, Mellere et al. 2016). In the Dutch Central Graben, evidence of lateral sediment input is demonstrated by the occurrence of distributary channels and bird foot deltas on the margin of the Dutch Central Graben, identified on 3D seismic data from the Oxfordian Middle and Upper Graben formations (Bouroullec et al. 2018, figs 15, 16).

TS-1.1. Initiation of rifting. Opening of the Søgne Basin, Tail End Graben and Salt Dome Province.

**Lithostratigraphy:** Denmark: Bryne Formation. The Netherlands: No deposition.

**Age:** Bathonian–Early Callovian (168–165 Ma; Fig. 2).

The oldest sediments that can be attributed to the TMS-1 are Aalenian or earliest Bajocian sediments from the Bryne Formation (Andsbjerg 2003; Andsbjerg & Dybkjær 2003; Mellere et al. 2016; see also Figs 4–6), although Husmo et al. (2003) suggest that most of the Bryne Formation can be attributed to the Bathonian. TS-1.1 represents the oldest part of the Middle Jurassic–Early Cretaceous rift phase and expresses the rift initiation. TS-1.1 is limited in occurrence to the Danish Graben area where it is present in the Søgne Basin, the Tail End Graben and in the Salt Dome Province. TS-1.1 may possibly extend into the German sector, but no published information is available to corroborate this. In the Dutch Central Graben, sediments older than Middle Callovian and younger than Aalenian have not been observed (Van Adrichem Boogaert & Kouwe 1993; Munsterman et al. 2012; Bouroullec et al. 2018). This implies that, during the whole of TS-1.1, subsidence was limited to the Danish Graben.

The Bryne Formation consists of fluvo-deltaic–estuarine deposits (Andsbjerg 2003) and is associated with a clay-rich, tidally influenced delta system that prograded SSE into the Søgne Basin (Mellere et al. 2016). The Bryne Formation is in part

---

**Fig. 12.** Age reference for the Danish ‘Outer Rough Sand’ and the Bo Member of the Farsund Formation. Well Saxo-1 is located in the Danish Outer Rough Basin. The wireline log is the gamma ray (GR). See Figure 1 for location and Figure 2 for abbreviations of palynological events.
**Fig. 13.** Age reference for the Dutch Kimmeridge Clay Formation and for the Noordvaarder Member of the Skylge Formation. Well B14-02 is located near the margin of the northern part of the Dutch Central Graben axis. Wireline logs as for Figure 8. See Figure 1 for location and Figure 2 for abbreviations of palynological events.
Fig. 14. Age reference for the Danish Farsund Formation and its Bo Member. Well Lone-1 is located in the Danish basins adjacent to the Central Graben axis. Wireline logs as for Figure 8. See Figure 1 for location and Figure 2 for the abbreviations of the palynological events.
Fig. 15. Panel displaying the facies change of TMS-3 occurring from the Danish offshore to the Dutch offshore. Wireline logs as for Figure 8. The coloured dashed lines correlate the trends of the GR curves from well to well. The log correlations are underpinned by palynological events, indicated on the panel by coloured stars. The tight correlation clearly shows the gradual transition from the glauconitic sandstones of the Scruff Greensand Formation (wells B18-02 and B18-03) in the Dutch offshore to the high gamma-ray, organic-rich mudstones of the Bo Member (Gert-2, Bo-1, Edna-1) in the Danish offshore. See Figure 1 for location of the wells.
equivalent to the coal-bearing non-marine Pentland Formation in the UK sector (Fraser et al. 2003). The Bryne Formation is difficult to date since marine microfossils, such as dinoflagellate cysts, are lacking or very rarely found. In addition, the fluvial and estuarine deposits of the succeeding depositional sequence TS-1.2 are similar to the fluvial deposits of TS-1.1. As such, it is challenging to determine the exact timing of the rift initiation and to correlate TS-1.1 across large distances and determine its exact geographic distribution. Unlike the succeeding TS-1.2 sequence, active faulting appears to be lacking or is minimal at during this period. The average thickness observed for TS-1.1 is 100 m; the maximum thickness attained in well penetration is 220 m in West Lulu-1 (Andsbjerg 2003; Andsbjerg & Dybkjær 2003).

**TS-1.2.** Increasing rift activity. Shoreface complex development in adjacent Danish basins. Opening of the Dutch Central Graben.

**Lithostratigraphy:** Denmark: Lulu Formation and the top of the Bryne Formation. The Netherlands: Lower Graben Formation and part of the Rifgronden Member of the Friese Front Formation.

**Age:** Early or Middle Callovian to Late Callovian (165–163.5 Ma; Figs 2, 8, 9).

In contrast to TS-1.1, TS-1.2 is present in the entire graben axis from Denmark to The Netherlands and, as such, reflects the southwards propagation of the Middle Jurassic–Lower Cretaceous rift. At the time of deposition, active faulting occurred along the graben margins. The Central Graben rift system reached its southernmost tip at the border of the Central Offshore Platform, offshore The Netherlands Blocks L05 and L06 (Fig. 1). Seismic sections from the Tail End Graben in Denmark indicate the presence of a small angular unconformity between TS-1.1 and TS-1.2 (Middle Jurassic unconformity in Figs 5, 6) (Møller & Rasmussen 2003). This unconformity likely correlates to the erosive base of fluvial and estuarine sandstones near the top of the Bryne Formation (Andsbjerg & Dybkjær 2003; Mellere et al. 2016). In the Dutch Central Graben, TS-1.2 consists mostly of fluvial sandstones, overbank claystones and thin coal layers indicating swamp environments, but towards the top the unit becomes sandier and marine and tidal influence becomes prominent (Bouroullec et al. 2018, fig. 3). In well F03-05-S1 (Fig. 8) and F06-01 (Bouroullec et al. 2018), TS-1.2 reaches an overall thickness of 500 m with a distinct marine shoreface sandstone at the top (Fig. 16; Bouroullec et al. 2018, fig. 3). In the Tail End Graben and Salt Dome Province, TS-1.2 shows more facies variation (Fig. 5; see also Andsbjerg & Dybkjær 2003). The base is usually terrestrial, but marine influence is more prominent than in the Dutch Central Graben. In the Danish/Norwegian Sogne Basin TS-1.2 is largely represented by the Sandnes Formation, a sand-prone, outbuilding series of tidally influenced deltas (Mellere et al. 2016).

In the northern part of the Dutch Central Graben, TS-1.2 is represented by the Lower Graben Formation (Figs 8, 9). The basal part of the Lower Graben Formation is non-marine fluvial (Van Adrichem Boogaert & Kouwe 1993; Munsterman et al. 2012; Bouroullec et al. 2018). The Lower Graben Formation becomes more marine towards the top, which is sand-rich and interpreted as tidal shoals and tidal channels by Bouroullec et al. (2018). In the southernmost tip of the southern part of the Dutch Central Graben, where the Middle Jurassic–Lower Cretaceous sequence pinches out, only the marine flooding surface near the top of TS-1.2 is preserved in the sedimentary record, indicating low accommodation near the hinge of the graben (Fig. 5). This thin, shallow-marine sandstone interval is the Rifgronden Member of the Friese Front Formation.

In the northern part of the Dutch Central Graben, truncation of TS-1.2 occurs locally along the basin margin (Bouroullec et al. 2018). Truncation is caused by increased axial subsidence related to the loading on Zechstein salt underneath. In the Danish sector, basin development is controlled by faulting (Møller & Rasmussen 2003).

**TS-1.3.** Rift climax and east–west-oriented extension phase.

**Lithostratigraphy:** Denmark: Middle Graben and the Lola Formation. The Netherlands: Middle Graben, Upper Graben, Friese Front formations, Kimmeridge Clay and the Puzzle Hole Formation.

**Age:** Oxfordian–Early Kimmeridgian (163.5–154.7 Ma; Figs 2, 8, 9).

Characteristic of both the Danish and Dutch Central Graben is the transition from sandstone-dominated successions of TS-1.2 to mudstone-dominated successions of TS-1.3. An important difference between the Danish and the Dutch Central Graben is the amount of marine influence. Marine conditions prevailed in the Sogne Basin, Tail End Graben and Salt Dome Province, while in the Dutch Central Graben marine influence remained weak and was limited to specific horizons, based on the occasional occurrences of dinoflagellate cysts in the otherwise pollen- and spore-dominated Middle Graben Formation. In addition, three distinct and regionally extensive coal layers occur at the base of the TS-1.3 in the Middle Dutch Central Graben (Figs 5, 8, 9, 16; Bouroullec et al. 2018, figs 3, 9, 11, 13, 16). The coal layers are up to 3 m thick and can be correlated across large distances. The lateral continuity of the coal layers indicates sediment starvation and a relatively flat basin-floor topography. The sudden lack of sediment supply is notable,
Fig. 16. N–S correlation panel (corresponding to the Wheeler diagram shown in Fig. 5) along the Central Graben axis, from the Danish offshore in the north to the Dutch offshore in the south. Wireline logs as for Figure 8. TMS-1 to TMS-3 are indicated in colour shading. SGF: Scruff Greensand Formation; MGF: Middle Graben Formation. See Figure 1 for location of the wells.
considering the abundant tidal and shoreface sandstones in the underlying TS-1.2 and the narrow (20 km wide) basin configuration during this period. Apparently, the area became starved from any sources of sand for a prolonged period of time, suggesting that the regional transgression at the top of TS-1.2 flooded the graben shoulders and forced the deposition of marginal-marine sands onto the adjacent plateau areas and away from the graben axis. These sands were likely eroded shortly afterwards, as no Early–Late Oxfordian sandstones are present on these bordering plateaus. However, supportive evidence for a marine transgression on the adjacent plateaus is present in so-called ‘caprock’ sequences. These are heterolithic complexes consisting of anhydrite, breccia, sandstone and shale, together making up the crests of salt diapirs. In the Jurassic, the Schill Grund Platform (Fig. 1) was perforated by a number of salt diapirs. Palynofloras occurring in the basal part of these heterolithic indicate a latest Callovian to earliest Oxfordian age and a marine depositional setting. This suggests that these diapirs have been flooded, partly dissolved and collapsed and filled in with sediments during the latest Callovian–earliest Oxfordian.

The Middle Graben Formation is predominantly non-marine, as indicated by the general lack of marine palynomorphs. Marine palynomorphs are only encountered in specific intervals, associated with maximum flooding surfaces. An estuarine palaeoenvironment with occasional open-marine influence is inferred, probably an embayment with poor connection to the open sea (Fig. 3).

Two sandstone units, the Middle Graben Sandstone Member and the Upper Graben Formation (Fig. 8), were deposited during TS-1.3 in the northern Dutch Central Graben. Both are reservoir levels that form the main producing units in the Dutch offshore F03-FB gas-condensate field (Lott et al. 2010). The Upper Graben Sandstone Formation is interpreted as a prograding delta front, based on the coarsening upwards trend of the sediments (Van Adrichem Boogaert & Kouwe 1993). Bourrouillec et al. (2018) demonstrate that small bird-foot deltas are also present along the eastern margin of the graben within the Upper Graben Formation.

In the middle part of the Dutch Central Graben, a delta-plain environment with sandstones, coals and mudstones developed from the Middle Oxfordian onwards. These deposits are part of the Puzzle Hole Formation (Figs 5, 9).

In the Danish sector, marine mudstones of TS-1.3 are found in the Søgne Basin, Tail End Graben and the Salt Dome Province. The maximum thickness is attained in the Tail End Graben, but many wells do not reach the Lower Kimmeridgian Lola Formation.

**TMS-2 (154.7–146.6 Ma)**

During this phase, the basins and plateau areas adjacent to the graben axis, such as the Heno Plateau, Gertrud Plateau and the Terschelling Basin, became active and depocentres shifted away from the graben axis to its margins. TMS-2 is characterized by active faulting and salt movement.

From the Early to the Late Kimmeridgian, an important change in the tectonic regime occurred with a change in extension direction from east—west to SW–NE (Zanella & Coward 2003). As a result, Paleozoic NW–SE-trending faults were reactivated and new faults appeared. The adjacent basins started to subside and large amounts of sediments were deposited. In the Danish Graben axis, the depocentres move away from the Coffee Soil Fault hanging wall to the southwestern side of the graben axis and to the adjacent Danish basins (Gertrud Plateau, Gert Ridge and Heno Plateau) which started to subside and eventually became inundated (Fig. 17; 500–1000 m of TMS-2 sediments). These successions comprise the shallow-marine sandstones of the Heno Formation, overlain by open-marine mudstones of the Farsund Formation.

In the Danish Graben axis, in the Søgne Basin and Tail End Graben, gravity-flow sandstones intercalate with offshore mudstones from the Farsund Formation. In the Dutch Graben axis, much of the geological record from this time period is not preserved due to later erosion as a result of a Late Cretaceous inversion phase (Van Adrichem Boogaert & Kouwe 1993; De Jager 2007).

In the northern part of the Dutch Central Graben, mudstone deposition from the Kimmeridge Clay Formation continues without any visible change in lithology from TMS-1 to TMS-2 (Fig. 8). A transitional area is observed in the eastern part of the southern Dutch Central Graben, from non-marine in the western part of the graben to shallow-marine in the Terschelling Basin (Fig. 7). The newly developed Terschelling Basin was subsiding more rapidly than the southern part of the Dutch Central Graben. The average thickness of TMS-2 in the Terschelling Basin is 350 m, with a maximum of 800 m in well L03-01 (Fig. 18). Towards the end of TMS-2, during the Middle Volgian, large parts of the Dutch Central Graben became subjected to erosion. A conformable contact between TMS-2 and TMS-3 is only observed in the Terschelling Basin. In the northern part of the Dutch Central Graben many wells, such as well F03-05-S1, display a hiatus below the base of TMS-3 (Fig. 8). The erosion in the graben axis of the Dutch Central Graben is related to salt movement. Salt migrated from beneath the axial zone towards the lateral margins of the rift basin, which triggered tilt and erosion in the basin axis (Bourrouillec et al. 2018; Figs 9, 12, 13). In the southern part of
Fig. 17. W–E correlation panel (corresponding to the Wheeler diagram shown in Fig. 6) perpendicular to the Central Graben axis in the Danish offshore. Wireline logs as for Figure 8. TMS-1 to TMS-3 are indicated in colour shading. See Figure 1 for location of the wells.
Fig. 18. W–E correlation panel (corresponding to the Wheeler diagram shown in Fig. 6) perpendicular to the Central Graben axis in the Dutch offshore Terschelling Basin. Wireline logs as for Figure 9. TMS-1 to TMS-3 are indicated in colour shading. See Figure 1 for location of the wells.
the Dutch Central Graben, evidence for intra-Middle Jurassic–Lower Cretaceous erosion is found in wells L05-03, L05-04 and F17-04 (Figs 7 and 18), where TMS-1 lies directly underneath TMS-3 or TMS-4. Widespread erosion could also explain the sand-prone Noordvaarder Member in well B13-02 and B14-02 (Fig. 13; see also Bouroullec et al. 2018, figs 12, 13).

**TS-2.1.** Change of extension trend from east–west to NE–SW. Inundation of the Heno and Gertrud Plateaus.

**Lithostratigraphy:** Denmark: Heno and Farsund formations. The Netherlands: Kimmeridge Clay Formation and lower part of the Friese Front Formation.

**Age:** Late Kimmeridgian (Mutabilis Chronozone, 154.7–153.5 Ma; Figs 2, 9–11, 13).

On the Gert Ridge and the Heno and Gertrud plateaus, the base of the Middle Jurassic–Lower Cretaceous succession is represented by the base of the Upper Kimmeridgian Heno Formation. The Heno Formation marks the inundation of the Heno and Gertrud plateaus resulting from a change in tectonic regime (Møller & Rasmussen 2003). The Heno Formation consists of two sandstone members, separated by mudstones (Figs 5, 6, 10, 17). The Gert Member is the basal and oldest sandstone member and is composed of non-marine to marginal-marine deposits (Johannessen et al. 1996, 2010a, b; Johannessen 2003). The Gert Member is locally sourced from the Inge and Mads highs (Weibel et al. 2010) and by erosion from the edges of the fault-bounded plateaus (Johannessen et al. 2010a). The youngest Ravn Member is sourced from the Mid North Sea High (Weibel et al. 2010). Most of the Danish plateaus were inundated during this period and preserved from erosion.

Mudstone deposition continues in the Dutch Central Graben, but sandier non-marine sediments of the upper part of the Friese Front Formation (sometimes referred to as Main Friese Front Member, Bouroullec et al. 2018) are observed in the southern part of the graben and in the western part of the Terschelling Basin. It is assumed that these sediments originated from the eroding plateaus areas and were transported to the graben axis via incised valleys (Fig. 3; see also Bouroullec et al. 2018). The base of the rift succession in the Terschelling Basin is dated as Early Kimmeridgian (Mutabilis Chronzone) based on pollen and spores (Fig. 11). In general, TS-2.1 consists of fluvial deposits in the Terschelling Basin.

In the northern part of the Dutch Central Graben, TS-2.1 is represented by mudstones from the Kimmeridge Clay Formation. In that area, no visible change in lithology occurs from TS-1.3 to TS-2.1.

**TS-2.2.** Opening of the Terschelling Basin. Sandy sediment gravity flows in the Søgne Basin.

**Lithostratigraphy:** Denmark: Farsund formation. The Netherlands: Kimmeridge Clay Formation and the upper part of the Friese Front Formation.

**Age:** Late Kimmeridgian (Eudoxus and Autisiodorensis Chronozones, 153.5–152 Ma; Figs 2, 8–11, 13).

In the Danish peripheral basins such as the Heno and Gertrud plateaus the base of TS-2.2 is a regionally traceable flooding event, reflected by the transition from shoreface sandstones of the Heno Formation to the open-marine mudstones of the Farsund Formation (Figs 6, 10, 17). The Farsund Formation consists of distal, open-marine mudstones, often organic-rich. As such, the Farsund Formation can be regarded as a facies equivalent of the Kimmeridge Clay Formation. Open-marine mudstone deposition persisted in the entire Danish Central Graben during TS-2.2. A thickness of 600 m is recorded in the Tail End Graben (Fig. 16). In the deepest parts of the basins, sediment gravity-flow sandstones occur (Johannessen et al. 2010a), such as seen in well Svane-1 where intercalations of such sandy sediments are frequent.

In the Terschelling Basin, marine influence gradually increases during TS-2.2 (Figs 7, 11, 18). The TS-2.2 sediments in the Terschelling Basin are fluvial deposits and belong lithostratigraphically to the upper part of the Friese Front Formation, referred to as the Main Friese Front Member (Muntean et al. 2012; see also Bouroullec et al. 2018).

**TS-2.3.** Opening of the Outer Rough Basin. Marine incursions and development of sandy shoreface complexes.

**Lithostratigraphy:** Denmark: ‘Outer Rough Sand’ and the Farsund Formation. The Netherlands: lower part of the Skylge Formation (Oyster Ground and Terschelling Sandstone Member, lower parts of the Lies and Noordvaarder Member) and the Kimmeridge Clay Formation.

**Age:** Early Volgian (152–149.6 Ma; Figs 2, 8–14).

In the Terschelling Basin (Fig. 1), TS-2.3 is represented by the Oyster Ground Member and the Terschelling Sandstone Member of the Skylge Formation. The Oyster Ground Member is the oldest unit of the Skylge Formation, which consists of parallel laminated claystones with thin, silt-dominated storm beds (Bouroullec et al. 2018, fig. 4) and shelly horizons. The Oyster Ground Member is interpreted as lower shoreface and marks fully marine conditions in the Terschelling Basin during the early stages of TS-2.3. The succeeding Terschelling Sandstone Member represents a shoreface complex with a variety of depositional environments such as tidal inlet sequences, upper shoreface, lagoonal and back-barrier washover fans (Fig. 3; see also Bouroullec...
et al. 2018, fig. 4). The base of the Terschelling Sandstone Member is sharp and reflects a regression. The development of a shoreline complex in the Terschelling Basin is coeval with the development of shoreline sandstones in the Danish and German Outer Rough Basin. This local regressive sandstone unit is known informally as the ‘Outer Rough Sand’ (Johannessen et al. 2010a).

During TS-2.3, parts of the structurally elevated area of the Hantum Fault Zone (southern edge of the Terschelling Basin; see Fig. 1) are transgressed where Early Volgian thin, sandy deposits are preserved. Overall, subsidence appears to have decreased in the Dutch Central Graben axis during this period as most of the Zechstein salt withdrew from underneath the basin margin areas (due to welding out axially) rather than from underneath the basin axis itself (as for TMS-1; see Bouroullec et al. 2018). Sediment catchment therefore shifted from the Dutch graben axis to the margins.

Two other lithostratigraphic units reflect erosion due to fault activity and salt movement: the ‘Outer Rough Sand’ in the Outer Rough Basin (Figs 6, 12); and the Noordvaarder Member of the Skylge Formation in the Terschelling Basin and in some parts of the northern Central Graben (Figs 5, 13). The ‘Outer Rough Sand’ is a shallow-marine sandstone unit sandwiched between the pre-Jurassic and Cretaceous Valhall–Asgard Formation, indicating marine conditions in the Outer Rough Basin (Johannessen et al. 2010a). The Noordvaarder Member of the Skylge Formation is a sandy unit, directly resulting from fault activity such as displayed in well B14-02 (Fig. 13) but also along the northwestern margin of the Terschelling Basin (Munsterman et al. 2012; Bouroullec et al. 2018, fig. 7B).

TS-2.4. Local erosion in the graben axis and on the platforms.

Lithostratigraphy: Denmark: Farsund formation. The Netherlands: Skylge (Terschelling Sandstone, Noordvaarder and Lies Members) and the Kimmeridge Clay formations.

Age: Middle Volgian–earliest Late Volgian (149.6–144.6 Ma; Figs 2, 10–14).

The upper part of the Skylge Formation comprises shallow-marine sandstones and shales that are mainly found in the Terschelling Basin and in the southeastern part of the Dutch Central Graben. In the northern part of the Terschelling Basin, the Skylge Formation becomes increasingly sand-rich (Noordvaarder Member). Evidence for erosion at the graben axis can be seen in the northern part of the Dutch Central Graben in well F03-03, where an erosional hiatus separates the Early Volgian shales of the Kimmeridge Clay Formation (TS-2.3) from the Late Volgian sands of the Scruff Greensand Formation (TMS-3) (Fig. 5).

In the Danish area, the overall mud-dominated Farsund Formation is gradually becoming more silty in TS-2.4 than in the underlying TS-2.3, reflected by lower gamma ray values (Figs 14, 17). It is proposed that erosion occurred on a large scale in the area at that time, leading to increased supplies of coarser material even in the deepest parts of the basin.

TMS-3 (146.6–139 Ma)

Sedimentation extends to the adjacent plateaus such as the Schill Grund Plateau and Ameland Block. Sand starvation and organic-rich shale deposition is evident in the Danish sector.

In the Terschelling Basin and Dutch Central Graben, the base of TMS-3 is traceable in well-log seismic reflection patterns due to the lithological contrast between the sandy lower part of TMS-3 and the often mud-prone sediments of TMS-2 (Figs 16, 18; see also Bouroullec et al. 2018).

In the Danish Graben axis, it is more difficult to trace the base of the TMS-3. A small excursion towards lower values in the gamma ray trend is observed on wireline logs, pointing to increased silt and sand supply at this time. These intervals are poorly constrained stratigraphically since they are rarely cored and have limited stratigraphic thickness. It is suggested that local uplift affected the entire area, leading to erosion in the shallowest parts of the basin. Indeed, there are indications that the Upper Volgian is missing in the Outer Rough Basin (Johannessen et al. 2010a).

Large parts of the Danish Central Graben area became subjected to basin restriction during the Early Ryazanian (Ineson et al. 2003), reflected in the organic-rich shale deposition of the Bo Member of the Farsund Formation. Sediment gravity-flow deposits have also been reported from the Gertrud and Tail End grabens around this time interval (Andsbjerg & Dybkjaer 2003; Ineson et al. 2003).

Sandstone deposition of the Scruff Greensand Formation continued in the Terschelling Basin at around the same time (Fig. 7; see also Bouroullec et al. 2018). This sandstone is likely sourced from the Hantum Fault Zone, the Ameland Block and the area to the SE of the Terschelling Basin. Mudstone deposition became dominant throughout most of the Danish and Dutch Graben areas during the Late Ryazanian, indicating a general decrease of tectonic activity and reflecting the final stages of rifting in the area.

TS-3.1. Widespread sand deposition in Dutch sector. Clay deposition and local gravity-flow sands in the Danish sector.

Lithostratigraphy: Denmark: Farsund formation. The Netherlands: Scruff Greensand and Lutine formations.
Age: Late Volgian (146.6–144.6 Ma; Figs 2, 8, 11, 12, 14–16).

The Scruff Greensand Formation is a complex of shallow-marine sandstones (often glauconitic- and sometimes spiculite-bearing) and marine mudstones (Figs 11, 16, 18). This unit occurs over a large area of the Dutch sector, but is absent from the Danish sector. The Danish sector is characterized by clay deposition of the Farsund Formation. Gravity-flow sands are deposited locally along the Coffee Soil Fault. Typically, during TS-3.1 the deposition area widened into plateaus located close to the graben and adjacent basins (e.g. Schill Grund Plateau, Ameland Block, Step Graben and Outer Rough Basin). As a consequence, TS-3.1 reflects the initiation of the Cretaceous transgression.

TS-3.2. Reflects the start of widespread basin anoxia related to the Lower Cretaceous transgression and sand starvation of most of the basins.

Lithostratigraphy: Denmark: Bo Member (Farsund Formation). The Netherlands: Scruff Greensand and Lutine formations.

Age: Latest Volgian–Early Ryazanian (144.6–139 Ma; Figs 8, 12, 14, 15).

TS-3.2 is characterized by widespread shale deposition. In the Danish area, organic-rich shales of the Bo Member (Farsund Formation) are deposited over a large area (Figs 5, 17). The transition from the marine mudstones of the Farsund Formation to the organic-rich facies of the Bo Member is gradual (from the base of TS-3.1 based on gamma ray logs; Ineson et al. 2003). The maximum gamma ray values associated with the organic-rich facies are reached in the Early Ryazanian Kochi Chronozone, bounded by the highest occurrence (HO) of the dinoflagellate cyst species Rotospheeropsis thula (Fig. 15). In the northern part of the Dutch sector, the Lutine Formation is also composed of organic-rich shales, but with lower total organic carbon (TOC) values (less than 3%) than the ‘hot shale’ or Bo Member further north (3–8%, locally exceeding 15%) (see also Fig. 15 for correlations). The absence of bioturbation and well-preserved laminations in the Bo Member suggests anoxic bottom-water conditions (Ineson et al. 2003) and therefore water-mass stratification which, in turn, can be linked to changes in basin configuration and/or climate. The first anoxia occurs roughly at the Volgian–Ryazanian transition (Ineson et al. 2003), close to the base of TMS-3. Slightly later, near the base of the Early Ryazanian Kochi Chronozone, a climate shift is recorded. This climate change is based on palynology and is reflected in the composition of the pollen and spore assemblages (Abbink 1998). The pollen and spore assemblages change from dominant ‘warm and dry’ elements to dominant ‘warm and moist’ elements. The climate change may well have been caused by a change in directional pattern of the proto-North Atlantic seaway connecting the Boreal and Tethys oceans, as suggested by Abbink et al. (2001). The same oceanic water-mass reconfiguration could also be responsible for introducing stratification in the Central Graben. Relative sea level was high during most of the Ryazanian, pushing the shoreline southwards and preventing coarse-grained clastics from reaching the central parts of the study area. The transition from the sandstone-dominated Scruff Greensand Formation to the shale-dominated Lutine Formation in the Dutch area indicates that erosion in the Dutch Central Graben decreased, likely due to rift cessation. Subsidence was still high in the Terschelling Basin, however, resulting in a thick succession of TS-3.2.

TMS-4 (139–126 Ma)

Alongside the Cretaceous transgression, the Middle Jurassic–Early Cretaceous rift phase ended. As such, the entire region, including the study area, became subject to subsidence.

The Cretaceous transgression continued and, with the cessation of rifting, the depositional area widened to encompass the entire North Sea (Cromer Knoll Group in the Danish, UK and Norwegian sectors). This interval is generally mud prone, but inspection of these intervals using well data often reveals thin sandy deposits at the base of the Cretaceous transgression (e.g. Vlieland Sandstone Formation on the Schill Grund Platform and Vlieland Basin, or the Leek Member of the Valhall/Asgard Formation in the Tail End Graben; Figs 1, 5–7). This change in lithology can be traced seismically, suggesting that the base of the Cretaceous transgression also reflects a short-lived tectonic event related to a change in intra-plate stress regime. An angular unconformity is occasionally observed at this level (see Abbink et al. 2006, fig. 10). The entire area, including the plateau areas, then acted as one structural province subjected to regional subsidence. This caused the sea to transgress much further onto the mainland of the Friesland Platform and the West Netherlands basins, where marginal-marine sandstone deposition prevailed (Jeremiah et al. 2010; Zwaan 2018).

Conclusions

Based on detailed palynological analysis and supported by seismic data interpretation (Bouroullec et al. 2018), it has been possible to define a series of tectonostratigraphic mega-sequences (TMS) that reflect the stepwise basin evolution of the Late Jurassic rift phase of the Central Graben. Rifting started in the north (Danish sector) and propagated southwards
during the initial rift phase. The sediments related to this initial phase are grouped into tectonostratigraphic mega-sequence TMS-1. The oldest sediments of TMS-1 are Bathonian–Middle Callovian in age and are only found in the Danish Søgne Basin, Tail End Graben and Salt Dome Province and belong to the Bryne Formation. At the time of the latest Callovian, marine conditions reached all the way to the southernmost tip of the Central Graben. Evidence from erosional remnants on salt diapirs shows that the latest Callovian marine transgression also extended across the plateau areas east and west of the Dutch Central Graben. During the next phase of basin development, TMS-2, the basins adjacent to the graben were affected. Subsidence in the graben axis continued, but the change in tectonic regime from east–west to NE–SW extension led to the (re-) activation of NW–SE-striking normal faults in certain areas. The Heno and Gertrud plateaus were affected by subsidence first, followed by the Terschelling Basin in the Dutch sector shortly after. Later, during the Early Volgan, the depositional area reached its maximum extent when the Inge and Mads highs, Outer Rough Basin and the Vlie-land Basin became active. This transgressive trend is reflected in the shoreface complex occurrences of the Terschelling Sandstone Member in the Terschelling Basin and the ‘Outer Rough Sand’ in the Outer Rough Basin. At the same time, basin development became increasingly complex as salt welded out in some parts of the Dutch Central Graben axis and subsidence shifted to marginal areas. As a result, thick sandstone occurrences from the Noordvaarder Member are found along the graben margins and erosion is observed at the graben axis. The next phase, TMS-3, demonstrated divergent basin development in the Danish and Dutch sectors. In the Terschelling Basin and parts of the Dutch Central Graben margin, TMS-3 is characterized by widespread sand deposition of the Scruff Greensand Formation. In the Danish area, coeval deposition of organic-rich mudstones of the Bo Member indicates (coarse-grained) sediment starvation and water column stratification. Basin differentiation ended during TMS-4 and the entire area was subjected to regional subsidence due to thermal cooling. Thin sandy units occur locally at the base of TMS-4, but the remainder of sediment accumulation was dominated by mudstones.

Implications and future perspective

The stratigraphic framework presented here coherently places the formations and members from the cross-border area in a stratigraphic framework. The basin evolution model links the spatial and stratigraphical occurrences of reservoirs and seals to regional changes in eustasy, climate and tectonics. These results provide a solid foundation for exploration activities focusing on the Jurassic synrift play. A next step could be the development of detailed cross-border palaeogeographic maps that could serve as a basis for play fairway analysis and for the establishment of common risk segment (CRS) maps. To reach that stage, a few research questions and topics still need to be addressed such as, for example: (1) the establishment of a high-resolution correlation of the Danish/Norwegian Bryne, Lulu and Sandnes formations with the Dutch Lower Graben and Friese Front formations; and (2) a feasible tectonic model to explain the divergent basin development in TMS-3. Additional research on source rocks from the study area, such as the Toarcian Posidonia Shale Formation, the earliest Cretaceous Clay Deep and Bo Members and the coal occurrences from the Middle Graben, Bryne and Sandnes formations would be beneficial for a more detailed understanding of petroleum systems.

The authors would like to thank the two reviewers Bruno Venderville (University of Lille) and Oscar Abbink (IHS Markit) for their constructive feedback and comments. Oscar is also thanked for the groundbreaking work that paved the way for this study. Ymke van den Berg is thanked for her continuous support. The editor Ben Kilhams is thanked for his patience and scrutiny, the latter of which improved the manuscript significantly. Continued financial support from GEUS and TNO is gratefully acknowledged. Geological insights were also gained via business-to-business and multi-client projects for oil and gas companies. Their contributions are also gratefully acknowledged.

References

ABBINK, O.A. 1998. Palynological investigations in the Jurassic of the North Sea region. LPP Contributions Series, 8, 7–192.
ABBINK, O.A., CALLOMON, J.H., RIDING, J.B., WILLIAMS, P.D.B. & WOLFARD, A. 2001. Biostratigraphy of the Jurassic-Cretaceous boundary strata in the Terschelling Basin, The Netherlands. Proceedings of the Yorkshire Geological Society, 53, 275–302, https://doi.org/10.1144/pygs.53.4.275
ABBINK, O.A., MIJNLIEFF, H.F., MUNSTERMAN, D.K. & VERREUSSEL, R.M.C.H. 2006. New stratigraphic insights in the ‘Late Jurassic’ of the southern central North Sea Graben and Terschelling basin (Dutch offshore) and related exploration potential. Netherlands Journal of Geosciences – Geologie en Mijnbouw, 85, 221–238.
ALLEN, P., ALVIN, K.L. ET AL. 1998. Purbeck–Wealden (early Cretaceous) climates. Proceedings of the Geologists’ Association, 109, 197–236.
ANDSBJERG, J. 2003. Sedimentology and sequence stratigraphy of the Bryne and Lulu Formations, Middle Jurassic, northern Danish Central Graben. In: INESON, J.R. & SURLYK, F. (eds) The Jurassic of Denmark and Greenland.
Central Trough, Danmarks geologiske undersøgelse, 17. I kommission hos C.A. Reitzels, Copenhagen, Denmark, 1–89.

Heilmann-Clausen, C. & Thomsen, E. 1995. Barremian-Aptian dinoflagellates and calcareous nanofossils in the Ahlum 1 borehole and the Otto Gott clay pit, Sarstedt, Lower Saxony Basin, Germany. Geologisches Jahrbuch Reihe A, 257–366.

Herngreen, G.F.W. & Wong, T.H.E. 1989. Revision of the ‘Late Jurassic’ stratigraphy of the Dutch central Graben. Geologie & Mijnbouw, 68, 73–105.

Herngreen, G.F.W., Kerstholt, S.J. & Munsterman, D.K. 2000. Callovian–Ryazanian (‘Middle Jurassic to Early Cretaceous’) palynostratigraphy of the Central North Sea Graben and Vlieland Basin, The Netherlands. Mededelingen Nederlands Instituut voor Toegepaste Geowetenschappen TNO, 63, 1–99.

Husmo, T., Hamar, G.P., Holiland, O., Johannesen, E.P., Rasmund, A., Spencer, A.M. & Titterton, R. 2003. Lower and middle Jurassic. In: Evans, D., Graham, C., Armour, A. & Bathurst, P. (eds) The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea. Geological Society, London, 129–156.

Ineson, J.R., Boejesen-Koefoed, J.A., Dybkjær, K. & Nielsen, L.H. 2003. Volgian–Ryazanian ‘hot shales’ of the Bo Member (Farsund Formation) in the Danish Central Graben, North Sea: stratigraphy, facies and geochemistry. The Jurassic of Denmark and Greenland. Geological Survey of Denmark and Greenland Bulletin, 1, 403–436.

Joannides, N.S., Colin, J.-P. & Jan du Chene, R. 1988. A preliminary investigation of Kimmeridgian dinoflagellates and ostracods from Quercy, Southwest France. Bulletin des Centres de recherches exploration-production Elf-Aquitaine, 12, 471–491.

Jansonius, J. & McGregor, D.C. 1996. Palynology: Principles and Applications, Vol. 1 Principles. American Association of Stratigraphic Palynologists Foundation, Publishers Press, Salt Lake City, Utah, USA, 1–451.

Japsen, P., Britze, P. & Andersen, C. 2003. Middle Jurassic to Early Cretaceous-Lower Cretaceous of the Danish Central Graben: structural framework and nomenclature. In: Ineson, J.R. & Surlyk, F. (eds) The Jurassic of Denmark and Greenland. Geological Survey of Denmark and Greenland Bulletin, 1, 233–246.

Jeremiah, J.M., Duxbury, S. & Rawson, P.F. 2010. Lower Cretaceous of the southern North Sea Basins: reservoir distribution within a sequence stratigraphic framework. Geologie en Mijnbouw, 89, 203–237.

Johannesen, P.N. 2003. Sedimentology and sequence stratigraphy of paralic and shallow marine Middle Jurassic to Early Cretaceous sandstones in the northern Danish Central Graben. In: Ineson, J.R. & Surlyk, F. (eds) The Jurassic of Denmark and Greenland. Geological Survey of Denmark and Greenland Bulletin, 1, 367–402.

Johannesen, P.N. & Andsberg, J. 1993. Middle to Late Jurassic basin evolution and sandstone reservoir distribution in the Danish Central Trough. In: Parker, J.R. (ed.) Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference. Geological Society, London, 271–283. https://doi.org/10.1144/0040271

Johannesen, P.N., Dybkjær, K. & Rasmussen, E.S. 1996. Sequence stratigraphy of Upper Jurassic reservoir sandstones in the northern part of the Danish Central Trough, North Sea. Marine and Petroleum Geology, 13, 755–770.

Johannesen, P.N., Dybkjær, K., Andersen, C., Kristensen, L., Hovikoski, J. & Vosgerau, H. 2010a. Upper Jurassic reservoir sandstones in the Danish Central Graben: new insights on distribution and depositional environments. In: Vining, B.A. & Pickering, S.C. (eds) Petroleum Geology: From Mature Basins to New Frontiers. Proceedings of the 7th Conference. Geological Society, London, Petroleum Geology Conference Series, 7, 127–143. https://doi.org/10.1144/0070127

Johannesen, P.N., Nielsen, L.H., Nielsen, L., Möller, I., Purup, M. & Andersen, T.J. 2010b. Architecture of an Upper Jurassic barrier island sandstone reservoir, Danish Central Graben: implications of a Holocene-Recent analogue from the Wadden Sea. In: Vining, B.A. & Pickering, S.C. (eds) Petroleum Geology: From Mature Basins to New Frontiers. Proceedings of the 7th Petroleum Geology Conference. Geological Society, London, Petroleum Geology Conference Series, 7, 145–155. https://doi.org/10.1144/0070145

Kirsch, K.-H. & Below, R. 1995. Quantitative Untersuchung der Dinoflagellatenverteilung in den hell/dunkel-Rhythmiten des Hauterive-Barrem-Grenzberics im Niedersächsischen Becken (Norddeutschland) am Beispiel des Profils der Tongrube Otto Gott bei Sarstedt. Palaeontographica Abteilung B, 236, 105–146.

Korte, C. & Hesselbo, S.P. 2011. Shallow marine carbon and oxygen isotope and elemental records indicate icehouse-greenhouse cycles during the Early Jurassic. Palaeoceanography, 26, 1–18.

Kunz, R. 1990. Phytoplankton and Palynofazies im Malm NW-Deutschlands (Hannoversches Bergland). Phytoplankton and palynofacies in the Malm of NW Germany (Hannoversches Bergland). Palaeoceanographica Abteilung B, 216, 1–105.

Lott, G.K., Wong, T.E., Dusar, M., Andsberg, J., Mönning, E., Feldman-Olszewska, A. & VerreusSEL, R.M.C.H. 2010. Jurassic. In: Doornenbal, J.C. & Stevenson, A.G. (eds) Petroleum Geological Atlas of the Southern Permian Basin Area. EAGE Publications b.v., Houten, 175–193.

Mellere, D., Mannie, A., Longhitano, S., Mazur, M., Kulusa, H., Brough, S. & Cotton, J. 2016. Tidally influenced shoal water delta and estuary in the Middle Jurassic of the Sogne Basin, Norwegian North Sea: sedimentary response to rift initiation and salt tectonics. In: Hampson, G.J., Reynolds, A.D., Kostic, B. & Wells, M.R. (eds) Sedimentology of Paralic Reservoirs: Recent Advances. Geological Society London, Special Publications, 444, 173.

Möller, J.J. & Rasmussen, E.S. 2003. Middle Jurassic-Early Cretaceous rifting of the Danish Central Graben. In: Ineson, J.R. & Surlyk, F. (eds) The Jurassic of Denmark and Greenland. Geological Survey of Denmark and Greenland Bulletin, 1, 247–264.

Munsterman, D.K., VerreusSEL, R.M.C.H., MieNleFF, H.F., Witmans, N., Kerstholt-Bogehold, S.J. & Abbink, O.A. 2012. Revision and update of the Callovian-Ryazanian Stratigraphic Nomenclature in the northern Dutch offshore, i.e. Central Graben Subgroup and Scruff Group. Netherlands Journal of Geosciences – Geologie en Mijnbouw, 91, 555–590.
Wong, T.E. 2007. Jurassic. In: Wong, T.E., Batjes, D.A.J. & De Jager, J. (eds) Geology of the Netherlands. Royal Netherlands Academy of Arts and Sciences, Amsterdam, 107–125.

Woollam, R. 1980. Jurassic dinocysts from shallow marine deposits of the East Midlands, England. Journal of the University of Sheffield Geological Society, 7, 243–261.

Zanella, E. & Coward, M.P. 2003. Structural framework. In: Evans, D., Graham, C., Armour, A. & Bathurst, P. (eds) The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea. Geological Society, London, 357, 45–59.

Zwaan, F. 2018. Lower cretaceous reservoir development in the North Sea Central Graben and potential analogue settings in the Southern Permian Basin and South Viking Graben. In: Kilhams, B., Kukla, P.A., Mazur, S., McKie, T., Minlief, H.F. & van Oijk, K. (eds) Mesozoic Resource Potential in the Southern Permian Basin Basin. Geological Society, London, Special Publications, 469. First published online January 4, 2018, https://doi.org/10.1144/SP469.3