Tectonostratigraphy of a rift basin affected by salt tectonics: synrift Middle Jurassic–Lower Cretaceous Dutch Central Graben, Terschelling Basin and neighbouring platforms, Dutch offshore

R. BOUROULLEC1*, R. M. C. H. VERREUSSEL2, C. R. GEEL1, G. DE BRUIN1, M. H. A. A. ZIJP2, D. KÖRÖSI1, D. K. MUNSTERMAN2, N. M. M. JANSSEN2 & S. J. KERSTHOLT-BOEGEHOLD1

1TNO Netherlands Organisation for Applied Scientific Research, Applied Geosciences, Princetonlaan 6, 3584 CB Utrecht, The Netherlands
2TNO Netherlands Organisation for Applied Scientific Research, Geological Survey of the Netherlands, Princetonlaan 6, 3584 CB Utrecht, The Netherlands

*Correspondence: renaud.bouroullec@tno.nl

Abstract: The Middle Jurassic–Lower Cretaceous in the eastern Dutch offshore provides excellent examples of sand-rich sediments that locally accumulated in the vicinity of rift basin margins affected by salt tectonics. These types of deposits are often geographically restricted and difficult to identify, but can be valuable targets for hydrocarbon exploration. The distribution, thickness and preservation potential of fluviolacustrine, shallow- and deep-marine sediments is discussed to provide new insights into the regional and local tectonostratigraphy of the Dutch Central Graben, the Terschelling Basin and their neighbouring platforms. New sedimentological, geochemical, biostratigraphic, stratigraphic and structural information have been analysed and integrated into a new tectonostratigraphic model for the Callovian Lower Graben Formation, Oxfordian Middle and Upper Graben formations, Early–Middle Volgian Terschelling Sandstone and Noordvaarder members, and the Late Volgian–Early Ryazanian Scruff Greensand Formation. It is demonstrated that salt withdrawal at the basin axis was the primary control on the generation of high accommodation during the Callovian–Early Kimmeridgian. Incised valleys developed on the platforms providing lateral sediment input. During the Late Kimmeridgian–Ryazanian salt migration shifted laterally towards the basin margins, providing accommodation adjacent to active salt bodies and deposition of overthickened sandy strata.

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During the Middle Jurassic–Early Cretaceous the North Sea area was subject to active rifting that initiated during the Triassic but reached a climax during the Late Jurassic. During this period, several Mesozoic Dutch rift basins were also heavily affected by Zechstein salt withdrawal and migration into autochthonous and shallow salt bodies, especially near riftbounding faults or other pre-existing faults. Several hydrocarbon fields with reservoirs of Middle Jurassic–Lower Cretaceous age, such as F03-FB and F15A, have been discovered in the Dutch offshore and neighbouring regions. In addition, the Middle Volgian–Early Ryazanian M07-B gas field, discovered in 2007, is located along the southern margin of the Terschelling Basin in a complex setting that involves syntectonic deposition and local sediment erosion and re-deposition. To understand such a complex play type and its economic potential elsewhere in the North Sea basin, a good understanding of the relationship between palaeotopography and sediment distribution and preservation is required.

Three Middle Jurassic–Lower Cretaceous tectonostratigraphic mega-sequences (TMS-1 to -3) are recognized in the Dutch, German and Danish offshore area; these reflect three main stages of basin evolution regarding the Central Graben and adjacent areas (Munsterman et al. 2012; Verreussel et al. 2018). In the Dutch sector, these sequences contain sand-rich reservoir intervals such as the Lower, Middle and Upper Graben and the Friese Front formations (TMS-1); the Terschelling Sandstone and the Noordvaarder members (TMS-2); and the Scruff Greensand Formation (TMS-3) (Fig. 1). The results of this work validate and support this subdivision by providing new detailed stratigraphic correlation anchored on chronostratigraphic, stratigraphic and seismic information across several structural elements. These elements include two main basins, namely the Dutch Central Graben and the Terschelling Basin, and six flanking platforms, namely the Cleaver Bank Platform, the Step Graben, the Central Offshore Platform, the Friesland Platform, the

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Fig. 1. Lithostratigraphic framework of the Middle Jurassic–Lower Cretaceous in the Terschelling Basin, Dutch Central Graben and Step Graben. The sand-rich intervals are shown as yellow polygons, while pale yellow polygons indicate locally derived depositional systems such as the Noordvaarder Member. Based on core data interpretation and published results (Munsterman et al. 2012), fluvial overbanks, delta plain and estuarine/lagoonal claystones are shown in green, while marine claystones are shown in light blue. Unconformities are shown as red lines and maximum flooding surfaces as blue lines. The three regionally extensive Middle Graben Formation coals are shown as thick black lines. Oblique dashed orange lines show the approximate lithostratigraphic limits of time-equivalent formations of the upper part of TMS-1. Proven reservoirs have been found in each TMS but with a predominance of TMS-1. The main source rocks are either Carboniferous coals and/or Middle Jurassic Posidonia Shales. The main seals are either the Valanginian to Albian Rijnland Group or internal Upper Jurassic intervals such as the Late Oxfordian–Middle Volgian (159–147 Ma) Kimmeridge Clay Formation or the Late Kimmeridgian–Middle Volgian (152.5–147 Ma) Lies Member. Ammonite zones after Gradstein et al. (2012). Eustatic sea-level curve after Carruthers et al. (1996). Maximum flooding surfaces after Partington et al. (1993).
The study area is 270 km long and on average 120 km wide, covering the eastern part of the Dutch A, B and E blocks (east of 3° 20’), the entire B and F blocks, and most of the L, M and G blocks. The area of interest comprises the Dutch Central Graben, the Terschelling Basin and the areas of the flanking platforms located close to the rift basins (Fig. 2). The data used in this research include 102 wells, 11 cores, 5 two-dimensional (2D) seismic surveys, 43 3D seismic surveys, as well as 550 palynological and 800 stable isotope analyses carried out on core and cuttings samples (see also Verreussel et al. 2018). The integration of palynological, stable isotope, core, well and seismic data into a single tectonostratigraphic model for the Dutch offshore will aid further hydrocarbon exploration by supplying an integrated framework for Middle Jurassic–Lower Cretaceous stratigraphy and tectonic events that can be followed at cuttings to seismic scale. This paper is closely linked to that of Verreussel et al. (2018); the latter discusses the relevant palynological information and controls used in both papers and presents a stratigraphic overview of the Middle Jurassic–Lower Cretaceous from the Dutch to the Danish sectors. In order to provide further context, an overview of the geological evolution of the area is first presented.

Geological evolution

Tectonic evolution

The Meso-Cenozoic structural evolution of the Dutch offshore region is complex as it involves several extensional, compressional and strike-slip phases, as well as a multiphase salt tectonic history (Van Hoorn 1987; Ziegler 1990a, b). Unravelling this structural evolution, as well as the stratigraphic response to the changing palaeo-landscapes, is difficult due to the large amount of the stratigraphy being removed during multiple significant erosional events, especially on low-accommodation areas such as the rift shoulders (e.g. Schill Grund Platform, Step Graben, Fig. 2) (Wong 2007). A short description of the key rift-related structural events that impacted the study area is given in the following.

The failed rift system of the Dutch offshore (sensu de Jager 2007) is composed of the NNE–SSW-trending Dutch Central Graben and the NW–SE-trending Terschelling Basin, which are bounded by several flanking platforms (Fig. 2). During the Triassic, Jurassic and Early Cretaceous, the structural setting of The Netherlands changed from a single extensional basin configuration (the Southern Permian Basin) to a series of smaller, fault-bounded basins and highs (De Jager 2007). Two main tectonic events shaped the North Sea Basin during the Mesozoic: (1) the break-up of Pangea and associated rifting during most of the Mesozoic (Ziegler 1990a); and (2) the closure of the Tethys Ocean/Alpine collision and associated inversion tectonics during the late Mesozoic, which subsequently culminated during the Cenozoic (Ziegler 1990b; Kley & Voigt 2008). The initiation of rifting during the Early Triassic was related to the inception of the proto-Atlantic between Greenland and the Fennoscandian High (Lott et al. 2010). The southwards propagation of the rift system towards the North Sea can be traced into the northern part of the study area (Ziegler 1990b; Roberts et al. 1995; Coward et al. 2003). As such, Middle and Late Triassic sequences thicken into the newly-formed Dutch Central Graben and Broad Fourteens Basin, where the Zechstein salt was actively withdrawing and was remobilized to form diapirs and rim synclines (De Jager 2007). The Late Triassic extension direction, recorded in faults locally affected by dextral transtension, was E–W aligned (Van Hoorn 1987).

The Early Jurassic was a period of relative tectonic quiescence, with little rifting occurring in the North Sea area (Pharaoh et al. 2010). Stagnant-water stratification led to the deposition of the Posidonia Shale Formation during the Toarcian, the principal source rock for the oil provinces of the southern North Sea and northern Germany (De Jager 2007). A key event during the Middle Jurassic was the uplift of the central North Sea domain. This started towards the end of the Aalenian, in response to the emplacement of a mantle plume at the base of the lithosphere (Underhill & Partington 1993) which persisted during the Bajocian and Bathonian. Development of this large thermal dome (700 × 1000 km) caused deep truncation of Lower Jurassic and even Triassic sediments, leading to the development of the regional-scale Mid Cimmerian Unconformity (Ziegler 1990a; Underhill & Partington 1993; Surlyk & Ineson 2003). By late Middle Jurassic times, the Central North Sea Dome had subsided sufficiently for open-marine conditions to be restored across the study area. Sedimentation resumed during the Callovian–Late Jurassic in the previously uplifted areas (Ziegler 1990a; Callomon 2003).

During the Late Jurassic–Early Cretaceous, crustal extension accelerated across the North Sea rift system driven by the reorganization of the stress field due to the opening of the Arctic–North Atlantic rift system and the related clockwise, westwards rotation of Laurentia–Greenland relative to Eurasia (Ziegler 1988, 1990a; Torsvik et al. 2002). This reorganization resulted in NW–SE-trending transtensional basins that formed along the southern margin of the Southern Permian Basin. This phase caused large areas outside of the rift basins to be uplifted, exposed and subsequently eroded (Duin
Fig. 2. Base map of the central and northern part of the Dutch offshore. Top Zechstein Group is shown as background surface. The main structural elements are delimited by dashed black lines: CBP, Cleaver Bank Platform; ESH, Elbow Spit High; SG, Step Graben; DCG, Dutch Central Graben; SGP, Schill Grund Platform; TB, Terschelling Basin; AP, Ameland Platform; FP, Friesland Platform; and COP, Central Offshore Platform. The position of the four transects shown in this paper (A, B, C and D; Figs 6–13) are shown as red lines. The regional seismic and correlation panels are shown in Figures 6–13. Key wells displayed in the regional panels are shown as white circles. Wells with studied cores are show as orange circles, while wells F06-01, L06-02 and M07-08 (yellow circles) have cores, the interpretation of which is shown in Figures 3–5.
In the Dutch sector, up to 1500 m of fluvio-lacustrine and shallow-marine sequences (TMS-1; Fig. 1) accumulated in the Dutch Central Graben during this period; adjacent highs, such as the dead Graben, Friesland and Schill Grund platforms, were uplifted and eroded (see Fig. 2 for location; Munsterman et al. 2012). During this period, the Terschelling Basin did not exhibit accommodation since it was not subsiding (Duin et al. 2006; Munsterman et al. 2012), but subsequently became a sediment catchment area during the following periods (depositional time of TMS-2 and 3; Fig. 1). Sediments of TMS-2 and 3 were also deposited in the Dutch Central Graben and accumulated only as thin intervals on the surrounding platforms (Munsterman et al. 2012). Salt pillows, stocks and walls developed along the main bounding faults of the Dutch Central Graben during this period, and created a complex basin configuration and stratigraphy (e.g. van Winden et al. 2018).

Contemporaneously to an end-Ryazanian transgression, rifting is documented to have ceased with the region subsequently undergoing post-rift sag. As such, the area of sediment accumulation broadens to encompass the entire North Sea (Cromer Knoll Formation in UK and Norwegian sectors; see Verreussel et al. 2018). This interval (TMS-4, Fig. 1) is generally mud-prone, but close inspection often reveals thin sandy deposits at the base of the Cretaceous transgression (e.g. Vlieland Sandstone Formation on the Schill Grund Platform and Vlie-land Basin; Munsterman et al. 2012).

Salt tectonics

The presence of Permian Zechstein salt, and the multi-stage deformation that affected this mobile substrate, had a pronounced impact on the Mesozoic evolution of the North Sea (Trusheim 1960). Locally, salt tectonics started as early as the latest Permian (Stewart 2007) but became more widespread during the Early Triassic, leading to the formation of minibasins and rafts (Stewart & Clark 1999; Penge et al. 1999). In the Dutch sector, such Early Triassic salt-controlled minibasins are rare and only observed in the A Block (insert map, Fig. 2). These minibasins are either due to Early Triassic prorogational fluvial systems or to the relative proportion of marginal Zechstein facies compared to the amount of salt (as proposed for the UK sector minibasins by Stewart & Clark 1999). The main period of salt movement in the study area was the Middle and Late Triassic (Geluk 2007), and continued during the Jurassic and Early Cretaceous (van Winden et al. 2018). The original depositional thickness of the salt layer was likely variable across the study area, with thicknesses ranging from 400 m in the south to a maximum of 900 m in the north (Ten Veen et al. 2012; Hernandez et al. 2018). van Winden et al. (2018) places the original thickness of the salt as high as 1500 m within the central part of the Dutch Central Graben. Thin-skinned normal faults formed during the Middle Triassic, detaching on the Zechstein salt. Diapirs and rim synclines developed during the Middle Jurassic–Early Cretaceous (De Jager 2007, 2012; Ten Veen et al. 2012). The partitioning of the Southern Permian Basin into several basins and platforms during the Triassic and Jurassic was accentuated by intense salt tectonics, primarily along fault-bounded basin margins (Wong 2007). For example, basin compartmentalization and minibasin formation are observed to be associated with salt withdrawal in much of the Dutch Central Graben and the Terschelling Basin (Fig. 2).

Methods

This research involved a series of core descriptions, palynological and geochemical analyses, and seismic and well log interpretation. This new information was combined with previous legacy material to build a robust depositional, stratigraphic, chronostratigraphic and structural framework for Middle Jurassic–Early Cretaceous sequences preserved in the Dutch offshore (Munsterman et al. 2012; Verreussel et al. 2018).

Sedimentological analysis included the description of 620 m of core data from 11 wells (F03-05, F06-01, F14-05, F15-01, F17-09, L05-05, L06-02, L06-03, M01-01, M07-07 and M07-08; Fig. 2). Based on the lithologies, facies, ichnofacies and resultant facies associations, several depositional settings were identified including fluvial, deltaic, lagoonal, lacustrine, tidal, shoreface and offshore. The cores described include 323 m of Lower Graben/Frieze Front formations (TMS-1) (e.g. Fig. 3), 77 m of Terschelling Sandstone Member/Oyster Ground Members (TMS-2) (e.g. Fig. 4), and 211 m of Scruff Greensand Formation (TMS-3) (e.g. Fig. 5).

A new series of palynological analyses was conducted, utilizing core and cuttings material from 24 wells, combined with legacy data from more than 100 exploration wells in the Danish and Dutch offshore (Abbink et al. 2006; Munsterman et al. 2012; Verreussel et al. 2018). This enabled the definition of a regional dinocyst zonation that includes 4 zones and 18 subzones for the Middle Callovian–Barremian (Verreussel et al. 2018, fig. 2). The new palynological results gave additional age constraints as well as new information regarding the depositional environments and the climatic variations. Readers are referred to Verreussel et al. (2018) for detailed information regarding the construction of this scheme and resulting palaeoclimate observations for the Middle Jurassic–Early Cretaceous. In
Fig. 3. Correlation panel for the Lower Graben Formation (lower part of TMS-1) between three wells located in the axis of the Dutch Central Graben. Wells F03-05, F06-01 and F14-05 have cores in this stratigraphic interval, which have been interpreted in terms of depositional environment using lithological, facies, ichnofacies and facies association classification. Palynological and stable isotope data were also collected and the results are shown for each well in terms of absolute abundance of dinocysts compared to pollen and spores (zero centred red bars) and $\delta^{13}$C moving average curves (purple curves). Maximum flooding surfaces (MSF), including the J46 MFS from Partington et al. (1993), were identified using core and palynological information, and correlated using additional constraints from stable isotope data. Gamma ray curve is to the left and sonic curve to the right on each display. Depth values are measured depth. See Figure 2 for location.
Fig. 4. L06-02 core description and interpretation of the upper part of the Oyster Ground and Terschelling Sandstone members (middle part of TMS-2) in the southern part of the Terschelling Basin. (a) Gamma ray/sonic and neutron/density curves of well L06-02 at the core depth. Gamma ray curve is to the left and sonic curve to the right on each display. The red bar shows the position of the core and the red markers (A–C) are placed to help the reader compare wireline log and core information. (b) Core description and interpretation. This 40 m long TMS-2 core shows the transition between the Oyster Ground and the Terschelling Sandstone members. (c) Legend of Figures 3–5. See text for detailed description and Figure 2 for location. See Verreusel et al. (2018, fig. 2) for chronostratigraphic overview, including palynological zonations and events.
addition to the palynological analysis, material from nine wells was also used for stable isotope analysis (e.g. Fig. 3). This provided information to allow better stratigraphic correlation constraints.

Tectonostratigraphic analysis was based on an integrated approach, which combined detailed stratigraphic correlation between 102 wells (44 of which are shown in this paper; Fig. 2) and seismic interpretation based on 5 2D surveys and 43 3D surveys (with ranges ranging from 1982 to 2010, with typical sampling rates of 4 ms and zero-phase European polarity; see Table 1 for list of seismic surveys). Well-to-seismic ties were performed using synthetic seismograms, and the seismic interpretation was performed in two-way travel time (TWTT). The initial 3D mapping of several key horizons was carried out at TNO (The Netherlands Organisation for Applied Scientific Research) and presented in Duin et al. (2006). For the present paper, 11 regional 2D transects were built to analyse the tectonostratigraphic evolution of the study area during the Middle Jurassic—Early Cretaceous using new and refined palynological constraints age controls. Four of those transects are presented in this paper (Figs 6–13). New 3D seismic mapping was also performed for this research, including the entire Terschelling Basin plus one area (F06 block, Figs 14–16) in the northern part of the Dutch Central Graben. A revised detailed 3D mapping of the rest of the study area is ongoing. The analysis workflow included the identification and mapping of faults, salt features, stratigraphic markers (tied to the wells using new stratigraphic constraints), and regional and local unconformities. Seismically identified stratigraphic terminations (erosion, onlap, downlap) and time–thickness maps of key intervals (e.g. Fig. 17) are also used to analyse the interplay between active structures (faults and salt features) and sediment deposition. In addition, seismic amplitude analysis and horizon slicing techniques were used in a 3D seismic survey in the F06 block (Figs 14, 16).

**Middle Jurassic–Lower Cretaceous stratigraphic overview**

The Middle Jurassic–Lower Cretaceous interval of The Netherlands is composed of the Schieland, Scruff and Rijnland groups, the former two being

the focus of this paper. Abbink et al. (2006), Münsterman et al. (2012) and Verreussel et al. (2018; figs 2–4) divide this interval into three major tectonostratigraphic phases (referred to here as tectonostratigraphic mega-sequences or TMS; Fig. 1).

Here the definitions provided by Verreussel et al. (2018) are summarized and contextualized in terms of the main stratigraphic divisions. The Early Callovian–Early Kimmeridgian TMS-1 comprises the Lower, Middle and Upper Graben formations, the Puzzle Hole Formation and the lower part of the Friese Front Formation (Fig. 1). A short description of the formations comprising TMS-1 is given in Table 2. The Early Kimmeridgian–Late Volgian TMS-2 was deposited during a period of increased accommodation in the Dutch Central Graben and Terschelling Basin as well as, to a limited extent, on their neighbouring platforms (e.g. Step Graben, Schill Grund Platforms; Fig. 2). This sequence is mainly composed of the time-equivalent Skylge and Kimmeridge Clay formations. The Main Friese Front Member of the Friese Front Formation is also of TMS-2 age, but is only present in the southern part of the Dutch Central Graben and in the Terschelling Basin (Fig. 1). The Skylge Formation is present in the southern part of the study area, mainly in the Terschelling Basin and the southern part of the Dutch Central Graben. This formation is composed of four members (Table 2), some of which are time-equivalent to each other. The Kimmeridge Clay Formation is present in the central and northern part of the study area, principally in the Dutch Central Graben and as erosional remnants in the Step Graben area (Figs 7b, 15, 16). Note that the lower part of the Kimmeridge Clay Formation is of TMS-1 age (Fig. 1). During the Late Volgian, the adjacent platforms such as the Schill Grund Platform and the Cleaver Bank High were flooded. TMS-3 was subsequently deposited, which comprises the high net-to-gross Scruff Greensand Formation and low net-to-gross Lutine Formation (Fig. 1).

**Tectonostratigraphic evolution of the Middle Jurassic–Lower Cretaceous**

The interplay between sediment deposition and active structuration creates complex tectonostratigraphic geometries within the study area. For example, the
stratigraphic record locally shows growth/expanded geometries in the form of stratigraphic wedges and troughs, as well as unconformities within and outside of the Dutch Central Graben and Terschelling Basin (Figs 6–13). The stratigraphic thicknesses and types of depositional systems, as well as their stratigraphic preservation potential, stratigraphic architectures and sediment pathways, also vary greatly depending on location and proximity to active structures, such as salt bodies and syndepositional faults.

Each of the three Middle Jurassic–Lower Cretaceous tectonostratigraphic mega-sequences described below are based on the integration of core descriptions, palynological and geochemical data. Table 1.

| Survey name on nlog.nl | Dutch blocks | Vintage | Type |
|------------------------|--------------|---------|------|
| Z3NAM1993A             | A08-A09      | 1993    | 3D   |
| Z3NAM1998C             | A10-A11-A13-A14 | 1998 | 3D   |
| Z3WIN-2000A            | A15          | 2000    | 3D   |
| Z3FUG-2002A            | All B blocks | 2002    | 3D   |
| Z3WIN2001B-1           | B10          | 2001    | 3D   |
| Z3PET1993A             | E09-E12      | 1993    | 3D   |
| Z3WIN1997A             | E18-F16      | 1997    | 3D   |
| Z3NAM1989E             | F02-F03-F05-F06 | 1989 | 3D   |
| Z3RWE1994A             | F02-F03      | 1994    | 3D   |
| Z3RWE1994E             | F02-F03      | 1994    | 3D   |
| Z3NAM1982A             | F03-B18      | 1982    | 3D   |
| Z3PET1992F             | F06          | 1992    | 3D   |
| Z3OXY1994A             | F08-F09      | 1994    | 3D   |
| Z3PET1994B             | F10          | 1994    | 3D   |
| Z3PET1994A             | F15-F16      | 1994    | 3D   |
| Z3WIN2003B             | F16-F17-L01  | 2003    | 3D   |
| Z3NAM1992A             | F17-F18      | 1992    | 3D   |
| Z3NAM1993C             | F18-G16      | 1993    | 3D   |
| Z3PET1991A             | G10-F12      | 1991    | 3D   |
| Z3NAM1997A             | G13_G14_G16_G17 | 1997 | 3D   |
| Z3GDF2005A-1           | G16          | 2005    | 3D   |
| Z3CLY1998A             | G16-G17      | 1998    | 3D   |
| Z3GDF2002A-3           | G17-G18      | 2002    | 3D   |
| Z3NAM1991E             | L01-L02      | 1991    | 3D   |
| Z3PET1992A             | L01-L04      | 1992    | 3D   |
| Z3NAM1994B             | L02-L03      | 1994    | 3D   |
| Z3NAM-1990B_Zero_European | L04-L05   | 1990    | 3D   |
| Z3WIN2003A             | L04-L05-L07-L08 | 2003 | 3D   |
| Z3NAM1990F             | L05-L06-L09-M04 | 1990 | 3D   |
| Z3WIN1995A             | L07-L08      | 1995    | 3D   |
| Z3PEN1985A             | L08          | 1985    | 3D   |
| Z3NAM1988D             | L09-L12      | 1988    | 3D   |
| Z3OXY1996A             | L11-L12      | 1996    | 3D   |
| Z3NAM1988A             | L09-L11-L12-M07 | 1988 | 3D   |
| Z3WIN2005B             | L06 - L02-L03- L05- L08-L09- M01- M04-M07 | 2005 | 3D   |
| Z3NAM1990E             | M01          | 1990    | 3D   |
| Z3NAM1991A             | M02          | 1991    | 3D   |
| Z3NAM1991D             | M04          | 1991    | 3D   |
| Z3PET1991B             | M04-M05      | 1991    | 3D   |
| Z3NAM1996A             | M04-M05-M07-M08 M10-M11 | 1996 | 3D   |
| Z3NAM1994A             | L09-L12-M07-M10 | 1994 | 3D   |
| Z3NAM1989B             | M09          | 1989    | 3D   |
| Z3NAM1989C             | M09          | 1989    | 3D   |
| SNST-83 (no access on Nlog) | All     | 1983    | 2D   |
| SNST-87; Z2NOP1987A    | All          | 1987    | 2D   |
| NSR10; Z2TGS2010A     | All          | 2010    | 2D   |
| Z2RWE1996A             | F            | 1996    | 2D   |
| Z2GTM1998A             | F            | 1998    | 2D   |

Note that most survey data are accessible from the nlog website (www.nlog.nl).
Fig. 6. Interpreted two-way travel time (TWT) for seismic panel A. This section is located in the southeastern part of the study area, oriented NNE–SSW and intercepts four structural elements, namely (from north to south): the Schill Grund Platform, the Terschelling Basin, the Friesland Platform (F.P.) and the Vlieland Basin. This seismic section is 91.5 km long and intercepts seven wells. Note that, along the southern part of the section, the Zechstein Group is offset by several normal faults forming within a large monocline (below salt body SB1). These faults are part of the Hantum Fault Zone (RGD 1991). Several syndepositional faults were active during the Middle Jurassic–Early Cretaceous, such as faults F1–F6. Large growth faults (F4–F7) were also active during the Late Cretaceous and Cenozoic. Most of the faults sole onto the autochthonous Zechstein salt with the exception of F4 that detached on a shallow level, which can be an in situ Upper Triassic salt layer (e.g. evaporites of the Röt Formation) or a remobilized upwards allochthonous Zechstein salt sheet that was later welded out. L1 and L2 refer to topographic lows shown in Figure 10. See Figure 2 for location and Figure 7 for equivalent stratigraphic correlation panel.
analyses (Verreussel et al. 2018), and seismic plus well data analyses. The following discussion relies on four regional seismic and stratigraphic correlation panels that are used to illustrate the evolution of the basins and their platforms. The stratigraphic correlation and seismic analysis were also performed on seven additional regional panels that are not presented in the present paper, but from which information was extracted to map the distribution of key stratigraphic units (Fig. 18). Panel A (Figs 6, 7) illustrates the evolution of the Terschelling Basin and its southern and northern platforms. Panel B (Figs 8, 9) approximately follows the central part of the Dutch Central Graben (panel linking wells located close to the rift axis, rather than the exact position of the axis), while Panel C (Figs 10, 11) illustrates a strike profile across the Dutch Central Graben and its western and eastern platforms. Finally, Panel D (Figs 12, 13) shows the configuration of the northern part of the Dutch Central Graben, transitioning to the NW to the Step Graben. The distribution of key stratigraphic intervals within the study area is presented in Figure 18.

TMS-1: Callovian–Early Kimmeridgian (165–154.7 Ma)

In general, TMS-1 is limited to the axis of the Dutch Central Graben (Figs 1, 8–13, 18a). The development of the basin at this stage reflects renewed rifting following thermal doming in the early Middle Jurassic (sensu Underhill & Partington 1993). Note that the base of TMS-1 in the Danish sector is 3 Ma older than in the Dutch sector, with deposits accumulating as early as during the Bathonian (Verreussel et al. 2018, figs 5, 8).

The first deposits recorded above the Mid Cimmerian Unconformity are the fluvio-deltaic, lacustrine and marginal-marine sediments of the lower part of the Middle–Late Callovian (165–164 Ma) Lower Graben Formation (Figs 1, 3, 9, 11, 13, 14, 18a; Verreussel et al. 2018, fig. 5). Up to 150 m thick, these deposits accumulated in the rift axis within the narrow (less than 10 km wide) zones in the central/northern part of the basin, such as seen in Figures 9 and 11, onlapping underlying strata. This basin configuration is likely due to active salt withdrawal beneath the basin axis, possibly enhanced by thick-skinned normal faulting occurring on bounding faults along the rift margins (Ten Veen et al. 2012). Fluvial channels have been identified in the F06 block using stratal slicing and seismic amplitude extraction techniques, such as ‘root mean square’ and ‘sweetness and frequency’ (Figs 13–16). However, the provenance areas for TMS-1 deposits are unclear since few deposits of that age have been identified outside of the Dutch Central Graben. In the Terschelling Basin for example, only well M01-01 exhibits thin deposits of TMS-1 age (see Fig. 17 for location). This well is located above a salt diapir in the central part of the Terschelling Basin, which could explain the presence of TMS-1 at that location. This is postulated to be a remnant accumulation left in the vicinity of an exposed (or near free surface) salt body. The bulk of the sediments bypassed the area, and was deposited further west into the Dutch Central Graben which was actively subsiding during this period. Several erosional features are identified on seismic in the western part of the Terschelling Basin (e.g. L1, L2, Fig. 6) and are associated with elongated depocentres (I.V., for incised valleys, in Fig. 17). These features are interpreted as incised valleys (or...
canyons) infilled by TMS-2-aged sediments. Similar features have also been identified on the Step Graben and in the NE Dutch Central Graben (Block F06, Figs 2, 16). It is proposed that these palaeo-conduits present in the Terschelling Basin were connected to the Dutch Central Graben area, possibly feeding the basin through a complex network of rivers controlled by structural fabric such as near-surface salt diapirs and fault escarpments. The rate of sediment accumulation is high (up to 330 m Ma$^{-1}$) during this period as indicated by the thick stratigraphic succession, especially in the northern part of the Dutch Central Graben where the Lower Graben Formation is locally more than 500 m thick (wells F03-03, F03-05-S1 and F03-06; Fig. 9). The youngest sediments of the Lower Graben Formation (164–163.5 Ma) were also confined to the Dutch Central Graben but within a larger zone (15–20 km wide, 110 km long; Fig. 18b), as observed by progressive onlaps continuously further away from the basin axis (Figs 8, 10–12, 15). These deposits are up to 400 m thick, sandy (Fig. 3) and display sedimentary features and ichnofacies consistent with tidally influenced shallow-marine environments. Features alluding to alternating freshwater and saltwater environments, such as synaeresis cracks, are abundant in wells F03-05-S1, F06-01 and F14-05 (Fig. 2). In the F14 block further south within the rift basin the presence of fine-grained offshore mudstones was identified in Upper Callovian strata (well F14-05, Lower Graben Formation core, Fig. 3), indicating drowning and pointing to a relatively lower sediment supply than in the southern/central part of the rift basin (see Verreussel et al. 2018 for further discussion of this topic).

The Early–Middle Oxfordian (163.5–160.5 Ma) deposits of the Middle Graben Formation, up to 450 m thickness, accumulated in the Dutch Central Graben within a 40 km (in the south) to 22 km (in the north) wide and 150 km long zone (Fig. 18c). This area extends further south than older units to the L05/F14 blocks. Three regionally extensive coal beds, individually up to 3 m thick, are identified in the lower part of the Middle Graben Formation (Figs 3, 9, 11, 14, 16). They have been identified in numerous wells separated by up to 120 km within the rift system (from well B18-03 to the north to well F02-FA-101 to the south, Fig. 8). These coal beds reflect a humid climate, dominated by wet, lowland palynological indicators (see Verreussel et al. 2018). The coal beds also likely reflect sediment starvation in the basin axis. The sudden switch off of sand supply can be ascribed to a regional transgression that flooded the graben shoulders and forced the deposition of marginal-marine sands onto the adjacent plateau areas (Verreussel et al. 2018). These sands were likely eroded later, as no Early–Late Oxfordian sandstones are present on these bordering plateaus. A single 200–300 m wide meandering channel is seismically observed in the F06 block where it cuts down into the regionally extensive coal layers (Figs 14–16). The trajectory of this large river is sinuous in the basin axis but shows more angular bends updip towards the eastern basin margin. At this location, the stratigraphic architecture observed on seismic data suggests updip confinement, interpreted as an incised valley (Fig. 16). This river is postulated to have developed on the Schill Grund Platform before reaching the rift axis in the Dutch Central Graben. This type of depositional model is uncommon in rift settings where lateral sediment input usually occurs along fault ramps (e.g. Gawthorpe & Leeder 2000). In the present case, it is proposed that differential subsidence between the rift axis and its shoulders is largely being controlled by smooth and regular salt withdrawal rather than fault propagation. This allows the lateral sediment input to reach the basin through fluviodeltaic depositional systems that show variable levels of physiographic confinement, from broad unconfined depositional patterns to sediment input through incised valleys or canyons.

The upper part of TMS-1 is composed of several formations that are time-equivalent to each other, from the proximal lower part of the 150–300 m thick Friese Front Formation (blocks L05 to F17), the up to 500 m thick Puzzle Hole Formation (blocks F08 to F14), to the distal up to 1200 m.

Fig. 8. Interpreted two-way travel time (TWT) for seismic panel B. This 170 km long section which intercepts 22 wells, is located along the axis of the Dutch Central Graben and extends southwards to the southern part of the Central Offshore Platform. For convenience, the section is split into two parts (a and b). The base Zechstein dips overall to the north from a highly faulted southern zone to the location of fault F1, which has a 1.5 s (TWT) vertical throw. This large fault bounds the deepest part of the Dutch Central Graben. Four shallow salt diapirs (SB1–4) are located within this section and are emplaced within the Cenozoic (SB1), the Cretaceous (SB2) and the Jurassic (SB3 and 4). Note two smaller salt features (SB5 and SB6) that are either remobilized Zechstein salt bodies emplaced intra-Trias sic, or over-thickened in situ Triassic salt layers (e.g. Röt Evaporites). Note the over-thickened Lower Jurassic Altena Group north of SB3 that is related to the asymmetric salt withdrawal beneath the F17 turtle structure. Numerous post-Zechstein faults are observed in this section. Seven large listric growth faults (F2–9) were active during the Jurassic and Cretaceous. Only F2 detached on the Zechstein, while other faults detached at the lower part of the Lower Jurassic (F3, F4 and F9) and intra-Trias sic (F5–F8). See Figure 2 for location, Figure 6 for legend and Figure 9 for stratigraphic correlation panel of the northern part of this panel.
Fig. 9. Stratigraphic correlation panel of TMS-1 in the northern part of the Dutch Central Graben, along the rift axis. This section corresponds to the northern part of panel B shown in Figure 8. The stratigraphic correlation for TMS-2 and 3 are not shown in the present paper. TMS-1 is thick in this part of the basin, locally reaching up to 1500 m at the location of well F03-03. Basal stratigraphic onlaps are observed on seismic showing that the Lower Graben Formation was filling up palaeotopographic lows inherited from the Middle Jurassic erosional events. Note the presence of the regionally extensive coal measures in the lower part of the Middle Graben Formation (shown as dashed outlined, grey filled unit). The sandy Upper Graben Formation is restricted to the central part of the section, correlates southwards to the time-equivalent Puzzle Hole Formation and pinches northwards toward the northern basin margin where it becomes mud-prone. The Kimmeridge Clay Formation is overall very fine-grained except in the northern part of the section (wells F03-05-S1 and F03-06) where a few 2–10 m thick sandy units are identified. These deposits are interpreted as deep-water sediment gravity flows generated by episodic structural movement along the basin margin. Red lines correspond to seismically constrained regional erosional surfaces. See Figure 2 for location, Figure 6 for legend and Figure 8 for corresponding seismic section. See Figure 3 for correlation of the F03-05, F06-01 and F14-05 Lower Graben Formation cores (red vertical bars along wells on Fig. 9).

thick upper part of the Middle and Upper Graben Formation and lowermost part of the Kimmeridge Clay Formation (blocks F08 to B13) (Fig. 18d–f). In the south the Friese Front Formation is mainly composed of fluvial deposits, while the Puzzle Hole Formation consists of fluvio-deltaic deposits. To the north the Upper Graben Formation is composed of higher net-to-gross strata deposited in a more marginal setting, likely in prodeltaic to shelfal environments (Munsterman et al. 2012). Figure 15 demonstrates three such deltas that are 3–5 km wide and are proposed to connect updip to a distributary and fluvial system that originated to the east, likely on the Schill Grund Platform. These fluvio-deltaic systems correlate northwards to the lower part of the marine Kimmeridge Clay Formation.

TMS-2: Late Kimmeridgian–Late Volgian (154.7–146.6 Ma)

TMS-2 is characterized by increased tectonic activity and the development of new secondary basins along the main rift. The Terschelling Basin developed during this period in the Dutch offshore, while the Heno Plateau/Feda Graben/Gertrud Plateau developed into active basins in the Danish western offshore (Andsbjerg & Dybkjaer 2003; Verreussel et al. 2018, fig. 8). The Terschelling Basin was affected by vertical movements along newly active or reactivated NW–SE-trending faults along its northern (Rifgronden Fault Zone) and southern (Hantum Fault Zone) basin margins (Duin et al. 2006). Deposition persisted in the Dutch Central
Graben during this period, but was primarily composed of fine-grained sediments of the marine Kimmeridge Clay Formation apart from local occurrences of the generally fine- to medium-grained Noordvaarder Member (Figs 1, 13). The Dutch Kimmeridge Clay Formation (159–147 Ma), which is up to 1100 m thick in the northern part of the Dutch Central Graben, represents the deepest water depositional setting of the Middle Jurassic–Lower Cretaceous succession (interpreted as deep-water mudstones with sandy sediment gravity flows of unknown reservoir qualities, since no core is available). Precise water depths are unknown. Note that the older part of the Kimmeridge Clay Formation in the northern part of the Dutch Central Graben is part of TMS-1 (Fig. 1). In a similar fashion, also note that the upper part of the Friese Front Formation (referred as the Main Friese Front Member) belongs to TMS-2 (see Fig. 1).

A significant flooding event occurred during the Late Kimmeridgian (J63 flooding of Partington et al. 1993; Fig. 1) that permanently set up marine conditions for the Late Kimmeridgian–Ryazanian in the entire Dutch offshore. In the Terschelling Basin, this flooding is expressed by the occurrence of organic-rich, fossiliferous, laminated shales belonging to the Late Kimmeridgian–Early Volgian Oyster Ground Member (152.4–150.8 Ma), which is up to 320 m thick in the western part of the Terschelling Basin (Figs 1, 4). Following a further significant flooding event, two geographically independent sandy systems became active in the Terschelling Basin. In the southern and central parts of the basin the tidally influenced sand-prone shoreface deposits of the Early–Middle Volgian Terschelling Sandstone Member (150.8–148 Ma), up to 160 m thick, were deposited. Detailed seismic mapping suggest that the palaeo-coastlines were oriented SSW–NNE (from block L09 to block M01; see Fig. 17 for location) during this period in the southern part of the basin. Meanwhile, in the northern part of the Terschelling Basin (blocks G16, L03 and F18) and along the central eastern part of the Dutch Central Graben (blocks F17), the Early Volgian–Middle Volgian finer-grained sandy Noordvaarder Member was deposited in lower shoreface/upper offshore settings (Figs 1, 2, 7b, 18c). The Noordvaarder Member is interpreted as being the result of local erosion off the Schell Grund Platform. A similar, locally sourced, sandy system of the same age is present in the northern part of the Dutch Central Graben in blocks B13 and B14 (Figs 1, 13, 18c), which is also referred to as the Noordvaarder Member. In this area, it is observed to have been deposited on the downthrown side of a large growth fault that seemingly detached on a salt pillow located...
Fig. 10. Interpreted two-way travel time (TWT) for seismic panel C. This 70 km long section is located across the Dutch Central Graben and extends westwards to the southern Step Graben and eastwards to the Schill Grund Platform. Three salt diapirs (SB1-3) are located above large normal faults that were active during and possibly prior to the Triassic–Jurassic rifting. The Altena Group is only present within the Dutch Central Graben and was eroded on the neighbouring platforms and even locally within the Graben (e.g. location of well F12-03 and around SB2). Note the asymmetric geometry of the Middle Jurassic–Lower Cretaceous infill, with a western over-thickened stratigraphy around well F11-03 compared to the eastern side of the graben around well F12-03. The central part of the graben was also uplifted and eroded during the Cretaceous and Cenozoic, likely due to Alpine shortening (e.g. no TMS-2 or -3 are preserved in well F11-01). The Alpine shortening is also illustrated by the presence of a pop-up structure (PU1) and the squeezing of salt body 3 (SB3). See Figure 2 for location, Figure 6 for legend and Figure 11 for equivalent stratigraphic correlation panel.
along the rift basin margin (Fault F1, Figs 12, 13). Figure 17 shows a time–thickness map of TMS-2 in the Terschelling Basin. This sequence is thickest in the western part of the basin (block L03), and thins towards the basin margins. A noticeable ramp geometry is seen in this map (dashed white line, Fig. 17) that represents the basin palaeo-margin at the end of the Oyster Ground Member deposition. The basin later widened, with the Terschelling Sandstone Member being deposited further to the east and north (area between the dashed white and solid white lines in Fig. 17). This widening of the Terschelling Basin continued during the deposition of the following mega-sequence (TMS-3). This is demonstrated in Figure 17 by the orange zone that represents the area located between the maximal extent of TMS-2 (white line) and TMS-3 (blue line).

TMS-3: Late Volgian–Ryazanian (146.6–139 Ma)

The base of TMS-3 is a regional unconformity that erodes into TMS-2 in the Dutch Central Graben (Figs 11, 13) and down to Permo-Triassic strata on the platform areas. TMS-3 is eroded in large parts of the Dutch Central Graben and is only preserved in a few zones, specifically in the south (blocks L02, F18, F17, F16 and E18), along the lateral margins of the graben (blocks F12 and western part of F11) and in the north (blocks F05, F02, F03, B18 and B17). TMS-3 is also locally preserved in the Step Graben (blocks F01, E03, A18, A15 and A12) (Fig. 18h).

TMS-3 is well preserved in the Terschelling Basin with little post-depositional erosion observed. In this basin, the transition from TMS-2 to -3 is mainly conformable in the basin axis and is usually expressed by a coarsening-upwards grain size trend seen in wireline logs (e.g. wells G16-05, L03-04, L09-02 in Fig. 7c; well in F12-03, Fig. 11a; well B18-03 in Fig. 13). At the basin margins, however, this surface is typically observed to be erosional (Figs 11, 13). The vast volumes of sand observed in the Middle Volgian–Early Ryazanian Scruff Greensand Formation (146.6–141.5 Ma) (up to 190 m thick at the axis of the Terschelling Basin, Fig. 7c) indicates substantial erosion in the hinterland and along the basins margins, likely related to denudation and re-deposition.

A geographically restricted sand-prone depositional system is observed along the southern margin of the Terschelling Basin (M07 block) and, based on palynological information, is time-equivalent (147–139 Ma) to the Scruff Greensand and Lutine formations (Figs 1, 5 between markers B and C). This sandy unit has been the subject of recent successful hydrocarbon exploration by Oranje Nassau Energie in (M07-B Field) and has the potential for being a new promising play type in the Dutch offshore and beyond. These deposits are postulated to result from the erosion of the Ameland Platform and Friesland Platform to the south (Zechstein and Triassic-age strata), as suggested by the extra-formational angular clasts of sandstone and limestone observed in the lower shoreface of M07-07 and M07-08 cores (Fig. 5, at depth of 4838 m). In this core, pebble-rich beds are interpreted as debris flows generated by the structurally active basin margin where salt diapirs and faults were active (see block M07, Fig. 17). The gamma ray trend of the well M07-08 (Fig. 5) is heavily biased by glauconite content, which explains the apparent discrepancy between the wireline log response and the lithologies seen in core.

Salt tectonics and synrift stratigraphy

The autochthonous Zechstein salt has been actively remobilized since the Late Triassic. Salt tectonics is often complex and several aspects are discussed below, from the migration and withdrawal of autochthonous (Zechstein) salt to the relationship between deep structures and shallow salt bodies, as well as the specific relationship between shallow salt bodies and Middle Jurassic–Lower Cretaceous stratigraphy. For example, TMS1-3 was heavily affected by contemporaneous salt tectonics, directly around salt bodies and indirectly by normal growth faults that detached into the ductile Zechstein salt.

Autochthonous salt withdrawal

Zechstein salt was actively migrating and withdrawing from its autochthonous level during the Late Jurassic and Early Cretaceous, creating locally strongly subsiding zones notably in the Dutch Central Graben and, in a more limited way, in the Terschelling Basin. In the central part of the Dutch Central Graben (see also Duin et al. 2006; van Winden et al. 2018) the salt-related strong subsidence occurred mainly during the Middle Triassic–Early Jurassic (245–200 Ma) at the basin axis and shifted to the basin lateral margins during the Middle Jurassic–Early Cretaceous (165–139 Ma), forming large turtle structures (e.g. in blocks F17, F18 and F11 turtles; Figs 8, 15).

Relationship between shallow salt bodies and Middle Jurassic–Lower Cretaceous stratigraphy

Numerous salt bodies were emplaced within the Middle Jurassic–Lower Cretaceous. They often greatly impacted the depositional style, stratigraphic thickness and preservation of sediments due to differential subsidence. This is known to have allowed growth of
stratigraphic wedges and troughs (e.g. salt bodies SB2 and SB3, Fig. 7; SB2 and SB3, Figs 10, 11) (see De Jager 2012; van Winden et al. 2018).

The evolution of these salt bodies often affected the geometry of surrounding stratigraphic units by forcing the rotation and tilting of neighbouring stratigraphic blocks that were later often eroded, creating complex progressive unconformities and rim synclines. One such example is in the western margin of the Dutch Central Graben in the F11 block (adjacent to salt body SB3, Figs 10, 11). In this example, TMS-1 is only 12 m thick in well F11-03 compared to more than 1000 m thick in well 11-01 at the basin axis (Fig. 11b). In contrast, in Figure 11, TMS-2 and TMS-3 are only present along the basin margins where salt withdrawal created differential subsidence and where rim synclines and troughs formed, likely due to tilted and eroded Triassic stratigraphy. The deformation and withdrawal of allochthonous salt sheets also played a role in the stratigraphic patterns of the Middle Jurassic to Lower Cretaceous. For example, in the B13/B14 area (Figs 2, 12) syndepositional extensional faulting occurred above a deflated allochthonous salt sheet (SB1, Fig. 12). Similar geometries are observed in other salt basins with extensive allochthonous salt systems such as the Deep-water Gulf of Mexico (Bouroullec & Weimer 2017).

Relationship between synsedimentary faults and Middle Jurassic–Lower Cretaceous stratigraphy

Numerous syndepositional faults were active during the deposition of the Middle Jurassic and Early Cretaceous stratigraphy. These faults vary in size and geometry; they detached in various intervals, including on the autochthonous Zechstein halites, along the flanks of shallow salt bodies, at the top or within the Upper Triassic and within the Lower Jurassic. These faults are locally thin-skinned listric growth faults with associated hanging-wall stratigraphic wedges (e.g. fault F1, Fig. 6; fault F7, Fig. 8; fault F1, Fig. 12). It is difficult to estimate the possible local lithological impact of such synsedimentary faults on the surrounding sediment, but previous research (Edwards 1976; Bouroullec 2001) indicates that thicker but non-amalgamated sandstone units are often prevalent in fluvio-deltaic and marginal-marine depositional systems affected by growth faults. The largest growth faults are observed in the Dutch Central Graben (faults F3-9, Fig. 8) and were active during the Middle Jurassic–Cretaceous, with up to 40% thickening during TMS-1 in the case of fault F8 located between well F08-02 and F08-01. Fault F1 (Figs 12, 13) detached on the flank of a salt pillow and was active during the deposition of TMS-2. The hanging wall of that fault is seen to be sandier (relative to the footwall) with up to 160 m of Noordvaarder Member sandstones observed in well B13-02. Such basin margin sand-rich deposits can be attractive stratigraphic plays if the trap geometry can be understood and an efficient seal is present. Small syndepositional faults are observed on the flanks of the salt turtle structure located in block F17 (Fig. 8a), detaching in the Upper Triassic and at the base of the Lower Jurassic. These faults are likely related to the oversteepening of the turtle flank and the sliding of the stratal block northwards on the northern turtle flank and southwards on the southern turtle flank during the deposition of TMS-2 and -3.

Effect of palaeotopography on sediment distribution

Salt migration and fault movement can create palaeotopographic features which can impact reservoir distribution (e.g. Booth et al. 2003). One reservoir-scale example is shown in Figures 14–16 where kilometre-scale, laterally offset, marginal deltas and large rivers developed along the basin margin in the F06 block. The geometry of these stratigraphic elements indicates that sediment input into the rift system was mainly lateral instead of longitudinal to the rift axis during those periods. Figure 16 illustrates the decreasing depositional confinement from the updip platform/marginal areas to the basin axis where distributary/unconfined architecture are prevalent. These rapid stratigraphic architecture changes

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Fig. 11. Seismic and stratigraphic correlation of panel C for the Middle Jurassic–Lower Cretaceous intervals. (a) Interpreted seismic section flattened on top of TMS-3. The unflattened version of this section is shown in Figure 10. TMS-1 shown in yellow, TMS-2 in green and TMS-3 in orange. TMS-1 is present in the axis of the Dutch Central Graben, while TMS-2 and -3 are only present on the lateral margins, within a rim-syncline to the west and a thin succession to the east. Note that post-depositional erosion was compensated for by the flattening procedure between wells F11-03 and F12-03. (b) Stratigraphic well correlation of TMS-1, -2 and -3. TMS-1 is thick in the axis of the Dutch Central Graben (980 m). During the deposition of TMS-1 the basin was relatively narrow (10 km wide originally, to 20 km by the end of TMS-1) and was rapidly subsiding, as shown by the trough-shaped geometry of the basin and the complex truncation and onlap configuration along the palaeo-margins. Red lines correspond to seismic-determined regional erosional surfaces. The eastern and western part of the TMS-1 were eroded prior to the deposition of TMS-2 and -3 (see high-angle truncation on the west side and lower angle on the east side). These zones became the loci of deposition for TMS-2 and -3 (wells F11-03 and F12-03). See Figure 2 for location and Figure 6 for legend.
Fig. 12. Interpreted two-way travel time (TWT) for seismic panel D. This 92 km long section is located in the northern part of the Dutch Central Graben and extends northwards to the Step Graben. The Mesozoic fill of the graben is folded, mainly due to differential salt withdrawal during the Middle Jurassic–Early Cretaceous, and partially due to Cenozoic Alpine contraction that extended the duration of the fold’s growth. TMS-1, -2 and -3 illustrate a thickness change between the over-thickened synclines (between wells B14-03 and B18-02, and between B18-02 and B18-03) and the over-thinned anticlines (at the location of wells B14-01, B18-02 and B18-03). Note that all three mega-sequences are increasingly eroded further north towards the basin margin (e.g. well B14-02). However, an exception is observed at the basin margin proper where TMS-2 is over-thickened on the downthrown side of a large SE-dipping growth fault F1. Note the intra-Triassic allochthonous salt sheet (SB1) located south of well B14-02, interpreted as an extruded Zechstein salt sheet that was nearly fully welded out during the Jurassic. Red line corresponds to an intra-TMS-1 erosional surface. See Figure 2 for location, Figure 6 for legend and Figure 13 for equivalent stratigraphic correlation panel.
Fig. 13. Stratigraphic correlation of panel D for the Middle Jurassic–Lower Cretaceous. All three mega-sequences are present within the Dutch Central Graben. The lower part of TMS-1 is confined to the axial part of the Dutch Central Graben, with the Lower and Middle Graben formations lapping out onto the palaeo-basin margin towards the NW and filling up palaeo-topography in the basin axis. TMS-2 shows a northwestwards lateral fining trend with well B14-03 showing little sand deposition at the basin axis. The exception is the over-thickened Noordvaarder Member on the downthrown side of a growth fault (F1) that is interpreted as locally derived redeposited sediments from the neighbouring Step Graben area. TMS-3 shows lateral facies change between well B18-03 and B18-02. Dashed red line corresponds to an intra-TMS-1 erosional surface. See Figure 2 for location, Figure 6 for legend and Figure 12 for corresponding seismic section.
illustrate the impact that differential salt withdrawal has on the local accommodation pattern by providing variable subsidence between the basin axis and its margins.

Multiple examples of palaeotopographic control on Middle Jurassic–Lower Cretaceous (165–139 Ma) depositional patterns can be observed in the regional seismic panels (Figs 6–9) where numerous basal and internal stratigraphic onlaps are observed, reflecting the role of local slope and changes in accommodation space and sediment accumulation. The onlap configuration at the base of the Middle–Upper Jurassic at the rift axis (e.g. between wells F03-08 and F03-05, between wells F06-01 and F08-01 in Fig. 8, between wells F11-02 and F12-03 in Figs 10, 11; and between wells B14-03 and B18-02 in Fig. 12) indicates that axial salt withdrawal already played an important role immediately after Middle Cimmerian erosional events. A progressive unconformity at the base of TMS-1 indicates that erosion, and likely re-deposition, of the Lower Jurassic or older strata along the palaeo-basin margins occurred simultaneously as the deposition of the Lower Graben Formation. This is the case between
wells F11-02 and F11-01 (Fig. 11), where the base TMS-1 is erosional and Lower Graben Formation strata lap onto the western basin margin. During the Early Kimmeridgian the depositional area broadened, reaching the rift shoulders. At the same time, the zones of maximum salt withdrawal shifted from the rift basin axis to the lateral basin margins, triggering rotation and sometimes erosion of the previously deposited Triassic and Jurassic (252–155 Ma, up to Oxfordian age) sediments. Lateral salt migration therefore resulted in the formation of internal and locally extensive unconformities and onlap surfaces, especially during the deposition of TMS-1 (Figs 10, 11). During this period, a type of stratigraphic cannibalism occurred since the depositional area within the rift basin episodically shrunk to narrower zones at the basin axis, possibly resulting in local erosion and re-deposition of Triassic–Upper Jurassic sediments that were originally deposited within the rift basin. Figure 11 shows internal erosional and onlap configuration between wells F11-02 and F11-01, as well as between wells F11-01 and F12-03 (especially within the Puzzle Hole Formation).

Detailed mapping of TMS-2 and -3 in the Terschelling Basin (Fig. 17) also revealed a variable basin margin configuration during the Middle Jurassic–Early Cretaceous. During TMS-2, the basin margin length – including the northern, eastern and southern margins (knowing that to the west the Terschelling Basin transitioned into the southern part of the Dutch central Graben) – was 170 km long and displayed four different basin margin types. Each of these margin types were identified from seismic data and individually mapped around the Terschelling Basin. The most common type of basin margin...
Fig. 16. (a) N–S and (b) E–W two-way travel time (TWT) seismic sections in the F06 block showing the variable seismic architecture of the fluvial channel shown on map (c). At its updip location (a) the channel is interpreted as a wide (1–2 km) confined incised valley (base shown as a dashed white line) that cuts down into the Lower Graben Formation. Downdip (b), the channel is narrower (200–300 m wide), less confined (location 1) and is not recognized further west (location) on this 2D seismic section. (c) Example of a RMS (root mean square) seismic attribute map of a stratal slice in the lower part of the Middle Graben Formation (see Fig. 14b for stratigraphic position). This stratal slice is located at the level of the regionally extensive coal layers (see Figs 1, 3, 9, 11, 13). The high amplitudes in the basin axis are related to these thick (2–3 m) coal layers sitting below the claystone of the Middle Graben Formation. A 200–300 m wide sinuous fluvial channel is observed (dashed red line) coming from the eastern basin margin area north of the buried salt body 1 (SB1), where it takes a few sharp turns before entering the basin axial zone, where it shows smoother sinuosity such as in a meandering river system (Parker et al. 2011). Note the amplitude changes in the channel itself from bright updip to dark downdip, which is attributed to a lithology change of the channel fill from sandy on the basin margin where the channel is confined (a) to muddier at the basin axis where the channel is more uncon confined (b) (Brown 2011).
is a thinning geometry (76% of the total length of the palaeo-basin margin) with TMS-2 strata thinning onto gently sloping margins. Rim syncline geometry is the second most common basin margin type (11%), with marginal strata accumulating in local topographic lows developing along the flanks of autochthonous salt pillows. The least common basin margin types are the conduits type (7%), consisting of major entry points for sediment entering the basin, and fault wedge type (6%), consisting of the hanging walls of large growth faults that detached on marginal salt pillows. The basin widened during TMS-3 (see Fig. 17, from the white line to the blue line) and the total length of its margin increased from 170 to 238 km, with the following five types of configurations: thinning (60%); fault wedge (17%); high-angle onlap against salt (14%); rim syncline (7%); and conduit (2%).
| Formation and member | Illustration | Dominant lithology | Sedimentary structures | Burrows | Environment of deposition |
|----------------------|--------------|--------------------|------------------------|---------|--------------------------|
| **TMS-1**            |              |                    |                        |         |                          |
| Lower Graben Formation | Cores: Figure 3; others: Figures 1, 9, 11, 13, 14, 16, 18a, b | Claystones, siltstones and fine-grained sandstones; coal layers; siderite bands and nodules; sandstone bodies 1–4 m thick | Cross-bedding, mud drapes (sometimes double), syn-aeresis cracks | In parts only rootlets and Planolites; in other parts Ophiomorpha, Asterosoma, Rosselia and Zoophycos | Fluvio-deltaic and marginal marine (tidal, lagoonal, storm-influenced shoreface) |
| Middle Graben Formation | Cores: Figure 3; others: Figures 1, 9, 11, 13, 14, 16, 18c | Grey, locally very silty, carbonaceous claystones with three thick, very extensive coal layers | No core studied | No core studied | Fluvial and lacustrine to marginal marine |
| Upper Graben Formation | Figures 1, 9, 13, 14, 15, 18d | Greyish-brown, fine-grained, carbonaceous sandstones, separated by silty clay successions | No core studied | No core studied | Marginal marine barrier-island |
| Puzzle Hole Formation | Figures 1, 9, 11, 18e | Light brownish-grey carbonaceous claystones with intercalations of siltstones and thin sandstones; coal seams are frequent | No core studied | No core studied | Lower delta plain and lagoonal settings with occurrence of bay head deltas, mouthbars, tidal flats and tidal channels |
| **TMS-1 and -2**     |              |                    |                        |         |                          |
| Friese Front Formation | Figures 1, 18e, f | Alternating claystones, siltstones, sandstones and some minor coals | No core studied | No core studied | Non-marine delta plain to lagoonal deposits |
| Kimmeridge Clay Formation | Figures 1, 9, 11, 13, 14, 18g | Olive-grey silty claystones with thin dolomitic streaks | No core studied | No core studied | Lower offshore setting |
| **TMS-2**            |              |                    |                        |         |                          |
| Main Friese Front Member (Friese Front Formation) | Figures 1, 7, 18f | Alternating claystones, sandstones and some coals | No core studied | No core studied | Delta plain and lagoonal |
| Member/Formation                  | Core/Additional Figures | Texture/Composition                                                                 | Fossil/Trace Fossil | Depositional Environment          |
|----------------------------------|-------------------------|-------------------------------------------------------------------------------------|---------------------|-----------------------------------|
| Oyster Ground Member (Skylge    | Core: Figure 4; others: | Non- to slightly silty claystones, with a few fossils and lignite fragments        | Shell beds, hummocky | Lower shoreface                    |
| Formation)                       | Figures 1, 7, 18g       | Well to poorly sorted, fine- to medium-grained sandstone (occasionally up to coarse sand and even gravel) | Trough cross-bedding, wave ripples, cross-lamination, low-angle lamination | Trough cross-bedding, wave ripples, cross-lamination, low-angle lamination |
| Terschelling Sandstone Member    | Core: Figure 4 Figures 1, 7, 18g | Well to poorly sorted, fine- to medium-grained sandstone (occasionally up to coarse sand and even gravel) | No core studied | Upper shoreface, back barrier and tidal lagoon with channels |
| (Skylge Formation)               |                         | Well to poorly sorted, fine- to medium-grained sandstone (occasionally up to coarse sand and even gravel) | No core studied | Upper shoreface, back barrier and tidal lagoon with channels |
| Noordvaarder Member (Skylge      | Figures 1, 7, 13, 18g   | Well to poorly sorted, fine- to medium-grained sandstone (occasionally up to coarse sand and even gravel) | No core studied | Lower shoreface to upper offshore |
| Formation)                       |                         | Well to poorly sorted, fine- to medium-grained sandstone (occasionally up to coarse sand and even gravel) | No core studied | Lower shoreface to upper offshore |
| Lies Member (Skylge Formation)   | Core: Figure 4, Figures 1, 7, 11, 18g | Well to poorly sorted, fine- to medium-grained sandstone (occasionally up to coarse sand and even gravel) | No core studied | Upper and lower offshore |
| TMS-3                            | Core: Figure 5; others: | Glaucocitic, fine- to medium-grained sand                                             | Completely bioturbated | Lower shoreface to open marine     |
| Scruff Greensand Formation       | Figures 1, 7, 11, 13, 14, 18h | Glaucocitic, fine- to medium-grained sand                                             | Asteroxoma, Diplocraterion, Rosselia, Thalassinoides, Phycosiphon | Lower shoreface to open marine     |
| Lutine Formation                 | Figures 1, 7, 11, 13, 18h | Olive-grey, grey-brown to black claystones and fine- to very fine-grained argillaceous sandstones | No core studied | Upper offshore                      |
| SYNRIFT TECTONOSTRATIGRAPHY, DUTCH CENTRAL GRABEN |                         |                                                                                      | No core studied | Upper offshore                      |
Fig. 18. (a–h) Distribution maps for the main lithostratigraphic units of the Middle Jurassic–Lower Cretaceous. Background maps for each time step is the base Rijnland Group subcrop map, in which areas mapped as unspecified Middle Jurassic–Lower Cretaceous strata are shown as white polygons. Each map shows the stratigraphic distribution as coloured thick lines along regional seismic panels (including those not shown in the present paper). Position of all the wells and seismic panels used to build these distribution maps shown in (a). Only the wells that have penetrated the given stratigraphic unit are shown. TMS-1 shown as yellow lines, TMS-2 as green and TMS-3 as orange. Note that the marginal sandy-rich Noordvaarder Member is also shown as dark blue lines in (g).
M07-B gas discovery is in a fault wedge configuration with reservoir sands of TMS-3.

The western part of the Terschelling Basin, the Step Graben and other low-accommodation zones such as the Schill Grund Platform and the Cleaver Bank Platform were subject to little or no deposition of TMS-1 and -2. Only small remaining areas on the platforms, often located within topographic lows,
exhibit strata of that age (e.g. L1 and L2, Fig. 6; I.V. in Fig. 17). Based on the elongated geometry of these lows in map view, their erosional bases and the presence of basal onlaps of their fills, these features are interpreted as incised valleys (or possibly continental canyons) that developed during the deposition of TMS-1, providing sediment conduits into the rift basin within the Dutch Central Graben. The development of these incised valleys (or canyons) started during the deposition of TMS-1 in a few areas, such as the western part of the Terschelling Basin; in most cases however, based on 3D seismic mapping of TMS-1-3 in the Terschelling Basin, the fills of these palaeo-conduits were composed exclusively of TMS-2 sediments during a period of significant sea-level rise. This indicates that these conduits were long-lasting features that provided pathways for sediment transport into the rift basin during TMS-1 and were later drowned and sediment-filled during TMS-2. It is also important to notice that the platform areas suffered high amounts of erosion during multiple phases related to Middle Jurassic doming (Mid Cimmerian Unconformity, Bajocian–Bathonian, 170–166 Ma). The multiple Middle Jurassic–Early Cretaceous rifting phases may have triggered hundreds of metres of rift shoulder uplift and generated relative sea-level drops in the Early Volgian (150.3 Ma) (base of Terschelling Sandstone and Noordvaarder members) and Late Volgian (146.6 Ma) (Scruff Greensand Formation) (Verreussel et al. 2018). These erosional events likely frequently reshaped the physiography of the rift shoulders and, subsequently, the hydrographic characteristics of these areas. Most of these palaeo-surfaces were also later eroded during the latest Upper Jurassic (base of TMS-3; 146.6 Ma), Early Cretaceous (base of TMS-4, 139 Ma; Verreussel et al. 2018) and/or during the Paleocene (Laramide tectonic phase, 63 Ma).

The results of this study, demonstrating the tectonostratigraphic evolution of a failed rift system affected by salt tectonics in the Dutch offshore, are important for local geological knowledge and for hydrocarbon exploration. These results are also relevant for other areas of the North Sea where salt tectonics was contemporaneous to thick-skin extensional tectonics. In this paper, the effects of combined brittle/ductile deformation on continental and shallow-marine depositional systems have been discussed. The study also constitutes an important addition to the topic of syntectonic effects on depositional systems. This topic has been considered extensively in clastic deep-water settings affected by salt tectonics (e.g. Booth et al. 2003; Prather 2003), carbonate settings affected by salt tectonics (e.g. Giles & Rowan 2012), continental settings (e.g. Banham & Mountney 2013) and for clastic continental settings affected by brittle deformation (e.g. Gawthorpe & Leeder 2000; Cowie et al. 2005). However, relatively little documentation on the impact of rifting and salt tectonics on shallow-marine settings has previously been published (Mannie et al. 2016). It is acknowledged that additional tectonostratigraphic analyses are required in other parts of the basin, via detailed 3D mapping and seismic amplitude analysis, to better understand the temporal and spatial evolution of the depositional systems affected by both salt tectonics and brittle deformation. Such topics are the subject of new research by the authors.

The results presented here regarding the Middle Jurassic–Early Cretaceous tectonostratigraphy of the Dutch offshore complement the already extensive knowledge of the interval in the North Sea (Andsbjerg & Dybkjær 2003; Fraser et al. 2003; Wonham et al. 2014). The article by Verreussel et al. (2018) applies knowledge of the Dutch Sector northwards to the offshore German and Danish sectors and, despite being primarily focused on the stratigraphic framework of this larger area, should be considered alongside this work to fully understand the tectonostratigraphic evolution of the entire failed rift system.

Conclusions and perspectives

Based on the integrated results of the tectonostratigraphic analysis, core description and palynological analyses carried out in the Dutch offshore, as well as regional stratigraphic analysis of Verreussel et al. (2018), this study acknowledges and strengthens the recently developed tectonostratigraphic three-fold subdivision for the Middle Jurassic–Lower Cretaceous interval in the Dutch offshore (Abbink et al. 2006). The new chronostratigraphic framework proposed in the present paper (Fig. 1) clarifies the lateral equivalencies of known lithostratigraphic units. The Middle Jurassic–Lower Cretaceous interval was deposited during a period of intense rifting and salt movements. Deep-skinned and thin-skinned tectonic structures were active during this period and resulted in a complex basinal configuration. The withdrawal of Zechstein salt beneath the axis of the Dutch Central Graben and, to a lesser extent the Terschelling Basin, was the primary control affecting high accommodation and subsequent thick accumulation of Middle–Upper Jurassic strata (TMS-1) at the basin axis (e.g. 1.6 km in the F03 block). During TMS-2 and -3, the salt migration shifted laterally from the basin axis towards marginal-shallow salt bodies and locally formed large turtle structures. These salt bodies played a critical role in generating heterogeneous stratigraphy by creating zones of differential subsidence that experienced variable stratigraphic accumulation and preservation. With this improved
understanding of the tectonostratigraphy of the Middle Jurassic–Lower Cretaceous in the Dutch offshore, new insights are offered on the complex interplay between active structures and depositional systems. The potential for new play types along the basin margins of rift affected by salt tectonics, as well as possible combined stratigraphic/structural traps in association with salt features in this part of the North Sea Basin, has also been highlighted.

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