The Jurassic of the Netherlands

G.F. Waldemar Herngreen, Wim F.P. Kouwe and Theo E. Wong

A recent revision of the lithostratigraphy of the Netherlands has triggered an extensive re-evaluation of existing ideas on the Jurassic structural and depositional history. Significant advances can be attributed to the incorporation of sequence stratigraphic concepts. In the course of the Triassic and Jurassic, structural complexity increased progressively. The Jurassic sedimentary succession can be subdivided into three depositional megasequences. Megasequence I (Rhaetian–Aalenian) reflects the period between the so-called early and mid-Cimmerian tectonic phases. Megasequence II (Aalenian – Middle Callovian) covers the period of activity of the mid-Cimmerian phase. Megasequence III (Middle Callovian – Ryazanian) corresponds with the period between the mid-Cimmerian and late Cimmerian phases (particularly after pulse II). In this latter megasequence, six stages (IIIa–f) are recognised. Sediments deposited during the Rhaetian and Ryazanian bear a stronger affinity with the Jurassic succession than with Triassic and Cretaceous sediments respectively. These stages are thus treated here as an integral part of the Jurassic succession. During the Rhaetian–Bajocian the area subsided relatively uniformly. A sheet of predominantly fine-grained marine sediments of great lateral uniformity was deposited. During the Toarcian, in particular, basin circulation was largely restricted.

The cooling that followed the thermal Central North Sea dome uplift triggered an important extensional phase during the Aalenian–Callovian. The rift phase resulted in the formation of several smaller basins, each with its own characteristic depositional succession. The basins fall into three structural provinces: the eastern province (Lower Saxony Basin, E–W-striking); the northern province (Central Graben, N–S-striking); and the southern–central system (Roer Valley Graben – Broad Fourteens, with a strong NW–SE strike). The mid-Cimmerian event started to affect the Dutch basins during the Bajocian. Sedimentation ceased in the Dutch Central Graben while it persisted in a predominantly coarse-grained, shallow marine facies in the southern basins (Roer Valley Graben, West Netherlands Basin). Extensional tectonics in the Central Graben were initiated during the Middle Callovian, with the deposition of continental sediments. During the Oxfordian–Kimmeridgian, marine incursions gradually became more frequent. Marine deposition in the other basins in the south persisted into the Oxfordian, at which time deposition became predominantly continental. Marine conditions gradually returned in the south during the Ryazanian–Barremian, with a series of advancing partial transgressions from the north. The present-day distribution of Jurassic strata in the Netherlands was determined largely by erosion associated with Late Cretaceous – Paleocene uplift.

Keywords: The Netherlands onshore and offshore, Jurassic, lithostratigraphy, sequence stratigraphy, tectonics, regional geology

---

G.F.W.H.* & T.E.W., *Netherlands Institute of Applied Geoscience TNO – National Geological Survey, P.O. Box 80015, NL-3508 TA Utrecht, The Netherlands.* *Retired. E-mail: *G.F.W.Herngreen@bio.uu.nl*

W.F.P.K., *Wintershall Noordzee B.V., Eisenhowerlaan 146, NL-2517 JL The Hague, The Netherlands.*

The Jurassic succession in the Netherlands has significant hydrocarbon source rock and reservoir potential and the stratigraphy of the succession is thus a subject of particular interest. The Jurassic lithostratigraphic nomenclature in the Netherlands has recently been updated in a joint effort by the Geological Survey of the Netherlands (RGD) and NOGEPA, the organisation of oil companies active in the Netherlands. This project has benefited significantly from integration of new knowledge on Jurassic biostratigraphy. In addition, sequence stratigraphic concepts have been used to explain the observed distribution of facies in time and space. The results have been published in part in van Adrichem Boogaert & Kouwe (1994–1997). In this study, we treat the most recent ideas about the Jurassic geological history of the Netherlands.

The geological history of the Jurassic in the Netherlands has been presented previously by Haanstra (1963), Heybroek (1974) and van Wijhe (1987). Ziegler (1990) treated the area from a Northwest European perspective, whereas Burgers & Mulder (1991) summarised certain aspects of the Late Jurassic and Cretaceous history. Regional stratigraphic overviews of the Jurassic in the southern North Sea have been presented by Brown (1990) and Cameron *et al.* (1992). Michelsen & Wong (1991) presented a stratigraphic correlation between the Dutch, Danish and southern Norwegian sectors of the Central Graben. Underhill & Partington (1993) discussed the effect of Middle Jurassic thermal doming on regional Jurassic stratigraphy in a sequence stratigraphic context. Kimmeridgian to Ryazanian sequence stratigraphy, biostratigraphy and the distribution of the main reservoir intervals in the North Sea were dealt with by Partington *et al.* (1993).

During the last two decades, several authors from the Geological Survey of the Netherlands (RGD) have published detailed review papers on the Middle–Late Jurassic history of the Dutch Central (North Sea) Graben, the Vlieland Basin and adjoining onshore areas: Herngreen & de Boer (1984), Herngreen & Wong (1989), Herngreen *et al.* (1988, 1991), Wong *et al.* (1989), Geological Atlas of the Subsurface of the Netherlands, sheets I–V (RGD 1991a, b, 1993a, b, 1995) and X (NITG–TNO 1998; map sheet VI is in press and sheets VII and VIII are currently in preparation).

The accumulated RGD knowledge, combined with contributions by several oil companies, served as a basis for the revision of the existing lithostratigraphic nomenclature for the Netherlands (van Adrichem Boogaert & Kouwe 1994–1997). The revision of the Jurassic involved two working groups: Permian – Middle Jurassic and Upper Jurassic – Lower Cretaceous. A correlation of the current Dutch Jurassic – Lower Cretaceous lithostratigraphy with the stratigraphic subdivisions of the neighbouring countries is presented in Figure 1.

Structural setting

During Triassic–Jurassic times, the structural style of the Netherlands gradually changed from the single, extensive Southern Permian Basin into a complex of smaller, largely fault-controlled, highs and lows. This transformation, related to the break-up of Pangea (Ziegler 1990), took place in several discrete extensional phases: Scythian (Hardegsen), Norian–Rhaetian (early Cimmerian), Aalenian – Callovian/Oxfordian (mid-Cimmerian) and Kimmeridgian–Valanginian (late Cimmerian). The intervening periods were dominated by regular thermal subsidence.

The result can be seen by comparing Figures 2 and 3, which display the Triassic and Late Jurassic basin configurations, respectively. In the northern half of the Netherlands' offshore territory, the segregation between highs and basins was enhanced by halokinesis in the Permian–Triassic successions along the structural boundaries. Associated salt withdrawal commonly determined the distribution of Jurassic depocentres.

Throughout the Jurassic, the area comprised three interactive structural provinces (Fig. 3).

1. The Lower Saxony Basin system (previous Ems Low), extending into central Germany.
2. The North Sea Central Graben – Vlieland Basin system, trending north–south across the Mid-North Sea High – Ringkøbing–Fyn High complex.
3. A block-faulted basin system extending NW–SE through the Netherlands, connecting the Roer Valley Graben, the Central Netherlands Basin, the West Netherlands Basin and the Broad Fourteens Basin (previous Off-Holland Low), and linked with the Sole Pit Basin in the UK offshore.

During the Early Jurassic, the area subsided relatively uniformly. A sheet of open marine, fine-grained sediments of great lateral uniformity was deposited. Structural complexity gradually increased during Early and Middle Jurassic times, and reached a maximum in the Callovian. During the Middle and Late Jurassic, in particular, each of the above-mentioned provinces accumulated its own characteristic depositional succession.

The impact of the uplift of the Central North Sea thermal dome during the Aalenian–Bathonian is most

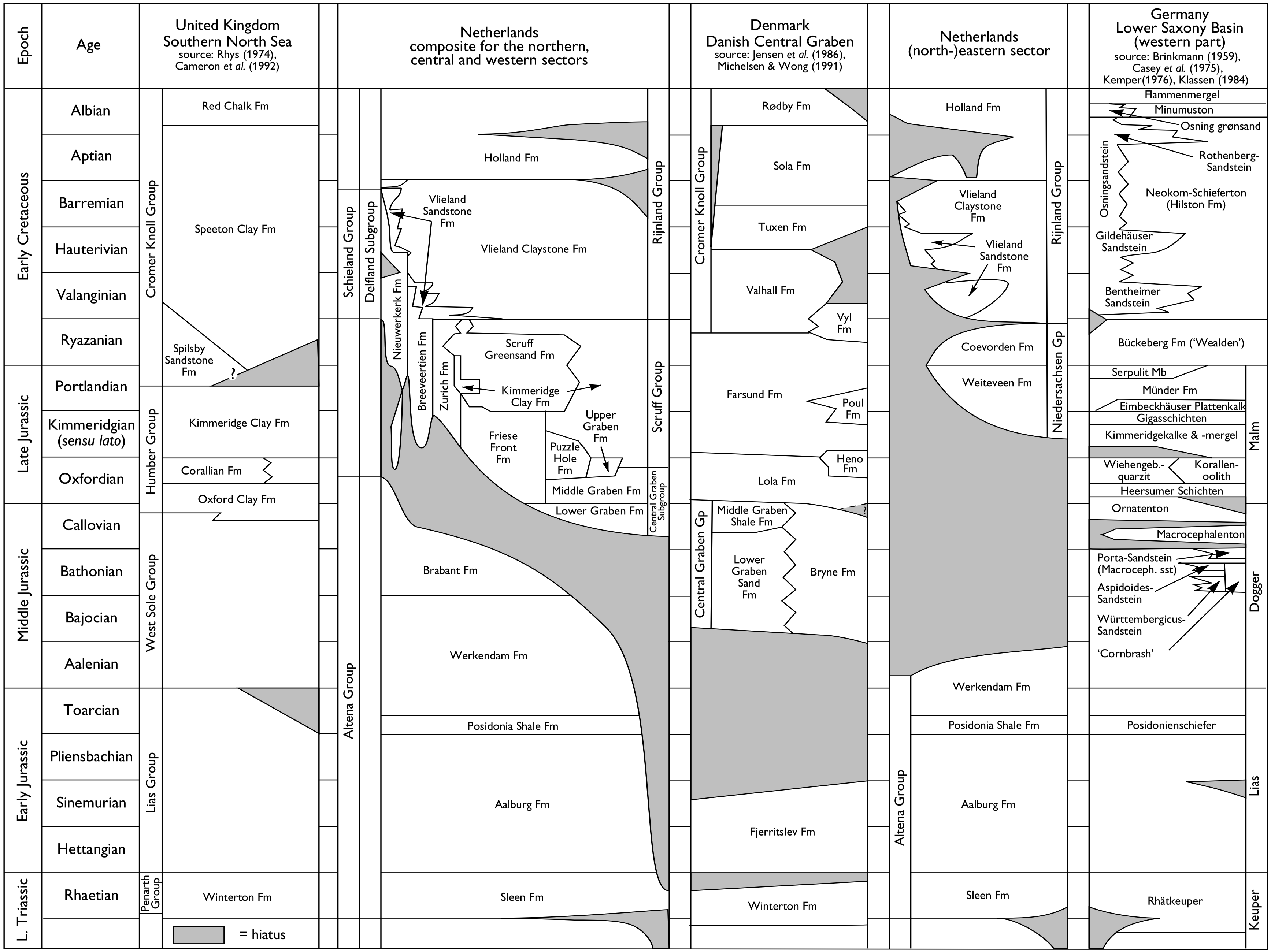

Fig. 1. Regional lithostratigraphic correlation chart of the Jurassic – Lower Cretaceous for the Netherlands and neighbouring countries. Kimmeridgian *sensu lato* equals Kimmeridgian *sensu anglico*. For recent revisions of the Danish scheme, see Michelsen *et al.* (2003, this volume). Modified from van Adrichem Boogaert & Kouwe (1994–1997).

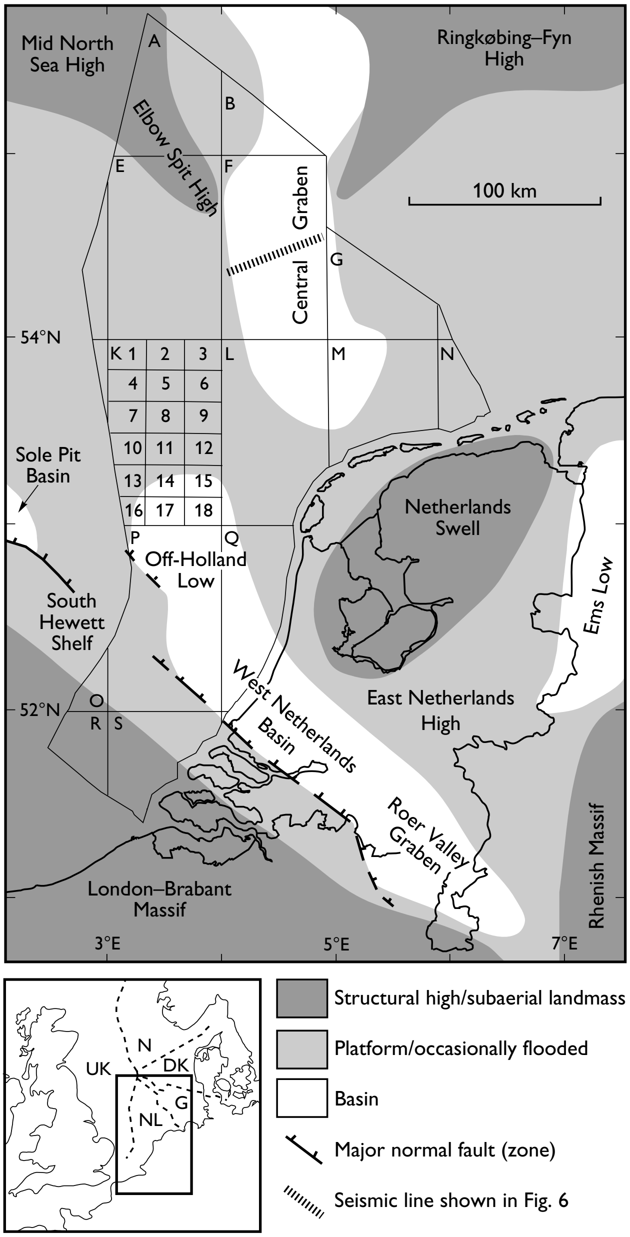

Fig. 2. Main Triassic to Early Jurassic structural elements in the Netherlands. The K-quadrant shows the block numbering system used for the Netherlands' continental shelf. Each complete quadrant (1°N × 1°E) is divided into 18 blocks measuring 10´N × 20´E, numbered from NW to SE. Incomplete quadrants are numbered as if they were complete (e.g. the O-quadrant only comprises blocks 12, 15, 17 and 18). National sectors of the North Sea: **DK**, Denmark; **G**, Germany; **N**, Norway; **NL**, the Netherlands; **UK**, United Kingdom. Modified from van Adrichem Boogaert & Kouwe (1994–1997).

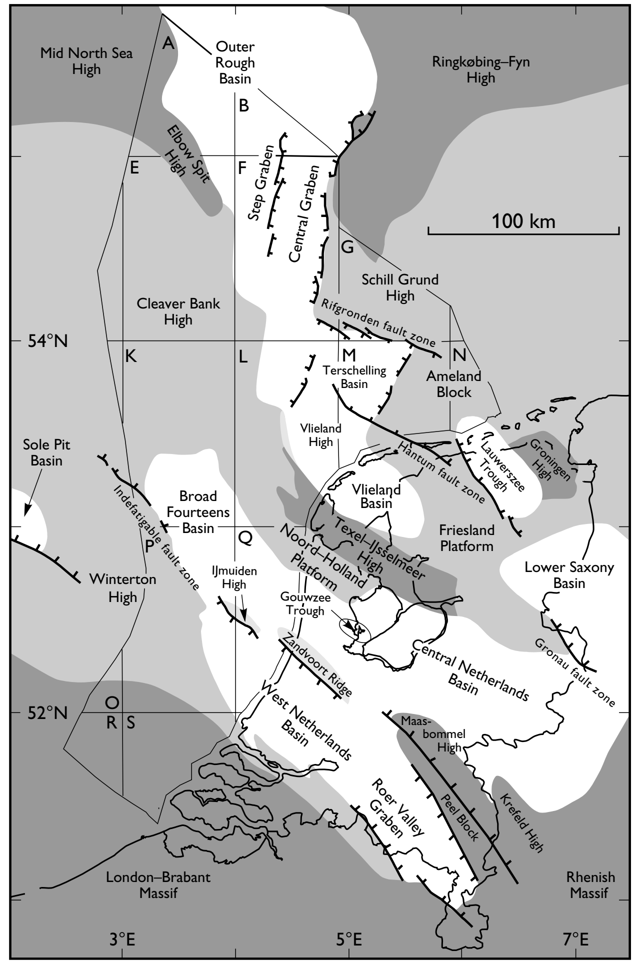

Fig. 3. Middle–Late Jurassic to Early Cretaceous structural elements in the Netherlands. For legend, see Fig. 2. Modified from van Adrichem Boogaert & Kouwe (1994–1997).

evident in the northern offshore area of the Netherlands, where Lower Jurassic successions are deeply truncated. The combination of initial cooling of the thinned crust under the dome and an overall transtensional tectonic regime triggered Callovian–Kimmeridgian rifting, resulting in the formation of the North Sea Central Graben rift system.

The uplift phase terminated the uniform subsidence and sheet-like deposition that characterised the Early and Middle Jurassic. Rifting induced structural differentiation into rapidly subsiding basins with high sediment infill rates and more stable, sediment-starved, platform areas. This differentiation persisted until the Early Cretaceous. Outside the main basins depicted in Figure 3, Upper Jurassic deposits are rare and thin, and associated with salt domes (rim synclines) or transverse fault zones.

The north-eastern part of the Netherlands formed the western fringe of the German Ems Low – Lower Saxony Basin system. The Ems Low, a north–south elongated, fault-bounded basin during Carboniferous–Triassic times, evolved into the slightly east–west-trending, sag-like Lower Saxony Basin during the Middle Jurassic. A relatively undisturbed, continuous Jurassic succession is found in the central parts of the basin in Germany (Fig. 1). In the eastern Netherlands' development, a hiatus spanning the Aalenian – Early Kimmeridgian reflects the situation along the western margin of the basin.

The West Netherlands Basin, the Roer Valley Graben and the Broad Fourteens Basin formed a different depositional province, connected with the Sole Pit Basin of the UK sector of the North Sea. Since Permian–Triassic salts are largely absent in the subsurface here, these basins demonstrate a pure block-faulted nature. The three mentioned provinces merge in the onshore Netherlands, where the Central Netherlands Basin and the Vlieland Basin (a small pull-apart basin) were positioned. The transitions between these provinces are now obscured as a result of later erosion which has stripped Jurassic sediments from most of the country.

Application of sequence stratigraphy

In connection with the revision of the existing lithostratigraphic nomenclature for the Netherlands (van Adrichem Boogaert & Kouwe 1994–1997), sequence stratigraphic analysis was seen as a valuable additional tool for a better understanding of the complex geological settings and stratigraphic relationships. The Lower and Middle Jurassic successions in the Netherlands are of open marine origin, and developed in regionally uniform facies. Depositional cycles are commonly discerned in this interval, and some of these were already incorporated in the old lithostratigraphic subdivision by NAM & RGD (1980). In the recent revisions, therefore, it was not considered necessary to improve this scheme by incorporation of results from new biostratigraphic or sequence stratigraphic analyses. In the (Middle–)Upper Jurassic, however, the common intercalation of continental and marine deposits makes sequence stratigraphy especially effective. Therefore all available data (well and seismic correlations, biostratigraphic and palynological data) were integrated into a regional sequence stratigraphic framework. This framework was used to select those units which were suitable candidates for lithostratigraphic units. Criteria for unit selection included mappability, relevance for exploration geology and the existence of diagnostic lithological and/or biostratigraphical criteria for their recognition.

With the available data and time, the construction of a specific, local sequence framework fell outside the scope of the working group. Instead, the group tied the recognised transgressive and regressive events to the best-fitting sequences in the cycle chart published by Haq *et al.* (1988). This Haq *et al.* (1988) time-scale has been recalibrated numerically to the scale of Harland *et al.* (1990), which was chosen as the current standard for Dutch stratigraphy. For the sake of completeness, Figures 4 and 5 (facing pages 226 and 227, respectively) indicate the Haq *et al.* (1988) sequence subdivision for the whole of the Jurassic; Figure 5 provides an overview of some significant biostratigraphic marker horizons that were used for calibration of Dutch lithostratigraphy with the cycle chart. Sequence stratigraphic analysis was carried out using concepts defined by the Exxon school, viz. sequences are stratal units bounded by unconformities and their correlative conformities (Van Wagoner *et al.* 1988). In contrast, concepts of genetic sequence stratigraphy (*sensu* Galloway 1989), in which genetic sequences are bounded by maximum flooding surfaces, are commonly invoked for regional correlation studies. An example of this approach is found in Partington *et al.* (1993), for their regional correlation of the Jurassic of the North Sea area. It should be noted that their interpretation of Dutch Jurassic sediments was based on obsolete ideas derived from NAM & RGD (1980). Figure 4 presents the most modern ideas on the Dutch chrono-lithostratigraphic development in the context of the development in the surrounding countries.

Depositional history

The Jurassic succession of the Netherlands can be subdivided into three depositional megasequences. Megasequence I (Rhaetian–Aalenian) reflects the period between the early and the mid-Cimmerian tectonic phases. Megasequence II (Aalenian – Middle Callovian) covers the period of activity of the mid-Cimmerian phase. Megasequence III (Middle Callovian – Ryazanian) corresponds to the period between the mid-Cimmerian and the late Cimmerian (pulse II) phases (RGD 1991a).

Rhaetian–Aalenian (Megasequence I)

This period was characterised by the deposition of a very uniform blanket of marine shales across large parts of Northwest Europe. In the Netherlands, these deposits are placed in the Altena Group. After a long period of restricted marine to continental deposition in the Triassic, the last pulse of the early Cimmerian extensional phase in the earliest Rhaetian caused a marine transgression across large parts of Europe. Very fine-grained deposits of Rhaetian age, containing abundant lacustrine and marine fossils, are placed in the Sleen Formation. Hettangian–Pliensbachian or lowermost Toarcian sediments, consisting of a uniform succession of dark grey or black silty claystones with abundant pyritised fossil remains, are called the Aalburg Formation. Towards the London–Brabant Massif (the southern basin fringe during the Early Jurassic), an increasing number of thin limestone beds are intercalated in this unit.

Basin circulation became restricted during the Toarcian, with anoxic bottom waters and deposition of a bituminous shaly claystone, called the Posidonia Formation, over large parts of Northwest Europe. It constitutes the most prominent oil source rock in the Netherlands. Basin circulation returned to normal during the Late Toarcian – Bajocian, as indicated by the deposition of the Werkendam Formation, consisting of marine silty mudstones and greensands.

Aalenian – Middle Callovian (Megasequence II)

This was a period of significant tectonic activity, which caused important structural differentiation (Figs 2, 3). The main effect of the tectonic phase traditionally addressed in the Netherlands as 'mid-Cimmerian' was the uplift of the Central North Sea dome. The deformation front gradually shifted southwards with time, resulting in a considerable delay between the timing of deformation of the dome crest in the Central North Sea (mid-Aalenian) and the southernmost Dutch provinces (Kimmeridgian). The amount of intra-Jurassic truncation decreases away from the dome (Underhill & Partington 1993), and consequently is most severe within the area of this study in the Dutch Central Graben, the northernmost province of the Netherlands, where open marine deposition of the Altena Group ceased in the Bajocian. The Dutch part of the Central Graben remained non-depositional during the Bathonian – Early Callovian. In the Middle Callovian, deposition gradually resumed, in a continental facies. The uplift event probably also affected the Terschelling Basin, the Dutch Lower Saxony Basin and the Central Netherlands Basin. However, the evidence for the impact of this phase was removed by later, more severe truncation in the Jurassic successions of these basins.

The impact of the mid-Aalenian Central North Sea uplift is negligible in the southern basins (Broad Fourteens Basin, West Netherlands Basin, Roer Valley Graben). Werkendam Formation deposition continued, with an important Bajocian influx of marine sandstones along the southern basin margin. Depositional facies changed to shallow marine, sandy carbonates and marls during the Bathonian (Brabant Formation, 'Cornbrash facies'). At least three carbonate–marl cycles were deposited in the Bathonian to Oxfordian, which are at present only preserved as erosional remnants in the southern basins.

In the Dutch Achterhoek (eastern onshore), on the south-western fringe of the Lower Saxony Basin, a special development is found (Herngreen *et al.* 1984). The sedimentary succession up to the Middle Bathonian shows strong parallels with successions of the Roer Valley Graben and the German Lower Saxony Basin proper (Fig. 1). The whole area appears to have been a single depositional province during this period. At the transition to the Late Bathonian, however, a differentiation occurred. During the Late Bathonian – Callovian, an open marine claystone facies was deposited in Germany and the Achterhoek (informally termed the Klomps member, Fig. 4). In contrast, deposition of shallow marine sandy carbonates and marls in the Roer Valley Graben and the West Netherlands Basin persisted into the Oxfordian.

Middle Callovian – Ryazanian (Megasequence III)

Upper Jurassic – Lower Cretaceous deposits in Northwest Europe demonstrate a step-by-step overall transgression from north to south. Periods of marine transgression alternated with phases of short-term progradation of, partly tectonically controlled, continental siliciclastics. The continuous shifting of marine and terrestrial realms in response to syndepositional tectonism and sea-level fluctuations is reflected by the recurrent intertonguing of marine and continental sediments. The predominantly marine Scruff Group (Upper Jurassic – Ryazanian) and Rijnland Group (Lower Cretaceous) interfinger with the mainly continental Schieland Group (Upper Jurassic – Barremian) and the paralic to restricted marine Niedersachsen Group (Upper Jurassic – Ryazanian). Differential movement of fault blocks was caused by a combination of oblique-slip effects in an overall extensional regime and halokinesis in areas with salts in the subsurface (Wong *et al.* 1989). Together with a high sediment input, this resulted in complex sediment distribution patterns and continuously shifting depocentres. The cyclic alternation of marine and continental sediments indicates that sediment deposition was also strongly controlled by sea-level changes.

Middle Callovian – Oxfordian (Stage IIIa)

In the Middle–Late Callovian, predominantly continental sedimentation (Schieland Group) resumed along the axis of the northern Dutch Central Graben (Fig. 4). The basal alluvial plain deposits are referred to the Lower Graben Formation. This unit displays huge thickness variations due to onlap onto syndepositional topography, and due to differential subsidence. The depositional area gradually extended into the southern Dutch Central Graben in the course of the latest Callovian, Oxfordian and Kimmeridgian. Deposition in the latest Callovian started with the marginal marine Rifgronden Member of the Friese Front Formation. It indicates connections to open marine areas in the northern Central Graben (Central North Sea), or possible links with the marine realm in the southern and central Dutch basins.

The shift to deposition of the Middle Graben Formation in the latest Callovian – Early Oxfordian reflects an abrupt change to more fine-grained, lake- and swamp-dominated sedimentation. This shift was accompanied by a short-lived, marine incursion into the whole Dutch Central Graben, which is correlated with the maximum flooding surface of sequence LZA-4.1 of Haq *et al.* (1988). During the Middle Oxfordian, lacustrine conditions prevailed throughout the Dutch Central Graben. Marine incursions were scarce and restricted to the far north during the rest of the Oxfordian.

The Oxfordian was a period of significant transgression and onlap. Areas adjacent to the northern Dutch Central Graben, such as the southern Dutch Central Graben, Terschelling Basin and Step Graben were incorporated into the depositional area. Simultaneously, the open marine realm started to expand southwards into the Dutch Central Graben, first into block F03 (Middle–Late Oxfordian, sequence LZA-4.2 of Haq *et al.* 1988). Initially, a stacked prograding coastal-barrier sand complex (Upper Graben Formation) developed, behind which a paralic delta plain formed, represented by the deposits of the Puzzle Hole Formation (blocks F08–F14). North of the barrier complex, the Kimmeridge Clay Formation represents the open marine environment. The coastal sand bodies of the Upper Graben Formation in the area of block F03 drowned at the end of the Oxfordian (sequence LZA-4.4 of Haq *et al.* 1988). By this time, Kimmeridge Clay deposition also invaded the Step Graben, onlapping the Upper Permian Zechstein Group.

Non-marine deposition of the Schieland Group had already commenced in the Dutch Central Graben during the Callovian, but deposition of the marine Brabant Formation (Altena Group, Oisterwijk Limestone Member) persisted into the Early–Middle Oxfordian in the southern Netherlands (Haanstra 1963; NAM & RGD 1980). Cessation of marine Altena Group deposition in the Roer Valley Graben, the West Netherlands Basin, the Broad Fourteens Basin and probably the Central Netherlands Basin – Lower Saxony Basin during the Late Oxfordian – earliest Kimmeridgian was triggered by tectonic pulse I of the late Cimmerian. In the Roer Valley Graben and the West Netherlands Basin, the Brabant Formation is locally overlain unconformably by erosional remnants of Late Oxfordian – Portlandian deposits in continental floodplain facies (Schieland Group, Nieuwerkerk Formation).

Early–Late Kimmeridgian (Stage IIIb)

During the Kimmeridgian and Portlandian, the northern Dutch Central Graben became a major depocentre, accumulating a thick succession of increasingly marine sediments. The area of deposition once more expanded significantly. Deposition resumed in continental facies in the Broad Fourteens Basin, the Dutch Lower Saxony Basin and the Vlieland Basin (Fig. 4). The depositional style in the Broad Fourteens and Vlieland Basins remained continental (floodplain, lacustrine, with occasional sandy fluvial intercalations), with a few marine incursions. The Vlieland Basin was the site of volcanic activity in the Middle–Late Jurassic, as the Zuidwal volcanic dome formed (Perrot & van der Poel 1987; Herngreen *et al.* 1991). Depending on the time-scale used, volcanic activity (dated radiometrically at 155–143 Ma) may have taken place somewhere between the Callovian and the Early Ryazanian.

In the course of the Kimmeridgian, deposition of the paralic Puzzle Hole Formation in the central Dutch Central Graben gradually gave way to the open marine Kimmeridge Clay Formation in the area of blocks F08–F11. Thin marine sand bodies are found locally in the uppermost parts of the Puzzle Hole Formation, suggesting the existence of a backstepping coastal-barrier system. However, much of the character of the transgression cannot be reconstructed due to Subhercynian and/or Laramide erosion (Late Cretaceous – Paleocene). To the south (blocks F15–F17), the paralic Puzzle Hole Formation grades into deposits characterised by continental alluvial plain facies (Delfland Formation of Herngreen & Wong, 1989; now called Friese Front Formation). In the southern Dutch Central Graben, alluvial plain deposition replaced the predominantly lacustrine deposition around the end of the Oxfordian. During the Early Kimmeridgian (LZA-4.4 of Haq *et al.* 1988), the depositional area in the southern Dutch Central Graben expanded. Seismic and palaeogeographic information suggest that the boundaries between the areas of deposition of the Puzzle Hole Formation, the Kimmeridge Clay Formation and the Friese Front Formation were determined by faults.

In the Broad Fourteens Basin, widespread deposition commenced in the Early Kimmeridgian (LZA-4.5 of Haq *et al.* 1988), with the accumulation of sandy alluvial plain sediments referred to the Aerdenhout Member of the Breeveertien Formation (Fig. 4). This member unconformably overlies deposits of the Altena Group or the Upper Germanic Triassic. The progressive transgression observed in the Central Graben coincides with a shift from alluvial plain (Aerdenhout Member) to lacustrine and lagoonal deposition (Fourteens Claystone Member) in the Broad Fourteens Basin (associated with the maximum flooding surface of sequence LZA-4.6 of Haq *et al.* (1988). Deposition of the Basal Weiteveen Clastic Member in the Dutch Lower Saxony Basin (= Niedersachsen Basin) seems to have started close to the end of the Early Kimmeridgian.

The introduction of coarser siliciclastics in the Dutch Central Graben (main Friese Front member, Puzzle Hole Formation and Upper Graben Formation), the Broad Fourteens Basin (Breeveertien Formation, Aerdenhout Member) and the Dutch Lower Saxony Basin (Weiteveen Basal Clastics Member) coincided with the start of the late Cimmerian phase (Haanstra 1963; 't Hart 1969; 'Late Kimmerian I pulse' of RGD 1991b). The resulting uplift terminated the first depositional phase of the Nieuwerkerk Formation in the most rapidly subsiding areas of the Roer Valley Graben and the West Netherlands Basin.

Late Kimmeridgian – earliest Portlandian (Stage IIIc)

In the Late Kimmeridgian, the ongoing transgression led to the first marine influence on sedimentation in the southern Dutch Central Graben and the Terschelling Basin. This is witnessed by the deposition of the marine-influenced Oyster Ground Member (Friese Front Formation, Fig. 4). Two distinct transgressive phases are identified; in the early Late Kimmeridgian, the transgression reached block F18, while block L02 became transgressed by the latest Kimmeridgian. These events are tentatively correlated with the transgressive systems tracts of sequences LZA-4.7 and LZB-1.1 of Haq *et al.* (1988). The latter flooding event is associated with onlap onto exposed Triassic and Permian rocks in the Terschelling Basin (Oyster Ground Member in block F15) and the Vlieland Basin – Central Netherlands Basin area (continental Zurich Formation). At the same time, tectonic tilting and associated halokinesis caused the depocentre of the Dutch Central Graben to shift from the central–eastern axis (from block F03, extending southwards into blocks L03–F18) to the western graben margin (block F02–L05). The seismic cross-section of the graben system shows this westwards shift (Fig. 6).

During the Late Kimmeridgian – Portlandian, siliciclastic deposition in the Lower Saxony Basin was periodically replaced by accumulation of evaporites and carbonates (evaporitic and marl members of the Weiteveen Formation, Fig. 4). These cycles may be correlatable with the alternation of coarser clastics and fines with minor evaporites found in the Broad Fourteens Basin (Breeveertien Formation, several members). The lithofacies (carbonates, marls, evaporites, coals) of the Zurich Formation in the remnants of the Central Netherlands Basin ('Voorthuizen subbasin' of Haanstra 1963; Gouwzee Trough of RGD 1993a) are similar to those in the Niedersachsen Group in the Dutch Lower Saxony Basin.

In the West Netherlands Basin and the Roer Valley Graben, lacustrine and alluvial plain deposition was restricted to those fault blocks undergoing strongest subsidence. A progressive depositional onlap is seen in the Portlandian–Ryazanian section. In each consecutive depositional sequence, higher basin-fringe fault blocks became part of the depositional area. Very thick successions of proximal alluvial plain deposits can be found in places.

In the Portlandian and Ryazanian, deposition resumed in the Central Netherlands Basin. The depositional style is transitional between the mainly lacustrine and evaporitic facies of the Lower Saxony Basin and the paralic and restricted marine facies of the Central Graben – Vlieland Basin. Deposition in the southern province (West Netherlands Basin and the western Roer Valley Graben) ceased due to uplift in the Kimmeridgian (around the lower sequence boundary of LZB-1.1 of Haq *et al.* 1988). Non-deposition lasted until the latest Portlandian – Ryazanian. From then on, continental sediments were deposited; marine conditions did not reach this area until the Late Hauterivian – Barremian.

Portlandian (Stage IIId)

During the Early Portlandian, the ongoing transgression resulted in deposition of the Terschelling Member of the Friese Front Formation, reflecting coastal deposition along the southern fringe of the Dutch Central Graben (blocks L09–L12, sequences LZB-1.2, -1.3 of Haq *et al.* 1988). To the north, the Friese Front Formation grades into the open marine Scruff Greensand Formation in the southern Dutch Central Graben. Thick, sand-dominated successions of Portlandian–Ryazanian age were deposited here (blocks F15–F18, sequences LZB-1.3 to -1.5 of Haq *et al.* 1988). Equivalent, thinner sand tongues are found in the eastern Terschelling Basin, the Vlieland Basin and the northern Dutch Central Graben (blocks F03–F05). During this period, the Vlieland Basin became divided into two subbasins, separated by the Zuidwal volcanic dome (Herngreen *et al.* 1991). During the Early Portlandian, marine conditions only prevailed in the northern subbasin. The southern subbasin was characterised by continental (lacustrine to lagoonal) deposition.

The Scruff Greensand Formation grades into the Kimmeridge Clay Formation in the northern Dutch Central Graben. The depocentre of the open marine Kimmeridge Clay Formation, which prior to the Portlandian was situated in this northern area, abruptly shifted to the southernmost Central Graben and the northern Vlieland Basin. In the southern B-quadrant, basin circulation stagnated during the Portlandian. This resulted in deposition of the bituminous claystones of the Clay Deep Member. Euxinic marine conditions became more widespread in the northern Dutch Central Graben during the Ryazanian (sequence LZB-1.5 and particularly LZB-1.6 of Haq *et al.* 1988).

Late Portlandian – Ryazanian (Stage IIIe)

During the Late Portlandian (sequence LZB-1.5 of Haq *et al.* 1988), marine conditions (Scruff Greensand Formation) briefly reached the entire Vlieland Basin. In the southern Dutch Central Graben, the marine basin became shallower, inducing the northwards progradation of shallow marine, spiculitic greensands (Scruff Spiculite Member). Even the more elevated areas (for example over salt domes) of the Dutch Lower Saxony Basin and Central Netherlands Basin, which had thus far remained exposed, became inundated by the sea. In the latter basin, the depositional area expanded to the north-west.

In the Broad Fourteens Basin, this overall regressive tendency is reflected by the transition within the Breeveertien Formation from lacustrine and lagoonal coastal plain fines (Fourteens Claystone Member and Driehuis Mottled Claystone Member) to widespread sandy alluvial plain deposits (Bloemendaal Member). In the Dutch Lower Saxony Basin, the Late Portlandian shoaling trend is demonstrated by the Serpulite Member of the Weiteveen Formation. This widespread carbonate deposit marks the culmination of clastic starvation in this area.

Deposition of evaporites and carbonates with subordinate siliciclastics (Weiteveen Formation) in the Lower Saxony Basin was replaced by open water lacustrine deposition (Coevorden Formation) at the beginning of the Ryazanian. This event is interpreted as indicative of a flooding phase that correlated with the transition from the sandy fluvial Bloemendaal Member to the lagoonal Neomiodon Claystone Member (both of the Breeveertien Formation) in the Broad Fourteens Basin. This period was also marked by widespread deposition of sediments referred to the Nieuwerkerk Formation in the Roer Valley Graben and West Netherlands Basin; thick successions of locally coarse alluvial plain sediments were deposited on rapidly subsiding fault blocks along the axes of the basins. The depositional area continued to expand gradually. The basin margins were either covered by a thin, condensed succession (e.g. locally in the province of Groningen), or remained exposed and non-depositional.

Late Ryazanian (Stage IIIf)

During the Ryazanian (sequence LZB-1.6 of Haq *et al.* 1988), the stagnant marine basin area in the northern Dutch Central Graben expanded southwards into block F05. Deposition of the Clay Deep Member completely superseded Scruff Greensand Formation deposition around the mid-Ryazanian. This change in depositional style coincided with the first signs of tectonic pulse II of the late Cimmerian (RGD 1991a). This also caused local truncation of the Scruff Greensand Formation and the Friese Front Formation in the southern Central Graben (parts of blocks L02–05). Initially, sedimentation of the Scruff Greensand Formation resumed briefly (Stortemelk Member, correlated with the lowstand of sequence LZB-1.6 of Haq *et al.* 1988). Subsequently, the deep marine basin expanded markedly southwards, depositing Kimmeridge Clay Formation sediments (Schill Grund Member) in the previously shallow marine to continental realm. This marine incursion also reached the Vlieland Basin, where the Stortemelk Member is found intercalated with lagoonal–lacustrine deposits of the Zurich Formation. In the Broad Fourteens Basin, tectonic pulse II of the late Cimmerian is expressed as two minor unconformities (base and intra-Neomiodon Claystone Member, Breeveertien Formation).

In the Dutch Central Graben, large-scale differential subsidence ended with tectonic pulse II of the late Cimmerian (mid-Ryazanian and earliest Valanginian). From then on (sequence LZB-2.1 of Haq *et al.* 1988), a more uniform sedimentation pattern started, associated with the post-rift thermal sag phase. This is illustrated by the contrast between the highly variable thickness of the succession underlying the Stortemelk Member and the more uniform development of the post-uplift succession (Clay Deep Member, Stortemelk Member and Schill Grund Member). In the Broad Fourteens Basin, the West Netherlands Basin and the Roer Valley Graben, the highly differential subsidence patterns continued at least throughout the Valanginian.

Subsequent history

The expansion of the marine sedimentation area continued during the Cretaceous, until eventually the London–Brabant Massif became flooded in the Campanian–Maastrichtian. The Jurassic successions in the Dutch subsurface were deformed by several later tectonic phases. The Santonian–Campanian (Subhercynian) and Early Paleogene (Laramide) inversion phases had the most severe impact. During these compressive events, the Jurassic depocentres were inverted (van Wijhe 1987). Practically all Jurassic sediments were removed along the inversion axes of these basins. At present, the occurrences of Jurassic rocks are restricted to the basinal areas (Fig. 3). Subsequent Tertiary subsidence in the Netherlands was more or less evenly distributed. Subsidence rates were highest in the northern Dutch offshore, however, and Tertiary (particularly Neogene) sediment distribution patterns are dominated by large-scale progradation in this direction.

Petroleum geology

Several Jurassic formations have economic significance in the Netherlands, either as reservoirs or as oil source rocks. Figures 1 and 4 show the stratigraphic positions of the units mentioned in this context below, and their equivalents in neighbouring countries. The Toarcian Posidonia Formation is the most prominent oil and wet gas source rock in the Dutch subsurface (Bodenhausen & Ott 1981), to which the majority of the oil reserves in the country can be attributed. Additional oil sourcing potential can be attributed to certain lacustrine strata of the Coevorden Formation (Ryazanian) in the Lower Saxony Basin. This interval is also known to act as an oil source rock in adjacent parts of Germany. The highly bituminous Clay Deep Member (Ryazanian) of the Kimmeridge Clay Formation in the northern sector of the Dutch Central Graben has oil-sourcing potential. However, the areal distribution and stratigraphic range of this deposit is much smaller than that of equivalent bituminous intervals in the Kimmeridge Clay Formation (and equivalents) in the UK, Danish and Norwegian offshore, where it constitutes one of the major oil source rocks.

Coal occurrences in the Lower Graben Formation (Middle–Upper Callovian), the Middle Graben Formation (Oxfordian), the Puzzle Hole Formation (mainly Kimmeridgian) and the Friese Front Formation (uppermost Callovian – Portlandian) may locally have sourced wet gas. However, in most areas, burial was insufficient to reach the gas window (Wong *et al.* 1989). On the other hand, gas source rocks of Late Carboniferous age are more or less ubiquitous throughout the Netherlands. The main problem for gas generated from these older rocks is to pass through the cover of Permian salts and reach the Jurassic. Furthermore, the maximum burial depths of the Carboniferous strata, for instance in the Central Graben, may have caused these rocks to become overmature.

At present, oil and gas reserves have been discovered in the Lower Graben Formation (Middle–Upper Callovian), Upper Graben Formation (uppermost Oxfordian), Scruff Greensand Formation (Portlandian) and Friese Front Formation (uppermost Callovian – Portlandian) in the Central Graben area. Some sandstone members of the Breeveertien Formation (Kimmeridgian–Ryazanian) in the Broad Fourteens Basin were found to be oil-bearing. In the West Netherlands Basin, the Ryazanian and younger levels of the Nieuwerkerk Formation are prospective. The Middle Werkendam Member (Bajocian) and carbonate members of the

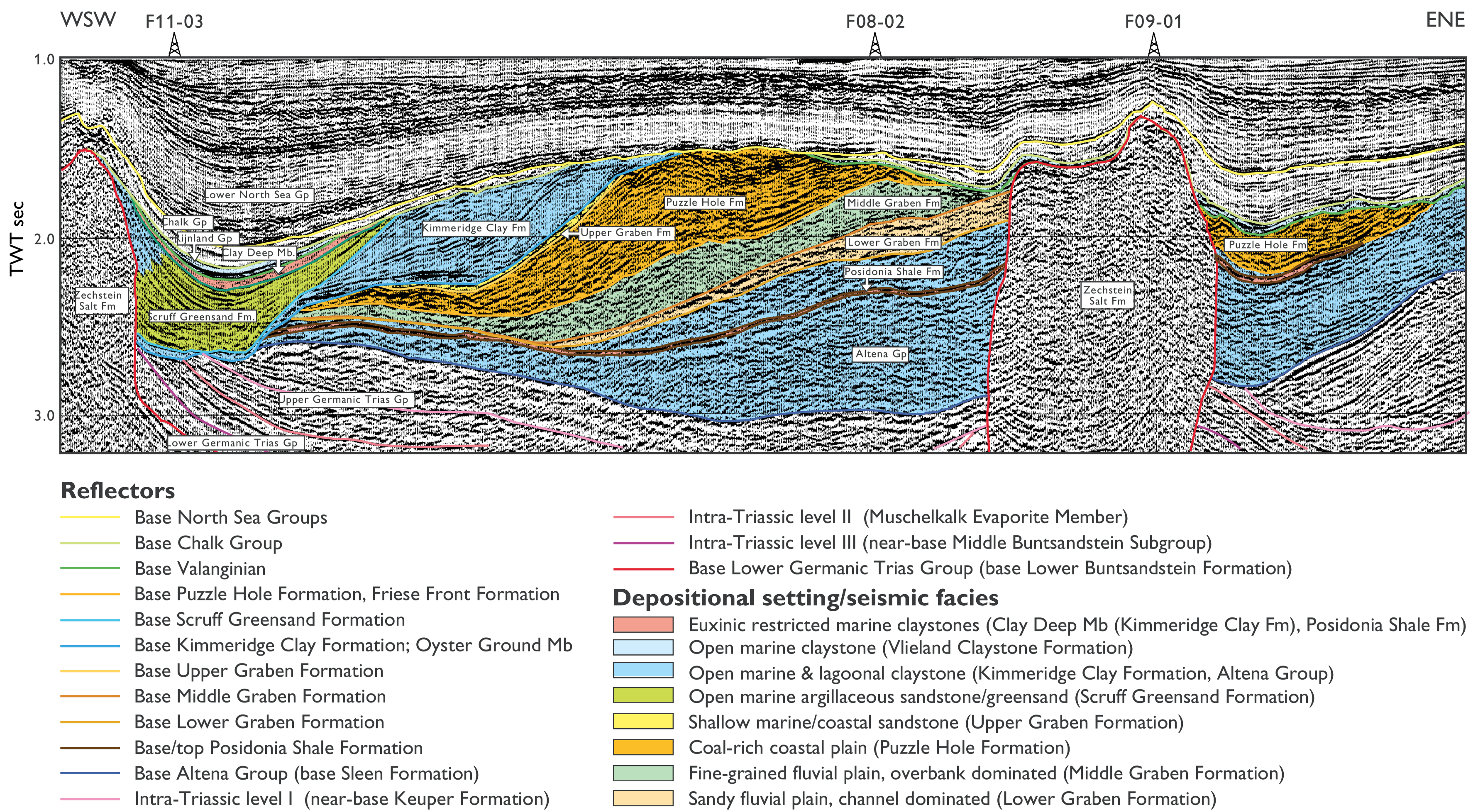

Fig. 6. Seismic cross-section, running WSW–ENE across the Dutch sector of the Central Graben (Fig. 2). The Jurassic – Lower Cretaceous section has been colour-coded according to the main depositional facies.

Brabant Formation (Callovian–Oxfordian) have locally been shown to be oil-bearing in the Roer Valley Graben and the West Netherlands Basin.

Exploration of the Jurassic in the Netherlands has reached a mature stage. The acquisition of high-quality seismic and well data and the good biostratigraphic control obtained in recent years have resulted in a clear regional geological picture. These data also allow, for the first time, the application of sequence stratigraphy. Integration of sequence stratigraphic concepts into the revision of Dutch lithostratigraphy (van Adrichem Boogaert & Kouwe 1994–1997) has resulted, in particular, in a far better understanding of the Upper Jurassic stratigraphy of the Netherlands.

Acknowledgements

The authors wish to thank the Geological Survey of the Netherlands (Rijks Geologische Dienst – RGD/NITG) for permission to publish the presented data. The authors are indebted to R. Rijkers, A. Hollen and F. Rispens (all RGD) for providing information on the regional distribution and petroleum exploration successes in the Dutch Jurassic. H.A. van Adrichem Boogaert and M.C. Geluk (RGD) gave valuable comments to the manuscript and its precursors. Similarly, the manuscript has benefited significantly from earlier discussions with the various members of the working group on the Upper Jurassic – Lower Cretaceous Stratigraphy for the new Stratigraphic Nomenclature of the Netherlands.

References

Bodenhausen, J.W.A. & Ott, W.F. 1981: Habitat of the Rijswijk Oil Province, onshore, the Netherlands. In: Illing, L.V. & Hobson, G.D. (eds): Petroleum geology of the continental shelf of North-West Europe, 301–309. London: Institute of Petroleum.

Brinkmann, R. 1959: Abriss der Geologie, 8th edition, 360 pp. Stuttgart: Enke Verlag.

Brown, S. 1990: Jurassic. In: Glennie, K.W. (ed.): Introduction to the petroleum geology of the North Sea, 219–255. Oxford: Blackwell Scientific Publications.

Burgers, W.F.J. & Mulder, G.G. 1991: Aspects of the Late Jurassic and Cretaceous history of the Netherlands. Geologie en Mijnbouw **70**, 347–354.

Cameron, T.D.J., Crosby, A., Balson, P.S., Jeffery, D.H., Lott, G.K., Bulat, J. & Harrison, D.J. 1992: United Kingdom offshore regional report: The geology of the southern North Sea, 152 pp. London: Her Majesty's Stationery Office for the British Geological Survey.

Casey, R., Allen, P., Dörhöfer, G., Gramann, F., Hughes, N.F., Kemper, E., Rawson, P.F. & Surlyk, F. 1975: Stratigraphic subdivision of the Jurassic–Cretaceous boundary beds in NW Germany. Newsletter on Stratigraphy **4**, 4–5.

Galloway, W.E. 1989: Genetic stratigraphic sequences in basin analysis I: architecture and genesis of flooding-surface bounded depositional units. American Association of Petroleum Geologists Bulletin **73**, 125–142.

Haanstra, U. 1963: A review of Mesozoic geological history in the Netherlands. Geologie en Mijnbouw **21**, 35–57.

Haq, B.U., Hardenbol, J. & Vail, P.R. 1988: Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. In: Wilgus, C.K. *et al.* (eds): Sea-level changes – an integrated approach. Society of Economic Paleontologists and Mineralogists Special Publication **42**, 71–108.

Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G. & Smith, D.G. 1990: A geologic time scale 1989, 263 pp. Cambridge: Cambridge University Press.

Herngreen, G.F.W. & de Boer, K.F. 1984: Palynology of the 'Upper Jurassic' Central Graben, Scruff and Delfland Groups in the Dutch part of the North Sea continental shelf. In: Michelsen, O. & Zeiss, A. (eds): International Symposium on Jurassic stratigraphy (Erlangen 1984) **3**, 695–714. Copenhagen: Geological Survey of Denmark.

Herngreen, G.F.W. & Wong, Th.E. 1989: Revision of the 'Late Jurassic' stratigraphy of the Dutch Central North Sea Graben. Geologie en Mijnbouw **68**, 73–105.

Herngreen, G.F.W., de Boer, K.F., Romein, B.J., Lissenberg, T. & Wijker, N.C. 1984: Middle Callovian Beds in the Achterhoek, eastern Netherlands. Mededelingen Rijks Geologische Dienst **37**, 95–123.

Herngreen, G.F.W., Lissenberg, T. & Witte, L.J. 1988: Dinoflagellate, sporomorph, and micropalaeontological zonation of Callovian to Ryazanian strata in the North Sea Central Graben, the Netherlands. 2nd International Symposium on Jurassic stratigraphy (Lisbon 1987) **2**, 745–762. Lisbon: Universidade Nova de Lisboa.

Herngreen, G.F.W., Smit, R. & Wong, Th.E. 1991: Stratigraphy and tectonics of the Vlieland Basin, the Netherlands. In: Spencer, A.M. (ed.): Generation, accumulation and production of Europe's hydrocarbons. European Association of Petroleum Geoscientists Special Publication **1**, 175–192.

Heybroek, P. 1974: Explanation to tectonic maps of the Netherlands. Geologie en Mijnbouw **53**, 43–50.

Jensen, T.F., Holm, L., Frandsen, N. & Michelsen, O. 1986: Jurassic – Lower Cretaceous lithostratigraphic nomenclature for the Danish Central Trough. Danmarks Geologiske Undersøgelse Serie A **12**, 65 pp.

Kemper, E. 1976: Geologischer Führer durch die Grafschaft Bentheim und die angrenzenden Gebiete mit einem Abriss der emsländischen Unterkreide, 5th edition, 206 pp. Nordhorn–Bentheim: Verlag Heimatverein der Grafschaft Bentheim.

Klassen, H. (ed.) 1984: Geologie des Osnabrücker Berglandes, 672 pp. Osnabrück: Naturwissenschaftliches Museum.

Michelsen, O. & Wong, Th.E. 1991: Discussion of Jurassic lithostratigraphy in the Danish, Dutch and Norwegian Central Graben areas. In: Michelsen, O. & Frandsen, N. (eds): The

Jurassic in the southern Central Trough. Danmarks Geologiske Undersøgelse Serie B **16**, 20–28.

Michelsen, O., Nielsen, L.H., Johannessen, P.N., Andsbjerg, J. & Surlyk, F. 2003: Jurassic lithostratigraphy and stratigraphic development onshore and offshore Denmark. In: Ineson, J.R. & Surlyk, F. (eds): The Jurassic of Denmark and Greenland. Geological Survey of Denmark and Greenland Bulletin **1**, 147–216 (this volume).

NAM & RGD 1980: Stratigraphic nomenclature of the Netherlands. Verhandelingen van het Koninklijk Nederlands Geologisch en Mijnbouwkundig Genootschap **32**, 77 pp. (Nederlandse Aardolie Maatschappij & Rijks Geologische Dienst).

NITG–TNO 1998: Geological atlas of the subsurface of the Netherlands. Explanation to map sheet X, 142 pp. Haarlem: Netherlands Institute of Applied Geoscience – National Geological Survey.

Partington, M.A., Copestake, P., Mitchener, B.C. & Underhill, J.R. 1993: Biostratigraphic calibration of genetic stratigraphic sequences in the Jurassic – lowermost Cretaceous (Hettangian–Ryazanian) of the North Sea and adjacent areas. In: Parker, J.R. (ed.): Petroleum geology of Northwest Europe: proceedings of the 4th conference, 371–386. London: Geological Society.

Perrot, J. & van der Poel, A.B. 1987: Zuidwal – a Neocomian gas field. In: Brooks, J. & Glennie, K.W. (eds): Petroleum geology of North West Europe, 325–335. London: Graham & Trotman.

RGD 1991a: Geological atlas of the subsurface of the Netherlands. Explanation to map sheet I, 79 pp. Haarlem: Geological Survey of the Netherlands (Rijks Geologische Dienst).

RGD 1991b: Geological atlas of the subsurface of the Netherlands. Explanation to map sheet II, 87 pp. Haarlem: Geological Survey of the Netherlands (RGD).

RGD 1993a: Geological atlas of the subsurface of the Netherlands. Explanation to map sheet IV, 127 pp. Haarlem: Geological Survey of the Netherlands (RGD).

RGD 1993b: Geological atlas of the subsurface of the Netherlands. Explanation to map sheet V, 126 pp. Haarlem: Geological Survey of the Netherlands (RGD).

RGD 1995: Geological atlas of the subsurface of the Netherlands. Explanation to map sheet III, 113 pp. Haarlem: Geological Survey of the Netherlands (RGD).

Rhys, G.H. (compiler) 1974: A proposed standard lithostratigraphic nomenclature for the southern North Sea and an outline structural nomenclature for the whole of the (UK) North Sea. Institute of Geological Sciences Report **74/8**, 14 pp. London: Her Majesty's Stationery Office.

't Hart, B.B. 1969: Die Oberjura- und Unterkreide-Sedimentation in den nördlichen und östlichen Niederlanden. Erdöl und Kohle, Erdgas, Petrochemie **22**, 253–261.

Underhill, J.R. & Partington, M.A. 1993: Jurassic thermal doming and deflation in the North Sea: implications of the sequence stratigraphic evidence. In: Parker, J.R. (ed.): Petroleum geology of Northwest Europe: proceedings of the 4th conference, 337–345. London: Geological Society.

van Adrichem Boogaert, H.A. & Kouwe, W.F.P. (compilers) 1994–1997: Stratigraphic nomenclature of the Netherlands, revision and update by RGD and NOGEPA. Mededelingen Rijks Geologische Dienst **50**, sections A–J (sections paginated independently).

Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S. & Hardenbol, J. 1988: An overview of the fundamentals of sequence stratigraphy and key definitions. In: Wilgus, C.K. *et al.* (eds): Sea-level changes – an integrated approach. Society of Economic Paleontologists and Mineralogists Special Publication **42**, 39–45.

van Wijhe, D.H. 1987: Structural evolution of inverted basins in the Dutch offshore. In: Ziegler, P.A. (ed.): Compressional intraplate deformations in the Alpine Foreland. Tectonophysics **137**, 171–219.

Wong, Th.E., van Doorn, Th.H.M. & Schroot, B.M. 1989: 'Late Jurassic' petroleum geology of the Dutch North Sea Central Graben. Geologische Rundschau **78**, 319–336.

Ziegler, P.A. 1990: Geological atlas of western and central Europe, 2nd edition, 239 pp. Amsterdam: Elsevier for Shell Internationale Petroleum Maatschappij.

Manuscript received 11 September 1995; revision accepted 17 January 1997.

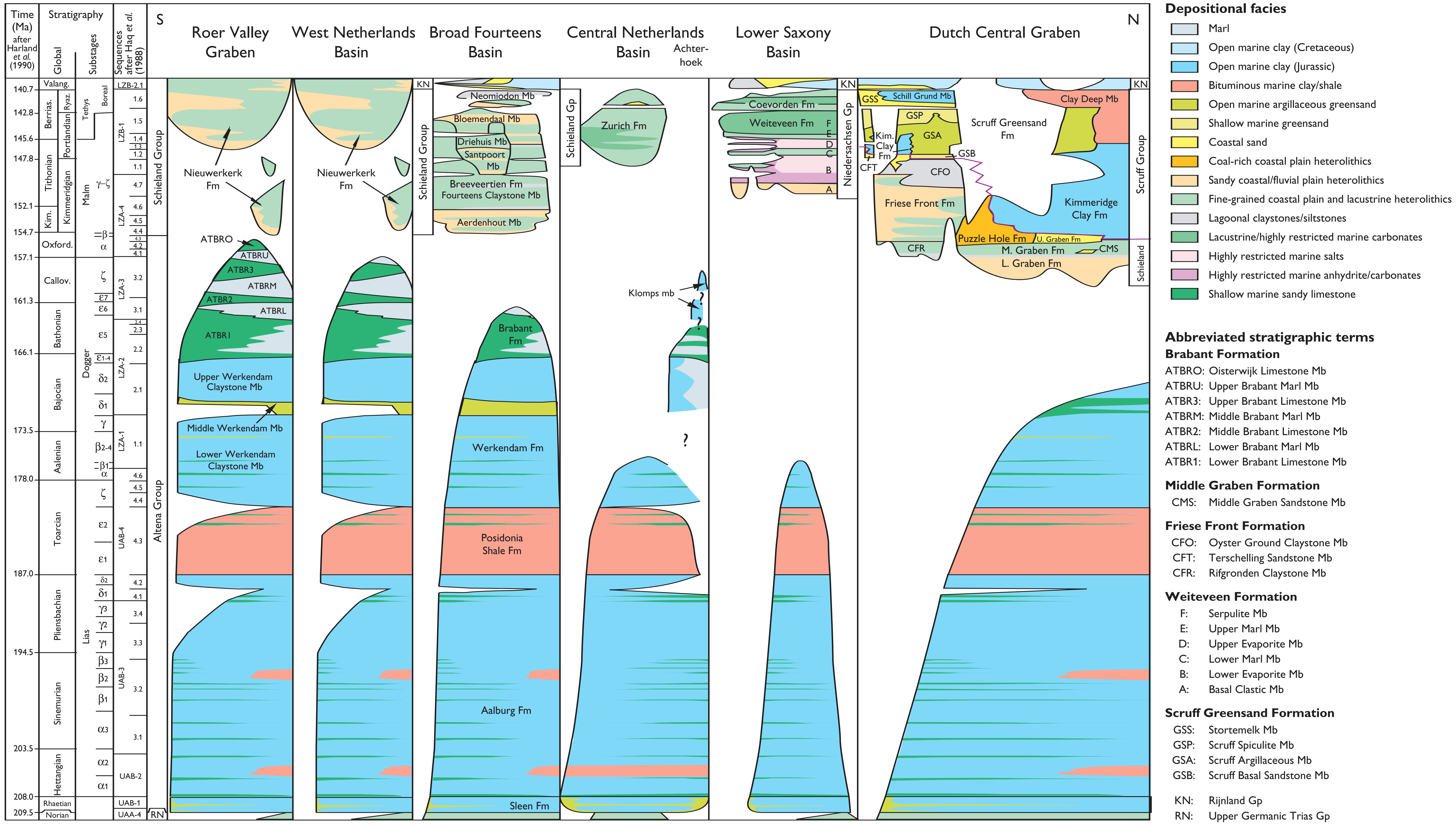

Fig. 4. Litho-chronostratigraphic scheme of the Rhaetian–Ryazanian succession of the five main Jurassic basin systems in the Netherlands: (1) Roer Valley Graben – West Netherlands Basin, (2) Off-Holland Low – Broad Fourteens Basin, (3) Central Netherlands Basin, (4) Ems Low – Lower Saxony Basin and (5) Vlieland Basin, Terschelling Basin and Dutch Central Graben. Abbreviated stage names are given in full in Fig. 1; **Berrias.**, Berriasian. Compiled and modified from van Adrichem Boogaert & Kouwe (1994–1997, sections F, G).

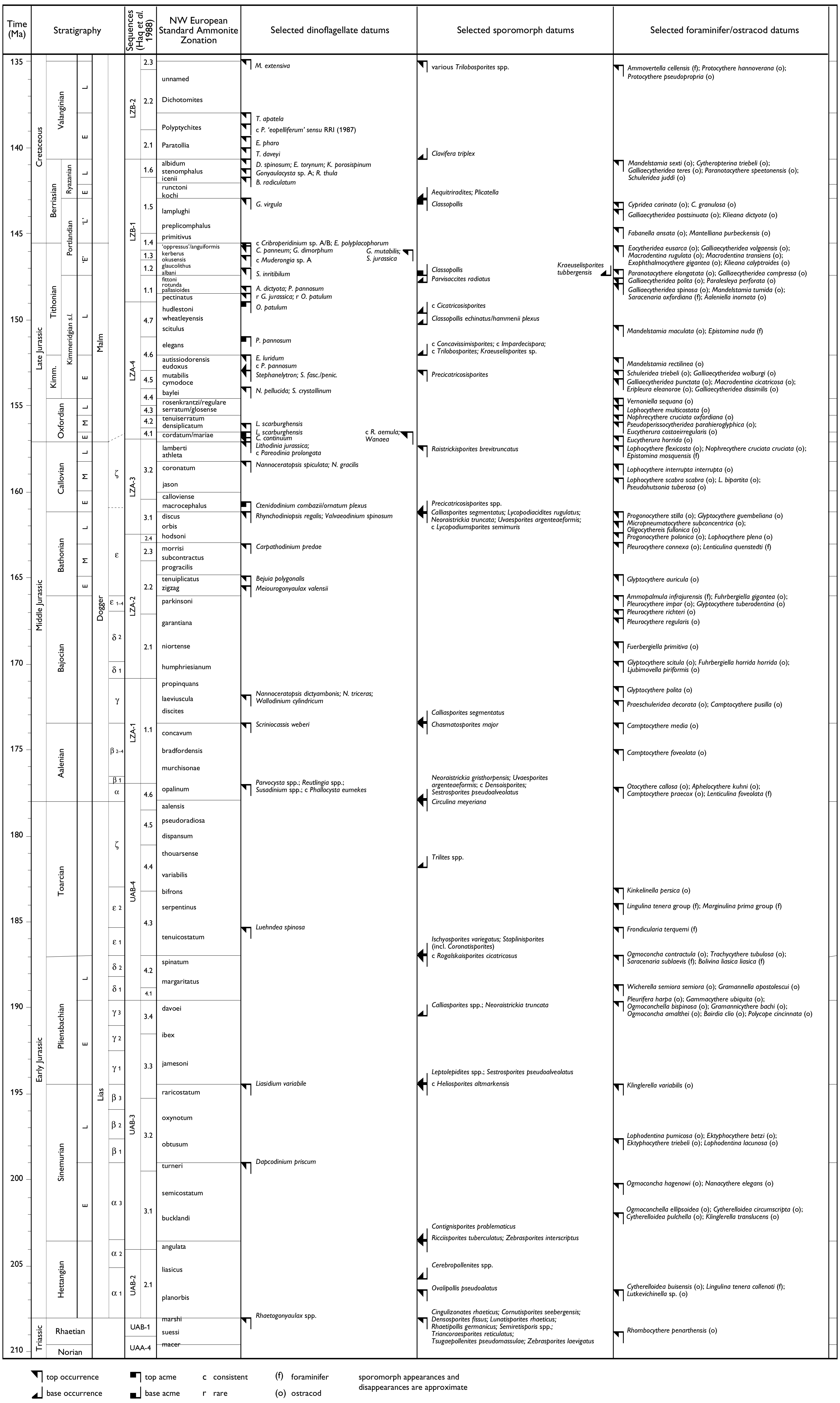

Fig. 5. A selection of diagnostic biomarker horizons for the Rhaetian–Valanginian, correlated with the Northwest European standard ammonite zonation. The Haq *et al.* (1988) cycle chart has been recalibrated to fit the time-scale of Harland *et al.* (1989). Kimmeridgian *s.l.* equals Kimmeridgian *sensu anglico*. The terms Lias, Dogger and Malm and their classic regional subdivisions as depicted in the various figures are used in order to show the stratigraphic position of the sediments found in the Netherlands in a European context of well-established zonations. Compiled and modified from van Adrichem Boogaert & Kouwe (1994–1997, sections F, G).