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Lower Cretaceous of the southern North Sea Basins: reservoir distribution within a sequence stratigraphic framework

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Abstract

Facies belts exhibit a back-stepping trend towards the London Brabant/ Rhenish Massif through the Early Cretaceous. The overall eustatic sea-level rise was punctuated by short-term tectonic events identified either as localised or North Sea wide in extent. The biostratigraphically constrained sequences have, for the first time, allowed a detailed calibration of tectonic and eustatic events on a North Sea scale. The most extensive database available to any North Sea Cretaceous study was available to the authors together with a comprehensive suite of new high-resolution biostratigraphy and sedimentology. This has allowed unique insights into provenance, depositional environment, extent of sequence stratigraphical events and the degree to which unconformities have been tectonically accentuated.

Keywords: Early Cretaceous, event stratigraphy, tectonically accentuated

Introduction

This paper describes the results of a detailed sequence and biostratigraphic study of the southern North Sea Basins (Fig. 1) with the aim of consolidating the central North Sea (Moray Firth) Lower Cretaceous sequence stratigraphical schemes of Jeremiah (2000) and Copestake (2003), both of which focused on turbidites. This has allowed, for the first time, a detailed North Sea basin-wide calibration of eustatic and tectonically accentuated events by encompassing the deep sea, shallow marine and non-marine parts of the basin fill.

Fully quantitative biostratigraphical analysis of wells throughout the southern North Sea Basin has been undertaken using key palynofloral and nannofloral markers already described in Duxbury, 2001 and Jeremiah, 2000 respectively, together with several newly-recognised events of local significance. This framework has allowed the identification and 'typing' of the key maximum flooding surfaces and sequence boundaries as either regional, eustatically controlled or more localised and tectonically accentuated. Field reviews incorporating seismic, biostratigraphy, sedimentology and outcrop data have allowed individual areas to be presented in a coherent, regional sequence stratigraphic model.

This paper firstly presents the new biostratigraphic framework (Fig. 2), the result of an in-depth calibration of macrofossil, nannofossil and palynomorph data from onshore sections at Speeton, NE England and the Lower Saxony Basin, onshore Germany (Fig. 1, 3) together with numerous cored borehole sections (Appendix 1). This is followed by facies distribution maps and sequence stratigraphic nomenclature (Fig. 4a-4i) for the southern North Sea Basin and onshore. The detail within the facies maps is based on log, lithological and biostratigraphical analysis of hundreds of Dutch and UK sector exploration wells available to Nederlandse Aardolie Maatschappij BV (NAM) drilled prior to 2001 (when the analysis for this study was concluded). Key maximum flooding surfaces (MFS's) and sequence boundaries are discussed and evidence is presented on the extent of these surfaces,

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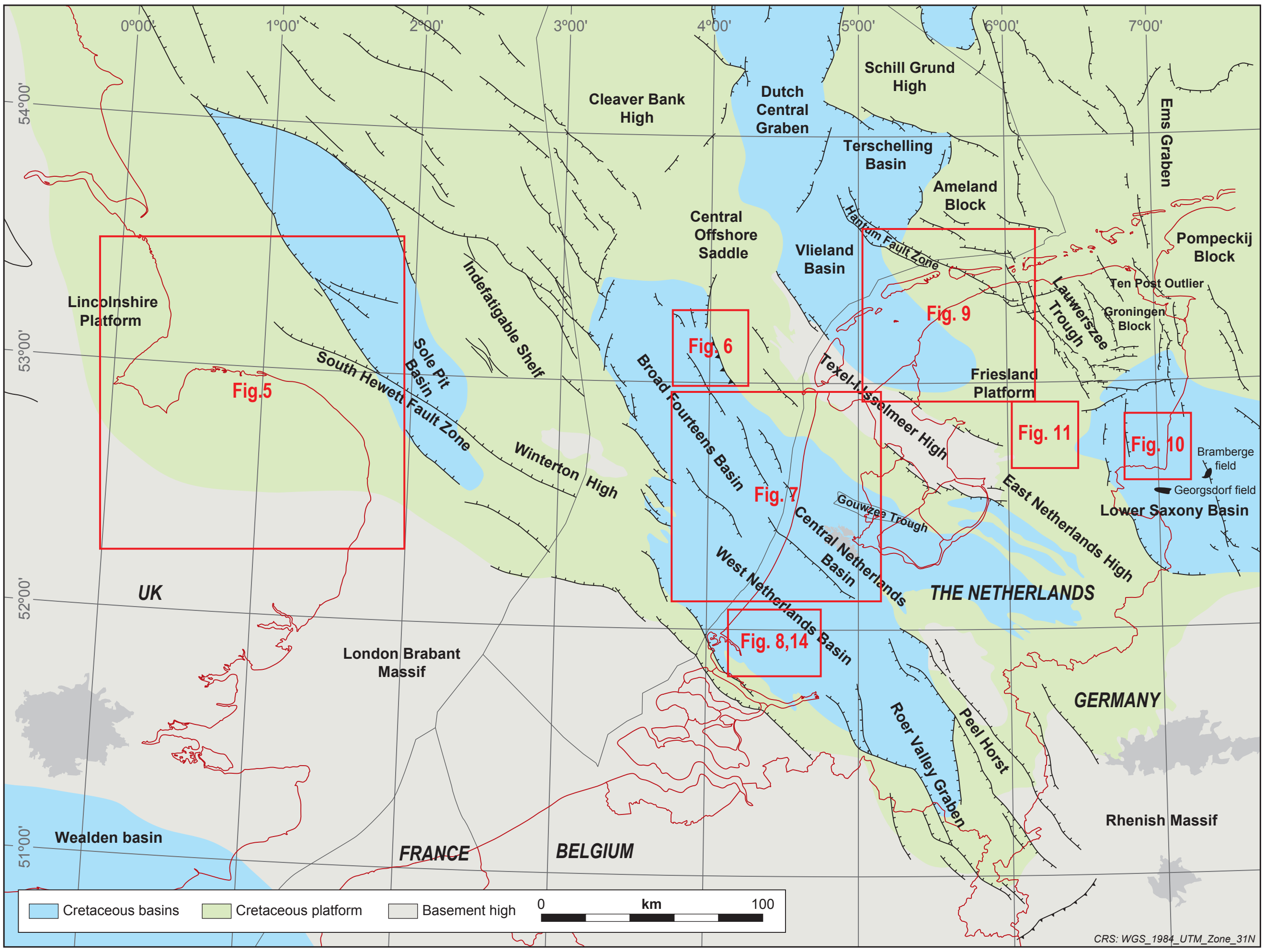

Fig. 1. Location map and study areas.

lithological expression of events and calibration to key surfaces identified by previous workers. Finally, in Appendix 2 all the biostratigraphic events utilised in well correlations (Fig. 5-11, 14) are presented.

The regional theme of this work has identified the North Sea-wide importance of a number of sequence boundaries and MFS's already published in Jeremiah (2000), Duxbury (2001) and Copestake et al. (2003). By contrast, a number of unconformities are shown to be tectonically accentuated and localised in extent. Accompanying seismic sections and correlation panels are provided. Often cited North Sea-wide unconformities such as the 'Base Cretaceous' K10 and 'Base Aptian' K60 Unconformities (Crittenden et al., 1991) have not been linked to a major sea-level low in this study, instead they have been calibrated to important transgressions initially recognised by Rawson and Riley (1982), a reflection of proven tectonism in the Proto-Atlantic and Bay of Biscay. Overall the southern North Sea Basin geology reflects a rise in sea level through the Early Cretaceous, punctuated by local, tectonically accentuated uplift; e.g. the K20 Bentheim Sandstones of the Lower Saxony Basin (Fig. 1). The distribution of uppermost Ryazanian /Lower Valanginian K10/K20 sandstones are also found to be developed in a more linear east-west system than considered by Ziegler (1990). Isolated outliers have proved that the shoreface belt continues across the northern margins of the Friesland Platform and is not just restricted to the major grabens.

Biostratigraphic data have confirmed the basin-wide significance of both the Hauterivian K30 and Late Aptian K70/K80 tectonic events (Fig. 3). The culmination of K30 turbidite deposition in the Moray Firth can be calibrated to renewed progradation of clastics in the southern North Sea. Likewise, the culmination in Austrian (Ziegler, 1982) tectonism during the Late Aptian (*jacobi*) K80 interval in the southern North Sea can be calibrated precisely to the maximum distribution of Aptian turbidites in the UK Moray Firth and Norwegian sectors.

A number of maximum flooding surfaces are found to be easily recognised and basin-wide (Fig. 3), the most important being the basal Upper Valanginian *Prodichotomites* MFS, Lower Barremian *Fissicostatum* MFS (Munk Marl of Jensen et al., 1986) and the lowermost Aptian *Forbesi* MFS (Fischschiefer Bed, Copestake et al., 2003).

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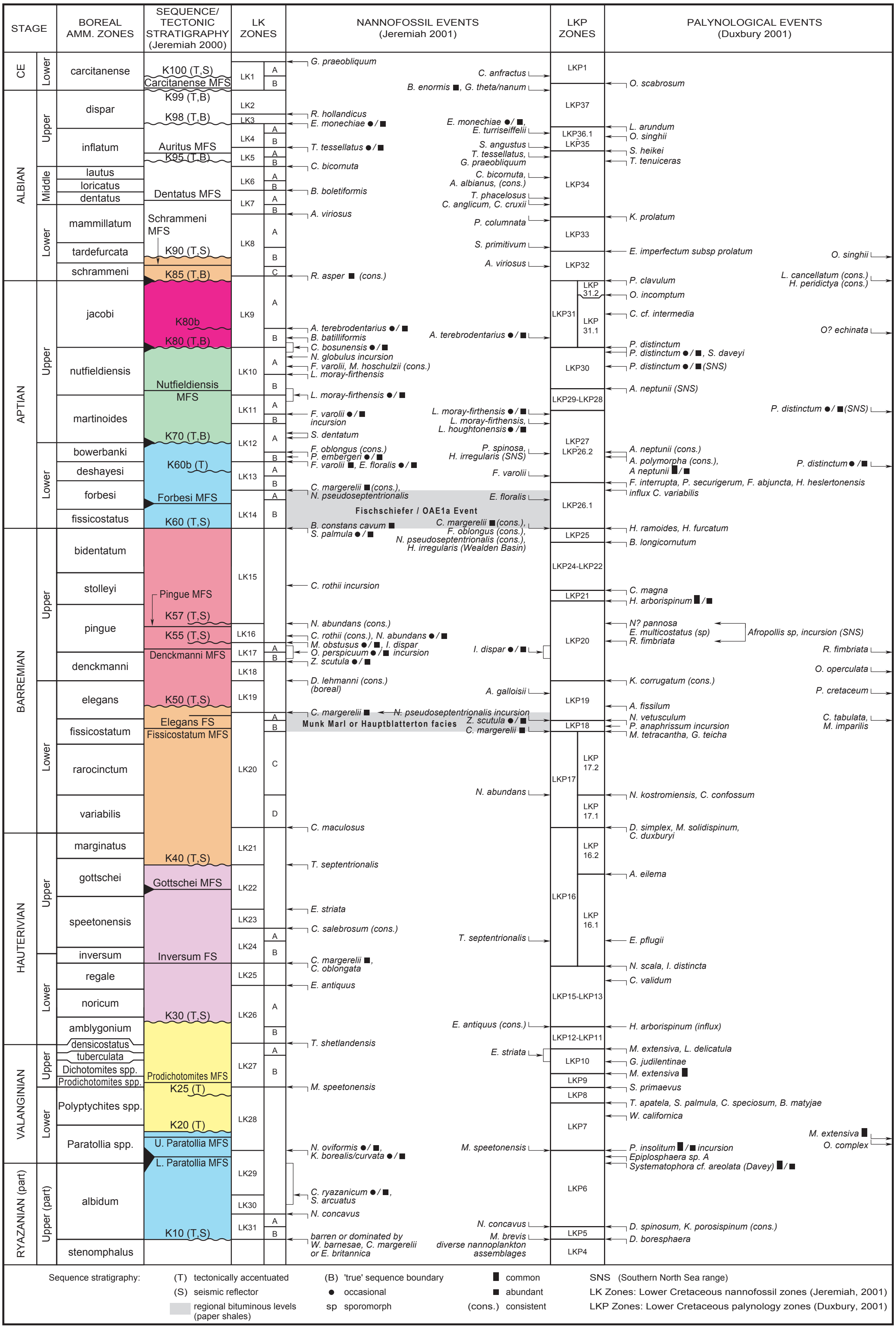

Fig. 2. Lower Cretaceous sequences and biostratigraphic calibration. The palynological LKP Zones/Subzones of Duxbury 2001 have been merged where no definitive evidence of the zonal markers could be confirmed from the southern North Sea / onshore basins.

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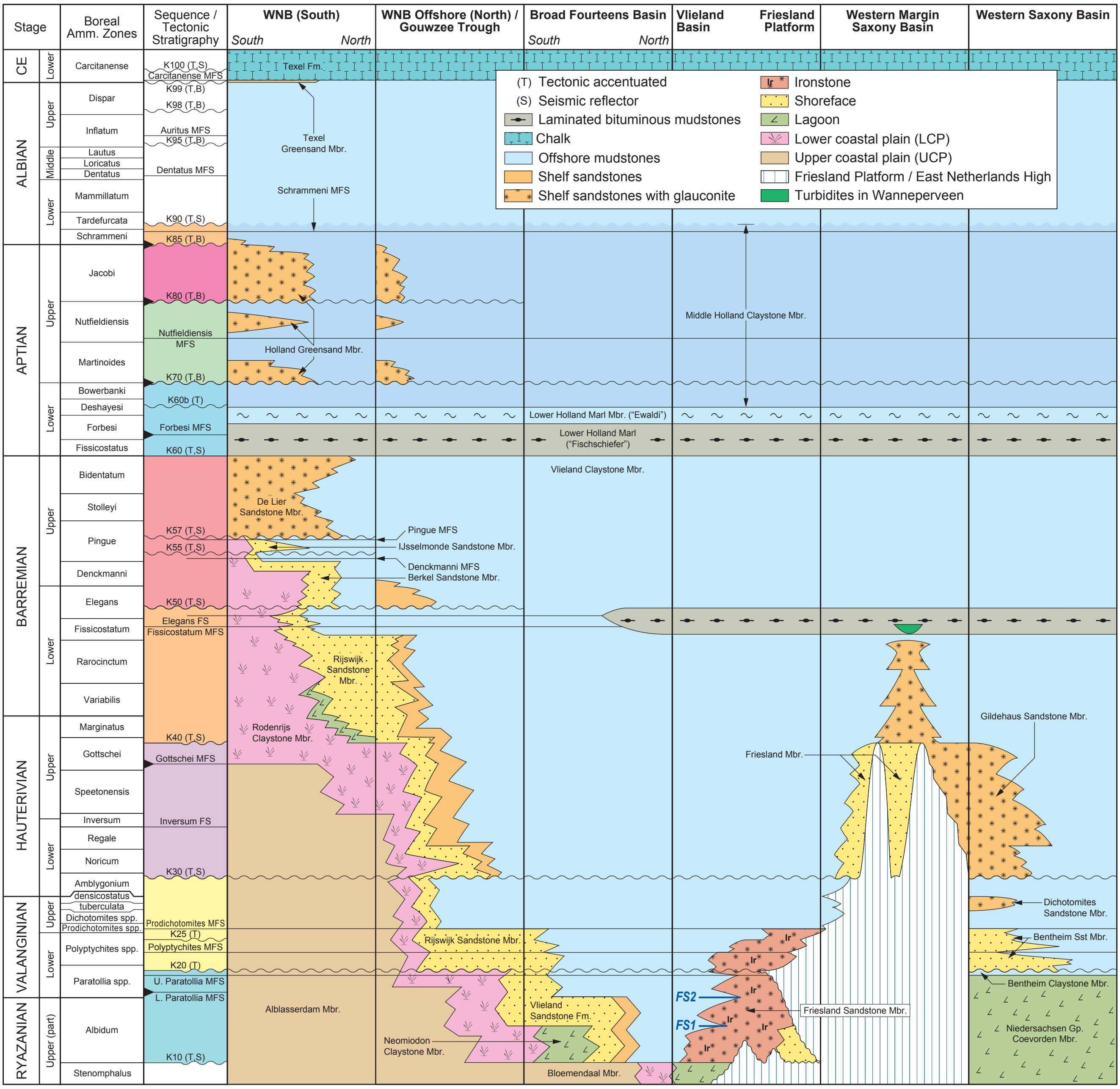

Fig. 3. Chronostratigraphic synopsis of southern North Sea basins.

Biostratigraphic calibration

In the course of this study, cores from the Netherlands and Germany have been complimented with outcrop data from England and Germany. This has allowed a calibrated nannofossil and palynological zonation to be constructed. In all, about 95-cored sections were re-analysed for both nannofossil and palynological data (Appendix 1), many wells never having been previously analysed for biostratigraphy. Key wells are presented in the correlation panels and seismic sections (Fig. 5-11, 14) with sequences tied to the relevant biostratigraphic events collated in Appendix 2. This work has allowed a direct comparison with events recorded within the Moray Firth area (Jeremiah, 2000; Duxbury, 2001) a result of consistent disciplines (nannofossils and palynology) and experts having been involved in both studies. This is an advantage over previous studies in which biostratigraphic results of different vintages, utilising various contractors and disciplines, may have resulted in unreliably calibrated datasets. This study has also, for the first time in the offshore North Sea Basin, incorporated ammonite records (see Appendix 2 and Fig. 6, 9, 10) that have allowed a direct comparison with the palynological and nannofossil zonation schemes. The detailed results indicate that the nannofossil zonation (Jeremiah, 2001) remains little changed whereas new macrofossil and palynology data from the Valanginian/Latest

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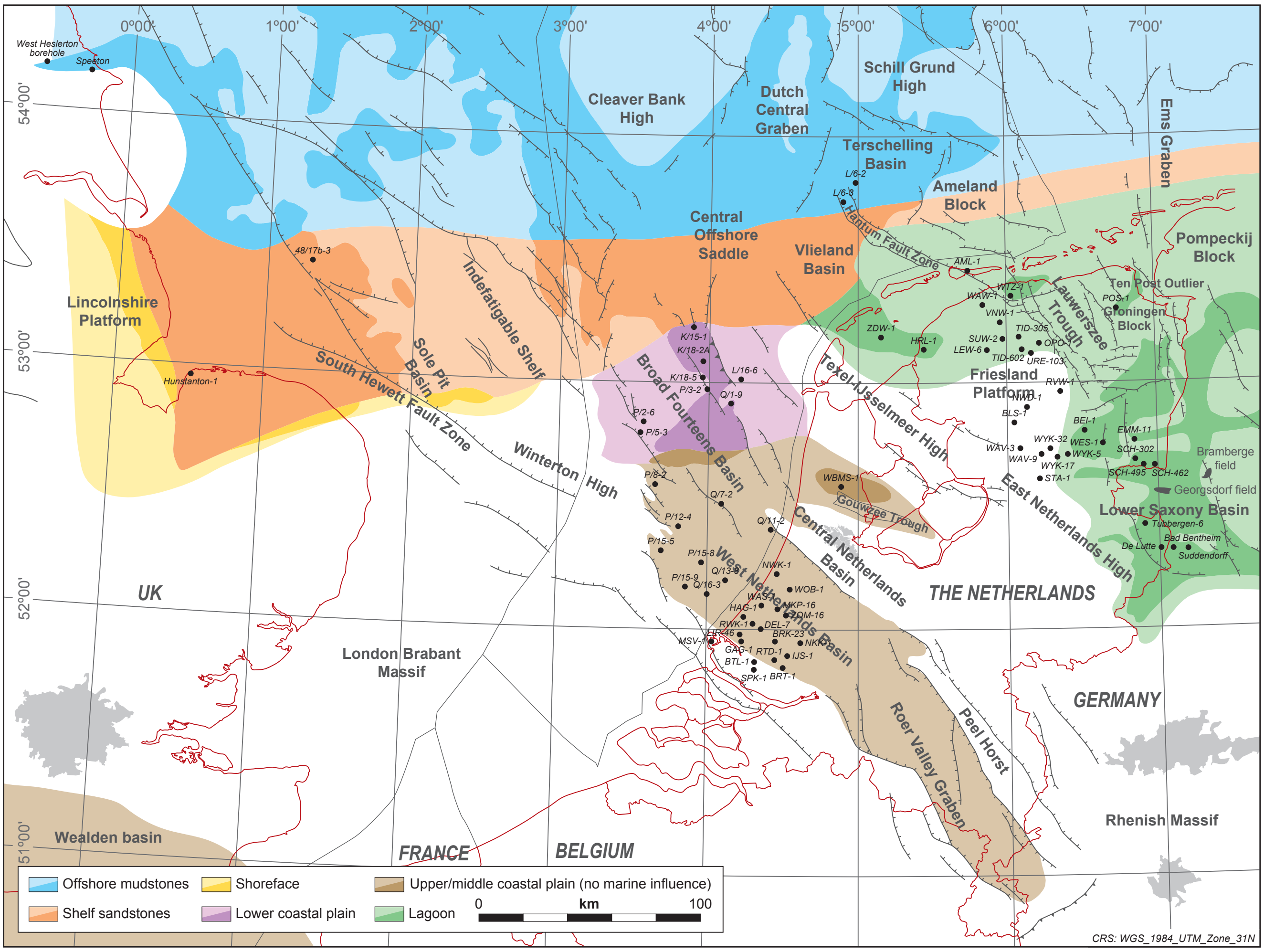

Fig. 4. Regional facies maps. Note for all facies; lighter shading depicts areas of post and syn-depositional erosion. a. Regional facies map: stenomphalus Zone (Late Ryazanian). A widespread lagoonal system is recorded from this sequence in outliers from the Vlieland Basin, Hantum Fault Zone and over much of the Lower Saxony Basin. No evidence is seen for any base-level sea fall within the Late Ryazanian that could be linked to a major K10 tectonic event. Marine shales (Kimmeridge Clay facies) of the Schill Grund Member (Abbink et al 2006) are recorded at this time in the Terschelling Basin.

Ryazanian suggests that the Lower Cretaceous palynology zonation of Duxbury (2001) may be further refined. Fig. 2 includes an updated calibration between disciplines, biostratigraphic data from many of the studied wells are documented in Appendix 2.

Reservoir distribution and sequence stratigraphy of the southern North Sea Basins

The sequence stratigraphic scheme of Jeremiah (2000) identified seismically mappable sequences and MFS's from the Moray Firth. During the Early Cretaceous the Moray Firth was a deep-water basin dominated by turbidites and mudstones with a shoreface depositional system and associated stacking patterns inherently absent. Jeremiah (2000) attempted to calibrate the sequences identified to the southern Dutch North Sea sector shoreface systems.

The current study has expanded on these initial findings and has been able to differentiate Third Order sequences (Vail et al., 1977; Cloetingh, 1988) and MFS's (Vail et al., 1977; Posamentier et al., 1988) that are of regional and localised extent. Results confirm that the rejuvenation of the hinterland by tectonic overprinting (tectonically accentuated sequence boundaries of Cloetingh, 1988; Ruffel, 1998) has had a more important role in the development of some regional sequences (e.g. K20 sequence of the Friesland Platform and western Saxony Basin) than eustatic sea-level change.

The sequence stratigraphic scheme below follows the published nomenclature of Jeremiah (2000) and DeVault & Jeremiah (2002) that utilises a sequence stratigraphic naming convention bounded by sequence boundaries (albeit a tectonic unconformity in many instances). In the present study it was difficult to identify all but a few MFS's throughout the basin. The sequence stratigraphic scheme of Copestake et al. (2003) is not utilised since there is a fundamental difference in interpretations of age diagnostic markers, both palynological and nannofossil (compare Fig. 2, this paper with fig. 12.6 in

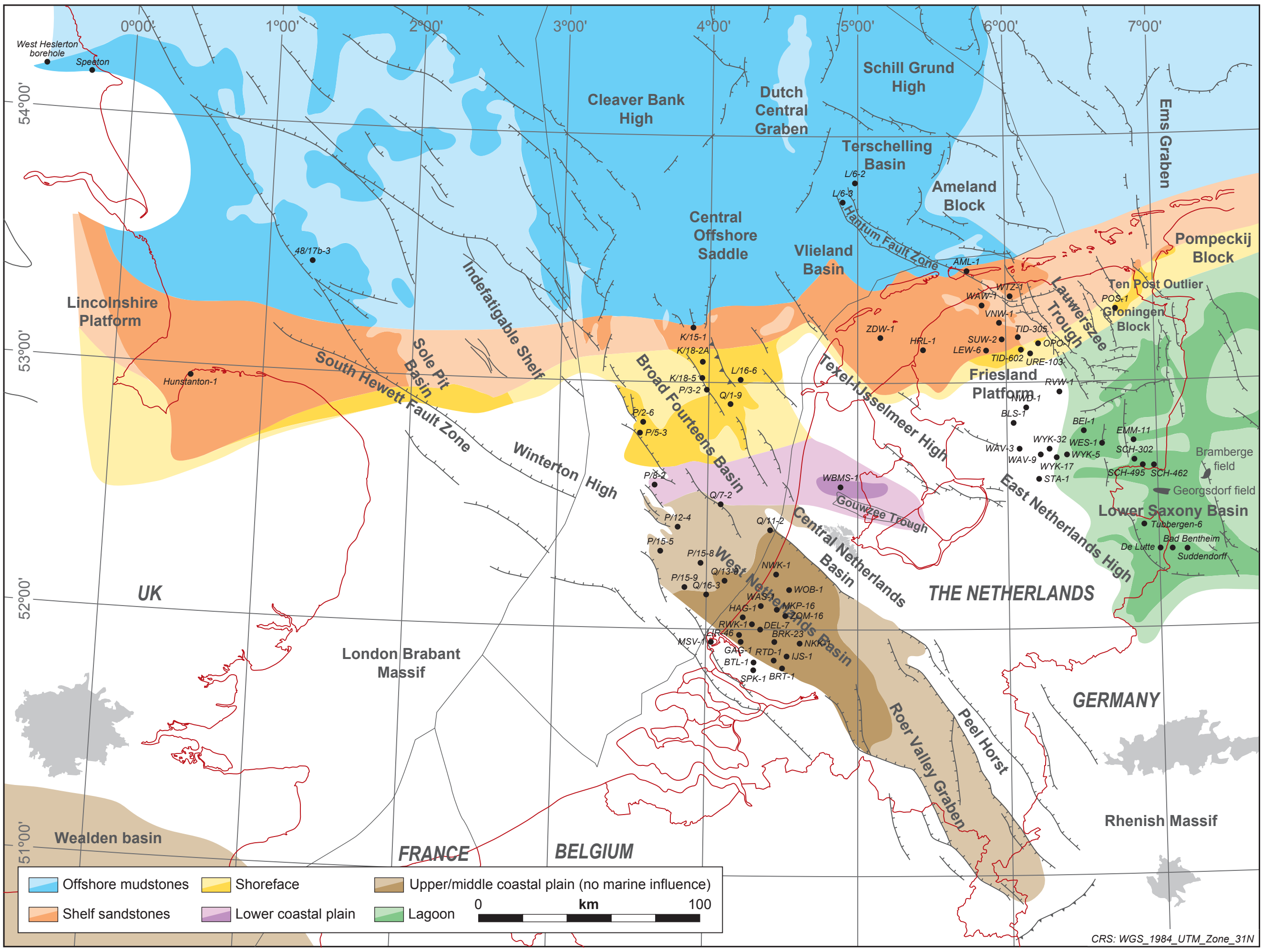

Fig. 4b. Regional facies map: base K10 sequence albidum Zone (Latest Ryazanian). The Uppermost Ryazanian Albidum TS initiates a major retrogradation of facies belts southwards towards the London-Brabant massif, a major transgression after the sea level drop at the end of the North Sea-wide Middle Volgian Cimmerian event.

Copestake et al., 2003). Foraminifera, although providing locally excellent correlation markers, have a much more limited potential for regional correlations and have not been utilised.

Hoedemaeker and Herngreen (2003) attempted to correlate sequences recognised in the subsurface of the Netherlands with the standard Tethyan Berriasian-Barremian successions in Spain and France. Unfortunately the sequences are only taken up to the base of the Aptian. In addition, with the absence of correlation diagrams it is not always easy to compare the placement of sequence boundaries in Dutch sections of Hoedemaeker and Herngreen (2003) with the current study.

The following section gives a regional overview of the facies development over the region, the key events being summarised in Fig. 3. The basins of interest are shown in Fig. 1. A more detailed synopsis of the structural development of individual basins of interest can be found in De Jager (2003) and Herngreen & Wong (2007). Fields and wells are also discussed; the locations of these are shown in Fig. 5-11, 14.

Latest Ryazanian through Earliest Valanginian K10 sequence

The end Ryazanian Albidum transgression marks a major backstep of Cretaceous facies onto the northern margins of the London Brabant Massif (compare Fig. 4a with Fig. 4b) after the North Sea wide Mid Volgian Cimmerian Uplift (Rawson & Riley, 1982; Erratt et al., 1999; Jeremiah & Nicholson 1999; Rawson, 2006; Abbink et al., 2006). In the Southern North Sea, this regional Mid Volgian Cimmerian event is recognised by

a. The marked progradation of clastics over the Kimmeridge Clay Formation in Eastern England (Fig. 5).
b. The marked progradation of the Scruff Greensand Formation (Van Adrichem Boogaert & Kouwe, 1993) over the Kimmeridge Clay Formation in the Dutch offshore Terschelling Basin. Abbink et al. (2006) considered this the base of their Sequence 3 but placed the sequence boundary at the top of the Middle Volgian (*oppressus* ammonite Zone). The current study suggests this unconformity lies within the early Middle Volgian (*fittoni* Zone) as in UK well 48/17b-3 (Fig. 5) and in the Dutch Central Graben (pers. obs. Duxbury). The stratigraphy in 48/17b-3 is similar to that of the Early Ryazanian to Late Volgian ammonite-dated L6-2 and L6-3

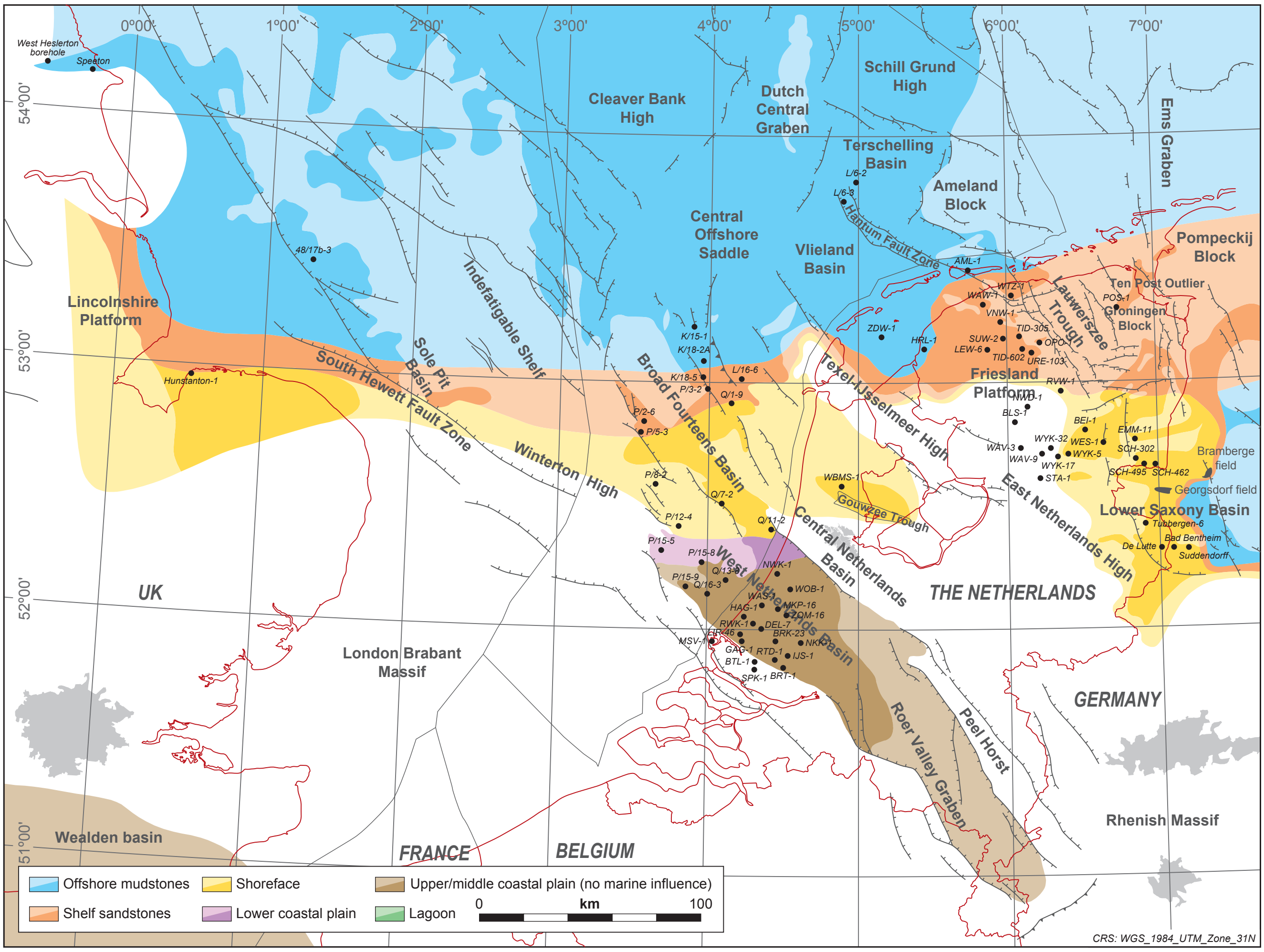

Fig. 4c. Regional facies map: K20 sequence Polyptychites Zone (Early Valanginian). Establishment after a brief marine transgression (Bentheim Shale) of rapidly prograding Bentheim Sandstone into the western Saxony Basin.

succession recovered from the Scruff Greensand Formation (Abbink et al., 2001). In the Terschelling Graben the Scruff Sandstone Formation is transgressed within the Late Ryazanian (*icenii* to *stenomphalus* Zones), Kimmeridge Clay facies (Schill Grund Member; Abbink et al., 2006) re-established in this basin.

c. Separation of the Weald Basin from the North Sea Basins, the Weald Basin (Fig. 1) becoming a non-marine depositional basin after the Mid Volgian event and disconnected from the marine basins north of the London Brabant Massif until the Early Aptian.
d. A major regression at the top of the Fourteens Claystone Member (NAM & RGD, 1982) in the Dutch Broad Fourteens Basin (Fig. 6).

The absence of a major hiatus at the basal K10 boundary in basin successions of the Moray Firth and Central Grabens, UK sector, was discussed by Jeremiah (2000); K10 turbidite bodies occurring here are considered a result of localised tectonism.

In contrast with the level of the Mid Volgian Unconformity, no regional K10 lowstand can be recognised in this study, the base K10 being more often reflected by localised inversion and an associated angular unconformity such as along the margins of the Broad Fourteens Basin (Roelofsen et al., 1991 and this paper, Fig. 6), West Netherlands Basins (De Jager et al., 1996; DeVault & Jeremiah, 2002) and Terschelling Basin (Abbink et al., 2006). The comparative distribution of preserved pre-K10 Upper Ryazanian *stenomphalus* Zone sediments (Fig. 4a) with that in the post-K10 uppermost Ryazanian (Fig. 4b) gives some indication of the main areas of Base K10 uplift although this also incorporates uplift by earlier Cimmerian events, particularly towards the margins of the main depocentres (Ameland Block, Friesland Platform, Cleaver Bank High). Nowhere in the study area can the base K10 uplift be linked to any regional base-level sea fall or increased hinterland uplift and clastic progradation. The base K10 sequence over much of the study area is represented by a major transgressive surface, the Albidum transgressive surface (TS) which steps out of the Jurassic depocentres onto the bordering highs (e.g. Friesland Platform-Lauwersee Trough-Pompeckij Block; compare Fig. 4a with Fig. 4b).

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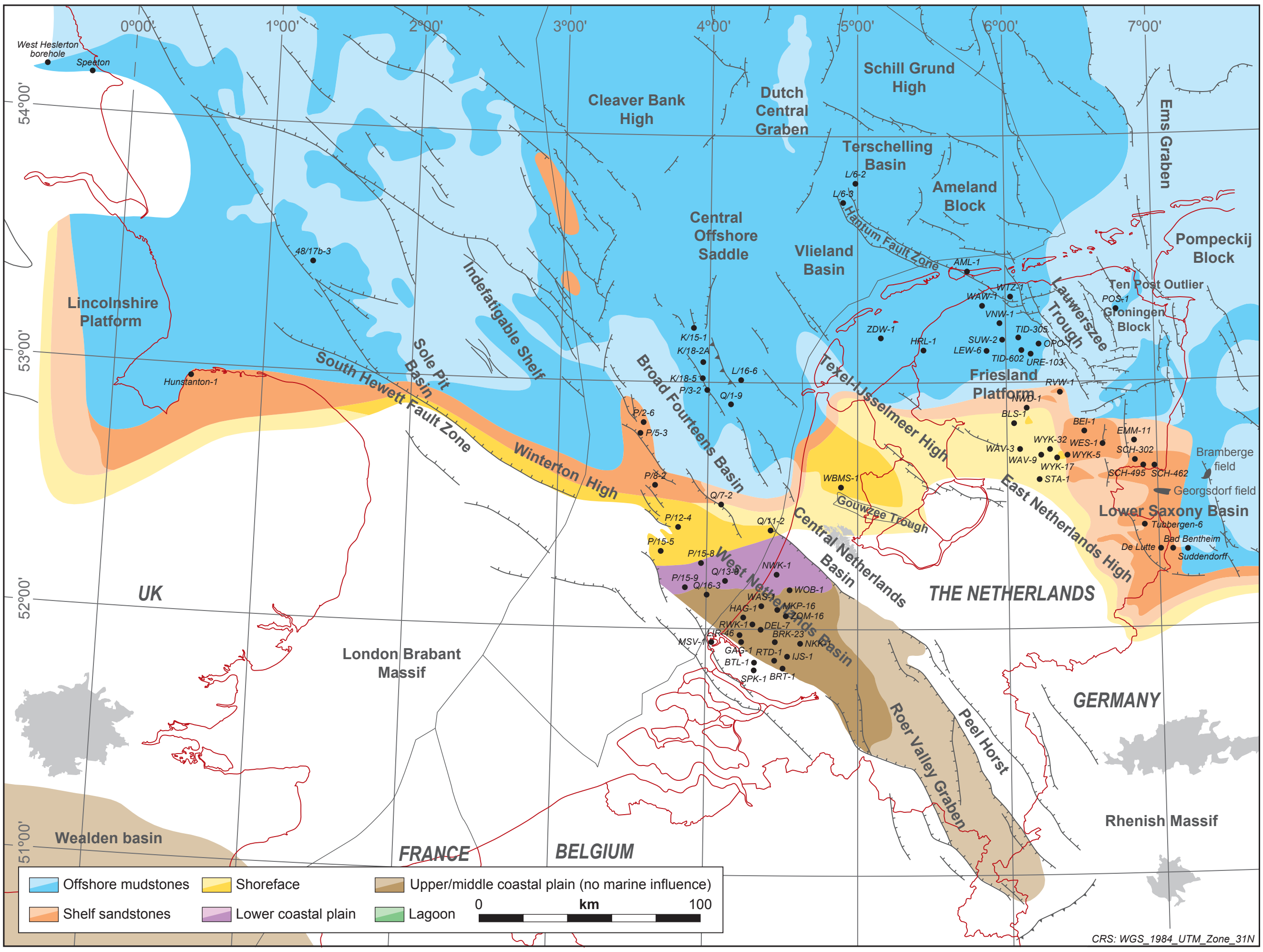

Fig. 4d. Regional facies map: K30 sequence regale Zone (Early Hauterivian). K30 prograding sandstones over Upper Valanginian mudstones are documented from all the southern North Sea Basins.

The evidence from the southern North Sea Basins suggests, in contrast to earlier conclusions by Jeremiah (2000), that the base K10 sequence marks a true increase in base-sea level. This flooding was possibly linked to tectonic re-adjustments in the Proto-Atlantic (McMahon & Turner, 1998; Hawkes et al., 1998) that allowed a 'flushing' of the anoxic North Sea Basin towards the end of the Ryazanian (Rawson & Riley, 1982). McMahon & Turner (1998) studied data from the Western Approaches and found evidence of major uplift during this time. Hawkes et al. (1998) suggested that active rifting along the Biscay continental margin also lead to fault reactivation.

New biostratigraphic data confirms, for the first time, outliers of uppermost Ryazanian sediments within the Friesland Platform and Groningen Block (NW Pompeckij-Groningen Block, Fig. 4b). These outliers indicate that K10 sandstones were developed in an essentially west – east belt from Eastern England through northern Germany over many areas that were considered high blocks by Ziegler (1990) and Mutterlose & Bornemann (2000).

Broad Fourteens Basin (K10 sequence)

The uppermost Ryazanian Albidum TS (Base K10 sequence) rapidly flooded the Broad Fourteens Basin from the north establishing condensed offshore muds and siltstones in the northern part of the basin (e.g. Fig. 3, compare Fig. 4a with Fig. 4b and K15-1; Fig. 6) whilst further south over Kotter and Q-Blocks (K18-2A; Fig. 6) the Albidum TS is expressed as an expanded paralic mudstone succession, the Neomiodian Claystone Member (Van Adrichem Boogaert & Kouwe, 1993).

Roelofsen & De Boer (1991) considered the Neomiodian Claystone as an integral part of the pre-Albidum Breeveertien Formation (Van Adrichem Boogaert & Kouwe, 1993). However, ammonite data from the condensed offshore succession in K15-1 (Fig. 6) and palynological calibration with the Neomiodian Claystone Member indicate these sediments are a lagoon equivalent of the shelfal *Peregrinoceras* ammonite-bearing (*albidum* Zone) siltstones cored in K15-1. In K15-1, the Albidum TS is marked by a basal transgressive lag of macrofossil debris bearing belemnites.

At Kotter Field a K10 shoreface is preserved overlying the K10 Neomiodian Claystone Member, the K10 sandstones being primarily of Latest Ryazanian age. Sedimentological analysis of

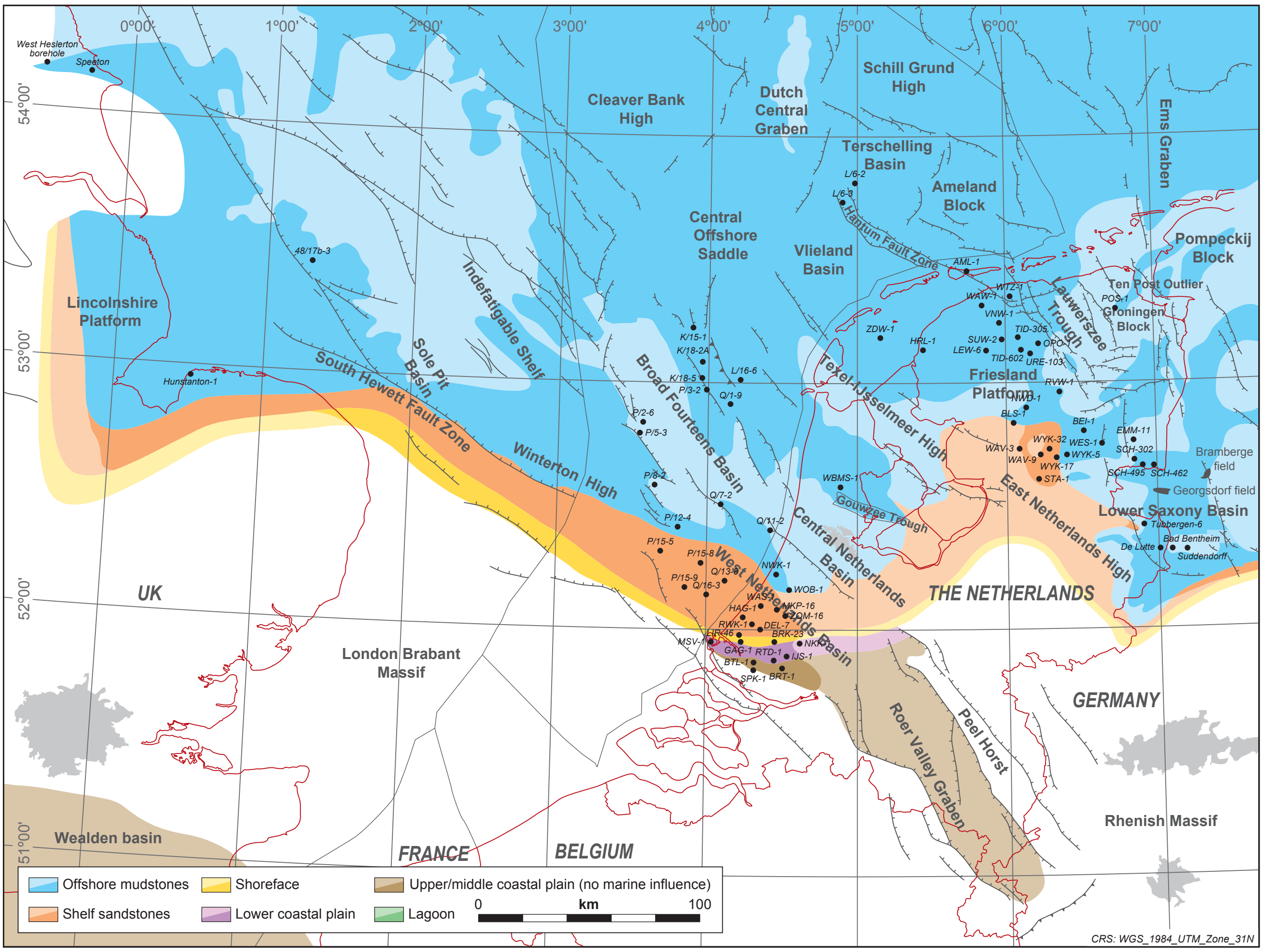

Fig. 4e. Regional facies map: base K40 sequence marginatus Zone (Latest Hauterivian). This sequence marks the last vestiges of siliciclastic sedimentation north of the W-E trending London-Brabant-Rhenish Massif. Shelf sandstones remain along the flanks of the East Netherlands High until the late Early Barremian, the Fissicostatum MFS (Munk Marl) finally drowning the last vestiges of this northern siliciclastic shelf.

the K10 sands reveals upward coarsening parasequences marked by an erosive transgressive drowning at the top of each cycle (Roelofsen & De Boer, 1991; De Jong & Laker, 1992). Intercalated lagoon deposits in Kotter and Q-blocks are suggestive of coastal barrier complexes.

At the beginning of the Early Valanginian the whole system was rapidly drowned and backstepped onto the L16 platform (compare L16-6; Fig. 4b with Fig. 4c) and southwards (Fig. 3 and Q1 to Q01-9 transect; Fig. 7). L16 Logger-2 (Fig. 6) exhibits a thin K10 through K20 succession resting directly on Lower Jurassic deposits. The seismic line in Fig. 6 that traverses the L16 Platform north of Logger Field exhibits K10/K20 sandstones directly on Lower Triassic deposits. The Cretaceous sandstones are predominantly bioturbated lower shoreface deposits with intercalations of better reservoir quality upper shoreface deposits. Two fining-up cycles are described (Goh, 1993, 1996), the lower corresponding to the K10 sequence, the upper, Lower Valanginian K20 deposits.

West Netherlands Basin (K10 sequence)

The oldest Cretaceous sediments in the West Netherlands Basin belong to K10 syn-rift fluvial deposits (Fig. 4b) of the Alblasserdam Member (Van Adrichem Boogaert & Kouwe, 1993). These sediments are entirely non-marine and exhibit a strong tectonic overprint. Large variations in thickness are seen at this level across faults, testimony to rifting as a factor in the deposition of this sequence (DeVault & Jeremiah, 2002). Fig. 8 shows the marked expansion of the K10 Alblasserdam Member in the hanging-wall of both the Moerkapelle and Rotterdam Fields.

Vlieland Basin / Friesland Platform and Hantum Fault Zone (K10 sequence)

K10 inversion does not appear to have affected the Vlieland Basin (Herngreen et al., 1991) and Hantum Fault Zone (Fig. 1). K10 shelf sandstones overlie Ryazanian lagoonal mudstones with no unconformity (Fig. 3). The base Albidum TS rapidly inundated the Vlieland Basin (e.g. Zuidwal and Harlingen Fields, location in Fig. 9), Hantum Fault Zone and Friesland Platform (Opeinde, Leeuwarden and Tietjerksteradeel Fields;

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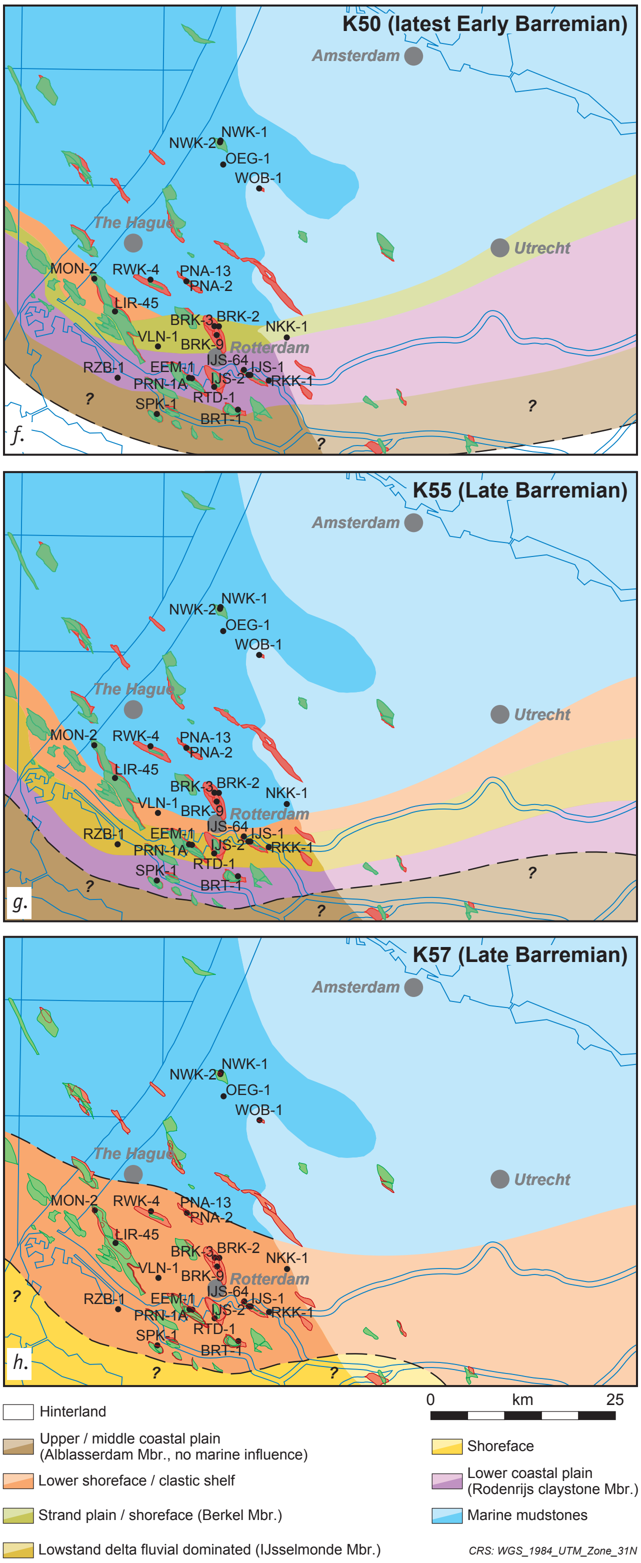

Fig. 4f-h. Regional facies map: West Netherlands Basin (Late Barremian K50 sequence, K55 and K57 parasequences). Oil fields filled red; gas fields, green.

Fig. 9) where a broad clastic shelf is preserved, the shoreface belt being bypassed and only patchily preserved in the far south of the area (Fig. 4b and Opeinde Field; Fig. 9).

Above the Albidum TS, a coarsening-up sequence is exhibited with a basinward shift of facies. This earliest progradational parasequence, K10 parasequence-1, prograded furthest northwards over the platform and is associated with reservoir quality sandstones as far north as the northern part of the Tietjerksteradeel Field (e.g. TID-305; Fig. 9). Subsequent parasequences exhibit shoreface progradational cycles of a diminished northwards extent linked to the overall retro-gradational nature of K10 sandstones (compare TID-901 with TID-305; Fig. 9). Flooding surface 1 (FS1) is accurately dated with macrofossils as lying within the uppermost Ryazanian *albidum* Zone (*Peregrinoceras* ammonites in Veenwouden-1, VNW-1, location map Fig. 9) whilst palynological data confirms an Earliest Valanginian age (lower *Paratollia* Zone) for FS2 (Lower Paratollia MFS).

The remaining Lower Valanginian section is 'locked up' within a condensed facies association of greensands and oolitic ironstones over much of the Friesland Platform. Further south in the southern part of Leeuwarden, Akkrum, Opeinde, Ureterp and Tietjerksteradeel Fields no sediments of this age are recorded, having been truncated by K20 uplift (e.g. Ureterp-103; Fig. 9). This is in contrast to Hoedemaeker & Herngreen (2003) who considered the entire shelf succession to be of Early Valanginian age.

K20 uplift and subsequent erosion only appear to have affected the southern Friesland Platform and explain the limited distribution of K10 shoreface sediments in the present day rock record (no upper shoreface/beach facies are recorded, presumably eroded). This littoral facies zone may have extended far to the south of its limited present day distribution. The southernmost preserved sequences of the Friesland Sandstone Member (southern Tietjerksteradeel, Opeinde and Akkrum Fields) show no evidence of onlap and thinning. The lower parasequences para1 and para2 remain thick (see Fig. 9; TID-901 to OPE-2), their southernmost extent ultimately being controlled by base K20 truncation, above which a thin succession of late K20 sequence transgressive siltstones onlap the inherited topography (Fig. 9; URE-103). This transgression culminates in marine mudstone deposition at the Late Valanginian Prodichotomites MFS.

The Albidum transgression (Base K10) also inundated other platform areas east of the Friesland Platform such as the Groningen Block in the Netherlands and north-western parts of the Pompeckij Block in Germany (Fig. 4b). Past regional facies maps have indicated these areas as hinterland (Ziegler, 1990). Well data however indicates the Albidum TS (Base K10) inundated these palaeoswells, with penecontemporaneous erosion having removed much of the evidence. However, occasional fault-bounded outliers within the highs have preserved the facies belts as depositional remnants. The

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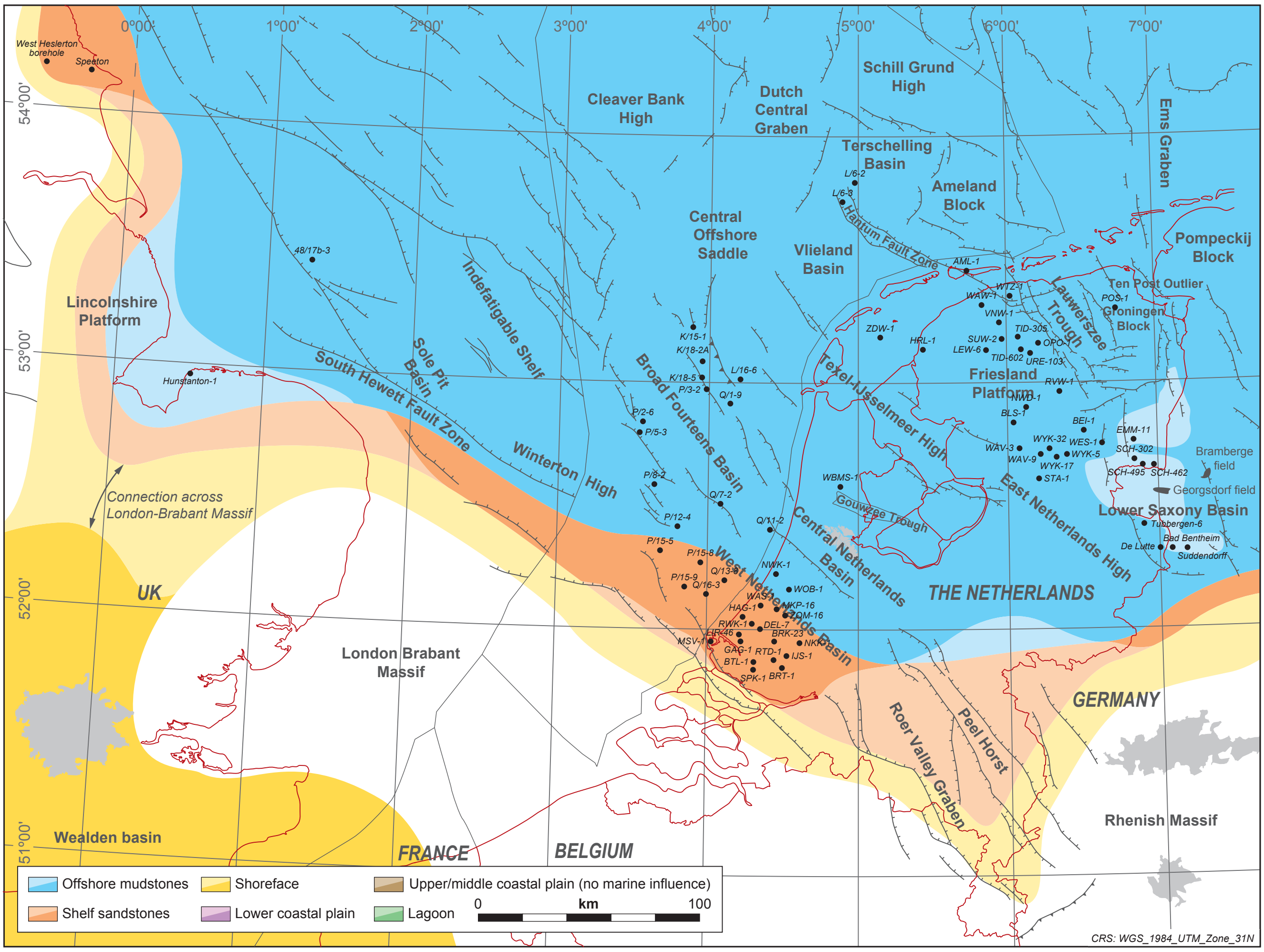

Fig. 4i. Regional facies map: base K80 jacobi Zone (Late Aptian). A marine connection exists between the Wealden and southern North Sea Basins. A tidally influenced shelf with coarse clastics dominates southern Britain. In the southern North Sea basin, however the margins of the basin have been eroded, the preserved sequence represented by fine-grained, glauconitic shelf sands in the west Netherlands Basin, southern margins of Saxony basin and the eastern margins of the Lower Cretaceous seaway near Speeton (NE England).

Ten-Post outlier within the Groningen Block (Fig. 4b) exhibits highest Ryazanian K10 shoreface and shelf transition deposits. The Albidum TS (Base K10) did not totally inundate southwards into the Saxony Basin although a marine connection is evident in the Earliest Valanginian with the deposition of kerogenous lagoonal deposits (W6 Beds of the upper Niedersachsen Group; Mutterlose & Bornemann, 2000) exhibiting a marginal marine palynofloral signal (Fig. 4b and Appendix 2; Westerbork-1).

In the Early Valanginian a rapid transgression finally inundated the Saxony Basin and is correlated with the Upper Paratollia MFS (Fig. 2, 4c, 10) based on palynological and nannofossil data (incorrectly calibrated to the Polyptychites Zone and called the *Polyptychites* MFS in Jeremiah, 2000). Here fully marine K10 shales (Platylenticeras Beds, Mutterlose & Bornemann, 2000; Bentheim Claystone Member, Herngreen & Wong, 2007) rest conformably upon K10 lagoonal shales with no shoreface belt developed (Fig. 3). Kemper (1976) and Mutterlose & Bornemann (2000) considered that the transition from lacustrine to marine (Platylenticeras Beds) in the Saxony Basin occurred at the beginning of the Valanginian. Palynological and nannofossil calibration with limited ammonite data from Speeton (eastern England) would suggest this flooding occurred later, in mid Early Valanginian times. This apparent anomaly is to be investigated further.

The deposition of the Bentheim Claystone Member was strongly influenced by local topography. Along the western margin of the Saxony Basin (Fig. 10) the Upper Paratollia MFS (Bentheim Claystone Member) rapidly onlaps and thins to the east. Here the shale is replaced by a condensed *Platylenticeras* bearing carbonate bed and marl (0.1m-1.5m thick as in Schoonebeek 366A; Fig. 10).

The absence of any major sandstone deposits within either the upper Niedersachsen Group (predominantly ostracod and gastropod limestone, minor evaporates and organic mudstones) or the Bentheim Claystone Member indicates a periodically arid hinterland with minimal siliciclastic input.

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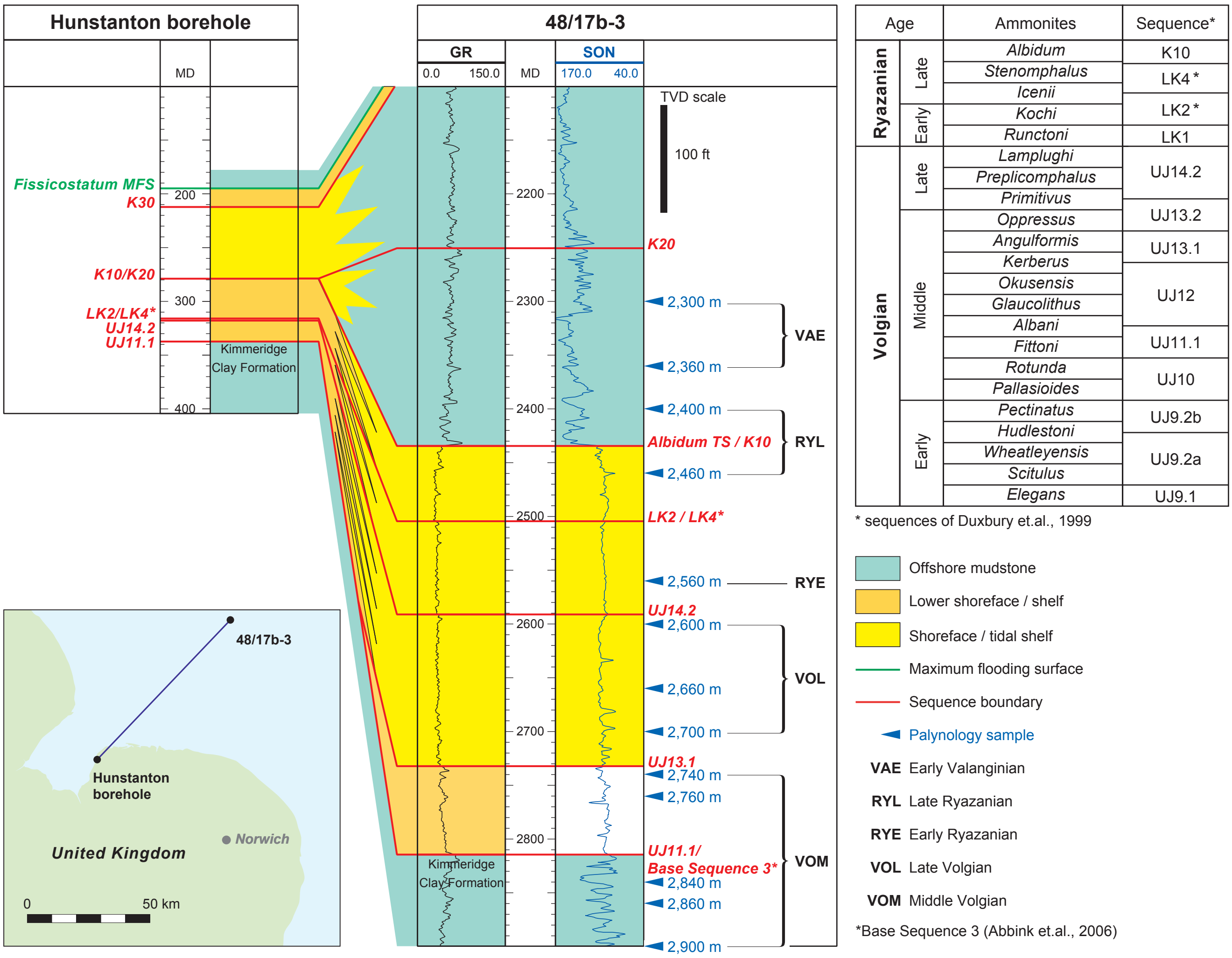

Fig. 5. Jurassic/Cretaceous boundary successions of the Hunstanton borehole and Sole Pit Basin. The UJ11.1 mid Volgian Cimmerian Unconformity marks the final separation of a marine connection between the Wealden Basin and the southern North Sea Basins.

Eastern England / Sole Pit Basin (K10 sequence)

In the Sole Pit Basin Ryazanian sandstones were rapidly transgressed by the Albidum TS (Base K10) (Fig. 5). Deposition appears to have been continuous across the K10 boundary with no evidence of a major hiatus in the Sole Pit Basin depocentre (48/17b-3; Fig. 5). This sequence of events is very similar in mid Lincolnshire where *albidum* ammonites are recorded from the basal Hundleby Clay overlying Ryazanian-dated *stenomphalus*-ammonite bearing sandstones (Casey, 1973). At other localities towards the basin margins, in north Lincolnshire, the albidum TS (Base K10) rests unconformably on Upper Jurassic (Volgian) sandstones, *Peregrinoceras* being recorded at Nettleton (Kelly & Rawson, 1983). At the Hunstanton borehole (Fig. 5) on the south-western margin of the Ryazanian sea-way a condensed littoral facies of shoreface sandstones and tidal shelf deposits was deposited continuously from the Mid Volgian Unconformity through to Early Hauterivian times.

Late Early Valanginian through Earliest Hauterivian K20 sequence

Deposition of Lower Valanginian K20 turbidites in the Inner Moray Firth (Jeremiah, 2000; Copestake et al., 2003) gave way to mudstone deposition by the Upper Paratollia MFS (Polyptychites MFS of Jeremiah, 2000). The termination of turbidite deposition can be linked to an overall increase in sea level documented from the southern North Sea Basin through the Valanginian, maximum sea level being reached during the latest K20 interval at the very beginning of the Hauterivian.

In the Broad Fourteens Basin and Lincolnshire platform area, onshore UK, the Valanginian-dated K20 sequence continues an overall retrogradational facies pattern already established in the underlying K10 sequence (compare Fig. 4b with Fig. 4c). In the southern parts of the Broad Fourteens Basin, northern West Netherlands Basin (Q11-2; Fig. 7) and the onshore Netherlands Gouwzee Trough (WBMS-1; Fig. 7), K20 shoreface sandstones rest upon K10 coastal plain deposits. This overall increase in sea-level was complicated by localised tectonically accentuated sequence boundaries, most notable recorded from the Friesland Platform and Saxony Basin.

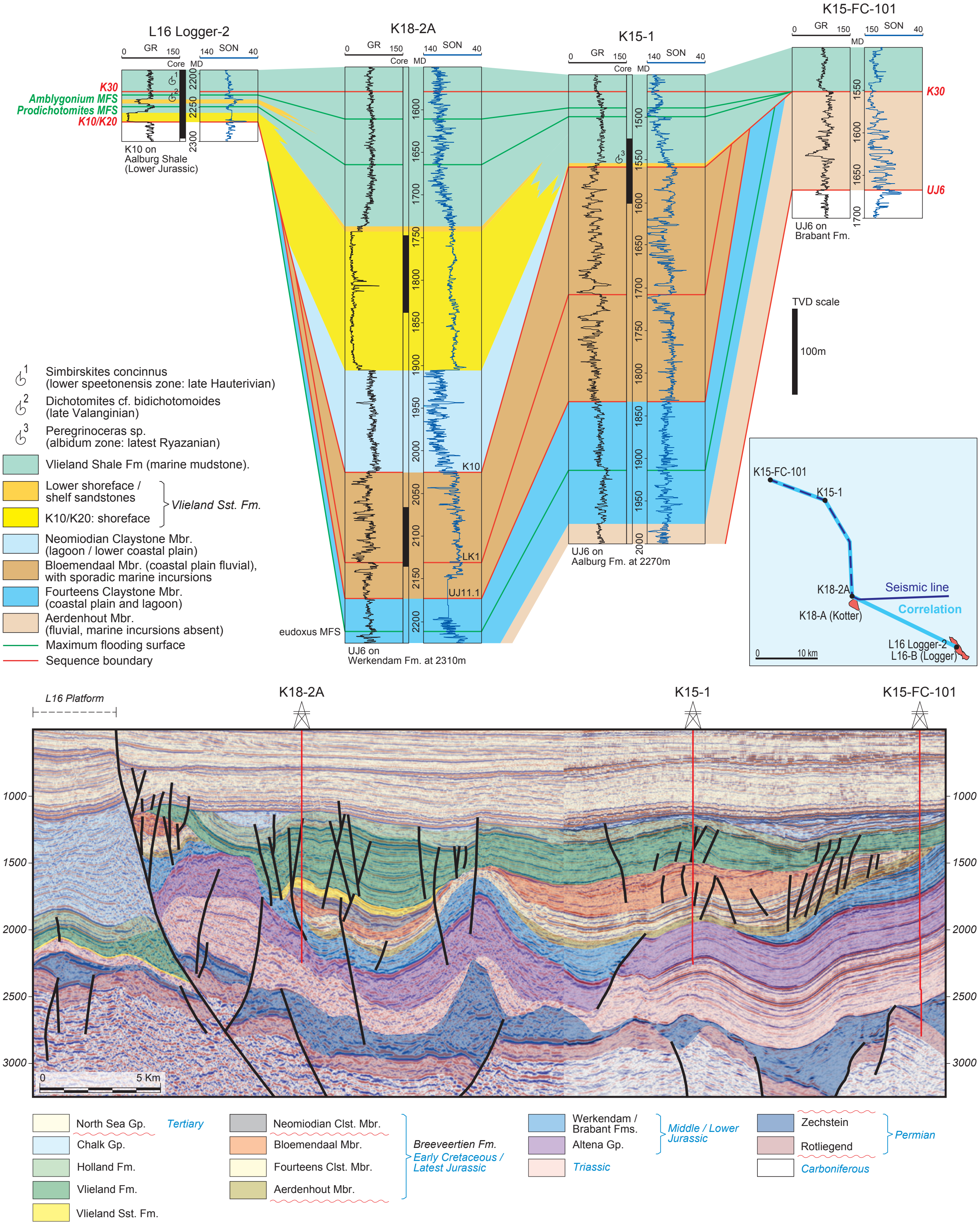

Fig. 6. Broad Fourteens Basin transect: The K10 inversion event truncates the Upper Jurassic / Lowermost Cretaceous Breeveertien Formation to varying levels. A near complete Breeveertien Formation is preserved at K15-1 whilst at K15-FC-101 only the basal beds are preserved. West of K15-FC-101, the Breeveertien Formation is entirely absent, Vlieland shales resting directly upon Middle Jurassic Brabant limestones.

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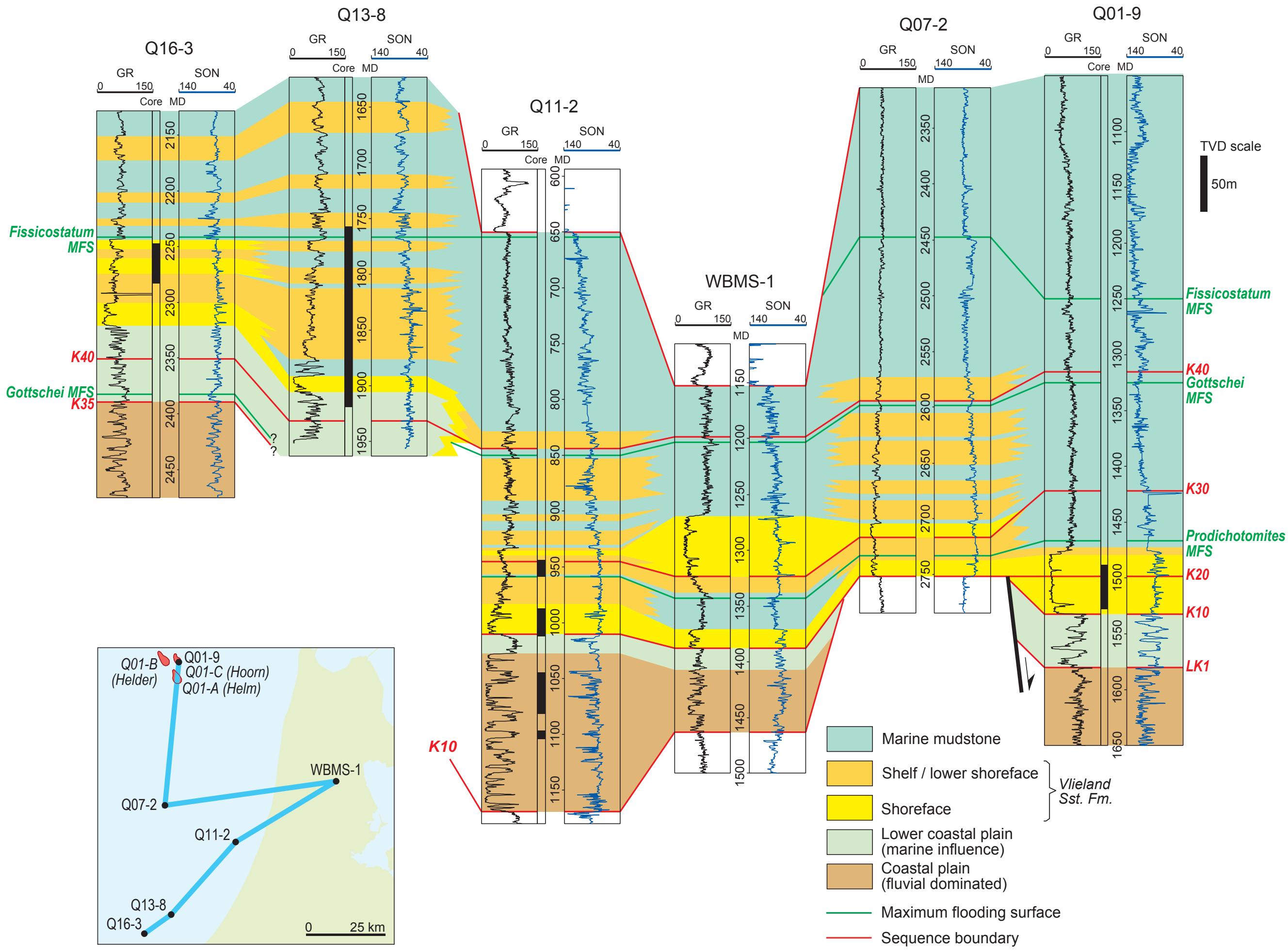

Fig. 7. West Netherlands Basin, Gouwzee Trough and Broad Fourteens Basin transect showing southwards retrogradation of shoreface and shelfal facies belt.

Ultimately the Upper Valanginian Prodichotomites TS and associated MFS terminated K20 sandstone deposition on the Friesland Platform (Fig. 9), Saxony Basin (Fig. 10), southern Broad Fourteens Basin (Logger; Fig. 6 and Q1 Block; Fig. 7) and the Gouwzee Trough (WBMS-1; Fig. 7). The earliest Late Valanginian Prodichotomites transgression and associated MFS appear to have been an important flooding event throughout the southern North Sea basins (Rawson & Riley, 1982; Mutterlose & Bornemann, 2000; Copestake et al., 2003). The overall sea-level rise continued into the basal Hauterivian *amblygonium* ammonite Zone.

Friesland Platform / Saxony Basin (K20 sequence)

The overall sea-level rise in the Valanginian is overprinted by a localised, tectonically accentuated unconformity on the Friesland Platform and Saxony Basin, the uplift occurring later than the Upper Paratollia MFS event (Fig. 3).

K20 uplift is marked by a hiatus surface that ultimately truncates the whole K10 sequence southwards on the Friesland Platform (compare TID-901, OPE-2 and URE-103; Fig. 9). A result of this uplift and erosion of K10 shorefaces was the redeposition of clastics towards the southeast into the Saxony Basin (Fig. 4c). Here, a sharp-based, tide-dominated shoreface prograded eastwards into the Saxony Basin over marine mudstones of the Upper Paratollia MFS (Bentheim Shales). In addition to a northwestern provenance area, indications from heavy mineral analysis of the Bentheim outcrops (Mutterlose & Bornemann, 2000) also suggest an additional southerly provenance area from the Rhenish Massif.

These sandstones (Bentheim Sandstone of Kemper, 1976) outcrop on the Dutch/German border and have been described in detail, together with borehole information by various authors (Kemper, 1968, 1976; Wonham et al., 1997). At the Suddendorf outcrop in Germany (Kemper, 1976) cross-bedded and mud draped foresets of the base K20 Bentheim sandstone lie sharply upon open marine ammonite-bearing mudstones, the junction between the two sequences being an extremely abrupt event. This marked facies change marks the transition in the Saxony Basin from a sand-starved basin to one that is characterised by major sandstone input. As such, this boundary is not a true 'forced regression' (Posamentier & Morris, 2000) since the regression was not forced by sea-level fall but was dependent on sediment flux variations from the provenance

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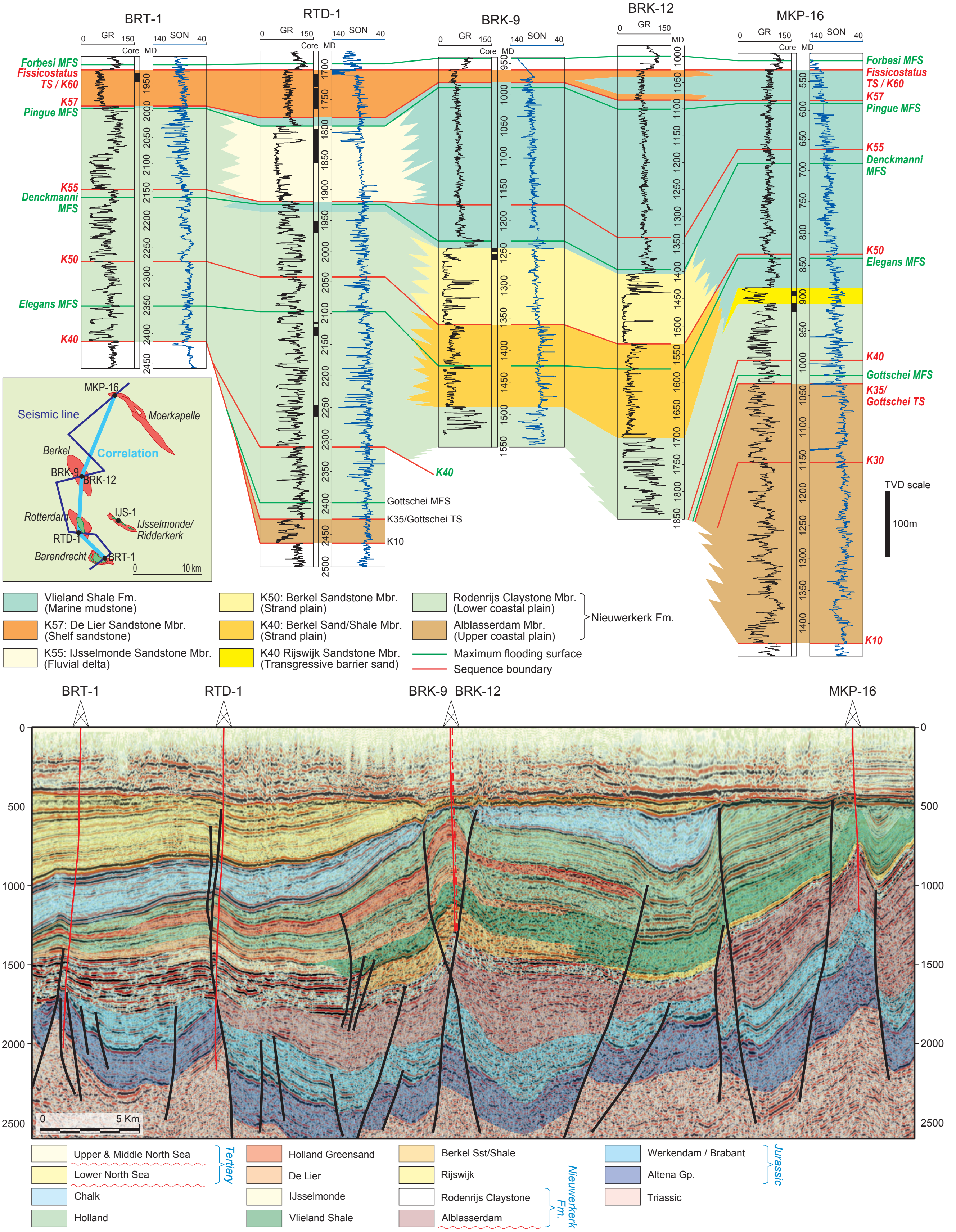

Fig. 8. Correlation panel exhibits the marked facies change from lower coastal plain deposits in BRT-1 through into open marine, shelf conditions, 20km north in MKP-16. The Tertiary Laramide event inverted the basin centre whilst subsidence continued in the south resulting in a southerly tilt to the basin.

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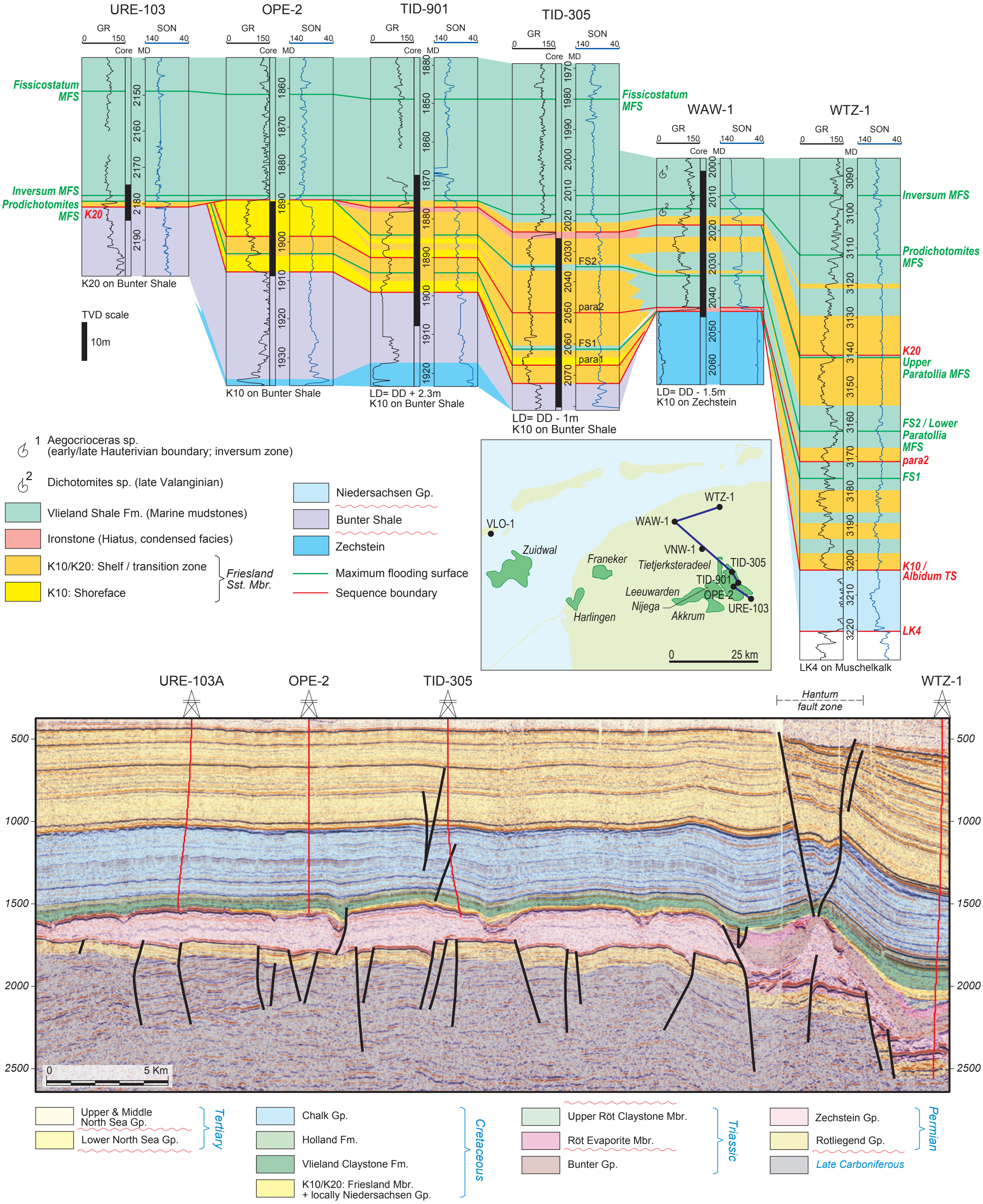

Fig. 9: Friesland Platform transect: The Jurassic sequence of the Vlieland basin onlaps eastwards towards the Friesland Platform. Here a Permian Zechstein sequence overlain by a thin Lower Triassic Bunter sequence (<30 m) is followed unconformably by a condensed Lower Cretaceous transgressive K10 sandstone, the Friesland Sandstone Member. Northwards, the Friesland Platform is bounded by the Hantum Fault Zone.
This Hantum sub-basin, in contrast to the Vlieland Basin, primarily appears to consist of a thick complete Triassic through lowermost Jurassic succession. Upper Jurassic sediments are absent. Renewed subsidence appears to have occurred in the Ryazanian with the development of a thin paralic sequence rapidly transgressed by the latest Ryazanian Albidum TS.

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areas. The eastwards transition of these K20 sandstones into marine shales has resulted in the stratigraphically trapped oil at Bramberge Field, Germany (Fig. 4c and Roll, 1972).

The Bentheim Sandstone at Schoonebeek is subdivided into three informal units, the Lower, Middle and Upper Bentheim (Fig.10). The Lower Bentheim is overlain by a sharp-based marine transgressive surface at the base of the overlying Romberg Shale (Kemper, 1992) that shows evidence of colonisation (intense bioturbation including *Ophiomoropha*, *Skolithos* and *Arenicolites*) both in outcrop at Romberg (Wonham et al., 1997) and in core from Schoonebeek. This regional flooding surface and important correlation datum is in turn overlain by prograding shoreface sands of the Middle Bentheim (Fig. 10). Transgressive sandstones and glauconites of the Upper Bentheim Sandstone unconformably overlie the Middle Bentheim. This surface marks a local, tectonically accentuated unconformity, the K25 Unconformity that truncates the Middle and Lower Bentheim Sandstone in a westerly direction (Fig. 10). K25 uplift has eroded the Middle Bentheim Sandstone from much of the western extension of the Bentheim Sandstone (western Schoonebeek, Emlichheim Field, Dommerskanaal (SND-1), Tubbergen, De-Lutte; see Fig. 4c, 10).

In the Saxony Basin, the K20 Bentheim sandstones are rapidly transgressed by the base Upper Valanginian Prodichotomites TS and associated MFS (Fig. 10), clastic deposition retreating to the northern margins of the Rhenish Massif. Over much of the western Saxony Basin the Late Valanginian was dominated by mudstone deposition. Local palaeoswells resulted in the sporadic occurrences of condensed successions of oolitic ironstones and glauconites (Dichotomites Sandstone; Kemper, 1976). A further increase in sea level is recorded from the Amblygonium TS at the beginning of the Hauterivian. This level marks the lithological change from primarily non-calcareous mudstones to calcareous mudstones and marls in the western Saxony Basin.

Early Hauterivian through early Late Hauterivian K30 sequence

The K30 sequence boundary is well expressed throughout the North Sea Basin (Jeremiah, 2000; Copestake et al., 2003, 'K20'). In mudstone dominated sequences of the Moray Firth and onshore at Speeton this sequence boundary is located within the basal Hauterivian *amblygonium* Zone (at Speeton this calibrates to the base of Bed D1). However, in areas of turbidite deposition (e.g. Scapa Field; McGann et al., 1991) the oldest preserved K30 sediments are *noricum* Zone in age, older *amblygonium* sediments having been eroded (Jeremiah, 2000). The majority of preserved K30 turbidite deposition in the Moray Firth is of latest Early through Late Hauterivian in age.

In the western Saxony Basin (Fig. 10), northern West Netherlands Basin (Q7-2 and Q11-2; Fig. 7) and the Gouwzee Trough (WBMS-1; Fig. 7) the K30 sequence is characterised by renewed progradation of coarser clastics into the basin. In the Saxony Basin the sediments are primarily glauconitic/oolitic shelf shoals (subdivided into Gildehaus and Noricum Sandstone by Kemper, 1976; here combined into the Gildehaus Sandstone Member after Herngreen & Wong, 2007) which grade into detached shorefaces on the eastern flanks of the southern Friesland Platform (Wanneperveen, De Wijk, Nijensleek and Noordwolde Fields; Fig. 11) and northern Rhenish Massif (Fig. 4d). In the mid Early Hauterivian (noricum ammonite Zone) the first K30 siliciclastics were deposited locally in the Saxony Basin (e.g. Tubbergen-6; location in Fig. 4d). These oolitic greensands are known in Germany as the Noricum sandstones (Kemper, 1976). In the western Saxony Basin the main clastic progradation occurred slightly later, across the Early/Late Hauterivian boundary (Gildehaus Sandstone; Kemper, 1976). In the western Saxony Basin, Earliest Hauterivian amblygonium-bearing mudstones are found below the Gildehaus Sandstone (SCH-309, SCH-495, SND-1 and Westerbork-1). Herngreen & Wong (2007) indicated that Upper Valanginian and Lower Hauterivian sediments are largely missing from the Dutch part of the Saxony Basin. The current study does not support this except along the basin margins.

The K30 shoreface over the Friesland Platform is preserved within small collapse grabens, a result of K30 faulting and salt dissolution (e.g. Wanneperveen Field (WAV-3; Fig. 11-12 and Bruijn, 1996). The eastwards transition into shelf deposits is preserved at the De-Wijk Field (Fig. 11; WYK-20 to WYK-5).

In the southern West Netherlands Basin rifting initiated at the K10 boundary continued into the Early Hauterivian and thick amalgamated fluvial deposits are recognised (DeVault & Jeremiah, 2002). K30 syn-rift fluvial deposits (Alblasserdam Member) are the primary reservoir in the abandoned Moerkapelle Field (Fig. 8). Locally in the southern West Netherlands minor inversion, the K35 tectono-sequence boundary (De Vault & Jeremiah, 2002) resulted in attenuation and erosion of much of the K30 sequence (e.g. Rotterdam-1; Fig. 8 and Eemhaven-1; De Vault & Jeremiah, 2002). In the southern West Netherlands Basin the overlying Gottschei MFS (termed Speetonensis MFS in De Vault & Jeremiah, 2002) is associated with the establishment of lower coastal plain floodplain and coal deposits interdigitated with marginal marine lagoon deposits (Moerkapelle-16; Fig. 8). This transgression marked the termination of rifting in this part of the basin and the disappearance of marked thickness variations typical of the syn-rift phase (DeVault and Jeremiah, 2002).

Onshore UK, the K30 Dersingham Beds are shelf sandstones (Gallois, 1994) that become more shale-prone northwards. In Lincolnshire, K30 offshore mudstones are known as the Tealby Formation (Gallois, 1994; Rawson, 2006).

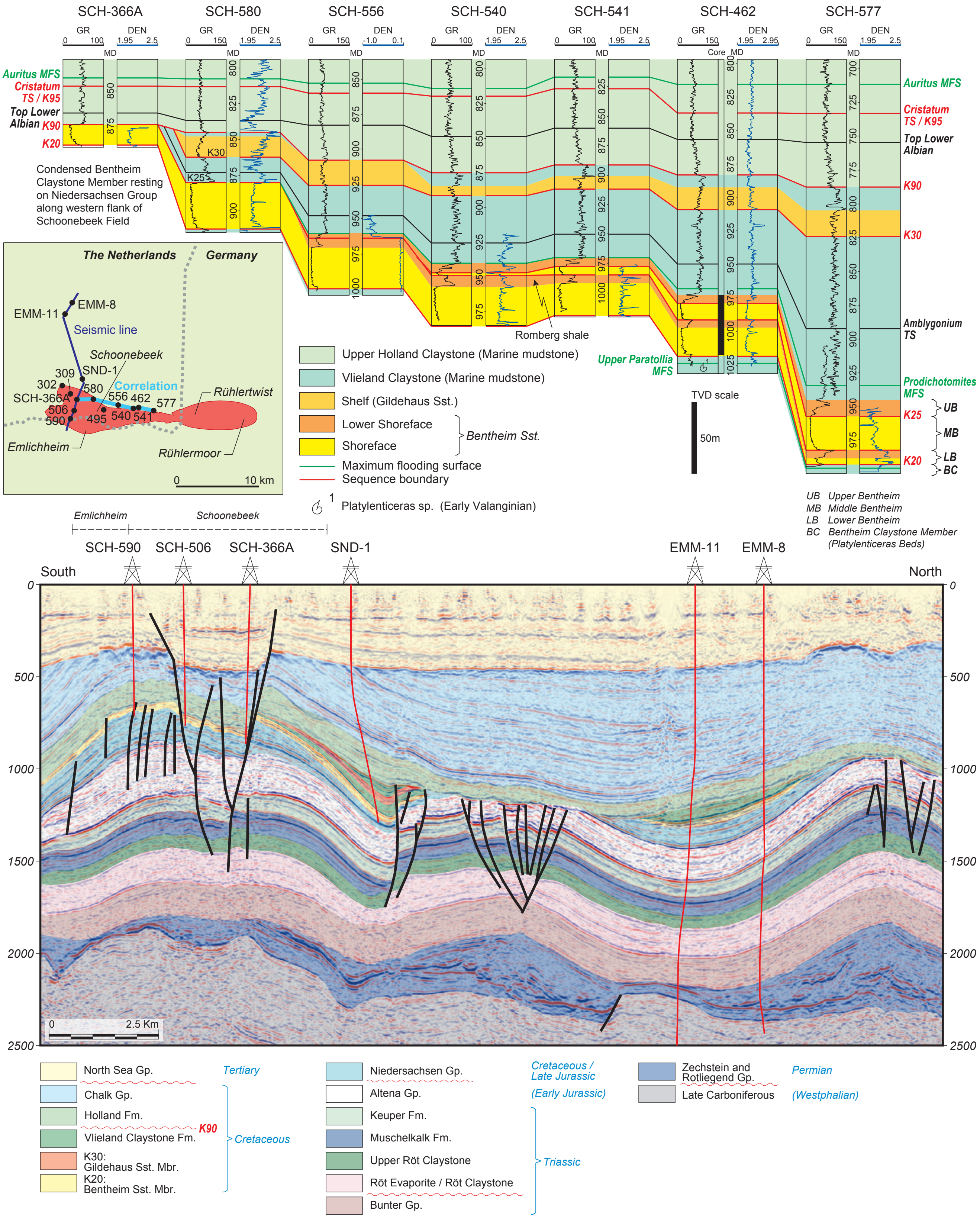

Fig. 10. Western Saxony Basin: Schoonebeek area. Cross-bedded and mud draped foresets of the base K20 Bentheim sandstone lie abruptly upon grey marine mudstones of the Bentheim Claystone Member. Two localised unconformities are documented from the western margins of the Saxony Basin; the K25 uplift progressively erodes K20 sandstones westwards. Ultimately, however, the western margins of this system are not preserved, eroded by a younger, Early Albian K90-dated, tilt of the basin.

Latest Hauterivian through Early Barremian K40 sequence

The K40 sequence encompasses the last vestiges of sandstone deposition north of the London Brabant/Rhenish Massif, the provenance for these sands possibly being the East Netherlands High (Fig. 4e). With the drowning of this stable intra-basin high post-K40 sequence, clastic facies belts withdrew southwards to form an east-west retrograding facies belt on the northern margin of the London Brabant/Rhenish Massif. No evidence of a eustatic sea-level fall is documented at this level from the southern North Sea basins. Renewed turbidite deposition locally within the Moray Firth Basin (Jeremiah, 2000) suggests the K40 sequence boundary is a localised tectonically accentuated sequence boundary in the Moray Firth region.

In the western Saxony Basin highest Hauterivian K40 shelf sandstones were short-lived, being mudstone-prone by the base Barremian (WYK-5; Fig. 11). The siliciclastic belt retrograded onto the south-east margins of the Friesland Platform (Friesland Member of Herngreen & Wong, 2007) where K40 shelf and erosive-based storm deposits are recorded as young as late Early Barremian (Fig. 3 and WAV-3; Fig. 11). The regional Lower Barremian Fissicostatum and Elegans MFS's (Hauptblatterton facies) finally terminated sandstone deposition in this area and the shelf facies belt withdrew southwards towards the Rhenish Massif for the remainder of the Early Cretaceous.

In the West Netherlands Basin (along a trend west of Moerkapelle Fields (Fig. 4e, 8; MKP-16) the K40 sequence shows a facies backstep from lower coastal plain with tidal deposits through an aerially extensive lagoon facies within the upper part of the Rodenrijs Claystone Member (Van Adrichem Boogaert & Kouwe, 1993) and finally into barrier shoreface systems of the Rijswijk Sandstone (Van Adrichem Boogaert & Kouwe, 1993). De Jager et al. (1996) proposed that the K40 barrier sands rested unconformably upon the lagoon mudstones. No unconformity can be recognised seismically, sedimentologically or biostratigraphically at this level and the Rijswijk K40 sandstones are interpreted as a retrogradational barrier complex. Ultimately this siliciclastic system is transgressed by the Fissicostatum and Elegans MFS's, sandstone deposition backstepping southwards (Fig. 3). In the northern West Netherlands Basin / southern Broad Fourteens Basin the last vestiges of K40 shelfal sandstones are rapidly transgressed at the beginning of the Barremian (P12-4; Appendix 2 and Q7-2, Q11-2; Fig. 7).

The Fissicostatum and Elegans MFS's are regional flooding surfaces (Fig. 2, 3). The Fissicostatum MFS is calibrated to the Munk Marl in Denmark (Jensen et al., 1986), Moray Firth and Central North Sea (Jeremiah, 2000; Mutterlose & Bornemann, 2000; Copestake et al., 2003) whilst both MFS's constitute the bituminous Hauptblatterton facies in the eastern Netherlands and Saxony Basins (Mutterlose & Bornemann, 2000). In onshore UK, the Hauptblatterton facies is also recognised in the Speeton Clay Formation (Rawson & Mutterlose, 1983), and at this time mudstone was deposited briefly in Norfolk – the Snettisham Clay (Gallois, 1994). In the southern West Netherlands Basin interdigitating shelf and shoreface deposits were established (BRK-9 and BRK-12; Fig. 8), the Berkel Sand/Shale Member (Van Adrichem Boogaert & Kouwe, 1993). In the southernmost part of the basin a marine incursion within K40 coastal plain facies (RTD-1 and BRT-1; Fig. 8) is biostratigraphically constrained to the Elegans MFS (see palynology data in Eemhaven-1 well; DeVault & Jeremiah, 2002).

Late Barremian K50 sequence

The overall transgressive nature of the Lower Cretaceous facies belts was punctuated in the Late Barremian by the progradation of shallow marine systems along the northern margin of the London Brabant Massif (Fig. 3, 4f-h). In the West Netherlands Basin the K50 sequence is further refined by the recognition of the K55 and K57 parasequences punctuated by marked flooding surfaces. The K50 sequence is also recognised in the Moray Firth Basin where sporadic K50 turbidites herald the onset of more widespread Austrian tectonism of the Aptian (Jeremiah, 2000; Copestake et al., 2003).

Late Barremian K50 parasequence

K50 sandstones in the West Netherlands Basin are characterised by parallel-stratified sandstones, massive unbedded sandstones, and thin, highly bioturbated lower shoreface sandstones with a rich marine palynoflora. The presence of rooted sandstones and pedogenic fabrics indicate that the shoreface was prone to periodic emergence (Fig. 13; Berkel-23 core description). Lagoon deposits have not been found associated with the K50 sandstones or in equivalent coastal plain deposits further south. Racero-Baena & Drake (1996) considered this succession a coastal barrier complex, based on east-west trending amplitude maps. The close relationship between beach and non-marine floodplain and fluvial channel sandstones in the absence of any lagoons indicates the K50 Berkel Sandstone Member (Herngreen & Wong, 2007) is better attributed to a strand-plain facies belt.

Further eastwards in Germany, on the northern flanks of the Rhenish Massif, the K50 Gravenhorst Sandstone prograded over Lower Barremian mudstones (Mutterlose & Bornemann, 2000). K50 sandstones, represented by the Roach (Gallois, 1994) shelf deposits in Norfolk, rest unconformably upon the marine, Lower Barremian Snettisham Clay (Gallois, 1994).

K50 sandstones in the West Netherlands Basin were rapidly transgressed by the Denckmanni MFS (De Vault & Jeremiah, 2002). This transgression flooded southwards and established lower shoreface / shelf deposition over coastal plain deposits in the Rotterdam (Fig. 8) and IJsselmonde Fields. This marine transgression is cored in IJsselmonde-1 (IJs-1; location map; Fig. 4, 8 and palynology data; Appendix 2) and exhibits a shell lag with belemnites resting upon floodplain deposits.

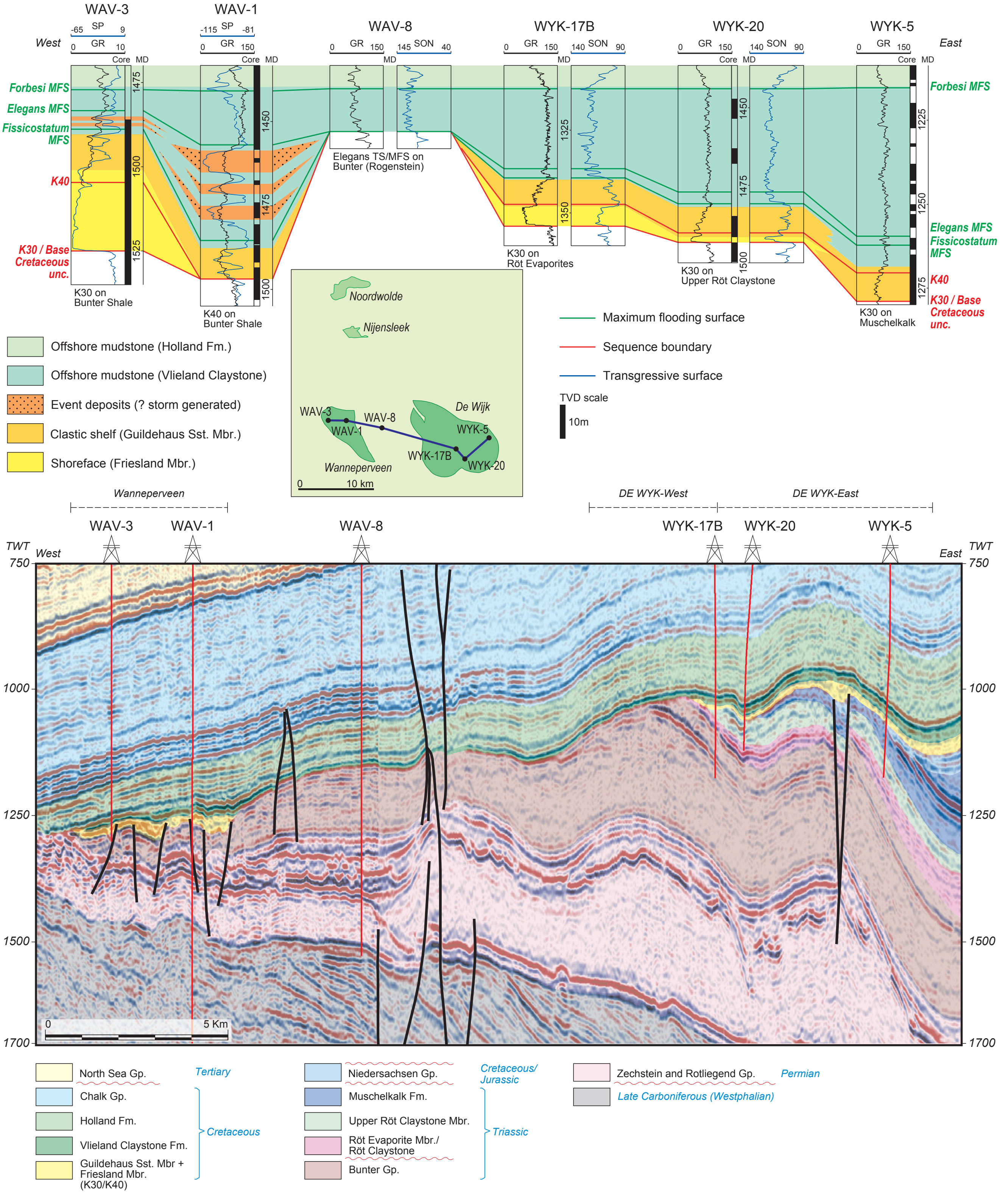

Fig. 11. SE Friesland Platform/western Saxony Basin transition: De-Wijk / Wanneperveen Fields. This transect shows the eastern margins of the Saxony Basin (WYK-5) passing west onto the isolated outliers of transgressive Hauterivian/Lower Barremian sandstones. The western shoreface equivalent (Friesland Member) of the K30 Gildehaus shelf sandstones are preserved in Wanneperveen, Nijensleek and Noordwolde Fields.

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Late Barremian K55 parasequence

Post-Denckmanni MFS there was renewed clastic progradation, the K55 delta front (Fig. 4f, 8). This tectonically induced progradation was extremely rapid and bypassed facies belts, lower shoreface deposits being overlain by distributary channels. This system, although exhibiting a similar E-W trend is situated southwards of the older K50 shoreface (DeVault & Jeremiah, 2002).

Racero-Baena and Drake (1996) considered the IJsselmonde Sandstone Member (Herngreen & Wong, 2007) as barrier sand complexes. This reservoir, however, cored at Rotterdam, Eemhaven and IJsselmonde, exhibits few marine indicators (Fig. 13 and Appendix 2). The succession, although high net to gross and of a very similar log expression as the older K50 Berkel sandstones, exhibits far fewer marine palaeofacies, primarily consisting of amalgamated distributary channel complexes exhibiting cross bedding and rippled sandstones, both lithologies rootlet bearing. Palaeosol development is more extensively developed than in the K50 Berkel sandstones. Marine indicators are restricted to sporadic marginal marine incursions recorded within thin mudstone successions interpreted as bay-floor muds. Restricted marine palynofloras are also occasionally recovered from mud clasts at the base of channel complexes (Fig. 13; Rotterdam-1 core description and Appendix 2).

Although it is tempting to consider the K55 IJsselmonde sediments as incised valley-fill (estuarine) deposits, there is no evidence from seismic of incision, or any sedimentological evidence of features characteristic of tidally influenced deposits. These amalgamated distributary channel complexes also appear laterally extensive (correlatable over at least 50 km E-W but within an extremely narrow facies belt (5 km N-S). The cored K55 sandstones are here interpreted as fluvially-dominated lowstand delta front deposits, possibly of forced-regressive origin i.e., sharp-based, top-truncated. Other examples of such systems have been documented by Bhatatcharya & Willis (2001) and Martinsen (2000).

The K55 siliciclastic belt was rapidly transgressed by the Pingue MFS that flooded the K55 coastal plain in the southernmost West Netherlands Basin (e.g. Rotterdam-1 to Barendrecht-1 transect; RTD-1 to BRT-1; Fig. 8).

Late Barremian K57 parasequence

Upper Barremian K57 shelf sandstones rapidly prograded over the Pingue MFS (Fig. 3, 4h, 8). This shelf system is predominantly glauconitic rich and highly bioturbated with multiple fining up cycles at the metre-scale. The K55, K57 parasequences and associated MFS's have only been differentiated in the southern West Netherlands Basin (DeVault & Jeremiah, 2002); their distribution possibly reflecting local hinterland rejuvenation rather than a more regional sea-level fall.

Early Aptian K60 sequence

The base of the K60 sequence is a marked North Sea wide regional transgression associated with the establishment of marine mudstones, often bituminous in nature and attributed to the Oceanic Anoxic Event 1a of Arthur et al. (1990).

In contrast to many authors (Bartenstein & Kaever 1973; Rawson & Riley 1982; Crittenden 1982; Crittenden et al. 1991), Jeremiah (2000) did not find any data to support a base sea-level fall or angular unconformity at the base of the Fissicostatus TS (base K60 sequence; Fig. 3). Copestake et al. (2003) re-established an unconformity at this level in the North Sea using the Captain Field (Pinnock & Clitheroe, 1997) as key evidence (no biostratigraphic data was cited). Nannofossil and palynological core data from Captain Field well 13/22a-2, however, clearly indicates this unconformity as the younger Upper Aptian K80 sequence boundary (Supplementary Publication No. SUP 18155; Jeremiah, 2000). The dataset from the southern North Sea Basins supports the absence of any regional base Aptian lowstand, disconformities being restricted to the basin margins and linked to the Fissicostatus transgressive event (e.g. Perna Beds in Weald Basin). In the southern North Sea Basins, the Lower Aptian K60 sequence was characterised by a high sea-level with predominantly mudstone and marl facies (Fig. 3, 14). In eastern England (Lincolnshire and the Wash) the sediments are represented by the Skegness and Sutterby Marls (Gallois, 1994), south of this area in Norfolk the equivalent sections are eroded. The lacustrine / fluvio-deltaic southern UK Weald/Wessex basins were flooded by the Fissicostatus TS to establish a fully marine sequence – the Perna Beds and Atherfield Clay Formation (Casey, 1961; Rawson, 2006).

In the Netherlands, the K60 sea-level high is lithologically expressed by bituminous mudstones and marls of the Lower Holland Marl (Van Adrichem Boogaert & Kouwe, 1993), the lower part bituminous and equivalent to the Fischschiefer (Kemper, 1976) of Germany (Fig. 14). Only along the northern fringes of the Rhenish Massif in Germany can littoral facies belts be identified in the Osning Sandstone (Mutterlose & Bornemann, 2000). Towards the top of the Lower Aptian K60 sequence (*bowerbanki* Zone) the appearance in the Netherlands of the Tethyan nannofossil, *Hayesites irregularis*, suggests that a marine connection with the Wealden Basin in southern Britain had finally been re-established.

Late Aptian to earliest Albian K70 through K80 sequences

At the beginning of the Late Aptian a fall in sea level together with an increase in tectonism (Austrian phase; Ziegler, 1982) resulted in the progradation of shoreface and shelf deposits. In Yorkshire (Speeton and West Heslerton boreholes; Fig. 4i) Aptian K70/K80 coarser clastics appeared for the first time (Jeremiah, 2000), the area having been mudstone-prone for the

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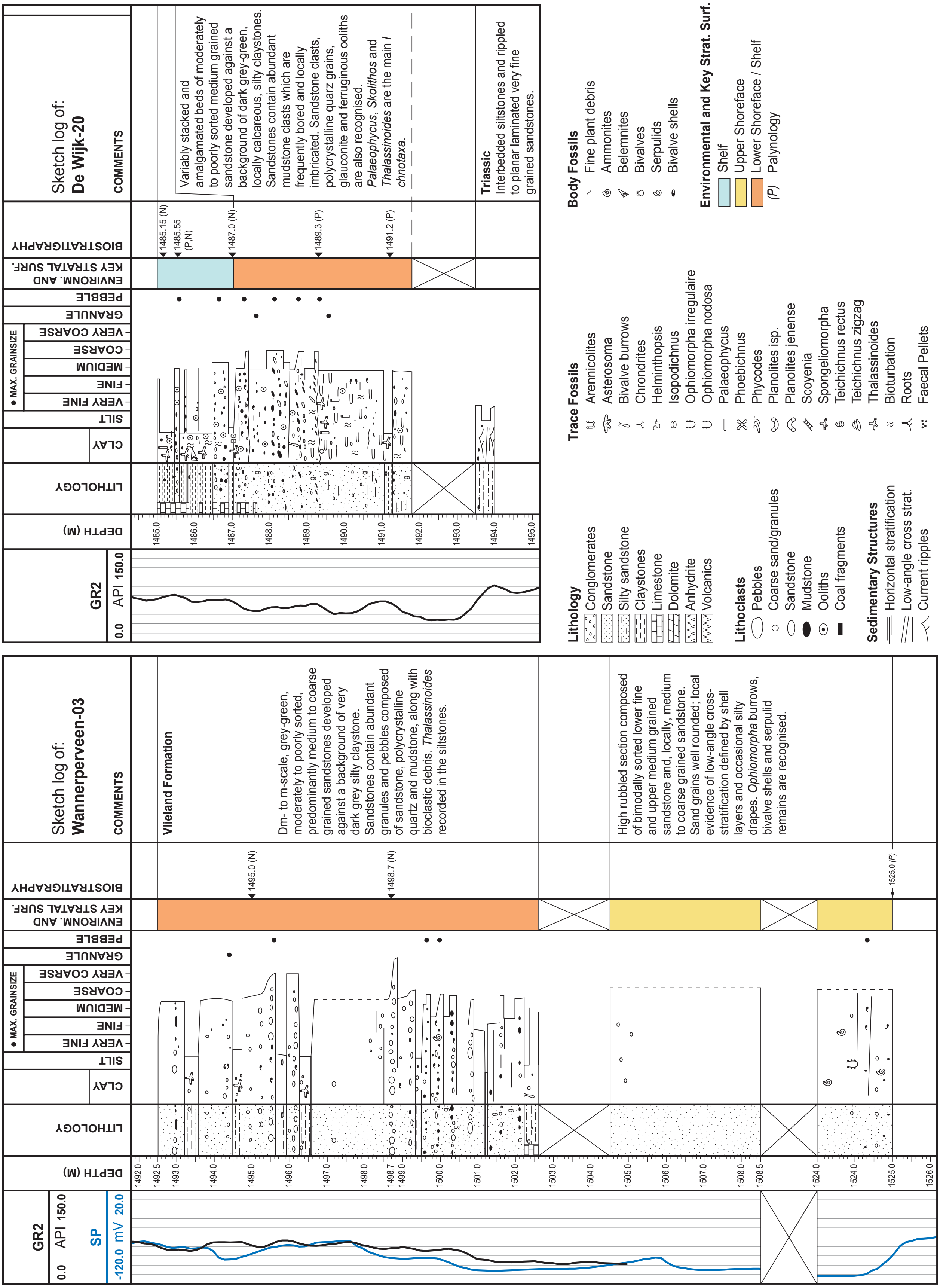

Fig. 12. Representative environments of deposition within the southern North Sea Early Cretaceous: Wannerperveen-03 shows the transition from shoreface deposits of the Friesland Member into glauconitic shelf deposits of the Guildehaus Sandstone Member. De Wijk-20 exhibits a condensed Guildehaus Sandstone Member with diverse ichnofauna grading upwards into offshore marine mudstones of the Vlieland Shale Formation.

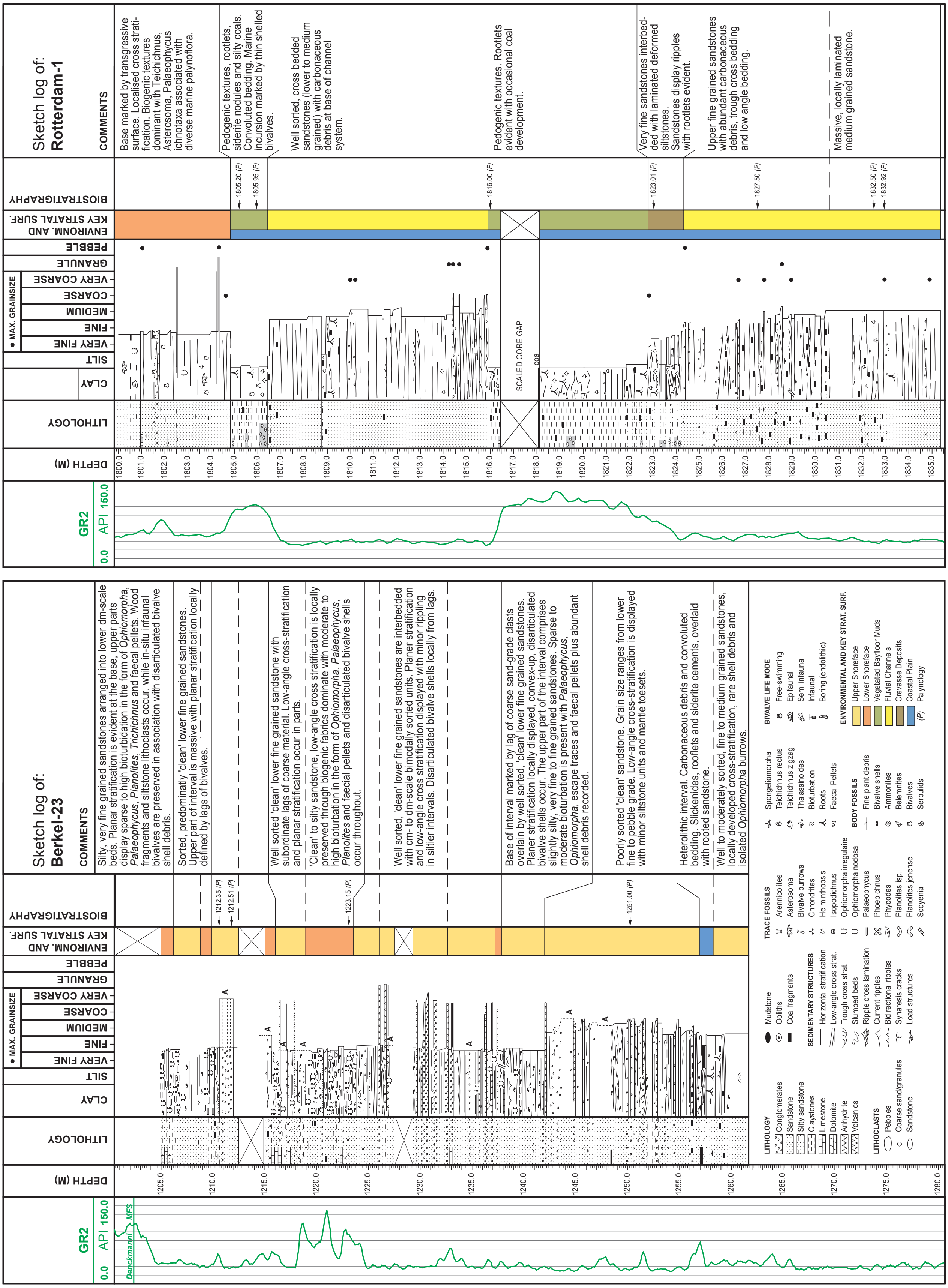

Fig. 13. Representative environments of deposition within the southern North Sea Early Cretaceous. Comparative sediment logs of the Berkel and Ijsselmonde Sandstone Member. Berkel –23 shows a thick stacked sandstone system with a strong marine overprint (diverse ichnofauna, bivalves and marine microplankton). The Ijsselmonde Sandstone Member in Rotterdam-1 shows a much more fluvial dominated system. Marine indicators are extremely rare, with pedogenic textures and coals more prevalent.

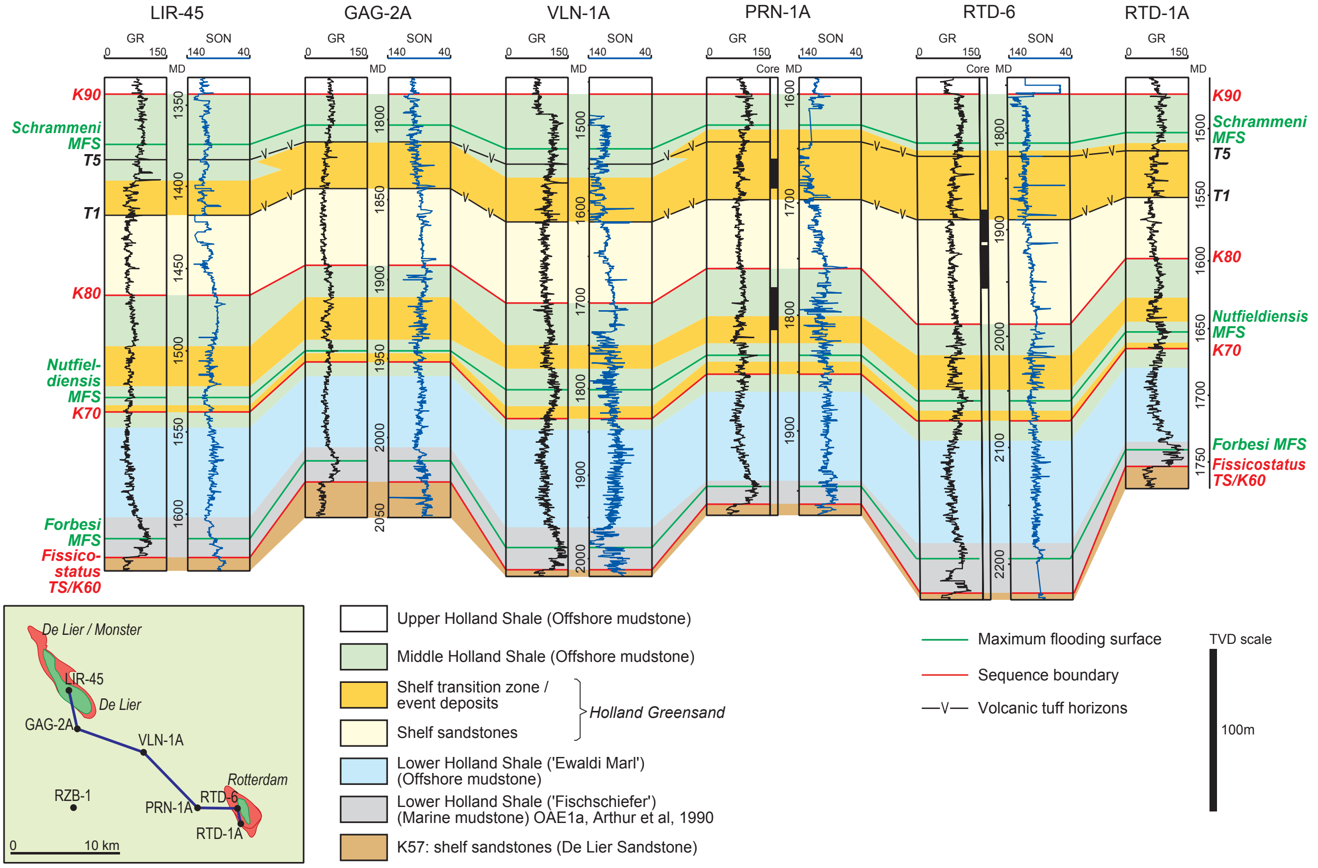

Fig. 14. West Netherlands Basin Aptian succession. Prograding K70/K80 Aptian sandstones above the regional sea-level high of the Lower Holland ewaldi and Fischschiefer. Regional volcanic tuffs can be correlated on logs throughout this region, the earliest associated with the Nutfieldiensis MFS. The culmination in volcanism appears to have occurred in Late Aptian jacobi *times with 5 regional tuff layers being regionally correlated. The Holland Greensand is finally flooded at the beginning of the Albian (Schrammeni MFS).*

whole of the preceding Cretaceous. In Germany, the Rothenberg and Dörenthe sandstones prograded northwards into the Saxony Basin (Mutterlose & Bornemann, 2000).

In the West Netherlands Basin the Holland Greensand Member is developed along an east-west trend similar to that of the De Lier Sandstone Member (Racero-Baena & Drake, 1996). Herngreen & Wong (2007) considered the Holland Greensand to be mostly of Early Albian age, but our biostratigraphic data shows that it is Aptian. The earliest Holland Greensand deposits are attributed to the K70 sequence (Fig. 14). These glauconitic siltstones were, however, rapidly transgressed by the basin-wide Nutfieldiensis MFS. A volcanic tuff associated with this MFS (note high-gamma-ray mudstone in Fig. 14) is recognised as far north as the Moray Firth (Copestake et al., 2003). Post-Nutfieldiensis MFS, K70 clastics again prograded northwards.

By the beginning of the Late Aptian K80 interval (Fig. 3, 4i, 14) the southern West Netherlands Basin was a sand-dominated shelf. K80 clastics are primarily highly bioturbated, very-fine glauconitic sands exhibiting erosive based fining-up cyclicity and interpreted at many horizons as storm event deposits. Dolomite and calcite beds are developed at the base of a number of event beds. Further south-west (e.g. Rozenburg-1; location in Fig. 14) reservoir parameters improve and fewer mudstone intercalations are preserved (Spijkenisse Greensand Member in Herngreen & Wong, 2007). Here, the background sands remain predominantly very fine grained, but now intercalated with medium to coarse-grained sandstones. The shoreface belt, presumably south of this area on the margins of the London Brabant Massif is no longer preserved (Fig. 4i), a result of Tertiary inversion. This Late Aptian maximum progradation of shelf sands along the northern margins of the London-Brabant Massif coincided with the culmination of Austrian tectonism and maximum distribution of deep-water Aptian turbidites in the Moray Firth and North Viking Graben (Jeremiah, 2000; Duxbury, 2002).

Renewed sea-level rise and waning of Austrian tectonism is reflected in the southern West Netherlands Basin by an increase in background clay content and the decreased frequency of bed sets to metre-scale cyclicity. The close of the Aptian was also characterised by widespread volcanic tuff horizons in the North Sea Basin (Zimmerle, 1979; Crittenden et al., 1991; Copestake et al., 2003). The West Netherlands Basin is no exception. Five regionally correlatable tuff horizons often associated with calcite beds can be traced east-west across the entire K80 shelf system. The basal T1 tuff and youngest correlatable tuff horizon, T5, are marked in Fig. 14.

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At the beginning of the Albian renewed sea-level rise and peneplanation of the hinterland resulted in siliciclastic deposition retreating southwards. Earliest Albian K80 shelf sandstones are restricted to Yorkshire (Heslerton II borehole) and Germany. The Schrammeni MFS also terminates the last aerially extensive Lower Cretaceous turbidite system (K85 sandstones of Jeremiah, 2000) in the Moray Firth.

Early Albian K90 through earliest Cenomanian K99 sequence

Lower and Upper Albian sediments of the southern North Sea Basins are predominantly mudstone prone, siliciclastics retreating to the margins of remnant highs. Sandstones are restricted to the Lower Albian condensed Carstone facies (Casey, 1973; Gallois, 1994) in eastern England (Lincolnshire, south Yorkshire and Norfolk) and a variety of nearshore lithologies in south-eastern England (Rawson, 2006). Here, in localised depocentres, K90 Gault mudstone deposition was already established by the late Early Albian *mammillatum* Zone (Eyers, 1995). It was not until the earliest Mid Albian Dentatus transgression that the last vestiges of siliciclastic deposition in eastern England were finally terminated; the Gault Clay became established in southern Norfolk southwards and Red Chalk facies north of this area (Gallois, 1994; Rawson 2006).

Lower Albian siliciclastics are also described on the northern margins of the Rhenish Massif within the Rothenberg Sandstone (Mutterlose & Bornemann, 2000), but as over much of Eastern England, are transgressed by the Dentatus TS. The base K90 sequence marks an important tectonically accentuated unconformity within the western Saxony Basin. At Schoonebeek, Lower Albian marine mudstones lie upon increasingly older sediments. At SCH-556 (Fig. 10), SCH-302, SCH-309 (Appendix 2), Lower Albian *tardefurcata* mudstones rest unconformably upon a truncated Gildehaus Sandstone Member. Ultimately the K90 sequence comes to rest directly upon the Lower Bentheim Sandstone (SCH-366A; Fig. 10) or Niedersachsen Group in the far west of the field. Away from Schoonebeek this unconformity may be even more pronounced (Schoonebeek-Emmen seismic line; Fig. 10).

Prior to a major sea-level rise within the earliest Cenomanian and establishment of pelagic chalk deposition, a short-lived sea-level fall and tectonic pulse (K99 event) prograded siliciclastics over the southern UK and northwards of the London Brabant Massif (Netherlands and Germany). Over much of eastern England a hiatus recorded at this level is often associated with glauconitic siltstones. In the West Netherlands Basin, earliest Cenomanian shelf sandstones, the K99 Upper Holland Greensand (Van Adrichem Boogaert & Kouwe, 1993), prograded into the basin. This short-lived earliest Cenomanian event was terminated by the subsequent Carcitanense MFS (Fig. 3).

Conclusions

Access to a vast borehole dataset and the consistent calibration of nannofossil, palynology and sporadic macrofossil data has allowed an accurate stratigraphic tie of key sequence boundaries and MFS's from throughout the shallow and non-marine successions of the southern North Sea Basin of England, Netherlands and north-western Germany. The calibrated sequences thus allow a direct comparison of the K10 through K90 sequences previously established for the deep marine Moray Firth successions and determine whether sequences are driven by eustatic seal-level fluctuations or are tectonically accentuated. The high resolution biostratigraphic data has allowed construction of detailed palaeogeographic maps and identified for the first time, the K10 Latest Ryazanian flooding of much of the northern Netherlands and north-western Germany that established a more east-west palaeofacies trend than documented by previous authors.

Well data confirms the base of K10 as a major transgressive event over the southern North Sea Basin, the Kimmeridge Clay / Valhall Formation boundary in the North Sea Basin resulting from a major increase in sea level during the Latest Ryazanian. Although tectonism is recorded from west of the British Isles no evidence for a North Sea wide sea-level fall can be supported in this paper, the base of the K10 sequence, tectonically accentuated and characterised by an angular unconformity along the margins of the Broad Fourteens, Terschelling and West Netherlands Basins.

Three other sequences cited as potential regional North Sea sequence boundaries have been proven to be a result of localised tectonic accentuation. Lower Valanginian K20 sandstones recorded from the Moray Firth do not calibrate to any sea-level fall in the southern North Sea Basins, facies trends here exhibiting an overall retrogradational stacking pattern. An anomaly here is the K20 Bentheim progradation into the western Saxony Basin. This sandstone system is, for the first time, linked not to a sea-level fall, but to localised tectonic accentuation, K20 uplift over the northern Friesland Platform eroding and redistributing uppermost Ryazanian K10 siliciclastics south-eastwards into the Saxony Basin.

Upper Hauterivian / lowest Barremian K40 sequence turbidites in the Moray Firth Basin also do not appear to be linked to any major sea-level fall and over the southern North Sea Basin this sequence exhibits retrogradational facies belts, hence the K40 sequence is considered tectonically accentuated in the Moray Firth Basin.

The presence of a 'Base Aptian' K60 Unconformity linked to any base sea-level fall is not supported in the southern North Sea Basin or in the Moray Firth Basin; any erosion being linked to the Fissicostatus transgressive surface and resultant disconformity at the basin margins. The base K60 sequence marks the Fissicostatus TS and establishment of anoxic mudstone deposition over the entire study area.

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A number of sequences have, however, been precisely calibrated to major sea-level falls, possibly linked to regional tectonism. The K30 Hauterivian sequence, as in the Moray Firth is characterised by renewed siliciclastic deposition above the lowermost Hauterivian Amblygonium MFS. In the southern North Sea basins shoreface systems prograded into the Gouwzee Trough and northern West Netherlands Basin whilst in the Saxony Basin, shelf sands prograded eastwards into the Saxony Basin over *amblygonium* ammonite-bearing mudstones. As in the Moray Firth Basin, maximum distribution of siliciclastics occurs over the Upper / Lower Hauterivian boundary (*regale* to *speetonensis* ammonite zones).

Post-Fissicostatum MFS the northern margins of the London-Brabant Massif exhibit a prograding clastic belt through much of the Late Barremian. In the West Netherlands Basin this sequence has been further subdivided into parasequences. Further north in the Moray Firth Basin penecontemporaneous K50 turbidites are documented.

The Upper Aptian K70 and K80 sequences record a major regional progradation of sandstone systems into the southern North Sea Basin. As in the Moray Firth Basin the initial K70 Austrian tectonic pulse was punctuated by the intra-Aptian Nutfieldiensis MFS only to culminate immediately after in the main phase of outbuilding during the uppermost Aptian K80 sequence. It is no coincidence that the maximum distribution of Aptian turbidite deposition in the Moray Firth Basin also occurred during the uppermost Aptian jacobi ammonite Zone.

Although the Lower Cretaceous succession exhibits a gradual rise in sea-level and backstepping of facies belts onto the northern margins of the London-Brabant Massif, three MFS's are of regional significance and can be correlated throughout the North Sea Basin. These are the Upper Valanginian, Prodichotomites MFS, Lower Barremian Fissicostatum MFS and Lowermost Aptian Forbesi MFS, the latter two MFS's associated with the extensive development of anoxic mudstones.

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Appendices

Appendix 1

List of cored sections analyed for biostratigraphy (nannofossil and/or palynology).
See facies maps or correlation diagrams for locations.

Broad Fourteens Basin

K15-1, K18-2A, K18-5, L-16-Logger-2, L16-6, L16-7, P2-6, P3-2, P5-3, P8-2, P12-4, P15-5, P15-8, P15-9, Q1-9.

West Netherlands Basin

Q11-2, Q13-8, Q16-3, Berkel-2 (BRK-2), Berkel-3 (BRK-3), Berkel-9 (BRK-9), Berkel-23 (BRK-23), Botlek-1 (BTL-1), De Lier-2A (LIR-2), De Lier-46 (LIR-46), Delft-7 (DEL-7), Den Haag-1 (HAG-1), Eemhaven-1 (EEM-1), Gaag-1 (GAG-1), IJsselmonde-1 (IJS-1), IJsselmonde-2 (IJS-2), IJsselmonde-44 (IJS-44), IJsselmonde-49 (IJS-49), Maasvlakte-1 (MSV-1), Moerkapelle-11 (MKP-11), Moerkapelle-16 (MKP-16), Nieuwekerk-1 (NKK-1), Noordwijk-1 (NWK-1), Noordwijk-2 (NWK-2), Pernis-1&A (PRN-1), Pijnacker-3 (PNA-3), Rijswijk-1 (RWK-1), Rotterdam-1 (RTD-1), Rotterdam-6 (RTD-6), Spijkenisse-1 (SPK-1), Wassenaar-1 (WAS-1), Woubrugge-1 (WOB-1), Zoetermeer-16 (ZOM-16).

Friesland Platform / Vlieland Basin

Ameland-1 (AML-1), Harlingen-1 (HRL-1), Leeuwarden-6 (LEW-6), Opende-Oost-1 (OPO-1), Opeinde-1 (OPE-1), Opeinde-2 (OPE-2), Suawoude-2 (SUW-2), Suawoude-3 (SUW-3), Tietjerksteradeel-305 (TID-305), Tietjerksteradeel-402 (TID-402), Tietjerksteradeel-501&A (TID-501), Tietjerksteradeel-602 (TID-602), Tietjerksteradeel-701A (TID-701), Tietjerksteradeel-901 (TID-901), Ureterp-102 (URE-102), Ureterp-103A (URE-103), Veenwoude-1 (VNW-1), Wanswerd-1 (WAW-1), Zuidwal-1 (ZDW-1).

Southern Friesland Platform

De-Blesse-1 (BLS-1), De-Wijk-2 (WYK-2), De-Wijk-4 (WYK-4), De-Wijk-5&5B (WYK-5), De-Wijk-14 (WYK-14), De-Wijk-17A (WYK-17), De-Wijk-20 (WYK-20), De-Wijk-31 (WYK-31), De-Wijk-32 (WYK-32), Noordwolde-1 (NWD-1), Ravenswoude-1 (RVW-1), Staphorst-1 (STA-1), Wanneperveen-1 (WAV-1), Wanneperveen-3 (Wav-3), Wanneperveen-4 (WAV-4), Wanneperveen-6 (WAV-6), Wanneperveen-9 (WAV-9).

Saxony Basin

Beilen-1 (BEI-1), Beilen-2 (BEI-2), Schoonebeek-217 (SCH-217), Schoonebeek-224 (SCH-224), Schoonebeek-302 (SCH-302), Schoonebeek-309 (SCH-309), Schoonebeek-462 (SCH-462), Schoonebeek-495 (SCH-495), Schoonebeek-586 (SCH-586), Schoonebeek-590 (SCH-590), Tubbergen-6, Westerbork-1 (WES-1).

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Appendix 2

Biostratigraphic data

- sws refers to side-wall cores, cr to core and unspecified are ditch cuttings samples.
- P refers to palynological marker, N to nannofossils and A to ammonite.
- FDO refers to first downhole occurrence; LDO, last downhole occurrence.
- All depths in metres unless indicated.

Barendrecht-1 (BRT-1)

Barremian (2019-2042 sws)

2019 sws: FDO of *Ephedripites multicostatus* (P).

Berkel-23 (BRK-23 see Fig. 13)

Late Barremian (1212.35-1277.93 cr)

1212.35 cr: LDO of *Odontochitina operculata* and presence of *Ascodinium fissilum* (P).

1212.50 cr: LDO of *Palaeoperidinium cretaceum* (P).

1223.15 cr: FDO of *Druggidium rhabdoreticulatum* and LDO of *Protoellipsodinium clavulum* (P).

1251.00 cr: influx of *Ephedripites multicostatus* (P).

1277.93 cr: presence of common *Cerbia tabulata* and *Kleithriasphaeridium corrugatum* (P).

Delft-7 (DEL-7)

Early Aptian (1136.70-1137.20 cr)

1136.70 cr: presence of *Prodeshayesites fissicostatus* (or early *Deshayesites*) (A).

1137.20 cr: presence of *Prodeshayesites fissicostatus* (or early *Deshayesites*) (A).

De Wijk-5 (WYK-5)

Late Barremian: (1238.3-1240.00 cr)

1238.3 cr: presence of *Nannoconus abundans*, *Seribiscutum dentatum* and abundant *Zeugrhabdodus scutula* (N).

Early Barremian (1244.00-1268.40 cr)

1244.00 cr: FDO of *Diazomatolithus lehmanii*; LDO of *Acaenolithus galloisii* (N).

1246.80 cr: presence of *Kleithriasphaeridium corrugatum*, *Cassiculosphaeridia* magna and common *Hystrichodinium voigtii* (P).

1260.00 cr: FDO of abundant *Cyclagelosphaera margerelii* below FAD of common/abundant *Zeugrhabdotus scutula* (N); FDO of *Nexosispinum vetusculum* (P).

1262.60 cr: FDO of common/abundant *Assipetra terebrodentarius*; presence of *Diadorhombus rectus* (N); FDO's of *Spiniferites dentatus* and *Cribroperidinium* cf. *sepimentum* (P).

1265.00 cr: LDO of common/abundant *Cyclagelosphaera margerelii* (N); FDO's of *Muderongia tetracantha* and *Gonyaulacysta teicha* (P).

1267.5 cr: LDO of common/abundant *Assipetra terebrodentarius* (N).

1268.40 cr: FDO of common/abundant *Diazomatolithus lehmanii*; presence of *Diadorhombus rectus* (N).

Earliest Barremian / Latest Hauterivian (1270.00-1271.80 cr)

1270.00 cr: FDO of *Clepsilithus maculosus* (N); FDO of *Canningia duxburyi* (P).

Late Hauterivian (1271.80-1274.00 cr)

1271.80 cr: FDO of *Metaridium solidispinum*; presence of *Cribroperidinium confossum* and *Meiourogonyaulax stoveri* (P).

1273.00 cr: FDO of *Tegulalithus septentrionalis* (N).

1273.80 cr: presence of common *Desmocysta simplex* (P).

1274.00 cr: LDO of *Tegulalithus septentrionalis* (N).

Early Hauterivian (1275.00-1278.40 cr)

1275.00 cr: FDO's of *Isthmocycstis distincta*, *Meiourogonyaulax pertusa* (P), abundant *Cyclagelosphaera margerelii*, *Eiffellithus striata* and *Stradnerlithus silvaradius* (N).

De Wijk-20 (WYK-20)

Late Hauterivian (1485.05-1491.45 cr)

1485.55core: FDO's of *Canningia duxburyi*, *Metaridium solidispinum*, *Desmocysta simplex* (P) and common *Diazomatolithus lehmanii* (N).

1487.00 cr: base nannofossil recovery above FDO of *Tegulalithus septentrionalis* (N).

1489.30 cr: presence of common *Metaridium solidispinum* (P).

1491.20 cr: FDO of *Aprobolocysta eilema* (P).

Pernis-1A (PRN-1A)

Late Aptian (1666.08-1830.00 cr)

1666.08 cr: presence of *Protoellipsodinium clavulum* (P).

1679.83 cr: FDO of abundant *Rhagodiscus asper* (N).

1730.00 cr: FDO of *Canninginopsis* cf. *intermedia* (P).

1745.50 cr: FDO of *Ovoidinium incomptum* (P).

1767.00 cr: FDO of *Cerbia tabulata* (P).

1789.00 cr: FDO of abundant *Crucibiscutum bosunensis* (N).

1819sws: presence of common *Crepidolithus burwellensis* (N).

Late/latest Early Aptian: 1855-1876 sws
1855 sws: FDO of abundant *Lordia xenota* (N).
1876 sws: presence of *Hayesites irregularis* (N).
Early Aptian: 1884.5sws-1935 sws
1884.5 sws: presence of common *Farhania varolii* (N).
1895-1918.5 sws: reappearance of consistent *Eprolithus floralis/orbiculatus* (N).
1927 sws: FDO of common/abundant *Cyclagelosphaera margerelii* and common *Assipetra terebrodentarius* (N).
1934 sws: presence of *Pickelhaube furtiva* and *Flabellites oblongus* (N).

Rotterdam-1 (RTD-1)

Late Barremian (1716.30-1816.00 cr)
1716.30 cr: FDO of *Hystrichodinium furcatum* (P).
1750.40 cr: FDO of *Hystrichodinium voigtii* (P).
1816.00 cr: presence of *Afropollis* sp. and *Ephedripites multicostatus* (P).

Rotterdam-1A (RTD-1A)

Late Albian: 1411.5-1441 sws (N)
1411.5 sws: presence of *Eiffellithus monechiae* and *Cribrosphaera ehrenbergii* (N).
1419 sws: presence of *Radiolithus hollandicus*, *Tegulalithus tessellatus* and *Staurolithites angustus* (N).
1430 sws: presence of common *Radiolithus hollandicus*, common *Staurolithites angustus* and common *Owenia hillii* (N).
1441 sws: presence of abundant *Ellipsagelosphaera britannica*, common *Radiolithus hollandicus* and common *Staurolithites angustus* (N).

Schoonebeek-302 (SCH-302)

Early Albian: 817.30-819.2 cr
817.30-817.6 cr: presence of *Leymeriella* sp. (A).
818.4 cr: presence of Leymeriella *tardefurcata* (A).
818.4-819.2 cr: presence of *Acaenolithus viriosus*, *Rhagodiscus achlyostaurion*, *Rhagodiscus splendens* and abundant *Repagulum parvidentatum* below evolutionary appearance of *Seribiscutum primitivum* (N).
Gildehaus Sandstones Member from 819.21cr to 827cr.
Late Valanginian: 833.60-833.75 cr
833.60 cr: occurrences of *Olcostephanus* sp. (*O. densicostatus* gp.) and *Olcostephanus* cf. *convoluta* (A) (?*densicostatus* ammonite Zone).
833.70 cr: presence of abundant *Cyclagelosphaera margerelii*, occurrence of *Helenea quadrata*, common *Stradnerlithus silvaradion* and *Eiffelithus striata* (N).
833.75 m: presence of *Triquetrorhabdulus shetlandensis* and *Eiffelithus windii* (N).

Schoonebeek-309 (SCH-309)

Lower Albian: 781.20 cr
781.20 cr: presence of influx of *Repagulum parvidentatum*, presence of abundant *Rhagodiscus asper*, common *Rhagodiscus splendens*, *Rhagodiscus achlyostaurion*, *Prediscosphaera spinosa* and *Acaenolithus viriosus* below the evolutionary appearance of *Seribiscutum primitivum* (N). Gildehaus Sandstone Member from 781.37cr to 786.00cr.
Early Hauterivian: 781.55-788.60 cr
781.55 cr: FDO of common to abundant *Cyclagelosphaera margerelii* and common *Crucibiscutum salebrosum* (N).
785.45 cr: FDO of *Speetonia colligata* (N).
786.05 cr: FDO of *Eprolithus antiquus* (N).
787.00 cr: LDO of *Eprolithus antiquus* (N).
788.6m: presence of *Endemoceras amblygonium* (A): *amblygonium* Zone.
Late Valanginian: 789.70-792.00 cr
789.70 cr: presence of *Triquetrorhabdulus shetlandensis* and occurrence of abundant *Calculites percernis* (N).
792.00 cr: presence of *Eiffellithus windii* (N).

Schoonebeek-462 (SCH-462)

Hauterivian / ?Late Valanginian: 973.21 cr
973.21 cr: presence of *Batioladinium varigranosum* and *B. longicornutum* (P).
Early Valanginian: 973.72-1019.50 cr
973.72 cr: FDO of *Muderongia extensiva* and *Spiniferites primaevus* (P).
977.80 cr: LDO of *Nematosphaeropsis scala* (P).
994.50 cr: occurrence isolated *Systematophora palmula* (P).
997.00 cr: occurrence isolated *Tubotuberella apatela* (P).
997.50 cr: LDO of *Spiniferites primaevus* (P).
1006.00 cr: FDO of *Batioladinium matyjae* (P).
1016.30 cr: LDO's of *Muderongia extensiva* and *Batioladinium varigranosum;* presence of *Cantulodinium speciosum* (P).
1016.60 cr: presence of common *Oligophaeridium complex* (P).
1019.50 cr: presence of *Platylenticeras* sp. (A).

Schoonebeek-495 (SCH-495)

Earliest Hauterivian: 962.60-973.15 cr
962.60 cr: presence of *Endemoceras amblygonium* (A): *amblygonium* ammonite Zone
970.10-973.75 cr: presence of abundant *Cyclogelosphaera margerelii*, *Eiffellithus windii* and *Eiffellithius striata* (N).
Late/Early Valanginian: 974.65-1010.50 cr
974.65 cr: occurrences of *Lagenorhytis delicatula* and very common *Muderongia extensiva* (P).
976.60 cr: LDO *Nematosphaeropsis 'pseudoscala'* and occurrence of *Nelchinopsis kostromiensis* (P).

Early Valanginian: 1014.80-1021.40 cr
1014.80 cr: FDO *Spiniferites primaevus* (P).
1016.70 cr: FDO *Tubotuberella apatela*; LDO's *S. primaevus* and *Nematosphaeropsis scala* (P).
1020.00 cr: LDO *Oligosphaeridium complex* (P).
1021.40 cr: influx of *Muderongia extensiva*; LDO *Bourkidinium granulatum* (P).
Early Valanginian - ?Late Ryazanian: 1021.65-1024.60 cr
1021.65 cr: FDO's very abundant AOM and *Cantulodinium speciosum* (P).
1022.10 cr: FDO very abundant *Systematophora* cf. *fasciculigera* (P).
1024.00 cr: occurrence of *Dichadogonyaulax culmula* (P).
1024.60 cr: occurrences of *Muderongia simplex microperforata* and *Cantulodinium speciosum* (P).

Ten Post-1 (POS-1)

Early Hauterivian: 1722 sws
1722 sws: presence of *Cymososphaeridium validum, Nematospaeropsis scala* and *Batioladinium reticulatum* (P).
Early Valanginian: 1735-1745 sws
1735 sws: FDO *Batioladinium matyjae*; presence *Muderongia extensiva* and *Lagenorhytis delicatula* (P).
1740 sws: presence of *Systematophora palmula* (P).
1745 sws: presence of *Oligosphaeridium complex* and *Batioladinium matyjae*.
?Early Valanginian: 1752-1770 sws
1752 sws: restricted marine assemblage; miospore dominated (P).
1757 sws: presence *Bullasporis aequitorialis* (P).

Tietjerksteradeel-305 (TID-305)

Earliest Valanginian: 2027.00-2046.00 cr
2027.00 cr: LDO of *Oligosphaeridium complex* and presence of *Tubotuberella apatela* (P).
2034.00 cr: influx of *Perisseiasphaeridium insolitum* (P).
2036.20 cr: FDO of *Epiplosphaera* sp. A (P).
Latest Ryazanian: 2050.00-2074.50 cr
2050.00 cr: FDO of common *Systematophora* cf. *areolata* Davey (P).
2063.00 cr: influx of *Systematophora scoriacea* (P).

Tietjerksteradeel-901 (TID-901)

Early Hauterivian: 1873.40-1873.80 cr
1873.40 cr: FDO of *Cymosphaeridium validum* (P).
1873.80 cr: FDO of *Lagenorhytis delicatula* (P).
Late Valanginian / Early Valanginian
1874.55 cr: presence of common *Muderongia extensiva* (P).
Earliest Valanginian: 1875.15-1883.00 cr
1875.15 cr: FDO of *Tubotuberella apatela* (P).
1876.60 cr: FDO of *Endoscrinium pharo* (P).
1877.15 cr: LDO of *Oligosphaeridium complex* (P).
1880.00 cr: FDO of *Epiplosphaera* sp. A (P).
Latest Ryazanian: 1886.91-1896.70 cr
1886.91 cr: FDO of common *Systematophora* cf. *areolata* Davey (P).
1893.30 cr: presence of an influx of *Systematophora scoriacea* (P).

Ureterp-103A (URE-103A)

Late Valanginian / Early Valanginian
2177.20 cr: presence of common *Muderongia extensiva* (P).

Wanneperveen-1 (WAV-1)

Early Aptian: 1437.00-1439.50 cr
1437.00 cr: FDO of abundant *Cyclagelosphaera margerelii*, LDO of *Eprolithus floralis*; presence of common *Flabellites oblongus* (N).
1439.50 cr: LDO of abundant *Cyclagelosphaera margerelii* and *Flabellites oblongus* (N).
Late Barremian
1443.5 cr: presence of abundant *Biscutum constans cavum* and abundant *Staurolithites palmula* (N).
Early Barremian: 1476.00-1494.5.00 cr
1476.00 cr: FDO of abundant *Cyclagelosphaera margerelii* (N).
1484.6.00 cr: FDO of common *Assipetra terebrodentarius* (N).
1487.20 cr: LDO of common *Cyclagelosphaera margerelii* (N).
1494.50 cr: presence of common *Assiptra terebrodentarius* (N).

Wanneperveen-3 (WAV-3)

Early Barremian: 1495.00-1498.70 cr
1495.00 cr: FDO of common/abundant *Diazomatolithus lehmanii* (N).
Earliest Late Hauterivian / Early Hauterivian
1525.00 cr: presence of *Nematosphaeropsis 'pseudoscala'* and *Meiourogonyaulax pertusa* (P).

Wanswerd-1 (WAW-1)

Early Hauterivian: 2005.60-2011.80 cr
2005.60 cr: FDO of *Cymososphaeridium validum* (P).
Late Valanginian / Early Valanginian: 2013.70-2019.40 cr
2013.70 cr: presence of *Prodichotomites* sp. (A).
2016.90 cr: FDO of common *Muderongia extensiva* (P).
2018.00 cr: FDO of *Gochteodinia judilentinae* and LDO of common *Muderongia extensiva* (P).
2019.40 cr: LDO of *Gochteodinia judilentinae* (P).
Earliest Valanginian: 2022.00-2043.58.00 cr
2022.00 cr: FDO of *Sirmiodiniopsis frisa* (P).
2022.60 cr: LDO of *Oligosphaeridium complex* (P).

2026.00 cr: FDO's of *Endoscrinium pharo* and *Egmontodinium torynum* (P).
2028.00 cr: FDO of an influx of *Perisseiasphaeridium insolitum* (P).
2031.00 cr: LDO of an influx of *Perisseiasphaeridium insolitum* (P).
2033.80 cr: FDO of *Epiplosphaera* sp. A (P).

Westbeemster-1 (WBMS-1)

Upper Valanginian / Late Early Valanginian
1346sws-1370 sws: presence of *Muderongia extensiva* (P).

Westerbork-1 (WES-1)

Upper Hauterivian: 1080.00-1083.50 cr
1080.00 cr: presence of common/abundant *Tegulalithus septentrionalis*, FDO of *Eiffellithus striata* (N); occurrence of *Aprobolocysta eilema*, fairly common *Kiokansium polypes* and common *Subtilisphaera perlucida* (P).
Lower Hauterivian (1094.00-1129.00 cr)
1094.00 cr: FDO *Nematosphaeropsis 'pseudoscala'* and LDO *Kiokansium polypes* (P); FDO of consistently abundant *Cyclagelosphaera margerelii* (N).
1097.00 cr: FDO of common/abundant *Crucibiscutum salebrosum* and presence of *Helenea chiastia* (N).
1100.00 cr: FDO *Isthmocystis distincta* (P) and presence of common *Eprolithus antiquus* (N).
1103.00 cr: FDO *Cymososphaeridium validum* and occurrence of *Couperisporites complexus* (P); delayed FDO's of *Speetonia colligata* and *Stradnerlithus silvaradius* below LDO of *Eprolithus antiquus* (N).
1106.00 cr: delayed FDO of *Cruciellipsis cuvillieri* (N).
1110.00 cr: FDO *Meiourogonyaulax pertusa*; LDO's *Metaridium solidispinum* and *Nexosispinum vetusculum* (P).
1112.00 cr: presence of common *Calculites percernis* (N).
1116.00 cr: FDO *Nematosphaeropsis scala*; LDO *Protoellipsodinium spinosum* and occurrence of *Gonyaulacysta ordocava* (P).
1117.00 cr: occurrence of *Endemoceras amblygonium* (*amblygonium* Zone) (A).
1120.00 cr: LDO *Hystrichodinium furcatum* and a marked downhole increase in *Hystrichosphaeridium arborispinum* (common) (P).
1122.00 cr: LDO of a rich calcareous nannofossil assemblage; presence of abundant *Eiffellithus striata*; influx of *Rotellapillus crenulatus* (N).
1129.00 cr: occurrences of *Batioladinium longicornutum* and abundant *H. arborispinum* (P).
Upper-Lower Valanginian (1135.00-1177 cr)
1135.00 cr: FDO's *Muderongia extensiva* and *Lagenorhytis delicatula*; a marked downhole reduction in *Spiniferites multibrevis* (P).
1140.00 cr: FDO *Batioladinium reticulatum* (P).
1142.00 cr: occurrences of *Nematosphaeropsis* scala, *Discorsia nanna* and *Biorbifera johnewingii* (P).
1166.50 cr: LDO's *Cymososphaeridium validum*, *Oligosphaeridium* complex and *Bourkidinium granulatum* (P).
1177.00 cr: presence *Platylenticeras* sp., possibly *P. heteropleurum* (A).
Lower Valanginian / ? Ryazanian (1186.50 cr)
1186.50 cr: FDO *Dichadogonyaulax culmula* (common); occurrence of common *Muderongia simplex microperforata* (P).

K15-1

Early Hauterivian: 1458.2-1470.5 sws
1458.2sws-1470.5 sws: presence of *Eprolithus antiquus* (N).
Earliest Valanginian (1525.30-1537.5 cr)
1525.30 cr: FDO's of *Tubotuberella apatela*, *Systematophora palmula*, *Aprobolocysta extrema*, *Dicanthum hollisteri* and *Trilobosporites bernissartensis* (P).
1530.50 cr: influx of *Perisseisphaeridium insolitum* (P).
1535.40 cr: presence of *Warrenia californica* (P).
1536.30 cr: ?*Polyptychites* sp. (A).
1537.5 cr: FDO's of *Epiplosphaera* sp. A and *Egmontodinium torynum* (P).
Latest Ryazanian (1539.50-1556.50 cr)
1539.50 cr: FDO of common *Systematophora* cf. *areolata Davey* (P).
1546.00-1556.00 cr: presence of *Peregrinoceras* sp. (A); albidum Zone.
1552.00 cr: FDO of common *Tehamadinium daveyi* (P).
1553.90 cr: FDO of *Kleithriasphaeridium porosispinum* (P).
Volgian (1852-1882)
1852: FDO of common/abundant *Cribroperidinium* spp. (P).
Late Kimmeridgian (1900-1938)
1900: FDO of common *Geiselodinium paeminosum* (P).
1938: LDO of common *Geiselodinium paeminosum* (P).

K18-2A

Early Valanginian (1724-1830.00 cr)
1724: FDO's of *Endoscrinium pharo* and *Tubotuberella apatela* at 1739 (P).
1803.00 cr: FDO of *Warrenia californica* (P).
1830.00 cr: presence of *Warrenia californica* and *Epiplosphaera* sp. A (P).
Earliest Valanginian / Latest Ryazanian (1916-1925)
1916: influx of *Cantulodinium speciosum* (P).
1925: peak occurrence of *Muderongia simplex microperforata* (P).
Volgian / Late Kimmeridgian (2189-2225)
2189: FDO of common *Cribroperidinium* spp. (P).
2216: presence of *Geiselodinium paeminosum* (P).

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Late Hauterivian: 2195.50-2207.80 cr

2195.50 cr: FDO's of *Eiffelithus striata* (N) and *Endoceratium pflugii* (P).

2200.5-2202.70 cr: presence of *Simbirskites concinnus* (A) (lower *speetonensis* Zone); presence of *Aegrocrioceras* cf. *spathi* (A) at 2202.50 m is suggestive of the highest part of inversum Zone.

2201.50 cr: FDO of *Nematosphaeropsis 'pseudoscala'* (P).

Early Hauterivian: 2210.80-2239.00 cr

2210.80 cr: FDO of common/abundant *Cyclagelosphaera margerelii* (N), *Meiourogonyaulax pertusa* and *Isthmocystis distincta* (P).

2213.50 cr: FDO of *Cymososphaeridium validum* (P).

2227.50 cr: FDO of *Eprolithus antiquus* (N).

2228.50 cr: LDO of *Eprolithus antiquus* (N).

Late Valanginian (2235.80-2251.9 cr)

2235.80 cr: presence of *Dichotomites* cf. *bidochotomoides* (A), *densicostatus* Zone.

2238.5-2239.5 cr: acme of *Hystrichosphaeridium arborispinum* (P).

2239.00 cr: LDO of *Eiffellithus striata* (N).

Note: *Olacostephanus* sp. (A) is found at 2236.7 m and 2236.7 m and is characteristic of the *densicostatus* Zone in Germany but is known to range from mid Hauterivian to mid Valanginian.

Late/Early Valanginian (2251.9-2258.7 cr)

2251.90 cr: FDO of common *Muderongia extensiva* (P).

2252.50 cr: LDO of *Muderongia extensiva* (P).

2258.70 cr: LDO of *Oligosphaeridium complex* (P).

2268.50 cr: presence of *Spiniferites multibrevis* (P).

P3-2

Earliest Hauterivian (1568.60-1572.4 cr)

1568.60 cr: FDO of *Muderongia extensiva* (P).

1572.40 cr: FDO of *Lagenorhytis delicatula* (P).

Late Valanginian (1575-1584 cr)

1575.00 cr: FDO of common *Muderongia extensiva* (P) and occurrence of abundant *Cyclagelosphaera margerelii* and *Crucibiscutum salebrosum* (N).

1584.00 cr: presence of ?*Prodichotomites* sp. (A).

Early Valanginian (1637.50-1638.00 cr)

1637.50 cr: LDO's of *Muderongia extensiva* and *Oligosphaeridium complex* (P).

1638.00 cr: FDO's of *Warrenia californica* and *Systematophora palmula*; occurrence of *Batioladinium varigranosum* (P).

P12-4

Early Barremian (2307.70 cr)

2307.70 cr: presence of *Cribroperidinium confossum*, common *Nexosispinum vetusculum* (P), common *Diazomatolithus lehmanii* below evolutionary appearance of *Nannoconus abundans* (N).

Late Hauterivian (2310.70-2354.60 cr)

2310.70 cr: FDO of *Canningia duxburyi* (common) (P) and FDO of *Clepsilithus maculosus* (N).

2313.60 cr: FDO of *Desmocysta simplex* (common) (P).

2316.6 cr: presence of *Simbirskites toensbergensis* (*marginatus* to basal *variabilis* Zone (A).

2318.20 cr: presence of *Aprobolocysta eilema* (P).

2354.60 cr: presence of *Spiniferites fenestratus*, and common *Desmocysta simplex* (P).

Q1-9

Valanginian (1483.30-1494.60 cr)

1483.30 cr: FDO of common *Muderongia extensiva* (P).

1494.60m: peak occurrence of *Muderongia extensiva* (P).

Earliest Valanginian (1518.30 cr)

1518.30 cr: presence of *Tubotuberella apatela* and *Systematophora palmula* (P).

Earliest Valanginian to Ryazanian (1524.00-1527.25 cr)

1524.00 cr: influx of *Cantulodinium speciosum* (P).

1524.00 cr: LDO of abundant *Muderongia simplex microperforata* (P).

1527.25 cr: presence of *Aequitriradites spinulosus*, common *Cicatricosisporites purbeckensis* and rare *Cantulodinium speciosum* (P).

Q7-2

Early Barremian: 2577-2590 sws

2577 sws: FDO of common/abundant *Diazomatolithus lehmanii*; presence of abundant *Assipetra terebrodentarius* (N).

Late Hauterivian: 2627.5-2668.0 sws (N).

2627.5 sws: FDO of *Tegulalithus septentrionalis* (N).

2668 sws: LDO of *Tegulalithus septentrionalis* (N); presence of *Cribroperidinium sepimentum* (P).

Early Hauterivian (2708-2712 sws)

2708 sws: FDO's of *Meiourogonyaulax pertusa* and *Nematosphaeropsis scala*; presence of *Cymososphaeridium validum* (P).

Late Valangian (2743.2 sws)

2743.2 sws: influx of *Hystrichosphaeridium arborispinum* (P).

Q11-2

Early Hauterivian (946.00-990.00 cr)
946.00 cr: FDO of *Cymososphaeridium validum* (P).
Late to late Early Valanginian (997.50-1011.87 cr)
997.5 cr: FDO of *Muderongia extensiva* (P).
1009.09 cr: FDO of common *Muderongia extensiva* (P).
1010.12 cr: presence of *Trilobosporites aequiverrucosus* (P).
1011.87 cr: presence of *Discorsia nanna* (P).

Q13-8

Barremian / Late Hauterivian (1904.00-1717.05 cr)
1904.00 cr: FDO of a restricted palynoflora with *Taleisphaera hydra*, *Subtilisphaera terrula* and *Kiokansium polypes* (P).

Q16-3

Early Barremian (2253-2283.25 cr)
2253.00 cr: FDO's of *Muderongia tetracantha* and *Chlamydophorella trabeculosa* (P).
2253.90 cr: FDO of *Nexosispinum vetusculum* and presence of *Rugubivesiculites rugosus* (P).
2261.00 cr: presence of *Gonyaulacysta teicha* (P).

48/17b-3

Early Valanginian (2300-2380 ft)
2300 ft: FDO's of *Warrenia californica*, *Systematophora palmula* and *Endoscrinium pharo* (P).
2360 ft: FDO's of *Epiplosphaera* sp. A and common *Systematophora* cf. *areolata Davey* (P).
Ryazanian (2400-2560 ft)
2400 ft: FDO of *Kleithriasphaeridium porosispinum* (P).
2460 ft: FDO of *Dingodinium spinosum* (P).
2560 ft: FDO of *Rotosphaeropsis thula* (P).
Late Volgian (2600-2700 ft)
2600 ft: FDO of *Egmontodinium expiratum* (P).
2660 ft: FDO's of *Gochteodinia virgula* and common *Rotosphaeropsis thula* (P).
2700 ft: FDO of *Leptodinium eumorphum* (P).
Middle Volgian (2740-2900 ft)
2740 ft: FDO's of *Egmontodinium polyplacophorum*, *Senoniasphaera jurassica* and common *Cribroperidinium gigas* (P).
2760 ft: FDO of *Ctenidodinium panneum* (P).
2840 ft: FDO's of *Gochteodinia mutabilis*, common *Ctenidodinium panneum* and common *Muderongia* cf. *simplex* (P).
2860 ft: FDO of *Rhynchodiniopsis martonense* (P).
2900 ft: FDO's of *Oligosphaeridium patulum* and *Prolixosphaeridium granulosum* (P).

Outcrop data

Suddendorf Quarry near Bad Bentheim, Germany

- 5 samples taken at regular intervals from the top 10 metres of the Platylenticeras Beds (Paratollia Zone).
- 10 cm below base Benthem Sandstone (Base K20): presence of *Nematosphaeropsis scala* (P).
- 1.2 m below base Bentheim Sandstone: presence of *Nematosphaeropsis scala*, *Bourkidinium granulatum*, *Oligosphaeridium complex*, *Spiniferites ramosus* and *S. multibrevis*; occurrence *Tubotuberella apatela* (P).
- 9 m below base Bentheim Sandstone: very common *Muderongia extensiva*, fairly common *Bourkidinium granulatum* and *Hystrichodinium voigtii*, and a single, poorly preserved ?*Nelchinopsis kostromiensis* (P).
- 10 m below base Bentheim Sandstone: presence of *Bourkidinium granulatum* and common *Oligosphaeridium complex* (P).

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