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TNO report

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New stratigraphic framework for the Upper Jurassic-Lower Cretaceous in the southern North Sea using integrated novel techniques

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Project number	056.01784

How to read this report

This report describes in detail the Upper Jurassic to Lower Cretaceous basin development of a large part of the Dutch offshore. In addition, a composite stable isotope reference curve for the Upper Jurassic to Lower Cretaceous is presented.

The data underpinning the geological interpretations are mainly derived from palynological analyses. Large-scale seismic interpretations are not carried out, but seismic cross-sections are used to illustrate the stratal relationships.

The study focuses on two areas: the Step Graben, in the North, and the Broad Fourteens and offshore part of the West Netherland Basin, in the South. For practical reasons, general interpretations derived from previous work on the Terschelling Basin and the Central Graben are also included. The selected wells and samples are listed in Chapter 3.

The geological background and the up-to-date geological knowledge of the study area is described in Chapter 2, including the current basin evolution model for the Central Graben area (Appendix 2).

The results of the palynological analyses are summarized in Chapter 4 (Step Graben) and 5 (Broad Fourteens and West Netherlands Basin), with emphasis on the palaeoenvironmental interpretations. The actual zonal assignments, with the listings of the last and first occurrence datums, are added separately in an appendix (Appendix 1).

The results of the stable isotope analyses are presented in Chapter 6. The end-result, a composite stable isotope reference curve, is included. This curve is also added on A3-size in the appendices (Appendix 4). Note that Chapter 6 is regarded as a separate, non-confidential entity. This part of the report will be distributed among the companies that contributed to the reference curve by providing sample material.

In Chapter 7 and 8, the facies distribution and basin dynamics of the basins are described in detail. The basin development is described chronologically, from old to young, via simplified palaeogeographic maps and wheeler diagrams (see also Appendix 5). Correlation panels are added as Appendices (Appendix 6).

In Chapter 9, the stories of the two areas are combined into one single account on the basin evolution of the Late Jurassic to Early Cretaceous in the Dutch offshore.

The report remains confidential until the 1st of May 2017.

Summary

In this report from TNO to the sponsors of the Joint Industry Project JUSTRAT, the results are presented of a stratigraphic study on the Upper Jurassic to Lower Cretaceous of the Step Graben, Broad Fourteens and offshore West Netherlands Basins. In addition a composite stable isotope reference curve for the Upper Jurassic to Lower Cretaceous for the Dutch offshore is presented. The data underpinning the geological model presented here, are primarily derived from palynological and stbale isotope analyses, while seismic cross-sections are used to illustrate the stratal relationships. The general aim of the project is to improve the Upper Jurassic and Lower Cretaceous stratigraphy fo the Dutch offshore. More in particular, it is aimed to develop a tectono-stratigraphic framework for the studied interval, with special interest in the distribution of reservoir sandstones. The goals are met via numerous high resolution palynological and stable isotope analyses. The analyses provided accurate age datings and palaeoenvironmental interpretations which were compiled in palaeogeographic maps and in wheeler diagrams. An important result of the project was that the three-fold subdivision of the Late Jurassic rifting, that was established in the Central Graben area, can be now be extended the southern offshore, to the Broad Fourteens and West Netherlands Basin. Even more important, the complete absence of Late Volgian to Early Ryzanian sediments in the southern offshore, corroborates the earlier indications of a short-lived phase of uplift and erosion, that apparently led to basin inversion. The current findings therefore suggest that the Valanginian and Hauterivian sandstones of the Kotter and Rijn Members are sourced from the uplifted areas resulting from the inversion. The minor intra-Valanginian hiatuses that were observed in these sandstones are probably due to sea level variation, rather than basin dynamics. Another important finding is the recognition of the newly established Noordvaarder Member (Skylge Formation, Scruff Group) in the northern offshore. The mixed siliclastic Noordvaarder Member in the B14 Block reflects the increased tectonic activity, such as fault movement and salt displacement, for the Middle and Late Volgian. Another interesting finding is the recognition of the so-called Weissert event. The Weissert event is a rapid positive shift in the delta13Corg stable isotope trend. This event is well known from the literature and its occurrence in the Kotter Member provides an excellent means for correlation to the international Geological Time Scale.

Contents

Appendices

1 Introduction

1.1 Project framework

This report is the final report of the project: “New stratigraphic framework for the Upper Jurassic-Lower Cretaceous in the southern North Sea using integrated novel techniques”, also known under its acronym JUSTRAT.

The project is a Joint Industry Project set up and funded under the governmental programme “TKI (Topconsortium voor Kennis en Innovatie) Gas, Innovation Program Upstream Gas”. Within that programme, the project belongs to the Program Line New Fields and is funded via so-called co-financing from the Dutch Ministry of Economic Affairs (Ministerie van Economische Zaken). Stakeholders are listed in Table 1. Note that Sterling Resources made a late entry in the project, Sterling joined the project a couple of months after it started.

Table 1 Stakeholders and funding of the project.

Stakeholders	Contribution (EUR)
Petrogas Exploration and Production Netherlands B.V.	75,000
Centrica Energy Netherlands B.V.	75,000
EBN B.V.	75,000
Sterling Resources Netherlands B.V.	75,000
Ministry of Economic Affairs	225,000

The project started in March 2013 and ended with the close-out meeting in October 2014. The project was managed by Holger Cremer and Roel Verreussel (TNO), while the analyses and interpretations were carried out by Dirk Munsterman, Sander Houben, Susan Kerstholt-Boegehold, Roel Verreussel and Nico Janssen (TNO). The stakeholders were represented by Ewan Campbell and Bas Steins from Petrogas, Huibert van den Brink and Willke Smit from Centrica, Evelien Rosendaal and Guido Hoetz from EBN and Stephen Birrell and Hugh Riches from Sterling.

The deliverables of the project include an updated version of the report “Remaining Hydrocarbon Prospectivity of the Dutch Central Graben”. This non-exlcusive report was issued by Panterra Geoconsultants, in close cooperation with TNO, in 2010, and updated in 2013 to accommodate for the new lithostratigraphy of Munsterman et al. (2012). Digital and hard-copy versions of the report were submitted to the sponsors in the beginning of 2014.

1.2 Project outline and aim

The overall aim of the project is to improve the Upper Jurassic and Lower Cretaceous stratigraphy fo the Dutch offshore. More in particular, it is aimed to develop a tectono-stratigraphic framework for the Upper Jurassic to Lower Cretaceous interval in the southern North Sea. Such a tectono-stratigraphic framework has already been developed for the Central Graben area by Abbink et al. (2006) and Munsterman et al. (2012), but the assumptions and interpretations made by these authors will now be challenged and checked by moving the research into the Step Graben, the Broad Fourteens and the West Netherlands Basins (Figure 1). All samples analysed in this study are derived from wells from these basins.

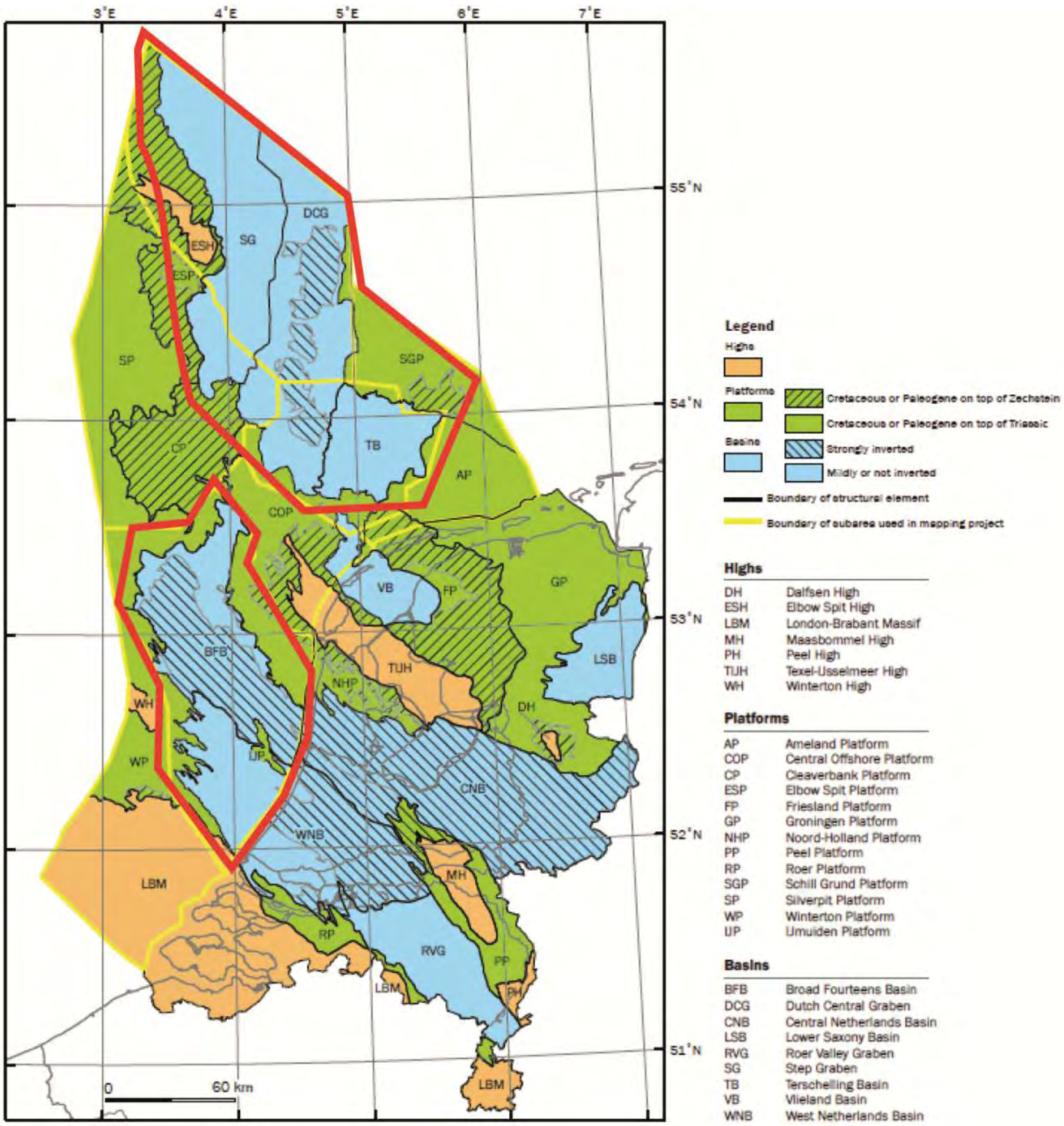


Figure 1 Study area (in red).

The approach followed in this study is to conduct numerous palynological analyses that will provide accurate and high resolution age datings and palaeoenvironmental interpretations. At the same time, stable isotope analyses will be carried out on core and side-wall core samples, in order to test the feasibility of this innovative tool in stratigraphic correlations.

It is foreseen that the combined results will lead to a new and improved regional geological model for the Upper Jurassic to Lower Cretaceous.

1.3 Rationale

Upper Jurassic and Lower Cretaceous sandstones are a primary target for exploration and production of hydrocarbons in the Southern North Sea. These units are predominantly deposited at the edges of active basins in tectonically dynamic settings. As a consequence, these reservoirs are often strongly compartimentalized and characterized by strong lateral facies heterogeneity. This complicates seismic interpretations and log correlations imposing problems for de-risking exploration targets in this interval. Especially the differentiation between local (salt) tectonics and regional sea level changes are crucial to understand trends between basins, specifically the Central Graben, Terschelling, Vlieland, West Netherlands, and Broad Fourteens Basins (Figure 1). Current lithostratigraphical concepts for this interval are outdated, not detailed enough and dispersed in a multitude of local studies. A consistent, regional overview to adequately comprehend the depositional history and prospect architecture, calibrated to international standards, is therefore lacking.

To date, the Late Jurassic-Early Cretaceous part of pre-Quaternary Stratigraphic Nomenclature of the Netherlands compiled by Van Adrichem Boogaert & Kouwe in 1993 is the primary framework for use by the Dutch geological community. Abbink et al. (2001) updated the bio- and chronostratigraphy of the Jurassic-Cretaceous transition in the Terschelling Basin. Duxbury (2001) provided a new dinoflagellate cyst zonation scheme for the UK Early Cretaceous. Abbink et al. (2006) recognized three genetic sequences for the Late Jurassic in the Central Graben and Terschelling Basin that enabled an improved reconstruction of the geological history of that area (see Geological Setting). Late Jurassic stratigraphy of the northern Dutch offshore was recently updated and revised (Munsterman et al., 2012). Furthermore, Jeremiah et al. (2010) describe the results of a sequence and biostratigraphic study of the southern North Sea Basin in the Early Cretaceous. This overview however misses high-resolution distinction of several lithostratigraphic units such as e.g., the Delft Sandstone Member in the West Netherlands Basin. Furthermore a large amount of scattered biostratigraphic data is lodged in the archives of operators, contractors and TNO.

2 Geological Setting

The sedimentary fill-up of basins and adjacent regions in the Upper Jurassic – Lower Cretaceous is predominantly controlled by the structural evolution of the region (Figure 2). Starting in the Triassic, rifting related to the break-up of Pangea in the North proto-Atlantic and between Greenland and Scandinavia caused an eastern branch of this rift system to protrude into the North Sea area. As a consequence, the structural outline of the Netherlands changed from a single large basin (Southern Permian Basin) into a multi-basinal pattern by times of the Late Jurassic. The slow and regional subsidence that characterized the (pre-/initial rift) Early Jurassic phase and resulting sheet-like marine clay deposits in the Southern North Sea terminated because of the development of a thermal dome in the central North Sea area (Middle Jurassic: Aalenian to Bathonian, Kimmerian tectonic phase). This caused major uplift, erosion and a widely recognized Early-Middle to Late Jurassic hiatus. In the Callovian, rifting reincepted again and continued until the Early Cretaceous (Valanginian). At first, this rift influenced the axis of the DCG and further to the southwest the Broad Fourteens Basin (BFB). Deposits of this phase are referred to as **Sequence 1** by Abbink et al. (2006) and as **Graben Axis** in Verreussel *et al.* (*in prep.,* see Figure 3*)*. During the Kimmeridgian, a dramatic change in structural setting and structural style occurred. The direction of the extension regime changes from E-W to SW-NE. In addition, normal faults become the dominant structural element. Numerous old NW-SE oriented lineaments and structures become rejuvenated, resulting in the opening of peripheral basins such as the Terschelling Basin, the Step Graben, and also lead to major basin development in the Broad Fourteens Basin. In some parts of the DCG, the opposite occurs: uplift and erosion. Most of the uplift and erosion in the DCG can be ascribed to salt movement. Salt is withdrawn from some parts (e.g. the F11 rim syncline) and is pushing up turthle-back structures (e.g. the F03-FB condensate Field) and diapirs (e.g. the F15-18 salt structure) in other part. This phase is referred to as **Sequence 2** in Abbink et al. (2006) and **Peripheral Basins** in Verreussel *et al.* (*in prep.*). This phase provided accommodation space for siliclastic deposits with hydrocarbon reservoir potential (non-marine Schieland Group and Scruff Group) in the peripheral basins. towards the end of the phase, fault activity and salt movement reached a peak (Figure 3). During the next phase, adjacent platforms like the Schill Grund Platforma and the Cleaver Bank High were flooded. In the Dutch Central Graben area, large accumulations of sandstone of the Scruff Greensand Fm. are associated with this phase. In the Danish Central Graben area, highly condensed organic-rich mudstones are associated with this phase. This phase, occurring around the Jurassic-Cretaceous boundary is referred to as **Sequence 3** in Abbink et al. (2006) and as **Adjacent Plateaus** in Verreussel *et al.* (*in prep.*)**.** Sequences 2 and 3 are relatively thick in the peripheral basins compared to the DCG. In the BFB, deposition continued in the axial region, whereas renewed tectonic activity in the Ryazanian led to major erosion on its margins. Overall, at the end of the Ryazanian rifting came to a halt. Fault activity in the DCG-area gradually ceased and the succeeding marine sandstones and shales of the Rijnland Group effectively cover the former graben and platform areas in the north of the Dutch offshore. As the basins continued to (thermally) subside differentially, characterizing **Sequence 4**, the coastal Vlieland Sandstone and the Vlieland Claystone Formation were deposited.

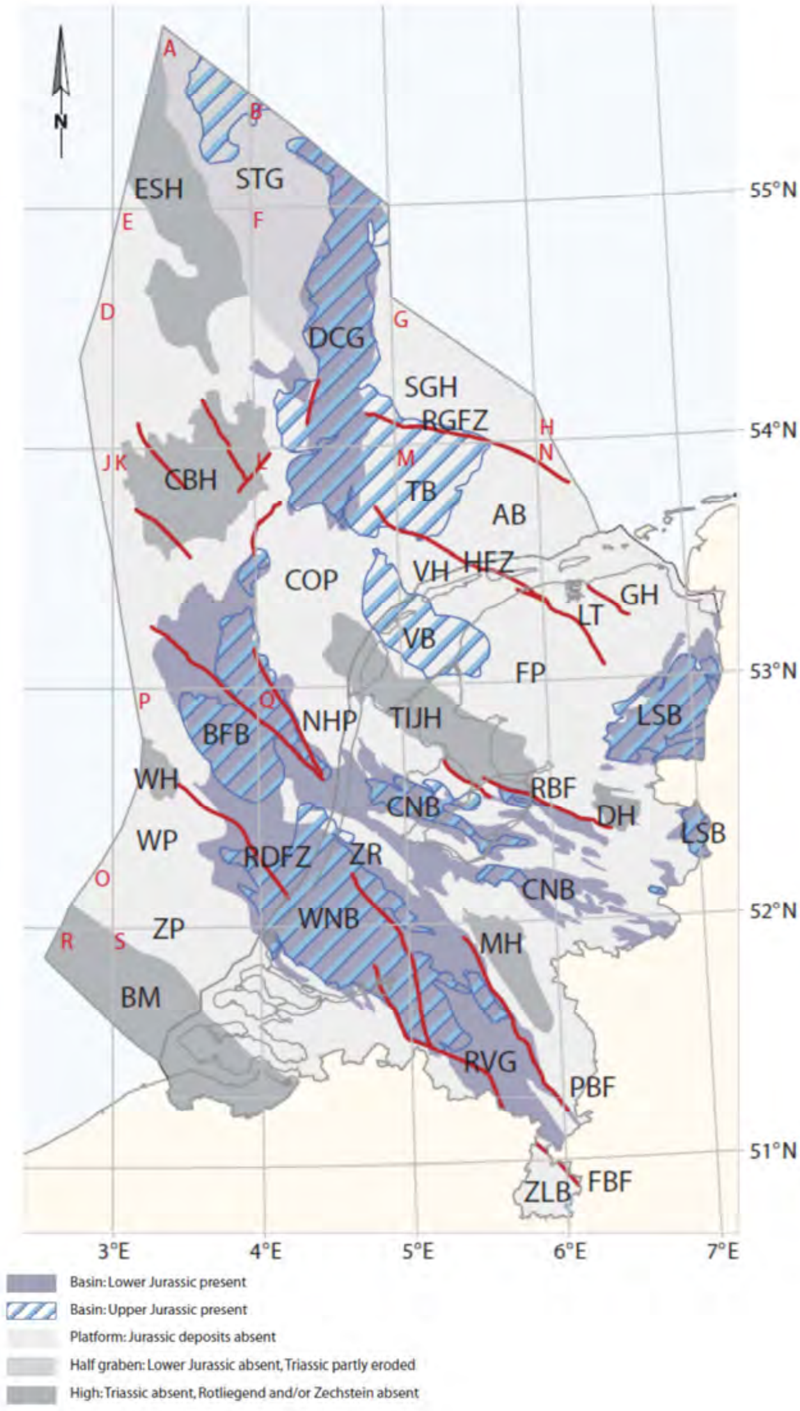
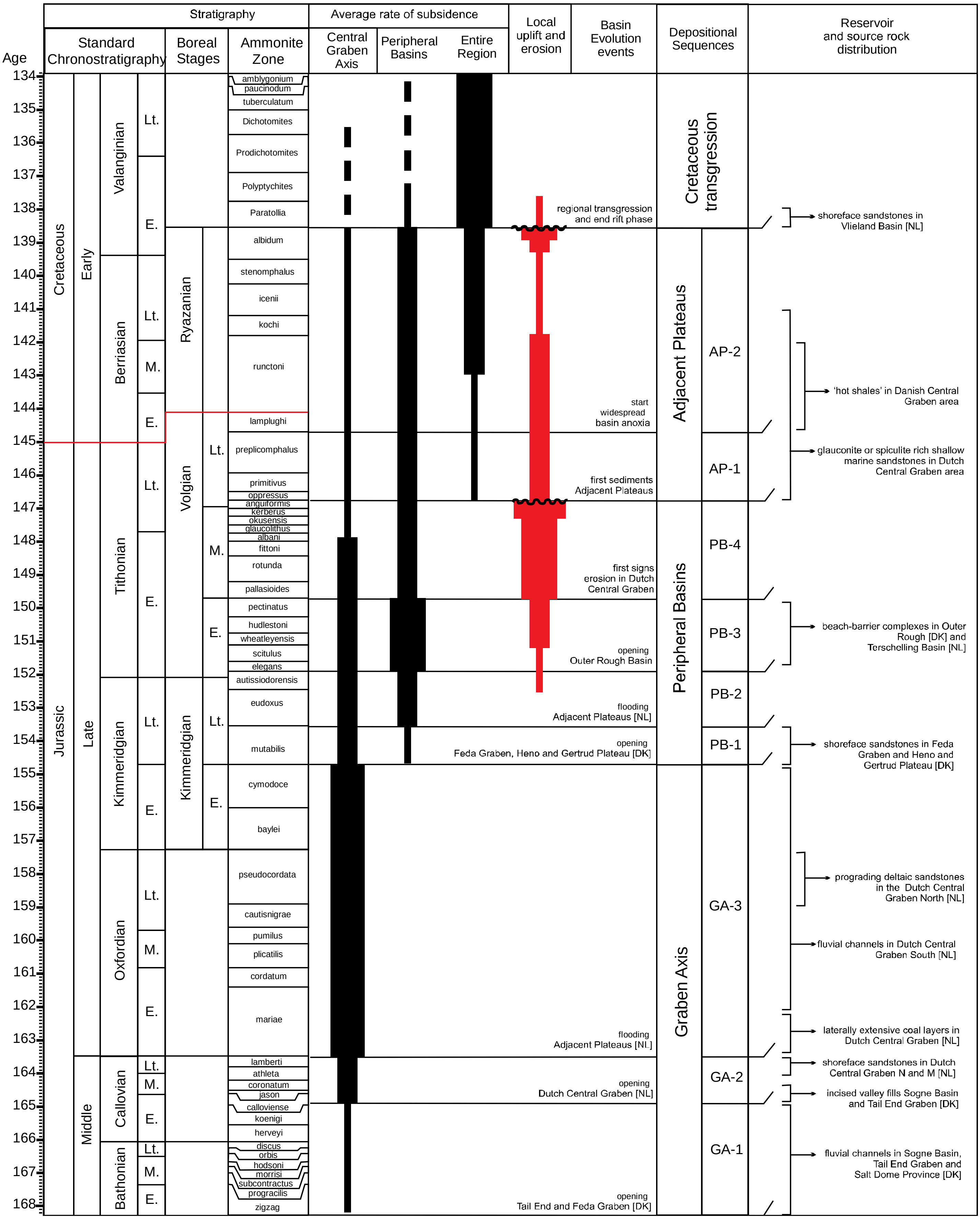


Figure 2 Late Jurassic-Early Cretaceous Structural Elements. Adapted from Duin et al. (2007)

Figure 3 (next page) Schematic representation of the Late Jurassic to Early Cretaceous basin evolution of the Central Graben area from Denmark, Germany and The Netherlands (from Verreussel et al., in prep.).



Stratigraphy
Average rate of subsidence
Local uplift and erosion
Basin Evolution events
Depositional Sequences
Reservoir and source rock distribution
Age
Standard Chronostratigraphy
Boreal Stages
Ammonite Zone
Central Graben Axis
Peripheral Basins
Entire Region
Cretaceous
Jurassic
Early
Late
Middle
Valanginian
Berriasian
Tithonian
Kimmeridgian
Oxfordian
Callovian
Bathonian
Ryazanian
Volgian
Kimmeridgian
amblygonium
paucinodum
tuberculatum
Dichotomites
Prodichotomites
Polyptychites
Paratollia
albidum
stenomphalus
icenii
kochi
runctoni
lamplughi
preplicomphalus
primitivus
oppressus
anguiformis
kerberus
okusensis
glaucolithus
albani
fittoni
rotunda
pallasioides
pectinatus
hudlestoni
wheatleyensis
scitulus
elegans
autissiodorensis
eudoxus
mutabilis
cymodoce
baylei
pseudocordata
cautisnigrae
pumilus
plicatilis
cordatum
mariae
lamberti
athleta
coronatum
jason
calloviense
koenigi
herveyi
discus
orbis
hodsoni
morrisi
subcontractus
progracilis
zigzag
regional transgression and end rift phase
start widespread basin anoxia
first sediments Adjacent Plateaus
first signs erosion in Dutch Central Graben
opening Outer Rough Basin
flooding Adjacent Plateaus [NL]
opening Feda Graben, Heno and Gertrud Plateau [DK]
flooding Adjacent Plateaus [NL]
opening Dutch Central Graben [NL]
opening Tail End and Feda Graben [DK]
Cretaceous transgression
Adjacent Plateaus
Peripheral Basins
Graben Axis
AP-2
AP-1
PB-4
PB-3
PB-2
PB-1
GA-3
GA-2
GA-1
shoreface sandstones in Vlieland Basin [NL]
'hot shales' in Danish Central Graben area
glauconite or spiculite rich shallow marine sandstones in Dutch Central Graben area
beach-barrier complexes in Outer Rough [DK] and Terschelling Basin [NL]
shoreface sandstones in Feda Graben and Heno and Gertrud Plateau [DK]
prograding deltaic sandstones in the Dutch Central Graben North [NL]
fluvial channels in Dutch Central Graben South [NL]
laterally extensive coal layers in Dutch Central Graben [NL]
shoreface sandstones in Dutch Central Graben N and M [NL]
incised valley fills Sogne Basin and Tail End Graben [DK]
fluvial channels in Sogne Basin, Tail End Graben and Salt Dome Province [DK]

3 Material and methods

3.1 Abbreviations

TNO's standard abbreviations as used in palynology reports are listed in Table 2.

Table 2 Abbreviations used by TNO

CO	Core sample
SC	Sidewall core sample
CU	Cuttings sample
m	Meter
ft	Feet
LOD	Last Occurrence Datum
LCOD	Last Common Occurrence Datum
FOD	First Occurrence Datum
FCOD	First Common Occurrence Datum
ND	Not Diagnostic
Amm	Ammonite
Fm	Formation
Mb	Member
BFB	Broad Fourteens Basin
WNB	West Netherlands Basin
SG	Step Graben
mfs	Maximum flooding surface

3.2 Samples

3.2.1 Samples for stable isotope analyses

For the stable isotope analyses, 596 samples from 13 wells were selected. Most of the stable isotope analyses are carried out on core or side-wall core samples, only 75 analyses are based on cuttings samples (see Figure 4). The samples originate from various sources: Jan Penninga and Elisa Guasti from the Nederlands Aardolie Maatschappij (NAM) were kind enough to provide both organic residues and raw material from rare side-wall core samples, Arjan van der Pijl from Total dug up raw side-wall core samples from their core-shed in Pau and Reinoud Veenhof from Oranje Nassau Energie (ONE) kindly provided samples from a well that was still confidential at the time. Also quite a few samples were derived from organic residues stored by the Rijks Geologische Dienst (RGD). The sample depths of the individual samples are provided as digital data, which are added on a USB-stick.

	CO		SWC		CU				
well	**org residue**	**raw sample**	**org residue**	**raw sample**	**org residue**	**raw sample**	**Subtotal**		**sample origin**
F03-03			74		34		**108**		NAM
F11-01			43		35		**78**		NAM
F17-04	39						**39**		RGD + NAM
L05-04	50						**50**		NAM
L03-01	9			72	6		**87**		RGD + NAM
L06-03			6				**6**		RGD
L06-03		41					**41**		TNO
F15-A-01				38			**38**		Total
L05-03	15						**15**		NAM
M07-07		60					**60**		ONE
P09-03	27						**27**		JUSTRAT
P08-03	21						**21**		JUSTRAT
P05-03	17						**17**		JUSTRAT
L16-06	9						**9**		JUSTRAT
Total								**596**	
org residue	187		123		75		**385**		
raw sample		101		110			**211**		
Total								**596**	
CORE	187	101					**288**		
SWC			123	110			**233**		
CU					75		**75**		
Total								**596**	

Figure 4 Overview of the samples for stable isotope analyses.

3.2.2 Samples for palynological analyses

A total of 397 samples were selected and analysed for palynology: 159 from the Step Graben and 238 from the BFB/WNB (Figure 5). The samples from the Step Graben are mostly cuttings samples, Upper Jurassic intervals with core samples are extremely rare in the Step Graben. The samples from the BFB/WNB are mostly core samples. Sample depths, together with the palynological occurrence data, are added as comma separated spreadsheet files, in the digital data set, which is added as a USB-stick.

Basin	Well	samples	
Step Graben	A12-01	17	
Step Graben	A18-02-S1	11	
Step Graben	B13-02	27	
Step Graben	B14-02	32	
Step Graben	B14-03	35	
Step Graben	F01-01	13	
Step Graben	F04-2A	15	
Step Graben	F10-01	9	
total			159
BFB/WNB	K14-01	7	
BFB/WNB	K15-01	12	
BFB/WNB	K18-Kotter-14	14	
BFB/WNB	P02-06	36	
BFB/WNB	P05-03	47	
BFB/WNB	P08-03	19	
BFB/WNB	P09-03	19	
BFB/WNB	P12-08	16	
BFB/WNB	L16-06	10	
BFB/WNB	Q01-Helm-A1	30	
BFB/WNB	Q01-18	6	
BFB/WNB	Q04-07	22	
total			238

Figure 5 Sample list for the palynological analyses.

3.3 Palynology

3.3.1 Processing

The samples were processed at the TNO laboratory, using the standard sample processing procedures (Janssen & Dammers, TNO report 2008), using traditional techniques, involving HCl, HF digestion, no oxidation, ultrasonic bath, 15 μm sieving and preparation of residue slides mounted in glycerine jelly.

3.3.2 Analysis

The microscopy analysis is according to standard procedures. The semi-quantitative analysis includes an estimation of the main palynomorph categories, the determinable sporomorphs, dinocysts and miscellaneous fossils. The remainder of the slide is then scanned qualitatively for additional sporomorph and dinocyst taxa.

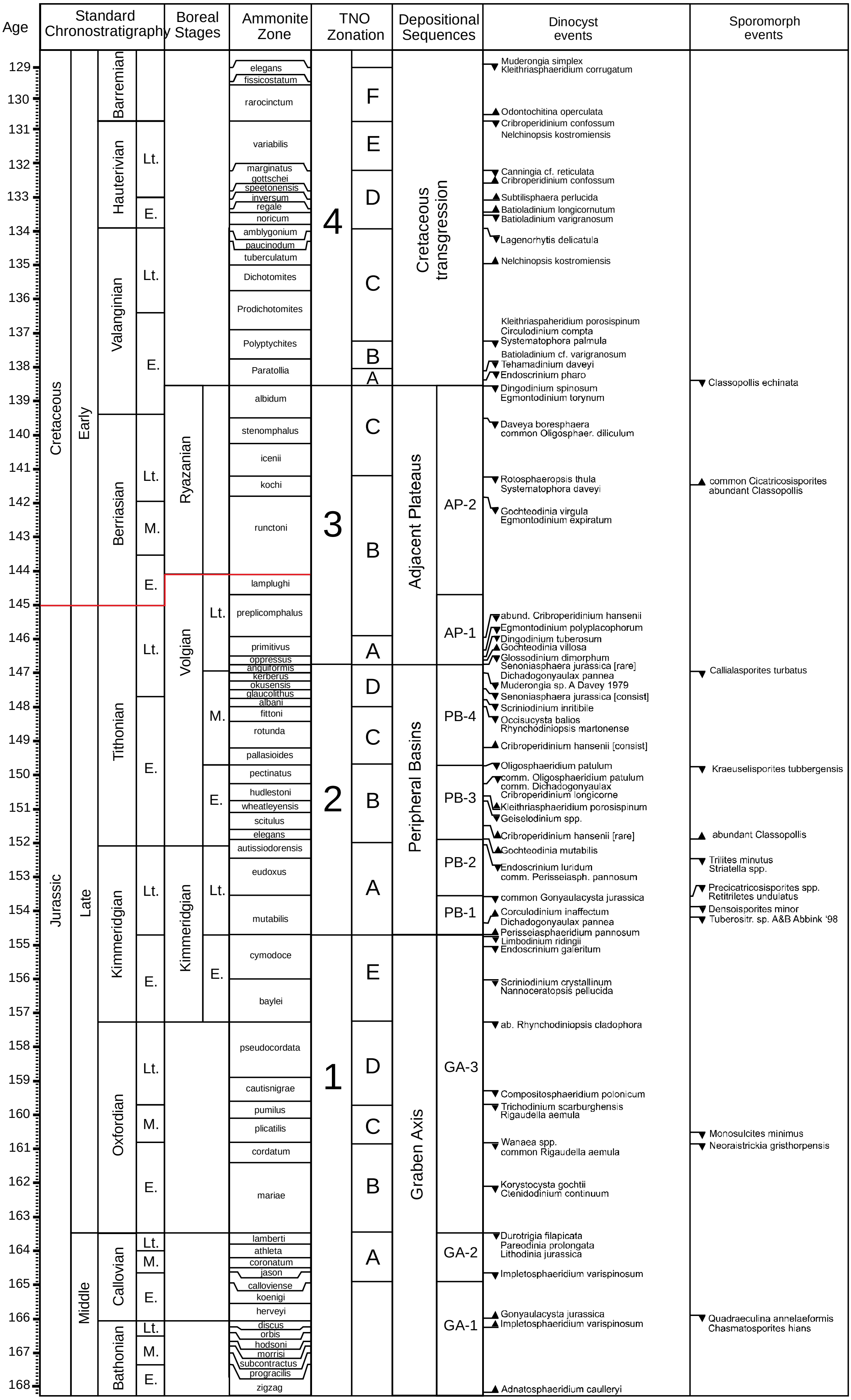
3.3.3 Taxonomy

For the dinoflagellate cyst taxonomy the so-called “Lentin and Williams index” is followed (Fensome & Williams, 2004). For the pollen and spore taxonomy such a single-volume index does not exist and reference is made to the in-house sporomorph compilation report “Jurassic and Cretaceous sporomorphs of NW Europe” (NITG-TNO report 2005-053-C).

3.3.4 Age interpretations

For the age interpretations, the TNO zonation for the Late Jurassic- Early Cretaceous is used (Figure 6). The 4 zones defined in the zonation line up with the 4 sequences that are defined to describe the basin evolution (see Chapter 2). The TNO zonation is based on the LODs (Last Occurrence Datum) and FODs (First Occurrence Datum) of palynomorphs. Key-references concerning the palynostratigraphy of the Upper Jurassic-Early Cretaceous are: Abbink (1998), Abbink *et al.* (2006), Bucefalo Palliani *et al.* (2002), Bucefalo Palliani & Riding (2000), Costa and Davey (1992), Davey (1979;1982), Duxbury *et al.* (1999), Heilmann-Clausen (1985), Herngreen *et al.,* (1989, 2000), Koppelhus & Nielsen (1994), Partington *et al.* (1993), Powell (1992), Riding and Thomas (1992) and Riding *et al.* (1999). The international geological timescale of Gradstein et al. (2012) is followed.

Figure 6 (next page) TNO's zonation and tectono-stratigraphic framework. The international geological time scale of Gradstein, 2012 (GTS 2012) is used.


Age
Standard Chronostratigraphy
Boreal Stages
Ammonite Zone
TNO Zonation
Depositional Sequences
Dinocyst events
Sporomorph events
129
130
131
132
133
134
135
136
137
138
139
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
155
156
157
158
159
160
161
162
163
164
165
166
167
168
Cretaceous
Early
Jurassic
Late
Middle
Barremian
Hauterivian
Valanginian
Berriasian
Tithonian
Kimmeridgian
Oxfordian
Callovian
Bathonian
Lt.
E.
M.
Ryazanian
Volgian
Kimmeridgian
elegans
fissicostatum
rarocinctum
variabilis
marginatus
gottschei
speetonensis
inversum
regale
noricum
amblygonium
paucinodum
tuberculatum
Dichotomites
Prodichotomites
Polyptychites
Paratollia
albidum
stenomphalus
icenii
kochi
runctoni
lamplughi
preplicomphalus
primitivus
oppressus
anguiformis
kerberus
okusensis
glaucolithus
albani
fittoni
rotunda
pallasioides
pectinatus
hudlestoni
wheatleyensis
scitulus
elegans
autissiodorensis
eudoxus
mutabilis
cymodoce
baylei
pseudocordata
cautisnigrae
pumilus
plicatilis
cordatum
mariae
lamberti
athleta
coronatum
jason
calloviense
koenigi
herveyi
discus
orbis
hodsoni
morrisi
subcontractus
prograciIis
zigzag
4
3
2
1
F
E
D
C
B
A
Cretaceous transgression
Adjacent Plateaus
Peripheral Basins
Graben Axis
AP-2
AP-1
PB-4
PB-3
PB-2
PB-1
GA-3
GA-2
GA-1
Muderongia simplex
Kleithriasphaeridium corrugatum
Odontochitina operculata
Cribroperidinium confossum
Nelchinopsis kostromiensis
Canningia cf. reticulata
Cribroperidinium confossum
Subtilisphaera perlucida
Batioladinium longicornutum
Batioladinium varigranosum
Lagenorhytis delicatula
Nelchinopsis kostromiensis
Kleithriaspaheridium porosispinum
Circulodinium compta
Systematophora palmula
Batioladinium cf. varigranosum
Tehamadinium daveyi
Endoscrinium pharo
Dingodinium spinosum
Egmontodinium torynum
Daveya boresphaera
common Oligosphaer. dilliculum
Rotosphaeropsis thula
Systematophora daveyi
Gochteodinia virgula
Egmontodinium expiratum
abund. Cribroperidinium hansenii
Egmontodinium polyplacophorum
Dingodinium tuberosum
Gochteodinia villosa
Glossodinium dimorphum
Senoniasphaera jurassica [rare]
Dichadogonyaulax pannea
Muderongia sp. A Davey 1979
Senoniasphaera jurassica [consist]
Scriniodinium inritibile
Occisucysta balios
Rhynchodiniopsis martonense
Cribroperidinium hansenii [consist]
Oligosphaeridium patulum
comm. Oligosphaeridium patulum
comm. Dichadogonyaulax
Cribroperidinium longicorne
Kleithriasphaeridium porosispinum
Geiselodinium spp.
Cribroperidinium hansenii [rare]
Gochteodinia mutabilis
Endoscrinium luridum
comm. Perisseiasph. pannosum
common Gonyaulacysta jurassica
Corculodinium inaffectum
Dichadogonyaulax pannea
Perisseiasphaeridium pannosum
Limbodinium ridingii
Endoscrinium galeritum
Scriniodinium crystallinum
Nannoceratopsis pellucida
ab. Rhynchodiniopsis cladophora
Compositosphaeridium polonicum
Trichodinium scarburghensis
Rigaudella aemula
Wanaea spp.
common Rigaudella aemula
Korystocysta gochtii
Ctenidodinium continuum
Durotrigia filapicata
Pareodinia prolongata
Lithodinia jurassica
Impletosphaeridium varispinosum
Gonyaulacysta jurassica
Impletosphaeridium varispinosum
Adnatosphaeridium caulleryi
Classopollis echinata
common Cicatricosisporites
abundant Classopollis
Callialasporites turbatus
Kraeuselisporites tubbergensis
abundant Classopollis
Trilites minutus
Striatella spp.
Precicatricosisporites spp.
Retitriletes undulatus
Densoisporites minor
Tuberositr. sp. A&B Abbink '98
Monosulcites minimus
Neoraistrickia gristhorpensis
Quadraeculina annelaeformis
Chasmatosporites hians

3.3.5 Palaeoenvironmental interpretations

Both the marine and terrestrial realm may be represented in palynological assemblages, rendering an ideal tool for palaeoenvironmental reconstructions of non-marine to open marine depositional settings. In particular with respect to trends in sea level and climate, palynology is very useful. Nevertheless, palaeoenvironmental interpretations based on palynology can not be compared one-on-one with depositional settings derived from sedimentology (Figure 7).The palaeoenvironmental interpretations derived from palynology are based on general assumptions, for example:

Open marine
Dominance of dinoflagellate cysts indicates open marine environments, in particular when the dinoflagellate cyst assemblages are highly diverse (many species).

Restricted marine
Dinoflagellate cyst associations of the type High Dominance – Low Diversity indicate a restricted marine environment, such as a lagoon, embayment or estuary.

Non-marine
Absence or near-absence of dinoflagellate cysts generally indicates non-marine or marginal marine environments.

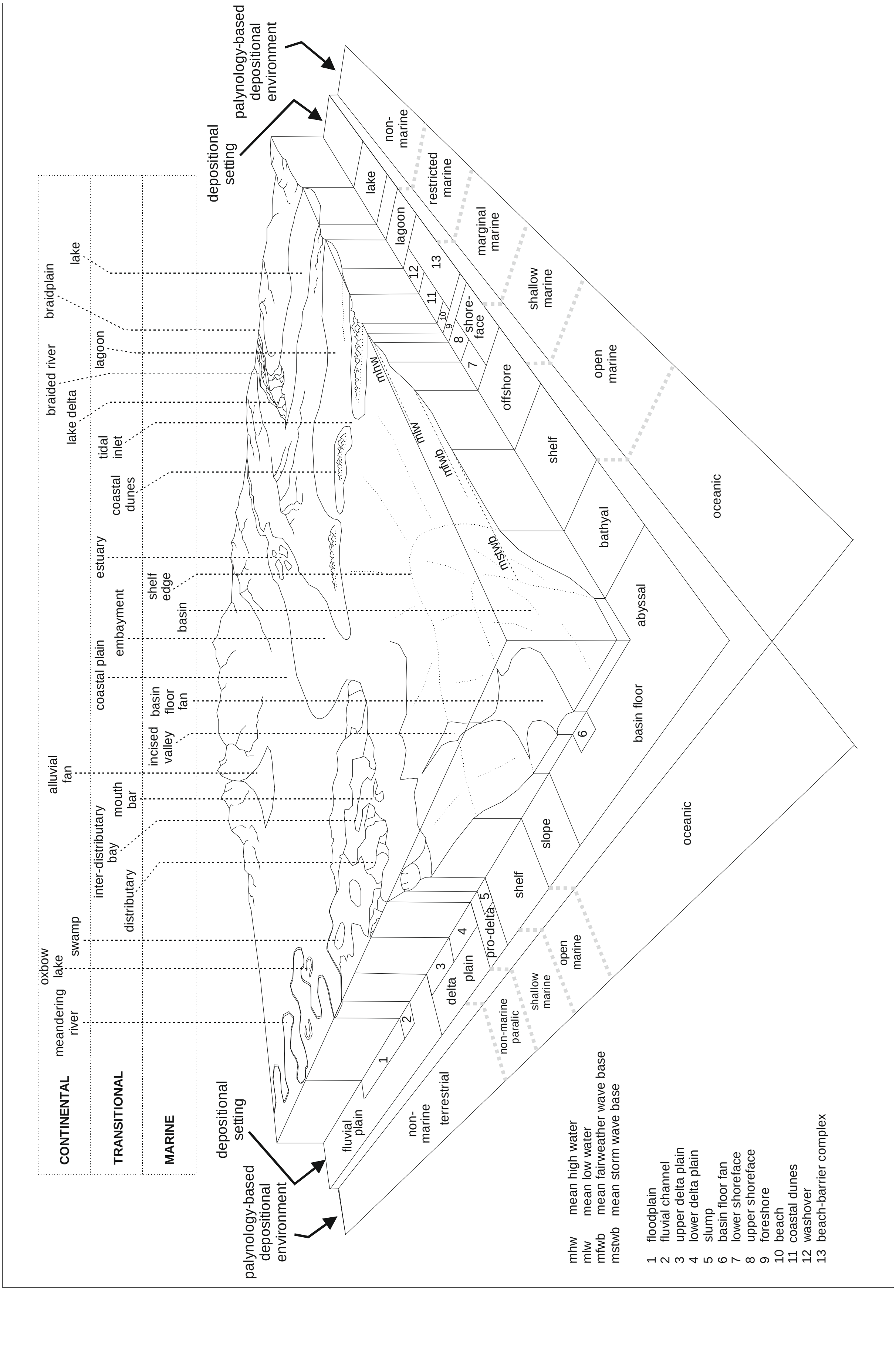
Transgression
An increase in the ratio between dinoflagellate cysts and pollen and spores indicates a sea level rise.

Regression
A decrease in the ratio between dinoflagellate cysts and pollen and spores indicates a sea level fall.

Low energy conditions
Excellent physical preservation of palynomorphs and other organic matter particles may indicate low energy conditions such as for instance a lagoon or a lake.

High energy conditions
Poor physical preservation of palynomorphs may indicate high energy conditions such as for instance a river channel, basin floor fan or a beach.

Figure 7 (next page) Block diagram displaying a variety of depositional settings with the corresponding depositional environments based on palynological interpretation.


CONTINENTAL
TRANSITIONAL
MARINE
meandering river
oxbow lake
swamp
alluvial fan
lake delta
braided river
braidplain
lake
distributary
inter-distributary bay
mouth bar
coastal plain
embayment
estuary
coastal dunes
tidal inlet
lagoon
incised valley
basin floor fan
basin
shelf edge
depositional setting
palynology-based depositional environment
fluvial plain
delta plain
pro-delta
shelf
slope
basin floor
abyssal
bathyal
shelf
offshore
shore-face
lagoon
lake
1
2
3
4
5
6
7
8
9
10
11
12
13
mhw
mlw
mfwb
mstwb
non-marine terrestrial
non-marine paralic
shallow marine
open marine
oceanic
oceanic
open marine
shallow marine
marginal marine
restricted marine
non-marine
mhw mean high water
mlw mean low water
mfwb mean fairweather wave base
mstwb mean storm wave base
1 floodplain
2 fluvial channel
3 upper delta plain
4 lower delta plain
5 slump
6 basin floor fan
7 lower shoreface
8 upper shoreface
9 foreshore
10 beach
11 coastal dunes
12 washover
13 beach-barrier complex

3.4 Lithostratigraphy

For lithostratigraphic references from the Broad Fourteens Basin and the West Netherlands Basin, the well-known stratigraphic nomenclature of Van Adrichem Boogaert & Kouwe (1993-1997) is followed (Figure 8 and Figure 9). For the Central Graben area, the update of the stratigraphic nomenclature by Munsterman *et al.* (2012) is followed. The update by Munsterman *et al.* (2012) mainly concerns the Upper Jurassic infill of the Terschelling Basin. At the time Van Adrichem Boogaert and Kouwe compiled their lithostratigraphic nomenclature, relialable stratigraphic data from the Terschelling Basin were scarce, resulting in a complex jigsaw puzzle of formation names. Munsterman *et al.* (2012) recognized a regionally traceable seismic marker, which was designated as the base of the Scruff Greensand Formation. All marine sandstones and shales from the Terschelling Basin occurring below this marker, were combined into the Skylge Fm. (Figure 10).

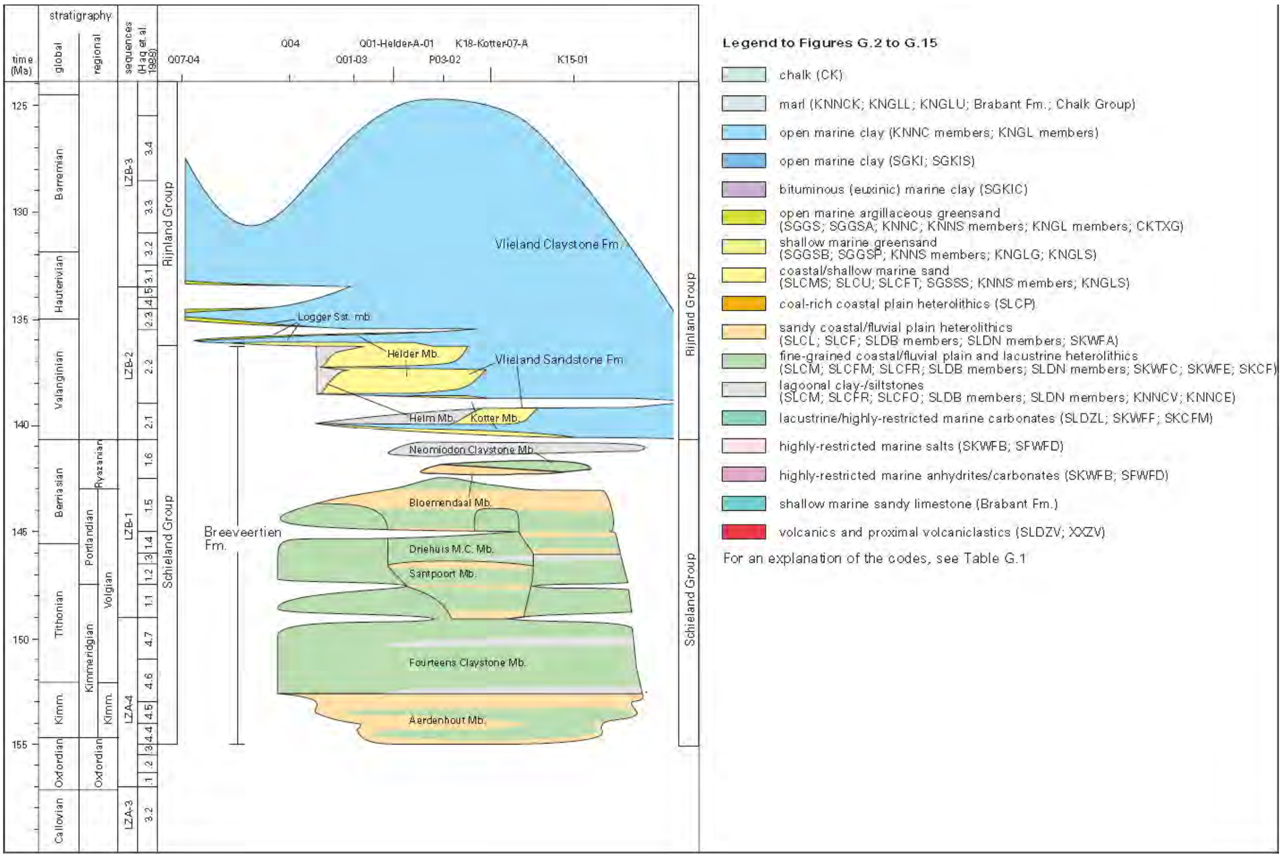


Figure 8 Lithostratigraphic framework for the Upper Jurassic and Lower Cretaceous of the Broad Fourteens Basin (Van Adrichem Boogaert & Kouwe, 1993-1997).

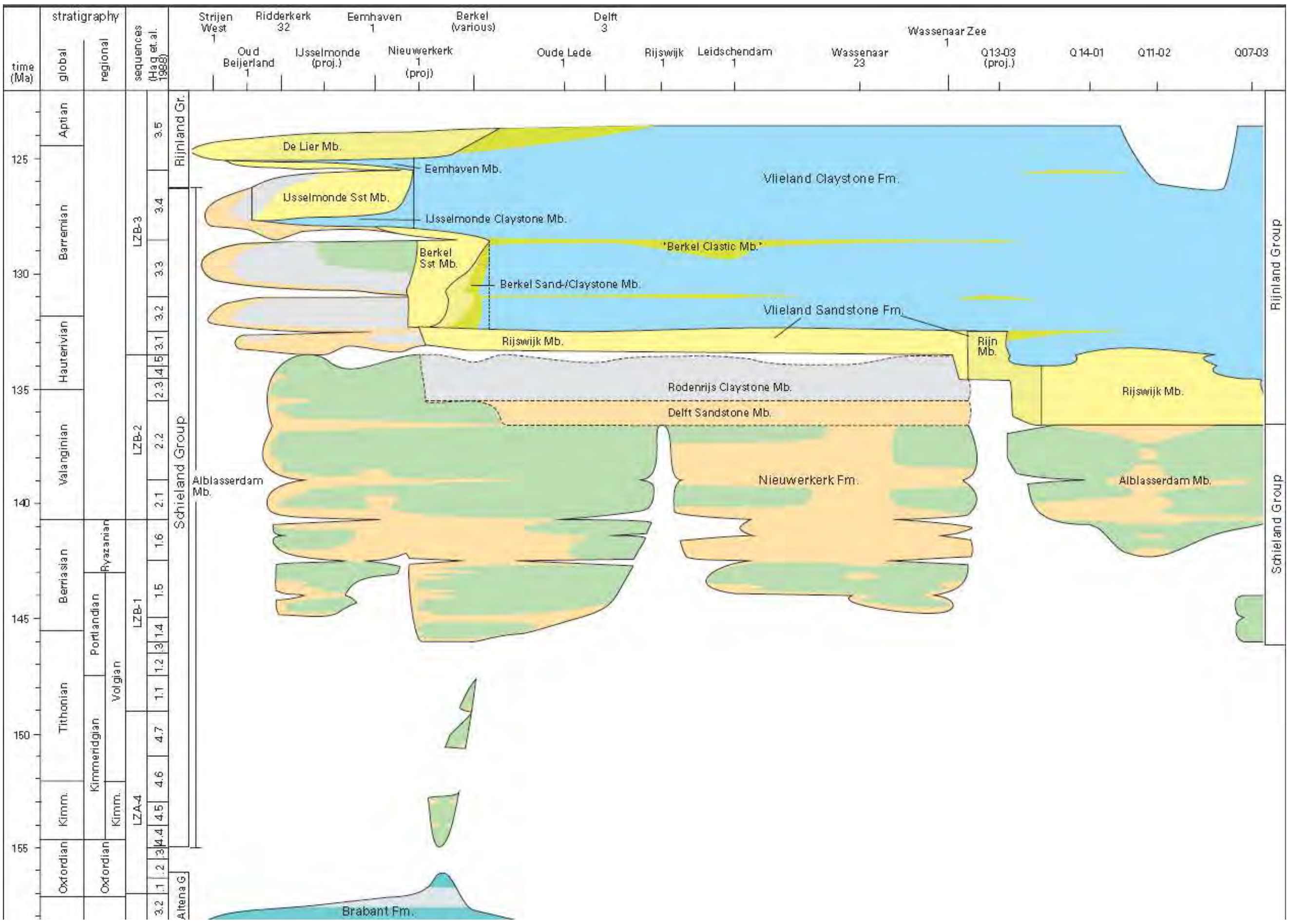
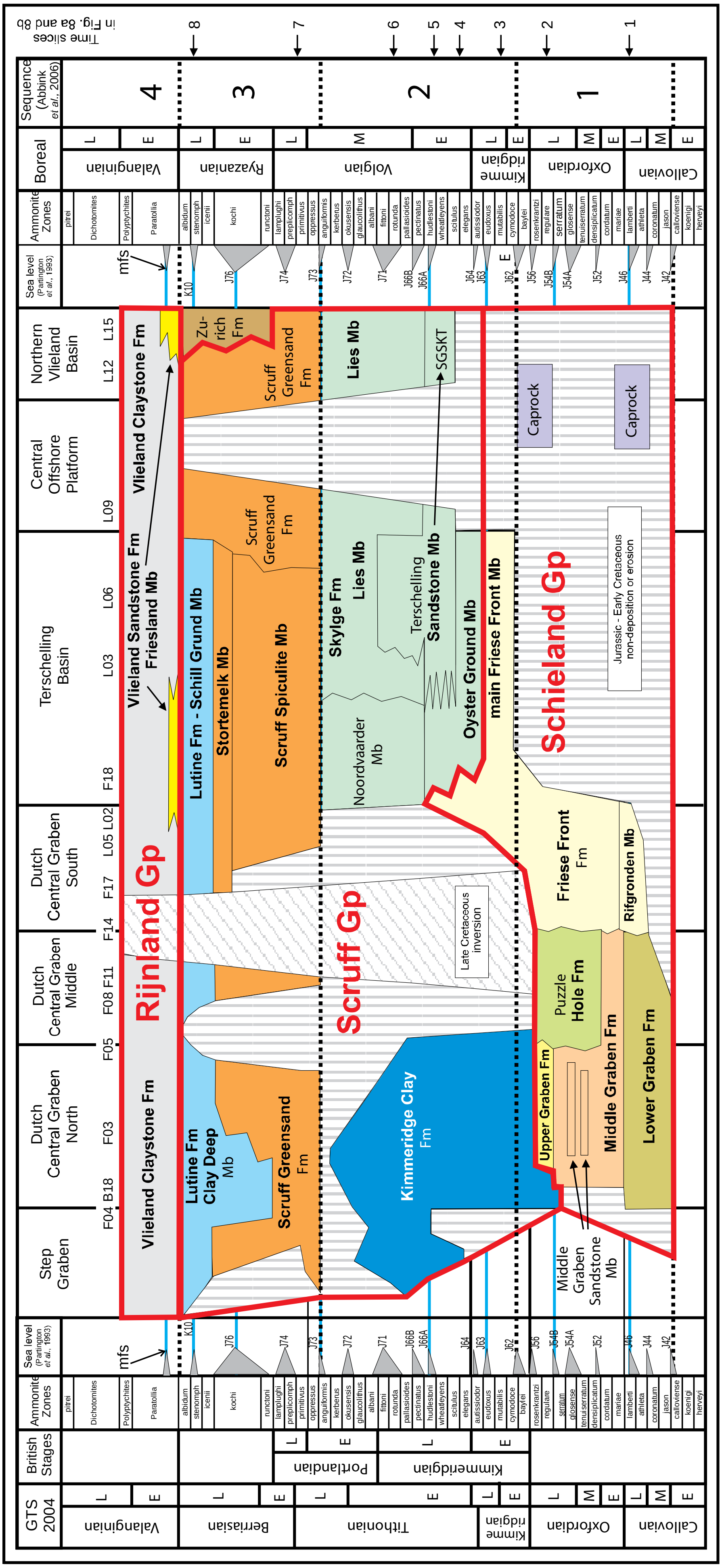


Figure 9 Lithostratigraphic framework for the Upper Jurassic and Lower Cretaceous of the West Netherlands Basin (Van Adrichem Boogaert & Kouwe, 1993-1997).

Figure 10 (next page)

Lithostratigraphic subdivision for the Central Graben area (Munsterman et al., 2012).


Time slices in Fig. 8a and 8b
Sequence (Abbink et al., 2006)
Boreal
Ammonite Zones
Sea level (Partington et al., 1993)
Northern Vlieland Basin
Central Offshore Platform
Terschelling Basin
Dutch Central Graben South
Dutch Central Graben Middle
Dutch Central Graben North
Step Graben
British Stages
GTS 2004
Valanginian
Ryazanian
Volgian
Kimmeridgian
Oxfordian
Callovian
Berriasian
Tithonian
Portlandian
Rijnland Gp
Scruff Gp
Schieland Gp
Vlieland Claystone Fm
Vlieland Sandstone Fm
Friesland Mb
Zurich Fm
Scruff Greensand Fm
Lies Mb
SGSKT
Caprock
Lutine Fm - Schill Grund Mb
Stortemelk Mb
Scruff Spiculite Mb
Skylge Fm
Noordvaarder Mb
Terschelling Sandstone Mb
Oyster Ground Mb
main Friese Front Mb
Jurassic - Early Cretaceous non-deposition or erosion
Friese Front Fm
Rifgronden Mb
Late Cretaceous inversion
Puzzle Hole Fm
Upper Graben Fm
Middle Graben Fm
Lower Graben Fm
Kimmeridge Clay Fm
Lutine Fm Clay Deep Mb
Middle Graben Sandstone Mb
mfs

4 Results of biostratigraphical analyses of wells in the Step Graben

The following section provides a summary of the palynological results from the Step Graben. Full age-breakdowns and implications for lithostratigraphic assingments per well are presented in Appendix 1. Palynological distribution charts are added in StrataBugs format (Appendices 2 to 9).

4.1 Well A12-01

Table 3 Summary of biostratigraphic age-assignment and updated lithostratigraphy

Interval (m)	**Lithostratigraphy**	**Age, *Amm. Zone*, TNO Zone**
2705-2723	Upper Holland Marl Mb	2710-2713 ND
2723-2727	Clay Deep Mb	2722-2725 Late Volgian, *oppressus-primitivus*, 3A
2727-2820	Kimmeridge Clay Fm	2731-2749 Middle Volgian, *fittoni* , 2C 2767-2782 Middle Volgian, *rotunda*, 2C 2782-2794 Early Volgian, *pectinatus*, 2B 2797-2815 Early Volgian, *hudlestoni*, 2B
2820-3438	Zechstein Group	2821-2824 ND

Paleo-environment

The associations are dominated by caving, hence it is rather questionable to differentiate facial changes between the cuttings samples. The conditions of Interval 2713-2815 m are roughly interpreted as shallow-open marine. The abundance of *Cribroperidinium hansenii* at 2722-2725 m may indicate the presence of stratification.

4.2 Well A18-02-S1

Table 4 Summary of biostratigraphic age-assignment and updated lithostratigraphy

Interval (m)	**Lithostratigraphy**	**Age, *Amm. Zone*, TNO Zone**
1987-2026	Vlieland Marl Member	2000 Late Aptian*, jacobi* 2010-2020 ND
2026-2036	Clay Deep Mb	2030 Late Ryazanian, *stenomphalus,* 3C
2036-2052	Lies Mb	2040 Middle Volgian, *fittoni*, 2C 2050 Early Volgian, *hudlestoni*, 2B
2052-2065.9	Noordvaarder Mb	2060-2062.30 Early Volgian, *hudlestoni*, 2B 2064.55 Early Volgian, *elegans/scitulus,* 2B
2065.9-2163	Zechstein Group	2065.90 Late Permian

Paleo-environment

The associations from interval 2000-2060 m are dominated by caving, the facies is roughly interpreted as shallow to open marine. The core samples at 2064.55-2064.6 m show near coastal shallow marine conditions. The marine dinoflagellate cyst genera *Cribroperidinium, Cyclonephelium* and *Systematophora* and sporomorphs *Perinopollenites*, psilatrilete spores and bisaccate pollen are present in common values. Core 2065.9 m is non-marine.

4.3 Well B13-02

Table 5 Summary of biostratigraphic age-assignment and updated lithostratigraphy

Interval (m)	**Lithostratigraphy**	**Age, *Amm. Zone*, TNO Zone**
1615-2204	Chalk Group	2190 ND
2204-2376	Skylge Fm	2209.63-2370 Early Volgian, *elegans* Ammonite, 2B
2376-2462	Kimmeridge Clay Fm	2380-2390 Early Volgian, *elegans* Ammonite, 2B 2400-2430 Late Kimmeridgian, *eudoxus*, 2A 2440-2460 Early Kimmeridgian, *cymodoce,* 1E

Paleo-environment

The palynofacies based on cuttings samples generally indicates near-coastal shallow to open marine conditions. *Perinopollenites*, bisaccate pollen and psilatrilte spores are the most common sporomorphs. *Cribroperidinium* and *Cyclonephelium* are the most common marine dinocyst genera.

4.4 Well B14-02

Table 6 Summary of biostratigraphic age-assignment and updated lithostratigraphy

Interval (m)	**Lithostratigraphy**	**Age, *Amm. Zone*, TNO Zone**
2465-2474	Holland Formation	2465-2475 ND
2474-2534	Noordvaarder Member	2480-2520 Early Volgian, *hudlestoni*, 2B
2534-2652	Kimmeridge Clay Fm	2535-2555 Early Volgian, *hudlestoni*, 2B 2565 Early Volgian, *wheatleyensis*, 2B 2575 Late Kimmeridgian, *autissiodorensis* 2A 2585-2600 Late Kimmeridgian, *mutabilis* 2A Sample/Interval Age 2605-2630 Early Kimmeridgian, *baylei*, 1E 2640-2650 ?Late Oxfordian, *pseudocordata* 1D
2652-2716	Rot Claystone Member	2655-2690 ND

Paleo-environment

The palynofacies based on the cuttings samples from interval 2480-2650 m generally indicates shallow to open marine conditions.

4.5 Well B14-03

Table 7 Summary of biostratigraphic age-assignment and updated lithostratigraphy

Interval (m)	**Lithostratigraphy**	**Age, *Amm. Zone*, TNO Zone**
1996-2325	Ommelanden Fm	2300-2320 Campanian
2325-2333	Skylge Formation	2325-2327 Middle Volgian, *kerberus,* 2D
2333-2362	Noordvaarder Mb	2335-2350 Early Volgian, *pectinatus* 2B (-basal part 2C)
2362-2666	Kimmeridge Clay Fm	2365 Early Volgian, *pectinatus*, 2B 2370 Early Volgian, *hudlestoni*, 2B 2380-2390 Late Kimmeridgian, *autissiodorensis*, 2A 2400-2665 Early Kimmeridgian, *cymodoce,* 1E

Paleo-environment

The palynofacies based on the cuttings samples from interval 2325-2665 m generally indicates shallow to open marine conditions.

4.6 Well F01-01

Table 8 Summary of biostratigraphic age-assignment and updated lithostratigraphy.

Interval (m)	**Lithostratigraphy**	**Age, *Amm. Zone*, TNO Zone**
1887-1909	Vlieland Marl Mb.	1905 Early Barremian, *fissicostatum*
1909-1920	Vlieland Claystone Mb.	1911-1920 Early Barremian, *fissicostatum*
1920-1964	Clay Deep Mb	1923-1960 Late Ryazanian, 3C 1963 Early Ryazanian, 3B
1964-1993	Zechstein Group	1969 Triassic/Permian

Paleo-environment

The palynofacies based on the cuttings samples from interval 1905-1963 m generally indicates shallow to open marine conditions.

4.7 Well F04-02

Interval (m)	Lithostratigraphy	Age, *Amm. Zone*, TNO Zone
2557-2632	Vlieland Claystone Formation	2605-2625 Early Barremian, *fissicostatum*
2632-ca 2635	?Friesland Member	2635m Valanginian, 4A
ca 2635-2666	Scruff Greensand Formation	2640-2650 Late Ryazanian, *stenomphalus* 3C 2655 Early Ryazanian, *kochi,* 3B 2660 earliest Ryazanian, *runctoni*, 3B 2665 Late Jurassic, Late Volgian, *primitivus,* 3A
2666-2715	Upper Röt Claystone Member	2670 Triassic

Paleo-environment

The palynofacies based on the cuttings samples from interval 2605-2665 m generally indicates shallow to open marine conditions.

4.8 Well F10-01

Table 9 Summary of biostratigraphic age-assignment and updated lithostratigraphy.

Interval (m)	Lithostratigraphy	Age, *Amm. Zone*, TNO Zone
2391-2467	Vlieland Claystone Formation	2454-2467m Early Hauterivian, *noricum,* 4D
2467-2489	Clay Deep Mb.	2472 Late Ryazanian, 3C 2477-2481 Early Ryazanian, *kochii* , 3B
2489-2527	Röt Claystone Mb.	2490-2513 Triassic

Paleo-environment

The palynofacies based on the cuttings samples from interval 2454-2481m generally indicates shallow to open marine conditions.

5 Results of biostratigraphical analyses of wells in the BFB and WNB

The palynological results are described per well, from top to bottom. Palynological distribution charts are added in StrataBugs format (Appendices 10 to 22).
The following section provides a summary of the palynological results from the Broad Fourteens and West-Netherlands Basin. Full age-breakdowns and implications for lithostratigraphic assingments per well are presented in Appendix 1. Palynological distribution charts are added in StrataBugs format (Appendices 10 to 22).

5.1 Well K14-01

Table 10 Summary of biostratigraphic age-assignment, updated lithostratigraphy and environmental assignment.

Interval (m)	Lithostratigraphy	*Age*	Environment
1220-1250	Vlieland Claystone Fm.	Early Valanginian	Shallow marine
1270	Werkendam Fm.	Early Bathonian or older	Shallow to open marine
1280-1300	Werkendam Fm.	Early Bathonian (? Aalenian) or older	Shallow to open marine

5.2 Well K15-01

Table 11 Summary of biostratigraphic age-assignment, updated lithostratigraphy and environmental assignment.

Interval (m)	Lithostratigraphy	Age	Environment
1526.5-1535.4	Vlieland Claystone Fm	latest Ryazanian/ earliest Valanginian transition	Coastal shallow marine conditions
1557.7-1558.7	Kotter Mb	Late Ryazanian-Ryazanian/Valanginian boundary	Shoreface setting (barrier sands)
1559.7-1575.5	Neomiodon Claystone Mb	Late Ryazanian	Fluctuating conditions from subaerial exposure to estuarine with marginal marine influence
1580.2-1670	Bloemendaal Mb	1580.2- 1597 m: Late Ryazanian 1629-1670 m: ND	Lower coastal plain with brackish and marginal marine influence ca1600-1670 m: ND; oxidation?

1670-1801	Santpoort Mb: 1670-1833 m	1670-1726.1 m: Middle Volgian 1750-1801 m: Early Volgian	Lower coastal plain setting with minor restricted marine influence
1837.9-2105.7	Fourteens Claystone Mb	1837.9-2017 m: Early Volgian 2028-2105.7 m: Late Kimmeridgian	Coastal plain with occasionally brackish water (estuarine) influence and marine floodings
2141.8-2270	Aerdenhout Mb	Late Kimmeridgian	Lower part of coastal to fluvial plain

Paleo-environment

Marine indicators are absent in the Upper Kimmeridgian Aerdenhout Member, interval 2210-2270 m. The palynomorph spectra are dominated by simple psilatriletes. *Eucommiidites minor* (2227. 3 m), *Callialasporites* spp. (2188.8 m) and *Perinopollenites elatoides* (2141.8 m) are, although fluctuating, relatively well-represented. Deposition occurred in the lower part of a fluvial plain.

Interval 1833-2110 m is interpreted as the Fourteens Claystone Member of Late Kimmeridgian-Early Volgian age. The basal part, 2095.3 - 2105.7 m is devoid of palynomorphs, referring to oxidation and possibly subareal exposure. At 2087.3 m a Taxodiaceae-dominated coastal lowland is inferred with marginal marine influence. Depth 2028 m shows a flooding surface with relatively higher diversity and numbers of dinocysts. High numbers of *Perinopollenites elatoides* and *Callialasporites*- with botanical affinity to Araucariaceae in the interval ca 1823-1995 m point to a coastal lowland setting with occasionally brackish (*Botryococcus)* influence (e.g. at 1933.2 and 1900.8 m). Evident marine influence seems to be missing in the interval 1920-1995 m, except for the very rare presence of a single acritarch.

The Lower-Middle Volgian Santpoort Member is recovered between 1670-1833 m. *Psilatrilete spores, Classopollis* and *Perinopollenites* are relatively well represented. The sporomorph assemblage is relatively diverse. Dinocysts are recorded in very low numbers and very low diversity, indicating deposition in coastal plain.

Marine dinocysts are absent in the Upper Ryazanian Bloemendaal Member, interval 1579-1670 m. Acritarchs and foraminiferal test linings are very rare indicating marginal marine (estuarine) influence. The sporomorphs are dominated by psilatrilete spores, bisaccate pollen and *Perinopollenites. With Botryococcus* present, this points towards deposition on the coastal plain.

Interval 1559.7-1575.5 m is classified lithostratigraphically as the Neomiodon Claystone Member, also of Late Ryazanian age. Most of the palynological slides are poor comprising just a few psilatrilte spores, bisaccate pollen, *Glaeicheniidites, Perinopollenites elatoides* and (fragments) of dinocysts and *Botryococcus*. Well-preserved associations show 99.5 % sporomorphs of the total sum palynomorphs. The sporomorphs are dominated by psilatrilete spores (50%) and bisaccate pollen (22-24 %). A single dinocyst is recorded and *Botryococcus* is moderately present. The conditions fluctuate from ”subaerial exposed” to restricted marine (lagoonal).

Interval 1557.7-1558.7 m is defined as the Kotter Member and is of Early Valanginian age. The palynomorph recovery fluctuates strongly. The preservation of the palynomorphs is poor. Dinocyst are rare to absent. Trilete spores (65%) and bisaccates (32 %) dominate the spectrum. The facies is interpreted as a shoreface setting (barrier sands).

The samples from the Vlieland Claystone , interval 1526.5-1535.4 m, are diverse and rich in dinocysts (ca 20 % of the total sum of palynomorphs). The sporomorphs are dominated by bisaccates (26-27 %), psilatrilte spores (25 %) and *Perinopollenites elatoides* (13-22 %). Acritarchs are very common. The facies is interpreted as a coast-proximal open marine setting.

5.3 Well K18-Kotter-14

Table 12 Summary of biostratigraphic age-assignment, updated lithostratigraphy and environmental assignment.

Interval (m)	**Lithostratigraphy**	**Age**	**Environment**
1820-1970	Kotter Mb	Early Valanginian	?Barrier system: intermitted (sub)aerial to brackish-marginal marine conditions
1970-2060	Neomiodon Claystone Mb	Late Ryazanian	Restricted marine (lagoonal) to brackish (estuarine) conditions
2080-2210	Bloemendaal Mb	Late Ryazanian	Brackish water conditions prevailed (lower coastal plain)
Ca 2216	~~~~~~~~~	~~~~~~~~~	~~~~~~~~~~~~~~~~~~~~~~~~~~
2240-2592	Driehuis Mottled Claystone Mb	Middle Volgian	Fluvial/coastal plain. Periods of subaerial exposure are considered possible
2598-2760	Santpoort Mb	2598-2721m: Middle Volgian ~~~~~~~~~* 2739-2760 m: latest Early Volgian	A fluvial to coastal plain setting *A large part of the Middle Volgian, Zone 2C p.p., *pallasoiodes-albani* Ammonite zones is not recorded and is most likely missing.
2802-3090	Fourteens Claystone Mb	latest Kimmeridgian-Early Volgian	Coastal plain with occasionally brackish water (estuarine), marginal and restricted marine (lagoonal) influence, and terrestrial conditions. The J66 mfs (2823 m) and J64 mfs (3078 m) are recorded. The *elegans/scitulus* climate shift is shown in the interval 2943-2964 m

3096-3321	Aerdenhout Mb	Late Kimmeridgian	A fluvial to coastal plain setting with restricted marine to brackish and fluvial (fresh water) conditions
3329	~~~~~~~~~	~~~~~~~~~*	*(Late Bajocian/)Bathonian-Early Kimmeridgian is missing
3339-3399	Werkendam Fm	Bajocian, or older	Near coastal shallow marine

Paleo-environment

In the basal part of the succession, interval 3339-3399 m of Bajocian age, dinocysts are rare, although marine acritarchs may be very common. Sporomorphs (particularly bisaccates and *Perinopollenites*) dominate the associations, indicating a shallow marine setting nearby the coast.

The microflora in the interval 3000-3321 m of Late Kimmeridgian age, indicates fluctuating conditions from terrestrial to marginal and restricted marine (lagoonal). Partington et al. (1993) reported an acme of *Geiselodinium paeminosum* in the mid-*autissiodorensis* Ammonite Zone. The high numbers of this taxon at depth 3078 m are correlated to the J64 flooding event.

The so-called "*scitulus* climate event" spans the interval 2943-2964 m and is reflected by the change in dominance from the genus *Perinopollenites* to *Classopollis*. The event represents more arid conditions during the Volgian compared to the Kimmeridgian.

Dinocysts are rare or absent from 2739 to 2922 m (Early Volgian) with the exception of interval 2823-2841 m, where 12 % of the total sum palynomorphs is reached. The increased marine signal at depth 2823 m may be associated with the J66 (*hudlestoni* Ammonite Zone) flooding event of Partington et al. (1993). Within the sporomorph category the percentage of *Classopollis* increased. A coastal plain setting with alternating marine influence and brackish to even terrestrial conditions is conceivable.

In comparison with the overlying interval (2260-2340 m), *Botryococcus* occurs less frequently and in lower numbers from 2360 to 2721 m (Middle Volgian). In general dinocysts are rare or, in de lower part of this interval, even absent. The assemblages are dominated by bisaccates, *Perinopollenites* and, in particular from 2500 m and deeper, by psilatrilete spores. A coastal/fluvial plain is likely.
The palynological yield is relatively low in interval 2260-2340 m (Middle Volgian). The palynomorphs are poorly preserved as a result of oxidizing conditions (subaerial exposure?). *Botryococcus* occurs in fluctuating frequencies. Dinocysts are almost absent. Sporomorphs are dominated by *Perinopollenites*, bisaccates and especially psilatrilete spores. A fluvial/coastal plain with a fluctuating water table is suggested. The increase in dinocysts (13 % of total sum sporomorphs and dinocysts) at depth 2240 m may be associated with the J73 flooding event (Partington et al., 1993: *anguiformis* Ammonite Zone).

Fresh- and/or brackish water organisms (*Botryococcus* and/or *Celyphus rallus*) are common in all samples of the interval 1990-2200 m (Late Ryazanian). Marine dinoflagellate cysts are scarce (1-4 % of the total sum dinoflagellate cysts and sporomorphs) except at depth 1990 m (16 %). The relatively high representation of dinocysts *Cantulodinium speciosum* and *Muderongia simplex (microperforata)* at 1990 m also indicates restricted marine (lagoonal) conditions. Bisaccates, psilatrilete spores and *Perinopollenites* still dominate the assemblages.

The association at the top, interval 1820-1970 m (Early Valanginian), of the studied section is dominated by sporomorphs, especially psilatrilete spores, *Perinopollenites* and bisaccates. However several slides are devoid of palynomorphs, indicating (sub)aerial exposure. Marine dinocysts are relatively rare. *Botryococcus* is common. The facies indicates intermitted (sub)aerial to brackish-marginal marine conditions. A barrier system is conceivable.

5.4 Well P02-06

Table 13 Summary of biostratigraphic age-assignment, updated lithostratigraphy and environmental assignment.

Interval (m)	***Old Lithostrat.***	***New Lithostrat.***	***Age***	***Environment***
1234.4-1231 CO	Rijn Mb.	Kotter Mb.	Early Valanginian	Barrier island transgressing to shoreface
1241.48-1235.4 CO	Rijn Mb.	Upper Bloemendaal Mb.	Late Ryazanian	Fluvial plain
1265-1305 CU	Rijn Mb.	Bloemendaal Mb.	Late Ryazanian	Uncertain
1565-1325	Nieuwerkerk Fm.	Santpoort and Driehuis Mottled Mbs.	Middle Volgian	Lacustrine-Coastal plain
1595-1585	Nieuwerkerk Fm.	Aerdenhout Mb.	Late Kimmeridgian	Coastal-fluvial plain
1605-1615	Werkendam Fm.	Werkendam Fm.	Callovian	Shallow marine

Paleo-environment

The Callovian interval (Altena Gp., Werkendam Fm. below 1605-1615 mCU) was deposited under shallow marine conditions. The presence of fresh-water tolerant *Botryococcus* spp. and the green algae *Tasmanites* argues for fresh-water influence and surface stratification. The dominance of sporomorphs points towards substantial terrestrial input.

Upper Kimmeridgian strata (between 1585 and 1595 mCU) unconformably overly Callovian strata. This Late Kimmeridgian interval is characterized by alterations of sands, silt and thin coal-layers. Collectively, this suggests fluvial plain to floodplain setting. This is in agreement with the palynological associations which are overwhelmingly dominated by sporomorphs.

Middle Volgian deposits unconformably overly Upper Kimmerdigian deposits above 1565 m. The lithology consists of mudstones with up-section decreasing sand-content. The palynological signal (albeit from cuttings) indicates lagoonal to coastal plain settings. Therefore, inclusion in the Fourteens Claystone Mb. seems appropriate for the basal part (1565-1465 m). Up-section, the depositional regime does not markedly change. By correlating the GR-patterns to Well K18-Kotter-14, it becomes clear that the Santpoort and Driehuis Mottled Members of the Breeveertien Fm. are present between 1465 and 1325 m.

Between 1305-1265 mCU marine influence was substantial. Acritarchs and dinocysts reach relatively high abundance and *Botryococcus* is absent. Whether or not, these marine forms are in-situ or caved is unclear. Therefore an unambiguous environmental assessment is not possible.

Within the cored interval (1231.1-1241.58 mCO), the lowermost two samples are barren of palynomorphs (1239.77-1241/58 mCO). This is likely a consequence of oxidation in the sand-rich facies. Between 1237.05 and 1235.4 mCO we record only terrestrial and fresh-water palynomorphs indicating deposition on the fluvial plain.

Overlying, at 1234.4 mCO we note high abundance of the lagoonal dinocyst taxon *Muderongia simplex*, indicating marginal marine settings of variable salinity. High clay content is not observed, suggesting deposition on the lagoonal side of a barrier island. Up-section through the interval (1233.7-1231.1 mCO), we note increasing abundance of offshore dinocysts (*Systematophora* spp. and other chorate cysts), related to progressive flooding leading to deposition in a shoreface environment. We assign this interval to the Kotter Mb.

5.5 Well P05-03

Table 14 Summary of biostratigraphic age-assignment, updated lithostratigraphy and environmental assignment.

Interval (m)	Lithostratigraphy	Age	Environment
1150.05-1138.05 CO	Kotter Mb.	(Early to Late) Valanginian	Barrier sands
1160,19 CO	Uncertain?	Uncertain?	Barrier sand/Fluvial channel
1161.14 CO - 1164.45 CO	Breeveertien Fm.	Late Kimmeridgian	Fluvial plain
1170-1210 CU	Brabant Fm.	Late Bathonian-?Early Callovian.	Open marine
1520-1250 CU	Upper Werkendam Mb.	Bathonian	Open marine
1590-1530 CU	Lower-Middle Werkendam Mb.	Aalenian-Bajocian	Open marine, not stratified
1650-1600 CU	Aalburg Fm./Posidonia Shale Fm.	Pliensbachian	Open marine, stratified

Paleo-environment

The Pliensbachian and Toarcian (Aalburg Fm. and Posidonia Shale Fm.) are recovered at the base of the studied interval (1650-1600 mCU). Common Tasmanaceae indicate stratified surface water conditions. Sporomorphs are present in high abundance. It is therefore inferred that this interval was deposited in relatively near-shore, poorly ventilated yet open marine conditions.

More or less similar conditions persist through the Aalenian and Bajocian (Lower and Middle Werkendam Members, 1590-1540 mCU. Relatively diverse dinocyst assemblages indicate shallow open marine conditions. Further up-section, the Early-Middle Bathonian of the Upper Werkendam Member (1520-1250 m) is consistently more open marine. Different dinocyst groups become common (*Ctenidodinium* spp., *Durotrigia* spp., *Pareodinia* spp.).

Open marine conditions prevail through the (earliest) Callovian (Brabant Fm., 1210-1170 mCU). The sample at 1230 mCU is barren of palynomorphs. This may be because one of the limestone units characteristic for the Lower Brabant Limestone Member, was samples rather than a more clay-rich sample.

The basal part of the cored section (1164.19-1160.19 mCO) was provisionally considered to belong to the Rijn Mb. However, this interval now appears of Late Kimmeridgian age, unconformably overlying Callovian strata. High loadings of trilete spores, low loadings of bisaccates and the absence of dinocysts suggests deposition in a fluvial plain setting. Inclusion of this interval into the Breeveertien Fm., likely the Aerdenhout Mb. seems appropriate.

Above the Late Kimmeridgian, coarse sands are deposited that are devoid of palynomorphs, these either correspond to channel fill sands of the Bloemendaal Mb. or alternatively the shoreface-barrier sands of the Kotter Fm. Since no age-dating could be achieved no definitive conclusions can be drawn.

At 1150.05 mCO, we note a clear marine incursion of Early Valanginian age. This is reflected by abundance of dinocysts (reaching 52%). Yet, the environment remains relatively restricted as indicated by the low-diversity of the dinocyst assemblages and the presence of euryhaline forms such as *Ophiobolus* sp. A. Absence of clay-rich lagoonal (backbarrier) facies argues for inclusion in the Kotter Mb. rather than the Helm Mb.

5.6 Well P08-03

Table 15 Summary of biostratigraphic age-assignment, updated lithostratigraphy and environmental assignment.

Interval (m)	**Old Lithostrat**	**New Lithostrat**	**Age**	**Environment**
2823.5-2897 CO	Rijn Mb.	Rijn Mb.	Hauterivian	Open marine: Lower shoreface, progressive transgression
2872.8-2891.5 CO	Rijn Mb.	Kotter Mb.	Early Valanginian	Coast-proximal open marine: Shoreface
2892.4-2892 CO	Aalburg Fm.	Aalburg Fm.	Hettangian	Restricted, stratification

Paleo-environment

The lowermost Early Jurassic part of the studied succession exclusively yields sporomorphs and Tasmanaceae (2891.5-2892.4 mCO). These illustrate a restricted and stratified marine environment. The unconformably overlying Valanginian sediments (2888.8-2872.8 mCO) were deposited in coast-proximal, open marine conditions. Note that open marine taxa like *Spiniferites* are abundant whereas euryhaline taxa like *Muderongia* and *Cantulodinium speciosum* are not recorded in abundance. Given the sand-rich sediments, a shoreface environment environment seems plausible.

Immediately above the Early Valanginian age sediments, sands of Hauterivian age (2868,5 – 2801 mCO) contain a gradually increasing proportion of dinocysts reflecting the development of open marine conditions. At 2801 mCO, dinocysts comprise ~80%. This interval is best assigned to the transgressive lower shoreface sands of the Rijn Mb.

5.7 Well P09-03

Table 16 Summary of biostratigraphic age-assignment, updated lithostratigraphy and environmental assignment.

Interval (m)	Old Lithostrat	New Lithostrat	Age	Environment
2000-1996	Vlieland Claystone Fm.	Vlieland Claystone Fm.	E. Barremian	Open marine, no fresh-water influence
2054-2006	Rijn Mb.	Rijn Mb	Late Hauterivian	Upper shoreface: Transgressive
2102-2064.7	Rijn Mb.	Rijn Mb.	Early Hauterivian	Upper shoreface: MFS/Flooding at 2102 m
2147-2110	Rijn Mb.	Kotter Mb.	E. Valanginian	Shoreface (open marine) MFS at 2136 m
2151,1	Rijn Mb.	?Kotter Mb.	L. Ryazanian?	Shoreface (open marine)
2163.5-2173	Lower Werkendam	Lower Werkendam	Aalenian or older	Open marine

Paleo-environment

The lowermost part of the record of Aalenian age (Lower Werkendam Fm., 2163.5 mCO-2173 mCO) was deposited under marginal marine conditions. Only the lowermost sample yields well-preserved palynomorphs among which sporomorphs are clearly dominant (90%) and constitute relatively high loadings of *Perinopollenites elatoides* and psilate spores. Dinocyst associations are of low diversity and dominated by typical Early Jurassic taxa like *Nannoceratopsis* and *Parvocysta*.

The overlying Late(st) Ryazanian - Early Valanginian interval is characterized by abundance of open marine dinocysts (reaching 25% at 2147 mCO). Marine influence increases between 2151.1 and 2147 mCO. Subsequently, the abundance of dinocysts declines (13-20% at 2141 and 2139.5 mCO). The dinocyst assemblages remain characterized by dominant gonyaulacacean taxa, which indicate continuous open marine conditions. The GR-pattern for the uppermost Ryazanian-lowermost Valanginian interval (2151-2147 m) indicates (low-GR) sandy facies. Hence, we include this interval in the Kotter Mb.

Above the Early-Hauterivian-Early Valanginian unconformity, between 2102 mCO-2064.7 mCO, marine influence declines somewhat (29-34%). Among the sporomorphs, low-land elements like *Perinopollenites* and psilate spores become more dominant, illustrating a gradual increasing influence of coastal elements. Fresh-water algae are recorded at 2087 mCO. Overall, the conditions are now proximal marine, upper shoreface.

Through the Late Hauterivian, between 2054.7 and 2016 mCO relatively stable associations with dominant sporomorphs persist. Dinocysts represent ~20% and at 2054.7 m, fresh water algae are recorded in low abundance. The dinocyst assemblages are relatively diverse and constitute taxa that are tolerant to reduced salinity (e.g., *Muderongia* spp., *Palaeoperidinium* spp., *Ophiobolus* sp. A and *Subtilisphaera* spp.). The lithology remains sand-rich, hence it seems unlikely that a back-barrier environment was present. Upper shoreface conditions are more likely. At 2043 mCO a minimum in dinocyst abundance is recorded. Above this level (2032.2-2006 mCO), the abundance of dinocysts increases steadily. This may signify a subtle transgression. These Hauterivian marine sandstones likely correspond to the transgressive sheets sands of the Rijn Mb.

For the uppermost two samples, only drill-cuttings have been studied qualitatively. In contrary to the underlying interval, *Perinopollenites elatoides* is not a significant constituent of the sporomorph associations. This suggests that the influence of lowland marsh vegetation in which these flourish decreases, which would be in agreement with a rise in relative sea-level . The dinocyst assemblages constitute *Cribroperidinium* spp. and *Spiniferites* spp. in *common* numbers. The dinocysts reflect outer neritic conditions and indicate the absence of fresh water influence. These conditions are indeed indicative of the offshore mudstones of the Vlieland Claystone Fm
.

5.8 Well P12-08

Interval (m)	**Old Lithostrat**	**New Lithostrat.**	**Age**	**Environment**
2570	Vlieland Claystone Fm.	Vlieland Claystone Fm.	Latest Hauerivian – Earliest Barremian	ND
2580-2590	Rijn Mb.	Rijn Mb.	Late Hauterivian	ND
2620-2690	Rijn Mb.	Rijn Mb.	Early Hauterivian	ND
2710	Aalburg Fm.	Aalburg Fm.	Pliensbachian or older	ND

5.9 Well L16-06

Table 17 Summary of biostratigraphic age-assignment, updated lithostratigraphy and environmental assignment.

Interval (m)	**Old Lithostrat**	**Revised Lithostrat**	**Age**	**Environment**
1860.5-1870.75	Vlieland Claystone Fm.	Helm Mb.	Early Valanginian	Back-barrier lagoon, Brackish
1879.3	Kotter Mb.	Kotter Mb?	Uncertain	Uncertain
1887.75-1892	Aalburg Fm.	Aalburg Fm.	Pliensbachian or older	Open marine

Paleo-environment

The Pliensbachian (Aalburg Fm., 1892-1887.5 mCO) is characterized by poor palynological recovery. The lowermost sample only contains Early Cretaceous contamination. Following the general classification of the Aalburg Fm., the environment is interpreted as open marine.

The sample at 1879.3 mCO is palynologically barren, probably because of the sand-rich facies at this point. The overlying cored Valanginian section (1870 – 1860,5 mCO) was deposited under marine-brackish conditions, manifested by the presence of various forms of *Muderongia* spp. and the presence of *Botryococcus* spp. Furthermore, the lithology becomes more clay-rich. Together with the palynological indications for euryhaline conditions, the environment is best described as lagoonal. Initially this interval was assigned to the Vlieland Claystone Fm., which constitutes open marine mudstones. Therefore inclusion in the Helm Mb. of the Breeveertien Fm. seems more appropriate.

5.10 Well Q01-Helm-A1

Table 18 Summary of biostratigraphic age-assignment, updated lithostratigraphy and environmental assignment.

Interval (m)	Old Lithostrat	New lithostrat	Age	Environment
1217-1210	Vlieland Claystone	Vlieland Claystone	Hauterivian	Open marine
1237-1217	Helder	Helder Mb.	Late Valanginian	Lower shoreface: open marine
1356.52-1242	Helder Mb.	Kotter Mb.	Early Valanginian	Barrier sand-Lagoonal mud intercalations
1415-1316.57	Bloemendaal, Kotter, Helm.	Bloemendaal -Helm	Late Ryazanian	Alternating barrier sands and lagoonal mud

Paleo-environment

The lower half of the record is recovered in drill cuttings. For this interval, a quantitative assessment was not possible. The lowermost interval (1320-1415 m), is of Late Ryazanian age. It yields abundant fresh-water algae (*Botryococcus*) and is dominated by sporomorphs; bisaccates, psilatrilete spores and *Cicatricosiporites*. The latter illustrates the relatively warm and humid climate persisting after the *kochi* climate shift. Occasionally, also lagoonal euryhaline dinocysts are present, perhaps partly ascribed to caving from the overlying Valanginian strata. The environment is comparable to that of the “Wealden facies” i.e. alternations between barrier sands and lagoonal muds. The assignment to the Kotter and Helm Mb. is erroneous. The entire interval corresponds to the Bloemendaal Fm. The base of the cored interval stills belongs to the Late Ryazanian Bloemendaal Fm. The facies is similar, yet lagoonal dinocysts are abundant indicating lagoonal conditions.

At the base of the Early Valanginian section at 1316.52 mCO we note high abundance of dinocysts (60 %). This marks a clear flooding. Subsequently between 1316.52 mCO and 1242.2 mCO, we record several mass-occurrences of *Muderongia simplex*, *Cantulodinium speciosum* and *Cribroperidinium* spp. The former two of these taxa are indicative of lagoonal euryhaline conditions, whereas the latter is commonly encountered in more stable marine environments. This signal thus points to variable fresh-water influence throughout the inverval. High loadings of sporomorphs indicate a proximal marine environment. Indicators of fresh-water influence are not recorded. The environment is thus best described as a shoreface environment with variable salinity.

In the Late Valanginian, above 1242 mCO, we note by continuous marine influence (>40 % dinocysts). Hence, the Late Valanginian contains a renewed flooding. The proximal marine taxa *Muderongia extensiva*, *Muderongia simplex* ssp. *microperforata* and *Cantulodinium speciosum* are not present in abundance anymore. Rather, taxa like *Cyclonephelium distinctum*, *Spiniferites* spp. and *Hystrichosphaerina schindewolfii* become prominent. These are more indicative of open marine conditions. Also the lithology becomes more clay-rich.
Two samples of Early Hauterivian age were taken from the Vlieland Claystone Fm. These indicate open marine conditions, with abundant *Oligosphaeridium* spp.

5.11 Well Q01-18

Interval (m)	Old Lithostrat	New lithostrat	Age	Environment
2054-2070	Muschelkalk Fm.	Muschelkalk Fm.	(Middle) Triassic	ND
2042-2048	Kotter Mb.	Kotter Mb.	Early Valanginian	ND
2039	Kotter Mb.	Vlieland Claystone Fm.	Probably Early Valanginian	ND

5.12 Well Q04-07

Table 19 Summary of biostratigraphic age-assignment, updated lithostratigraphy and environmental assignment.

Interval (m)	Old Lithostrat	New Lithostrat	Age	Environment
2362-2460 CU	Aalburg Fm.-Posidonia Shale Fm.	-	Pliensbachian-E-Toarcian	Open marine, stratification, reduced salinity
2360-2330 CU	Werkendam Fm./Breeveertien Fm.	-	Callovian	Open marine
2330-2140 CU	Breeveertien Fm.	-	Kimmeridgian-Early Volgian	Fluvial/Coastal plain
2132	Breeveertien Fm.	?Bloemendaal Mb.	Latest Ryazanian	Wealden Facies: Deltaic
2128-2110 CU	Helder Mb.	Helder	Hauterivian	Open marine, Lower Shoreface
2110-2860 CU	Vlieland Claystone	-	Hauterivian	Open marine

Paleo-environment

For this well, core material was not available. We therefore rely on drill cuttings, which are affected by caving and have therefore not been studied quantitatively. The Early Jurassic (Pliensbachian-Toarcian) sediments of the Aalburg Fm. and Posidonia Shale Fm. are recovered at the base of the studied interval (2381-2369 m). Tasmanaceae are present indicating a stratified water column. In the sample from the Posidonia Shale Fm. (1369 mCU), dinocysts are virtually absent. Sporomorphs are present but not in overwhelming number. Hence, we interpret that this interval was deposited in relatively offshore, open marine, poorly ventilated conditions.

Between 2348-2333 mCU corresponding to the Callovian Werkendam Fm. we note common occurrences of *Cribroperidinium* spp., a group of dinoflagellates commonly encountered in open marine, yet relatively coast-proximal (inner neritic) conditions. Acritarchs are also present in substantial abundance. There are no indications for fresh water influence.

The sediments dated as Late Kimmeridgian and Early-Middle Volgian (2318-2147 mCU are characterized by substantially different palyno-associations. Marine palynomorphs are largely absent (except for some caving). Botryococcus an indicator for brackish-water conditions is consistently present. Hence, the interval is considered to have been very near-coastal with substantial fresh-water input. The log-patterns are indicative of high-order changes in sand and clay content. Hence, the depositional environment is best described as coastal-floodplain settings.

In the Early Cretaceous (Late Ryazanian) we observe a demise in *Classopollis*, related to the *kochi*-climate shift leading to colder-wetter conditions. Sporomorphs and *Botryococcus* are abundant, indicating substantial fluvial input. This interval is comparable to the “Wealden facies”. The environment is best described as deltaic to lagoonal.

The unconformably overlying Lower Hauterivian succession is characterized bya demise in the abundance of sporomorphs. Marine palynomorphs have became more prominent. *Botryococcus* is now absent. Dinocyst assemblages are dominated by open marine taxa like *Spiniferites* spp. The uppermost sample (2105 mCU) from the Vlieland Claystone Fm. marks a further reduction of terrestrial influence, suggesting a progressive flooding. The environment is best described as marine.

6 Towards a composite stable carbon isotope record for the Upper Jurassic-Lower Cretaceous

6.1 Introduction

Stable carbon isotope ratios are increasingly used to provide regional and even global correlations. Numerous carbon isotope stratigraphic studies have indicated that the Late Jurassic to Early Cretaceous interval was characterized by some prominent isotopic trends and shifts (>1.5 ‰). The variations in the carbon isotope composition reflect changes in the isotopic composition of the global carbon pool (i.e., the exchange between the oceanic, terrestrial and atmospheric reservoirs). Positive excursions often reflect fluctuations in the carbon partitioning between reduced and oxidized marine carbon sinks via organic carbon burial. Negative excursions often relate to reductions living biomass, oxidation of organic carbon and in extreme cases to the dissociation of seafloor methane hydrates. Furthermore, due to vital effects of different organisms contributing to substrate used for analysis, trends may arise. As a consequence, trends in bulk records can be caused by changes in substrate.

In the present study, we have constructed a composite stable isotope record for the Upper Jurassic to Lower Cretaceous on organic material composed of palynological residues and bulk organics from the Dutch Central Graben and the Broad Fourteens Basin. We have utilized material from sites included in the project and also requested dedicated samples from several operators (NAM, Total). The results will be shared with the contributors.

In order to compile a stacked, composite record of carbon isotope values all individual records need to be constrained in time. To do so, we have used the biostratigraphic results of this study or from internal reports. If unavoidable, we rely on lithostratigraphic characteristics and log-correlations to provide age-diagnostic criteria. These are presented in the following paragraph.

6.2 Individual records and age-diagnostic criteria

6.2.1 Well F03-03

Well F03-03 was drilled in the Dutch Cental Graben. We have generated bulk organic carbon isotope data on 108 samples (34 cutting samples, 74 side wall core samples) on the interval 1686-3652 m depth.

Based on biostratigraphic information, characteristic gammalog-events and isotope-ties, the interval could be correlated against the geologic timescale and the other records. The interval continuously spans the Callovian to Late Kimmeridgian between 3652 and 1800 m depth. At about 1800 m, we infer an unconformity separating strata of Late Kimmeridgian age from Middle Volgian age strata. Another unconformity at about 1690 m separates the Late Volgian from the Late Ryazanian. In between these tie-points, ages were calculated through linear interpolation.

Table 20 Age-diagnostic events used for correlation of well F03-03

Event	**Depth (m)**	**Numerical Age**	**Palynozone**
LOD *Daveya boresphaera*	1686	139,5	**3C**
Unconformity Base Cretaceous	1690	146-141	
LOD *Glossodinium dimorphum*	1770	146,8	**2D**
LOD *Occisuscysta balios*	1790	148	**2C**
Unconformity infra Seq. 2	1800	153-148,2	
LOD *Endoscrinium luridum*	1803	153	**2A**
LOD *Dichadogonyaulax chondrum*	2271	154,8	**1E**
LOD *Ellipsiodictyum cinctum*	2431,5	157,2	**1D**
GR-log event VIII	2550	158	**1D**
GR-log event V (onset sand)	2930	160,5	**1C**
LOD *Neoraistrickia gisthorpensis*	2943	160,8	**1C**
GR-log event IV (coal doublet)	3050	162	**1B**
Isotope Tie 3	3060	162,2	**1B**
LOD *Lithodinia jurassica*	3152	163,5	**1A**
Isotope Tie 2	3160	163,5	**1A**
GR-log event III	3250	163,8	**1A**
Isotope Tie 1	3320	164	**1A**
Base Lower Graben Fm.	3652	165	**1A**

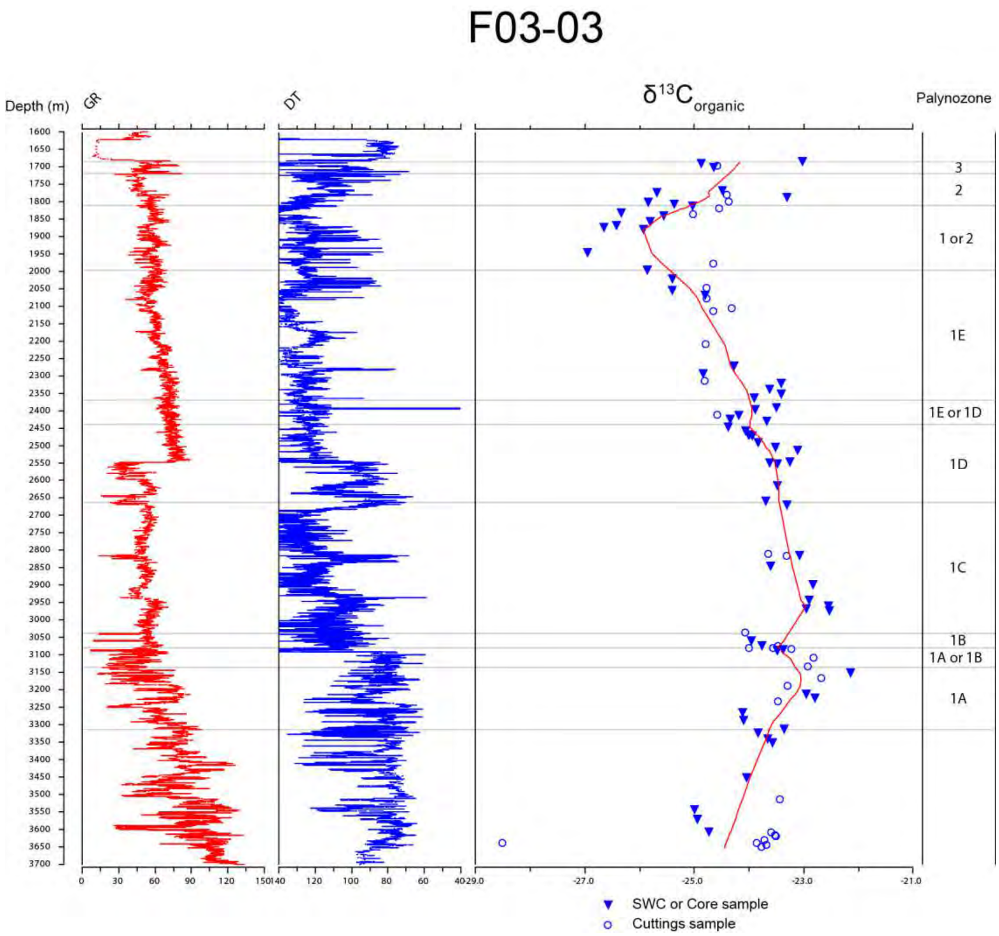


Figure 11 Carbon isotope results for well F03-03.

Overall, the variability from the running mean is overall relatively small (<1‰), even when cuttings are included. Therefore, the δ^{13}C-record from Well F03-03 represents an important reference section for the Callovian to Kimmeridgian interval. Through the Middle-Late Callovian (3650 m, Zone 1A to 3150, Zone 1A) we note a trend towards more positive values; from ~-25‰ at 3550 m to ~-22‰ at 3152 m. Subsequently, we note a transient negative excursion in both the cuttings as well as a few intermittent core samples culminating at 3038 m depth at ~24‰. This transient negative shift occurred in the Early Oxfordian (Zone 1B, mariae Ammonite Zone, 162-163 Ma) and is followed by a recovery, reaching values of -22.5‰ at 2960 m depth. The interval between 2960 and 1997 m depth, corresponding to most of the Oxfordian and Kimmeridgian is characterized by a gradual ~-3.5‰ shift (-25.8‰ at 1997 m depth). Note that the analyses on cuttings reflect more stable values. This is not very surprising given the fact these are more spread out and possibly affected by caving. Following this long-term shift towards more negative values, we note an abrupt addiontal negative shift to -27‰ at 1947 m depth, which is followed by a recovery towards more positive values reaching 24.3‰ at 1770 m. This negative shift is dated to occur in the Late Kimmeridgian *mutabilis-eudoxus* Ammonite Zones (~153 Ma). The recovery is thought to be rapid, also occurring in the Late Kimmeridgian. Samples taken between 1790 and 1692 are stratigraphically located in the younger Middle Volgian interval and are characterized by relatively high scatter (between -23.3‰ and -24.8‰). A single sample corresponds to the Late Ryazanian (139.5 Ma) and has a value of -23‰.

6.2.2 Well F11-01

Well F11-01 was drilled in the Dutch Cental Graben. We have generated bulk organic carbon isotope data on 97 samples (35 cutting samples, 43 side wall core samples) on the interval between 1520 - 2490 m depth.

Based on biostratigraphic information, characteristic gammalog-events, isotope-ties and lithostratigraphy, the interval was correlated against the geologic timescale. The interval spans the Callovian to Late Kimmeridgian between 2490 and 1520 m depth. In between these tie-points, ages were calculated through linear interpolation. The uppermost part of the record is difficult to gauge in time due to the highly variable facies and as a consequence fossil content.

Table 21 Age-diagnostic events used for correlation of well F11-01

Event	**Depth (m)**	**Numerical Age**	**Palynozone**
Top Puzzle Hole Fm	1500	152	2A
Infra Zone 1E	1837	156	1E
GR-log event VIII	1940	158	1D
LOD *Neoraistrickia gristhorpensis*	2080	160,8	1C
GR-log event IV (coal doublet)	2185	162	1B
Isotope Tie 3	2200	162,2	1B
Isotope Tie 2	2280	163,5	1A
GR-log even III	2310	163,8	1A
Isotope Tie 1	2445	164	1A
Unconformity Toarcian-Callovian	2490	175	-

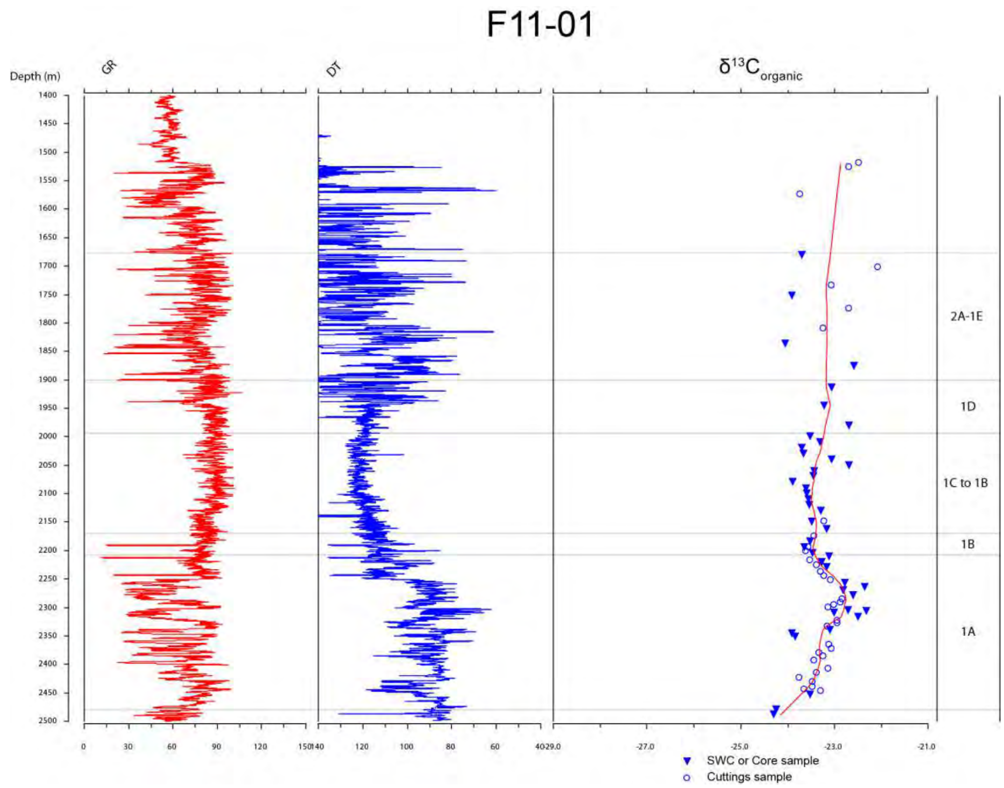


Figure 12 Carbon isotope results for well F11-01.

The lowermost two samples from well F11-01 are of Toarcian age and are not therefore not included in the carbon isotope compilation. Likewise the record from well F03-03, the variability in both cuttings and core-material from the Callovian to Kimmeridgian interval (2445 m to 2280 m) is relatively small (<1‰). Hence, also this record is important for construction of a reference for the Callovian to Kimmeridgian. Through this Middle-Late Callovian interval (2500-2300 m, Zone 1A), we note a 1‰ trend towards trend towards more positive values (i.e., from -23.5 to -22.5‰). This is similar to the coeval record from well F03-03. Subsequently, between 2263 and 2184 m, a ~-1‰ negative shift is culminating in strata corresponding to the Early Oxfordian (Zone 1B, mariae Ammonite Zone; 162-163 Ma). This pattern is also consistently recognized in F03-03. Between 2185 and 2080 m depth (Zone 1B, mariae-cordatum Ammonite Zones, 162-160.8 Ma) the δ^{13}C-values remain relatively stable around -23.5‰. Above 2080 m depth (Middle Oxfordian), the scatter in isotopic values becomes somewhat larger, average values are ~-23.3‰. Above 1960 m depth the scatter becomes substantially large (>2‰). This is probably caused by the depositional facies, which is characterized by high-frequency alterations of lacustrine, fluvial and marine conditions of the Puzzle Hole Fm., causing major changes in substrate.

6.2.3 *Well L05-4*

Well L05-04 was drilled in the Dutch Cental Graben. We have generated bulk organic carbon isotope data on 50 core samples on four cored intervals between 2825 and 2640 m depth.

The succession was palynologically correlated to the GTS (mainly the boreal ammonite zones) by Abbink 1998.

Table 22 Age-diagnostic criteria used for correlation of well L05-04.

Event	**Depth (m)**	**Numerical Age**	**Palynozone**
Top *baylei* Amm. Zone	2625	156	1E
Top *pseudocordata* Amm. Zone	2648	157,3	1D
Base *pseudocordata* Amm. Zone	2725	158,9	1D
Densiplicatus climate shift	2750	160,8	1C
Middle *cordatum* Amm. Zone	2800	161,1	1B
Base *mariae* Amm. Zone	2815	163,4	1B
Base *lamberti* Amm. Zone	2825	163,8	1A

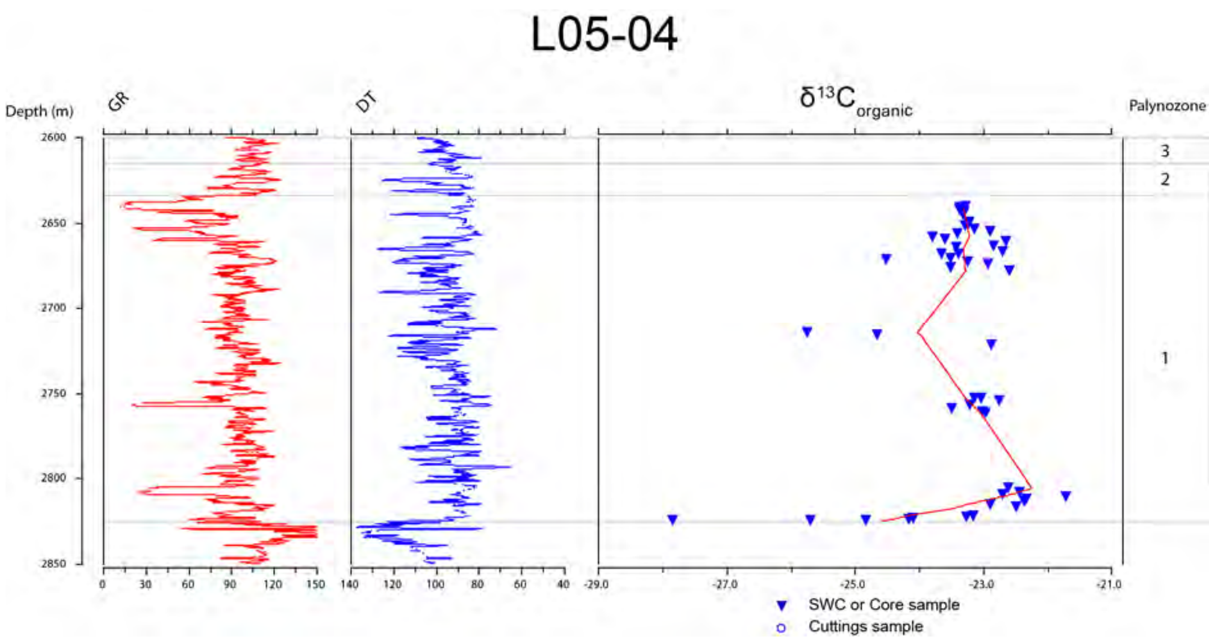


Figure 13 Carbon isotope results for well L05-04.

At the base of the studied interval we note three distinct negative values (2824,45-2824,41 m depth). The Early Toarcian Posidonia Fm., which is widely recognized to contain a distinct negative isotope shift is located just below the studied interval. In fact, these samples with a negative signature also appear to be part of the Posidonia Fm. This is exemplified by high (19 wt. %) TOC-values at this stratigraphic level (Verreussel et al. 2011). Therefore, these lowermost three samples (2824,45-2824,41) will not be included in the isotope compilation.

Lithostratigraphically, the entire overlying studied section belongs to the Friese Front Fm, coastal-delta plain deposits with sand-siltstones with lignite intercalations, coal layers etc. This lithology is particularly sensitive to changes in organic substrate, explaining the large variance in the dataset. The studied interval is of Oxfordian to Early Kimmeridgian age (163,8-156 Ma). The recorded values fluctuate between approximately -24‰ and -21.5‰.

6.2.4 Well F15-A-01

Well F15-A-01 was drilled in the Dutch Central Graben. We have generated organic carbon isotope data on 38 samples of sidewall core material. Analyses were performed on decalcified tock samples.

No biostratigraphy is reported on this well. We therefore rely on lithostratigraphic and log-pattern correlation to the nearby well F15-02, which is biostratigraphically tied (Munsterman et al., 2012). Consequently, the record from this site uniquely spans the Early Ryazanian (Zone 3B).

Table 23 Age-diagnostic criteria for well F15-A-01

Event	**Depth (m)**	**Numerical Age**	**Palynozone**
Base Lutine Fm. *albidum* Amm. Zone	2480	138,7	4A
Stortemelk Mb. *iceni* Amm. Zone	2540	141	3C
Scruff Spiculite Mb *opressus* Amm. Zone	2604	146,8	2D-3A
Infra Noordvaarder mb. fittoni Amm. Zone	2630	148,4	2C
Basal Noordvaarder mb. *hudlestoni-pectinatus* Amm. Zone	2685	150,2	2B
Oyster Gr. Mb. *scitulus-elegans* Amm. Zone	2736	151,8	2B

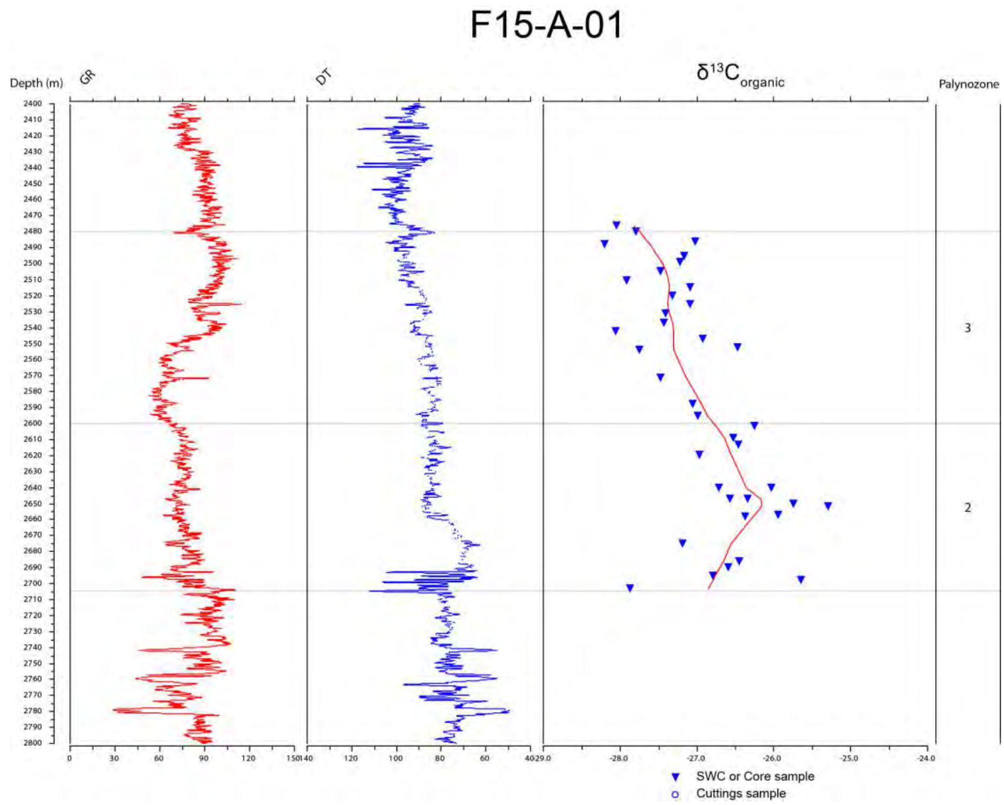


Figure 14 Carbon isotope results for well F15-A-01

The isotope values for well F15-A-01 are relatively scattered. The lower part of the record is of Early Volgian age; isotope values are scattered between -27,7 and -25,3‰. Samples between 2609 and 2554 m depth correspond to the Late Volgian and Early Ryazanian (~146-142 Ma). Data for this interval are characterized by a gradual negative shift (-26,2‰ to -27,7‰). The upper part of the record 2552-2476 m depth, of Ryazanian age is characterized by larger scatter (between -26,5 and -28‰).

6.2.5 Well F17-04

Well F17-04 was drilled in the Dutch Cental Graben. We have generated organic carbon isotope data on 50 core samples on four 37 cored intervals between 2453 and 2556 m depth. The samples are derived from palynological residues.
The biostratigraphic age-constrains are from Abbink, 1998.

Table 24 Age-diagnostic criteria used for correlation of well F17-04.

Event	**Depth (m)**	**Numerical Age**	**Palynozone**
Top Acme *Rigaudella aemula*	2432	159,5	1C
Densiplicatus climate shift	2455	160,8	1C
Gammalog Event III	2538	163,8	1A
Base lamberti Zone	2560	164,2	1A

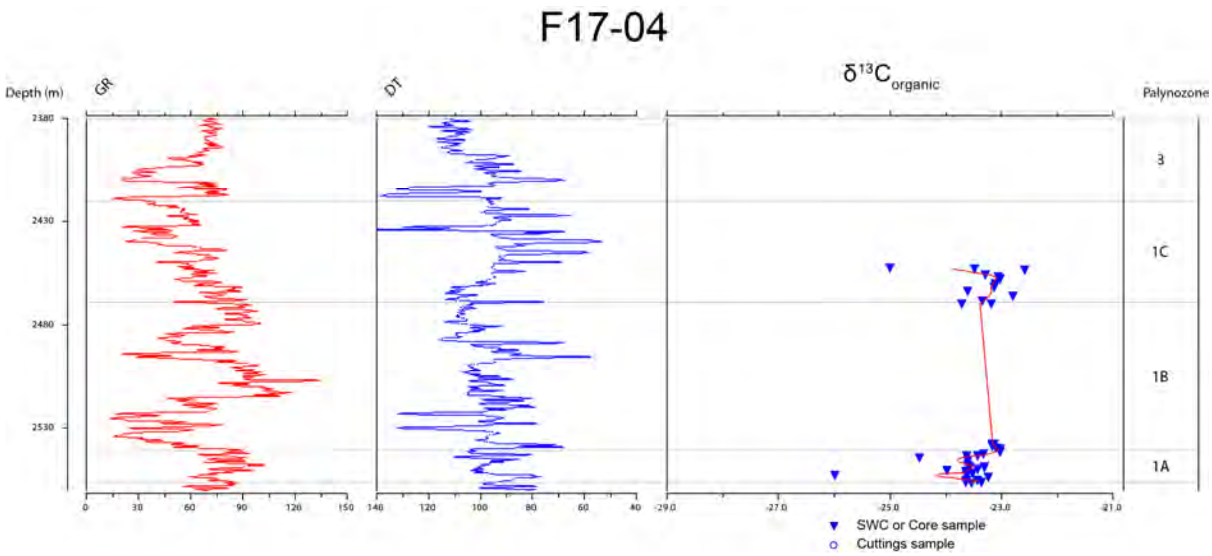


Figure 15 Carbon isotope results for well L17-04.

Samples from F17-04 cluster together between -22.5‰ and -23.5‰ with some negative outliers. The latter may relate to changes in organic facies, a feature commonly recorded in the Friese Front Fm. Samples from the lower cored section are of Late Callovian age, whereas samples from the upper cored section are of Middle Oxfordian age.

6.2.6 *Well L05-03*

Well L05-03 was drilled in the Dutch Cental Graben. We have generated organic carbon isotope data on 15 core samples between 2651 and 2610 m depth. The samples are derived from palynological residues. The age-model follows the calibration to the boreal ammonite zones by Abbink (1998).

Table 25 Age-diagnostic criteria used for correlation of well L05-03.

Event	**Depth (m)**	**Numerical Age**	**Palynozone**
Top *rosenkrantzi* Amm. Zone	2610,15	157,3	1D
Top *serratum* Amm. Zone	2634,05	159,2	1D
Top *glosense* Amm. Zone	2657	159,7	1C
Top *densiplicatus* Amm. Zone	2670	160,2	1C
Densiplicatus climate shift	2695	160,8	1C

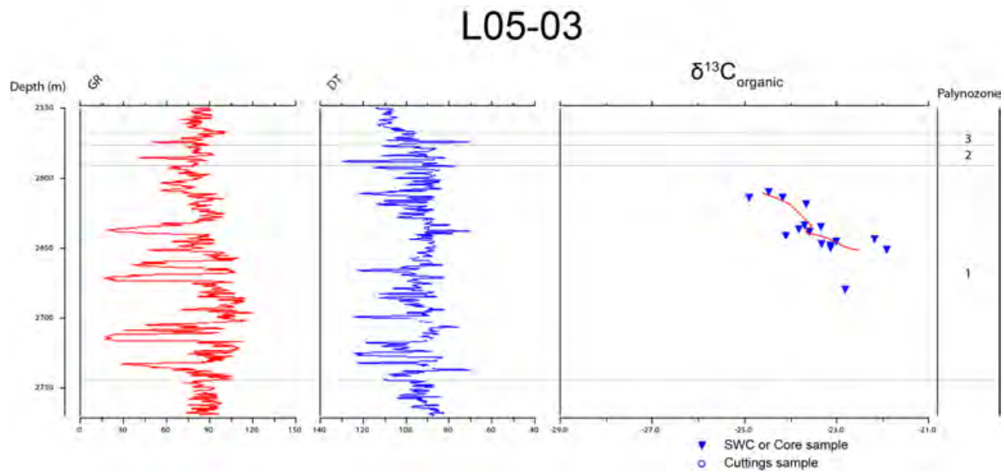


Figure 16 Carbon isotope results for well L05-03.

6.2.7 *Well L03-01*

The carbon isotope data are scattered between ~-21 and ~-25‰. The averaged signal however illustrate a trend towards more negative values, occurring in the Late Oxfodian.Well L03-01 was drilled in the Dutch Cental Graben. We have generated bulk organic carbon isotope data on 87 samples, 14 of which are derived from cuttings, the others from cores and sidewall cores. Measurements were performed on decalcified whole rock samples.

Table 26 Age-diagnostic criteria used for correlation of well L03-01.

Event	**Depth (m)**	**Numerical Age**	**Palynozone**
LOD *Daveya boresphaera*	1830	139,5	Top 3C
LOD *Rotosphaeraopsis thula*	1920	141,3	Top 3B
LAOD *Cribroperidinium hansenii*	2050	146	Top 3A
LOD *Glossodinium dimorphum*	2165	146,8	Top 2D
LOD *Occisucysta balios*	2210	148	Top 2C
LOD Common *Dichadogonyaulax*	2375	150,2	2B
Scitulus climate shift	2536,3	151,8	2B
LOD *Kraeuselisporites huntii*	2677,5	152,3	Top 2A
LOD *Retitriletes undulatus*	2906,2	153,5	2A

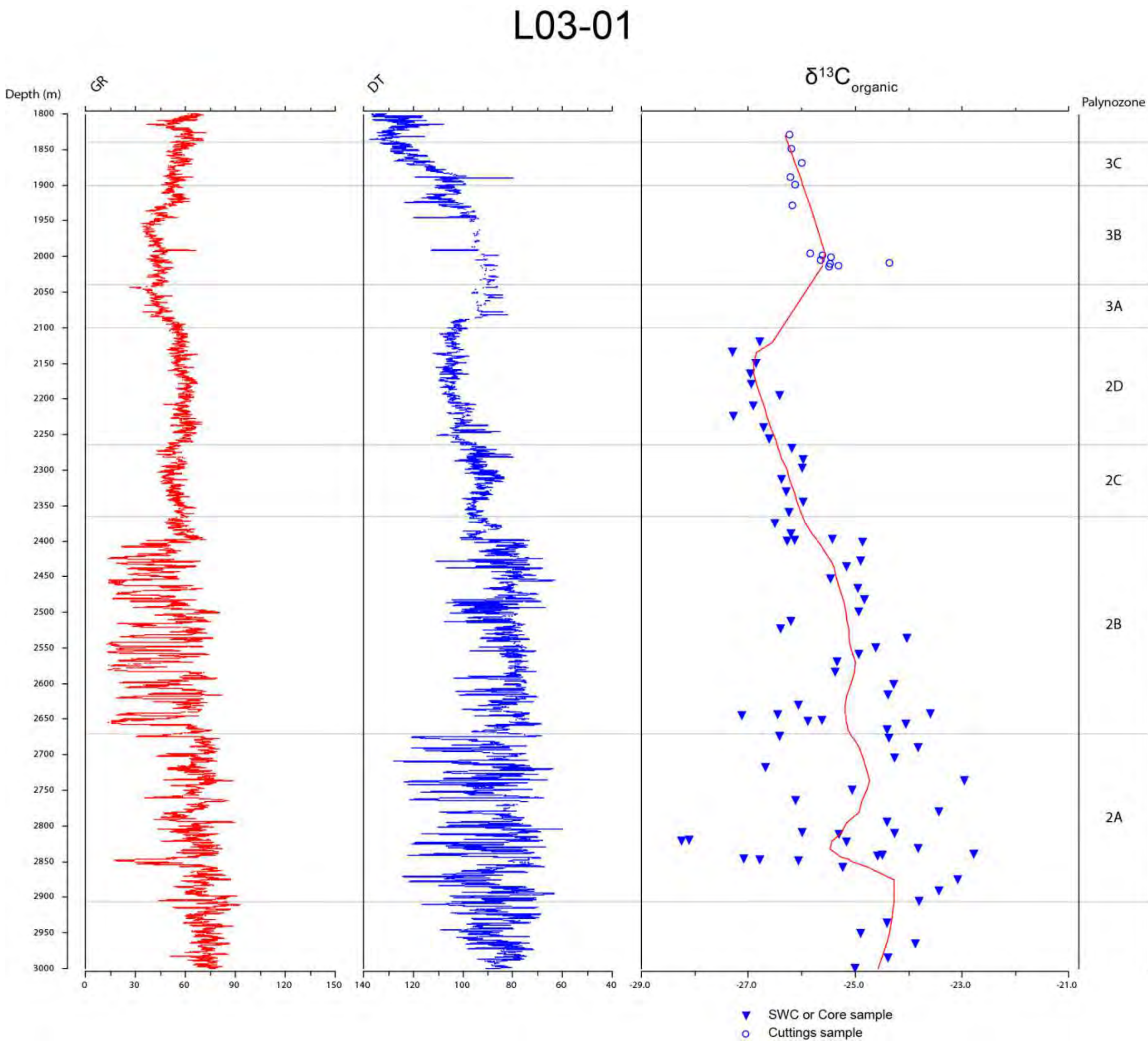


Figure 17 Carbon isotope results for well L03-01.

The δ^{13}C-values for the lower part of the studied succession (2906-2360 m depth)_ are characterized by large scatter. Lithostratigraphically this interval is part of the Friese Front Fm. and the Skylge Fm., which are both characterized as fluvial-coastal plain facies which are susceptible to substantial changes in organic substrate, explaining the high degree of variation. The age of this interval is Late Kimmeridgian to Early Volgian (154-150 Ma).

At 2400 m depth, the sedimentary facies becomes more clay-rich and stable (Kimmeridge Clay Fm.) and the scatter in δ^{13}C-values diminishes. A clear -1‰ negative shift is recorded (-26 ‰ to -27‰). This shift is dated to occur across the Middle Volgian (Zone 2C-D, 150-146.5 Ma). Cutting samples are analyzed from the upper part of the record from well L03-01. This interval is of Early Cretaceous (Early to Late Ryazanian) age (144,5 – 139,5 Ma) and the δ^{13}C-values are ~1‰ more positive than the underlying cored interval (~-26‰).

6.2.8 Well L06-03

Well L06-03 was drilled in the Terschelling Basin. We have generated $\delta^{13}C$-data on 6 side-wall core samples (palynological residues) and 41 core samples (decalcified whole rock). In total four intervals were sampled (2320-2305 m, 2266-2252 m, 2110-2095 m and 2043-2027 m depth.

Table 27 Age-diagnostic criteria used for correlation of well L06-03

Event	**Depth (m)**	**Numerical Age**	**Palynozone**
Top *lamplugh* Amm. zone	2028,9	143,9	3B
Top *prelicomphalus* Amm. Zone	2034	144,7	3B
Base *prelicomphalus* Amm. Zone	2044,57	145,9	3B
LOD *Glossodinium dimorphum*	2082	146,8	2D/3A
LOD *Occisucysta balios*	2100,05	148	2C
Unconformity Zone 2B-2C	2107,18	150,3-148,5	2B-2C
LOD Common *Dichadogonyaulax*	2107,63	150,3	2B
FOD *Gochteodinia mutabilis*	2110,3	150,5	2B
Scitulus climate shift	2258,55	151,8	2B
Infra-*eudoxus* Amm. Zone	2321,9	153	2A

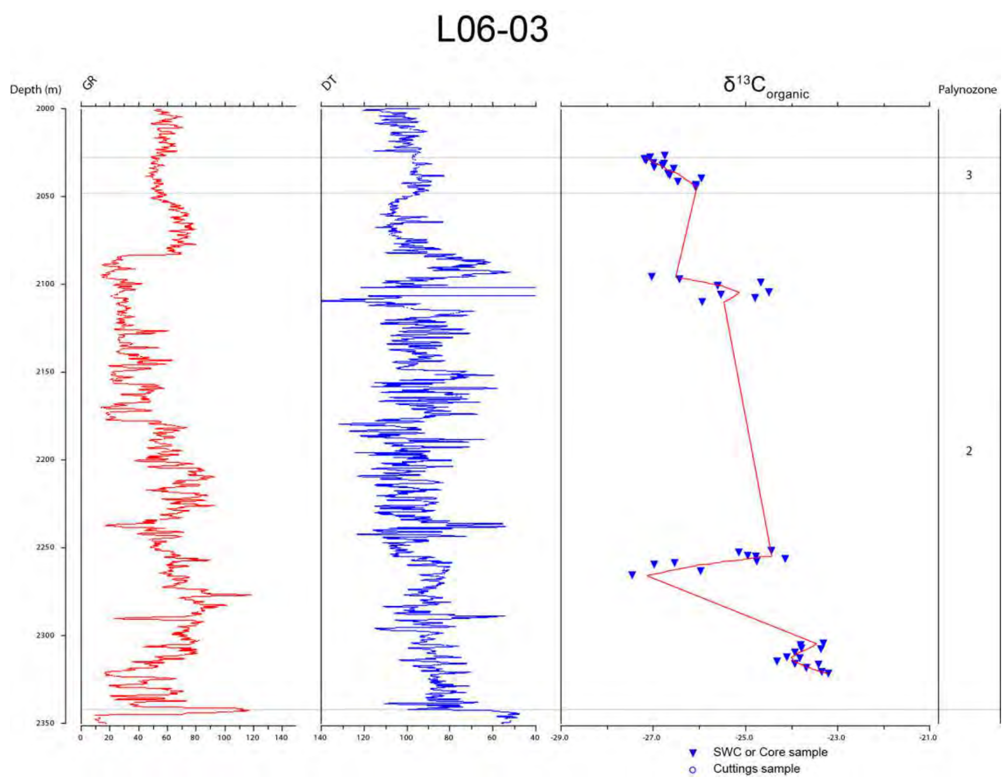


Figure 18 Carbon isotope results for well L06-03.

The lowermost cored section (2320-2305 m) is of Late Kimmeridgian age (~153 Ma). This relatively short interval is characterized by a relatively small transient negative shift and recovery (ranging between -23.3‰ to -24‰). This interval is part of the Friese Front Fm., with its characteristic high-order facies variability.

The cored interval between 2266 and 2252 m depth, captures a clear positive shift, starting at values that are substantially more negative (-27.5‰) than the underlying interval. At 2256 m, the $\delta^{13}C$ has increased to -24.2‰. This interval corresponds to the Kimmeridgian-Volgian transition (~152 Ma). No shifts of this magnitude have been reported from the literature (see e.g., Weissert and Mohr, 1996; Nunn and Price, 2010) across this interval. It therefore seems likely that this relatively short sampled interval represents variability partly driven by facies changes, which is not uncommon in the Friese Front Fm.

The same appears to be the case for the overlying cored section (2110-2095 m depth), where we record scattered values -24,5‰ and -27‰, which are dated as Middle Volgian (~148 Ma).

The uppermost cored section (2043-2027 m depth) spans the Late Volgian and Earliest Ryazanian (145,5-143,5 Ma). Lithostratigraphically, these samples are from the Scruff Greensand Fm., which is a fully marine unit. Hence, the clear observed ~-1‰ shift (-27‰ to -26‰) may appear to be a useful correlative feature.

6.2.9 Well M07-07

Well M07-07 was drilled in the Terschelling Basin. We have performed 60 carbon isotope analyses on the cored section between 3936 and 3988 m depth. The section spans the Ryazanian and Earliest Valanginian.

Table 28 Age-diagnostic criteria used for correlation of well M07-07

Event	Depth (m)	Numerical Age	Palynozone
Top *paratollia* Amm. Zone	3935,3	137,8	4B
LOD *Endoscrinium pharo*	3937,5	138,3	4A
LOD *Egmontodinium torynum*	3941,8	138,5	3C
LCOD *Oligosphaeridium diliculum*	3942,7	139,5	3C
Top *icenii* Amm. Zone	3954,6	140,2	3C
LOD *Rotosphaeropsis thula*/Top Kochi	3969,65	141,2	3B
Top *runctoni* Amm. Zone	3988,15	141,8	3B

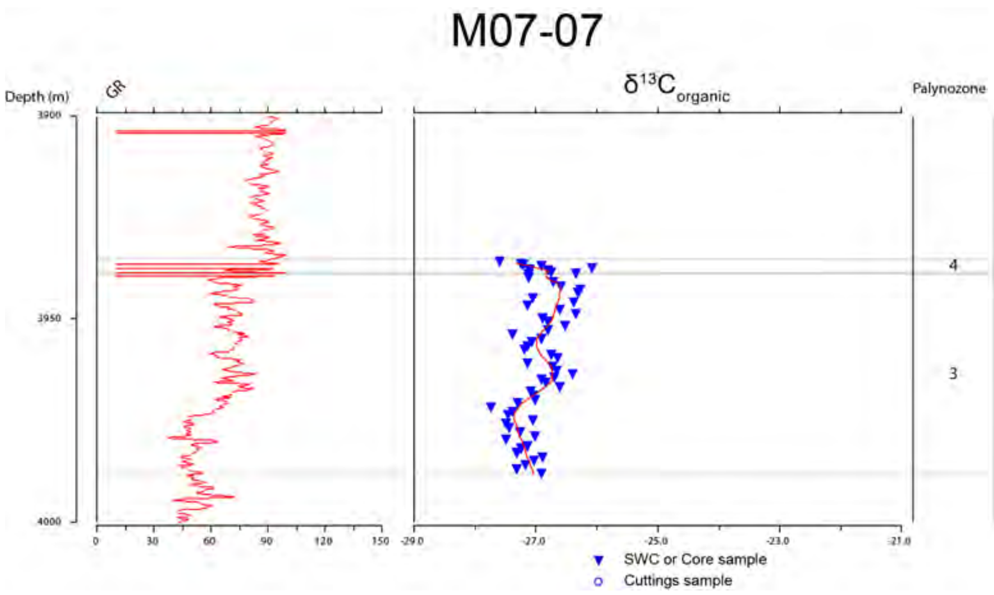


Figure 19 Carbon isotope results for well M07-07.

The record from well M07-07 depicts three high-order cycles. Average values are ~-27‰ and the variation is +-0,6‰. At the top of the investigated interval, in the Earliest Valanginian we note a negative -1,2‰ shift.

6.2.10 Well L16-06

Well L16-06 was drilled in the Broad Fourteens Basin. We have performed 9 carbon isotope analyses on the cored section between 1870 and 1860 m depth. The samples are derived from palynological residues. The interval is of Early Valanginian age (*polyptichites* Ammonite Zone).

Table 29 Age-diagnostic criteria for well L16-06.

Event	**Depth (m)**	**Numerical Age**	**Palynozone**
LOD *Canningia compta*	1860,5	137,2	4B
Infra 4B (absence of older markers)	1870,75	137,5	4B

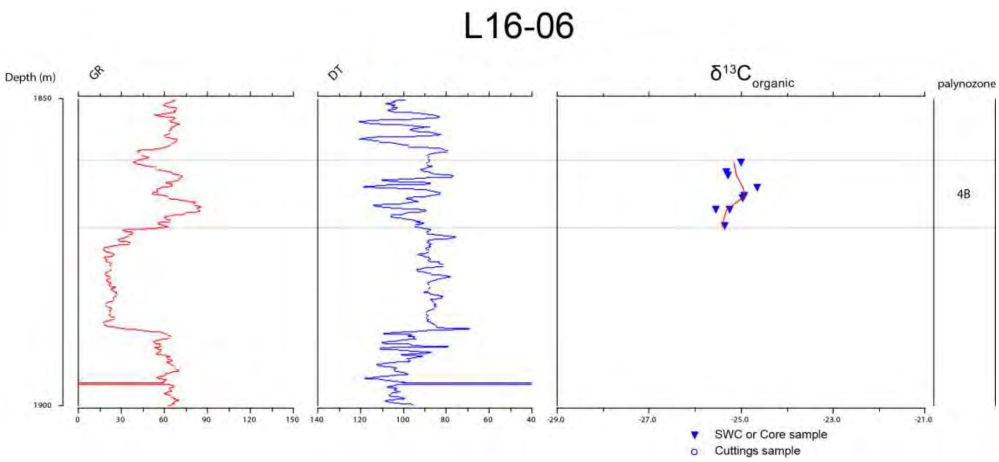


Figure 20 Carbon isotope results for well L16-06.

The isotope results of this Early Valanginian section closely cluster together around -25‰. The absence of clearly more negative values indeed suggests the interval overlies the earliest Valanginian.

6.2.11 Well P05-03

Well P05-03 was drilled in the Broad Fourteens Basin. We have performed 17 carbon isotope analyses on the cored section between 1165 and 1138 m depth. The samples are derived from palynological residues. The lower part of the record (1165-1161 m depth) is of Late Kimmeridgian age. The upper interval (1161-1138 m depth) is of Earliest Valanginian age (*Paratollia* Ammonite Zone) to Late Valanginian age.

Table 30 Age-diagnostic criteria for well P05-03

Event	Depth (m)	Numerical Age	Palynozone
LOD *Lagenorhytis delicatula*	1138,45	134	4C
Top Paratollia Amm. Zone	1150,05	137,1	4B
Unconformity into *Paratollia* Amm.Zone	1160,19	153,8-138	4A
LOD *Kraeselisporites/Densoisporites minor*	1161,14	153,8	2A
Lower Zone 2A	1164,45	154,5	2A

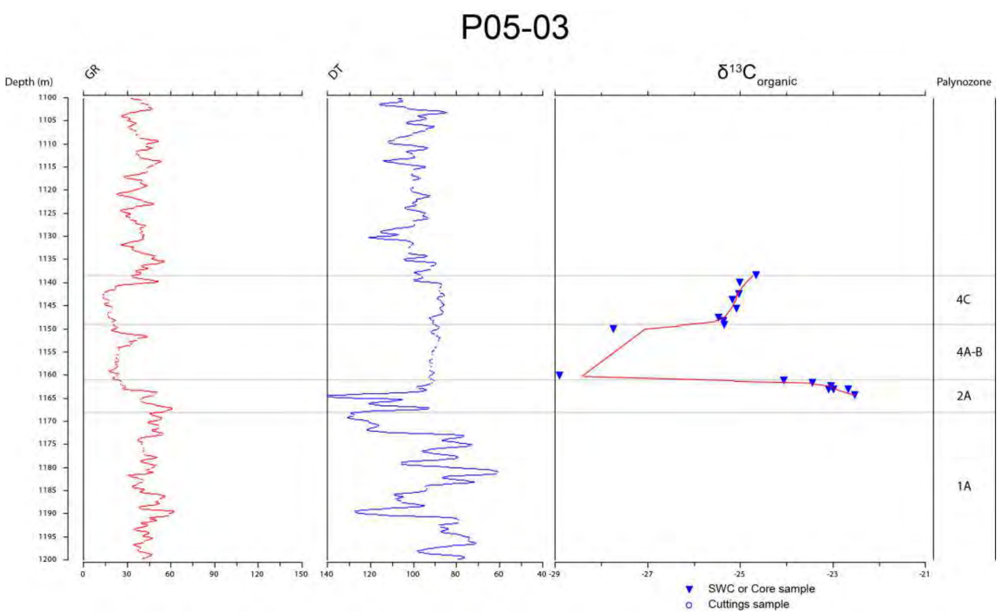


Figure 21 Carbon isotope results from well P05-03.

The lower samples are from the Late Kimmeridgian (Zone 2A, *mutabilis-eudoxus* Ammonite Zones) age and contain (part of a) trend towards more negative values(-22,5 to -24‰). A similar phenomenon is observed in coeval strata from the Dutch Central Graben (F03-03). Overlying we record two substantially more negative values (-28,8‰ and -27,7‰) of Early Valanginian age. This argues for the existence of an Early Valanginian negative event. Subsequently, through the Valanginian values become more stable around -25‰.

6.2.12 Well P08-03

Well P08-03 was drilled in the West Netherlands Basin. We have performed 21 carbon isotope analyses on the cored section between 2792 and 2891 m depth. The samples are derived from palynological residues. The record is of Early Valanginian (*paratollia* Ammonite Zone, Zone 4B) to Hauterivian age. An hiatus separates the Early Valanginian from the Early Hauterivian.

Table 31 Age-diagnostic characteristics for Well P08-03

Event	**Depth (m)**	**Numerical Age**	**Palynozone**
LOD *Kleithriasphaeridium corrugatum*	2797	129,3	4F
FOD *Subtilisphaera* spp.	2858,25	133,2	4D
Unconf: Val-Haut boundary	2868,5	134-137	4C-D
Top Zone 4B	2872,8	137,2	4B
Base Zone 4B	2891,5	137,8	4B

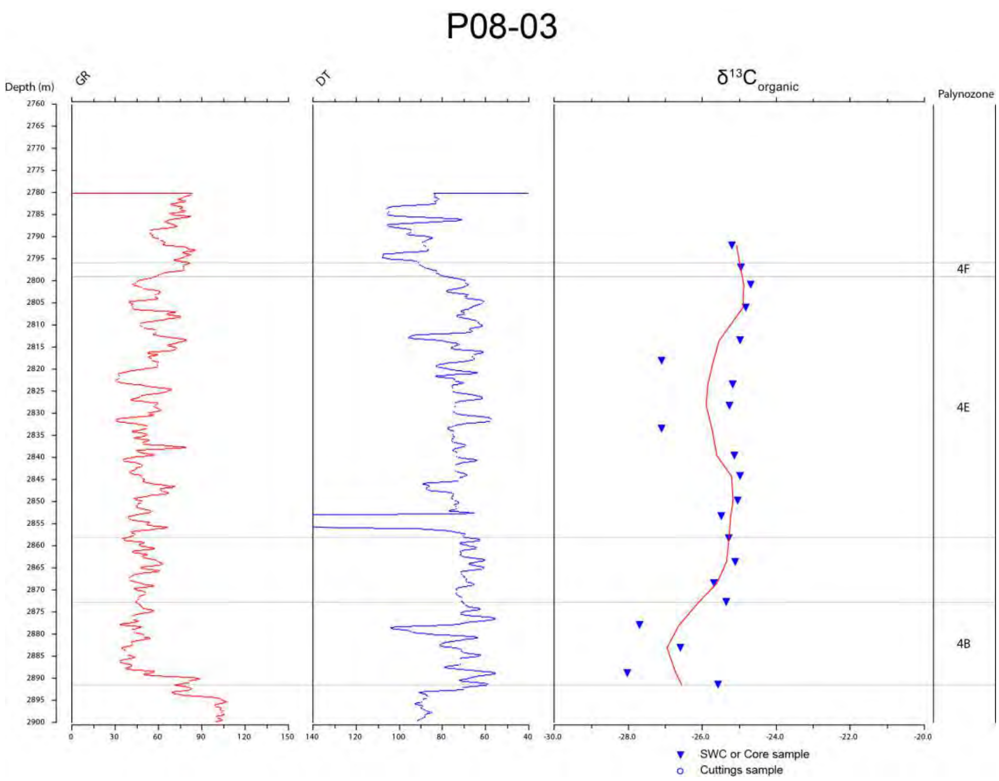


Figure 22 Carbon isotope results for well P08-03.

There are no obvious trends arising from the carbon isotope record of Well P08-03. Nevertheless, the samples of Early Valanginian age are more negative (on average -26,3‰). The Hauterivian age samples yield an average isotopic composition of -25,3‰.

6.2.13 *Well P09-03*

Well P09-03 was drilled in the West Netherlands Basin. We have performed 27 carbon isotope analyses on the cored section between 2151 and 2006 m depth. The samples are derived from palynological residues. The record is of Late Ryazanian (Zone 3C) to Late Hauterivian age. An hiatus separates the Late Ryazanian from the Early Hauterivian. Another hiatus is positioned in between the Late Valanginian and the Early Hauterivian. The base of the studied section is of Aalenian (Middle Jurassic) age. Samples from the latter interval are not included in the carbon isotope compilation.

Table 32 Age-diagnostic information for well P09-03.

Event	**Depth (m)**	**Numerical Age**	**Palynozone**
LOD *Kleithriasphaeridium corrugatum*	2006	129,3	4F
FOD *Subtilisphaera* spp.	2054,7	133,2	4D
LOD *Batioladinium varigranosum*	2077	133,7	4D
Base Zone 4D	2107	133,9	4D
LOD *Batioladinium* cf. *varigranosum*	2112	136,3	4C
Base Zone 4C	2147	137,2	4C
LOD *Egmontodinium torynum*	2151.1	138,6	4A

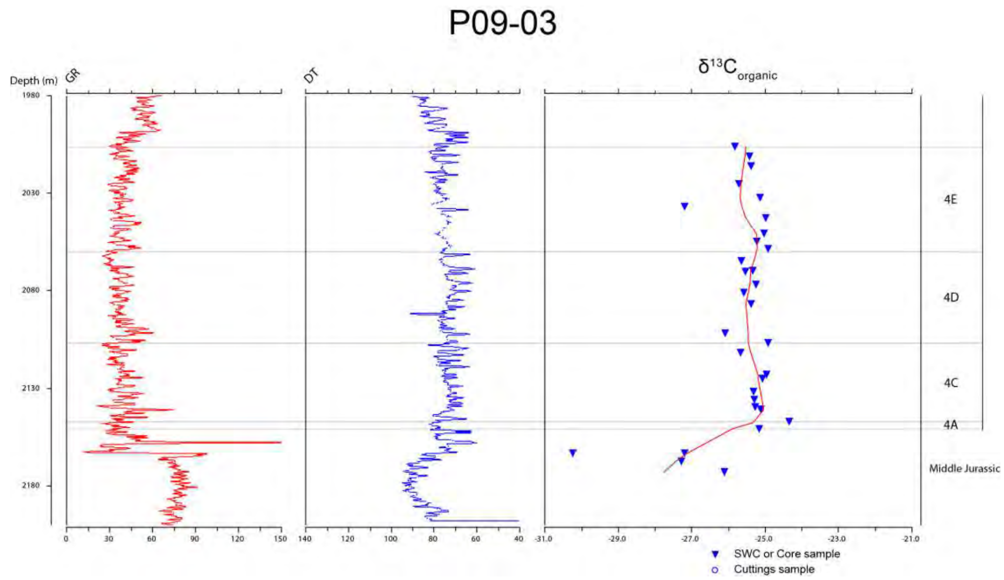


Figure 23 Carbon isotope results from well P09-03.

In the Earliest Valanginian, a single δ^{13}C-value yields -25,2‰). The values for the remaineder of the record representing the Late Valanginian through Hauterivian are relatively stable, -25,3‰ on average. There is no clear indication of a shift in isotope values across the Early-Late Valanginian or Late Valanginian-Early Hauterivian unconformities.

6.3 Compilation and discussion

We have compiled all the 583 $\delta^{13}C$ measurements by providing age-dates for every sample and following Gradstein et al. (2012). Next, we have calculated a 10 point moving average through the data points to best reveal trends in the data. The calculated standard deviation (grey bars) is a measure of the variation at a certain point in this record.

The following trends and patterns are indentified (see also Figure 24).

(A) A distinct ~+2‰ characterizes the Callovian-Oxfordian boundary, starting off at background values in the Late Callovian of ~-24‰. After this shift, the Earliest Oxfordian (mariae Ammonite Zone) is characterized by a subtle ~-1‰ shift.
(B) The remainder of the Oxfordian and Early Kimmeridgian are characterized by relatively stable values, varying between -23.5 and -22.5‰. The scatter in this interval is relatively small.
(C) In the Late Kimmeridgian, the scatter between data points becomes larger, yet prominent shift remain discernable. A ~-2‰ negative shift is recorded corresponding to the mutabilis – eudoxus Ammonite Zones. On average, the most negative values approximate -25.5‰, with extremes of about -28‰.
(D) Also across the Kimmerdgian-Volgian boundary, the scatter in $\delta^{13}C$ remains substantial. Following on the negative shift in the mutabilis-eudoxus Ammonite Zones, we note a latest Kimmeridgian (eudoxus-autissiodorensis Ammonite Zones) positive shift and an earliest Volgian (autissiodorensis-elegans Ammonite Zone) negative shift.
(E) In the Early Volgian (scitulus to pectinatus Ammonite Zones), we note a gradual shift towards more negative values, eventually balancing off at ~-26‰. The remainder of the Volgian remains relatively stable, despite large scatter.
(F) The base of the (boreal) Cretaceous is characterized by a ~-1‰ shift (lamplughi-runctoni Ammonite Zones). Since the newest revision of the International Timescale prescribes a very long duration for the interval corresponding to the runctoni Ammonite Zone, the duration of this shift may be exaggerated. Nevertheless, the pattern of a negative in the Early Ryazanian is an important observation.
(G) In the Late Ryazanian, we note distinct ~0.6‰ higher order cyclic variations superimposed on a subtle positive shift culminating during the interval corresponding to the stenomphalus Ammonite Zone. Overall, the Ryazanian values remain more negative than in the Volgian.
(H) The Early Valanginian is characterized by a distinct 2‰ positive shift, spanning the Paratollia and Polyptichites Ammonite Zones. Values stabilize around -25‰.
(I) The remainder of the Valanginian, Hauterivian and Barremain remais to yield remarkably stable values of ~25.2‰.

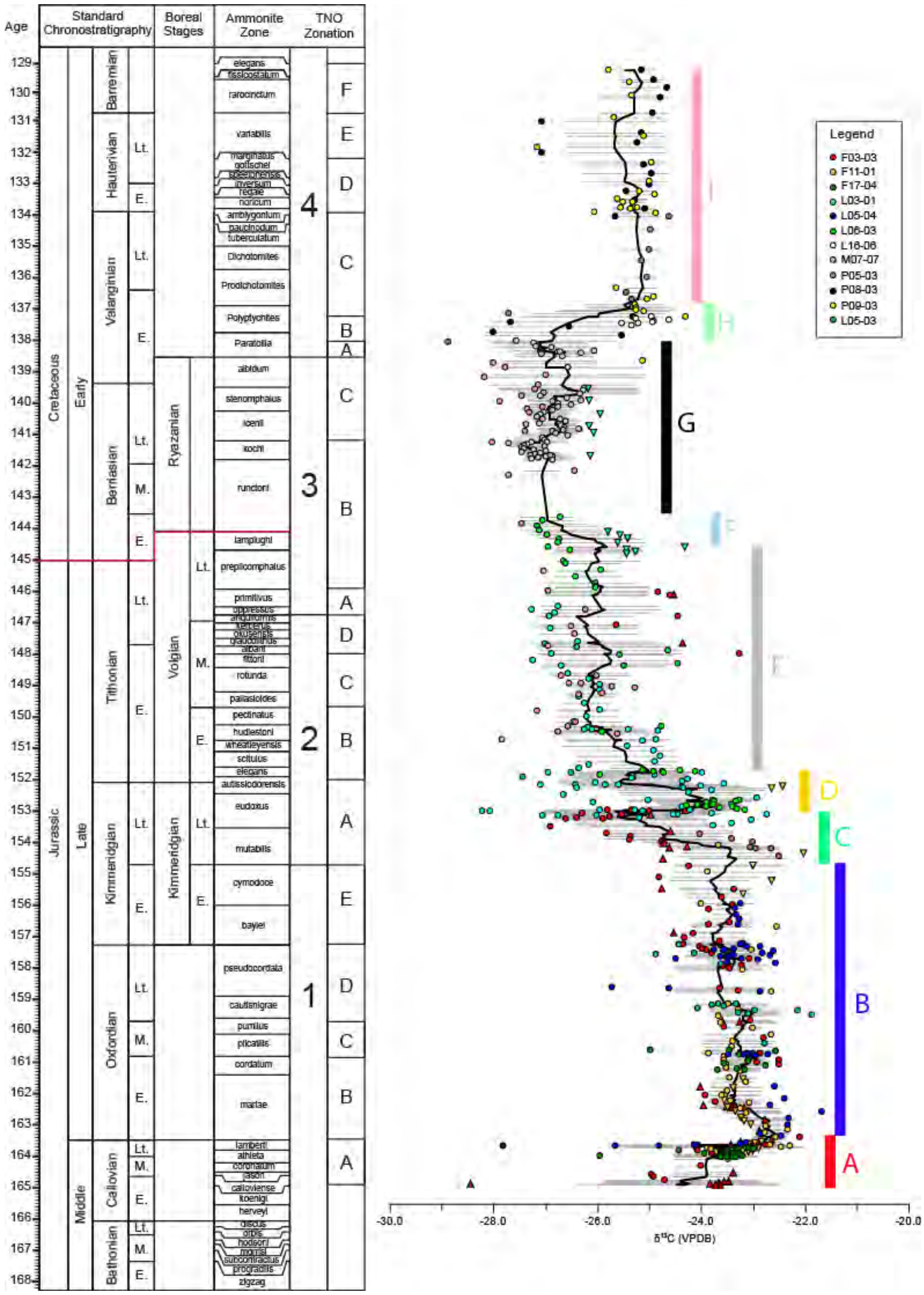


Figure 24 Compilation of organic δ^{13}C-values from the Upper Jurassic to Lower Cretaceous. The timescale and ammonite zonation is after Gradstein et al. 2012. The colours of the markers indicate the sampling locality. Circles refer to core- or sidewallcore material. Triangles indicate samples from cuttings. The thick black line is the 10-point-moving average. The horizontal grey bars represent the standard deviation of the running mean and can be interpreted as a measure of the variation in the dataset. At the right of the figure, the coloured bars indicate the intervals of isotope variation that are discussed in this report.

6.3.1 Discussion: Implications for stratigraphic correlation and suggestions for improvement

The carbon isotope analyses presented here, stem from organic matter, either derived from palynological residues or bulk material. There is no substantial offset between measurements that are based on bulk-rock material and from palynological residues. In this study, a large majority of samples are derived from core or sidewall core material. In the few cases where material was derived from cuttings (triangles in Figure 24), these are often consistently heavier than the running mean. The reason for this is still to be addressed, but it is conceivable that contamination, through caving from overlying strata is predominantly sourced from specific interval with high δ^{13}C-values.

Given that virtually all preserved organic matter stems from photosynthetic organisms, four major factors cause changes in the isotopic composition:

(I) The δ^{13}C-values through the record may vary with the **type organic substrate**. Marine (algal) organic matter is typically more depleted in ^{13}C than terrestrial plant matter.

(II) **Atmospheric CO_2 concentrations** (pCO_2) influence the photosynthetic fractionation of carbon isotopes. More negative values are associated with elevated pCO_2.

(III) The **isotopic composition of the atmospheric CO_2** may change through exogenic outgassing. This essentially refers to transient pulses of injection of carbon with a distinct (negative) isotopic signature. Examples include the present-day combustion of fossil fuels and the release of methane during the Early Toarcian and the Early Eocene, both leading to excess ^{12}C and thus more negative δ^{13}C-values.

(IV) The δ^{13}C of algal organic matter may also be influenced (locally and globally) by high levels of **primary production and/or burial of organic matter** in the water column. This is because high primary production will lead to uptake and burial of material rich in ^{12}C out of the surface layer. Successivley produced organic matter will therefore become increasingly more positive in δ^{13}C.

Although changes in photosynthetic fractionation of carbon isotopes can be very substantial, even among plant- or algal species (e.g., Benner et al., 1987, Farquhar et al., 1989), marine organic matter is typically more depleted in ^{13}C and therefore has more negative δ^{13}C-values. This relates to different photosynthetic enzymes used by marine organisms and the fact that dissolved CO^2 in sea-water is depleted by ~7‰ relative to atmospheric CO_2 (Chisholm et al., 1982). Hence, part of the variation in the record is expected to be explained by changes in whether "marine" or "terrestrial" substrate is analyzed. As a starting point, we can address for this factor by evaluating whether prominent changes in depositional facies co-occur with changes in δ^{13}C.

The Callovian-Oxford transition (Interval A in Figure 24) represents one of the more prominent isotope shifts. Key-wells for this interval are F03-03 (northern DCG) F17-04 (southern DCG) and F11-01 (middle DCG). In the entire area, deposition occurred in a fluvial- to coastal plain setting and shallow marine influence is observed only in the Upper Callovian of the Lower Graben Fm. (Munsterman et al., 2012). A similar depositional setting is sustained throughout the Early Oxfordian. Hence, there are no obvious indications for changes in organic-substrate. Hence, a more important contribution of global climate change is expected in relation to the positive carbon isotope shift recorded across the Callovian-Oxfordian boundary. In fact, it has been suggested, primarily on the basis of oxygen isotope studies, that the Callovian-Oxford transition was a phase of global cooling and its characteristic positive carbon isotope shift is also widely recognized (Dromart et al., 2003;.Tremolada et al., 2006; Nunn et al., 2009). This would be in-line with the increasing δ^{13}C-pattern, which would invoke a demise in pCO_2.

The relatively positive and stable values of the Oxfordian are also quite in-line with what is observed elsewhere. Dera et al. (2011) and Jenkyns (1996) present pelagic belemnite δ^{13}C-data, in which apart from relatively stable Oxfordian values, a gradual shift towards more positive values is recorded in the Middle Oxfordian. There is a well-claibrated record of the Oxfordian-Kimmeridgian transition from the Isle of Skye (Nunn et al., 2009), where the transition is reflected by stable values. Also, there is no reason to invoke major changes in depositonal facies, which potentially underestimate isotopic change in the Southern North Sea Basin.

The scattered but substantial negative isotope shift in the Late Kimmeridgian (Interval C in Figure 24, mutabilis-eudoxus Ammonite Zones) is recorded particularly in well F03-03 and falls well within the Kimmeridge Clay Fm., which is characterized by continuous deposition in an outer shelf environment. The recovery towards positive values may correspond to a positive shift (Interval D) that is also recorded in the Kimmeridgian Type Section in Dorset, UK (Morgans et al., 2001). Hence, the patterns recorded in this interval are not always supraregionally constrained, which may suggest that the isotope shifts reflect basinal and/or facies restricted patterns. Nevertheless, it appears that the Late Kimmeridgian (mutabilis to autissiodorensis Ammonite Zones) was a period of profound climatic and/or local productivity change in the SNB. This is examplified by restricted organic-rich intervals recognized within the formation (Munsterman et al., 2012) and by quantitative sporomorph distribution patterns (Abbink et al., 1998) that characterize the Late Kimmeridgian as a transitional phase to more arid continental climates.

The Tithonian/Volgian is represented by Interval E in Figure 24, is characterized by relatively stable values, with relatively high scatter, especially for the younger part. The records stem from wells F11-01, L03-01 (s-DCG) and L06-03 (Terschelling Basin) and are represented by the Noordvaarder and Lies Members of the Skylge Fm. This depositional system is characterized by shallow marine to restricted conditions, which may be susceptible to substantial changes in marine vs. fluvial influence, explain the highly scatter nature, which inreases up-section.

The negative shift recorded in Late Volgian to Early Ryazanian, particularly in well L06-03 is recorded in sediments assigned to Scruff Spiculite Member of the Scruff Greensand Fm. as part of a largely transgressive shorface complex, in which substantial changes in marine vs. fluvial input can not be excluded.

The record from Well M07-07 covering the upper part of the Ryazanian is characterized by three cycles which have an overall positive shift (Interval G). One of the positive shifts corresponds to the kochi-icenii Ammonite Zone interval. This interval is characterized by a prominent climatic, particularly manifested by more humid conditions. The latter shift would appear to results from an increase in fluvial influence on the interval.

A very prominent feature of the isotope record (Interval H) is the increase recorded in the Lower Valanginian (inception in the Polyptichites Ammonite Zone). Although this part of the record stems from the BFB, this does likely not explain this prominent shift, which is also clearly recorded *within* the single record from well P05-03. The ~+2‰ positive shift is a widely documented phenomenon that is often described as the 'Weissert Event' (Nunn et al., 2010, Lini et al., 1992; Weissert et al., 1998, Greselle et al,. 2011). Consequently, its fast onset and global distribution make it an excellent correlative isotope marker. Overall, this positive shift is now thought to be linked to a period of cooling that was possibly brought about by extensive organic carbon deposition and drawdown of atmospheric CO_2 (Nunn et al., 2010, Price and Mutterlose, 2004). The remainder of the Valanginian is remarkably stable, which is also in agreement with the global record.

In summary, the most important trends that may be useful for future stratigraphic correlation are the following:

(I) The positive shift across the Callovian-Oxfordian boundary
(II) Stable, relatively positive values in the Oxfordian to Early Kimmeridgian
(III) A sharp positive shift in the Late Kimmeridgian
(IV) Stable, relatively negative values for Volgian and Ryazanian
(V) The sharp positive excursion in the Early Valanginian
(VI) Stable, relatively positive values in the Late Valanginian to Hauterivian.

The present record presents the first, complete carbon isotope compilation of a single region. The applicapility of the record for stratigraphic purposes can strongly benefit from a better understanding of local vs. global isotopic change. Important steps towards such understanding may be achieved by:

(I) A thorough assessment of organic substrate change using log-based transfer functions and palynological evaluation
(II) Enhanced age-control for specific sections. In particular, the Oxfordian and Kimmeridgian
(III) Validation of the patterns in coeval intervals in stratigraphic reference sections.

7 Facies development and depositional dynamics in the Step Graben

In this chapter, the Late Jurassic to Early Cretaceous basin evolution of the Step Graben is described (Figure 1). The age and palaeoenvironmental interpretations from the palynological analyses are used to construct palaeogeographic maps of the Step Graben area. In addition, the facies maps from the Central Graben and the Terschelling Basin from Munsterman et al. (2012) are incorporated. For the Step Graben area data points (wells) are used to indicate the facies, for the Central Graben and Terschelling Basin, colored shading is used (after Munsterman et al., 2012). The maps display the facies changes of the basin in 8 time slices. For age reference, the TNO Zonation is applied (Figure 6), for the paleo-environmental interpretations, reference is made to Figure 7. Wheeler diagrams are constructed to capture the basin evolution in two diagrams (Figure 40 and Figure 41).

7.1 Structural setting of the SG

The name of the Step Graben is not derived from a geographical feature, but from the fact that it is considered to be an intermediate block, stair-stepping from the Elbow Spit Platform into the Central Graben. According to Van Adrichem Boogaert & Kouwe (1993-1997): "the Step Graben was considerably less affected by Late Jurassic to Early Cretaceous rifting than the Central Graben (Figure 25). The Upper Jurassic successions are relatively thin. Halokinesis accelerated during the Late Jurassic and Early Cretaceous, and resulted in the formation of salt walls that are parallel to the main north-south faults".

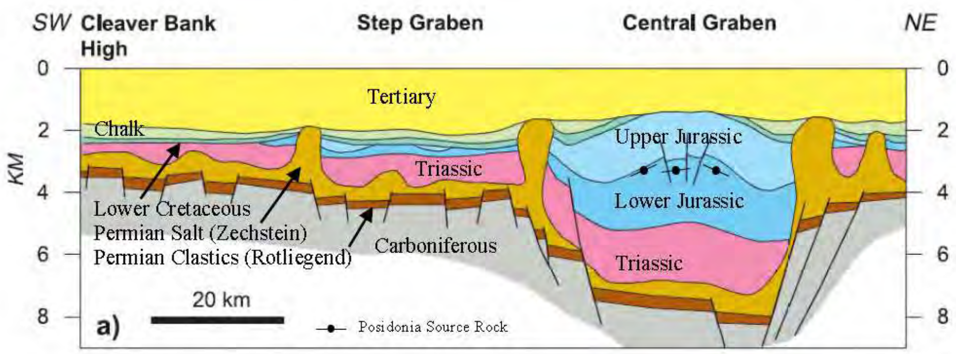


Figure 25 Schematic cross-section through the Step Graben and Central Graben. Note the strong thickness variation of the Triassic and Jurassic successions (from De Jager, 2007).

In general, the Step Graben is structured as a series of gentle synclinal and anticlinal folds in the eastern part, gradually changing into more half-graben structures with a rotational component in the western part (Figure 26). The normal faults bordering the half grabens dip Eastward. All folds and faults are associated with salt and are roughly aligned in a North-South direction. In several places, chimneys are visible above the crests of the anticlines and faults, sometimes associated with bright spots in the deltaic deposits of the Upper North Sea Group (Figure 27).

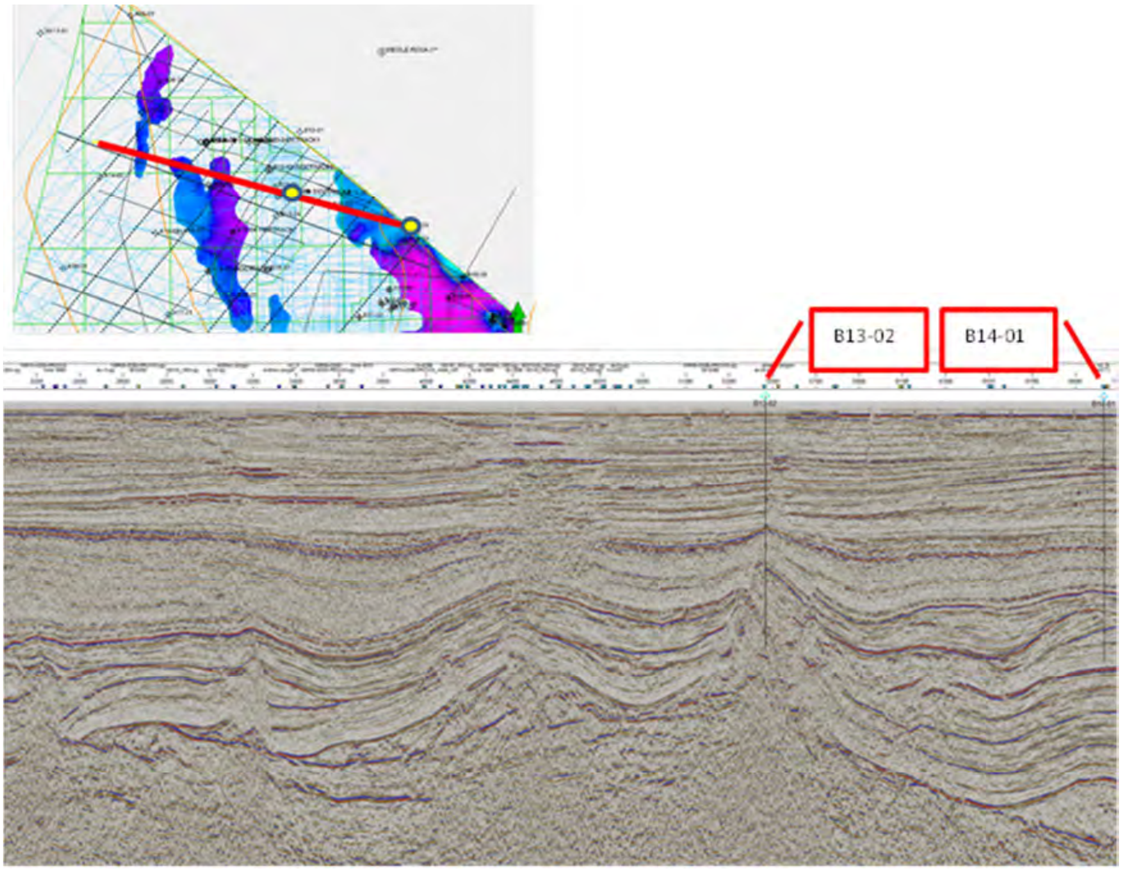


Figure 26 Seismic cross-section from West to East through the Step Graben. Two wells are located on this line: B13-02 and B14-01.

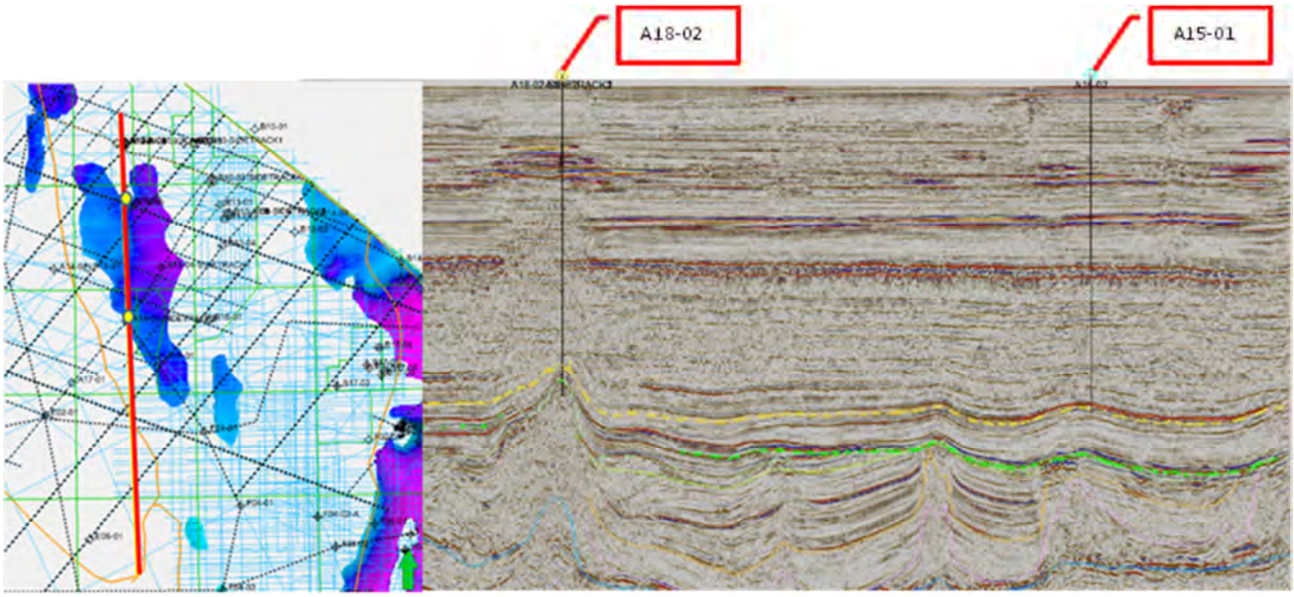


Figure 27 Seismic cross-section from South to North though the Step Graben. In between wells A18-02 and A15-01, the Upper Jurassic Schieland Group is present (in between the green markers). Note the occurrence of a chimney and a bright spot, above the salt structure of A18-02.

7.2 Palaeogeographic development of the SG

Middle Callovian to Early Kimmeridgian (Graben Axis Phase = TNO Zone 1)

In principal, Middle Callovian to Early Kimmeridgian deposits are limited in occurrence to the axis of the Dutch Central Graben. This time interval represents the initiation of the Late Jurassic rift phase. During this basin evolution phase a variety of non-marine, transitional marine and marine sediments fill the accommodation space created by E-W extension of the Late Jurassic rift phase. The sediments comprise a variety of fluvial, marginal marine, lacustrine, coastal plain and open marine deposits.

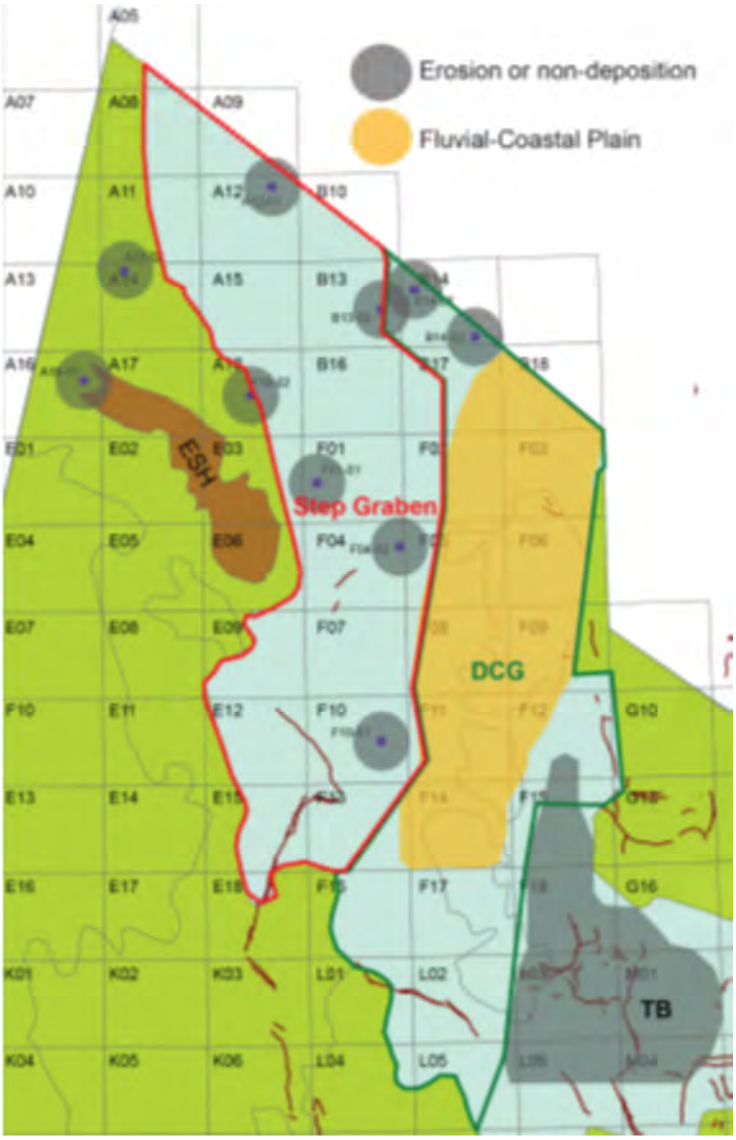


Figure 28

Paleogeography of the Middle Callovian (**lower part of TNO Subzone 1A).**

Note: For the Step Graben, single data points (circles) are used to indicate the facies. These data are derived from this study. For the Dutch Central Graben (DCG) and Terschelling Basin (TB), colored shading is used (polygons) to indicate the facies. These data are modified after Munsterman et al., 2012.

Jurassic basins in light blue, plateau areas in green and structural highs in brown.

In the oldest part of the succession, corresponding to **Subzone 1A**, predominantly fine-grained sandstones occur in beds generally less than 10 m thick, with intercallations of silty to sandy claystones. These sediments belong to the Lower Graben Fm., entirely consisting of fluvial to coastal plain deposits (Figure 28).

Within the Lower Graben Fm, a transgressive trend is observed, culiminating in a maximum flooding surface (mfs) near the top of the Lower Graben Fm. This mfs corresponds to the **uppermost part of TNO Subzone 1A** and to the J46 *lambertii* mfs sensu Partington et al., 1993. The distinctly marine horizon can be correlated all the way from the northernmost F03 Block to the southernmost L05 Block. In the southern part of the Central Graben axis, the marine sediments are developed in a more fine-grained facies, the Rifgronden Mb. (Figure 29). Interestingly, Callovian sediments do not occur in the Step Graben, but marine sediments correlating to the mfs of Subzone 1A can be found at the base of caprock sequences on top of diapirs and salt walls in the greater Central Graben area. Apparently, the latest Callovian transgression flooded a large area outside the basin axis, but the associated sediments only got preserved in the mini-basins on top of the salt structures.

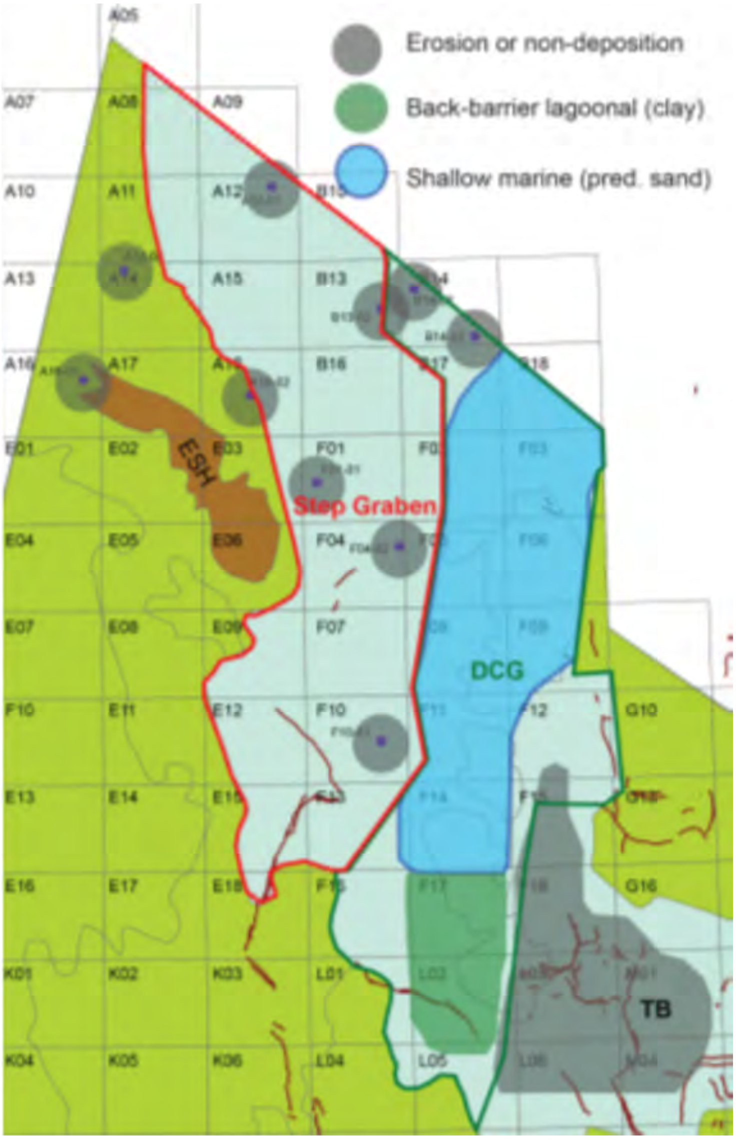


Figure 29

Paleogeography of the latest Callovian (J46 mfs, **top of TNO Subzone 1A**).

Note: For the Step Graben, single data points (circles) are used to indicate the facies. These data are derived from this study. For the Dutch Central Graben (DCG) and Terschelling Basin (TB), colored shading is used (polygons) to indicate the facies. These data are modified after Munsterman et al., 2012.

Jurassic basins in light blue, plateau areas in green and structural highs in brown.

After the Late Callovian transgression, the sand-prone marine facies of the Lower Graben Fm was abruptly replaced by organic-rich mudstone facies of the Middle Graben Fm. Three thick coal beds, exceeding 1 meter in thickness, occur in the lower 75 meters, correlating to the base of the Oxfordian (**Subzone 1B**). It is possible to correlate the coal layers all the way from the northermost F03 Block to the southermost L05 Block, indicating 1) sediment starvation, 2) a flat and tectonically undisturbed basin floor, 3) a wet climate, suitable for large-scale peat development. During the the course of the Late Oxfordian and earliest Kimmeridgian, corresponding to **Subzones 1C to 1E**, distinct facies belts develop in the Central Graben axis (Figure 30). In the southern part of the Central Graben axis (F17-L02-L05), a predominant non-marine sequence belonging to the Friese Front Fm. occurs, in the middle part of the Central Graben axis (F09-F11-F14), delta plain deposites belonging to the Puzzle Hole Fm. develop. Towards the North (F03-F06), the Puzzhole Fm grades into into deltaic sandstones (mouth bars and beach-barrier complexes) of the Upper Graben Fm. (see also Figure 10). Further North (B14-B18), the deltaic sandstones are absent, only offshore marine mudstones of the Kimmeridge Clay Fm. occur. The deltaic sandstones are limited in stratigraphic occurrence to **TNO Subzone 1D.** Note that the transitions between the facies belts seem to line up with existing NW-SE trending faults, such as the Rifgronden Fault for example. Possibly, these are the first indications of the eminent change in the regional tectonic regime.

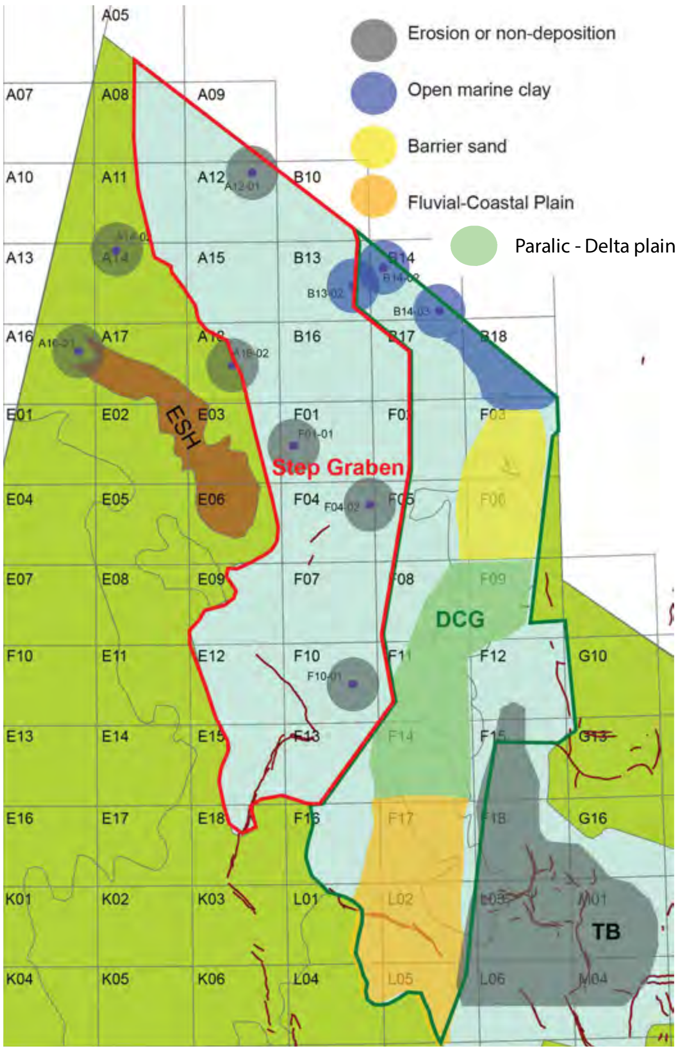


Figure 30

Palaeogeography of the Late Oxfordian to Early Kimmeridgian (**TNO Subzone 1D to 1E**)

Note: For the Step Graben, single data points (circles) are used to indicate the facies. These data are derived from this study. For the Dutch Central Graben (DCG) and Terschelling Basin (TB), colored shading is used (polygons) to indicate the facies. These data are modified after Munsterman et al., 2012.

Jurassic basins in light blue, plateau areas in green and structural highs in brown.

Late Kimmeridgian to Middle Volgian (Peripheral Basins Phase = TNO Zone 2)

After the change in tectonic regime, at the onset of the Peripheral Basins Phase, the Step Graben and the Terschelling Basin become active basins and starts receiving sediments. In the DCG, the transition from the Graben Axis Phase to the Peripheral Basins Phase is rather gradual, no abrupt changes are observed. Nevertheless, the change from TNO Zone 1 to TNO Zone 2 is detectable on wireline logs. In wells **B14-03** or **F03-03** for instance, the typical Kimmeridge Clay wireline log - a cyclic hour-glass pattern of the GR and DT together with numerous peaks caused by dolomite streaks - is followed up by a rather indistinct and non-cyclic shaly pattern, reflecting perhaps less pelagic sedimentation and more influence from sediment transport (). In the Step Graben proper, the first locations where Upper Jurassic sediments of Subzone 2 were deposited and preserved are wells **A18-02-S1, A16-01** and **A14-02** (Figure 31)**.** Surprisingly, these wells are located farthest away from the Central Graben and closest to the Elbow Spit High. The sediments, belonging to **Subzone 2A**, are rather indistinct shaly (**A14-02, A16-06**), in which case these are assigned to the Lies Mb of the Skylge Fm (see e.g. Figure 10) or a bit more sandy (**A18-02-S1**), in which case assignment to the Noordvaarder Mb of the Skylge was made. Note that nowhere significant thicknesses are attained.

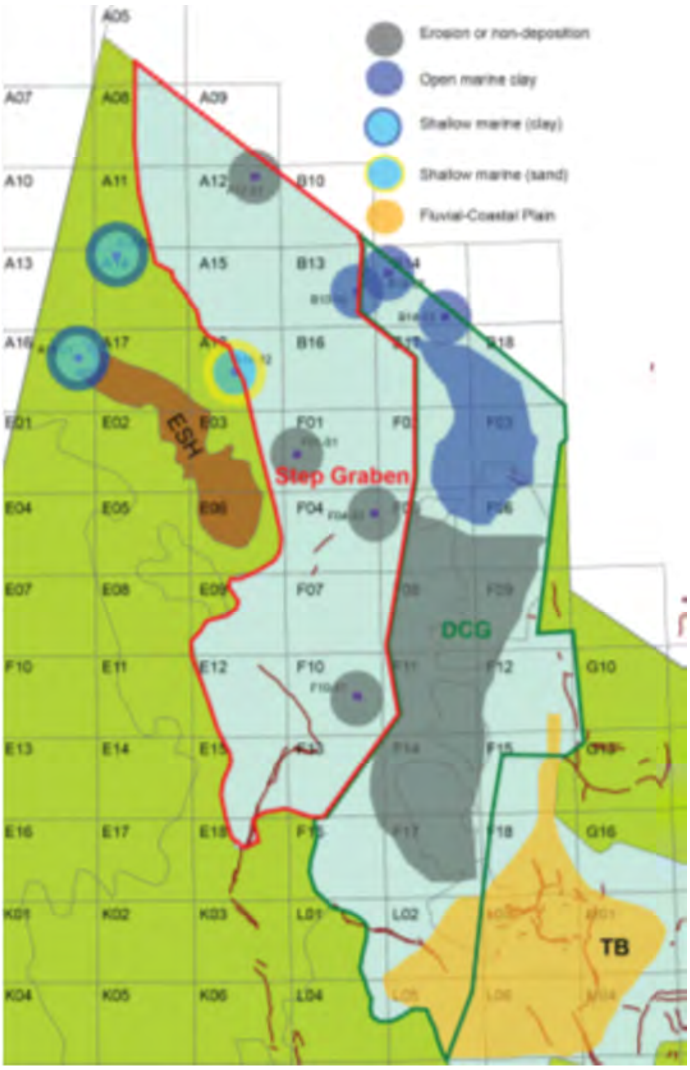


Figure 31

Palaeogeography of the Late Kimmeridgian (**TNO Subzone 2A**)

Note: For the Step Graben, single data points (circles) are used to indicate the facies. These data are derived from this study. For the Dutch Central Graben (DCG) and Terschelling Basin (TB), colored shading is used (polygons) to indicate the facies. These data are modified after Munsterman et al., 2012.

Jurassic basins in light blue, plateau areas in green and structural highs in brown.

During the Early Volgian (**TNO Subzone 2B**), the re-activated NW-SE salt structure in the northern B13 and B14 Blocks starts shedding sediments to the NE, effectively killing the pelagic mudstone deposition of the Kimmeridge Clay Fm (Figure 32, Figure 33, Figure 34). The coarsening upward sequence end with sandstones, which are assigned to the Noordvaarder Mb of the Skylge Fm. A thickness of 172 m is attained in well B13-02 (Figure 34). These sands are time-equivalent to the sandstones of the Terschelling Sandstone Mb in the Terschelling Basin (Figure 10). The Noordvaarder sands of wells A18-02-S1, B13-2 and B14-2 do not continue into the Middle Volgian (**TNO Subzone 2C and D**), probably due to minor uplift and erosion in the Late Volgian (TNO Zone 3). The youngest Zone 2 sands (**TNO Subzone 2C**) in this northern area are found in well B14-03 (Figure 34).

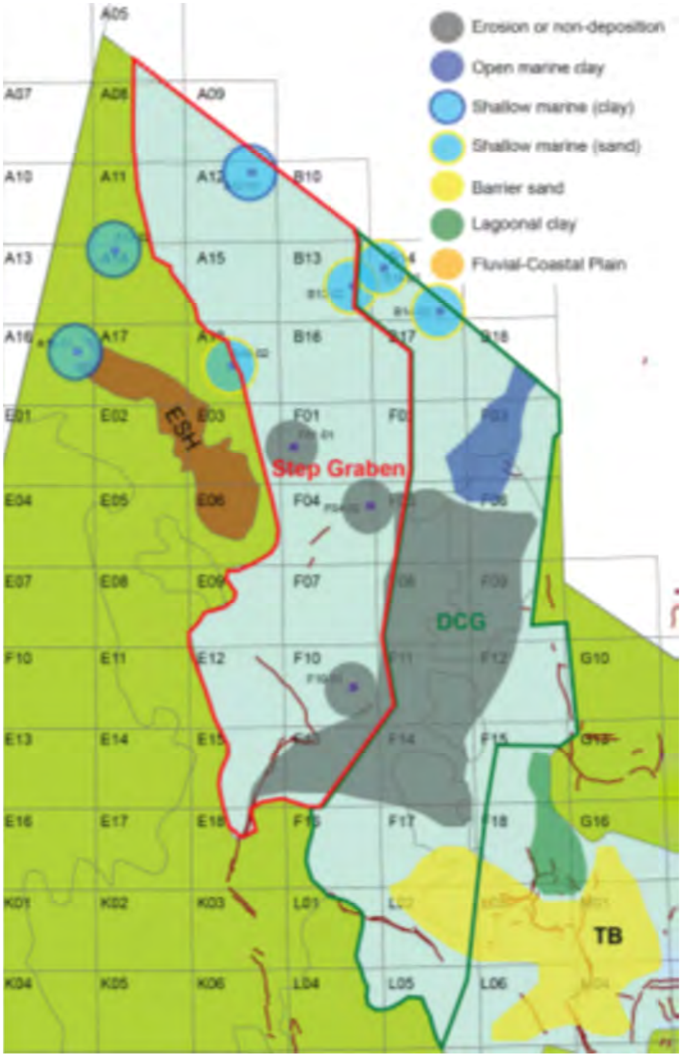


Figure 32

Palaeogeography of the Early Volgian (**TNO Subzone 2B**)

Note: For the Step Graben, single data points (circles) are used to indicate the facies. These data are derived from this study. For the Dutch Central Graben (DCG) and Terschelling Basin (TB), colored shading is used (polygons) to indicate the facies. These data are modified after Munsterman et al., 2012.

Jurassic basins in light blue, plateau areas in green and structural highs in brown.

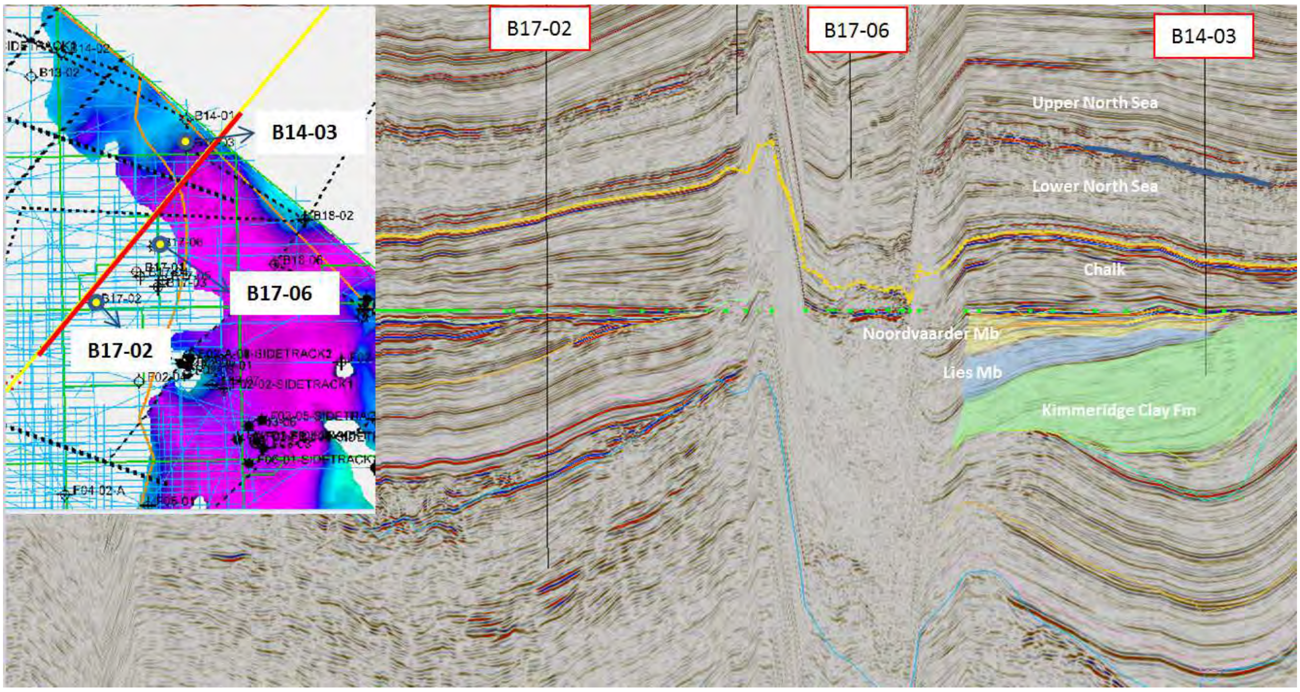


Figure 33 Seisimic SE – NW cross-section – flattened on Chalk - displaying the salt structure that separates the Central Graben – to the right – from the Step Graben – to the left. Note the prism-shaped sediment wedge of the Noordvaarder Mb (Skylge Fm), lodged against the salt structure.

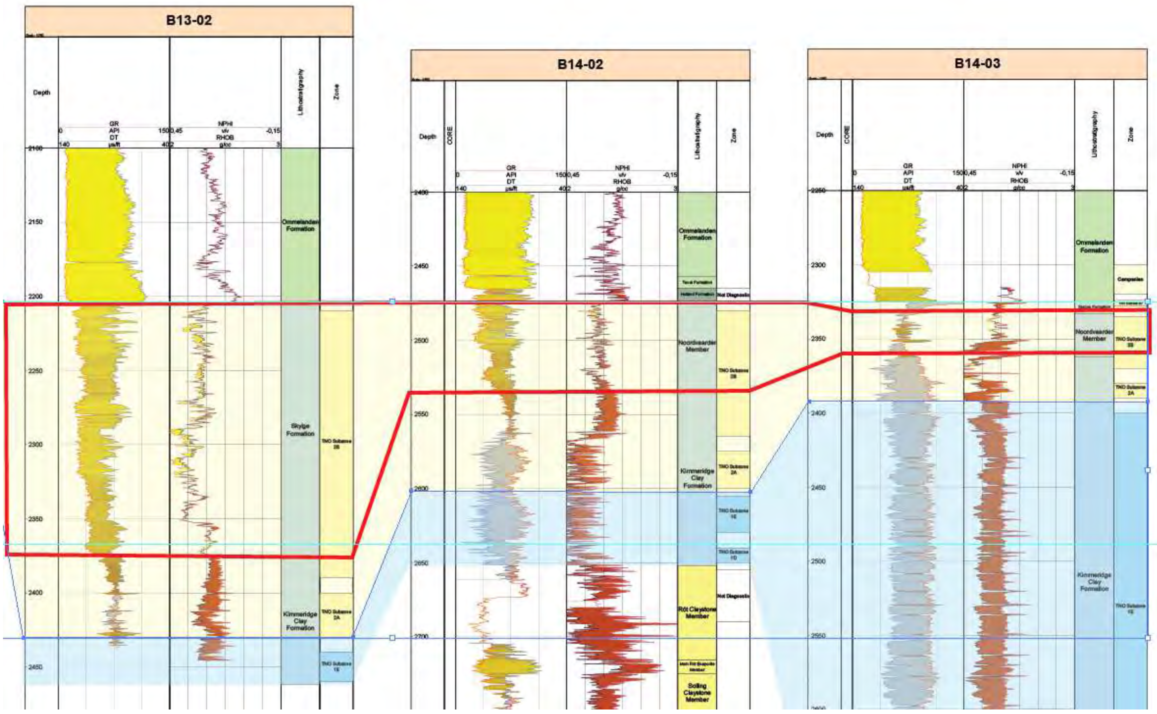


Figure 34 Correlation panel from West to East, displaying the sandy deposits of the Noordvaarder Member (red box) in the northern parts of the B13 and B14 Blocks (see also Figure 35). In well B13-02, the Noordvaarder Mb reaches 175m in thickness.

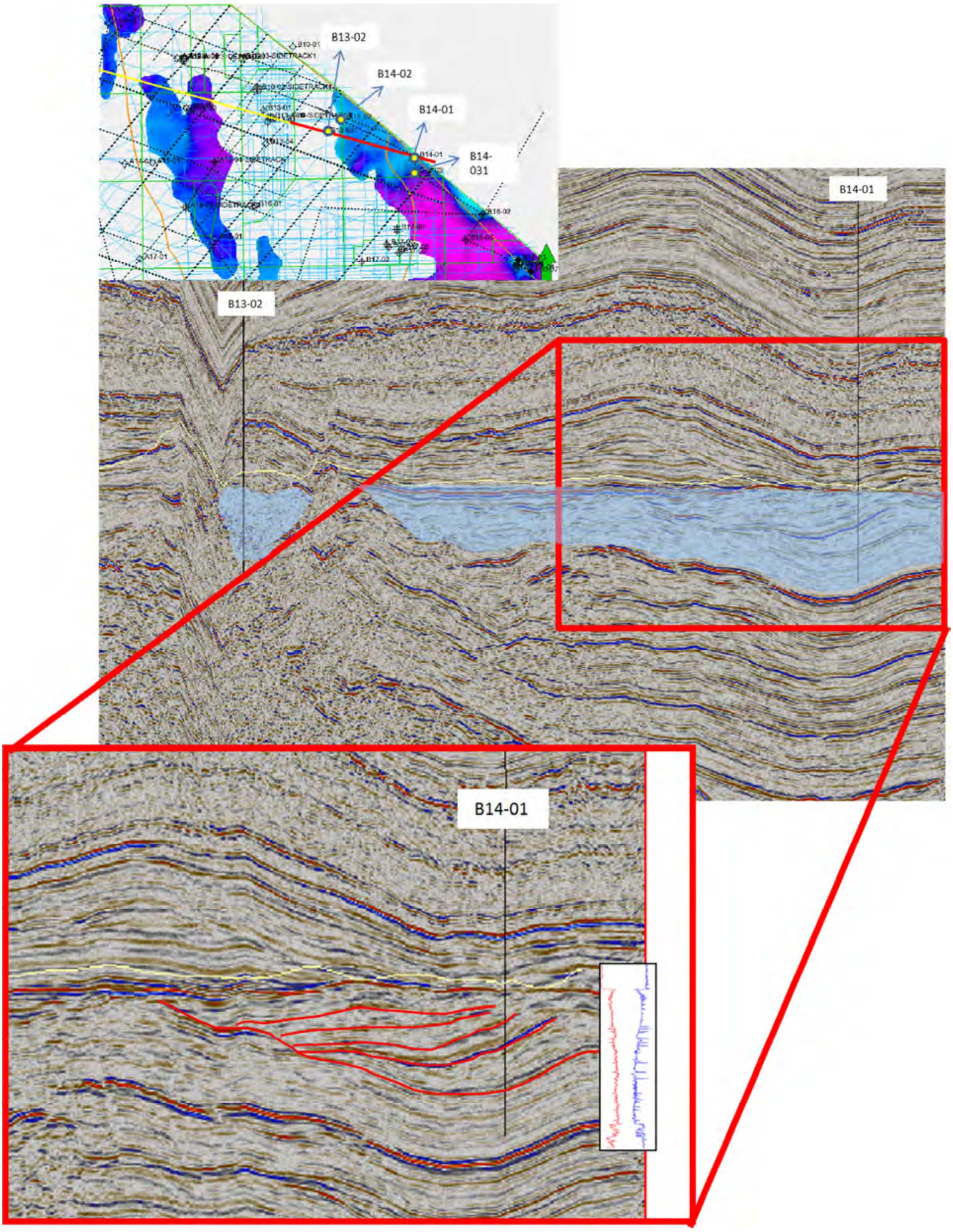


Figure 35 Seismic NW – SE cross-section – flattened on the base of the Chalk - through the transition of the Step Graben into the Central Graben. The Upper Jurassic sediment stack is marked in blue. The insert dsiplays complex stratal relationships, indicating local uplift and subsidence, in the upper part of the Upper Jurassic succession. The GR (red) and DT (blue) of well B14-01 illustrates the coarsening upward trend.

During the Middle Volgian (**TNO Subzone 2C**), the Step Graben is subjected to erosion or non-deposition (Figure 36). The only places where thin layers of mudstone are preserved are wells A14-02 and A18-02, which lie at the edge or even outside the Step Graben. Apparently, the uplift and tectonic activity, characteristic for for the upper part of TNO Zone 2, mainly occurred in the eastern part of the Step Graben.

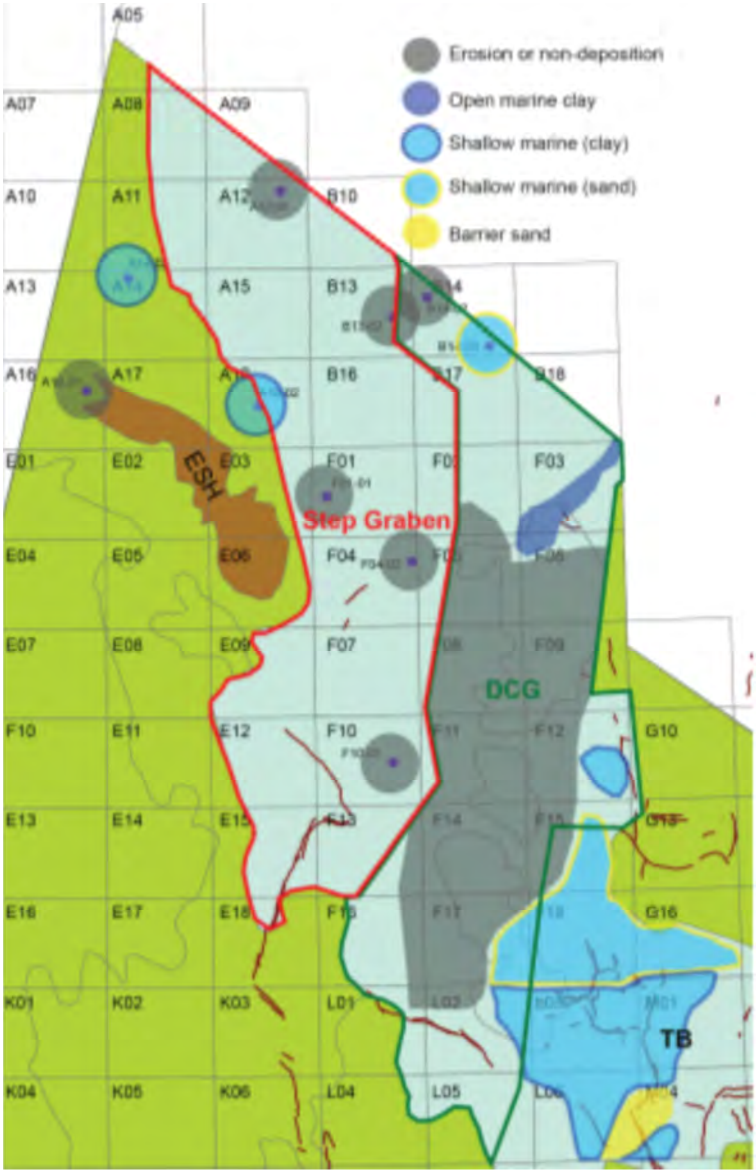


Figure 36

Palaeogeography of the Middle Volgian (**TNO Subzone 2C)**

Note: For the Step Graben, single data points (circles) are used to indicate the facies. These data are derived from this study. For the Dutch Central Graben (DCG) and Terschelling Basin (TB), colored shading is used (polygons) to indicate the facies. These data are modified after Munsterman et al., 2012.

Jurassic basins in light blue, plateau areas in green and structural highs in brown.

Late Volgian to Ryazanian (Ajacent Plateaus Phase = TNO Zone 3)

In the Late Volgian to Ryazanian of the Dutch Central Graben area, glauconitic and spiculite-rich sandstones are widespread. In the Terschelling Basin, thicknesses of up to 300 meters are attained for the Scruff Greensand Fm. In the Step Graben, sandstones belonging to the Scruff Greensand Fm also occur, but these occurrences are rare and the sandstones are relatively thin. Away from the Central Graben, the sediments belonging to Zone 3 quickly loose their sandy character and become more and more fine-grained (Figure 37). Apparently, the provenance for the sands does not lie in the West but somewhere in or around the graben axis itself. The best examples for the Zone 3 sands are found in the F04 Block, right at the edge of the Central Graben. Note that the Upper Jurassic deposition in the eastern part of the Step Graben, wells A01-01, F04-2-A and F10-01, kicks in at Late Volgian times. Sediments belonging to Zone 2 are not presented here. Such a scenario (Zone 1 and 2 absent) is more in line with the basin development of the so-called plateau areas, such as the Schill Grund Plateau, than with the basin development of a peripheral basin (Zone 1 absent, Zone 2 well developed), such as the Terschelling Basin.

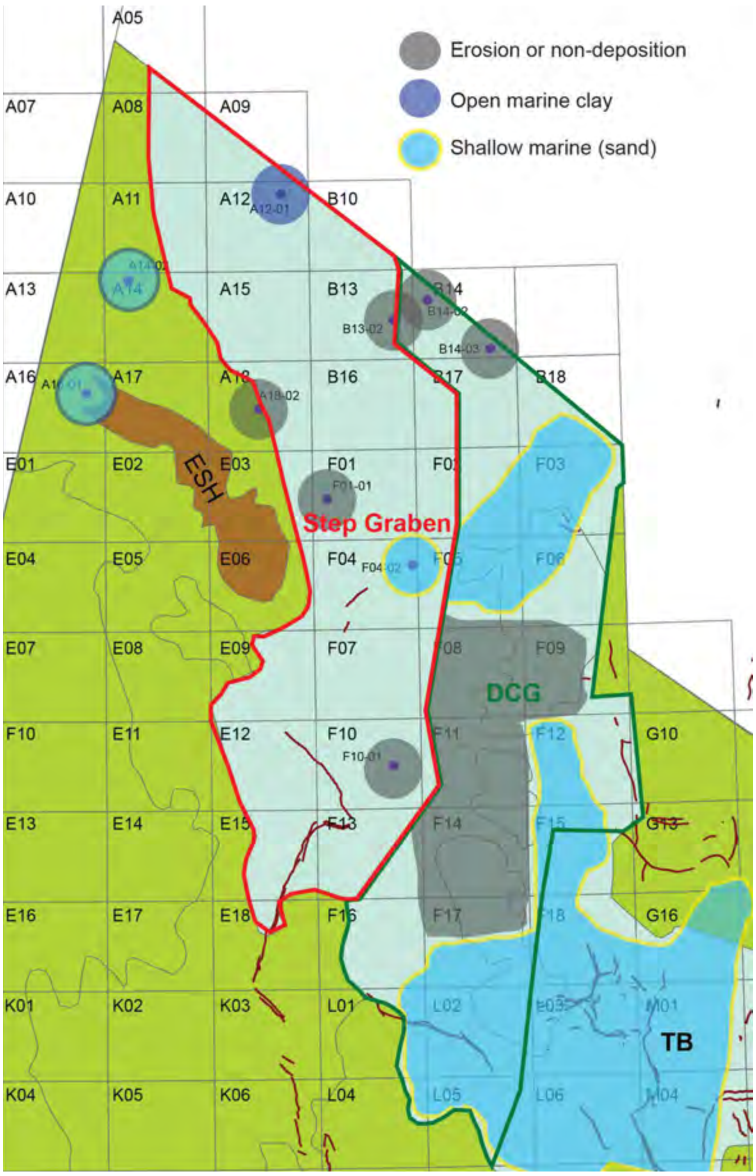


Figure 37

Palaeogeography of the Late Volgian (**TNO Subzone 3A**)

Note: For the Step Graben, single data points (circles) are used to indicate the facies. These data are derived from this study. For the Dutch Central Graben (DCG) and Terschelling Basin (TB), colored shading is used (polygons) to indicate the facies. These data are modified after Munsterman et al., 2012.

Jurassic basins in light blue, plateau areas in green and structural highs in brown.

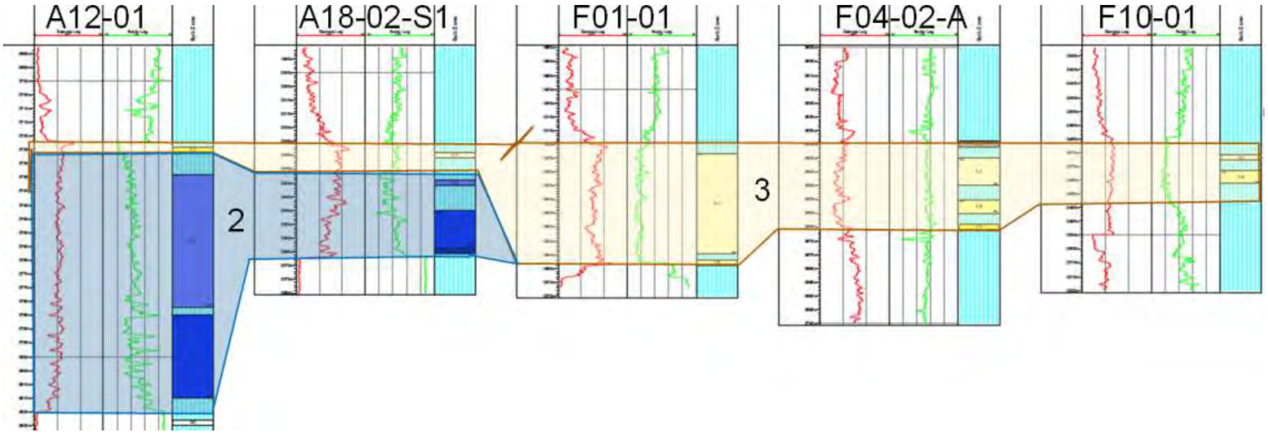


Figure 38 NW - SE Correlation panel through the Step Graben. The Ryazanian Scruff Greensand Fm, belonging to TNO Zone 3, is best developed in Block F04. Towards the NW, deposits of Zone 3 become more shaly. Note that sediments of Zone 2 are absent in the eastern part (F01, F04 and F10) of the Step Graben.

In the course of the Ryzanian, but primarily in the Late Ryazanian (**TNO Subzone 3C**), thin layers of organic-rich mudstones are deposited in the northern and western parts of the Step Graben (wells **A12-01, A18-02-S1 F01-01,** see Figure 39). These claystones, attributed to the Clay Deep Mb of the Lutine Fm, indicate a relatively enclosed setting with poor ventilation. These claystones are comparable in age and sedimentary facies as the Bo Mb of the Farsund Fm from the Danish offshore (Ineson *et al.,* 2003).

Valanginian to Hauterivian (Cretaceous Transgression = TNO Zone 4)

There are no deposits of Valanginian age in the Step Graben. This absence is also recorded in the northern part of the Central Graben. The middle part of the Central Graben shows marine Vlieland sands in the north and lateral clays occur simultaneously further southwards. The earliest Vlieland clays in the Step Graben occur in the utmost southeastern part (well F10-1) during the Early Hauterivian. Marine clays indicate flooding in a South to North direction in the Step Graben in the Early Barremian. Depositoin remains absent from the northernmost part of the Step Graben.

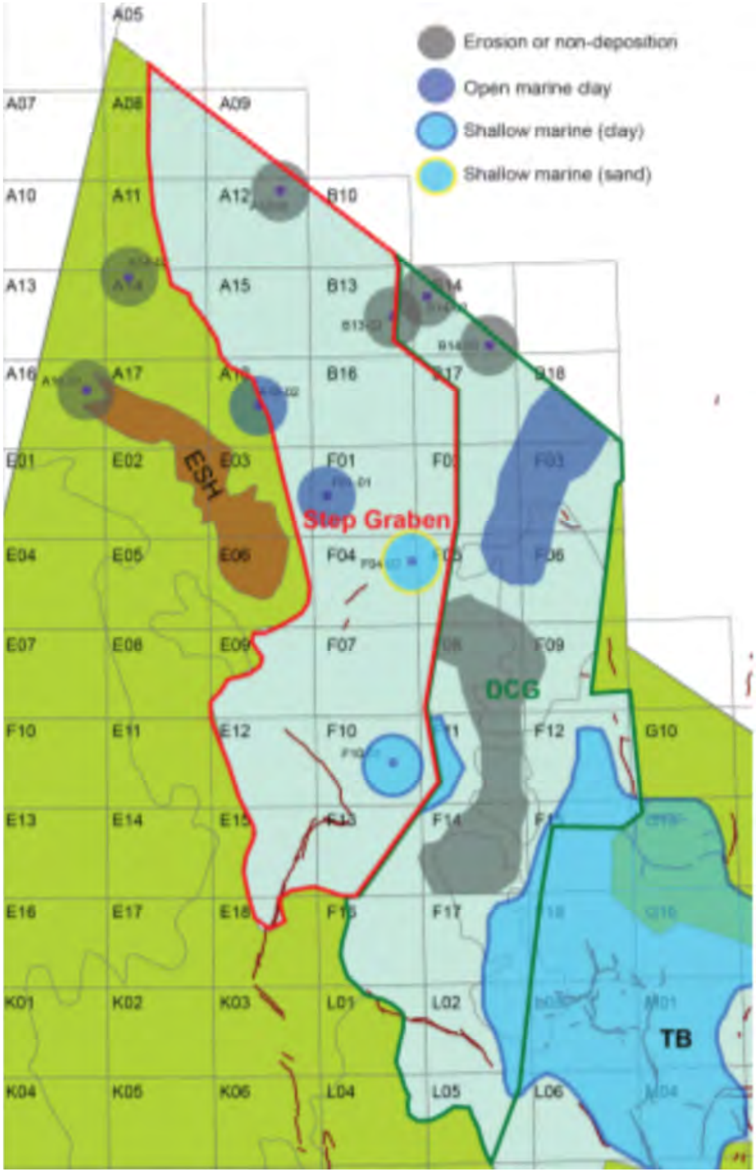


Figure 39

Palaeogeography of the Late Ryazanian (**TNO Subzone 3C**)

Note: For the Step Graben, single data points (circles) are used to indicate the facies. These data are derived from this study. For the Dutch Central Graben (DCG) and Terschelling Basin (TB), colored shading is used (polygons) to indicate the facies. These data are modified after Munsterman et al., 2012.

Jurassic basins in light blue, plateau areas in green and structural highs in brown.

7.3 Wheeler diagrams of the SG

In Figure 40 and Figure 41 wheeler diagrams are presented in order to illustrate and summarize the basin evolution of the Step Graben. In Figure 40, the transition of the graben axis to the Step Graben is displayed. Deposits belonging to TNO Zone 1 are represented in the wells situated in the graben axis, albeit with a small hiatus (spanning Subzone 1B and 1C). The transition from TNO Zone 1 to Zone 2, is smooth and the Kimmeridge Clay deposition continues uninterrupted. In the Early and Middle Volgian, the first signs of tectonic activity are reflected in the occurrence of sandstones in well B13-02 and B14-01. Typical Danish-style organic-rich mudstone deposition starts as early as Late Volgian (**TNO Subzone 3A**) in the remote A12 Block. In the B18 Block, glauconitic sandstones are deposited in the Late Volgian. This is taken over by organic-rich mudstone deposition in the Early Ryazanian (**TNO Subzone 3B and 3C**).

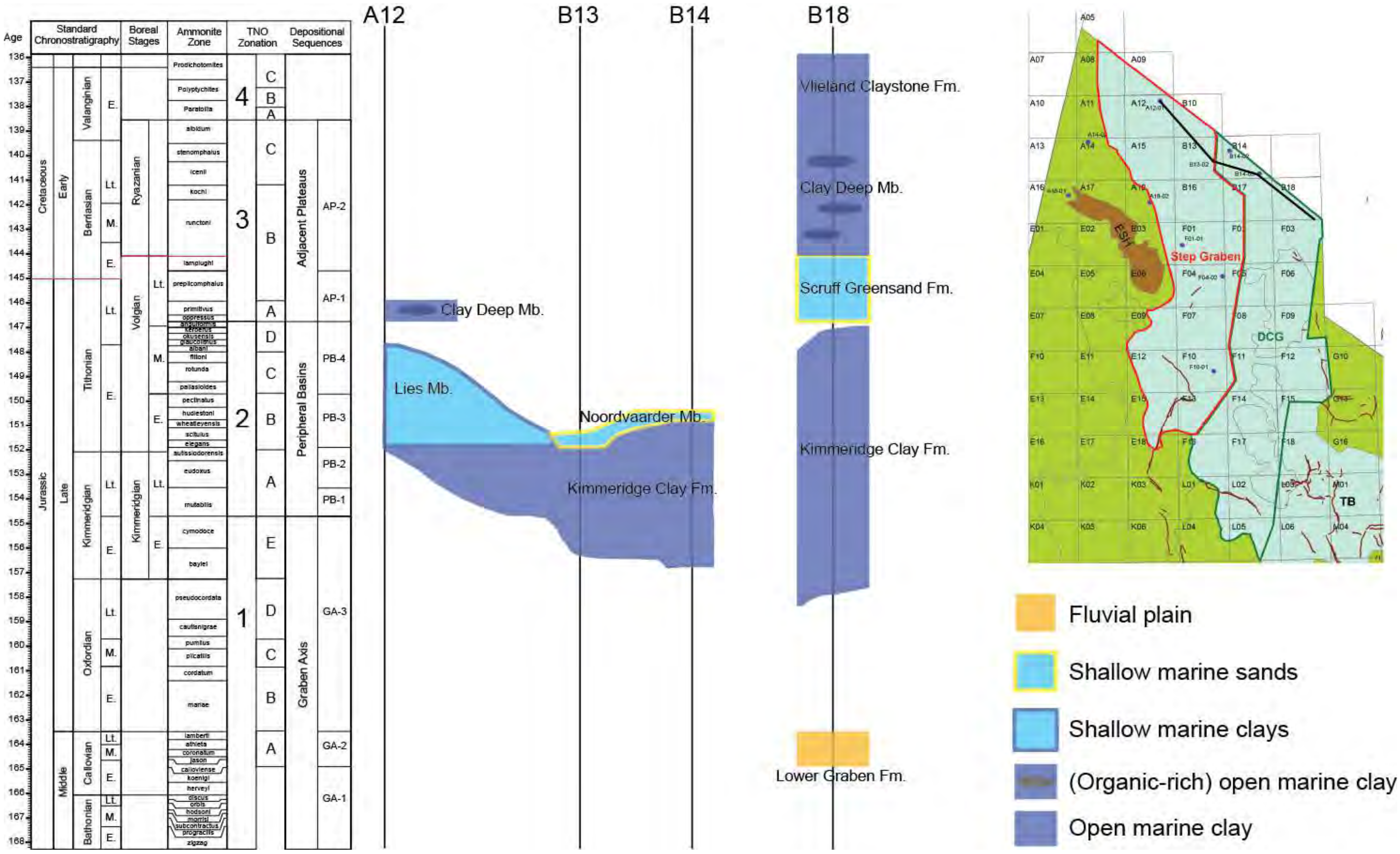


Figure 40 Wheeler diagram of a NW-SE transect across the Step Graben into the Central Graben (see inset map at upper right corner). The colors reflect the stratigraphic distribution of different facies types. White indicates non-deposition or erosion

In the transition from the plateau area around the Elbow Spit High to Step Graben is displayed. In the Step Graben, deposits of Late Kimmeridgian to Middle Volgian age (TNO Zone 2) are absent, reflecting a basin evolution style of an Adjacent Plateau. Typical Peripheral Basin style successions are found in the western part, in and around Block A14. It would be interesting to figure out how the Upper Jurassic geology continues across the UK border, but that is outside the scope of the current project.

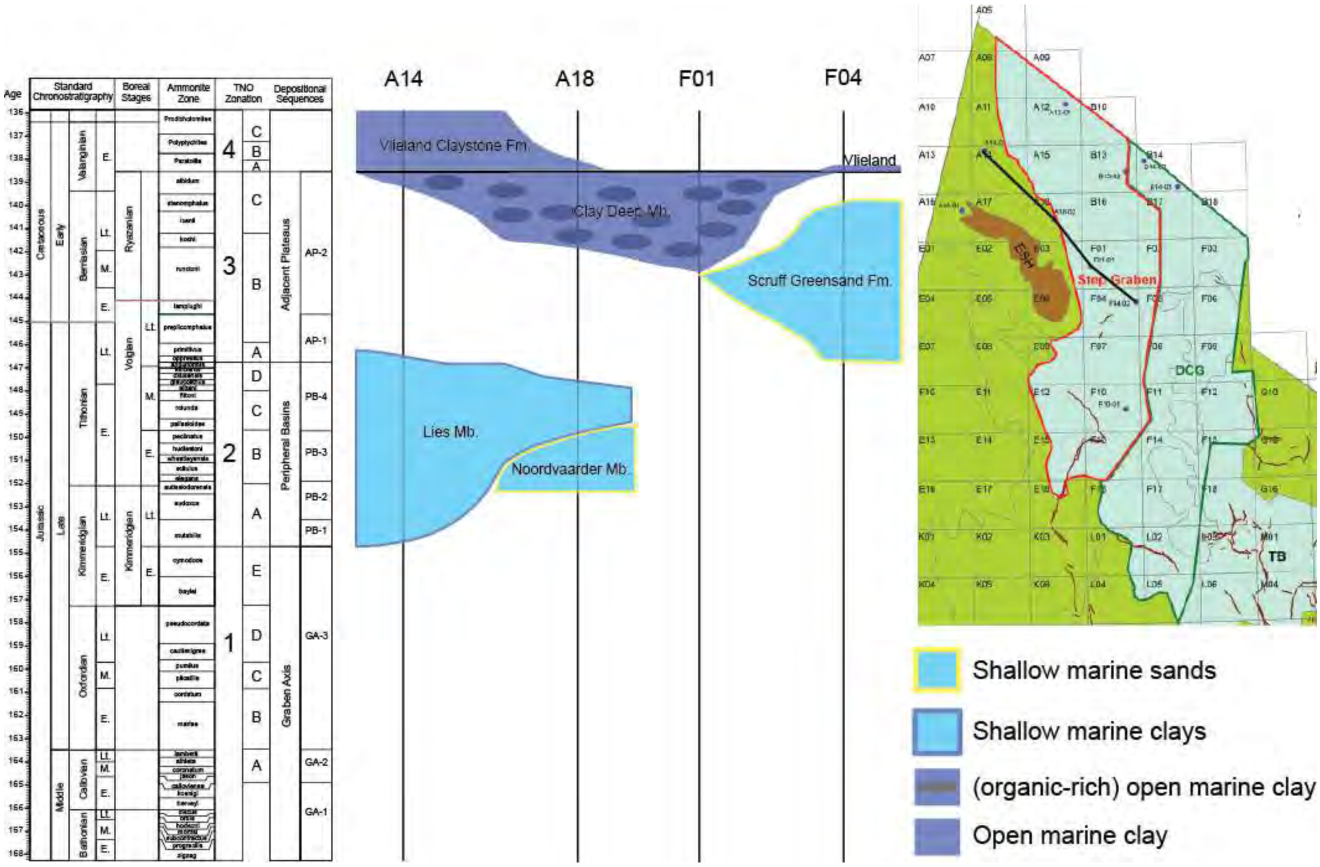


Figure 41 Wheeler diagram of a NW-SE transect across the Step Graben (see inset map at upper right corner). The colors reflect the stratigraphic distribution of different facies types. White indicates non-deposition or erosion.

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8 Facies development and depositional dynamics in the Broad Fourteens and offshore West-Netherlands Basin

In this chapter, the Late Jurassic to Early Cretaceous basin evolution of the BFB and offshore WNB is described (Figure 1). The age and palaeoenvironmental interpretations from the palynological analyses are used to construct palaeogeographic maps. The maps display the facies changes of the basin in 7 time slices. For age reference, the TNO Zonation is applied (Figure 6), for the paleo-environmental interpretations, reference is made to Figure 7.

8.1 Structural setting of the BFB and WNB

The BFB and WNB are two NW-SE oriented extensional basins. The basis are located *en echelon;* the WNB covers large parts of the Dutch provinces of Brabant and Zuid Holland and extends into the offshore where the BFB takes over (Figure 42).

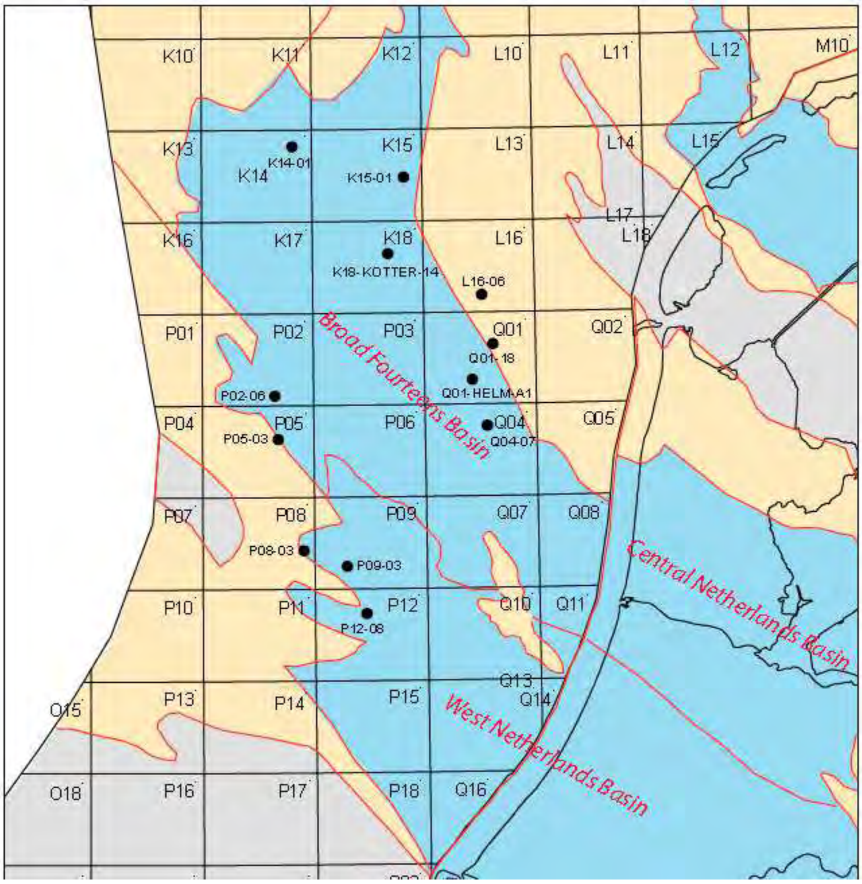

Figure 42 Location map of the wells studied in the BFB and offshore WNB. The basins are indicated in blue.

The basins differ from the Central Graben basin in being bounded and controlled by faults, rather than by salt structures. Furthermore, the BFB and WNB are more strongly inverted during the Late Cretaceous inversion phase, resulting in major hiatuses and in the development of flower structures (Figure 43).

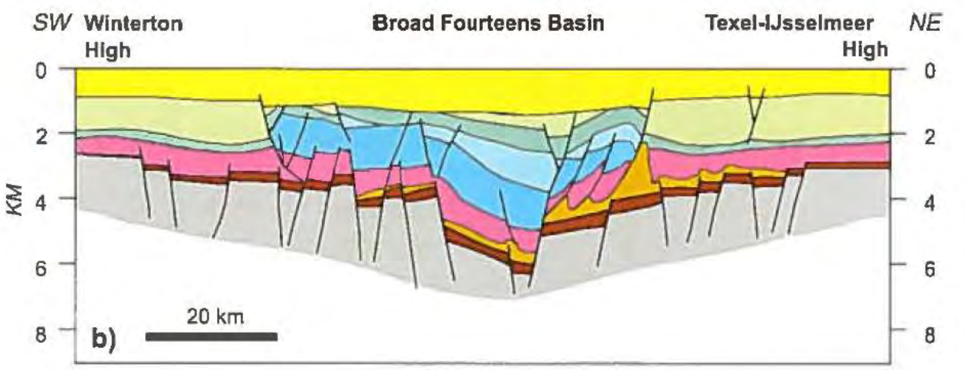

Figure 43 Schematic cross-section through the Broad Fourteens Basins with the Triassic in pink, the Lower and Middle Jurassic in bright blue, the Upper Jurassic in light blue and the Lower Cretaceous in greyish blue (from De Jager, 2007). Note the strong inversion of the basin, reflected in the near absence of Chalk (light green).

In both basins, the Upper Jurassic to Lower Cretaceous succession shows a two-fold subdivision, an essentially non-marine lower part, the Schieland Group, and a marine upper part, the Rijnland Group (Figure 44 and Figure 45). In the WNB, the marine Rijnland Group shows a basin-scale onlap pattern towards the Southeast.

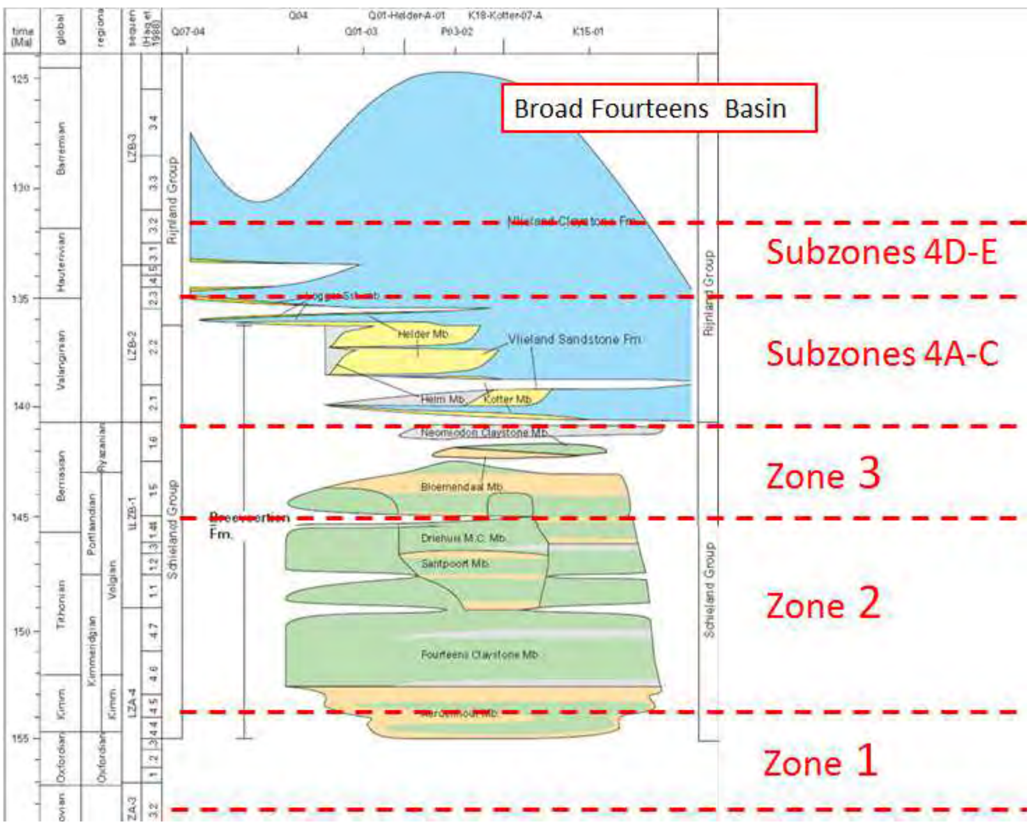

Figure 44 Lithostratigraphic framework of the BFB (after Van Adrichem Boogaert and Kouwe, 1993-1997) with the TNO Zonation superimposed.

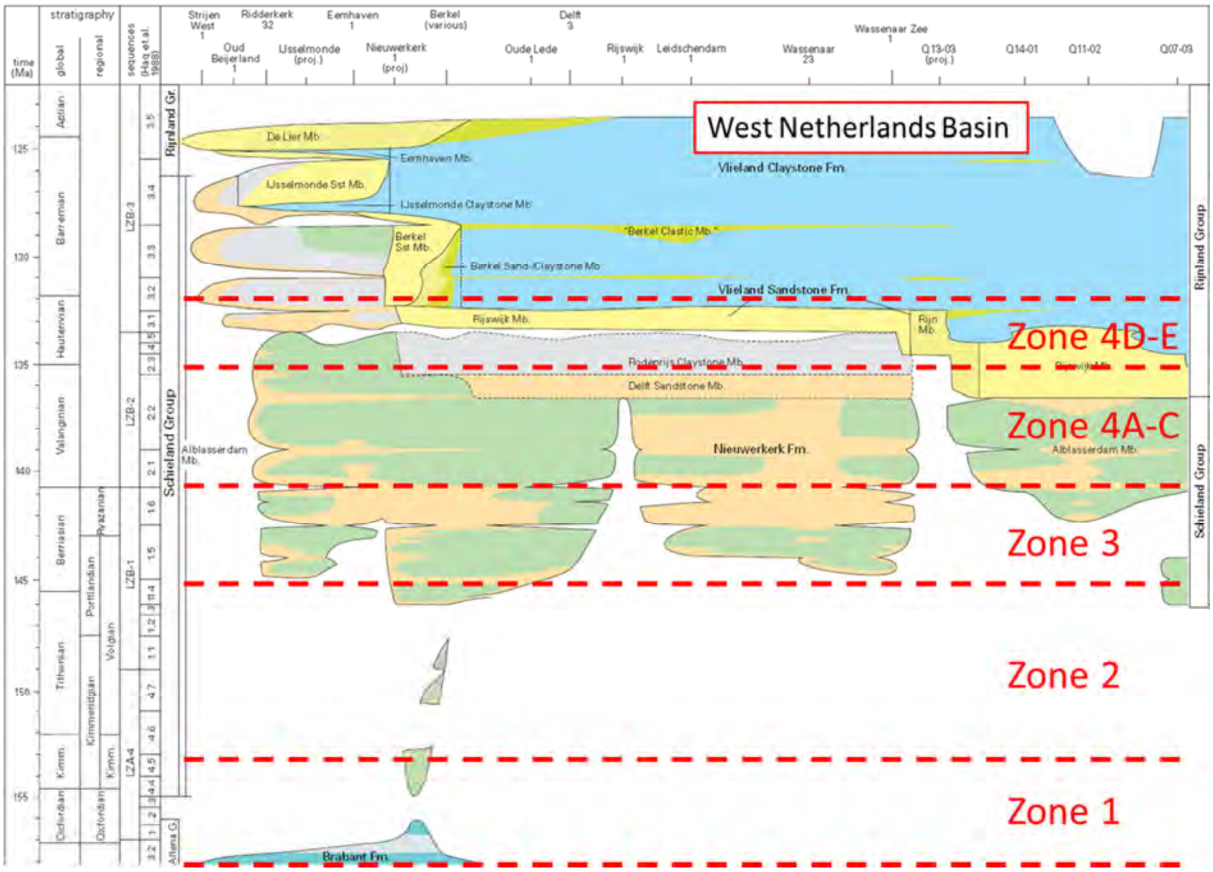

Figure 45 Lithostratigraphic framework of the WNB (after Van Adrichem Boogaert and Kouwe, 1993-1997) with the TNO Zonation superimposed.

8.2 Palaeogeographic development of the BFB and WNB

Middle Callovian to Early Kimmeridgian (Graben Axis Phase = TNO Zone 1)

Sediment of Middle Callovian to Early Kimmeridgian (TNO Zone 1) are typically absent in the BFB and offshore WNB. Only in blocks P02, P05 and Q01, slivers of Callovian age deposits are found. The extensional direction during this part of the Late Jurassic rift phase was East – West. Therefore, the Central Graben Axis was mainly affected and acting as an active basin. The NW-SE structured BFB and WNB were not actively subjected to extension. However, along specific fault blocks, some slivers belonging to Zone 1 are preserved. Also in the onshore WNB, sediments from the Callovian to Early Kimmeridgian are relatively rare. The sandy Brabant Fm. of Callovian age is characteristic for the infill of the onshore WNB during that time. Also the Nieuwerkerk Fm. (Oxfordian and Early Kimmeridgian) is only found in slivers, reflecting minor subsidence in the BFB and offshore WNB.

Late Kimmeridgian to Middle Volgian (Peripheral Basins Phase = TNO Zone 2)

The regional change in the tectonic regime that occurred at the start of the Late Kimmeridgian, triggered the NW-SE faults to become active and brought the BFB and WNB to life. The BFB started to subside substantially and became filled in with a thick package of the essentially non-marine deposits of the Broad Fourteens Fm. Near the edge of the basin, along the surrounding platforms (e.g., the P02, P05 and Q04 Blocks), isolated fluvial to coastal plain deposits (also Breeveertien Fm.) developed (Figure 47). To the north, in Block K18, e.g. in well K18-Kotter-14, the first marine deposits are recorded, the restricted marine Fourteens Claystone Mb. (Figure 46). In Early Volgian times, the offshore WNB is still not actively involved in basin development, no deposits of Early Volgian age are recorded.

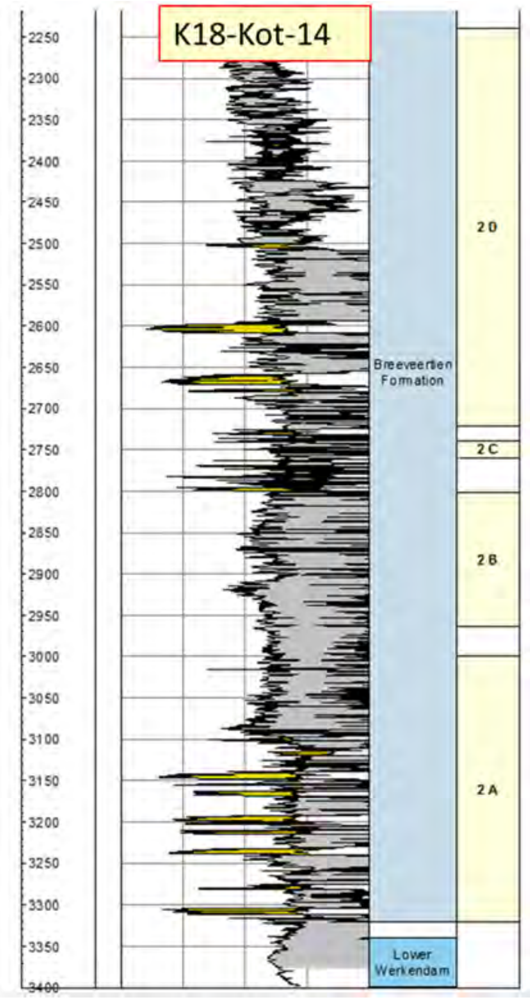

Figure 46 The first marine deposits in the BFB are represented in well K18-Kotter-14 by the restricted marine Fourteens Claystone Mb (**TNO Subzone 2A**). Yellow (low GR , high DT) represents sand, grey (high GR, low DT) represents clay.

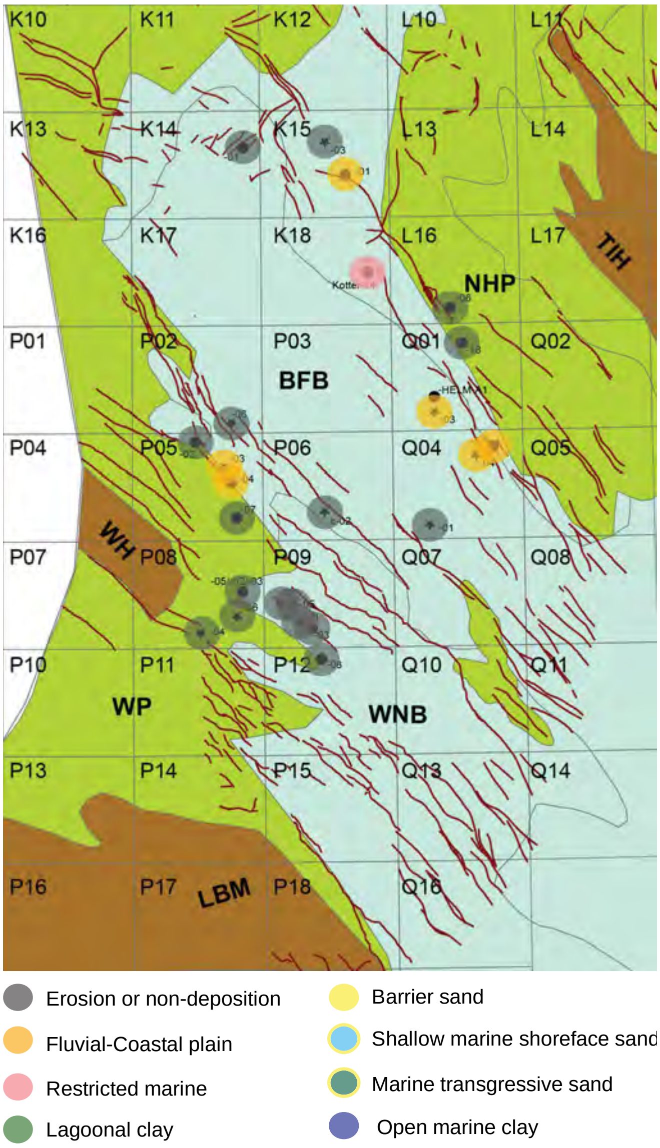

Figure 47 Palaeogeography of the Late Kimmeridgian (**TNO Subzone 2A**)

Through the Late Kimmeridgian and Early to Middle Volgian (**TNO Subzone 2B and 2C**), fluvial to coastal plain deposition progressed along the basin edges, now expanding further towards the south into the Q04 and Q07 Blocks (Figure 48). An onlapping pattern of thick restricted marine deposits from the Breeveertien Fm is observed from the southeast (K18 Block) to the Northwest (K15 Block, see Figure 49). The main depocenter is located around the K18 area. Along the northern margin of the eastern side of the BFB, the basin boundary fault was very active, resulting in a thick pile of Upper Jurassic deposits at its foot wall (Figure 50). Across the basin, at its western side, fault activity is reflected in the occurrence of isolated fluvial deposits in Block P02 (Figure 48). In the offshore WNB, Early to Middle Volgian deposits are not recorded, apparently this area was (still) not subjected to subsidence.

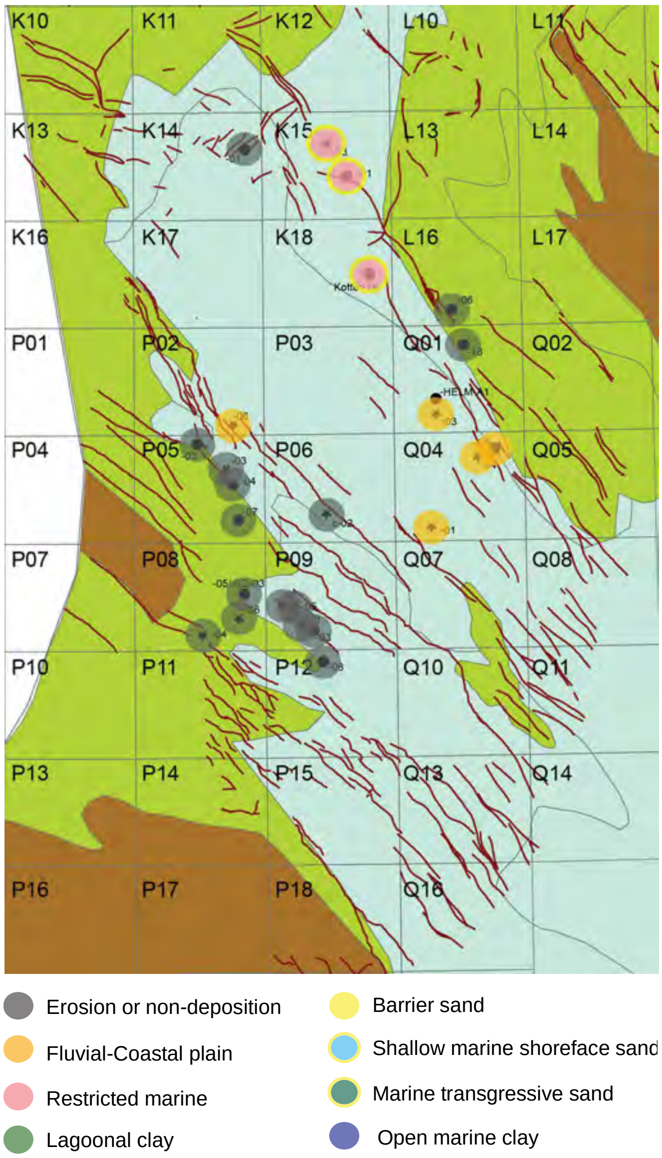

Figure 48 Palaeogeography of the Early to Middle Volgian (**TNO Subzone 2B and 2C**)

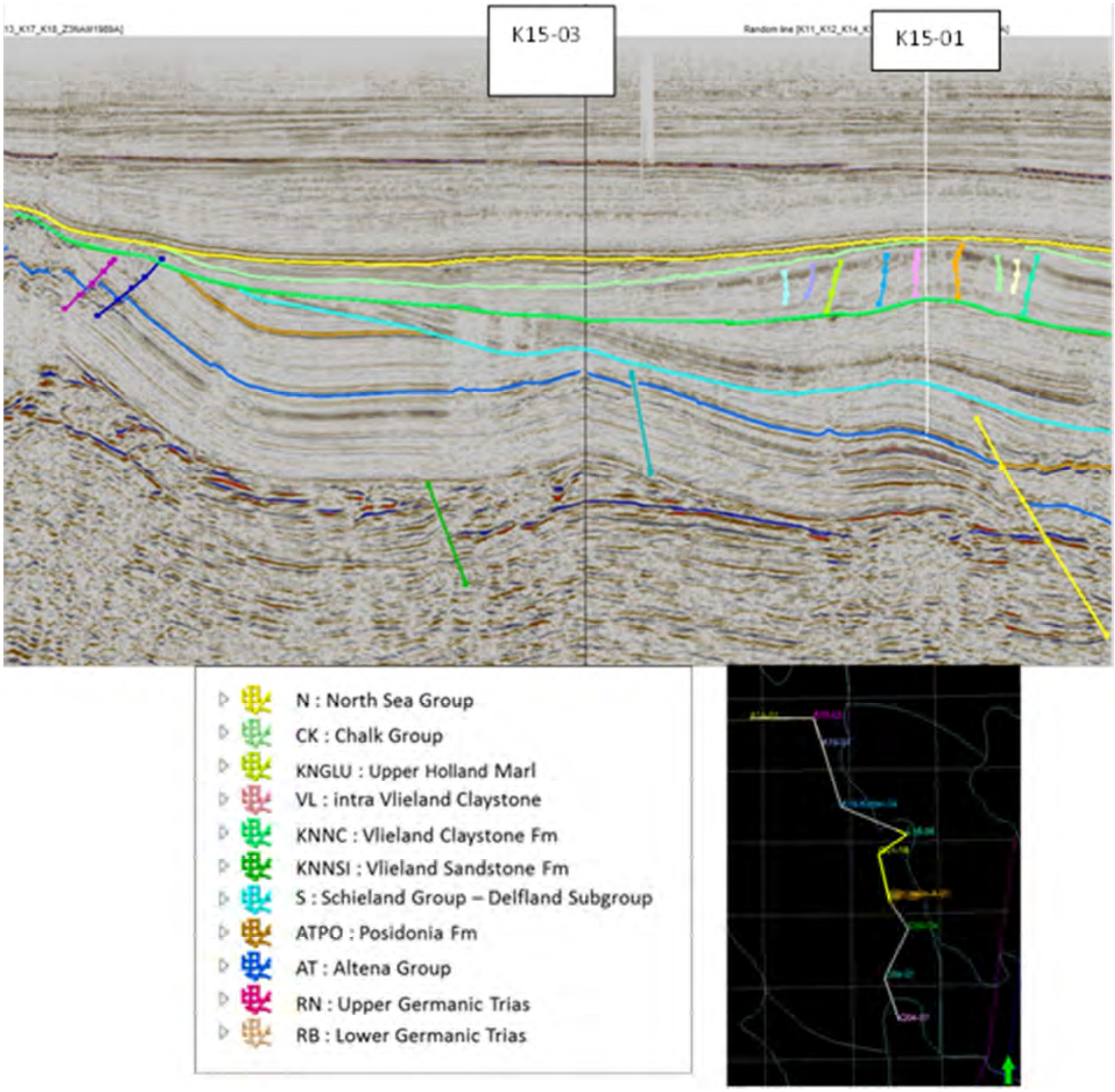

Figure 49 Seismic cross-section through the eastern part of the BFB. Note the angular unconformity at the base of the Schieland Group (light blue) and another one at the base of the Vlieland Sandstone Fm. (seismic horizons represent bases).

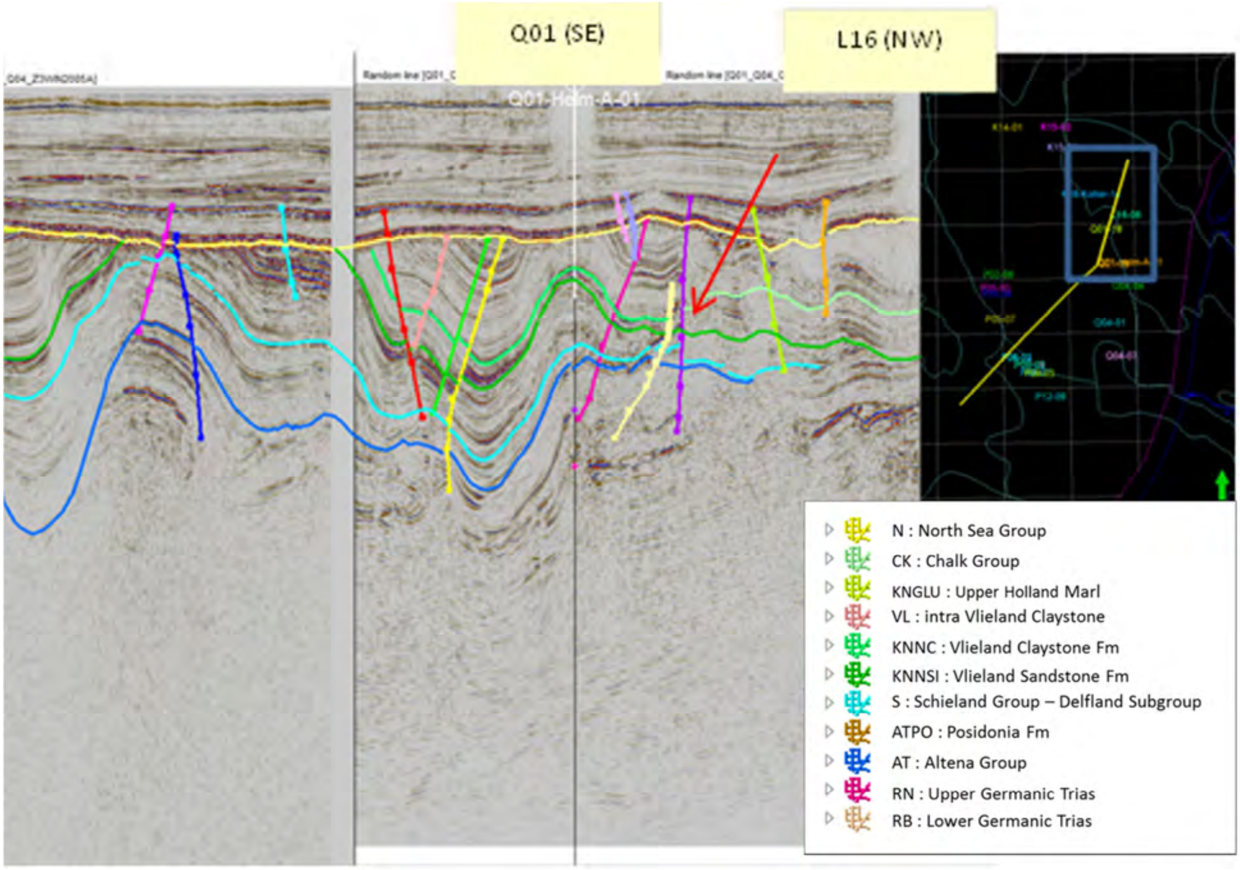

Figure 50 Seismic cross section from Q01-Helm-A1 through L16-06 showing the steep normal fault bounding the basin at its eastern side. affected the distribution and thickness of the Schieland Group (Sequence 2).

Late Volgian to Ryazanian (Adjacent Plateaus Phase = TNO Zone 3)

Both in the BNB and the WNB, a major episode of erosion and/or non-deposition characterizes the Late Middle Volgian to Early Ryazanian, thus spanning the Jurassic-Cretaceous boundary (Sequence 2D-3A). As shown in Figure 51, sediments of Late Volgian – Early Ryazanian age are missing in all studied wells. Apparently, the basin development was interrupted by a phase of uplift and erosion. This observation corroborates findings from the Central Graben area (Verreussel *et al.,* in prep.), where the occurrence of the Late Volgian – Early Ryzananian Scruff Greensand Fm reflects widespread erosion. It is suggested here that the short-lived inversion phase was mainly caused by isostatic rebound following the waning activity of the boundary faults.

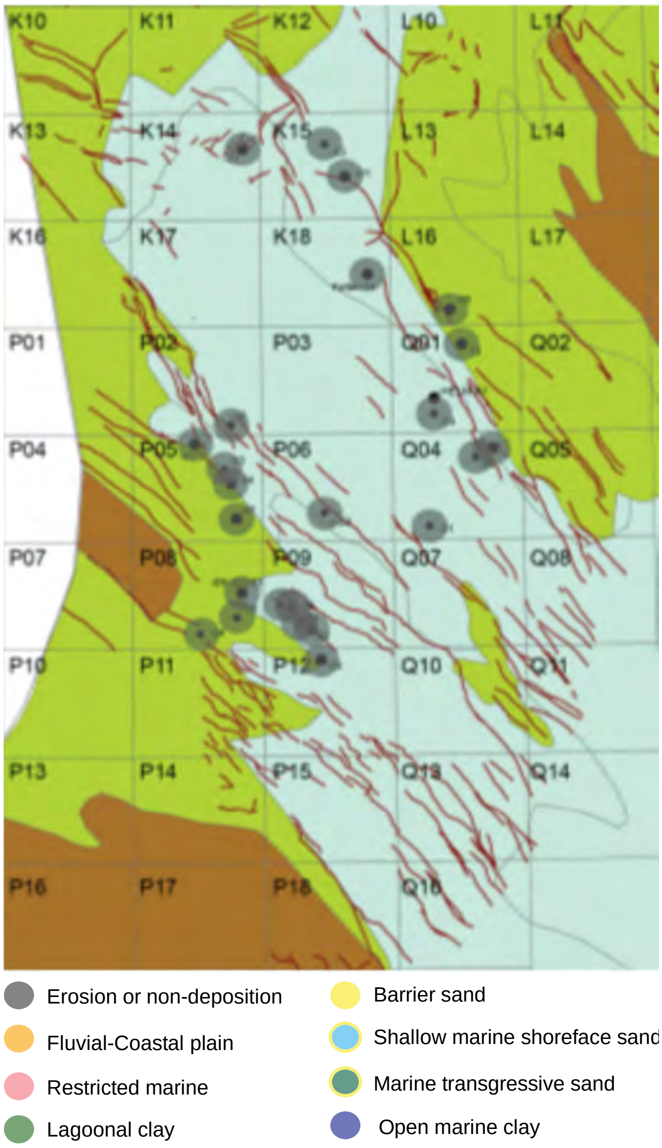

Figure 51 Palaeogeography of the Late Volgian and Early Ryazanian (**TNO Subzone 3A and 3B**)

In the Latest Ryazanian (Subzone 3C and 4A) deposition resumed in the BFB and in parts of the offshore WNB. In the northern Blocks K15 and K18, lagoonal mudstones (Neomiodon Claystone Mb.) and associated restricted marine sandy facies of the Bloemendaal Mb. develop (Figure 52 and Figure 53). The renewed deposition in Subzone 3C coincides with the Albidum Ammonite Maximum Flooding Surface (MFS), so this probably relates to a eustatic rise in relative sea level by that time which affects the basin centre. In basin edge blocks (Block P09, Q01-helm and Block Q04), restricted marine deposits onlap on the basin edge. For blocks P02, P05, P09 and well Q01-18, the nature of the succession in combination with seismic profiles suggests that relay-faults were activated, driving subsidence and deposition on the one hand and erosion of Upper Ryazanian deposits on the other hand. For instance, in well P02-06, extensive (>70 m) Upper fluvial to coastal sandstones were deposited as part of a hanging wall feature of such a relay fault (Figure 54 and Figure 55).

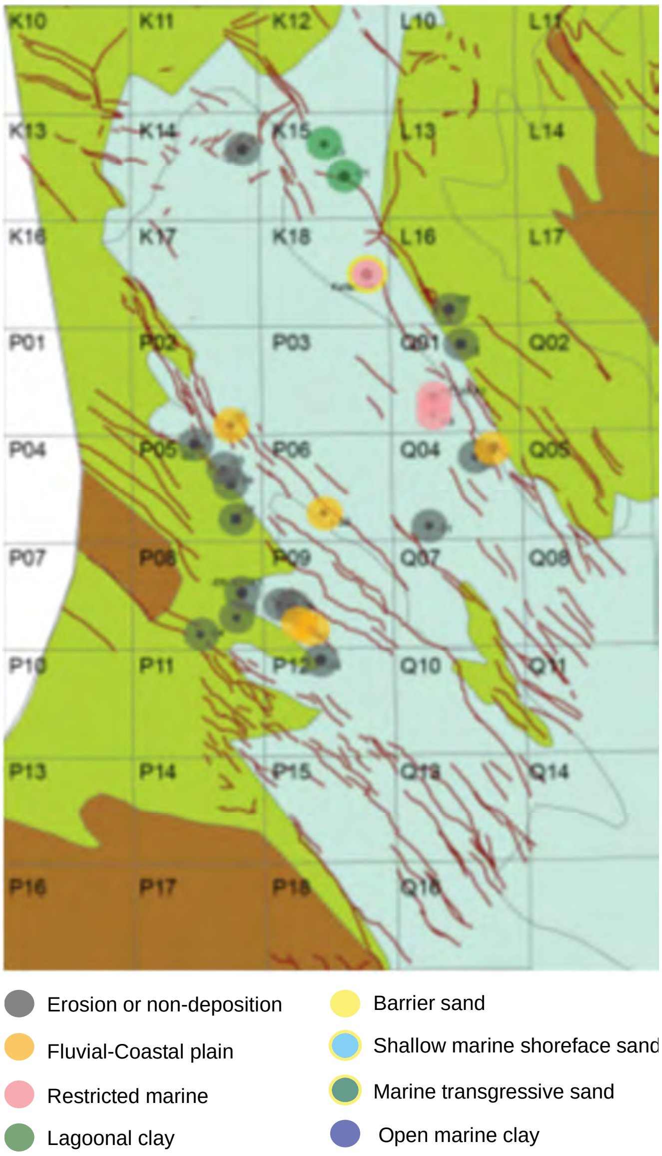

Figure 52 Palaeogeography of the Late Ryzanian (**TNO Subzone 3C and 4A**)

Similarly, fluvial to coastal sandstones also occur in block P09. In contrast, just at the other side of the fault system near P02-06, the deposits in wells P05-03 and P05-04 are tilted and erosion of Uppermost Ryazanian deposits has occurred (Figure 56 and Figure 57). This implies that extensive but isolated sand bodies are preserved through relay-fault activity near the basin edges. In contrast to the eustatic sea-level driven re-inception of deposition in the north, the fault activity started somewhat earlier, in the early late Ryazanian (see also Section 8.3).

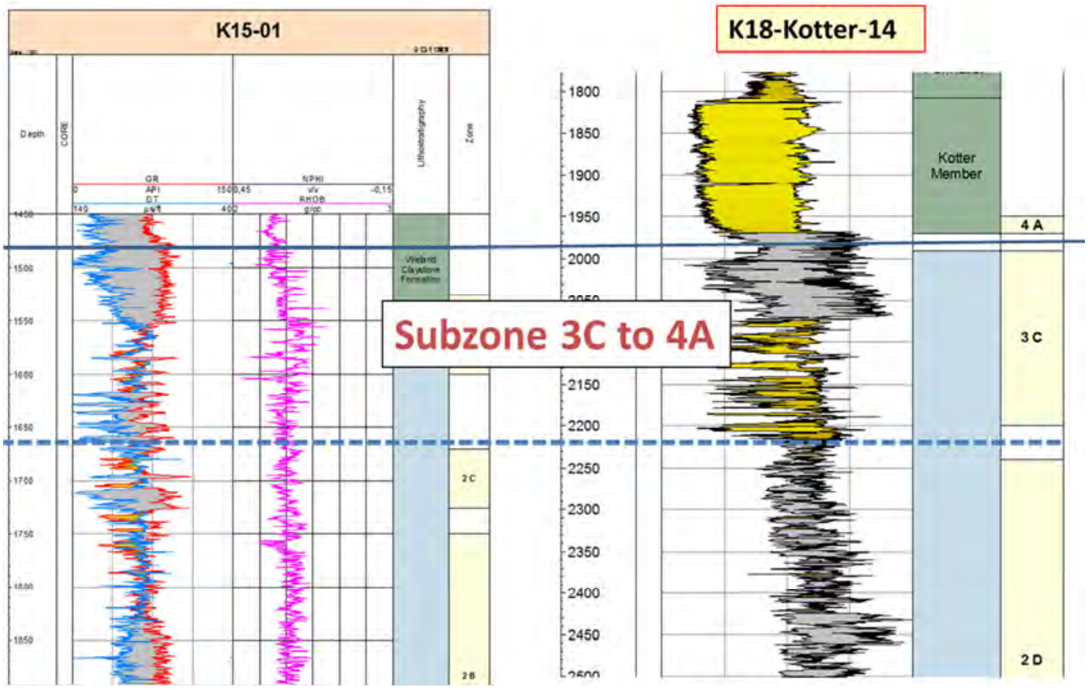

Figure 53 After the short-lived uplift phase in the Late Voligan to Early Ryazanian, basin development resumed in the Late Ryazanian (**TNO Subzone 3C**) with lagoonal mudstones and restricted marine sandstones of the Bloemendaal and Neomiodon Mbs.

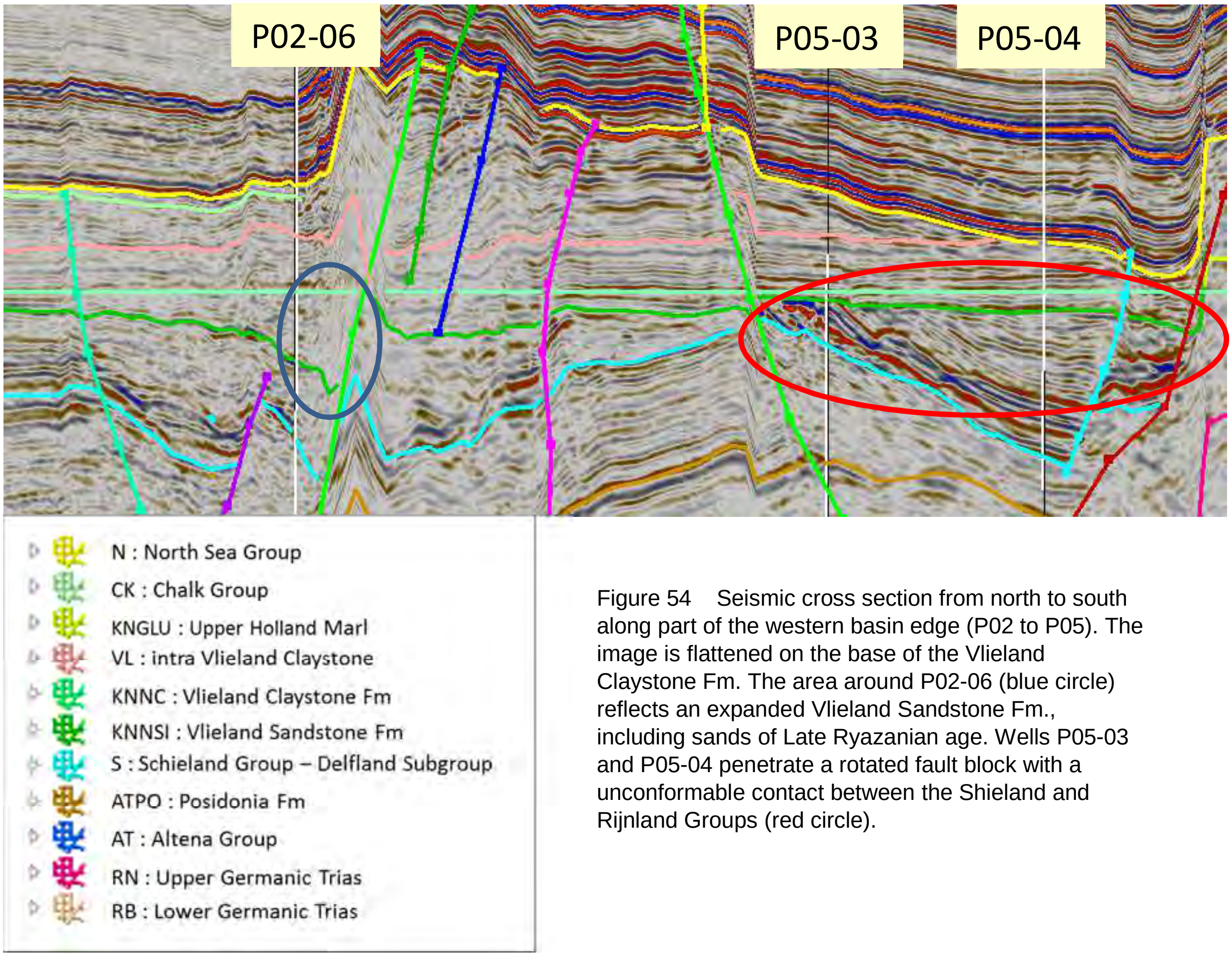

Figure 54 Seismic cross section from north to south along part of the western basin edge (P02 to P05). The image is flattened on the base of the Vlieland Claystone Fm. The area around P02-06 (blue circle) reflects an expanded Vlieland Sandstone Fm., including sands of Late Ryazanian age. Wells P05-03 and P05-04 penetrate a rotated fault block with a unconformable contact between the Shieland and Rijnland Groups (red circle).

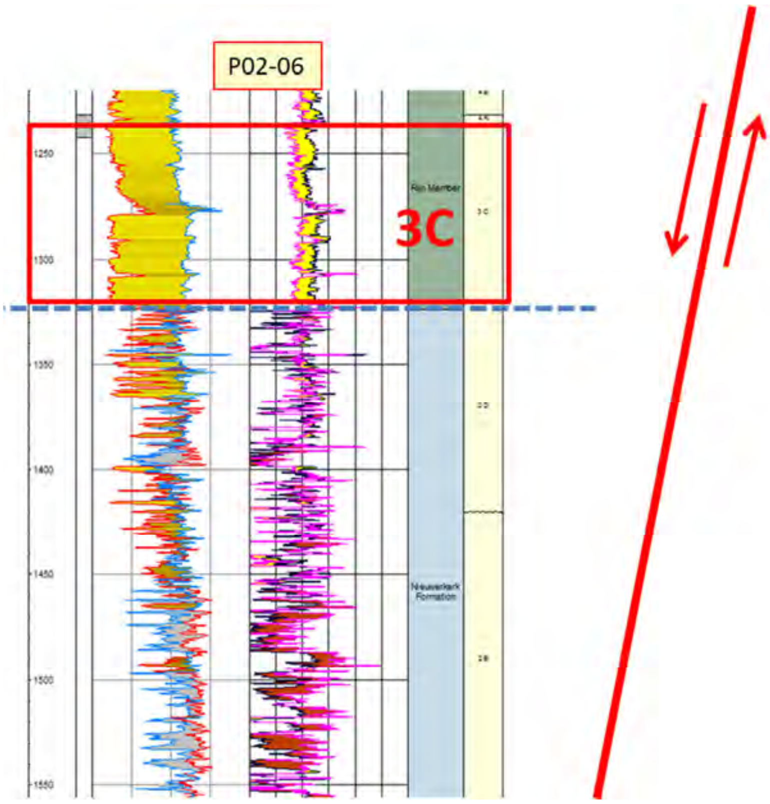

Figure 55 Late Ryazanian to earliest Valanginian sand development in hanging wall of relay fault, well P02-06.

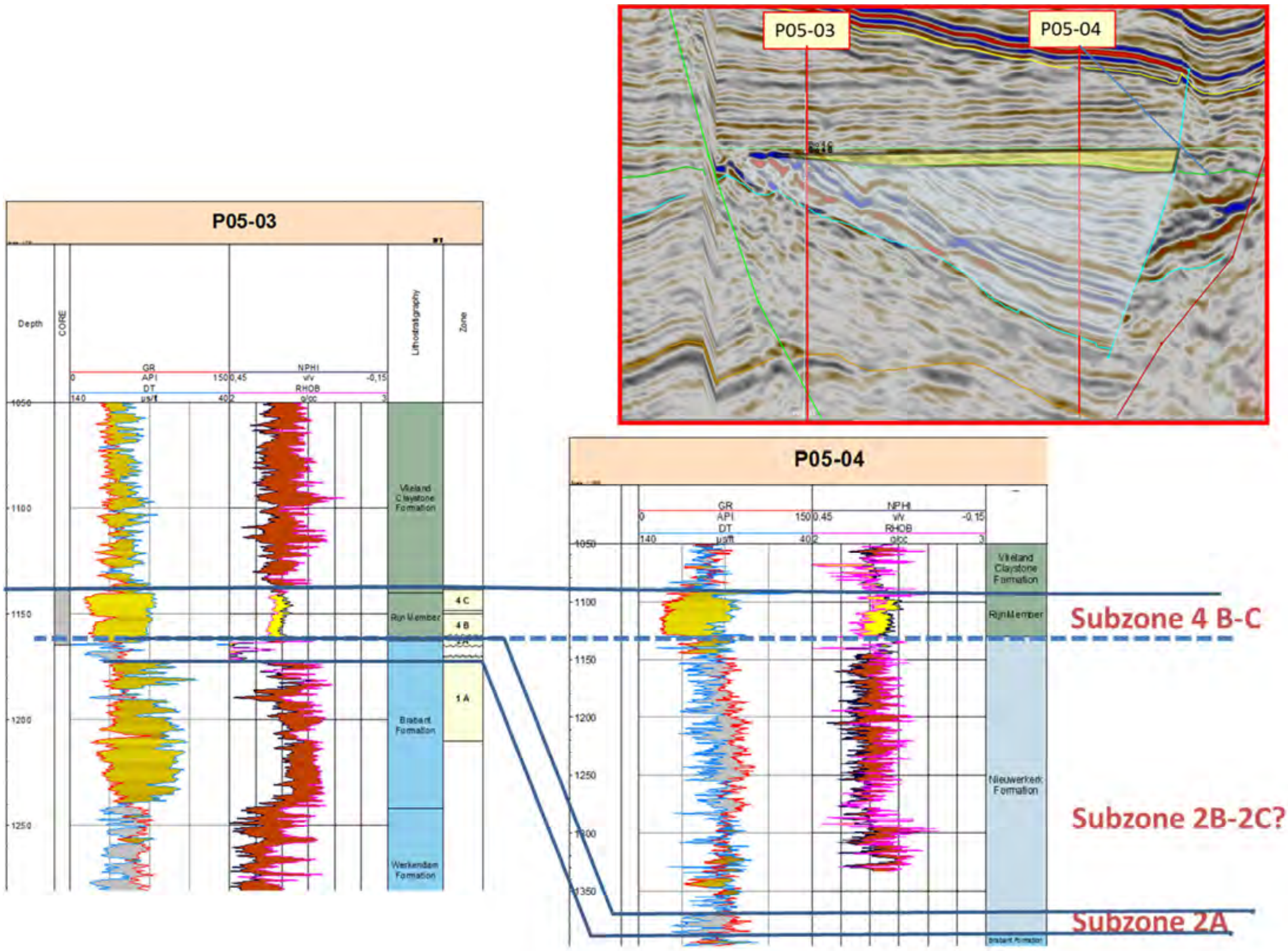

Figure 56 Rotated fault block in the P05 area. The seismic cross-section is flattened on the Vlieland Claystone Fm. and clearly shows how the Valanginian Rijn Member (Subzone 4B-C) unconformably overlies deposits of the Schieland Group (Subzones 2A to 2C).

Valanginian to Barremian (Cretaceous transgression = TNO Zone 4)

At the base of the Valanginian (**TNO Subzone 4A**), the central northern part of the BFB (K15-K14) is flooded as shown by the transition of the lagoonal Neomidon Claystone into short-lived barrier sands. Near K18, similar coeval barrier sand appear, coinciding with the earliest Valanginian Albidum Maximum Flooding Surface (MFS, see Jeremiah et al., 2010 and references therein).
A next major step in the development of the Lower Cretaceous succession occurred slightly later in the Early Valanginian, in **TNO Subzone 4B**. At that time, mudstones of the open-marine Vlieland Claystone Fm. appear in the northern blocks (K14, K15 and K18, Figure 57). Around the western edge (Block P02 and P05) and around the eastern edge (Block K18, L16, Q01 and Q04) of the BFB, distinct shallow marine barrier sands develop (Figure 57 and Figure 58). At the same time, on the northwestern rim of the offshore WNB (Blocks P06, P09 and P12), sandstones are deposited that typically display a more distal open-marine character, interpreted as shoreface complexes (indicated as Kotter Mb in Figure 59), but the depositional environment differs from that of the Kotter Mb in the P02 and P05 Blocks.

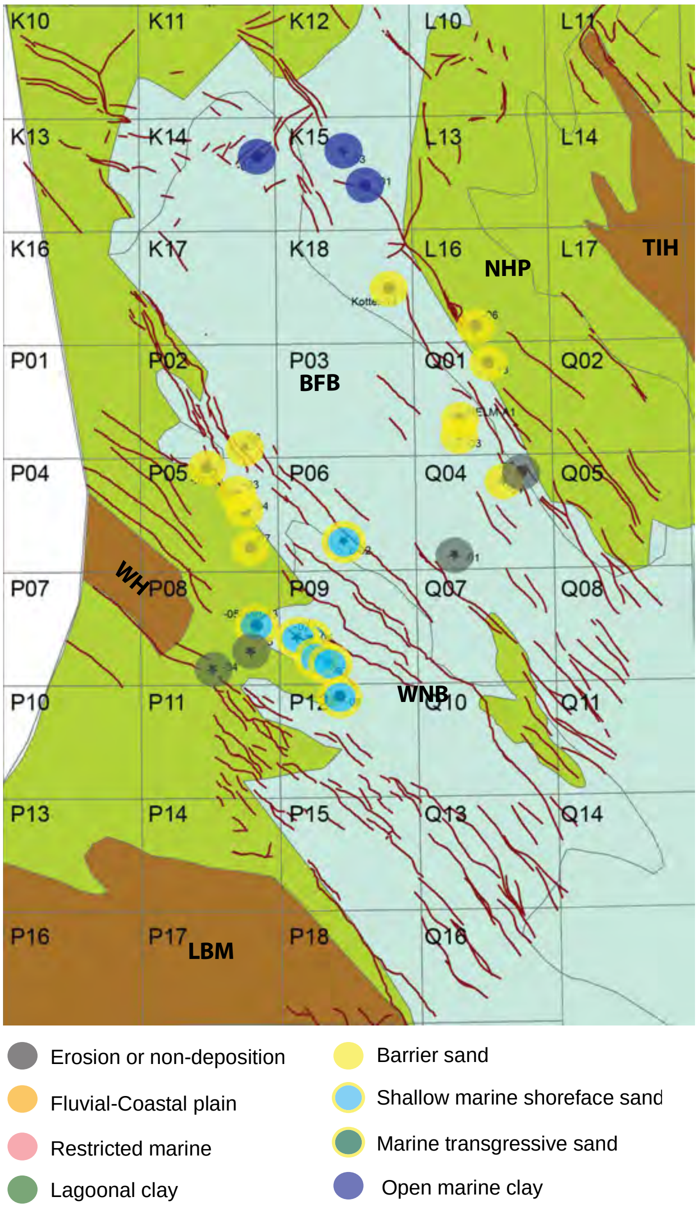

Figure 57 Palaeogeography of the Early Valanginian (**TNO Subzone 4B**)

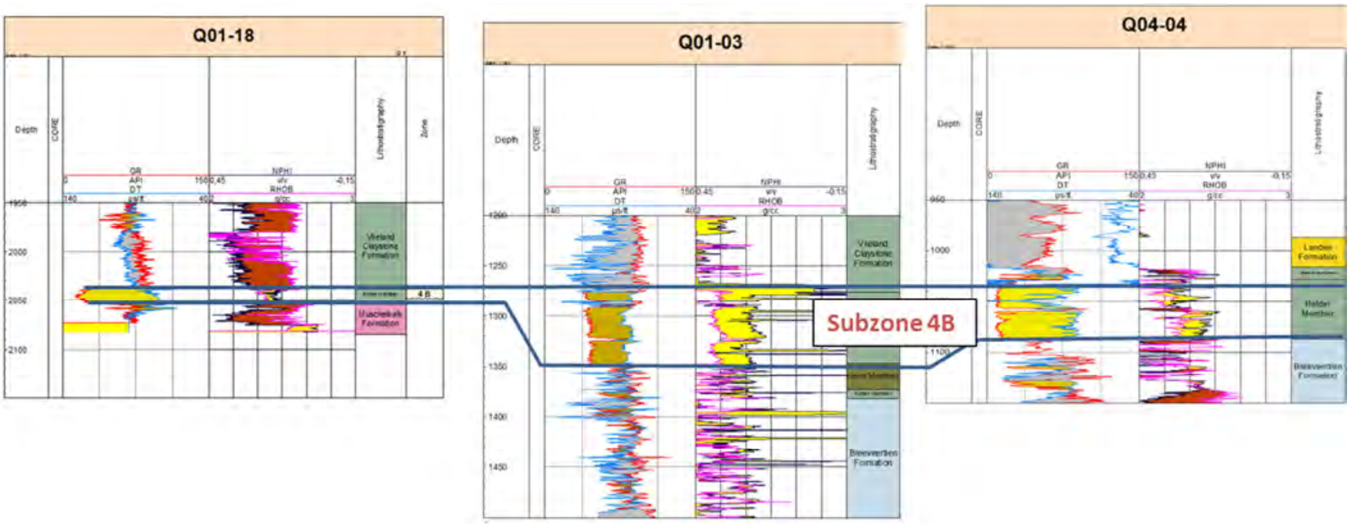

Figure 58 The beach-barrier system of the Kotter Mb. that developed during the Early Valanginian (**TNO Subzone 4B**) in the Q01 and Q04 Blocks. In well Q01-18, the Kotter sands unconformably overlie the Triassic Muschelkalk.

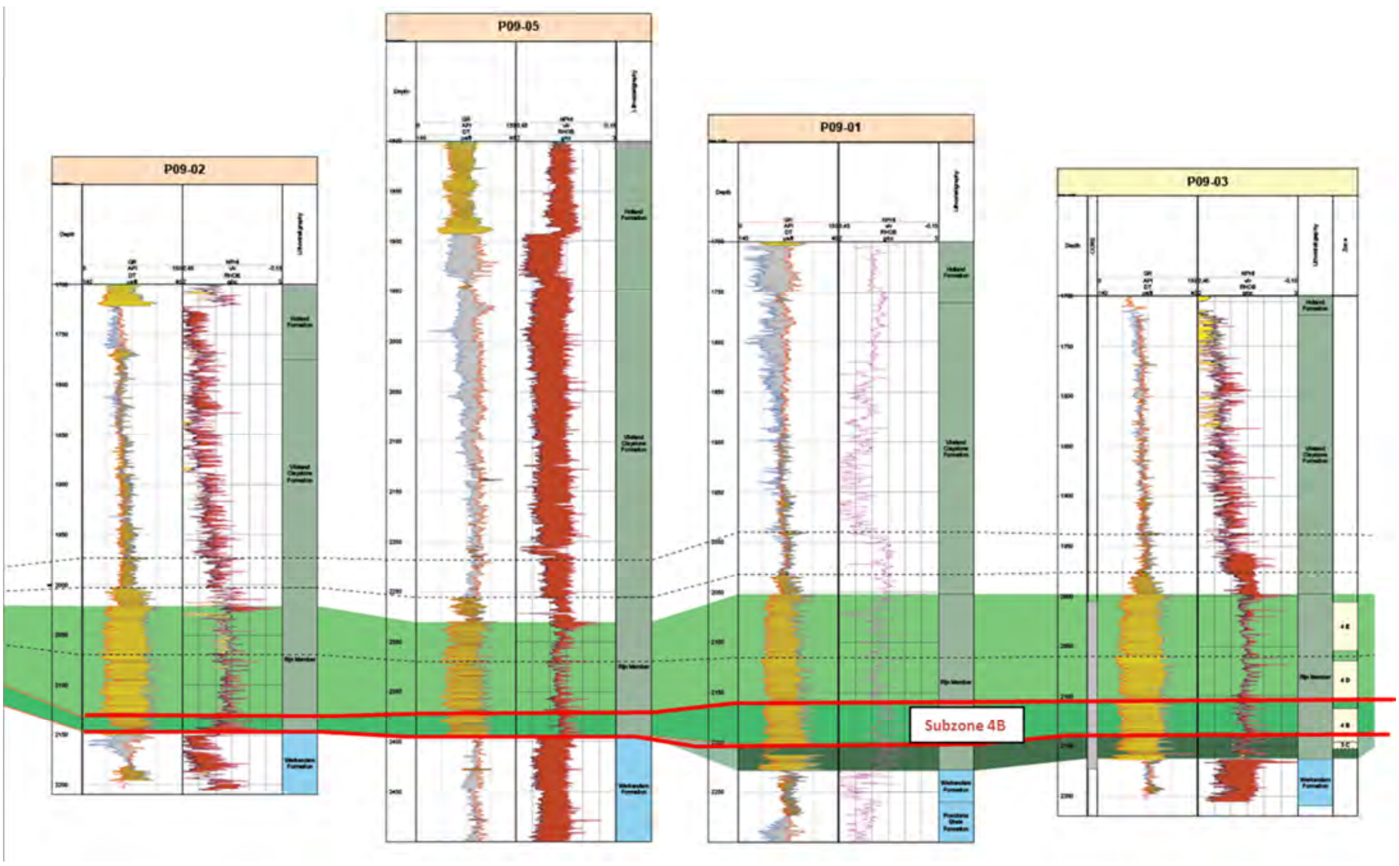

Figure 59 The more open marine shoreface complex of the Kotter Mb. that developed in the Early Valanginian (**TNO Subzone 4B**) in the P09 Block.

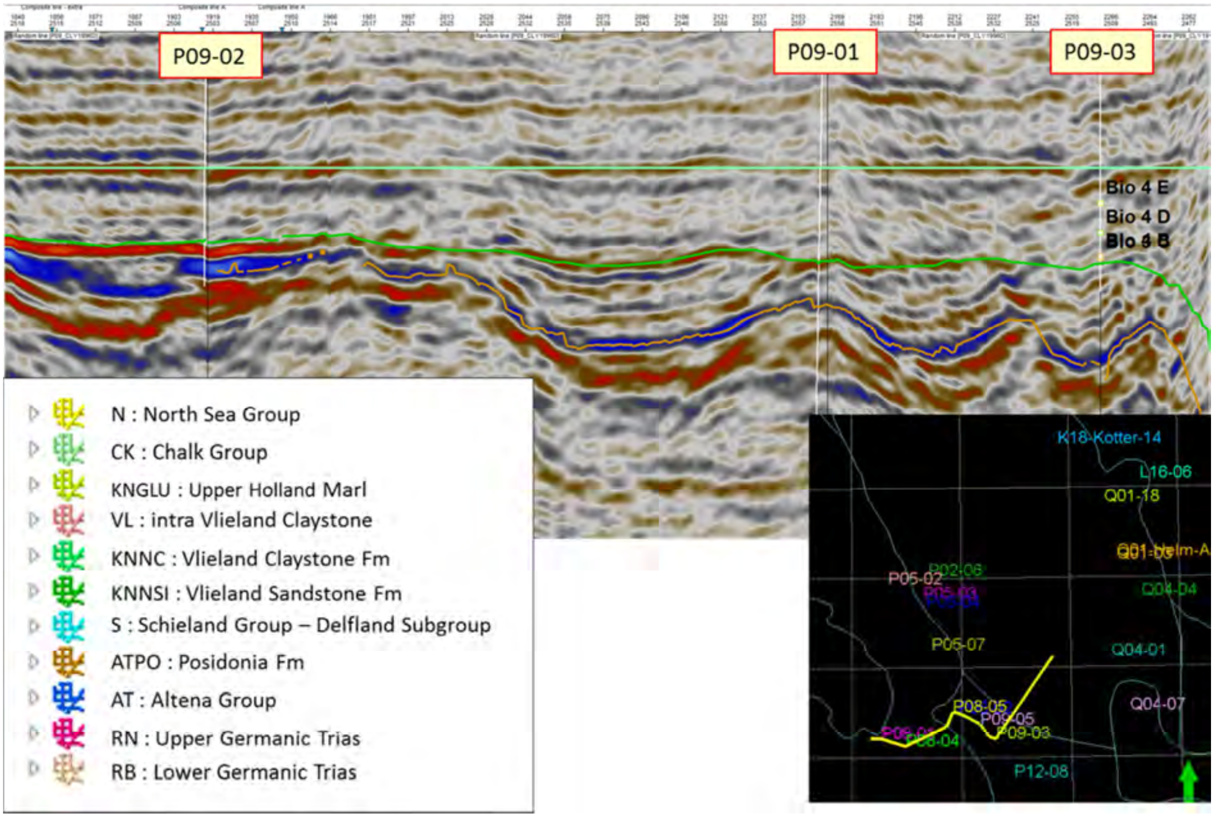

Figure 60 Seismic cross-section in Block P09, flattened on the Vlieland Claystone Fm. The Vlieland Sandstone Fm consists of the Kotter Mb (**TNO Subzone 4B**) and the Rijn Mb (**TNO and 4E Subzone 4D**). The small intra-formational hiatus spanning the Late Valanginian **TNO Subzone 4C**, can not be distinguished with the seismic resolution at hand. Note that the underlying Lower Jurassic Werkendam and Posidonia Shale Fm are folded, prior to deposition of the Vlieland Sandstone Fm. Seismic horizons represent bases. .

The underlying cause for the consipicuous basin-wide facies change of the Early Valanginian (**TNO Subzone 4B**) is primarily attributable to a major sea-level rise. The MFS, known in the literature as the *paratollia* MFS, is associated with a remarkable carbon isotope excursion, known in the literature as the *Weissert event* (see Chapter 6). The positive isotope excursrion may be a response to global sea-level rise via the expansion of shelf areas and elevated productivity (see e.g., Jenkyns et al., 1996). On the other hand, thickness variations and the recorded facies-differentiation suggest that there was also a tectonic control on the depositional patterns, with the northern part of the BFB subsiding at a faster pace than the southern part and the WNB.

The Early Valanginian transgression was followed by a regression in the Late Valagninian (lower part of **TNO Subzone 4C**). The regression caused a minor interruption of the sedimentation in the P09 Block (see Figure 61), resulting in a small hiatus, spanning the Late Valanginian (**TNO Subzone 4C**). The hiatus is small and did not lead to significant erosional features, it can not be distinguished on seismic (Figure 60).

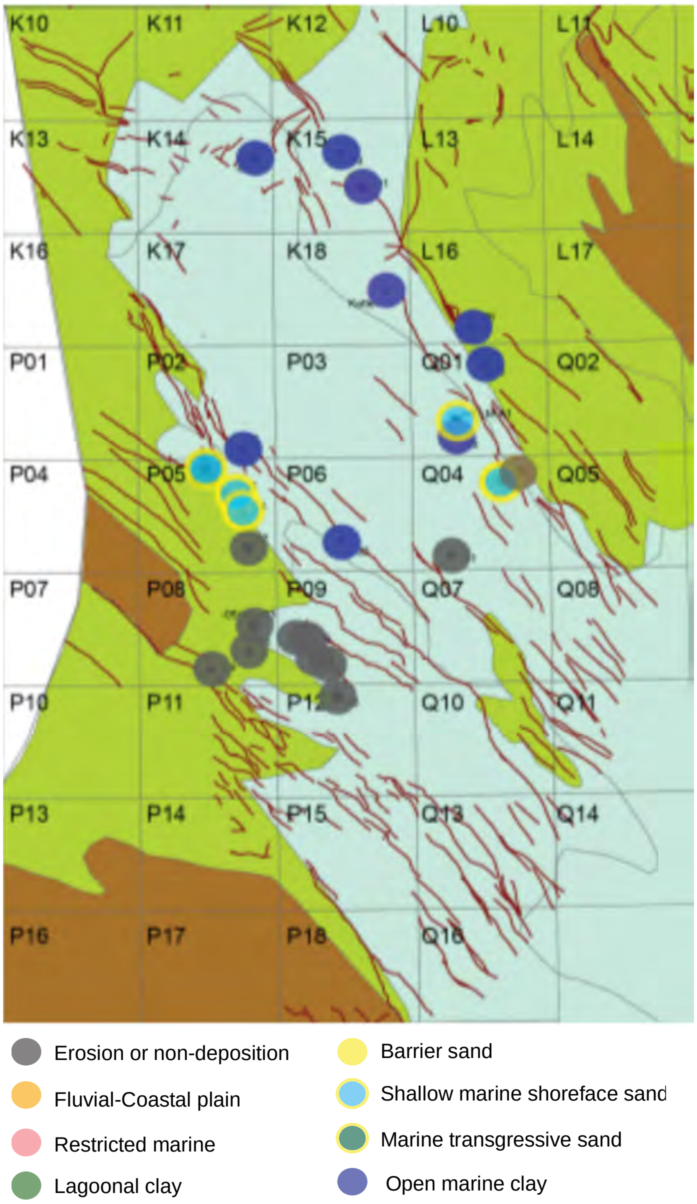

Figure 61 Palaeogeography of the Late Valanginian (**TNO Subzone 4C**)

After the Late Valanginian regressive phase, sedimentation resumed In the P08 and P09 Blocks with open marine sandstone deposition of the Rijn Member, around the Valanginian – Hauterivian boundary (Figure 62).

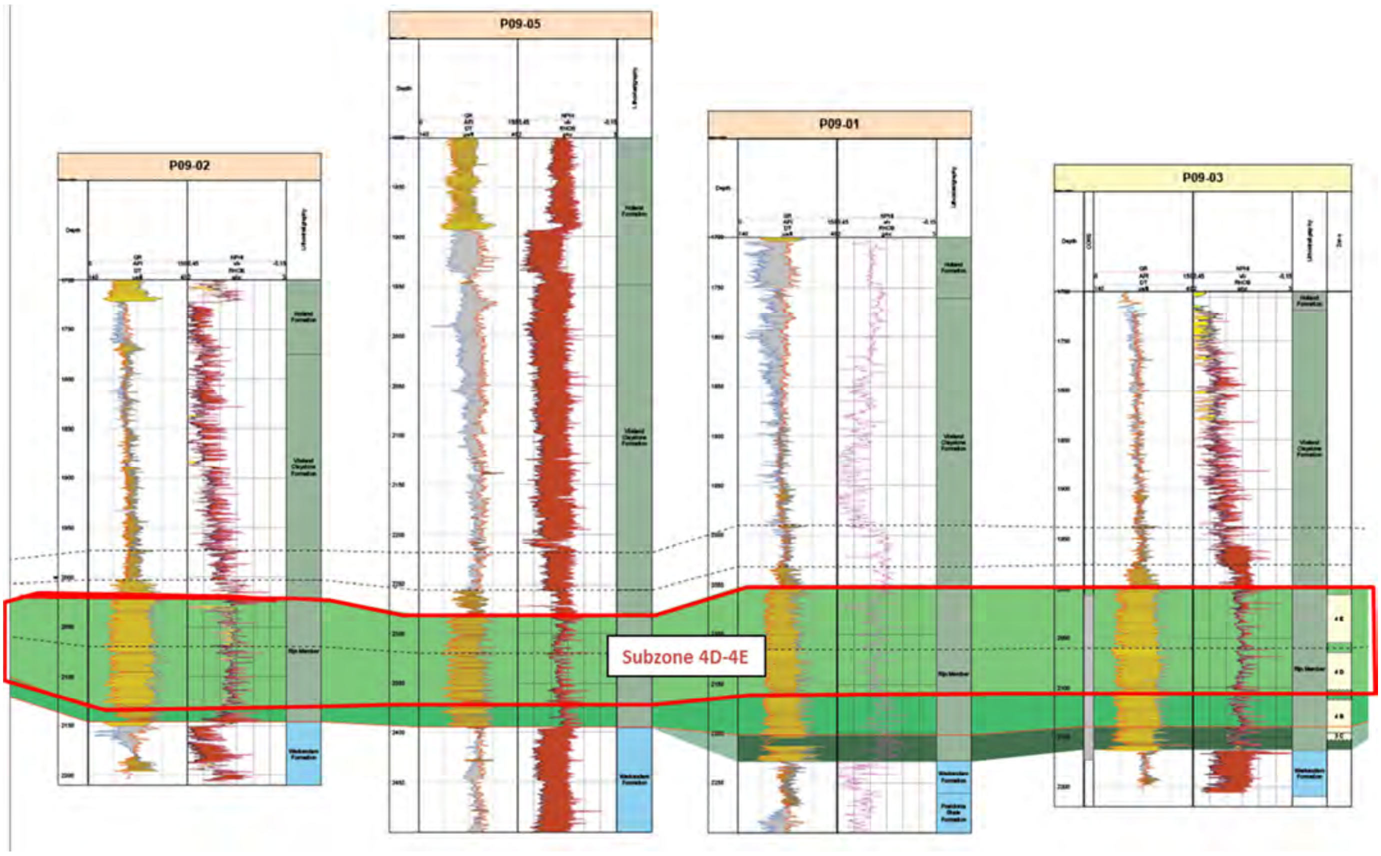

Figure 62 Open marine transgressive sandstones of the Rijn Mb in the P09 Block.

At the same time, almost the entire BFB was dominated by offshore mudstone deposition, indicating a relatively offshore setting (Figure 63). On the Southeastern side of the BFB, in Block Q01 and Q04, a lateral facies change can be observed from the (at that time still) sandy deposits of the Helder Mb in well Q04-07, to the time-equivalent shales of the Vlieland Claystone Fm in well Q01-03 (Figure 64)

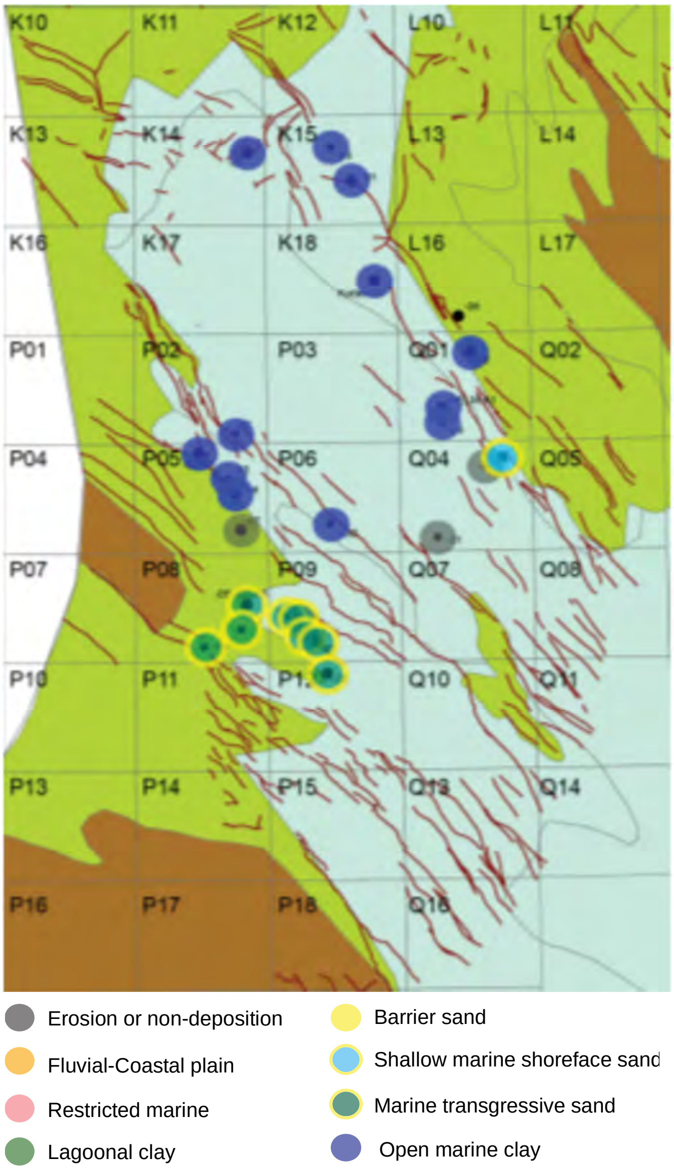

Figure 63 Palaeogeography of the Early Hauterivian (**TNO Subzone 4D and 4E**)

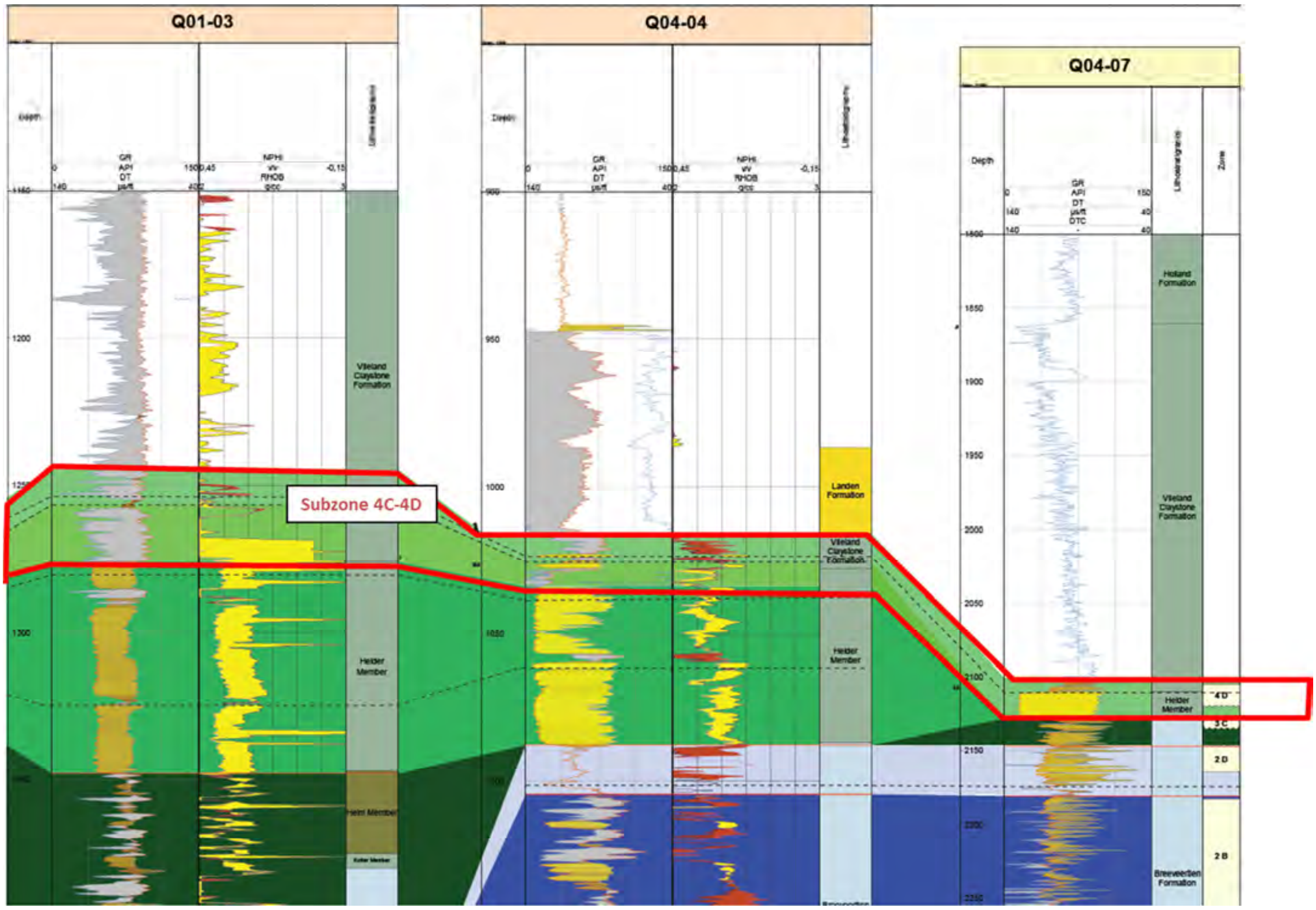

Figure 64 Correlation panel from well Q01-03 to Q04-07 with **TNO Subzones 4C and 4D** framed in red. From South (Q04-07) to North (Q01-03), a lateral facies transition can be observed: from the coarse-grained Helder Mb, in well Q04-07, to the fine-grained Vlieland Claystone Fm, in well Q01-03.

8.3 Wheeler diagrams of the BFB and WNB

In Figure 65 and Figure 66, wheeler diagrams are presented in order to illustrate and summarize the basin evolution of the BFB and WNB. In Figure 65, the Eastern side of the BFB is displayed. With the lithostratigraphic units scaled on time, the hiatus in the Late Volgian and Early Ryazanian stands out immediately. Such a gap in the sedimentary succession can not be explained by a sea-level lowering alone, uplift and erosion occurred during this time. Also very well visible is the lateral facies change in the Late Valanginian and Hauterivian: from sandstone, in the South, to mudstone, in the North. This trend indicates that the basin subsided fastest in the North. Note also that sediments belonging to the Peripheral Basin Phase (TNO Zone 2) are absent in many well along this transect. Unfortunately, it is not certain if this is also the case for the central part of the basin, because well control is lacking in that area.

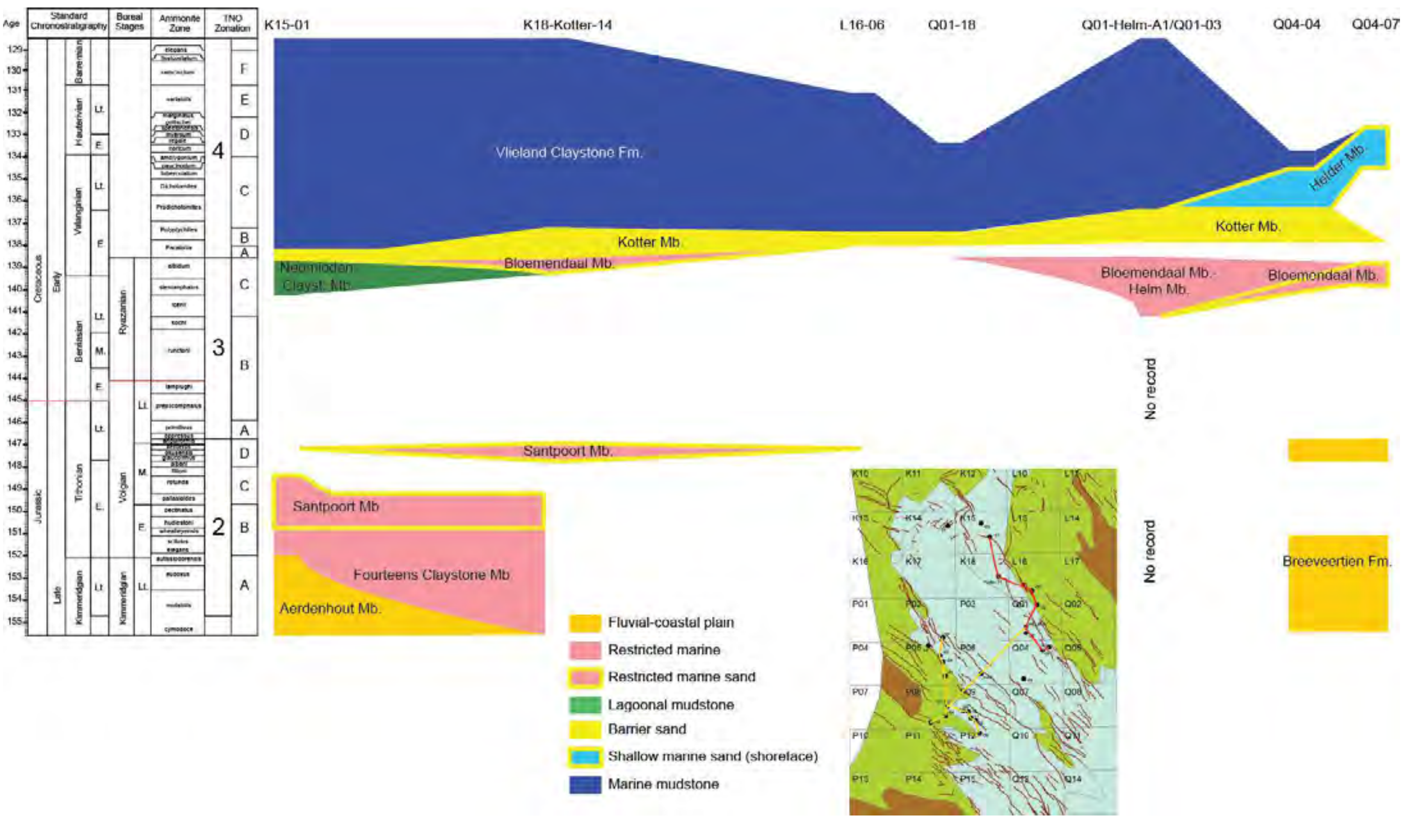

Figure 65 Wheeler diagram showing the temporal and spatial facies distribution along the eastern edge of the study area (K15 to Q04, see inset map).

In the western edge of the BFB and the offshore WNB, the same trend is observed: from sandstone in the South (Rijn Mb.) to offshore mudstone in the North (Vlieland Claystone Fm., see Figure 66). The only difference is that the transition is abrupt, in Block P05, the Vlieland Claystone Fm. occurs in the Hauterivian of all wells, in Block P08 the Rijn Mb. occurs in the Hauterivian of all wells. This apparent well-defined facies change is also observed the expression of the Early Valanginian transgression (**TNO Subzone 4B**). In the P05 Block, The Kotter Mb. contains low diversity dinocyst assemblages which are interpreted as barrier sandstones, in the P08 and P09 Block, the Kotter Mb. displays a more open marine character, these sandstones are interpreted as shoreface sands. Note that also at the western edge, Subzone 3A and 3B are completely missing, emphasizing the widespread occurrence of the basin inversion around that time.

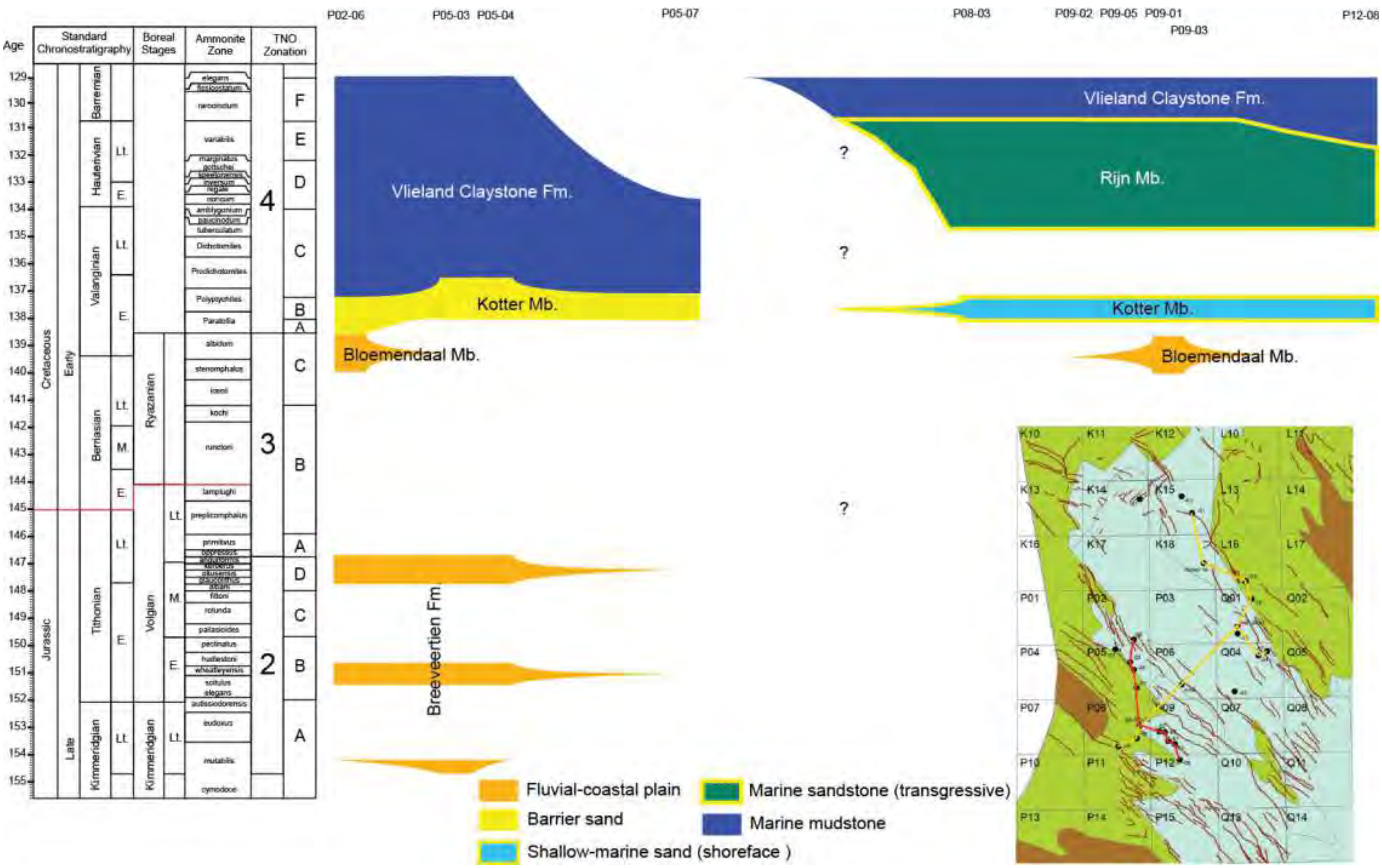

Figure 66 Wheeler diagram showing the temporal and spatial facies distribution along the western edge of the study area (P02 to P12, see inset map).

9 Synthesis

In the previous two chapters the basin evolution and basin fill of the Step Graben, Broad Fourteens Basin and offshore West Netherlands Basin is described in detail. In this chapter, an attempt is made to zoom out to a regional scale and to combine the geological histories of the individual sub-basins into one single story explaining the entire regional geology.

During the Late Jurassic an important change in the tectonic regime occurred. When the rifting begins, roughly in the Callovian, the extensional direction is East – West. Around the Early to Late Kimmeridgian transition, the extensional regime changed to Northeast – Southwest. This is reflected in the isopach patterns of the Upper Jurassic Schieland Group and the Lower Cretaceous Rijnland Group (Figure 67). The Upper Jurassic sediment stack is distributed in a narrow curved strip with a clear North – South trend up to the BFB where it bends towards the Southeast. The Lower Cretaceous sediment stack shows two major bowl-shaped depocenters, one centered around the Terschelling and Vlieland Basin, the other one centered in the BFB and offshore WNB.

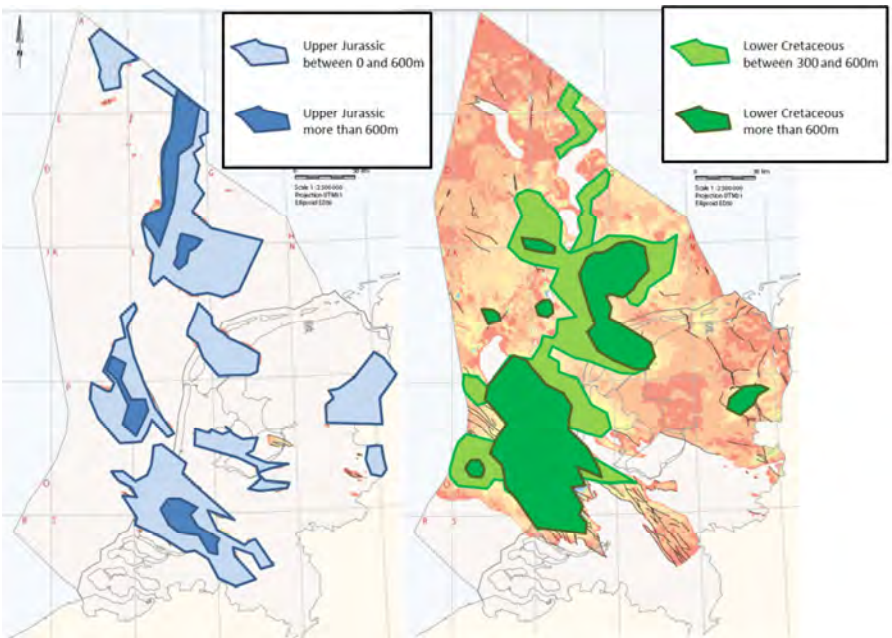

Figure 67 Isopach maps of the Upper Jurassic Schieland and Scruff Groups (in blue) and the Lower Cretaceous Rijnland Group (in green). Adapted from Duin *et al.,* 2006.

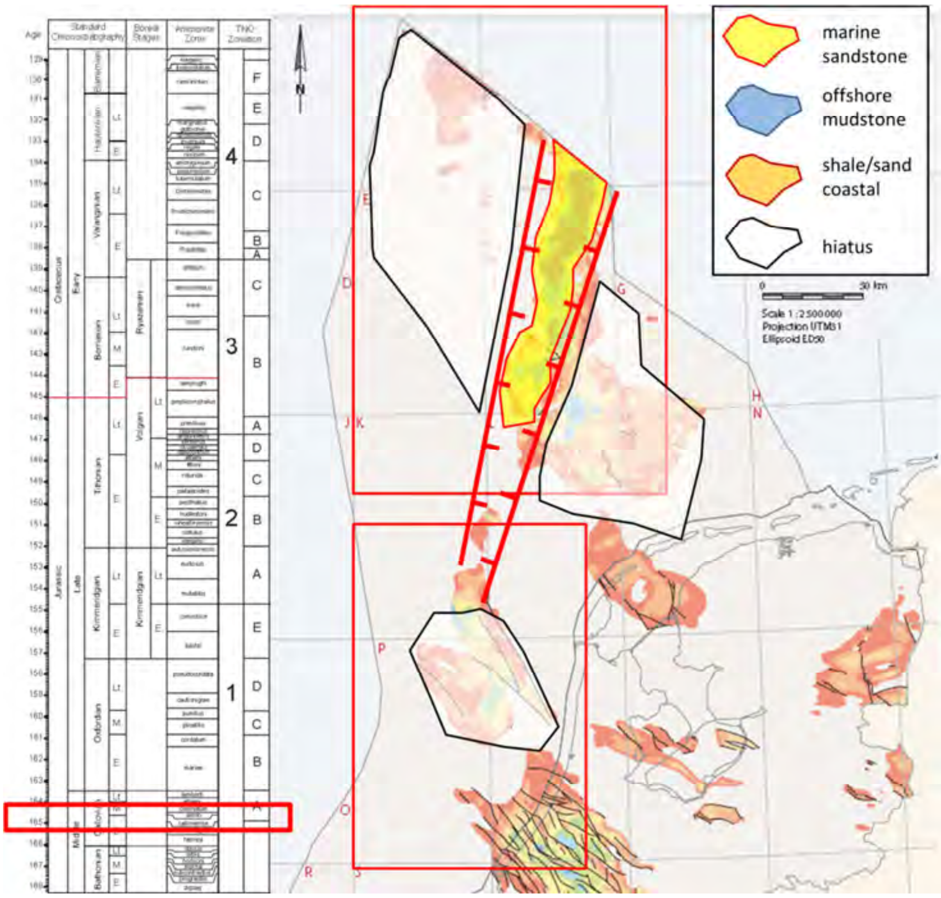

Figure 68 Schematic representation of the basin configuration during the Late Callovian.

When we take a closer look and into the details of the basin evolution, a more complex picture arises. The Upper Jurassic rifting starts with the Middle Callovian to Early Kimmeridgian Graben Axis Phase (TNO Zone 1). Subsidence during this phase is mainly restricted to the axis of the North – South trending Central Graben in the northern offshore (Figure 68). In terms of basin development, not much is happening in the southern offshore, although is suggested here that the Central Graben was connected to the Broad Fourteens Basin, based on the occurrences of isolated Upper Jurassic pockets in the L07 Block. The basin development of the graben axis was quite uniform over large distances. This is reflected for instance by the occurrence of three continuous coal layers at the base of the Middle Graben Fm (**TNO Subzone 1B**).

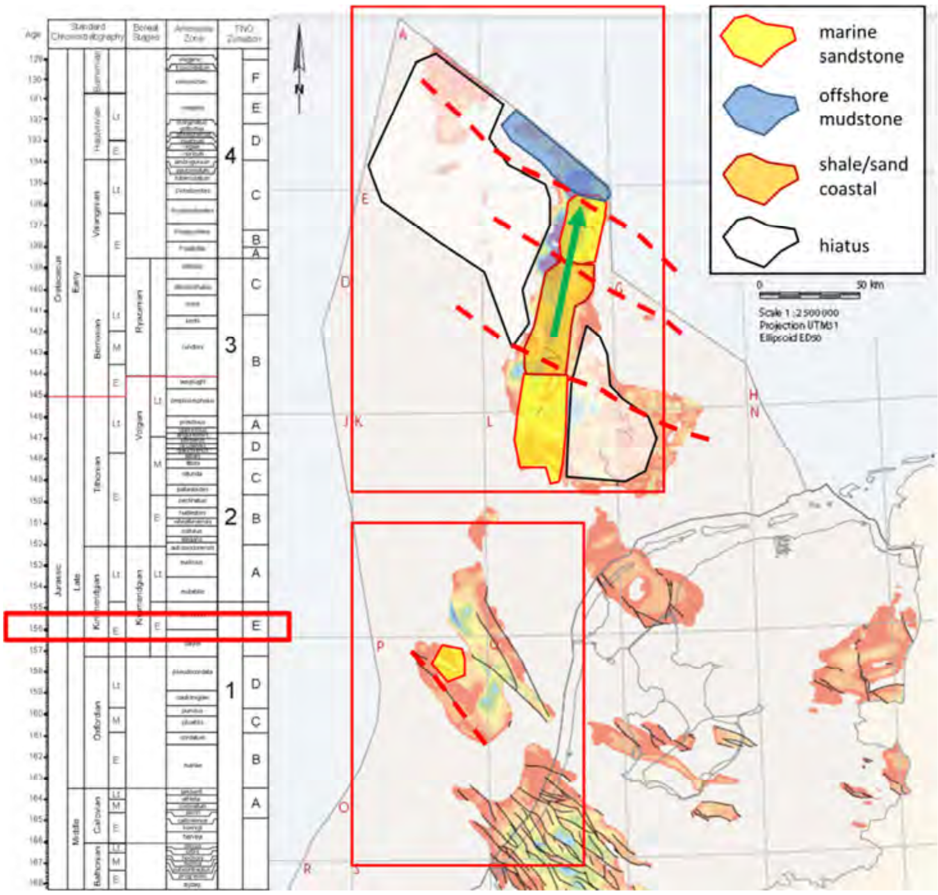

Figure 69 Schematic representation of the basin configuration during the Early Kimmeridgian.

This all changes in the Late Oxfordian to Early Kimmeridgian, when the central graben axis becomes compartmentalized into sub-basins with distinct facies boundaries (Figure 69). It is suggested here that the basin segregation foreshadows the change in the extensional direction.

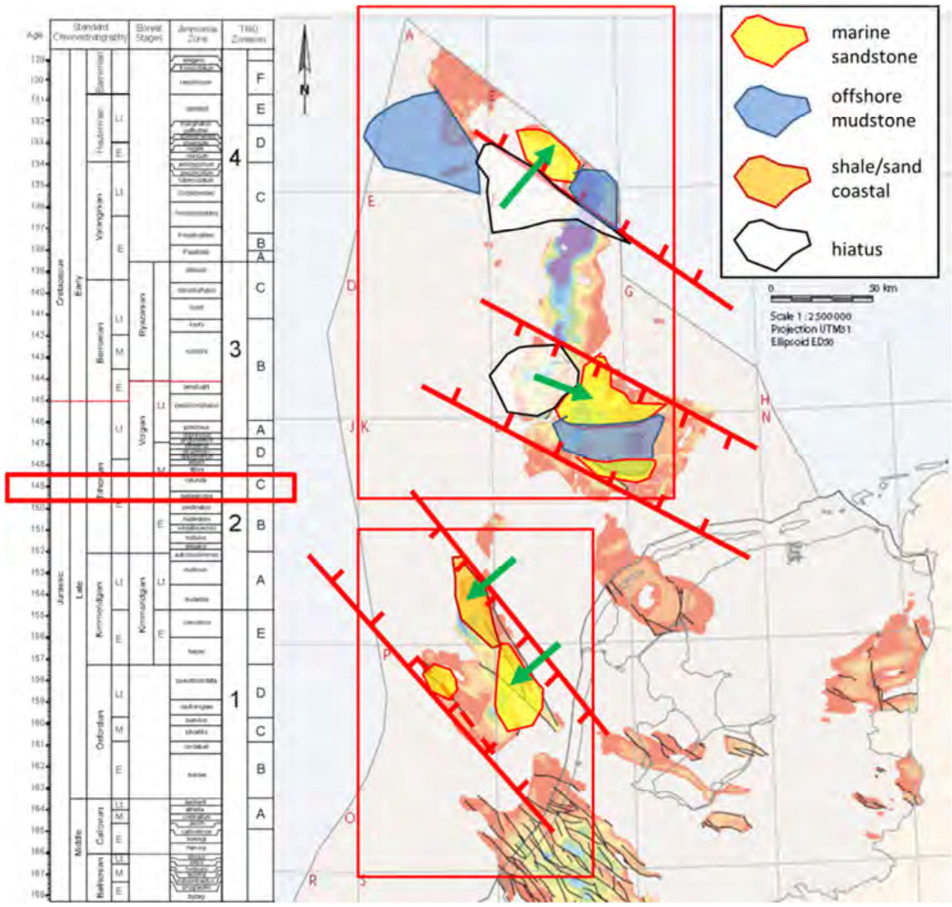

Figure 70 Schematic representation of the basin configuration during the Middle Volgian.

The change in extensional direction also brings a change in structural style: during the Late Kimmeridgian and Volgian all NW-SE trending faults become very active. This brings the Terschelling Basin and the Broad Fourteens Basin to life. The depocenters shift towards the L03 Block in the Central Graben and towards the K18 and K15 Blocks in the BFB. The fast rate of subsidence in the L03 Block causes the southern Central Graben to tilt towards the East, causing erosion of its western edge and sheds sand into the Terschelling Basin (Figure 70). Salt movement is also at its peak during the Middle and Late Volgian. More evidence for erosion is found in the B14 Block, where the active NW-SE fault sheds sand into the NW branch of the graben axis (Figure 70). Also the BFB is receiving sand, probably from the footwalls of the boundary faults.

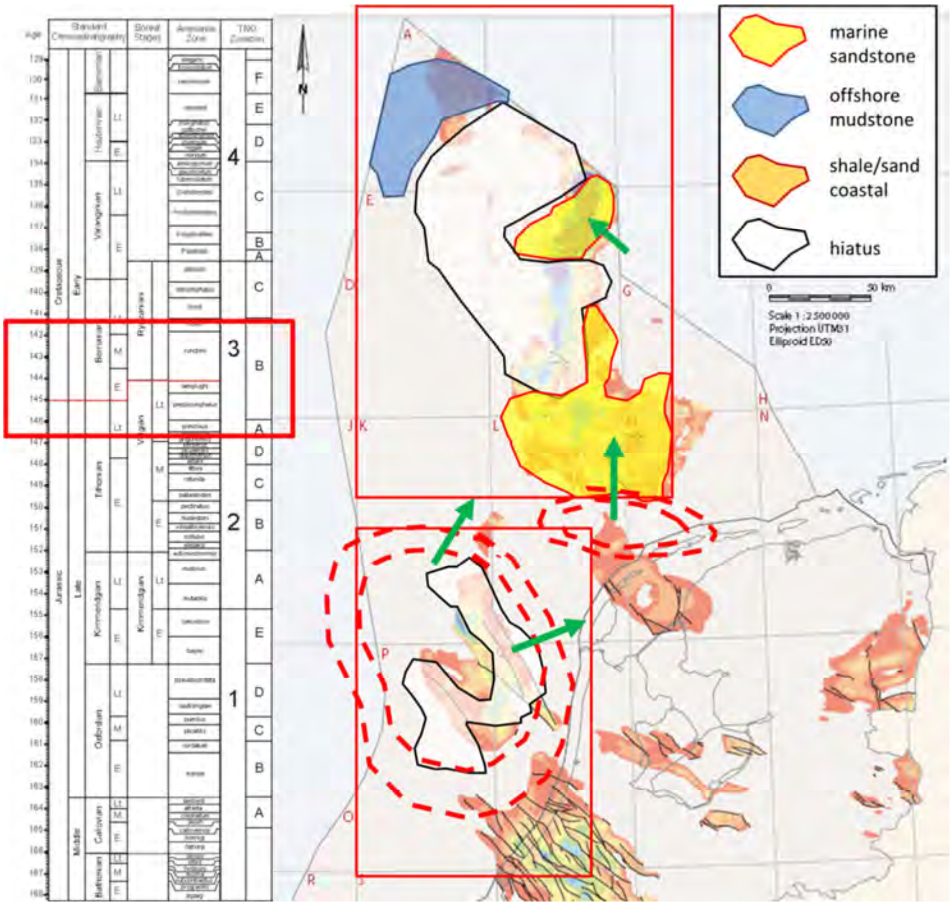

Figure 71 Schematic representation of the basin configuration during the Late Volgian to Early Ryazanian. The areas indicated by the dashed lines are probably uplifted.

The next phase of the basin evolution occurs in the Late Volgian and Early Ryazanian. A basin wide unconformity or a time-equivalent conformable seismic marker reflect a tectonic event. The ins and outs are not yet entirely clear, but the absence of Late Volgian – Early Ryazanian deposits in all studied wells from the BFB and offshore WNB indicate a - short-lived - phase of erosion (Figure 71). At the same time, the Terschelling Basin is filled with glauconitic sands, spreading out and onlapping on to the adjacent plateaus. Whatever the reason, the widespread occurrence of sand and unconformities provides strong evidence for uplift and erosion. Fault locking followed by isostatic rebound migh be a conceivable, albeit speculative, scenario. This might also explain why the BFB and offshore WNB became inverted and the Terschelling Basin not, because the Terschelling Basin in mainly controlled by salt movement while the BFB and WNB are mainly controlled by fault movement.

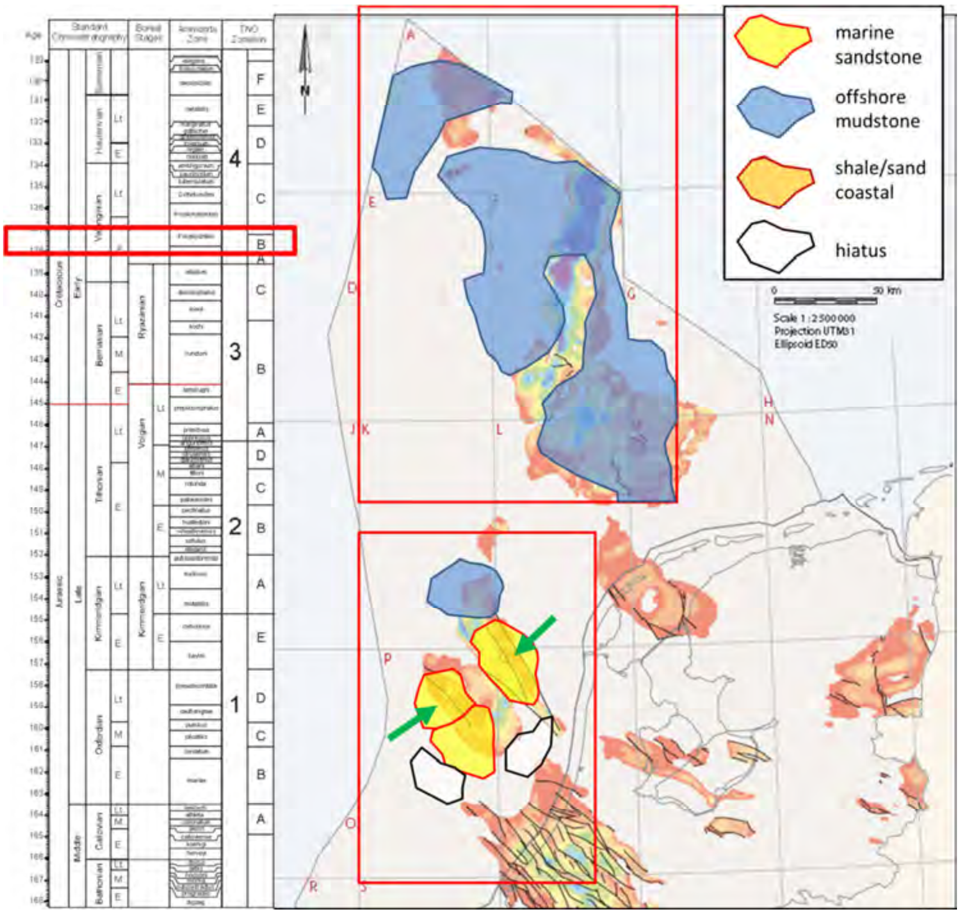

Figure 72 Schematic representation of the basin configuration of the Early Valanginian.

In the Valanginian, the rifting has come to an end. In the BFB and offshore WNB, sand deposition dominates after the erosional phase fo the Late Volgian - Ryazanian. Apparently good sources for erosion were provided by the uplifted areas around the basin. The detailed facies distribution of the various sandstones is quite complex and governed by the subsequent activity of relay faults dissecting the edges of the basin. Eustacy now becomes the main control for the various generations of sandstones in this area. The Central Graben area, including the Terschelling Basin is dominated by mudstone deposition by now.

10 Conclusions

The broad geological insights that have been gained from this stratigraphic study are summarized in Chapter 9. In this chapter, an attempt is made to select those findings which are considered important with respect to petroleum geology. All conclusions are based on palynological and stable isotope data, with a minor contribution from seismic data.

Conclusions concerning the **Step Graben:**

1. In general, the Upper Jurassic to Lower Cretaceous sedimentary successions are thin.
2. The eastern side of the Step Graben displays a depositional style which is most comparable to the so-called “adjacent plateaus”, such as the Schill Grund Plateau: only Ryazanian deposits are present, no Late Kimmeridgian to Late Volgian sediments,
3. The western side of the Step Graben displays a depositional style which is more comparable to the “adjacent plateaus”, in particular to the plateaus from the German/Danish offshore, such as the Heno Plateau and Outer Rough Basin.
4. Evidence for tectonic activity along NW-SE faults in the Middle and Late Volgian, is found in the thick pile of sandy deposits of the Noordvaarder Mb in the B14 and B13 Blocks.
5. Occurrences of the Scruff Greensand Fm are rare, these are limited to the eastern-most side.

Conclusions concerning **the Broad Fourteens and offshore West Netherlands Basin**:

1. In general, the Upper Jurassic to Lower Cretaceous sedimentary successions are thick.
2. Both sub-basins display a depositional style that superficially resembles that of the socalled “peripheral basins”, such as the Terschelling Basin: Middle Callovian to Early Kimmeridgian sediments are (almost) absent, thick piles of Late Kimmeridgian to Middle Volgian sediments occur in the deepest parts of the basins.
3. Both sub-basins differ from the Terschelling Basin in the complete absence of Late Volgian to Early Ryzanian sediments, indicating a short-lived phase phase of uplift and erosion, or in other words, indicating basin inversion.
4. Main sandstone development occurs in two generations, one in the Valanginian and one in the Hauterivian, separated by a minor hiatus.
5. In the Valanginian and Hauterivian, a trend from sandstone to mudstone is noticed from the South to the North.
6. The Kotter Mb displays a more open marine character in the P08 and P09 Blocks than in the P05 Block, where it displays a more restricted marine character.
7. The Valanginian and Hauterivian sandstones are probably sourced from the uplifted areas resulting from the Late Volgian to Early Ryazanian inversion.

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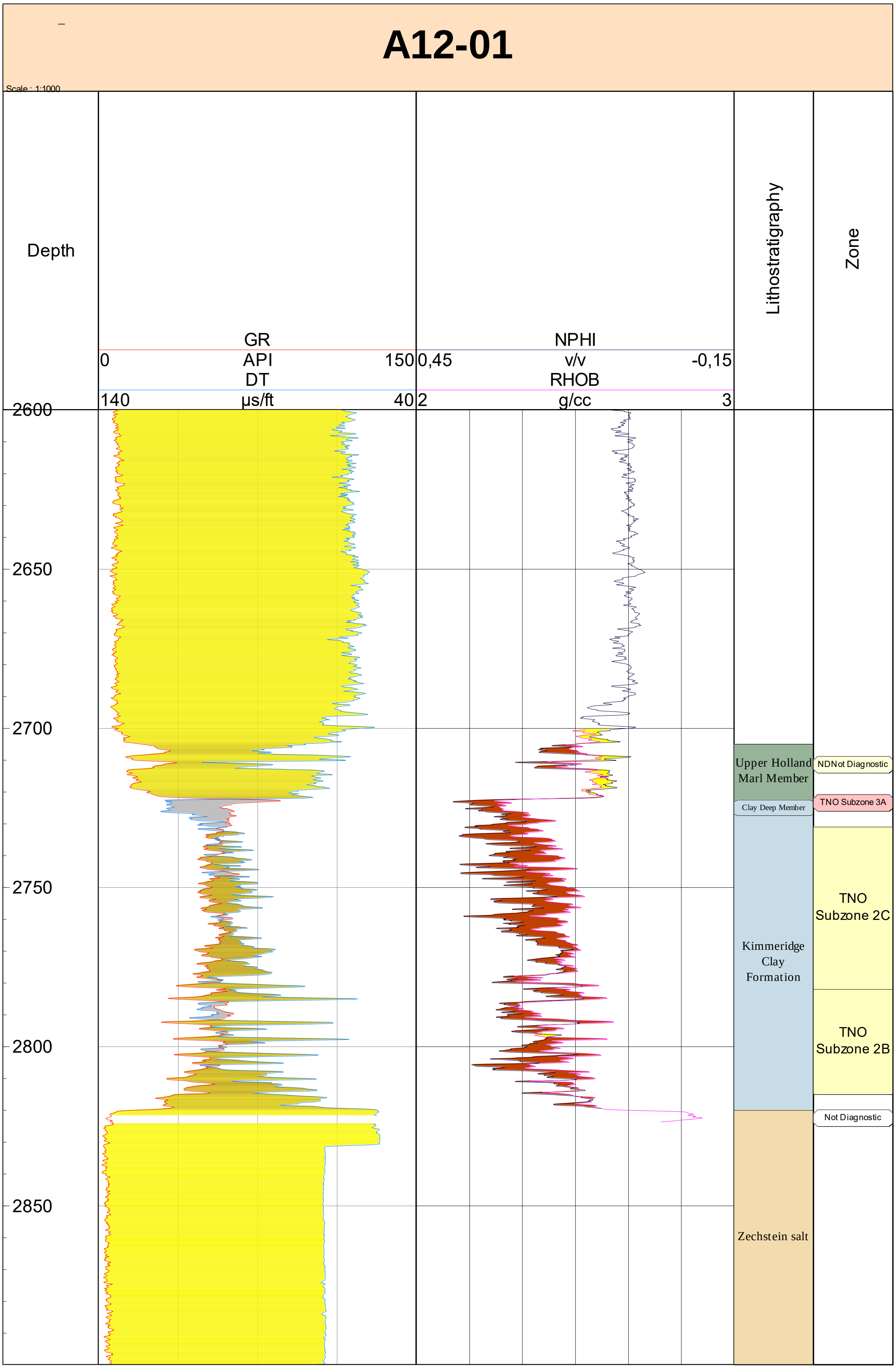


A12-01
Scale : 1:1000
Depth
GR
0 API 150
DT
140 µs/ft 40
NPHI
0,45 v/v -0,15
RHOB
2 g/cc 3
Lithostratigraphy
Zone
2600
2650
2700
2750
2800
2850
Upper Holland Marl Member
Clay Deep Member
Kimmeridge Clay Formation
Zechstein salt
NDNot Diagnostic
TNO Subzone 3A
TNO Subzone 2C
TNO Subzone 2B
Not Diagnostic

Age assessments of well A12-01

<u>Sample/Interval</u> | <u>Age</u>
2710-2713 mCU | ND

Remarks: the microflora is dominated by Tertiary caving

Sample/Interval	Age
2713-2719 mCU	latest Aptian/earliest Albian, *jacobi-tardefurcata* Ammonite Subzone, or older

The age interpretation is based on:

- LOD *Dingodinium cerviculum* at 2713-2716 m

Remarks: Duxbury (1983) records the LOD of *Dingodinium cerviculum* in the uppermost Aptian, *jacobi* Ammonite Subzone, while Davey (1982) indicated the lowermost Albian, *tardefurcata* Ammonite Subzone.

Sample/Interval	Age
2722-2725 mCU	Late Volgian, *oppressus-primitivus* Ammonite Subzones, Sequence 3, TNO SubSubzone 3A

The age interpretation is based on:

- LOD abundant *Cribroperidinium hansenii*

Sample/Interval	Age
2731-2749 mCU	Middle Volgian, *fittoni* Ammonite Subzone, or older, Sequence 2, TNO Subzone 2C

The age interpretation is based on:

- LOD *Rhynchodiniopsis cladophora* at 2731-2734 m
- LOD *Aldorfia dictyota* at 2737-2740 m
- LOD *Egmontodinium ovatum* at 2746-2749 m
- LOD *Rhynchodiniopsis martonense* at 2746-2749 m

Sample/Interval	Age
2767-2782 mCU	Middle Volgian, *rotunda* Ammonite Subzone, or older, Sequence 2, TNO Subzone 2C

The age interpretation is based on:

- LOD *Oligosphaeridium patulum* at 2767-2770 m

Sample/Interval	Age
2782-2794 mCU	Early Volgian, *pectinatus* Ammonite Subzone, or older, Sequence 2, TNO Subzone 2B

The age interpretation is based on:

- LOD *Atopodinium haromense* at 2782-2785 m
- LOD *Perisseiasphaeridium pannosum* at 2782-2785 m

Sample/Interval	Age
2797-2815 mCU	Early Volgian, *hudlestoni* Ammonite Subzone, or older, Sequence 2, TNO Subzone 2B

The age interpretation is based on:

- LOD *Cribroperidinium longicorne* at 2797-2800 m
- LCOD *Oligosphaeridium patulum* at 2797-2800 m

Sample/Interval	Age
2821-2824 mCU	ND

Remarks: the association is dominated by Early-Middle Volgian caving. Late Permian sporomorphs are not preserved and/or absent.

Lithostratigraphy of well A12-01

The lithostratigraphic interpretation of well A12-01 (NLOG 2013) is listed in Table 1.

Table 1 Outdated lithostratigraphic interpretation of well A12-01 (NLOG 2013)

Interval (m)	Lithostratigraphy
0-2038	North Sea Supergroup
2038-2123	Ekofisk Formation
2123-2705	Ommelanden Formation
2705-2723	Upper Holland Marl Member
2723 -2773	Kimmeridge Clay Formation
2773 -2820	Middle Graben Formation
2820-3438	Zechstein salt

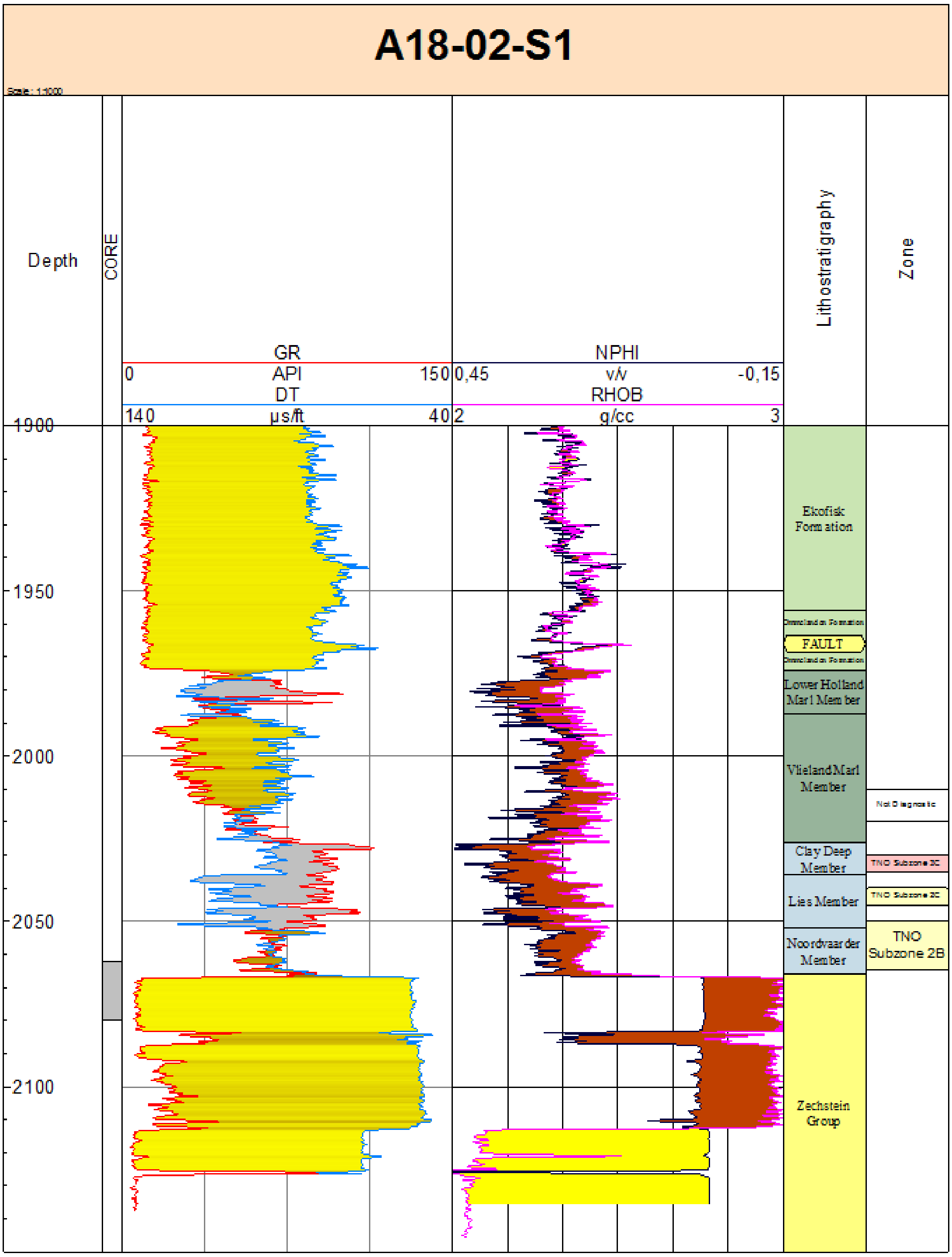
An age in the latest Aptian/earliest Albian, *jacobi-tardefurcata* Ammonite Subzone at depth interval 2713-2716 m confirms an interpretation in the Rijnland Group, Holland Formation.

The clayey interval 2722-2725 m is dated ca. Early/Late Portlandian boundary, *oppressus-primitivus* Ammonite Subzones. This age corresponds with Sequence 3 sensu Abbink et al. (2006) and disagrees with a position in the Kimmeridge Clay Formation that is associated with Sequence 2. Hence, the lithostratigraphic interpretation of the clayey interval is changed in the Lutine Formation, Clay Deep Member (Scruff Group).

The lower part 2767-2815 m of the studied succession is still Late Kimmeridgian in age. The part of this stage belongs to Sequence 2 sensu Abbink et al. (2006) and therefore does not fit with the NLOG interpretation of the Middle Graben Formation (= Sequence 1). The succession that overlies the Zechstein Group at 2820 m is classified as Scruff Group, Kimmeridge Clay Formation (2727-2820 m).

Table 2 Updated lithostratigraphic interpretation of well A12-01

Interval (m)	Lithostratigraphy
0-2038	North Sea Supergroup
2038-2123	Ekofisk Formation
2123-2705	Ommelanden Formation
2705-2723	Upper Holland Marl Member
2723-2727	Lutine Formation, Clay Deep Mb
2727 -2820	Kimmeridge Clay Formation
2820-3438	Zechstein Group


A18-02-S1
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CORE
GR
0
API
150
DT
140
µs/ft
40
NPHI
0,45
v/v
-0,15
RHOB
2
g/cc
3
Lithostratigraphy
Zone
1900
1950
2000
2050
2100
Ekofisk Formation
FAULT
Lower Holland Marl Member
Vlieland Marl Member
Clay Deep Member
Lies Member
Noordvaarder Member
Zechstein Group
Not Diagnostic
TNO Subzone 2C
TNO Subzone 2C
TNO Subzone 2B

Age assessments of well A18-02-S1

Sample/Interval	Age
2000mCU	Late Aptian, *jacobi* Ammonite Subzone, or older

The age interpretation is based on:
- LOD *Achomosphaera neptunii*
- LOD *Dingodinium cerviculum*

Sample/Interval	Age
2010-2020mCU	ND

Remarks: only a few long-ranging (Cretaceous) dinoflagellate cysts are present.

Sample/Interval	Age
2030mCU	Late Ryazanian, *stenomphalus* Ammonite Subzone, or older, Sequence 3, TNO Subzone 3C

The age interpretation is based on:
- LOD *Daveya boresphaera*

Sample/Interval	Age
2040mCU	Middle Volgian, *fittoni* Ammonite Subzone, or older, Sequence 2, TNO Subzone 2C

The age interpretation is based on:
- LOD *Rhynchodiniopsis martonense*

Remarks: the presence of *Glossodinium dimorphum* (LOD Late Volgian, *anguiformis* Ammonite Subzone) fits with this interpretation.

Sample/Interval	Age
2050-2062.30m CU+CO	Early Volgian, *hudlestoni* Ammonite Subzone, or older, Sequence 2, TNO Subzone 2B

The age interpretation is based on:
- LOD *Cribroperidinium longicorne* at 2050 m

Remarks: the LOD of *Gonyaulacysta jurassica* confirms an age in the Middle Volgian, older than the *pectinatus* Ammonite Subzone. The occurrence of *Stephanelytron* at 2060 m is considered as reworking from the Kimmeridgian.

Sample/Interval	Age
2064.55mCO	Early Volgian, *elegans/scitulus* Ammonite Subzone, Sequence 2, TNO Subzone 2B

The age interpretation is based on:
- FCOD *Classopollis*
- LCOD *Perinopollenites*

Remarks: the so-called "*scitulus* climate shift" is present. The event represents less arid conditions during the Kimmeridgian compared to the Early Volgian.

Sample/Interval	Age
2064.60mCO	Kimmeridgian, *autissiodorensis* Ammonite Subzone + very common Late Permian reworking, Sequence 2, TNO Subzone 2A

The age interpretation is based on:
- LOD *Endoscrinium luridum*
- LOD *Ctenidodinium chondrum*

Remarks: the FODs of *Dichadogonyaulax pannea* and *Perisseiasphaeridium pannosum* confirm an age within Sequence 2 (base not older than *mutabilis* Ammonite Subzone). The association yields very common reworking from the Late Permian, because the sample comprises a clast from the Zechstein Group.

Sample/Interval	Age
2065.90mCO	Late Permian

The age interpretation is based on:
- LOD *Lueckisporites virkkiae*
- LOD *Vittatina* spp.

Lithostatigraphy of well A18-02-S1

The lithostratigraphic interpretation of well A18-02-S1 (NLOG 2013) is listed in Table 3.

Table 3 Outdated lithostratigraphic interpretation of well A18-02-S1 (NLOG 2013).

Interval (m)	Lithostratigraphy
0-1853	North Sea Supergroup
1853-1856	Ekofisk Formation
1956-1966	Ommelanden Formation
1966	FAULT
1966-1974	Ommelanden Formation
1974-1987	Lower Holland Marl Member
1987-2052	Vlieland Marl Member
2052-2066	Scruff Greensand Formation
2066-2163	Zechstein Group

The interpretation of an age in the Late Aptian or older at depth 2000 m verifies a position in the Rijnland Group. A Vlieland Marl Member is here conceivable.

The Late Ryazanian at depth 2030 m lithostratigraphically points to the Lutine Formation, Clay Deep Member. Based on logs, this member may span the interval ca. 2026-2036 m or alternately (in case of caving) 2026-2028 m.

At 2040 m the Late Kimmeridgian is already reached. This dating indicates a lithostratigraphical classification in the Kimmeridge Clay Formation instead of the Vlieland Formation.

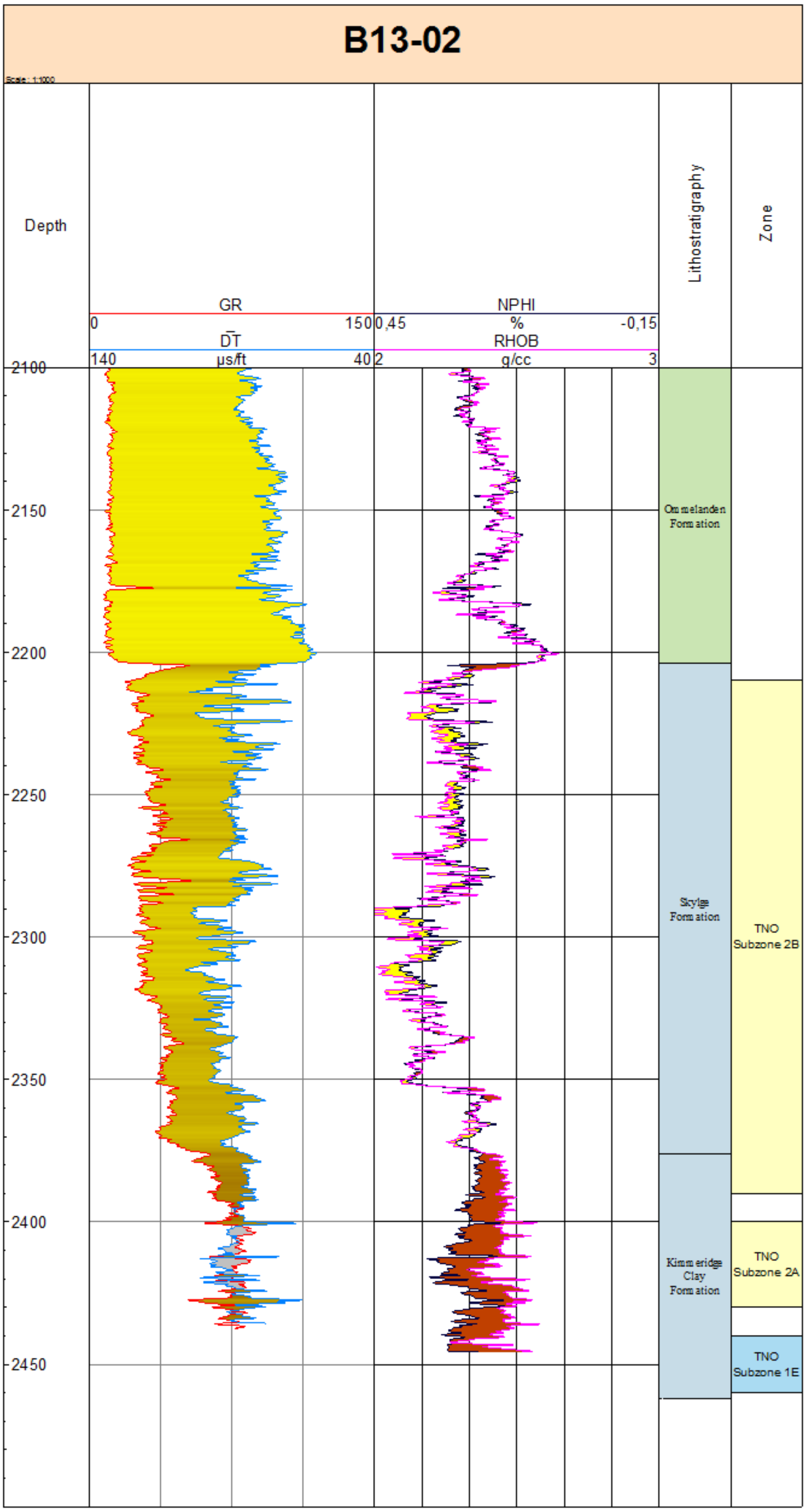
A dating in the Kimmeridgian for the interval 2052-2066 m (NLOG 2013) is too old for the Scruff Greensand Formation. The Sequence 2 sands belong to the Skylge Formation, Noordvaarder Member.

The clasts (e.g. 2064.6 m) within the matrix (Noordvaarder Member) are dated as Late Permian and originate from the Zechstein Group. The brecciated interval is a typical succession on top of a salt structure referred to as a “caprock” sensu Munsterman et al (2012).

At depth 2065.9 m the Zechstein Group is reached.

Table 4 Updated lithostratigraphic interpretation of well A18-02-S1.

Interval (m)	**Lithostratigraphy**
0-1853	North Sea Supergroup
1853-1856	Ekofisk Formation
1956-1966	Ommelanden Formation
1966	FAULT
1966-1974	Ommelanden Formation
1974-1987	Lower Holland Marl Member
1987-2026	Vlieland Marl Member
2026-2028/2036	Lutine Formation, Clay Deep Mb
2028/2036-2052	Kimmeridge Clay Formation
2052-2065.9	Skylge Formation, Noordvaarder Mb
2065.9-2163	Zechstein Group



B13-02
Scale: 1:1000
Depth
GR
0
150
DT
140
μs/ft
40
NPHI
0,45
%
-0,15
RHOB
2
g/cc
3
Lithostratigraphy
Zone
2100
2150
2200
2250
2300
2350
2400
2450
Ommelanden Formation
Skylge Formation
Kimmeridge Clay Formation
TNO Subzone 2B
TNO Subzone 2A
TNO Subzone 1E

Age assessments of well B13-02

Sample/Interval	Age
2190mCU	ND

Remarks: the microflora is dominated by Tertiary caving.

Sample/Interval	Age
2209.63-2390m	Early Volgian, *elegans* Ammonite Subzone or older, Sequence 2, TNO Subzone 2B

The age interpretation is based on:

- LOD *Perisseiasphaeridium pannosum* at 2209.63-2209.71mCO

Remarks: a single occurrence of *Dichadogonyaulax chondrum, ?Stephanelytron scarburghense* at 2209.63 mCO and of ?*Tubotuberella dangeardii* at 2350 m is considered as reworking. The relatively high values of *Perinopollenites elatoides* and relatively low numbers of *Classopollis* indicate a pre-*elegans/scitulus* Ammonite Subzone boundary.

Sample/Interval	Age
2400-2430mCU	Late Kimmeridgian, *eudoxus* Ammonite Subzone, Sequence 2, TNO Subzone 2A

The age interpretation is based on:

- LOD *Trilites minutus* at 2400mCU
- LOD *Striatella reticulata* at 2410mCU

Sample/Interval	Age
2440-2460mCU	Early Kimmeridgian, *cymodoce* Ammonite Subzone, Sequence 1, TNO Subzone 1E

The age interpretation is based on:

- Presence of *Limbodinium* aff. *ridingii* at 2440mCU

Remarks: the presence of *Lycopodiumsporites semimuris* at 2460mCU is considered as reworking from the Bathonian.

Lithostratigraphy of well B13-02

The lithostratigraphic interpretation of well B13-02 (NLOG 2013) is listed in Table 5

Table 5 Outdated lithostratigraphic interpretation of well B13-02 (NLOG 2013).

Interval (m)	**Lithostratigraphy**
0-1615	North Sea Supergroup
1615-2204	Chalk Group
2204-2376	Scruff Greensand Formation
2376 -2462	Kimmeridge Clay Formation

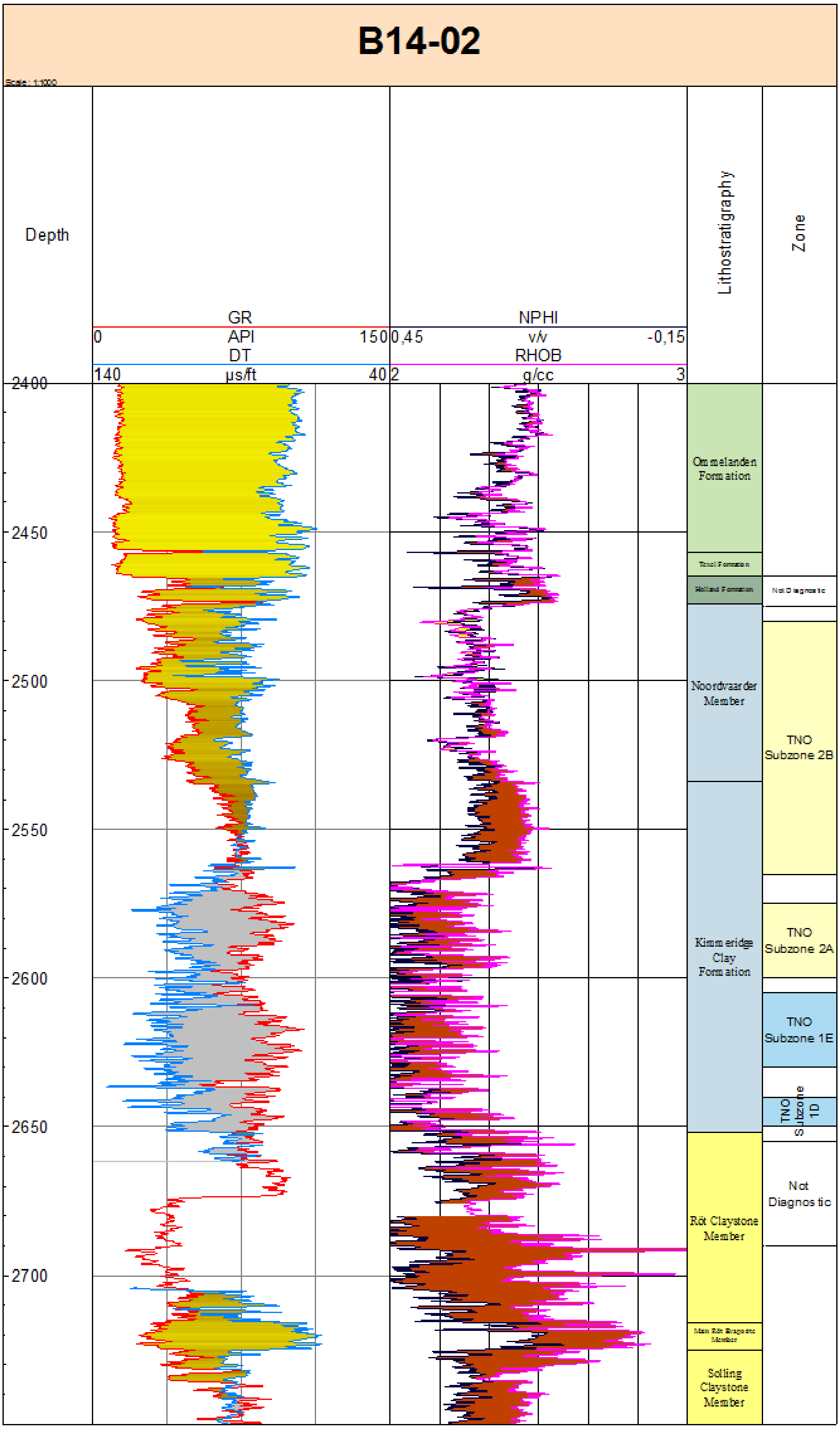
The sample 2190 mCU at the base of the Chalk Group only yielded Tertiary caving.

Core sample 2209.63-2209.71mCO at the top of the sandy succession is dated as Early Kimmeridgian, *mutabilis-eudoxus* Ammonite Subzone. The base of the studied interval is assigned to the Early Kimmeridgian, *cymodoce* Ammonite Subzone. These ammonite Subzones fit with the lithostratigraphical interpretation of the Scruff Group, but do not match with the Scruff Greensand Fm. The sands may be associated with the Skylge Formation.

An Early Kimmeridgian age, *cymodoce* Ammonite Subzone, verifies the Kimmeridge Clay Fm classification for the clayey section from 2376 to 2462 m.

Table 6 Updated lithostratigraphic interpretation of well B13-02.

Interval (m)	**Lithostratigraphy**
0-1615	North Sea Supergroup
1615-2204	Chalk Group
2204-2376	Skylge Formation
2376 -2462	Kimmeridge Clay Formation


B14-02
Scale : 1:1000
Depth
GR
0 API 150
DT
140 µs/ft 40
NPHI
0,45 v/v -0,15
RHOB
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Lithostratigraphy
Zone
2400
2450
2500
2550
2600
2650
2700
Ommelanden Formation
Texel Formation
Holland Formation
Noordvaarder Member
Kimmeridge Clay Formation
Röt Claystone Member
Solling Claystone Member
Not Diagnostic
TNO Subzone 2B
TNO Subzone 2A
TNO Subzone 1E
TNO Subzone 1D
Not Diagnostic

Age assessments of well B14-02

Sample/Interval	Age
2465-2475mCU	ND

Remarks: the microflora is dominated by Tertiary caving.

Sample/Interval	Age
2480-2555mCU	Early Volgian, *hudlestoni* Ammonite Subzone, Sequence 2, TNO Subzone 2B

The age interpretation is based on:
- LOD *Systematophora fasciculigera/penicillata* at 2480 m
- LOD *Cribroperidinium longicorne* at 2485 m
- LOD *Rhynchodiniopsis martonense* at 2490 m
- LOD *Occisucysta balios* at 2500 m

Sample/Interval	Age
2565mCU	Early Volgian, *wheatleyensis* Ammonite Subzone, Sequence 2, TNO Subzone 2B

The age interpretation is based on:
- LOD *Geiselodinium inaffectum*

Sample/Interval	Age
2575mCU	Late Kimmeridgian, *autissiodorensis* Ammonite Subzone, Sequence 2, TNO Subzone 2A

The age interpretation is based on:
- LOD *Endoscrinium luridum*

Sample/Interval	Age
2585-2600mCU	Late Kimmeridgian, *mutabilis* Ammonite Subzone, Sequence 1, TNO Zonation 2A

The age interpretation is based on:
- LCOD *Gonyaulacysta jurassica* at 2585 m
- LOD *Manumia* spp. at 2585 m
- LOD *Densoisporites minor* at 2600 m
- LOD *Precicatricosisporites irregularis* at 2600 m

Sample/Interval	Age
2605-2630mCU	Early Kimmeridgian, *baylei* Ammonite Subzone, Sequence 1, TNO Subzone 1E

The age interpretation is based on:
- LOD consistent *Taeniophora iunctispina* at 2605 m
- LOD *Tuberositriletes* sp. A sensu Abbink (1998) at 2605 m
- LOD (*cymodoce*) *Dichadogonyaulax chondrum* at 2610 m
- LOD *Endoscrinium crystallinum* at 1615 m

Sample/Interval	Age
2640-2650mCU	?Late Oxfordian, *pseudocordata* Ammonite Subzone, Sequence 1, Subzone 1D

The age interpretation is based on:

- LCOD *Rhynchodiniopsis cladophora* at 2640 m

Sample/Interval	Age
2655-2690mCU	Not diagnostic

Lithostratigraphy of well B14-02

The lithostratigraphic interpretation of well B14-02 (NLOG 2013) is listed in Table 7.

Table 7 Outdated lithostratigraphic interpretation of well B14-02 (NLOG 2013)

Interval (m)	Lithostratigraphy
2035-2457	Ommelanden Formation
2457-2465	Texel Formation
2465-2474	Holland Formation
2474-2534	Scruff Greensand Formation
2534 -2613	Kimmeridge Clay Formation
2613 -2652	Middle Graben Formation
2652-2716	Rot Claystone Member

The samples from the studied top interval 2465-2475 m (Holland Formation) only yielded Tertiary caving.

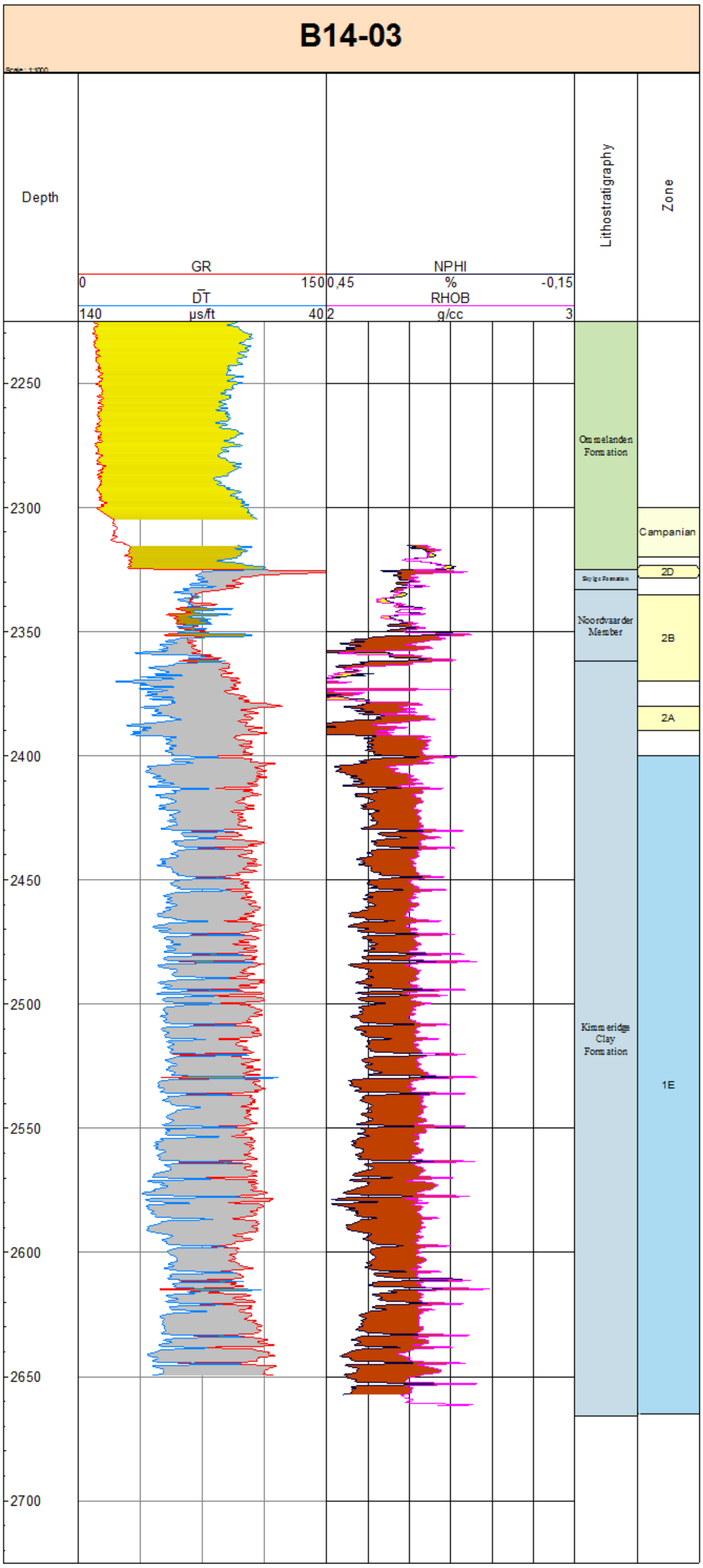
The relatively sandy interval from 2474-2534 m is dated as Late Kimmeridgian and can not be associated with the Scruff Greensand Formation. The sequence 2 succession fits with the Skylge Formation, Noordvaarder Member.

The Kimmeridge Clay Formation is verified by its lithology and age, however its base is extended down to 2652 m.

The classification of interval 2613-2652 m in the Middle Graben Formation is unlikely, because the palynological assemblages indicate a Late(st) Oxfordian age for the base (2640-2650 m) and distinct marine conditions prevail. The top of the Middle Graben Formation should be older (Middle Oxfordian) and higher up in this unit only terrestrial palynomorph assemblages were encountered with occasionally a weak marine influence. Hence the current interval is also interpreted as Kimmeridge Clay Formation.

Table 8 Updated lithostratigraphic interpretation of well B14-02

Interval (m)	Lithostratigraphy
2035-2457	Ommelanden Formation
2457-2465	Texel Formation
2465-2474	Holland Formation
2474-2534	Skylge Formation, Noordvaarder Member
2534 -2652	Kimmeridge Clay Formation
2652-2716	Rot Claystone Member



B14-03
Depth
GR
0
150
DT
140
μs/ft
40
NPHI
0,45
%
-0,15
RHOB
2
g/cc
3
Lithostratigraphy
Zone
2250
2300
2350
2400
2450
2500
2550
2600
2650
2700
Ommelanden Formation
Noordvaarder Member
Kimmeridge Clay Formation
Campanian
2D
2B
2A
1E

Age assessments of well **B14-03**

Sample/Interval	Age
2300-2320mCU	Campanian, or older

The age interpretation is based on:
- LOD *Operculodinium operculata* at 2300 m

Remarks: the associations are dominated by Tertiary caving. A few late Early to Late Cretaceous dinoflagellate cysts are present, like *Operculodinium operculata, Operculodinium* spp. and *Senoniasphaera* spp.

Sample/Interval	Age
2325-2327mCU	Middle Volgian, *kerberus* Ammonite Subzone, or older, Sequence 2, TNO Subzone 2D

The age interpretation is based on:
- LOD *Glossodinium dimorphum* at 2325 m
- LOD *Senoniasphaera jurassica* at 2325 m
- LOD *Dichadogonyaulax pannaea* at 2325 m
- LOD *Muderongia* sp. A sensu Davey 1979 at 2325 m

Sample/Interval	Age
2335-2365mCU	Early Volgian, *pectinatus* Ammonite Subzone, or older, Sequence 2, TNO Subzone 2B (-basal part 2C)

The age interpretation is based on:
- LOD *Gonyaulacysta jurassica (*inconsistent) at 2335 m
- LOD *Aldorfia dictyota* at 2340 m
- LOD *Occisucysta balios* at 2340 m
- LOD *Systematophora fasciculigera/penicillata* at 2345 m
- LOD *Rhynchodiniopsis martonense* at 2345 m
- LOD *Hystrichosphaerina orbifera* at 2345 m
- LOD *Oligosphaeridium patulum* at 2365 m

Sample/Interval	Age
2370mCU	Early Volgian, *hudlestoni* Ammonite Subzone, or older, Sequence 2, TNO Subzone 2B

The age interpretation is based on:
- LCOD *Oligosphaeridium patulum* at 2370 m

Sample/Interval	Age
2380-2390mCU	Late Kimmeridgian, *autissiodorensis* Ammonite Subzone, or older, Sequence 2, TNO Subzone 2A

The age interpretation is based on:
- LOD *Gonyaulacysta jurassica (*consistent) at 2380 mCU

Sample/Interval	Age

2400-2665mCU	Early Kimmeridgian, *cymodoce* Ammonite Subzone, or older, Sequence 1, TNO Subzone 1E

The age interpretation is based on:

- LOD *Limbodinium ridingii* at 2400 m

Remarks: the LOD's of *Dichadogonyaulax chondrum* (2420 m) and *Manumia* cf. *delcourtii* (2460 m) fit with the interpreted dating. *Dichadogonyaulax sellwoodii* at depth 2420 m is considered as reworking. A lot of reworking is present at 2500 m, e.g. *Lithodinia* spp., *Chasmatosporites magnolioides, Circulina/Classopollis* trans. form and *Raistrickisporites brevitruncatus.*

Sample/Interval	Age
2669mCU	ND

Lithostratigraphy of well B14-03

The lithostratigraphic interpretation of well B14-03 (NLOG 2013) is listed in Table 9.

Table 9 Outdated lithostratigraphic interpretation of well B14-03 (NLOG 2013)

Interval (m)	Lithostratigraphy
0-1996	North Sea Supergroup
1996-2325	Ommelanden Formation
2325-2333	Clay Deep Formation
2333 -2362	Scruff Greensand Formation
2362 -2666	Kimmeridge Clay Formation

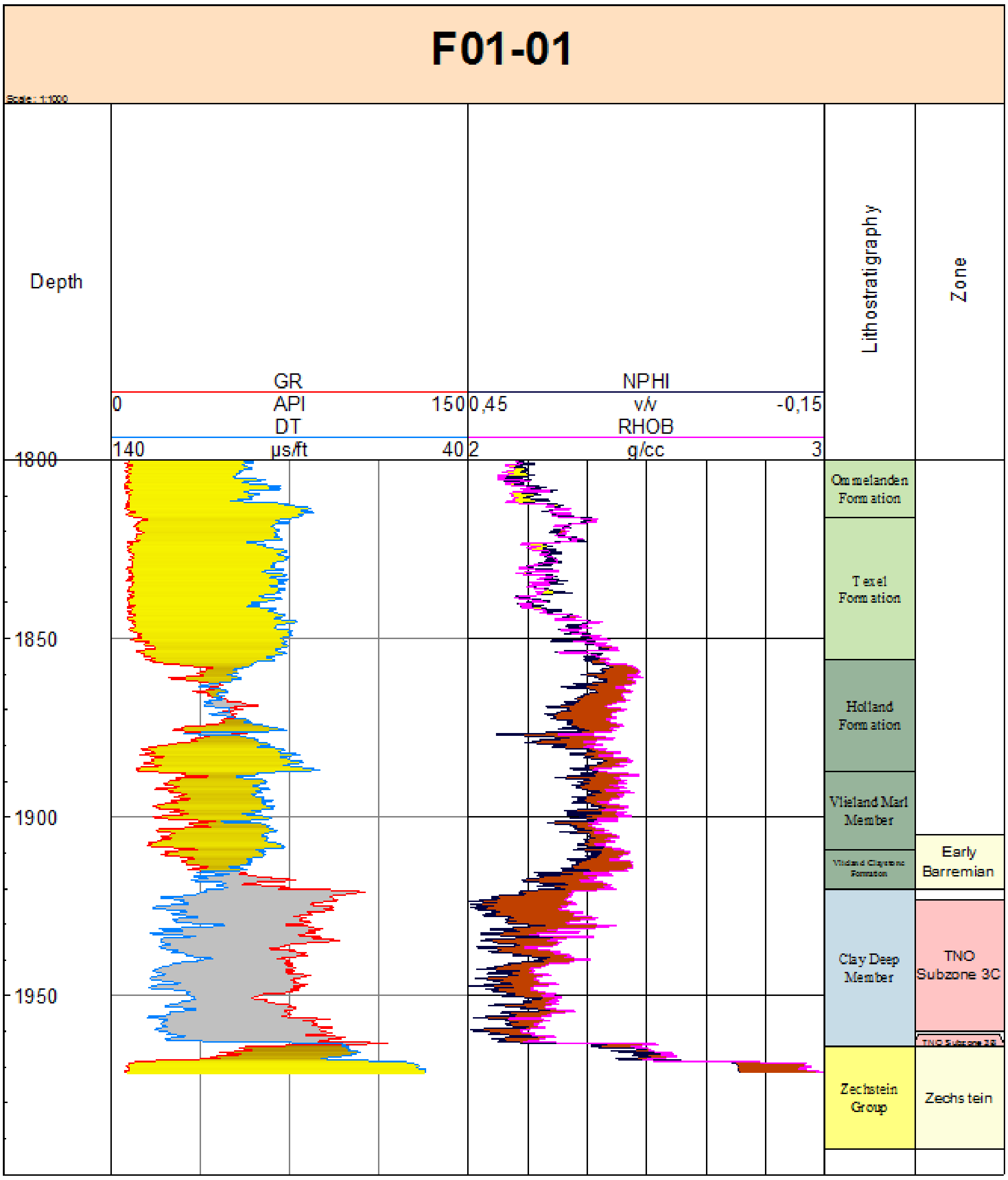
The cuttings samples from the uppermost studied interval 2300-2320m (base Ommelanden Formation) were dominated by Tertiairy caving and yielded a few indifferent late Early-Late Cretaceous dinocysts. These results are not in contradiction with an lithostratigraphical interpretation in the Ommelanden Formation.

The interval 2325-2665 m is interpreted as Sequence 2 sensu Abbink et al (2006). Hence the classification of the Clay Deep (2325-2333 m) and Scruff Greensand (2333-2362 m) formations are an anachronism, because both units fit into the younger Sequence 3. The interval 2325-2362 m is more appropriately associated with the Skylge Formation. The former and now outdated Scruff Greensand Formation is replaced by the Noordvaarder Member.

The Kimmeridge Clay Formation, interval 2362-2666 m, is confirmed by the palynological interpretation.

Table 10 Updated lithostratigraphic interpretation of well B14-03 (NLOG 2013)

Interval (m)	Lithostratigraphy
0-1996	North Sea Supergroup
1996-2325	Ommelanden Formation
2325-2333	Skylge Formation
2333 -2362	Skylge Formation, Noordvaarder Mb
2362 -2666	Kimmeridge Clay Formation



F01-01
Scale : 1:1000
Depth
GR
0
API
150
DT
140
µs/ft
40
NPHI
0,45
v/v
-0,15
RHOB
2
g/cc
3
Lithostratigraphy
Zone
1800
1850
1900
1950
Ommelanden Formation
Texel Formation
Holland Formation
Vlieland Marl Member
Clay Deep Member
Zechstein Group
Early Barremian
TNO Subzone 3C
Zechstein

Age assessments of well F01-01

Sample/Interval	Age
1905-1920mCU	Early Cretaceous, Early Barremian, *fissicostatum* Ammonite Subzone, or older

The age interpretation is based on:
- LOD *Pseudoceratium anaphrissum* at 1905 m

Sample/Interval	Age
1923-1960mCU	Early Cretaceous, Late Ryazanian, Sequence 3, TNO Subzone 3C

The age interpretation is based on:
- LOD *Canningia* spp. at 1923 m
- LOD *Batioladinium pomum* at 1929 m
- LOD *Daveya boresphaera* at 1932 m
- LOD *Batioladinium* cf. *varigranosum* at 1945 m
- LOD *Dingodinium spinosum* at 1945 m
- LOD *Endoscrinium pharo* at 1954 m

Sample/Interval	Age
1963mCU	Early Cretaceous, Early Ryazanian, Sequence 3, TNO Subzone 3B

The age interpretation is based on:
- LOD *Rotosphaeropsis thula*
- LOD *Systematophora daveyi*

Sample/Interval	Age
1969mCU	Triassic/Permian

The age interpretation is based on:
- LOD taeniate bisaccates

Lithostratigraphy of well F01-01

The lithostratigraphic interpretation of well F01-01 (NLOG 2013) is listed in Table 11.

Table 11 Outdated lithostratigraphic interpretation of well F01-01 (NLOG 2013)

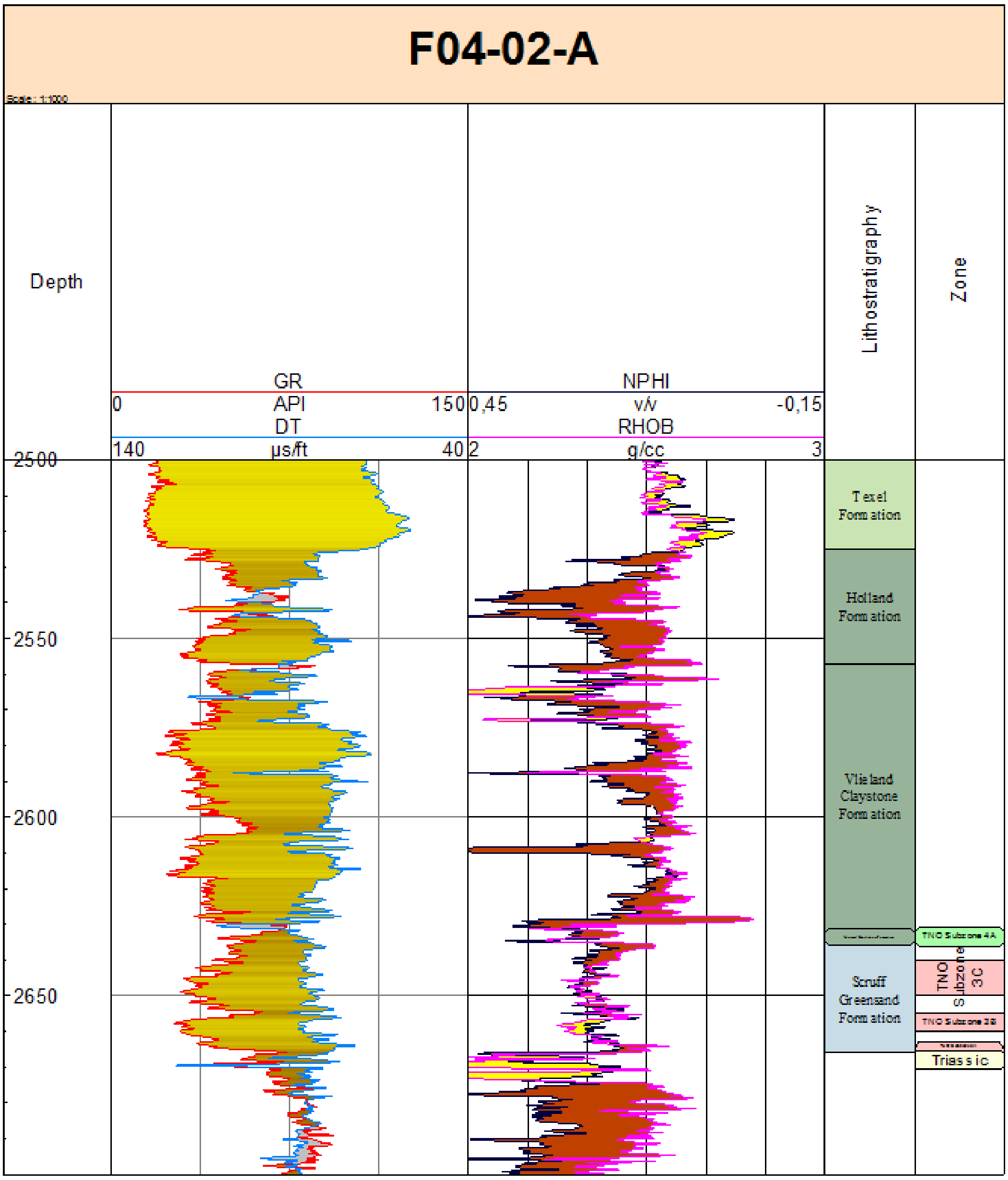
Interval (m)	Lithostratigraphy
0-1600	North Sea Supergroup
1600-1816	Ommelanden Formation
1816-1856	Texel Formation
1856-1861	Upper Holland Marl Member
1861-1877	Middle Holland Claystone Member
1877-1887	Lower Holland Marl Member
1887-1909	Vlieland Marl Member
1909-1920	Vlieland Claystone Member
1920-1935	Clay Deep Member
1935-1964	Kimmeridge Clay Formation
1964-1993	Zechstein Group

The interpreted age of interval 1900-1923 m, Early Barremian, *fissicostatum* Ammonite Subzone, or older fits very well with a lithostratigraphical interpretation in the Vlieland Claystone Formation. Although a more clayey interval seems not to be recognized in the description of the composite well log, the basal part evidently shows higher values on the gamma-ray log. A transition from a marl section (interval 1887-1909 m) into a more clayey interval, 1909-1920 m, as lithostratigraphically interpreted as a change in members from the Vlieland Marl into the Vlieland Claystone on NLOG seems tenable.

A Late to Early Ryazanian age for interval 1923-1963 m fits with the Clay Deep Member, Lutine Formation (interval 1920-1964). The distinction between the Clay Deep Member (1920-1935) and Kimmeridge Clay Formation (1935-1964) on NLOG 2013 is incorrect (based on Munsterman et al. 2012) and confusing (even based on Van Adrichem Boogaert & Kouwe, 1993).

Table 12 Updated lithostratigraphic interpretation of well F01-01 (NLOG 2013)

Interval (m)	**Lithostratigraphy**
0-1600	North Sea Supergroup
1600-1816	Ommelanden Formation
1816-1856	Texel Formation
1856-1861	Upper Holland Marl Member
1861-1877	Middle Holland Claystone Member
1877-1887	Lower Holland Marl Member
1887-1909	Vlieland Marl Member
1909-1920	Vlieland Claystone Member
1920-1964	Clay Deep Member, Lutine Formation
1964-1993	Zechstein Group


F04-02-A
Scale : 1:1000
Depth
GR
0
API
150
DT
140
µs/ft
40
NPHI
0,45
v/v
-0,15
RHOB
2
g/cc
3
Lithostratigraphy
Zone
2500
2550
2600
2650
Texel Formation
Holland Formation
Vlieland Claystone Formation
Scruff Greensand Formation
TNO Subzone 4A
TNO Subzone 3C
TNO Subzone 2B
Triassic

Age assessments of well F04-02-A

Sample/Interval	Age
2605-2625mCU	Early Cretaceous, Early Barremian, *fissicostatum* Ammonite Subzone, or older

The age interpretation is based on:
- LOD *Aptea anaphrissa* at 2605 m
- LOD *Kleithriasphaeridium fasciatum* at 2605 m
- LOD *Muderongia crucis/tetracantha* at 2605 m
- LOD *Nexosispinum vetusculum* at 2610 m

Sample/Interval	Age
2635mCU	Early Cretaceous, Valanginian, Sequence 4A

The age interpretation is based on:
- LOD *Systematophora palmula*
- LOD *Tehamadinium* spp.

Sample/Interval	Age
2640-2650mCU	Early Cretaceous, Late Ryazanian, *stenomphalus* Ammonite Subzone, or older, Sequence 3, TNO Subzone 3C

The age interpretation is based on:
- LOD *Daveya boresphaera* at 2640 m
- LOD *Dingodinium spinosum* at 2650 m
- LOD *Egmontodinium torynum* at 2650 m
- LOD *Endoscrinium pharo* at 2650 m

Sample/Interval	Age
2655mCU	Early Cretaceous, Early Ryazanian, *kochi* Ammonite Subzone, Sequence 3, TNO Subzone 3B

The age interpretation is based on:
- LOD *Rotosphaeropsis thula*

Sample/Interval	Age
2660mCU	Early Cretaceous, earliest Ryazanian, *runctoni* Ammonite Subzone, Sequence 3, TNO Subzone 3B

The age interpretation is based on:
- LOD *Gochteodinia virgula*

Remarks: the presence of *Systematophora daveyi confirms an age* in the Early Ryazanian.

Sample/Interval	Age
2665mCU	Late Jurassic, Late Volgian, *primitivus* Ammonite Subzone, or older, Sequence 3, TNO Subzone 3A

The age interpretation is based on:
- LCOD *Cribroperidinium hansenii*

<u>Sample/Interval</u>	<u>Age</u>
2670mCU	Triassic

The age interpretation is based on:
- LOD *Triadispora* spp.
- LOD *Infernopollenites* spp.

Lithostratigraphy of well F04-02A
The lithostratigraphic interpretation of well F04-02A (NLOG 2013) is listed in Table 13.

Table 13 Outdated lithostratigraphic interpretation of well F04-02A (NLOG 2013)

Interval (m)	Lithostratigraphy
0-1230	Upper North Sea Group
1230-1282	Asse Member
1282-1370	Brussels Marl Member
1370-1840	Ieper Member
1840-1850	Basal Dongen Tuffite Member
1850-1948	Landen Formation
1948-2035	Ekofisk Formation
2035-2484	Ommelanden Formation
2484-2525	Texel Formation
2525-2535	Upper Holland Marl Member
2535-2545	Middle Holland Claystone Member
2545-2557	Lower Holland Marl Member
2557-2632	Vlieland Claystone Formation
2632-2665	Friesland Member
2665-2715	Upper Röt Claystone Member

The upper part (2605-2625 m) of the studied interval is dated as Early Cretaceous, Early Barremian, *fissicostatum* Ammonite Subzone, or older. The age and marine facies confirm a lithostratigraphic position in the Vlieland Claystone Formation.

At depth 2635 m the Valanginian is reached. This interpretation is not in contradiction with the associated top of the Friesland Member (2632-2635 m). However at depth 2640 m the Early Cretaceous, Late Ryazanian, *stenomphalus* Ammonite Subzone, or older is recorded. This sequence 3 sensu Abbink et al. (2006) does not fit with the lithostratigraphic interpretation of the Friesland Member (= Sequence 4 succession).

Interval 2640-2665 m comprises a Sequence 3 succession and should be associated with the Scruff Greensand Formation instead of the Friesland Member (sensu NLOG 2013).

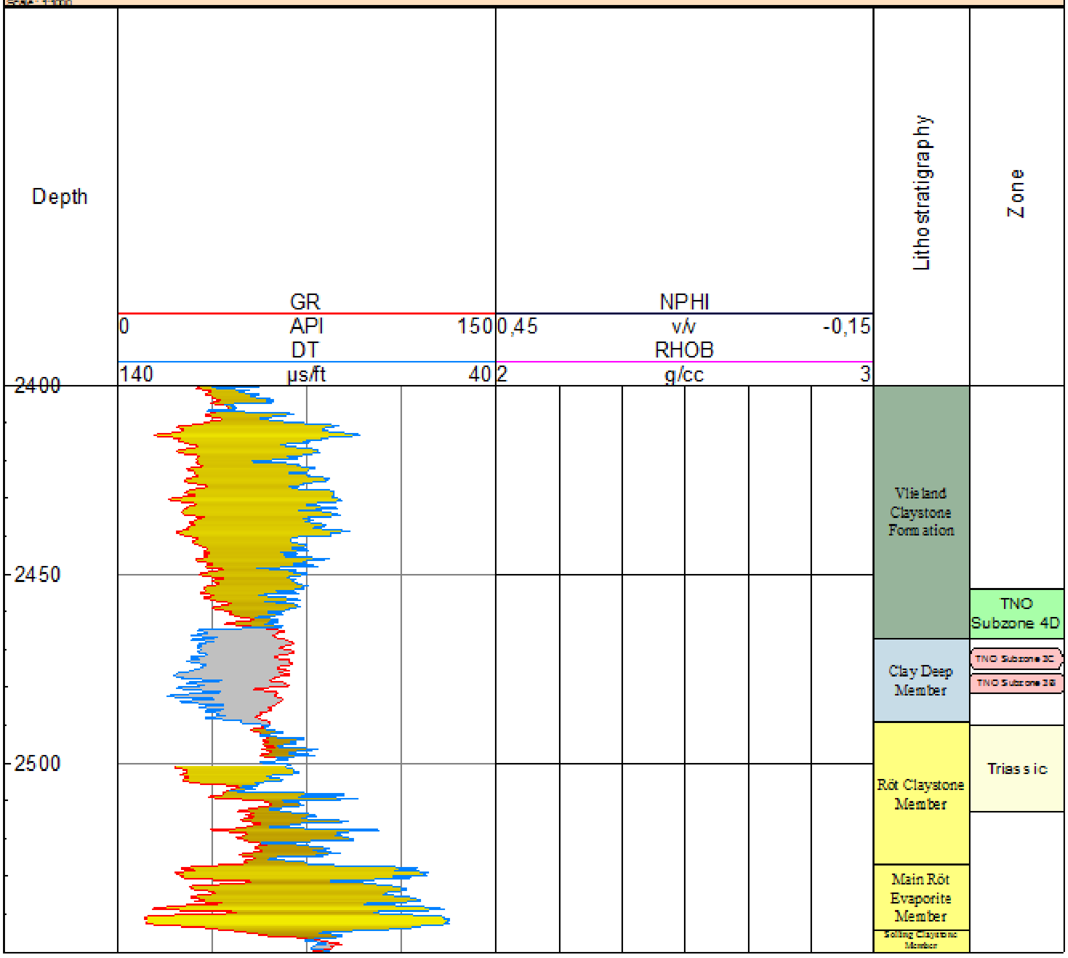
Deeper at 2670 m the Triassic is recorded. An Upper Röt Claystone Member seems to be possible.

Table 14 Updated lithostratigraphic interpretation of well F04-02A

Interval (m)	Lithostratigraphy
0-1230	Upper North Sea Group
1230-1282	Asse Member
1282-1370	Brussels Marl Member
1370-1840	Ieper Member

1840-1850	Basal Dongen Tuffite Member
1850-1948	Landen Formation
1948-2035	Ekofisk Formation
2035-2484	Ommelanden Formation
2484-2525	Texel Formation
2525-2535	Upper Holland Marl Member
2535-2545	Middle Holland Claystone Member
2545-2557	Lower Holland Marl Member
2557-2632	Vlieland Claystone Formation
2632-ca 2635	?Friesland Member
ca 2635-2666	Scruff Greensand Formation
2666-2715	Upper Röt Claystone Member

F10-01


Scale : 1:1000
Depth
GR
0 API 150
DT
140 µs/ft 40
NPHI
0,45 v/v -0,15
RHOB
2 g/cc 3
Lithostratigraphy
Zone
2400
2450
2500
Vlieland Claystone Formation
Clay Deep Member
Röt Claystone Member
Main Röt Evaporite Member
Solling Claystone Member
TNO Subzone 4D
TNO Subzone 3C
TNO Subzone 3B
Triassic

Age assessments of well F10-1

Sample/Interval	Age
2454-2467mCU	Early Cretaceous, Early Hauterivian, *noricum* Ammonite Subzone, or older, TNO Subzone 4D

The age interpretation is based on:

- LOD *Isthmocystis distincta* at 2454mCU
- LOD *Muderongia extensiva* at 2454mCU

Sample/Interval	Age
2472mCU	Early Cretaceous, Late Ryazanian, Sequence 3, TNO Subzone 3C

The age interpretation is based on:

- LOD *Canningia* spp.
- LOD *Batioladinium* cf. *varigranosum*

Sample/Interval	Age
2477-2481mCU	Early Cretaceous, Early Ryazanian, *kochii* Ammonite Subzone, Sequence 3, TNO Subzone 3B

The age interpretation is based on:

- LOD *Perisseiasphaeridium insolitum* at 2477mCU
- LOD *Rotosphaeropsis thula* at 2477mCU

Remarks: the presence of *Egmontodinium torynum* and *Endoscrinium pharo* confirm an age in the Ryazanian.

Sample/Interval	Age
2490-2513mCU	Triassic

The age interpretation is based on:

- LOD *Protodiploxypinus* spp. at 2490mCU
- LOD *Lunatisporites* spp. at 2490mCU
- LOD *Microcachryidites* spp. at 2490mCU

Lithostratigraphy of well F10-01

The lithostratigraphic interpretation of well F10-01 (NLOG 2013) is listed in Table 15.

Table 15 Outdated lithostratigraphic interpretation of well F10-01 (NLOG 2013)

Interval (m)	Lithostratigraphy
0-1952	North Sea Supergroup
1952-2019	Ekofisk Formation
2019 -2280	Ommelanden Formation
2280 -2305	Texel Formation
2305 -2360	Upper Holland Marl Member
2360 -2375	Middle Holland Claystone Member
2375 -2391	Lower Holland Marl Member
2391-2489	Vlieland Claystone Formation
2489 -2527	Röt Claystone Member

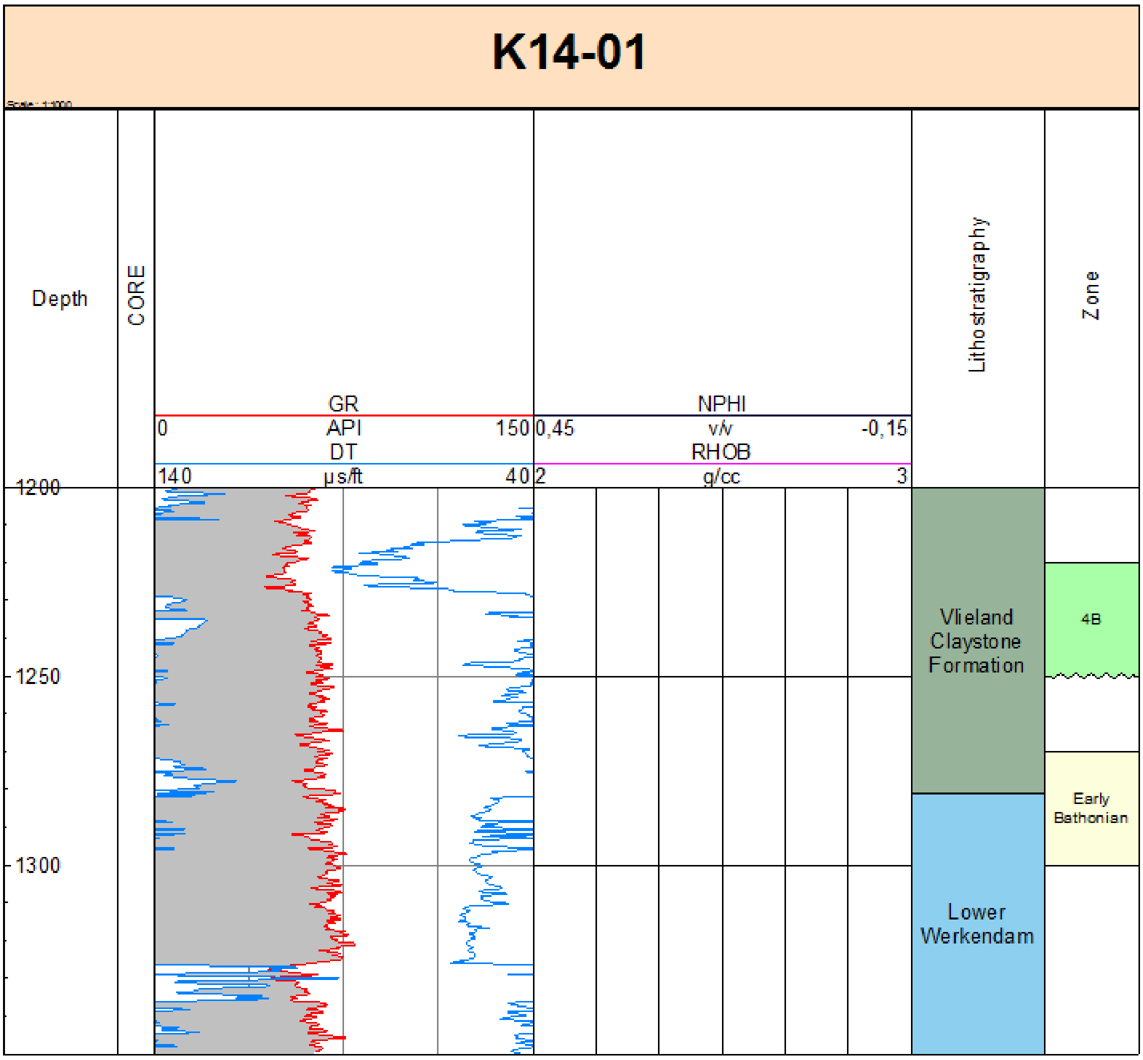
Interval 2454-2467m is dated as Early Cretaceous, Early Hauterivian, *noricum* Ammonite Subzone, or older. This age fits very well with the interpreted lithostratigraphy: Vlieland Claystone Formation (Rijnland Group).

The basal part of the Vlieland Claystone Formation (sensu NLOG 2013), interval 2472-2489 m, is however recorded as Sequence 3. The basal Vlieland Formation is never older than Sequence 4 (Valanginian, or younger). The Ryazanian is reached at 2472 m. This dating is associated with the Lutine Formation, Clay Deep Member (Scruff Group).

A Triassic age could be inferred for interval 2490-2513 m. The dating is not in contradiction with the Röt Claystone Member.

Table 16 Updated lithostratigraphic interpretation of well F10-01 (NLOG 2013)

Interval (m)	**Lithostratigraphy**
0-1952	North Sea Supergroup
1952-2019	Ekofisk Formation
2019 -2280	Ommelanden Formation
2280 -2305	Texel Formation
2305 -2360	Upper Holland Marl Member
2360 -2375	Middle Holland Claystone Member
2375 -2391	Lower Holland Marl Member
2391-2467	Vlieland Claystone Formation
2467-2489	Lutine Formation, Clay Deep Member
2489 -2527	Röt Claystone Member



K14-01
Scale: 1:1000
Depth
CORE
GR
0 API 150
DT
140 µs/ft 40
NPHI
0,45 v/v -0,15
RHOB
2 g/cc 3
Lithostratigraphy
Zone
1200
1250
1300
Vlieland Claystone Formation
Lower Werkendam
4B
Early Bathonian

Age assessments of well K14-01

The associations are (very) rich in dinocysts, spores and pollen. Caving from overlying successions is present in all cuttings samples. Reworking is recorded in low abundances.

Sample/Interval	Age
1220-1250 mCU	Early Cretaceous, Early Valanginian, TNO Subzone 4B, *Polyptychites* Ammonite Subzone

The interpretation is based on:

- LOD *Canningia compta* at 1220 m
- LOD *Hystrichosphaeridium scoriaceum* at 1220 m
- LOD *Kleithriasphaeridium porosispinum* at 1230 m

Remarks: the presence of *Maduradinium* sp. A sensu Davey (1982) fits with the chronostratigraphic interpretation. *Chasmatosporites apertus*, aff. *Densoisporites minor*, aff. *Lycopodiumsporites semimuris* and ?*Dissiliodinium* spp. are considered as reworking from the Jurassic.

Sample/Interval	Age
1270 mCU	Middle Jurassic, Early Bathonian or older

The interpretation is based on:

- LCOD *Lycopodiumsporites semimuris* at 1270 m

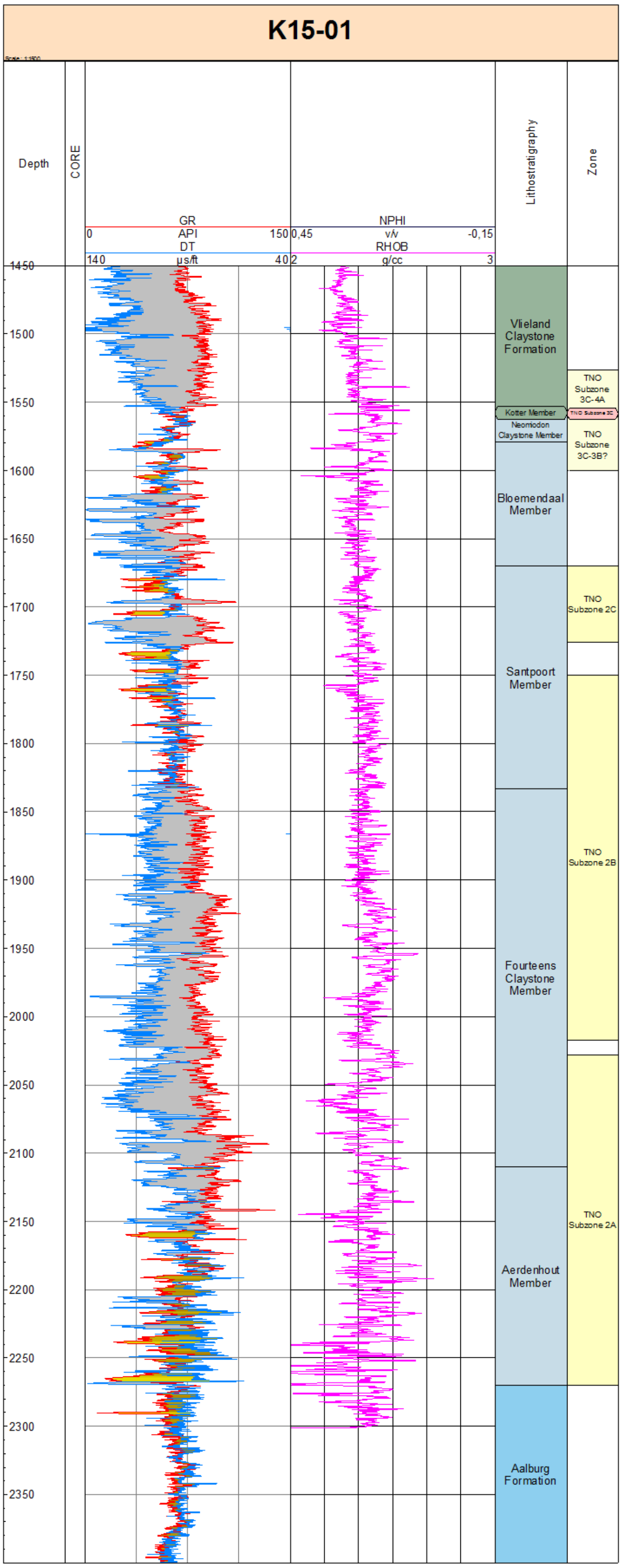
Remarks: the LOD's of *Chasmatosporites magnolioides* and *Lycopodiacidites rugulatus* confirm an age in the Middle Jurassic.

Sample/Interval	Age
1280-1300 mCU	Middle Jurassic, Early Bathonian or older (?Aalenian or older)

The interpretation is based on:

- LOD *Dissiliodinium "ventrogranum"* at 1290 m
- LOD *Durotrigia* cf. *omentifera* at 1290 m
- LOD *Gongylodinium erymnoteichos* at 1290 m

Remarks: additional dinocysts verifying a Bathonian age or older are *Nannoceratopsis gracilis*, *Nannoceratopsis spiculata*, *Valvaeodinium spinosum* and *Valvaeodinium* spp. Taxa indicating an Aalenian age or older are *Classopollis/Circulina* spp. (transitional form: several specimens at 1280 m and 1290 m) and *Nannoceratopsis deflandrei senex* (1280 m). It is doubtful whether the latter are in situ or can be related to reworking. Reworking from the latest Triassic, Rhaetian (*Rhaetipollis germanicus* at 1280 m) and from the Late Triassic/Early Jurassic (*Ovalipollis pseudoalatus* at 1290 m) is present in low numbers.



K15-01
Depth
CORE
GR
0 API 150
DT
140 µs/ft 40
NPHI
0,45 v/v -0,15
RHOB
2 g/cc 3
Lithostratigraphy
Zone
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000
2050
2100
2150
2200
2250
2300
2350
Vlieland Claystone Formation
Kotter Member
Neomiodon Claystone Member
Bloemendaal Member
Santpoort Member
Fourteens Claystone Member
Aerdenhout Member
Aalburg Formation
TNO Subzone 3C-4A
TNO Subzone 3C-3B?
TNO Subzone 2C
TNO Subzone 2B
TNO Subzone 2A

Age assessments of well K15-01

Sample/Interval	Age
1526.50 -1535.4mCO	latest Ryazanian to earliest Valanginian, TNO Subzone 3C - 4A, *albidum- Paratollia* Ammonite Subzone

This interpretation is based on :

- LOD *Egmontodinium torynum* at 1526.5 m
- FOD *Lagenorhytis delicatula* at 1535.4 m
- FOD *Surculosphaeridium* sp III in Davey 1982 at 1535.4 m
- FOD *Hystrichosphaeridium scoriaceum* at 1535.4 m
- LOD *Gochteodinia villosa* at 1535.4 m

Remarks: *Batioladinium* sp. 1 sensu Davey 1982, *Batioladinium varigranosum, Exiguisphaera phragma, Pareodinia* sp.1 sensu Davey 1982 and *Tehamadinium evitti* fit with the interpretation.

Sample/Interval	Age
1557.70-1558.7 mCO	Latest Ryazanian, TNO Subzone 3C, *stenomphalus-albidum* Ammonite Subzones

This interpretation is based on:

- Superposition
- FOD *Oligosphaeridium diluculum* op 1558.7 m

Sample/Interval	Age
1559.7-1600 mCO+ CU	Late Ryazanian (post- base *kochi* Ammonite Subzone)

This interpretation is based on:

- *Classopollis* in low values

Sample/Interval	Age
1629-1636.8 mSWC	Not diagnostic

Remarks: apart from a single bisaccate pollen and a trilte spore the slides are devoid of palynomorphs.

Sample/Interval	Age
1670-1726.1 mSWC	Middle Volgian, TNO Subzone 2C, *pallasioides* Ammonite Subzone, or older

The interpretation is based on:

- LCOD *Lycopodiacidites irregularis* at 1670 m (10 % of the total sum palynomorphs)

Sample/Interval	Age
1750-2017 mSWC	Early Volgian, TNO Subzone 2B, *elegans-hudlestoni* Ammonite Subzone

The interpretation is based on:

- LOD *Couperisporites jurassicus* at 1750 m
- LOD *Rotverrusporites granularis* at 1837.9 m
- LOD *Geiselodinium paeminosum* at 1895 m (RRI report, 1984)
- FOD *Leptodinium antigonium* at 1996.2 m

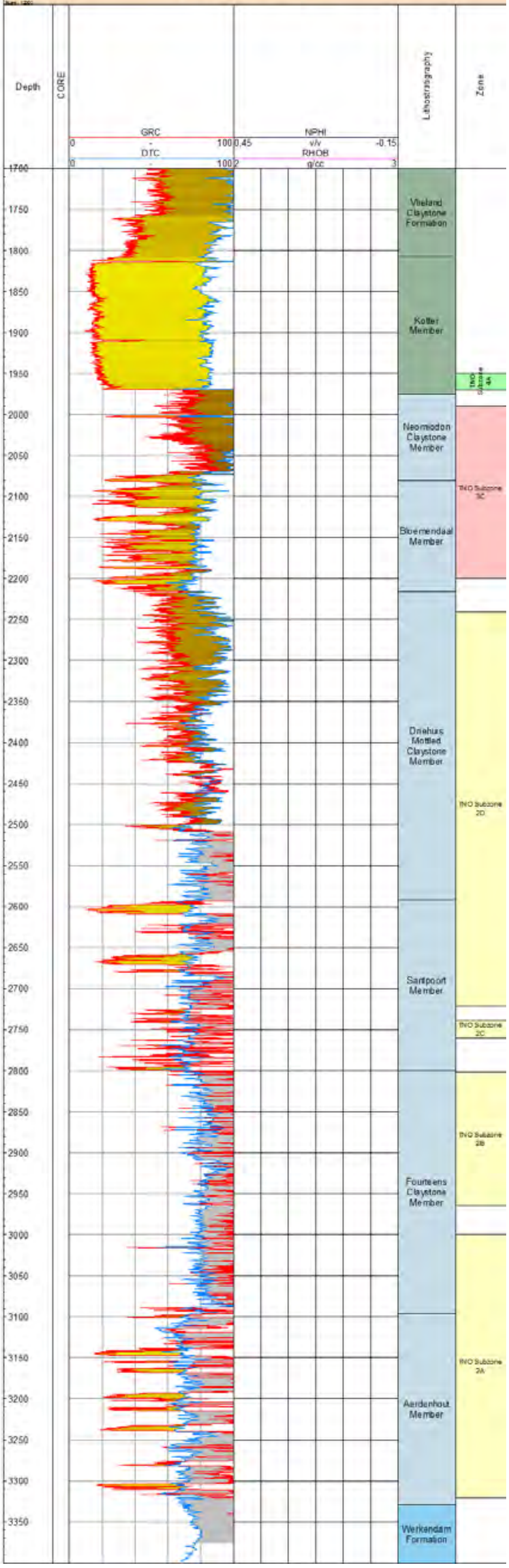
Remarks: the LCOD (54 % of the total sum palynomorphs) of *Perinopollenites elatoides* is recorded at 1837.9 m. This event may be associated with the so-called *"scitulus* climate event" and represents less arid conditions during the Kimmeridgian compared to the Volgian.

Sample/Interval	Age
2028-2270 m	Late Kimmeridgian, TNO Subzone 2A, *eudoxus-autissiodorensis* Ammonite Subzone

The interpretation is based on:
- LOD *Endoscrinium luridum* at 2028m

Remarks: all marker taxa for Sequence/Subzone 1 are absent.

K18-KOTTER-14



Age assessments of well K18-Kotter-14

<u>Sample/Interval</u> — <u>Age</u>

1820-1970 mCU — Early Valanginian, TNO Subzone 4B, *Polyptychites* Ammonite Subzone

This interpretation is based on:

- LOD *Canningia compta* at 1820 mCU
- LOD *Surculosphaeridium* sp. III sensu Davey 1982 at 1820 mCU

<u>Sample/Interval</u> — <u>Age</u>

1990-2210 mCU — Late Ryazanian, TNO Subzone 3C, or older

The age interpretation is based on:

- LCOD *Canningia compta* at 1990 m
- LOD *Kleithriasphaeridium porosispinum* at 2020 m

Remarks: acmes of *Cantulodinium speciosum*, like at 1990 m, were also recorded in the Helm Member (of wells P03-02, Q01-03, Q01-07) and at the top of the Neomiodon Claystone Member (well K18-02). Isolated presences of *Callialasporites turbatus* at interval 1990-2060 m and *Manumia* spp., interval 2080-2160 m, are considered as reworking from the Jurassic.

<u>Sample/Interval</u> — <u>Age</u>

2240 m CU — Middle Volgian, TNO Subzone 2D, anguiformis Ammonite Subzone, or older

The age interpretation is based on:

- LOD *Senoniasphaera jurassica*

Remarks: the presence of *Manumia* spp. matches with the age assessment. The relatively high numbers of *Cantulodinium speciosum* (FOD in the Late Ryazanian, *stenomphalus* Ammonite Subzone) are considered as caved.

<u>Sample/Interval</u> — <u>Age</u>

2260-2340 mCU — Middle Volgian, TNO Subzone 2D, *kerberus* Ammonite Subzone, or older

The age interpretation is based on:

- LOD *Amphorula* spp. at 2260 m

Remarks: the single occurrence of *Contignisporites* pre-major in Herngreen et al. (2000) at 2280 m, also indicates an age in the Middle Volgian.

<u>Sample/Interval</u> — <u>Age</u>

2360-2721 mCU — Middle Volgian, TNO Subzone 2D, *glaucolithus/ okusense* Ammonite Subzone, or older

The age interpretation is based on:

- LOD *Protobatioladinium imbatodinense* at 2360 m
- LOD *Rubinella* sp. A in Abbink (1998) at 2400 m

Remarks: reworking from older Jurassic successions, e.g. *Couperisporites* spp., *Raistrickisporites brevitruncatus*, *Striatella imperfecta* and *Striatella* sp. A sensu Abbink (1998) is present.

Sample/Interval	Age
2739-2811 mCU	Early Volgian, TNO Subzone 2C, *pectinatus* Ammonite Subzone

The age interpretation is based on:
- LOD *Kraeuselisporites tubbergensis* at 2739 m
- LOD *Rotverrusporites granularis* at 2760 m

Sample/Interval	Age
2823-2922 mCU	Early Volgian, TNO Subzone 2B, *scitulus-hudlestoni* Ammonite Subzones

The age interpretation is based on:
- LOD *Aldorfia dictyota* at 2823 m
- LOD *Pareodinia asperata* at 2823 m

Remarks: the LOD of *Kraeuselisporites huntii* at 2841 m confirms the interpretation.
The increased marine influence at depth 2823 m is associated with the J66 (*hudlestoni* Ammonite Subzone) flooding event of Partington et al (1993).

Sample/Interval	Age
2943-2964 mCU	Early Volgian, TNO Subzone 2B, *elegans/scitulus* climate shift

The age interpretation is based on:
- *Perinopollenites-Classopollis* abundance transition
- LOD *Cingulatisporites* sp. A in Abbink (1998)

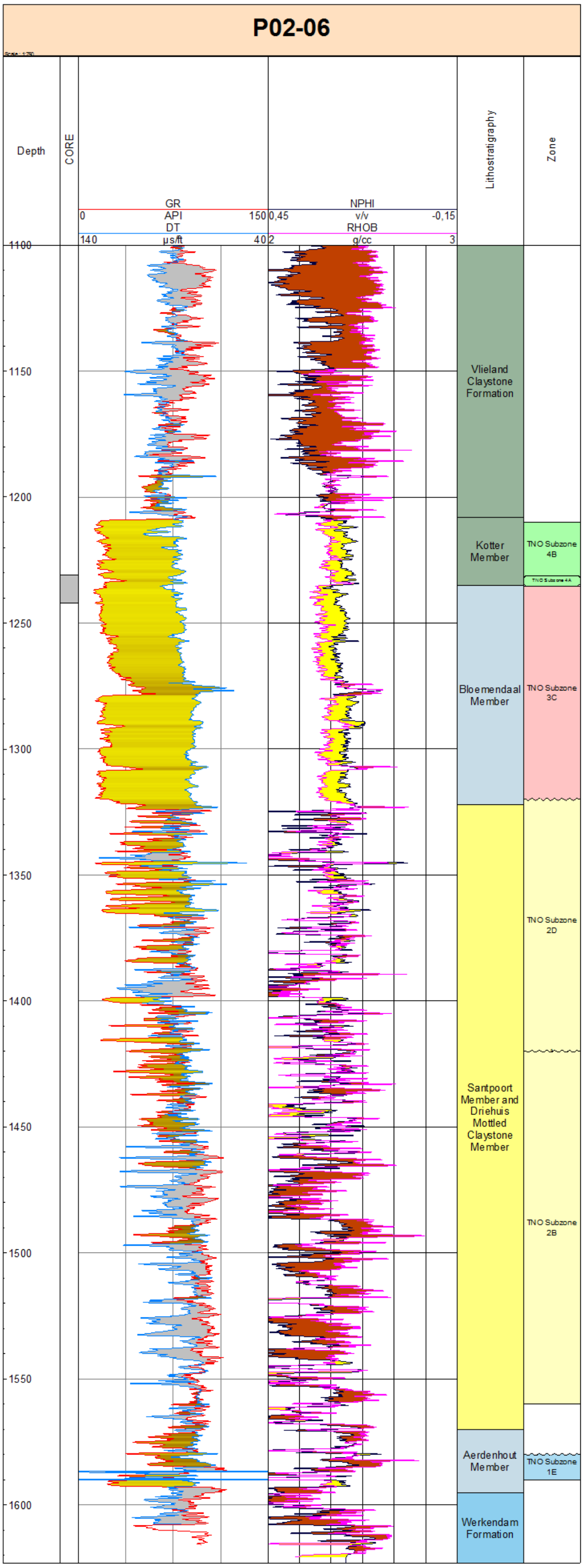
Sample/Interval	Age
3000-3321 mCU	Late Kimmeridgian, TNO Subzone 2A, *autissiodorensis* or older Ammonite Subzones

The age interpretation is based on:
- LCOD *Geiselodinium paeminosum* at 3060 m

Remarks: The LOD of *Quadraeculina anellaeformis* at 3135.4 m verifies a dating in the Kimmeridgian.

Sample/Interval	Age
3339-3399 mCU	Bajocian, or older

The age interpretation is based on:
- LOD *Nannoceratopsis gracilis* at 3339 m
- LOD *Nannoceratopsis spiculata* at 3339 m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GR
0
API
150
DT
140
µs/ft
40
NPHI
0,45
v/v
-0,15
RHOB
2
g/cc
3
Lithostratigraphy
Zone
1100
1150
1200
1250
1300
1350
1400
1450
1500
1550
1600
Vlieland Claystone Formation
Kotter Member
Bloemendaal Member
Santpoort Member and Driehuis Mottled Claystone Member
Aerdenhout Member
Werkendam Formation
TNO Subzone 4B
TNO Subzone 3C
TNO Subzone 2D
TNO Subzone 2B
TNO Subzone 1E

Age assessments of well P02-06

Sample/Interval	Age
1210 mCU -1231.6 mCU	Early Valanginian, TNO Subzone 4B, Polyptichites Ammonite Subzone

This interpretation is based on:

- LOD of *Canningia compta* at 1215 mCU
- LOD of *Batioladinium* cf. *varigranosum* at 1215 mCU
- LOD of *Muderongia* sp.1 cf. Heilmann-Clausen 1987 at 1215 mCU
- LOD of *Kleithriasphaeridium porosispinum* at 1225 mCU

Remarks: In the cored section at levels 1231.6 and 1231.1 mCO we note remarkably high loadings of an undescribed species of *Dichadogonyaulax* (sp. A).

Sample/Interval	Age
1232.15 mCO-1234.4 mCO	Early Valanginian, TNO Subzone 4A, Paratollia Ammonite Subzone, or older

This interpretation is based on:

- LOD of *Tehamadinium daveyi* at 1232.15 mCO

Remark: Reworking of Late Jurassic dinocysts is present throughout.

Sample/Interval	Age
1235.4 mCO-1305 mCU	Late Ryazanian, TNO Subzone 3C, stenomphalus-albidum Ammonite Subzones

This interpretation is based on:

- LOD of *Classopollis echinatus* at 1237.05 mCO
- LOD of *Oligosphaeridium diluculum* at 1265 mCU
- LOD of *Gochteodinia villosa* at 1265 mCU

Remark: Samples at 1239.77 and 1241.58 mCO are barren of palynomorphs. The LOD of *Oligosphaeridium diluculum* and *Gochteodinia villosa* indicate an age older than the Earliest Valanginian. Correlation of the GR-pattern to that of well K18-Kotter-14 shows that a Late Ryazanian age is most likely for the interval above1285 mCU.

Sample/Interval	Age
1325 mCU-1335 mCU	Late Jurassic: Middle Volgian, TNO Subzone 2D, anguiformis-kerberus Ammonite Subzones

This interpretation is based on:

- LOD of *Systematophora daveyi* at 1325 mCU

- LOD of *Callialasporites turbatus* at 1325 mCU

Remark: The LOD of *S. daveyi* indicates an age older than Early Ryazanian (TNO Subzone 3B, or older) for the top of this interval. However, the presence of *C. turbatus* indicates an age not younger than the Middle Volgian (TNO Subzone 2D, *anguiformis* Ammonite Subzone) for the top of the interval.

<u>Sample/Interval</u>	<u>Age</u>
1355-1425 mCU	Late Jurassic: Middle Volgian, TNO Subzone 2D, glaucolithus- okusensis Ammonite Subzones

This interpretation is based on:

- LOD of *Protobatioladinium imbatodinense* at 1355 mCU
- LOD of *Mendicodinium* spp. at 1355 mCU
- LOD of *Pareodinia halosa* at 1365 mCU

<u>Sample/Interval</u>	<u>Age</u>
1445-1565 mCU	Late Jurassic: Middle Volgian, TNO Subzone 2B, wheatleyensis-scitulus Ammonite Subzones, or older.

This interpretation is based on:

- LOD of *Kraeuselisporites* spp. at 1445 mCU
- LOD of *Geiselodinium* spp. at 1445 mCU

<u>Sample/Interval</u>	<u>Age</u>
1595-1585 mCU	Late Kimmeridgian, TNO Subzone 2A, mutabilis Ammonite Subzone or older

This interpretation is based on:

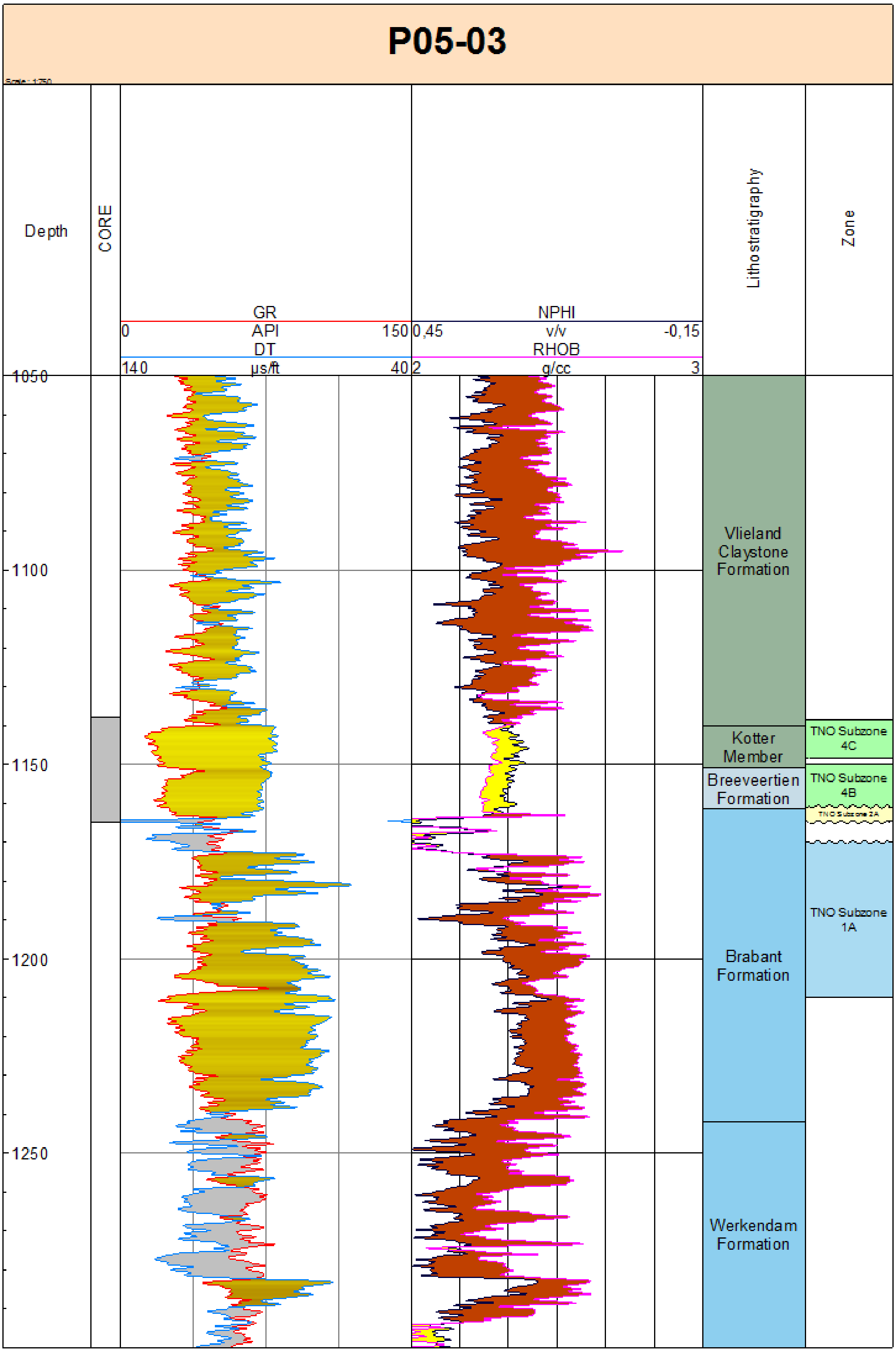
- LCOD *Densoisporites minor* at 1585 mCU
- LOD *Varirugosisporites* at 1595 mCU

Remark: The presence of *D. minor* provides an age not older than the Early Oxfordian (*densiplicatum* Subzone) and not younger than the Late Kimmeridgian *mutabilis* Subzone.

<u>Sample/Interval</u>	<u>Age</u>
1605-1615 mCU	Late Jurassic, Early Callovian, TNO-Subzone 1B, mariae Ammonite Subzone

This interpretation is based on:

- LOD *Dichadogonyaulax chondrum* at 1605 mCU
- LOD *Ctenidodinium combazii* at 1615 mCU
- Absence of *Durotrigia* suite.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0
API
150
DT
140
µs/ft
40
NPHI
0,45
v/v
-0,15
RHOB
2
g/cc
3
Lithostratigraphy
Zone
1050
1100
1150
1200
1250
Vlieland Claystone Formation
Kotter Member
Breeveertien Formation
Brabant Formation
Werkendam Formation
TNO Subzone 4C
TNO Subzone 4B
TNO Subzone 2A
TNO Subzone 1A

Age assessments of well P05-03

Sample/Interval	Age
1138.45 -1148.38 mCO	Early Cretaceous: Late Valanginian, TNO-Subzone 4C

This interpretation is based on:

- LOD *Lagenorhytis delicatula* at 1138.45 mCO
- FOD *Batioladinium longicornutum* at 1138.45 mCO
- LOD *Gochteodinia vilosa multifurcata* at 1148.38 mCO

Remark: An acme of *Ophiobolus* sp. A occurs at 1148.38 mCO. Between 1148.38 and 1138.45 mCO, samples are barren of palynomorphs.

Sample/Interval	Age
1150.05 -1161.14 mCO	Early Valanginian, TNO-Subzone 4B, *Paratollia* Ammonite Subzone

This interpretation is based on:

- LOD *Perisseiasphaeridium* spp. at 1150.05 mCO
- Low abundance of *Cicaticosisporites* spp.

Remark: *Cicatricosisporites* spp. is commonly encountered in the Ryazanian and declines in the Early Valanginian. The exact stratigraphic position of sample 1161.14 remains uncertain.

Sample/Interval	Age
1161.14-1164.45 mCO	Late Kimmeridgian, TNO Subzone 2A *mutabilis* Ammonite Subzone

This interpretation is based on:

- LOD *Densoisporites minor* at 1161.2 mCO
- LOD *Precicaticosisporites inae* at 1161.8 mCO
- LOD *Retitriletes undulatus* at 1161.8 mCO
- LOD *Varirugosisporites* spp. at 1161.8 mCO
- FOD *Densoisporites minor* at 1163.15 mCO

Remark: The lowermost samples of this interval are barren of palynomorphs (1164.45-1163.75 mCO).

Sample/Interval	Age
1170 mCU	Late Callovian, ?TNO SubSubzone 1A, *athleta* Ammonite Subzone

This interpretation is based on:

- LCOD *Ctenidodinium*/*Dichadogonyaulax stauromatos*/*sellwoodii* cpx at 1170 mCU
- LOD *Energlynia acollaris* at 1170 mCU
- LOD *Korystocysta kettonensis-gochtii* cpx at 1170 mCU
- LOD *Rigaudella aemula* at 1170 mCU

Sample/Interval	Age
1190-1210 mCU	Early Callovian, *koenigi* Ammonite Subzone

This interpretation is based on:

- LOD *Ctenidodinium combazii* at 1190 mCU
- LOD *Meiourogonyaulax reticulata* at 1190 mCU
- LOD *Pareodinia prolongata* at 1210 mCU

Remark: The sample at 1230 mCU is barren of palynomorphs.

Sample/Interval	Age
1250-1270 mCU	Late Bathonian, *discus* Ammonite Subzone or older

This interpretation is based on:

- LCOD *Korystocysta kettonensis-gochtii* cpx at 1250 mCU
- LOD *Nannoceratopsis gracilis* at 1270 mCU

Sample/Interval	Age
1290-1520 mCU	Early-Middle Bathonian

This interpretation is based on:

- LOD *Durotrigia asketa* at 1290 mCU
- LOD *Durotrigia filapicata* at 1290 mCU
- LOD *Gonyaulacysta* cf. *G. pectinigera* at 1290 mCU
- LOD *Durotrigia vesiculata* at 1310 mCU
- LOD *Neoraistrickia gristhorpensis* at 1350 mCU

Remark: *Durotrigia vesiculata* occurs in particularly high number during the early-middle Bathonian (Bailey, 1990).

Sample/Interval | Age
1530-1550 mCU | Bajocian

This interpretation is based on:

- LOD *Phallocysta* spp. at 1530 mCU
- LOD *Wallodinium cylindricum* at 1540 mCU
- LOD *Nannoceratopsis aff. dictyambonis* at 1550 mCU
- LOD *Mancodinium semitabulatum* at 1540 mCU

Sample/Interval | Age
1570-1590 mCU | Early Aalenian, or older

This interpretation is based on:

- LOD *Parvocysta* spp. at 1570 mCU (Early Aalenian)
- LOD *Susadinium* spp. at 1570 mCU
- LOD *Moesiodinium* spp. at 1605 mCU

Sample/Interval | Age
1600-1620 mCU | Early Toarcian

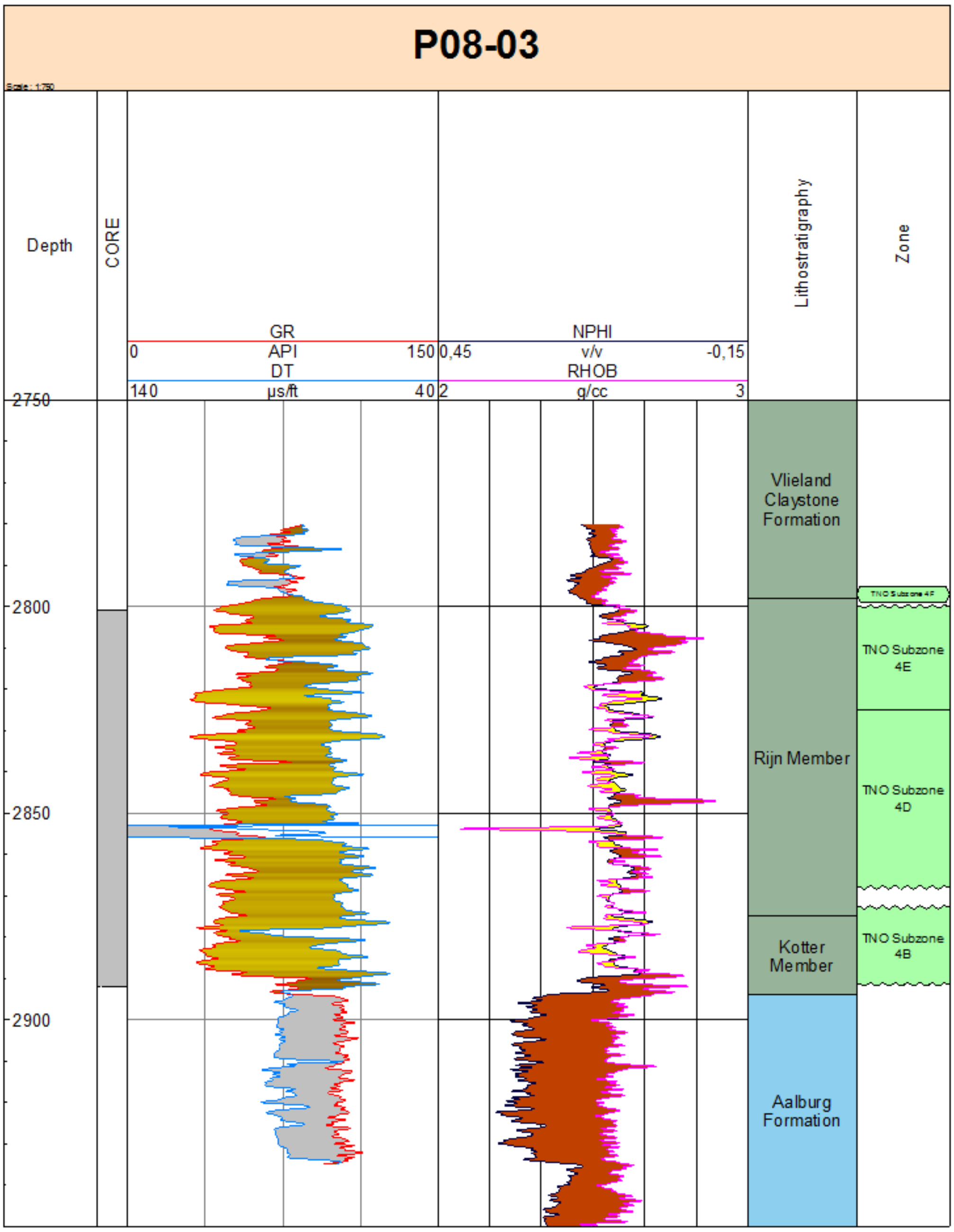
This interpretation is based on:

- LCOD Tasmanaceae at 1600 mCU

Sample/Interval | Age
1630-1650 mCU | Late Pliensbachian, or older

This interpretation is based on:

- LOD *Luehndea spinosa* at 1650 mCU
- LOD *Heliosporites altmarkensis* at 1650 mCU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API
150
DT
140
µs/ft
40
NPHI
0,45
v/v
-0,15
RHOB
2
g/cc
3
Lithostratigraphy
Zone
2750
2800
2850
2900
Vlieland Claystone Formation
Rijn Member
Kotter Member
Aalburg Formation
TNO Subzone 4F
TNO Subzone 4E
TNO Subzone 4D
TNO Subzone 4B

Age assessments of well P08-03

Sample/Interval	Age
2797 mCO	Early Cretaceous; Latest Hauterivian, TNO-SubSubzone 4F, *rarocinctum* Ammonite Subzone

This interpretation is based on:

- FOD *Meiourogonyaulax sagena* at 2797 mCO
- LOD *Kleithriasphaeridium corrugatum* at 2797 mCO
- LOD *Spiniferites dentatus* at 2797 mCO
- FOD *Diphasiosphaera stolidata* at 2797

Sample/Interval	Age
2801-2858.25 mCO	Late Hauterivian, TNO SubSubzones 4 D-E

This interpretation is based on:

- LOD of *Phoberacysta* cf. *tabulata* at 2801 mCO
- FOD of *Subtilisphaera* spp. at 2858.25 mCO

Sample/Interval	Age
2868.5 mCO	Early Hauterivian, TNO SubSubzone 4D

This interpretation is based on:

- LOD *Exiguisphaera phragma* at 2868.5 mCO
- LOD *Hystrichosphaeridium scoriaceum* at 2868.5 mCO

Sample/Interval	Age
2872.8-2891.5 mCO	Early Valanginian, TNO SubSubzone 4B, *Polyptichites* Ammonite Subzone

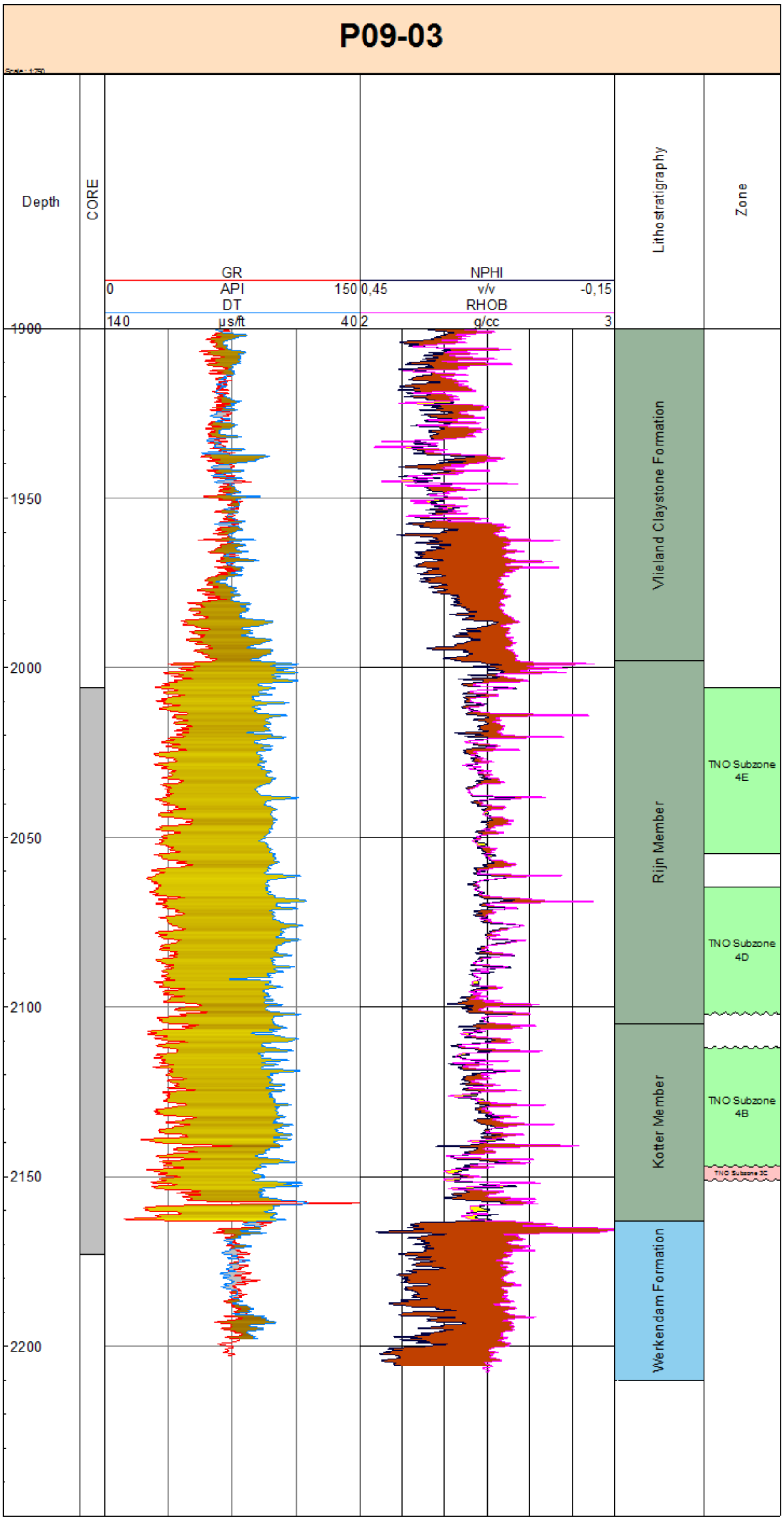
This interpretation is based on:

- LOD *Gochteodinia villosa* at 2872.80 mCO
- LOD *Muderongia* sp. 1 Heilmann-Clausen 1987 at 2872.8 mCO
- LOD *Batioladinium* sp. 1 Davey 1982 at 2872.8 mCO
- LOD *Oligosphaeridium diluculum* at 2891.5 mCO
- FOD *Oligosphaeridium complex* at 2891.5 mCO
- FOD *Spiniferites* spp. at 2891.5 mCO

Sample/Interval	Age
2892-2892.4 mCO	Early Jurassic; Hettangian

This interpretation is based on:

- LOD *Ovalipollis* spp. at 2892 mCO
- LOD *Brachysaccus microsaccus* at 2892 mCO
- LOD *Quadraeculina annellaeformis* at 2892 mCO



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GR
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API
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DT
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µs/ft
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NPHI
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v/v
-0,15
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2
g/cc
3
Lithostratigraphy
Zone
1900
1950
2000
2050
2100
2150
2200
Vlieland Claystone Formation
Rijn Member
Kotter Member
Werkendam Formation
TNO Subzone 4E
TNO Subzone 4D
TNO Subzone 4B

Age assessments of well P09-03

Sample/Interval	Age
1996-2000 mCU	Early Cretaceous; Early Aptian or older

This interpretation is based on:

- LOD *Pseudoceratium pelliferum* at 1996 mCU
- LOD *Heslertonia heslertonensis* at 2000 mCU
- LOD *Discorsia nanna* at 2000 mCU

Sample/Interval	Age
2006-2054.7 mCO	Early Cretaceous; Late Hauterivian, TNO SubSubzone 4E, *gottschei* to *variabilis* Ammonite Subzones

This interpretation is based on:

- LOD *Canningia* cf. *reticulata* at 2006 mCO
- FOD *Odonotochitina operculata* at 2006 mCO
- LOD *Nelchinopsis*/*Gonyaulacacysta kostromiensis* at 2006 mCO
- LOD *Kleithriasphaeridium corrugatum* at 2006 mCO
- FOD *Meiourogonyaulax sagena* at 2016 mCO
- FOD *Diphasiosphaera stolidata* at 2016 mCO
- LOD *Cribroperidinium confossum* at 2032 mCO
- FOD *Subtilisphaera perlucida* at 2054.7 mCO
- FOD *Cribroperidinium confossum* at 2054.7 mCO.

Sample/Interval	Age
2064.7-2102 mCO	Early Cretaceous; Early Hauterivian, TNO SubSubzone 4D, *amblygonium-regale* Ammonite Subzones

This interpretation is based on:

- FOD *Muderongia staurota* at 2077 mCO
- FOD *Callaiosphaeridium trycherium* at 2102 mCO
- LOD *Phoberacysta tabulata* at 2064.7 mCO
- LOD *Batioladinium varigranosum* at 2077 mCO
- FOD *Callaiosphaeridium asymmetricum* at 2102 mCO

Remark: At 2077 and 2087 mCO we note abundant occurrences of *Hystrichosphaeridium scoriaceum*. Heilmann-Clausen (1987) notes that such abundance peaks occur in short-lived intervals of the Early Hauterivian (*regale* Ammonite Subzone) and the Early Valanginian (*Paratollia* and *Polyptychites* Ammonite Subzones).

Sample/Interval	Age
2112-2147 mCO	Uncertain: Early Cretaceous; Early Valanginian; TNO SubSubzone 4B-C?, *Paratollia-Prodichotomites* Ammonite Subzone

This interpretation is based on:

- LOD *Batioladinium* cf. *varigranosum* at 2112 mCO
- FOD *Spiniferites ramosus* at 2136 mCO

Remark: The absence of *Canningia compta* suggests and age younger than the polyptichites Ammonite Subzone (TNO SubSubzone 4B). The LOD of *Batioladinium* cf. *varigranosum* at 2112 mCO suggests an older age (within SubSubzone 4B).

Sample/Interval	Age
2151.1 mCO	Early Cretaceous; Possibly Late Ryazanian, TNO SubSubzone 3C, *stenomphalus-albidum* Ammonite Subzones

This interpretation is based on:

- LOD *Dichadogonyaulax culmula* at 2151.1 at mCO
- LOD *Egmontodinium torynum* at 2151.1 at mCO
- FOD *Pseudoceratium brevicornutum* at 2151.1 mCO

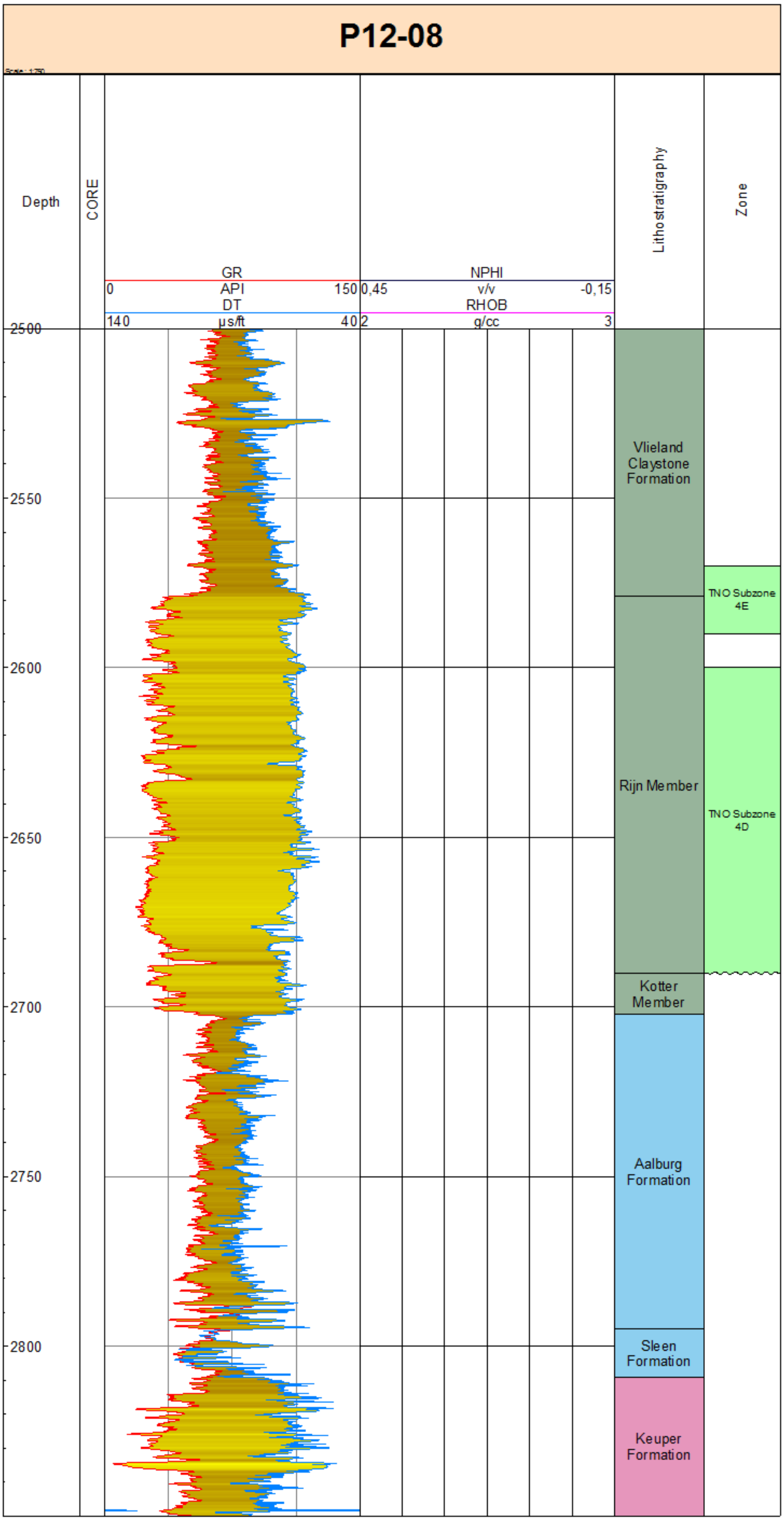
Remark: Another abundance peak of *Hystrichosphaeridium scoriaceum* occurs in this interval. This corroborates our latest Ryazanian age-assignment.

Sample/Interval	Age
2163.5-2173 mCO	Middle Jurassic; Aalenian *Opalinum* Ammonite Subzone or older

This interpretation is based on:

- LOD *Parvocysta cracens* at 2173 mCO

Remark: The sample at 2163.5 mCO only yields scarce palynomorphs. Yet of the few encountered specimens, all resemble that of the underlying association at 2173 mCO.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GR
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DT
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NPHI
0,45 v/v -0,15
RHOB
2 g/cc 3
Lithostratigraphy
Zone
2500
2550
2600
2650
2700
2750
2800
Vlieland Claystone Formation
Rijn Member
Kotter Member
Aalburg Formation
Sleen Formation
Keuper Formation
TNO Subzone 4E
TNO Subzone 4D

Age assessments of well P12-08

Sample/Interval	Age
2570 mCU	Early Cretaceous: Latest Hauterivian-Earliest Barremian, TNO-SubSubzone 4F, *variabilis-rarocinctum* Ammonite Subzone

This interpretation is based on:

- LOD *Chlamydophorella membranoidea* at 2570 mCU
- LOD *Hystrichodinium ramoides* at 2570 mCU
- LOD *Kleithriasphaeridium corrugatum*
- LOD *Muderongia simplex* at 2570 mCU
- LOD *Canningia* cf. *reticulata* at 2570 mCU

Remark: The *very common* occurrence of *Subtilisphaera pelucida* at 2580 mCU fits with this age-assignment.

Sample/Interval	Age
2580-2590 mCU	Early Cretaceous: Late Hauterivian, TNO-SubSubzone 4E, *ariabilis* Ammonite Subzone

This interpretation is based on:

- LOD of *Cribroperidinium confossum* at 2590 mCU
- LOD of *Phoberocysta* cf. *tabulata* at 2580 mCU

Sample/Interval	Age
2620-2690 mCU	Early Cretaceous: Early Hauterivian, not further differentiated

This interpretation is based:

- LOD *Nelchinopsis/ kostromiensis* at 2690 mCU
- FCOD *Cicatricosisporites* spp. at 2700 mCU

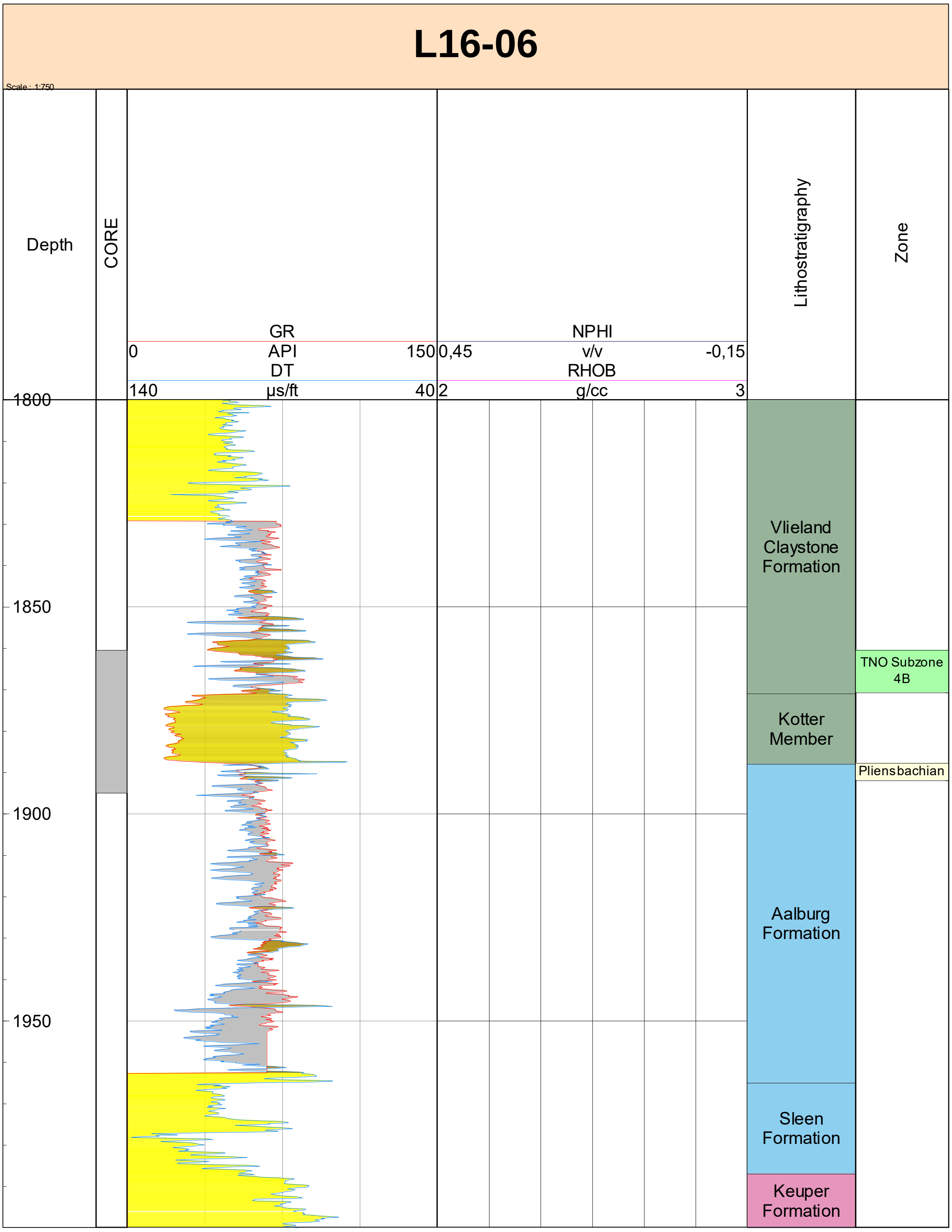
Remark: The absence of abundant *Muderongia* spp., throughout the interval confirm an age younger than the Valanginian. This group of taxa reaches high numbers in the Valanginian elsewhere in the Broad Fourteens Basin. Common *Cicactricosisporites* confirms an Early Cretaceous age.

Sample/Interval	Age
2710 mCU	Pliensbachian or older

This interpretation is based on:

- LOD *Heliosporites altmarkensis* at 2710 mCU

Remark: The palynological yield of this sample is minimal



L16-06
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API
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DT
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µs/ft
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NPHI
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RHOB
2
g/cc
3
Lithostratigraphy
Zone
1800
1850
1900
1950
Vlieland Claystone Formation
Kotter Member
Aalburg Formation
Sleen Formation
Keuper Formation
TNO Subzone 4B
Pliensbachian

Age assessments of well L16-06

Sample/Interval	Age
1860.5-1870.75 mCO	Early Cretaceous: Early Valanginian, TNO SubSubzone 4B, *Polyptichites* Ammonite Subzone

This interpretation is based on:

- LOD *Canningia compta* at 1862.05 mCO
- FOD *Hystrichosphaerina schindewolfii* at 1868.15 mCO
- LOD *Systematophora palmula* at 1868.15 mCO
- LOD *Kleithriasphaeridium porosispinum* at 1860.5 mCO
- LOD *Perisseiasphaeridium insolitum* at 1862.6 mCO

Remarks:

Abundant occurrences of *Muderongia*; e.g., *M. simplex*, *M. simplex* ssp. *microperforata* and *M. tetracanta* support an Early Valanginian age-assignment. *Cantulodinium speciosum*, commonly present in Late Ryazanian to Earliest Valanginian strata (see e.g. well Q01-Helm-A1) is not recorded. We note a conspicuous increase of *Classopollis* spp. at 1862.6. This may be ascribed to reworking.

Sample/Interval	Age
1887.75-1892	Pliensbachian or older

This interpretation is based on:

- LOD *Heliosporites altmarkensis* at 1887.75 mCO
- LOD *Circulina meyeriana* at 1887.5 mCO
- LOD *Quadraeculina anellaeformis* at 1887.75 mCO

Age assessments of well Q01-Helm-A1

Sample/Interval	Age
1210 mCU - 1217.03 mCO	Early Cretaceous: Early Hauterivian, TNO SubSubzone 4D, *noricum-regale* Ammonite Subzones

- FOD *Batioladinium longicornutum* at 1217.03 mCO
- LOD *Aldorfia spongiosa* at 1217.03 mCO

Remark:

The sample at 1210 mCU is nearly barren. A single of occurrence of *Dingodinium spinosum* is considered reworked.

Sample/Interval	Age
1226.61-1237.48 mCO	Early Cretaceous: Late Valanginian, TNO SubSubzone 4C, *tuberculata* Subzone to *amblygonium* Ammonite Subzone

- FOD *Gonyaulacysta/Nelchinopsis kostromiensis* at 1226.1 mCO
- FOD *Muderongia staurota* at 1226.1 mCO
- LOD *Muderongia extensiva* at 1226.1 mCO

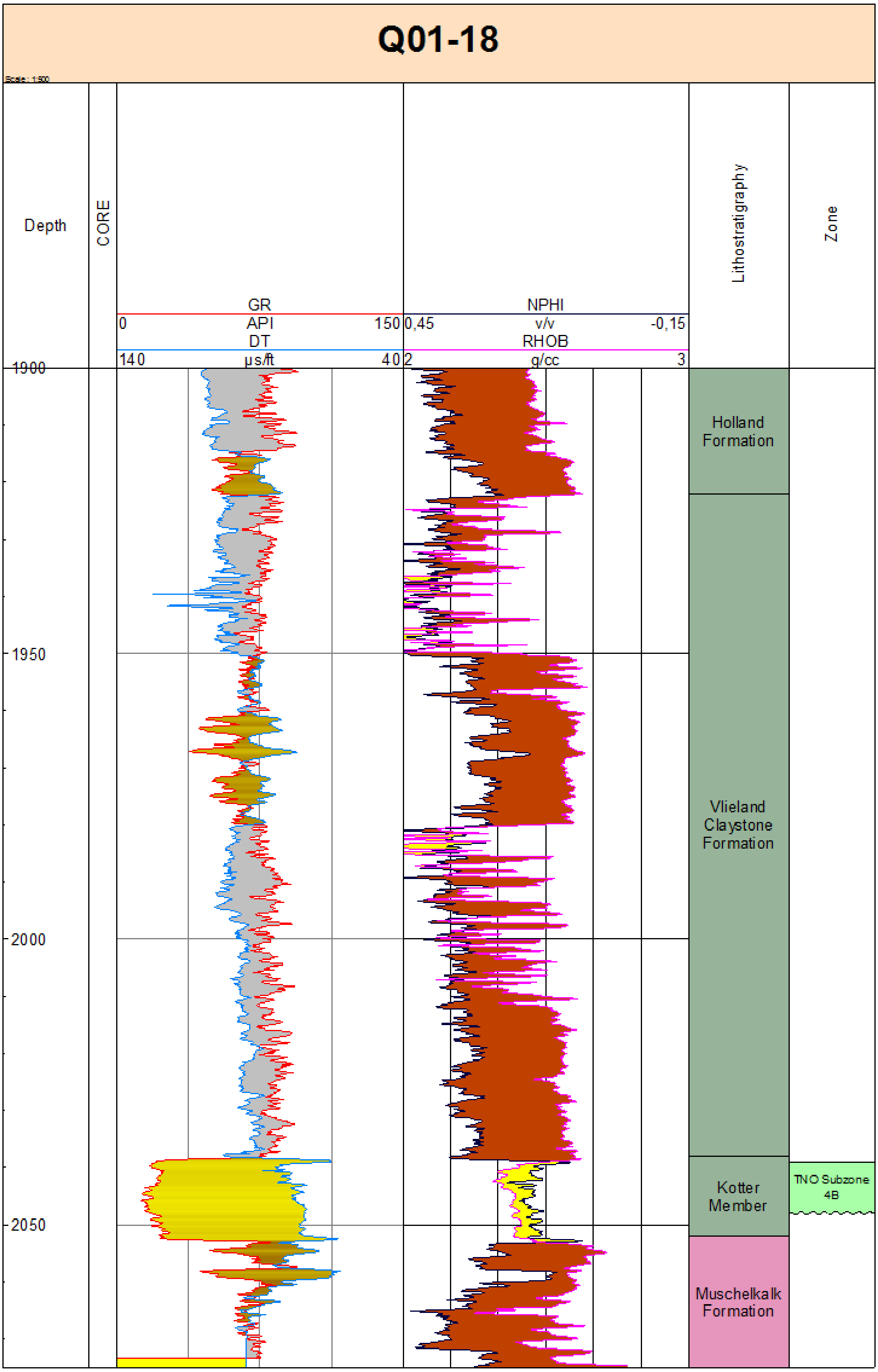
Sample/Interval	Age
1242.2-1316.52 mCO	Early Cretaceous: Early Valanginian, TNO-SubSubzone 4B, *Polyptichites/Paratollia* Ammonite Subzone

- LOD *Batioladinium* cf. *varigranosum* at 1242.2 mCO
- FOD *Muderongia extensiva* at 1258.28 mCO
- FOD *Spiniferites* spp. (*ramosus* cpx) at 1258.25 mCO
- LOD *Canningia compta* at 1258.25 mCO
- FOD *Ctenidodinium elegantulum* at 1311 mCO
- FOD *Hystrichosphaerina schindewolfii* at 1314.15 mCO
- FOD *Pseudoceratium pelliferum* at 1316.57 mCO

Remark: A variety of *Muderongia* forms (*M. simplex*, *M. simplex* ssp. *microperforata, M. extensiva*) and *Cantulodinium* speciosum reach high abundance in this interval.

Sample/Interval	Age
1316.57-1415 mCU	Late Ryazanian: TNO-SubSubzone 3C, post-*kochi* Ammonite Subzone

- LCOD *Canningia compta* at 1350 mCU
- LOD *Endoscrinium pharo* at 1316.57
- LCOD *Cicatricosisporites* spp. at 1316.57


Q01-18
Scale : 1:500
Depth
CORE
GR
0 API 150
DT
140 μs/ft 40
NPHI
0,45 v/v -0,15
RHOB
2 g/cc 3
Lithostratigraphy
Zone
1900
1950
2000
2050
Holland Formation
Vlieland Claystone Formation
Kotter Member
Muschelkalk Formation
TNO Subzone 4B

Age assessments of well Q01-18

Sample/Interval	Age
2039 mCU	Not diagnostic, ?TNO SubSubzone 4B

Remark: Palynomorphs associations are dominated by caving from Lower Cretaceous strata. *Canningia* spp. is still present. Hence, an Early Valanginian age cannot be excluded.

Sample/Interval	Age
2042-2048 mCU	Early Cretaceous: Early Valanginian, TNO SubSubzone 4B, *paratollia-polyptichites* Ammonite Subzones

This interpretation is based on:

- LOD of *Batioladinium* sp. 1 sensu Davey 1982 at 2042 mCU
- LOD of *Canningia compta* at 2042 mCU
- LOD of *Stiphrosphaeridium dictyophorum* at 2048 mCU

Remark/Paleo-environment:

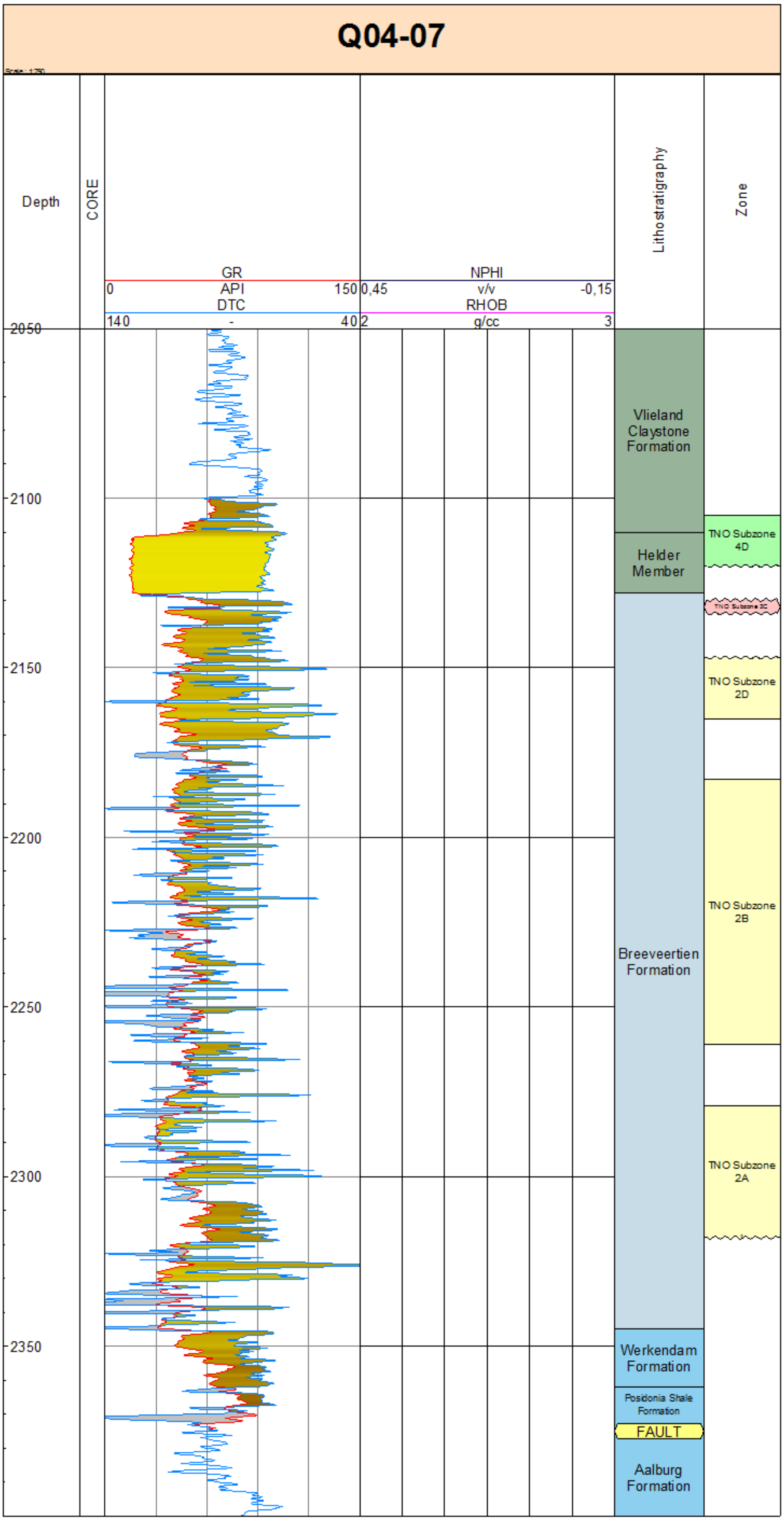
Spiniferites spp., a genus of predominantly open marine dinocysts is dominant. Possibly, these are caved from overlying strata.

Sample/Interval	Age
2054-2070 mCU	(Middle) Triassic

This interpretation is based on:

- Presence of taeniate bisaccate pollen grains
- LOD *Semiretisporites* spp. at 2054 mCU

Remark: The Muschelkalk (Middle Triassic) interval below 2048 mCU is very poor and largely yields caved palynomorphs.



Q04-07
Depth
CORE
GR
0 API 150
DTC
140 - 40
NPHI
0,45 v/v -0,15
RHOB
2 g/cc 3
Lithostratigraphy
Zone
2050
2100
2150
2200
2250
2300
2350
Vlieland Claystone Formation
Helder Member
Breeveertien Formation
Werkendam Formation
Posidonia Shale Formation
FAULT
Aalburg Formation
TNO Subzone 4D
TNO Subzone 2D
TNO Subzone 2B
TNO Subzone 2A

Age assessments of well Q04-07

Sample/Interval	Age
2105-2120 mCU	Early Cretaceous; Early Hauterivian, TNO-SubSubzone 4D, *noricum-regale* Ammonite Subzones

This interpretation is based on:

- LOD of *Phoberacysta* cf. *tabulata* at 2105 mCU
- LOD of *Batioladinium varigranosum* at 2114 mCU
- LOD of *Canningia* cf. *reticulata* at 2114 mCU
- LOD of *Gonyaulacysta* (aff.) *kostromiensis* at 2114 mCU

Sample/Interval	Age
2132 mCU	Early Cretaceous; Late Ryazanian, TNO SubSubzone 3C, *kochi* Ammonite Subzone or younger

This interpretation is based on:

- LCOD *Cicatricosisporites* spp. at 2132 mCU
- LOD *Aequitriradites verrucosum* at 2132 mCU

Remark: The common presence of the fresh-brackish-water algae *Botryococcus* is typical for the coeval Late Ryazanian “Wealden facies”.

Sample/Interval	Age
2147-2165 mCU	Late Jurassic: Middle Volgian, TNO SubSubzone 2D, *glaucolithus-okusensis* Ammonite Subzones

This interpretation is based on:

- LCOD *Classopollis* spp. at 2147 mCU
- LOD *Rubinella* sp. A of Abbink 1998 at 2147 mCU
- LOD *Callialasporites turbatus* at 2147 mCU

Sample/Interval	Age
2183-2261 mCU	Late Jurassic: Early Volgian, TNO SubSubzone 2B, *hudlestoni-scitulus* Ammonite Subzones

This interpretation is based on:

- LCOD of *Perinopollenites elatoides* at 2183 mCU
- LOD of *Cingulatisporites* sp. A at 2201 mCU
- LOD of *Geiselodinium* spp. at 2261 mCU

Remark: The “*scitulus*” climate shift marks a warming which caused a transition from cold-humid associations dominated by *Perinopollenites* to warm-dry associations dominated by *Classopollis* spp.

Sample/Interval	Age
2279-2318 mCU	Late Jurassic: Late Kimmeridgian, TNO SubSubzone 2A, *autissiodorensis* Ammonite Subzone

This interpretation is based on:

- LOD *Striatella* spp. at 2279 mCU
- LOD *Brachysaccum microsaccum* at 2300 mCU

Remark:

The LOD of *Adnatosphaeridium cauleryi* fits with this age-assessment.

Sample/Interval	Age
2333-2360 mCU	Not diagnostic: ?Middle Callovian or older

Remark: The presence of *Chamatosporites magnolioides* at 2333 mCU suggest a Middle Callovian or older age.

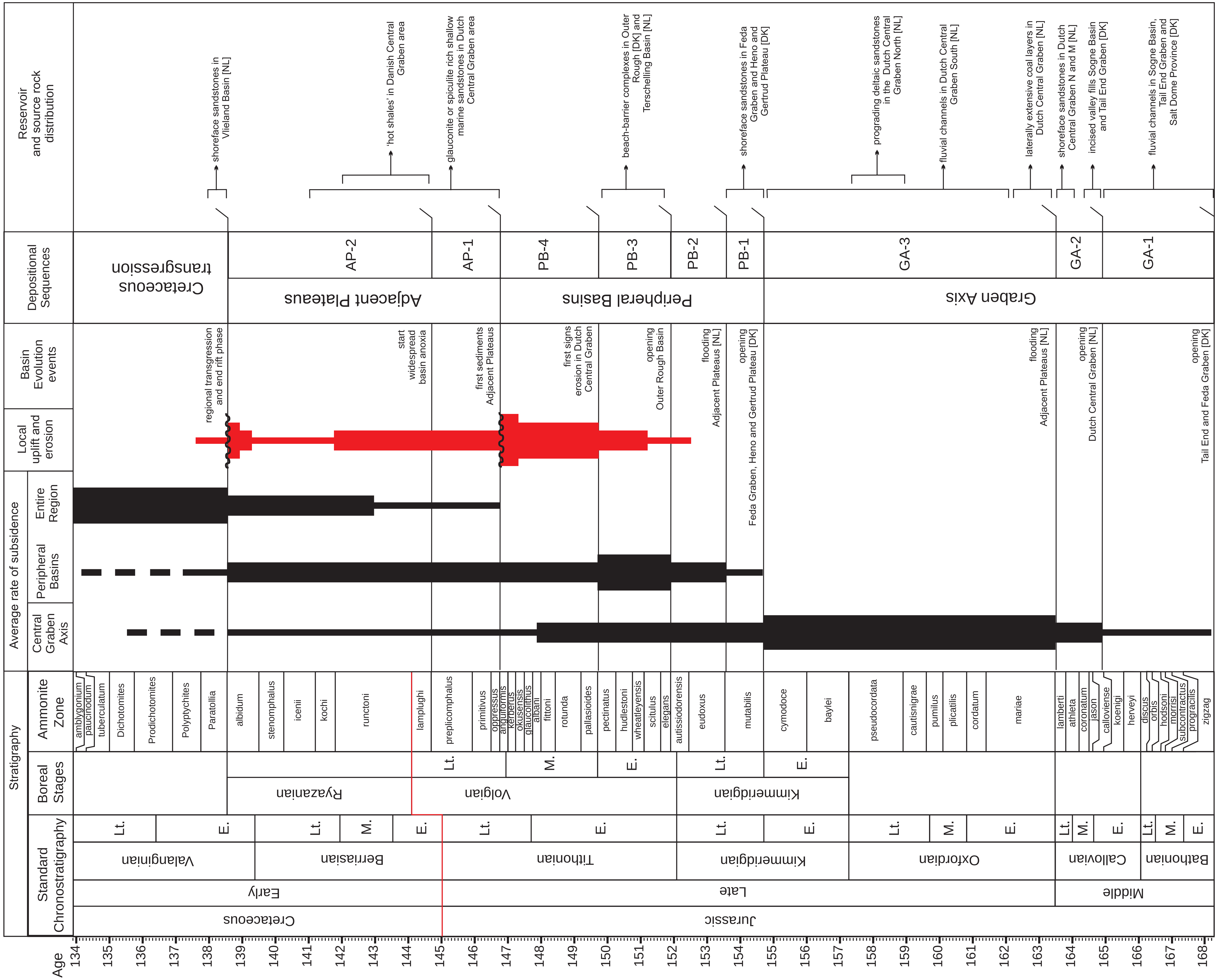
Sample/Interval	Age
2369 mCU	Early Toarcian

Remark: The presence of Tasmanaceae at 1369 mCU may be in correspondence with an early Toarcian age (Posidonia shale Fm.). Tasmanaceae are adapted to stratified water masses.

Sample/Interval	Age
2381 mCU	Late Pliensbachian

This interpretation is based on:

- LOD *Luehndea spinosa*
- LOD *Mancodinium semitabulatum*
- LOD *Nannoceratopsis gracilis-triceras*
- LOD *Parvocysta* spp.


Reservoir and source rock distribution
shoreface sandstones in Vlieland Basin [NL]
'hot shales' in Danish Central Graben area
glauconite or spiculite rich shallow marine sandstones in Dutch Central Graben area
beach-barrier complexes in Outer Rough [DK] and Terschelling Basin [NL]
shoreface sandstones in Feda Graben and Heno and Gertrud Plateau [DK]
prograding deltaic sandstones in the Dutch Central Graben North [NL]
fluvial channels in Dutch Central Graben South [NL]
laterally extensive coal layers in Dutch Central Graben [NL]
shoreface sandstones in Dutch Central Graben N and M [NL]
incised valley fills Sogne Basin and Tail End Graben [DK]
fluvial channels in Sogne Basin, Tail End Graben and Salt Dome Province [DK]
Depositional Sequences
Cretaceous transgression
AP-2
AP-1
PB-4
PB-3
PB-2
PB-1
GA-3
GA-2
GA-1
Adjacent Plateaus
Peripheral Basins
Graben Axis
Basin Evolution events
regional transgression and end rift phase
start widespread basin anoxia
first sediments Adjacent Plateaus
first signs erosion in Dutch Central Graben
opening Outer Rough Basin
flooding Adjacent Plateaus [NL]
opening Feda Graben, Heno and Gertrud Plateau [DK]
flooding Adjacent Plateaus [NL]
opening Dutch Central Graben [NL]
opening Tail End and Feda Graben [DK]
Local uplift and erosion
Average rate of subsidence
Entire Region
Peripheral Basins
Central Graben Axis
Stratigraphy
Ammonite Zone
amblygonium
paucinodum
tuberculatum
Dichotomites
Prodichotomites
Polyptychites
Paratollia
albidum
stenomphalus
icenii
kochi
runctoni
lamplughi
preplicomphalus
primitivus
oppressus
anguiformis
kerberus
okusensis
glaucolithus
albani
fittoni
rotunda
pallasioides
pectinatus
hudlestoni
wheatleyensis
scitulus
elegans
autissiodorensis
eudoxus
mutabilis
cymodoce
baylei
pseudocordata
cautisnigrae
pumilus
plicatilis
cordatum
mariae
lamberti
athleta
coronatum
jason
calloviense
koenigi
herveyi
discus
orbis
hodsoni
morrisi
subcontractus
progracilis
zigzag
Boreal Stages
Lt.
M.
E.
Ryazanian
Volgian
Kimmeridgian
Standard Chronostratigraphy
Valanginian
Berriasian
Tithonian
Kimmeridgian
Oxfordian
Callovian
Bathonian
Early
Late
Middle
Cretaceous
Jurassic
Age
134
135
136
137
138
139
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
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156
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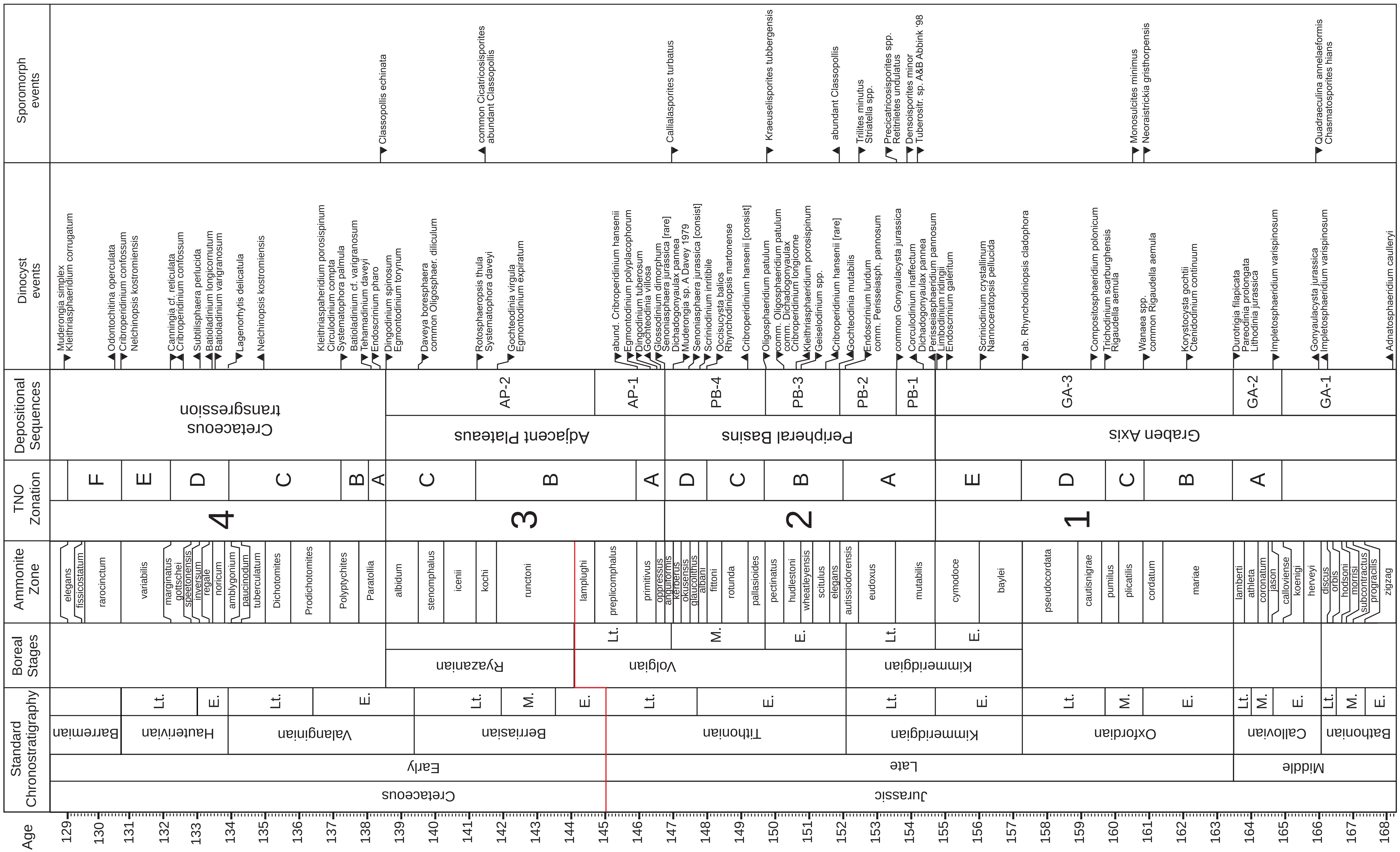
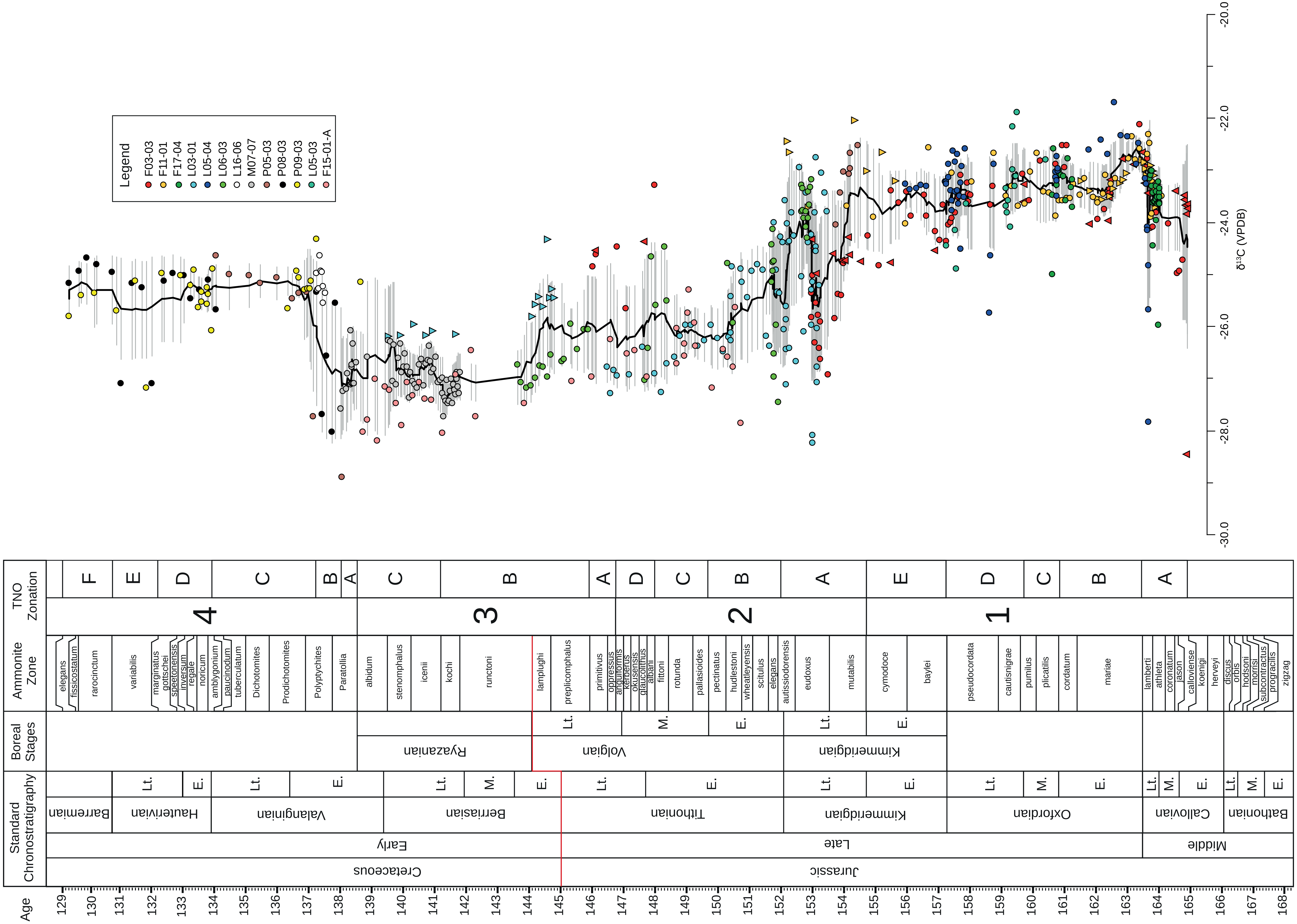
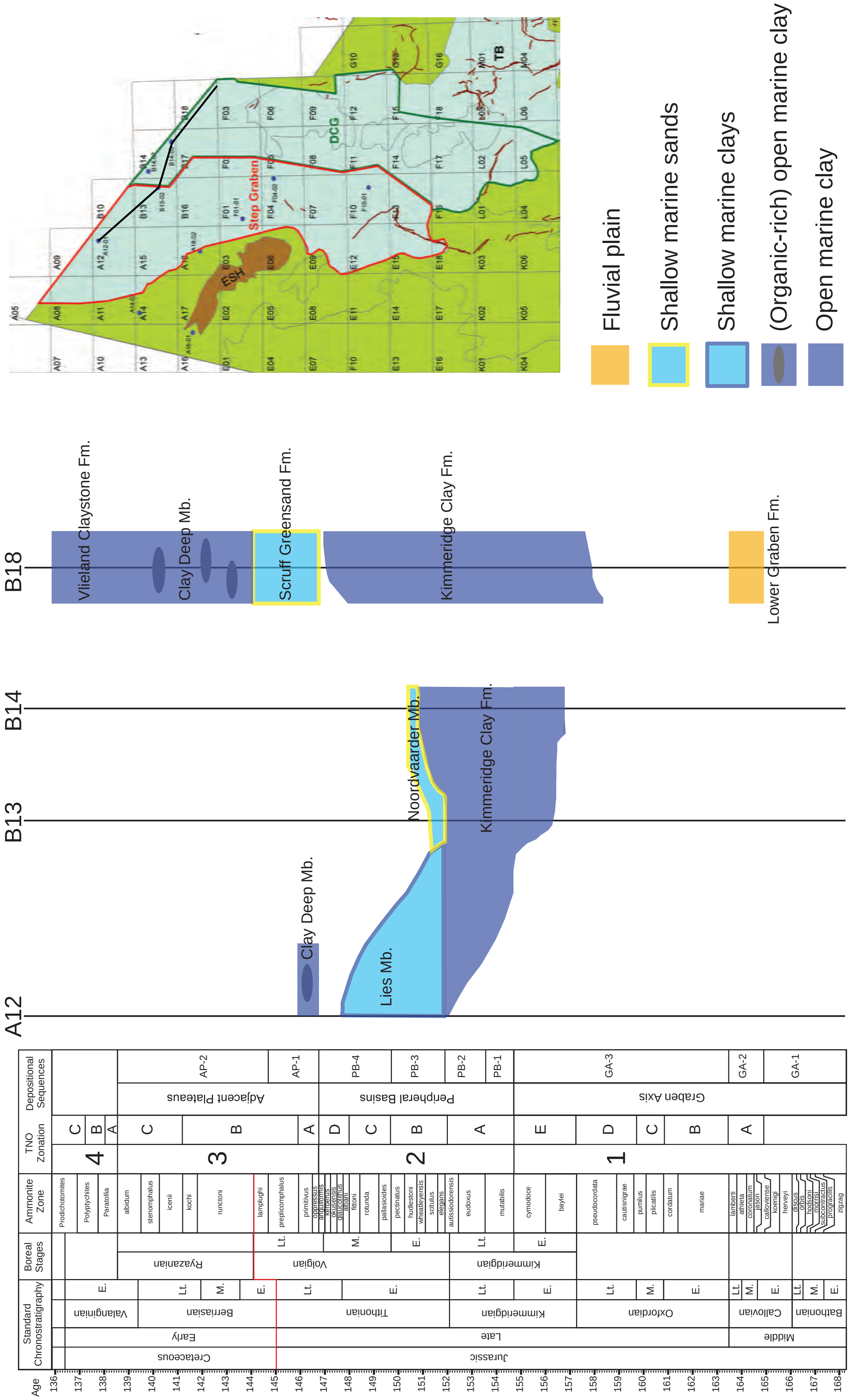
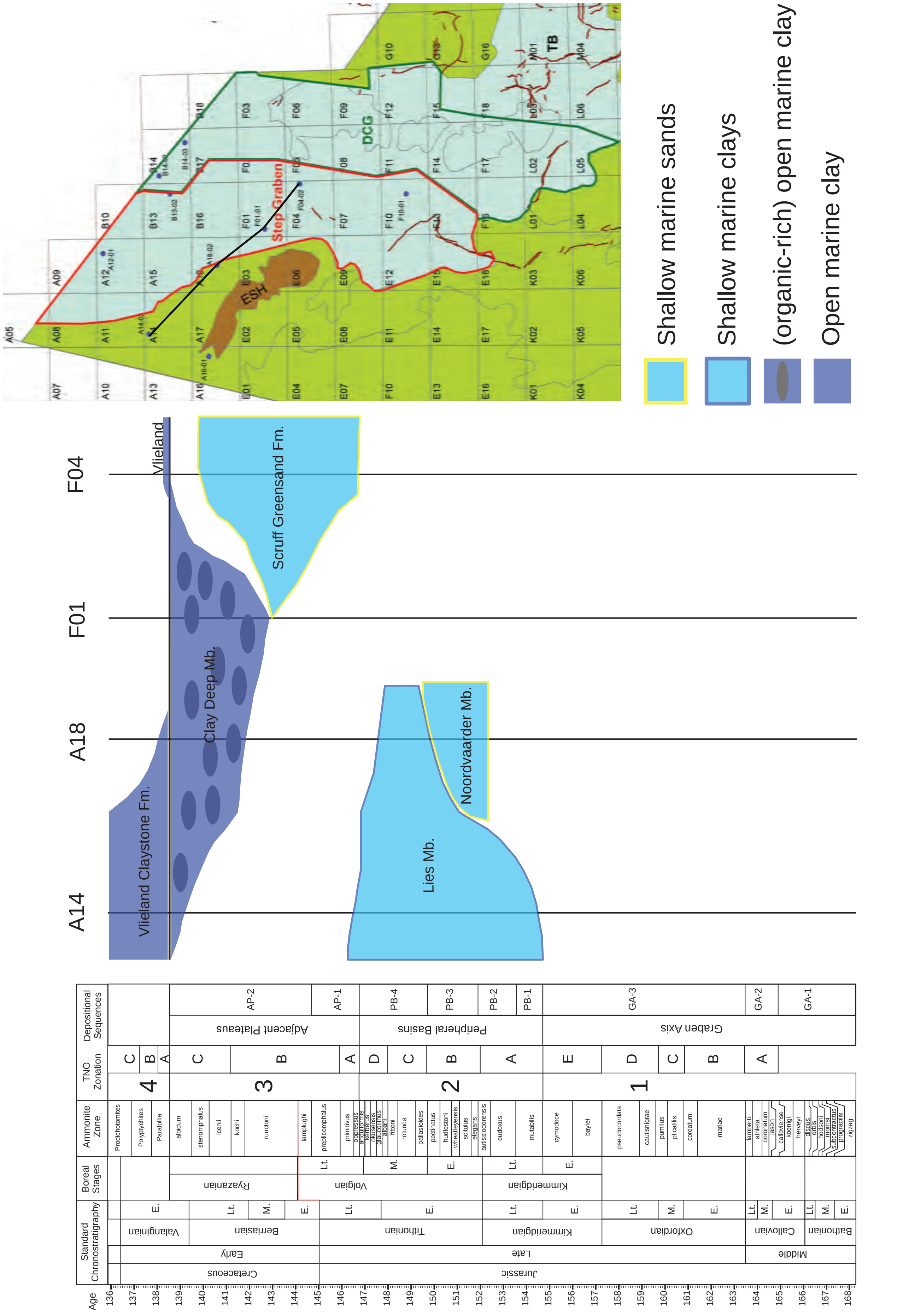
167
168


Age
Standard Chronostratigraphy
Boreal Stages
Ammonite Zone
TNO Zonation
Depositional Sequences
Dinocyst events
Sporomorph events
Cretaceous
Jurassic
Early
Late
Middle
Barremian
Hauterivian
Valanginian
Berriasian
Tithonian
Kimmeridgian
Oxfordian
Callovian
Bathonian
Ryazanian
Volgian
Cretaceous transgression
Adjacent Plateaus
Peripheral Basins
Graben Axis
AP-2
AP-1
PB-4
PB-3
PB-2
PB-1
GA-3
GA-2
GA-1
Classopollis echinata
common Cicatricosisporites
abundant Classopollis
Callialasporites turbatus
Kraeuselisporites tubbergensis
abundant Classopollis
Trilites minutus
Striatella spp.
Precicatricosisporites spp.
Retitriletes undulatus
Densoisporites minor
Tuberositr. sp. A&B Abbink '98
Monosulcites minimus
Neoraistrickia gristhorpensis
Quadraeculina anneleaeformis
Chasmatosporites hians

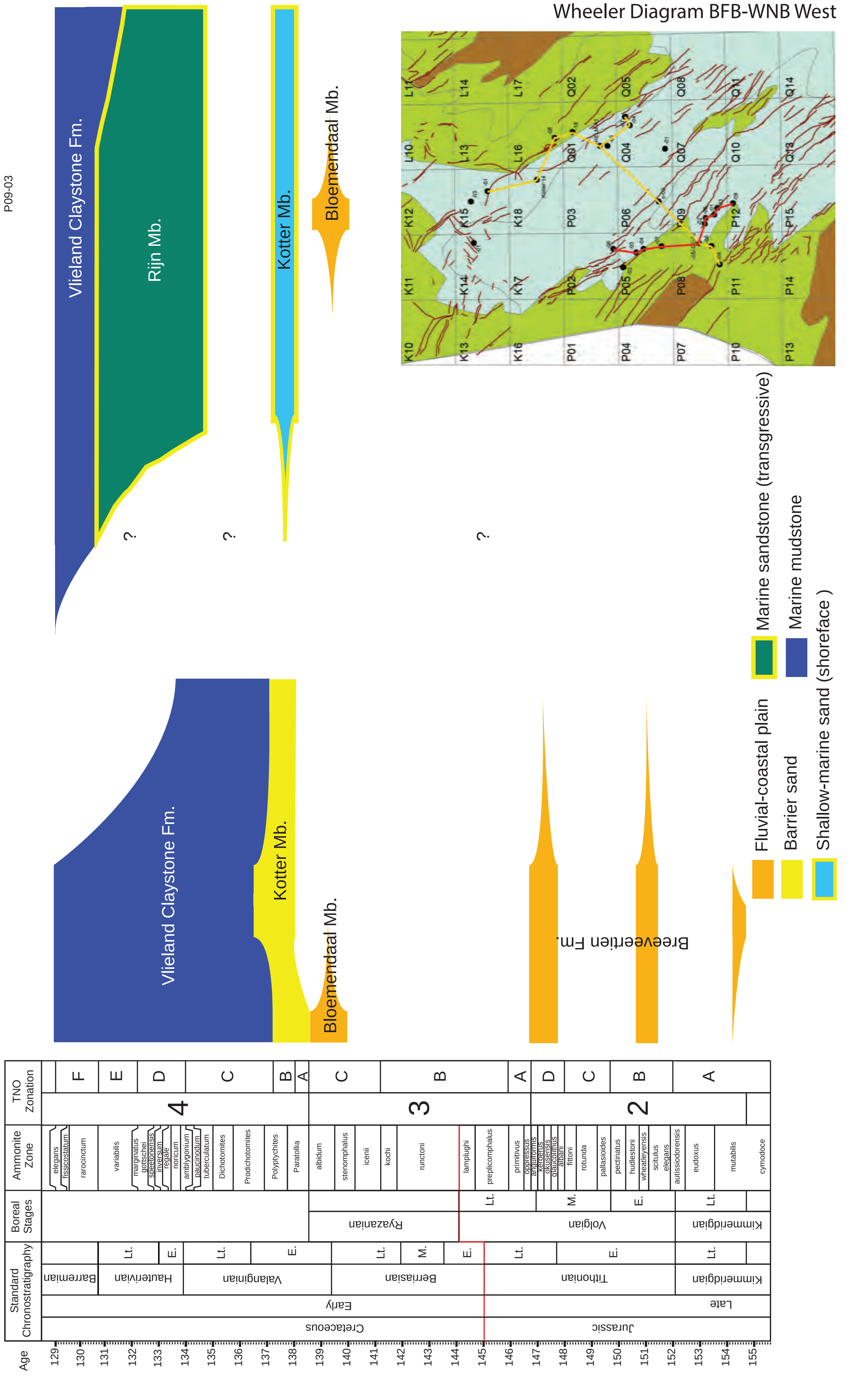

Legend
F03-03
F11-01
F17-04
L03-01
L05-04
L06-03
L16-06
M07-07
P05-03
P08-03
P09-03
L05-03
F15-01-A
δ13C (VPDB)
-20.0
-22.0
-24.0
-26.0
-28.0
-30.0
Age
Standard Chronostratigraphy
Boreal Stages
Ammonite Zone
TNO Zonation
Cretaceous
Jurassic
Early
Late
Middle
Barremian
Hauterivian
Valanginian
Berriasian
Tithonian
Kimmeridgian
Oxfordian
Callovian
Bathonian
Ryazanian
Volgian
Kimmeridgian
elegans
fissicostatum
rarocinctum
variabilis
marginatus
gottschei
speetonensis
inversum
regale
noricum
amblygonium
paucinodum
tuberculatum
Dichotomites
Prodichotomites
Polyptychites
Paratollia
albidum
stenomphalus
icenii
kochi
runctoni
lamplughi
preplicomphalus
primitivus
oppressus
anguiformis
kerberus
okusensis
glaucolithus
albani
fittoni
rotunda
pallasioides
pectinatus
hudlestoni
wheatleyensis
scitulus
elegans
autissiodorensis
eudoxus
mutabilis
cymodoce
baylei
pseudocordata
cautisnigrae
pumilus
plicatilis
cordatum
mariae
lamberti
athleta
coronatum
jason
calloviense
koenigi
herveyi
discus
orbis
hodsoni
morrisi
subcontractus
progracilis
zigzag
1
2
3
4

Wheeler diagram Step Graben North

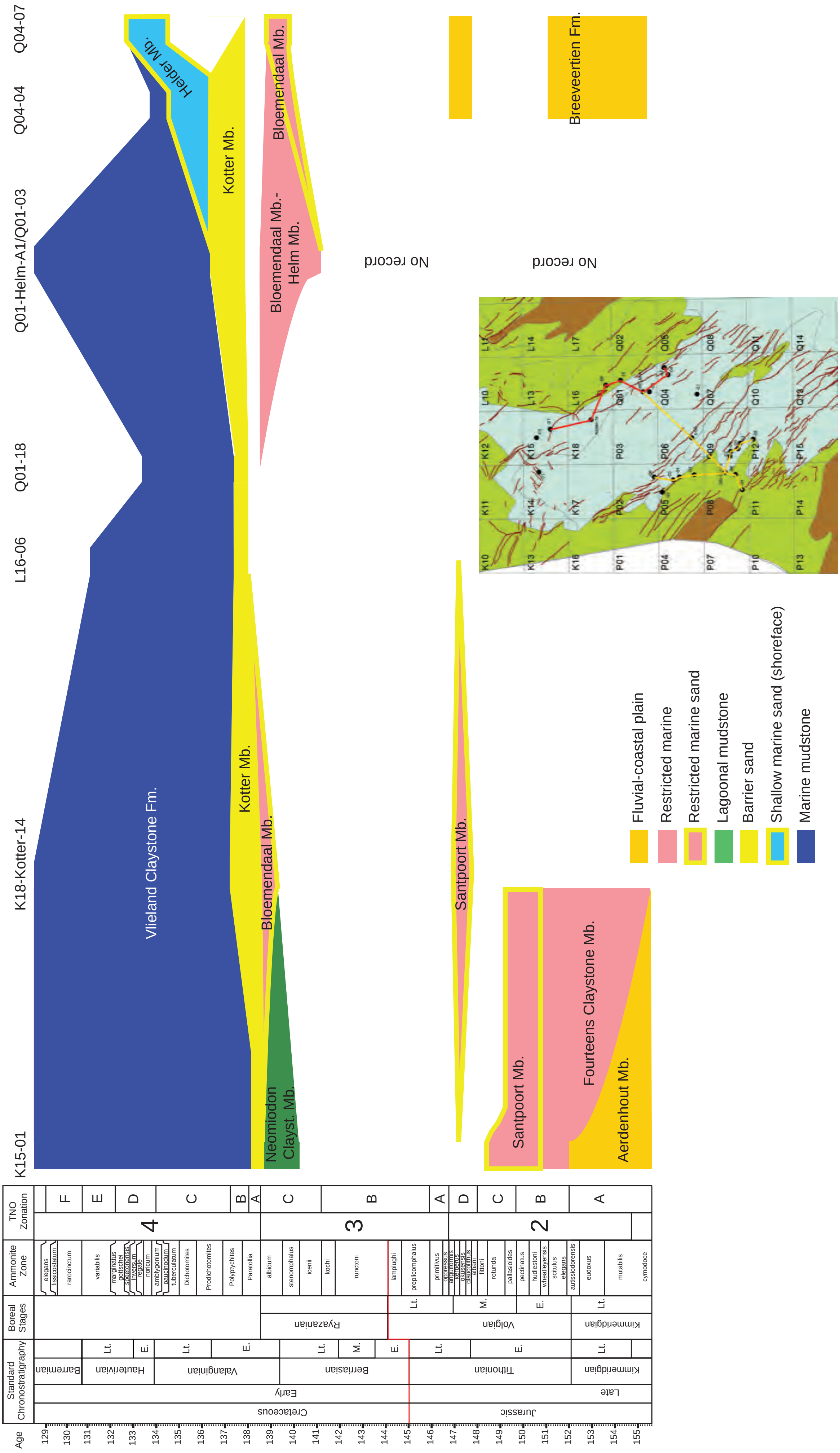



A14
A18
F01
F04
Vlieland Claystone Fm.
Vlieland
Clay Deep Mb.
Scruff Greensand Fm.
Lies Mb.
Noordvaarder Mb.
Shallow marine sands
Shallow marine clays
(organic-rich) open marine clay
Open marine clay
Step Graben
ESH
DCG
TB
Age
Standard Chronostratigraphy
Boreal Stages
Ammonite Zone
TNO Zonation
Depositional Sequences
Cretaceous
Jurassic
Early
Late
Middle
Valanginian
Berriasian
Tithonian
Kimmeridgian
Oxfordian
Callovian
Bathonian
Ryazanian
Volgian
Adjacent Plateaus
Peripheral Basins
Graben Axis

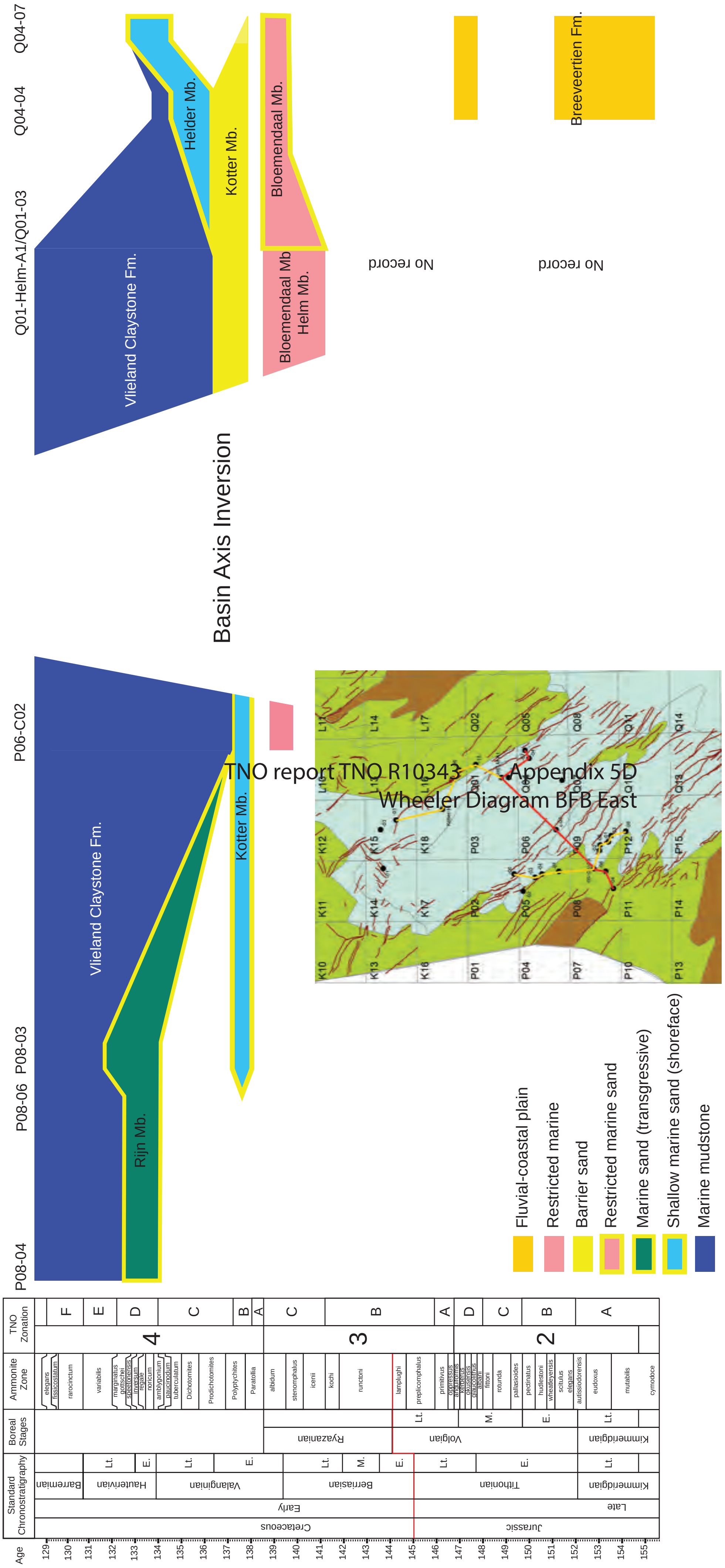
Wheeler Diagram BFB-WNB West



Wheeler Diagram BFB East



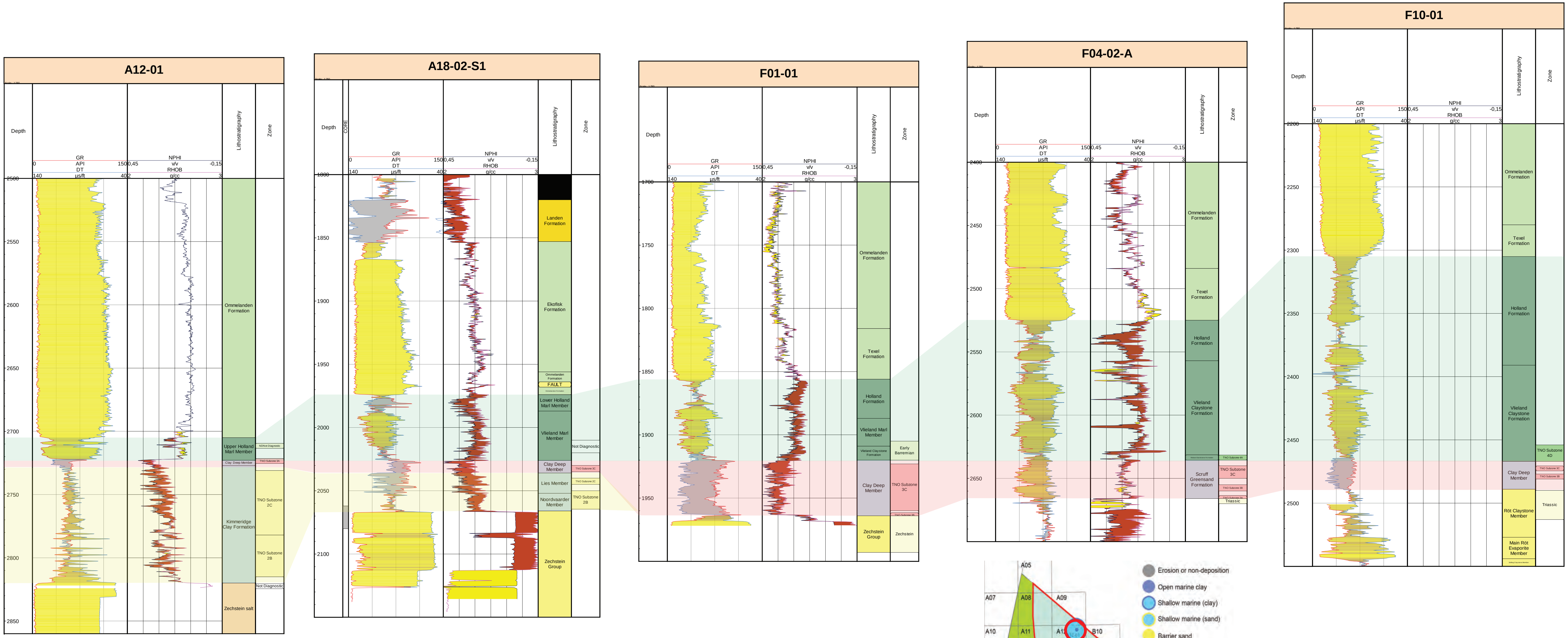
TNO report TNO R10343
Appendix 5E
Wheeler Diagram
BFB-WNB cross section

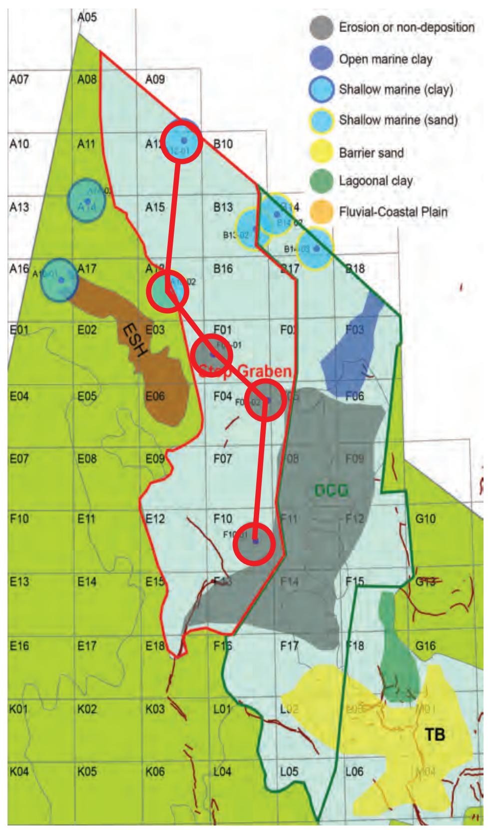


Correlation panel A12-01 - F10-01

North

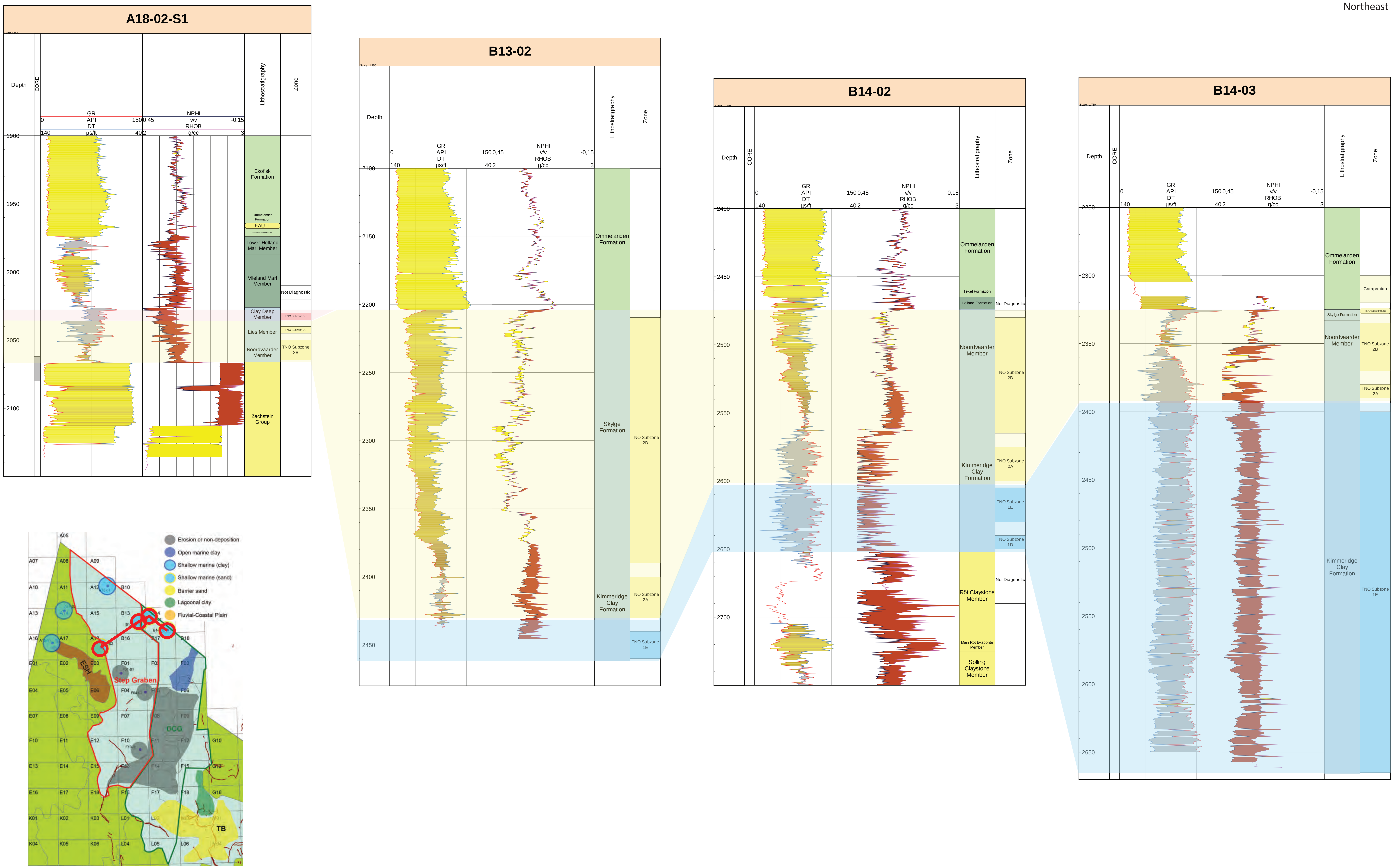
South



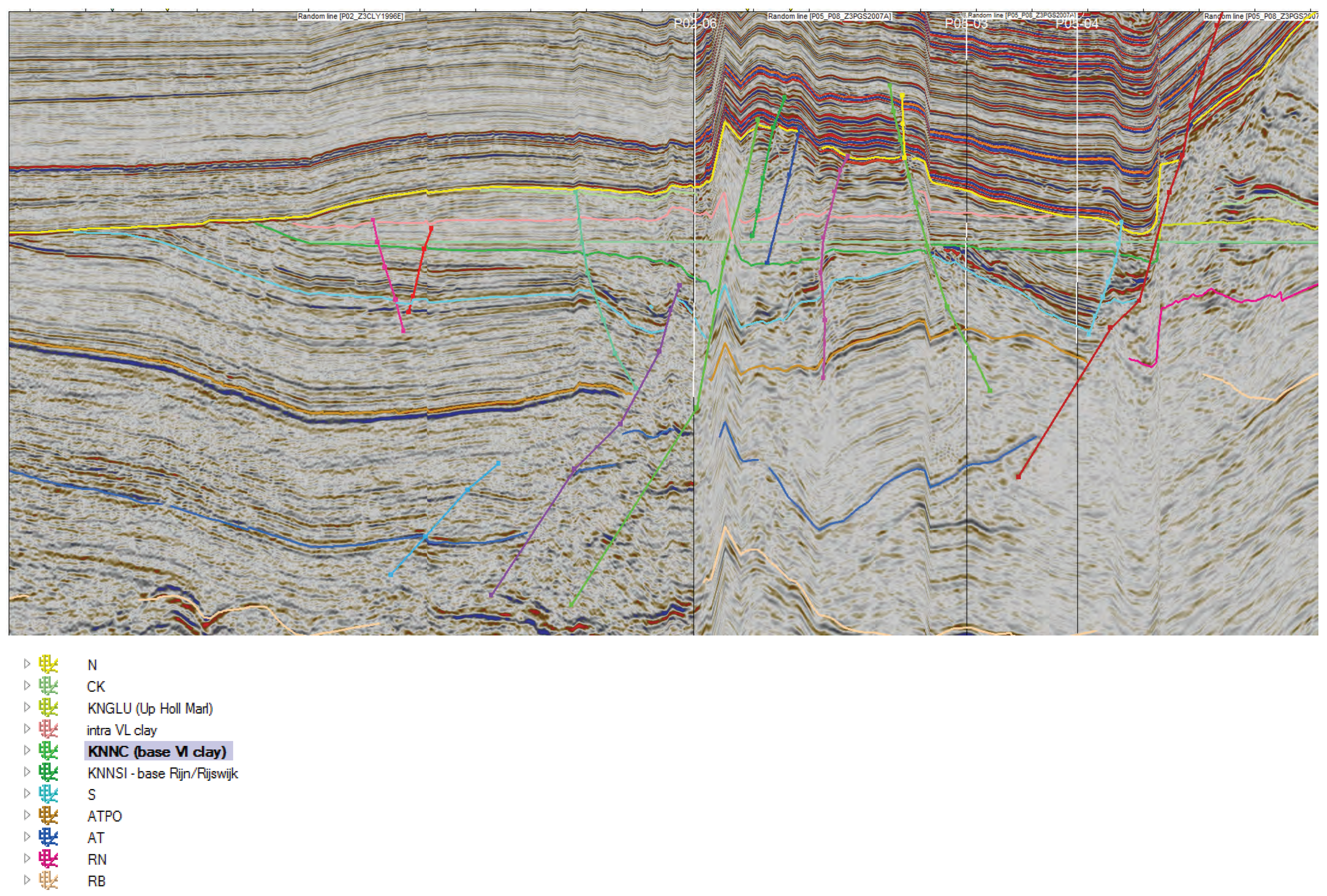


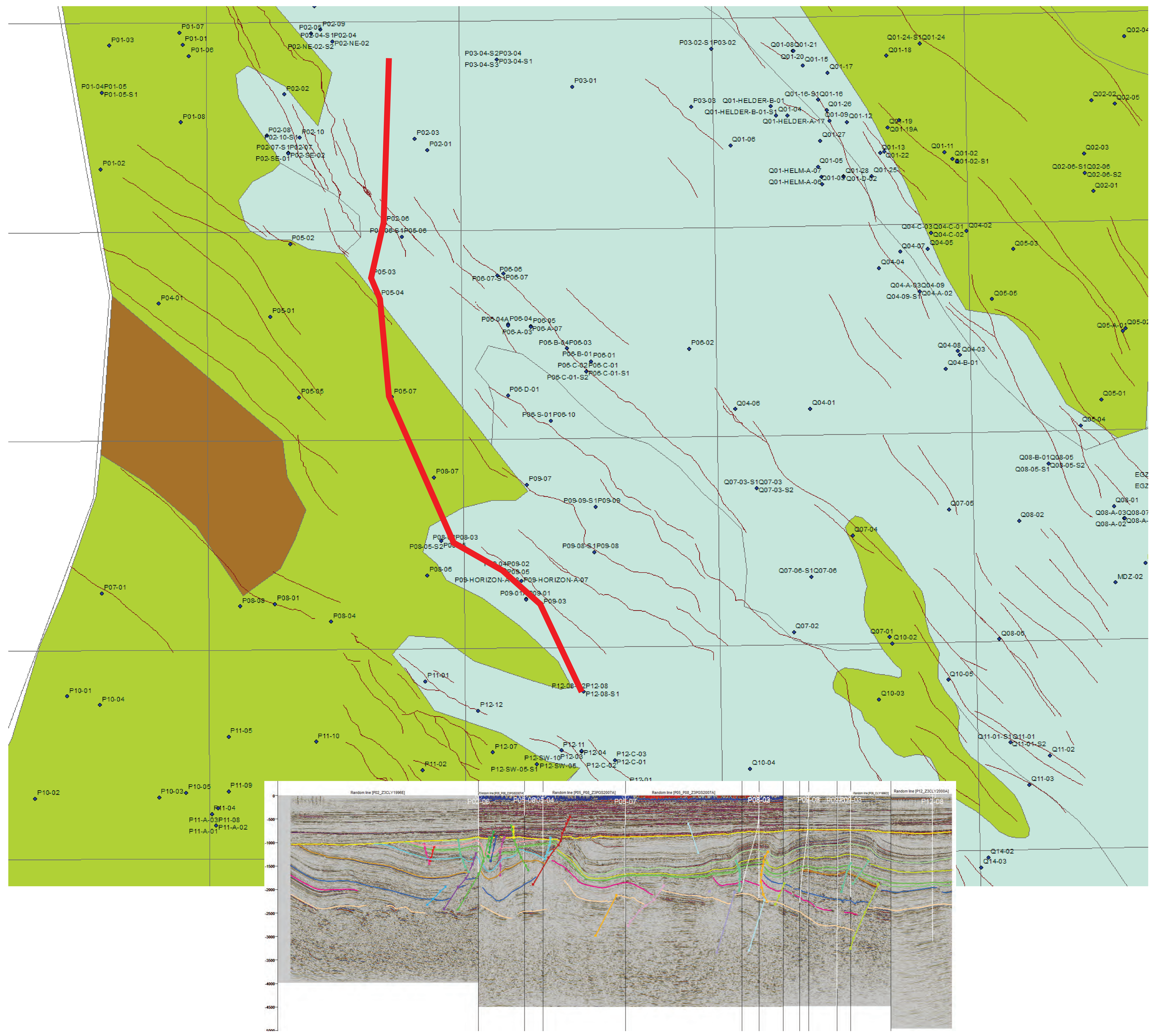
Southwest

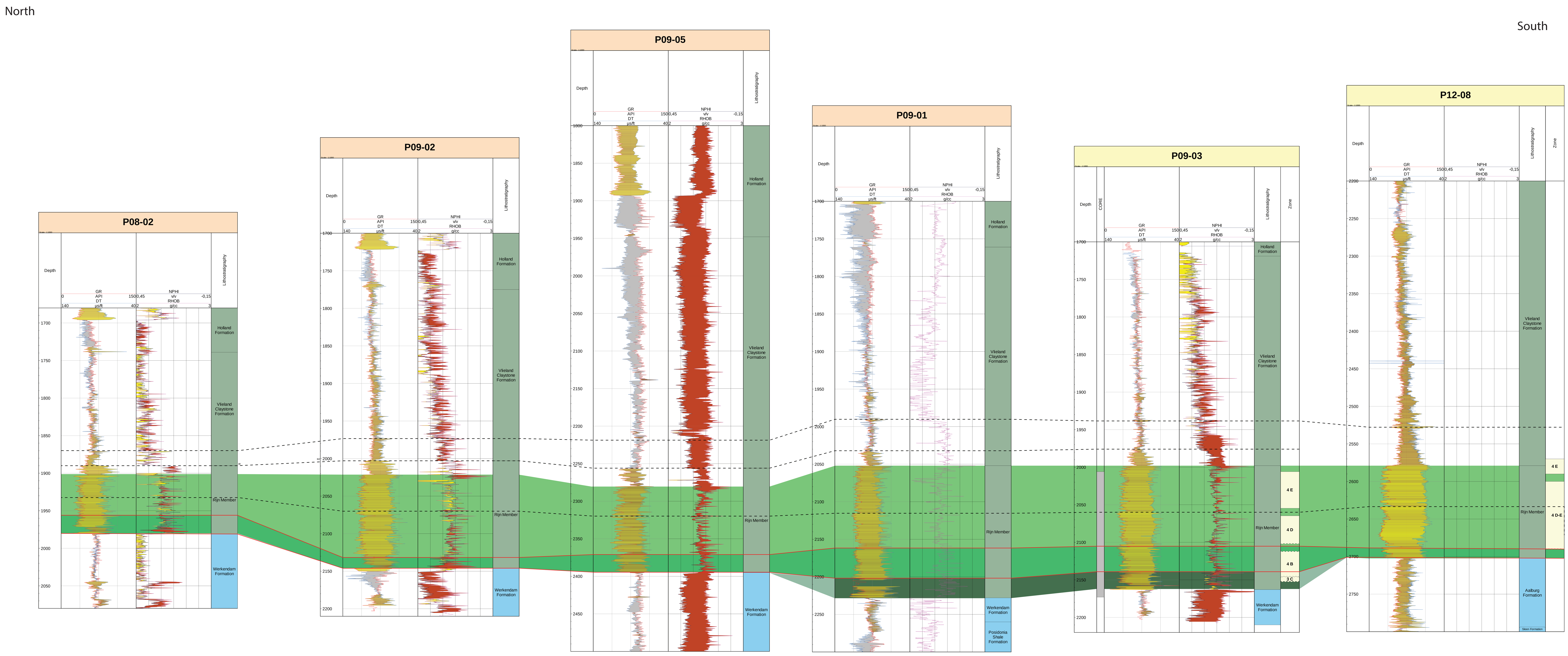
Northeast

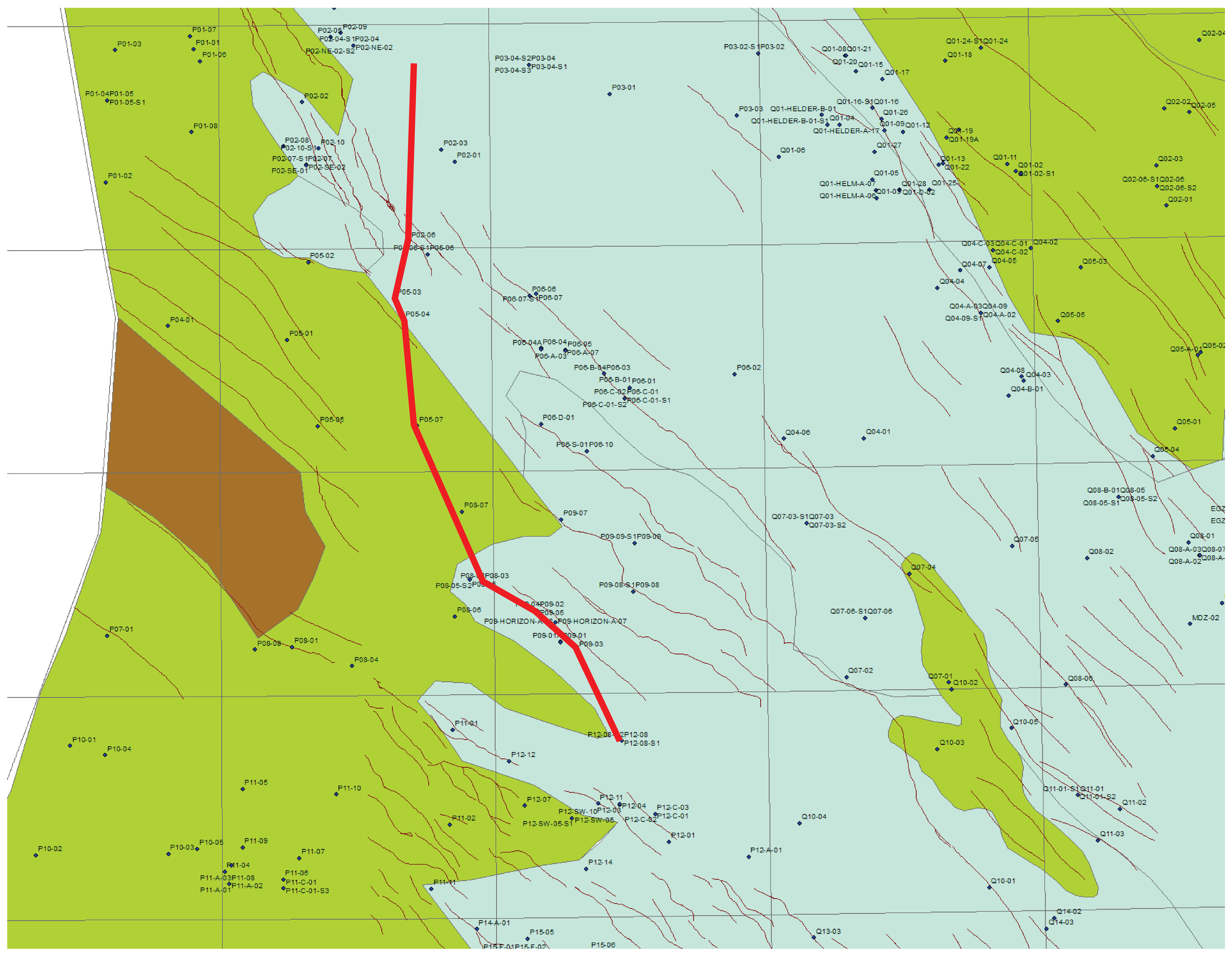


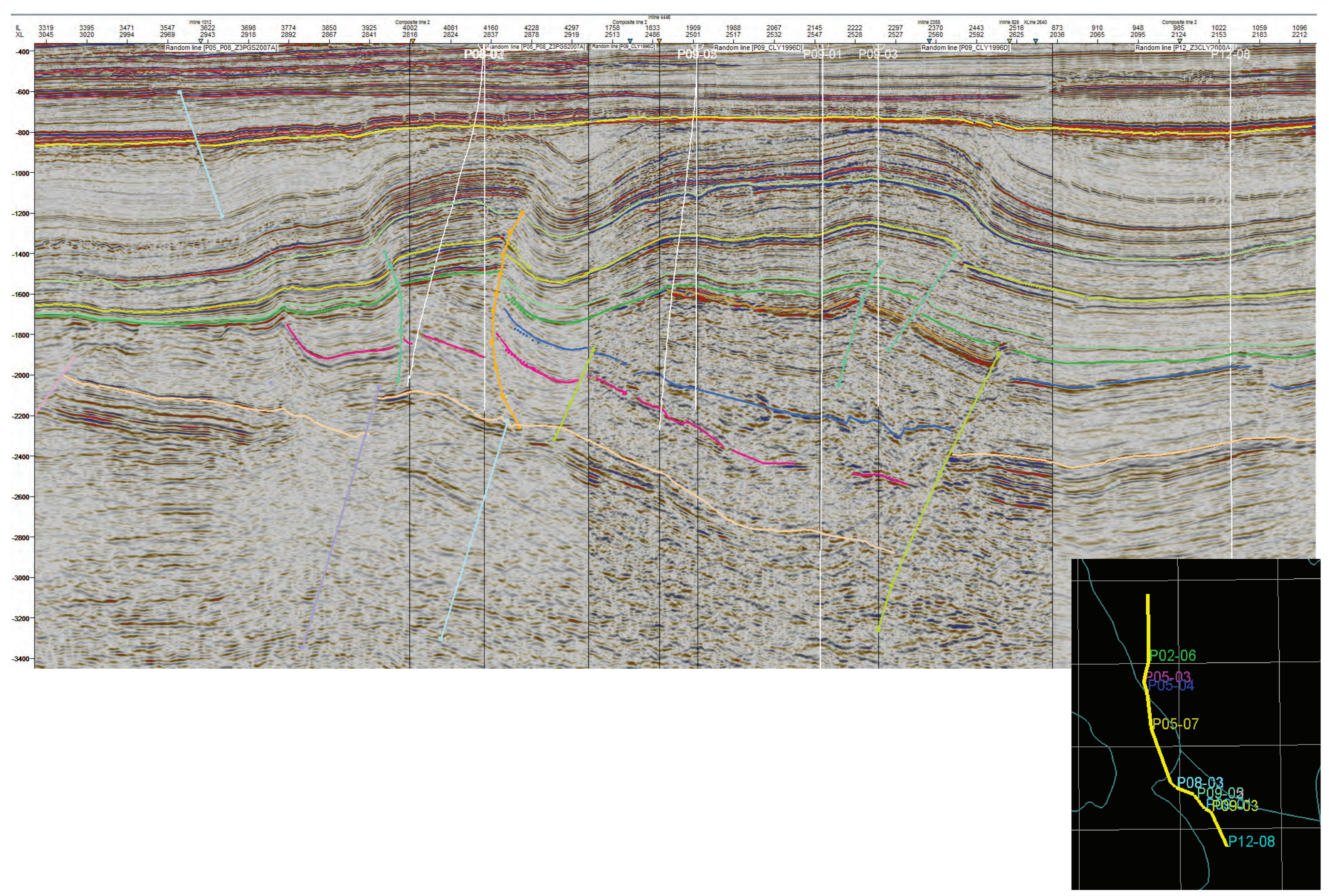

North
South
P02-06
P05-03
P05-04
P05-07
P08-03
P08-02
Depth
Vlieland Claystone Formation
Rijn Member
Nieuwerkerk Formation
Werkendam Formation
Brabant Formation
Holland Formation
Aalburg Formation
Keuper Formation
Muschelkalk Formation
Posidonia Shale Formation
Landen Formation
North Sea Super Group

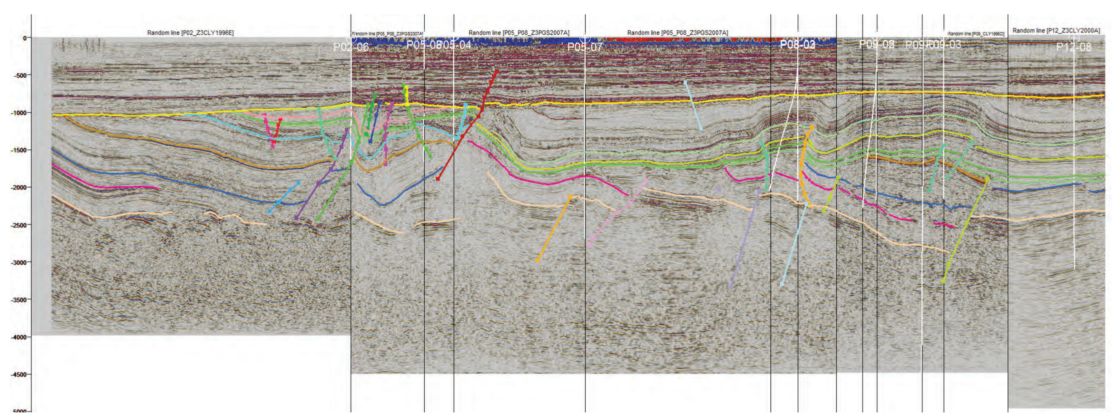

N
CK
KNGLU (Up Holl Marl)
intra VL clay
KNNC (base Vl clay)
KNNSI - base Rijn/Rijswijk
S
ATPO
AT
RN
RB



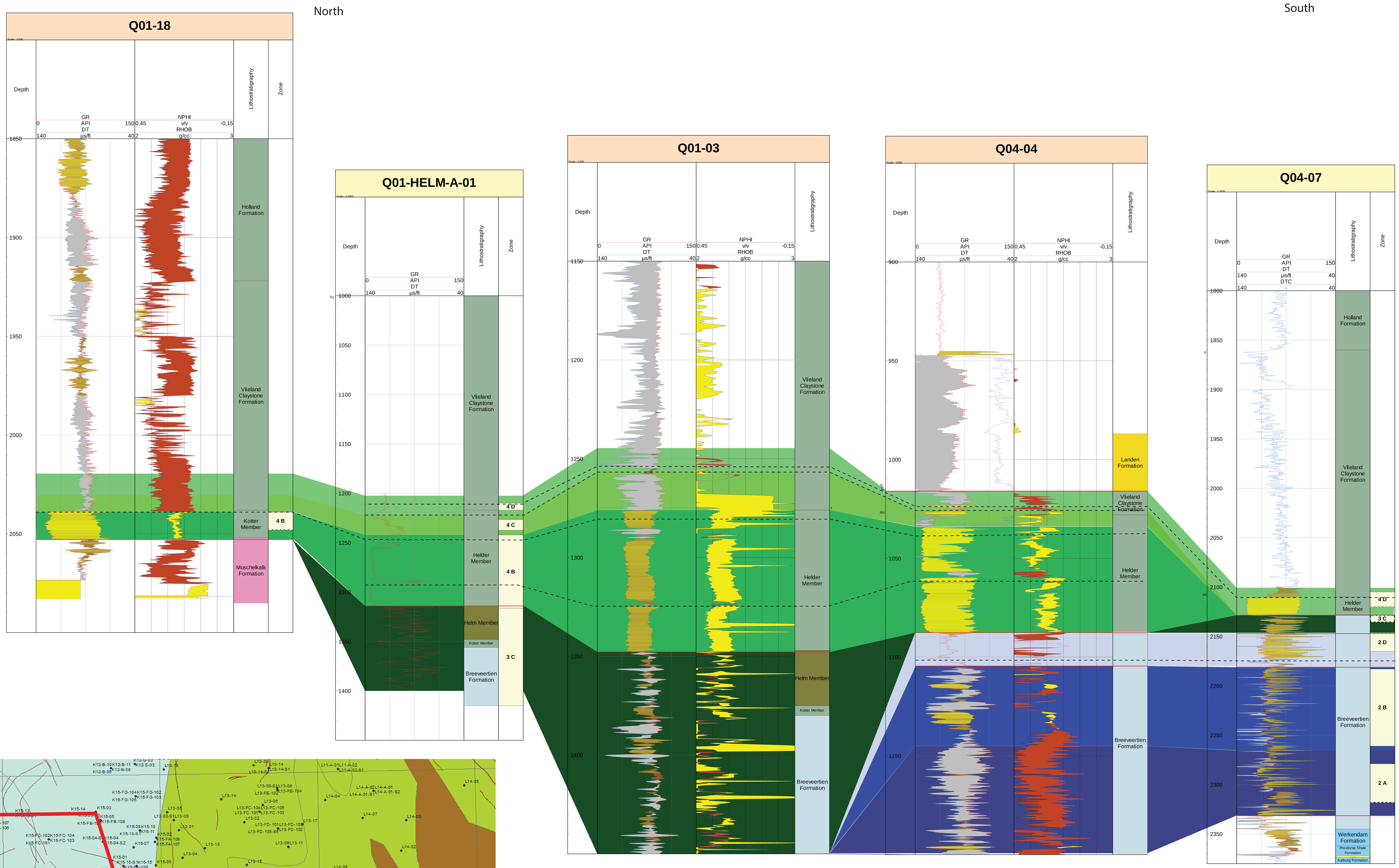

North
South
P08-02
P09-02
P09-05
P09-01
P09-03
P12-08
Depth
GR
API
DT
µs/ft
NPHI
v/v
RHOB
g/cc
Lithostratigraphy
Zone
CORE
Holland Formation
Vlieland Claystone Formation
Rijn Member
Werkendam Formation
Posidonia Shale Formation
Aalburg Formation
4 E
4 D
4 B
3 C
4 D-E

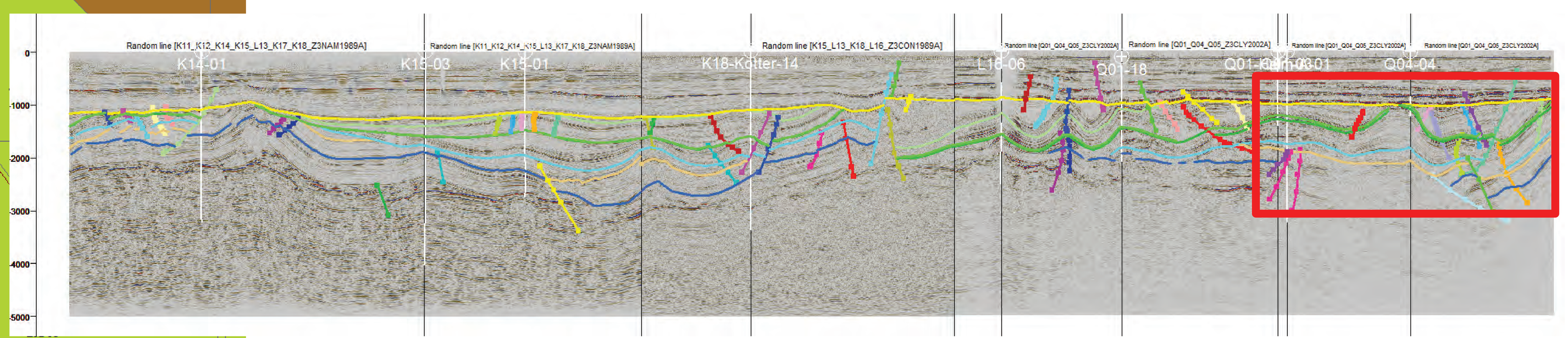


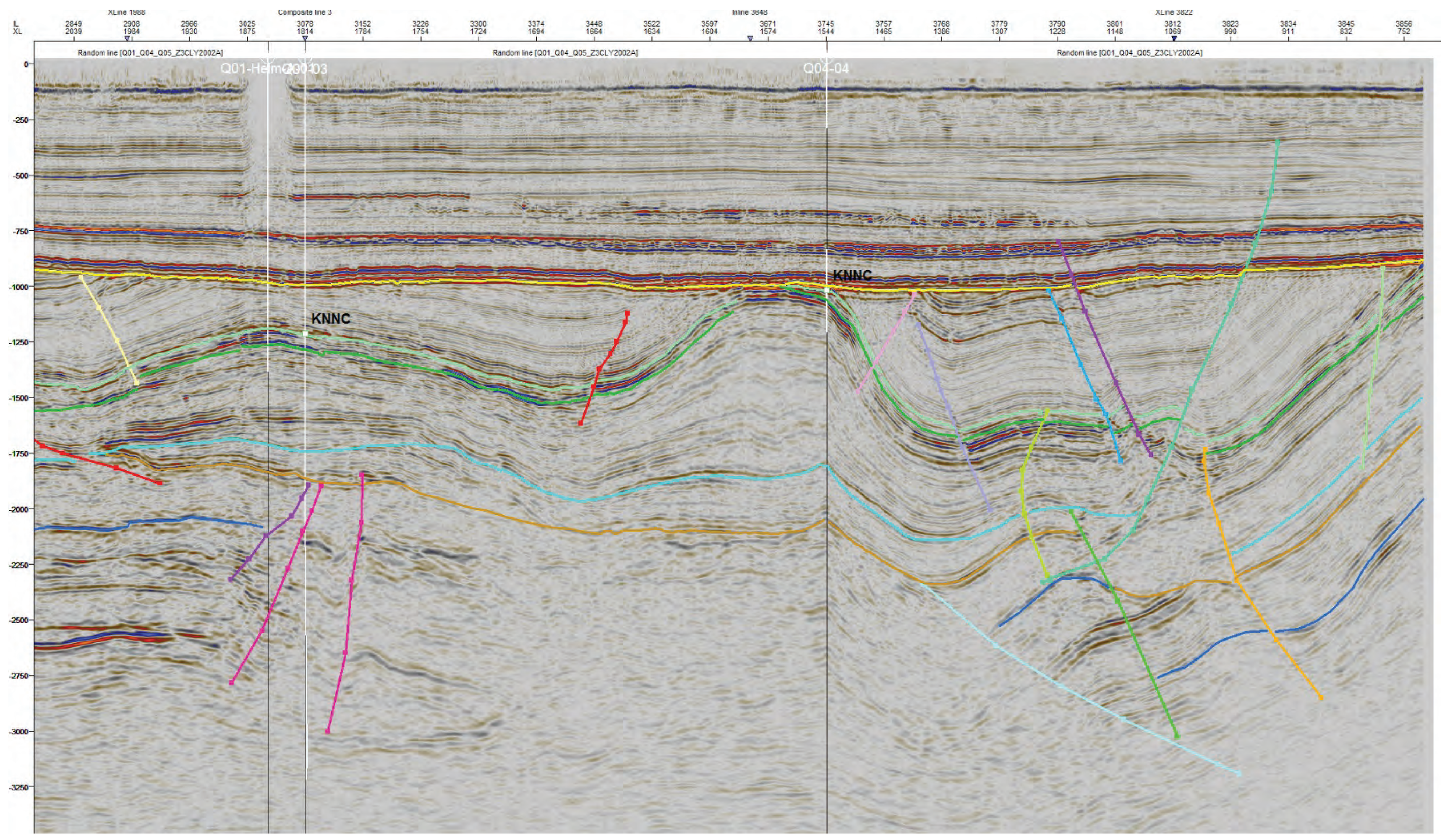





North
South
K14-01
K15-03
K15-01
K18-KOTTER-14
L16-06
Q01-18
Depth
CORE
GR
API
DT
µs/ft
NPHI
v/v
RHOB
g/cc
GRC
DTC
Lithostratigraphy
Zone
Holland Formation
Vlieland Claystone Formation
Kotter Member
Breeveertien Formation
Lower Werkendam
Aalburg Formation
Muschelkalk Formation
4 B
4 A - 3 C
3 C
4 A
2 C
2 B
2 A
2 D

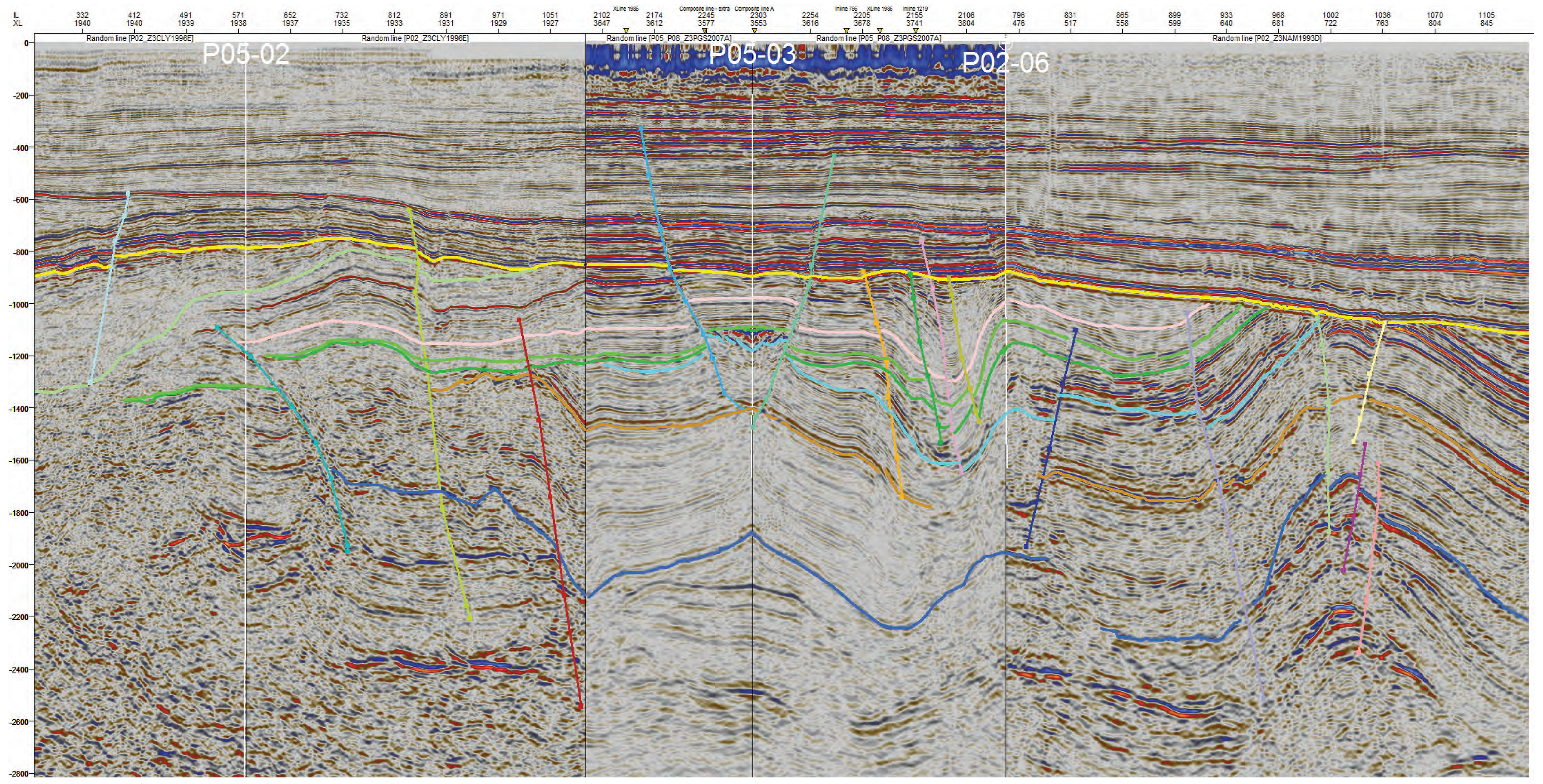

North
South
Q01-18
Q01-HELM-A-01
Q01-03
Q04-04
Q04-07
Depth
GR
API
DT
NPHI
RHOB
Lithostratigraphy
Zone
Holland Formation
Vlieland Claystone Formation
Kotter Member
Muschelkalk Formation
Helder Member
Helm Member
Breeverteen Formation
Landen Formation
Werkendam Formation
4 D
4 C
4 B
3 C
2 D
2 B
2 A

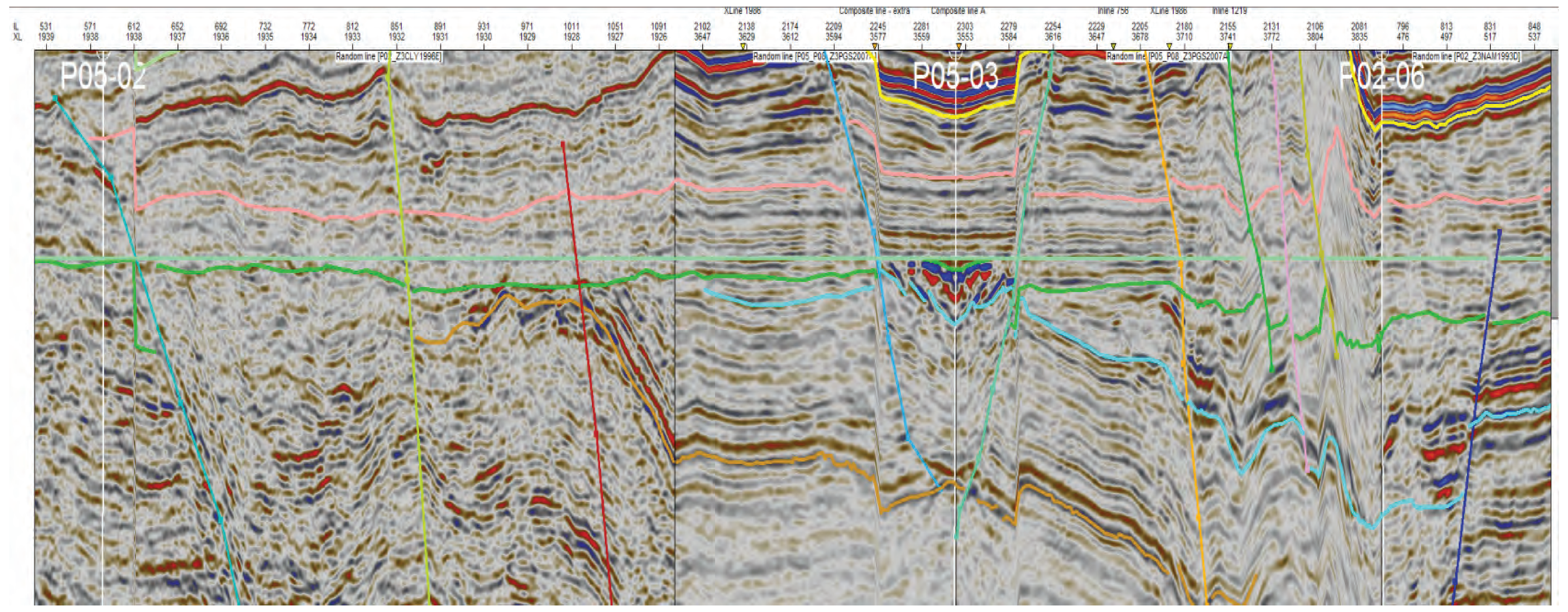


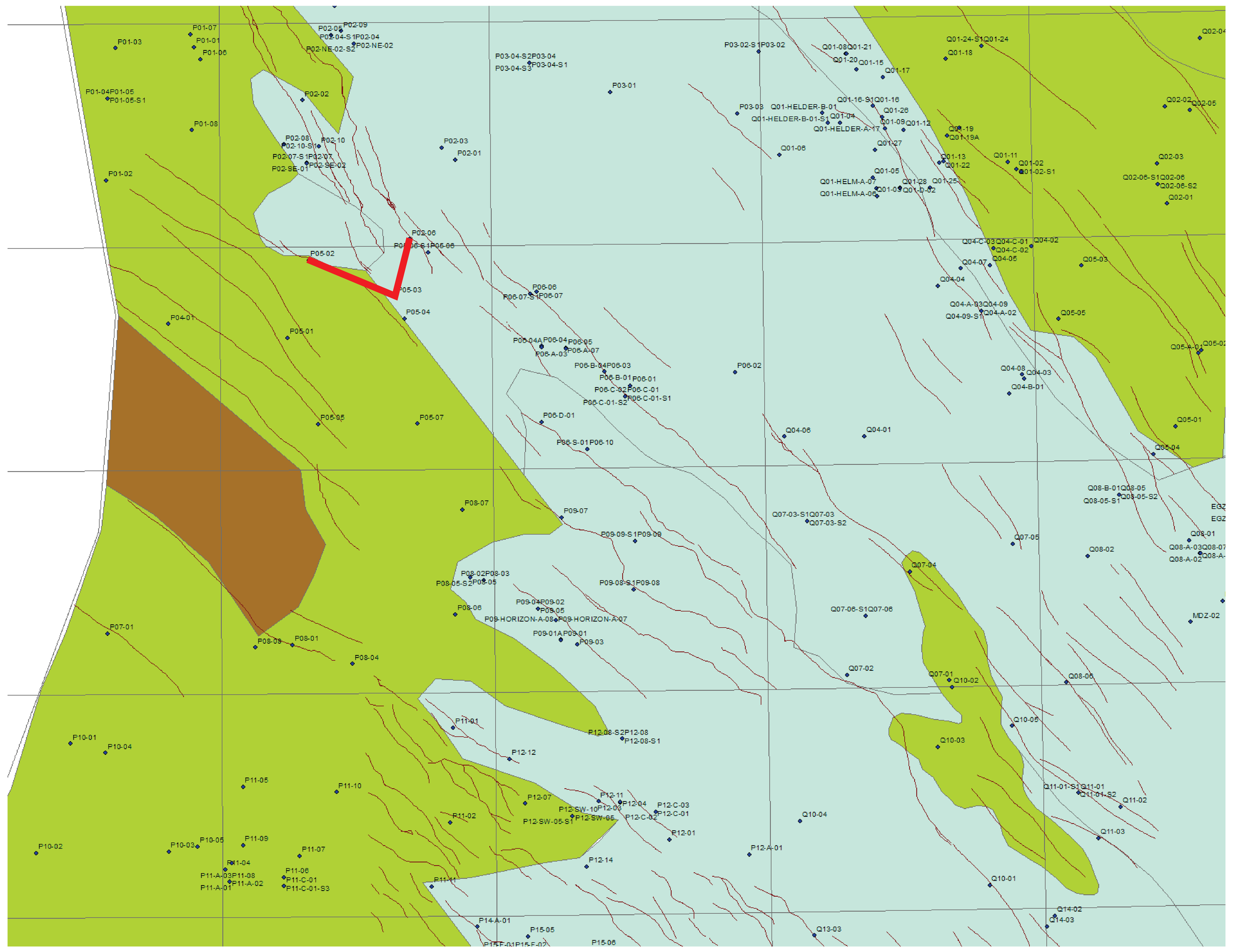

KNNC

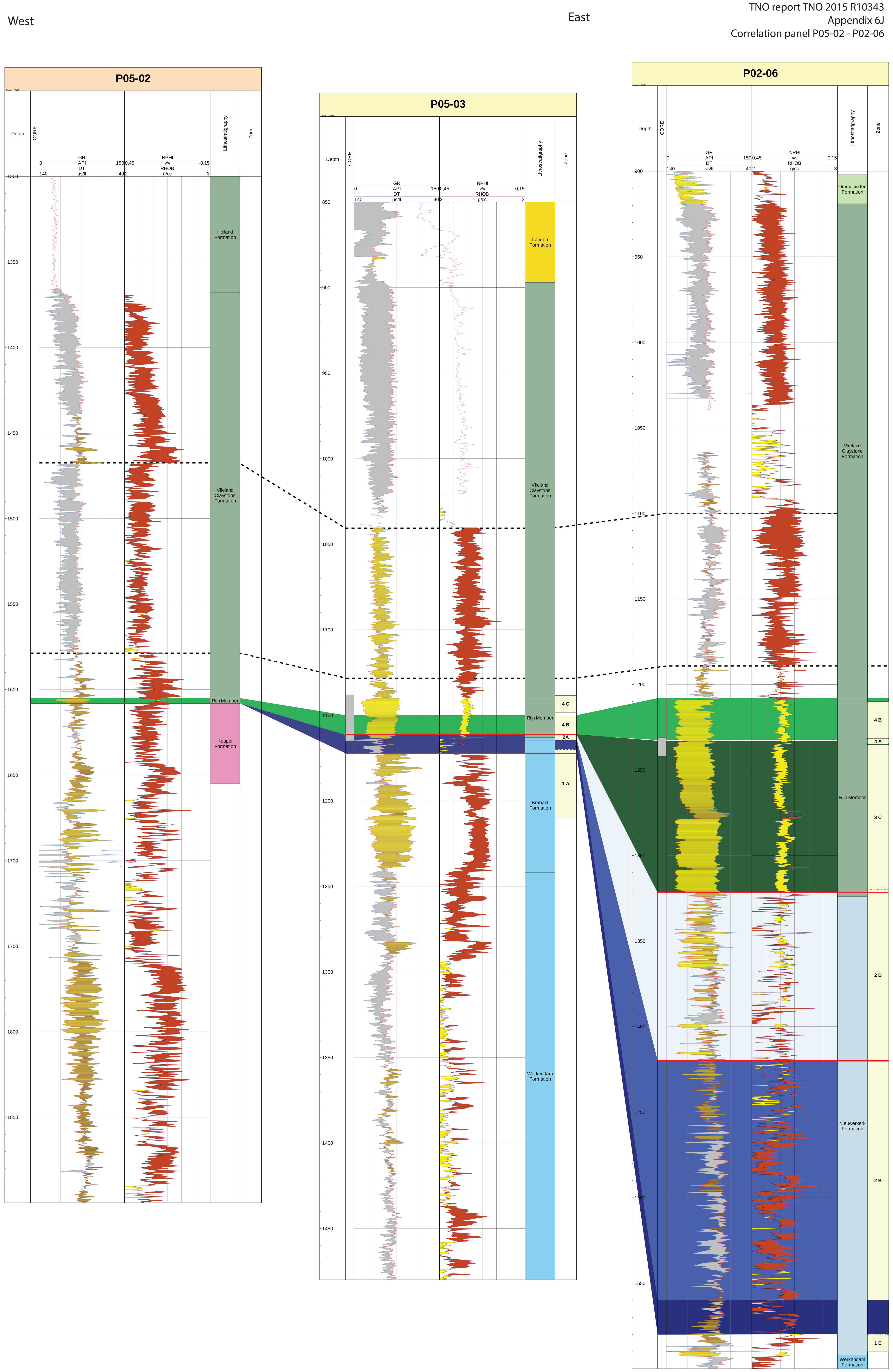

West
East
P08-04
P08-06
P08-05-S1
P08-05-S2
P08-02
Depth
Lithostratigraphy
Zone
GR
API
DT
NPHI
RHOB
Holland Formation
Vlieland Claystone Formation
Rijn Member
Hardegsen Formation
Aalburg Formation
Werkendam Formation
4D-E
4B


West
East
P08-02
P06-C-02
Q01-03
Q01-HELM-A-01
L16-06
Depth
Lithostratigraphy
Zone
CORE
GR
API
DT
NPHI
RHOB
CGR
Holland Formation
Vlieland Claystone Formation
Rijn Member
Werkendam Formation
Nieuwerkerk Formation
Helder Member
Helm Member
Kotter Member
Breeevertien Formation
Aalburg Formation
4 D
4 C
4 B
3 C
South


P05-02
P05-03
P02-06


P05-02
P05-03
P02-06




West
East
P05-02
P05-03
P02-06
Depth
CORE
GR
API
DT
NPHI
RHOB
Lithostratigraphy
Zone
Holland Formation
Vlieland Claystone Formation
Rijn Member
Keuper Formation
Landen Formation
Brabant Formation
Werkendam Formation
Ommelanden Formation
Nieuwerkerk Formation
4 C
4 B
4 A
2 A
1 A
3 C
2 D
2 B
1 E